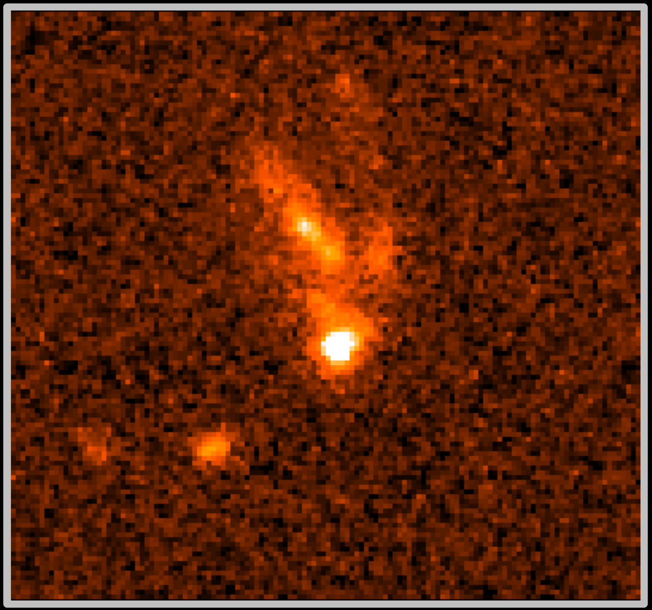
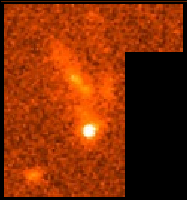
Gamma-Ray Bursts as Tracers of High-Redshift Star Formation: *Promises and Perils*

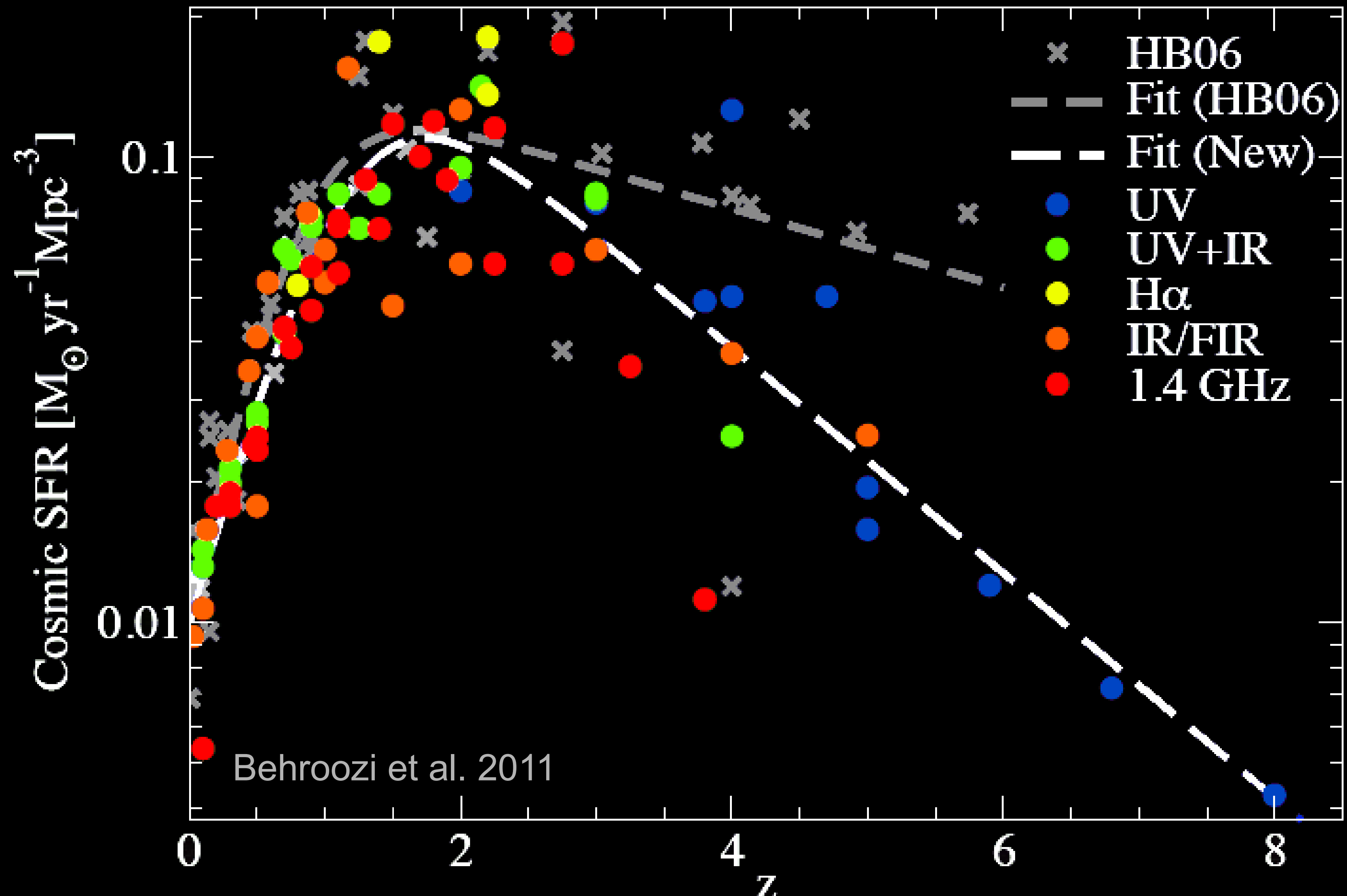
Daniel Perley
(Hubble Fellow, Caltech)



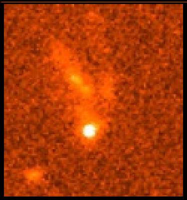
ArXiv:1301.5903
(+ abundant wild speculation)

