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

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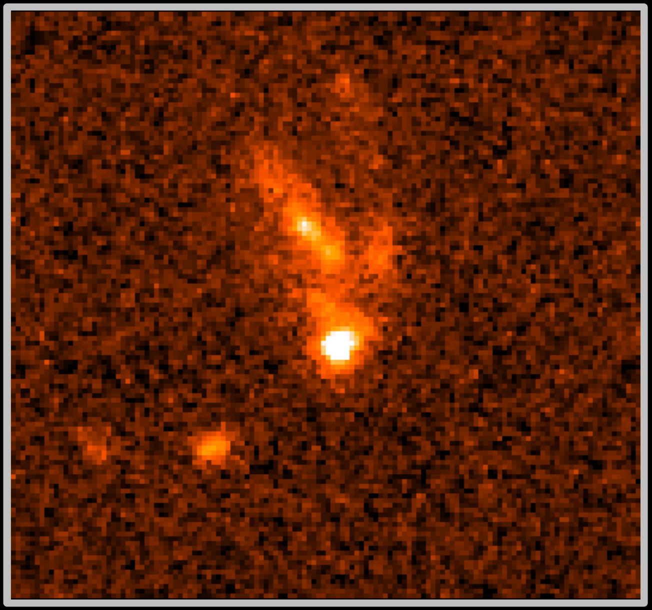
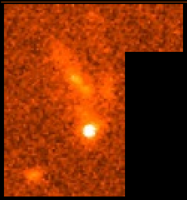
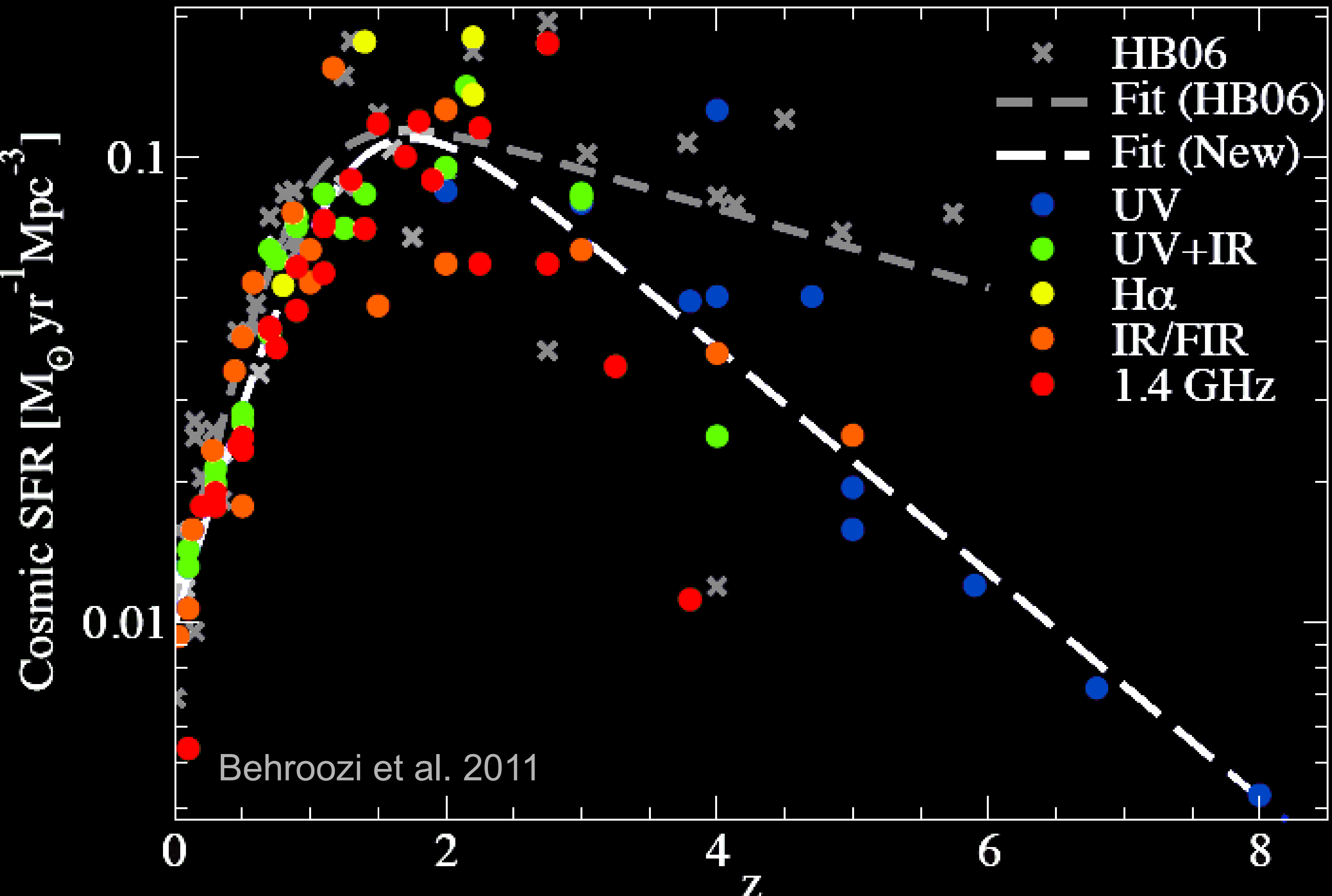
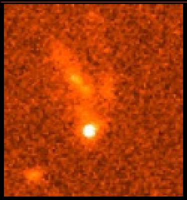


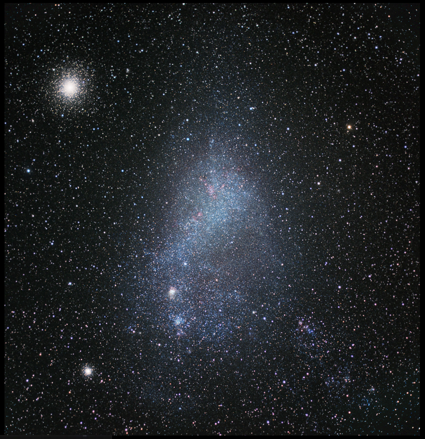
Cosmic Star-Formation History

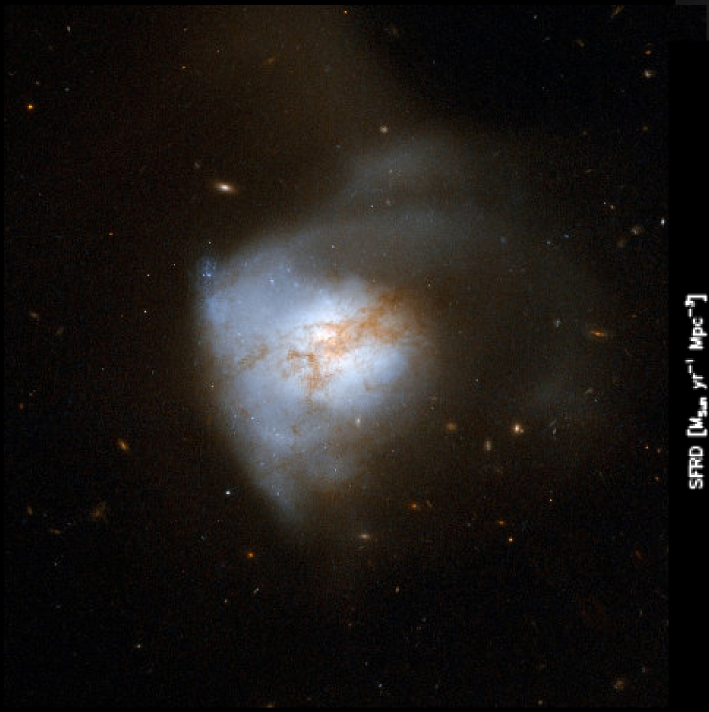


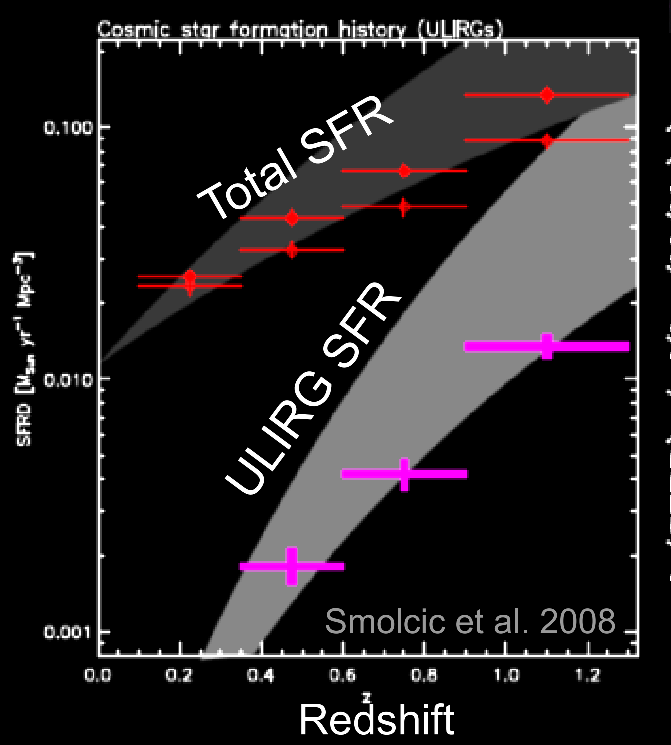


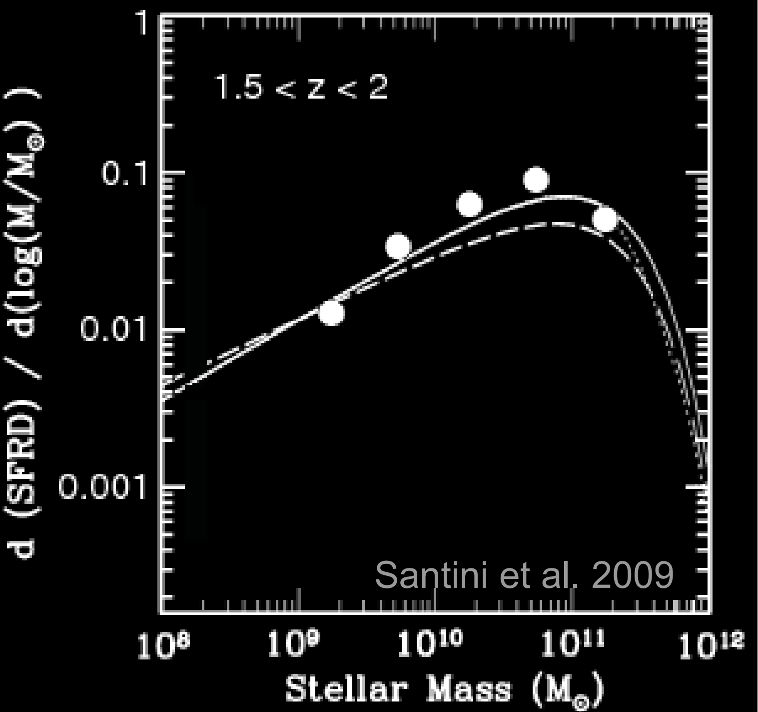
Cosmic Star-Formation Sites



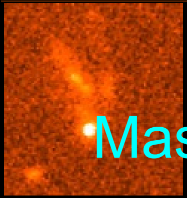








Star Formation Tracers



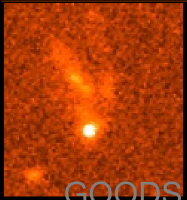
Massive stars signal recent/ongoing star formation.

Ultraviolet emission:

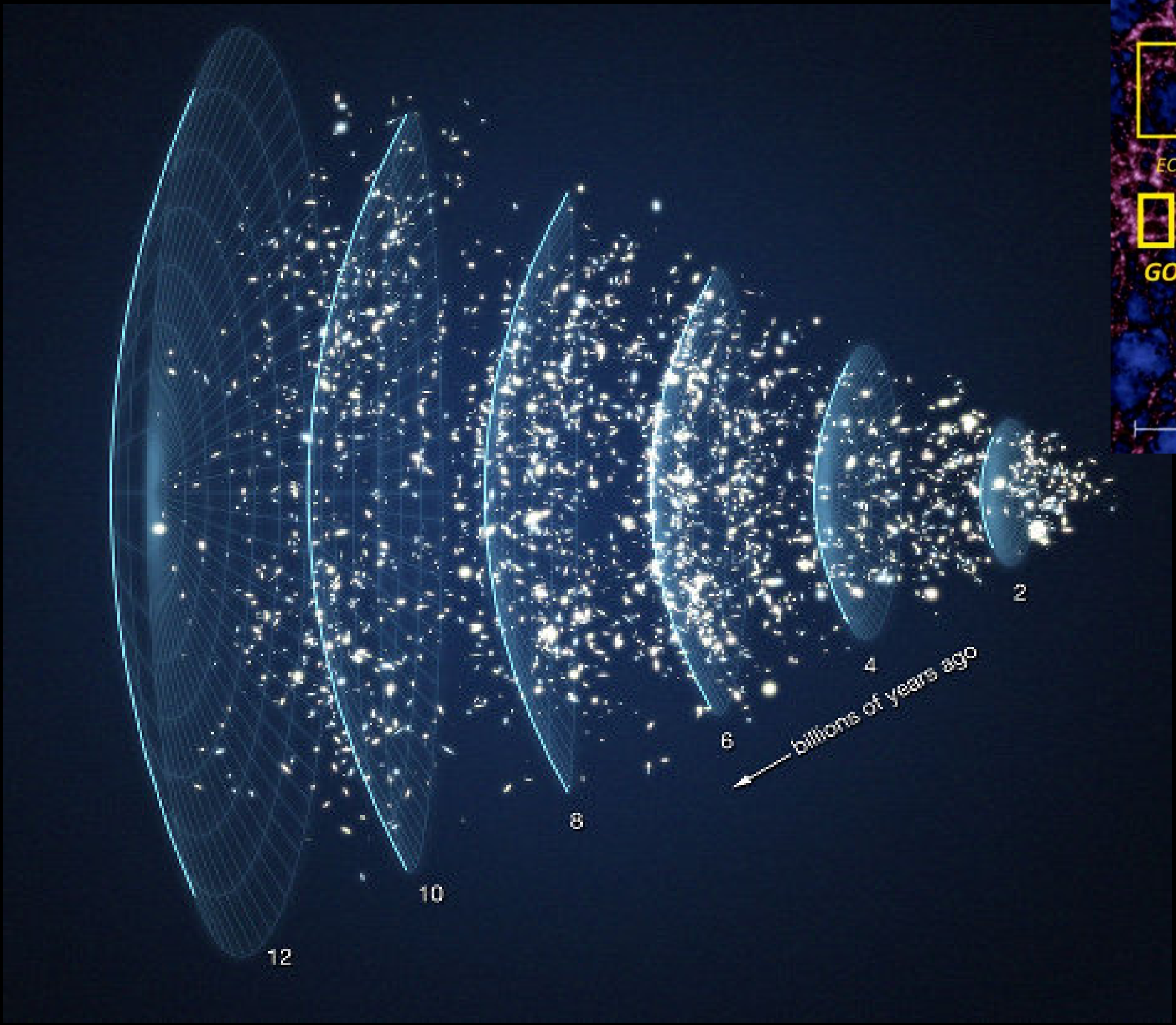
(+reprocessed analogs: nebular lines, PAH lines, FIR)
the star-formation indicator of choice.

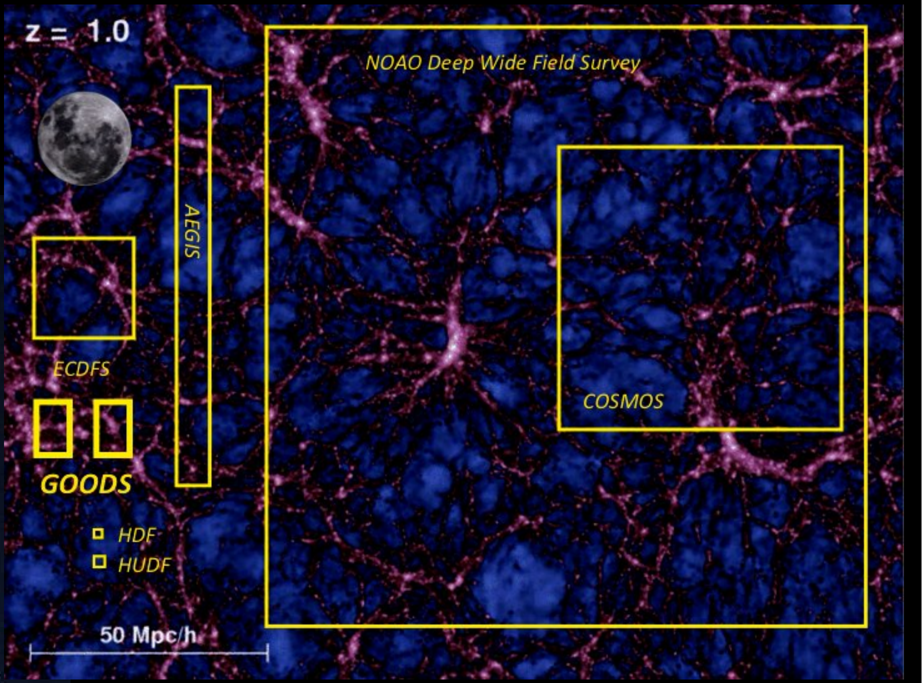
Some alternatives:
- X-rays (from high-mass X-ray binaries)
- radio free-free (electrons in nebulae)
- radio synchrotron (from supernova remnants)
- differential of NIR luminosity (stellar mass buildup)

Field-Survey Strategy



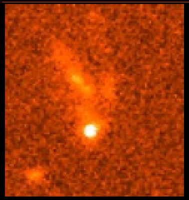
GOODS visualization from ESO.org

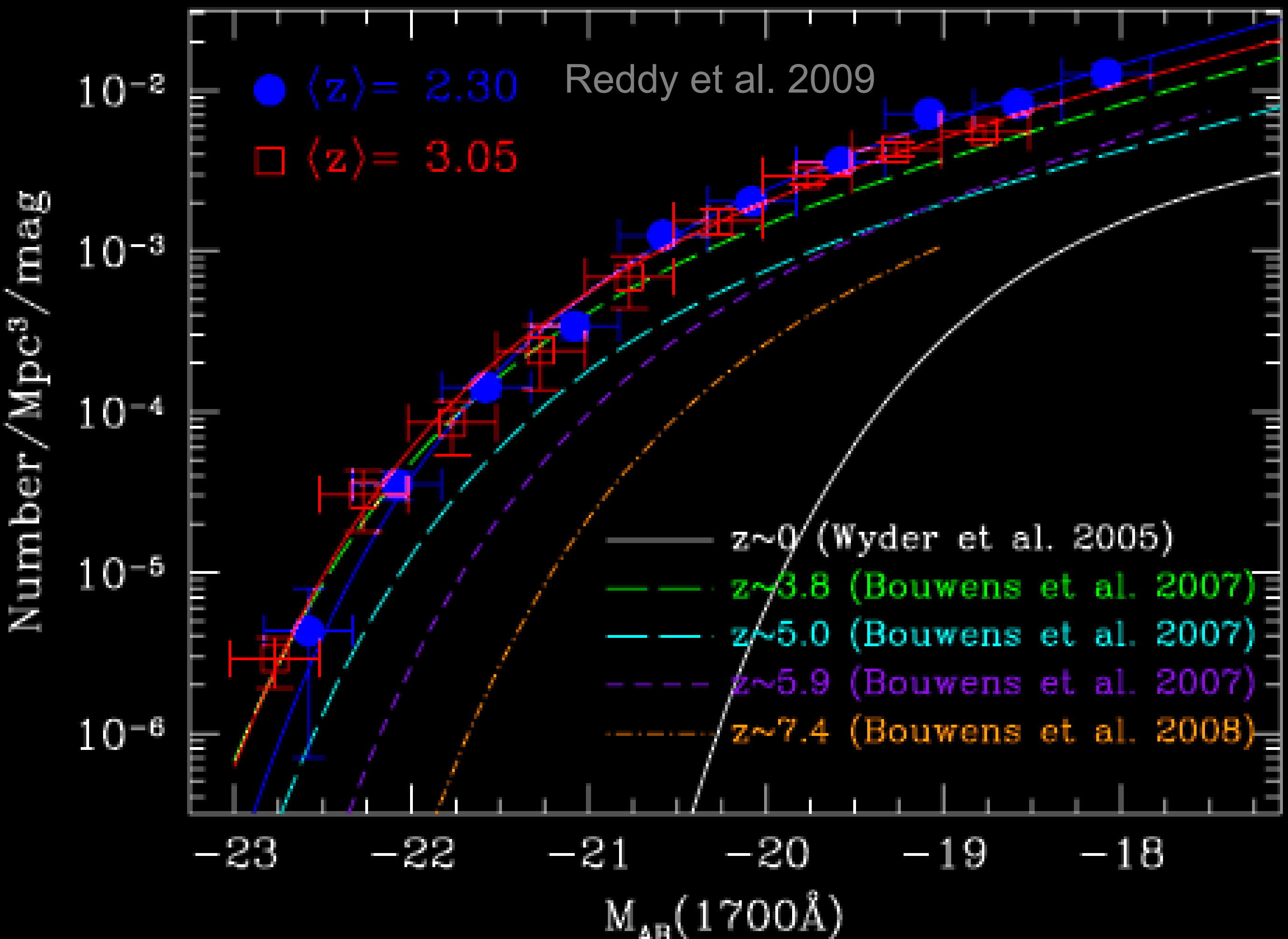




from CANDELS blog

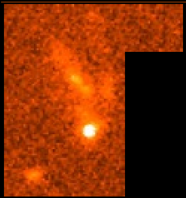
Field-Survey Strategy

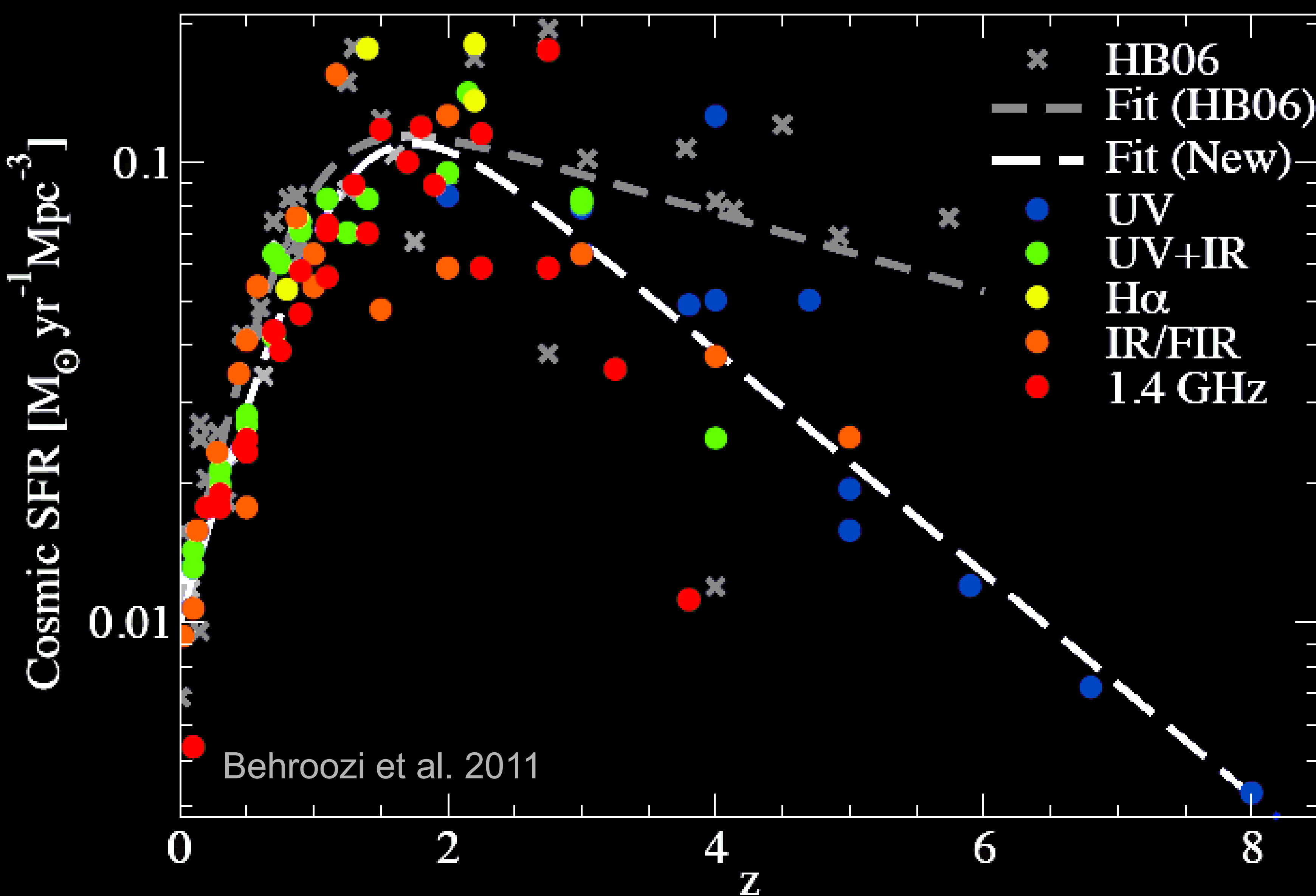




← Ultraviolet Luminosity

Cosmic Star-Formation History





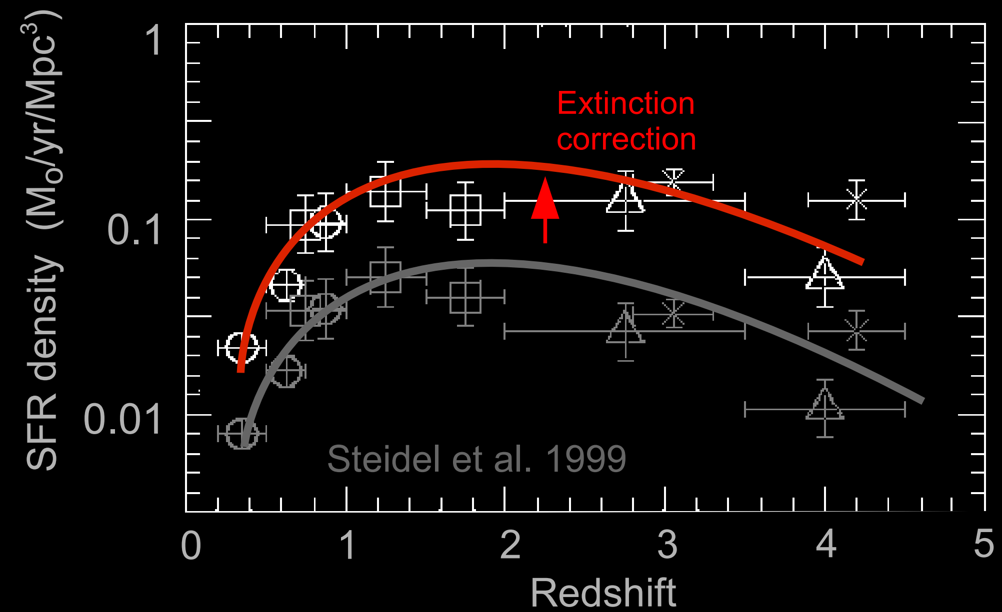
Limitations of Field Surveys

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.)

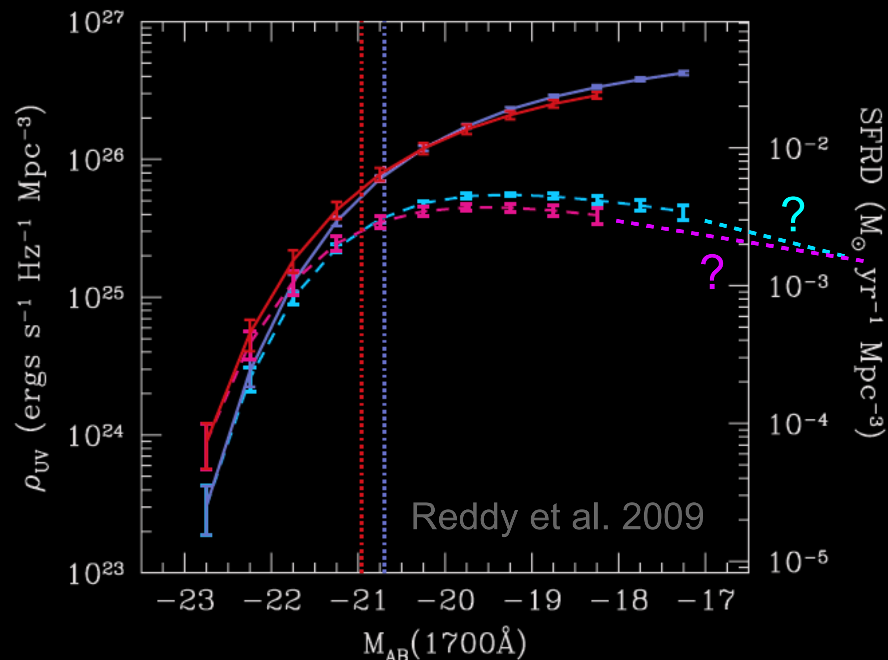
UV energy can be “recovered”
at 8μm / FIR / submm,
but these wavelengths have poor
sensitivity to faint galaxies



Missing galaxies

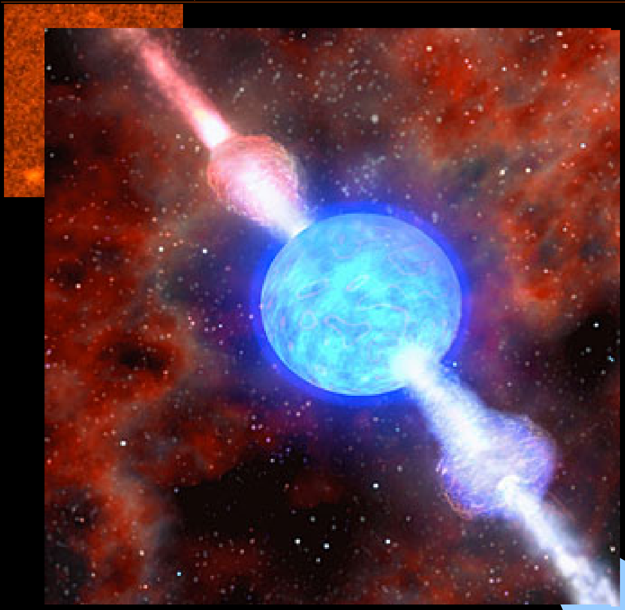
Faint galaxies (<0.1 L*) require
extrapolation from bright end

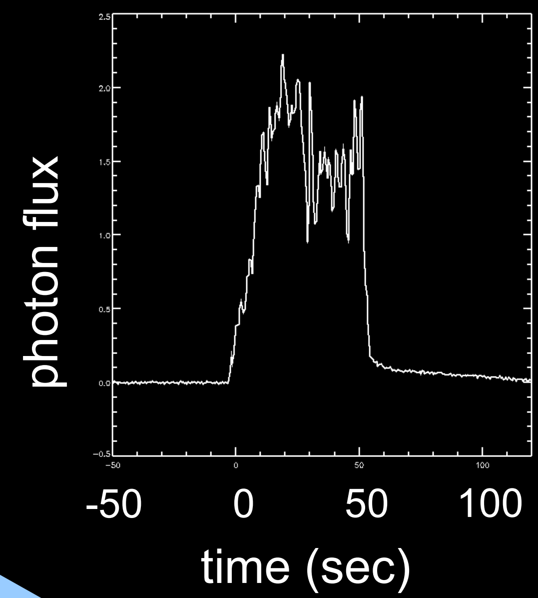
Redshift measurement imposes
further biases

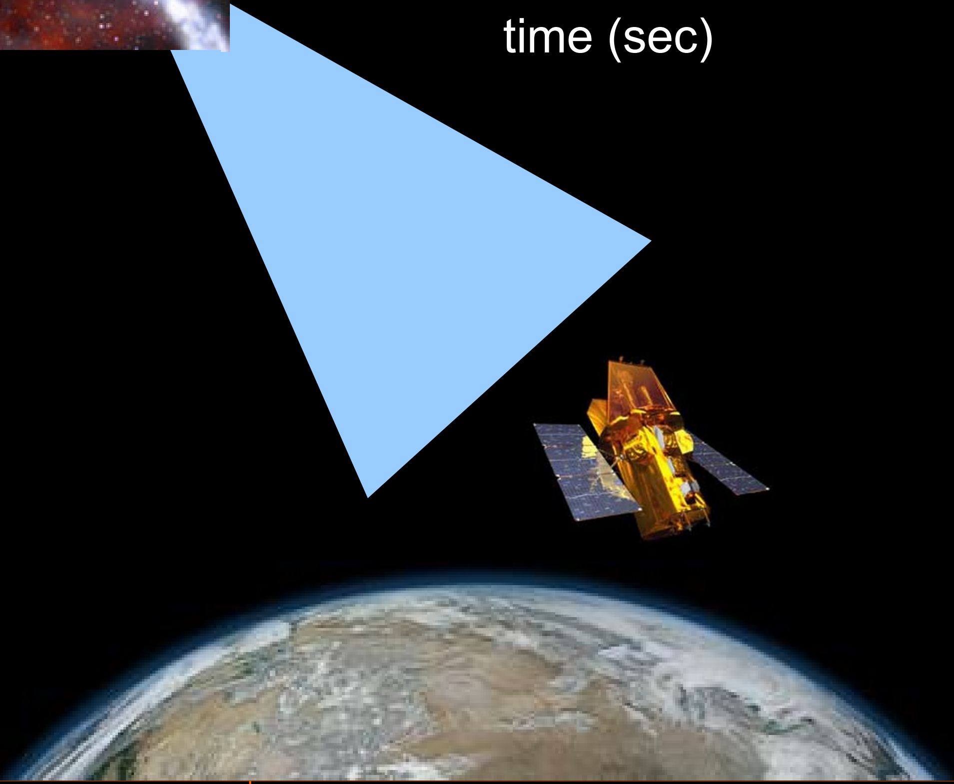


These problems are particularly limiting at z>3

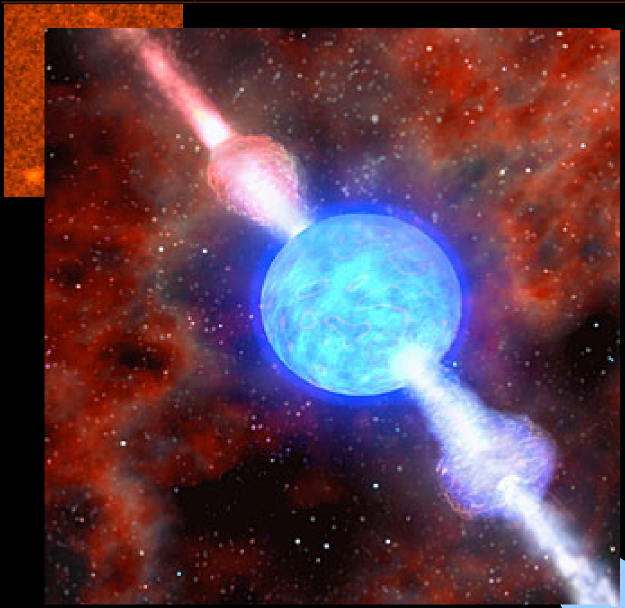
(Long-duration) Gamma-Ray Bursts

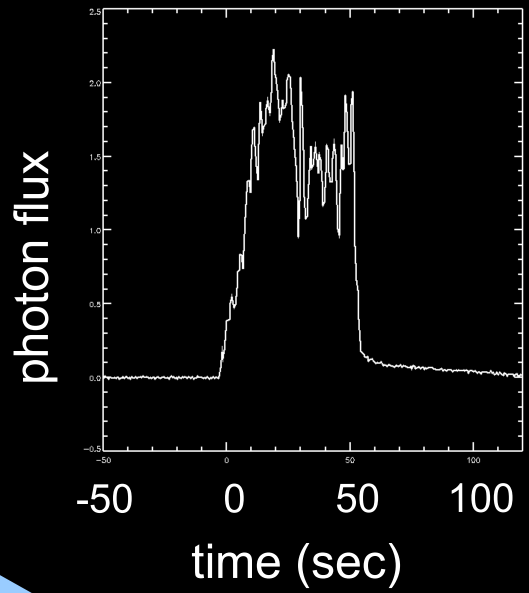


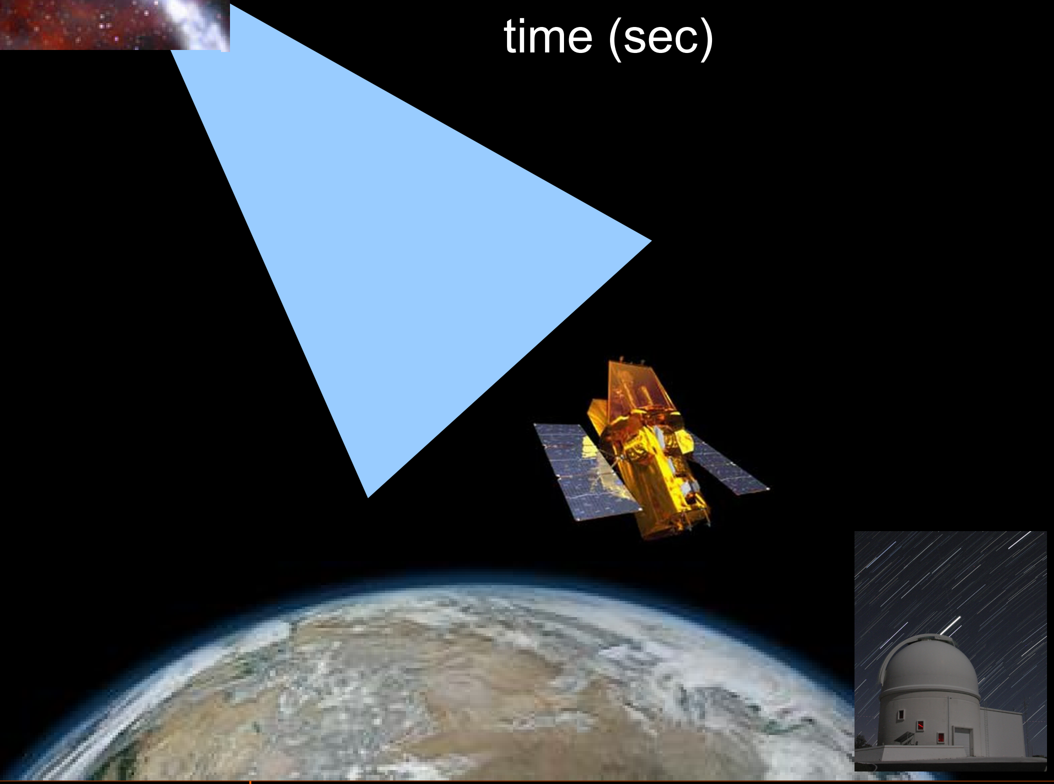




Gamma-Ray Bursts







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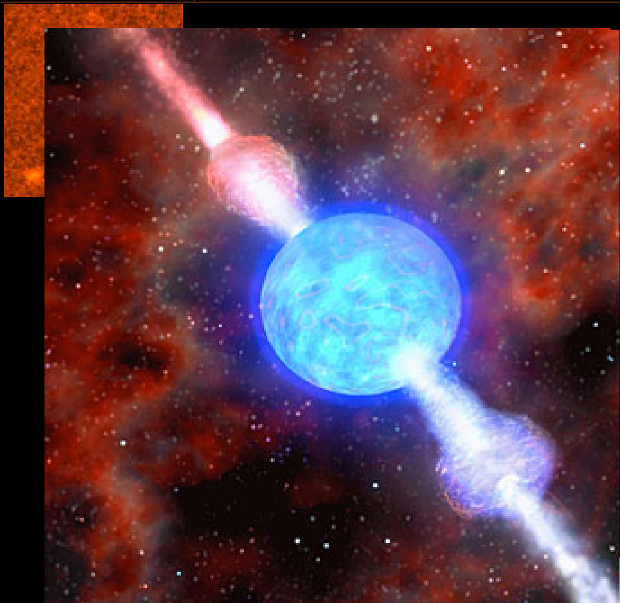
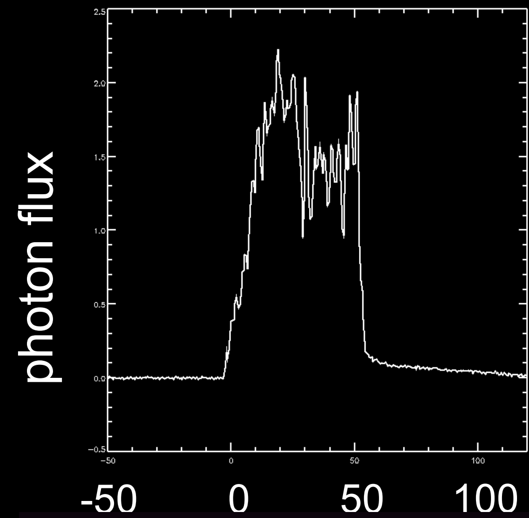
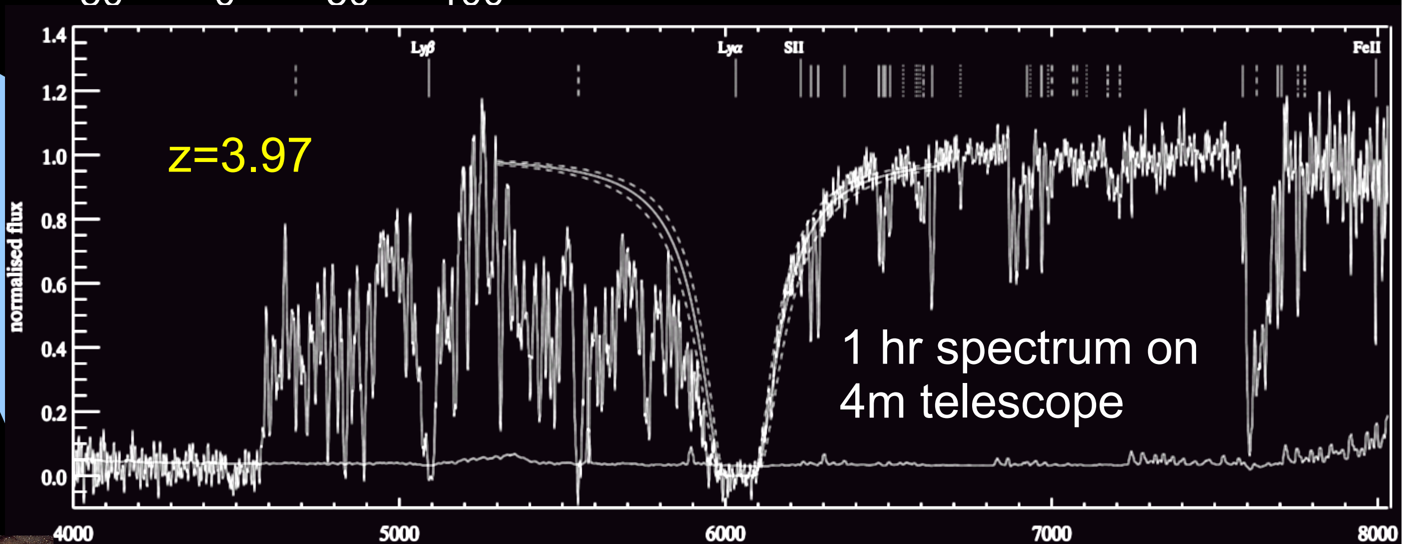
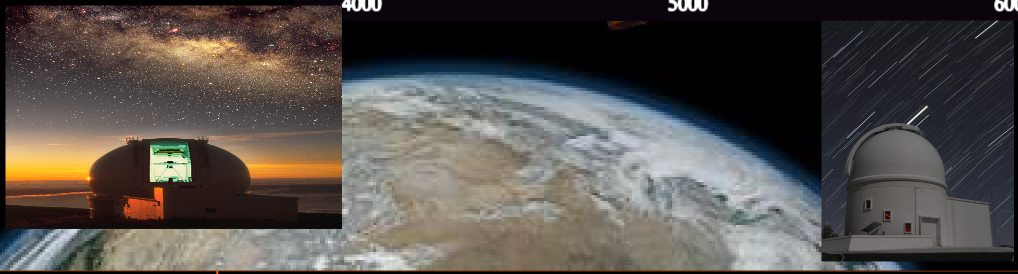






Starling+2005



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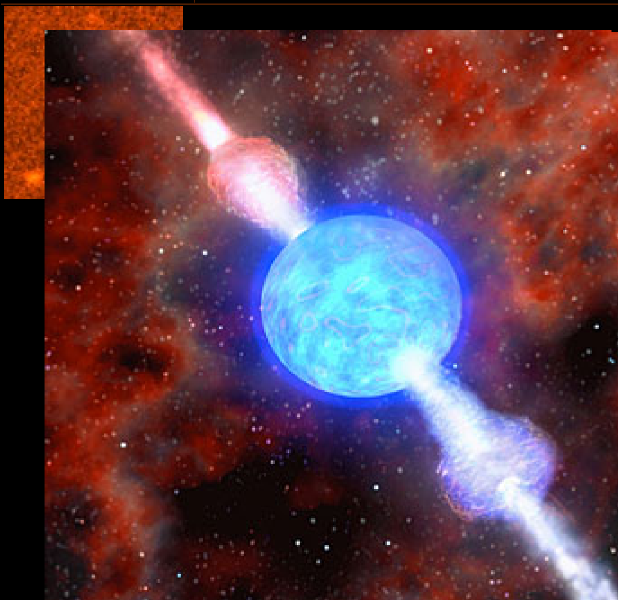
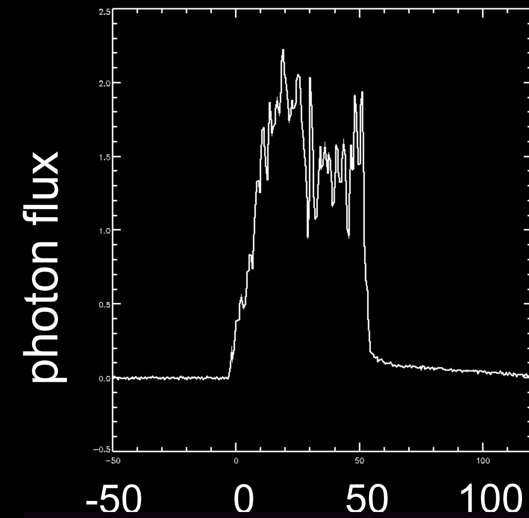
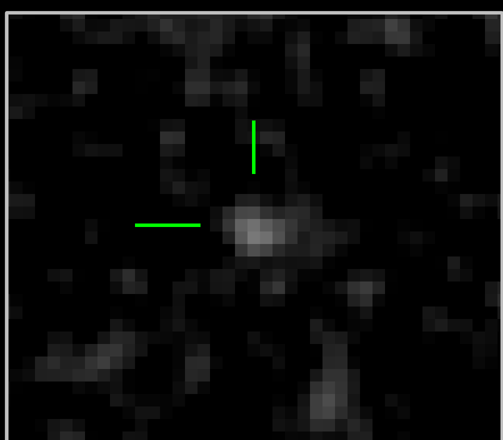
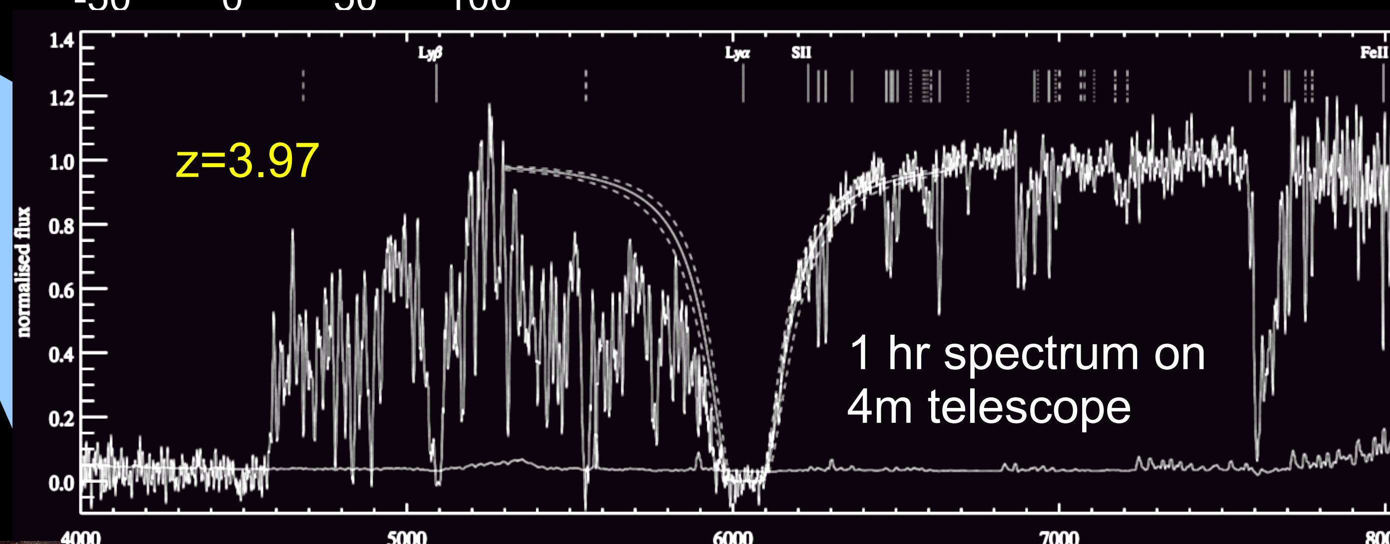


