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

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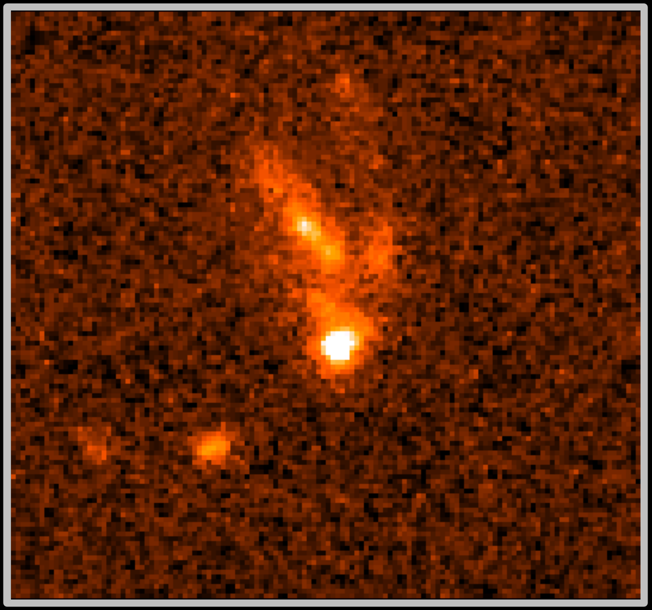
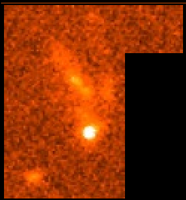
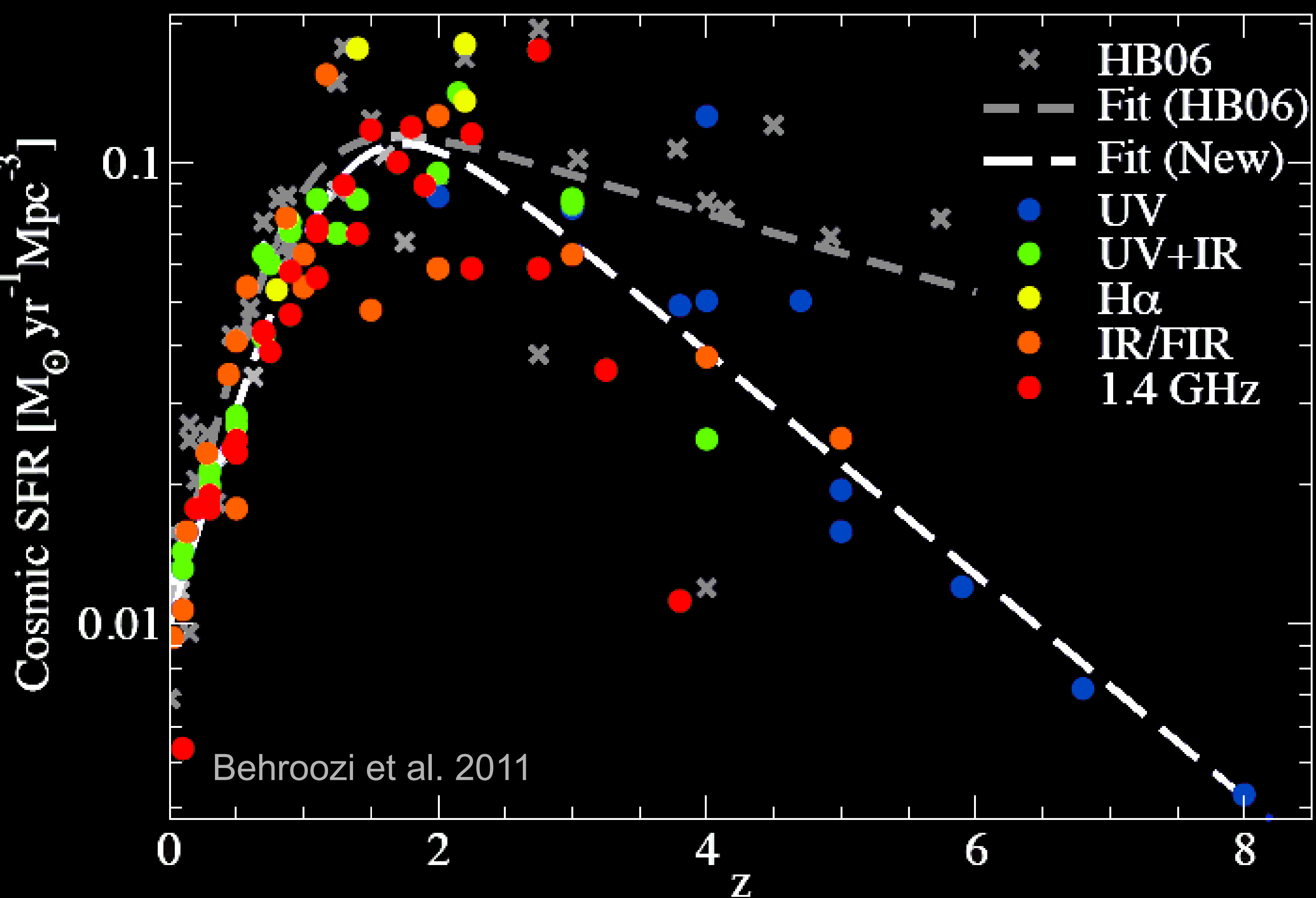
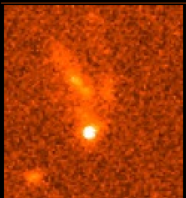


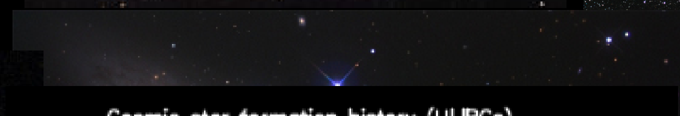
Cosmic Star-Formation History

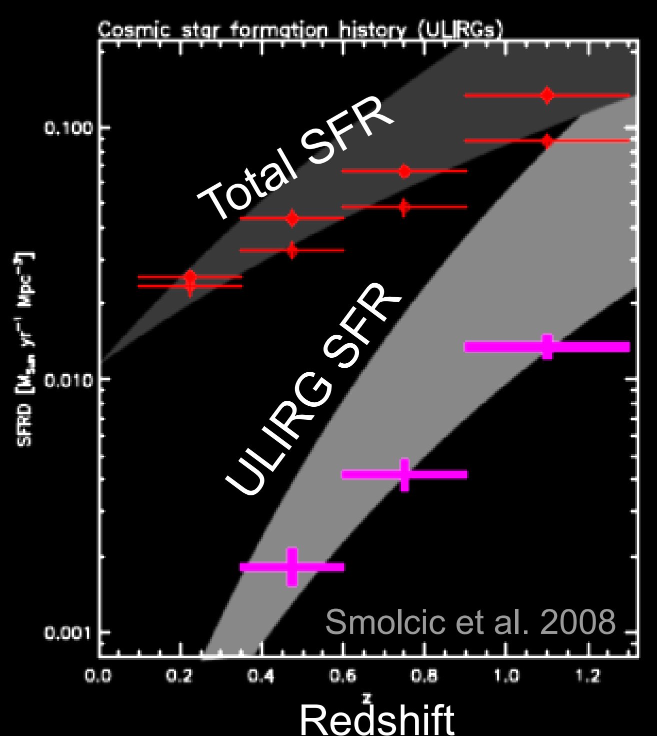


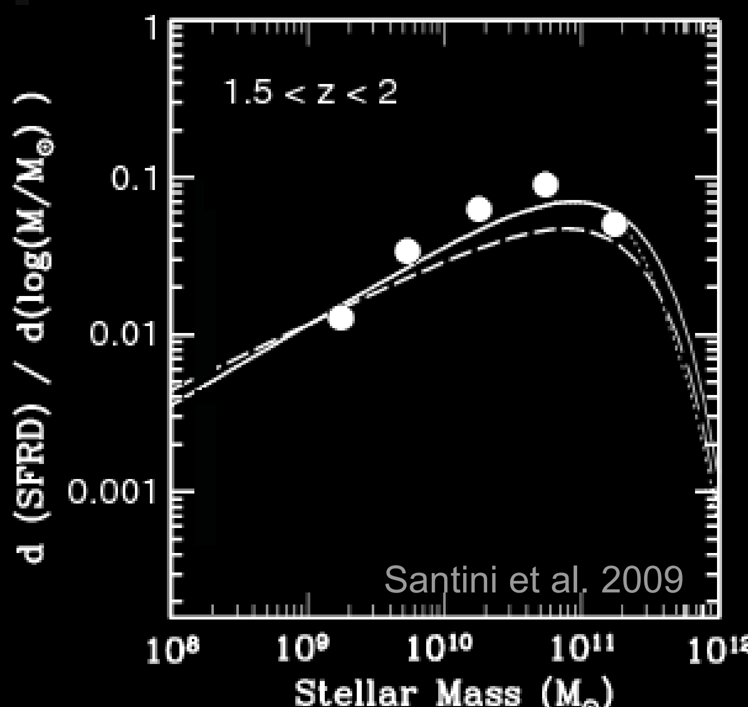


Cosmic Star-Formation Sites

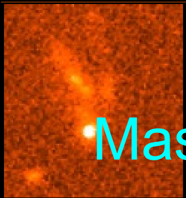








Star Formation Tracers



Massive stars signal recent/ongoing star formation.

Ultraviolet emission:

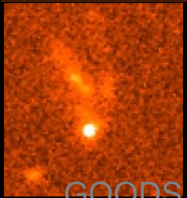
(+reprocessed analogs: nebular lines, PAH lines, FIR)

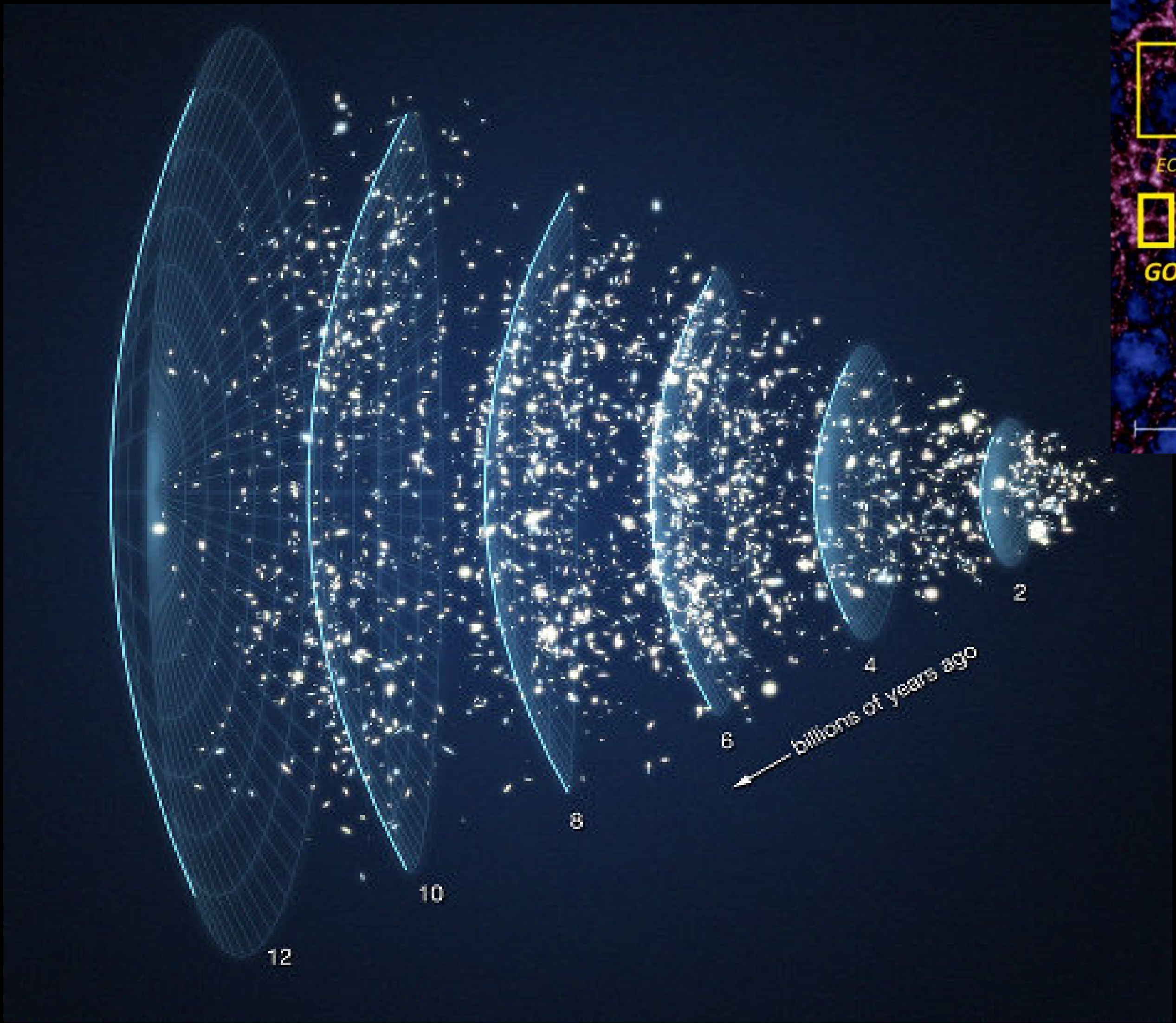
the star-formation indicator of choice.

Some alternatives:

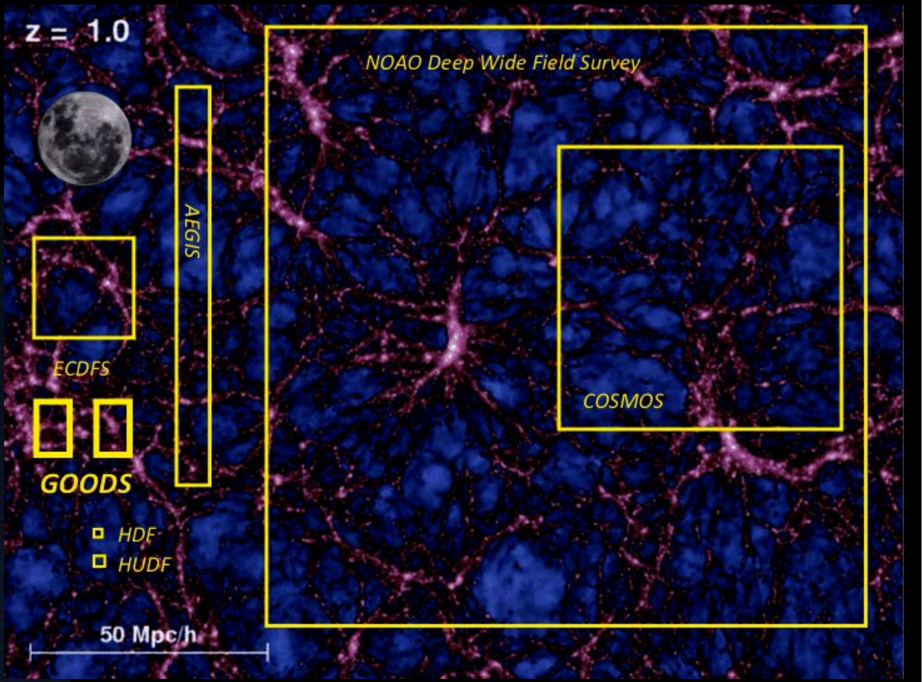
- X-rays (from high-mass X-ray binaries)
- radio free-free (electrons in nebulae)
- radio synchrotron (from supernova remnants)

Field-Survey Strategy



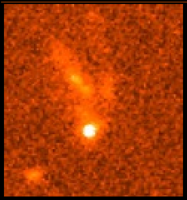


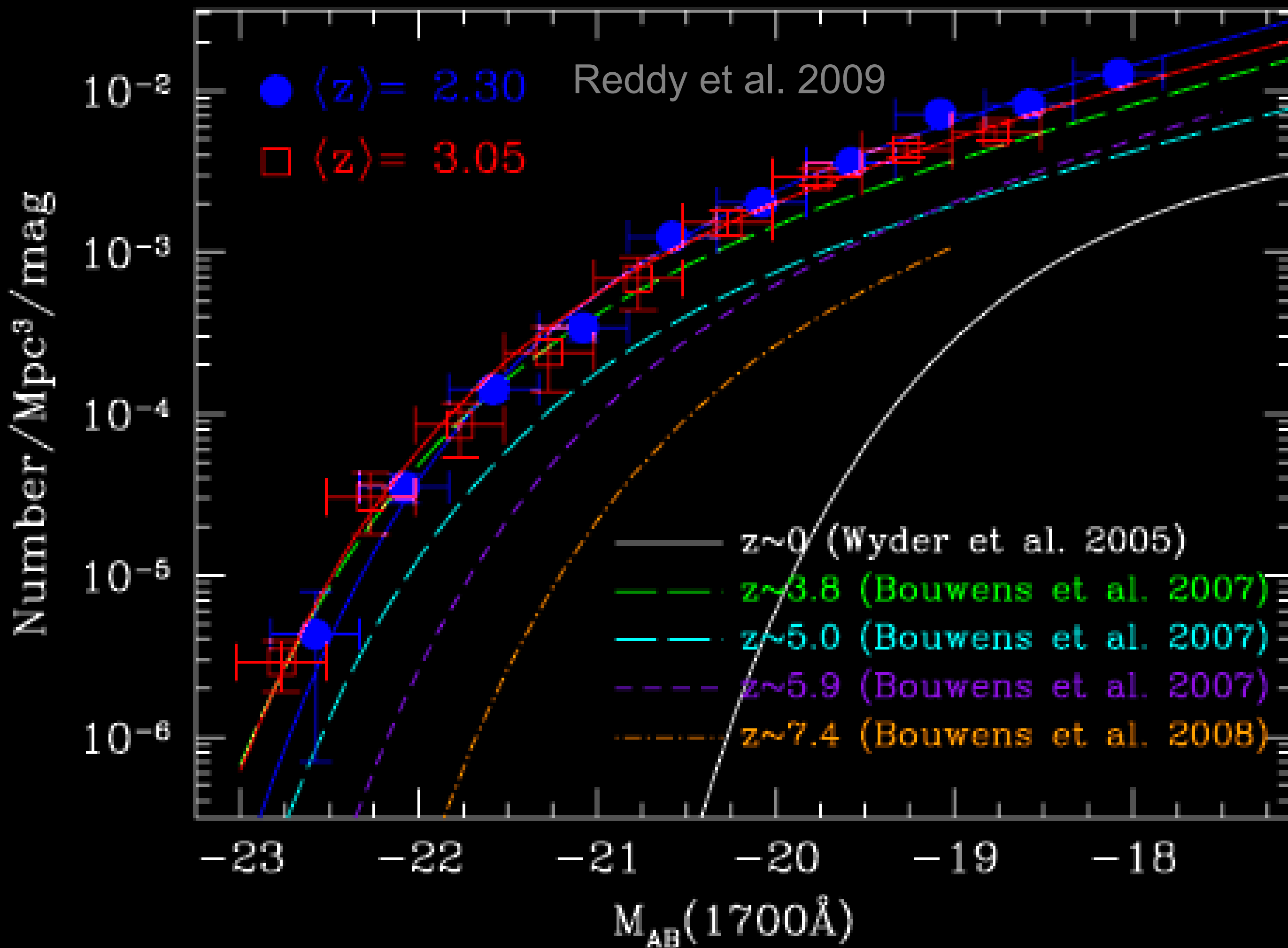
GOODS visualization from ESO.org



from CANDELS blog

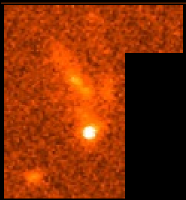
Field-Survey Strategy

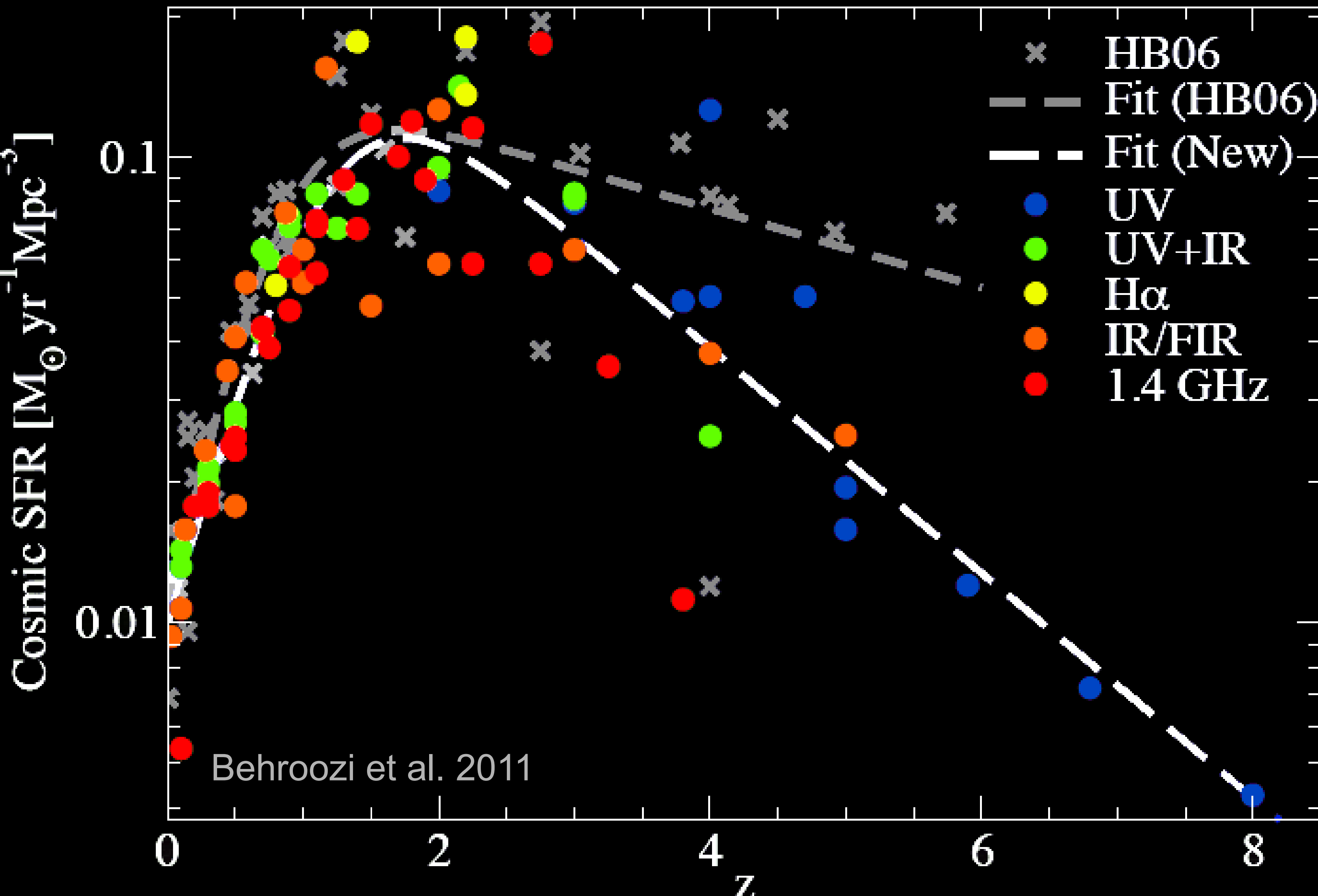




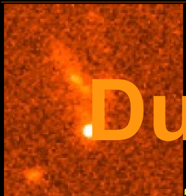
← Ultraviolet Luminosity

Cosmic Star-Formation History





Limitations of Field Surveys

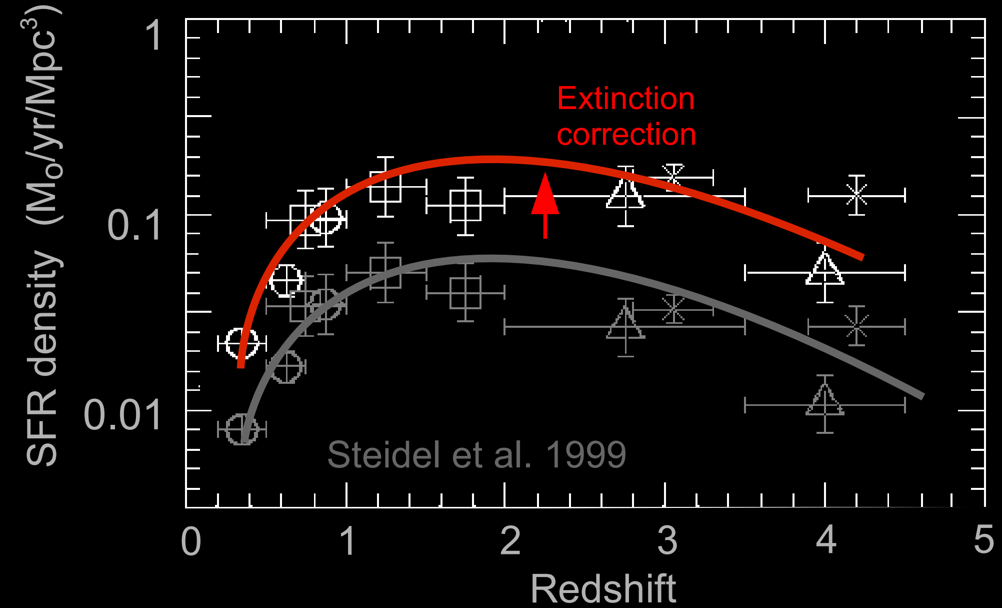


Dust Correction

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

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

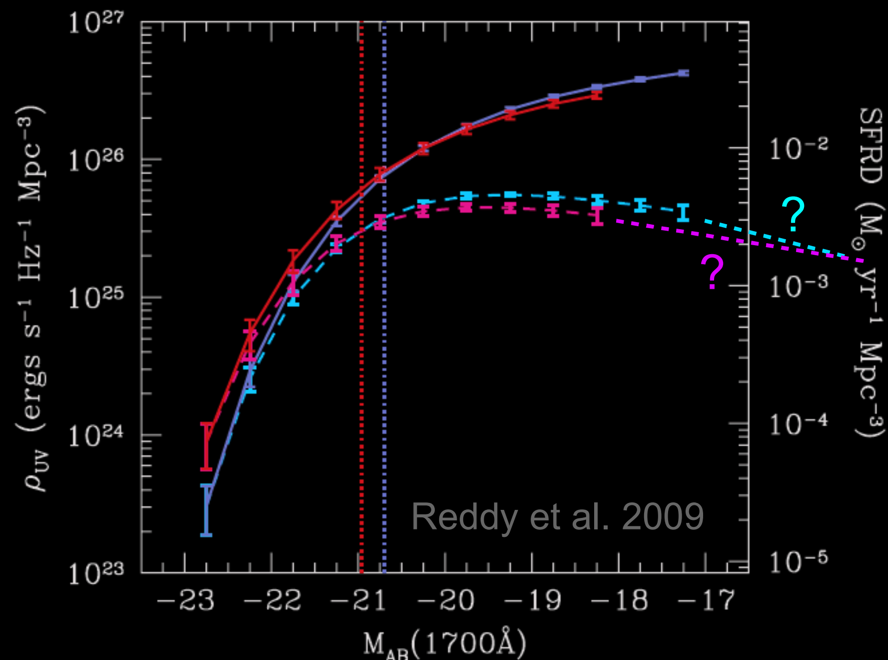
UV energy can be "recovered" at 8μm / FIR / submm, but these wavelengths have poor sensitivity to faint galaxies



Missing galaxies

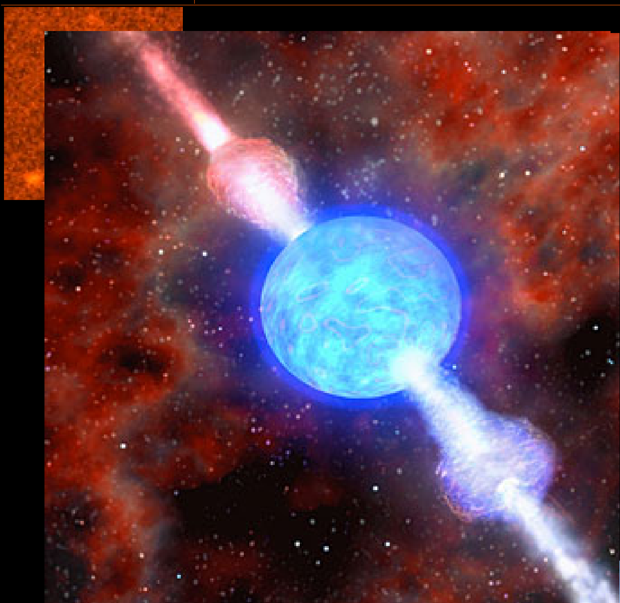
Faint galaxies (<0.1 L*) require extrapolation from bright end

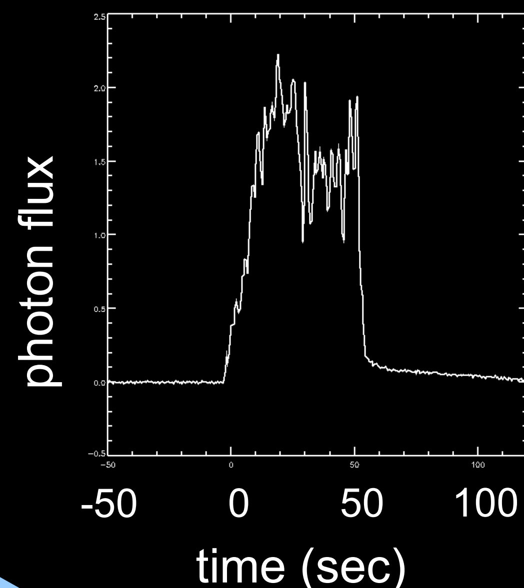
Redshift measurement imposes further biases

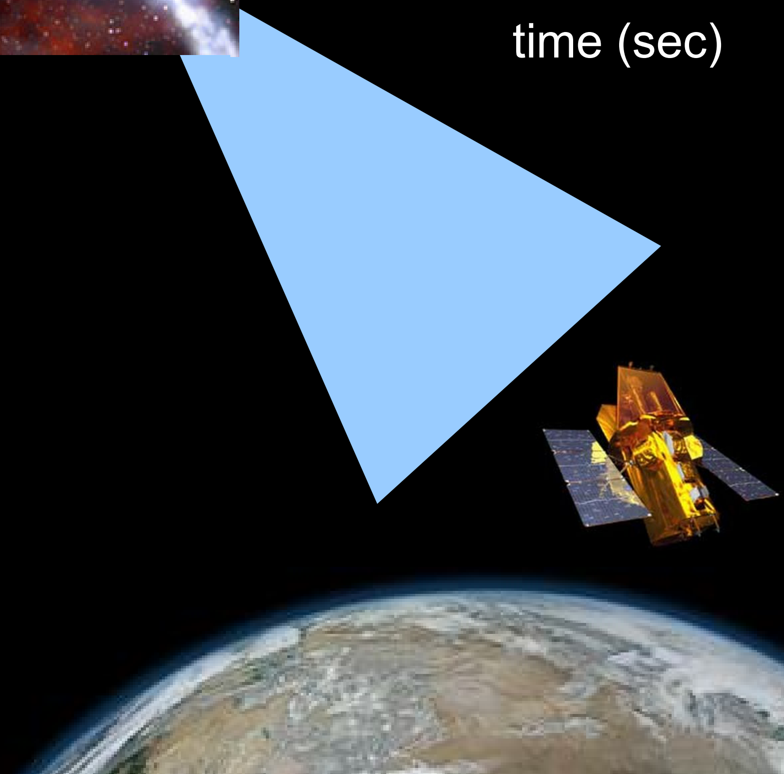


These problems are particularly limiting at z>3

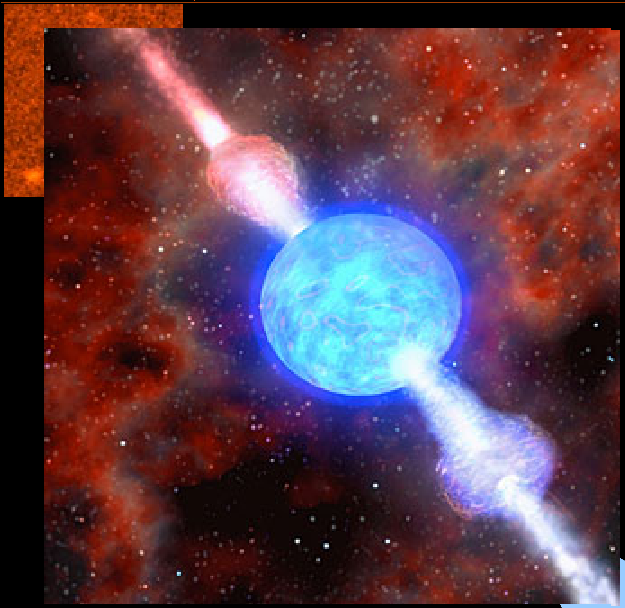
(Long-duration) Gamma-Ray Bursts

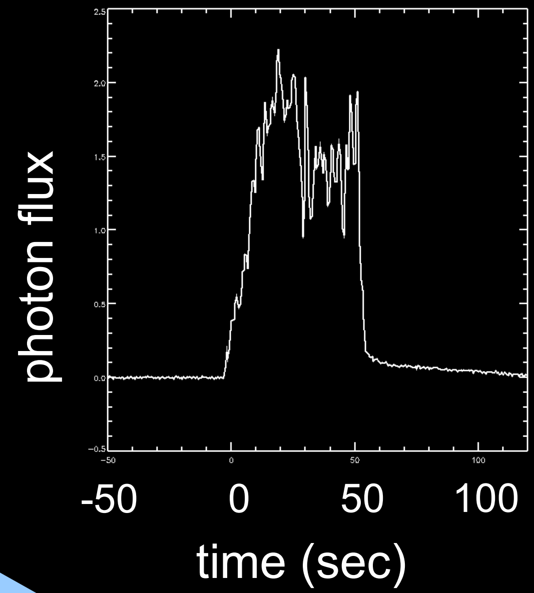


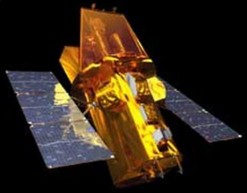




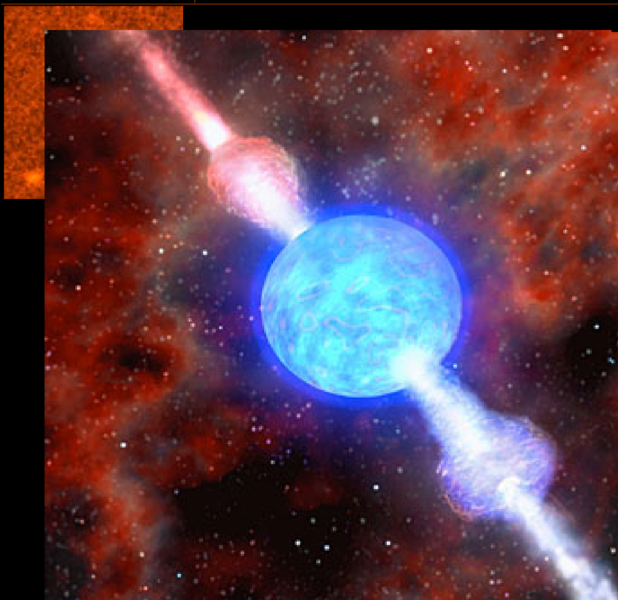
Gamma-Ray Bursts

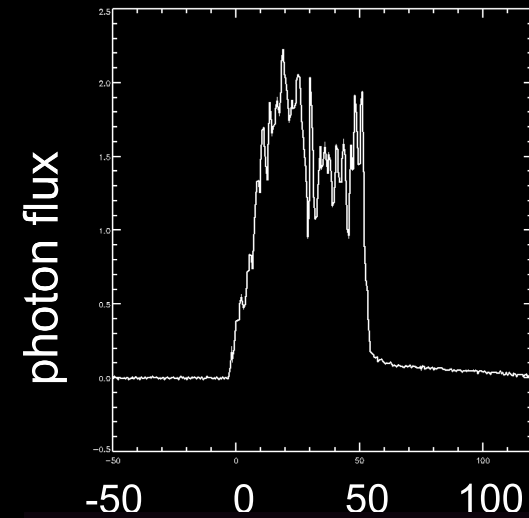


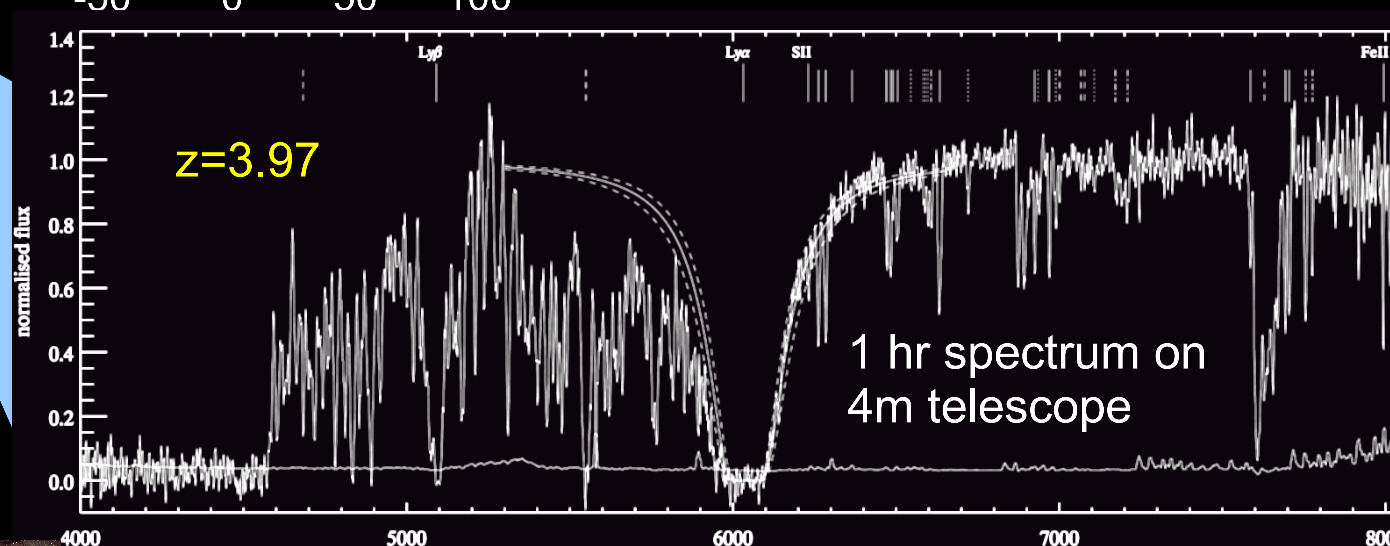




Gamma-Ray Bursts

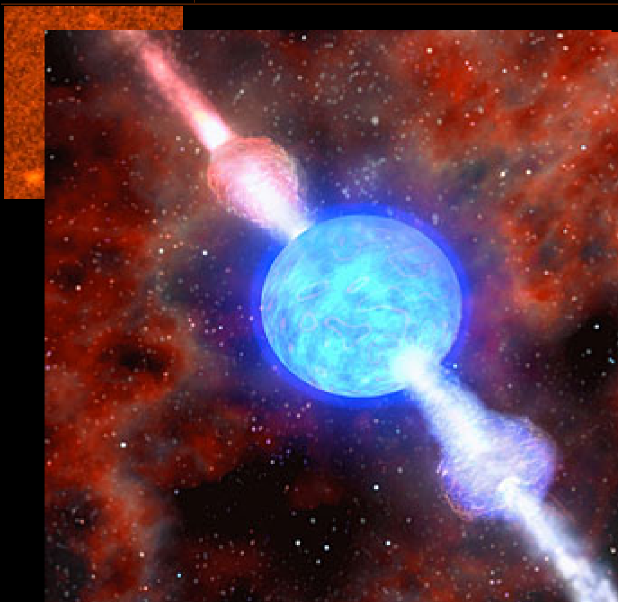


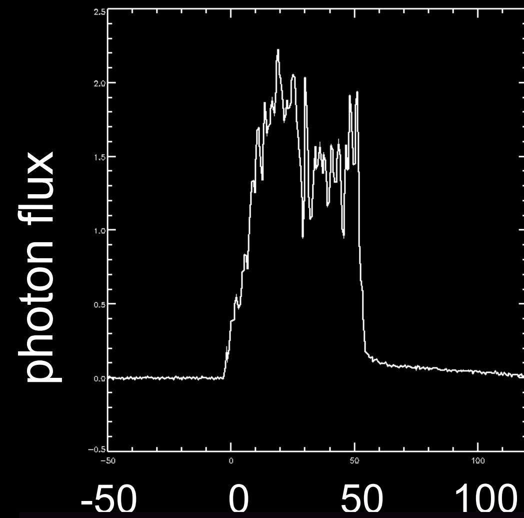


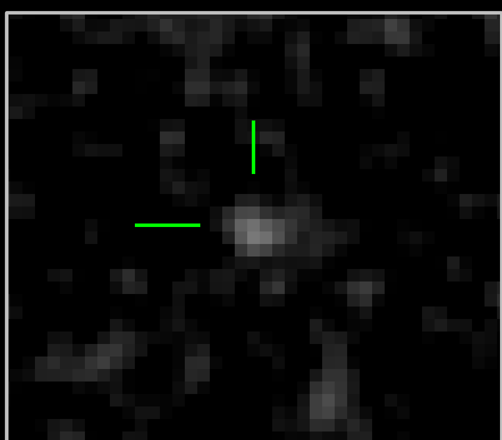


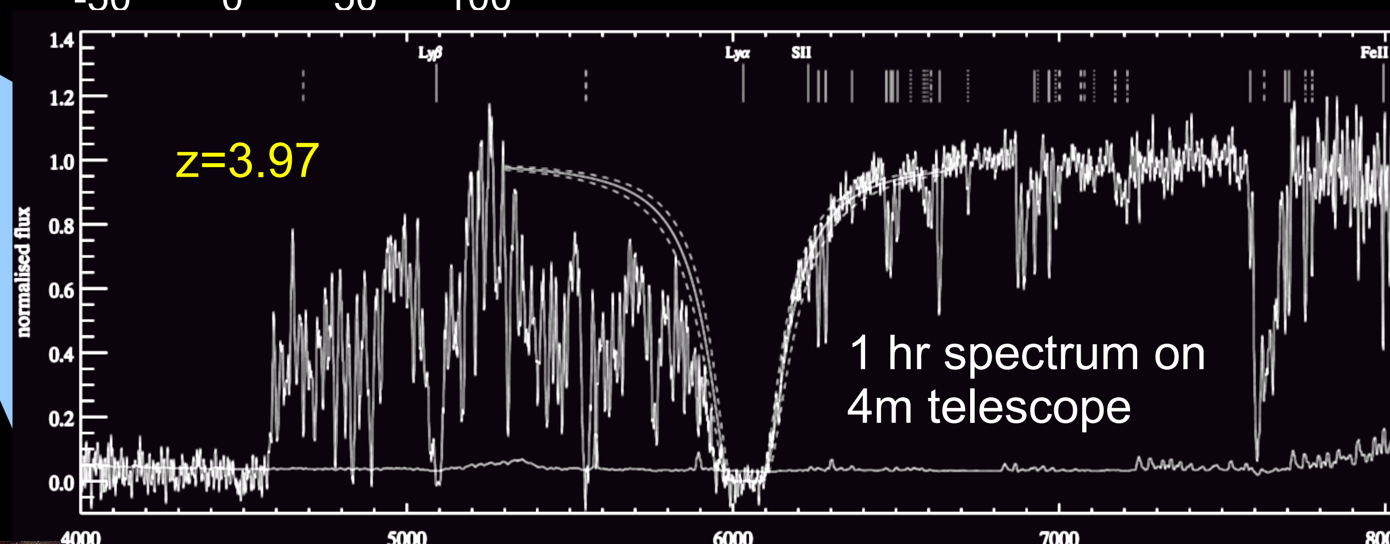
Starling+2005

Gamma-Ray Bursts



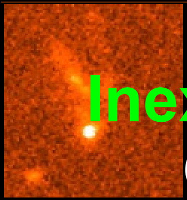






Starling+2005

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

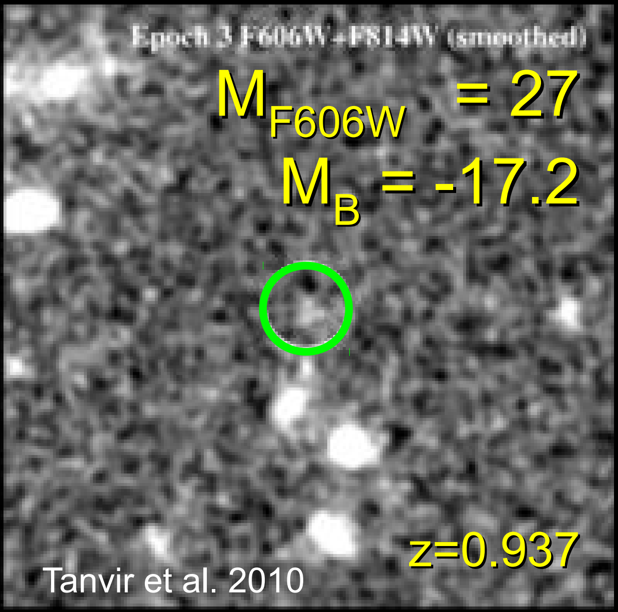
Sensitive to sub-threshold SFR

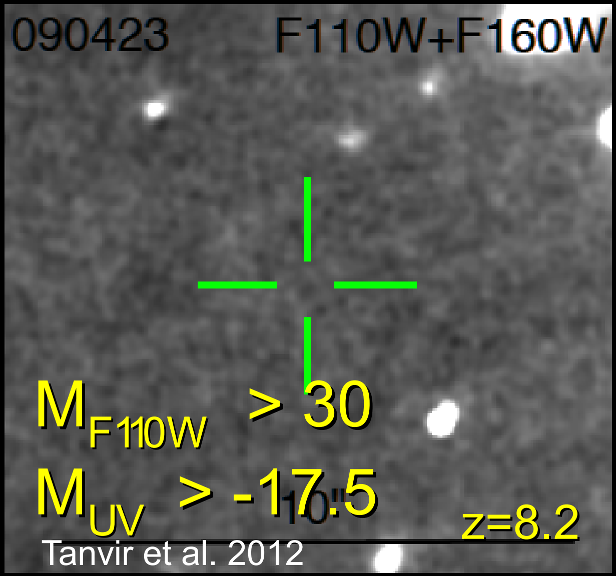
Host nondetections give a direct constraint on importance of undetectable galaxies