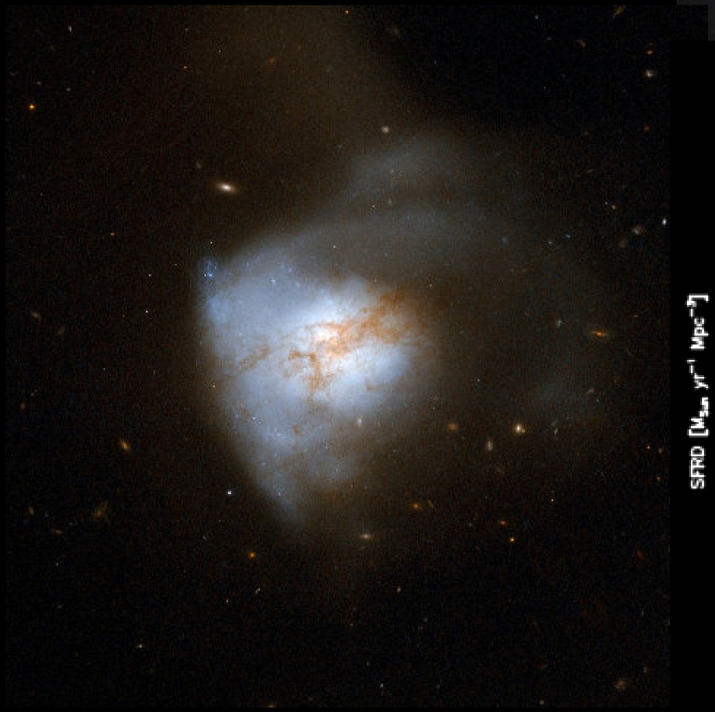
Cosmic Star-Formation History

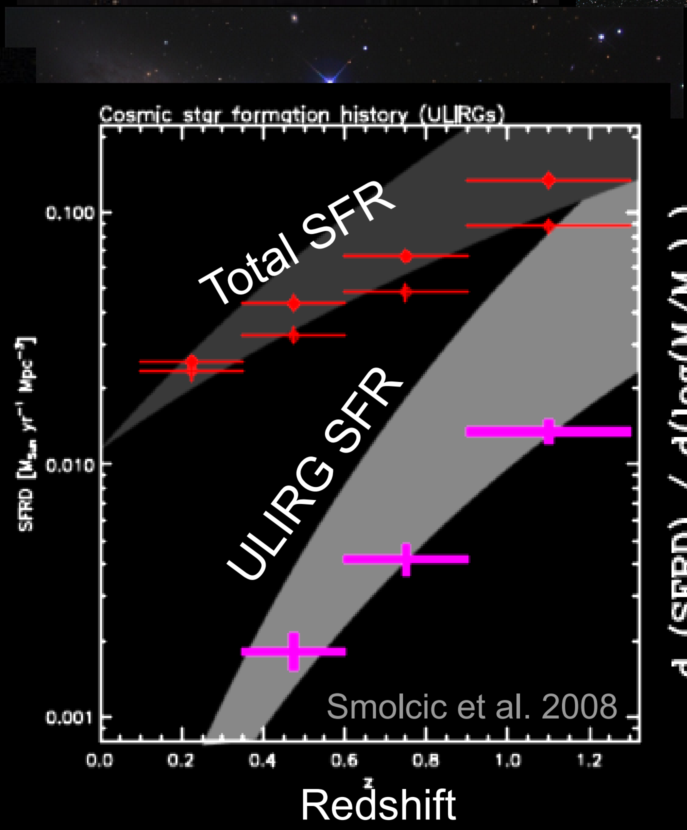


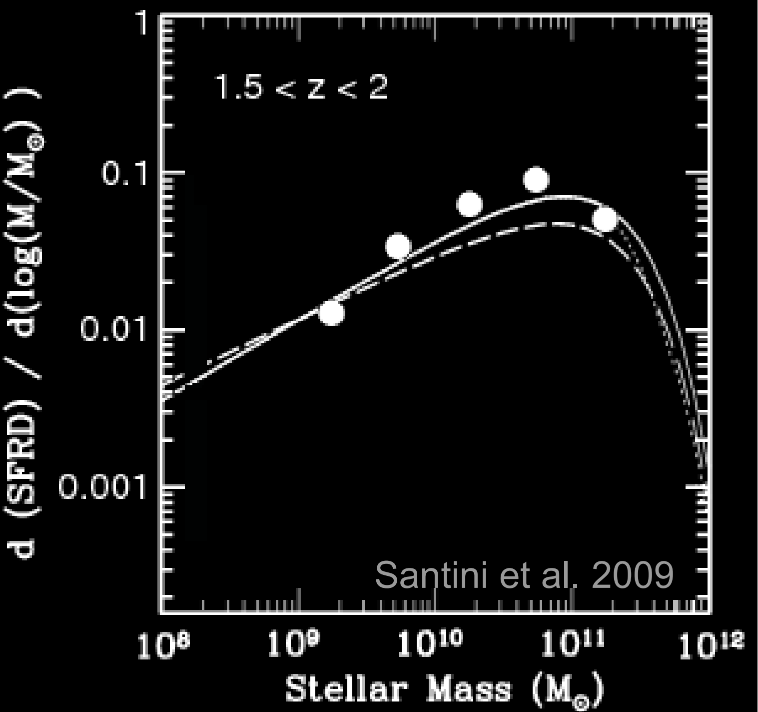


Cosmic Star-Formation Sites

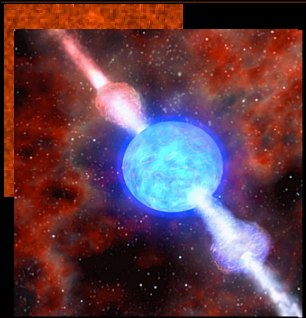


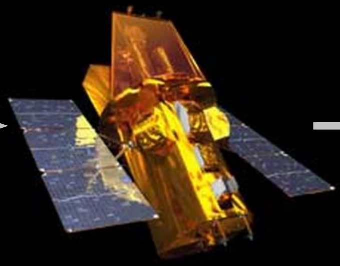


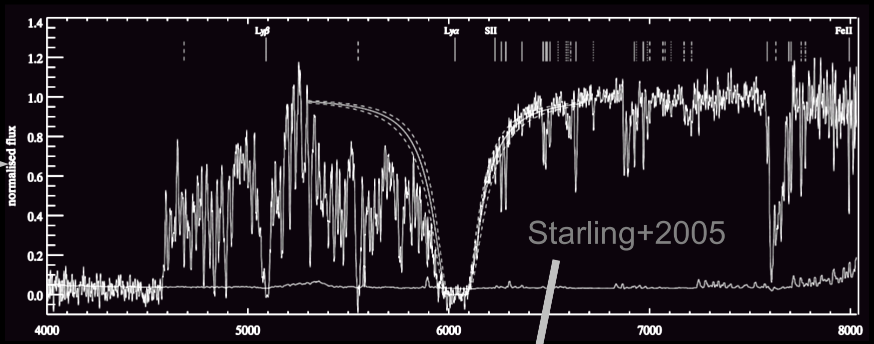


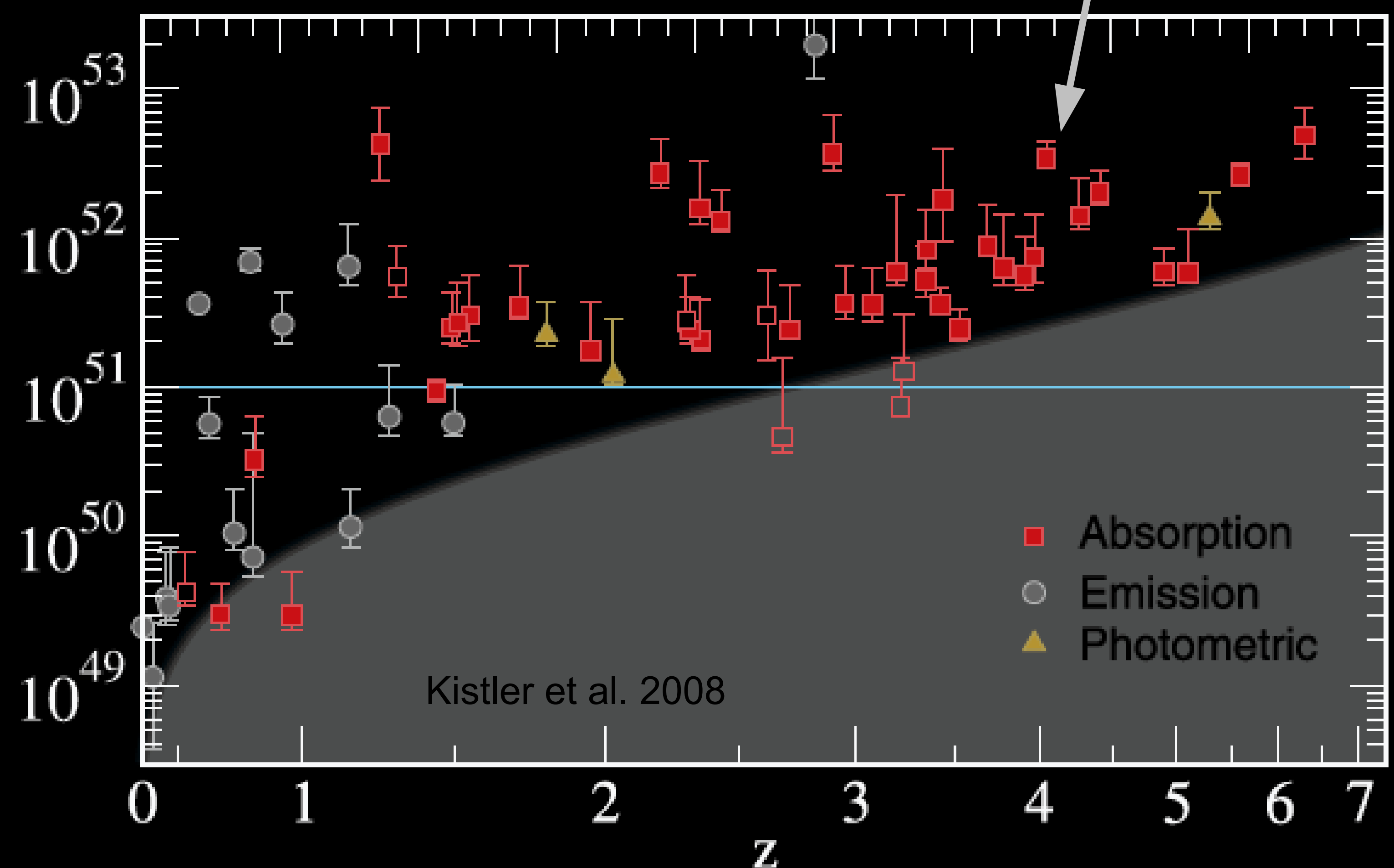


High-z SF History from GRBs

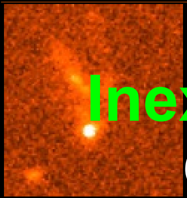








Advantages of GRB Selection



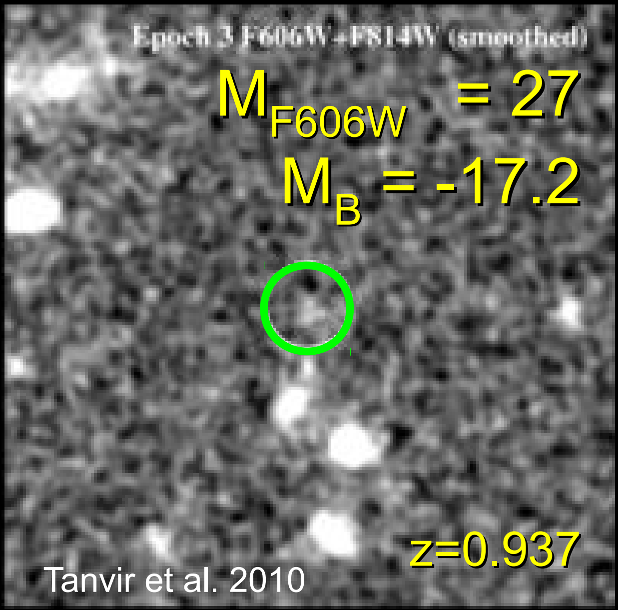
Inexpensive
Optical afterglow redshifts are “cheap”
(1 hr on a 4m telescope typically adequate)

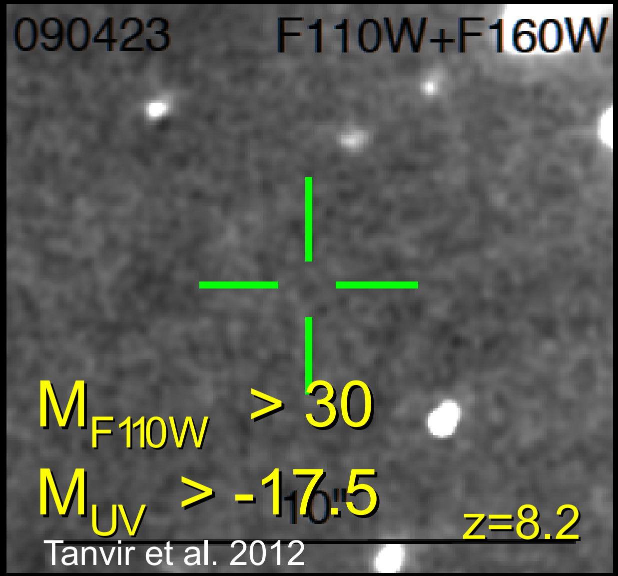
Dust-Unbiased, in principle
Gamma-ray burst and X-ray/radio afterglows unimpeded by dust

Sensitive to sub-threshold SFR
Host nondetections give a direct constraint on importance of undetectable galaxies

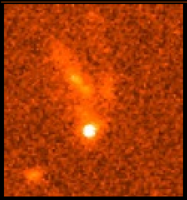
Extendable to **z>8** and potentially higher

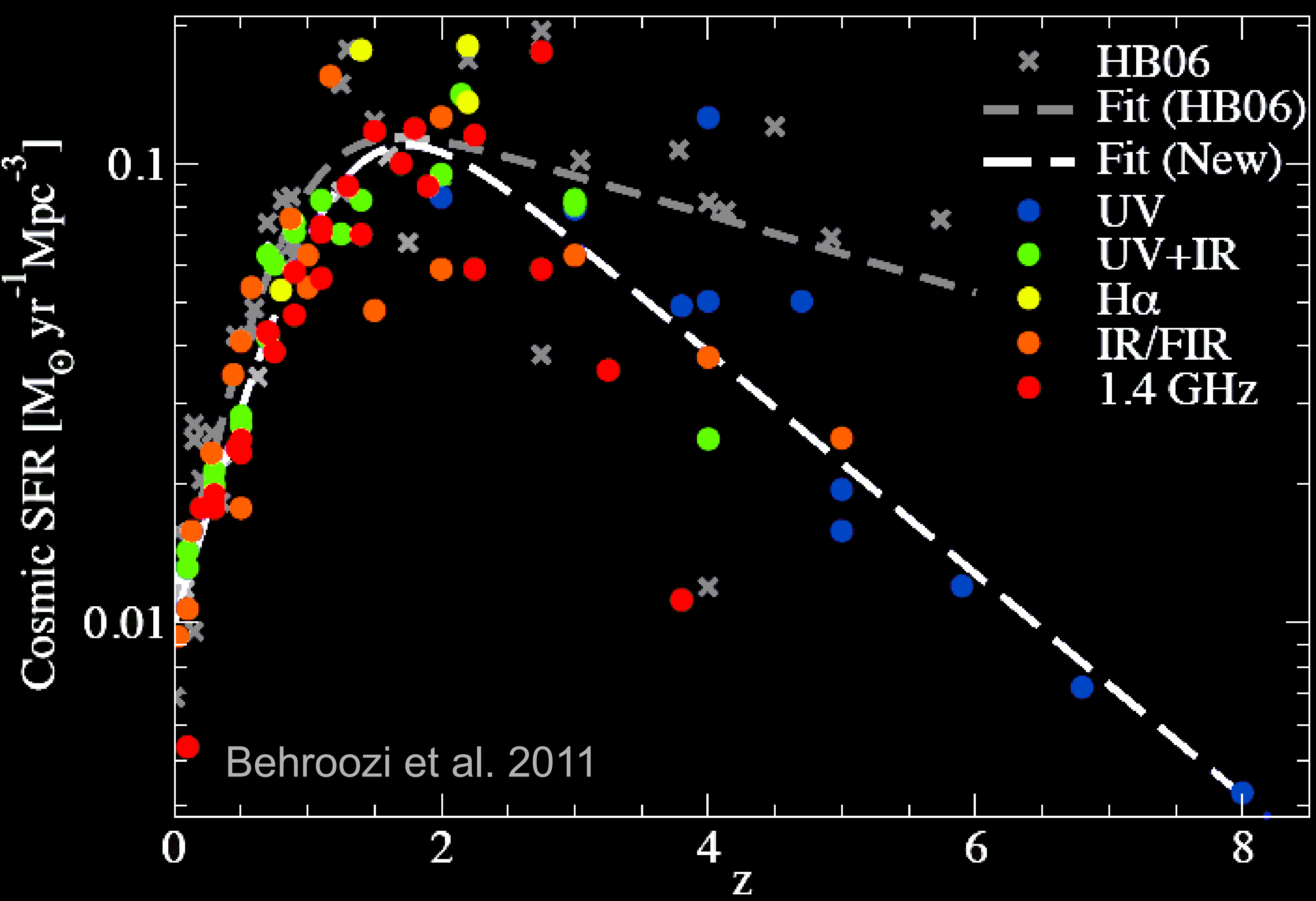
No Cosmic Variance
GRB satellites see (close to) the whole sky