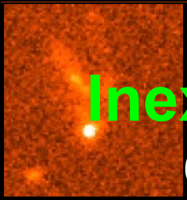






Starling+2005

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

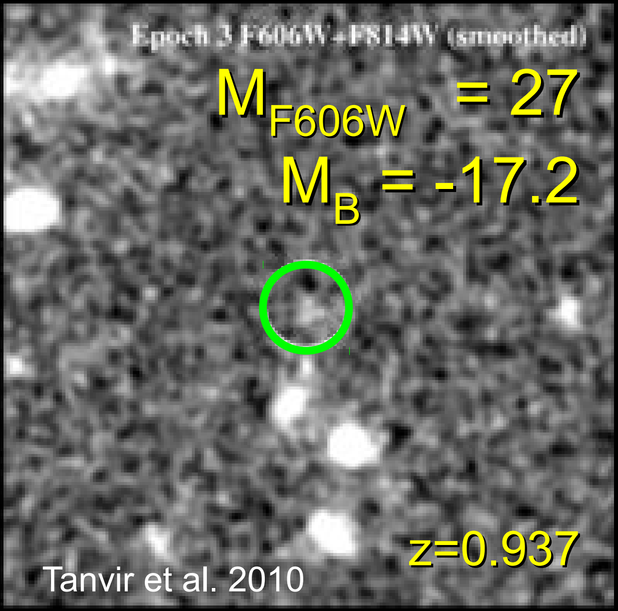
Sensitive to sub-threshold SFR

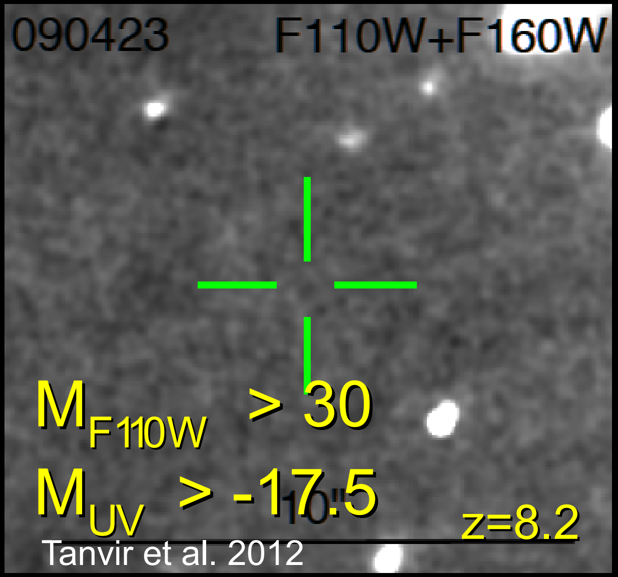
Host nondetections give a direct constraint on importance of undetectable galaxies

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

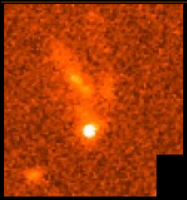
No Cosmic Variance

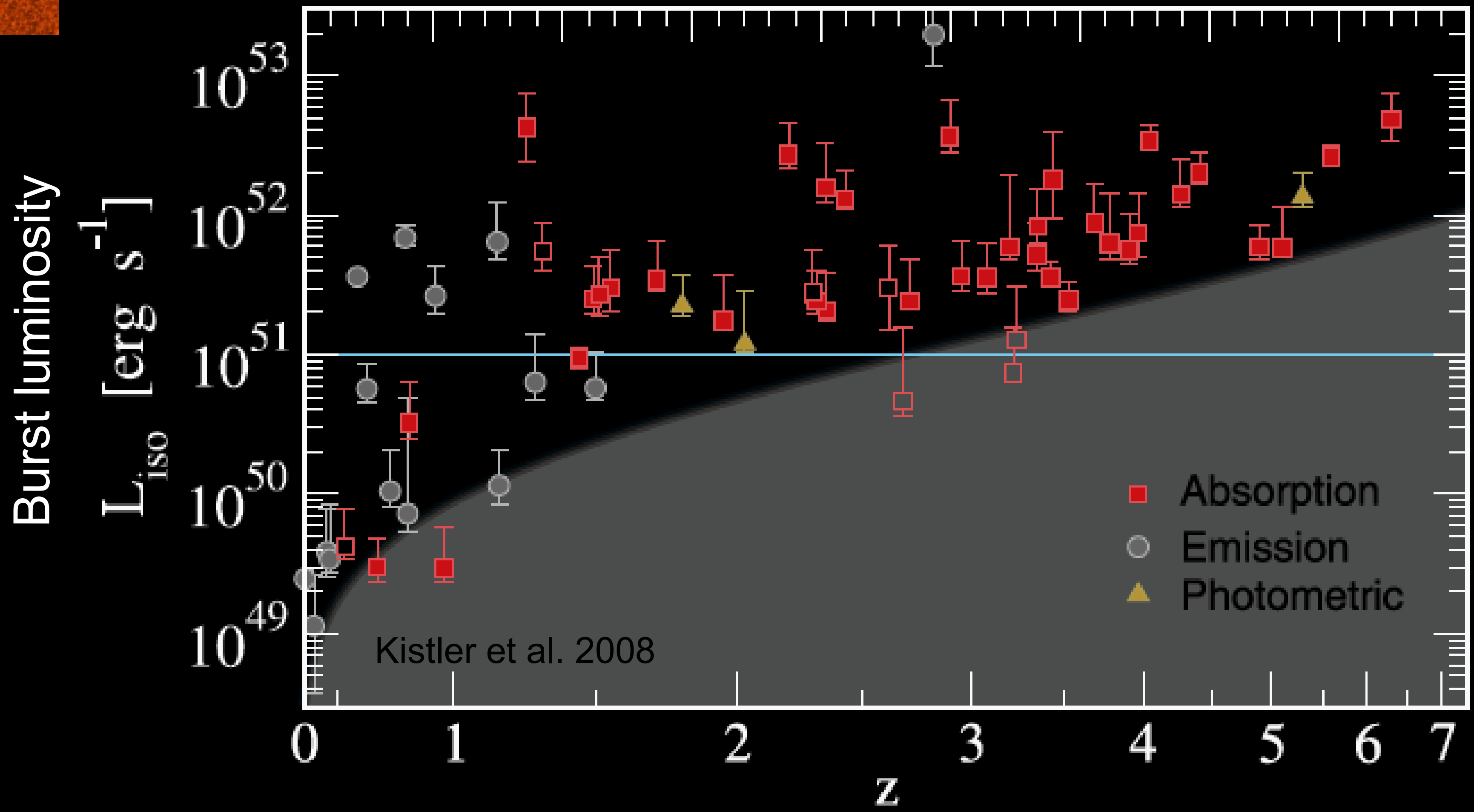
GRB satellites see (close to) the whole sky





High-z SF History from GRBs





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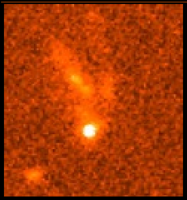

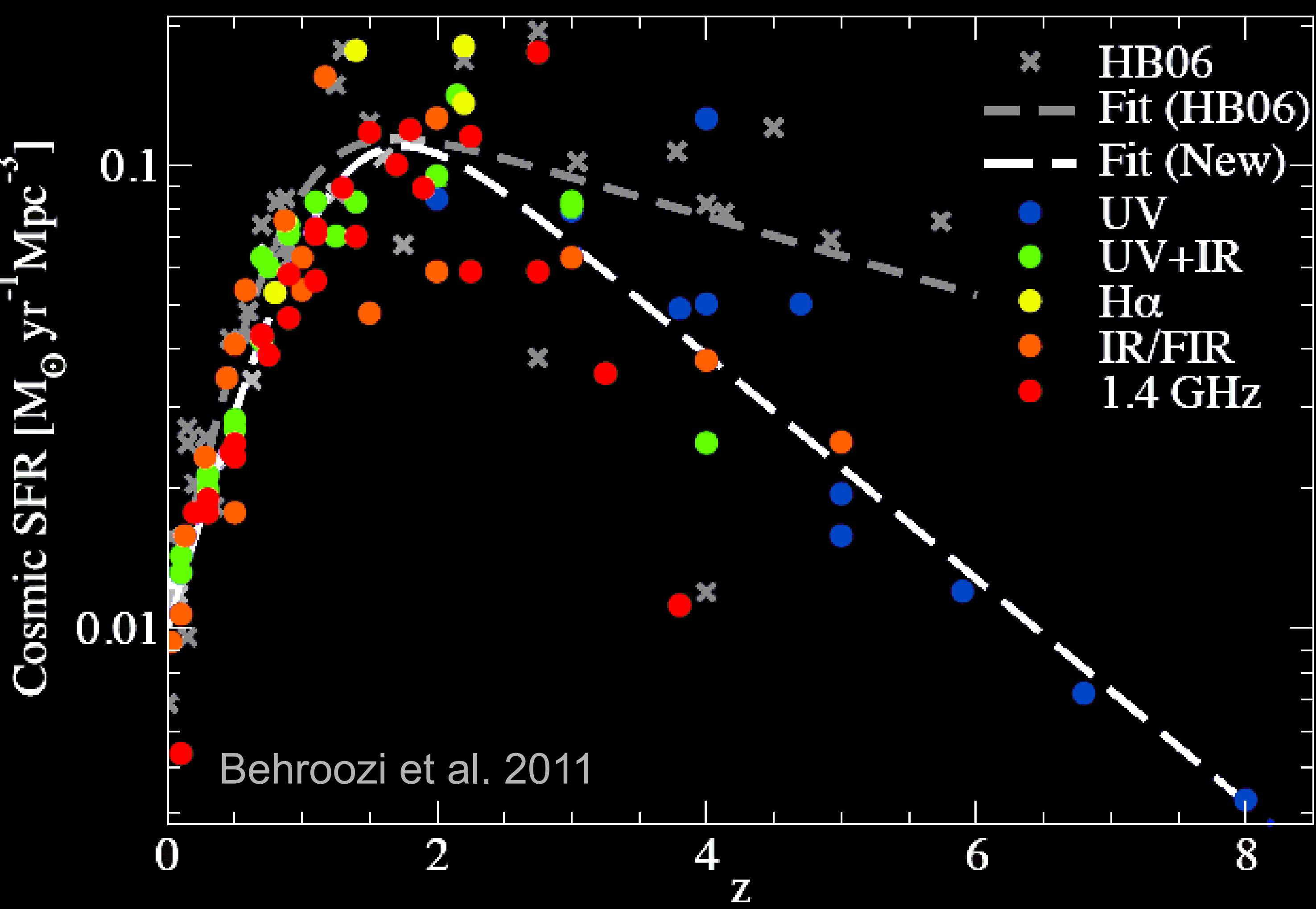

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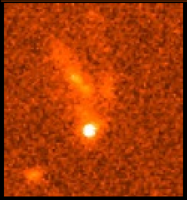

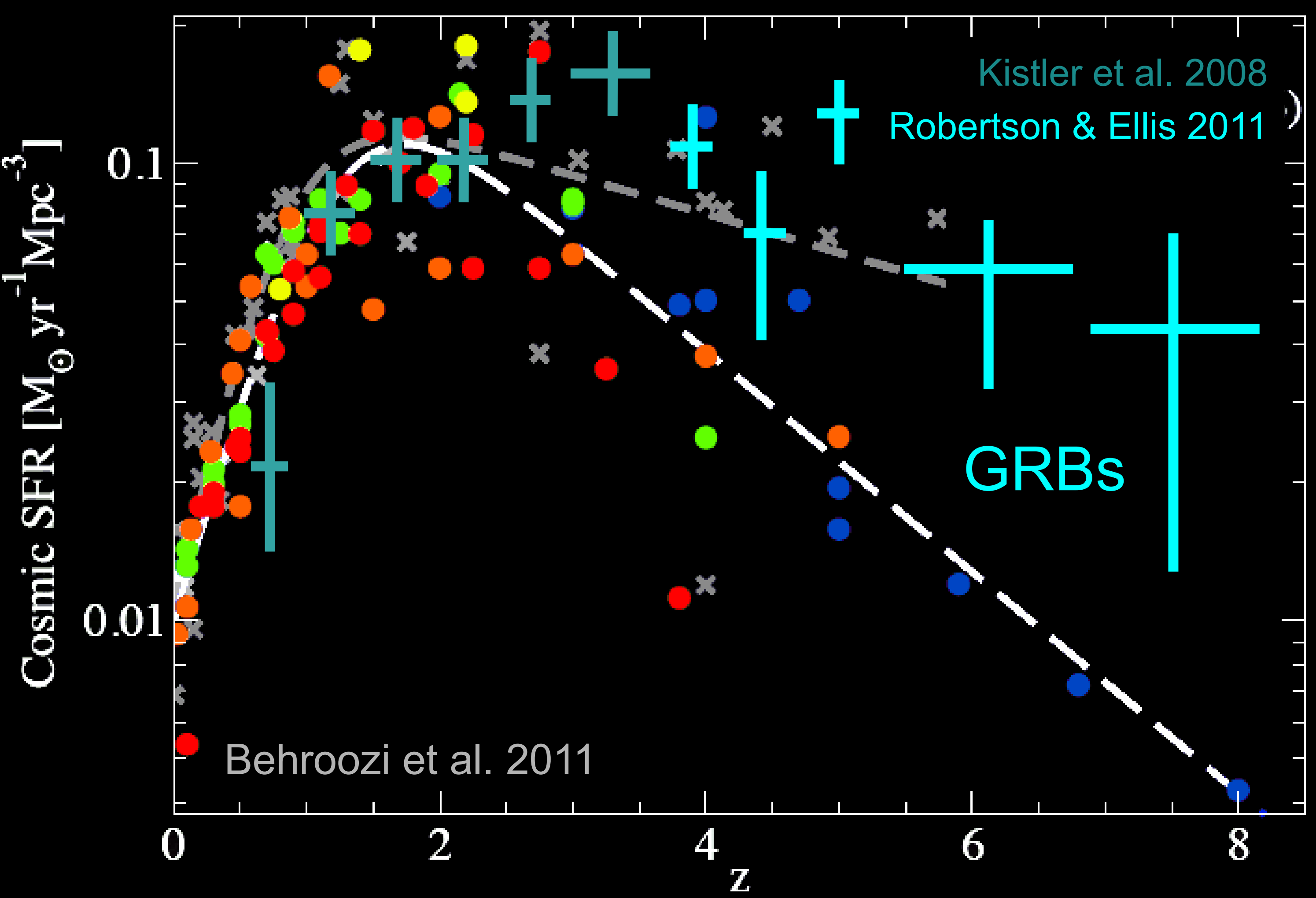

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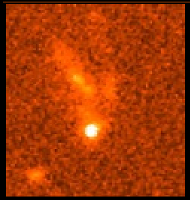

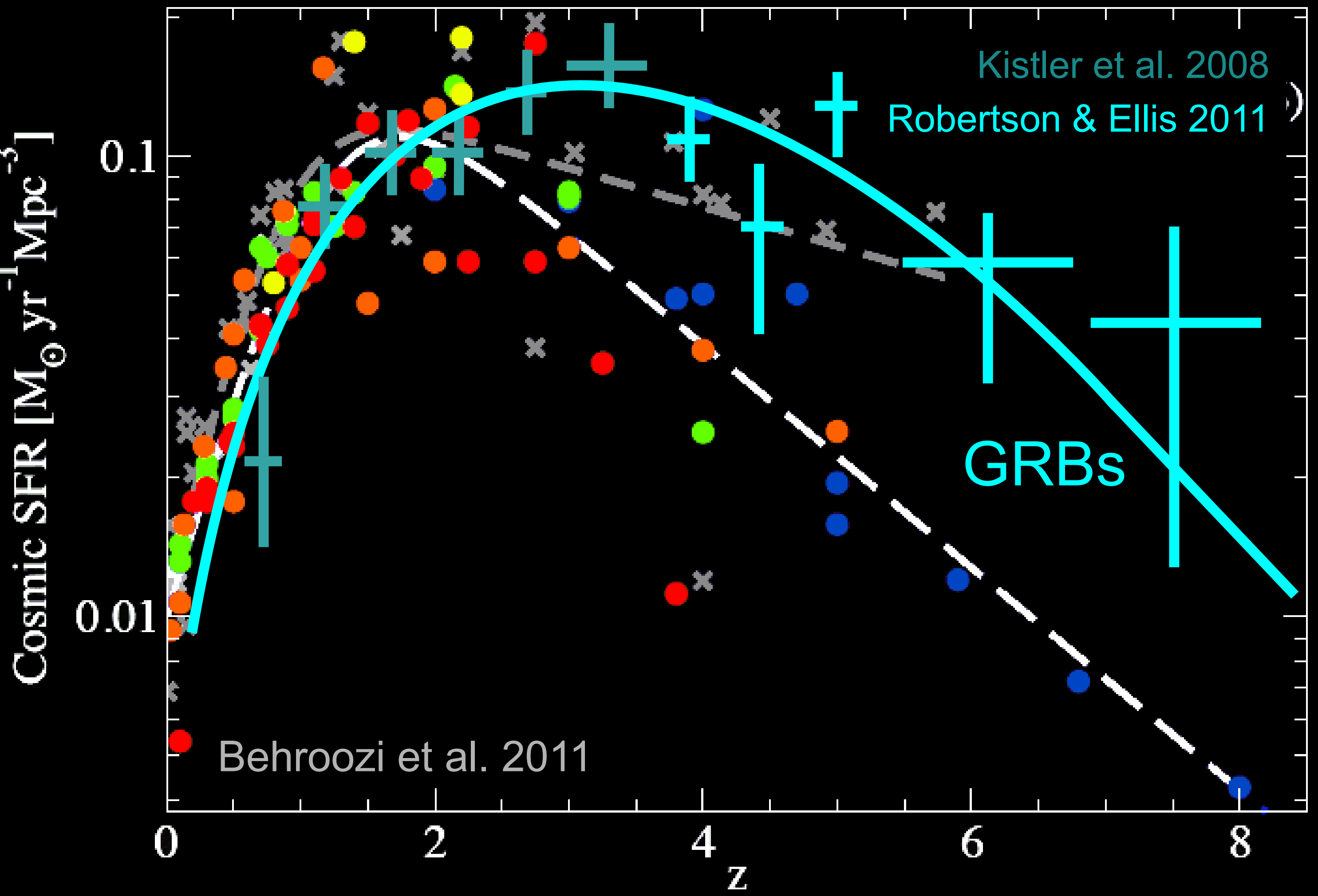

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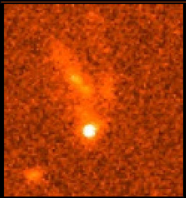
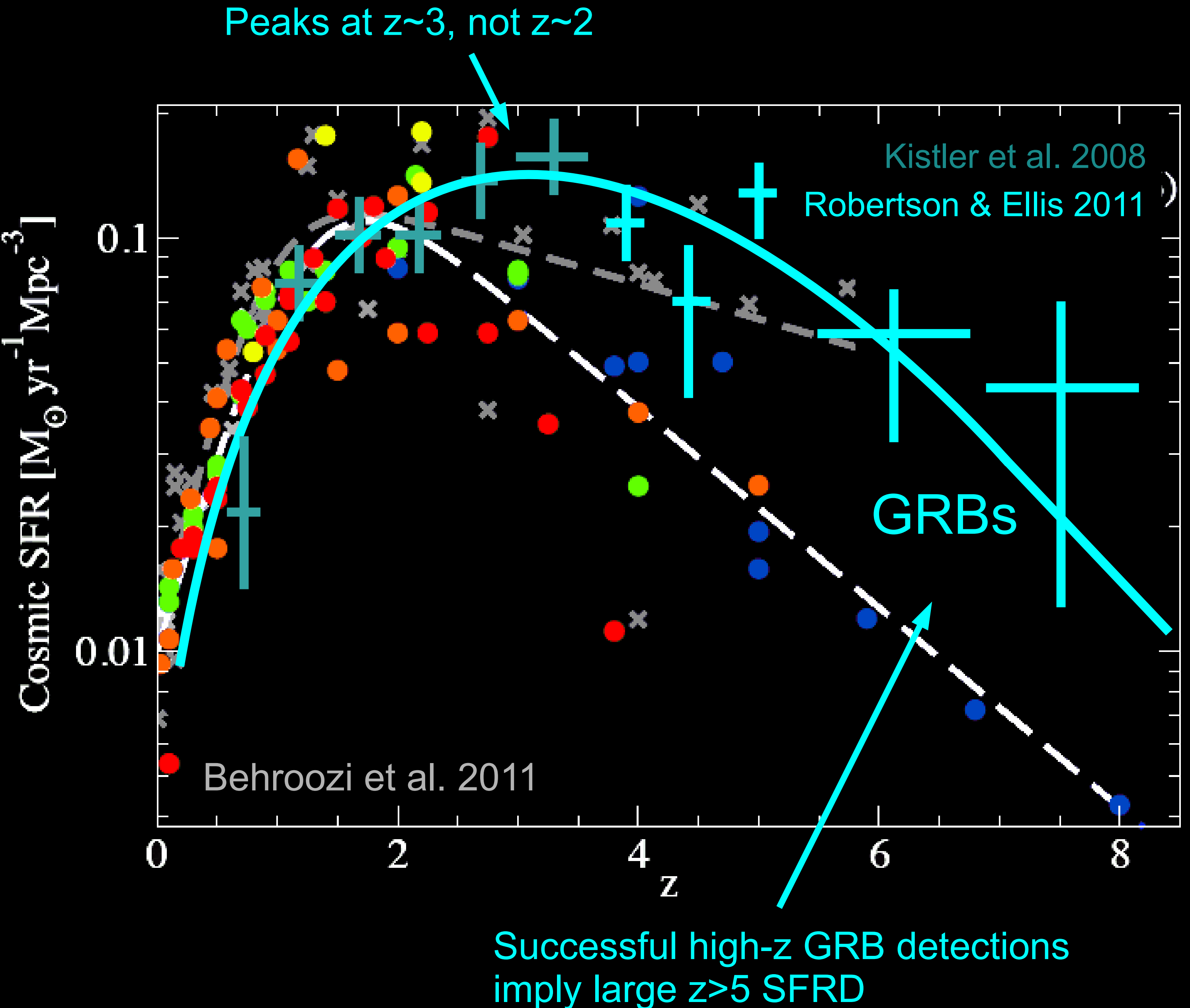




Interpretations

GRB and field-survey measurements of the SFRD do not agree. Why not?

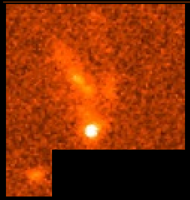
1. GRBs are not uniform star-formation rate tracers: the rate depends on environment (e.g., metallicity)

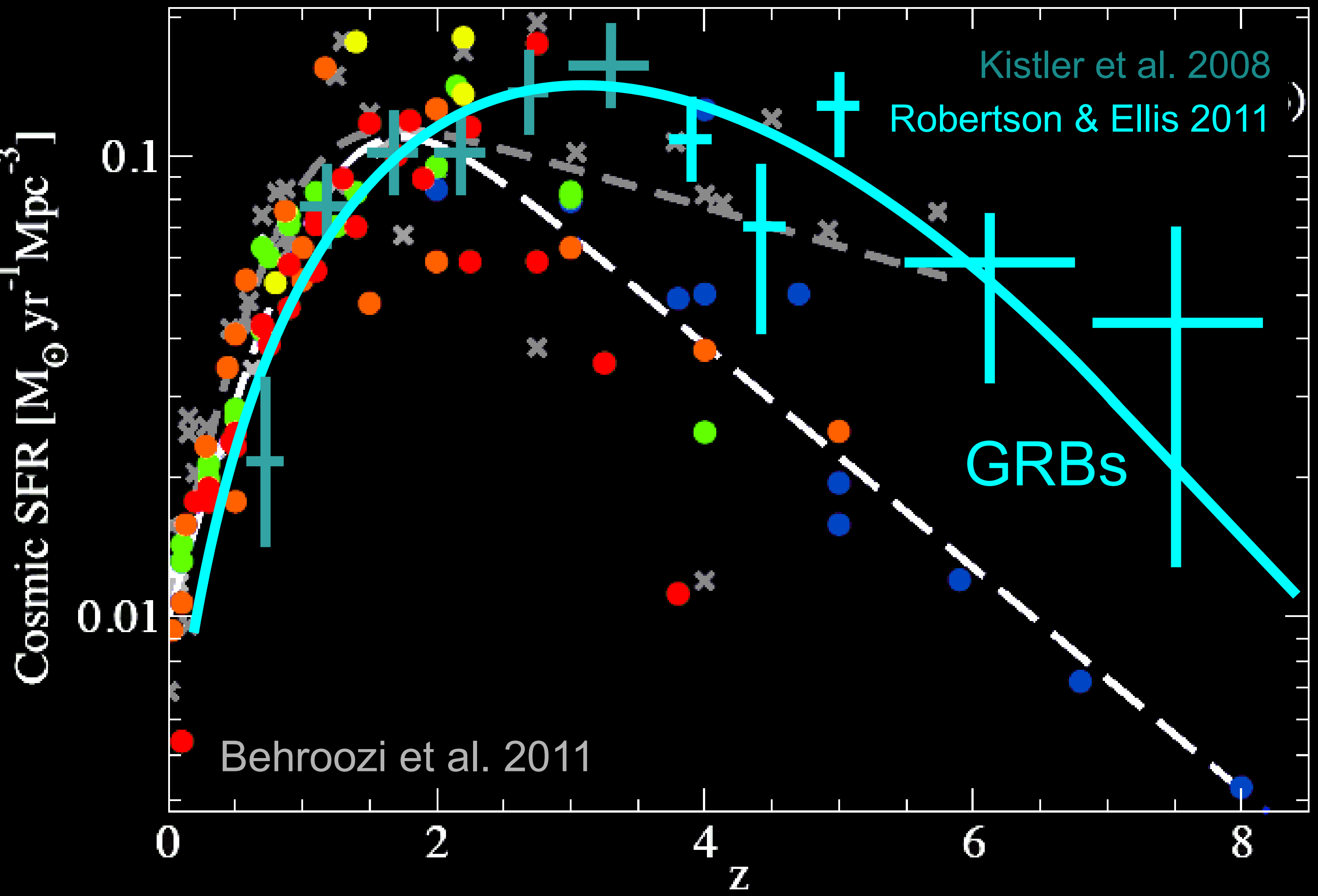
   e.g., Modjaz et al. 2008, Graham & Fruchter 2013

2. Field surveys systematically underestimate contributions from undetected, faint galaxies at high redshift, or undercorrect for dust.

   e.g., Jakobsson et al. 2012, Kistler et al. 2013

High-z SF History from GRBs





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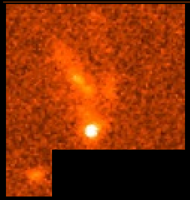

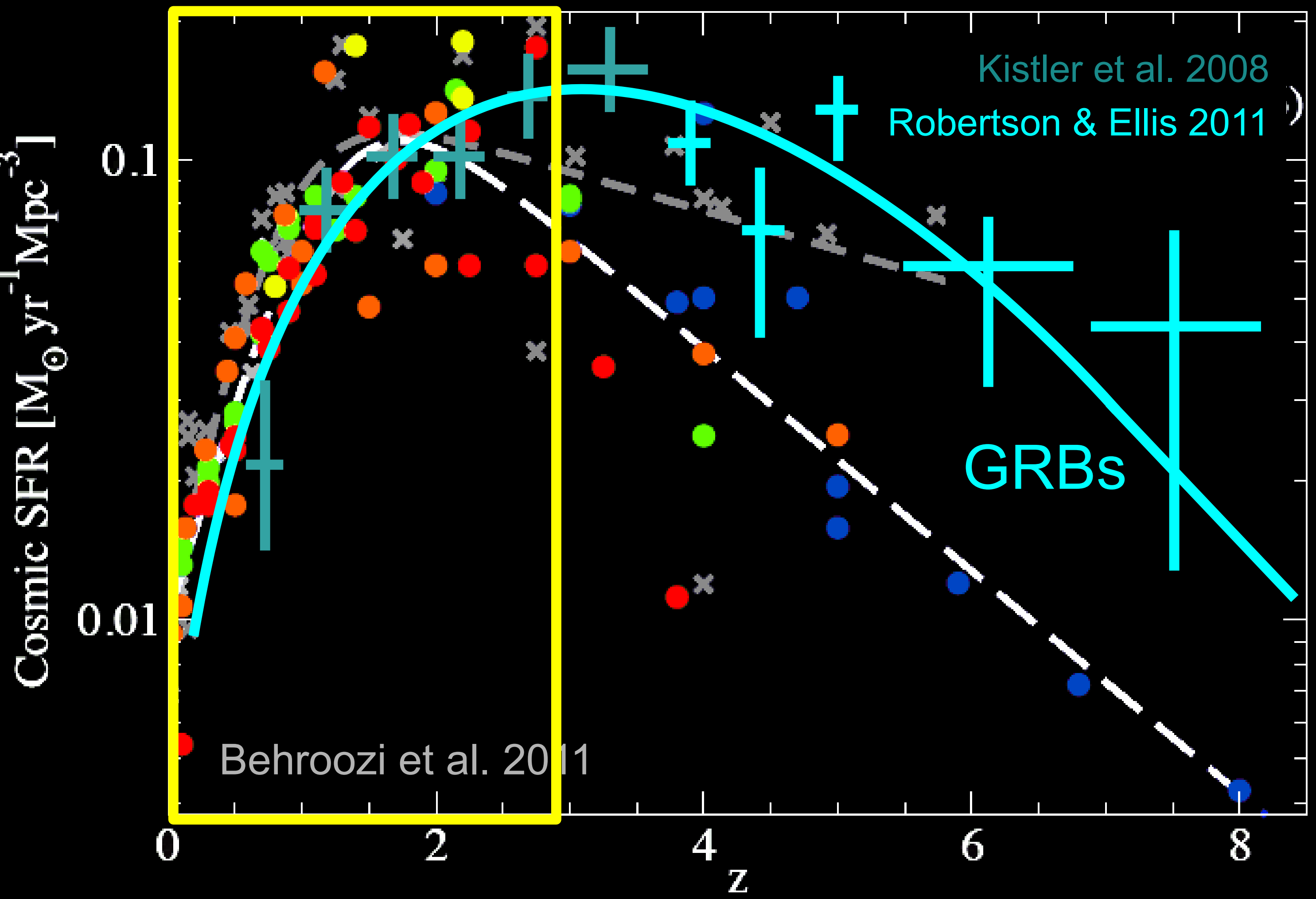

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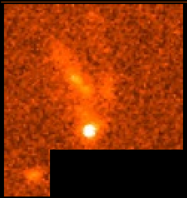
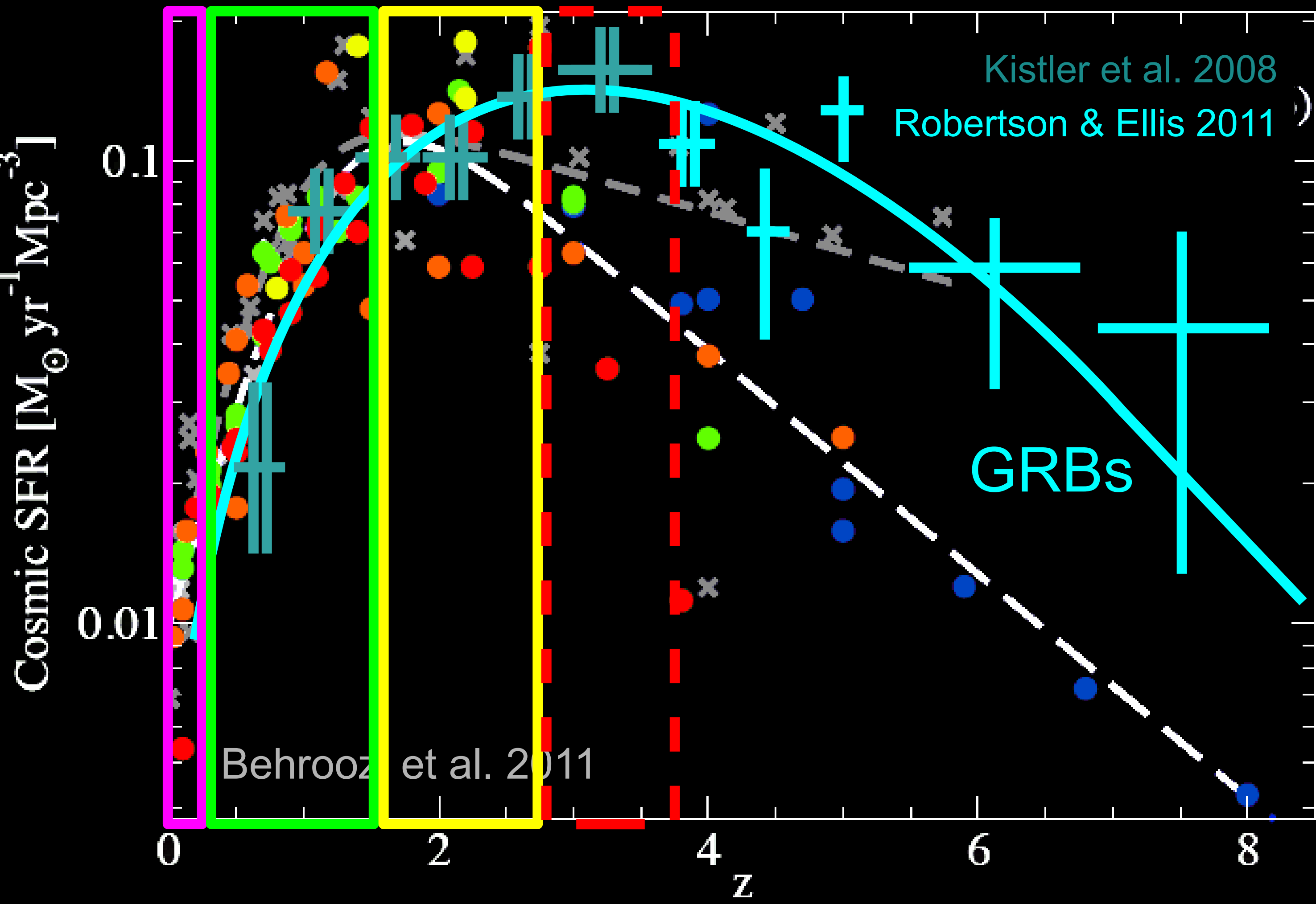




Outline:

GRBs vs SFR at:

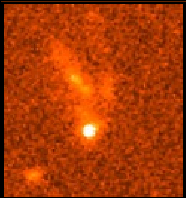
z~0 (literature overview)

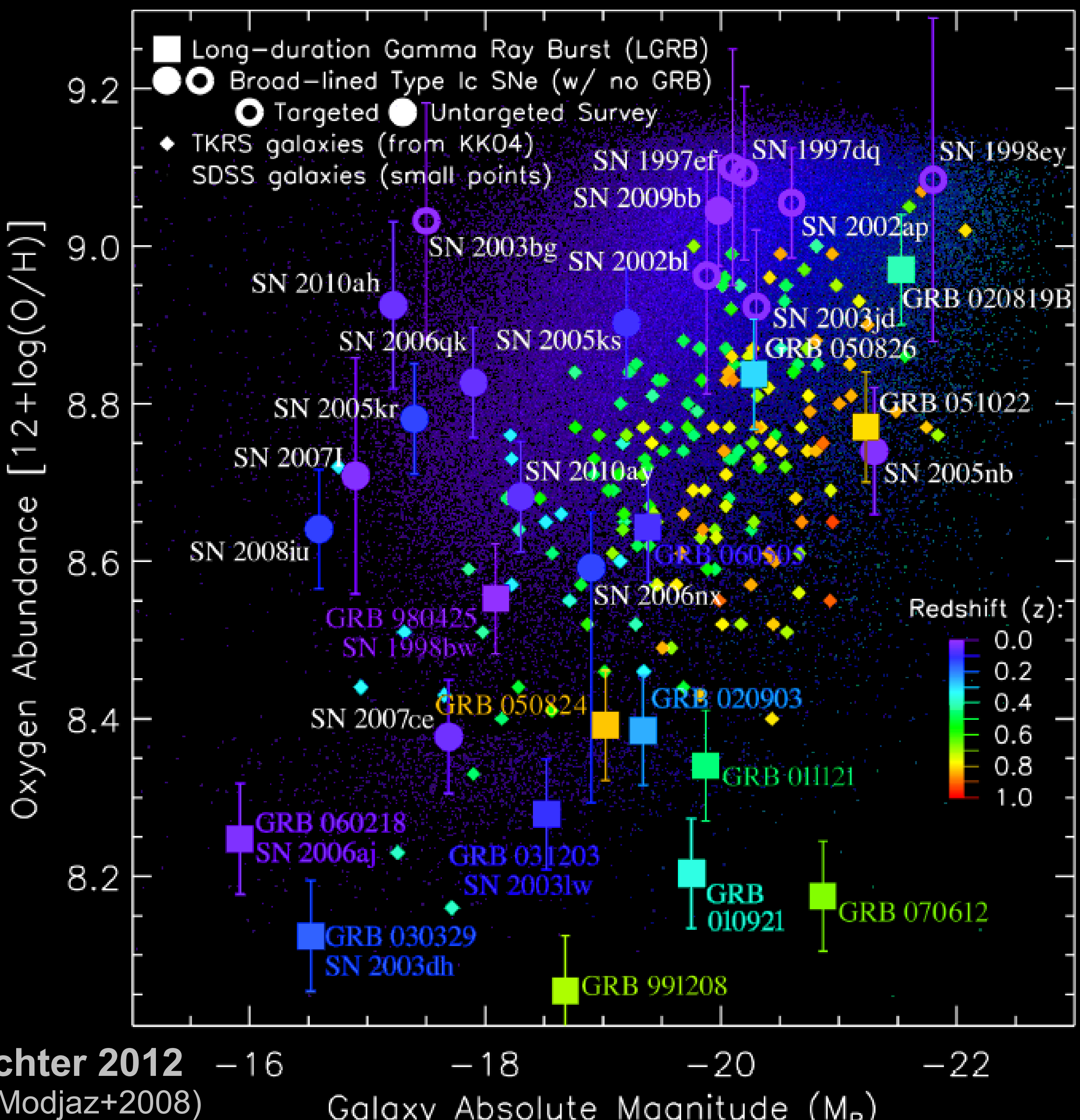
z~1 (SED fitting)

z~2 (magnitudes and colors)

z~3 (some extrapolated guesses)

Host Luminosity and Metallicity at z~0

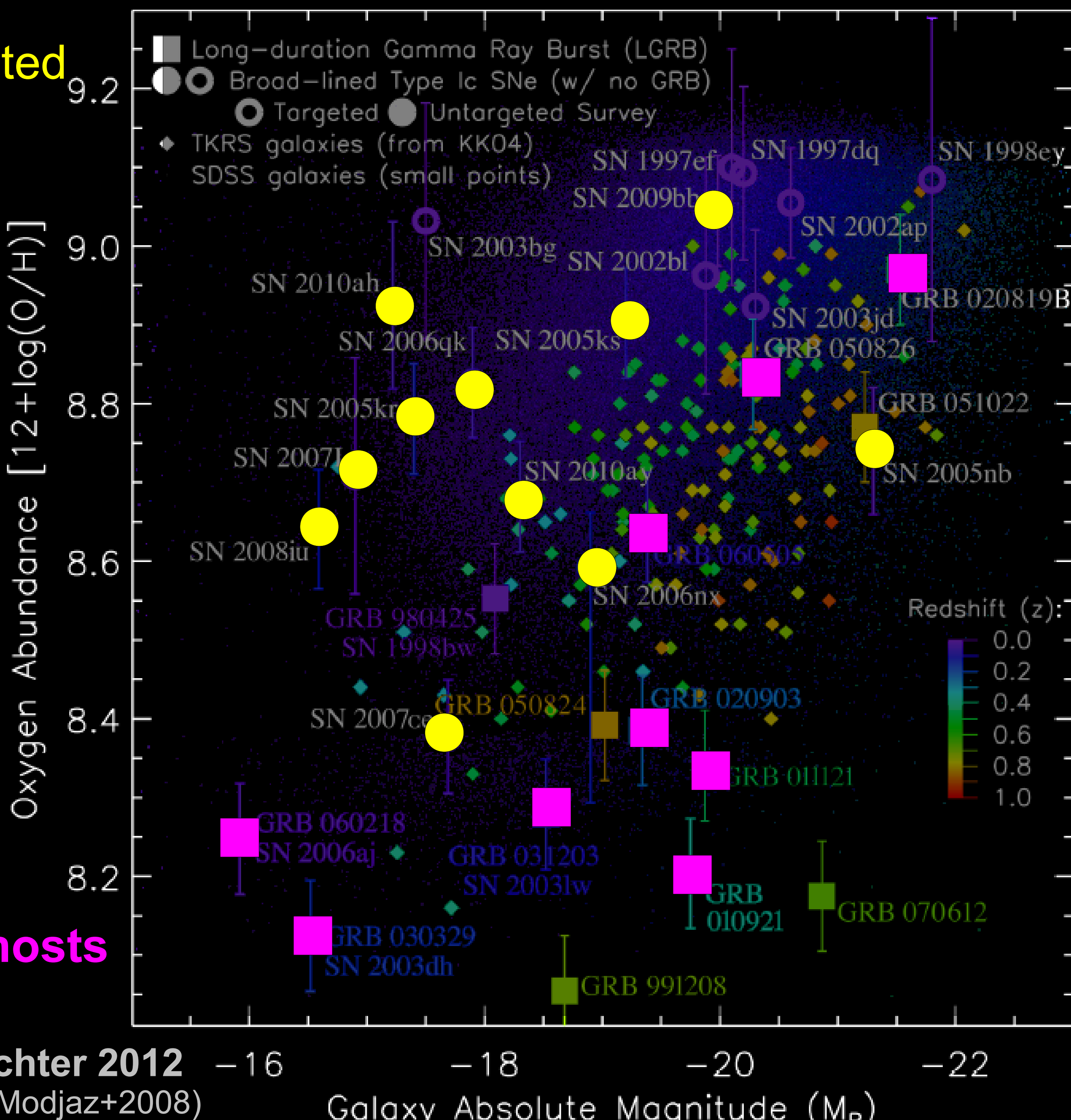




Graham & Fruchter 2012
(Levesque+2010, Modjaz+2008)

Host Luminosity and Metallicity at z~0

z~0 untargeted broad-lined Ic SNe



z<0.5 GRB hosts

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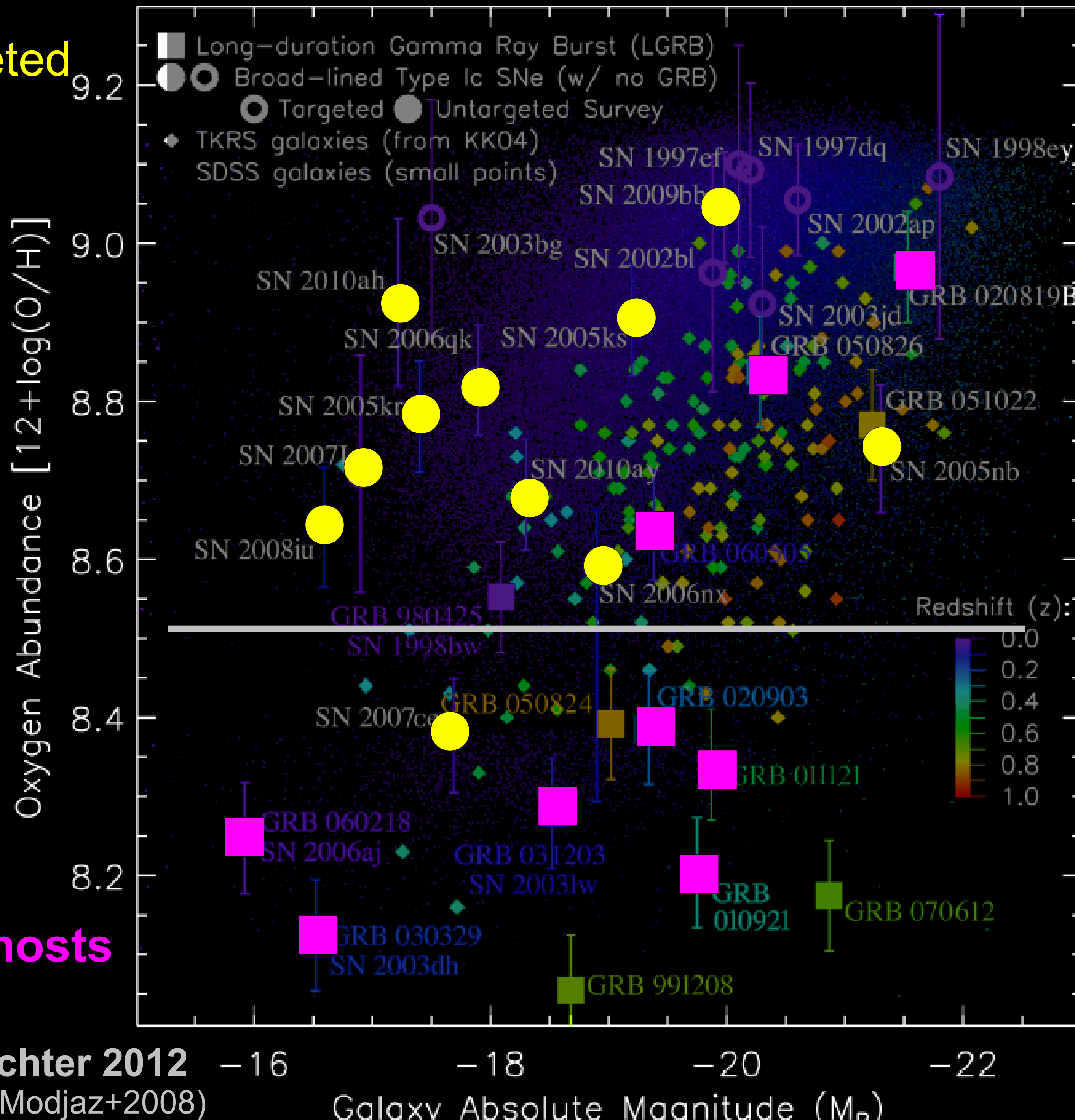


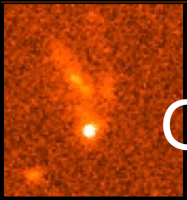
~0.7 $Z_\odot$

z<0.5 GRB hosts

Graham & Fruchter 2012

(Levesque+2010, Modjaz+2008)

Limitations of z~0 comparisons



GRBs "prefer" metal-poor galaxies at z~0, but:

- z~0 host sample is very small
  (9 events at z<0.5 with measured metallicity)

- z~0 host sample is potentially biased
  (high-SFR, low-dust systems required for metal measurement)

- Low-z GRBs are not much like high-z GRBs
  (with rare exceptions, orders of magnitude less energetic)

- Cause (metallicity alone?) is unresolved

- High-z cosmic environments very different from today
  (higher SFR, lower mass, lower metallicity)

Moving beyond low redshift

Method: Abandon expensive metallicity measurements; go for *photometric* comparisons of hosts vs. star-forming galaxies at z=1 and beyond.

Considerations: *Must avoid sample selection at all costs.*

1. *Avoid luminosity bias* – select a complete sample and include all hosts, no matter how faint.

2. *Avoid dust bias* – include events without detected optical afterglow (and without pre-determined afterglow redshift.)

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"Easy" way:
Choose the most complete sample you can from the literature; "fill in" the missing members

"Hard" way:
Design a new survey from the ground up and thoroughly observe everything yourself!

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✓ **done**

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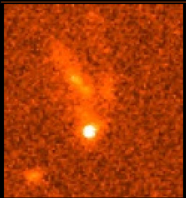
Design a new, unbiased survey from the ground up and thoroughly observe everything yourself!

in progress

Pre-Swift Sample



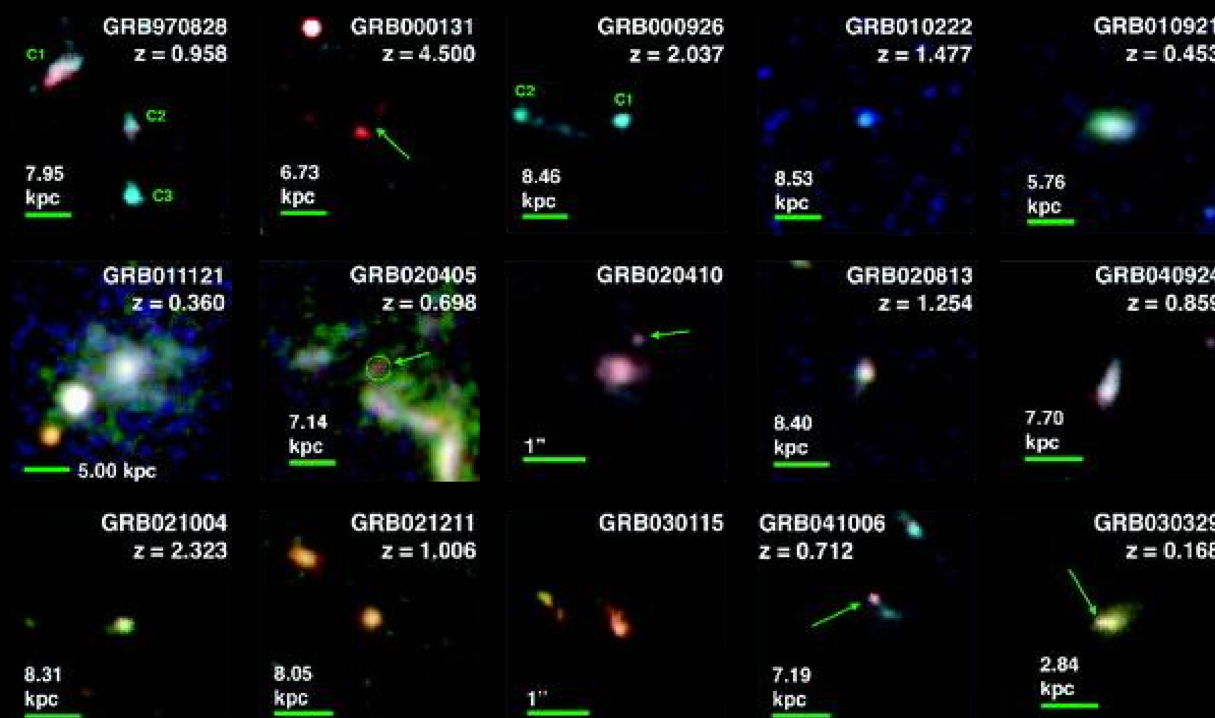
“Too many” *Swift* bursts (>100/yr), not enough telescope time!

Before 2004: ~10 localized bursts/yr; host surveys could “keep up”

- 31 pre-Swift GRBs with redshifts (65% of all with redshifts)
- have published multi-band host data suitable for SED fitting.