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

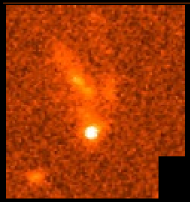
No Cosmic Variance

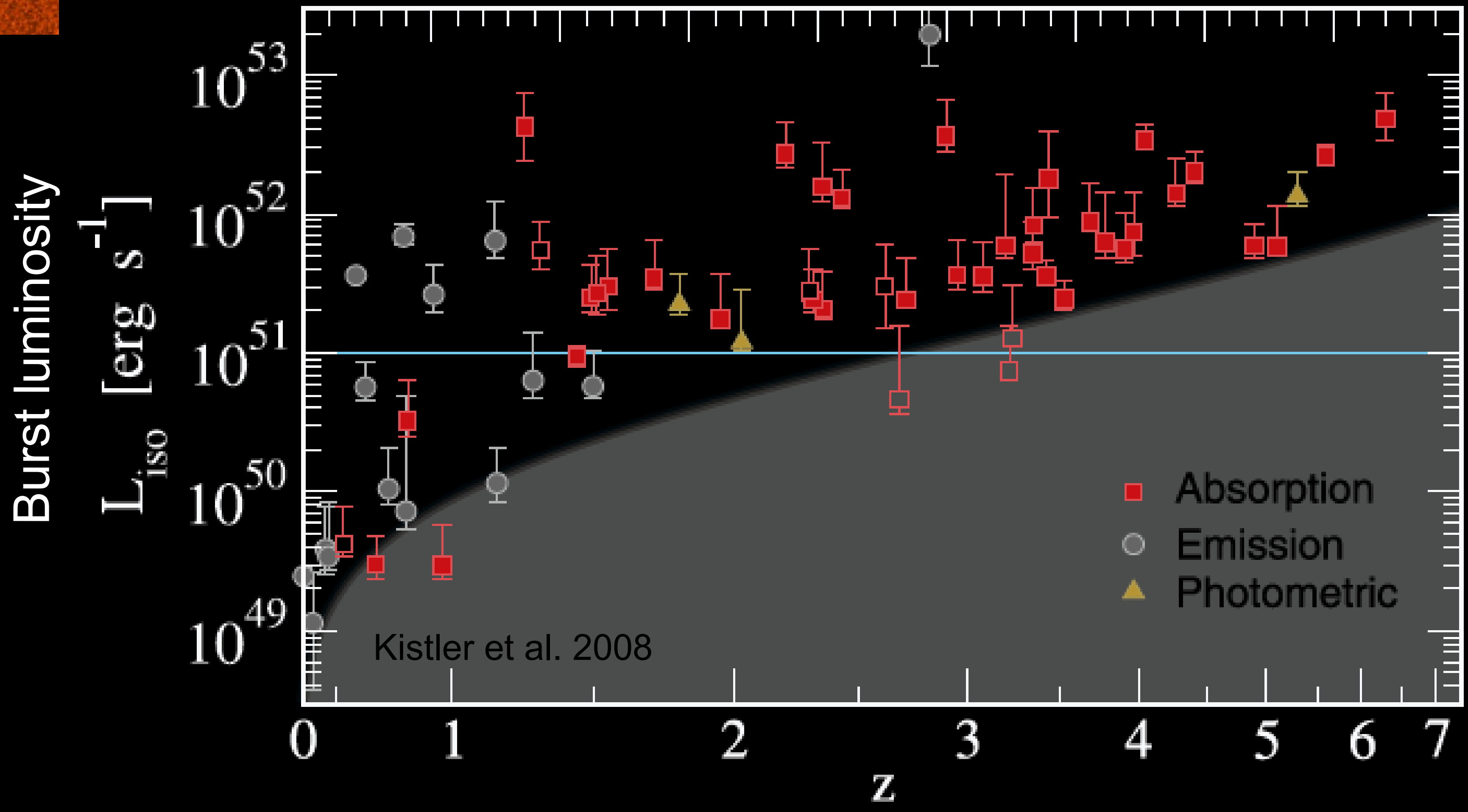
GRB satellites see (close to) the whole sky





High-z SF History from GRBs





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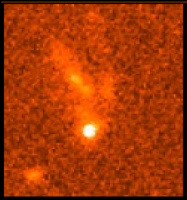

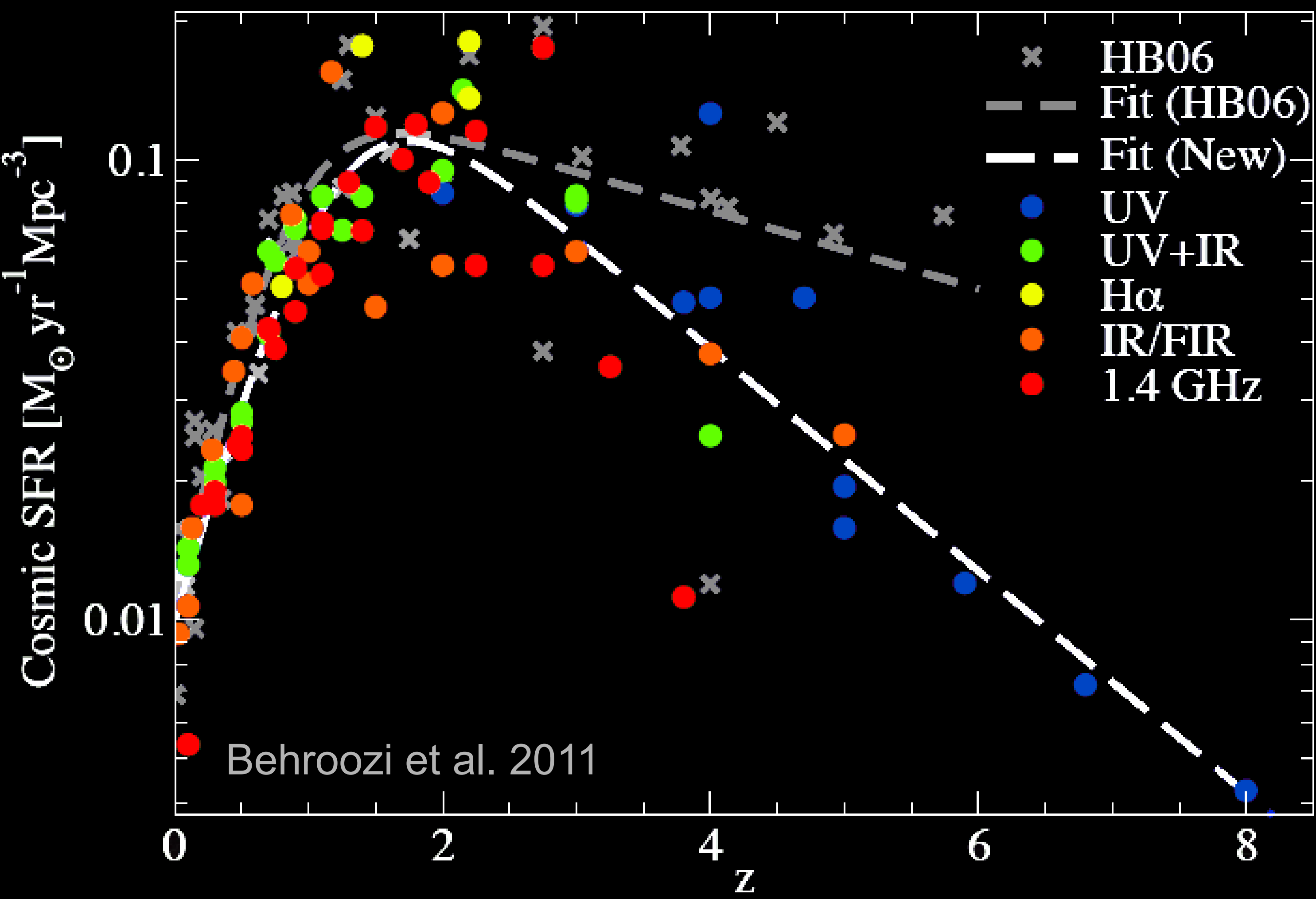

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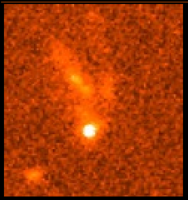

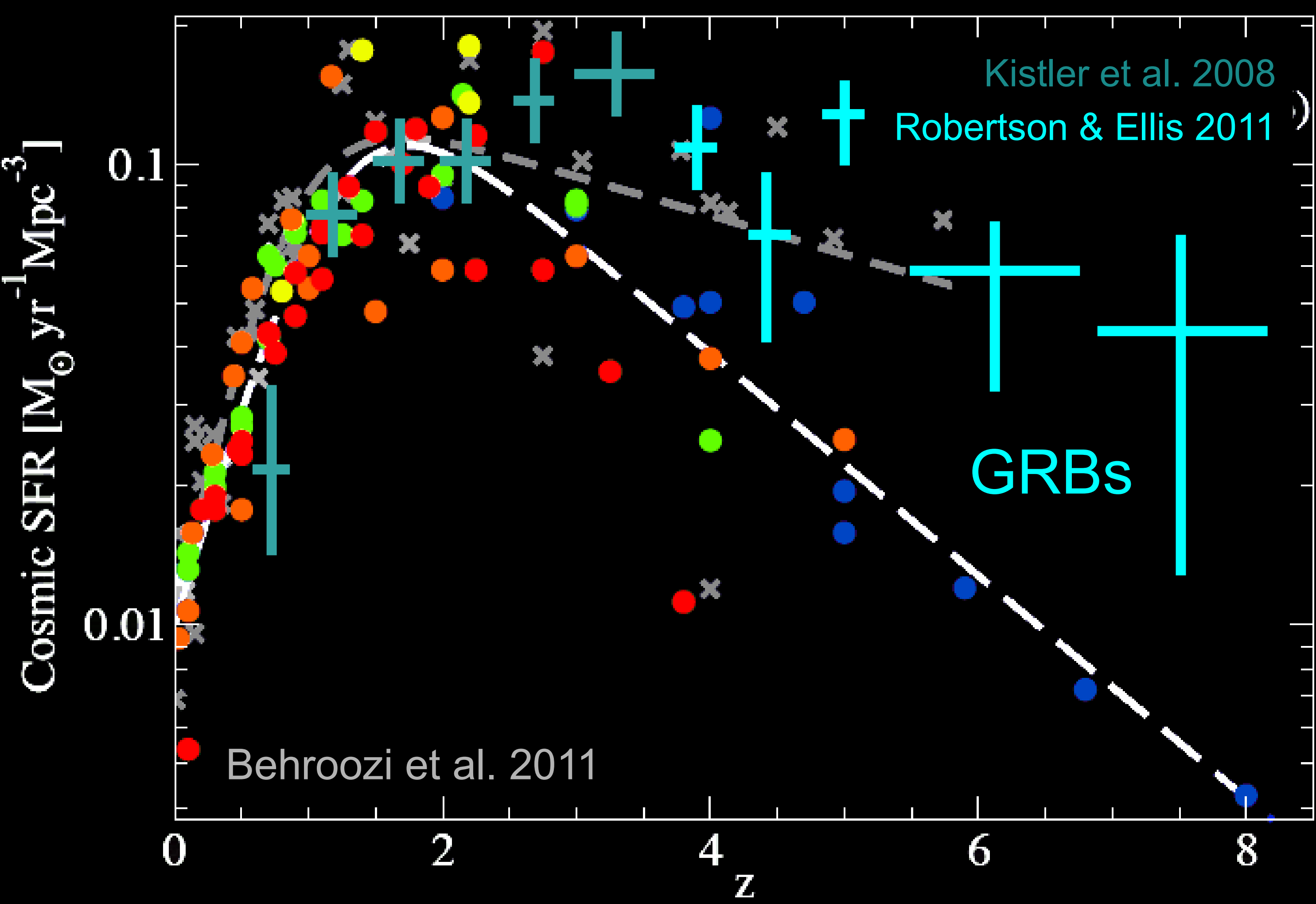

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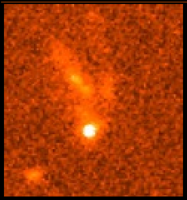

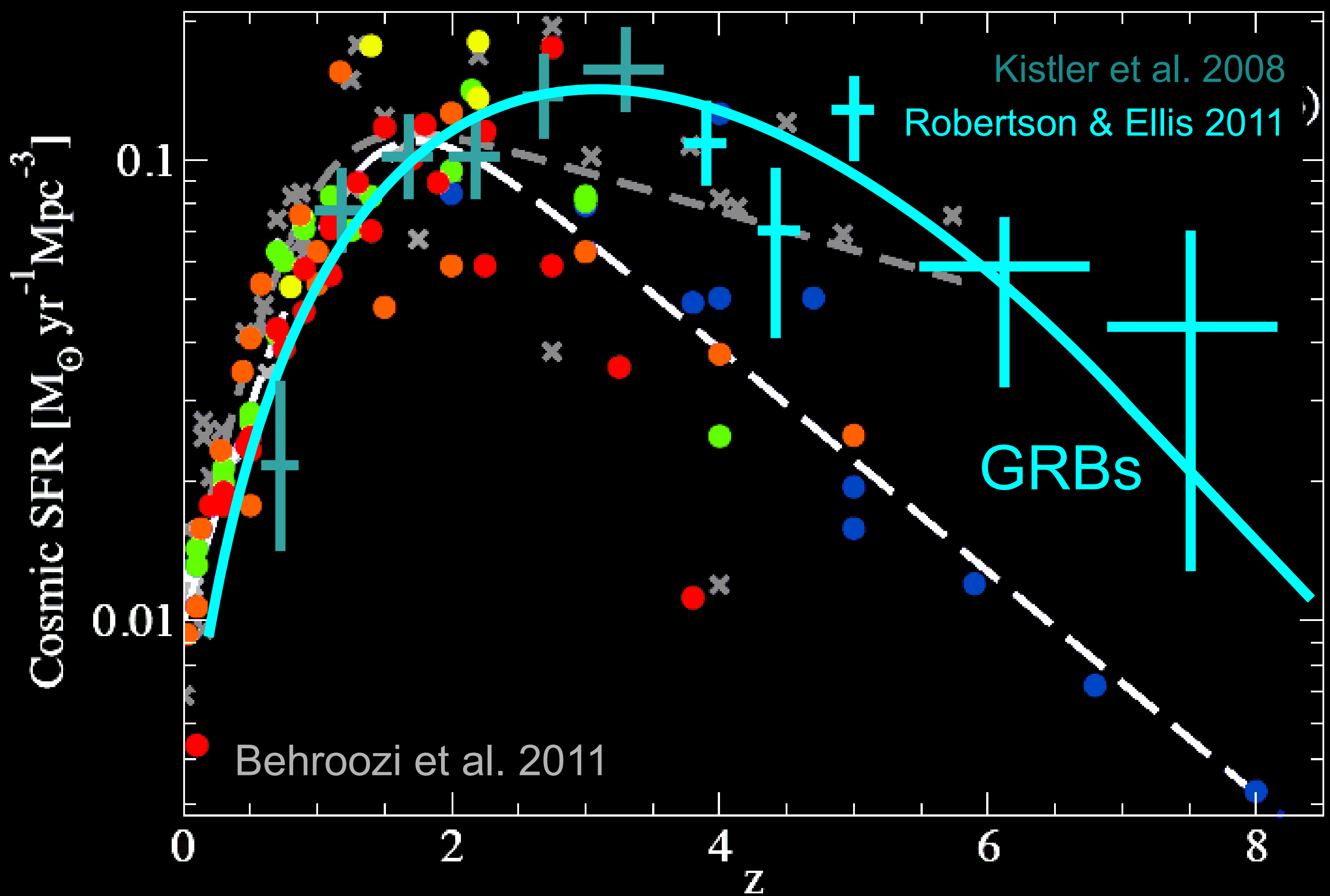

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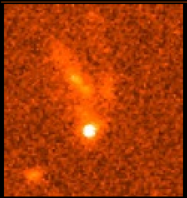
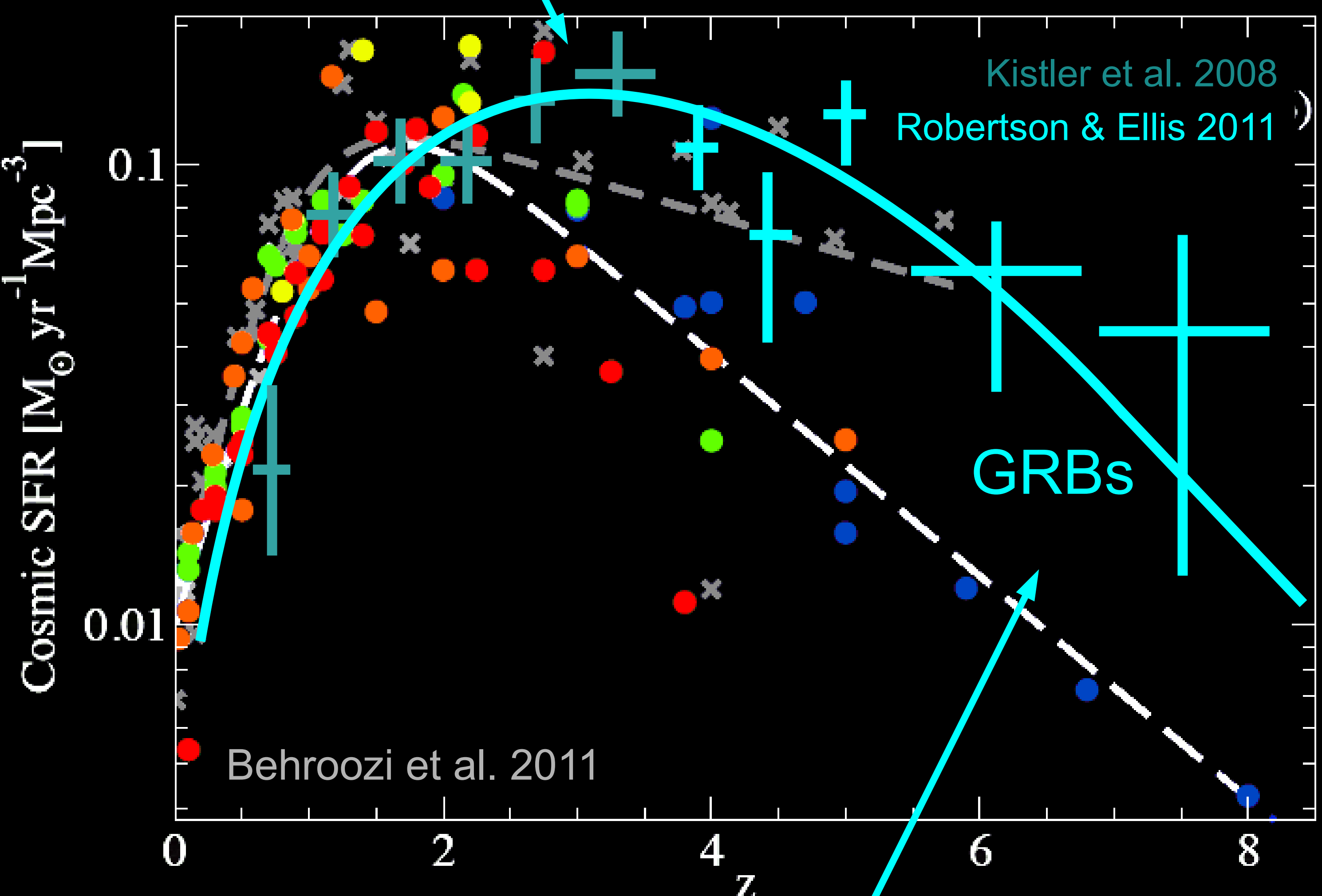
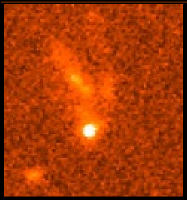


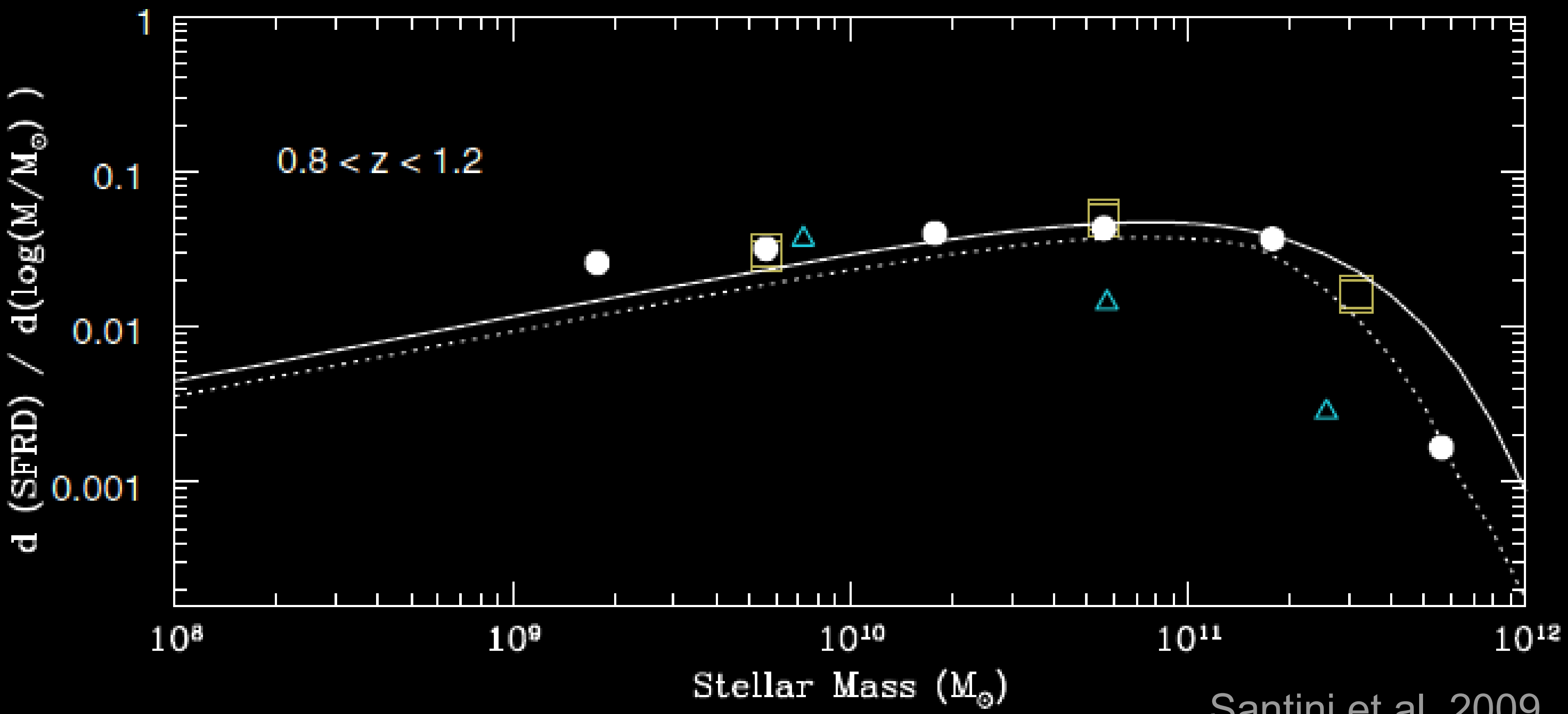
Peaks at z~3, not z~2



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

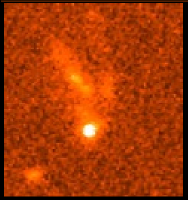
Mass Dependence of the SFRD

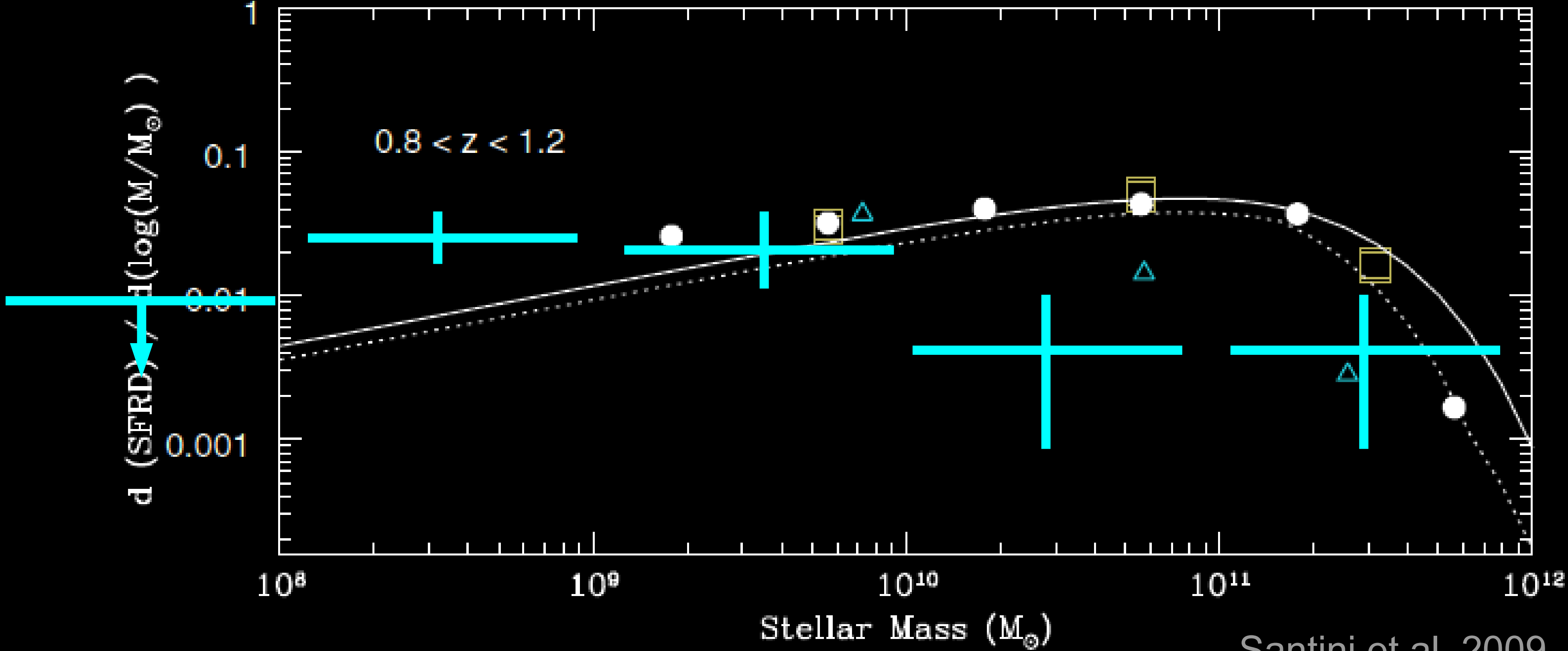




Santini et al. 2009

Mass Dependence of the SFRD





Santini et al. 2009

+ masses from pre-Swift z~1 hosts reported in literature

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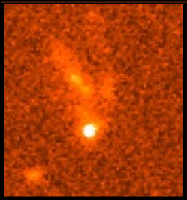

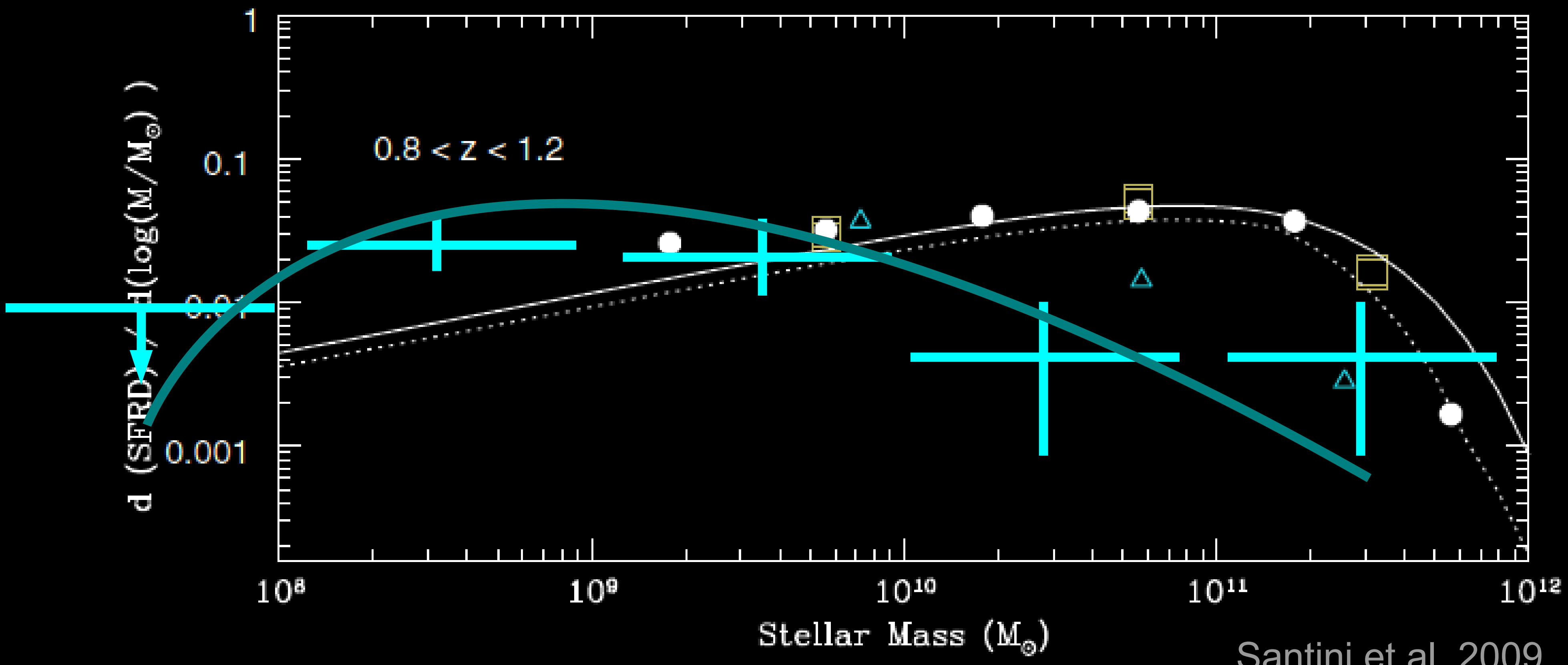

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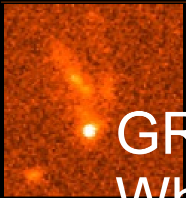
Interpretations



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

1. Field surveys systematically underestimate (by factor of ~5!) contributions from low-mass galaxies and high-z galaxies.
   e.g., Mannucci et al. 2011, Jakobsson et al. 2012

2. GRBs are not uniform star-formation rate tracers: the rate depends on environment (e.g., metallicity)
   e.g., Modjaz et al. 2008, Graham & Fruchter 2012

Dark GRBs

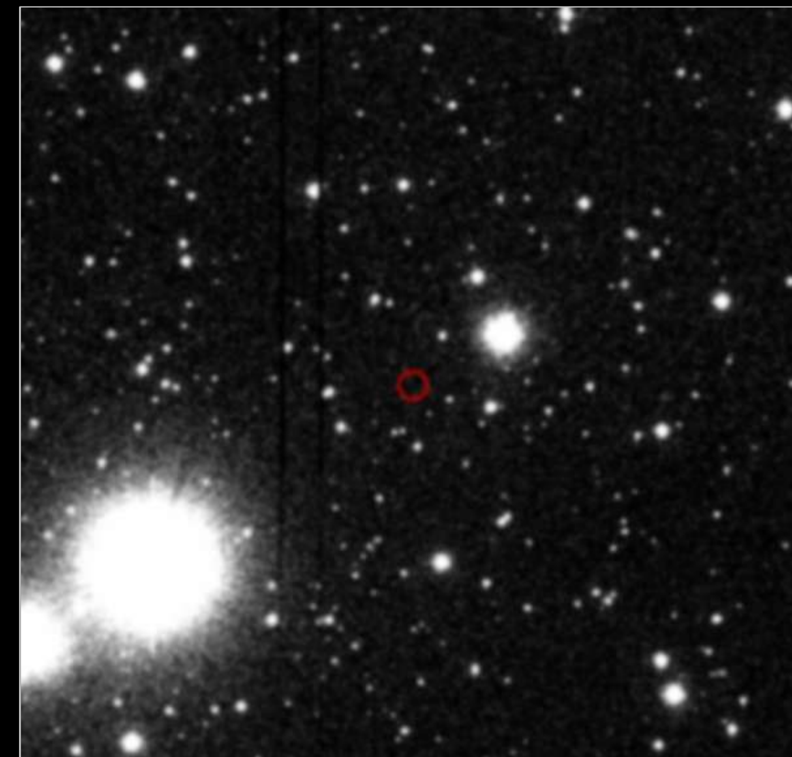
~25% of GRBs are **dark**:

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.)

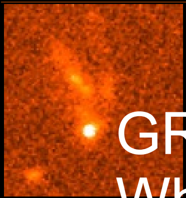
High-Redshift

(~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.)

Interpretations



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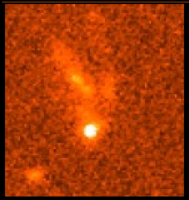
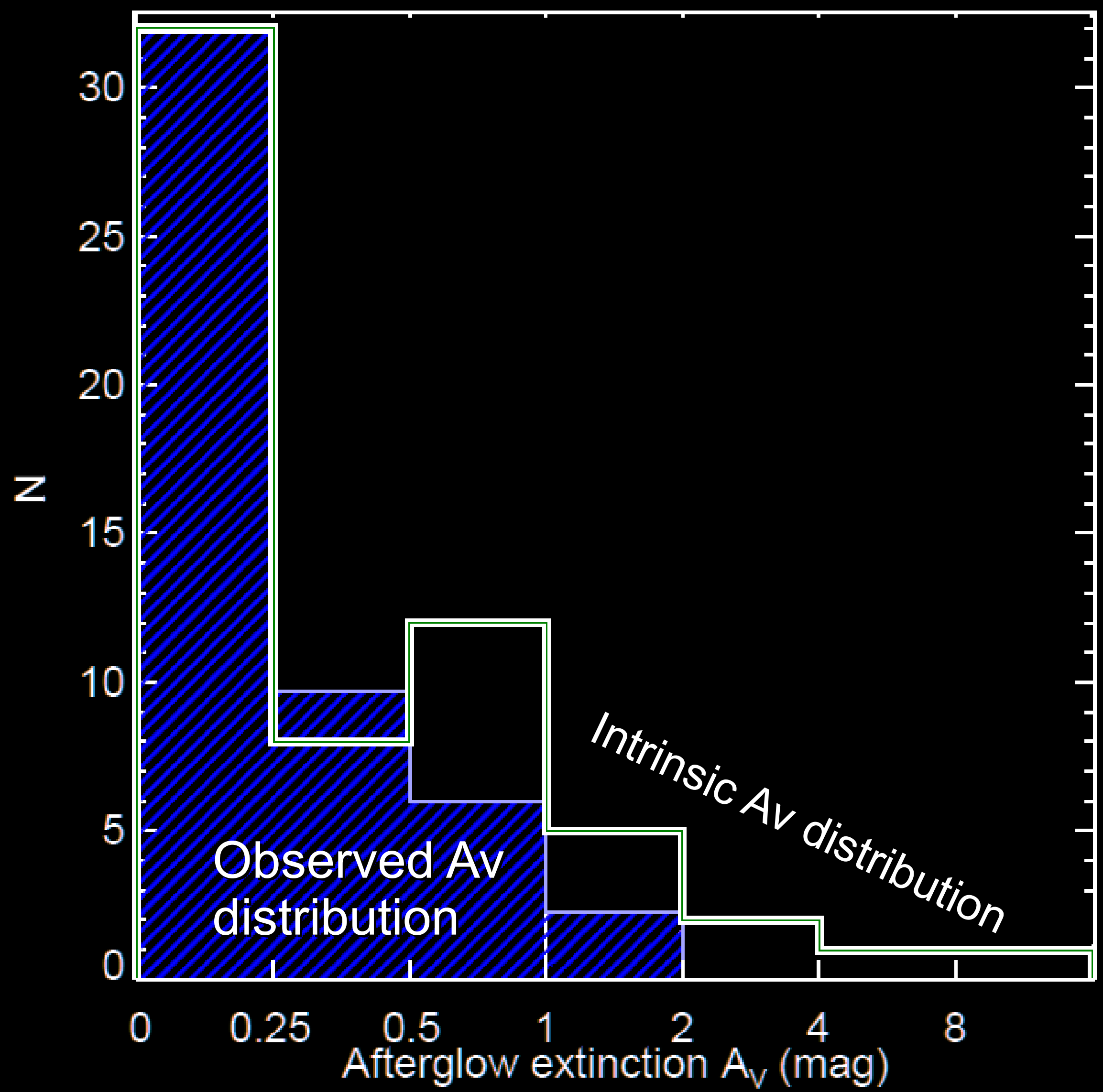
3. Some GRBs are being systematically missed (due to dust)

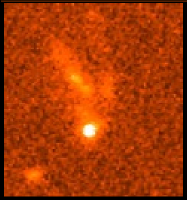
Dust and Selection Bias

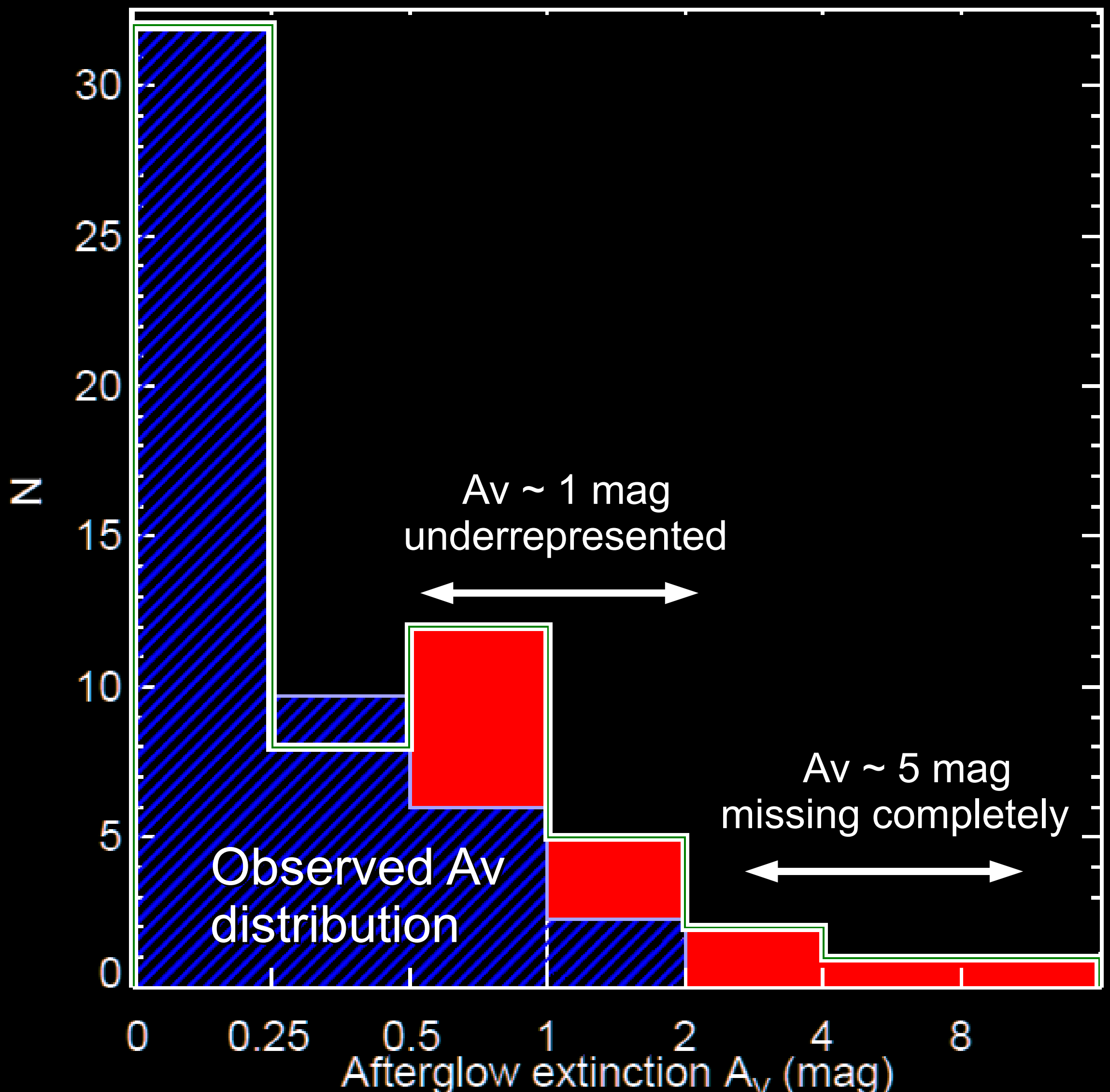




(Compiled from data in Kann et al. 2003 & 2010, Cenko et al. 2009, Perley et al. 2009, Greiner et al. 2011)

Dust and Selection Bias

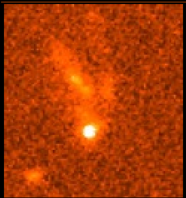


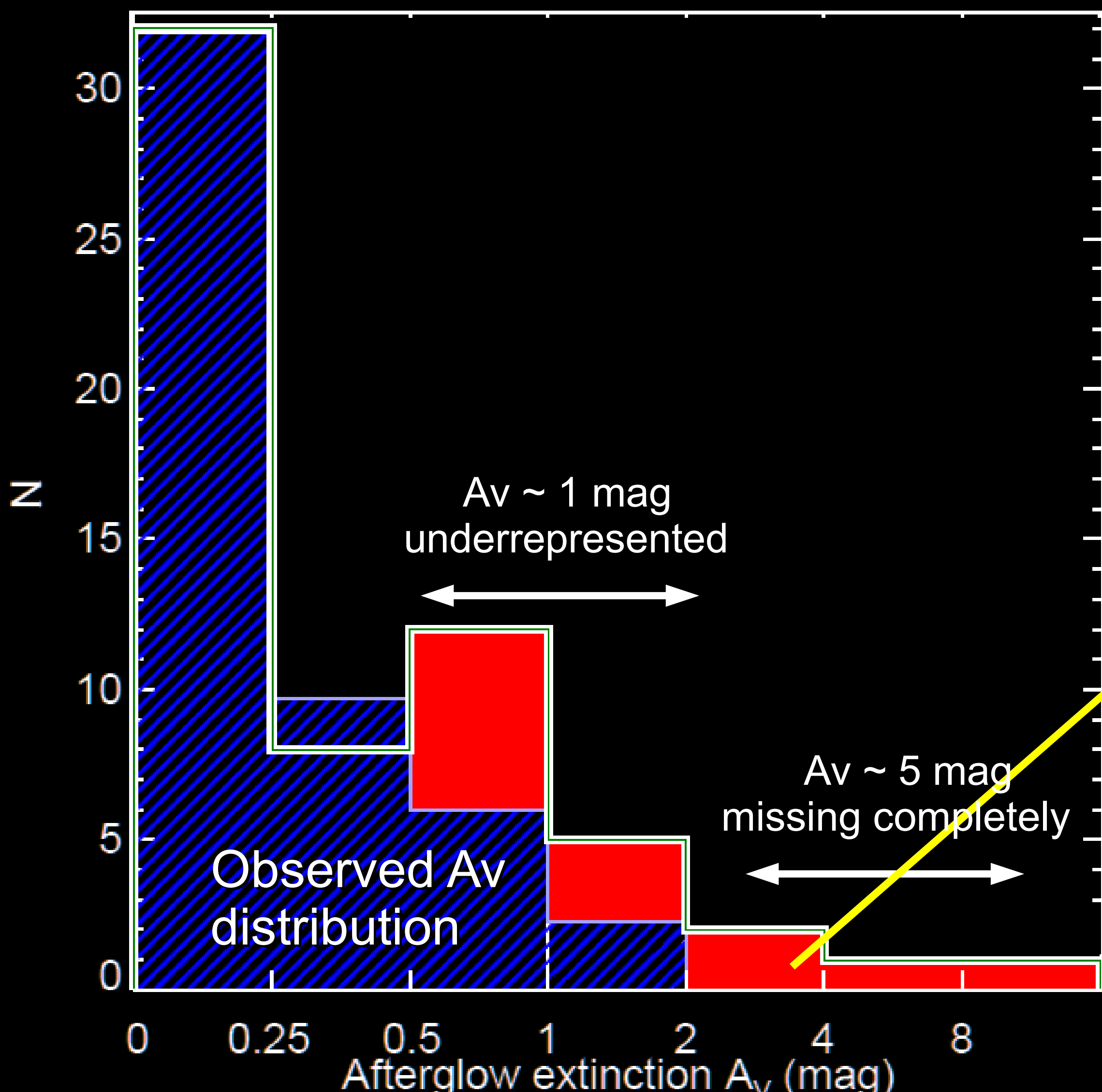


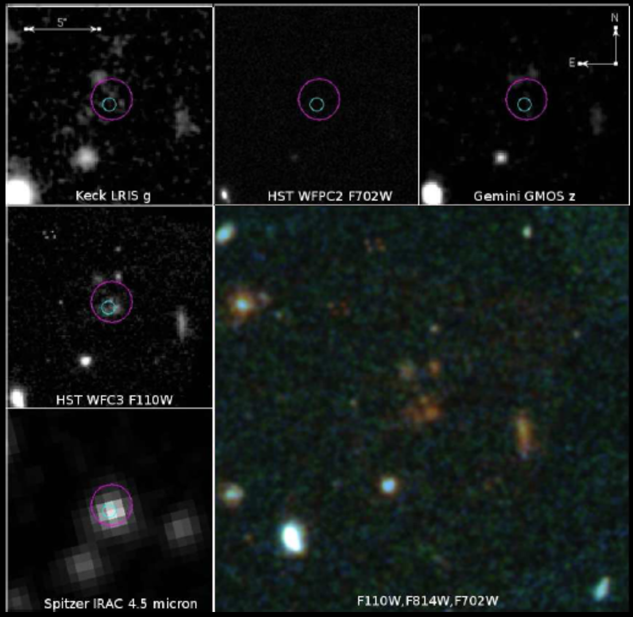
~15% of GRBs are systematically missing from optical afterglow searches as a result of dust.