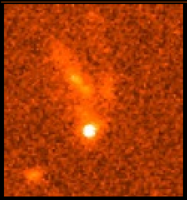


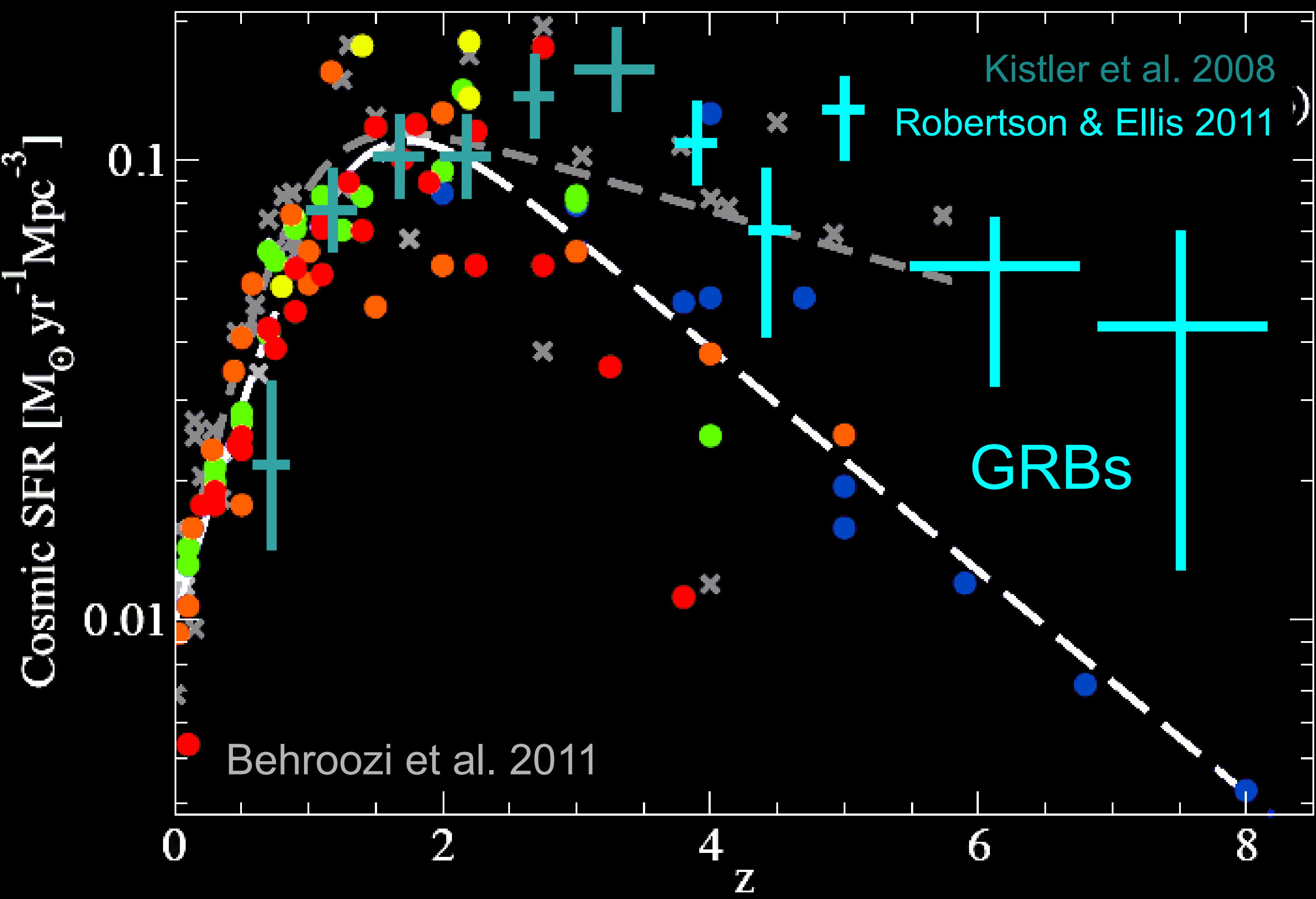
High-z SF History from GRBs



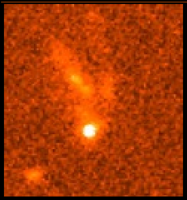


High-z SF History from GRBs

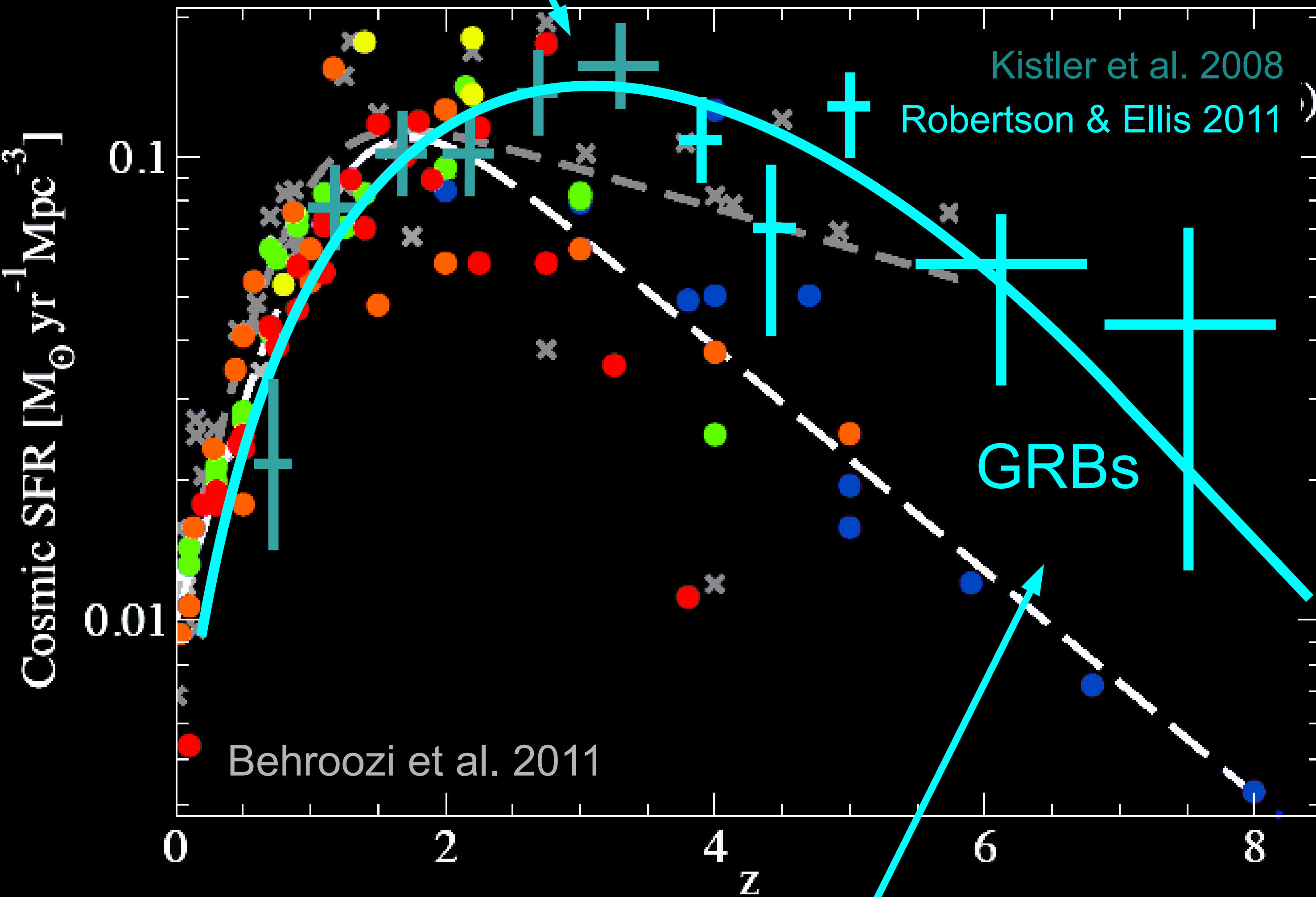




High-z SF History from GRBs



Peaks at z~3, not z~2



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

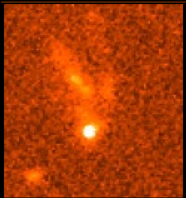
Interpretations

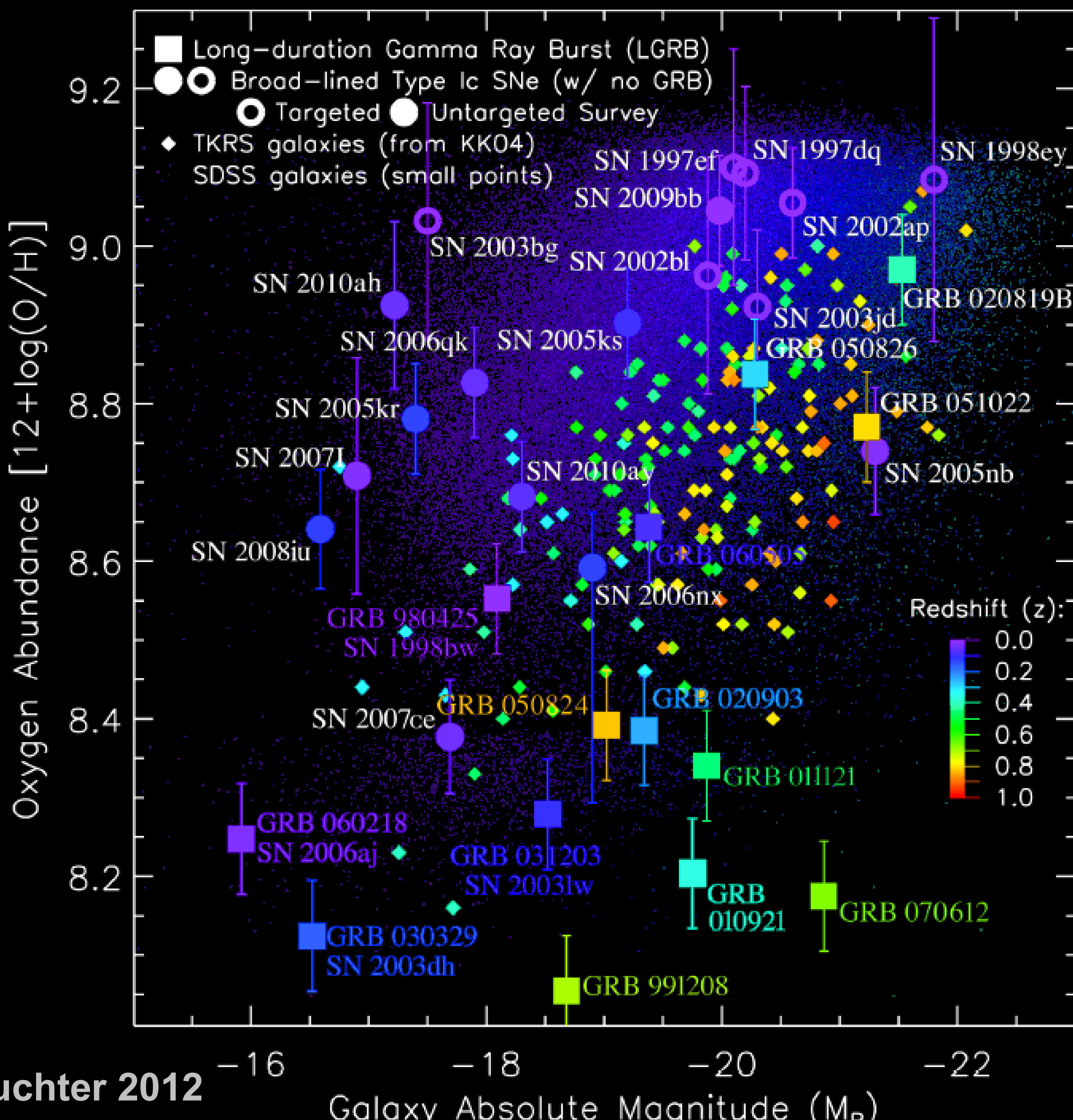
GRB and field-survey measurements of the SFRD do not agree. Why not?

1. Field surveys systematically underestimate (by factor of ~5!) contributions from low-mass galaxies and high-z galaxies.
   e.g., Jakobsson et al. 2012, Kistler et al. 2013

2. GRBs are not uniform star-formation rate tracers: the rate depends on environment (e.g., metallicity)
   e.g., Modjaz et al. 2008, Levesque et al. 2010, Graham & Fruchter 2012

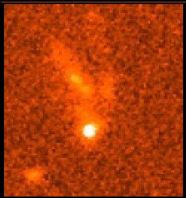
Dramatic Metallicity Bias at z~0.5

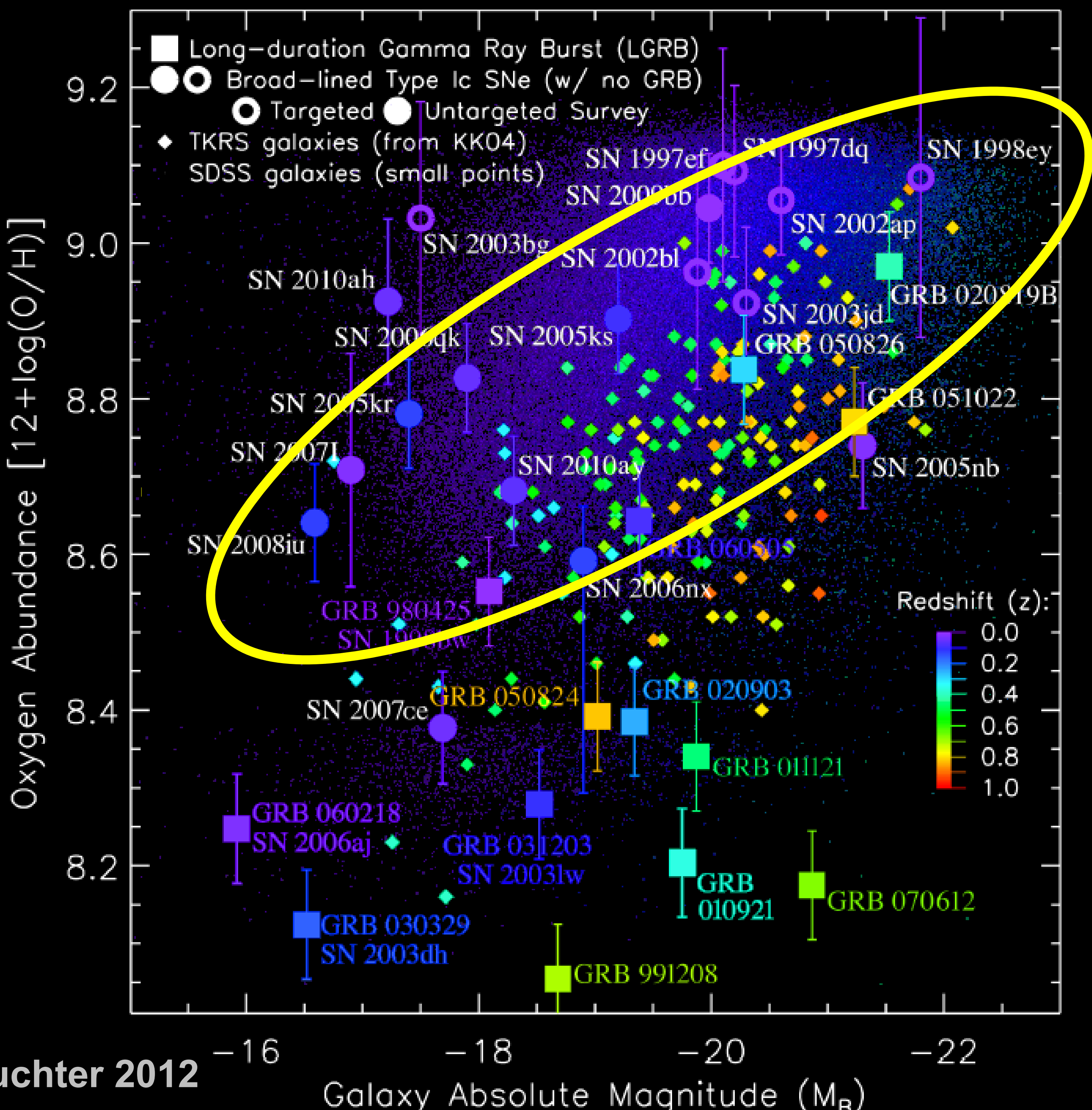




Graham & Fruchter 2012

Dramatic Metallicity Bias at z~0.5

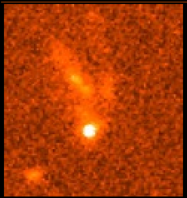


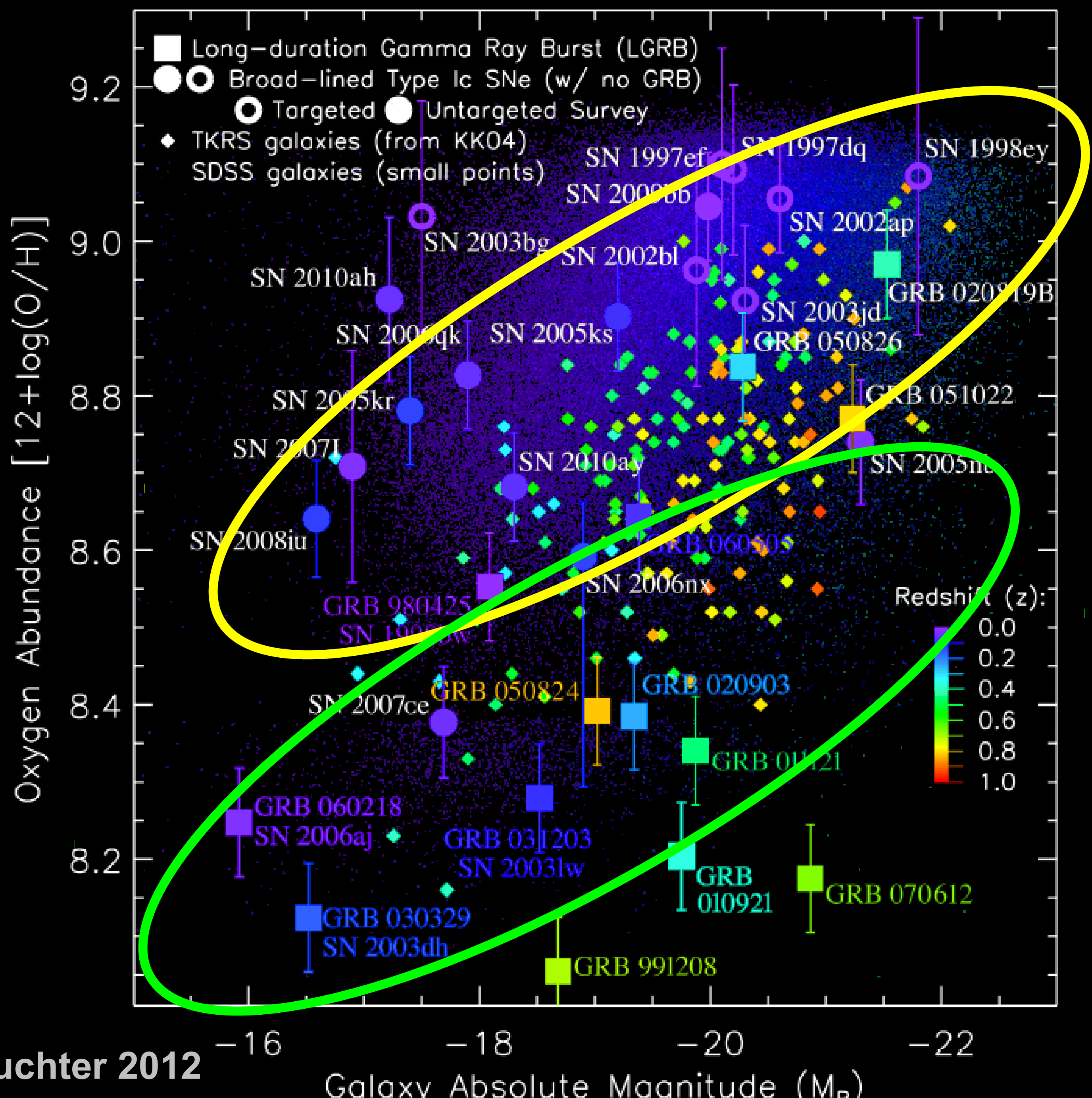


b/l Ic's

Graham & Fruchter 2012

Dramatic Metallicity Bias at z~0.5



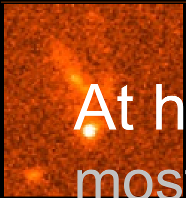


b/l Ic's

GRBs

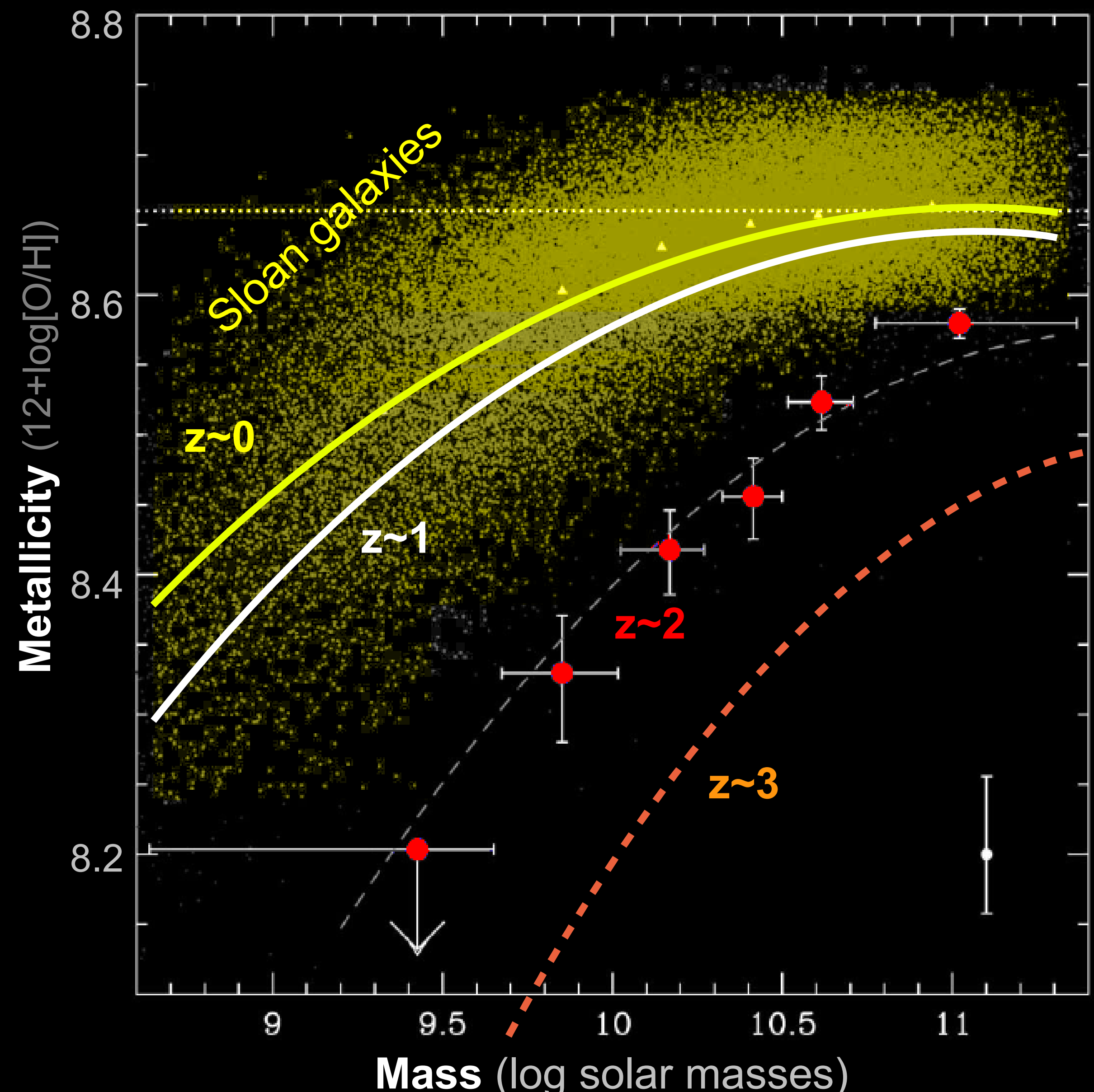
Graham & Fruchter 2012

What about at z>1?