Nearly all are at z<1.5 – early satellites saw only bright, nearby GRBs.

Photometry compiled from numerous sources via online database @ grbhosts.org (Savaglio et al. 2009)



HST images from Wainwright et al. 2007

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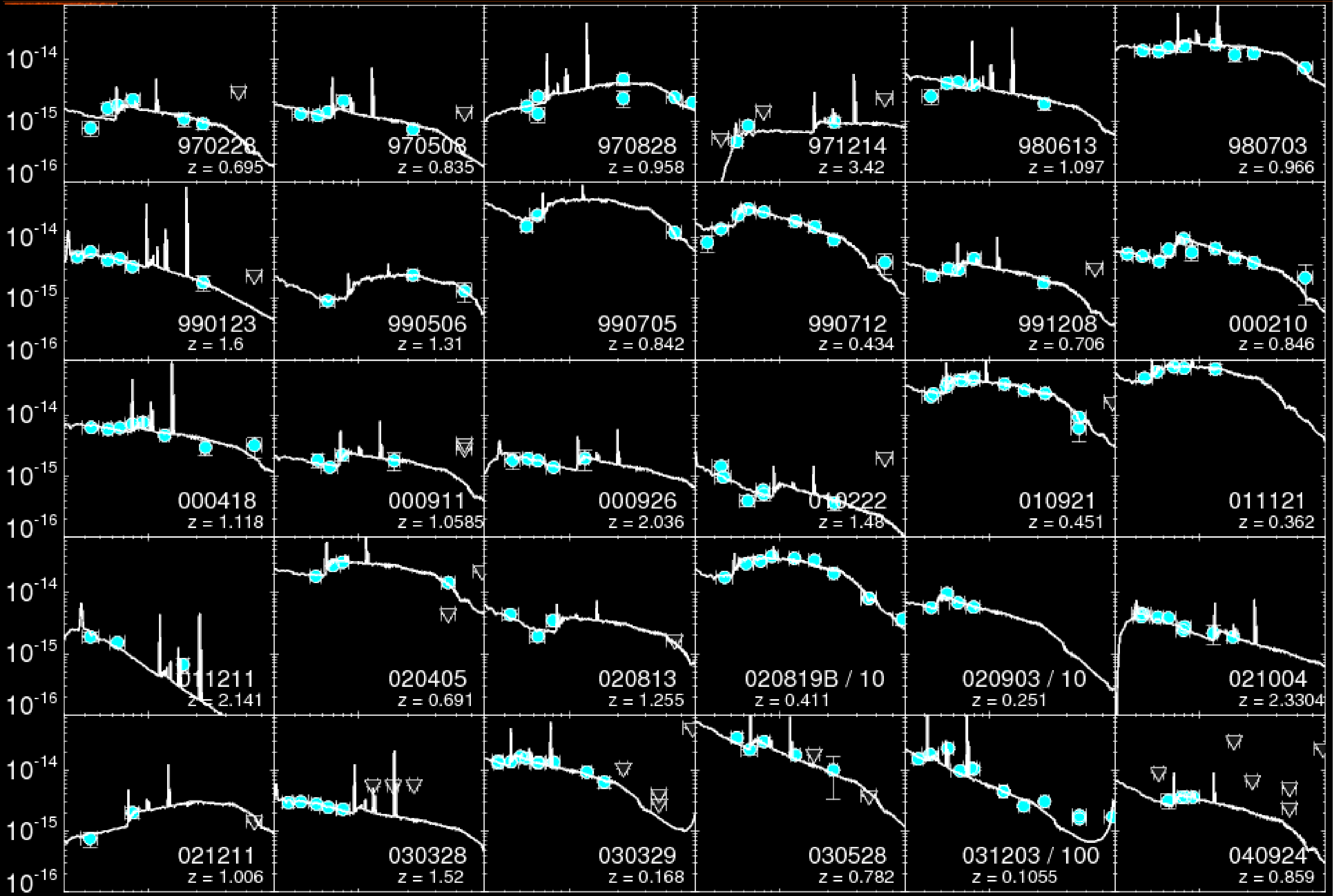

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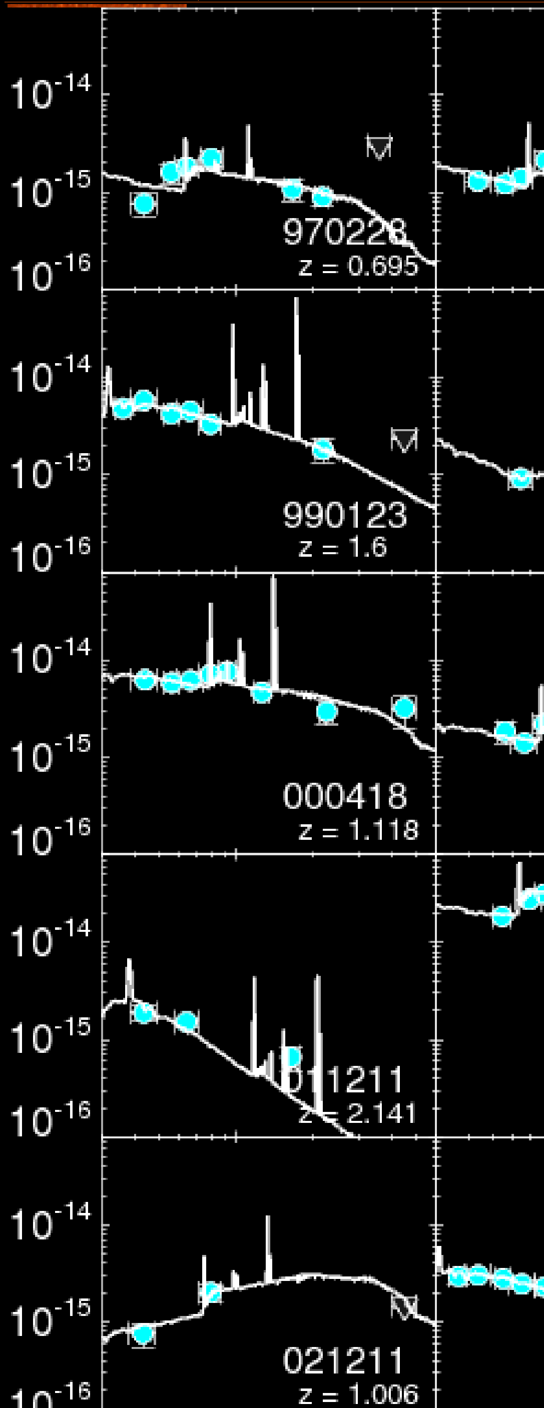
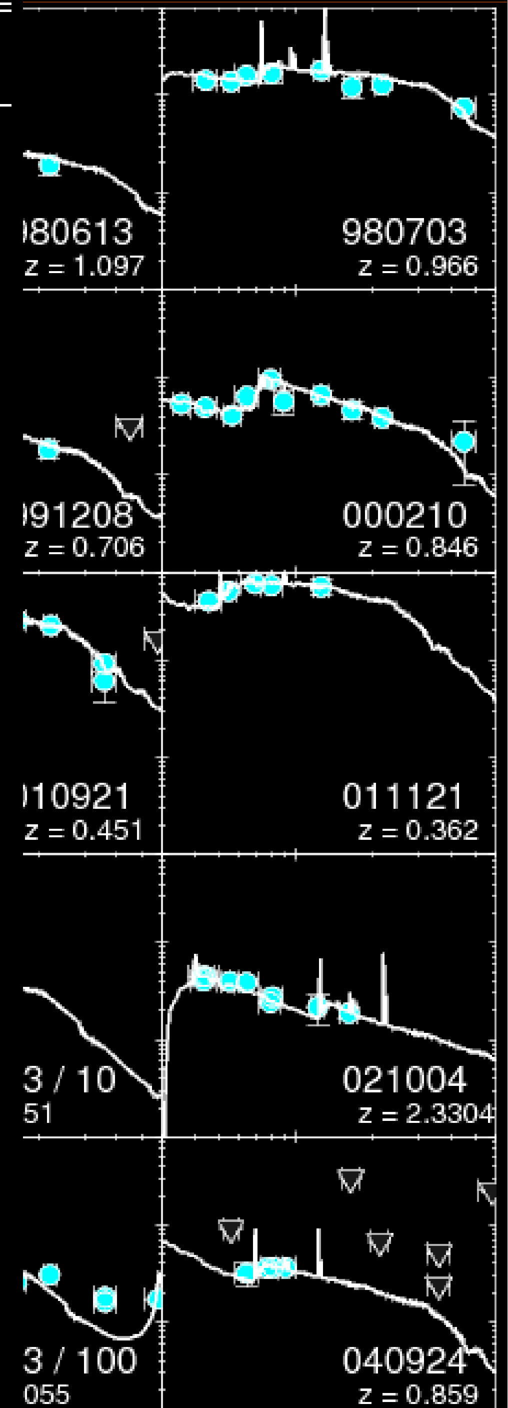
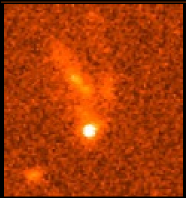
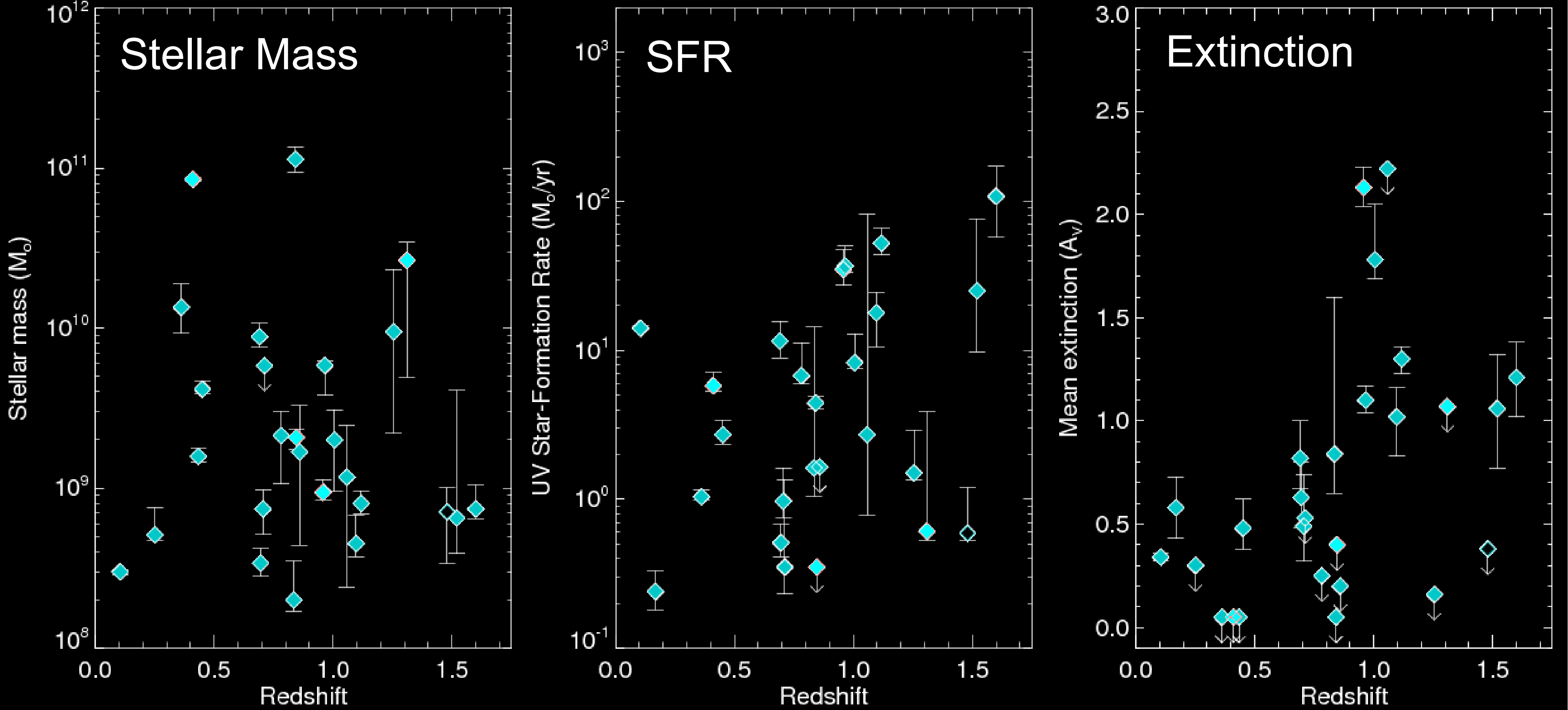


GRB[a]	z[b]	SFR[c] $M_\odot\,yr^{-1}$	M_*[d] $10^9\,M_\odot$	A_V[e] mag	χ^2/dof
970228	0.69	$0.5^{+0.2}_{-0.1}$	$0.3^{+0.1}_{-0.1}$	$0.63^{+0.17}_{-0.15}$	11.3/4
970508	0.83	$1.6^{+12.7}_{-0.6}$	$0.2^{+0.2}_{-0.0}$	$0.84^{+0.76}_{-0.19}$	8.3/3
970828	0.96	$35.0^{+12.6}_{-7.6}$	$0.9^{+0.2}_{-0.1}$	$2.13^{+0.10}_{-0.09}$	12.3/4
971214	3.42	$58.9^{+31.8}_{-8.9}$	$7.1^{+2.6}_{-2.4}$	$1.35^{+0.18}_{-0.10}$	4.3/3
980613	1.10	$17.9^{+6.7}_{-7.3}$	$0.4^{+0.2}_{-0.1}$	$1.02^{+0.14}_{-0.19}$	20.1/2
980703	0.97	$37.0^{+13.1}_{-3.3}$	$5.8^{+0.4}_{-2.0}$	$1.10^{+0.07}_{-0.06}$	23.5/5
990123	1.60	$108.2^{+63.6}_{-50.8}$	$0.7^{+0.3}_{-0.1}$	$1.21^{+0.17}_{-0.19}$	4.8/4
990506	1.31	$0.6^{+3.2}_{-0.1}$	$26.5^{+7.7}_{-21.5}$	$0.00^{+1.07}_{-0.00}$	0.0/0
990705	0.84	$4.4^{+0.5}_{-0.4}$	$113.0^{+22.0}_{-18.8}$	$0.00^{+0.00}_{-0.00}$	5.2/0
990712	0.43	$0.0^{+0.0}_{-0.0}$	$1.6^{+0.2}_{-0.1}$	$0.00^{+0.00}_{-0.00}$	13.7/5
991208	0.71	$1.0^{+0.6}_{-0.2}$	$0.7^{+0.2}_{-0.2}$	$0.49^{+0.25}_{-0.17}$	4.6/3
000210	0.85	$0.0^{+0.3}_{-0.0}$	$2.1^{+0.3}_{-0.3}$	$0.05^{+0.35}_{-0.05}$	17.0/6
000418	1.12	$52.4^{+13.7}_{-8.8}$	$0.8^{+0.2}_{-0.1}$	$1.30^{+0.06}_{-0.07}$	12.8/5
000911	1.06	$2.7^{+79.0}_{-1.9}$	$1.2^{+1.3}_{-0.9}$	$0.80^{+1.42}_{-0.80}$	1.3/3
000926	2.04	$8.2^{+19.9}_{-3.9}$	$4.4^{+60.8}_{-3.8}$	$0.58^{+0.39}_{-0.29}$	0.5/2
010222	1.48	$0.6^{+0.6}_{-0.1}$	$0.7^{+0.3}_{-0.4}$	$0.05^{+0.33}_{-0.05}$	11.6/4
010921	0.45	$2.7^{+0.7}_{-0.4}$	$4.1^{+0.5}_{-0.2}$	$0.48^{+0.14}_{-0.10}$	21.6/11
011121	0.36	$1.0^{+0.1}_{-0.1}$	$13.5^{+5.4}_{-4.2}$	$0.00^{+0.00}_{-0.00}$	2.2/2
011211	2.14	$7.0^{+19.4}_{-0.0}$	$0.1^{+0.3}_{-0.0}$	$0.19^{+0.70}_{-0.00}$	8.1/0
020405	0.69	$11.6^{+4.1}_{-2.7}$	$8.8^{+1.9}_{-1.3}$	$0.82^{+0.18}_{-0.15}$	18.5/3
020813	1.25	$1.5^{+1.4}_{-0.2}$	$9.5^{+13.8}_{-7.3}$	$0.00^{+0.16}_{-0.00}$	6.7/1
020819B	0.41	$5.8^{+1.4}_{-0.5}$	$84.9^{+2.1}_{-2.0}$	$0.00^{+0.05}_{-0.00}$	43.5/6
020903	0.25	$0.0^{+0.0}_{-0.0}$	$0.5^{+0.2}_{-0.0}$	$0.34^{+0.00}_{-0.34}$	3.2/0
021004	2.33	$14.8^{+3.7}_{-2.0}$	$2.8^{+1.0}_{-0.6}$	$0.42^{+0.09}_{-0.07}$	20.1/6
021211	1.01	$8.3^{+4.6}_{-0.7}$	$2.0^{+1.1}_{-1.0}$	$1.78^{+0.27}_{-0.09}$	2.4/0
030328	1.52	$25.1^{+51.2}_{-15.4}$	$0.6^{+3.5}_{-0.3}$	$1.06^{+0.26}_{-0.29}$	0.8/5
030329	0.17	$0.2^{+0.1}_{-0.1}$	$0.1^{+0.0}_{-0.0}$	$0.58^{+0.15}_{-0.15}$	11.2/11
030528	0.78	$6.8^{+4.5}_{-0.8}$	$2.1^{+0.9}_{-1.1}$	$0.00^{+0.25}_{-0.00}$	4.2/4
031203	0.10	$14.1^{+0.5}_{-0.3}$	$0.3^{+0.0}_{-0.0}$	$0.34^{+0.02}_{-0.02}$	239.8/1
040924	0.86	$0.9^{+0.7}_{-0.9}$	$1.7^{+1.6}_{-1.2}$	$0.00^{+0.20}_{-0.00}$	1.0/6
041006	0.71	$0.3^{+1.0}_{-0.1}$	$0.8^{+5.1}_{-0.7}$	$0.00^{+0.53}_{-0.00}$	0.1/1

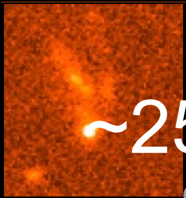


Pre-Swift host properties





Dark GRBs

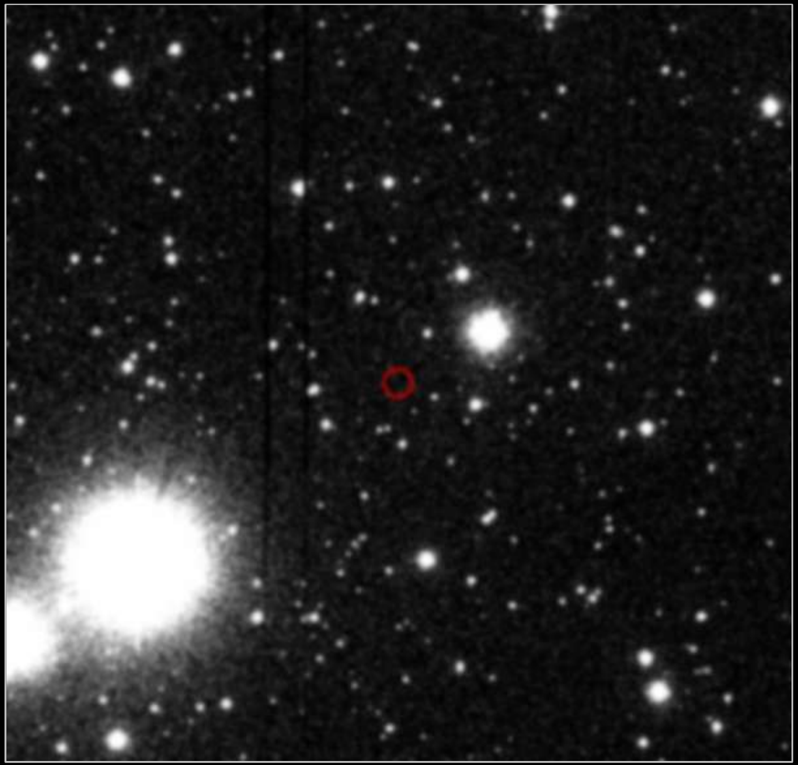


~25% of GRBs are **dark**:

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

Could be...

Intrinsically low-luminosity afterglow

(~5% of cases, identified by faint X-ray light curve.)

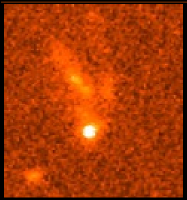
High-Redshift

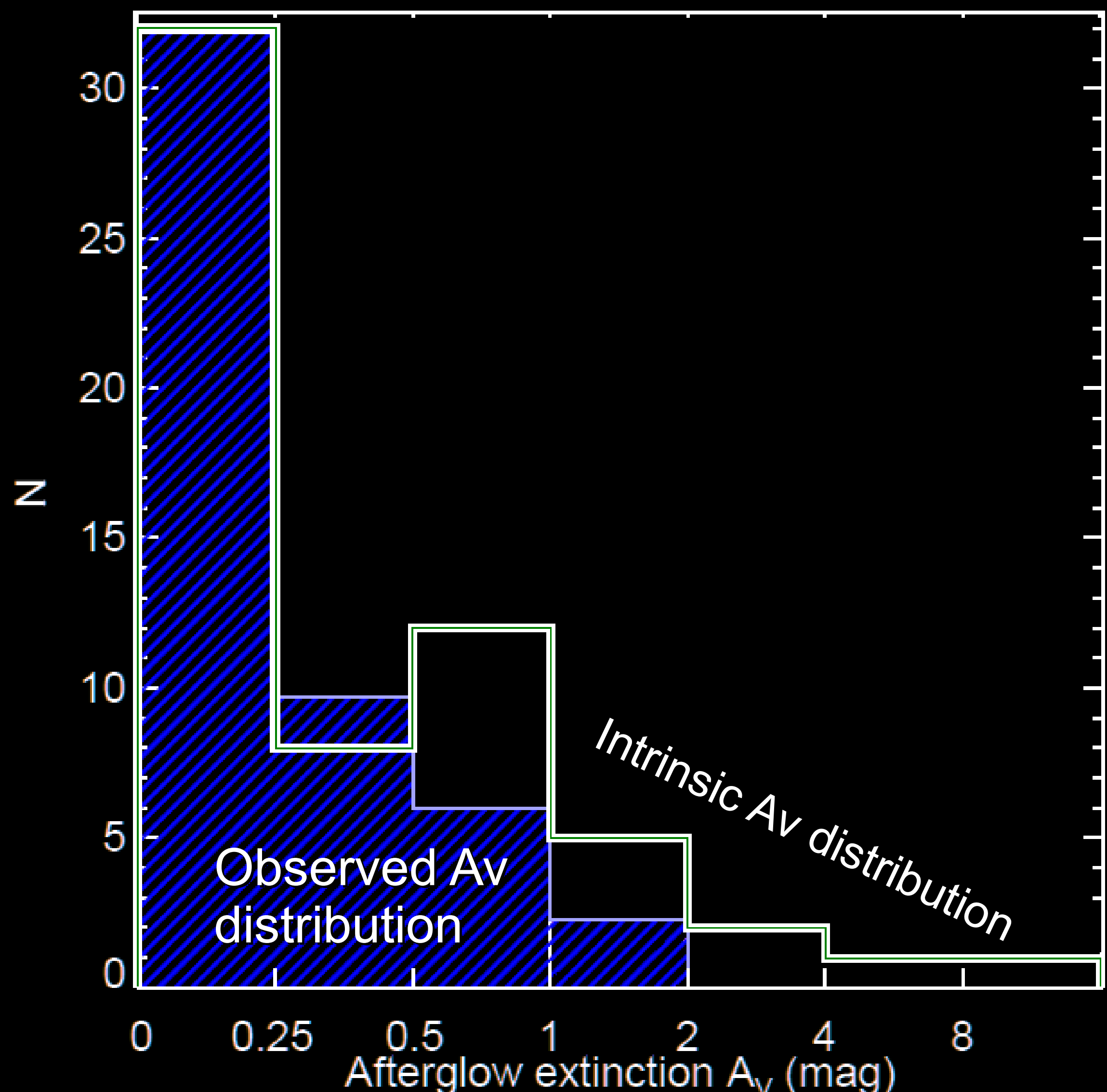
(~5% of cases, identified by Lyman break and lack of X-ray absorption.)

Dust-obscured

(~15% of cases, identified by colors + strong X-ray absorption.)

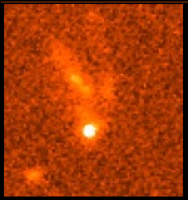
Dust and Selection Bias

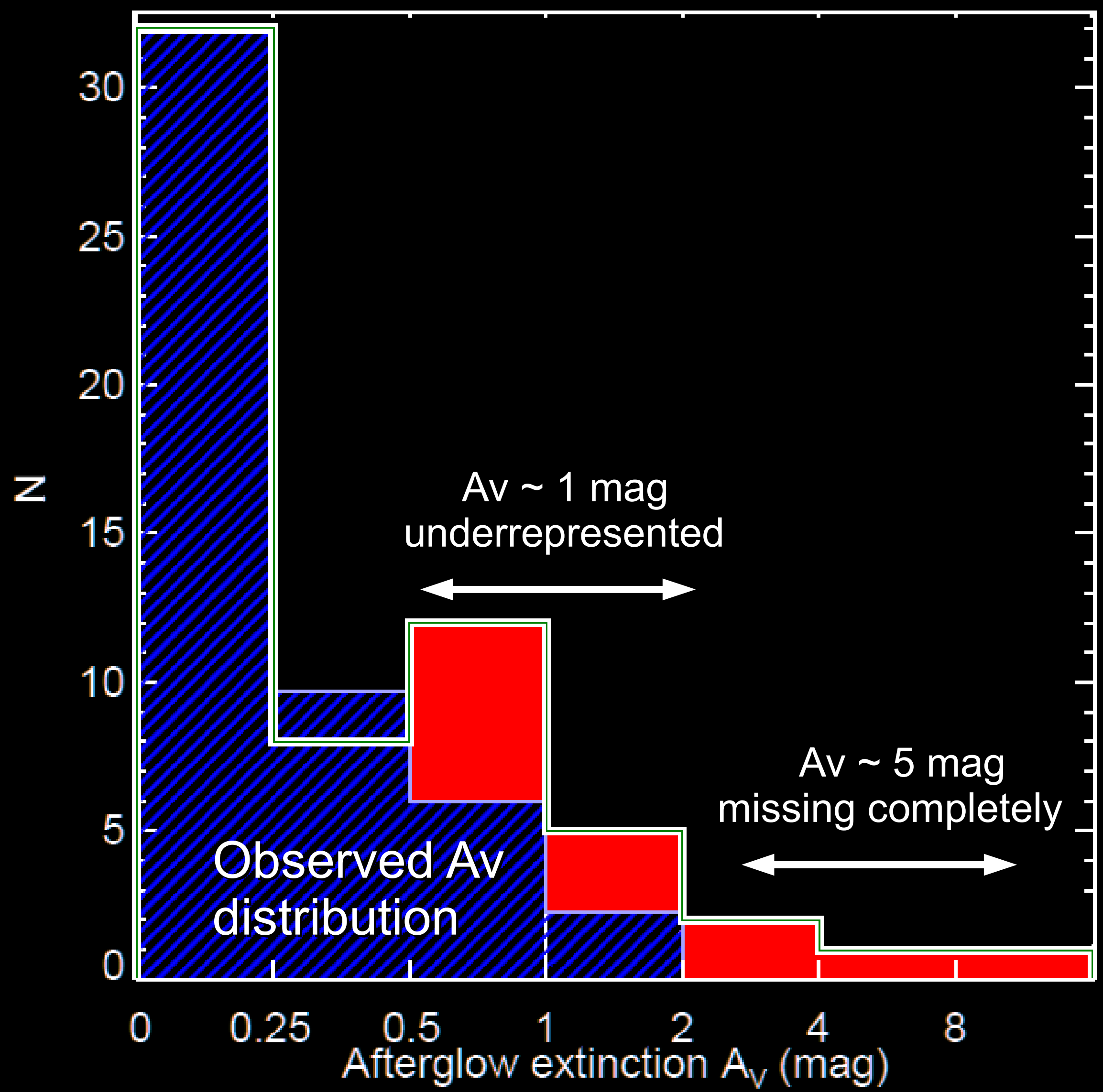




(Compiled from data in Kann et al. 2003 & 2010, Cenko et al. 2009, Perley et al. 2009, Greiner et al. 2011)

Dust and Selection Bias

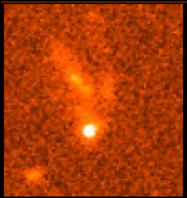


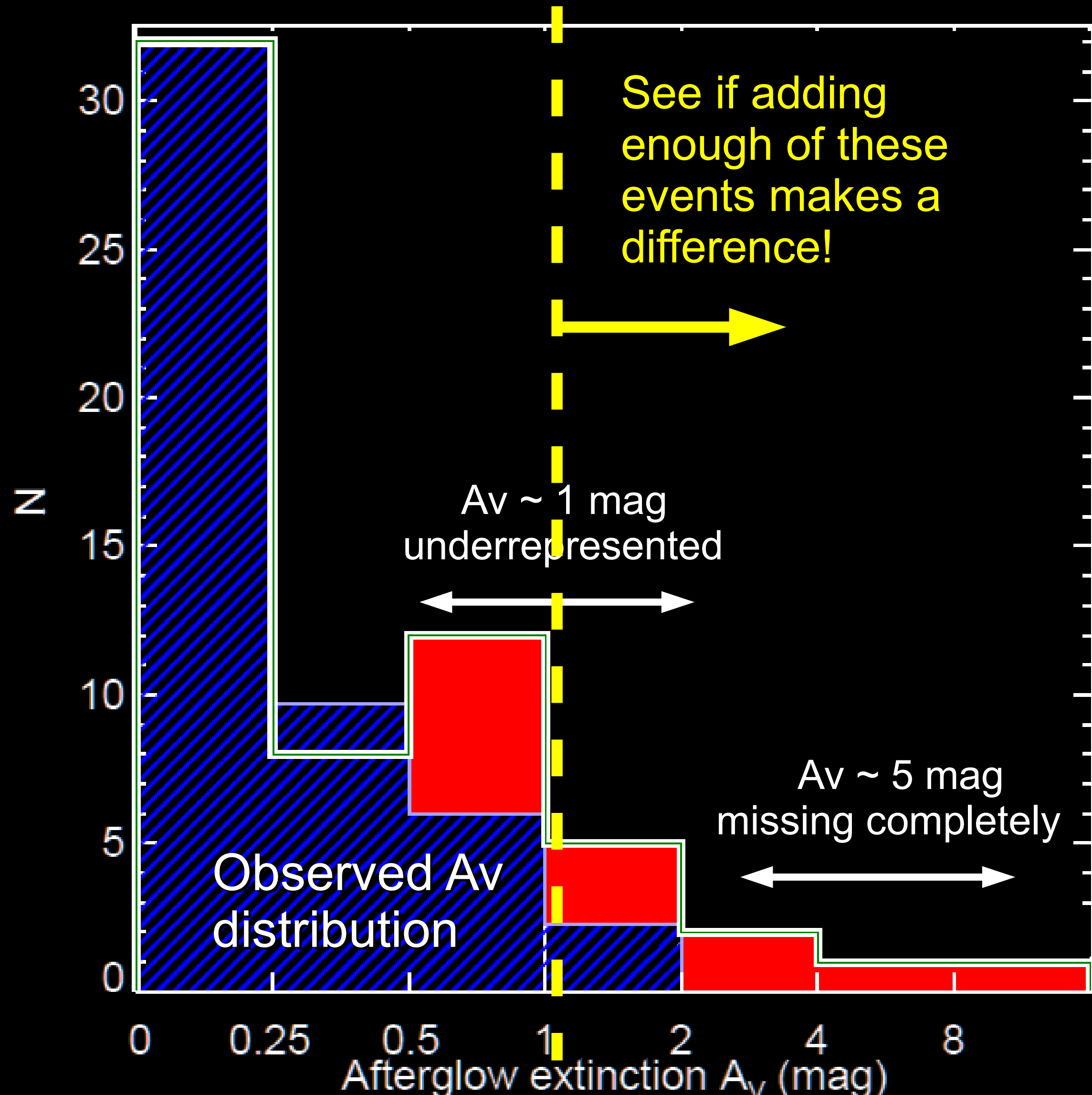


~20% of GRBs are systematically missing from optical afterglow searches as a result of dust.

(Compiled from data in Kann et al. 2003 & 2010, Cenko et al. 2009, Perley et al. 2009, Greiner et al. 2011)

Dust and Selection Bias



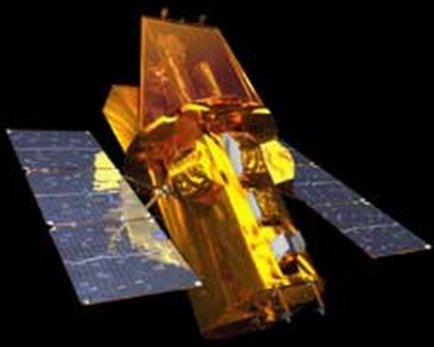


~20% of GRBs are systematically missing from optical afterglow searches as a result of dust.

(Compiled from data in Kann et al. 2003 & 2010, Cenko et al. 2009, Perley et al. 2009, Greiner et al. 2011)

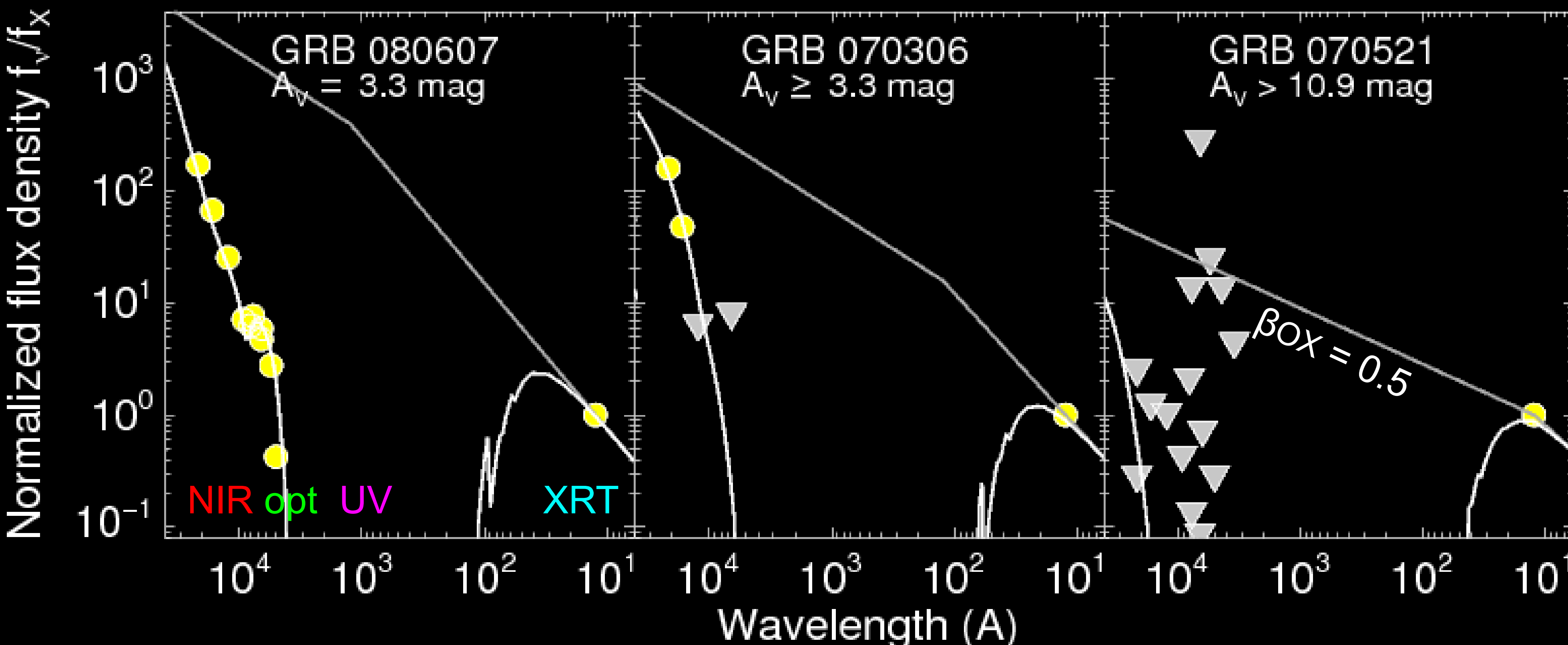
Selecting a Dusty-GRB Host Sample

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

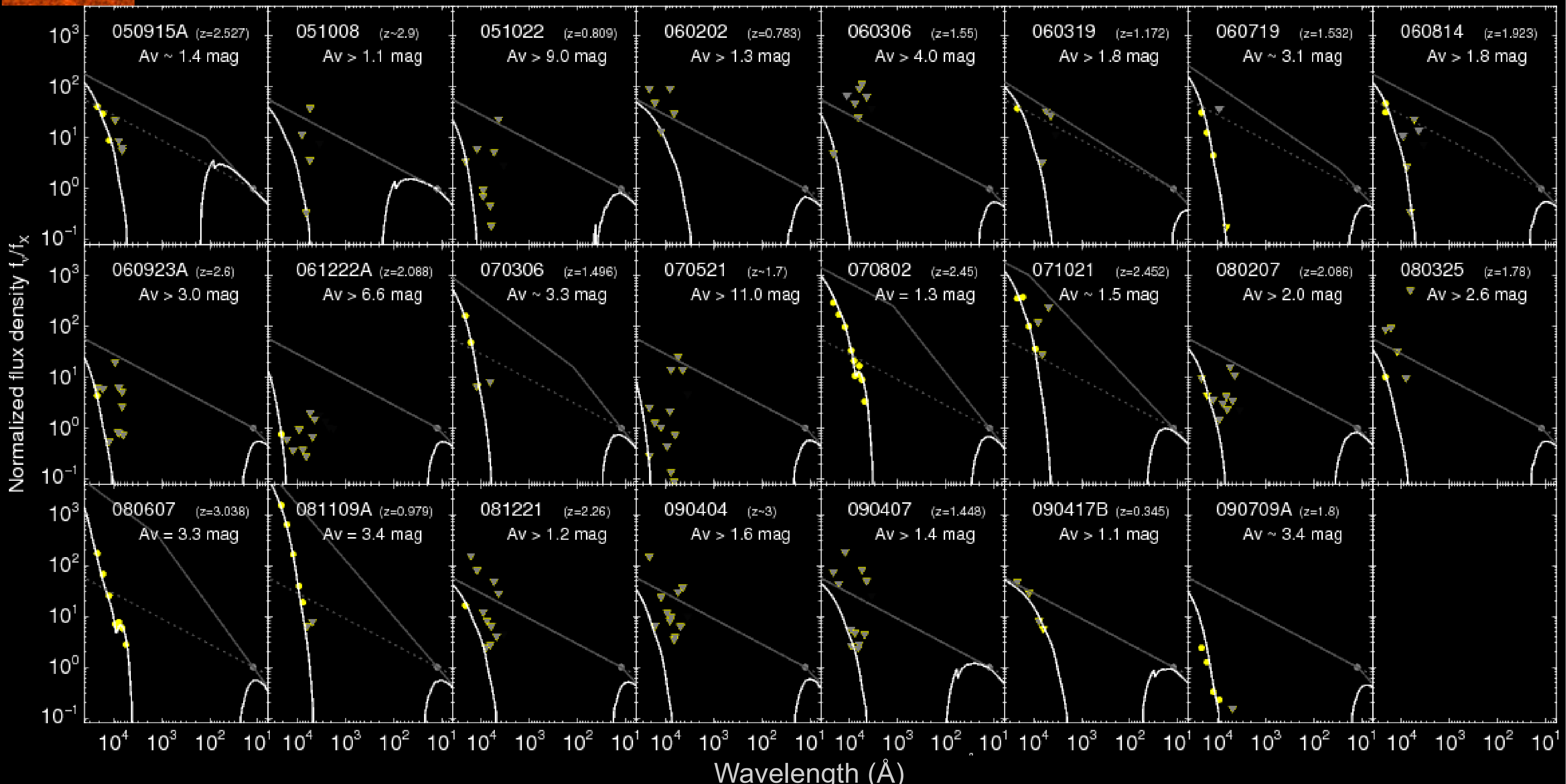


Compile all optical data, download all XRT data, construct co-eval SED, fit dust extinction...

Afterglow SEDs:



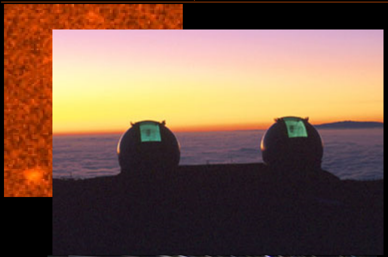
Selecting a Dusty-GRB Host Sample



23 events from 2005-2009

2 with optical afterglow redshift

Observing a Dusty-GRB Host Sample



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

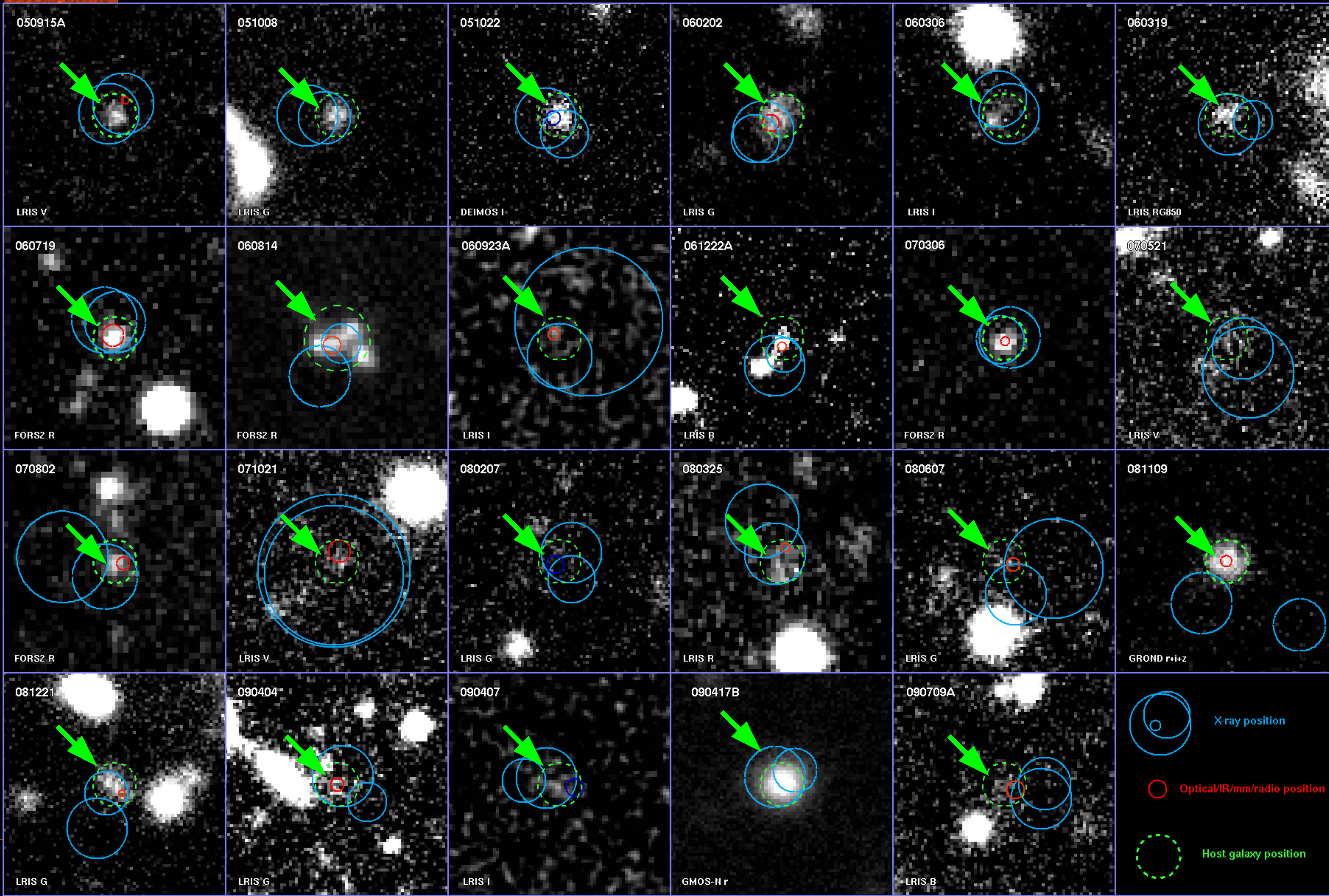
Gemini: NIR photometry for photo-z's, stellar masses.

Spitzer: Rest-frame NIR photometry for stellar masses.

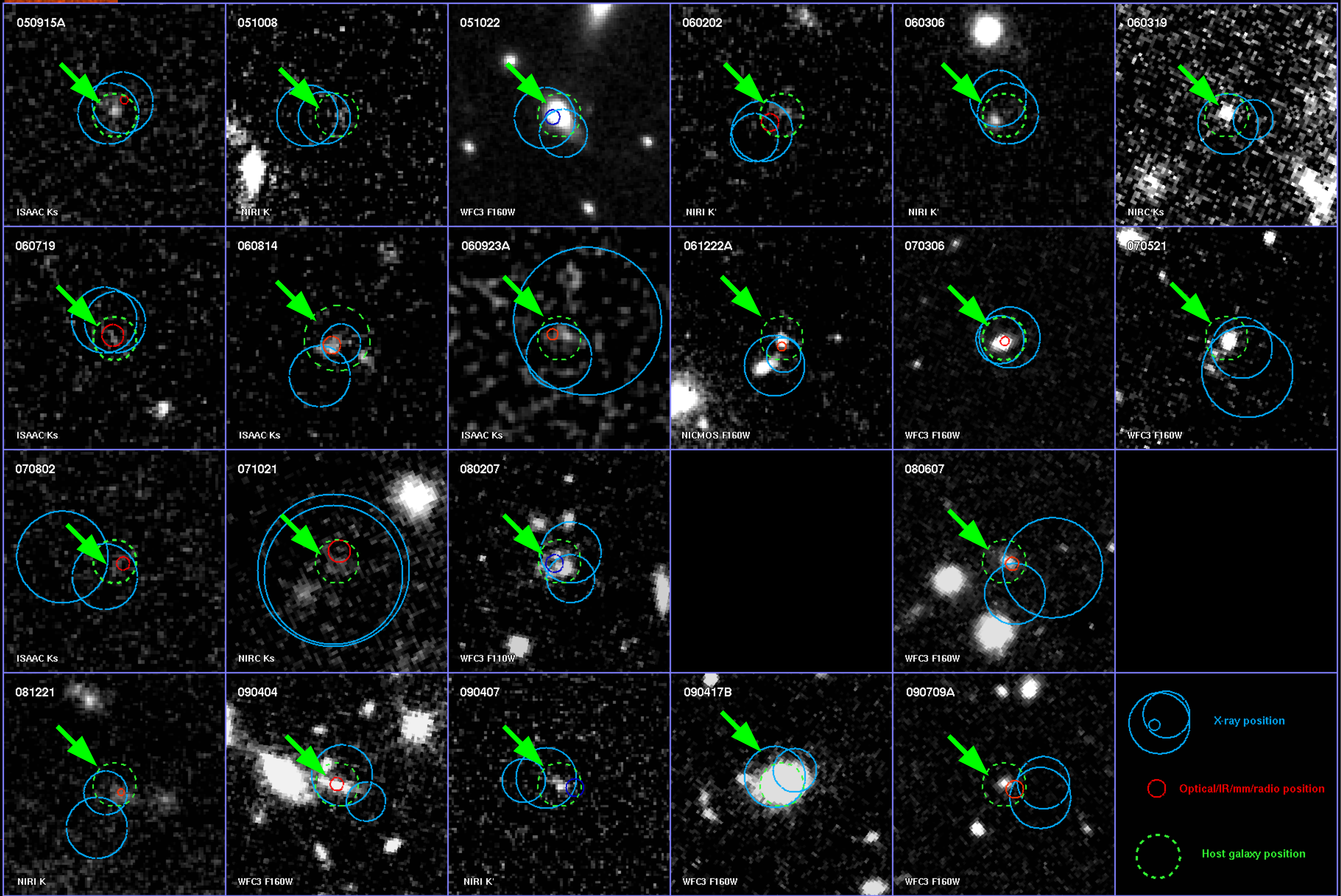
HST: NIR photometry, especially of faint targets.