(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







GRB 080207 host:
A ULIRG / ERO / DOG
at z=2.08
(Hunt et al. 2011,
Svensson et al. 2012,
Kruehler et al. 2012)

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

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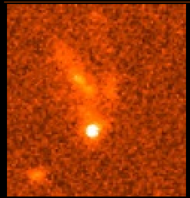
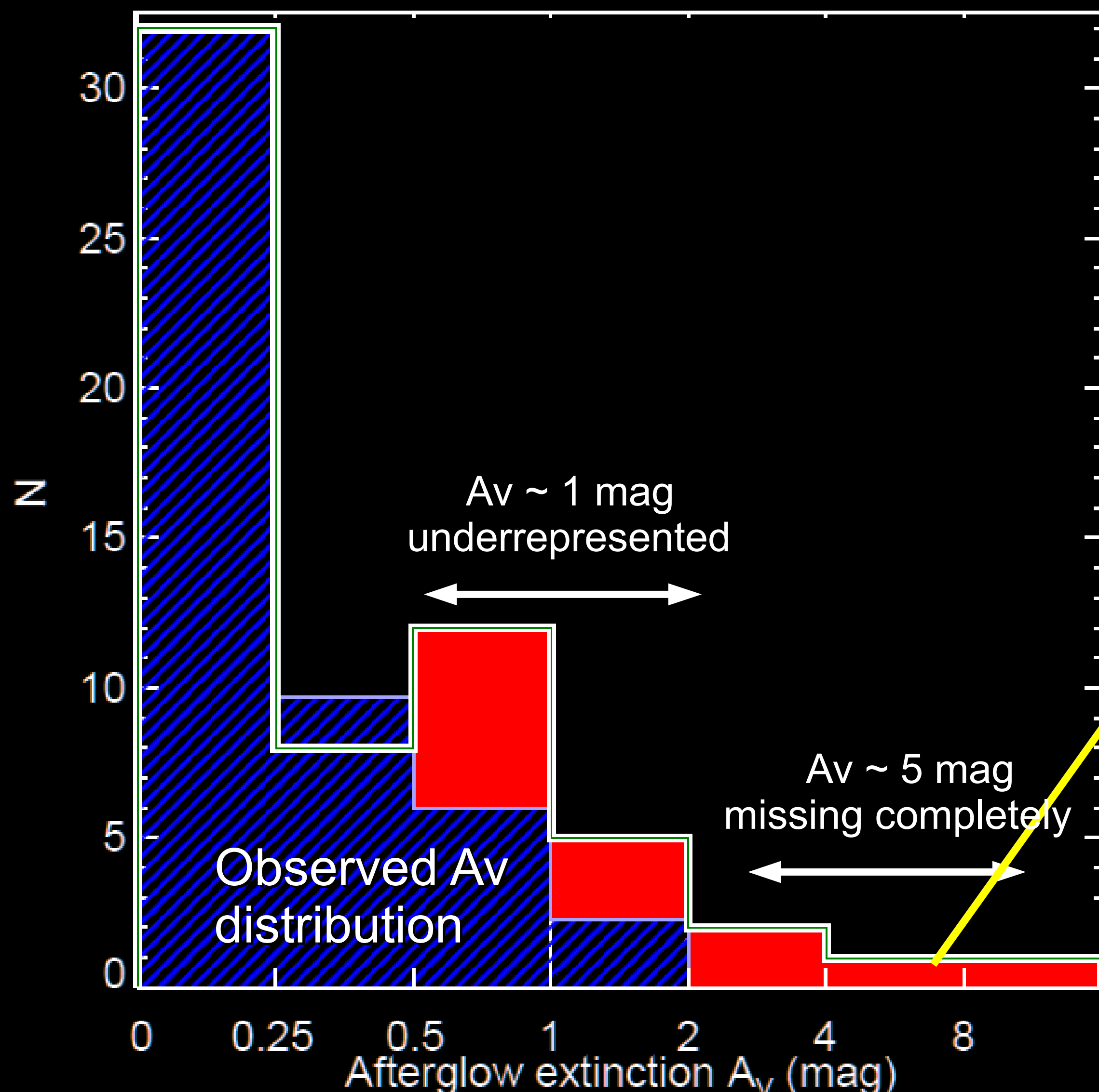
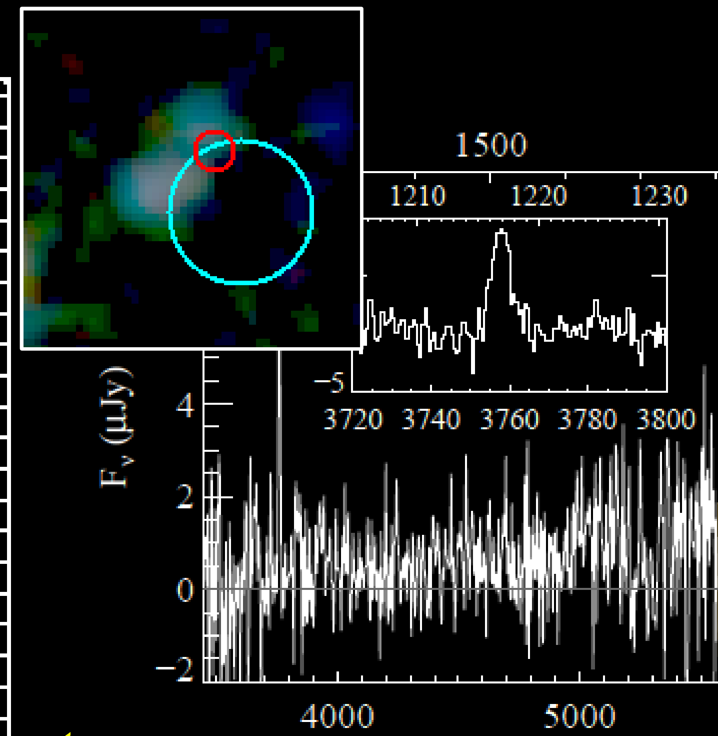


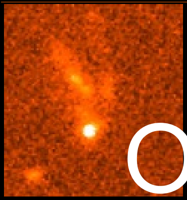




GRB 061222A host:
A Lyα emitter at z=2.08
(Perley et al. 2009)

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

Approach

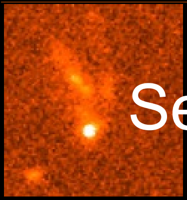


Observe and characterize the hosts of a *large, unbiased* sample of dust-obscured GRBs.

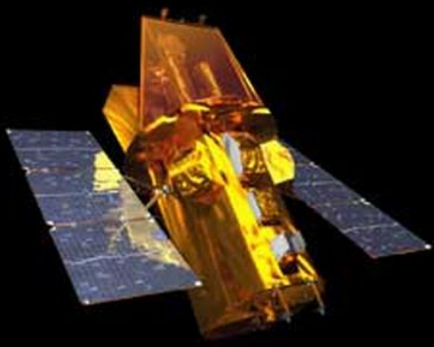
Then *contrast* and *combine* with "traditional" (optically-biased) surveys.

- Pre-Swift literature compilations
- VLT Unbiased Host Project (also includes some dark GRBs)
- HST IR Snapshot survey
- Spitzer high-z project

Selecting a Dusty-GRB Host Sample

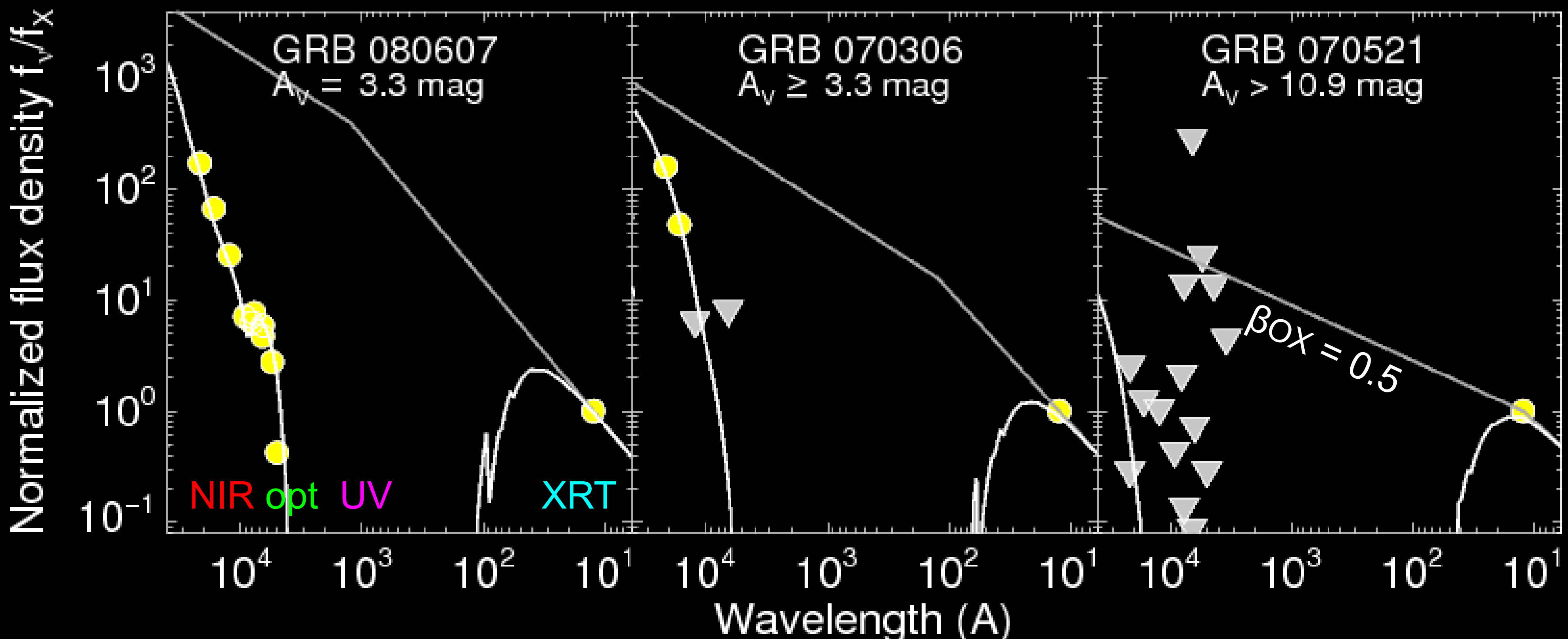


Selection: *Every* Swift-era burst with clear indication of Av > 1 mag

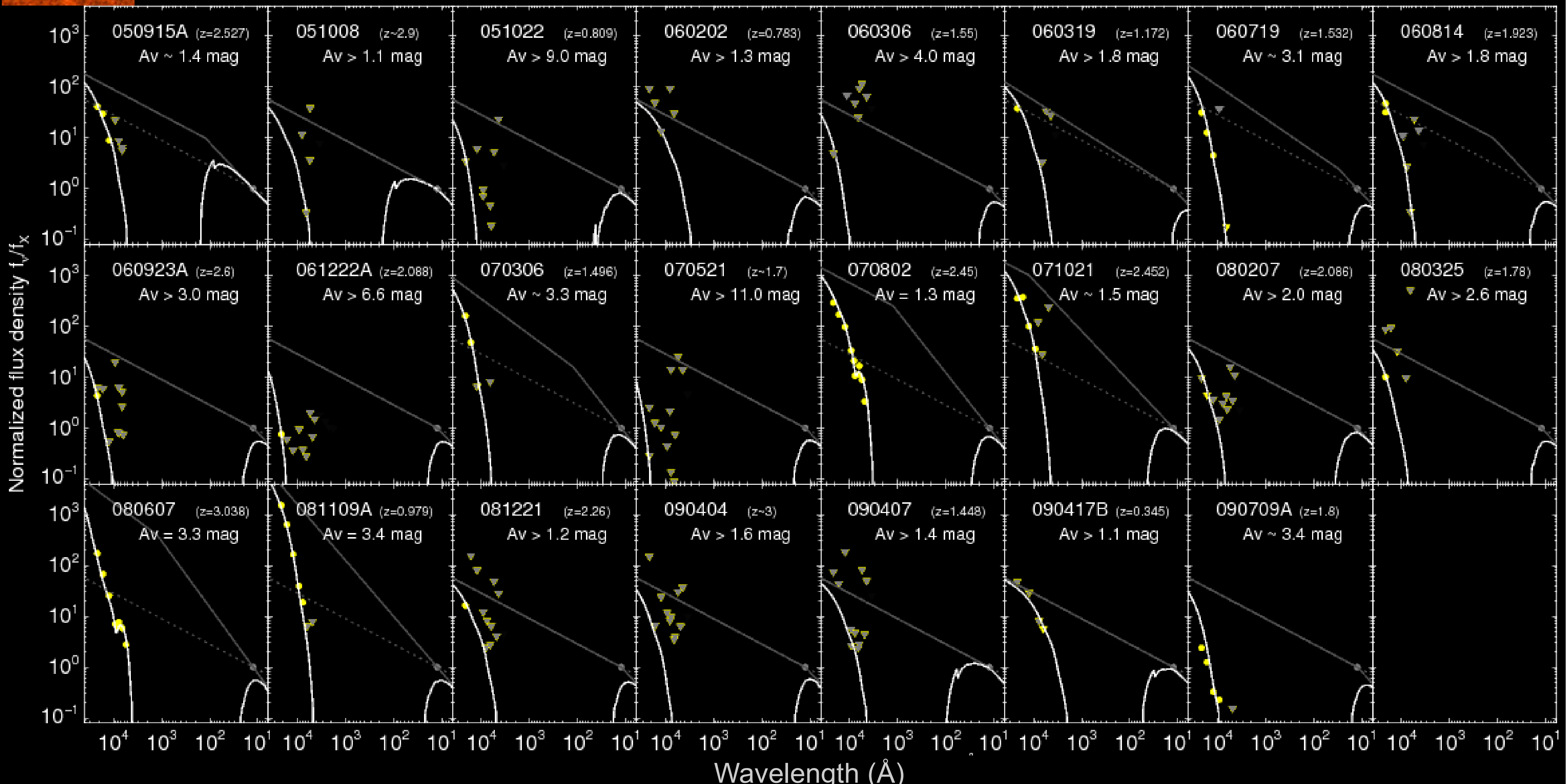


Compile all optical data, download all XRT data, construct co-eval SED, fit dust extinction...

Afterglow SEDs:



Selecting a Dusty-GRB Host Sample



23 events from 2005-2009

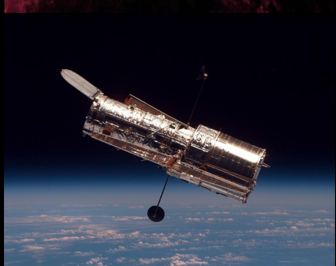
2 with optical afterglow redshift

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.

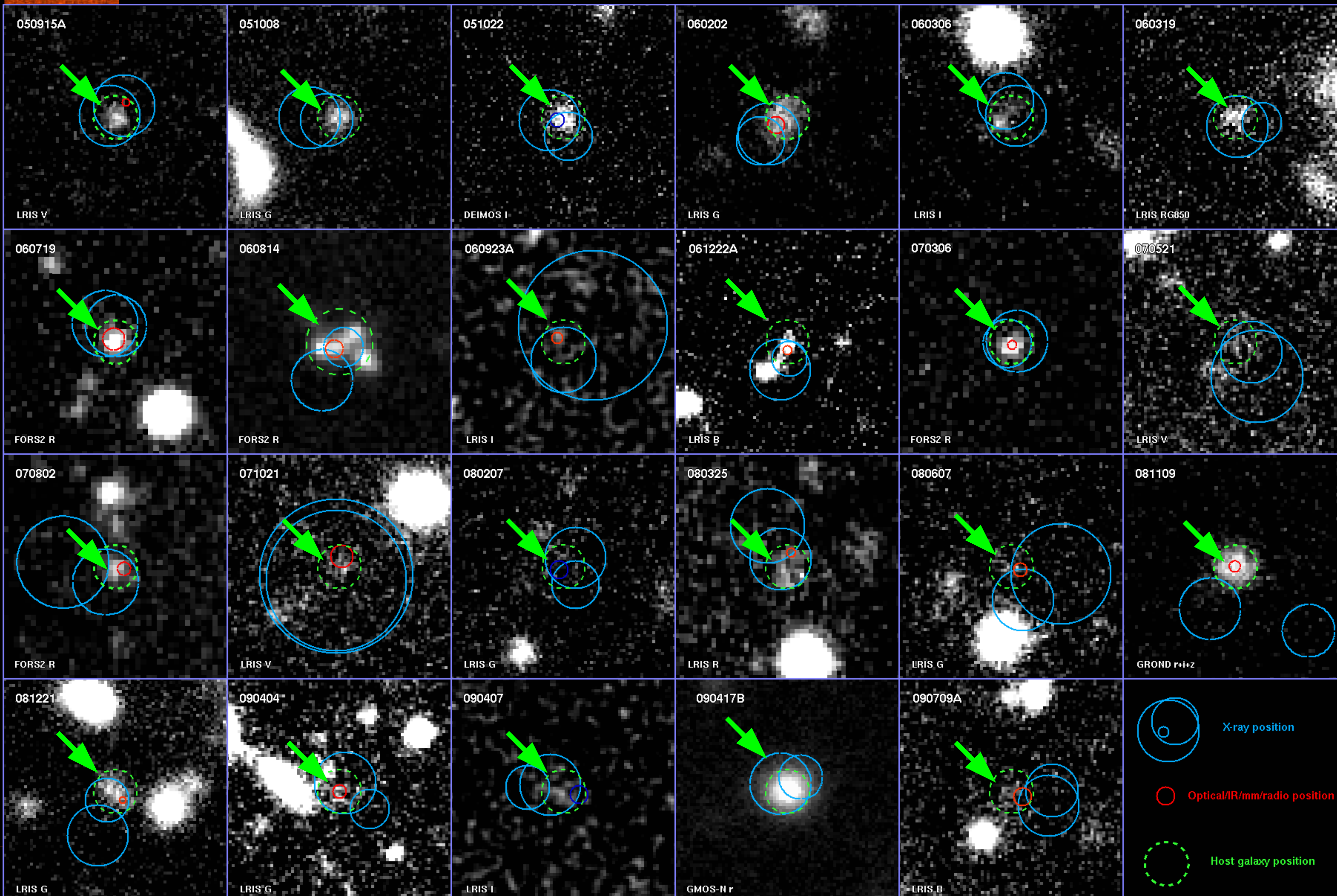
Spitzer: Rest-frame NIR photometry for stellar masses.



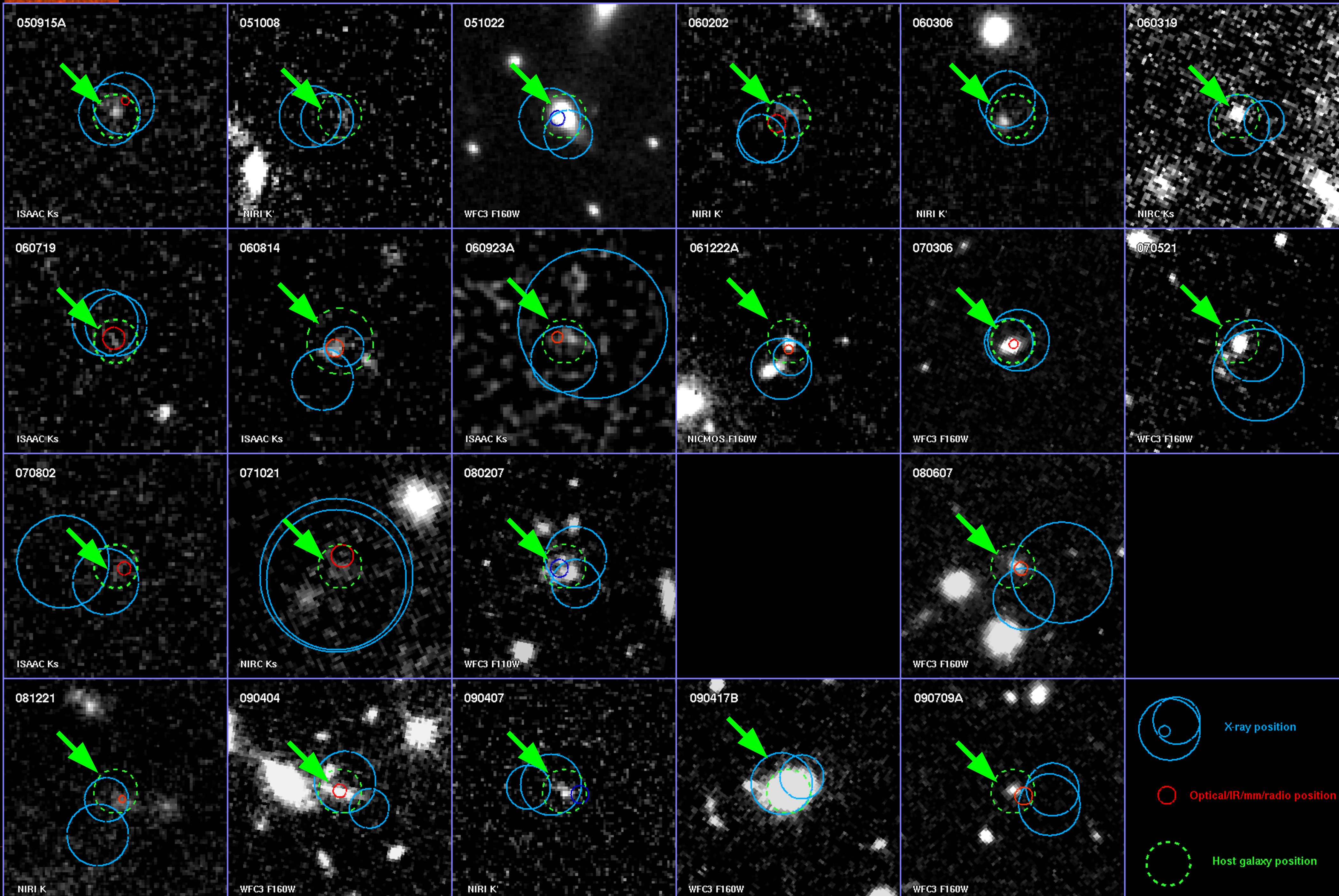
HST: NIR photometry, especially of faint targets.

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

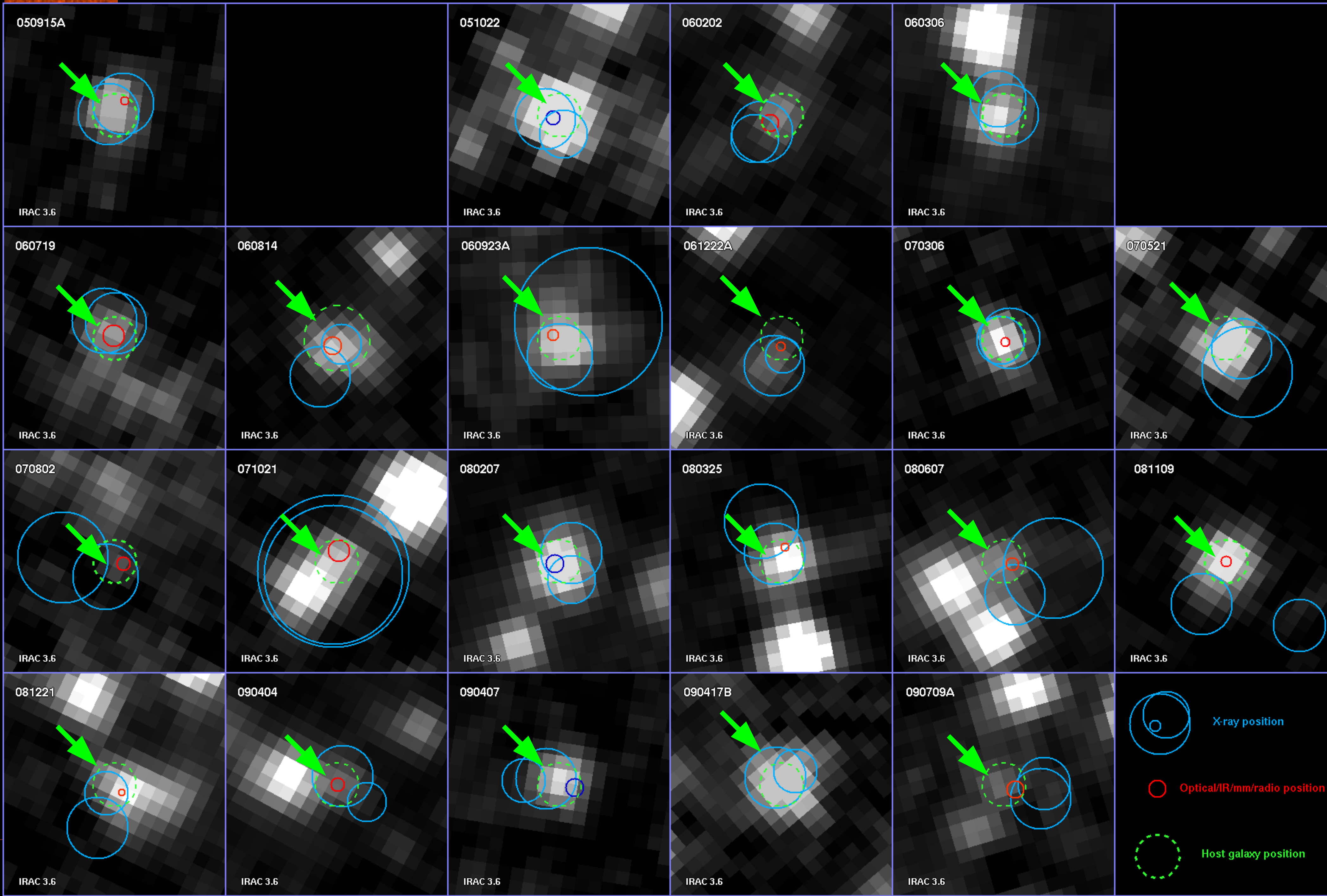
Optical Host Mosaic



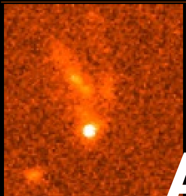
Near-IR Host Mosaic



Spitzer Host Mosaic



Detection Statistics



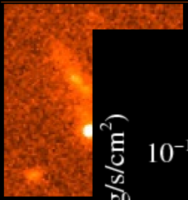
All 23 hosts detected in **all three bands**

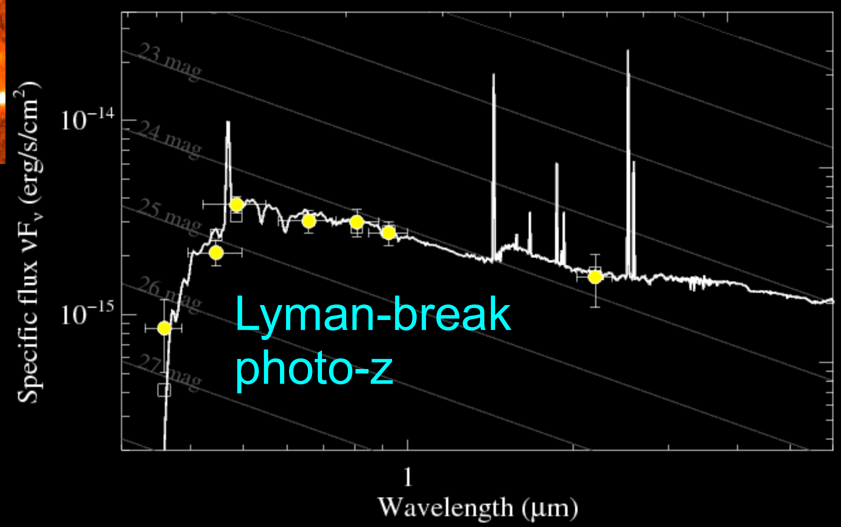
(2 not observed with IRAC yet.)

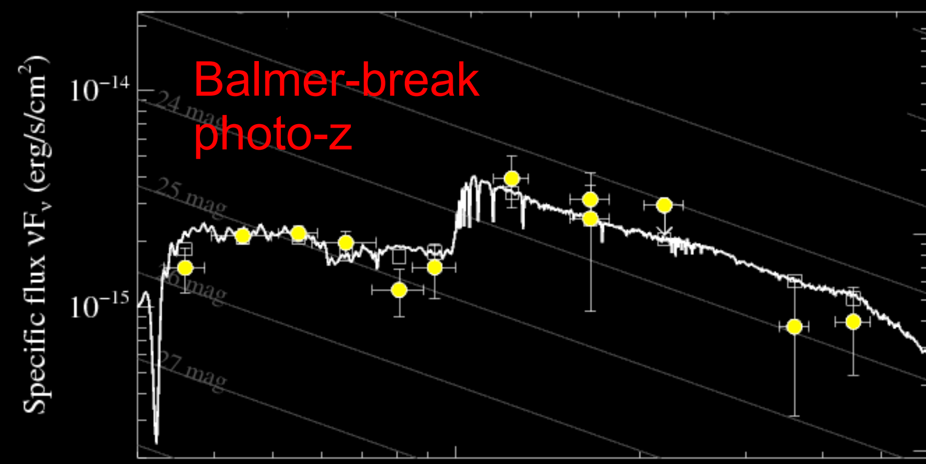
No "ultra-faint" hosts – every host galaxy would have been detected in a deep survey.
(This is *not* true of unobscured GRBs.)

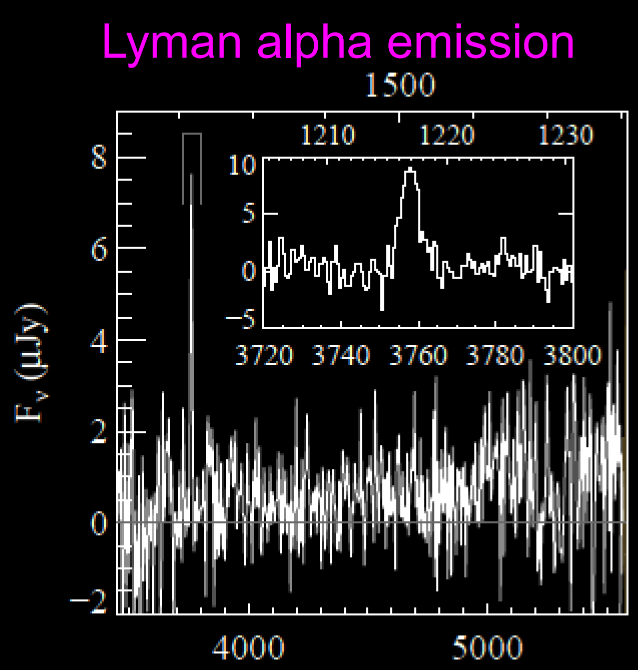
Most dust (in galaxies probed by GRBs) is in galaxies bright enough to detect and characterize.

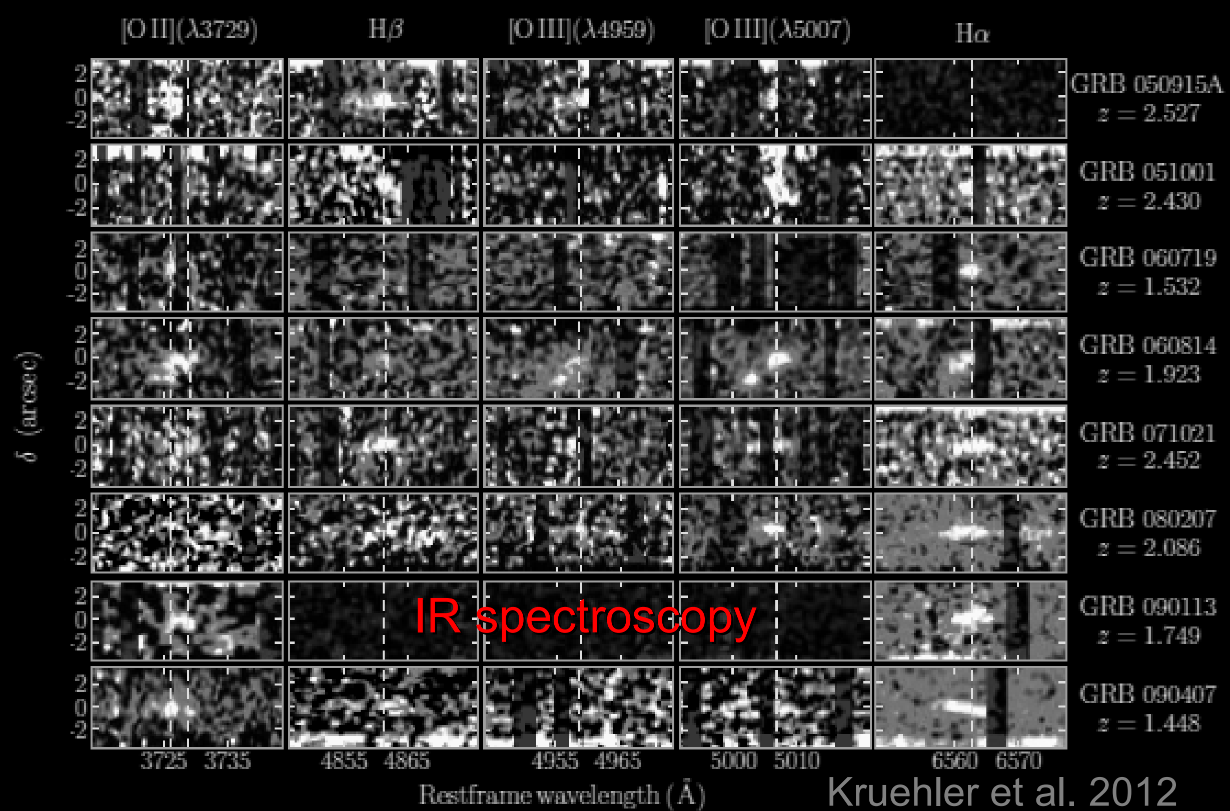
Redshift Measurement





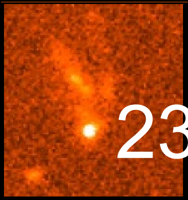






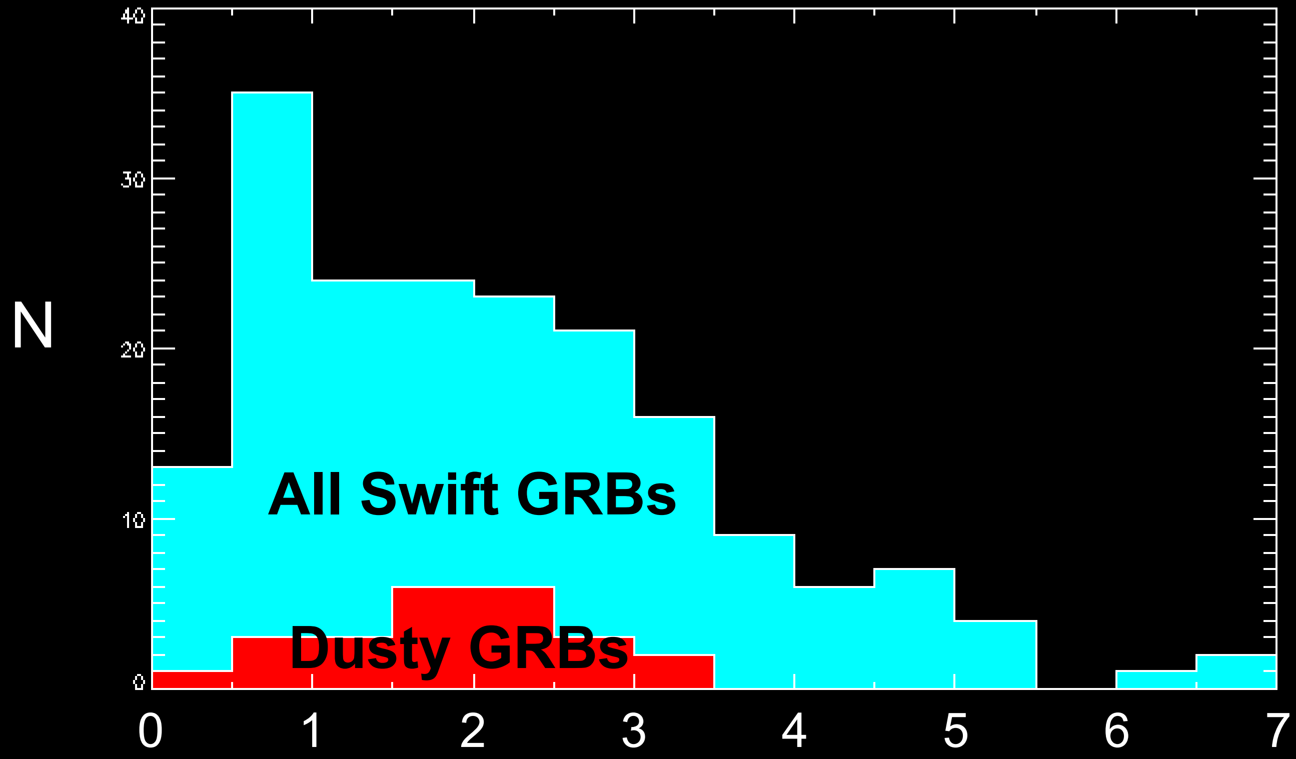
Kruehler et al. 2012

Redshift Distribution



23 / 23 successful redshifts!

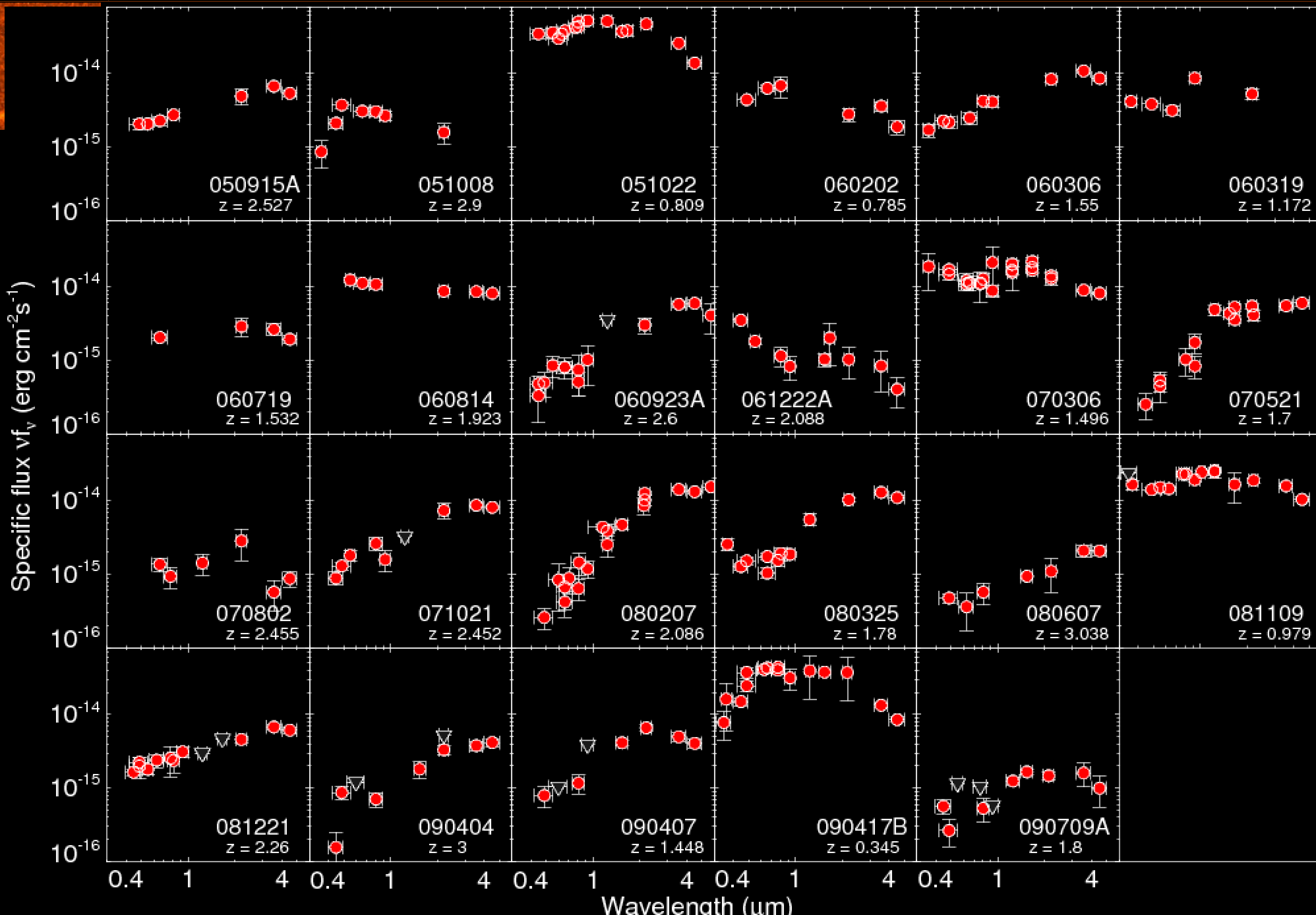
18 spectroscopic, 5 photometric



Broadly similar to overall GRB redshift distribution

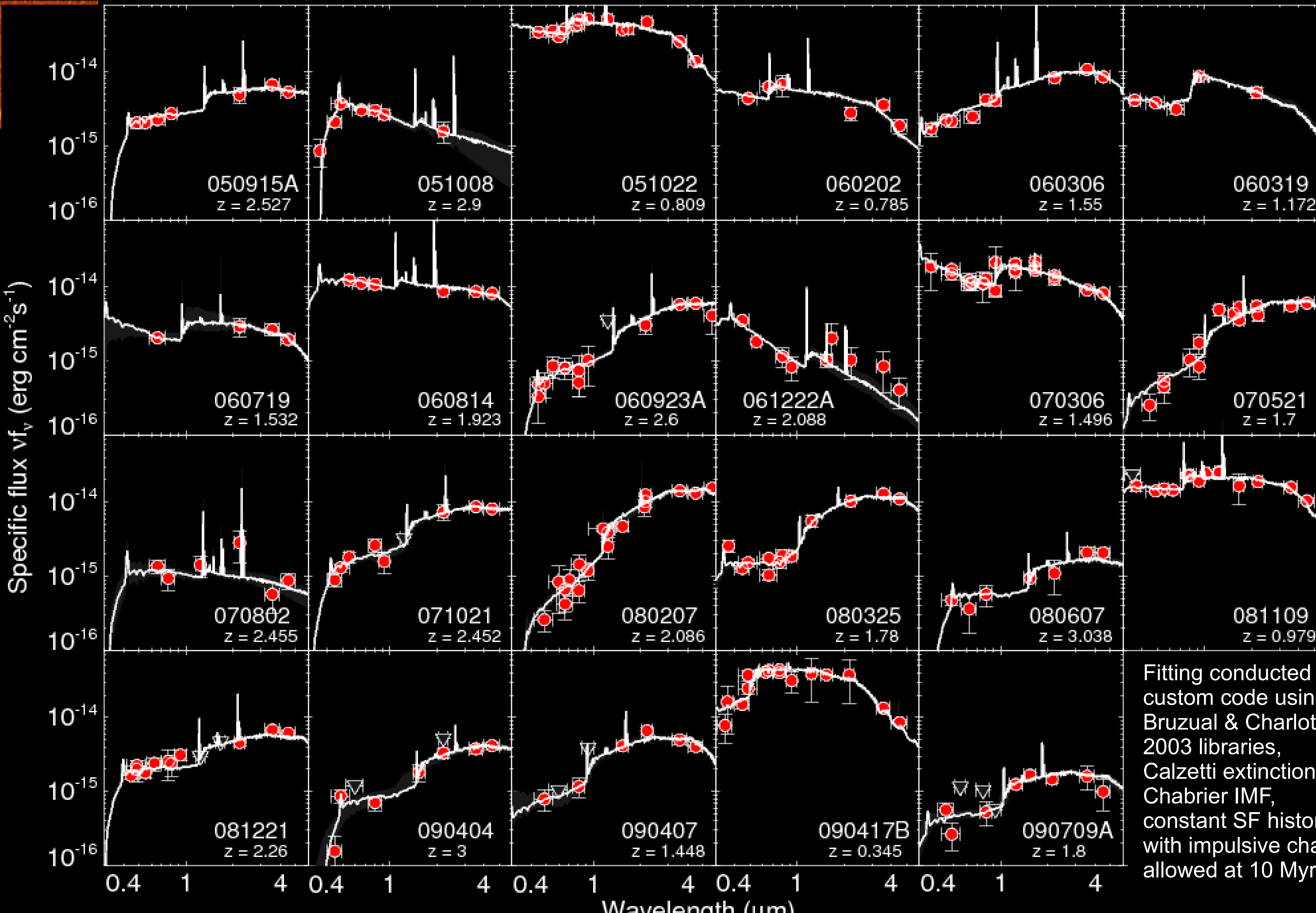
(possibly more strongly concentrated at z~2 –
not yet significant, and sample-selection biases could matter)

SED Fitting



Specific flux νf$_\nu$ (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

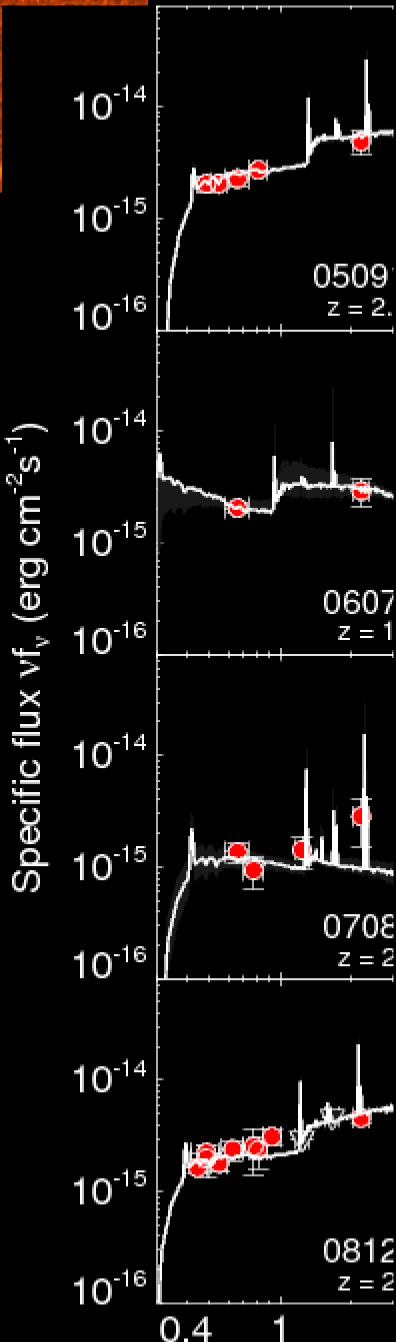
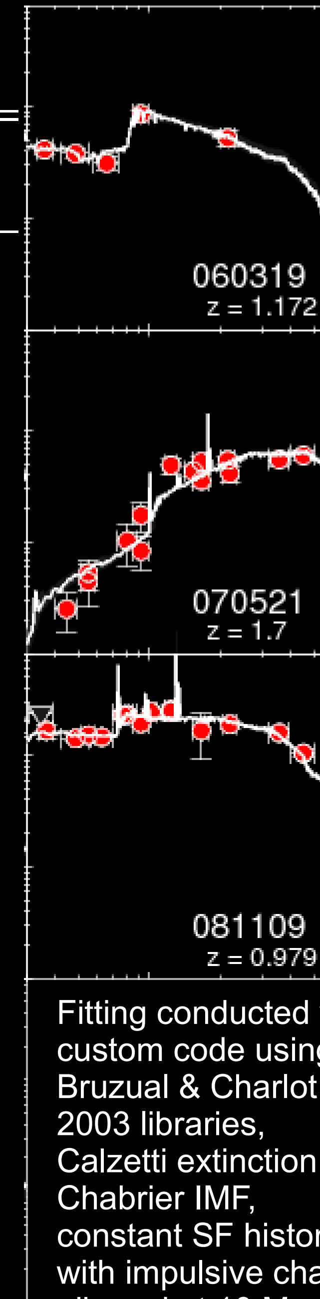
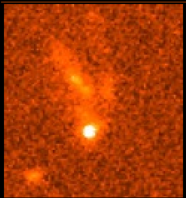


TABLE 4
GRB Host-Galaxy Properties

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



z~1 “control” sample: pre-Swift hosts

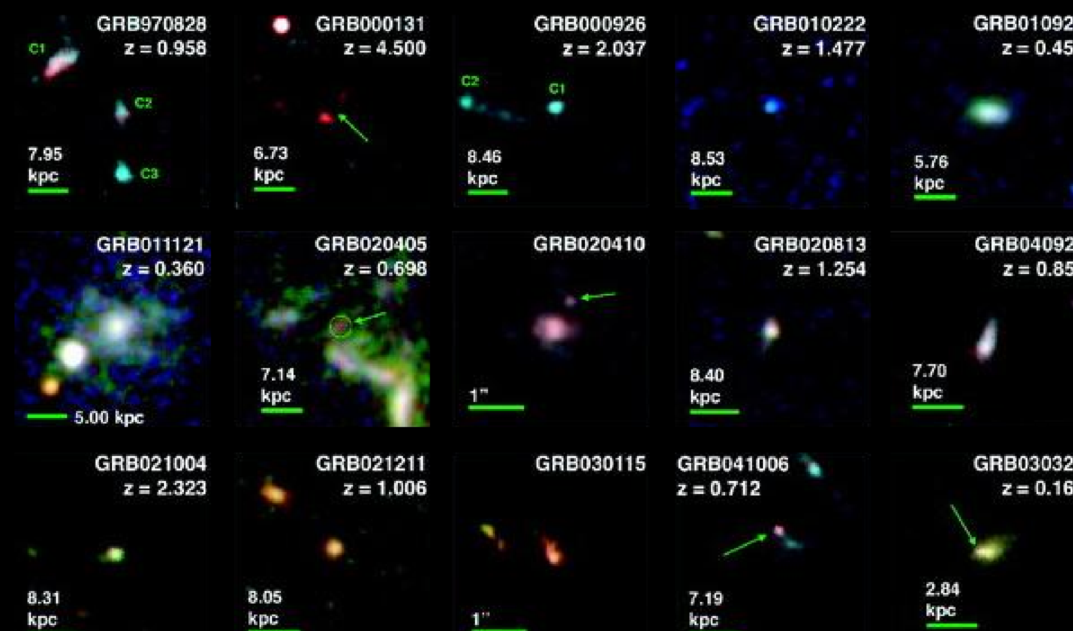
31 pre-Swift GRBs (65% of all with redshifts) with redshifts have published multi-band host data suitable for SED fitting.