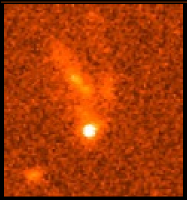
At high redshift (where most GRBs occur), *all* galaxies are metal “poor”.

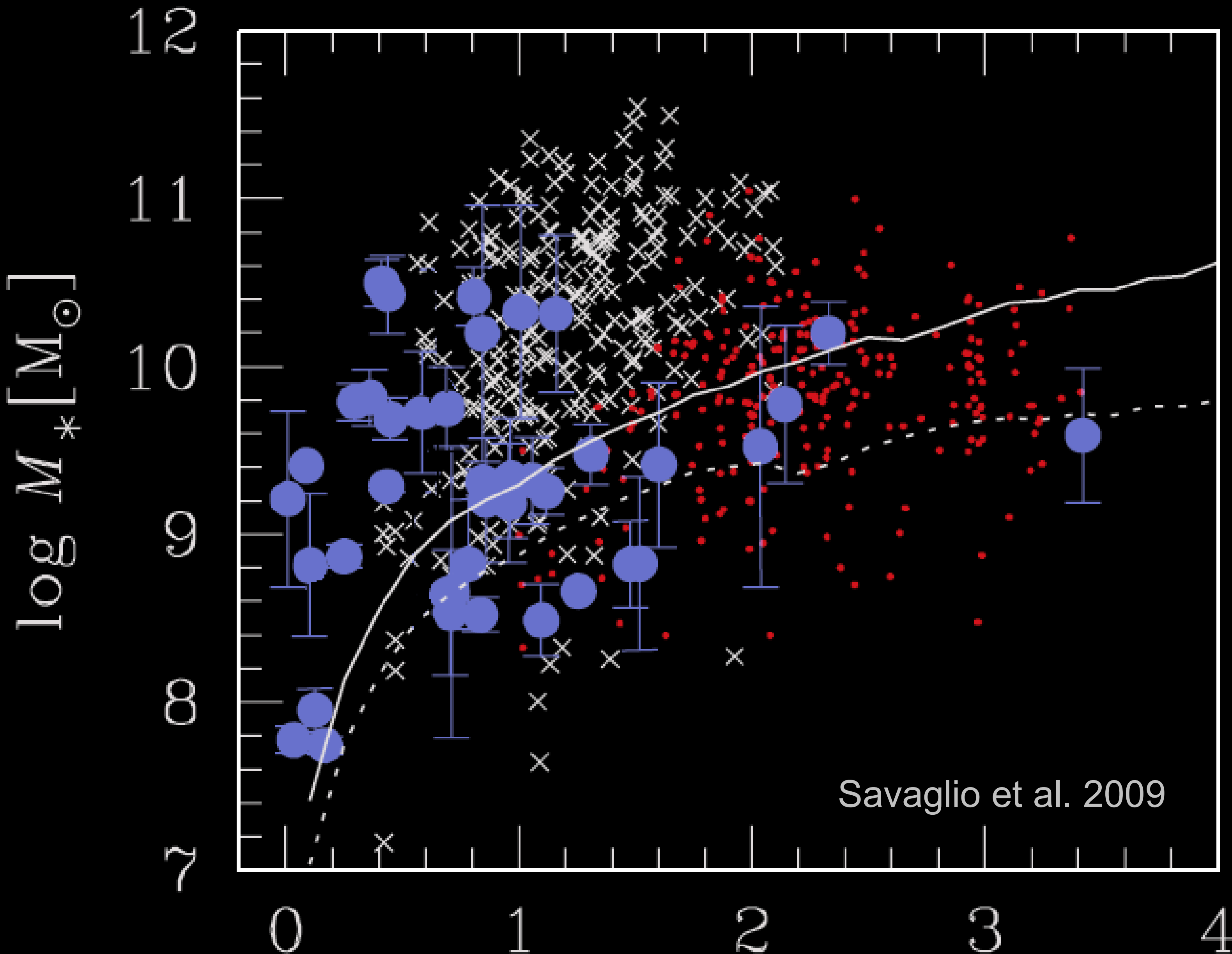
Direct metallicity measurement not usually practical (except for extremely luminous hosts)



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

Hosts at z>1

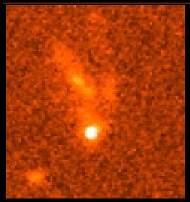


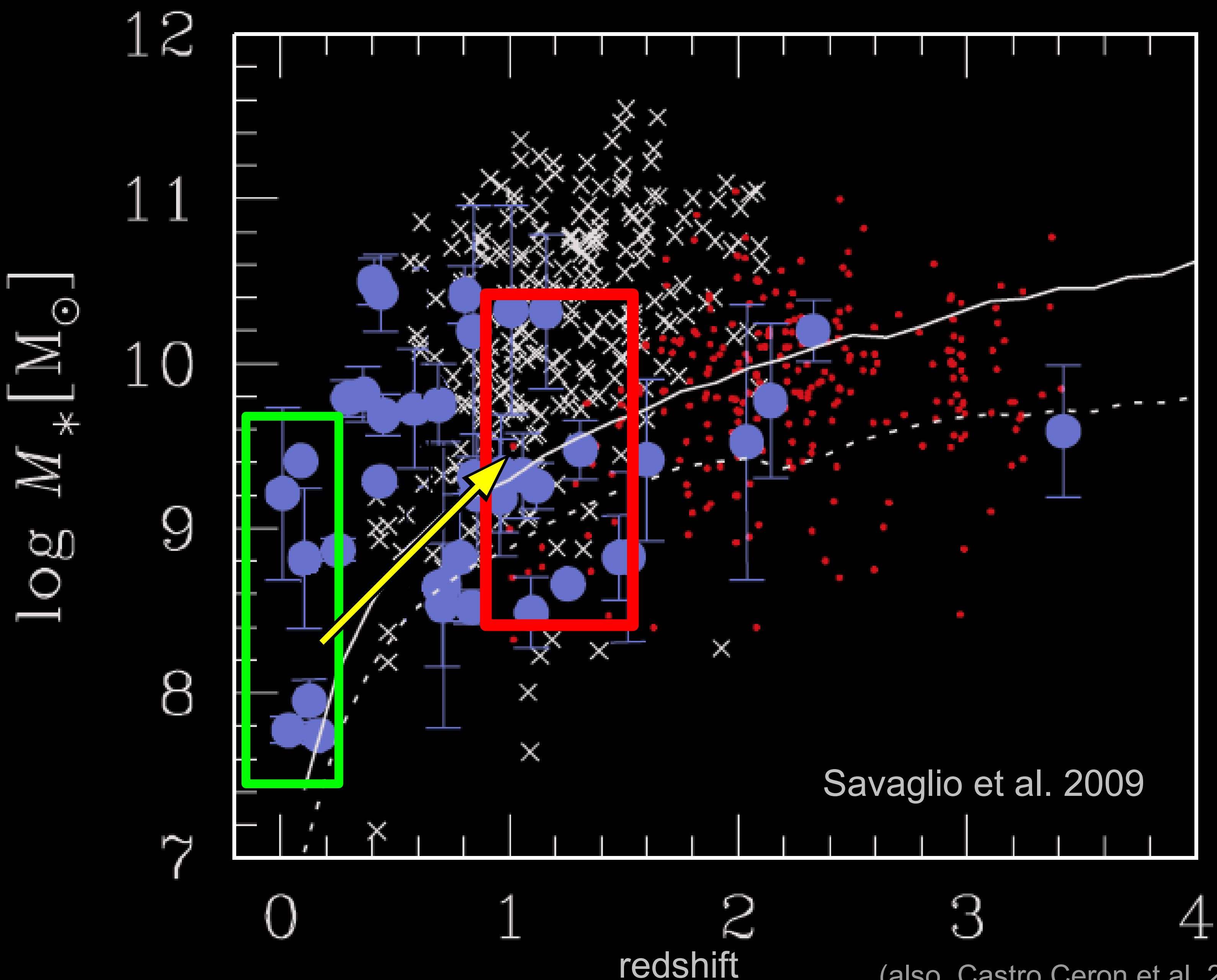


redshift

(also, Castro Ceron et al. 2010)

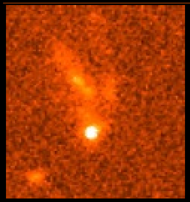
Hosts at z>1

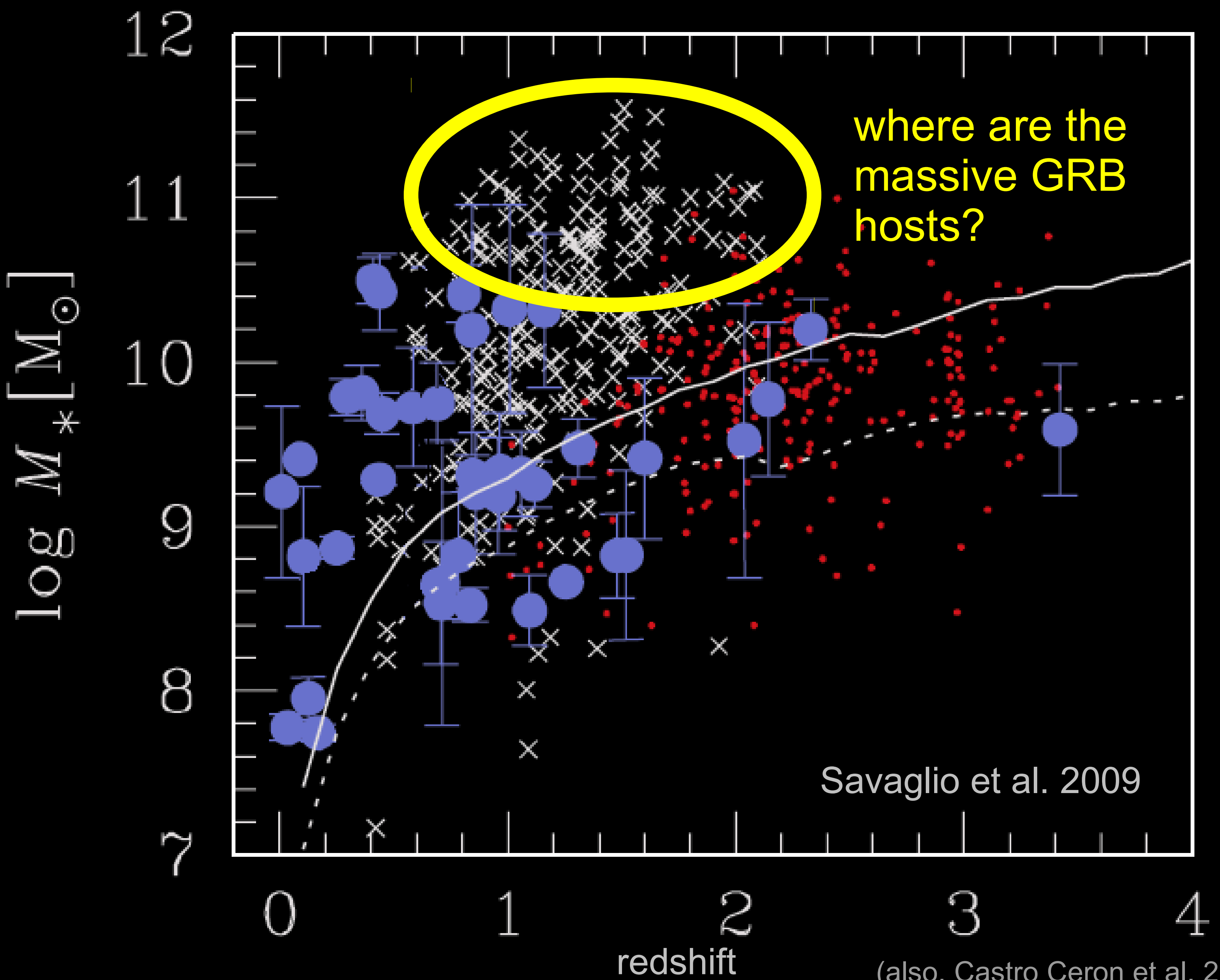




(also, Castro Ceron et al. 2010)

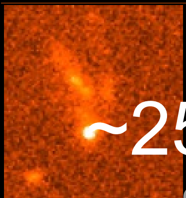
Hosts at z>1





(also, Castro Ceron et al. 2010)

Dark GRBs



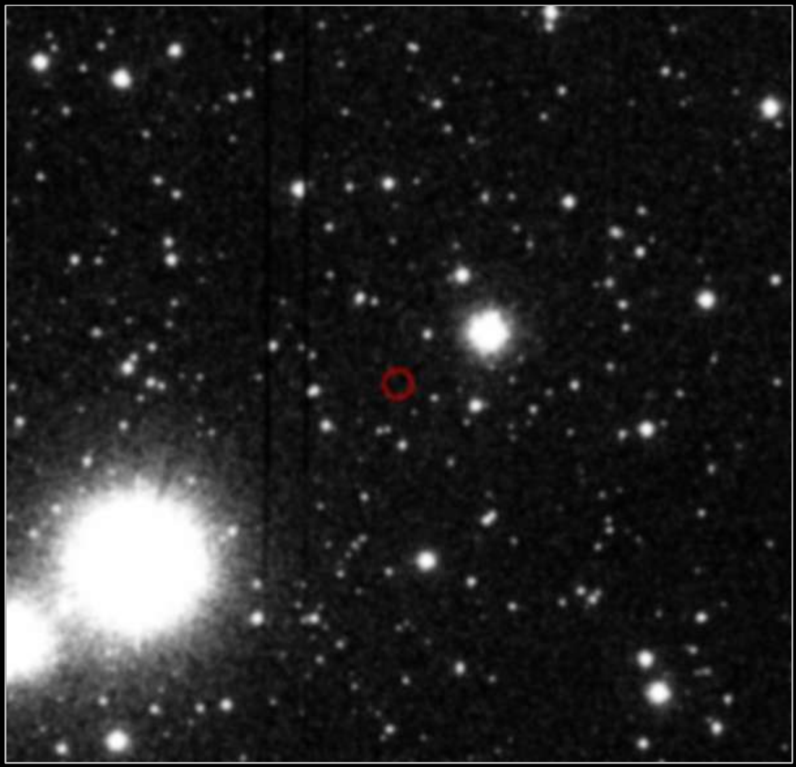
~25% of GRBs are **dark**:

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

No optical afterglow,
even with early follow-up.