VLT: R- and K-band photometry, spectroscopy for southern sources

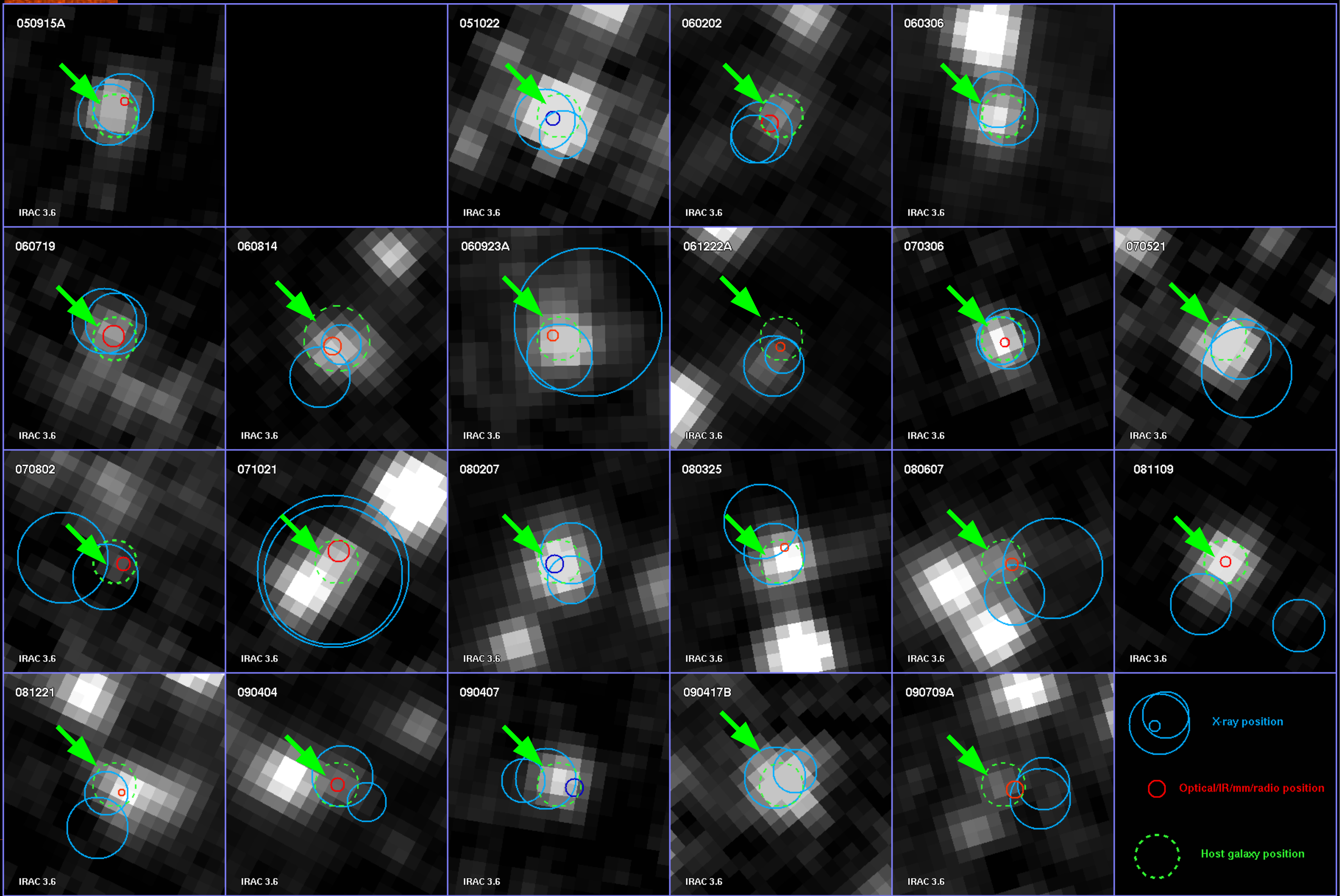
Optical Host Mosaic

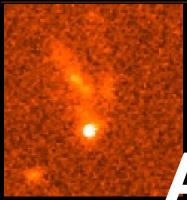


Near-IR Host Mosaic



Spitzer Host Mosaic



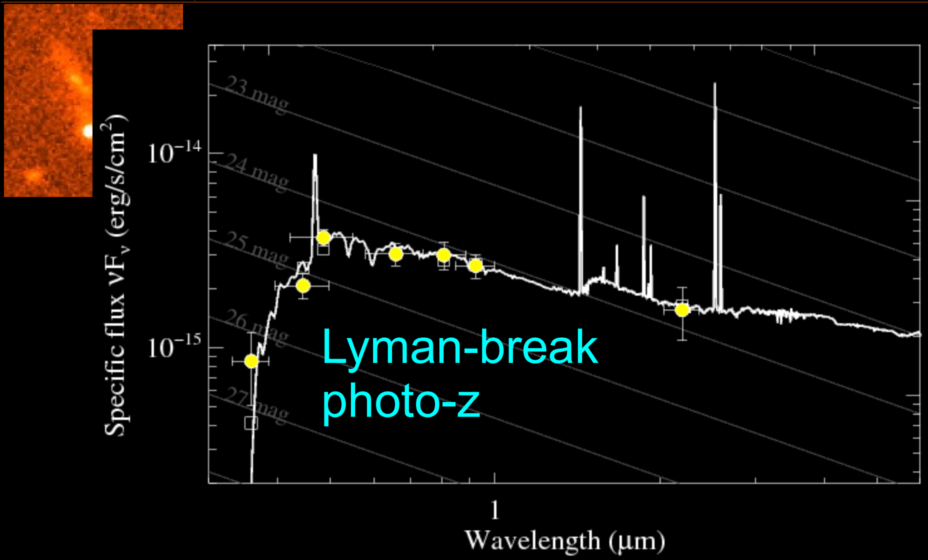


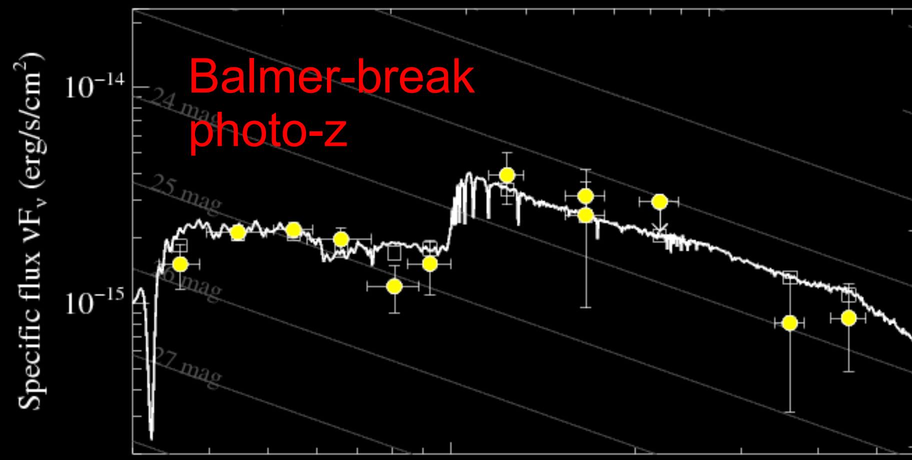
All 23 hosts detected in **all three bands**

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

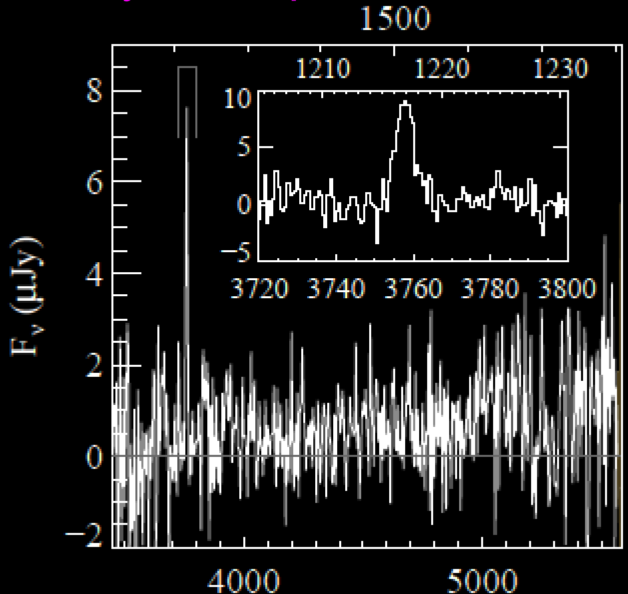
[Dusty + low-luminosity] galaxies are rare.

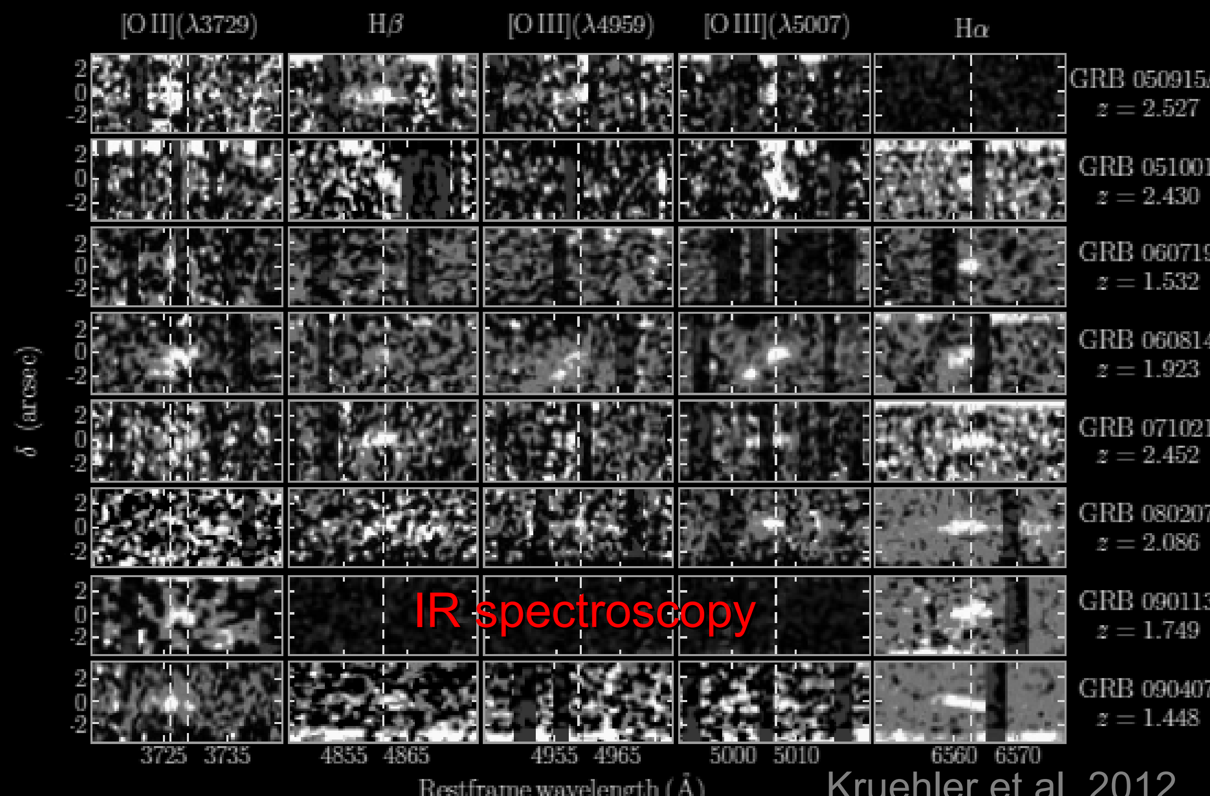
Redshift Measurement





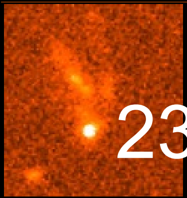
Lyman alpha emission





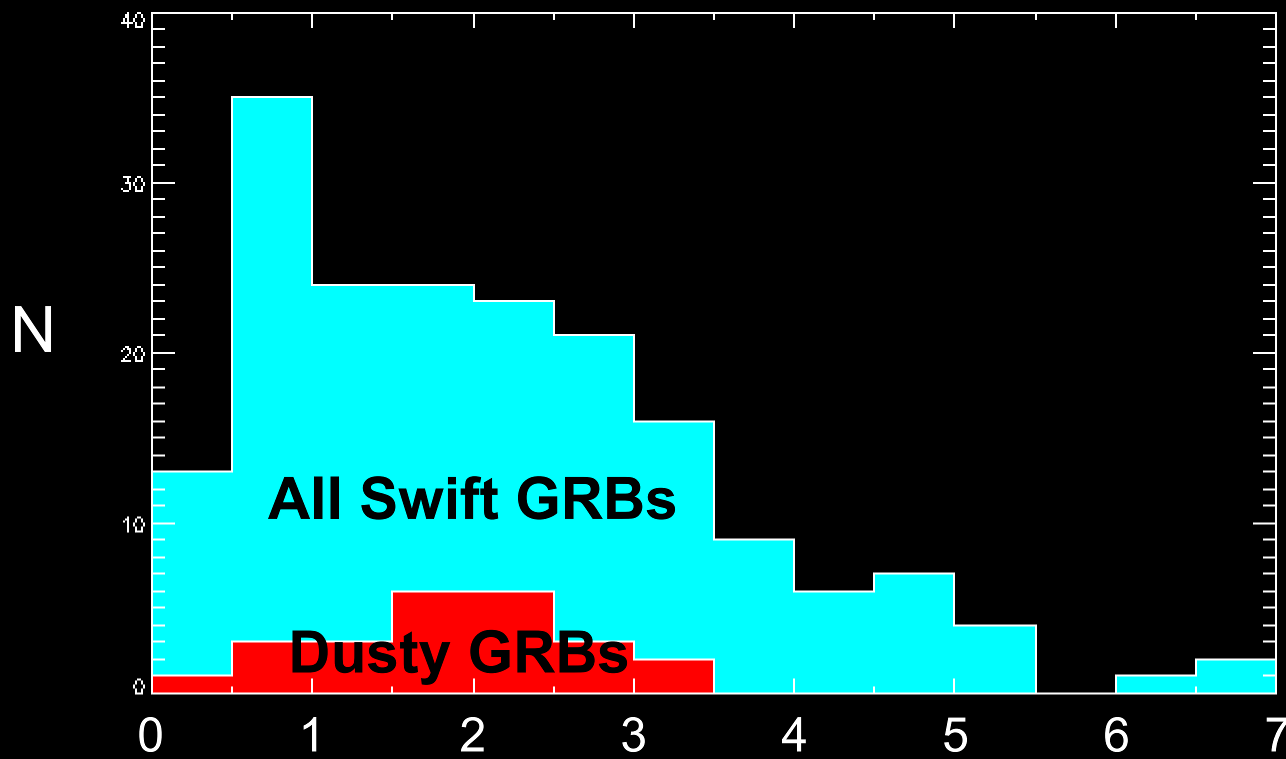
Kruehler et al. 2012

Redshift Distribution



23 / 23 successful redshifts!

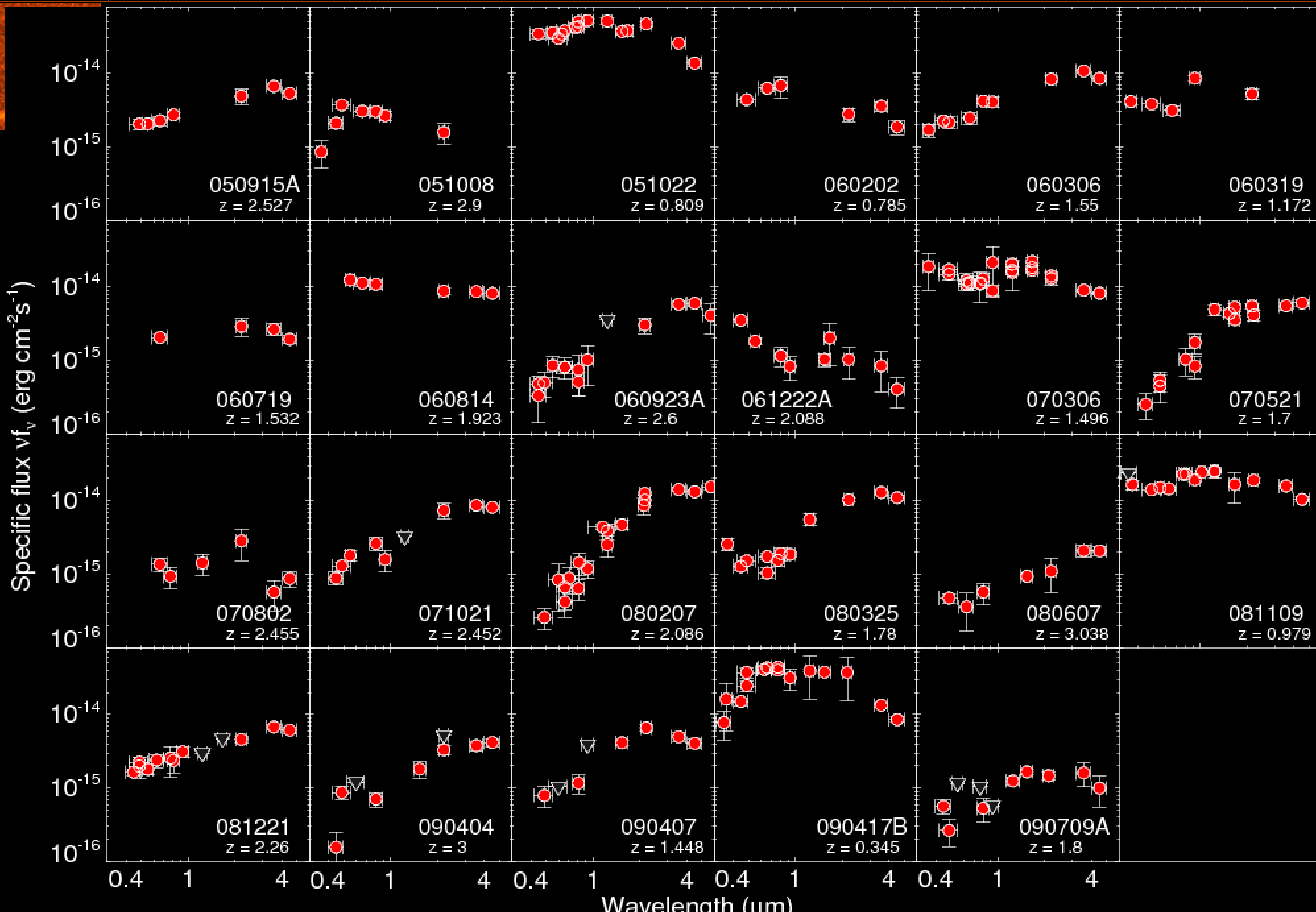
18 spectroscopic, 5 photometric



Broadly similar to overall Swift redshift distribution

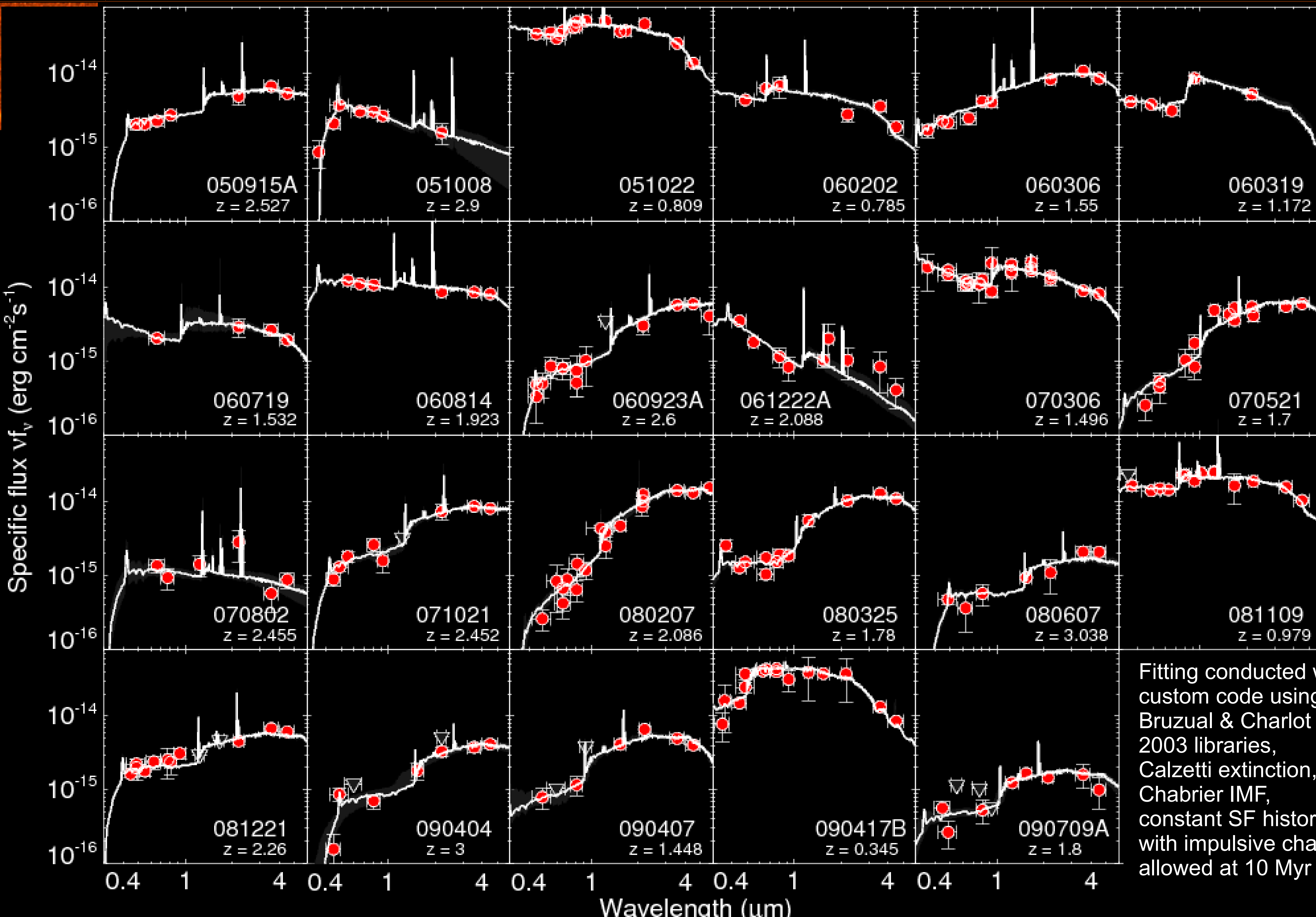
(possibly more strongly concentrated at z~2 –
not yet significant, and sample-selection biases could matter)

SED Fitting



Specific flux νf_ν (erg cm^{-2}s^{-1})
Wavelength (μm)
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

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

SED Fitting

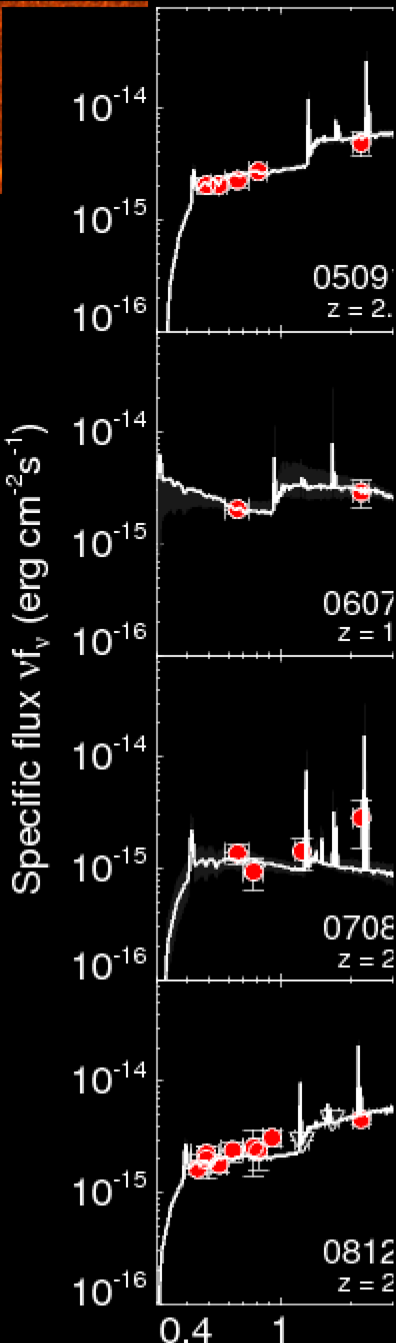
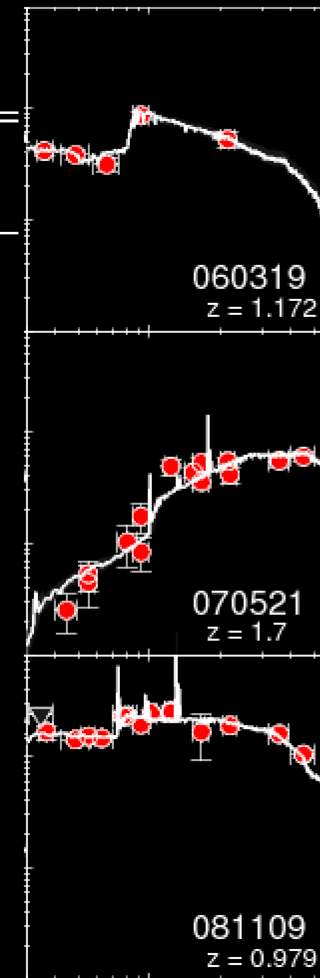


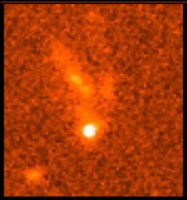
TABLE 4
GRB Host-Galaxy Properties

GRB[a]	z[b]	SFR[c] $M_\odot\ yr^{-1}$	M_*[d] $10^9\ M_\odot$	A_V[e] mag	χ^2/dof
050915A	2.53	$135.8^{+63.1}_{-48.3}$	$36.7^{+16.0}_{-10.4}$	$1.51^{+0.14}_{-0.20}$	4.8/4
051008	$2.90^{+0.29}_{-0.16}$	$80.4^{+282.3}_{-52.4}$	$2.2^{+6.4}_{-1.1}$	$0.84^{+0.29}_{-0.34}$	5.8/4
051022	0.81	$26.2^{+7.0}_{-6.6}$	$17.8^{+3.8}_{-3.0}$	$0.73^{+0.13}_{-0.17}$	18.2/12
060202	0.79	$5.8^{+1.3}_{-1.9}$	$1.1^{+0.4}_{-0.1}$	$1.00^{+0.11}_{-0.20}$	15.5/3
060306	1.55	$244.0^{+128.7}_{-67.1}$	$8.0^{+1.9}_{-0.9}$	$2.21^{+0.14}_{-0.12}$	11.5/6
060319	1.17	$0.0^{+0.4}_{-0.0}$	$6.8^{+1.4}_{-1.2}$	$0.07^{+0.17}_{-0.07}$	2.7/1
060719	1.53	$4.0^{+36.9}_{-4.0}$	$13.0^{+-0.5}_{-12.8}$	$0.37^{+1.10}_{-0.37}$	0.5/0
060814	1.92	$236.7^{+28.4}_{-18.3}$	$9.8^{+0.8}_{-0.8}$	$1.23^{+0.06}_{-0.04}$	3.2/3
060923A	$3.00^{+0.75}_{-1.08}$	$76.9^{+45.6}_{-33.0}$	$149.9^{+42.3}_{-38.7}$	$1.56^{+0.29}_{-0.27}$	10.8/11
061222A	2.09	$2.7^{+0.2}_{-0.2}$	$1.3^{+1.1}_{-0.6}$	$0.00^{+0.00}_{-0.00}$	13.3/6
070306	1.50	$7.7^{+2.9}_{-0.9}$	$39.7^{+5.9}_{-8.6}$	$0.00^{+0.15}_{-0.00}$	18.0/18
070521	$1.70^{+0.50}_{-0.33}$	$42.2^{+14.3}_{-10.7}$	$32.2^{+10.4}_{-4.7}$	$2.19^{+0.09}_{-0.13}$	22.3/11
070802	2.45	$79.8^{+111.5}_{-44.9}$	$1.1^{+0.7}_{-0.1}$	$1.40^{+0.34}_{-0.30}$	3.4/3
071021	2.45	$107.8^{+98.1}_{-54.5}$	$98.1^{+61.8}_{-38.5}$	$1.63^{+0.26}_{-0.27}$	9.7/6
080207	2.09	$47.2^{+267.6}_{-44.6}$	$120.1^{+54.4}_{-49.3}$	$2.36^{+0.45}_{-0.37}$	48.3/15
080325	1.78	$15.2^{+12.4}_{-4.4}$	$153.4^{+9.9}_{-25.0}$	$1.09^{+0.28}_{-0.13}$	18.4/8
080607	3.04	$18.3^{+5.0}_{-3.2}$	$36.2^{+5.9}_{-5.1}$	$1.08^{+0.13}_{-0.11}$	7.8/3
081109	0.98	$51.1^{+9.2}_{-8.6}$	$8.8^{+1.3}_{-1.2}$	$1.26^{+0.08}_{-0.09}$	19.3/15
081221	2.26	$73.0^{+16.4}_{-13.1}$	$65.9^{+5.5}_{-7.1}$	$1.39^{+0.09}_{-0.08}$	29.5/9
090404	$3.00^{+0.84}_{-1.75}$	$39.8^{+178.1}_{-21.6}$	$98.9^{+7.7}_{-92.8}$	$1.32^{+1.16}_{-0.22}$	10.8/5
090407	1.45	$16.6^{+1.8}_{-15.2}$	$20.1^{+115.8}_{-2.0}$	$1.77^{+0.11}_{-1.17}$	8.3/5
090417B	0.34	$0.5^{+0.3}_{-0.3}$	$3.4^{+0.3}_{-0.5}$	$0.87^{+0.12}_{-0.08}$	21.3/15
090709A	$1.80^{+0.55}_{-0.66}$	$8.3^{+4.4}_{-3.6}$	$10.0^{+3.7}_{-2.5}$	$1.40^{+0.12}_{-0.22}$	16.0/7



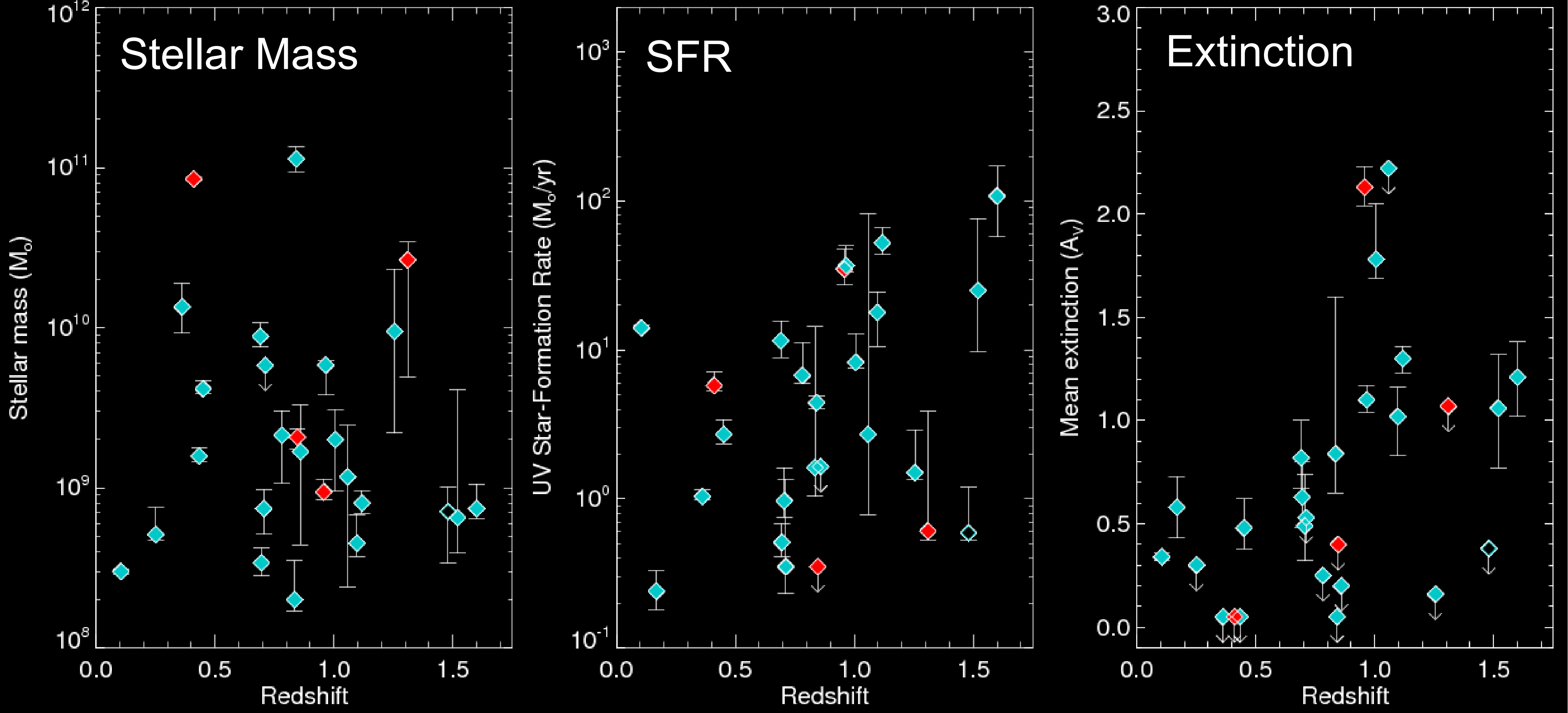
Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr

Comparisons at z~1

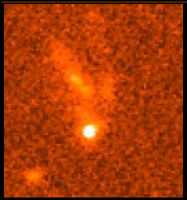


Pre-Swift events only:

Blue=unobscured GRB, Red = obscured GRB.

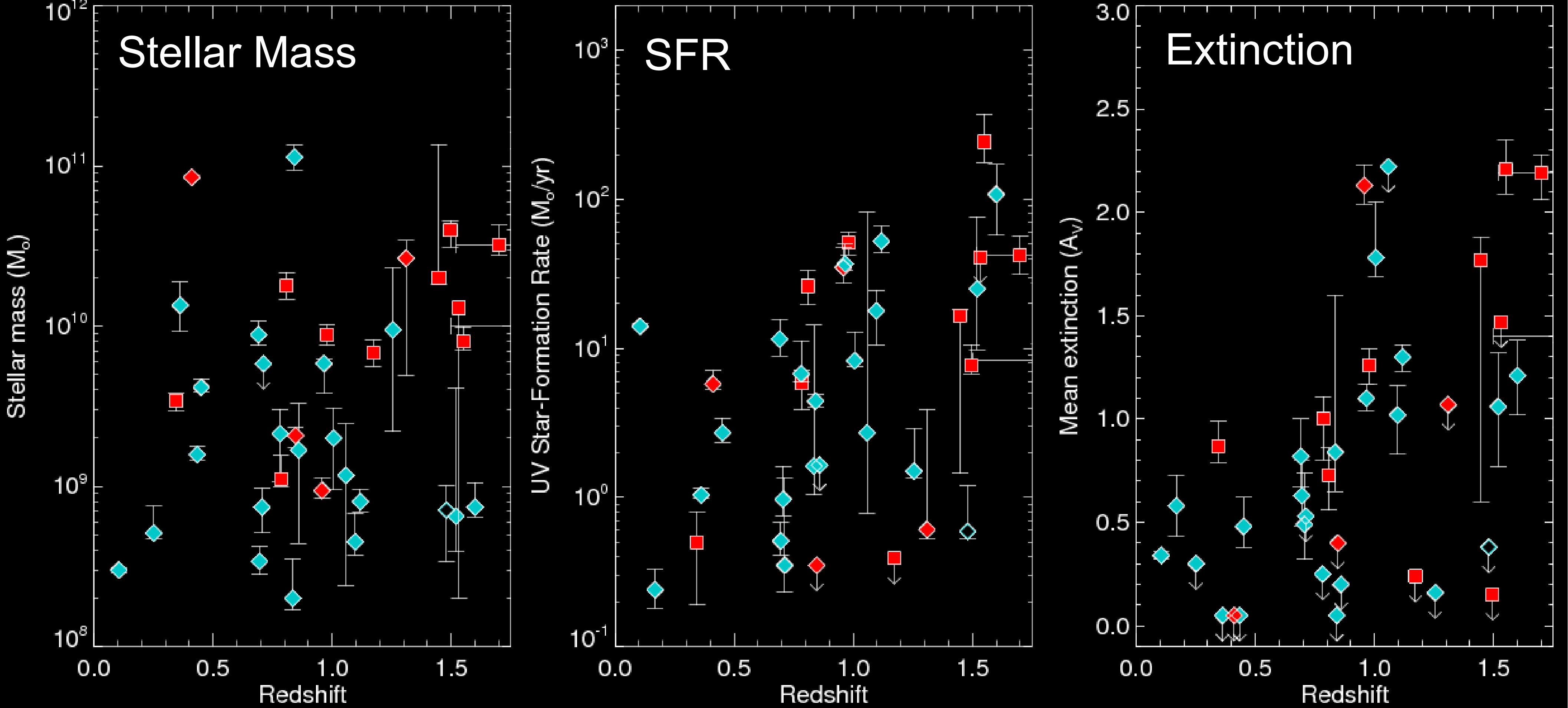


Comparisons at z~1



Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



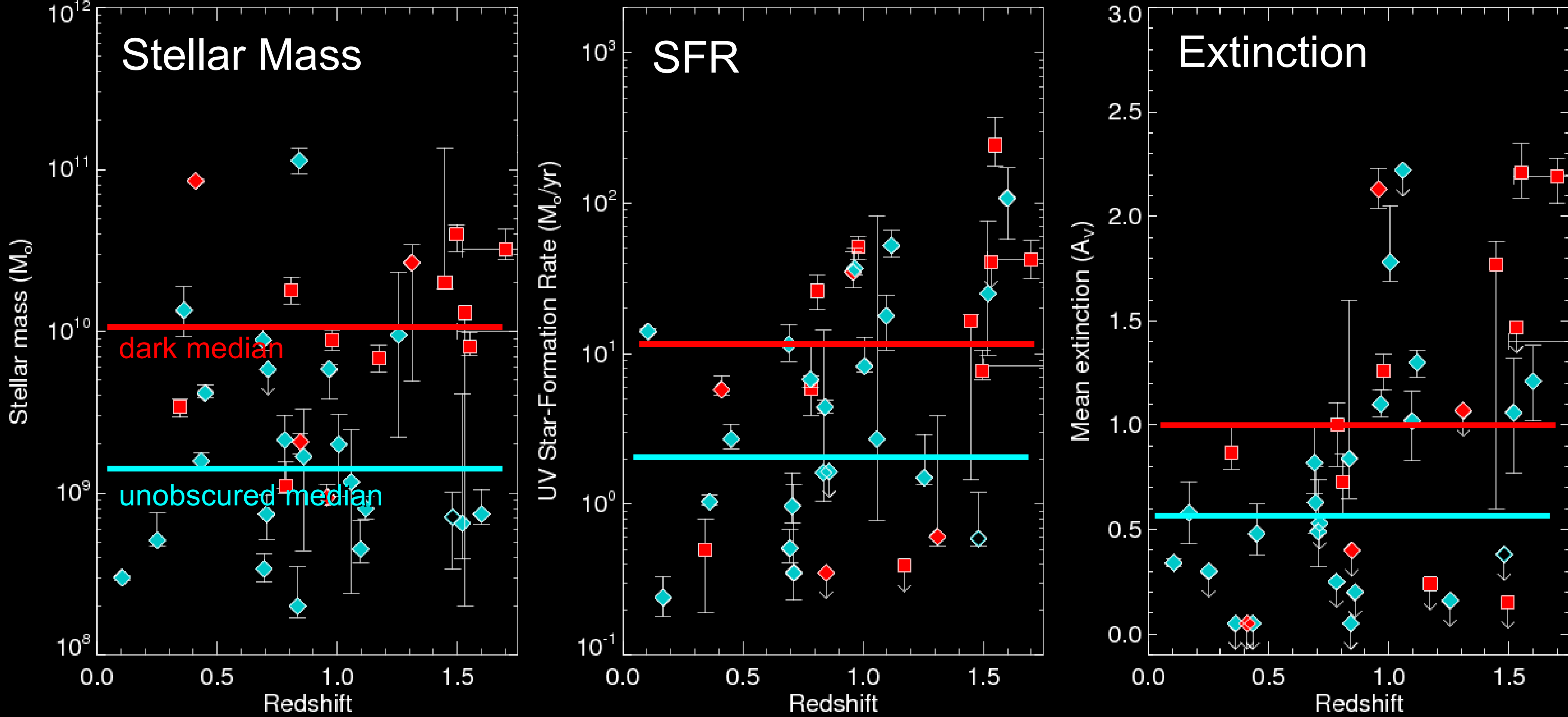
Comparisons at z~1

"Darkness" matters!

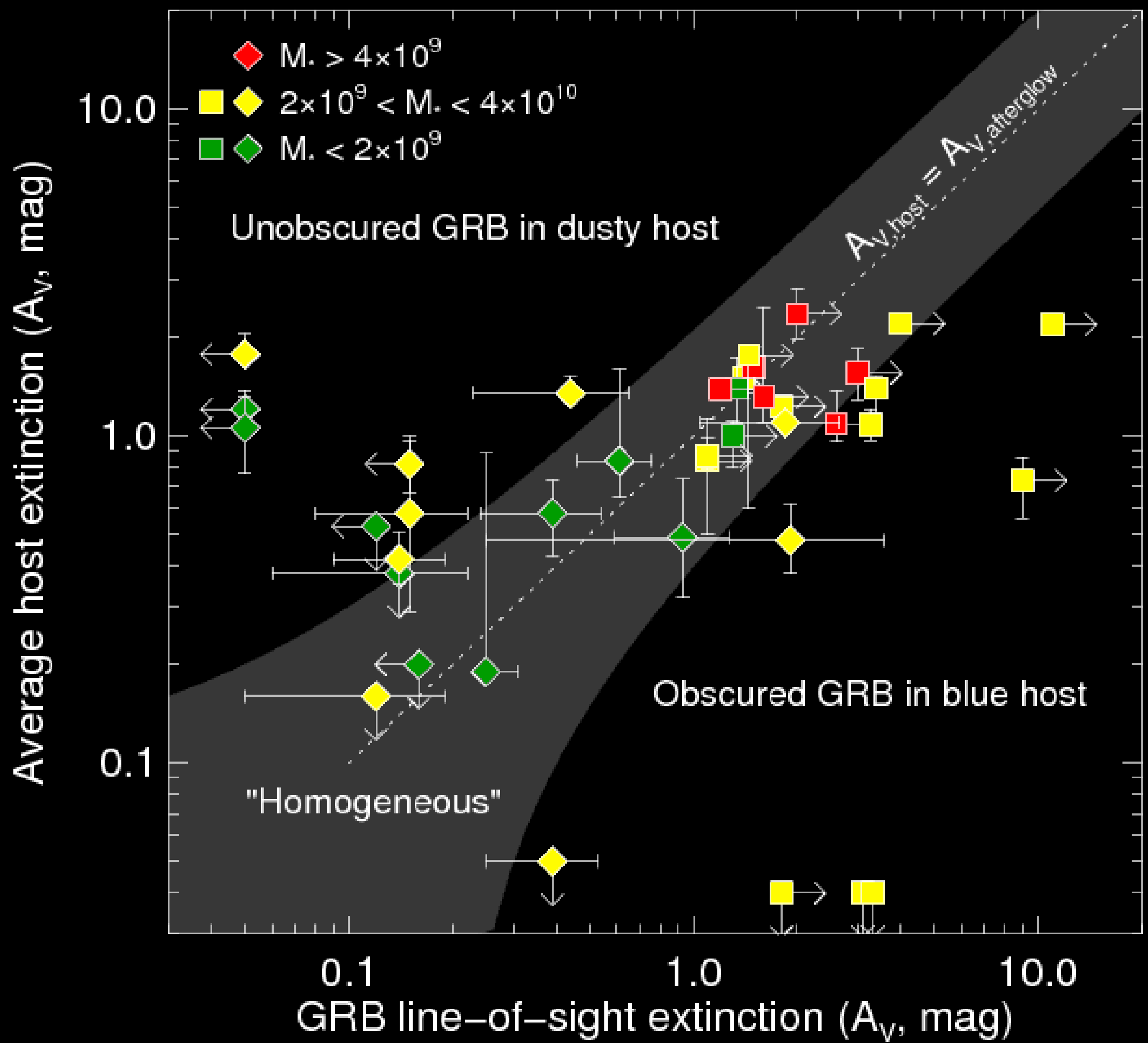
Obscured hosts are more massive, star-forming, and dusty.

Combined pre-Swift + dark sample:

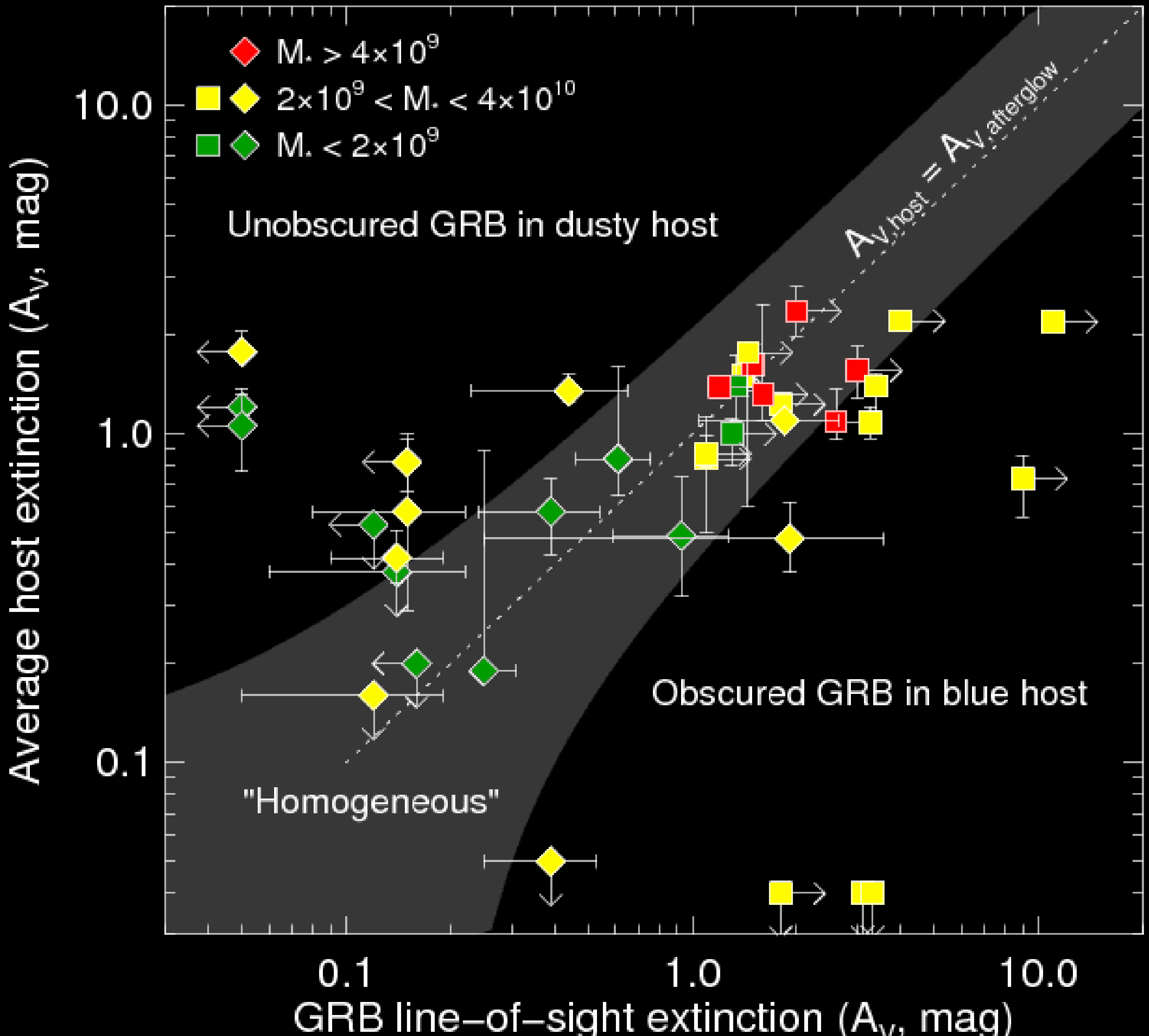
Blue=unobscured GRB, Red = obscured GRB.