(This is much higher than Swift completeness – 7 pre-Swift years to observe “only” 50 GRBs, versus 700 Swift GRBs in the same period.)

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

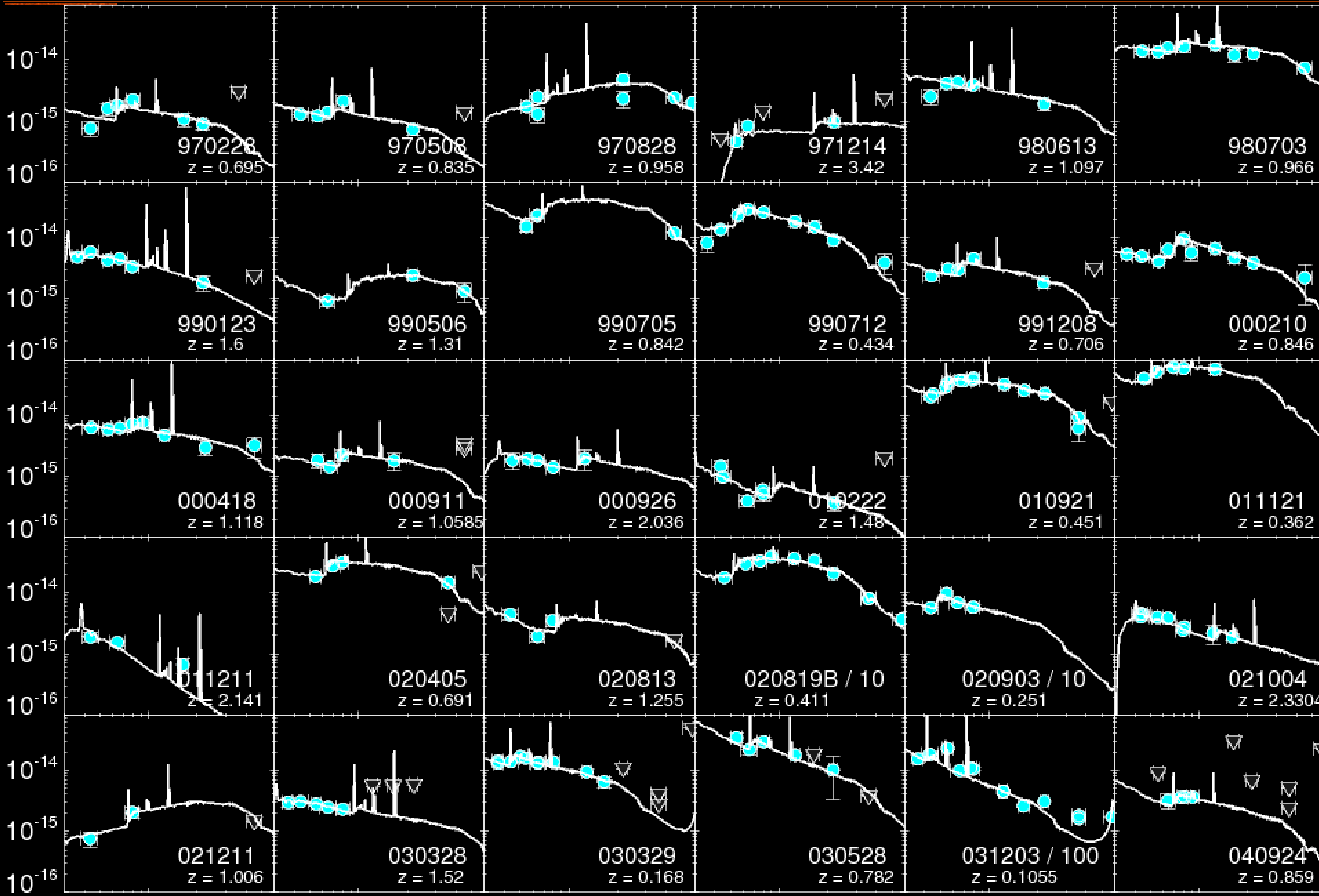
Four were probably dust-obscured (localized with radio or *Chandra*)

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

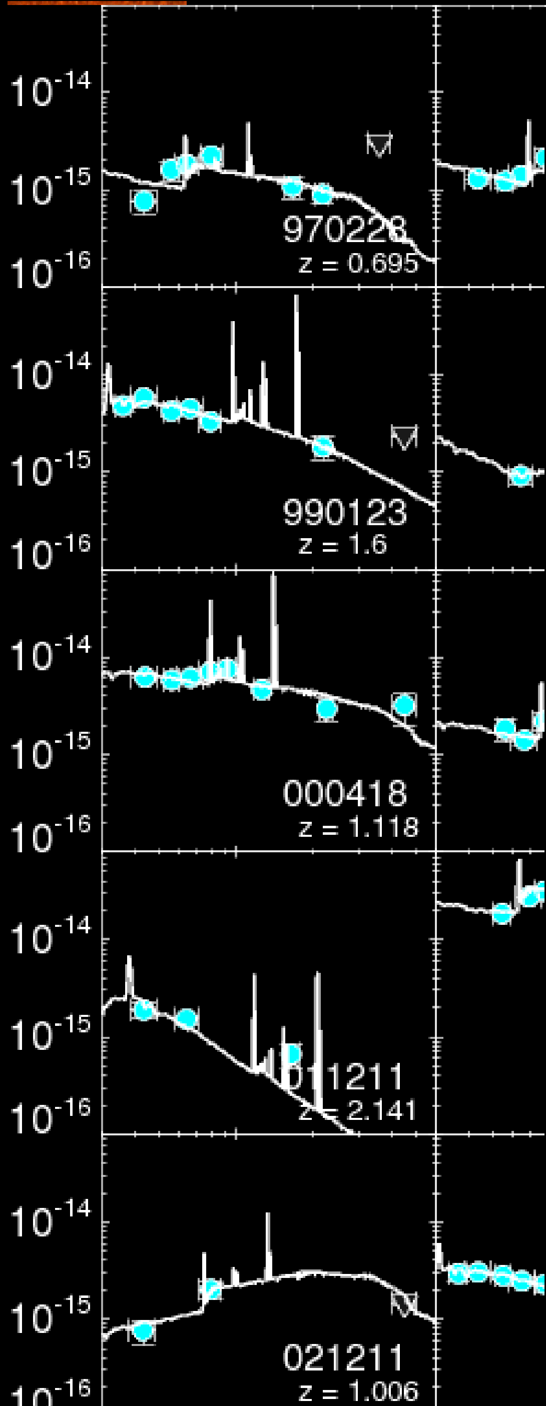


HST images from Wainwright et al. 2007

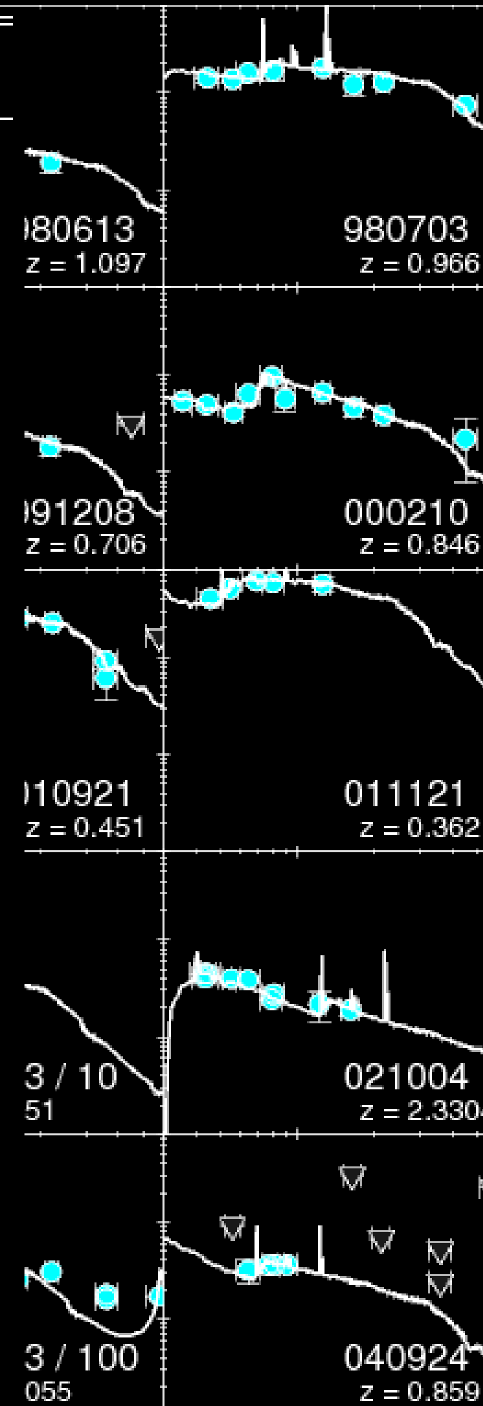
Pre-Swift Control Sample



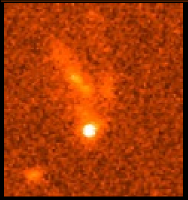
Pre-Swift Control Sample



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

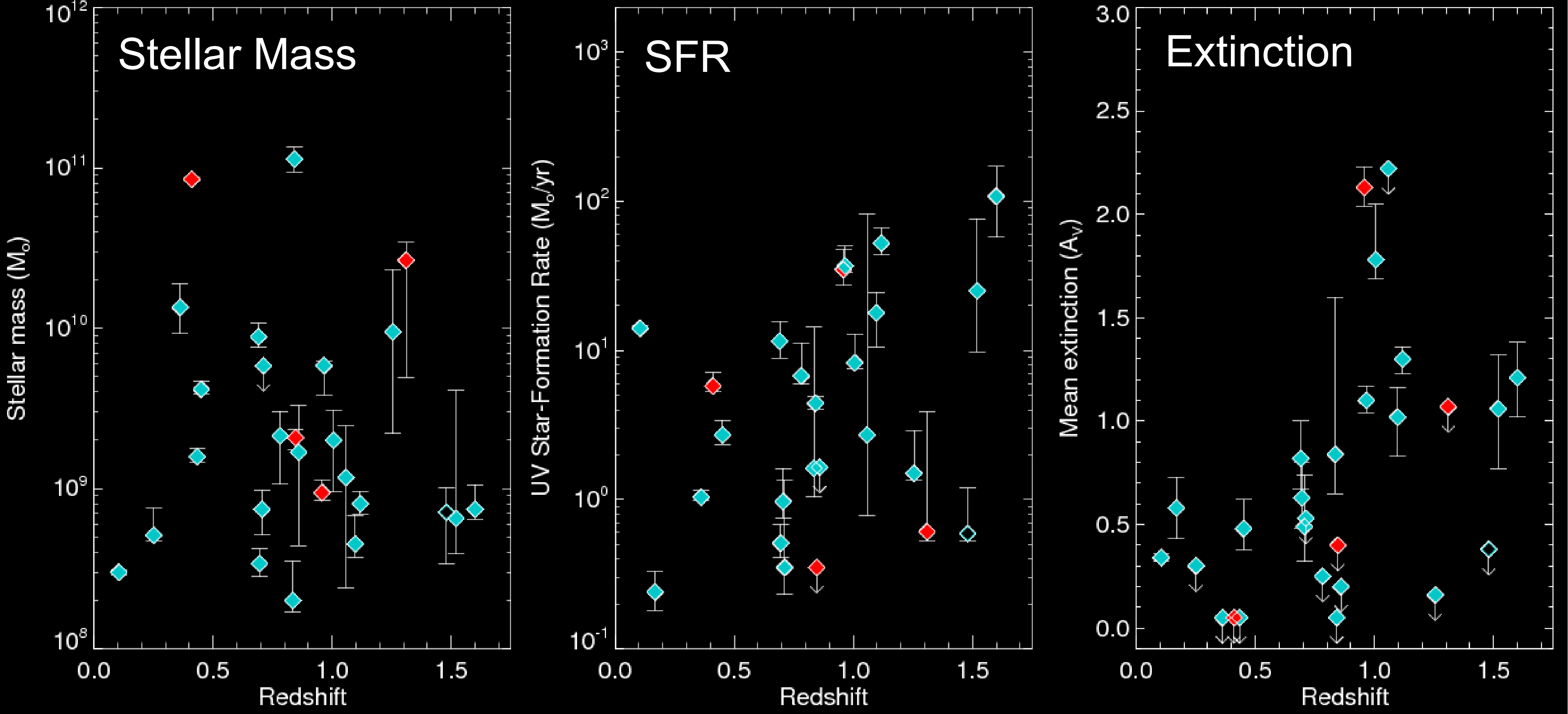


Comparisons at z~1

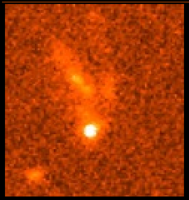


Pre-Swift events only:

Blue=unobscured GRB, Red = obscured GRB.

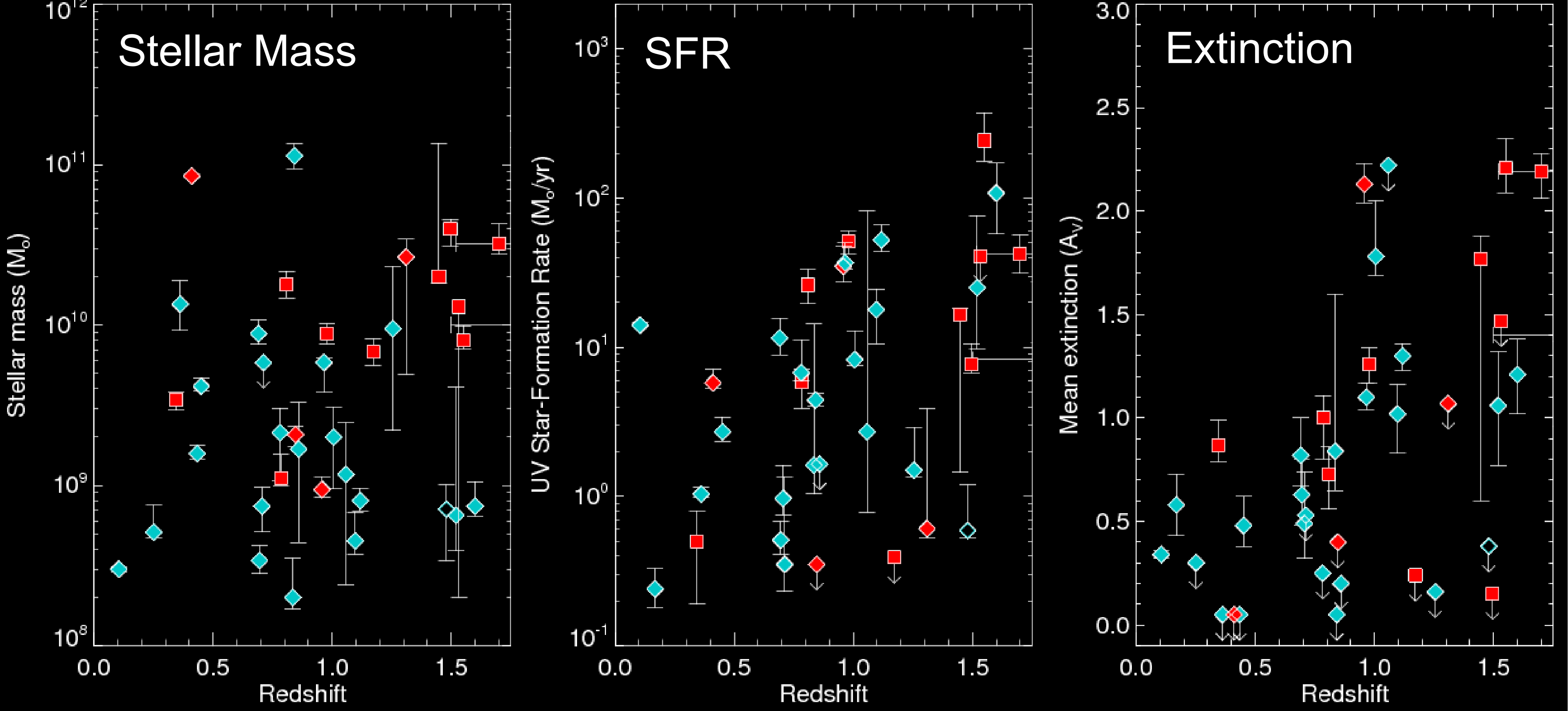


Comparisons at z~1



Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

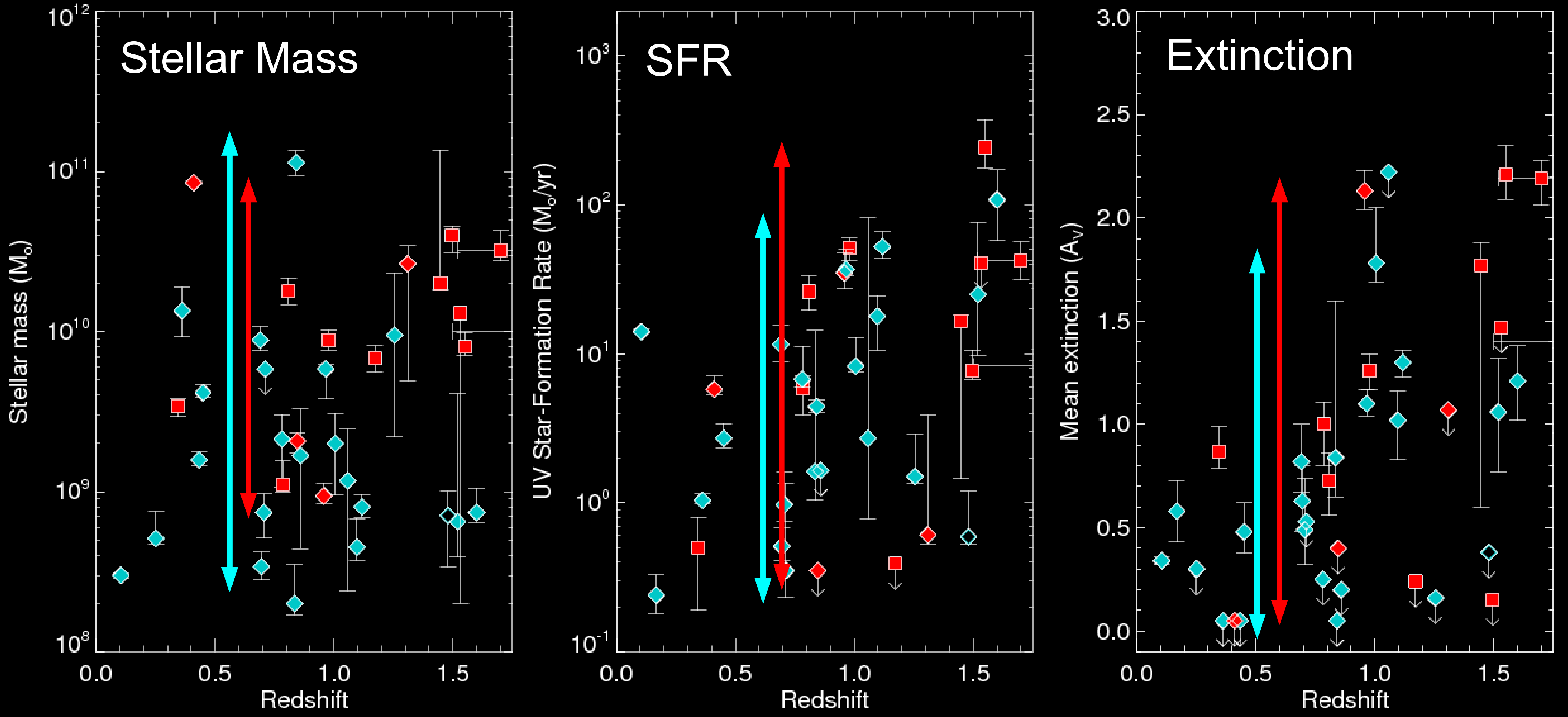


Comparisons at z~1

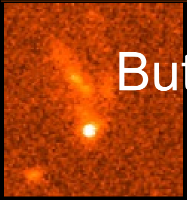
Dust-obscured GRB hosts are quite diverse – no simple generalizations.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



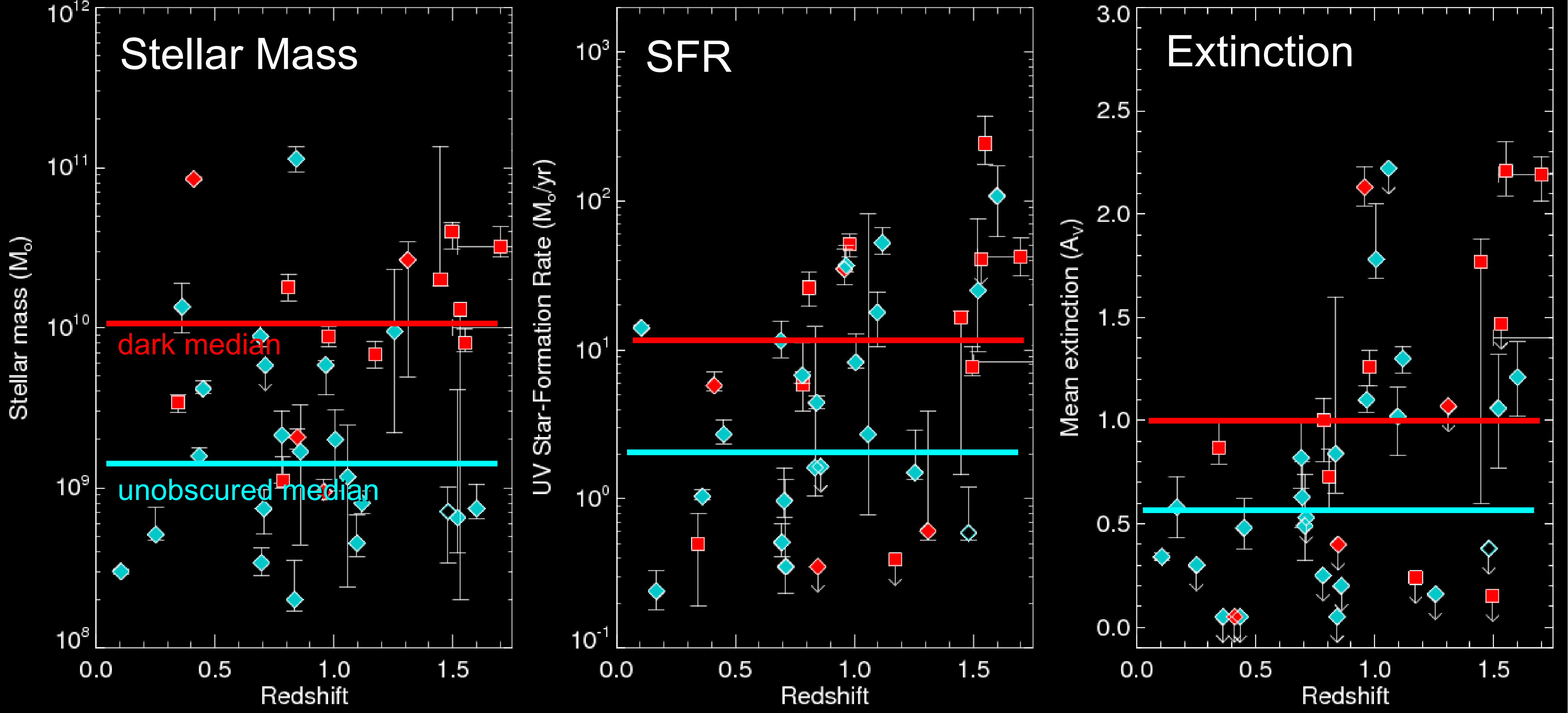
Comparisons at z~1



But *on average*, obscured hosts are more massive, star-forming, and dusty.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

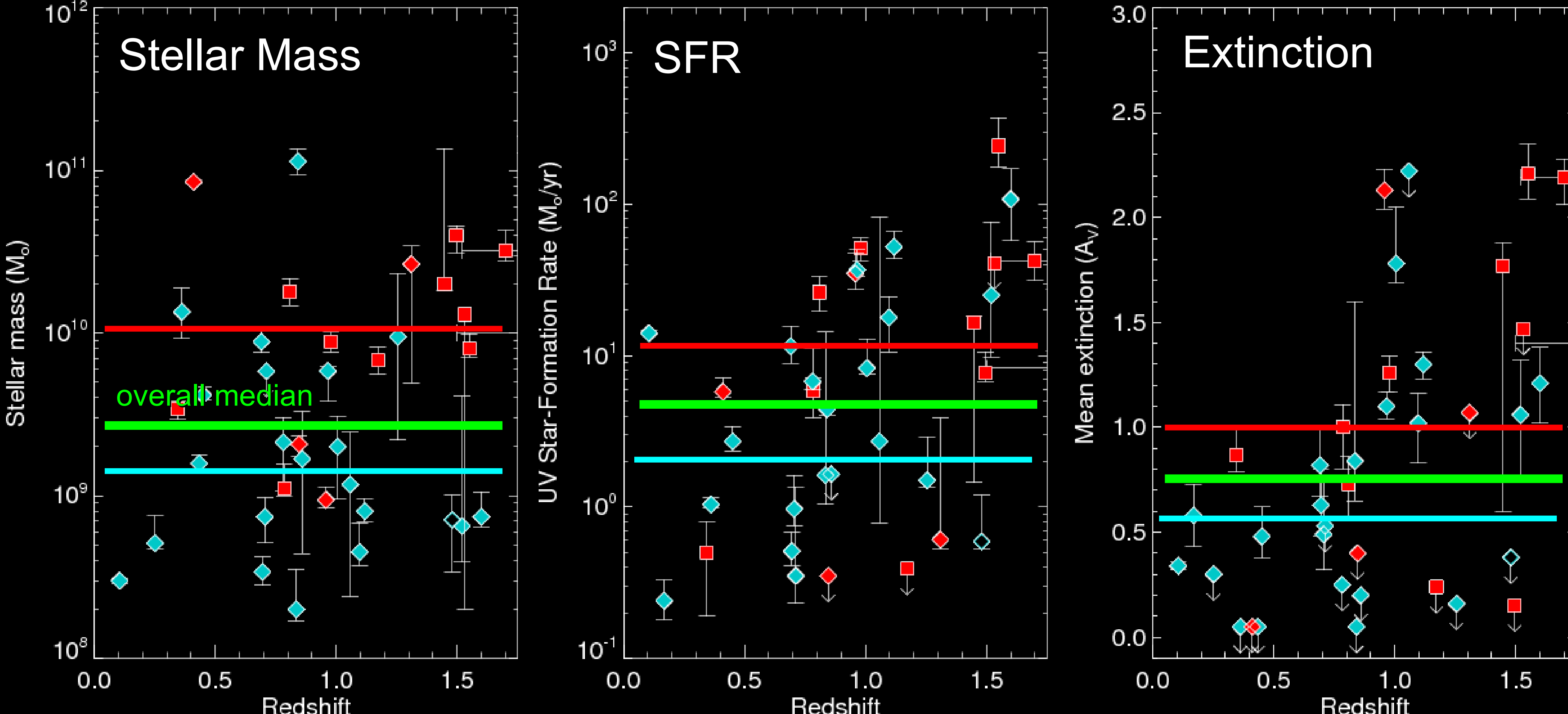


Comparisons at z~1

This produces modest changes in the population averages.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

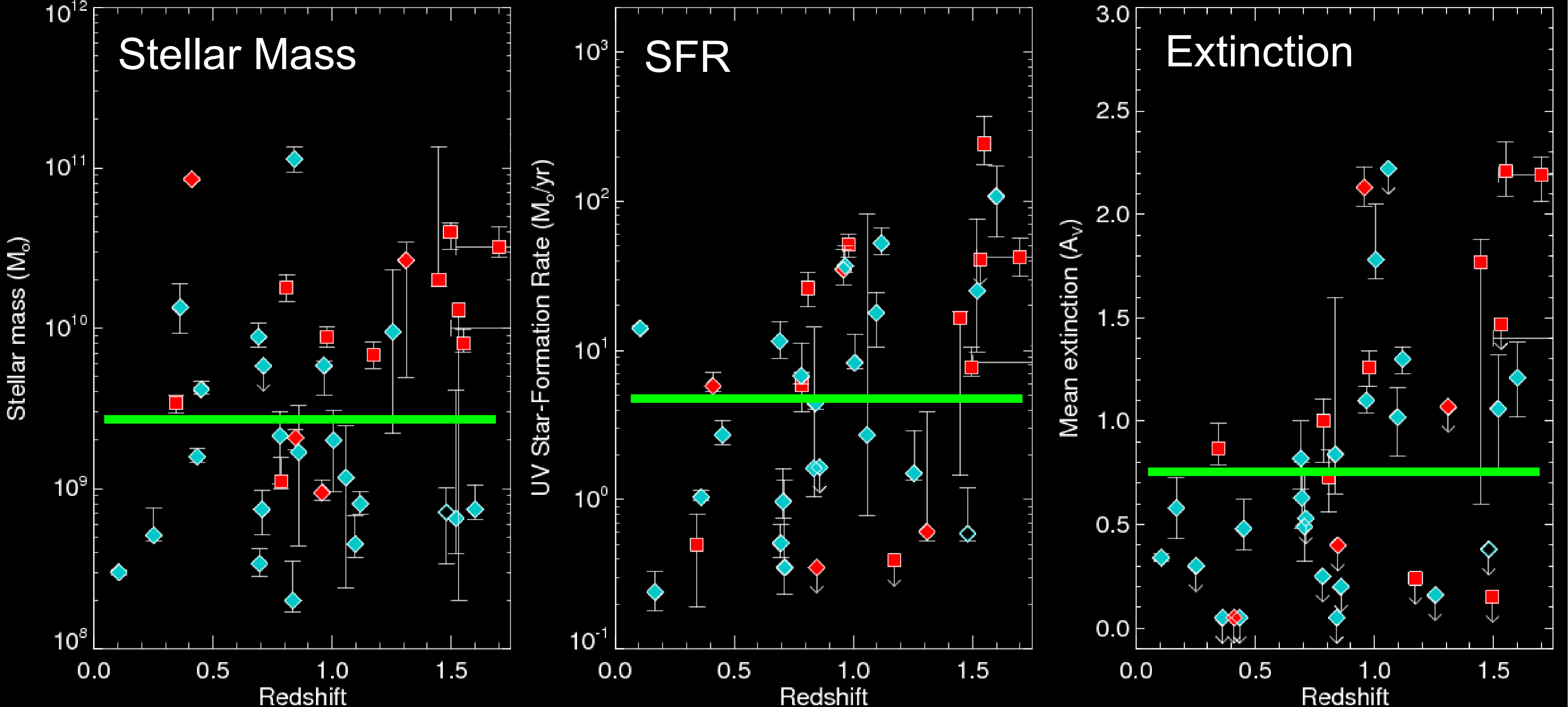


Comparisons at z~1

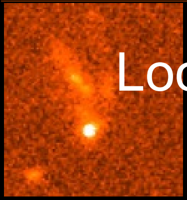
This produces modest changes in the population averages.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



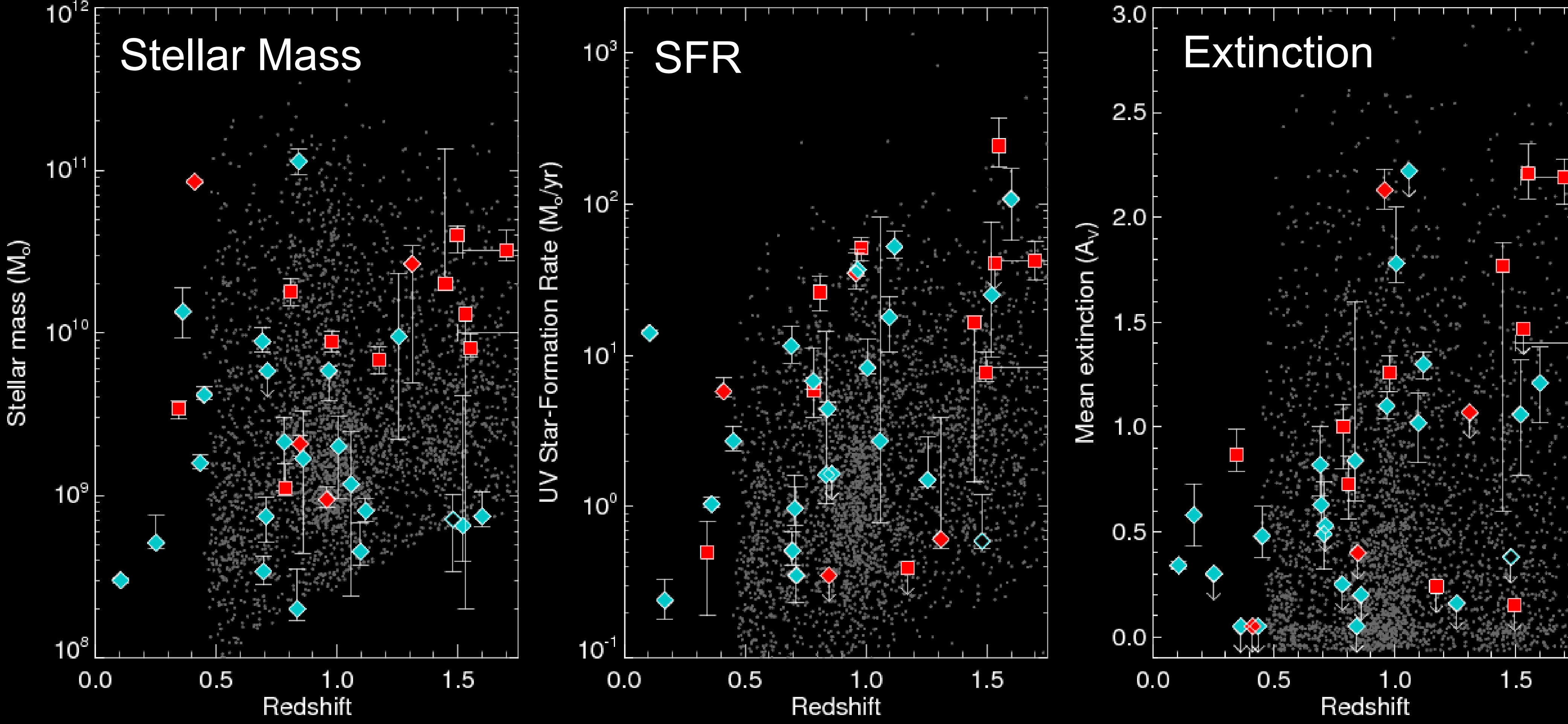
Comparisons vs. Field Galaxies at z~1



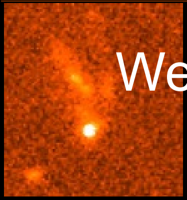
Looks “consistent” with field galaxy *number* distributions...

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

Combined sample versus field galaxies:



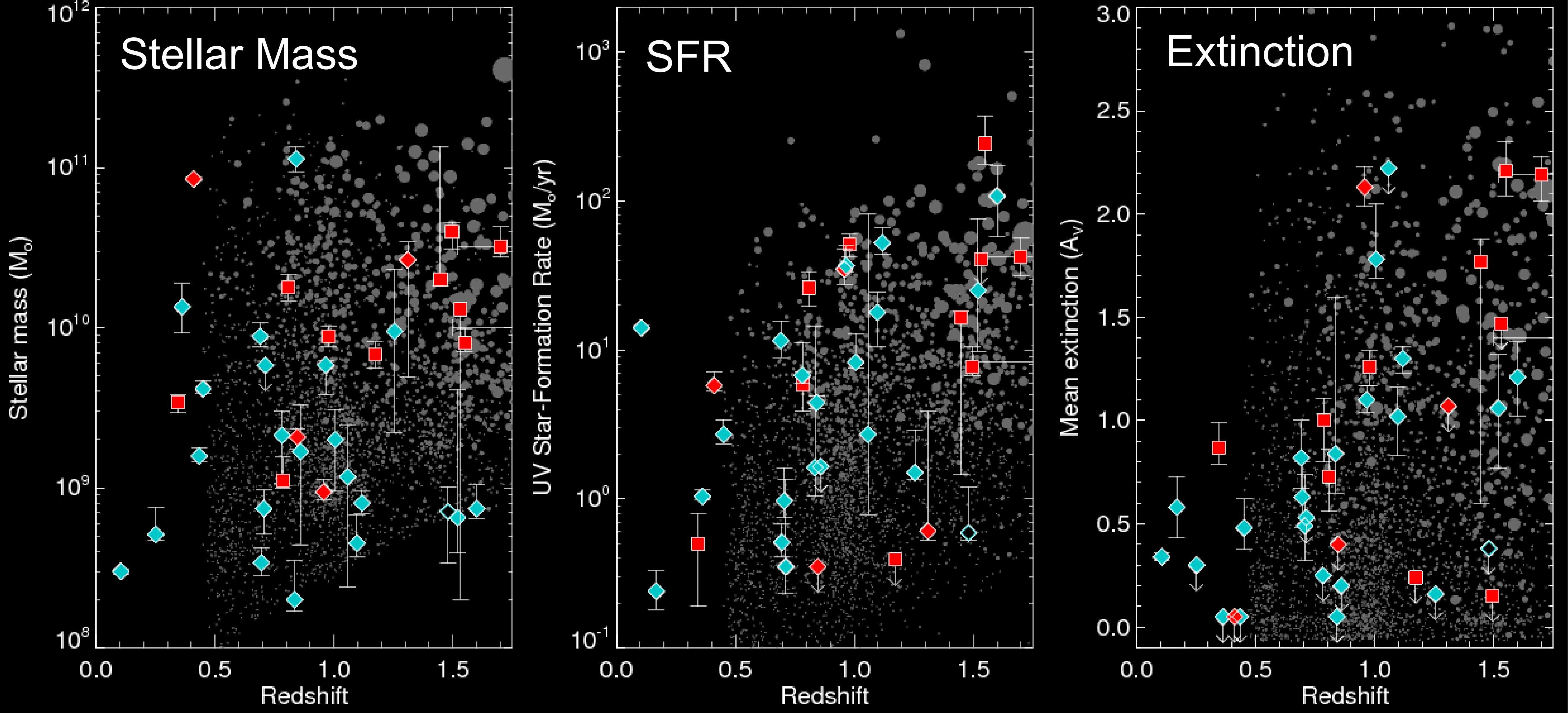
Comparisons vs. Field Galaxies at z~1



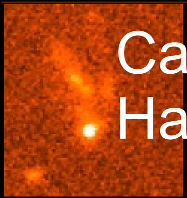
Weighting by SFR is essential. Null hypothesis is $R_{GRB} \propto$ SFR.

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.

Combined sample versus field galaxies:

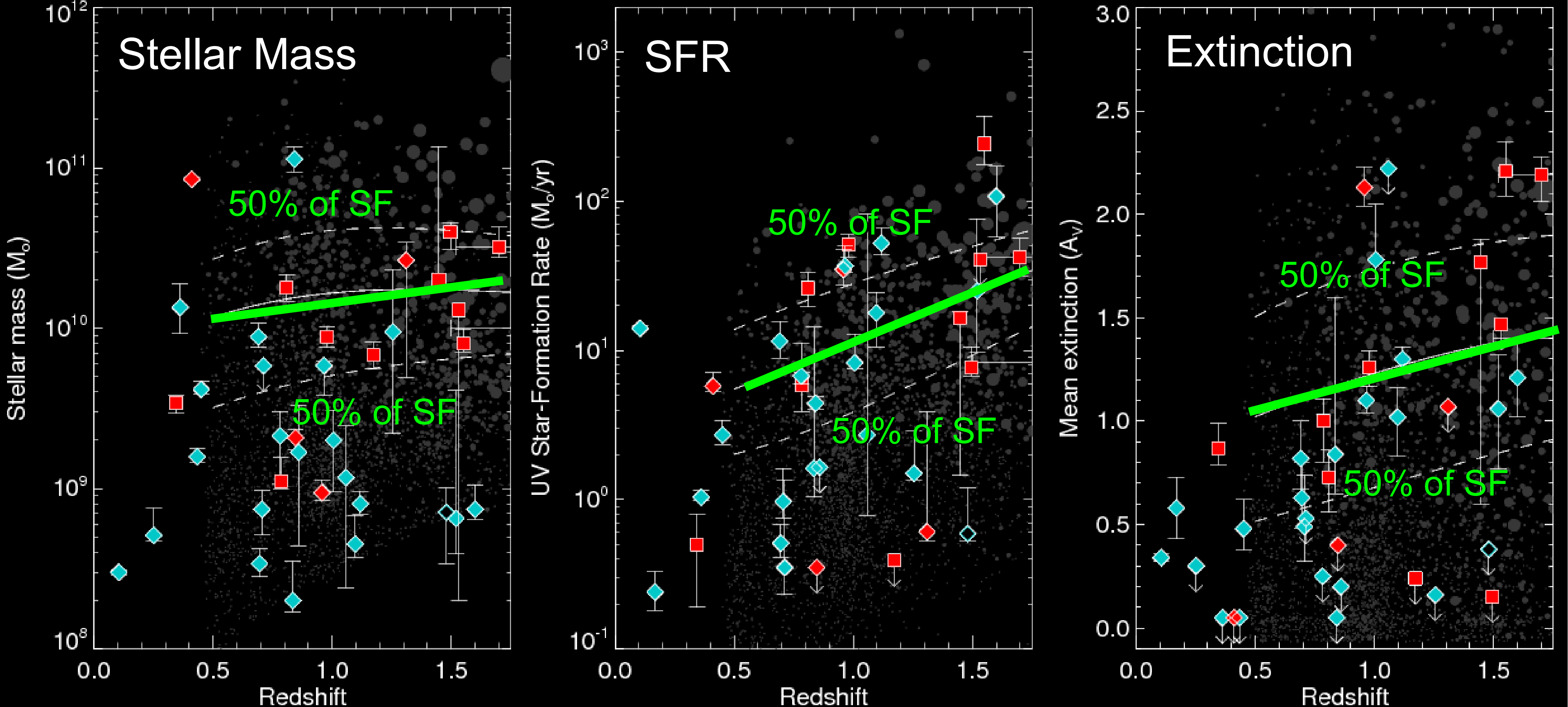


Comparisons vs. Field Galaxies at z~1

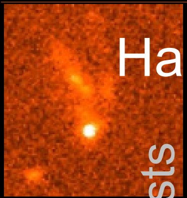


Calculate z-dependent median (mass,SFR,Av) of SFR-weighted population.
Half of GRBs should be above median, half below (if $R_{GRB} \propto SFR$)

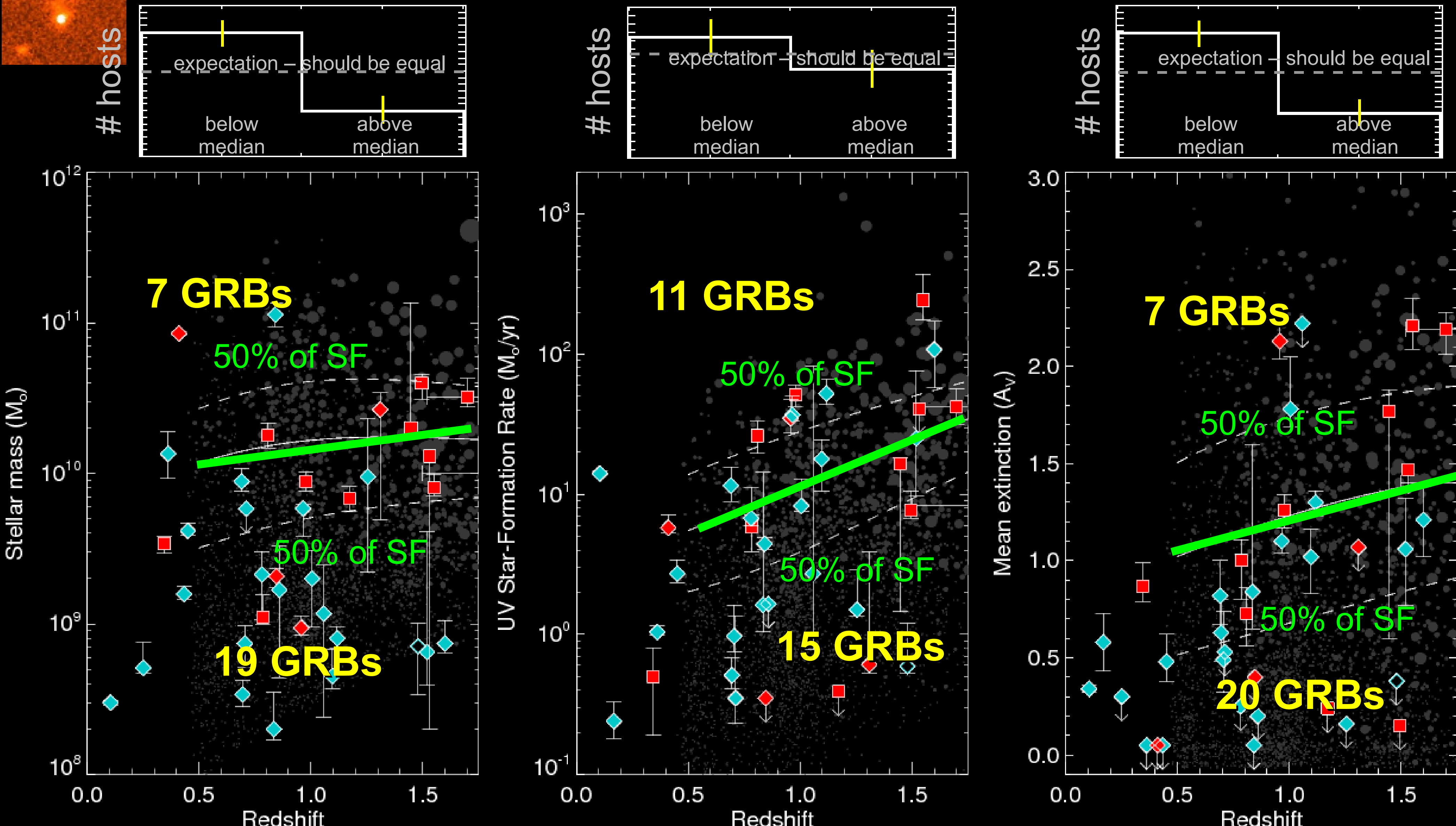
Combined sample versus field galaxies:



Comparisons vs. Field Galaxies at z~1

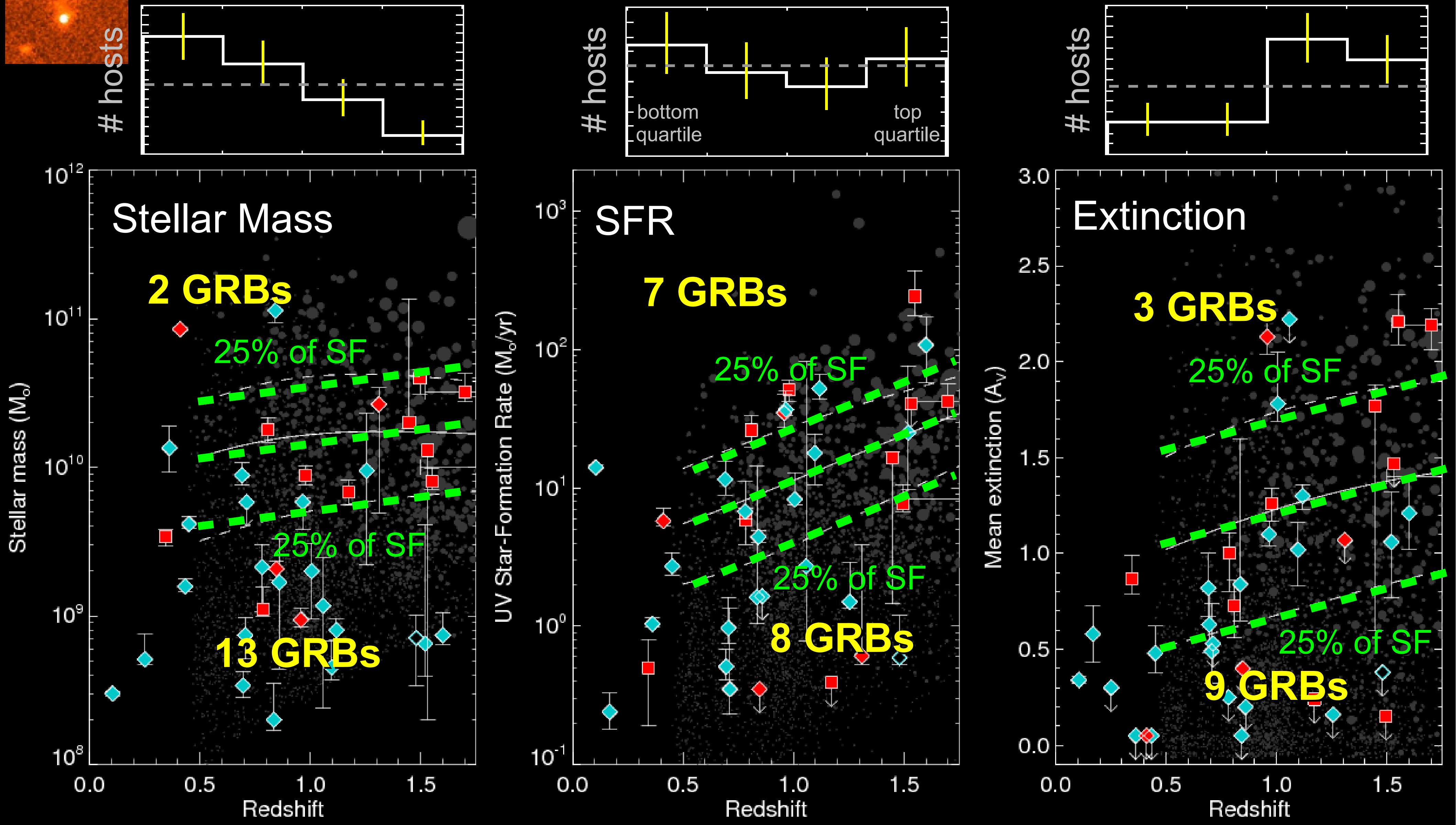


Half of GRBs should be above median, half below (if $R_{GRB} \propto$ SFR)

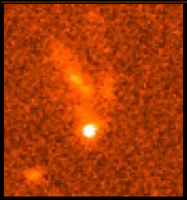


Comparisons vs. Field Galaxies at z~1

For more resolution, use SFR-weighted quartiles:



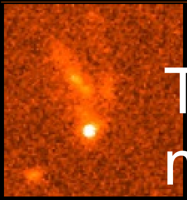
Comparisons vs. Field Galaxies at z~1



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:

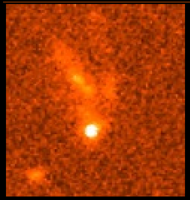
UV radiation field.