- Can't identify host without X-ray or radio follow-up.

- Can't measure redshift without large ground-based telescopes.



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

Most are **dust-obscured**

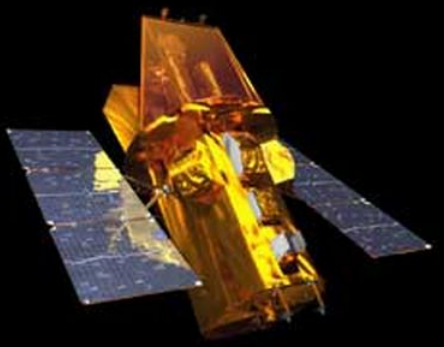
Perley et al. 2009, Greiner et al. 2011

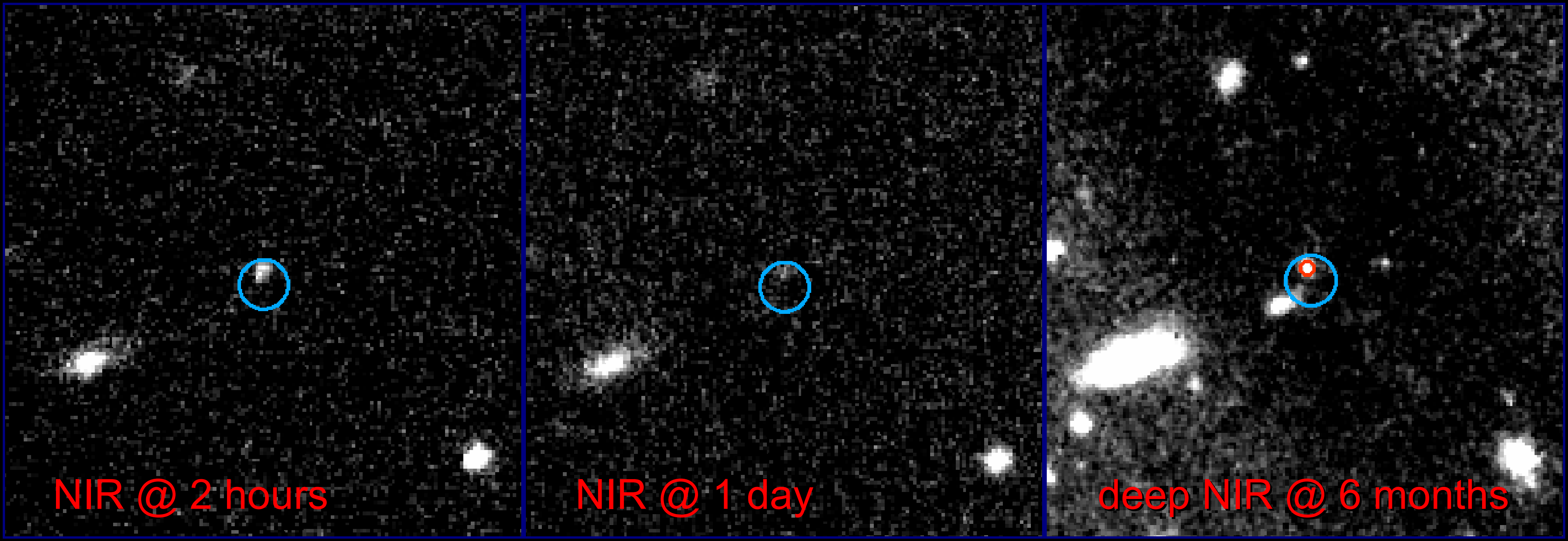
These hosts were *not routinely followed* in previous work: bias?

Dark GRBs & Hosts

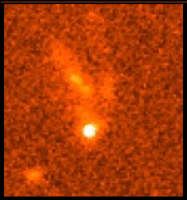
Swift's **XRT** (positional accuracy ~1.5”) lets us locate these bursts and find their hosts.

(At least one of: Chandra, radio, and/or fast NIR follow-up usually also available to confirm position / host ID)