Obscuration vs. Obscuration



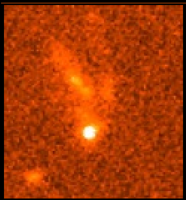
Obscuration vs. Obscuration



Dusty sightline (usually) implies a dusty, massive galaxy:

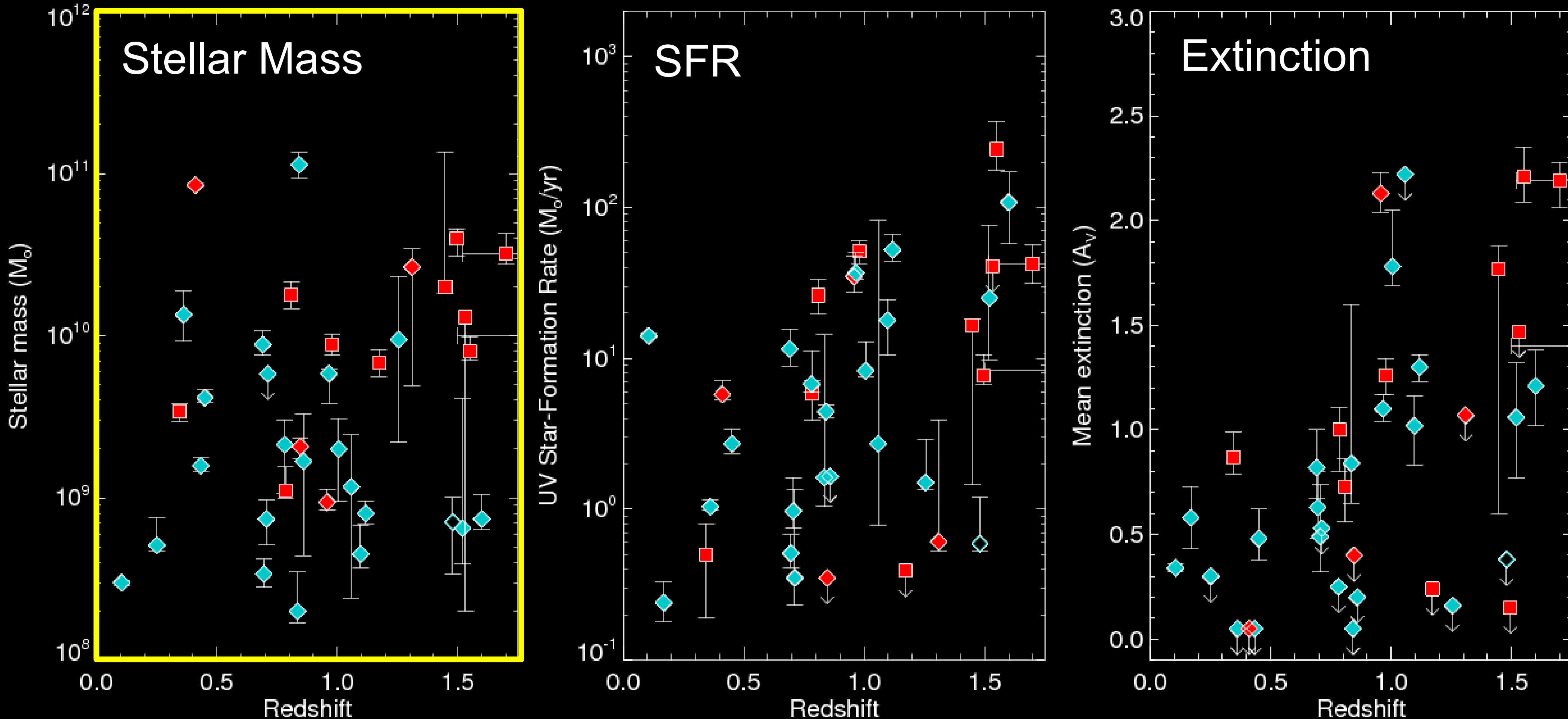
High-z galaxies are relatively dust-homogeneous

Comparisons at z~1

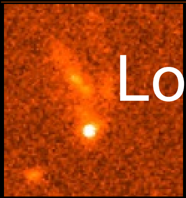


Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



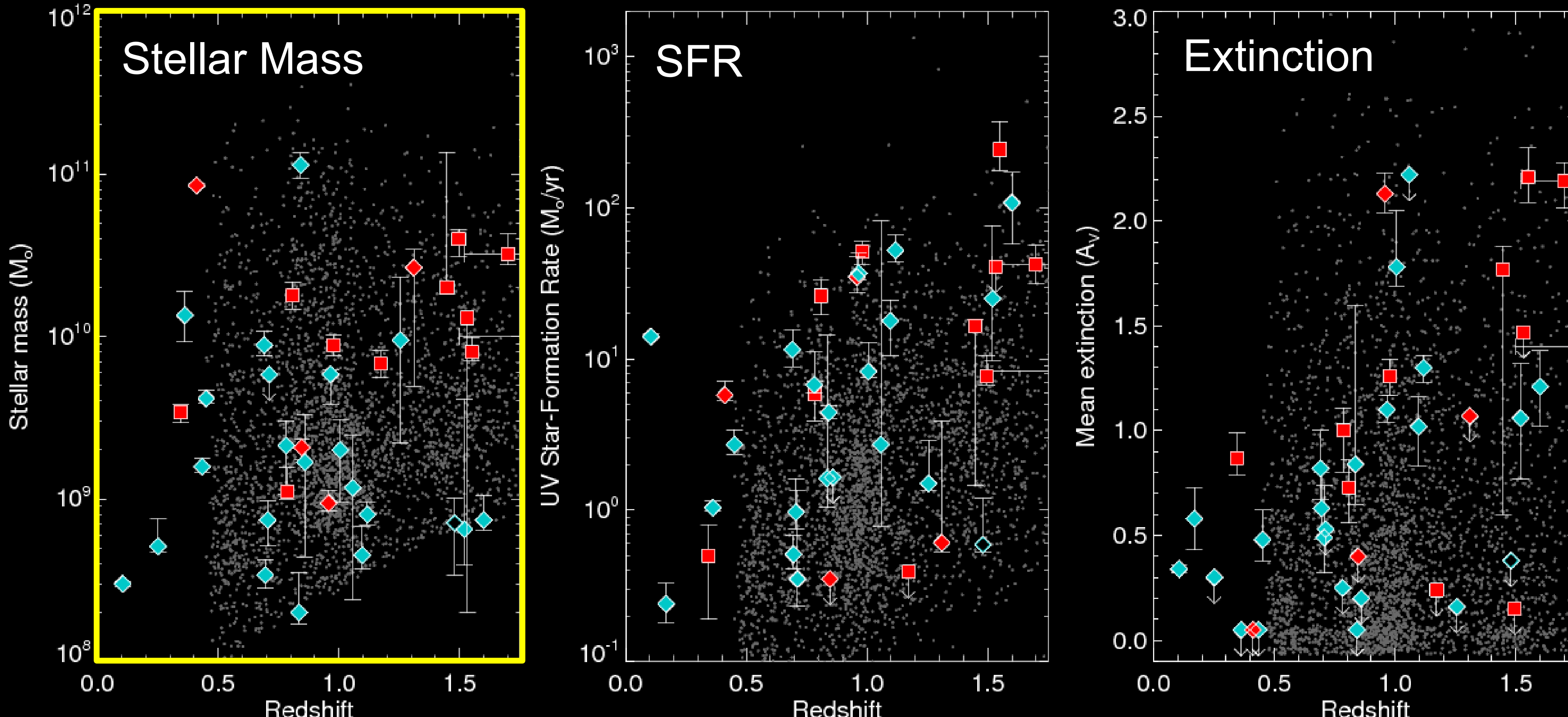
Comparisons vs. Field Galaxies at z~1



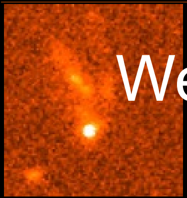
Looks “consistent” with field galaxy *number* distributions...

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

Combined sample versus field galaxies:



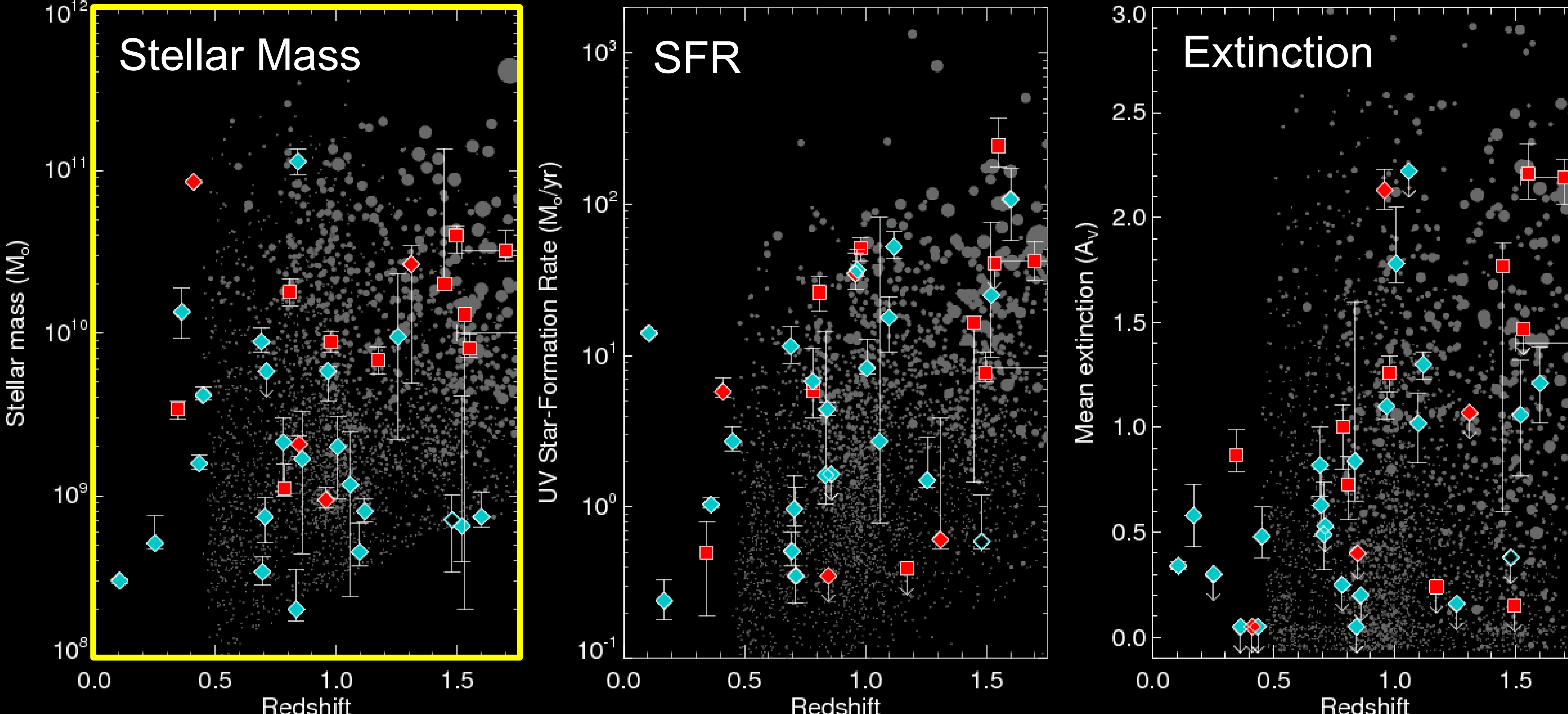
Comparisons vs. Field Galaxies at z~1



Weighting by SFR is essential. Null hypothesis is RGRB ∝ SFR.

Combined sample versus field galaxies:

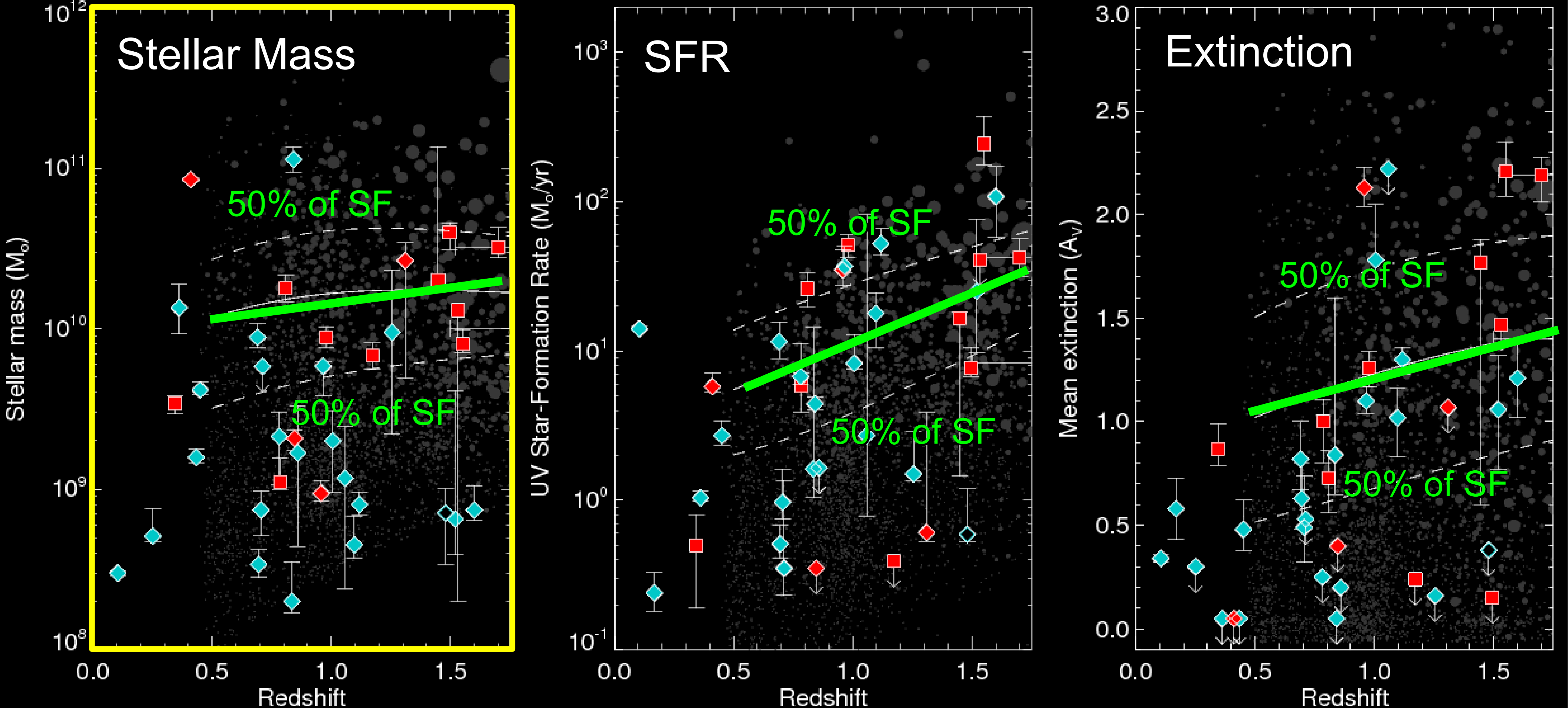
Grey points: field galaxies from MOIRCS deep survey (Kajisawa et al. 2011), omitting AGN (hard X-ray detection). Point size scaled by UV+IR SFR.



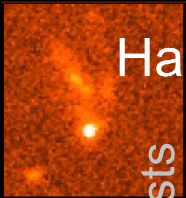
Comparisons vs. Field Galaxies at z~1

Calculate z-dependent median (mass,SFR,Av) of SFR-weighted population.
Half of GRBs should be above median, half below (if $R_{GRB} \propto$ SFR)

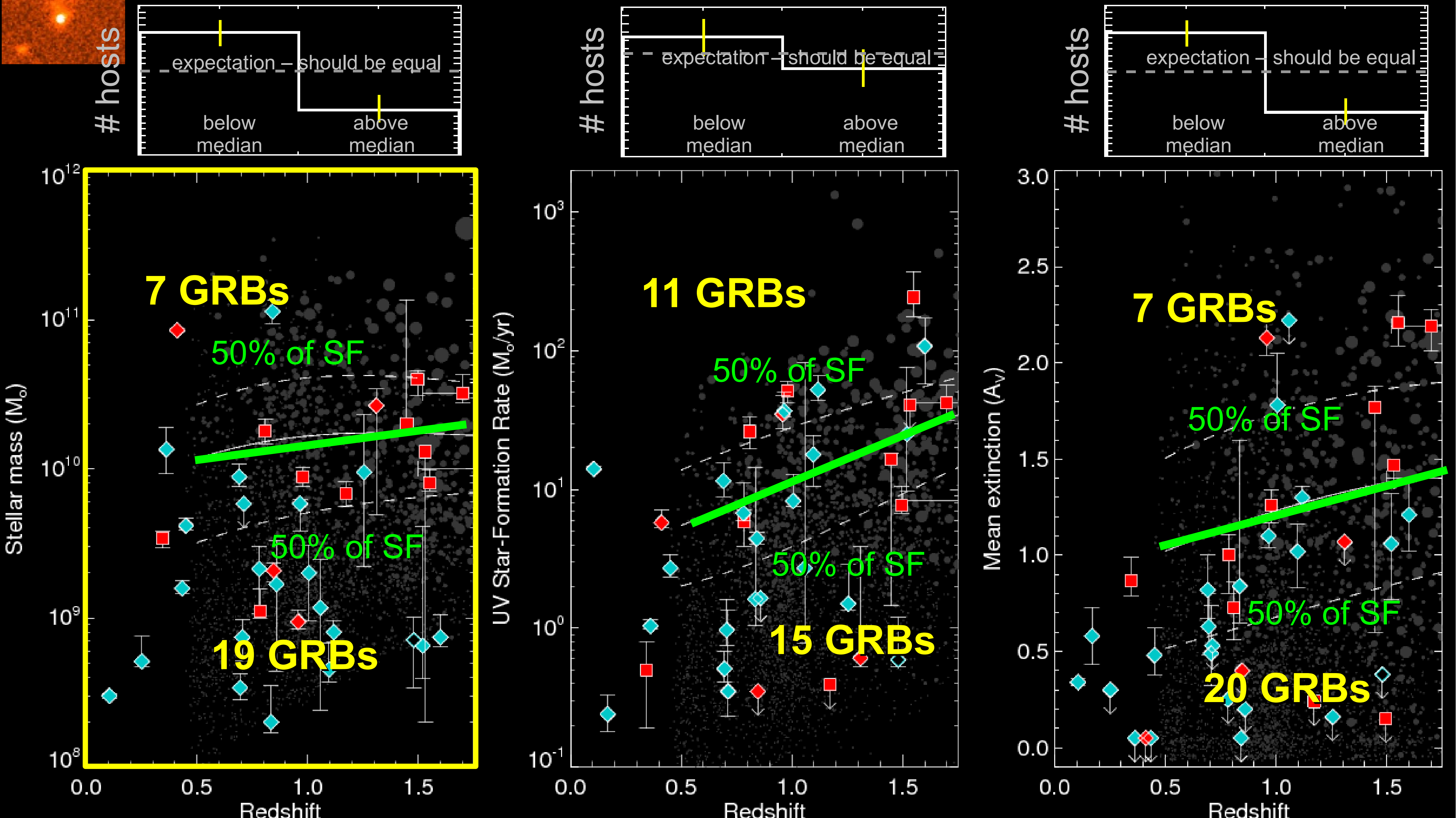
Combined sample versus field galaxies:



Comparisons vs. Field Galaxies at z~1

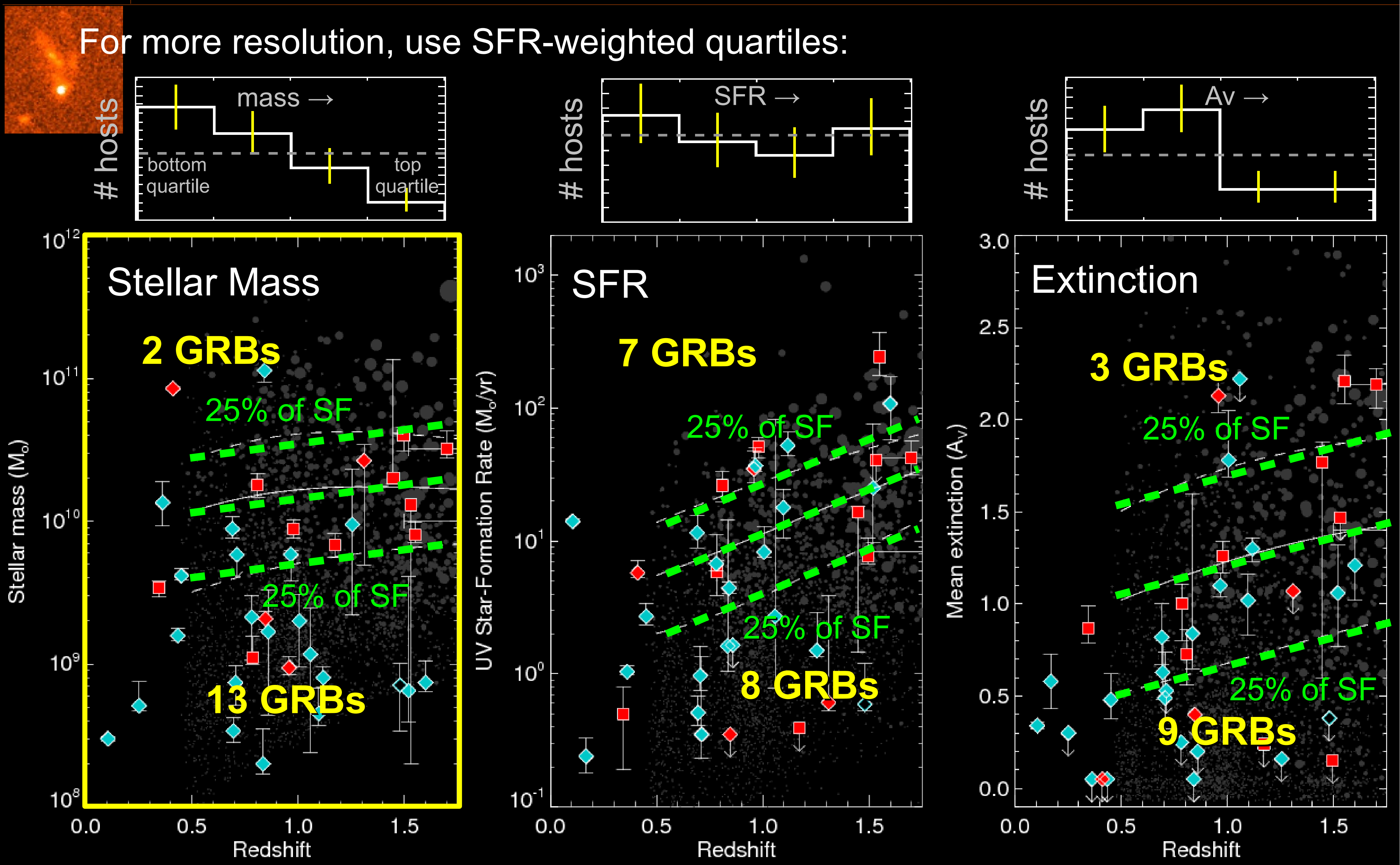


Half of GRBs should be above median, half below (if $R_{GRB} \propto$ SFR)



Comparisons vs. Field Galaxies at z~1

For more resolution, use SFR-weighted quartiles:



Comparisons vs. Field Galaxies at z~1

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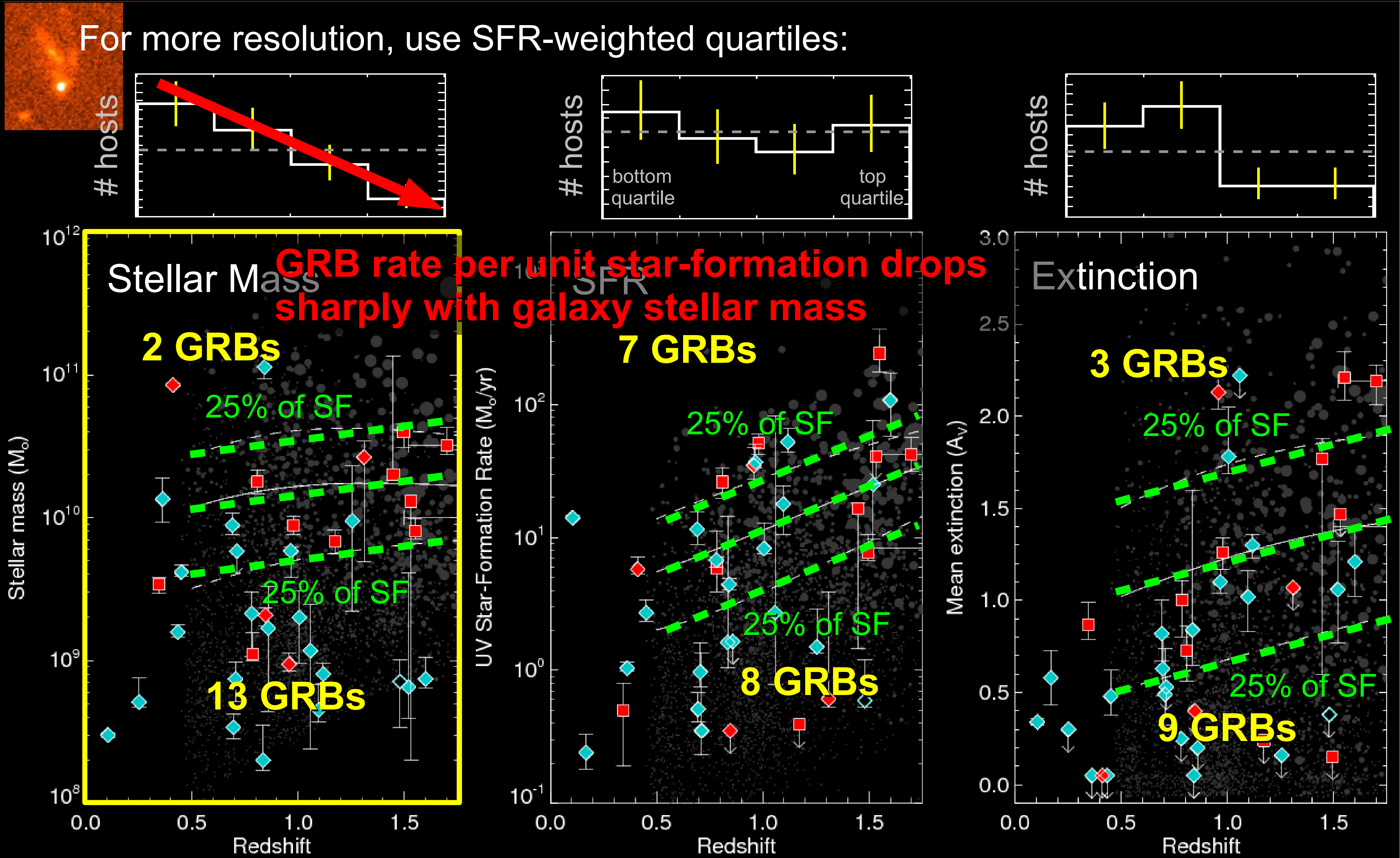
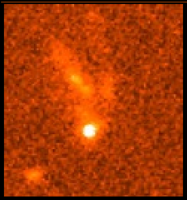


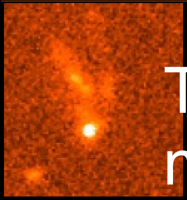
Comparisons vs. Field Galaxies at z~1



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

(Order-of-magnitude dependence on factor other than SFR.)

Origins of GRB Rate Variations



The GRB progenitor can't possibly care directly about the mass, Av, etc. of its host. What might it care about?

ISM chemical properties:

Metallicity (affects stellar evolution)

most strongly correlated with **mass**/**Av**.

ISM physical properties:

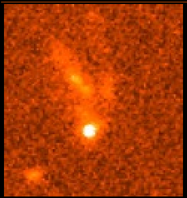
UV radiation field.

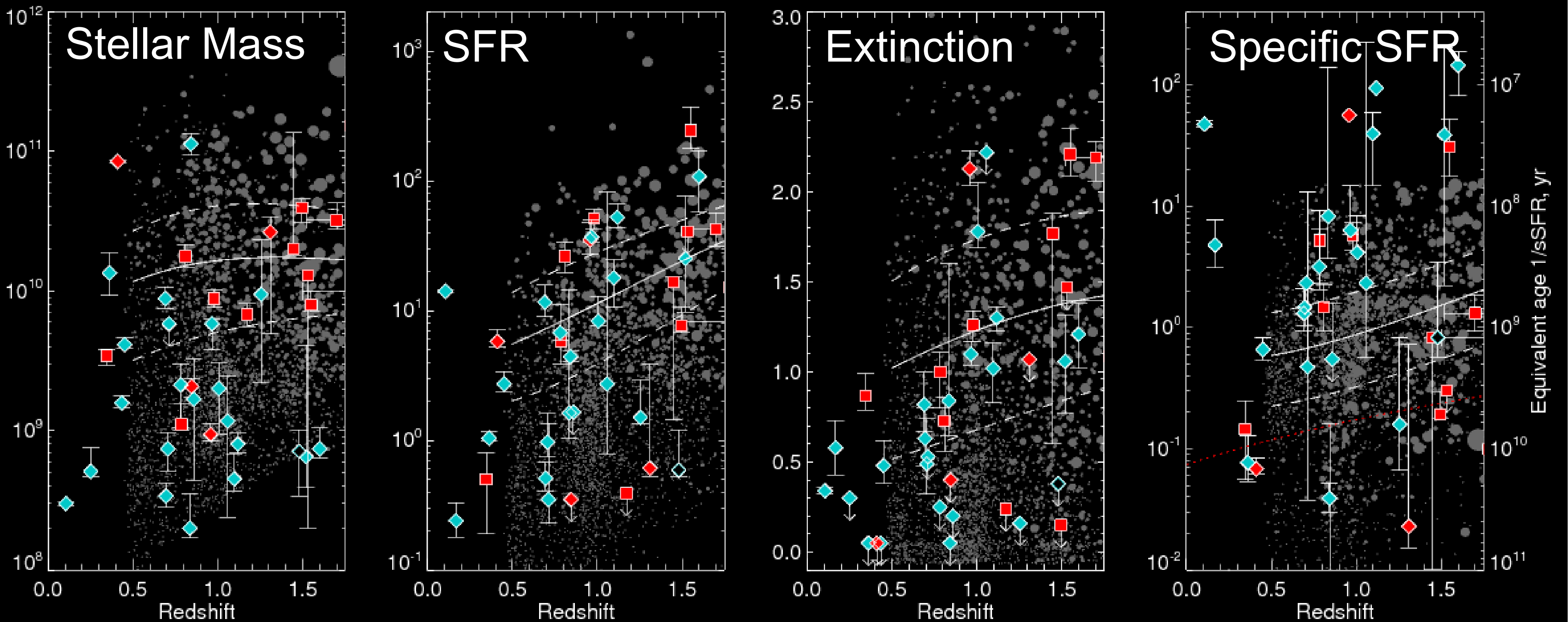
Gas density.

(could affect IMF, initial binarity properties, etc.)

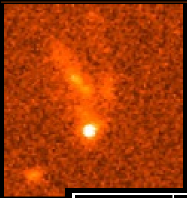
most strongly correlated with **SFR**/**sSFR**.

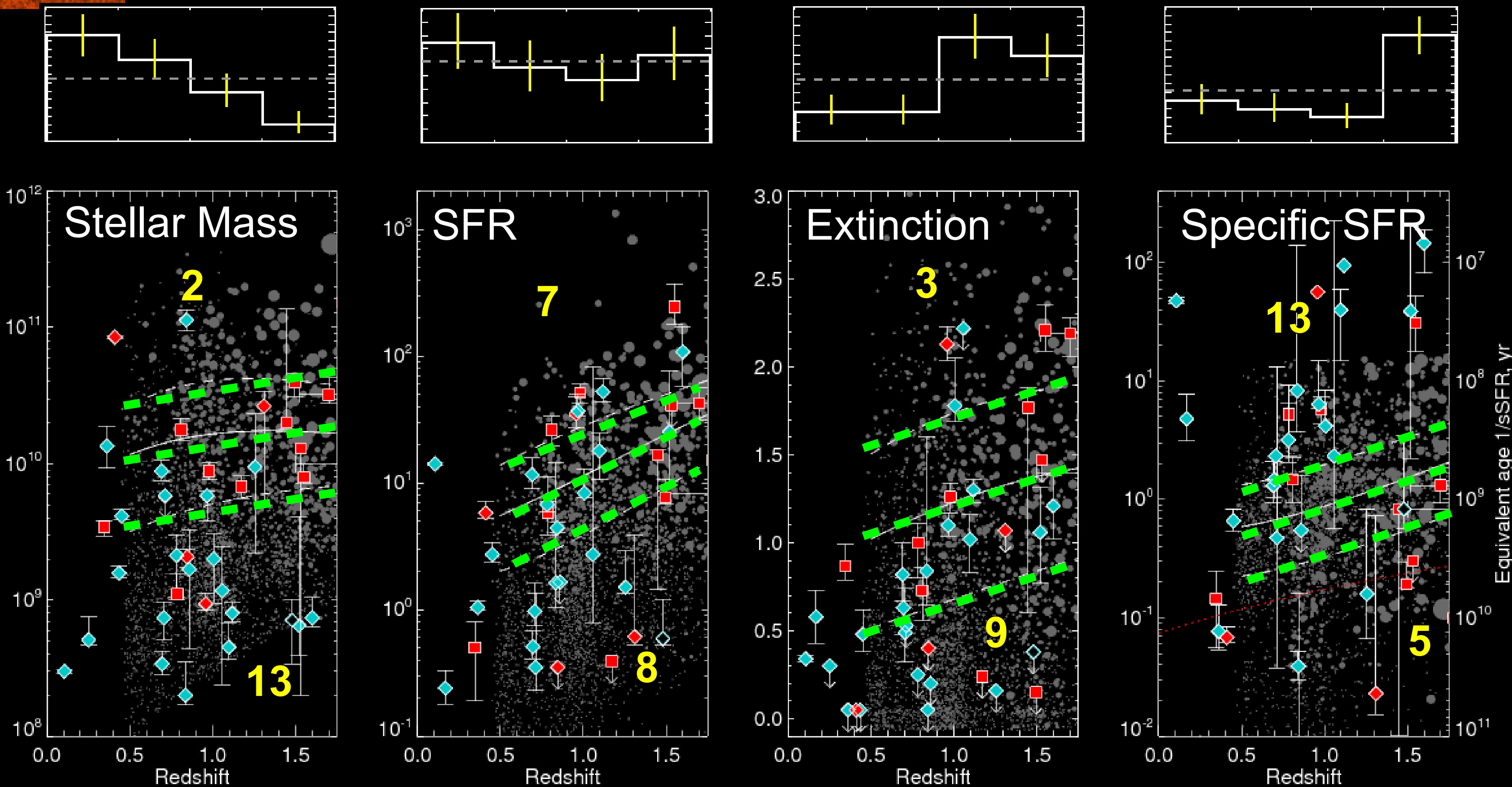
Origins of GRB Rate Variations



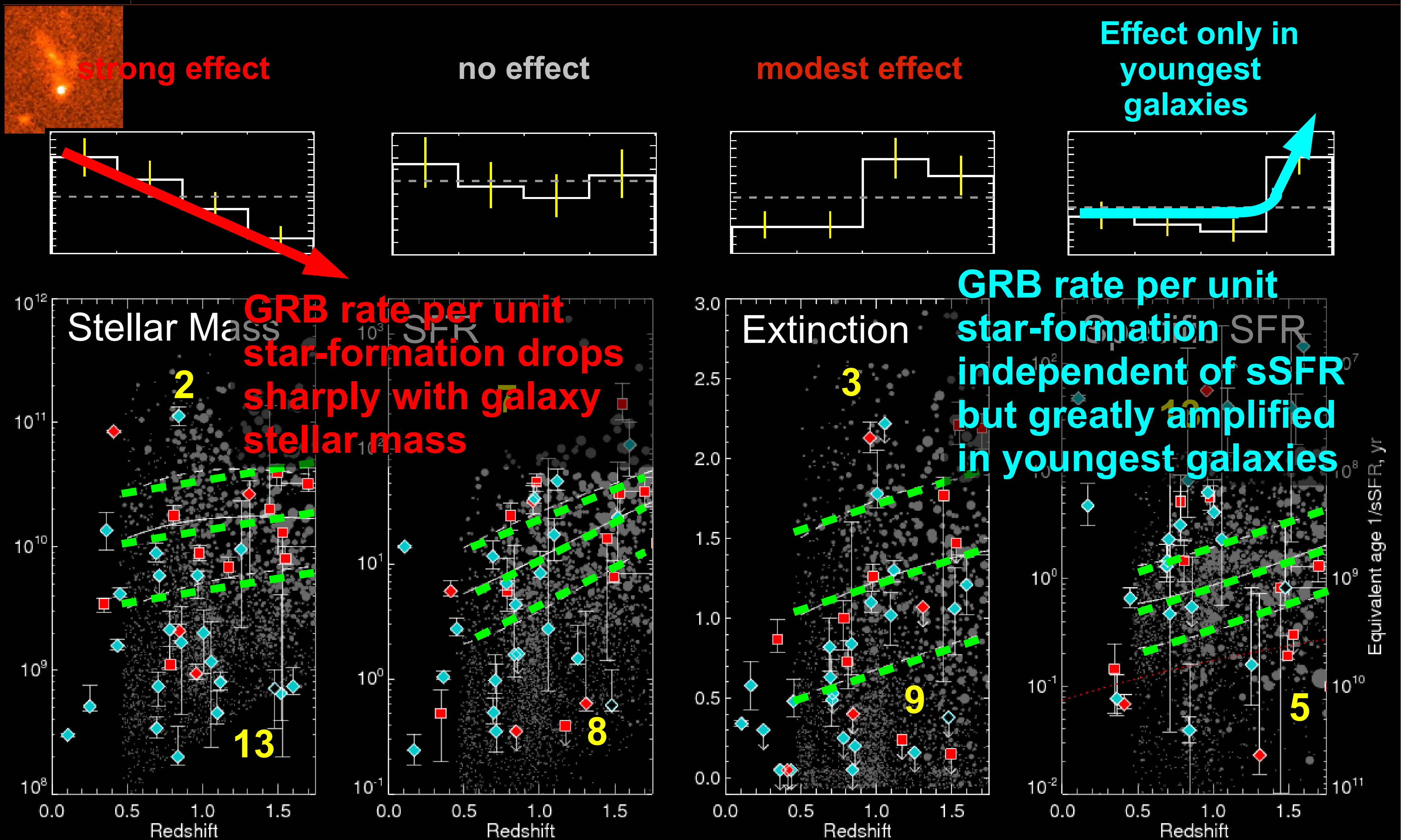


Origins of GRB Rate Variations





Origins of GRB Rate Variations



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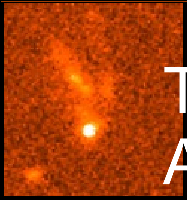


The GRB progenitor can't possibly care directly about the mass, Av, etc. of its host. What might it care about?

ISM chemical properties:

Metallicity (affects stellar evolution)

most strongly correlated with **mass**/**Av**.

Consistent with being dominant effect.

Emission-line metallicities (vs. SNe) show even stronger trends (e.g. Stanek et al. 2007, Modjaz et al. 2009, Graham & Fruchter 2012)

ISM physical properties:

UV radiation field.

Gas density.

(could affect IMF, initial binarity properties, etc.)

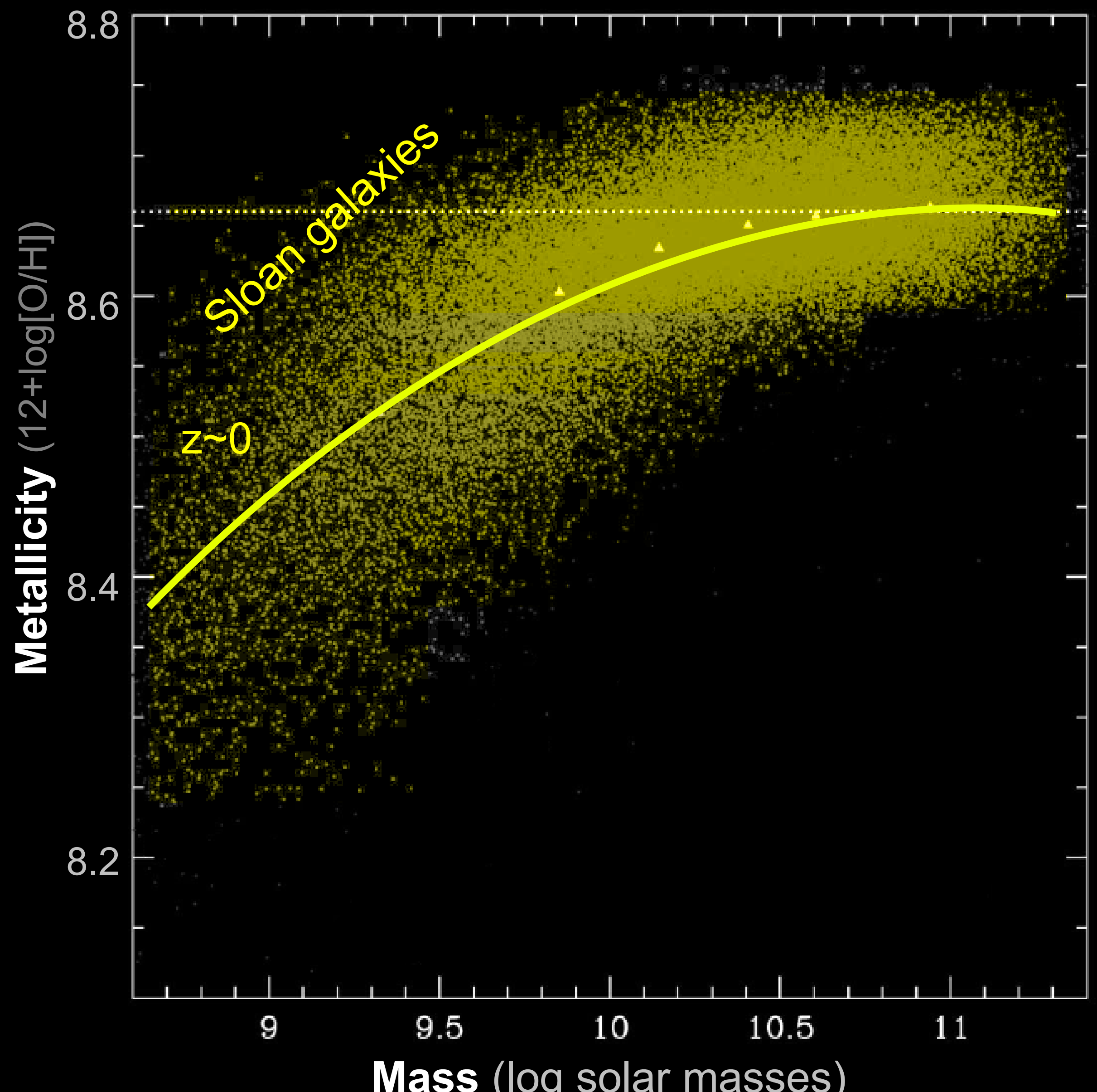
most strongly correlated with **SFR**/**sSFR**.

May play a secondary role in youngest galaxies?

(Not clear – needs to be separated from metallicity-sSFR trend [Mannucci et al. 2011])

Mass, Metallicity, Redshift

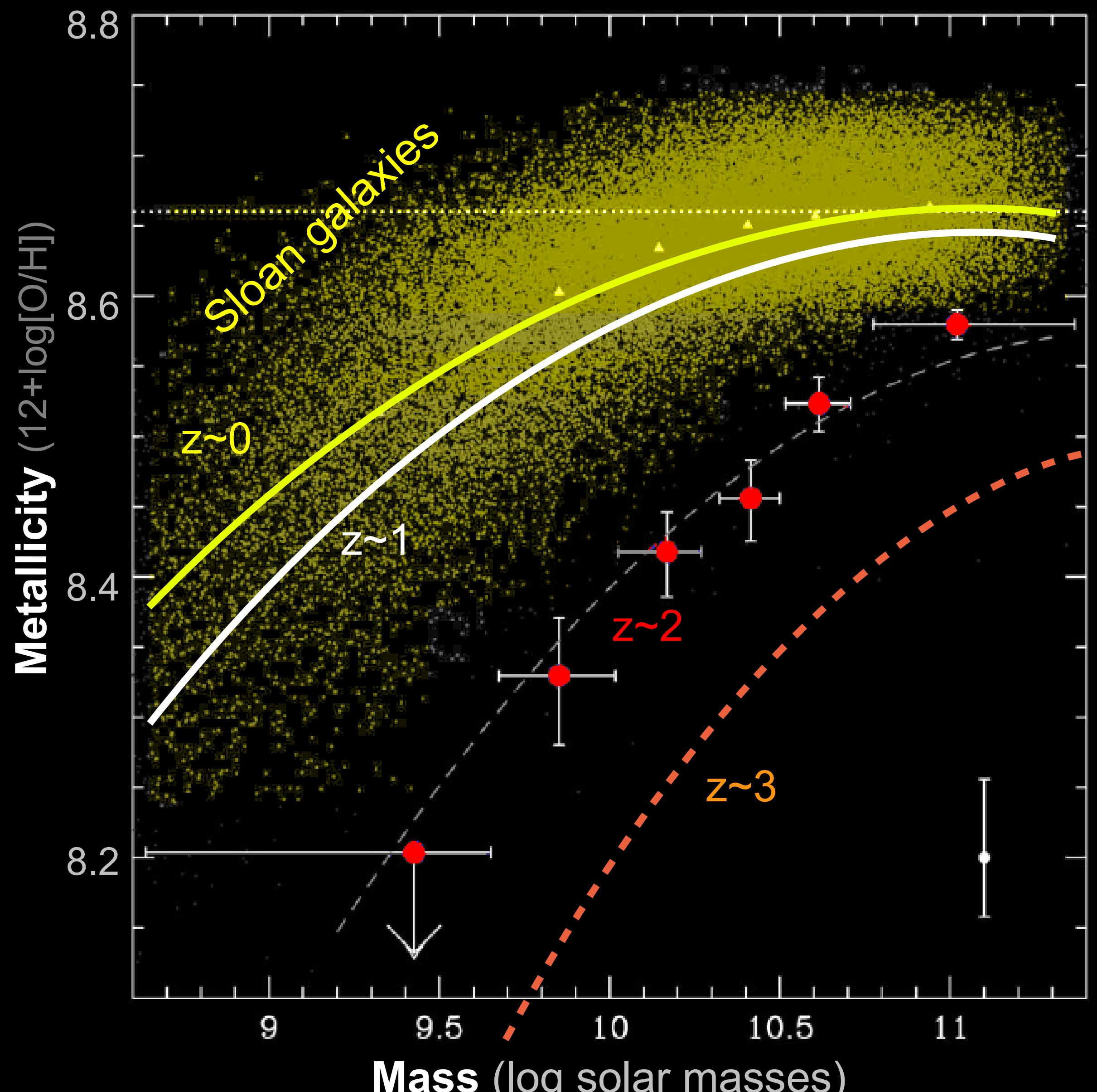
Mass and metallicity are correlated at low-z.



Kewley et al. 2008, Erb et al. 2006

Mass, Metallicity, Redshift

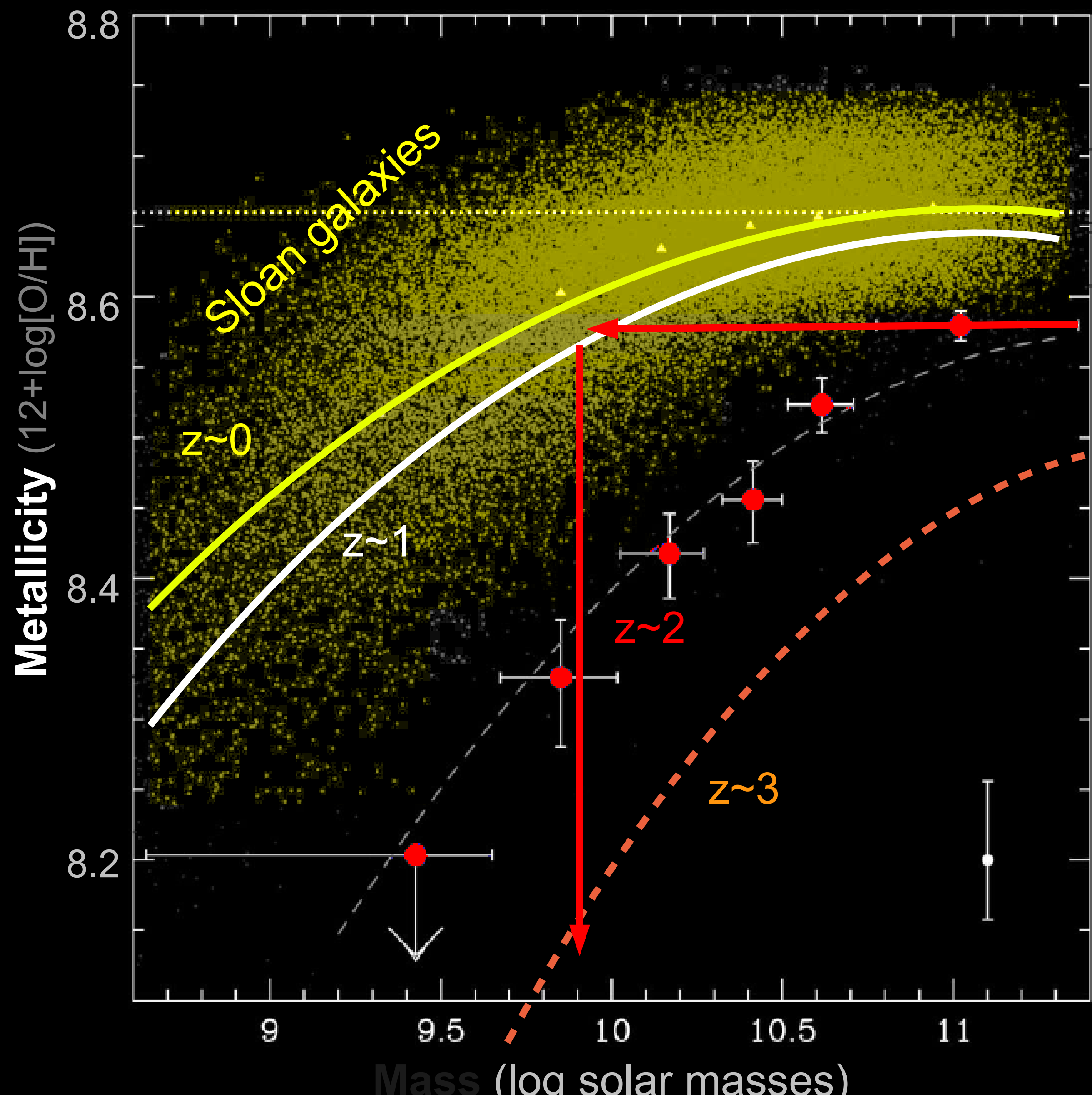
Mass and metallicity are correlated at low-z...
and at high-z.