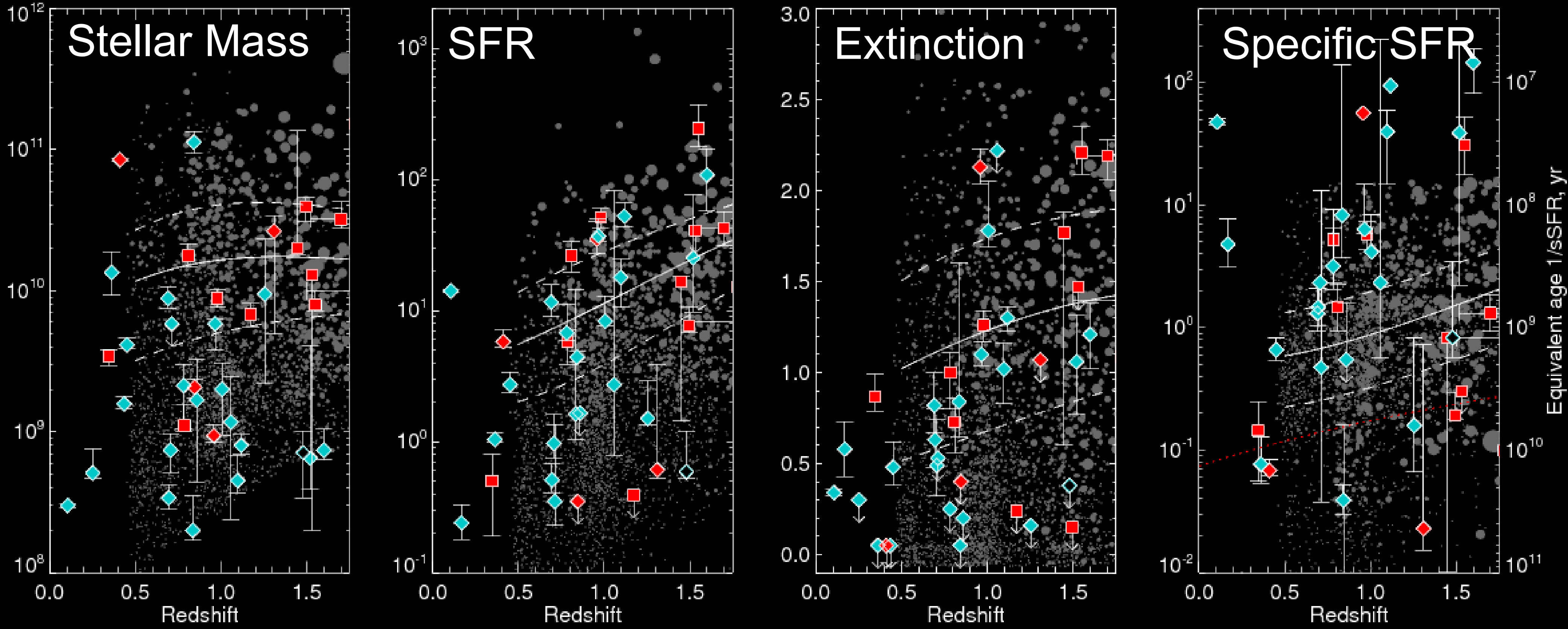
Gas density.

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

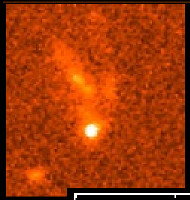
most strongly correlated with **SFR**/**sSFR**.

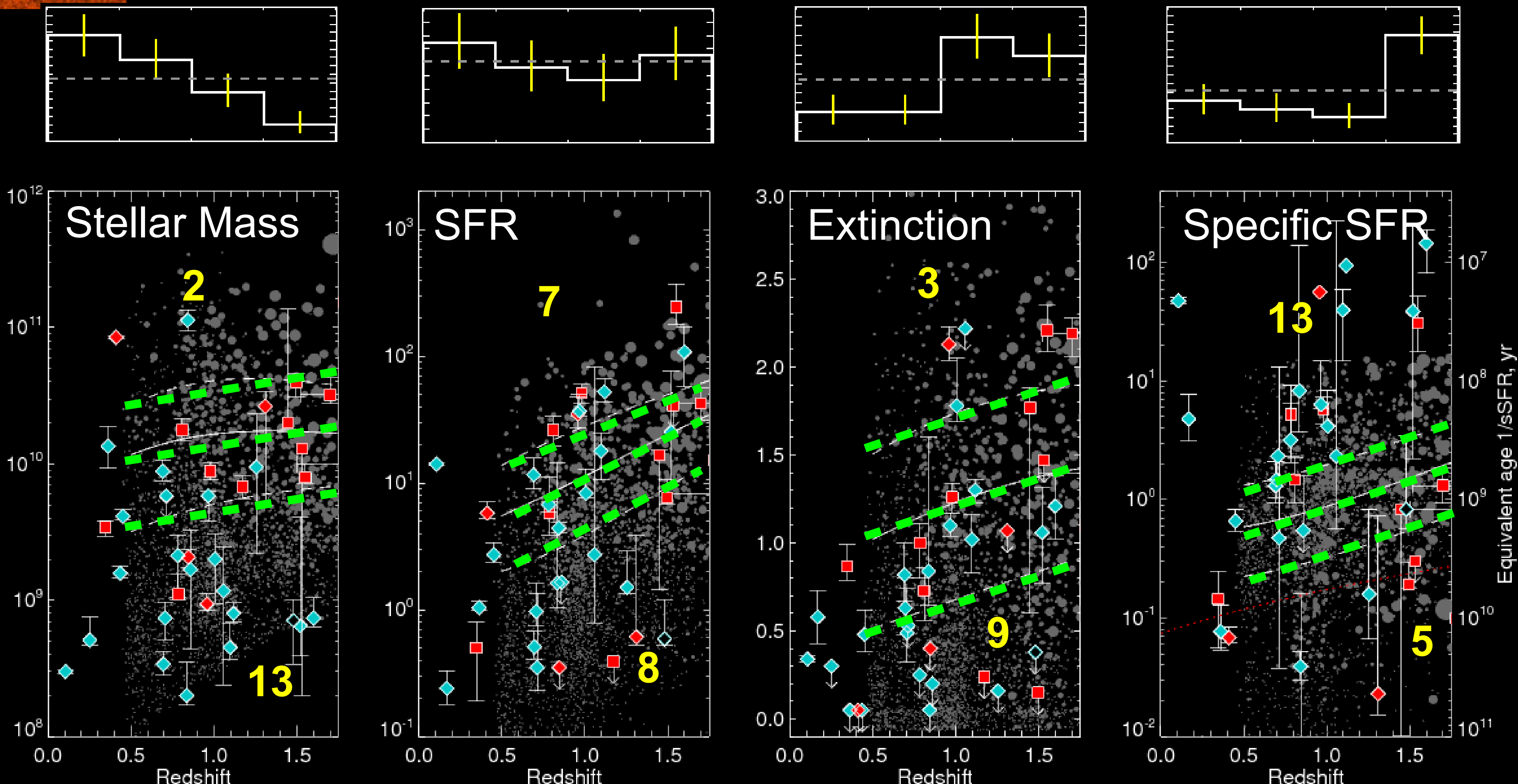
Origins of GRB Rate Variations



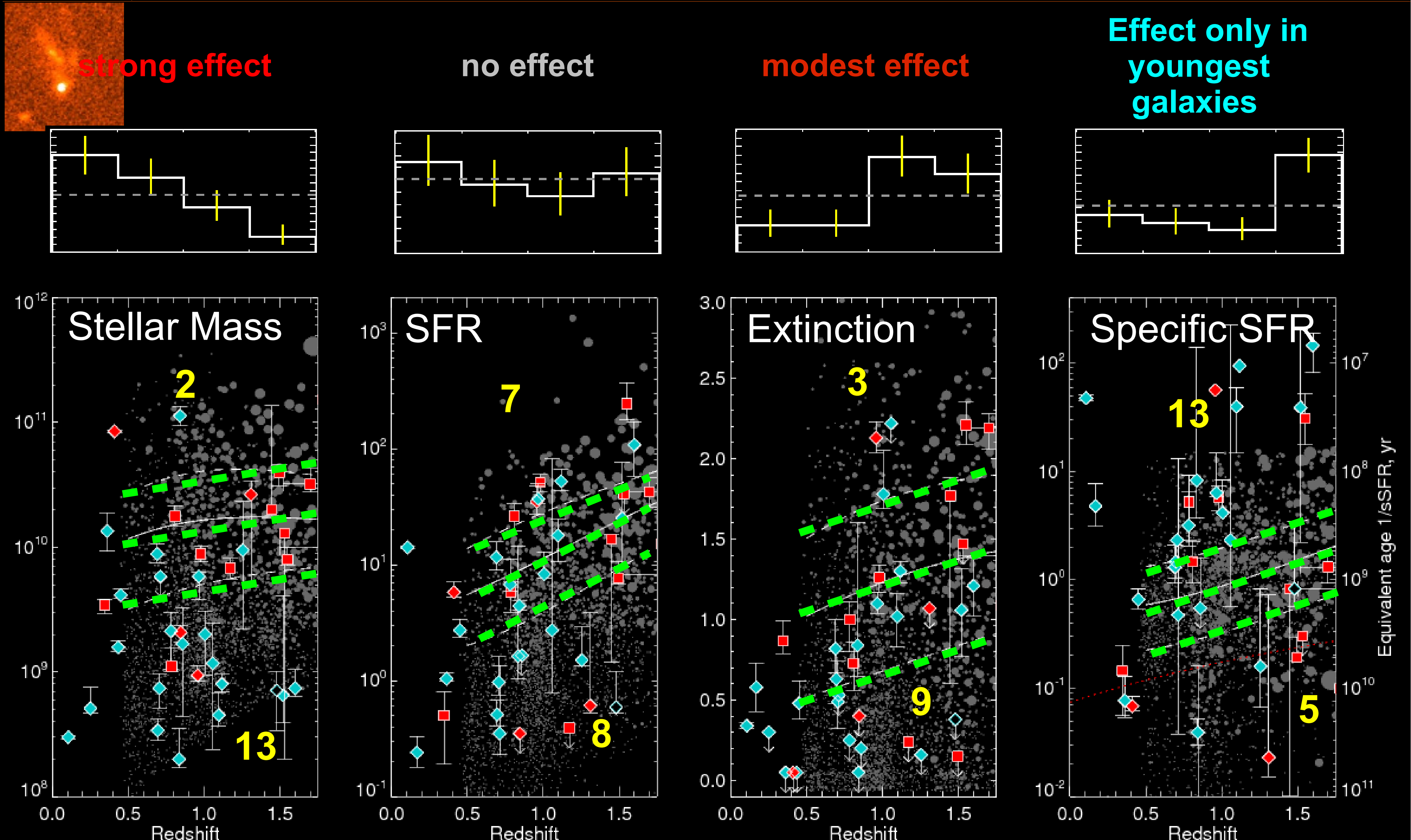


Origins of GRB Rate Variations

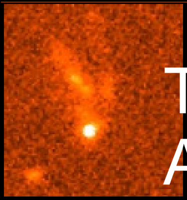




Origins of GRB Rate Variations



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**.

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.

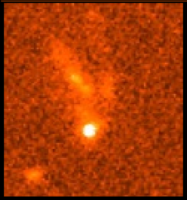
(could affect IMF, initial binarity properties, etc.)

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])

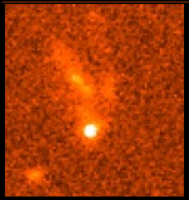
Moving beyond z>1.5

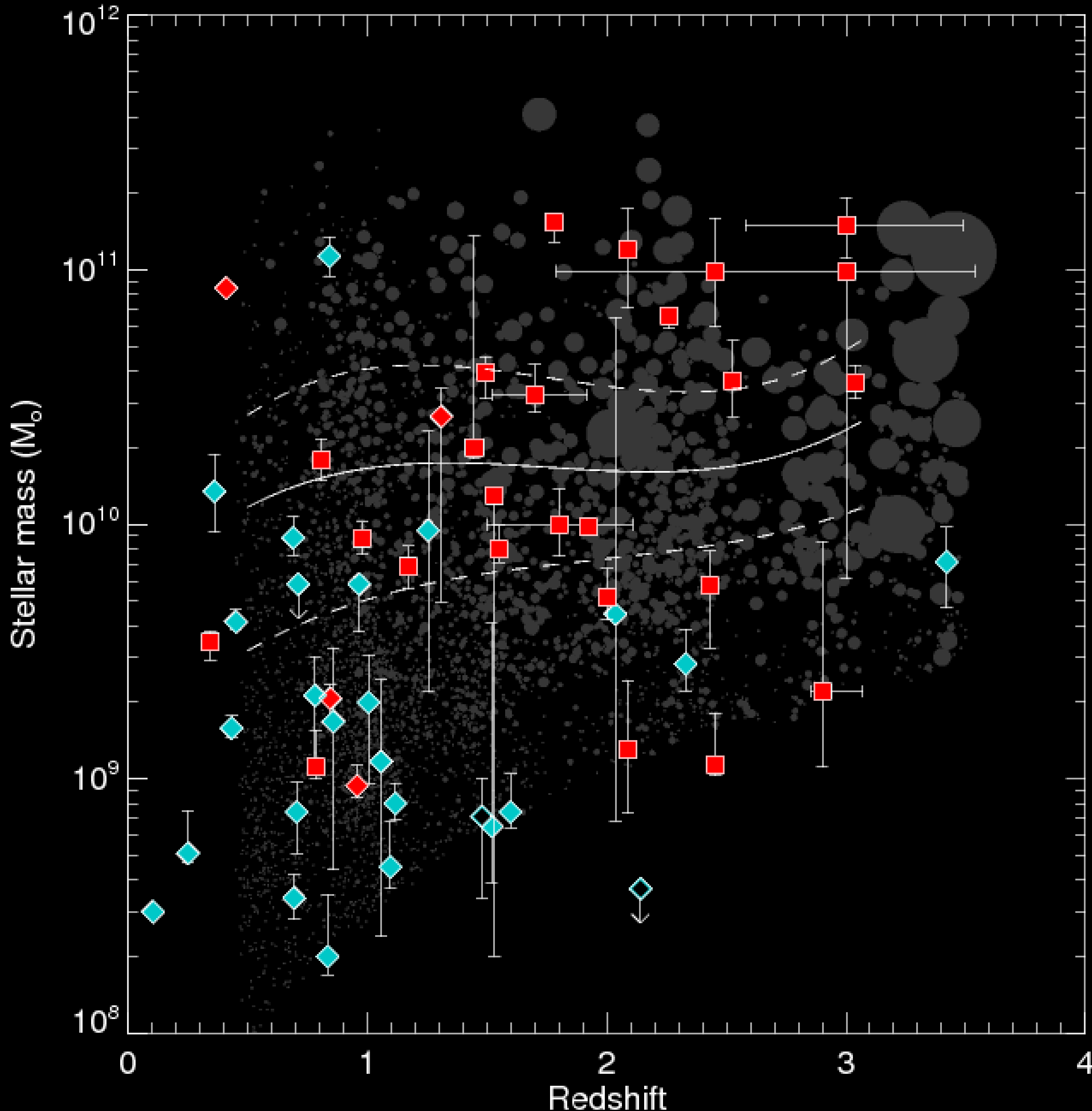


Are GRBs useful tracers of star-formation at...

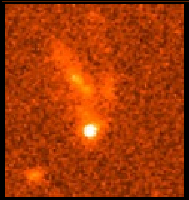
- [x] z ~ 1?
- [ ] z ~ 2?
- [ ] z ~ 3?
- [ ] z > 4?

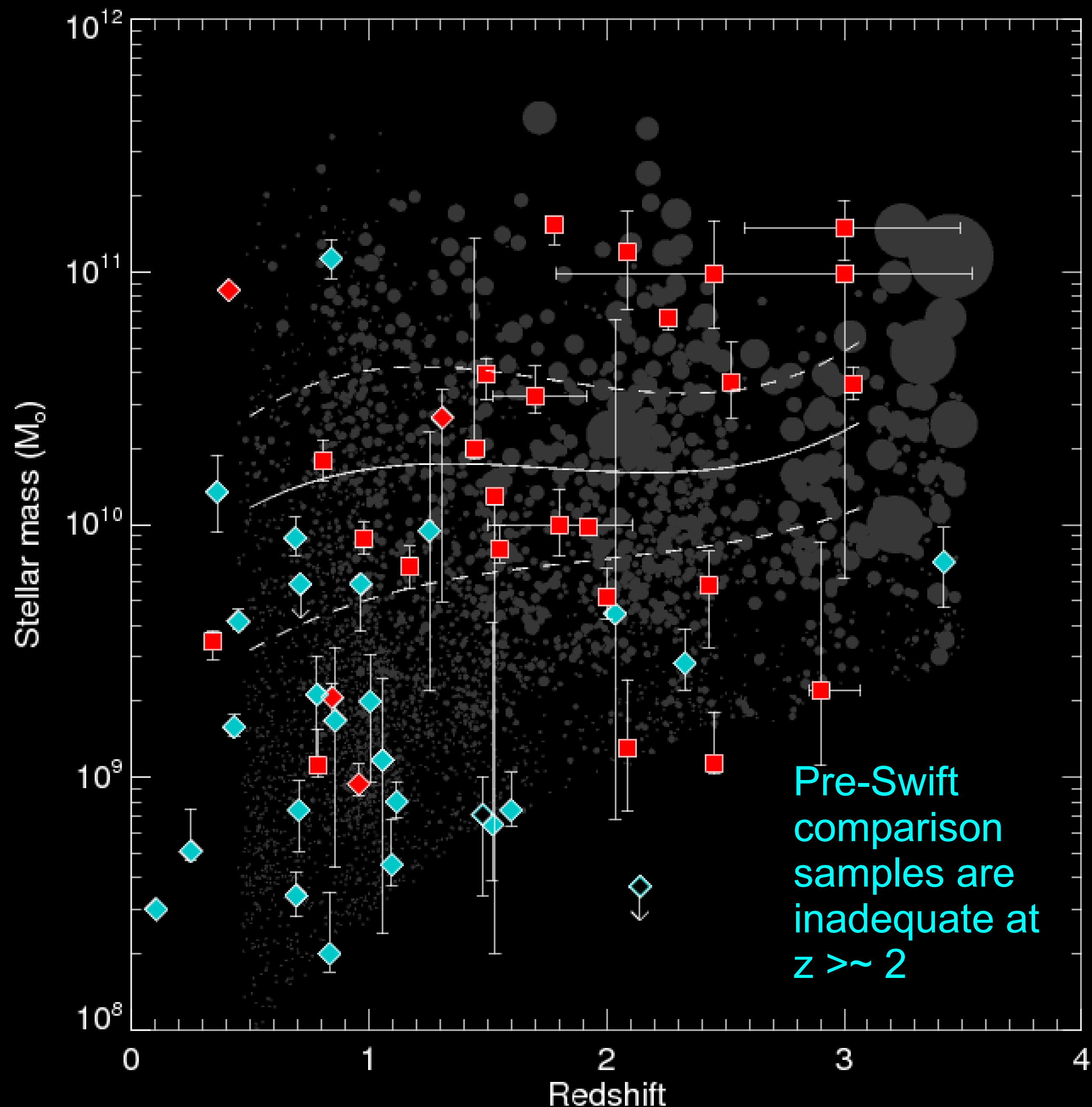
Moving beyond z>1.5



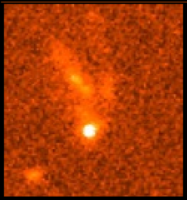


Moving beyond z>1.5





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

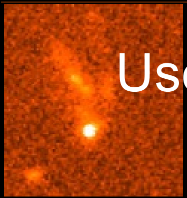
Tibbets-Harlow et al. in prep

VLT Optically Unbiased Host Project ("TOUGH")

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

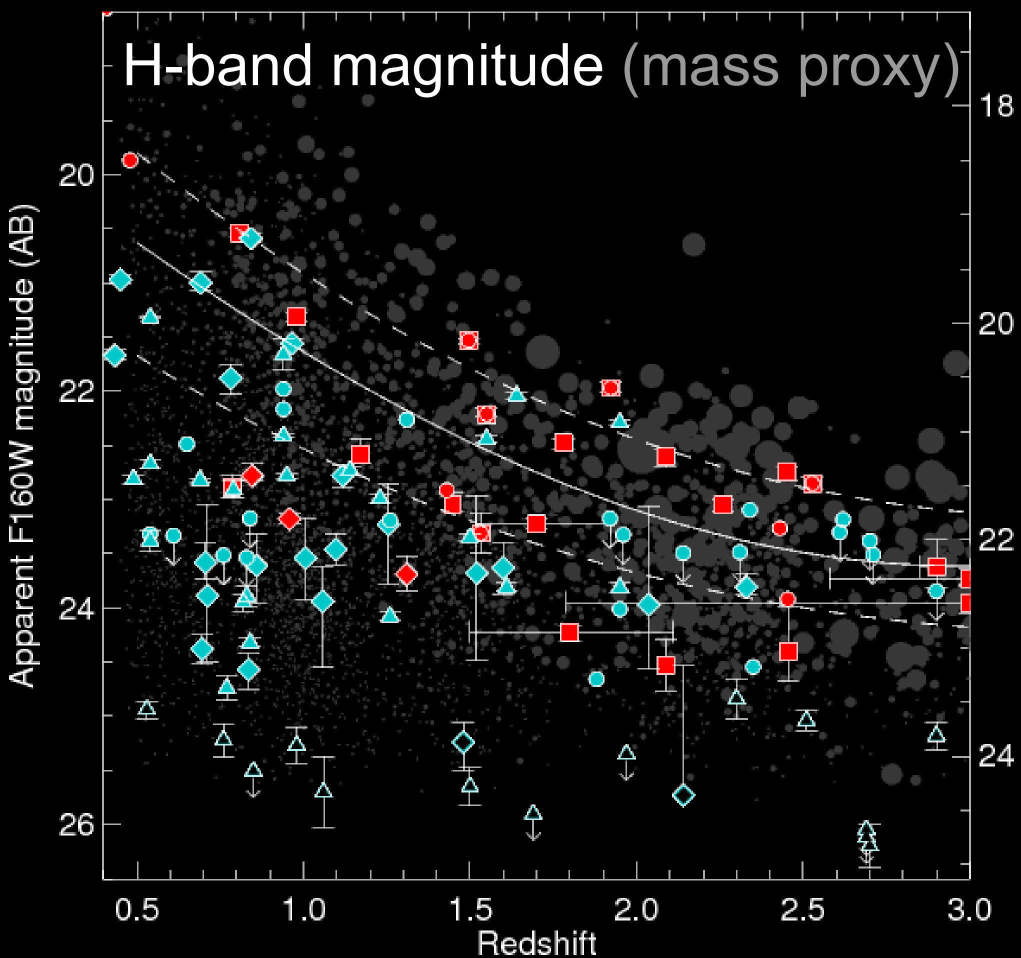
Hjorth et al. 2012
Malesani et al. in prep.
Jakobsson et al. 2012

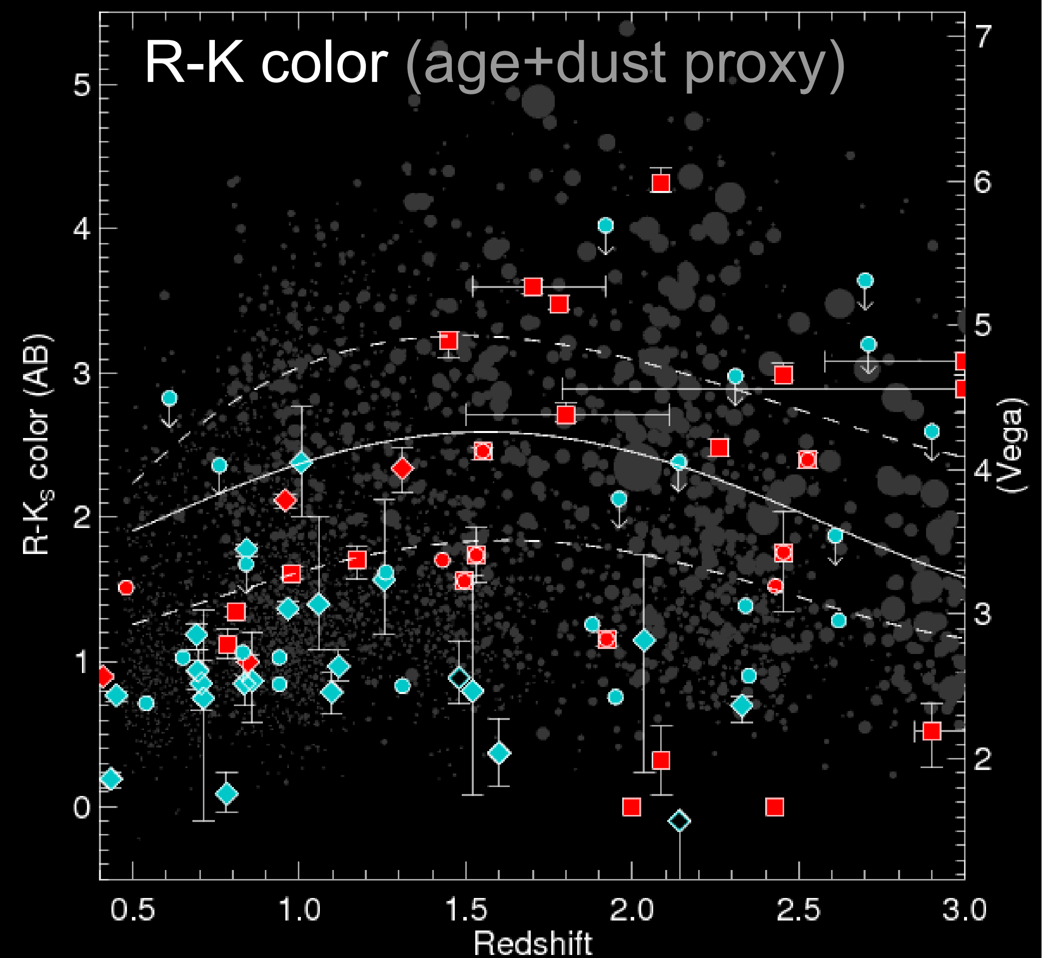
GRBs vs SFR at z~2



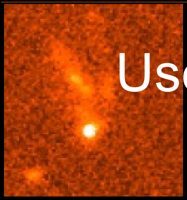
Use magnitudes and colors as substitutes for formal SED modeling.

Dark + pre-Swift + Snapshot + VLT





GRBs vs SFR at z~2



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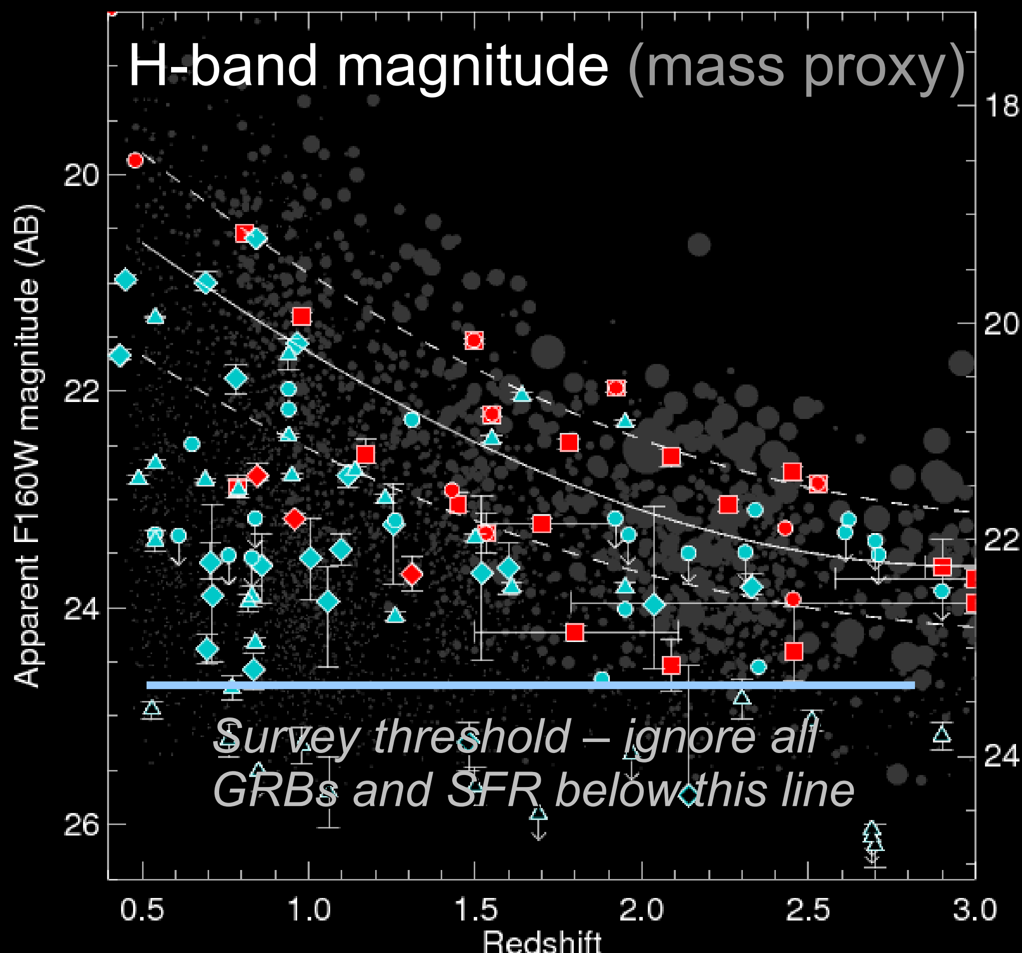
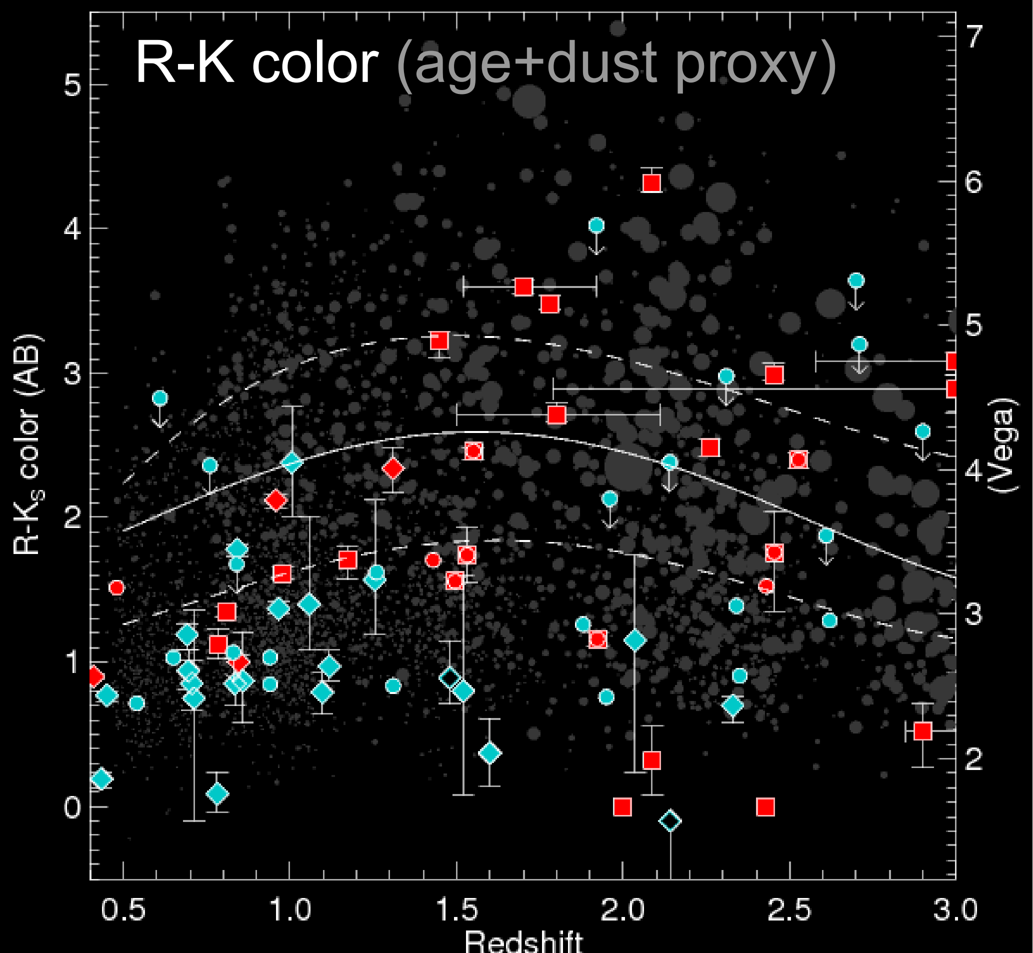
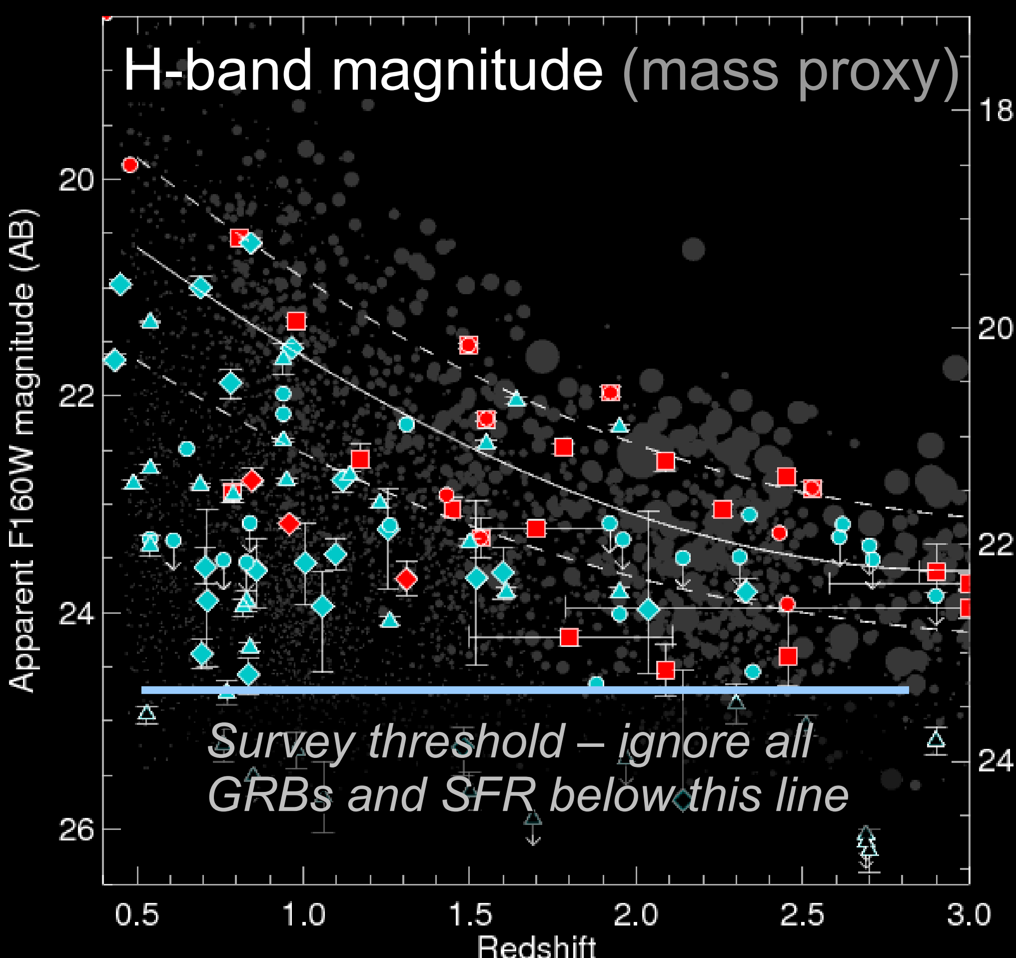