Some Dark GRB Hosts



GRB 080207
Svensson et al. 2012
Hunt et al. 2011

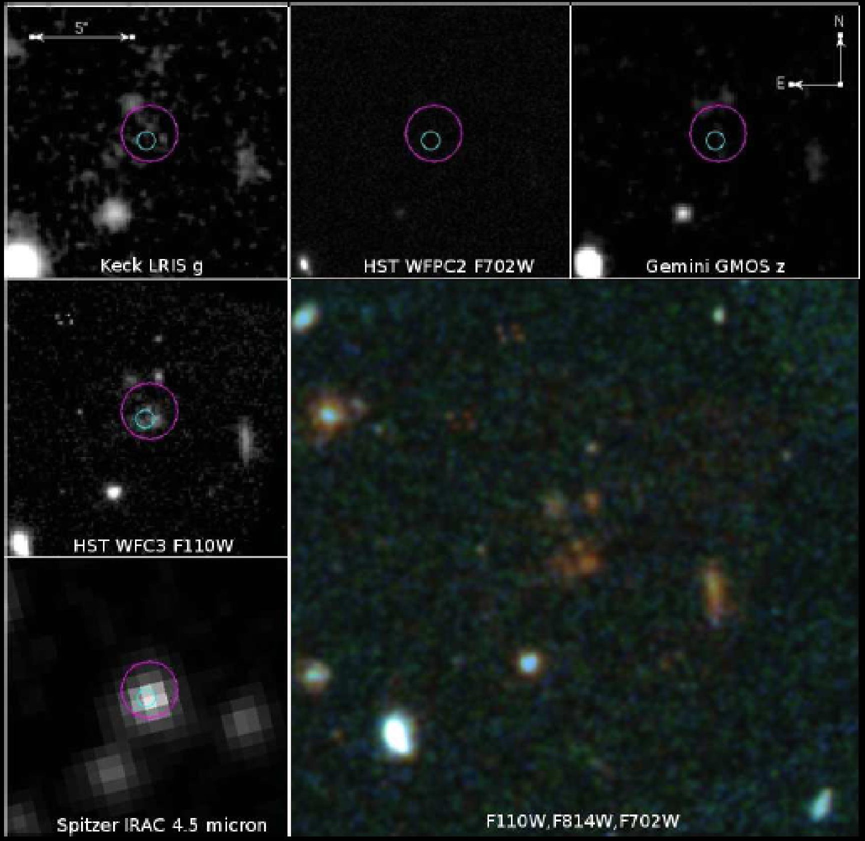
GRB 080607
Chen et al. 2011

GRB 080325
Hashimoto et al. 2011

GRB 051022
Castro-Tirado et al. 2007
Rol et al. 2007

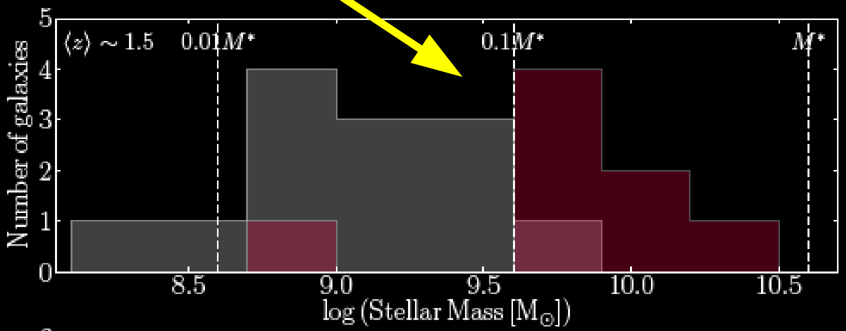
GRB 020819
Levesque et al. 2010

GRB 070306
Jaunsen et al. 2008

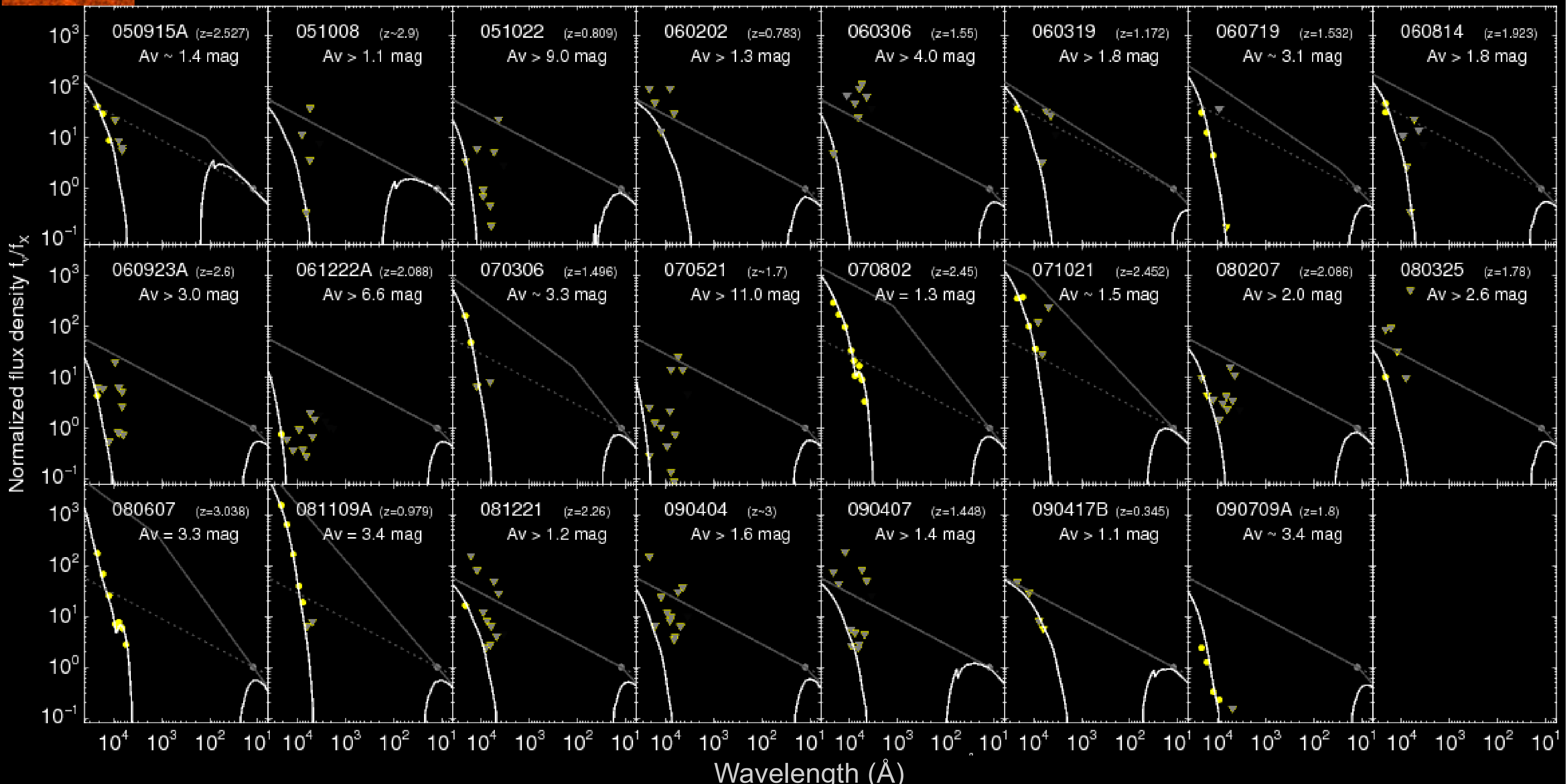


GRBs 070802, 080605, 080805, 081109, 090926B, 100621A
Krühler et al. 2011

+ Rossi et al. 2012

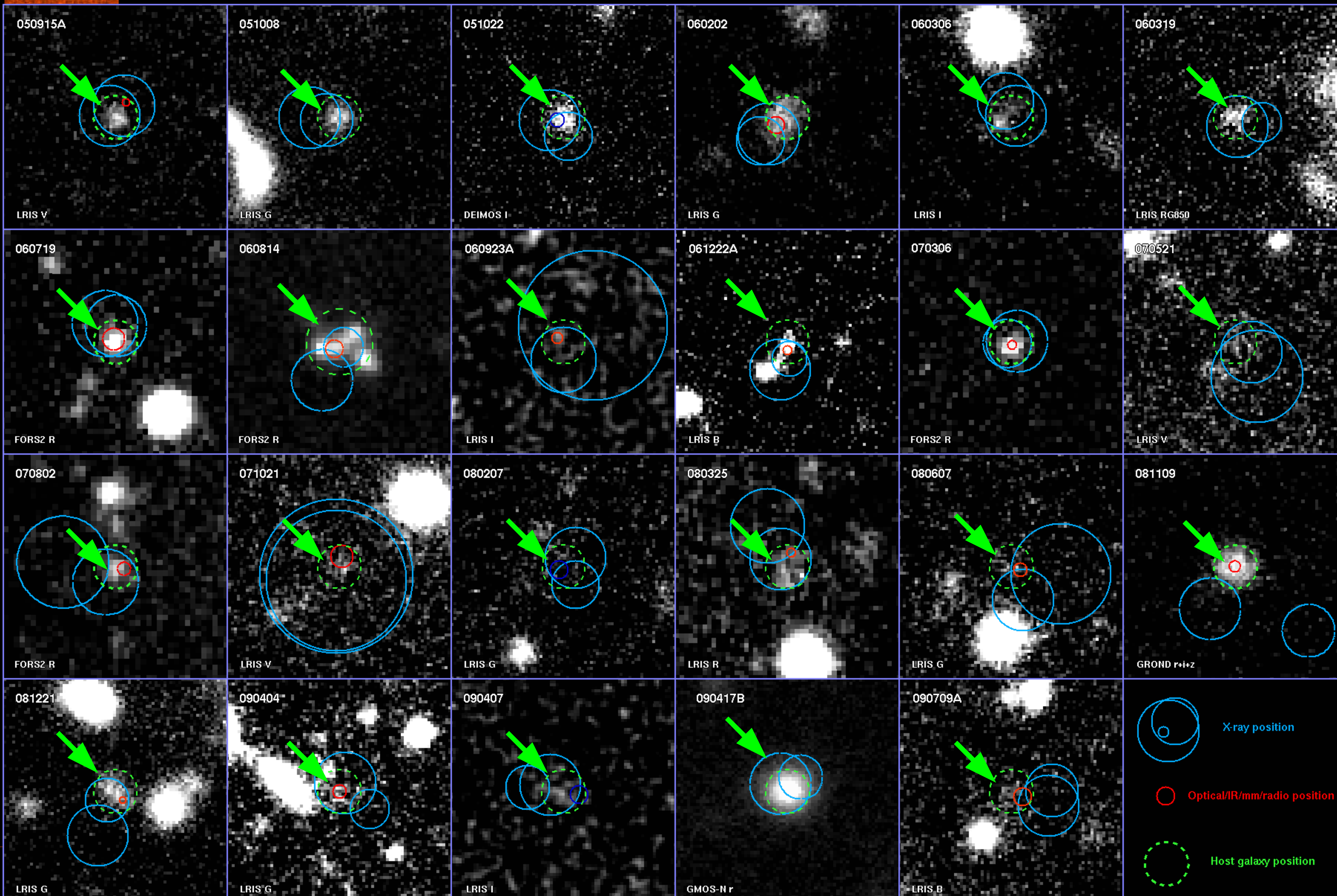


Sample Selection

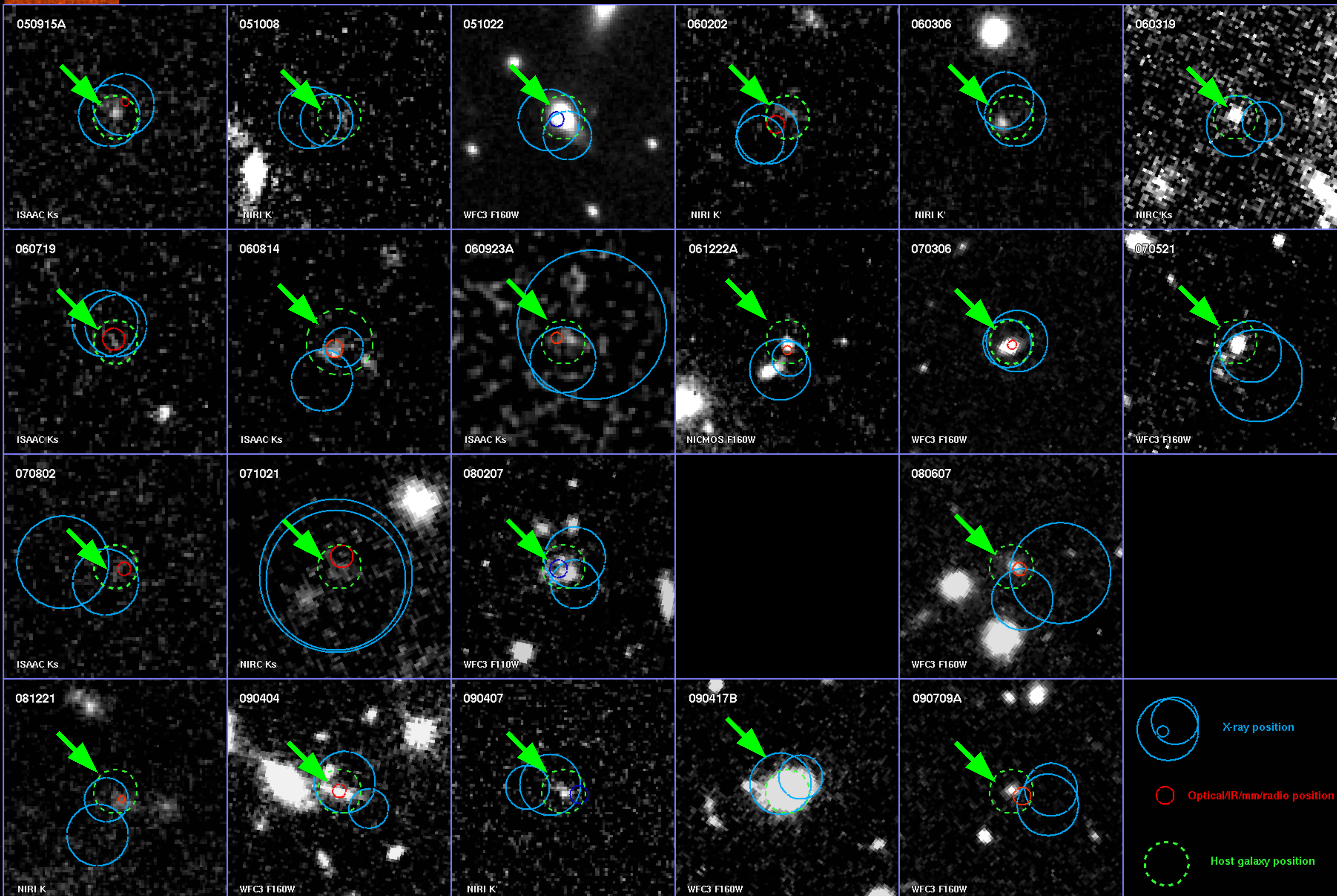


Quasi-complete sample of <u>all</u> GRBs from 2005-2009 with evidence of A_V > 1 mag (from afterglow color/SED)