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

Mass, Metallicity, Redshift

Massive z~2 galaxies
should have similar metallicity to
~10^{10} M$_\odot$, z~1 galaxies



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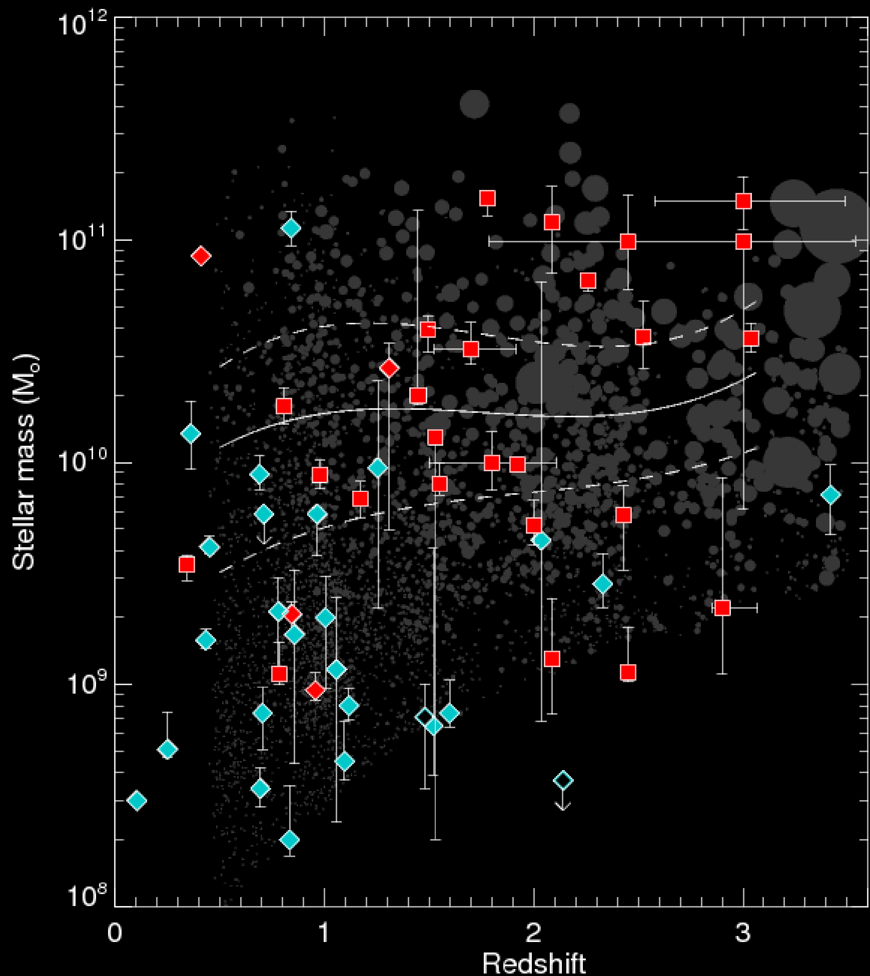

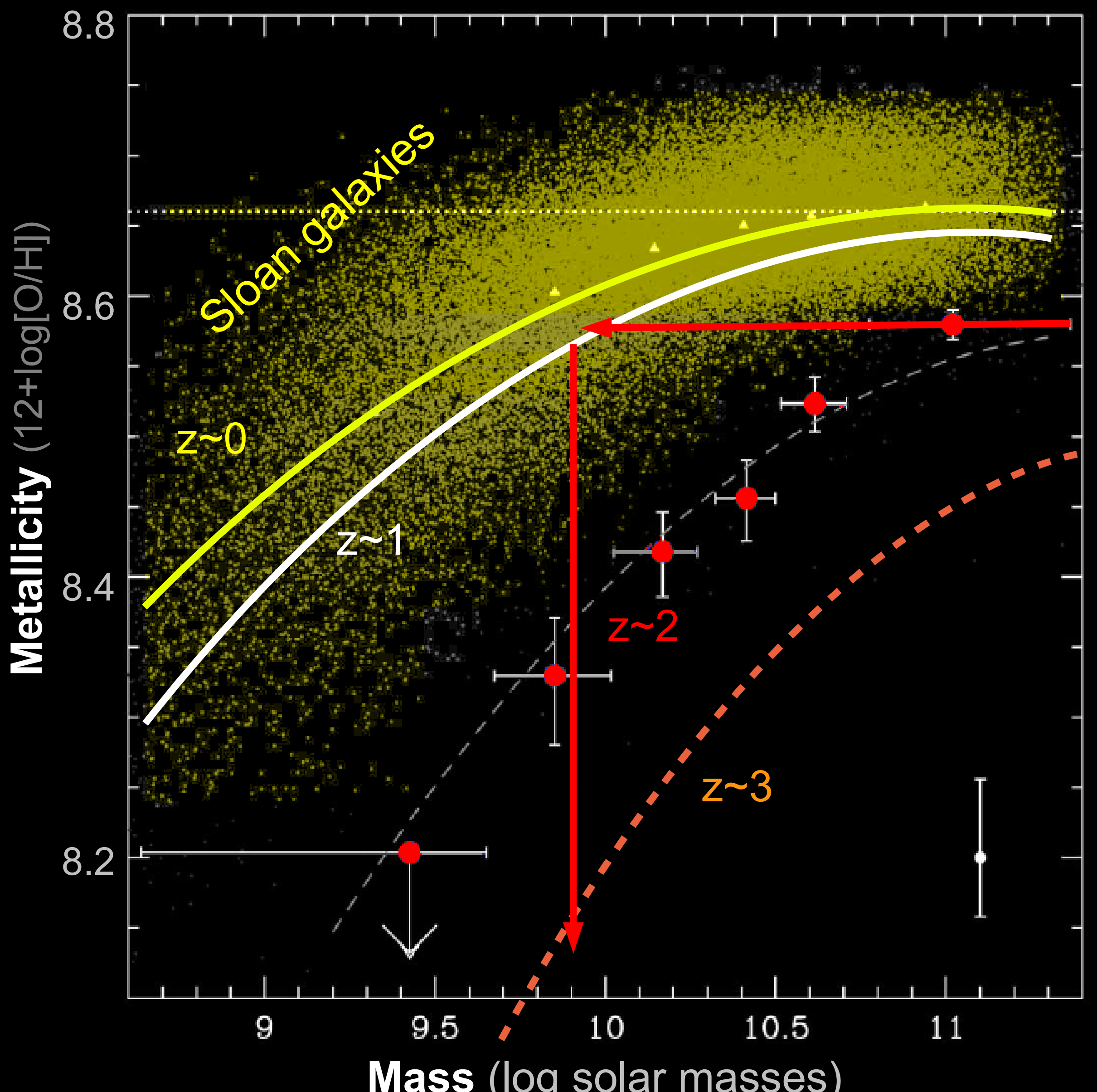

Kewley et al. 2008, Savaglio et al. 2005,, Erb et al. 2006, Maiolino et al. 2008,2009

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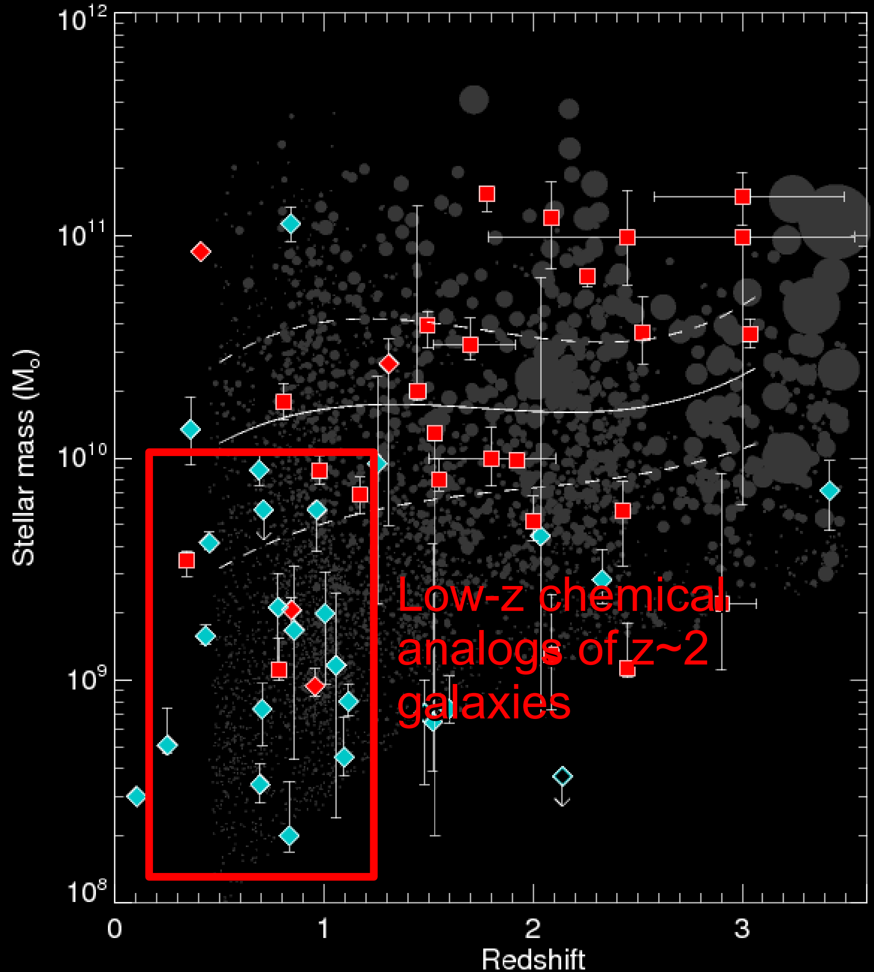
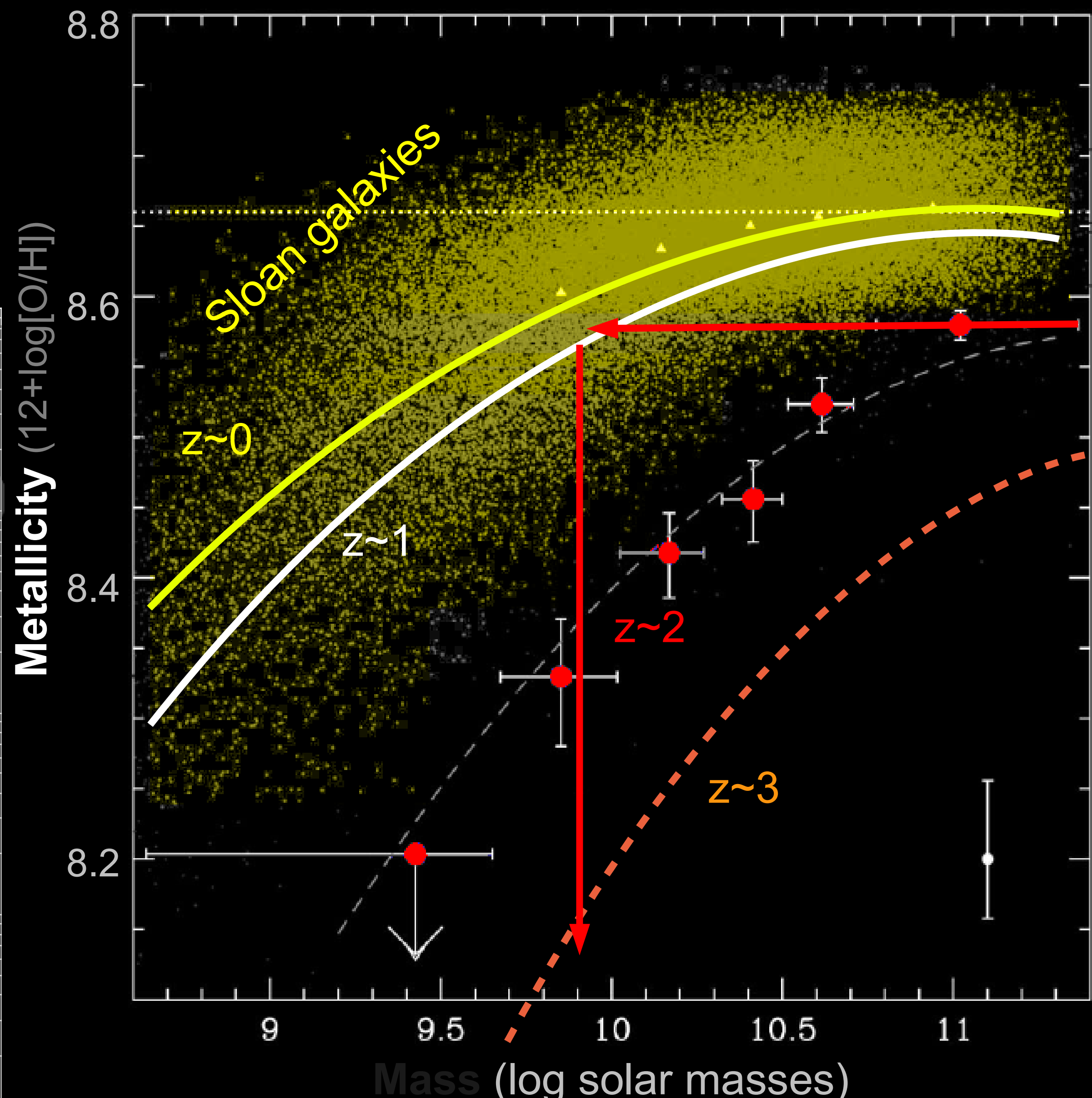
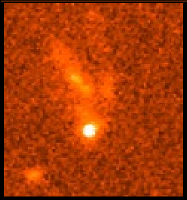
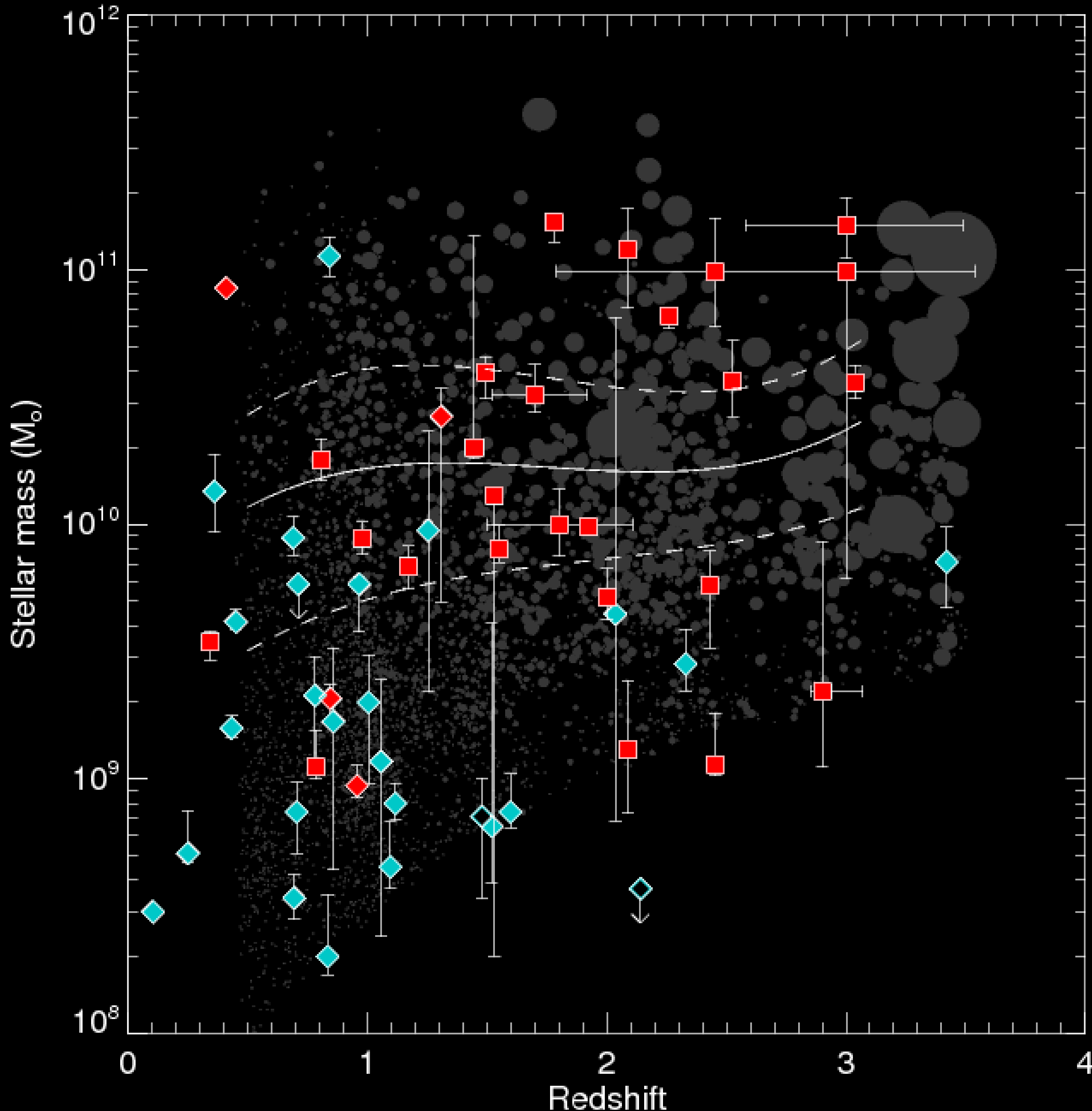




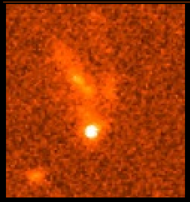
Kewley et al. 2008, Savaglio et al. 2005,, Erb et al. 2006, Maiolino et al. 2008,2009

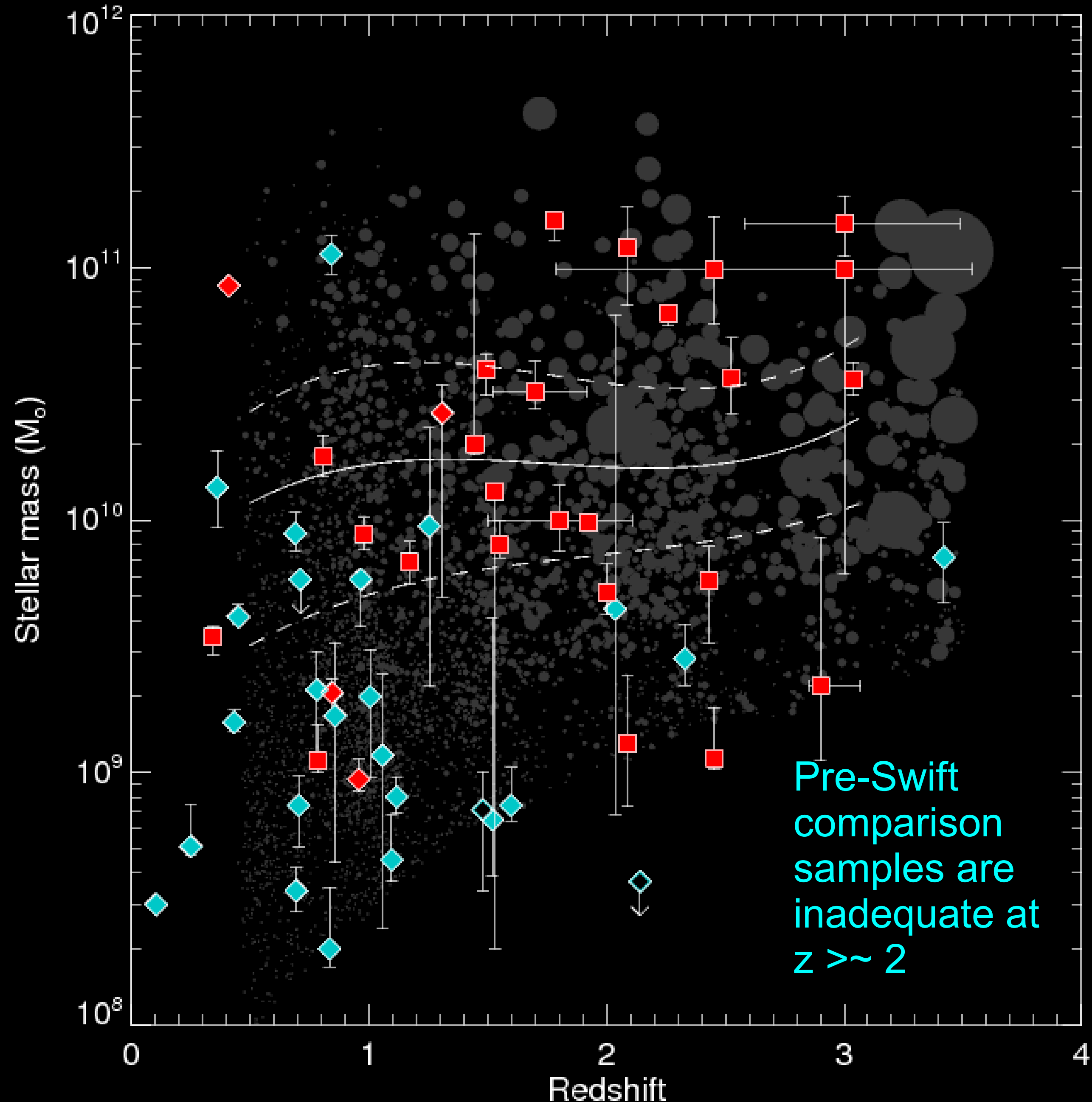
Moving beyond z>1.5



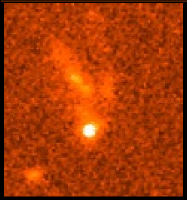


Moving beyond z>1.5





Swift-era Control Samples



HST IR Snapshot program

45 randomly selected optically-bright *Swift* GRBs (known z<3) observed to limit of H~25 AB mag

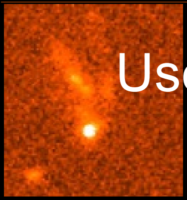
Tibbets-Harlow et al. in prep

VLT Optically Unbiased Host Project ("TOUGH")

69 uniformly selected *Swift* GRBs observed to limits of R~27 AB mag and K~23 AB mag

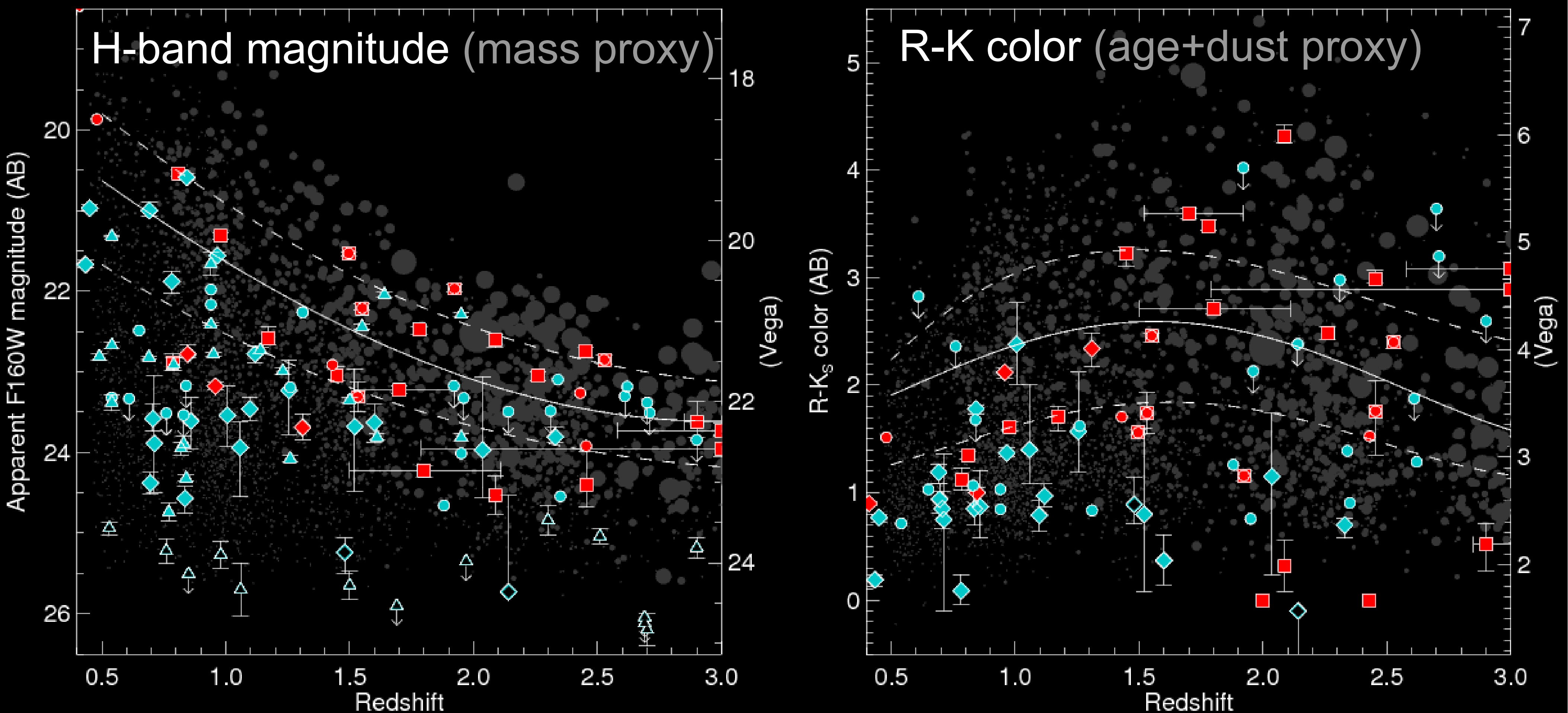
Hjorth et al. 2012
Malesani et al. in prep.
Jakobsson et al. 2012

GRBs vs SFR at z~2



Use magnitudes and colors as substitutes for formal SED modeling.

Dark + pre-Swift + Snapshot + VLT



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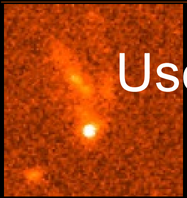

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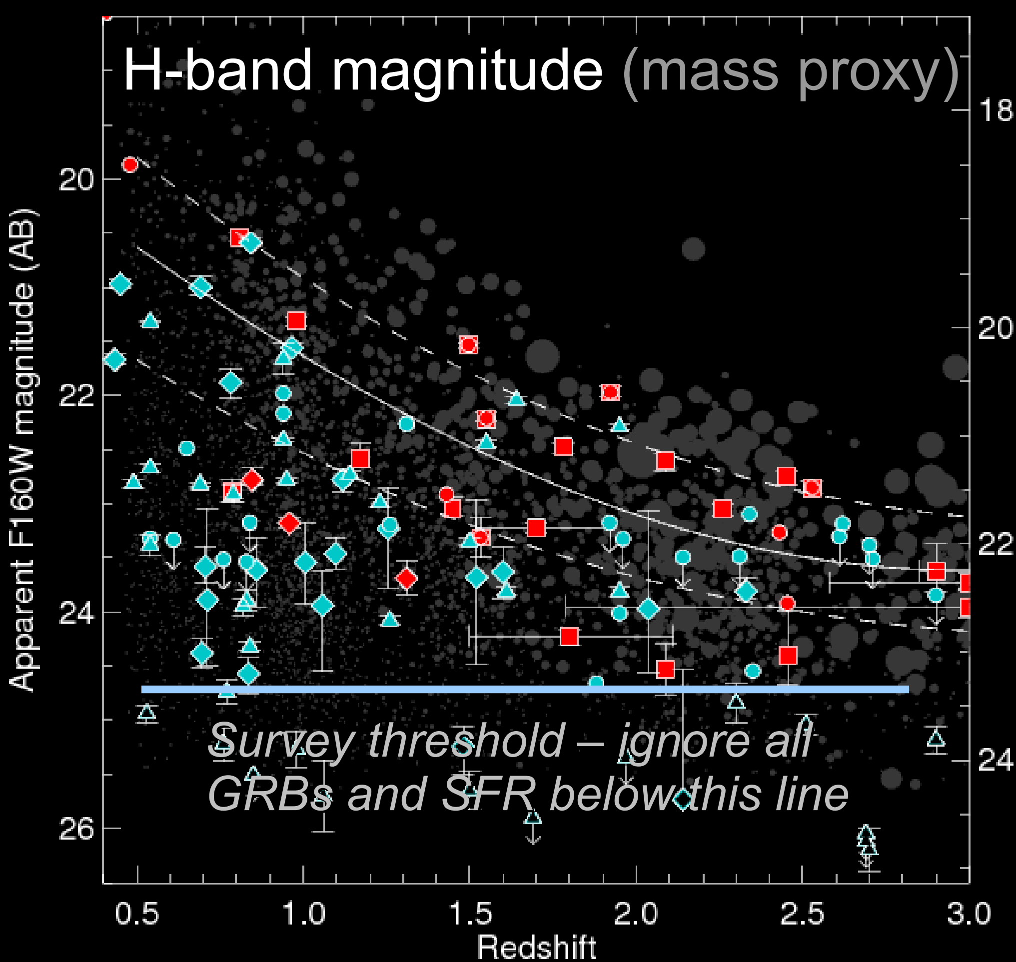
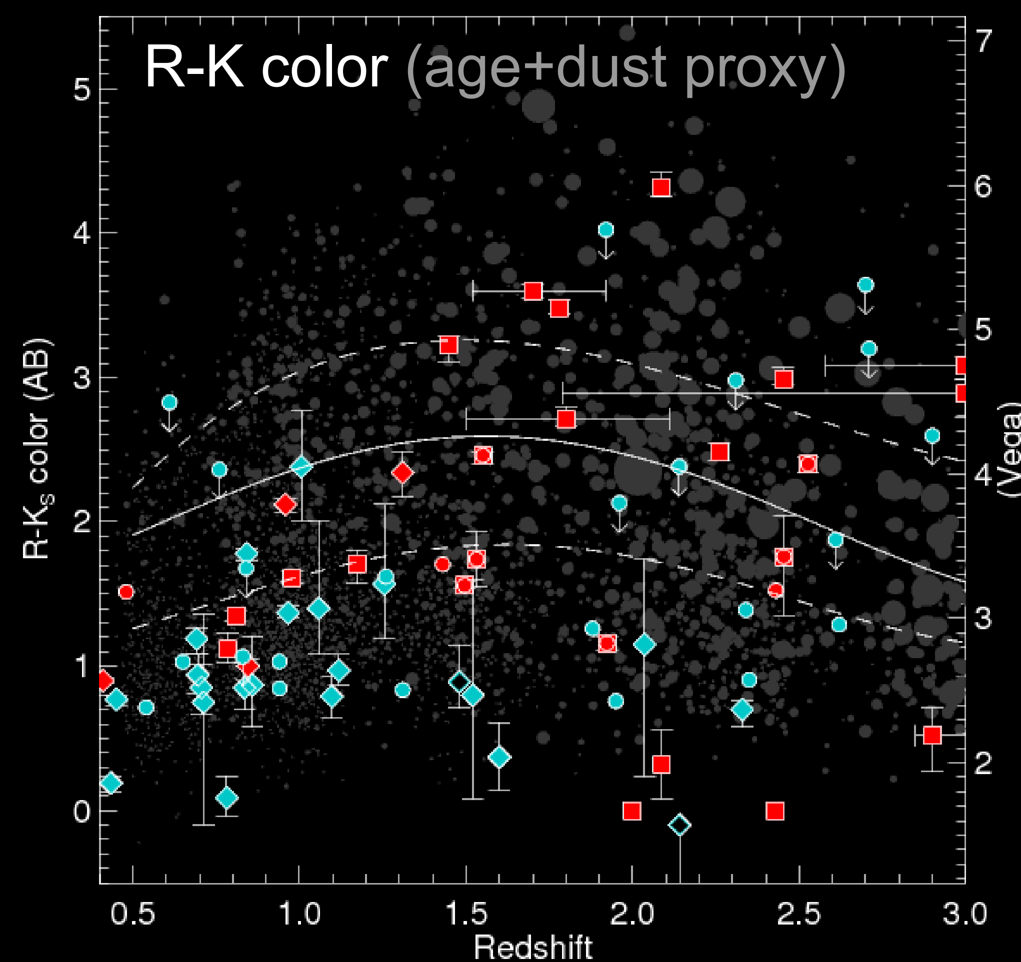
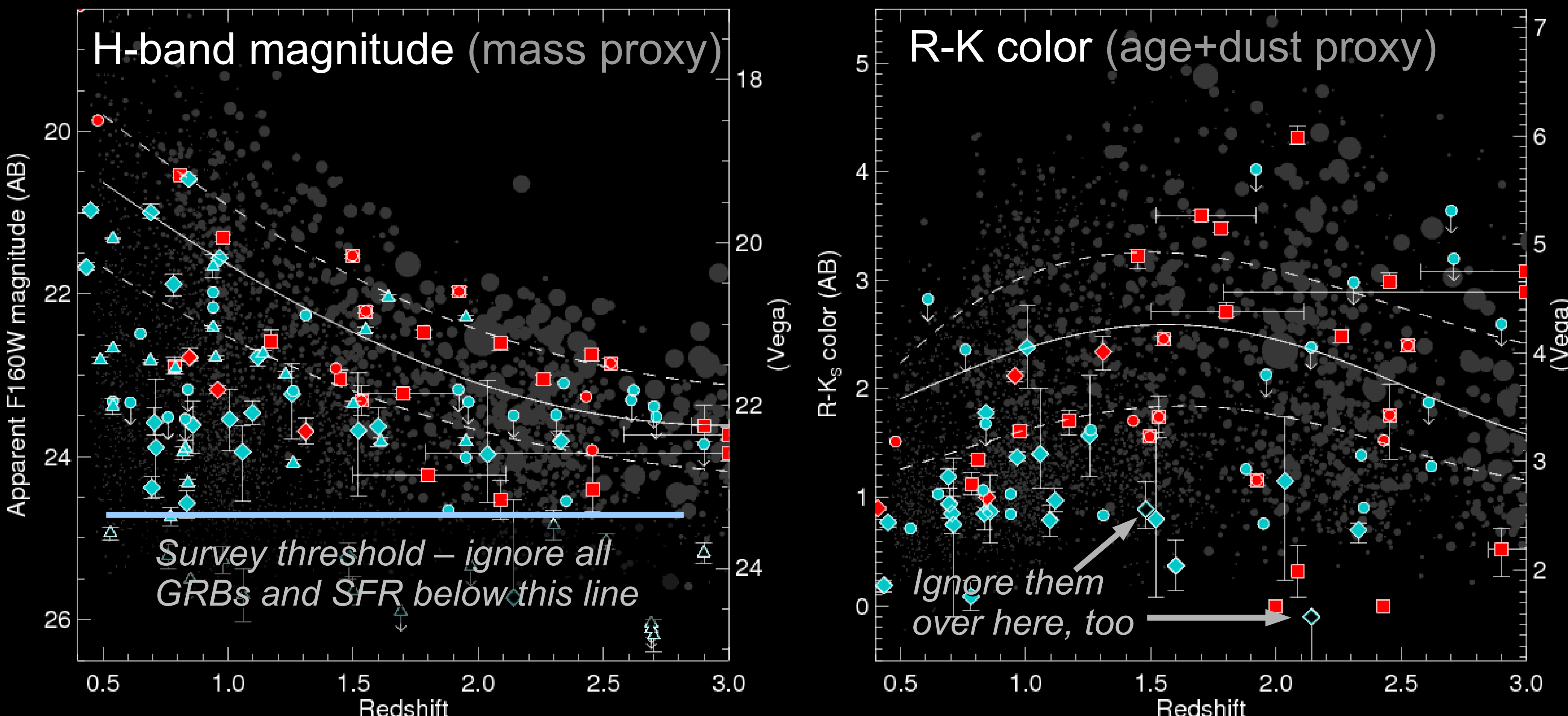




GRBs vs SFR at z~2

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



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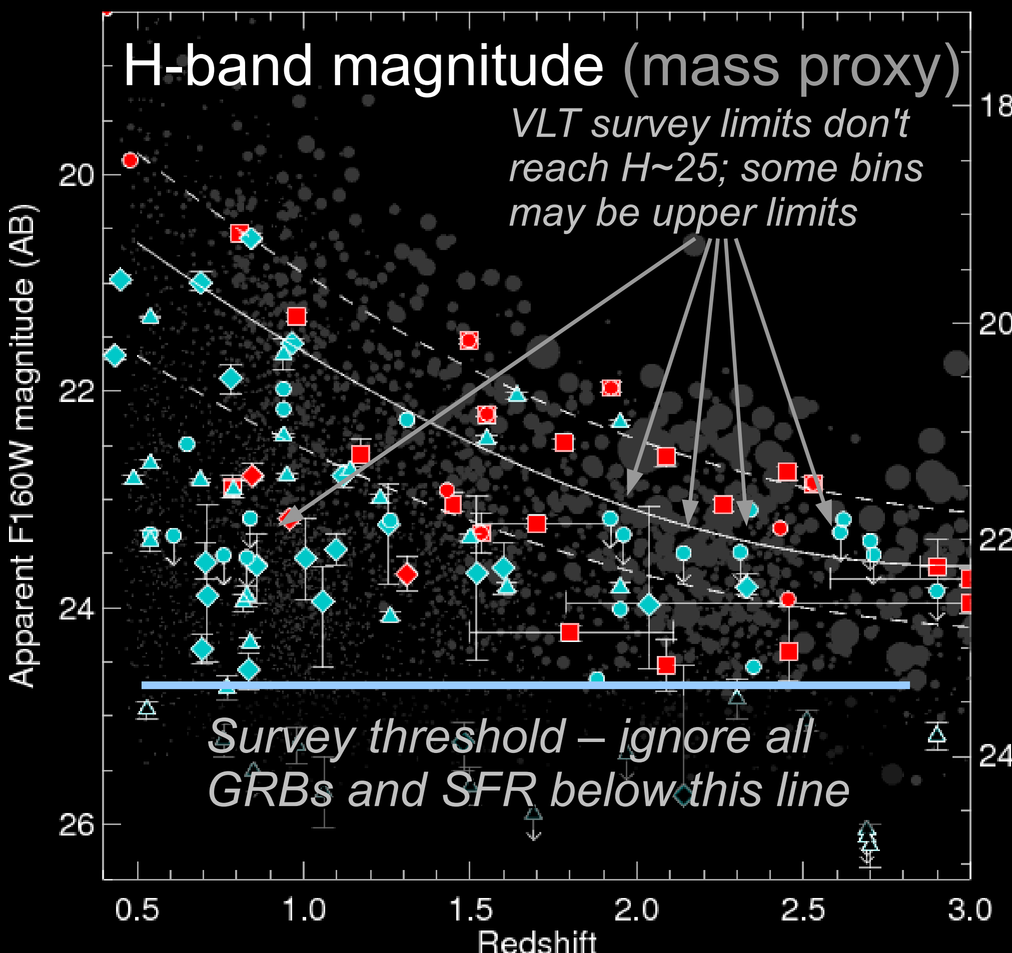
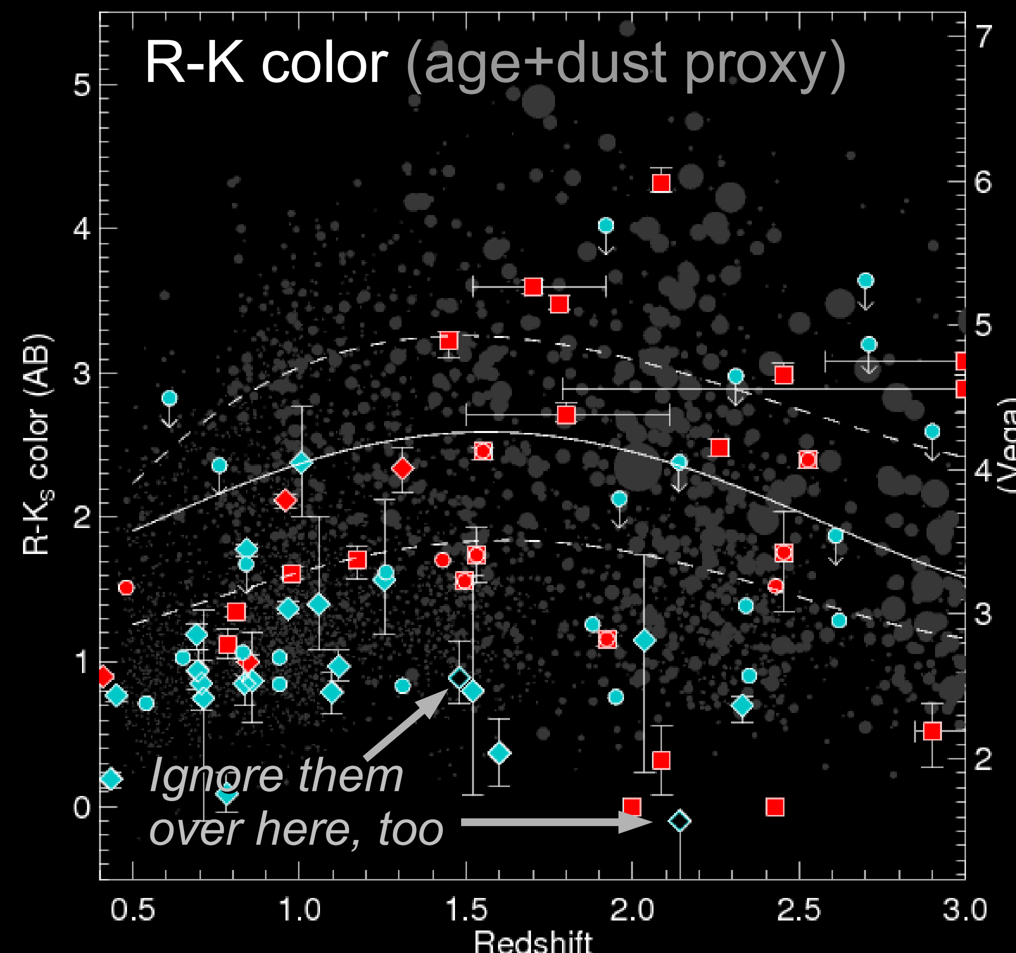
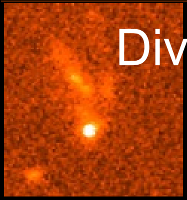
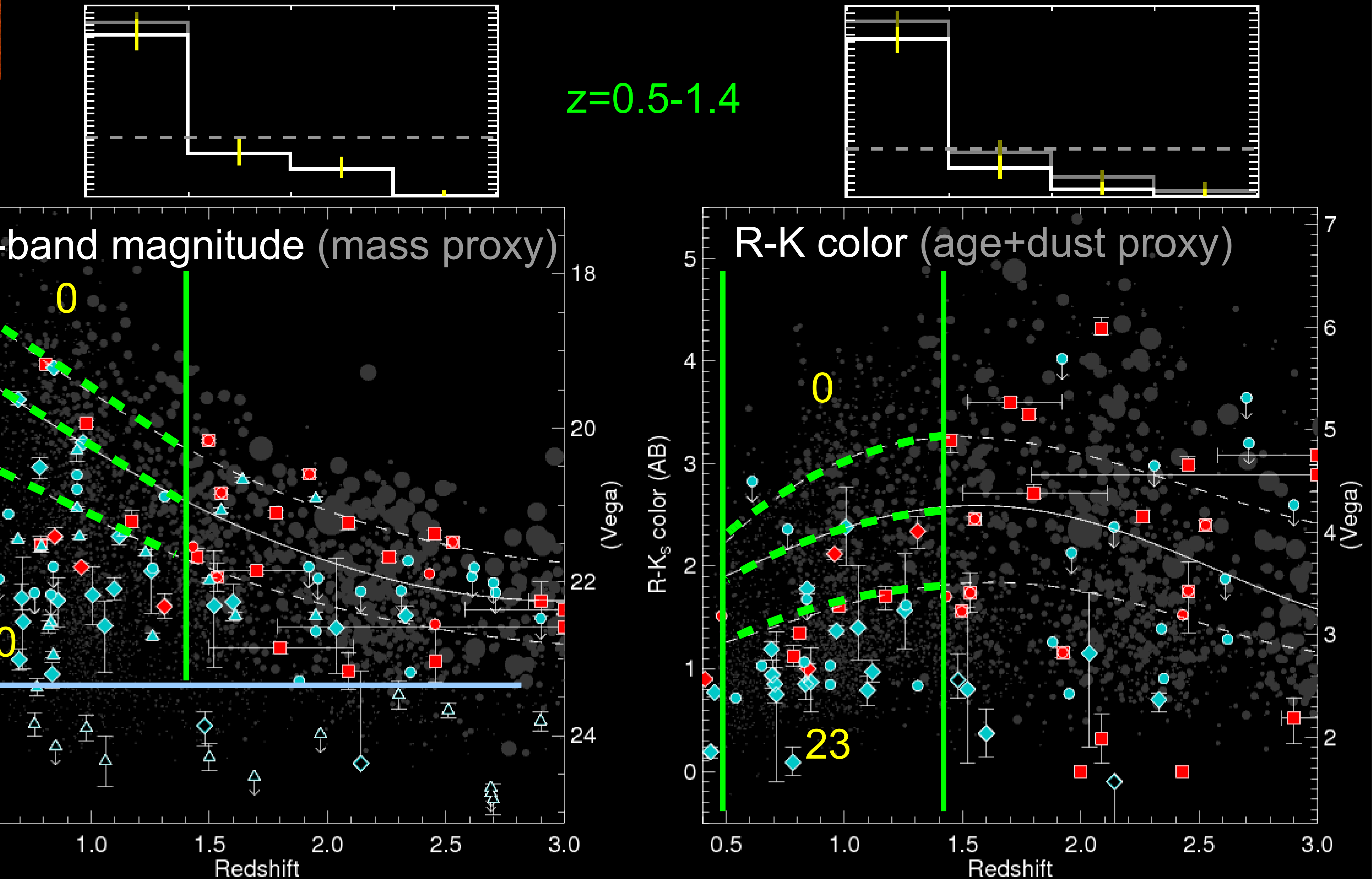




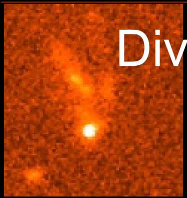
GRBs vs SFR at z~1



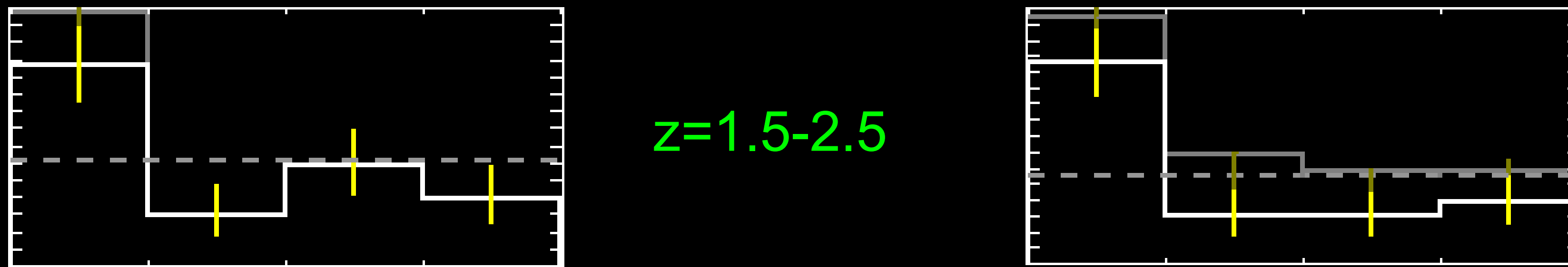
Divide by star-formation quartiles, repeating analysis at z~1 first:

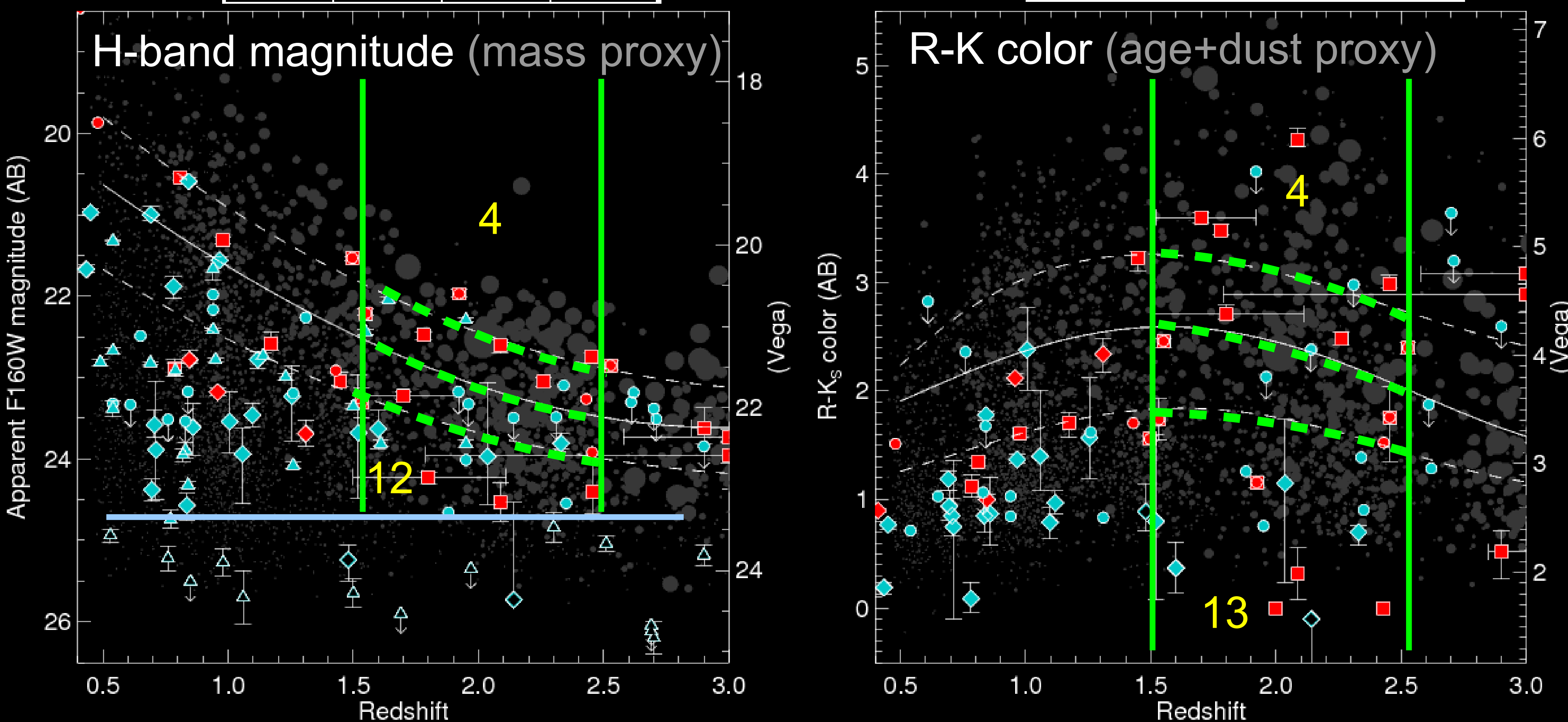


GRBs vs SFR at z~2

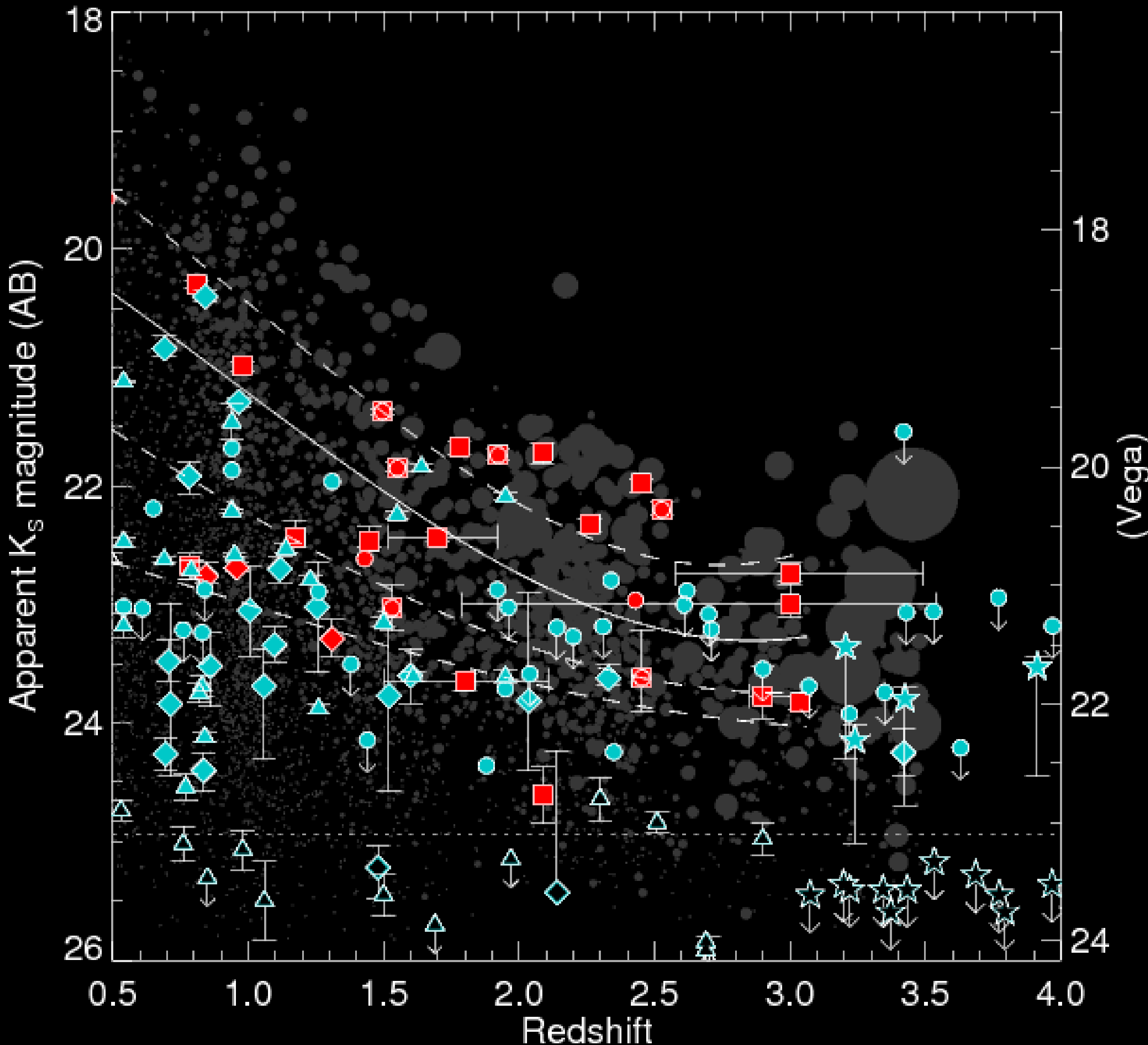


Divide by star-formation quartiles at z~2. Trend still present (but less pronounced)





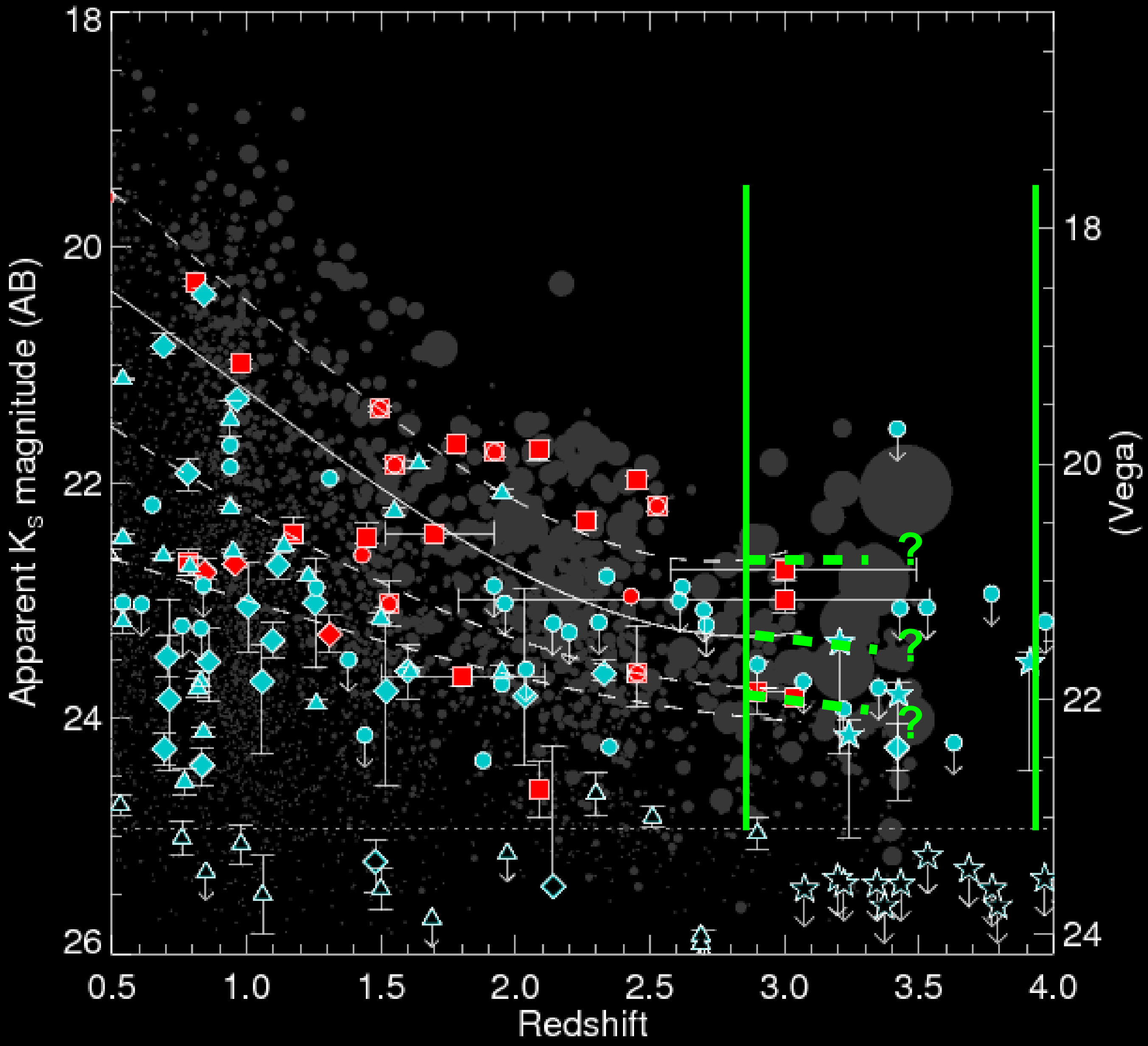
GRBs vs SFR at z>3



z>3 is challenging...