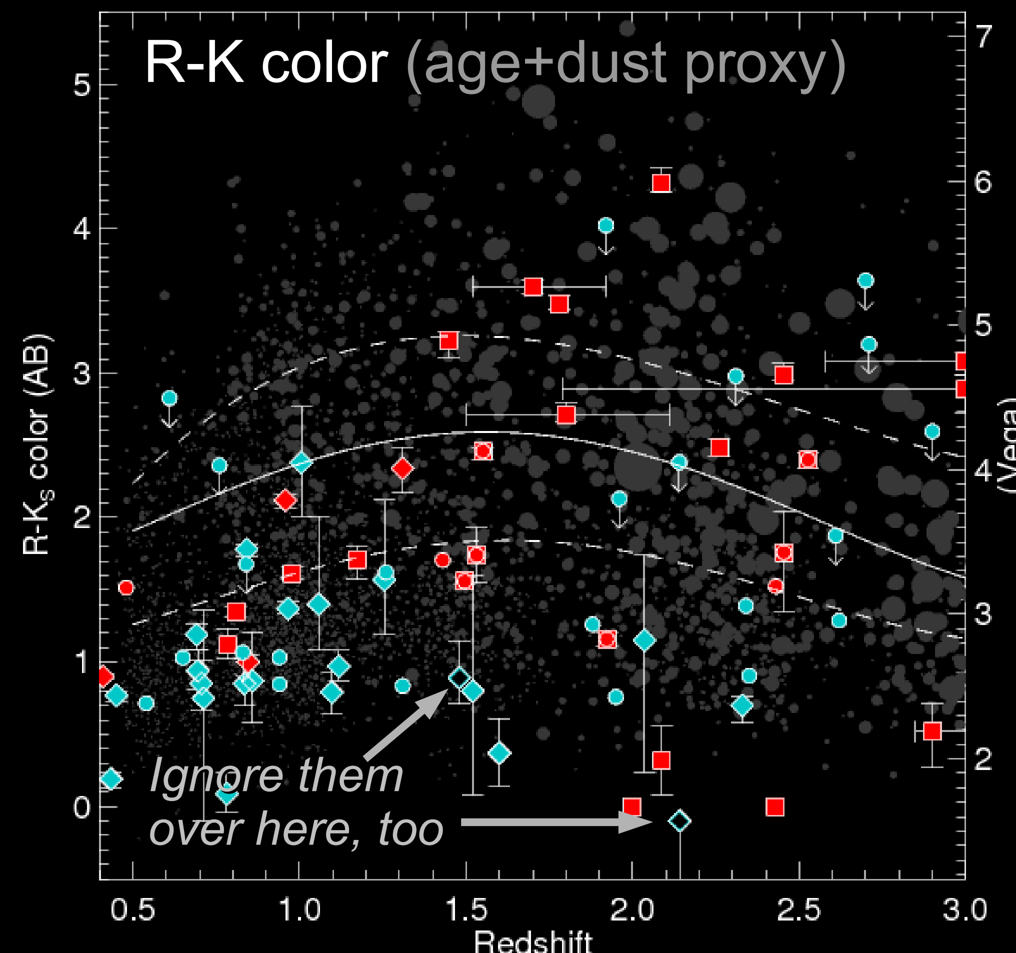


GRBs vs SFR at z~2

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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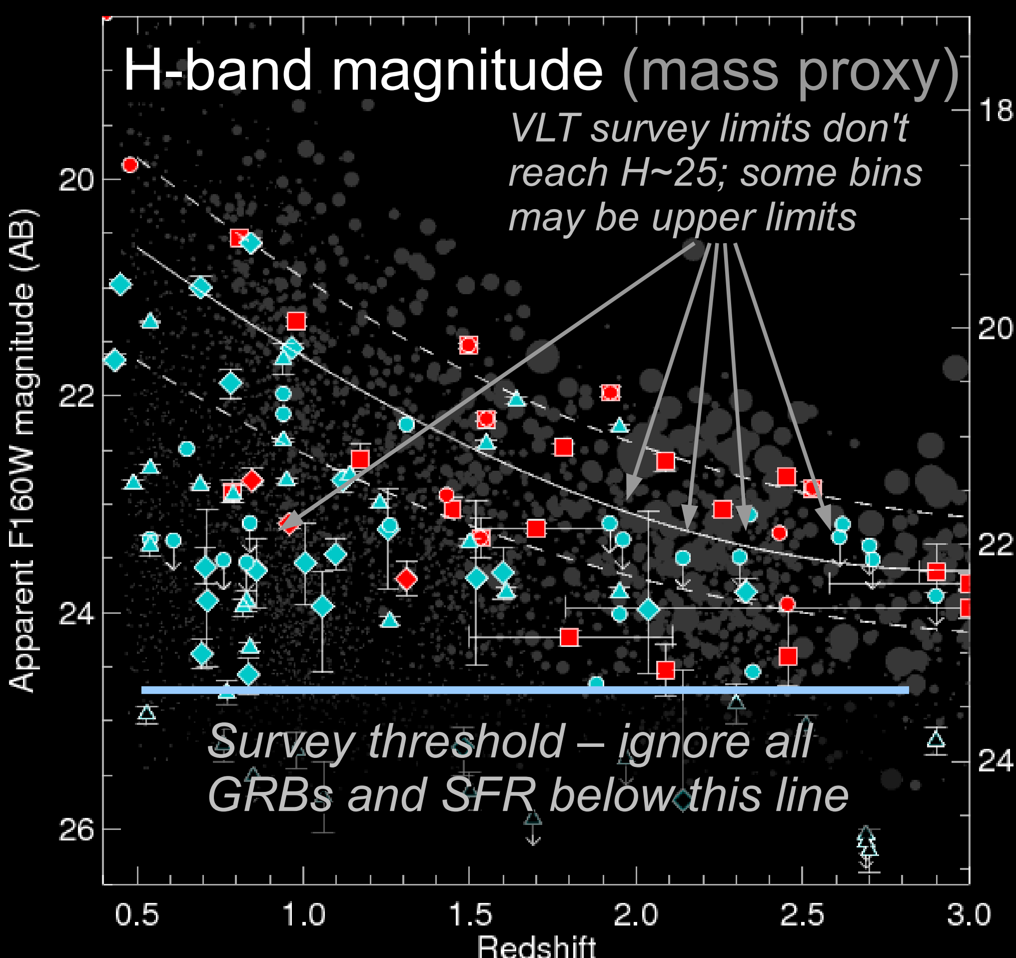
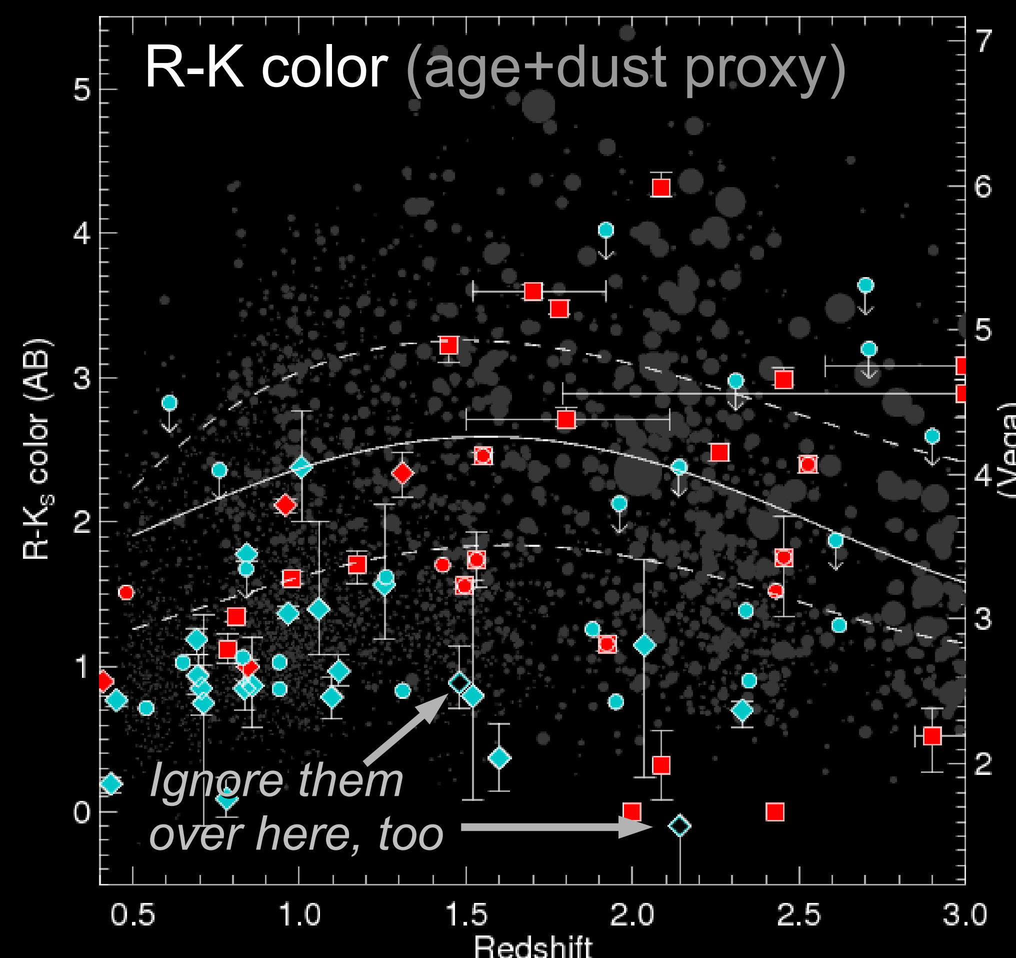
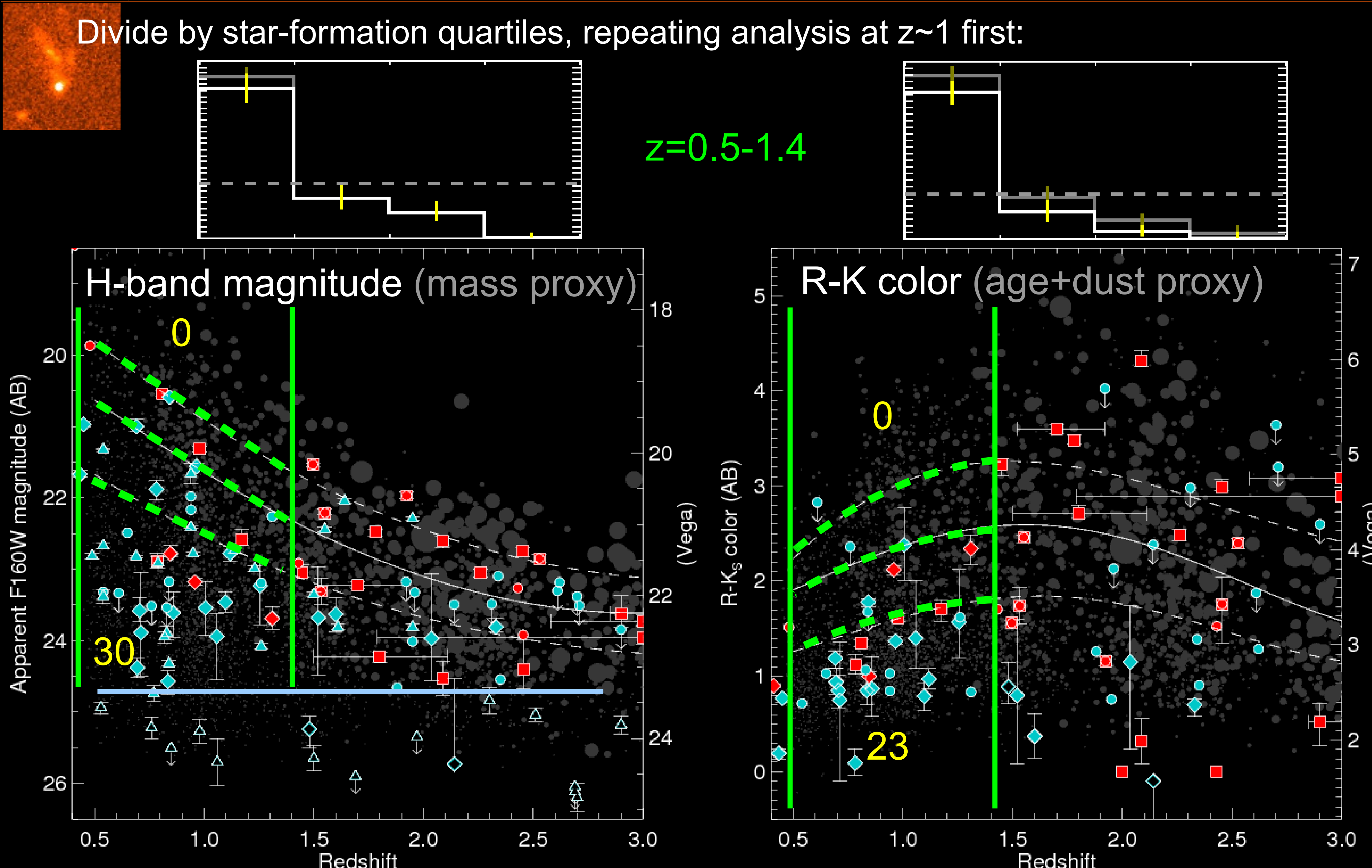




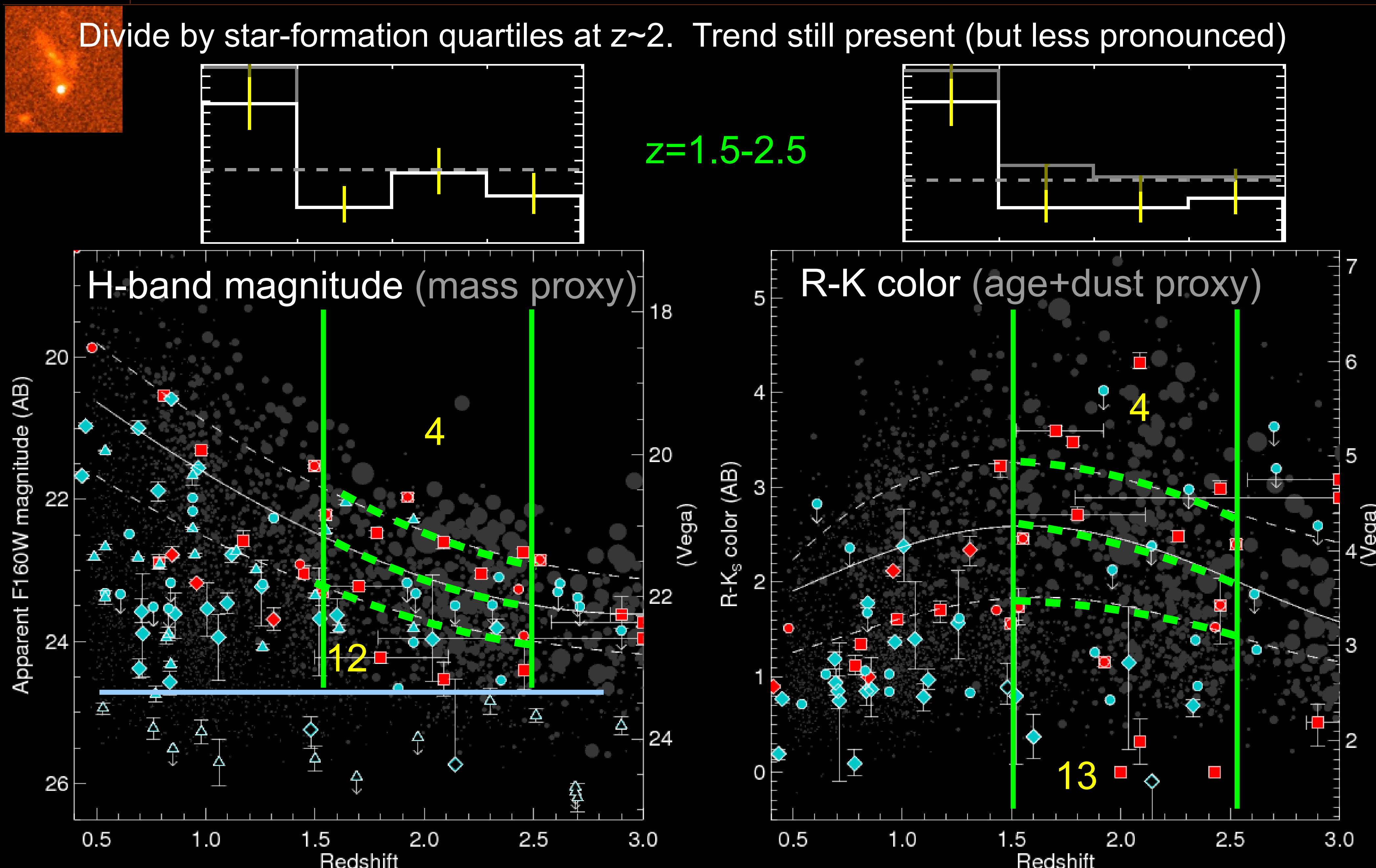
GRBs vs SFR at z~1

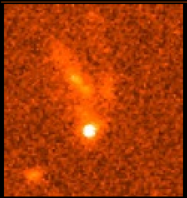
Divide by star-formation quartiles, repeating analysis at z~1 first:



GRBs vs SFR at z~2

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

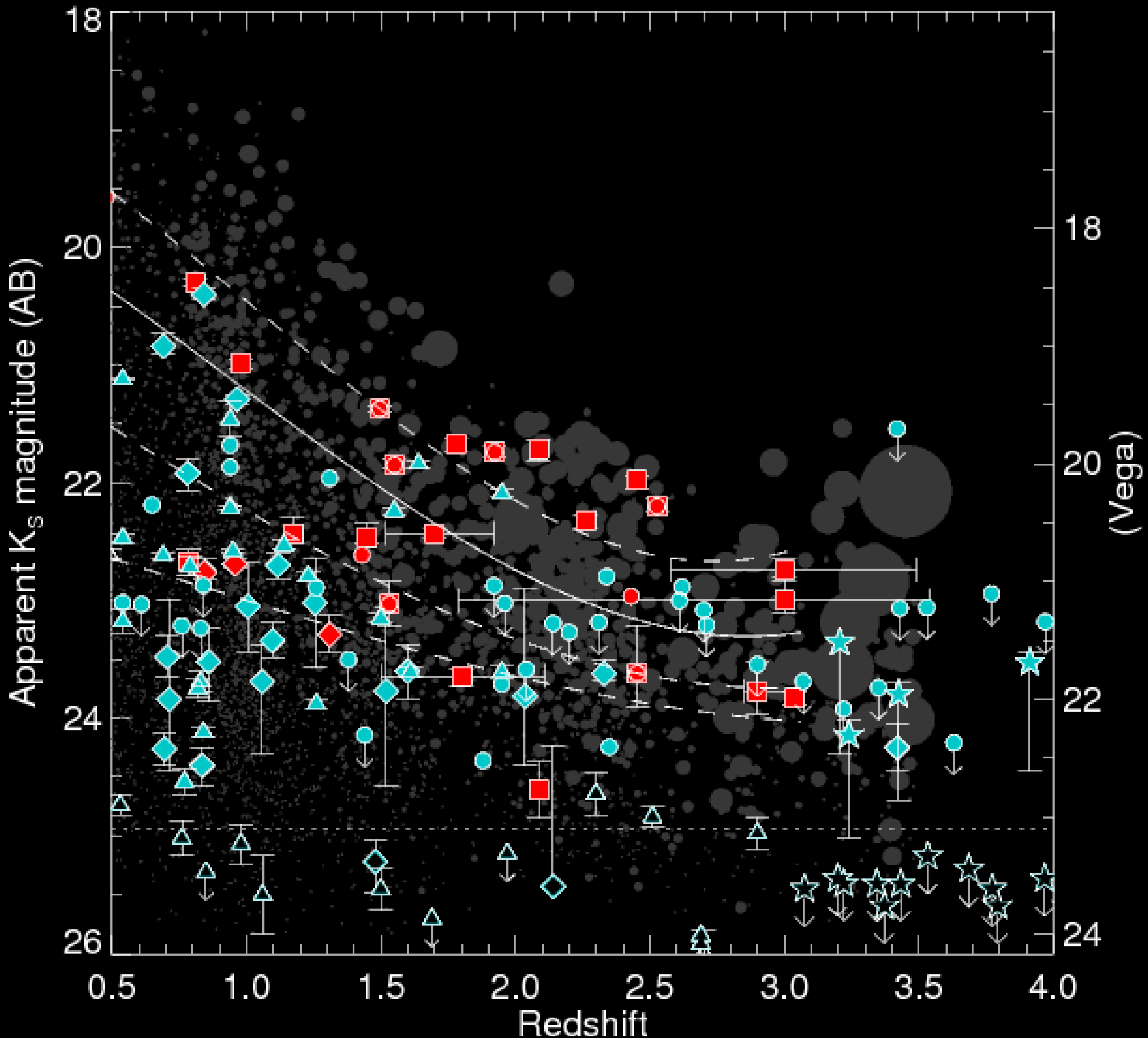




Are GRBs useful tracers of star-formation at...

- ☒ $z \sim 1$?
- ☒ $z \sim 2$?
- ☐ $z \sim 3$?
- ☐ $z > 4$?

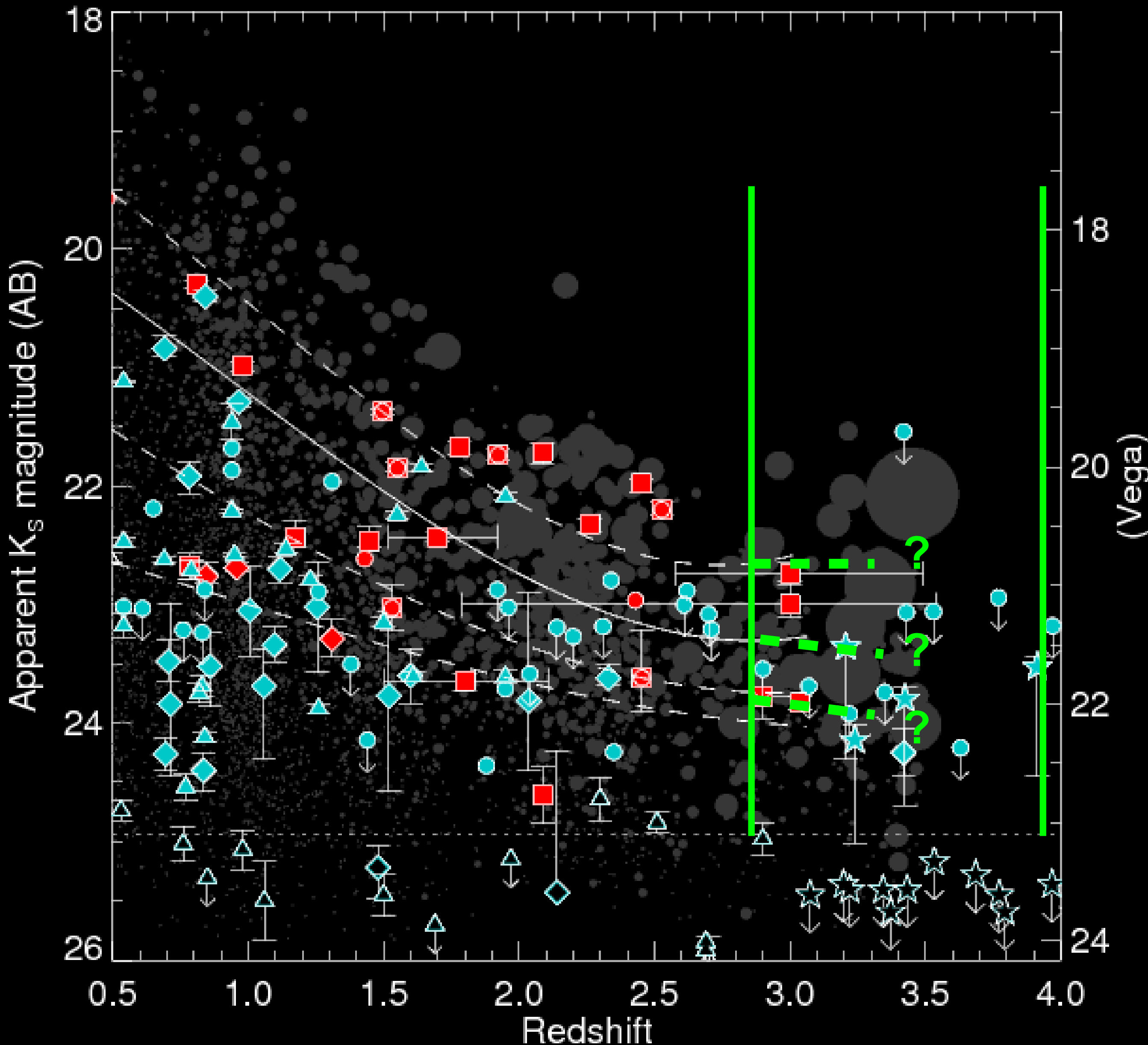
GRBs vs SFR at z~3



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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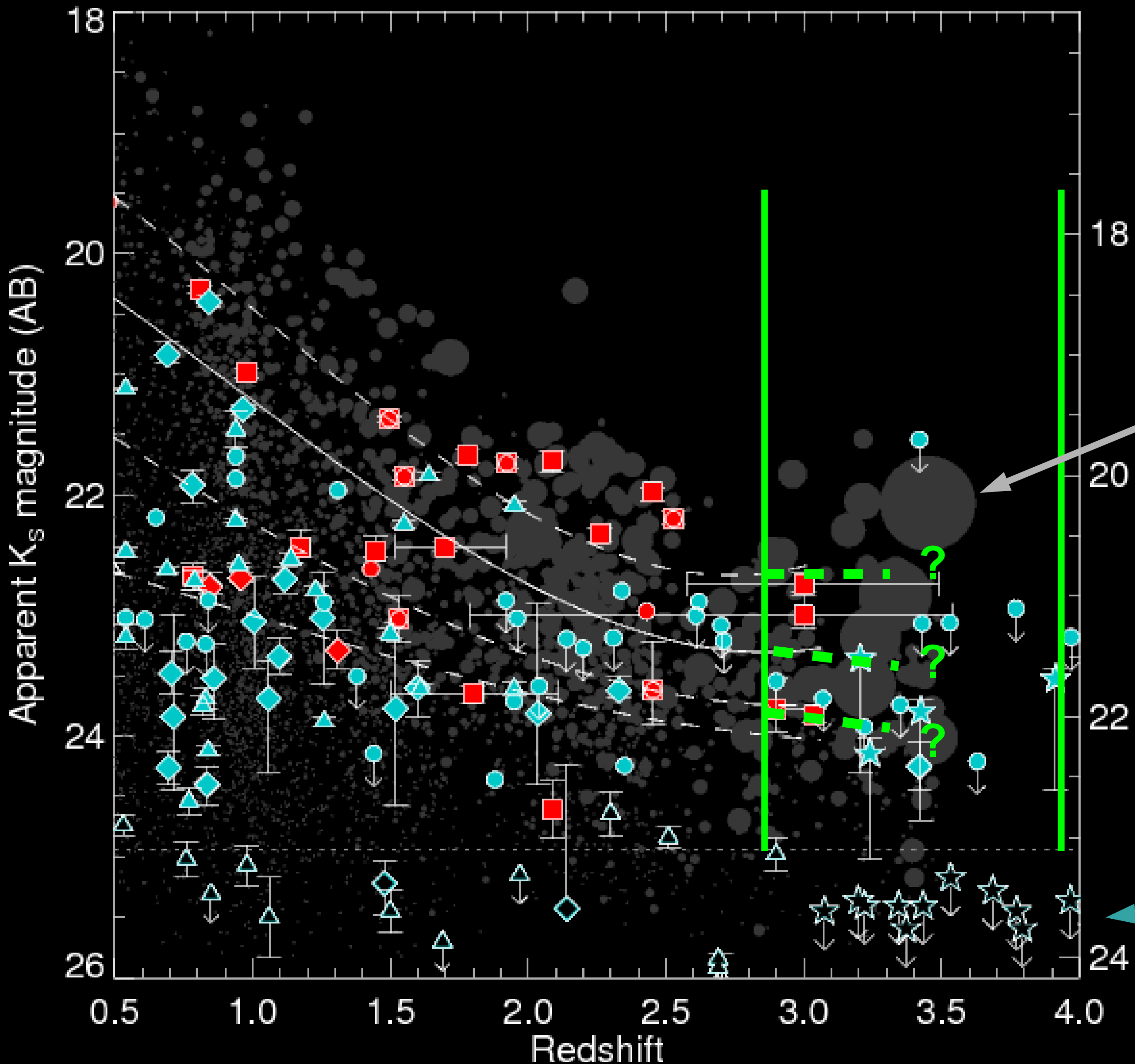
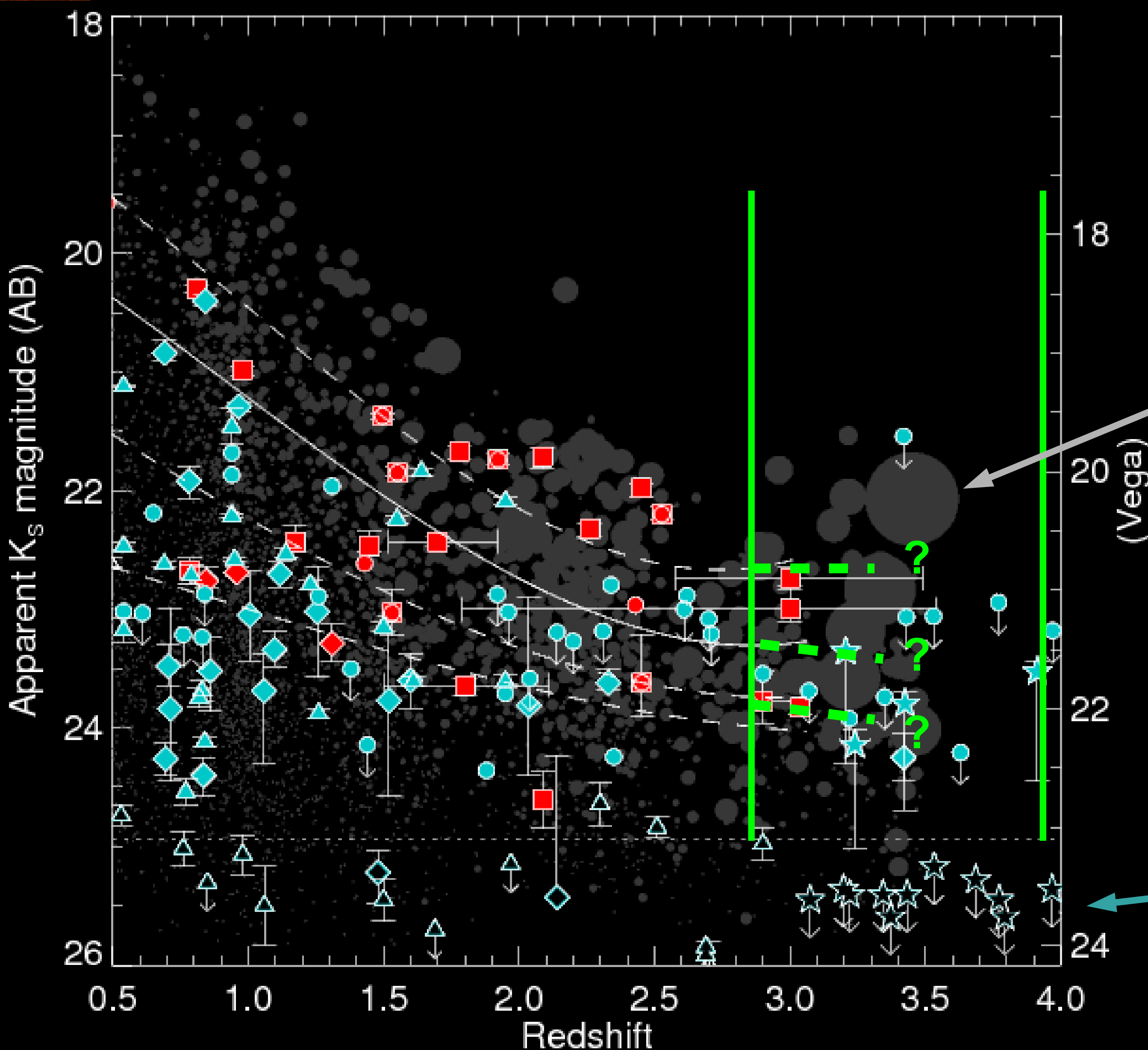


z>3 is challenging...

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



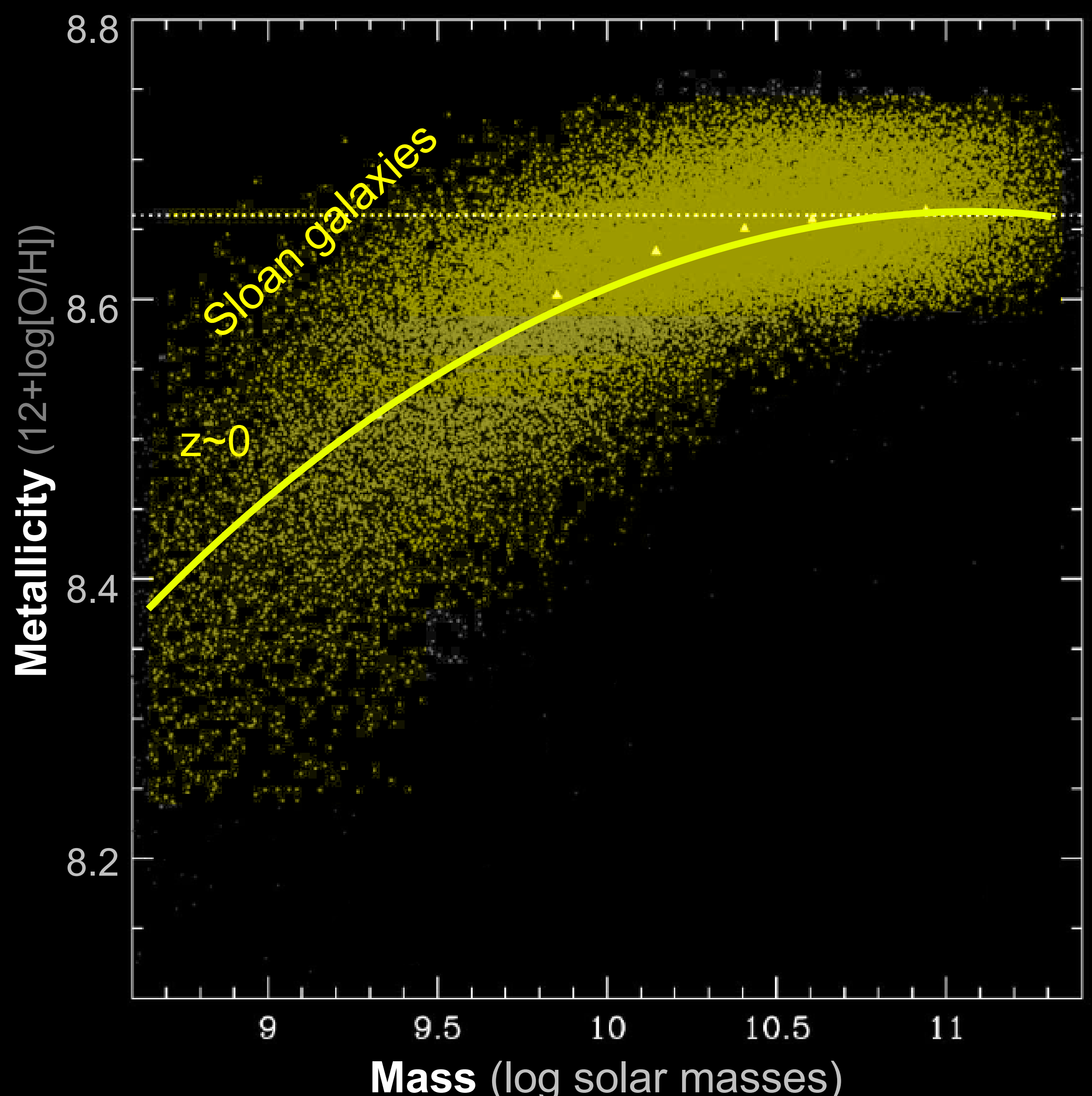
z>3 is challenging... No way to check directly. Can we use low-z results?

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?

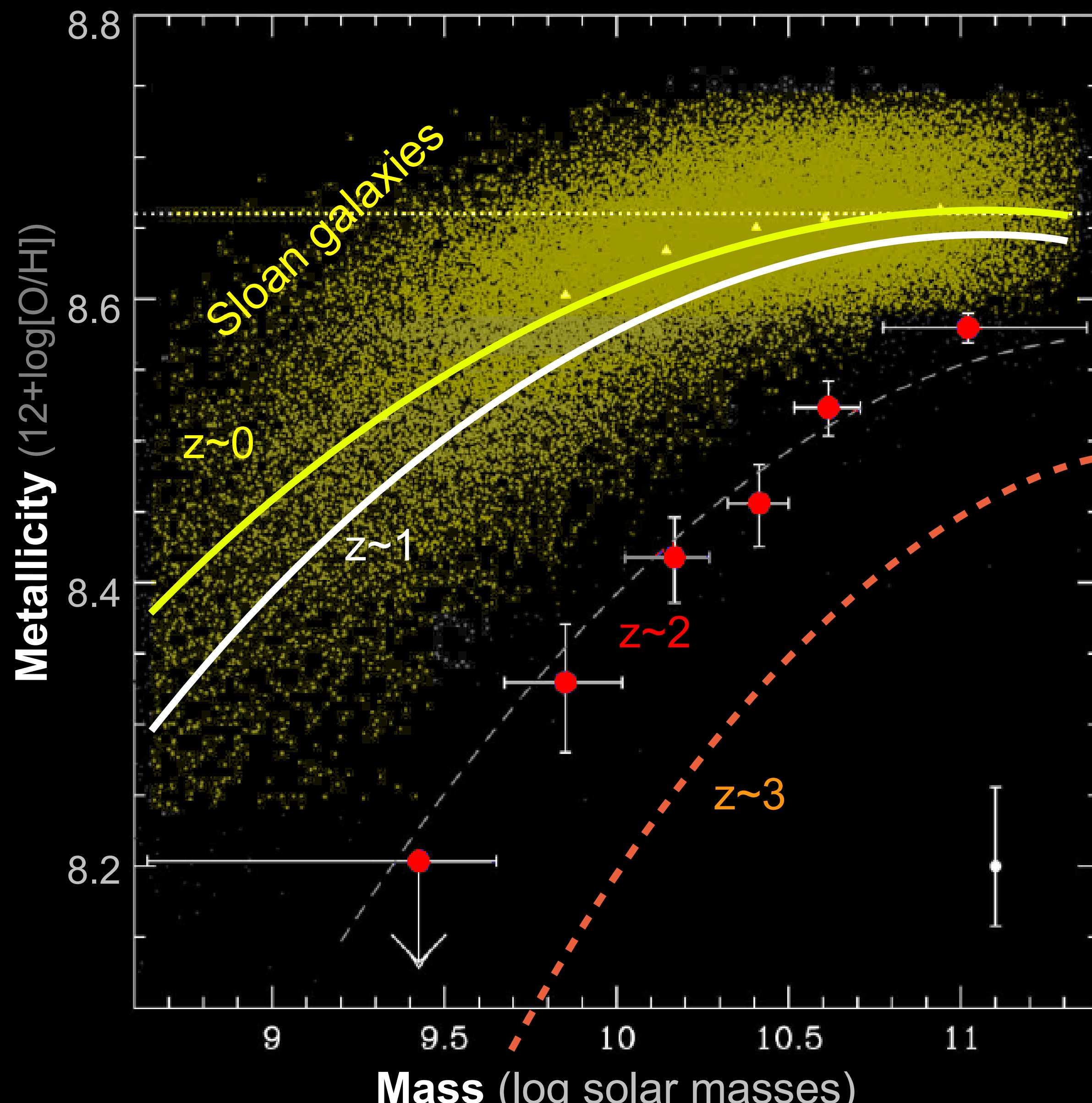
Mass and metallicity are correlated at low-z.



Kewley et al. 2008, Erb et al. 2006

Is There Hope for High Redshift?

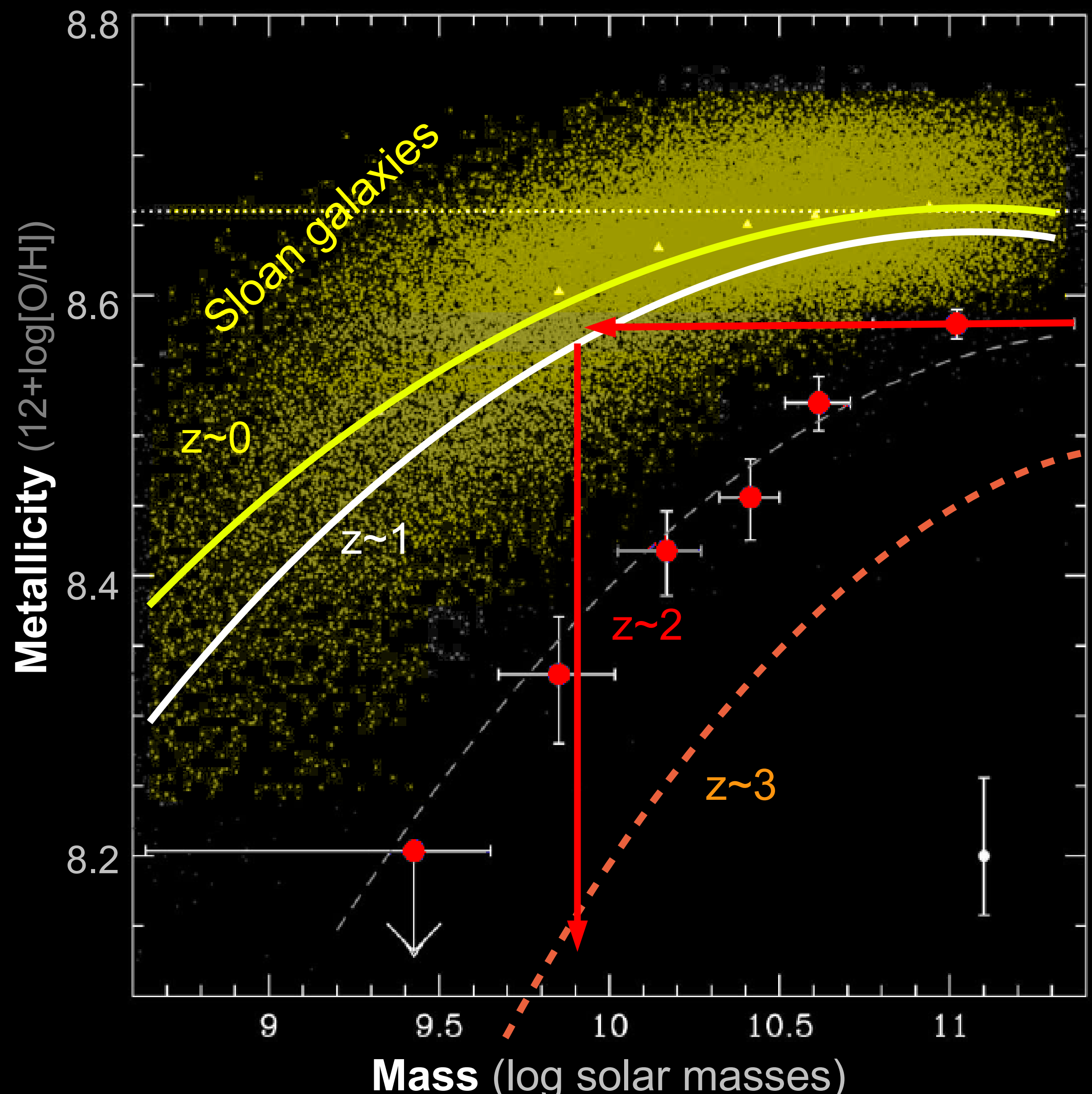
Mass and metallicity are correlated at low-z...
and at high-z.



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

Is There Hope for High Redshift?

Massive z~2 galaxies
should have similar metallicity to
~10^{10} M☉, z~1 galaxies



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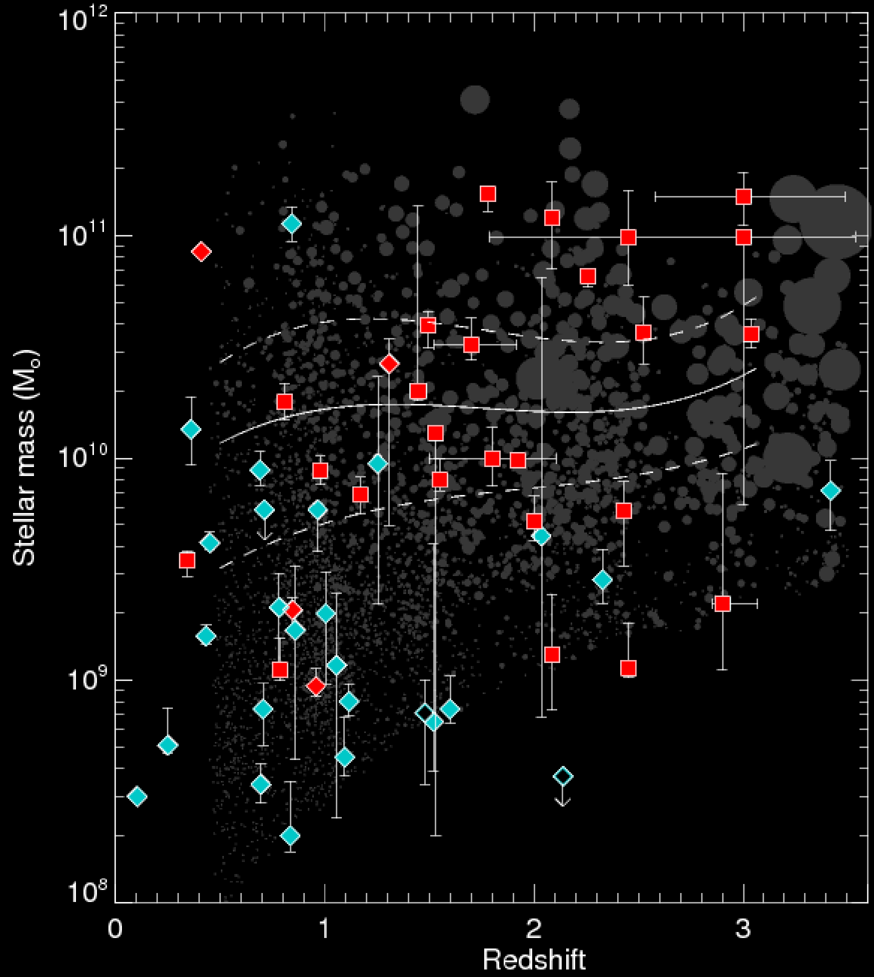

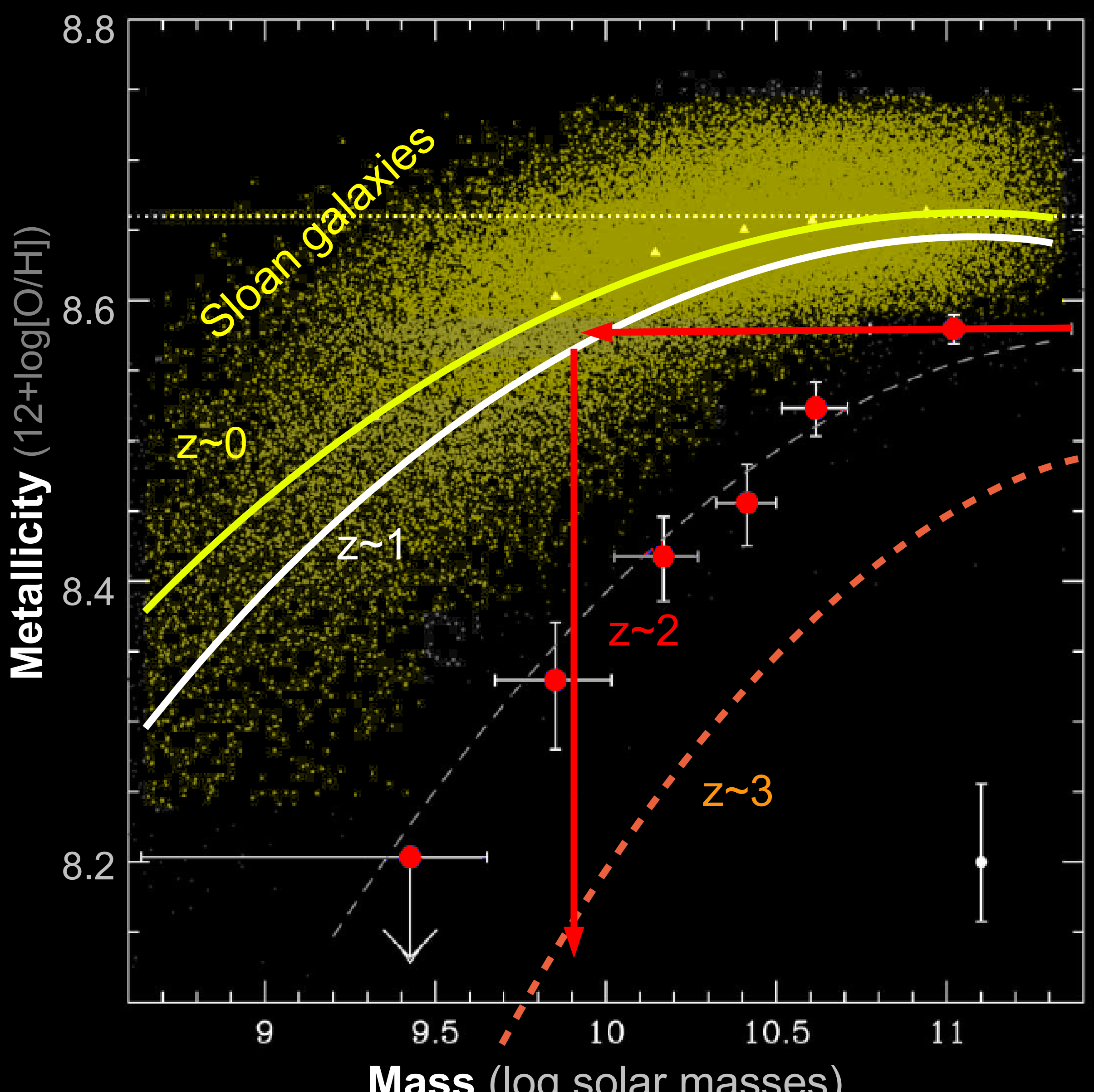

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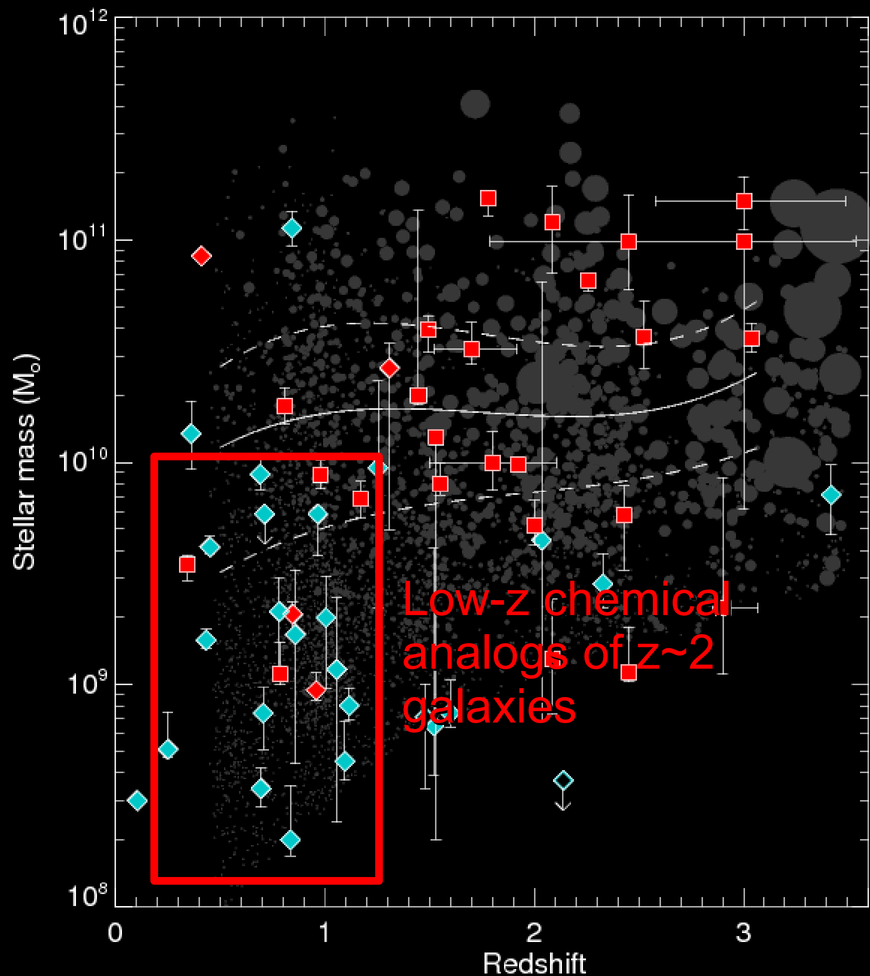
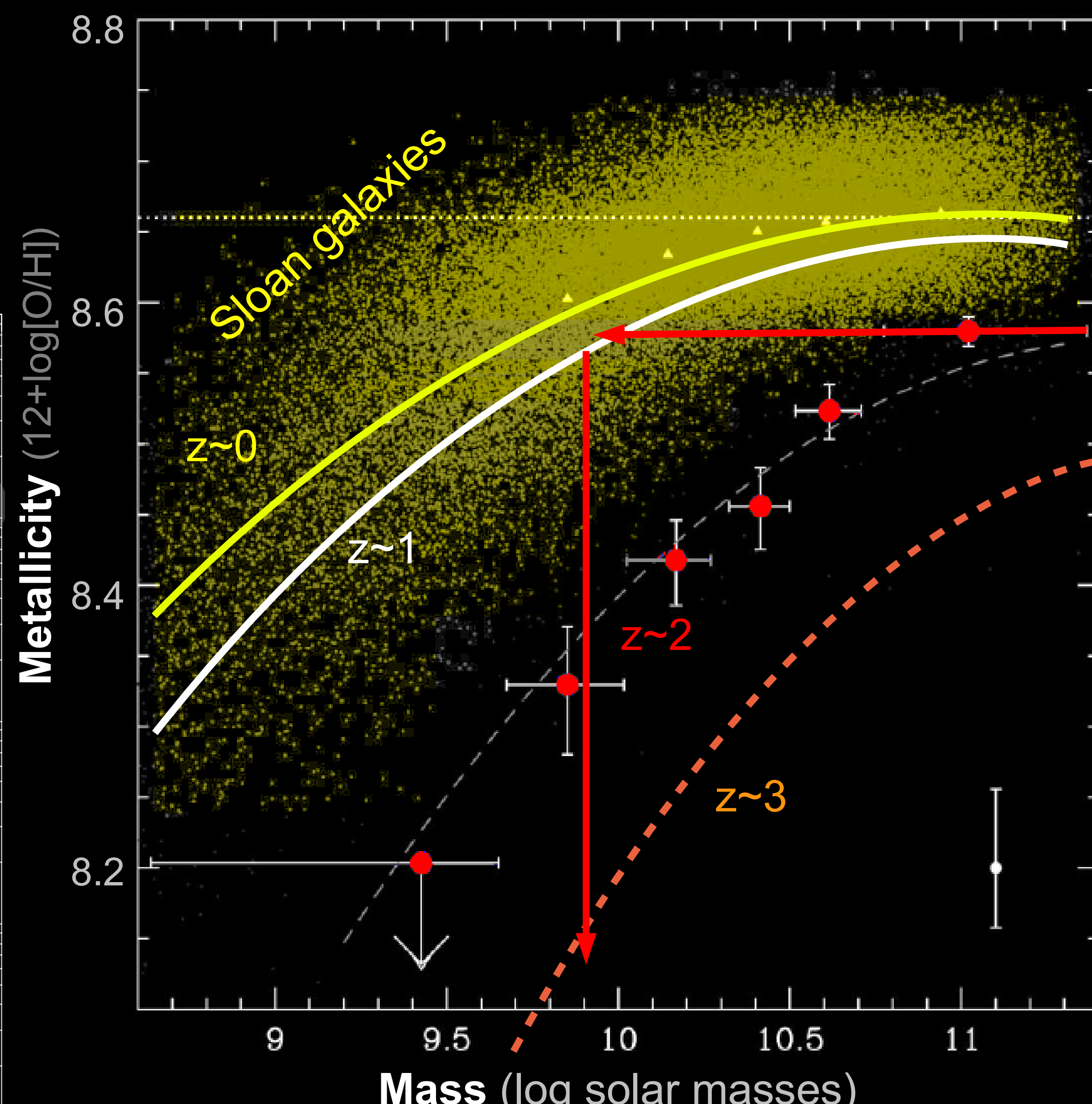
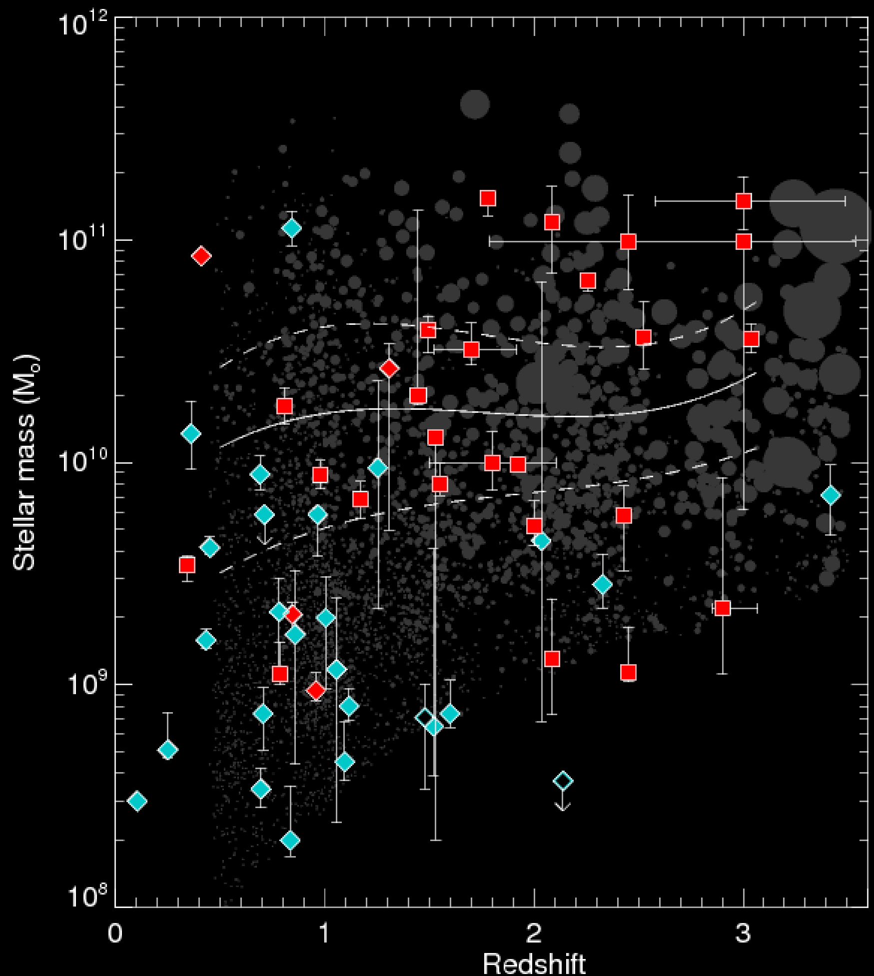