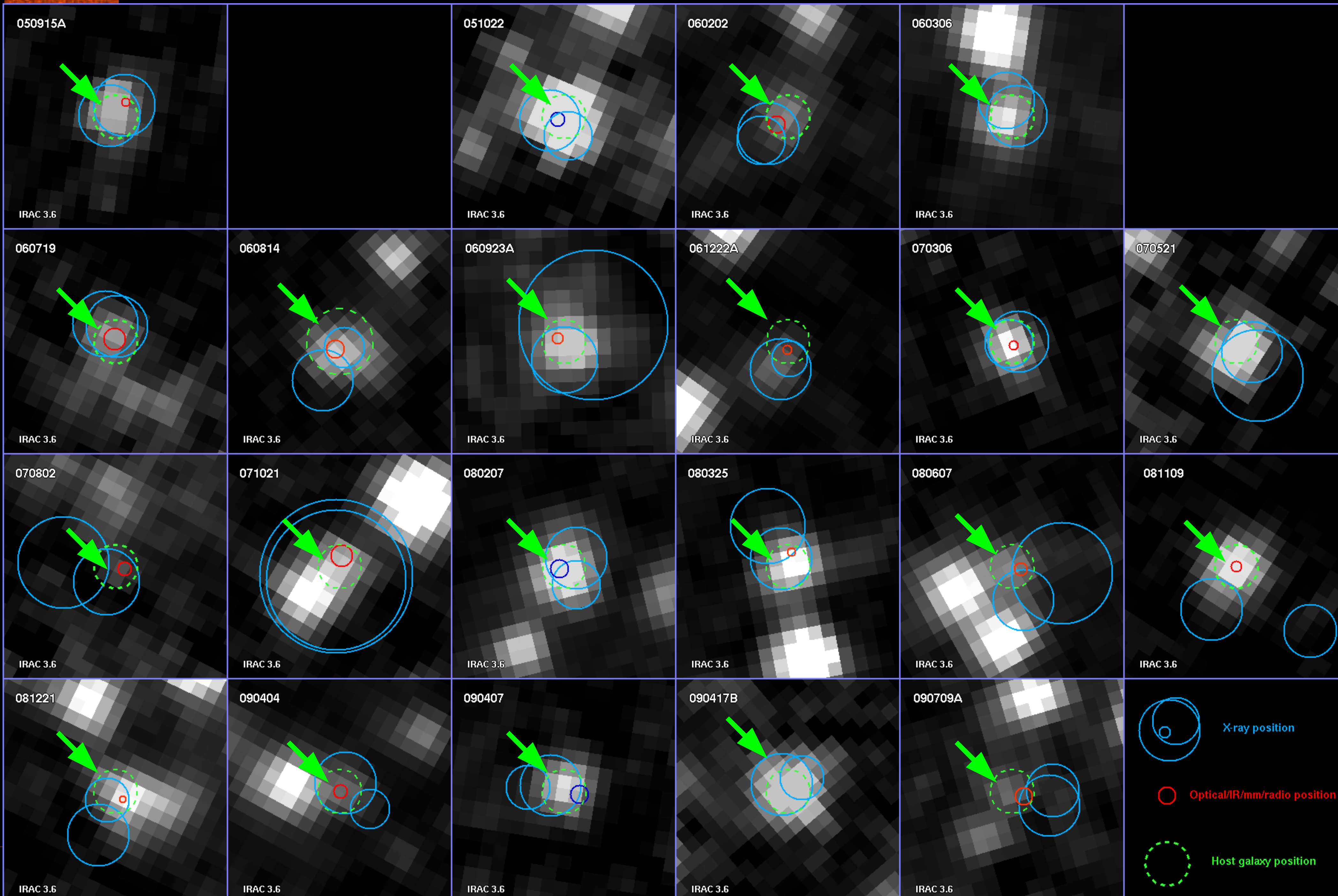
Optical Host Mosaic



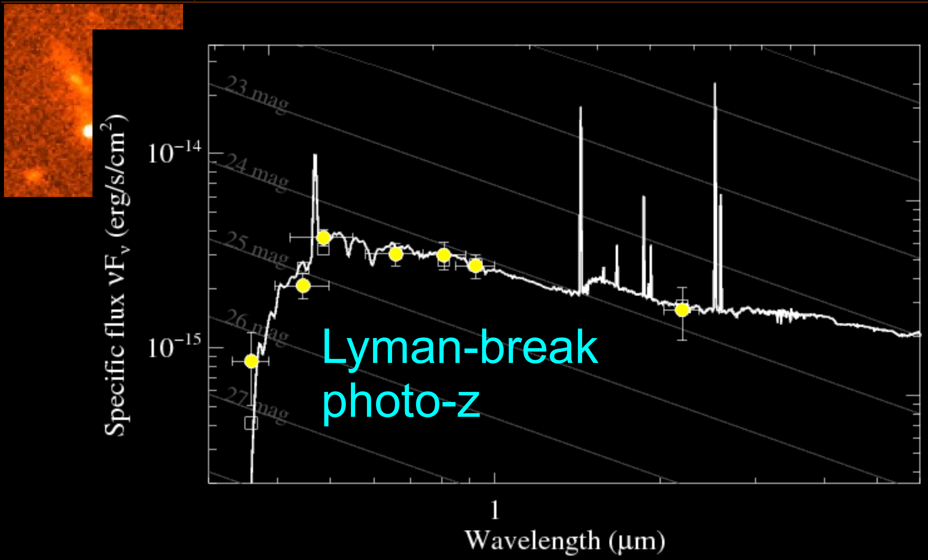
Near-IR Host Mosaic

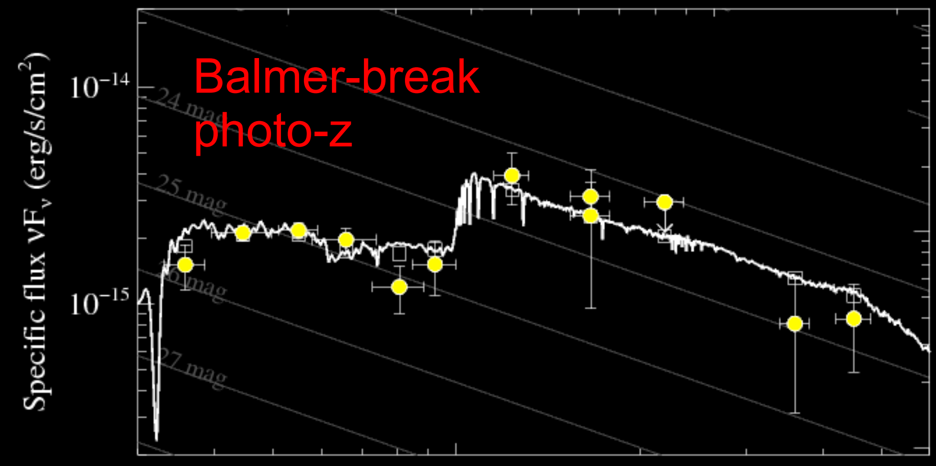


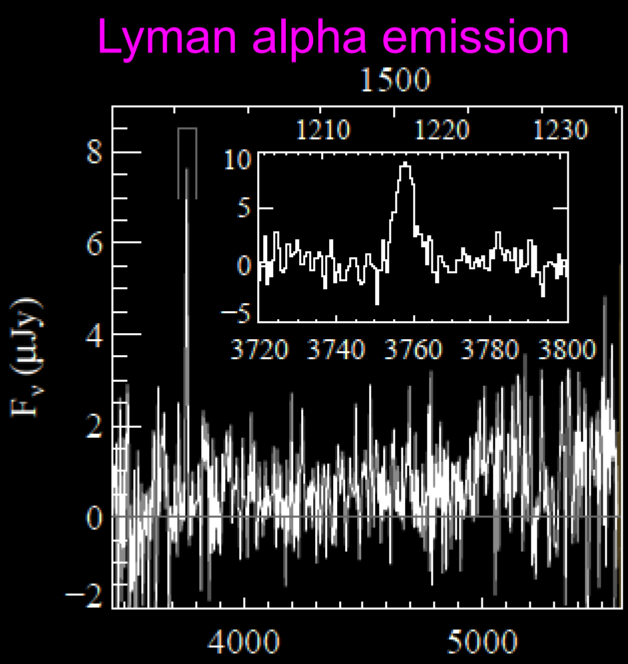
Spitzer Host Mosaic

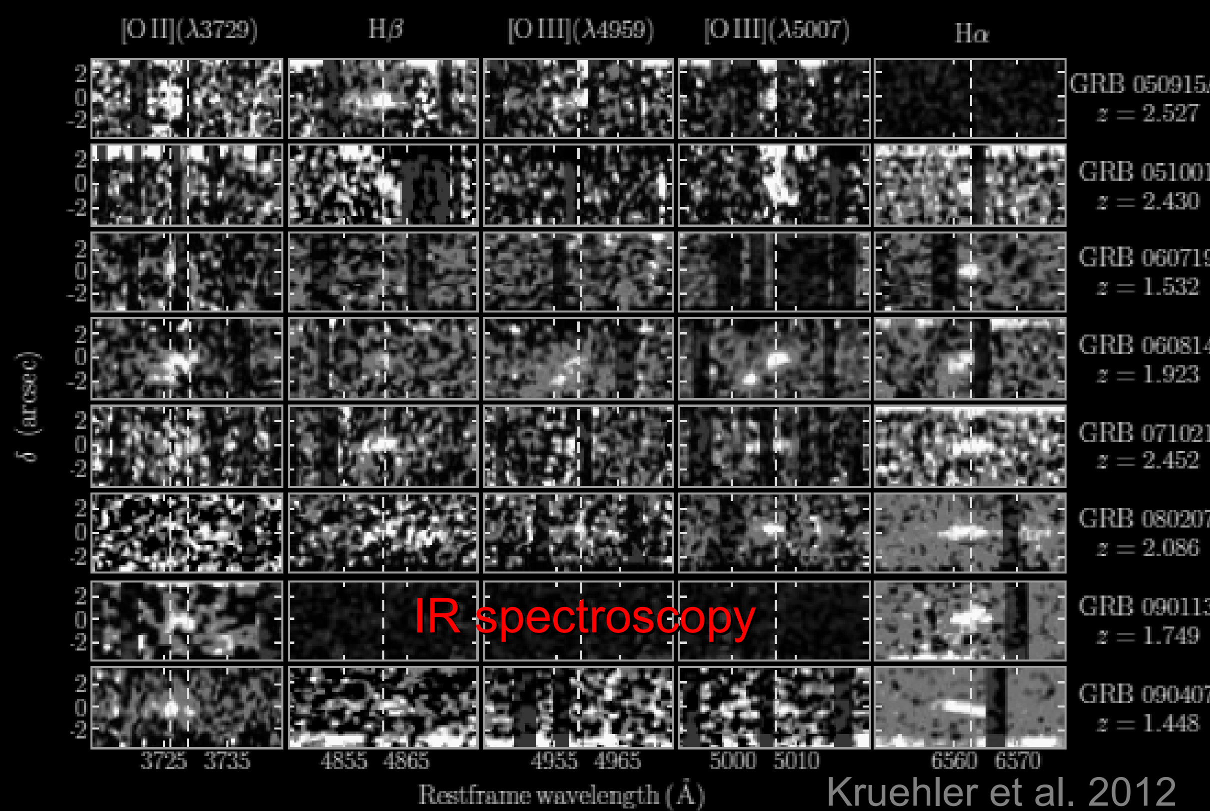


Redshift Measurement

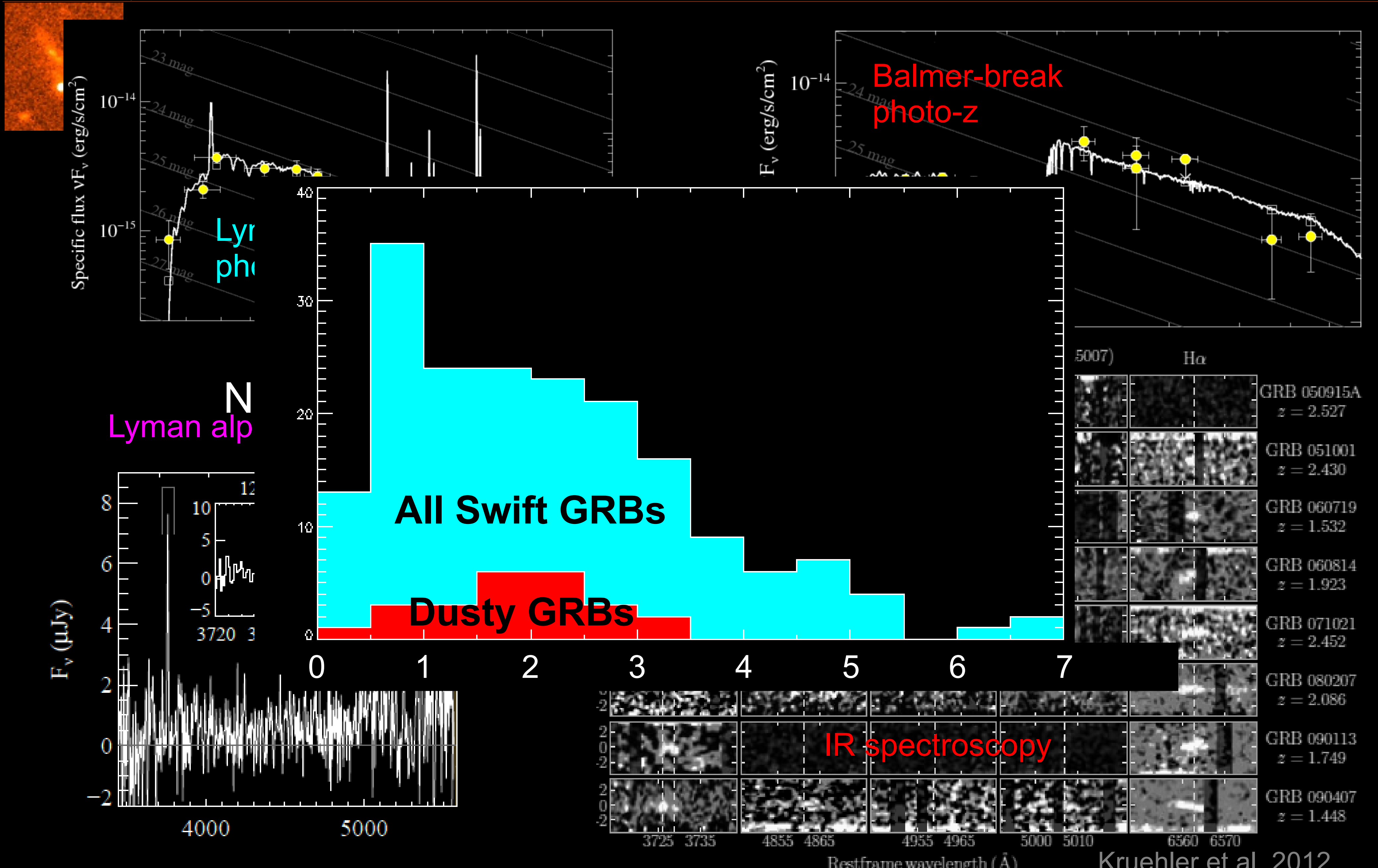




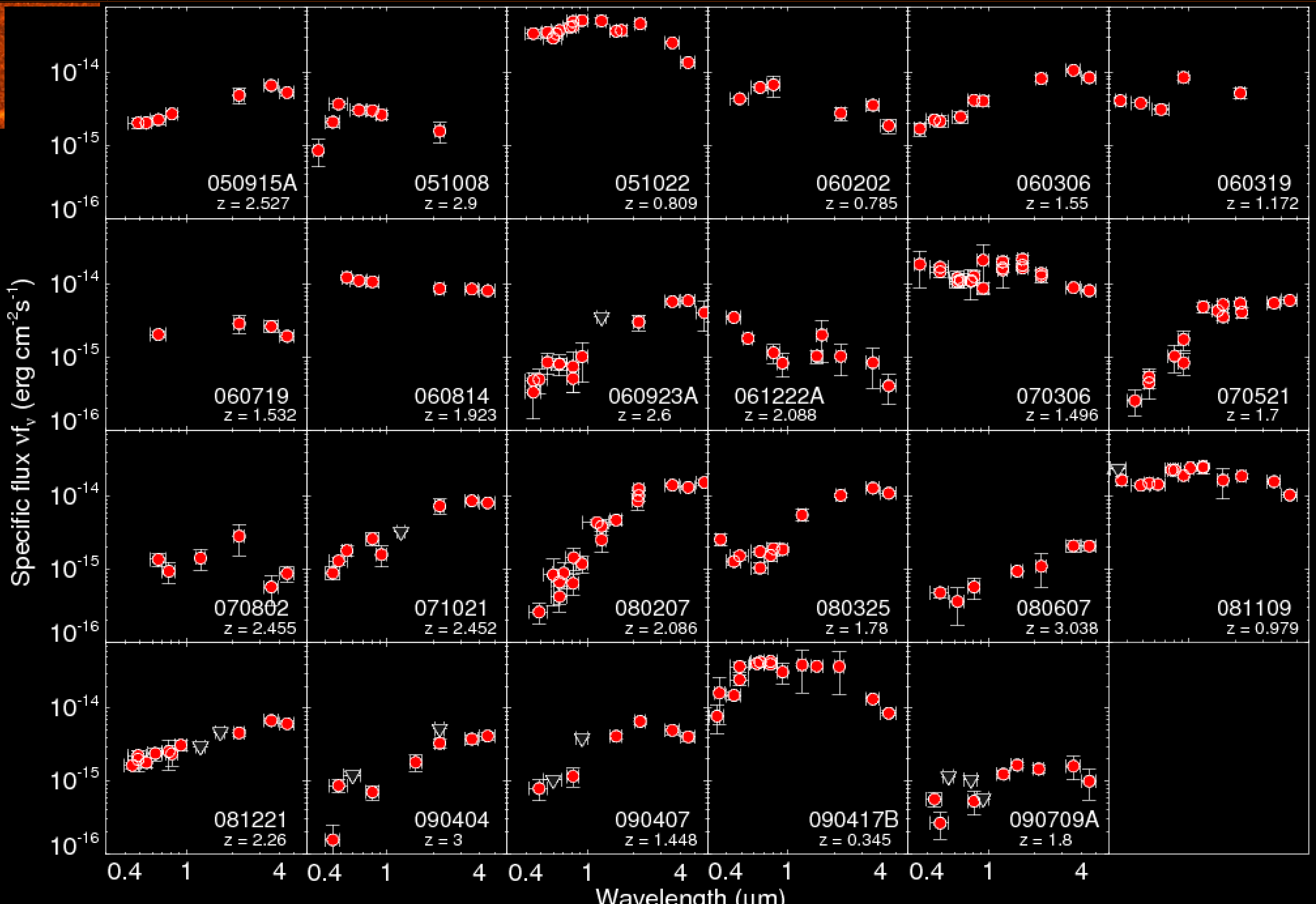




Redshift Measurement



SED Fitting



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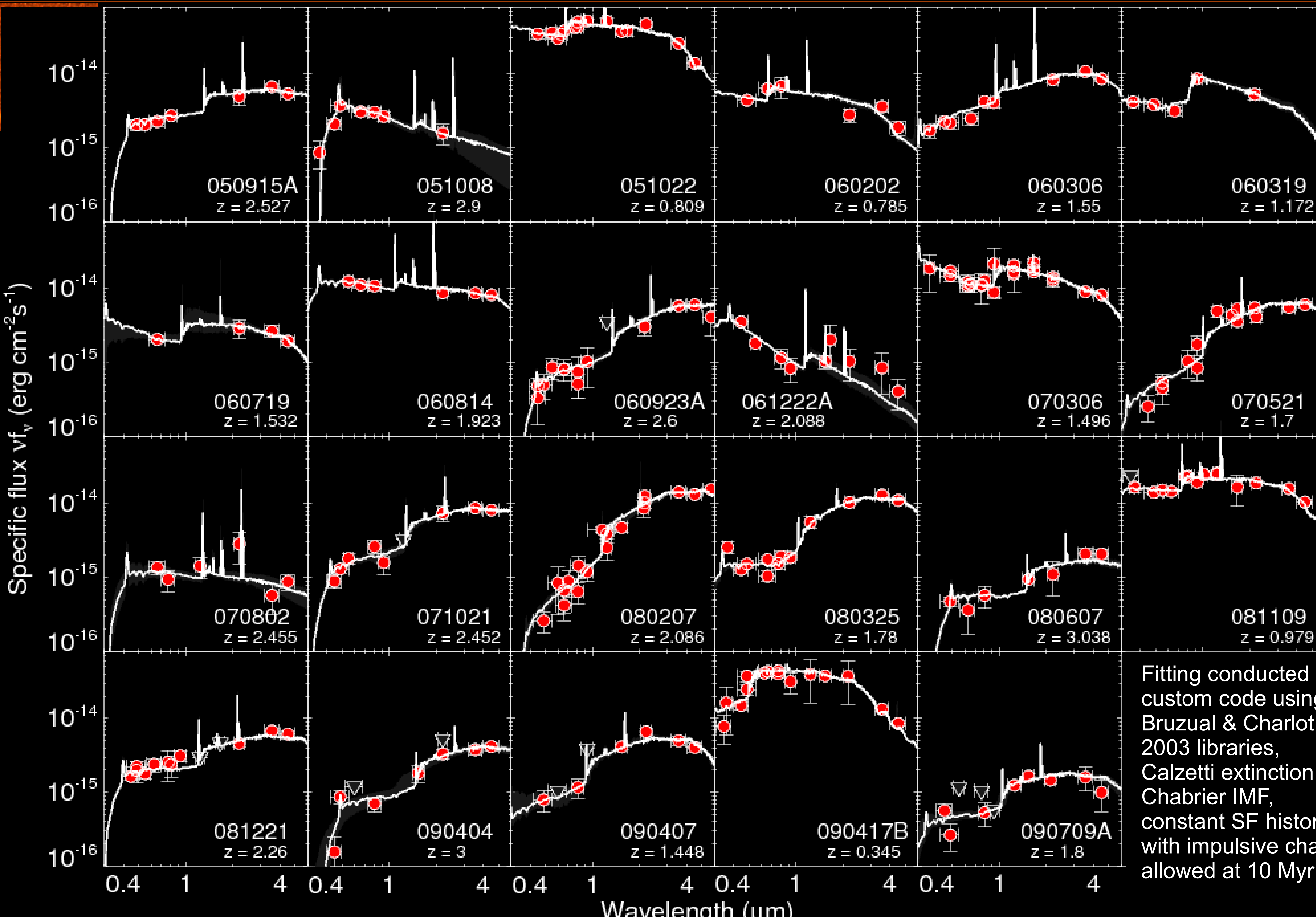
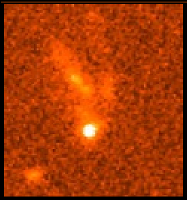
051008
z = 2.9
051022
z = 0.809
060202
z = 0.785
060306
z = 1.55
060319
z = 1.172
060719
z = 1.532
060814
z = 1.923
060923A
z = 2.6
061222A
z = 2.088
070306
z = 1.496
070521
z = 1.7
070802
z = 2.455
071021
z = 2.452
080207
z = 2.086
080325
z = 1.78
080607
z = 3.038
081109
z = 0.979
081221
z = 2.26
090404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

SED Fitting



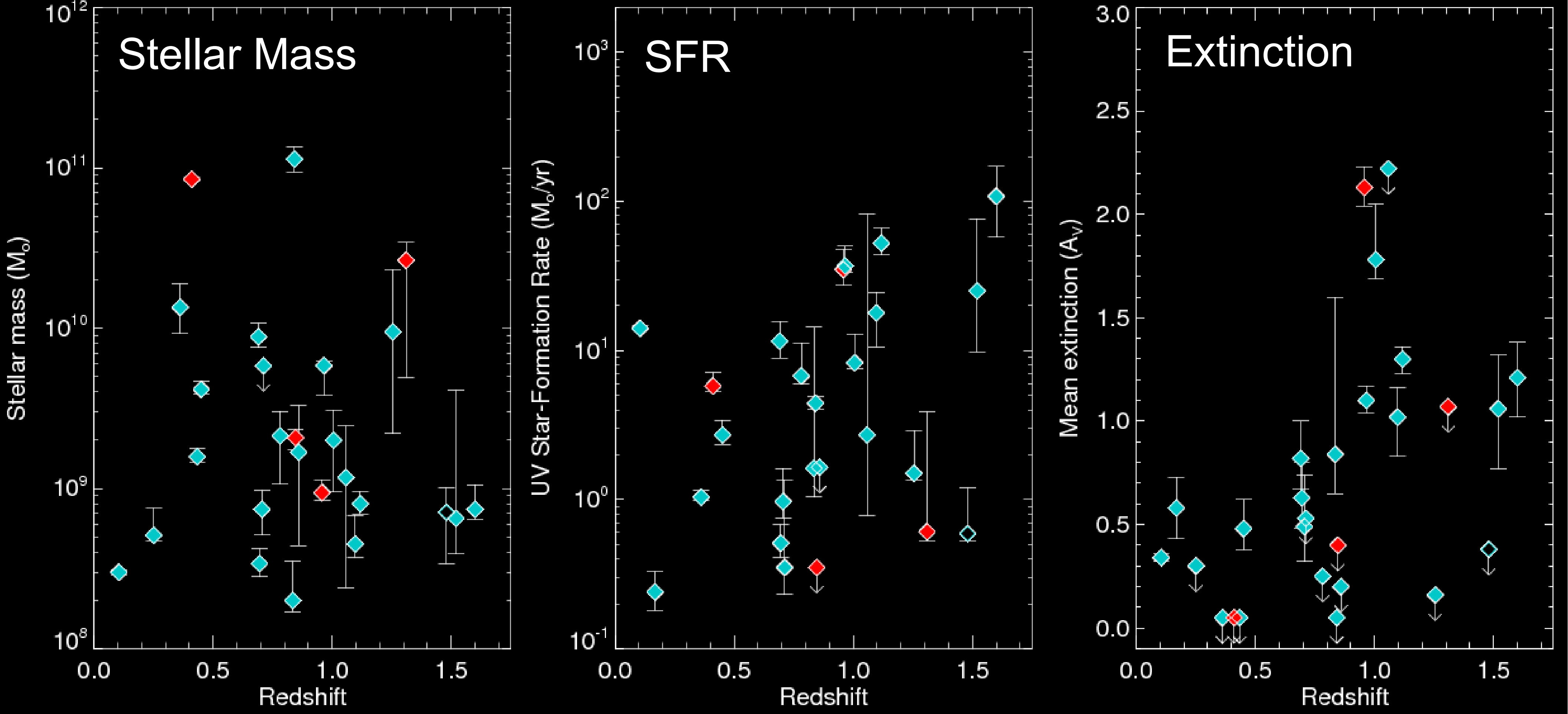
Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr

Comparisons at z~1



Pre-Swift events only:

Blue=unobscured GRB, Red = obscured GRB.