Spitzer sample of Laskar et al. 2011 (18 optically bright z>3 GRBs)

GRBs vs SFR at z>3



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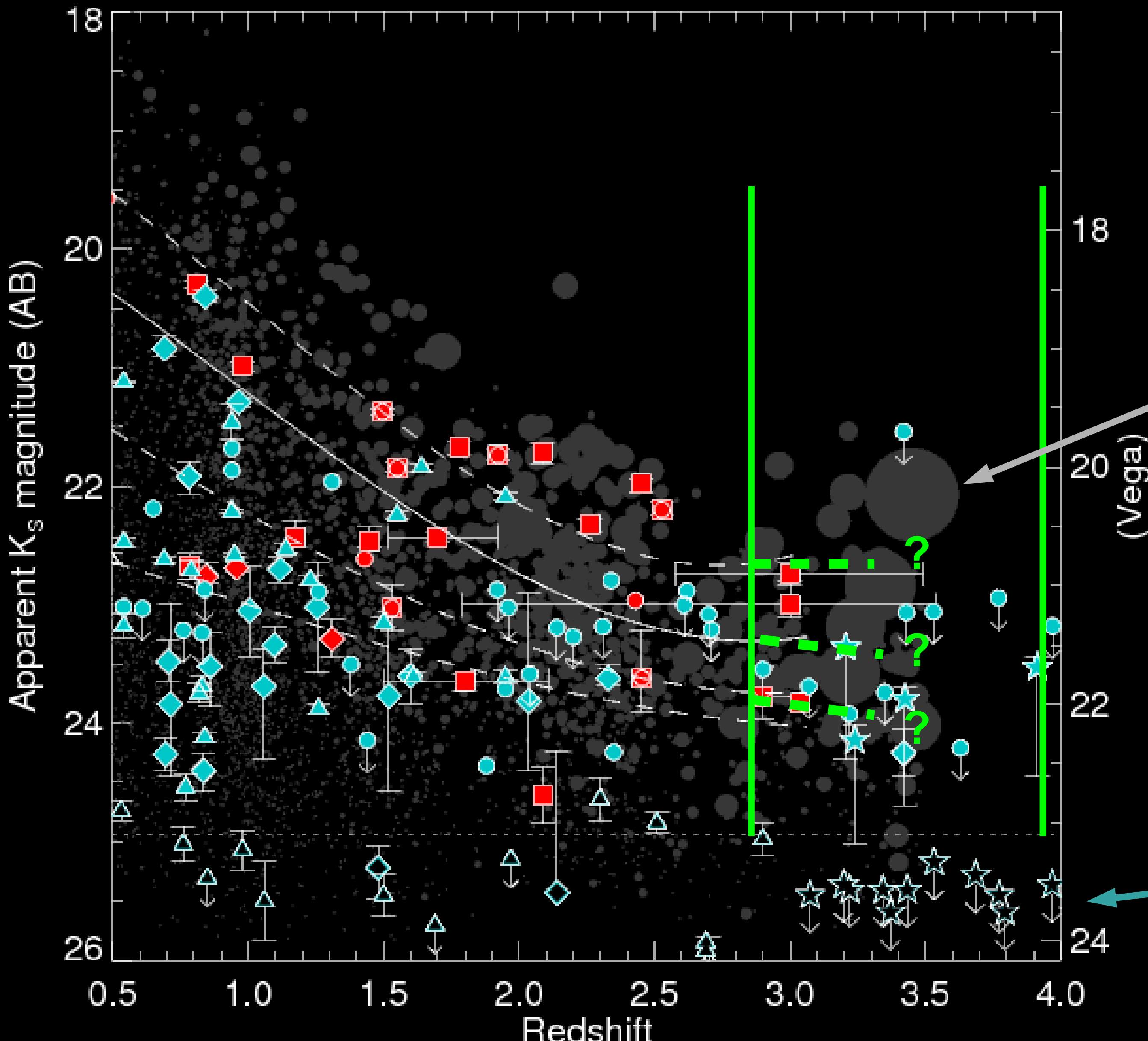
GRBs vs SFR at z>3

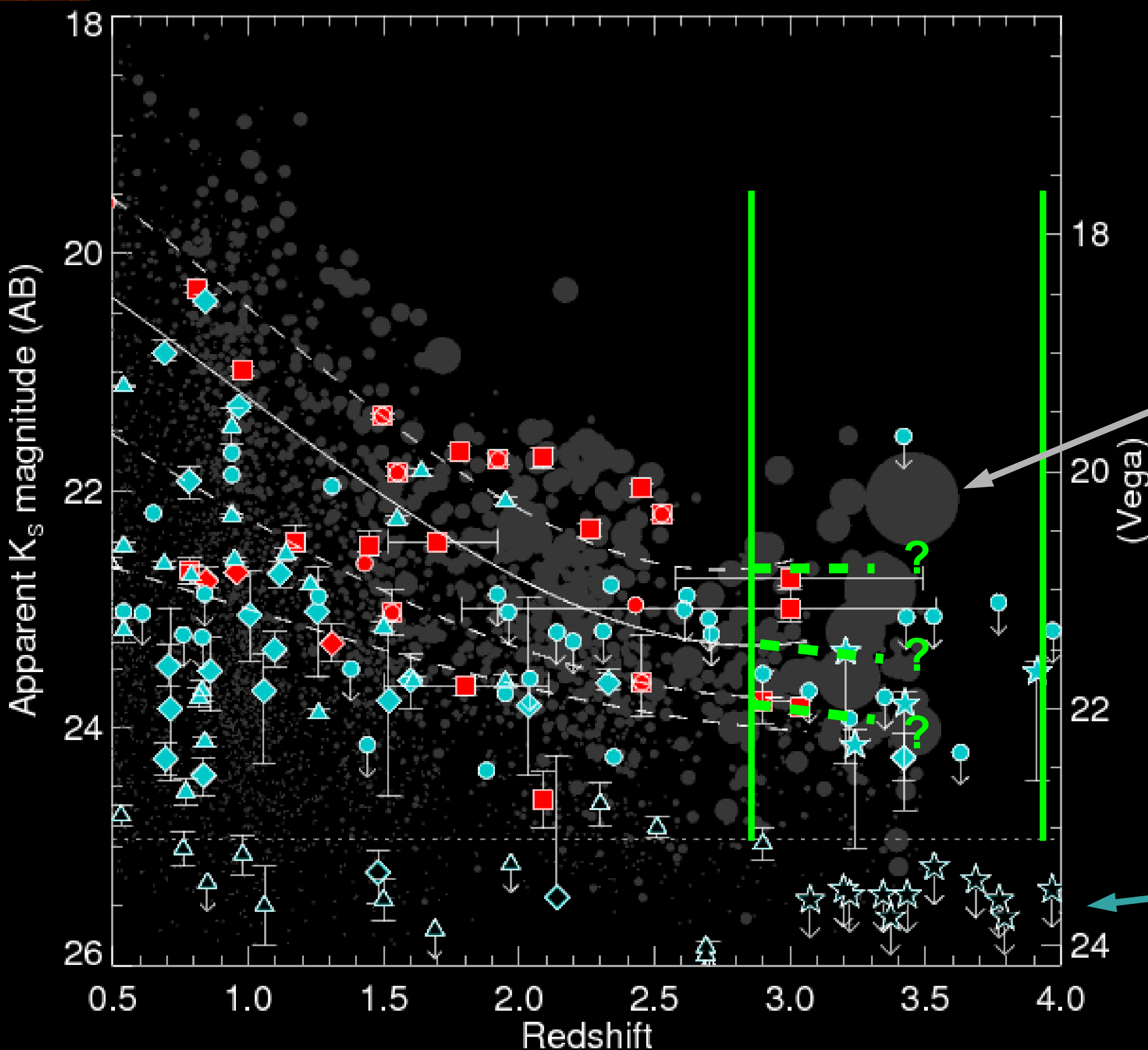


z>3 is challenging...

Field surveys not redshift complete; large statistical variance from small numbers of objects

Most GRBs (and probably most SF) in undetectable galaxies

GRBs vs SFR at z>3



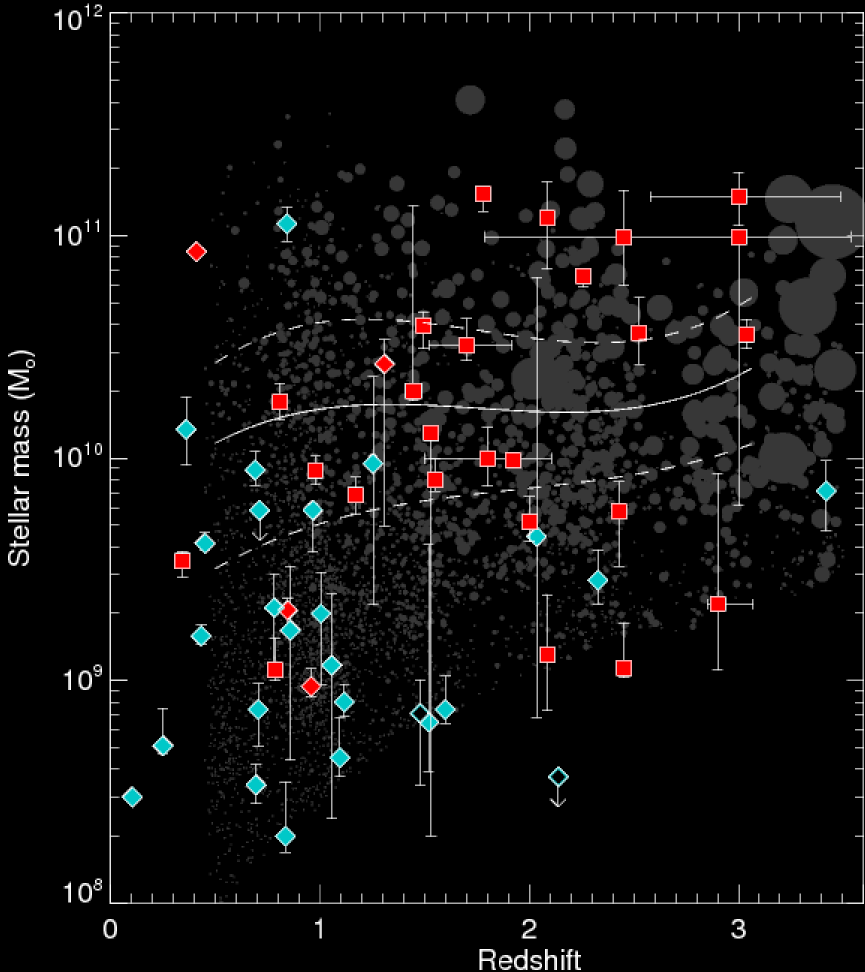
z>3 is challenging... No way to check directly. Can we use low-z results?

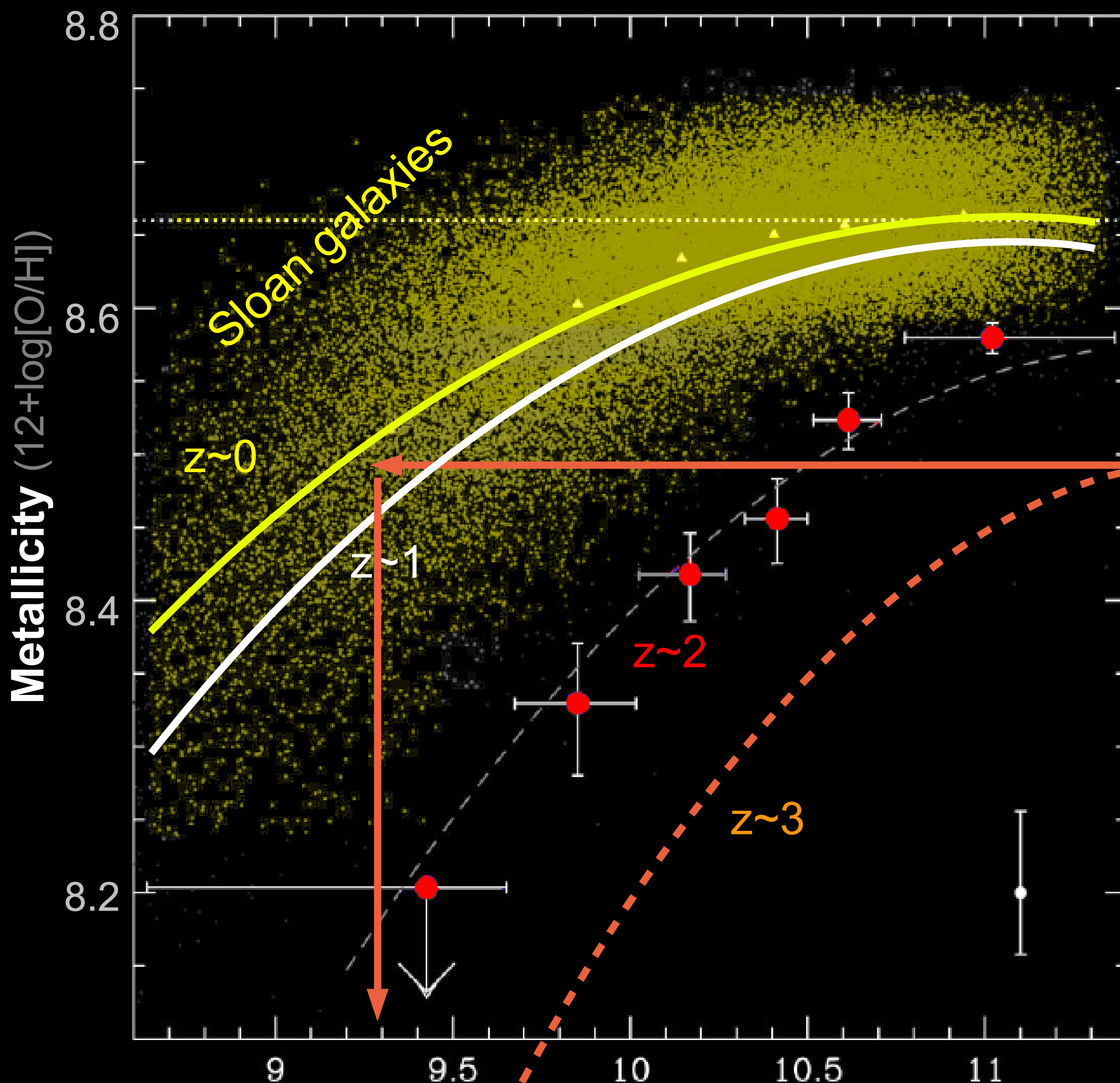
Field surveys not redshift complete; large statistical variance from small numbers of objects

Most GRBs (and probably most SF) in undetectable galaxies

Is There Hope for High Redshift?

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

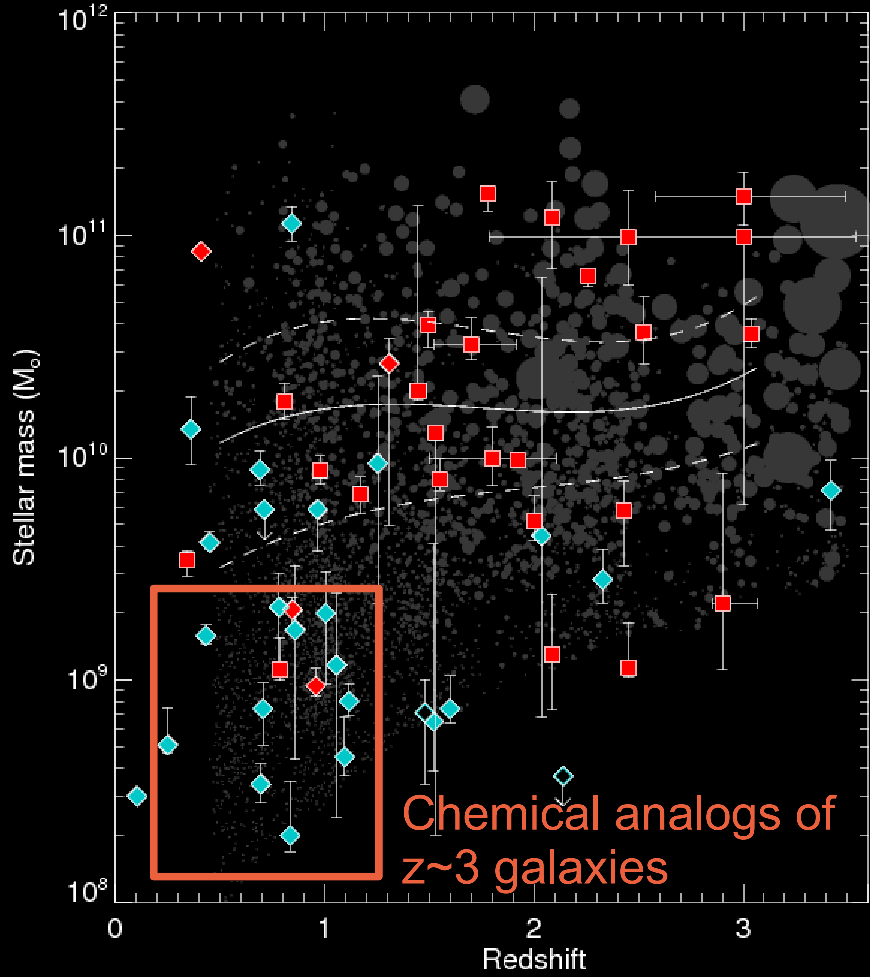


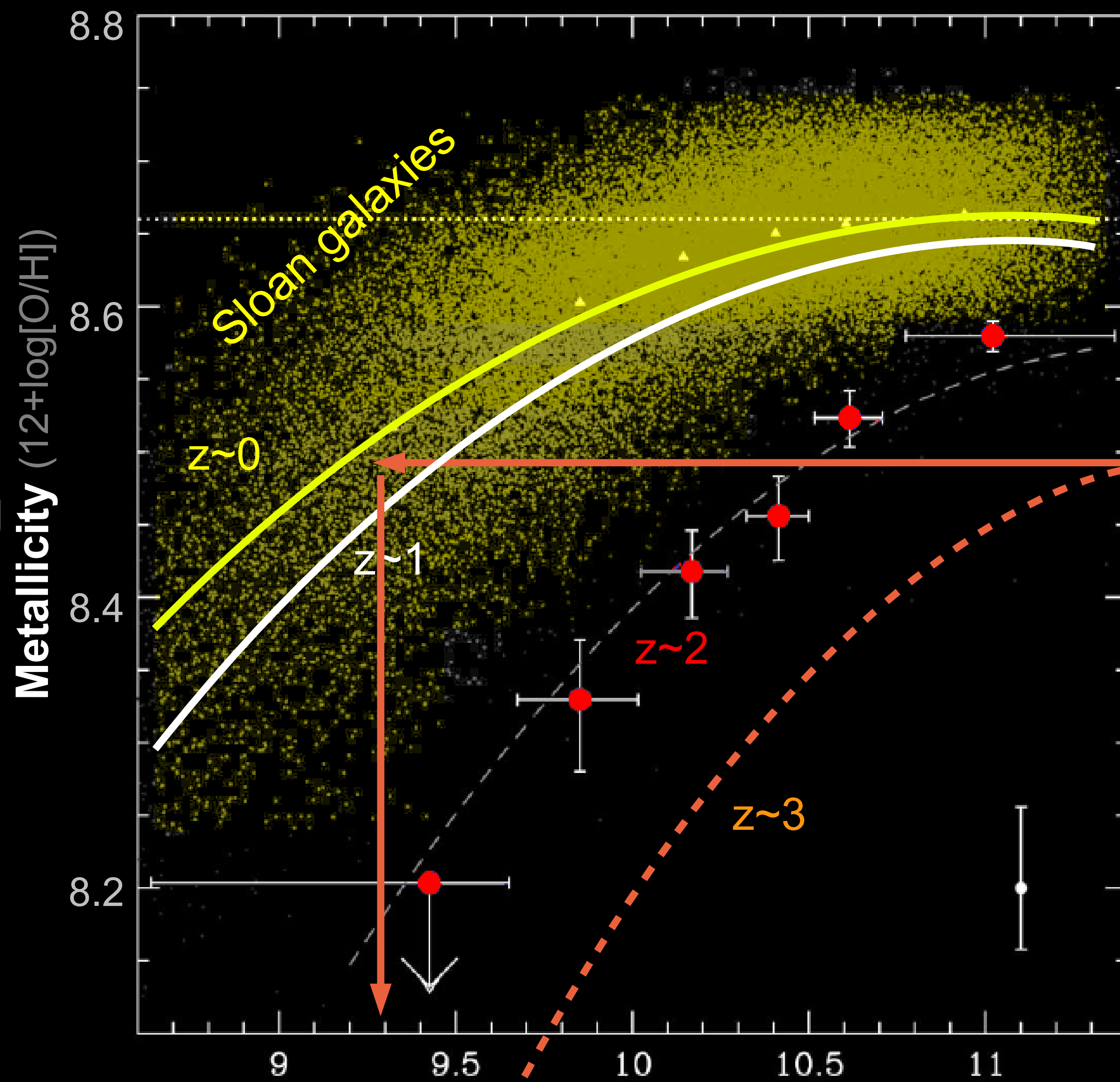


A massive z~3.5 galaxy should have similar metallicity to a typical (low-mass) z~0.5 GRB host.

Is There Hope for High Redshift?

Massive z~3 galaxies should have similar metallicity to ~2×10^9 M$_\odot$, z~1 galaxies





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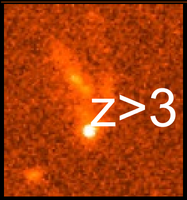
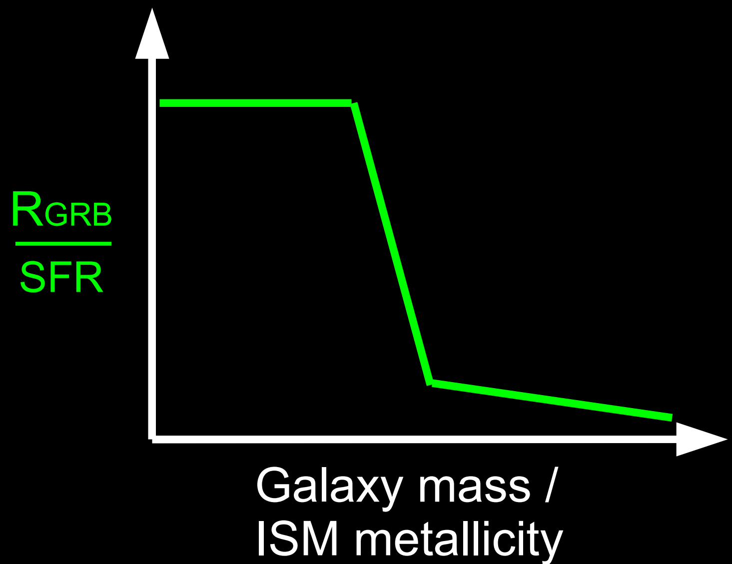
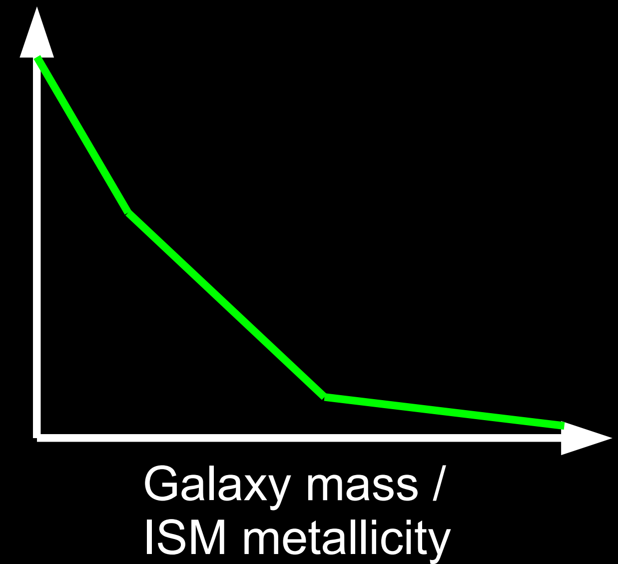
Does metal dependence level out?



z>3 galaxies should have similar chemical properties as typical z~0-1 GRB hosts.

But we still expect metallicity variations.
This won't matter *if* the dependence goes away below a threshold metallicity.





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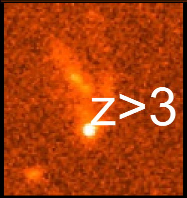

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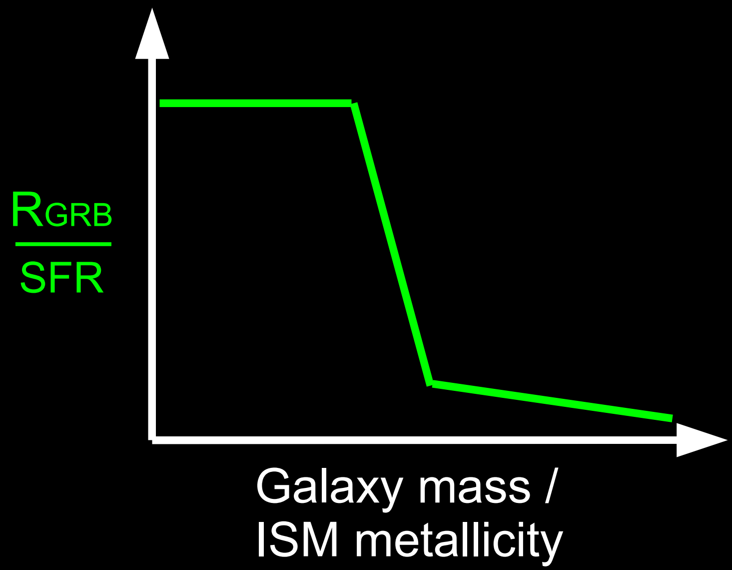
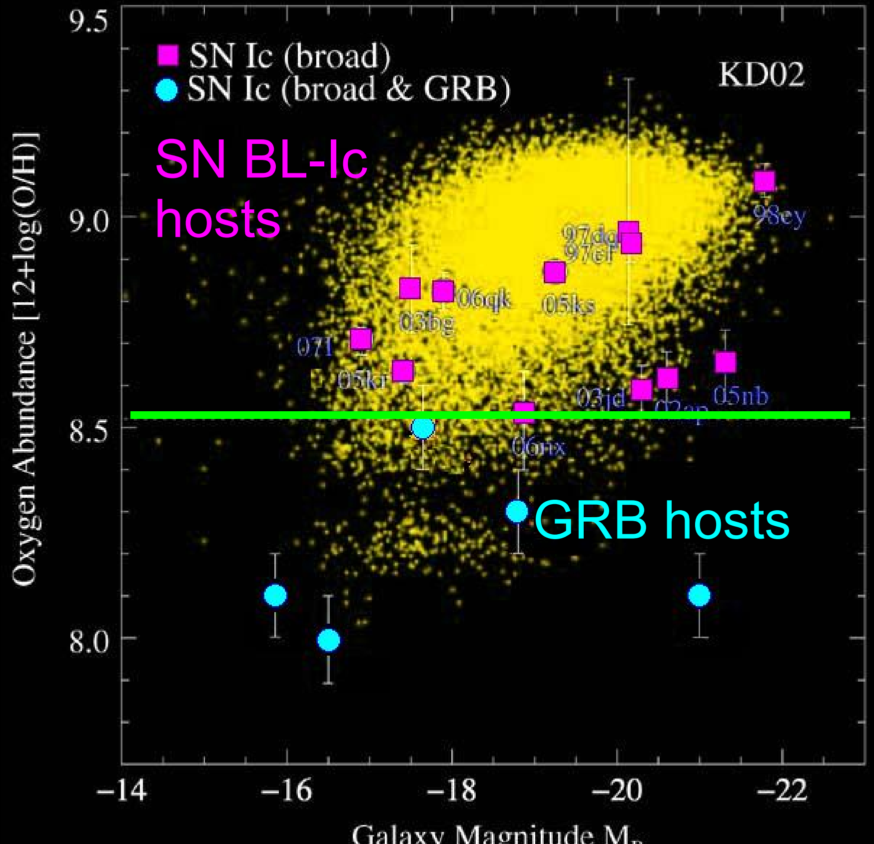
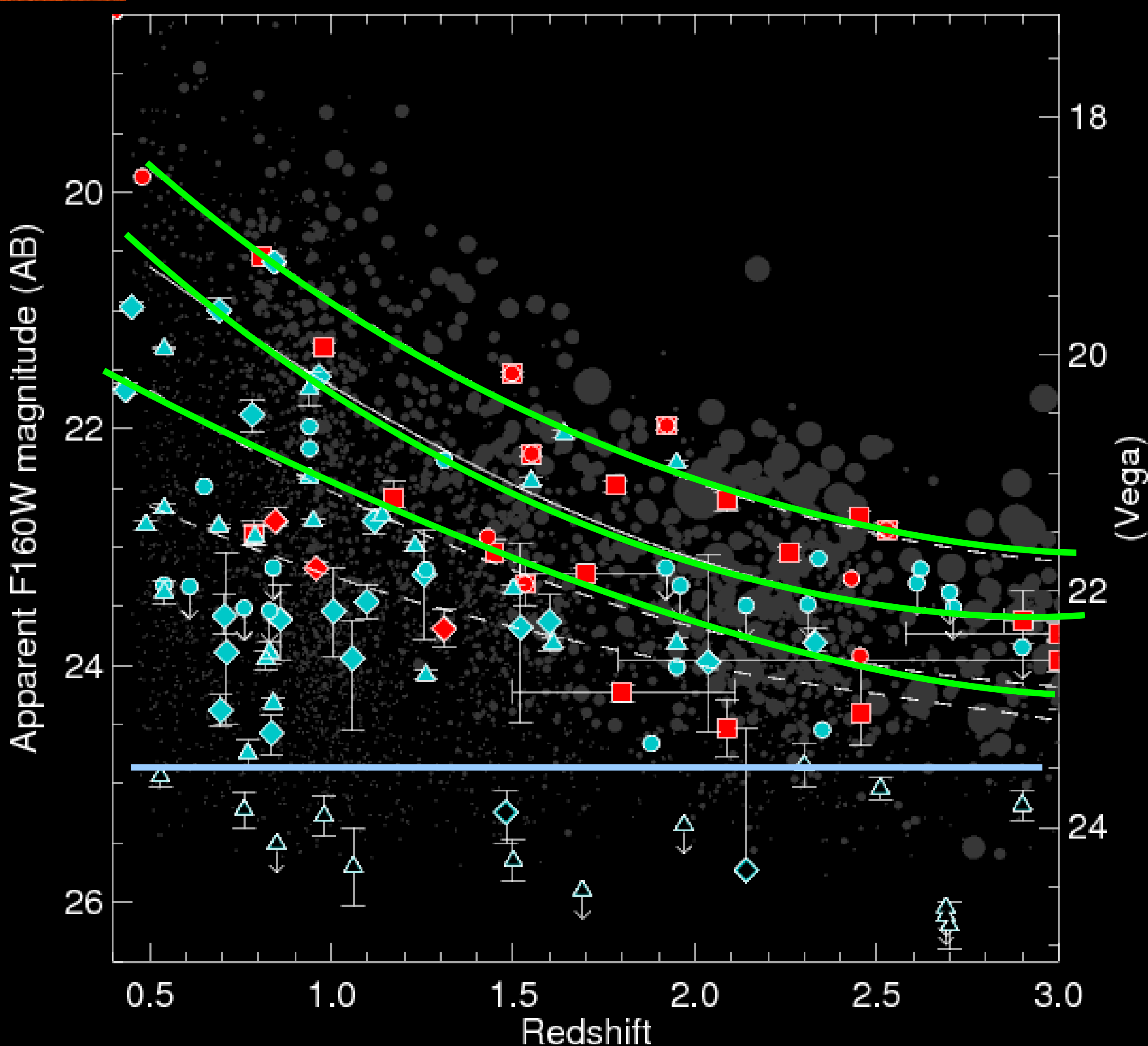




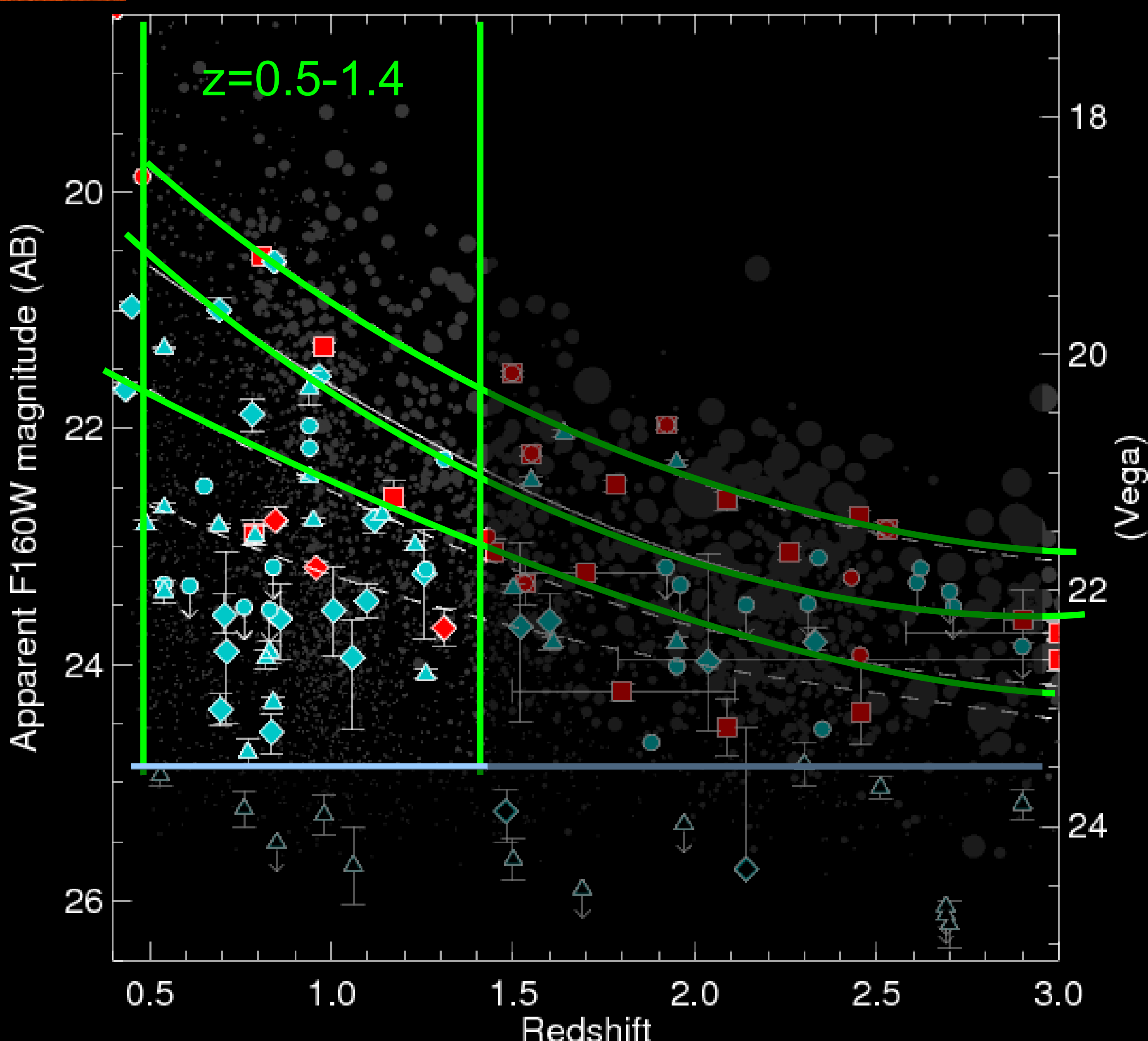
Modjaz et al. 2008

Does metal dependence level out?



Examine low-z chemical analogs.

Does metal dependence level out?



Examine low-z chemical analogs.

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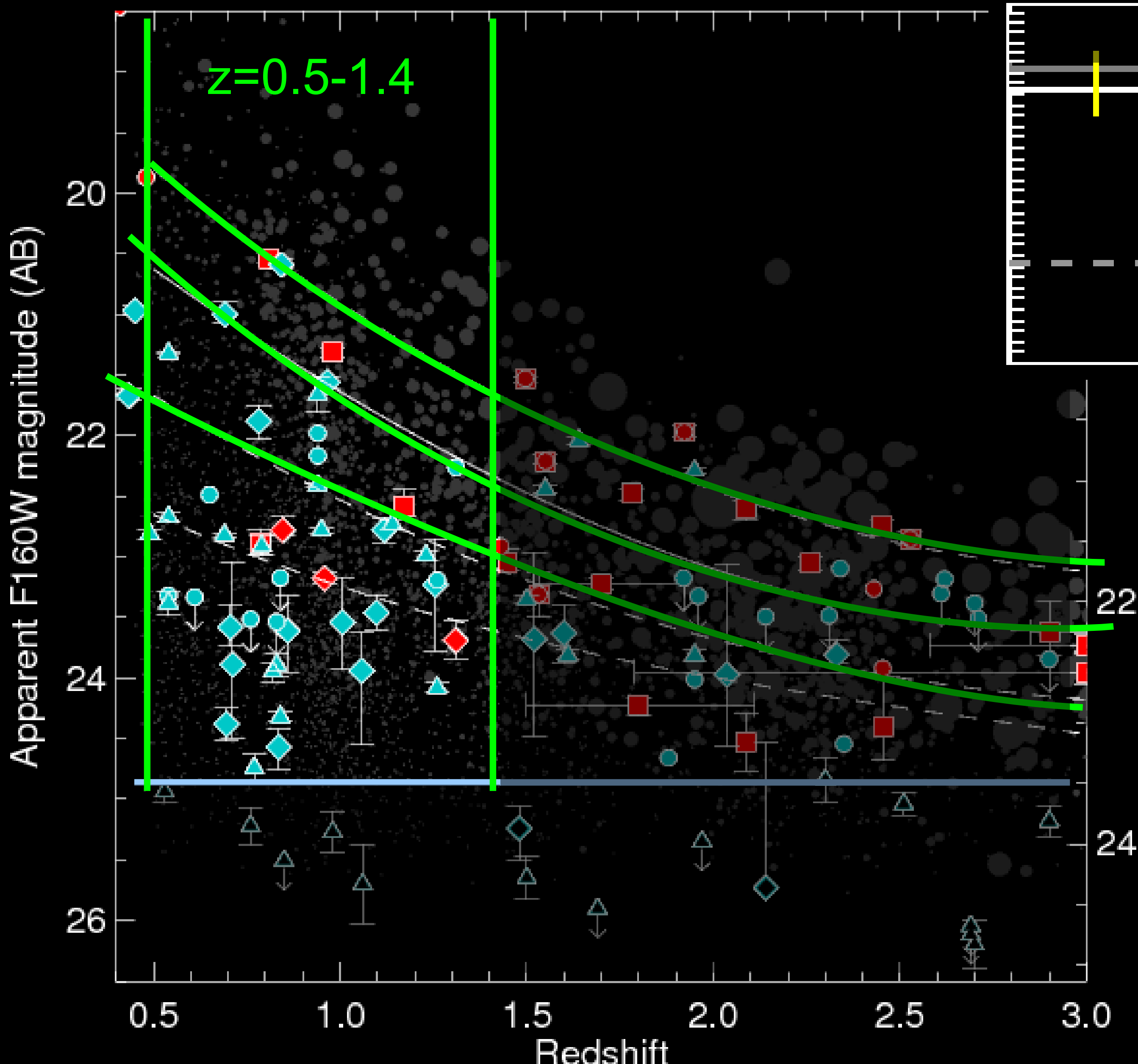
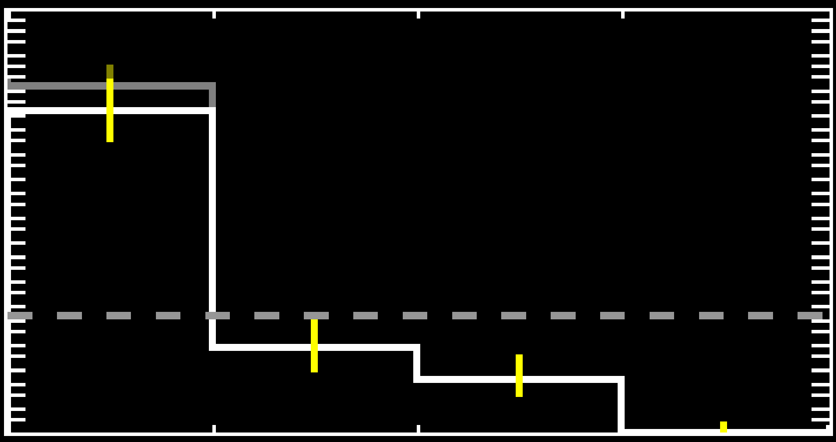
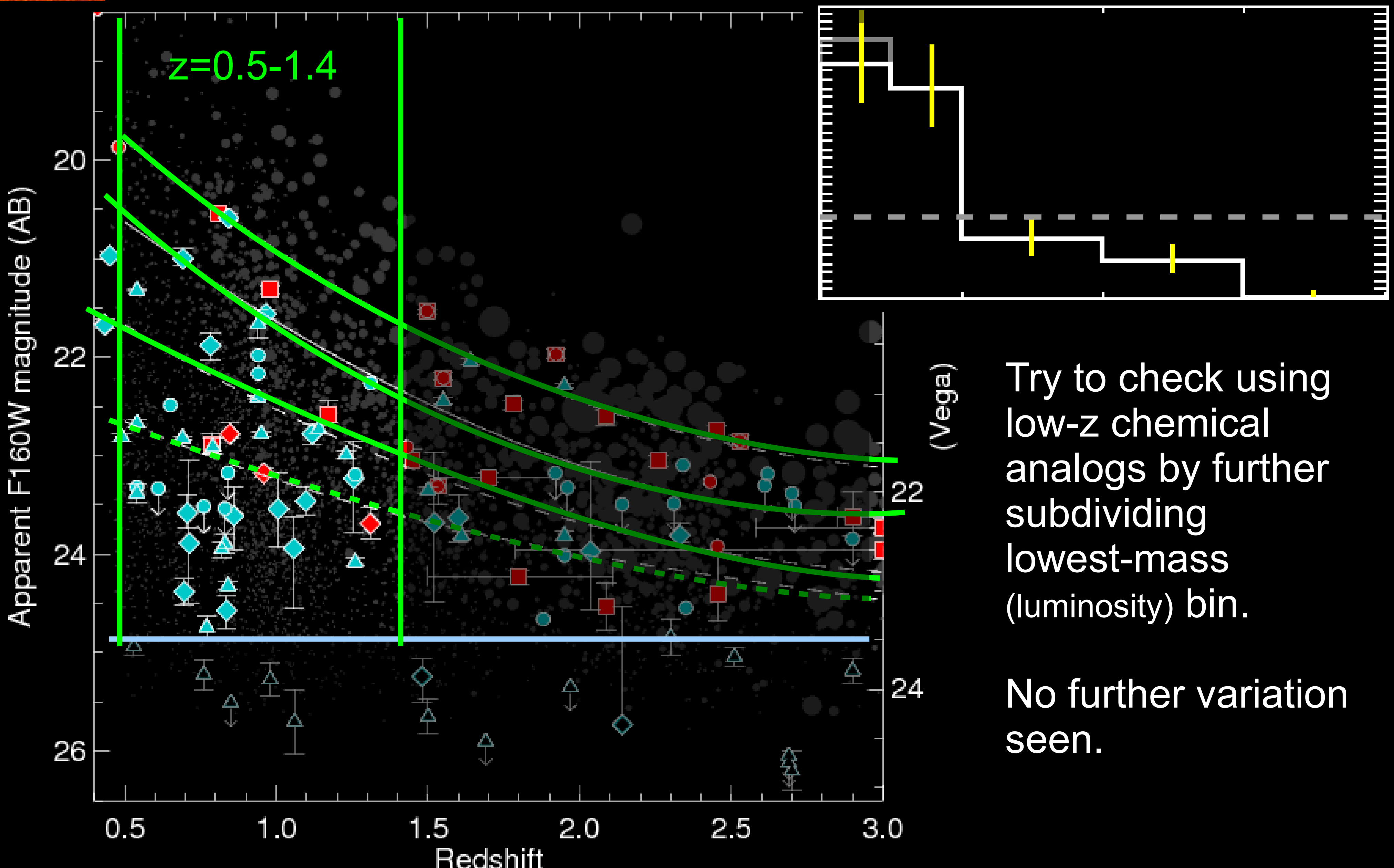




Examine low-z chemical analogs.