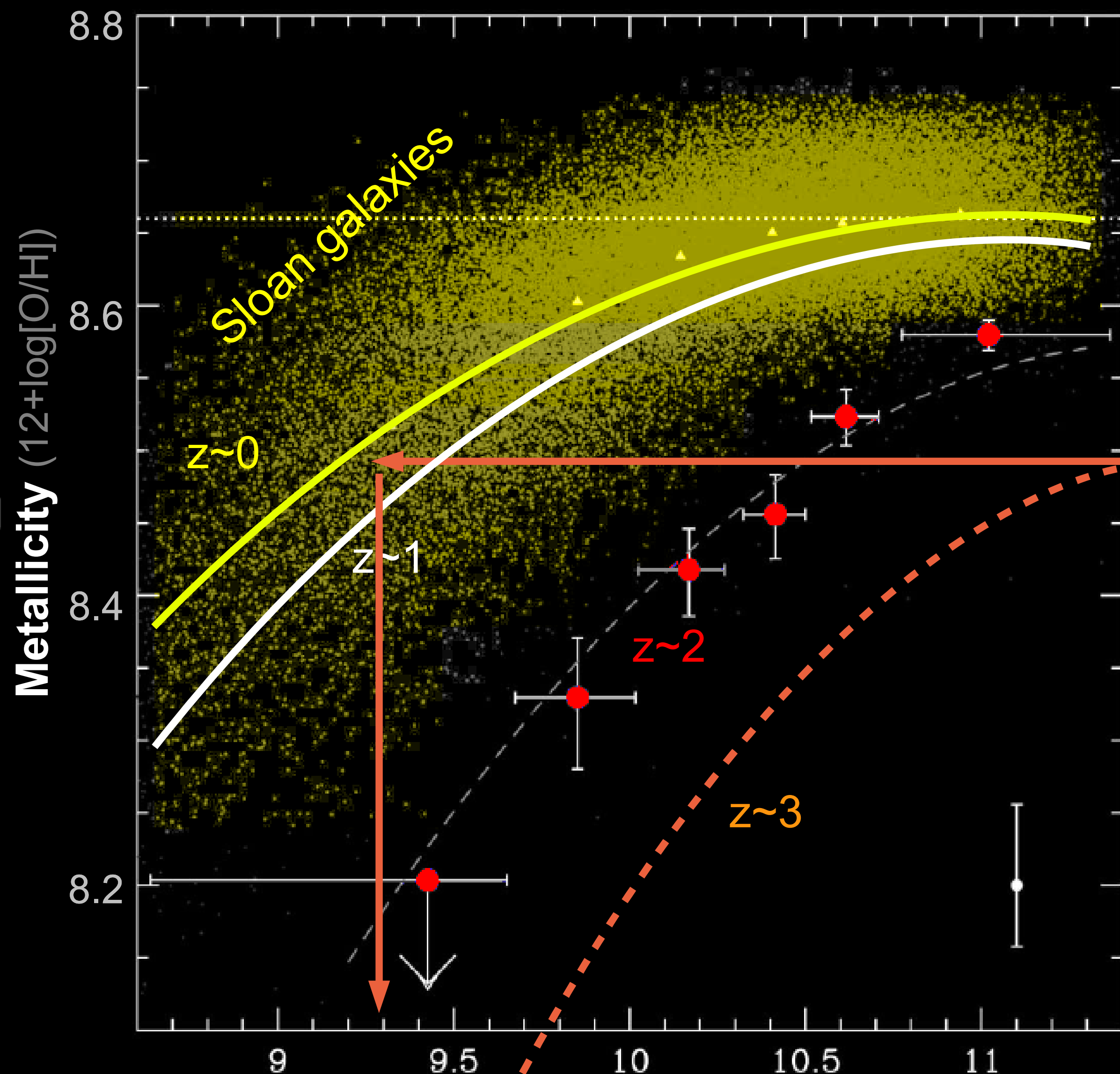


Kewley et al. 2008, Savaglio et al. 2005,, Erb et al. 2006, Maiolino et al. 2008,2009

Is There Hope for High Redshift?

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

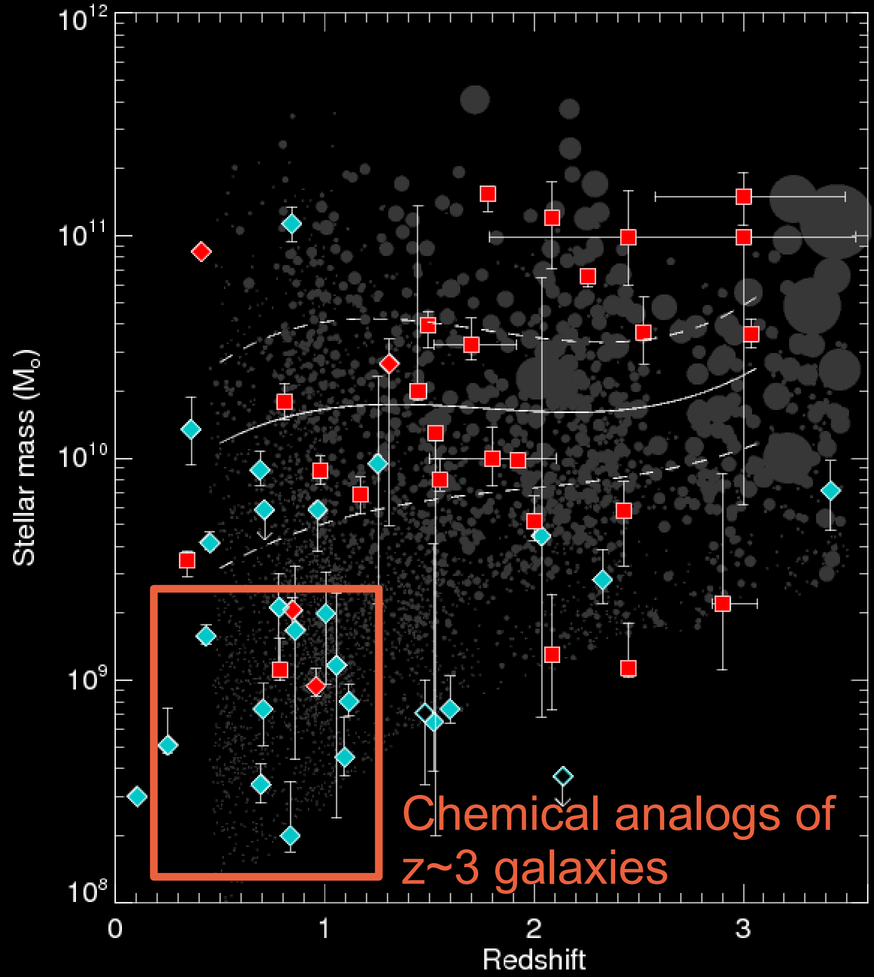


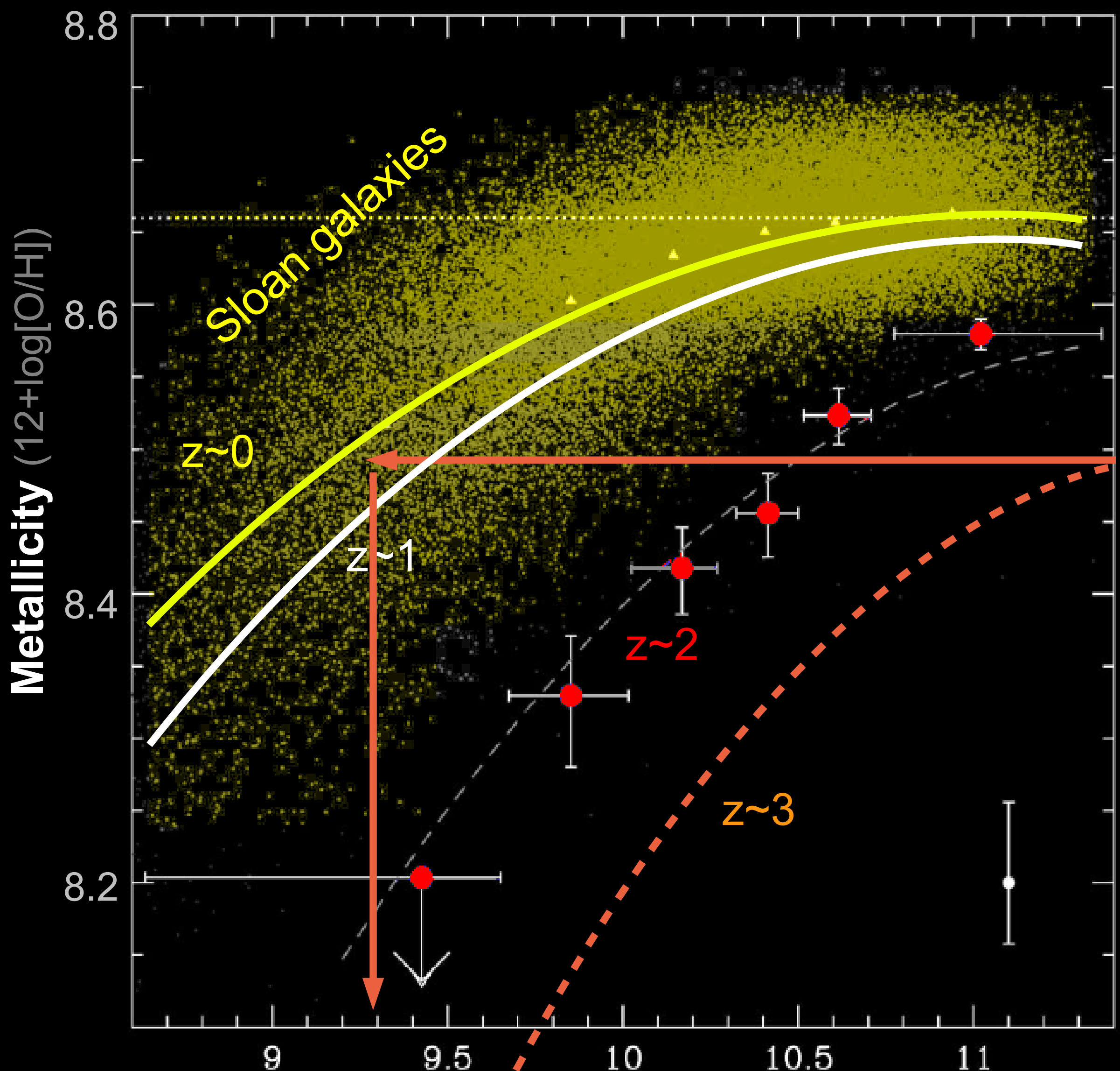


A massive z~3.5 galaxy should have similar metallicity to a typical (low-mass) z~0.5 GRB host.

Is There Hope for High Redshift?

Massive z~3 galaxies
should have similar metallicity to
~2×10[9] M☉, z~1 galaxies





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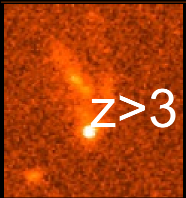
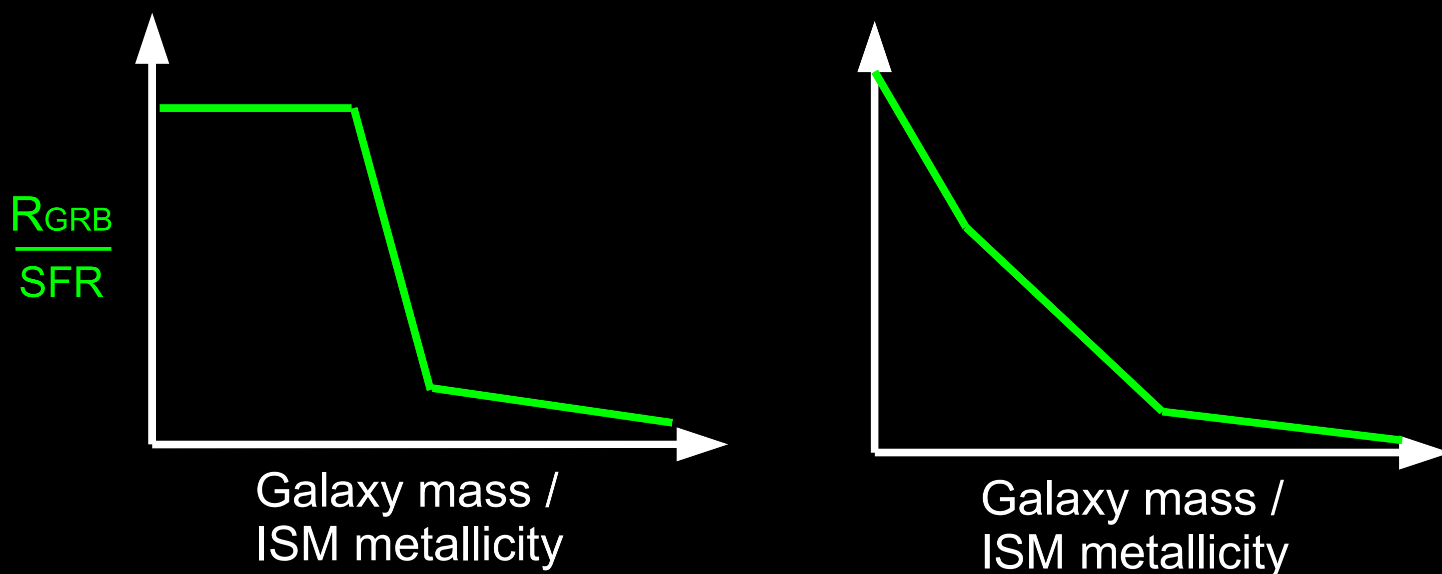
Does metal dependence level out?



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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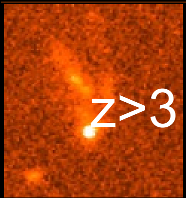

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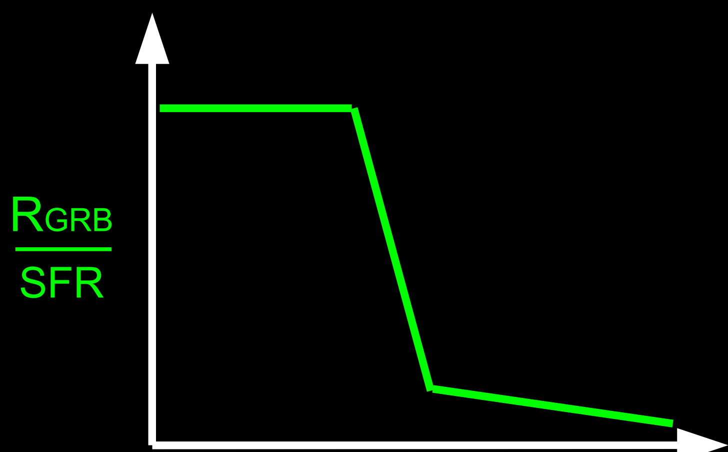
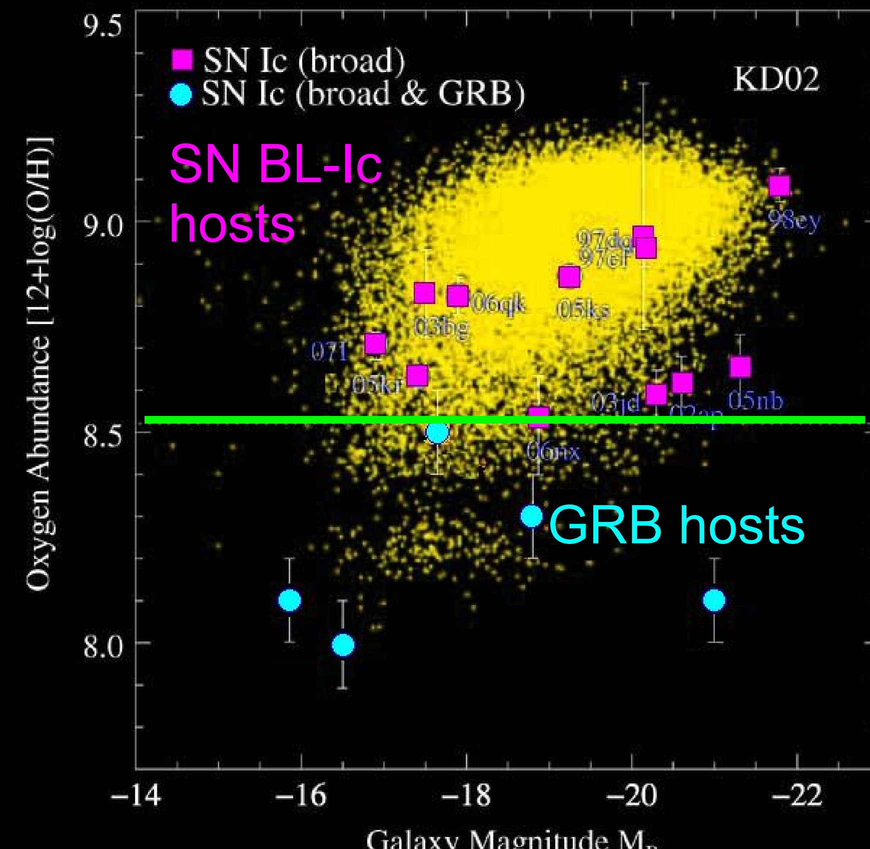
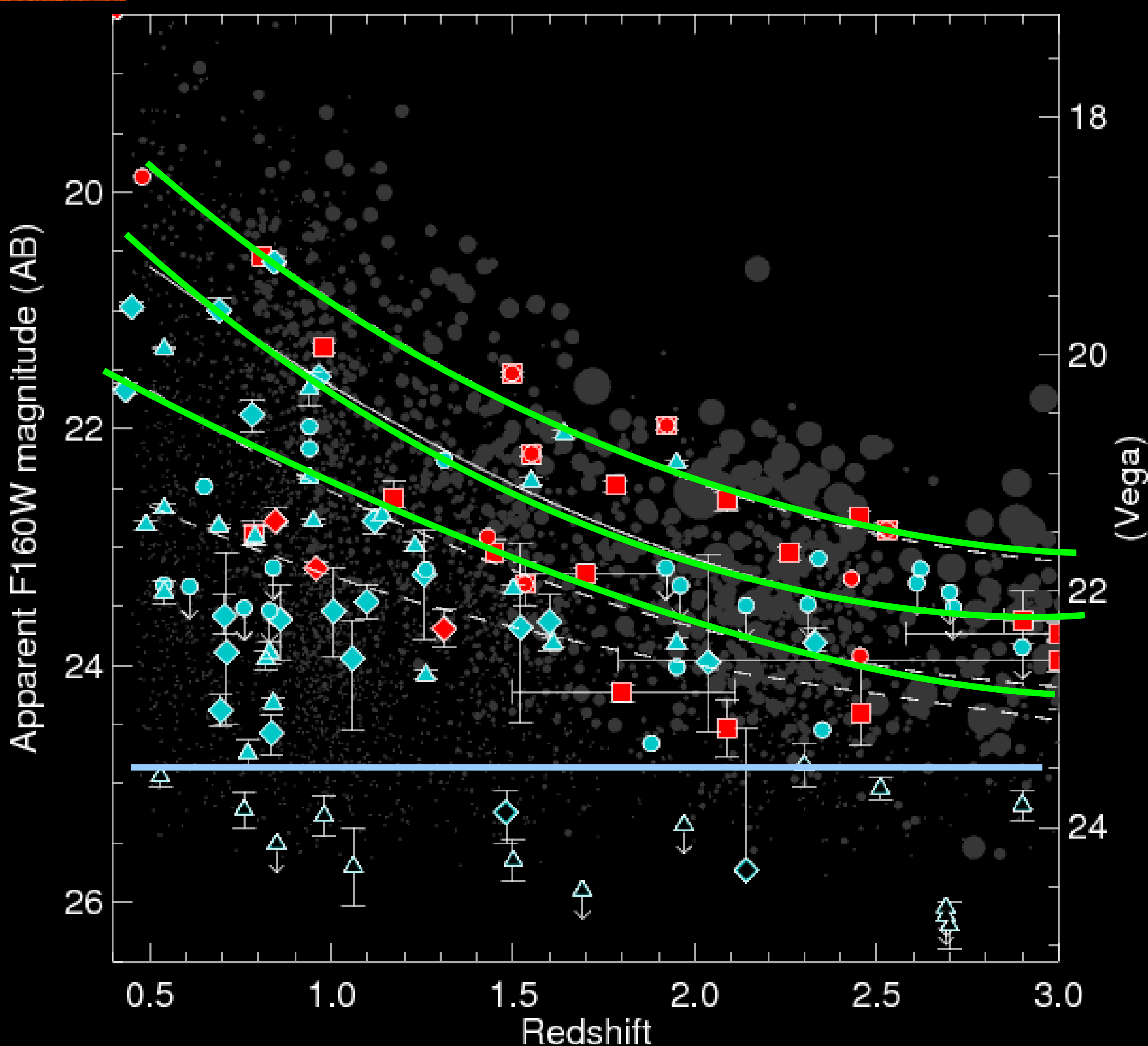




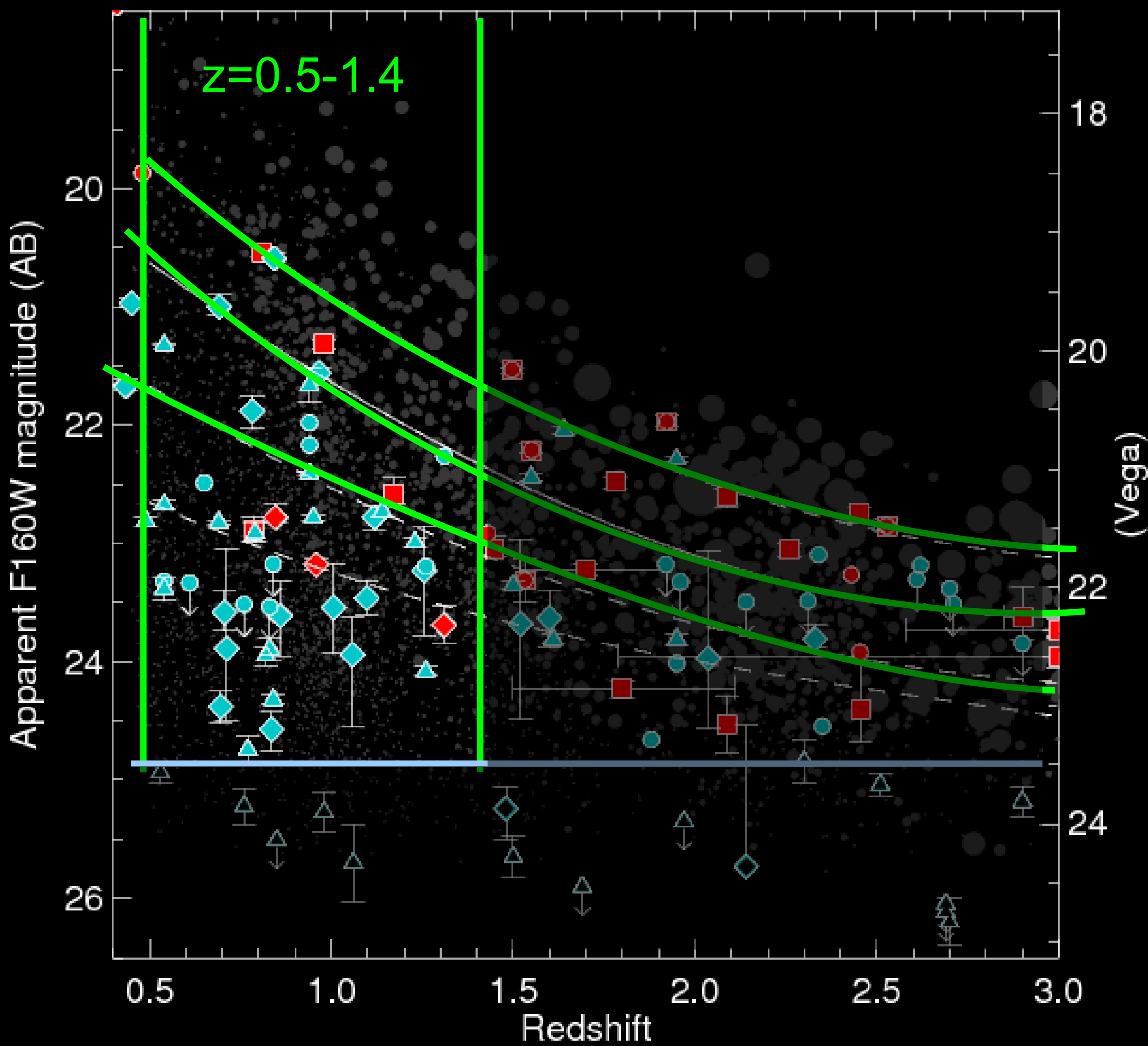
Modjaz et al. 2008

Does metal dependence level out?



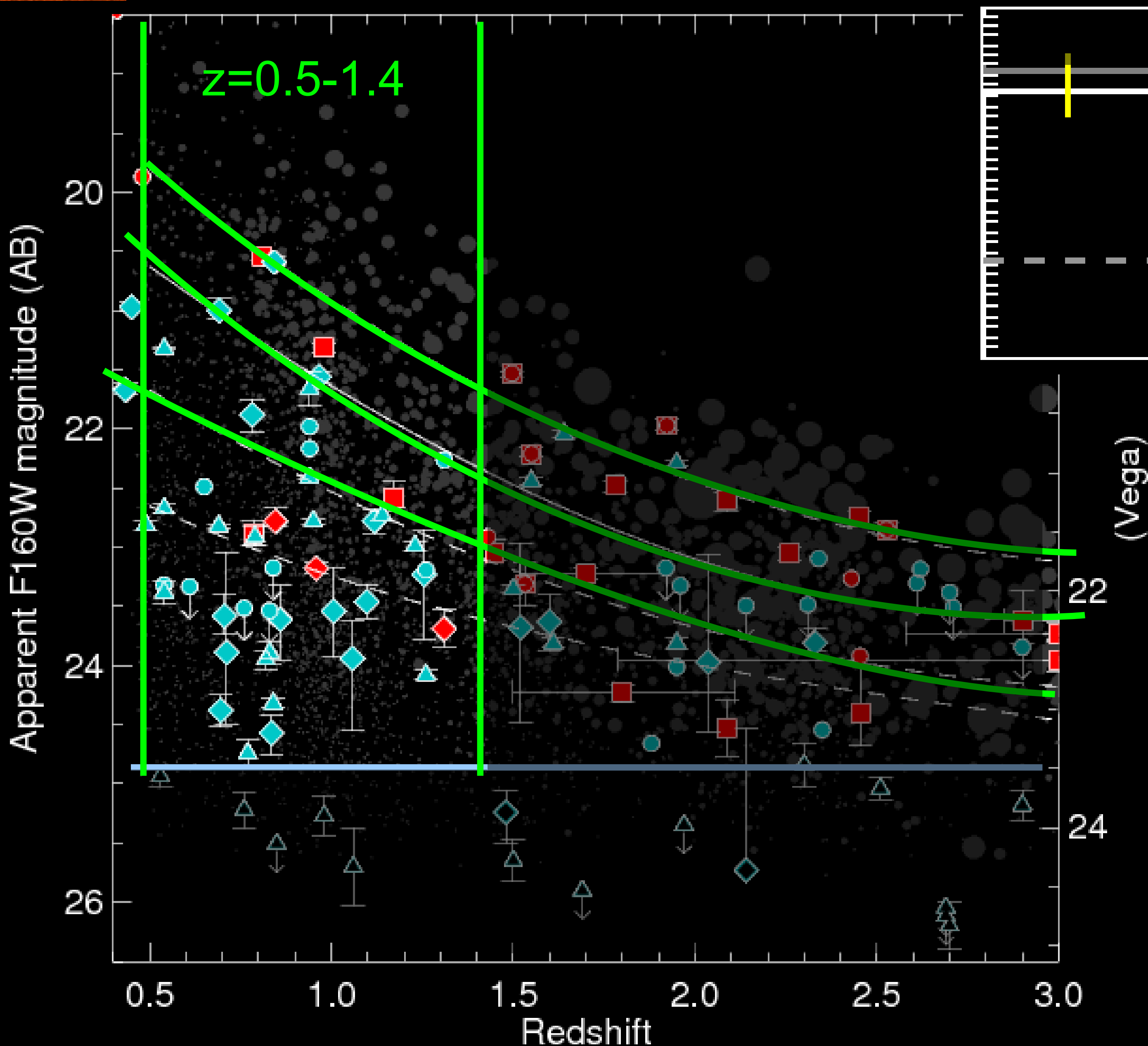
Examine low-z chemical analogs.

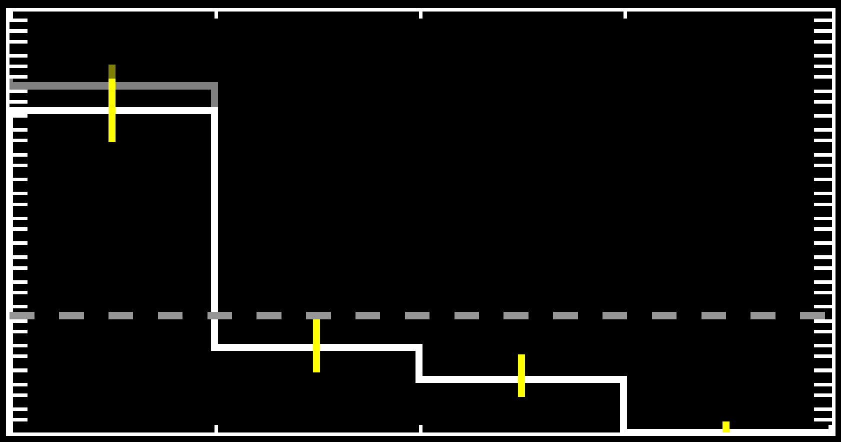
Does metal dependence level out?



Examine low-z chemical analogs.

Does metal dependence level out?





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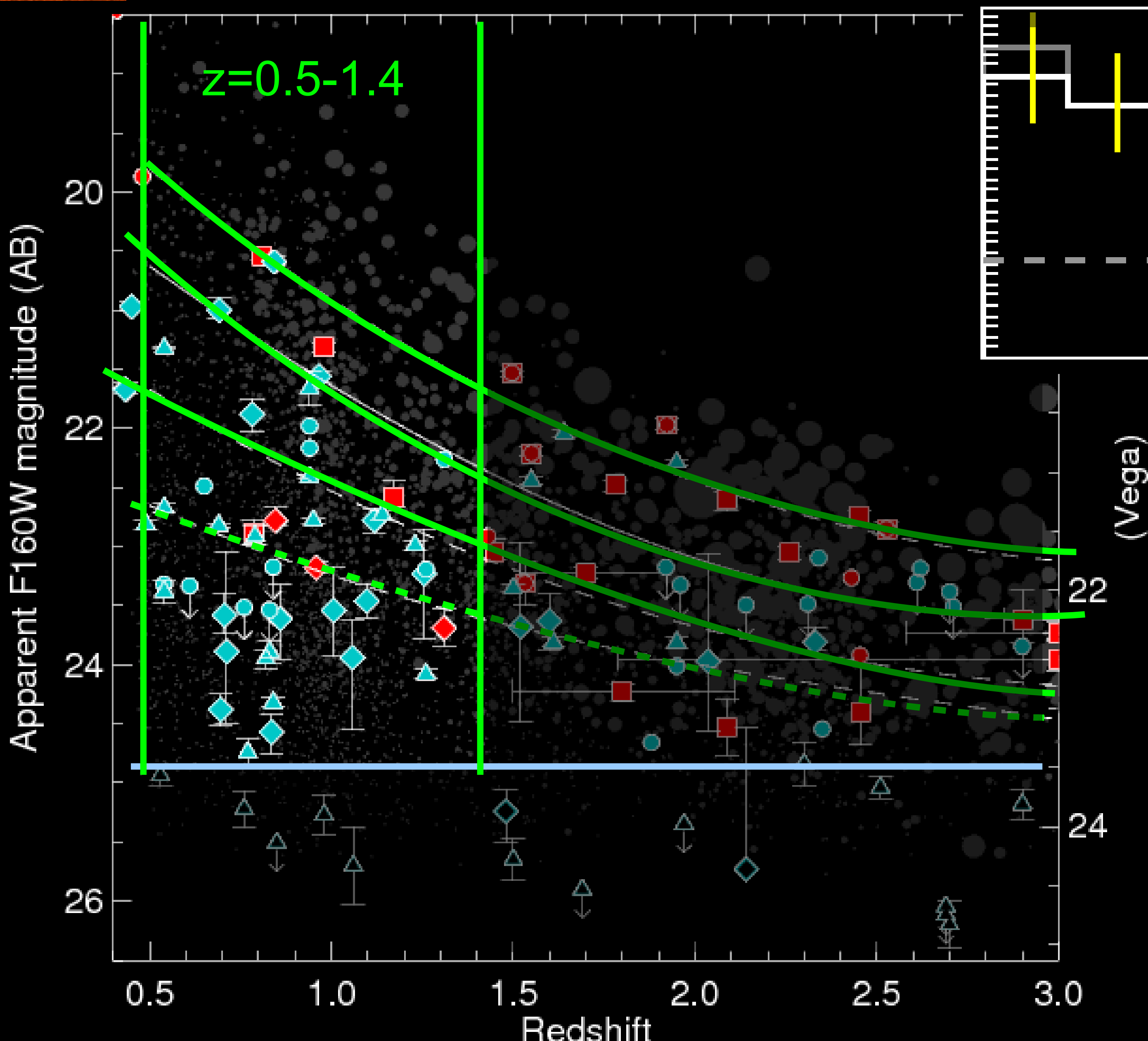
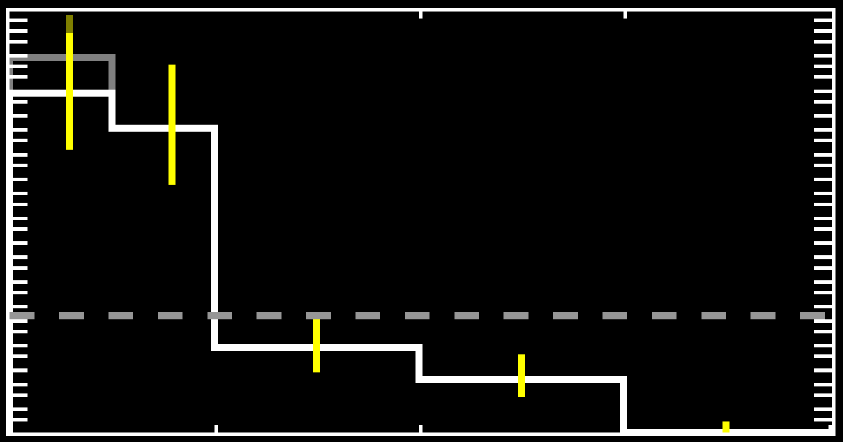


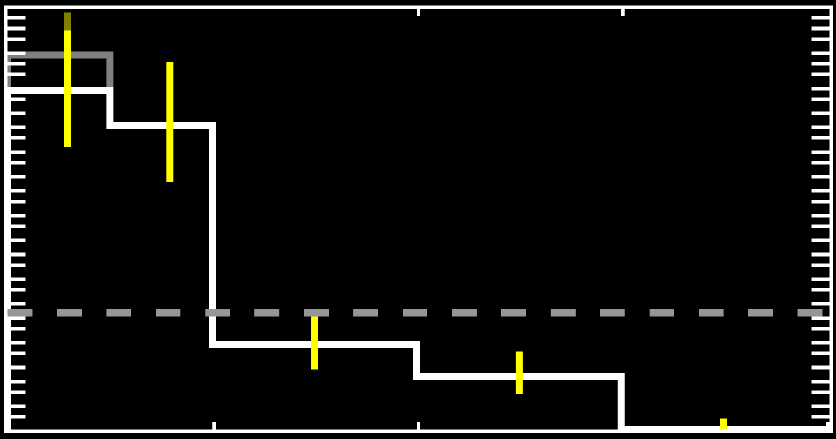


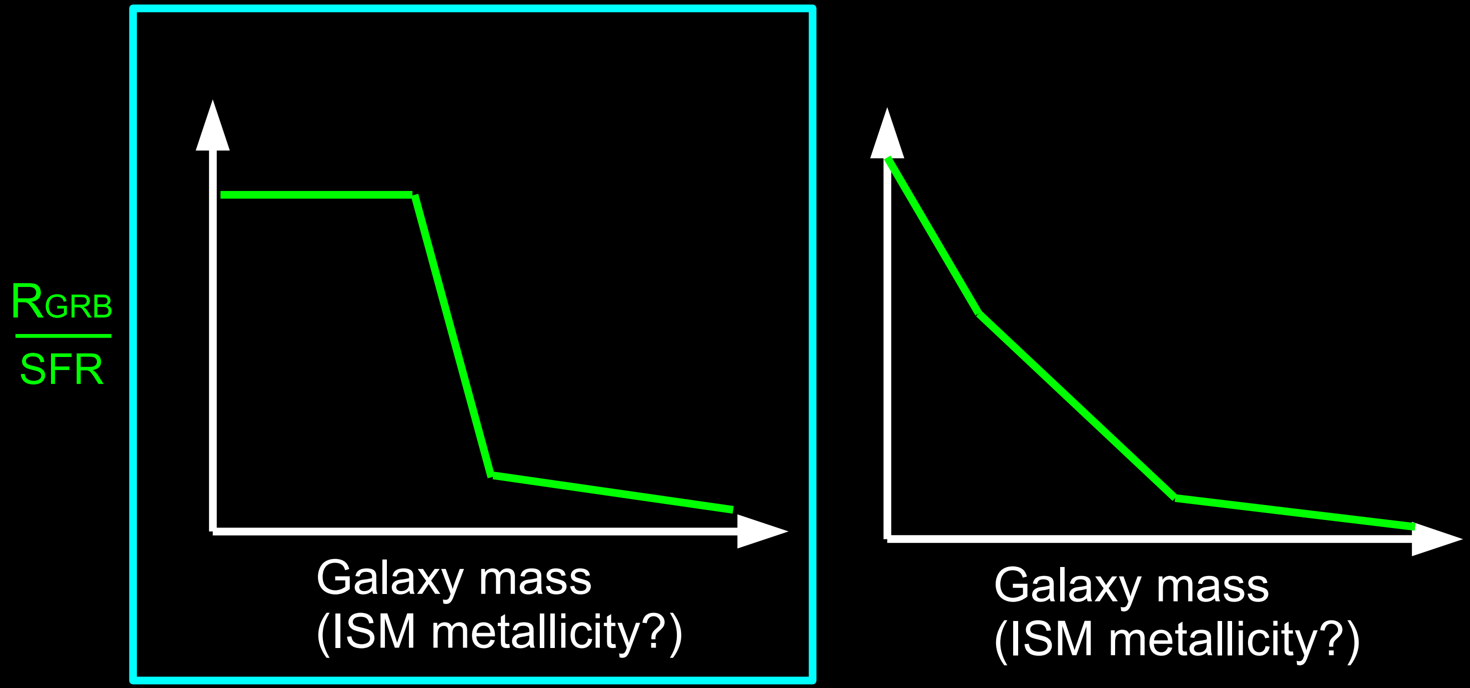
Try to check using low-z chemical analogs by further subdividing lowest-mass (luminosity) bin.

No further variation seen.

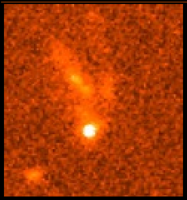
Does metal dependence level out?