Does metal dependence level out?

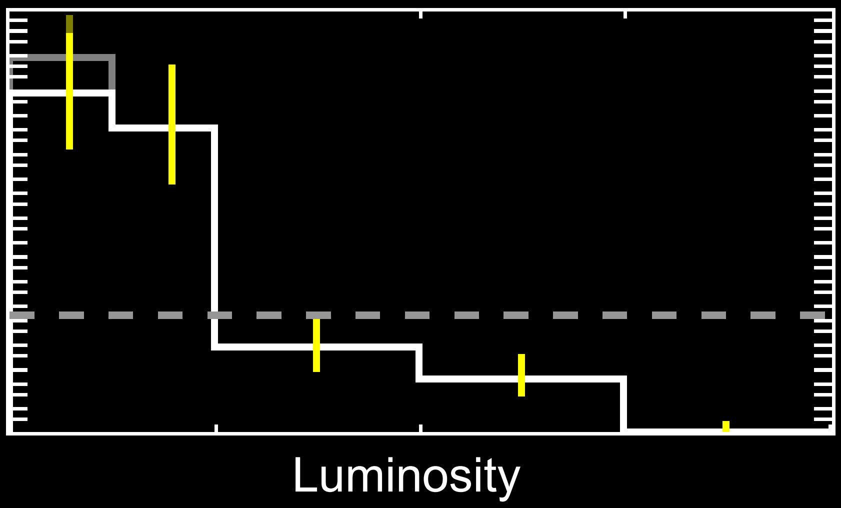


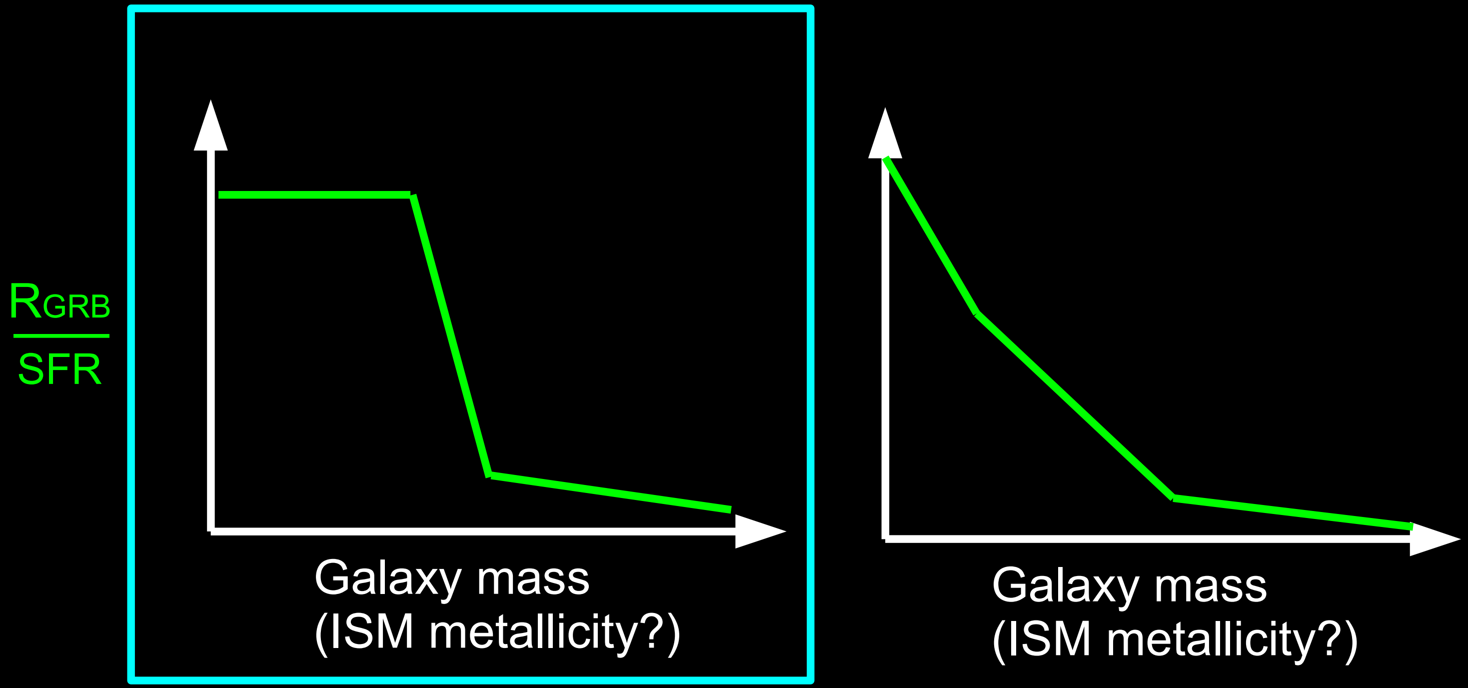
Try to check using low-z chemical analogs by further subdividing lowest-mass (luminosity) bin.

No further variation seen.

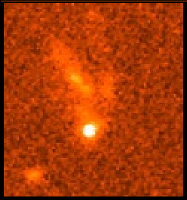
Does metal dependence level out?

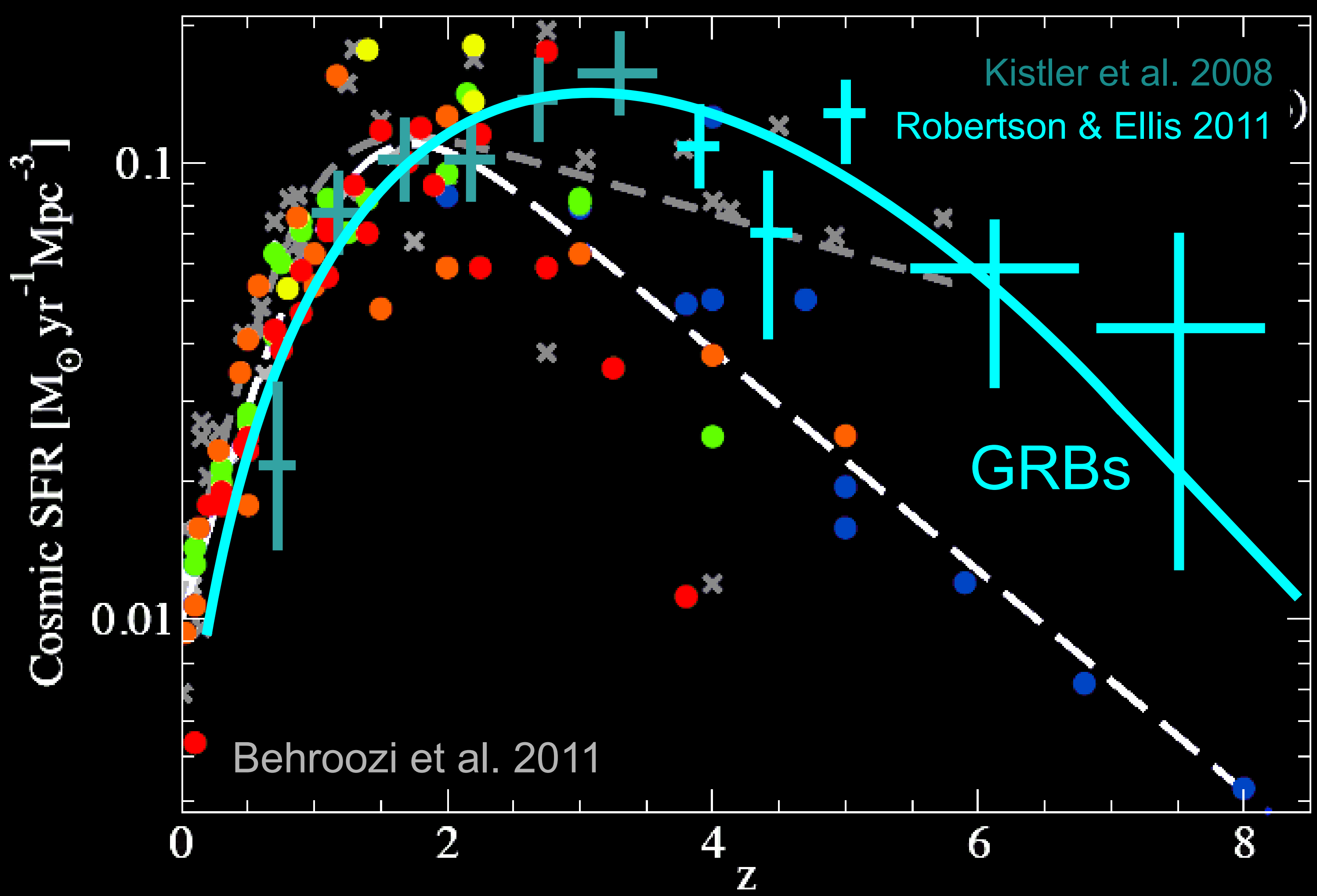
Yes, possibly – rate consistent with no further luminosity dependence below $M < 10^{9.5}\ M_{\odot}$ in z~1 chemical "analogs" of z>3 galaxies.



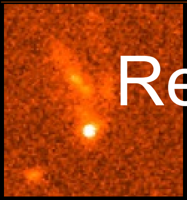


High-z SF History from GRBs

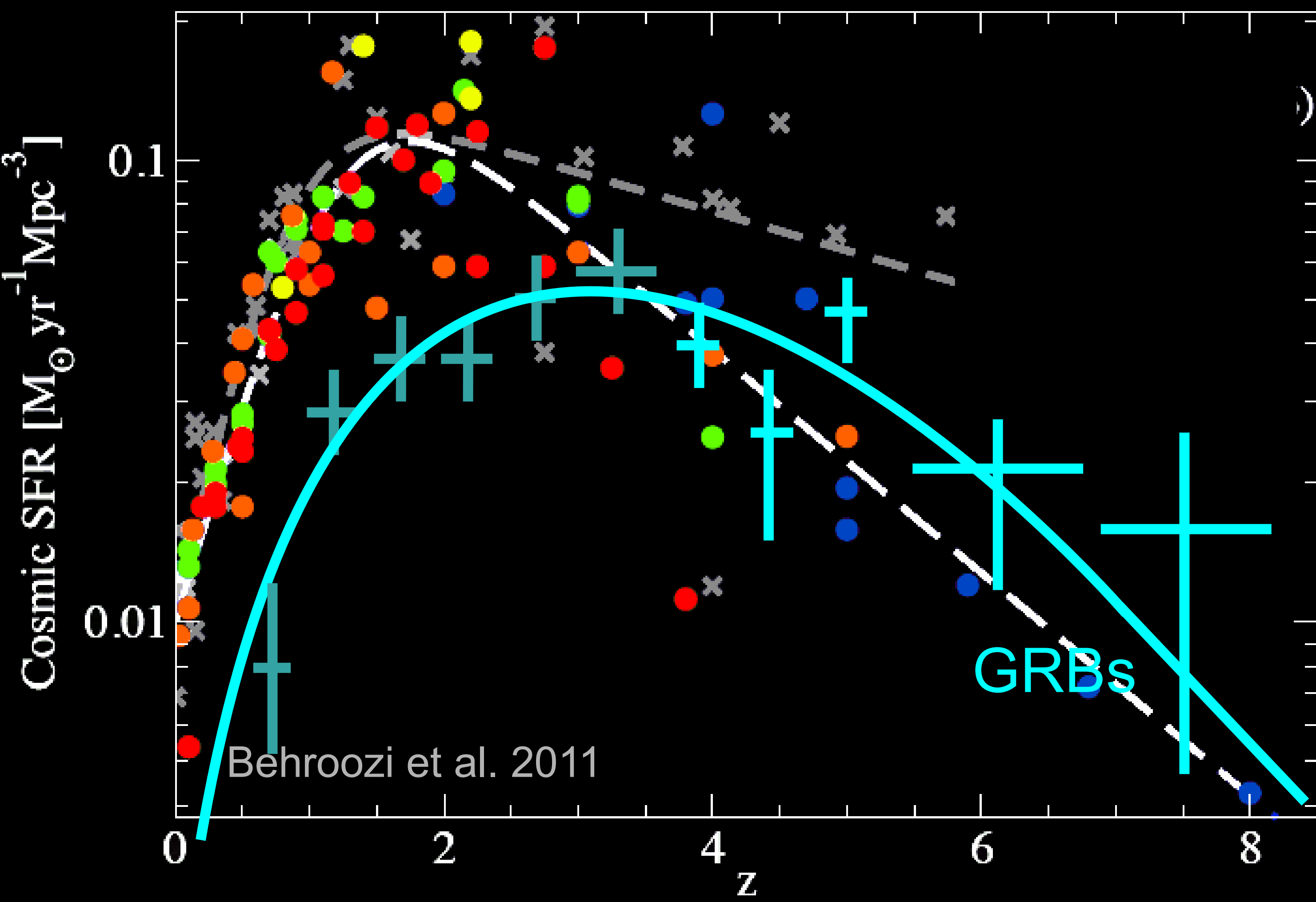




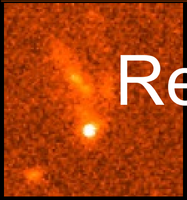
High-z SF History from GRBs



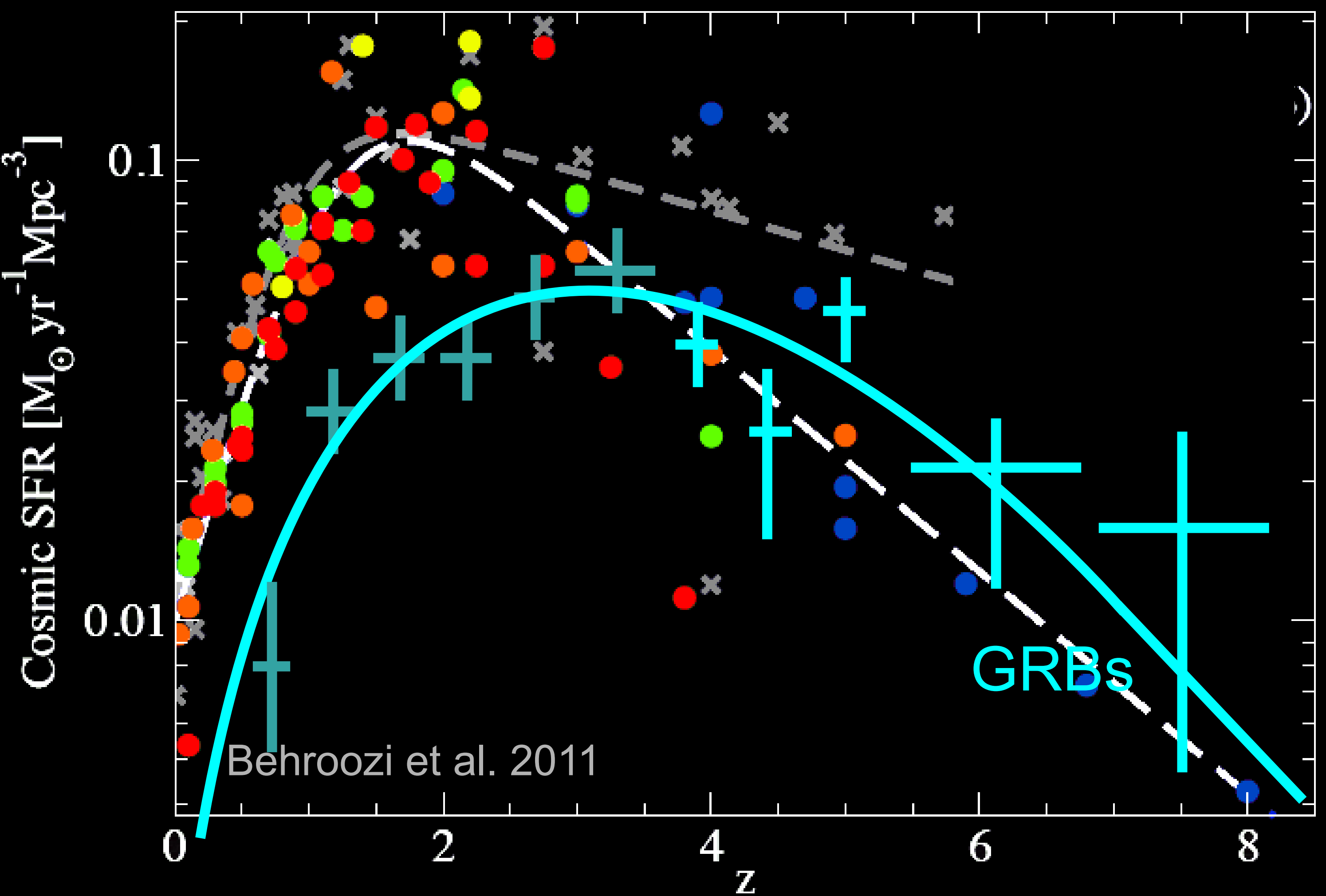
Re-normalize at z~3



High-z SF History from GRBs

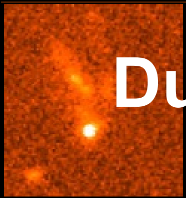


Re-normalize at z~3



Looks consistent.

Conclusions

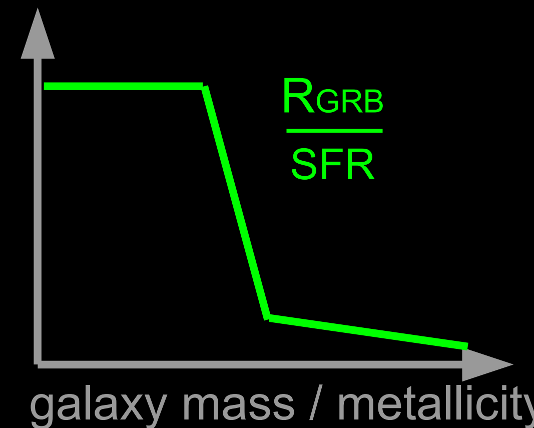


Dust-obscured GRB hosts: diverse, massive, luminous.

No dusty GRBs in lowest-mass galaxies.

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?

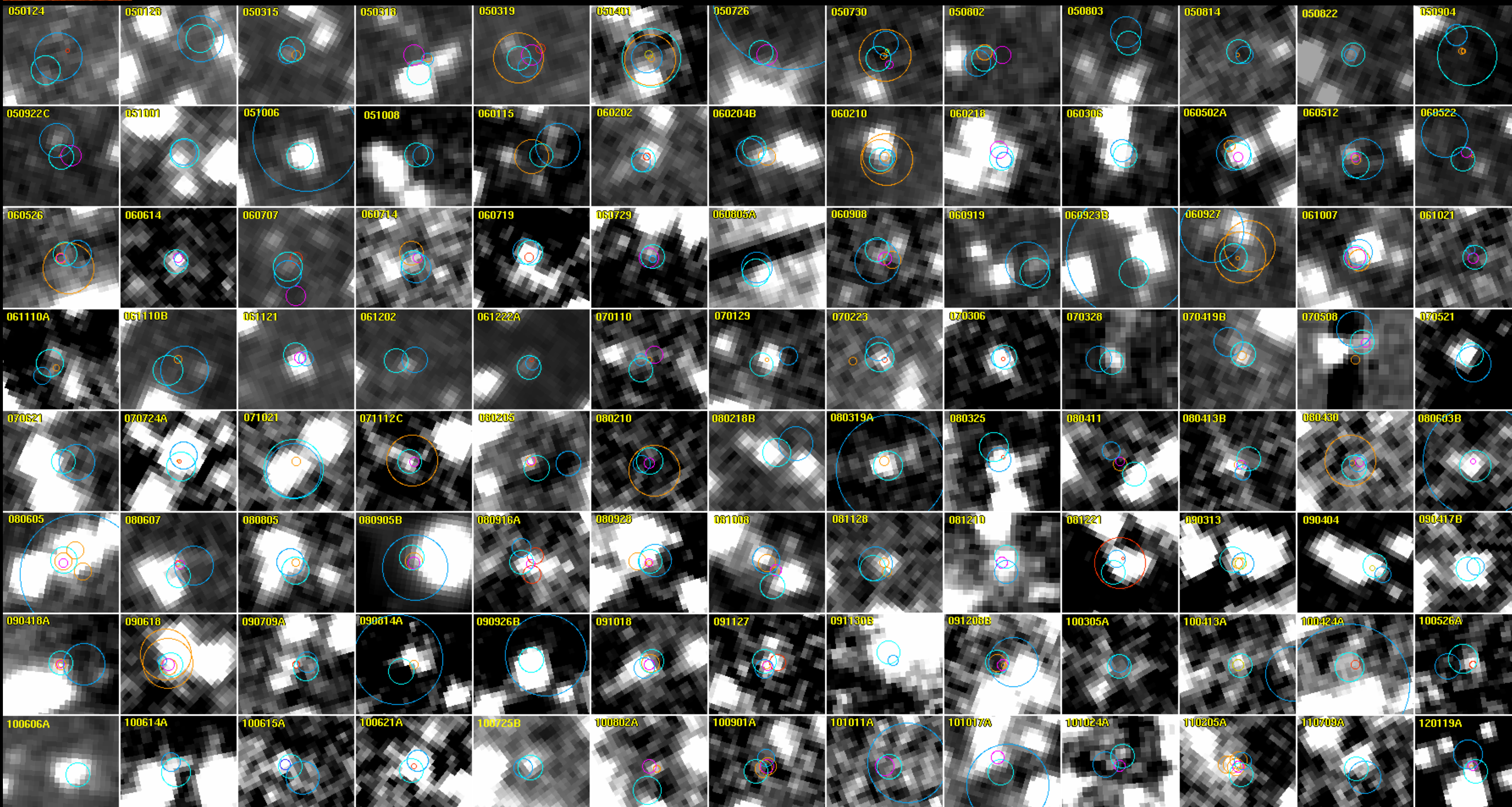
Rate variation levels off at low-mass end
- No further variation below $<10^9 M_\odot$ @ z~1
- Evidence supporting metallicity threshold $\sim 0.5 Z_\odot$
- Still viable tracers for low masses, z>3? Maybe...

Era of large-number host catalogs has arrived.

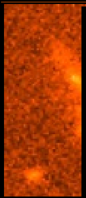
Ample material for more detailed models in future.

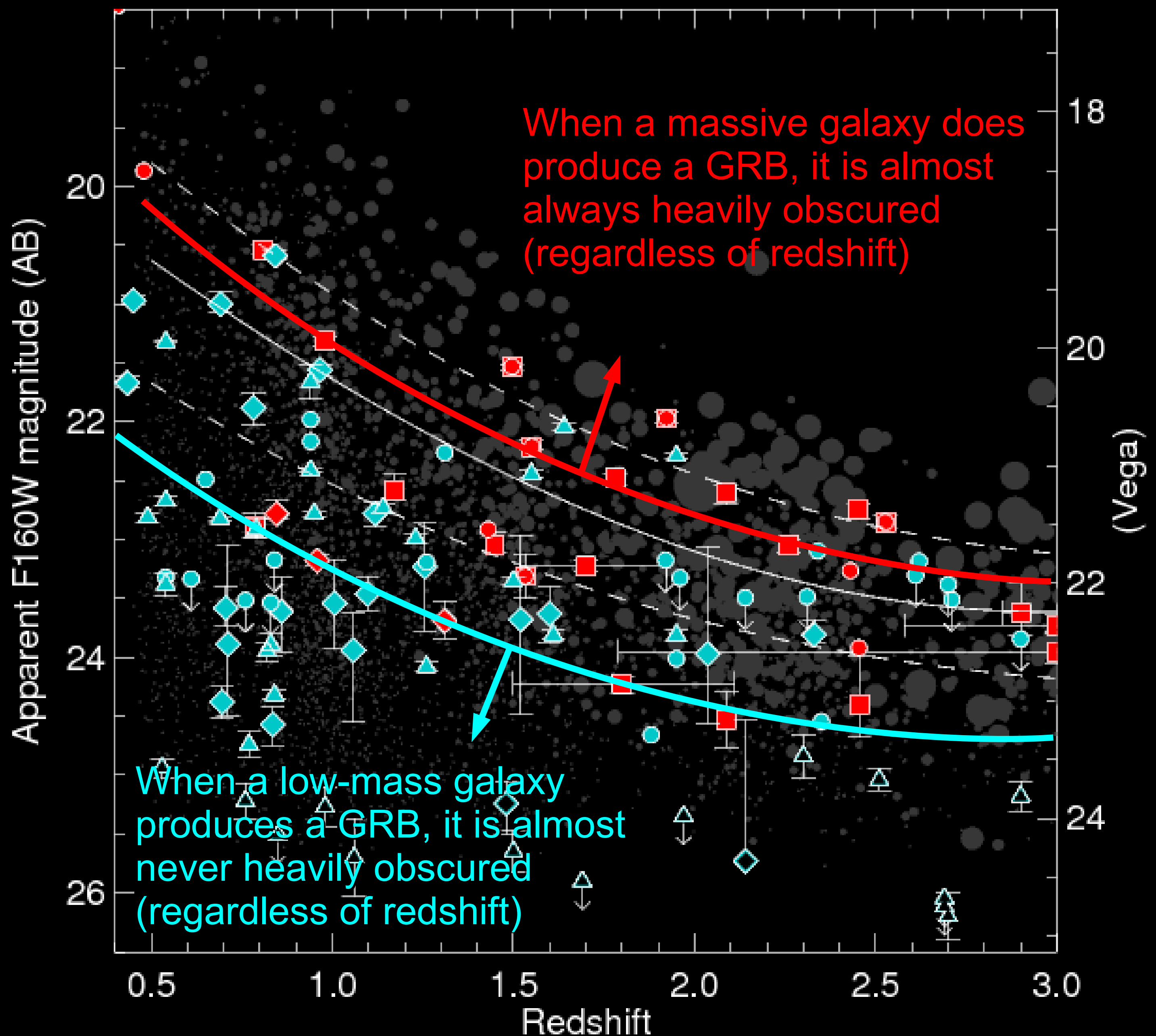
Spitzer Large Program

132 uniformly-selected GRB hosts spanning z = 0.03-6.29; currently 80% redshift complete
At survey's end, will have SEDs/physical parameters for ~30 objects per Δz~1 redshift bin.

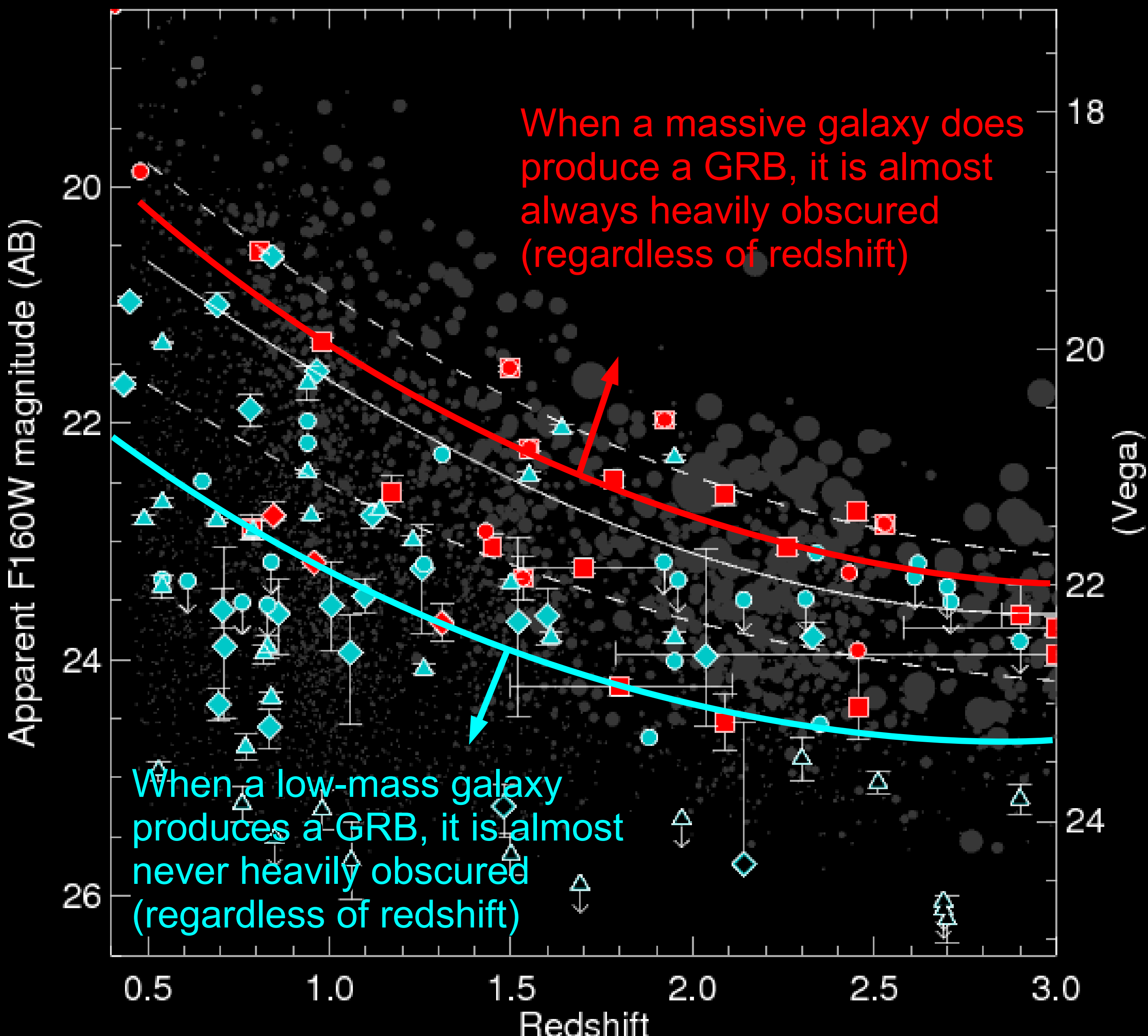


Mass versus Obscuration

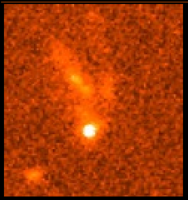


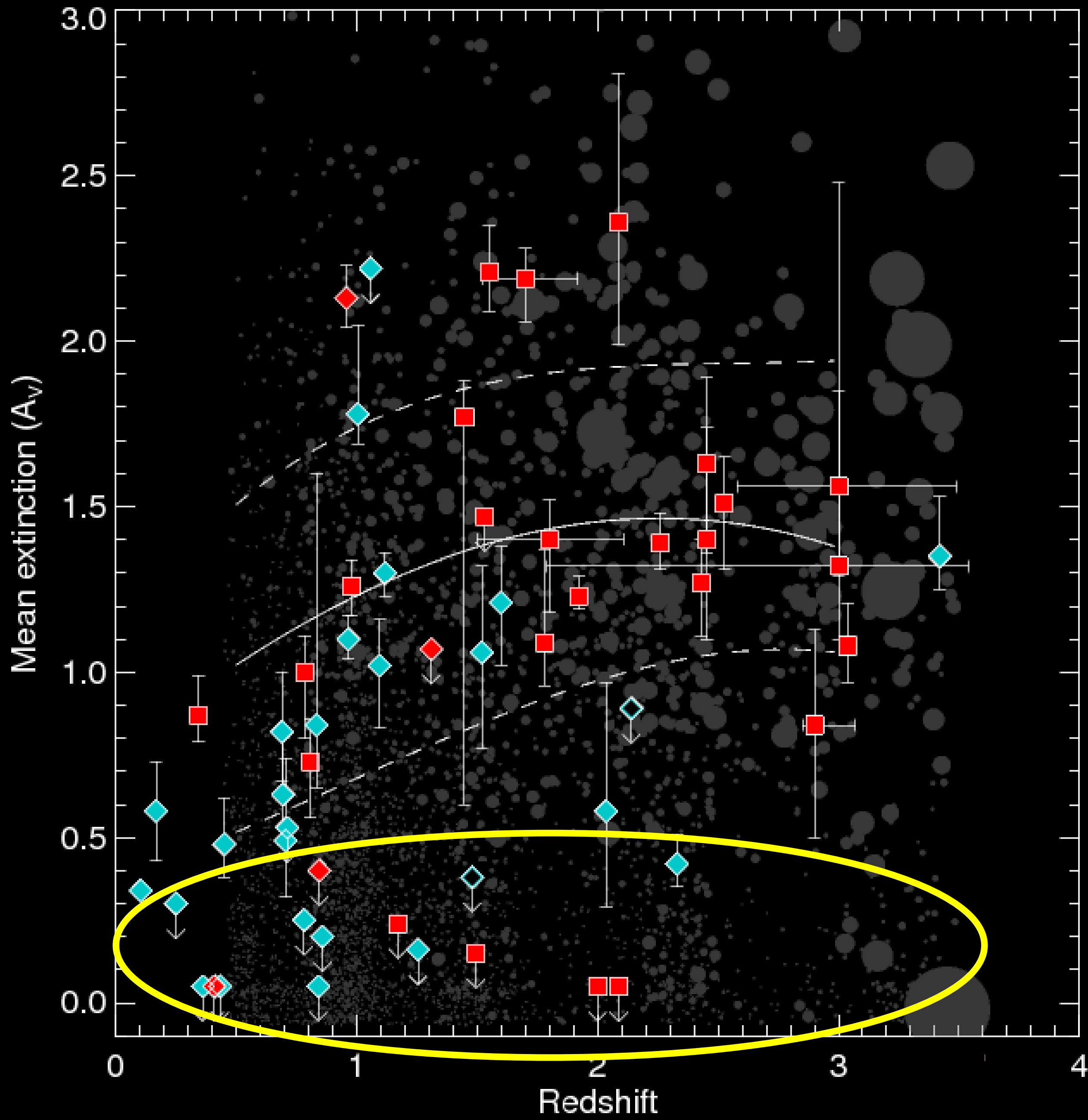


Mass versus Obscuration



Color versus Obscuration

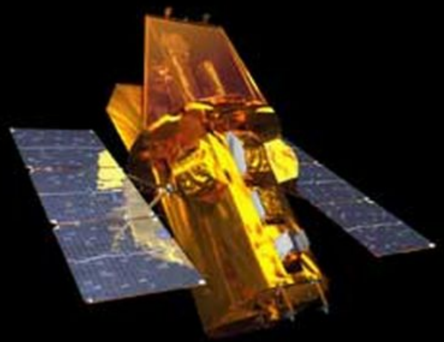


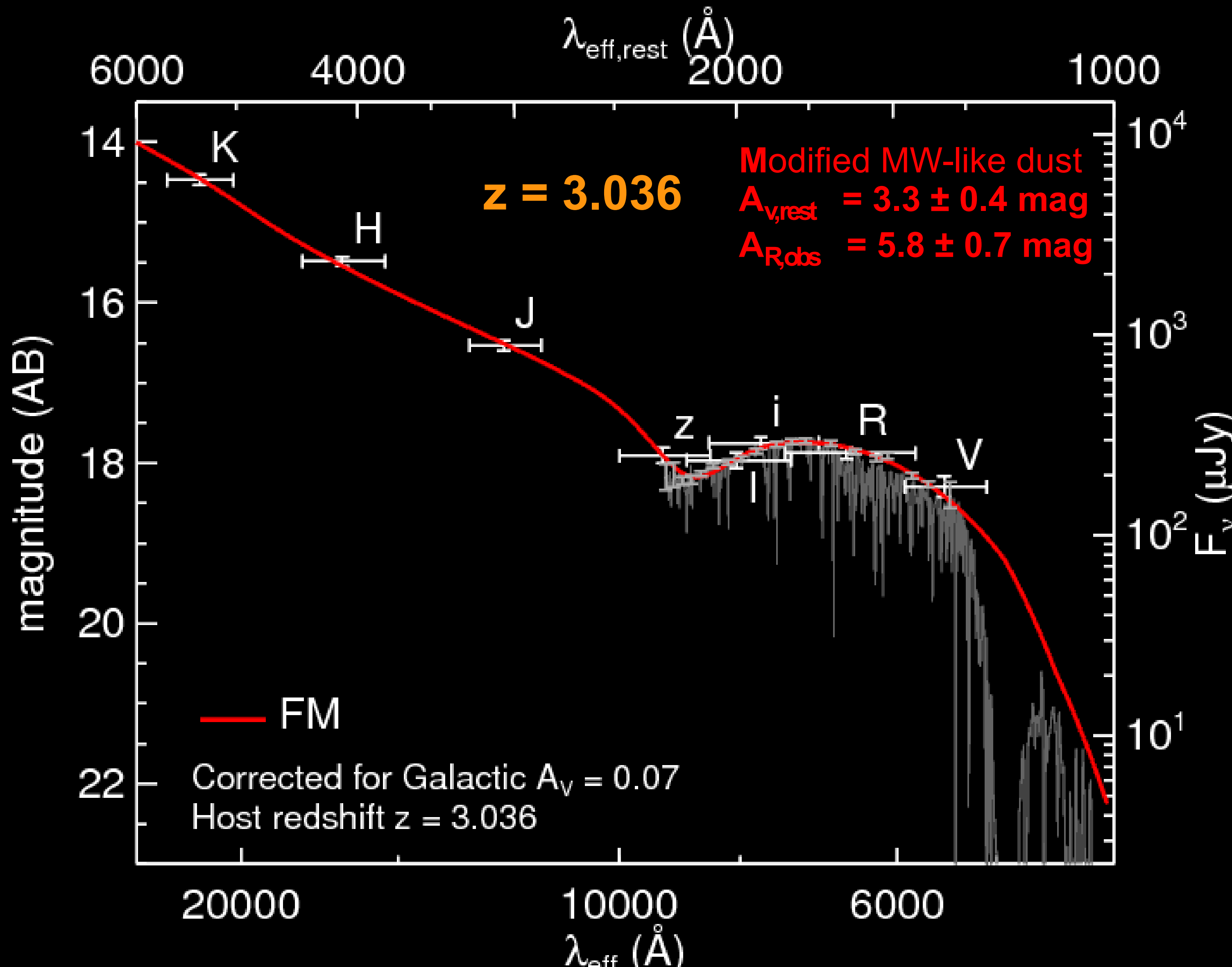


Red galaxies only produce obscured GRBs...

… but blue galaxies do sometimes produce heavily obscured GRBs.

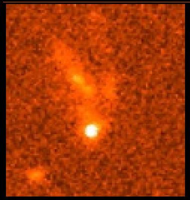
The Exceptionally Luminous GRB 080607

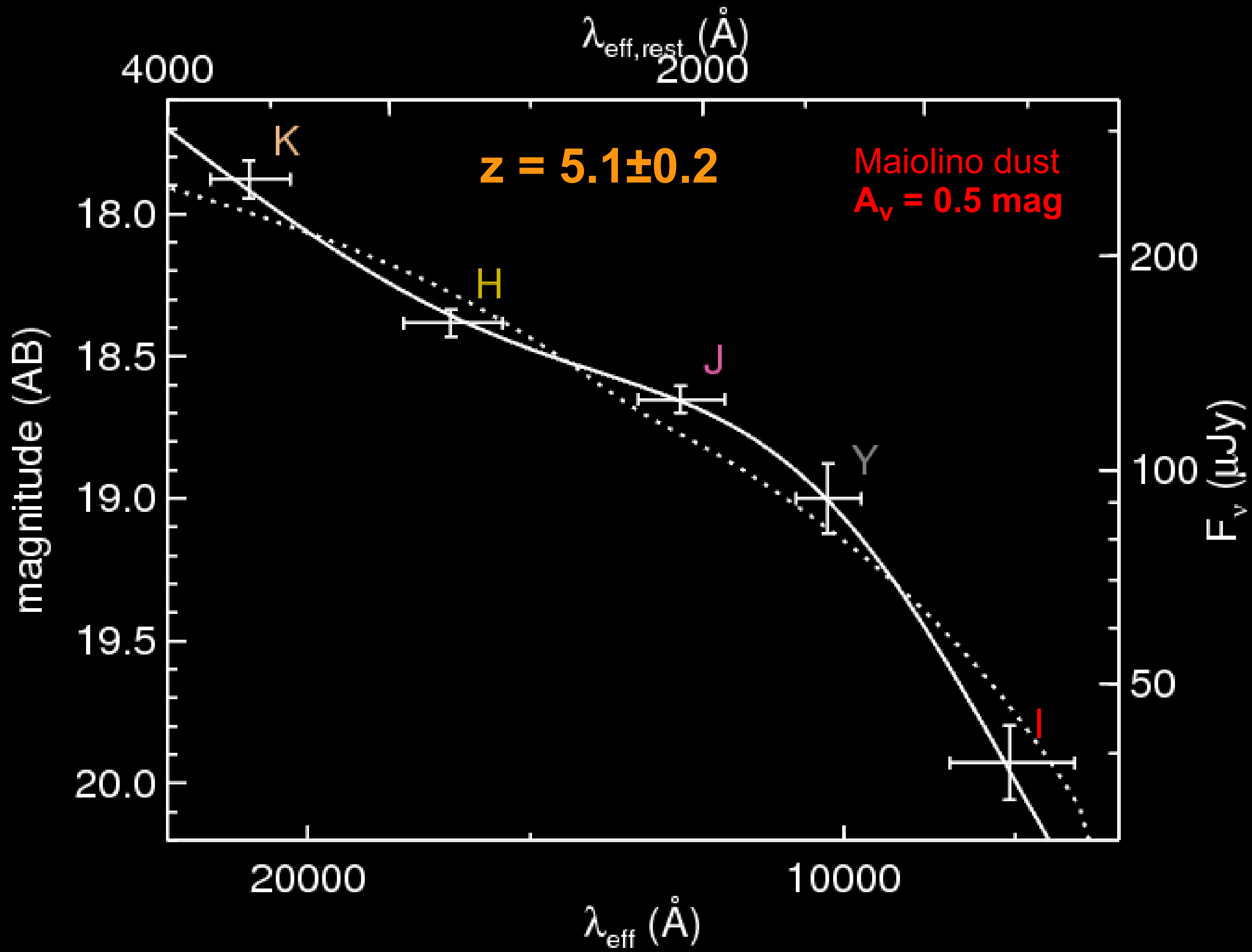




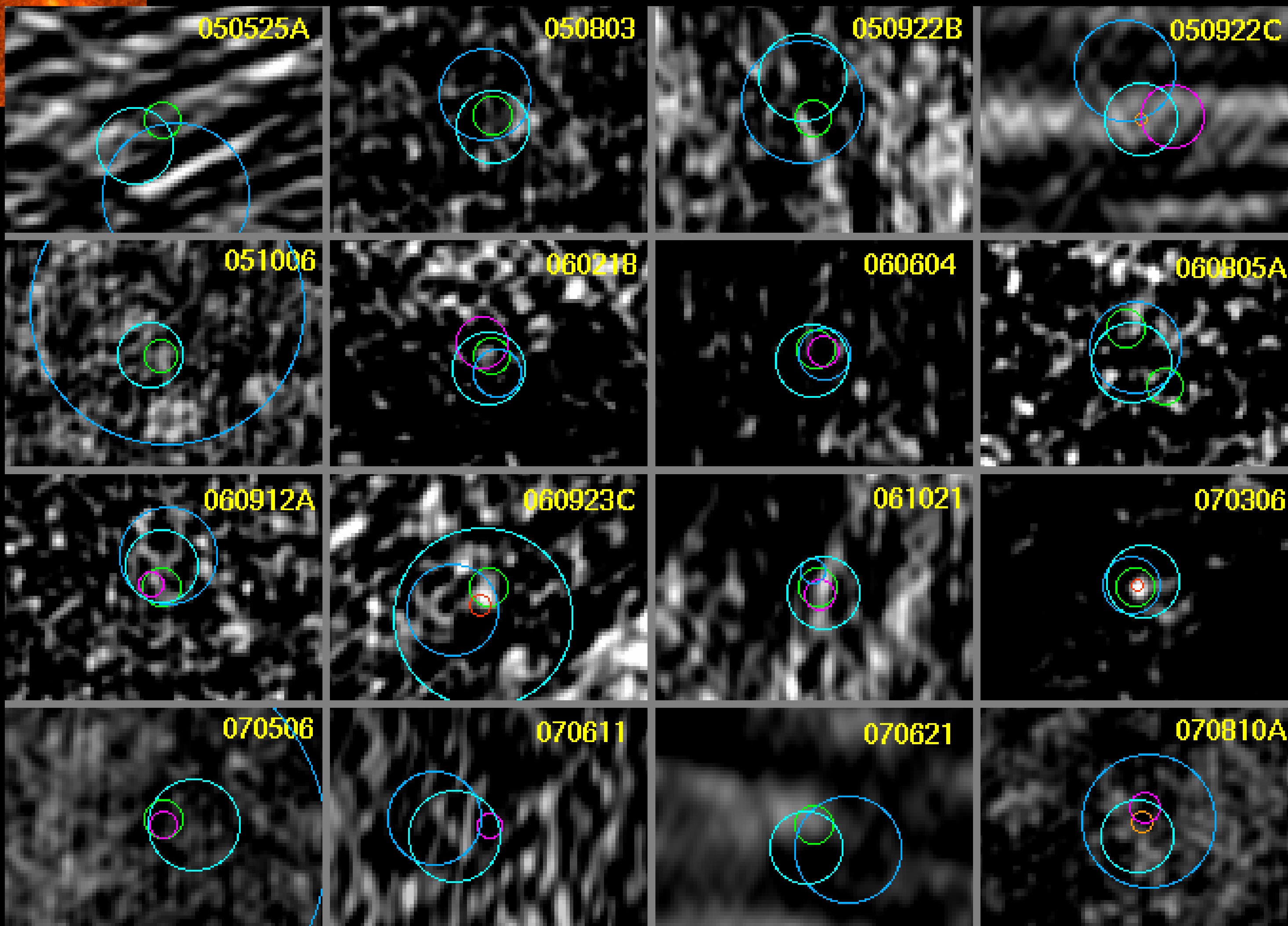
Perley et al. 2010b

Exotic dust at z~5 from GRB 071025



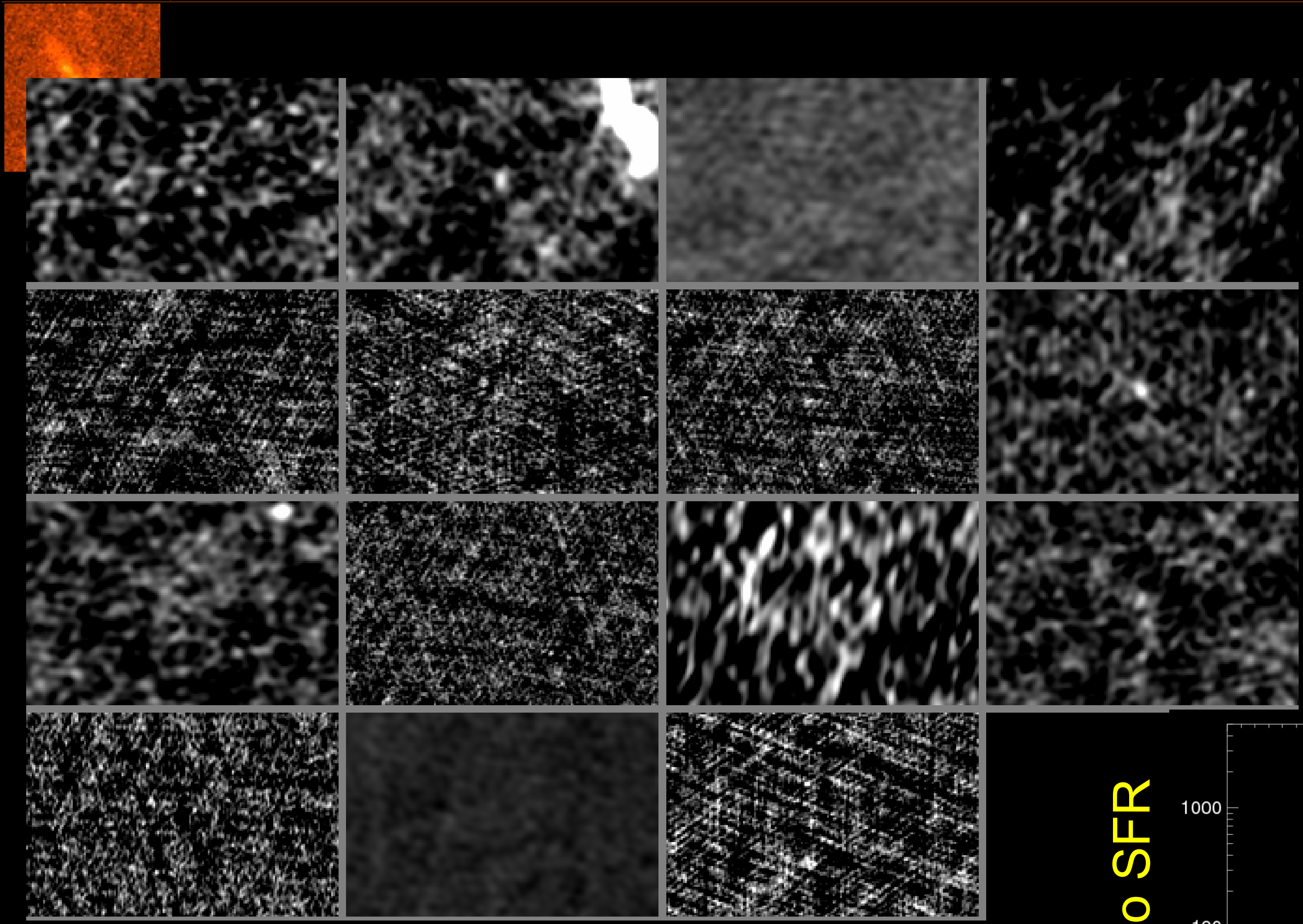


Few GRB hosts are SMGs



“Unbiased” sample:
1/16 detections with JVLA so far.

Few GRB hosts are SMGs



Dust-obscured
sample:
3/15 detections
with JVLA.