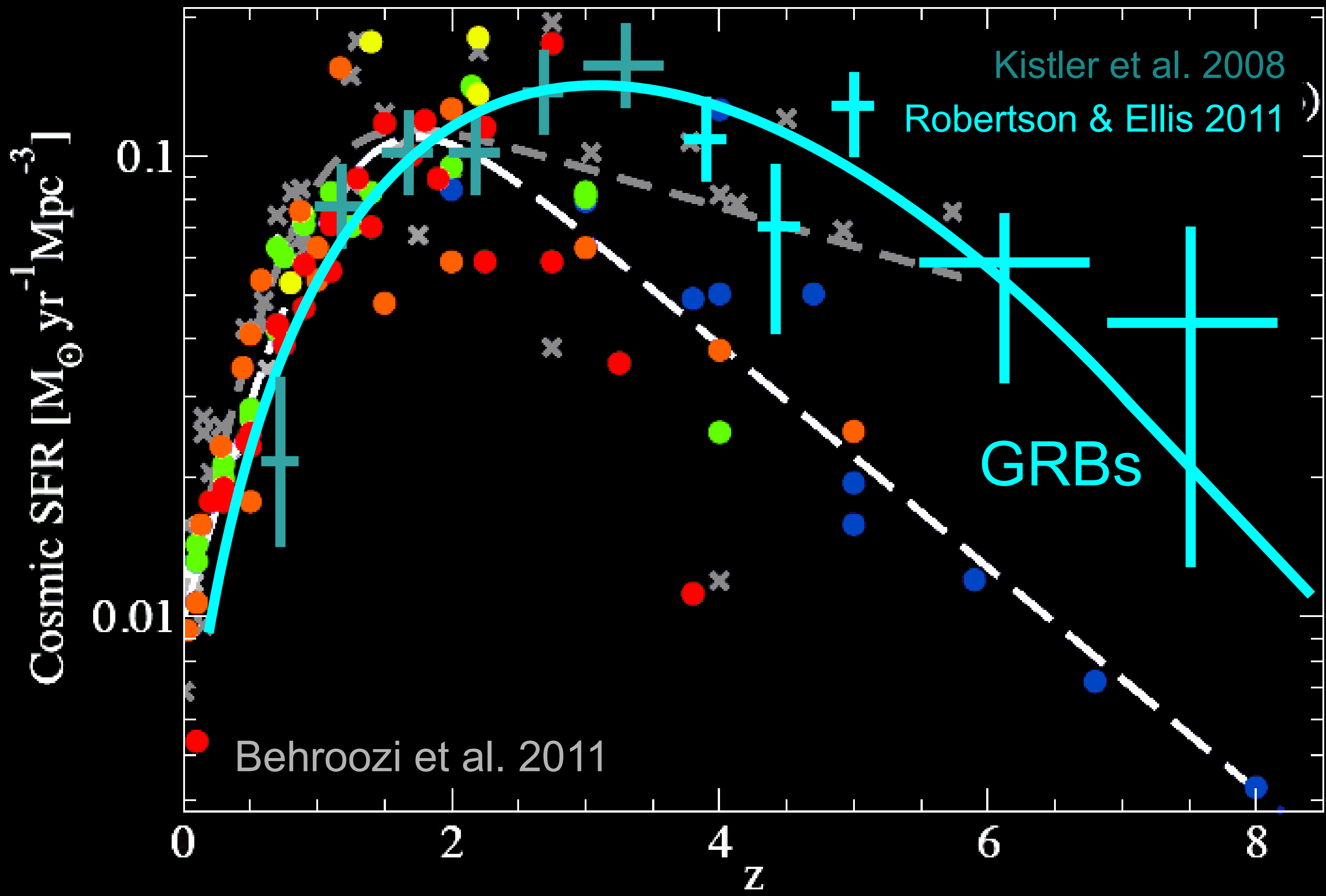
Yes, possibly – rate consistent with no further luminosity dependence below M < $10^{9.5}$ $M_{\odot}$ in z~1 chemical "analogs" of z>3 galaxies.



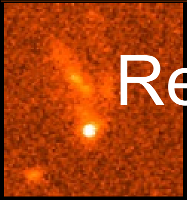


High-z SF History from GRBs

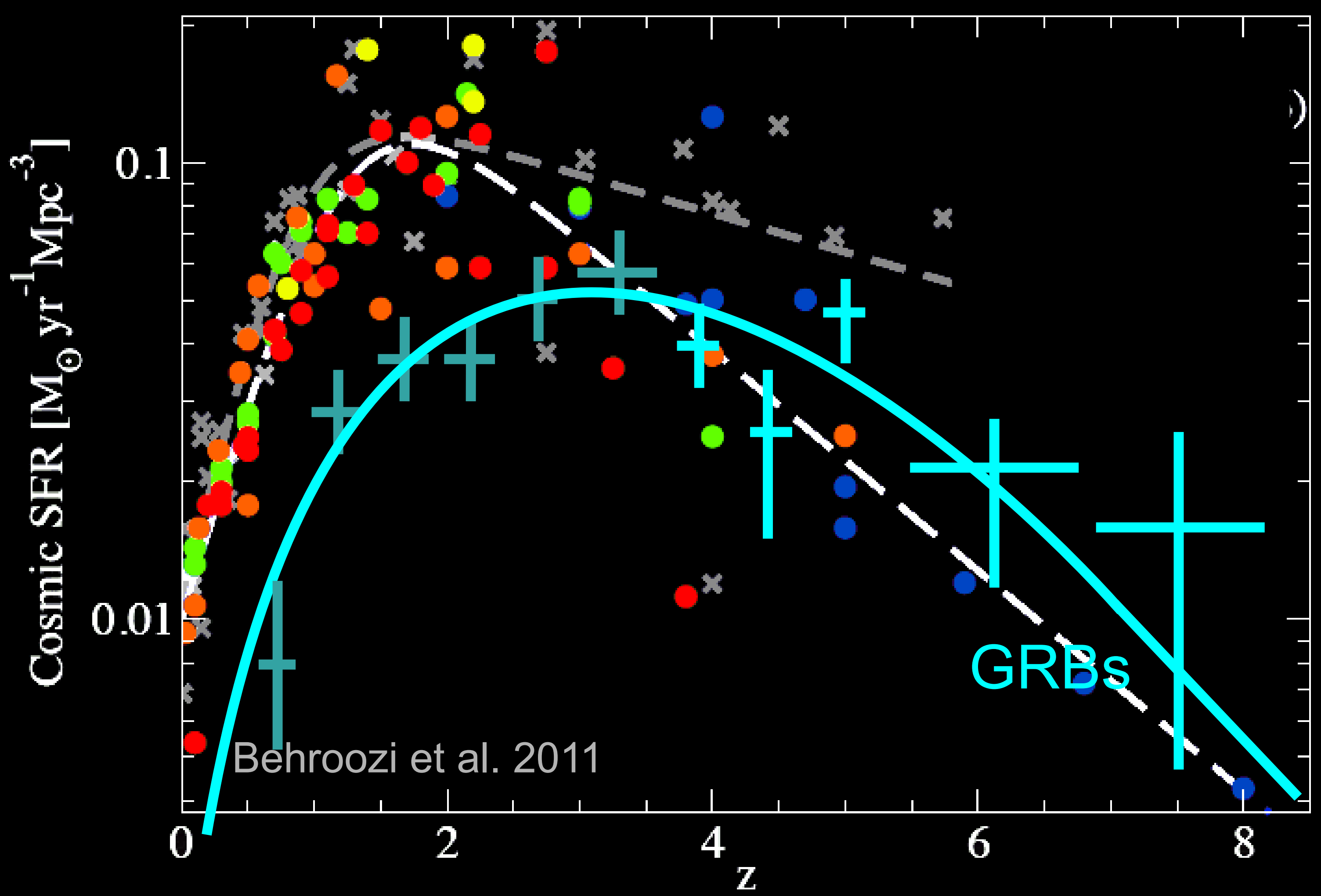




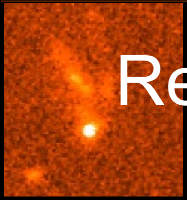
High-z SF History from GRBs



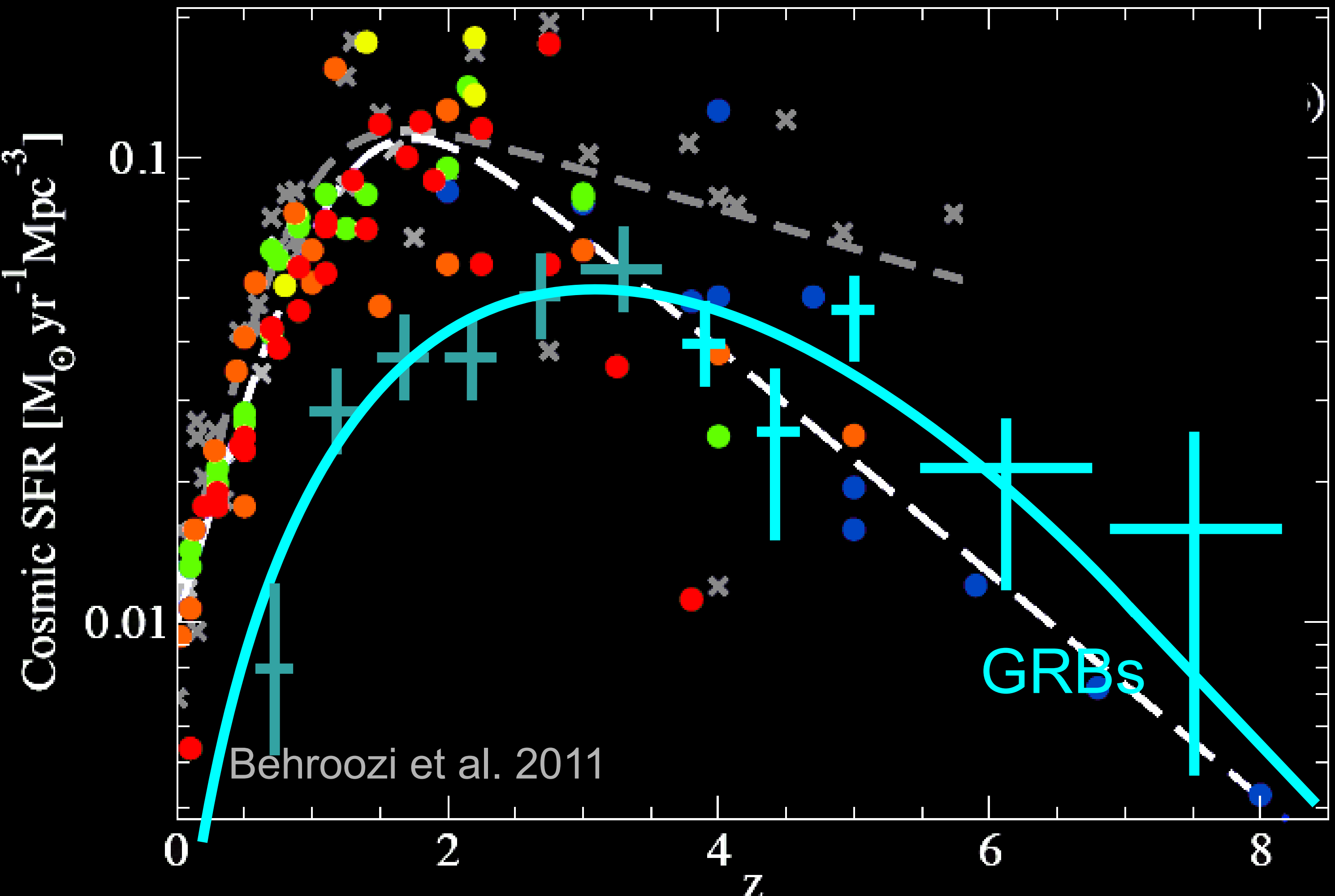
Re-normalize at z~3



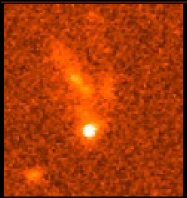
High-z SF History from GRBs



Re-normalize at z~3

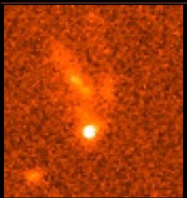


Looks consistent.



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

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

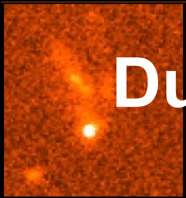


Are GRBs useful tracers of star-formation at...

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

But, we still have a while to go before producing a GRB constraint on the SFRD/SFRH that we can be fully confident in!

Conclusions

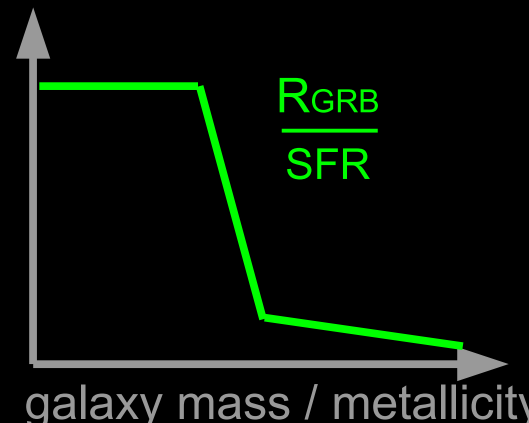


Dust-obscured GRB hosts: diverse, massive, luminous.

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



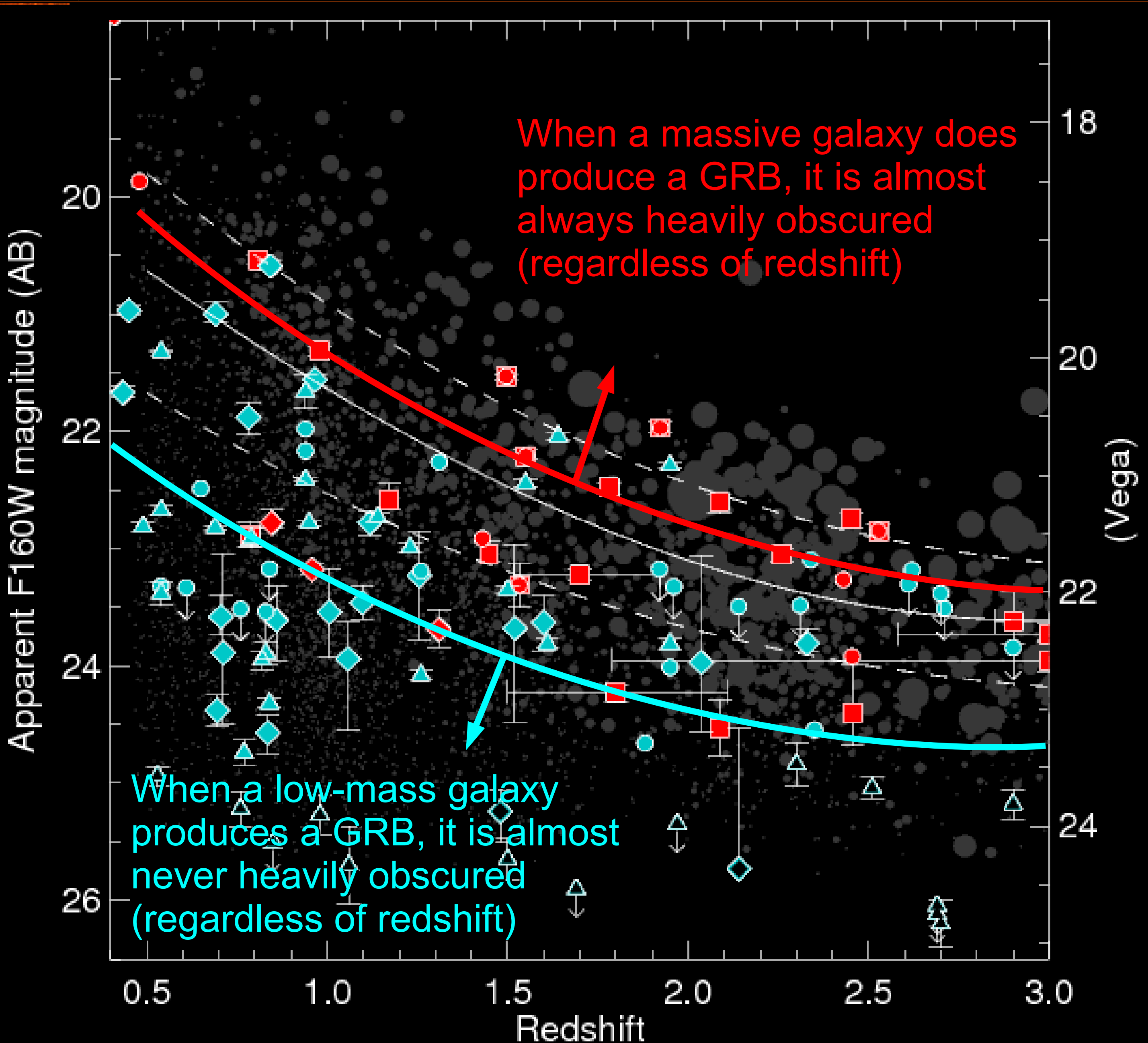
Consistent with metallicity dependence.
- Possible secondary effect in high-sSFR galaxies?
- Consolation prize – tracing metal-poor SFR?

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... but still a long way from being trustworthy.

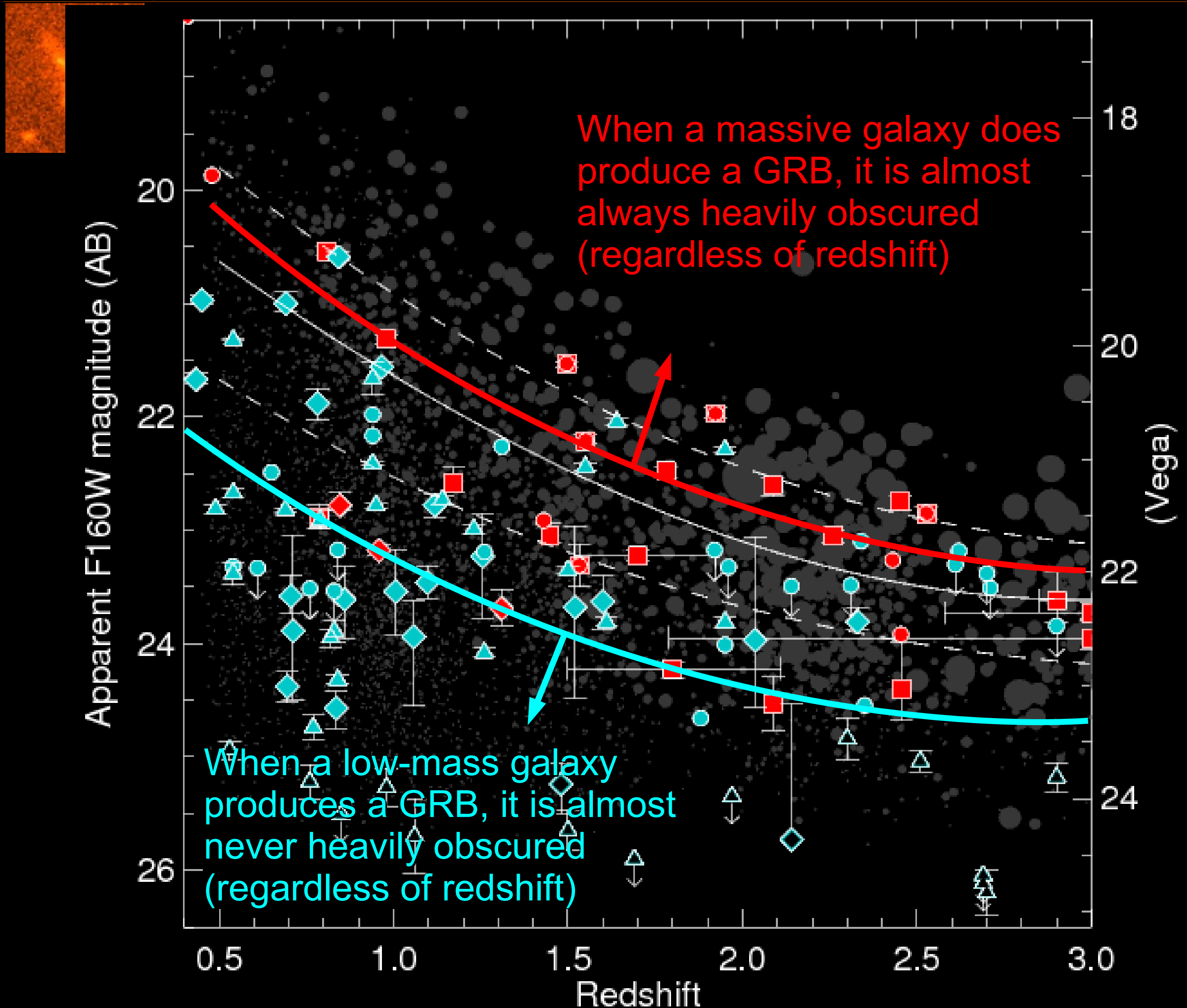
Era of large-number host catalogs has arrived.

Ample material for more detailed models in future.

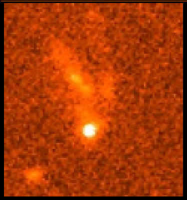
Mass versus Obscuration



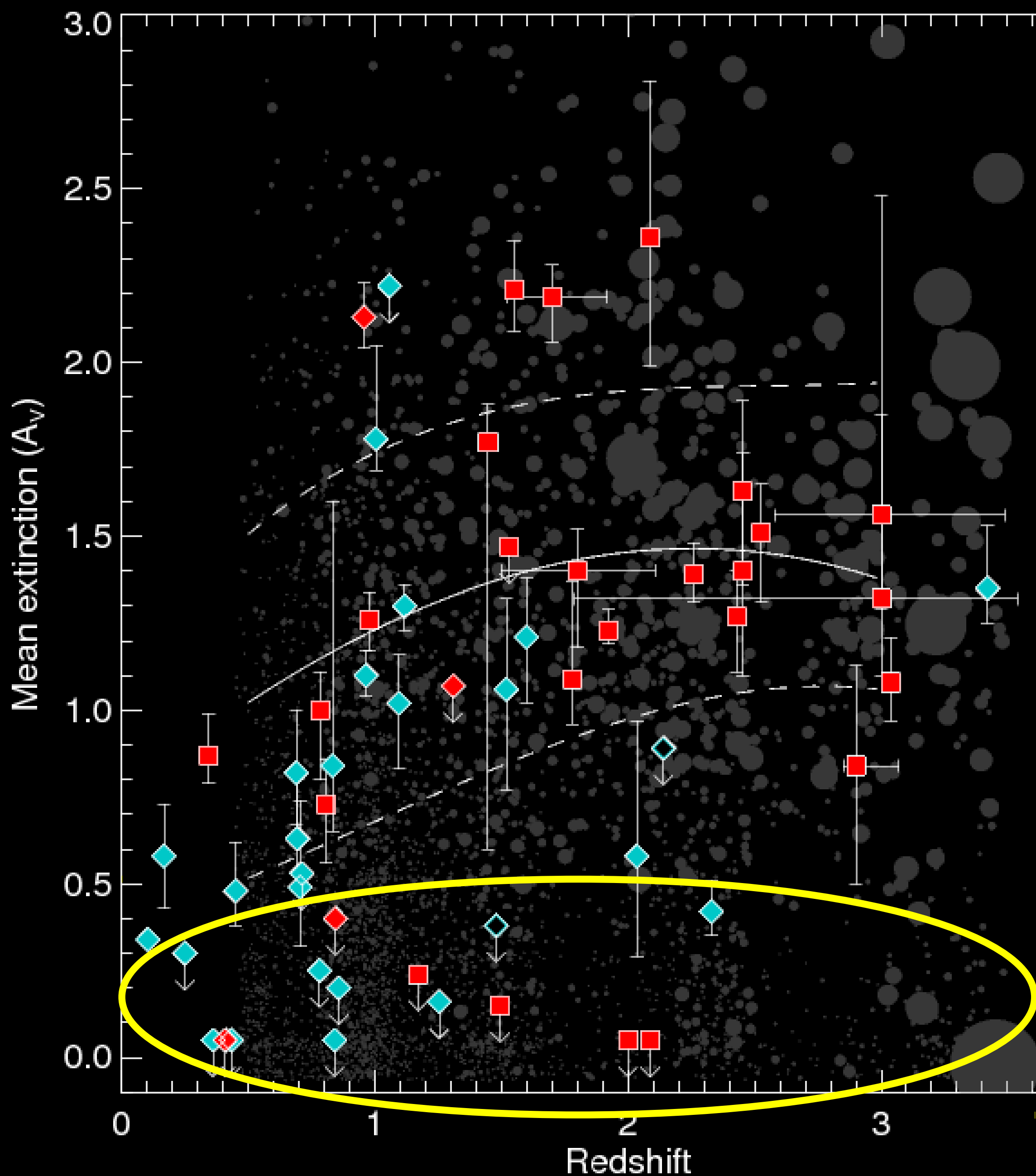
Mass versus Obscuration



Color versus Obscuration

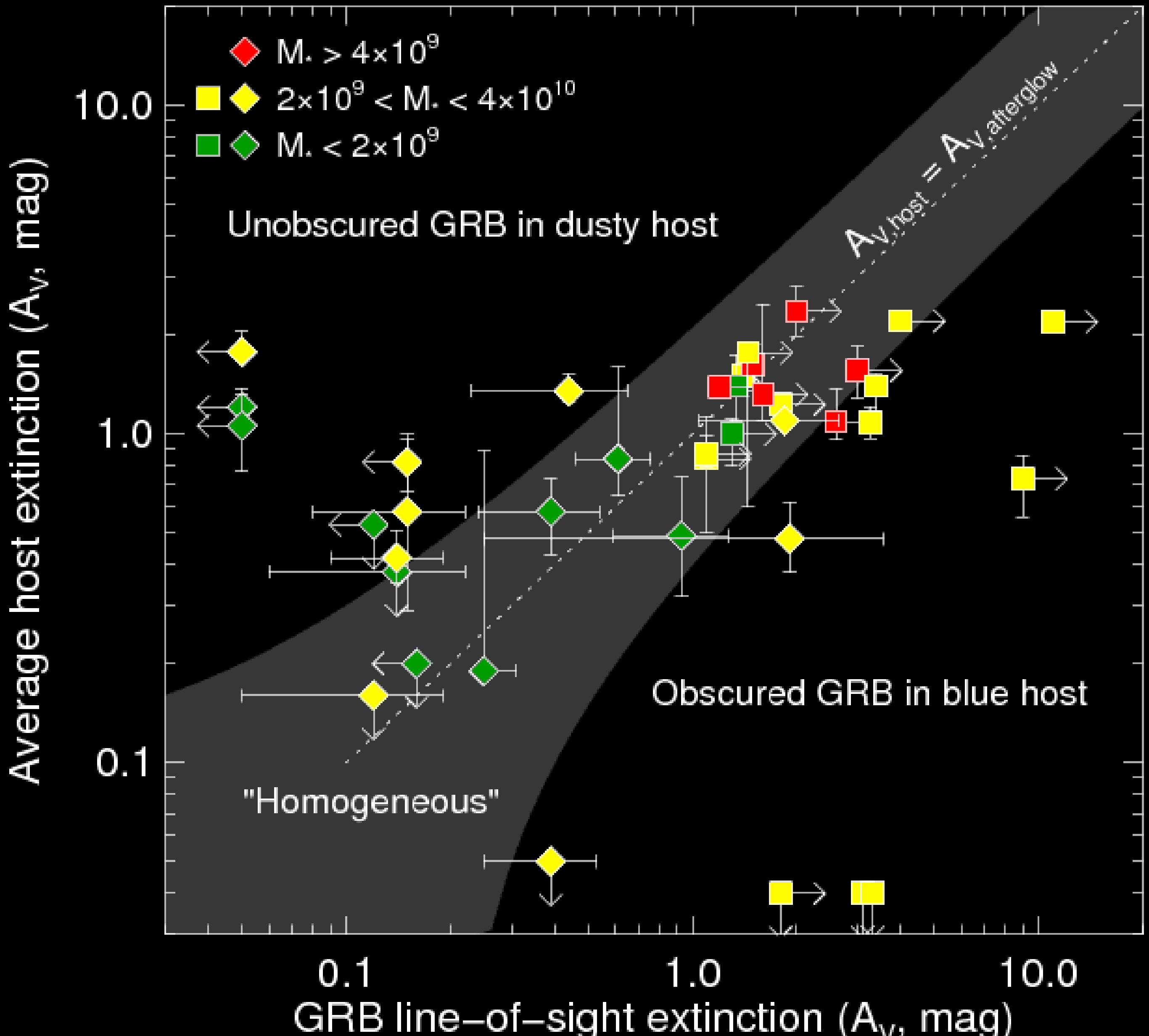


Red galaxies only produce obscured GRBs...



… but blue galaxies do sometimes produce heavily obscured GRBs.

Obscuration vs. Obscuration

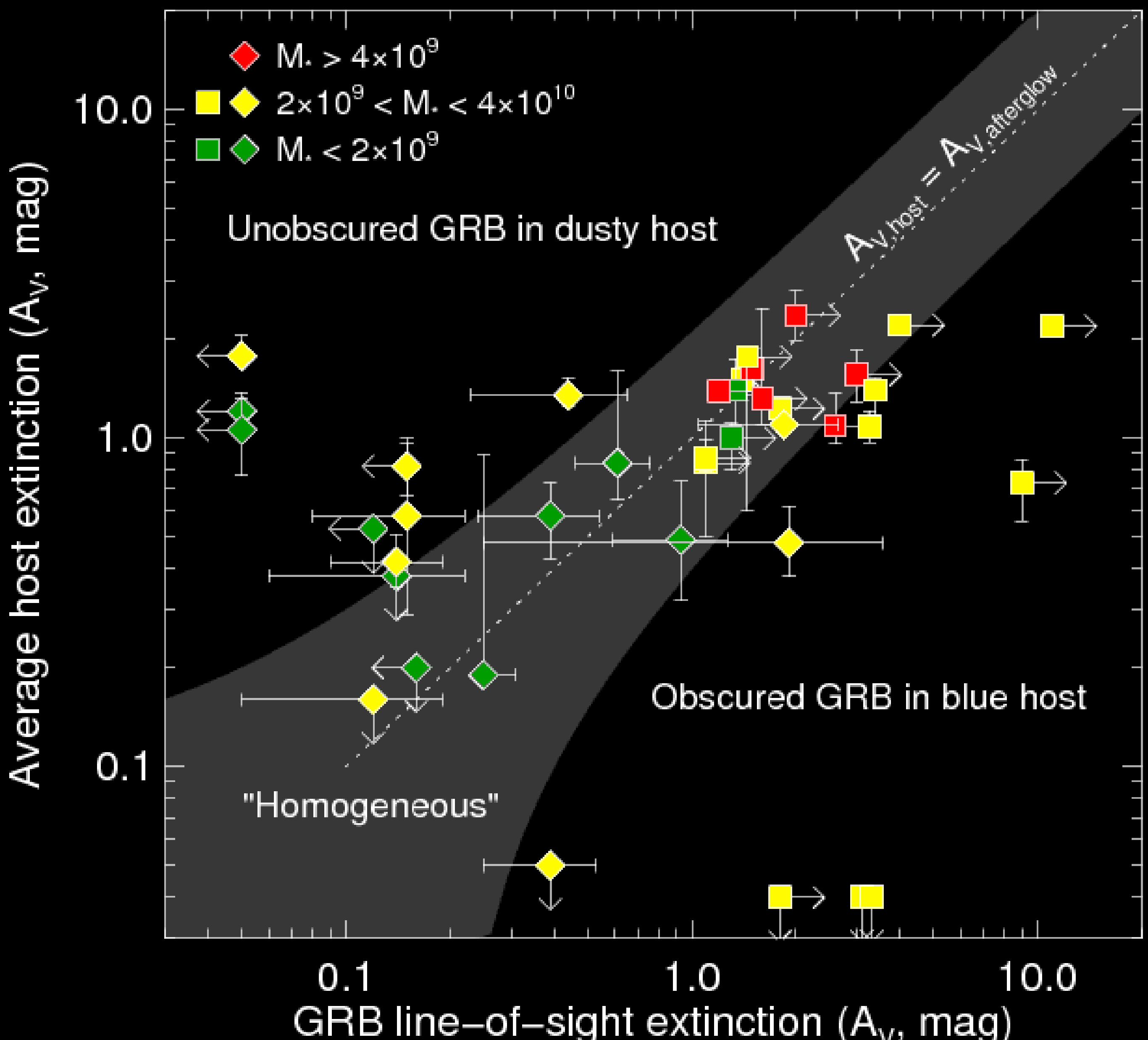


High-mass galaxy:
Heavy extinction.
Extinguishes everything *at least* somewhat (and may suppress certain sightlines much more)

Intermediate-mass galaxy:
Extremely diverse.

Low-mass galaxy:
Modest extinction.
Rarely extinguishes anything.

Obscuration vs. Obscuration

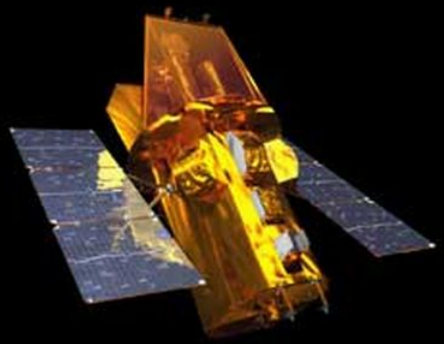


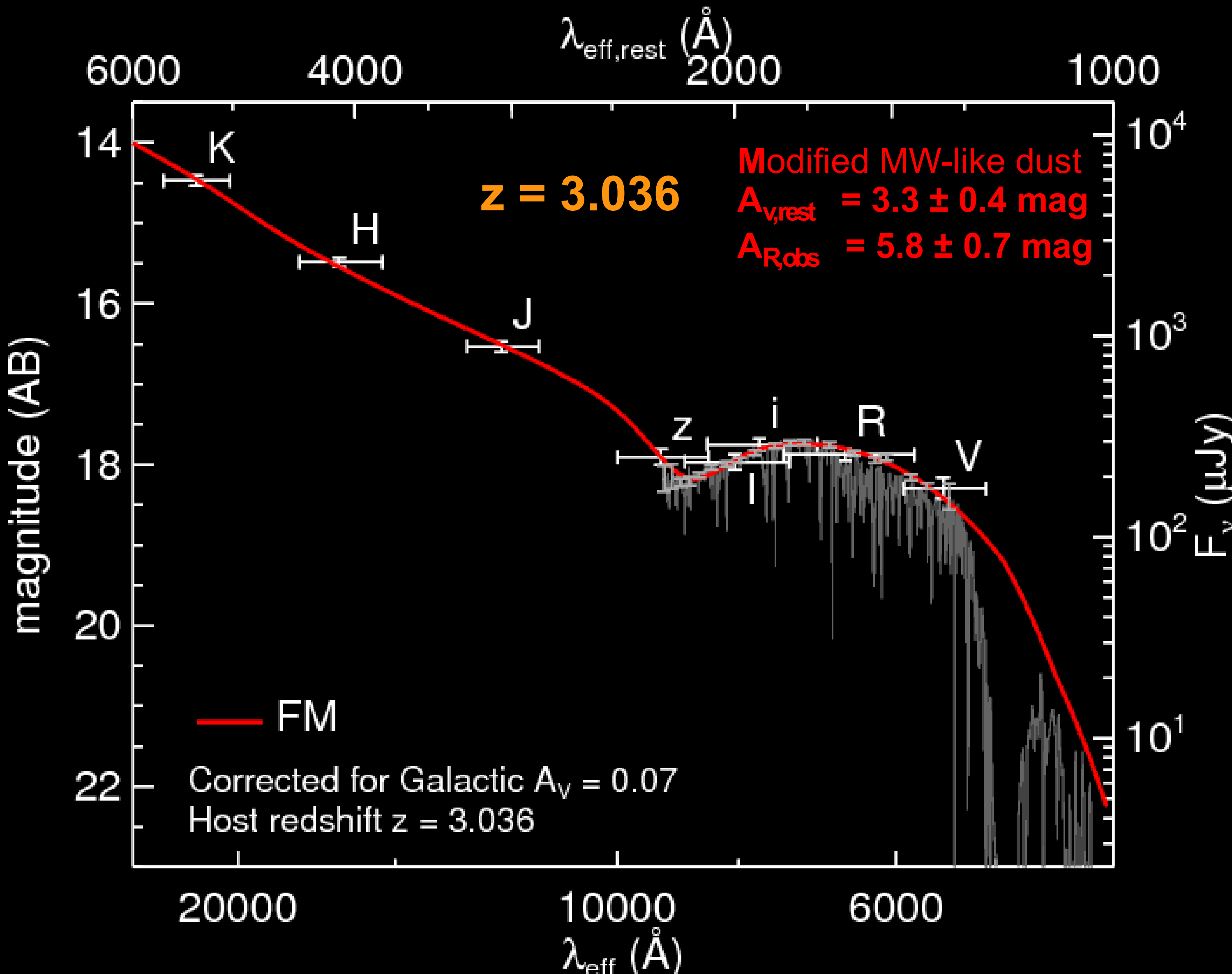
High-mass galaxy:
Heavy extinction.
Extinguishes everything *at least* somewhat (and may suppress certain sightlines much more)

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

Low-mass galaxy:
Modest extinction.
Rarely extinguishes anything.

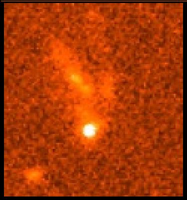
The Exceptionally Luminous GRB 080607

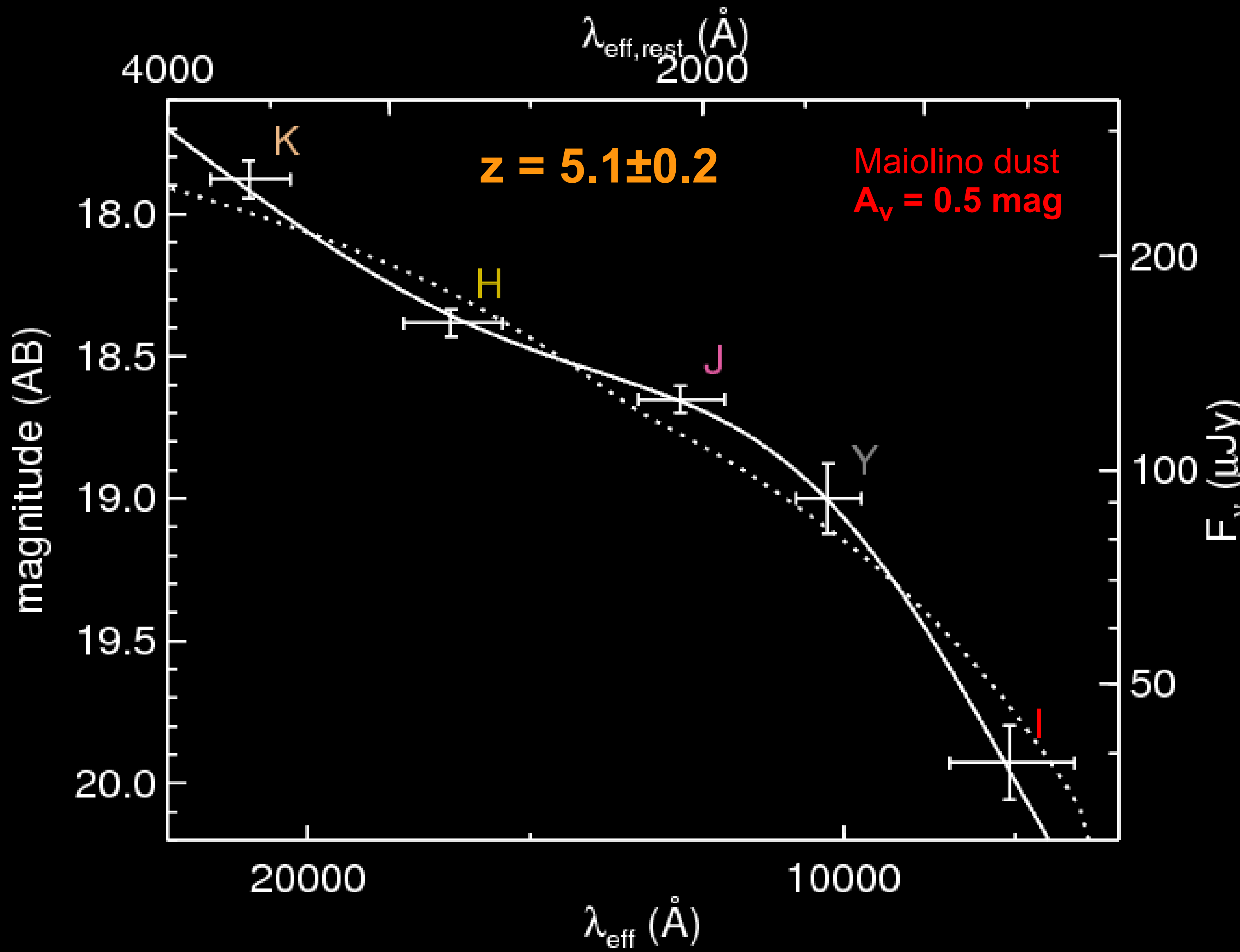




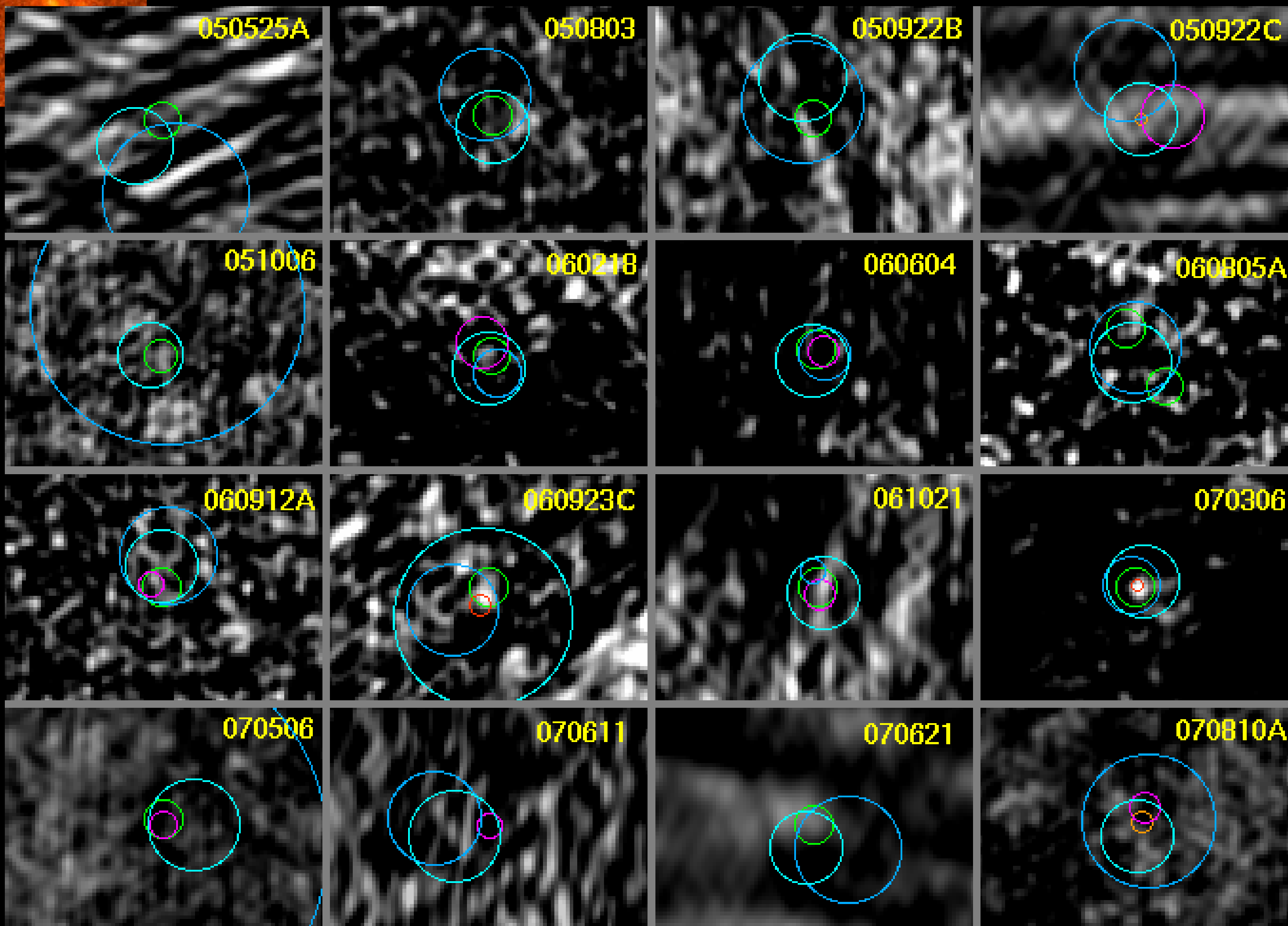
Perley et al. 2010b

Exotic dust at z~5 from GRB 071025



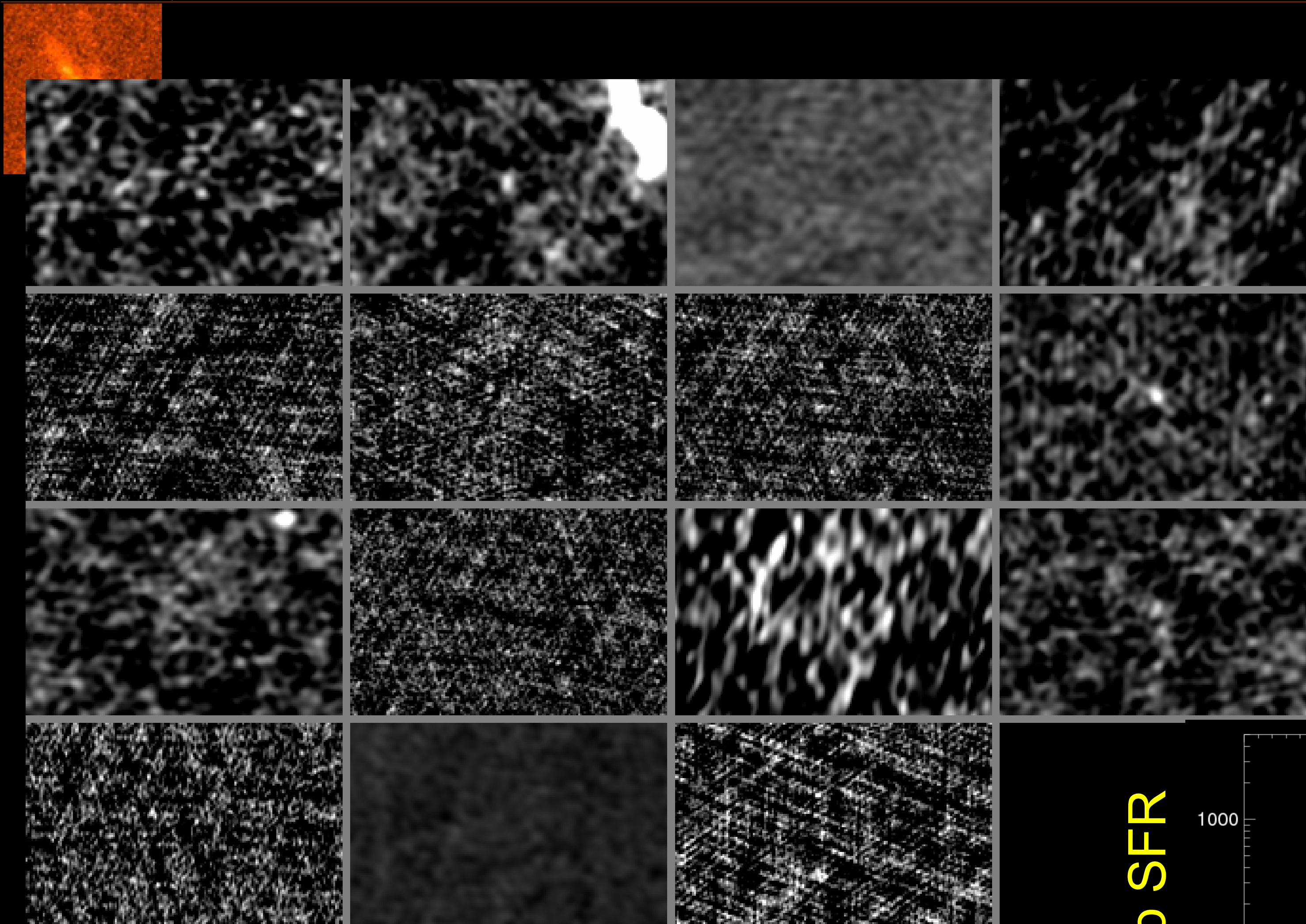


Few GRB hosts are SMGs



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

Few GRB hosts are SMGs



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