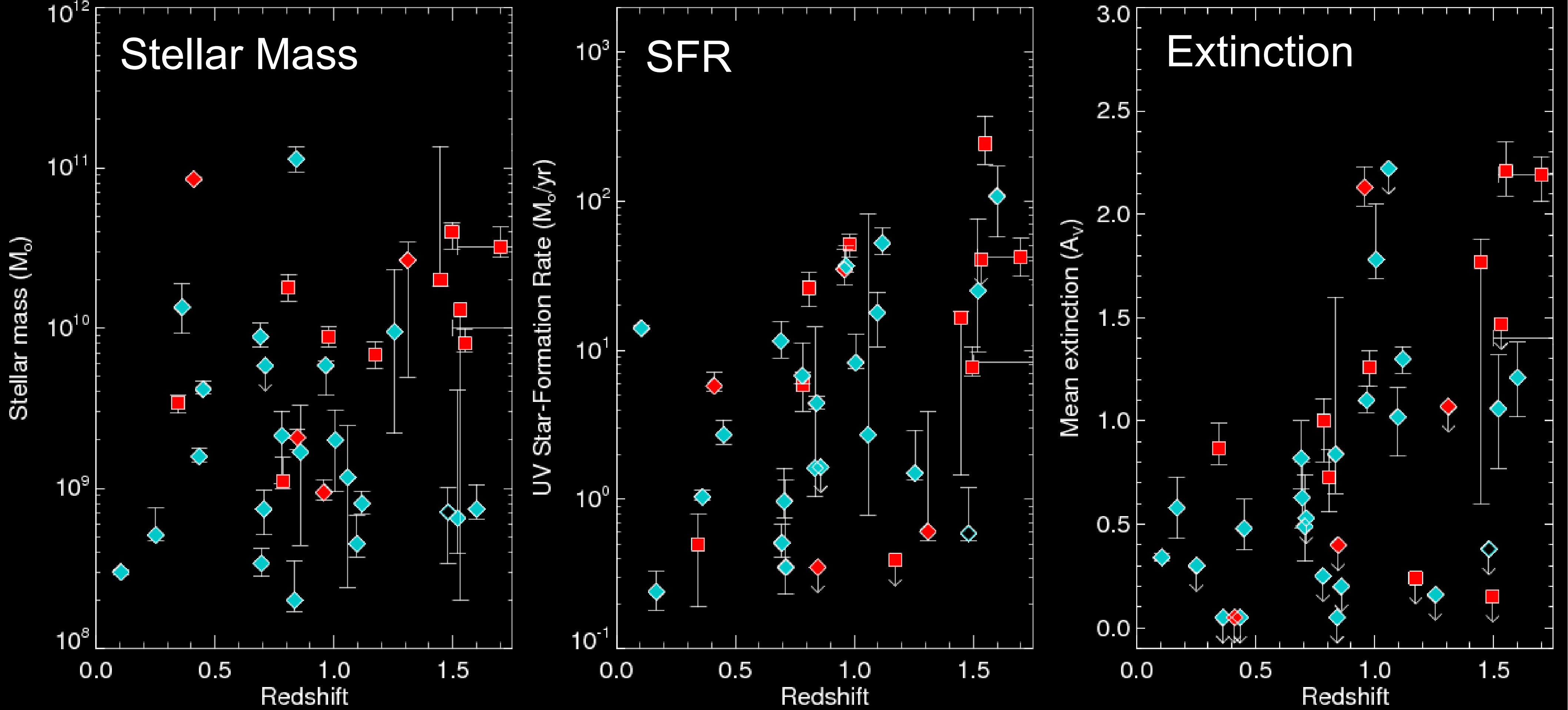


Comparisons at z~1

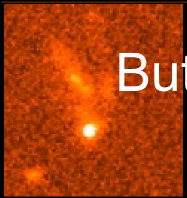
Samples overlap considerably...

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



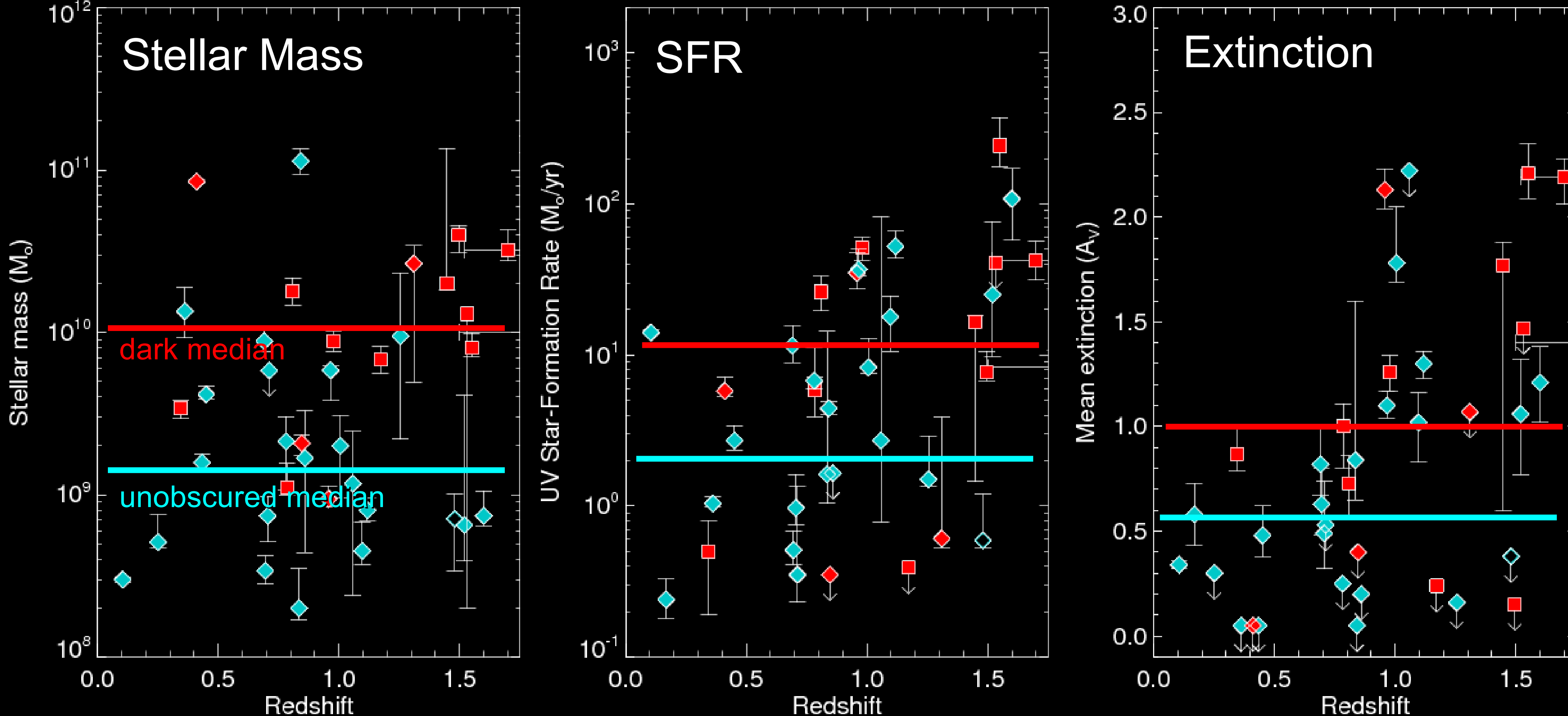
Comparisons at z~1



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

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

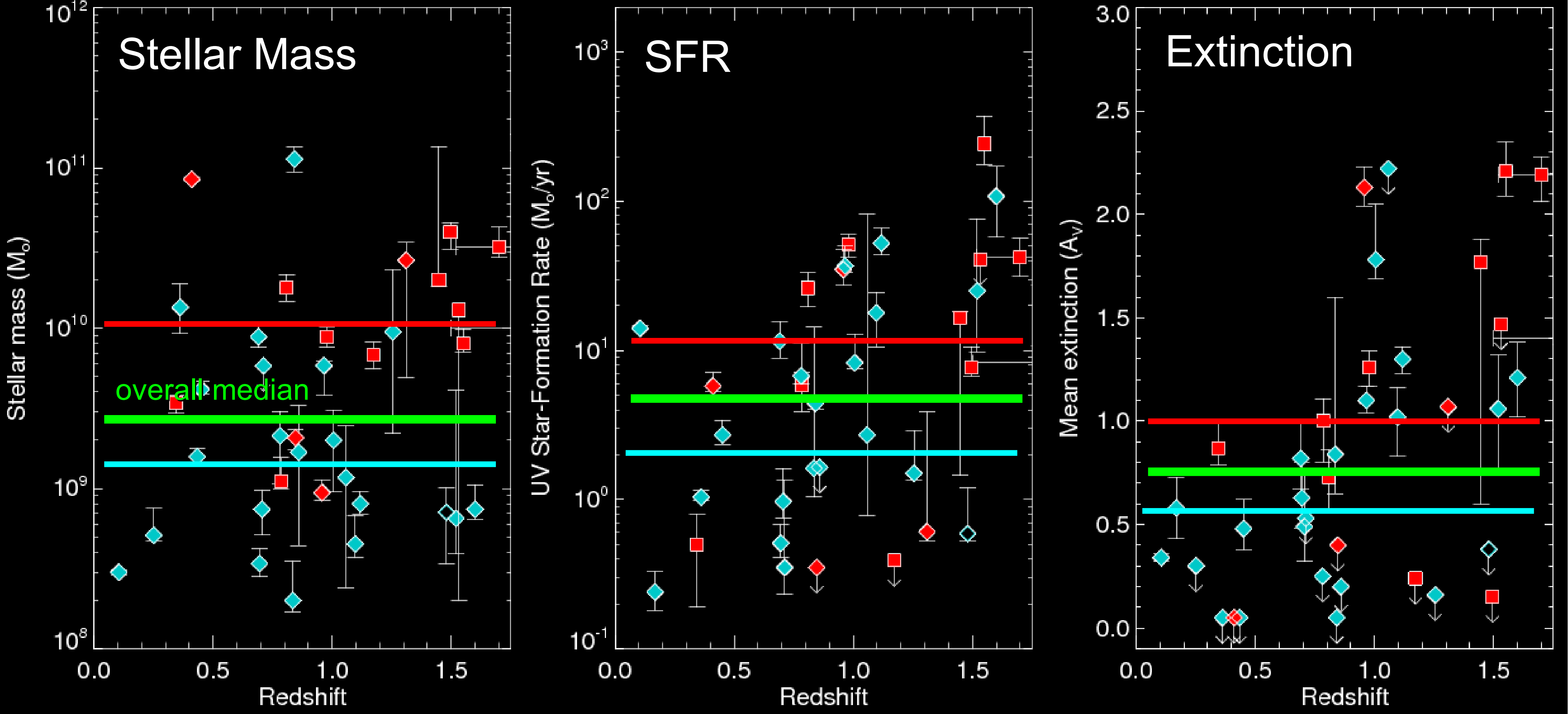


Comparisons at z~1

This produces modest changes in the population averages.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



Comparisons at z~1

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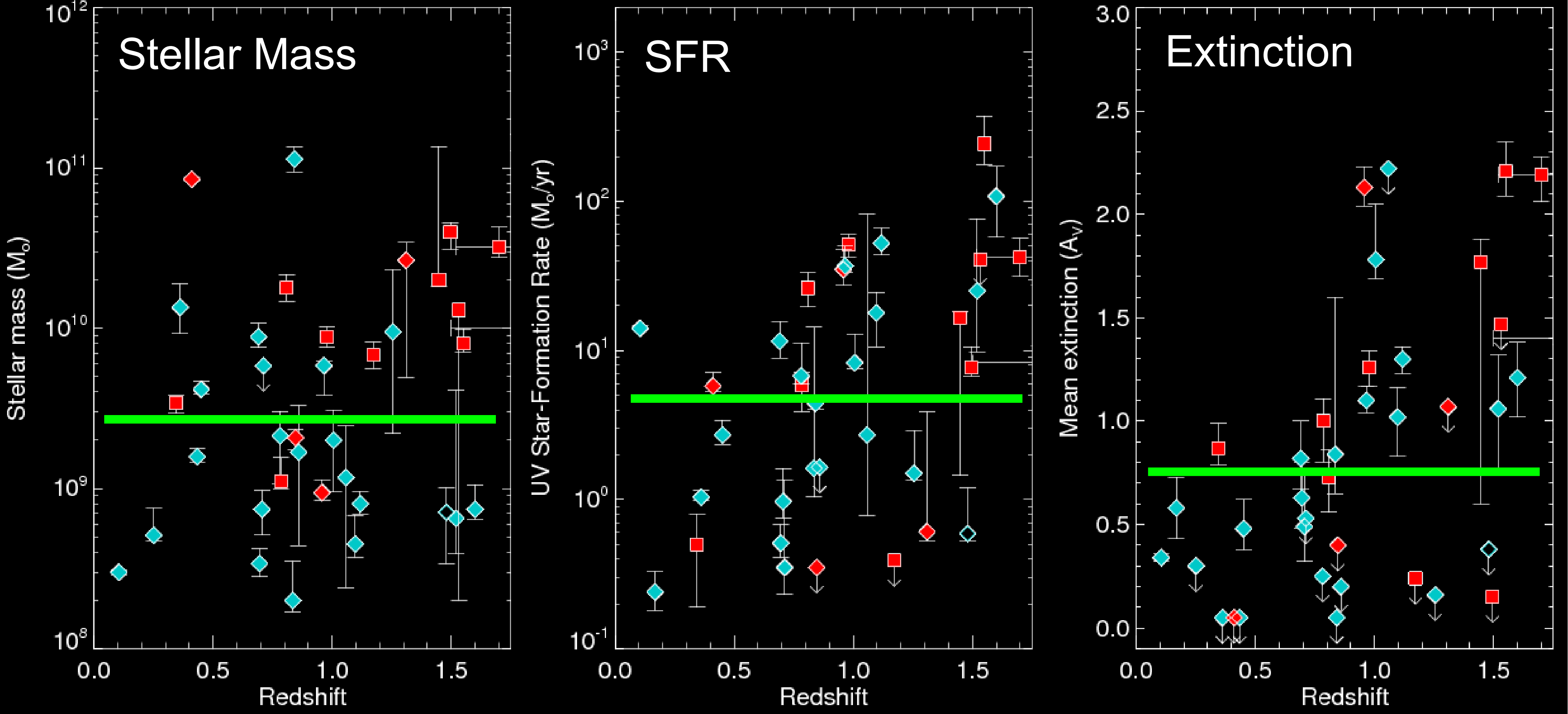
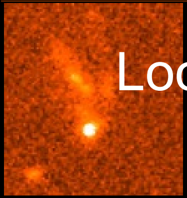
Combined pre-Swift + dark sample: Blue=unobscured GRB, Red = obscured GRB.



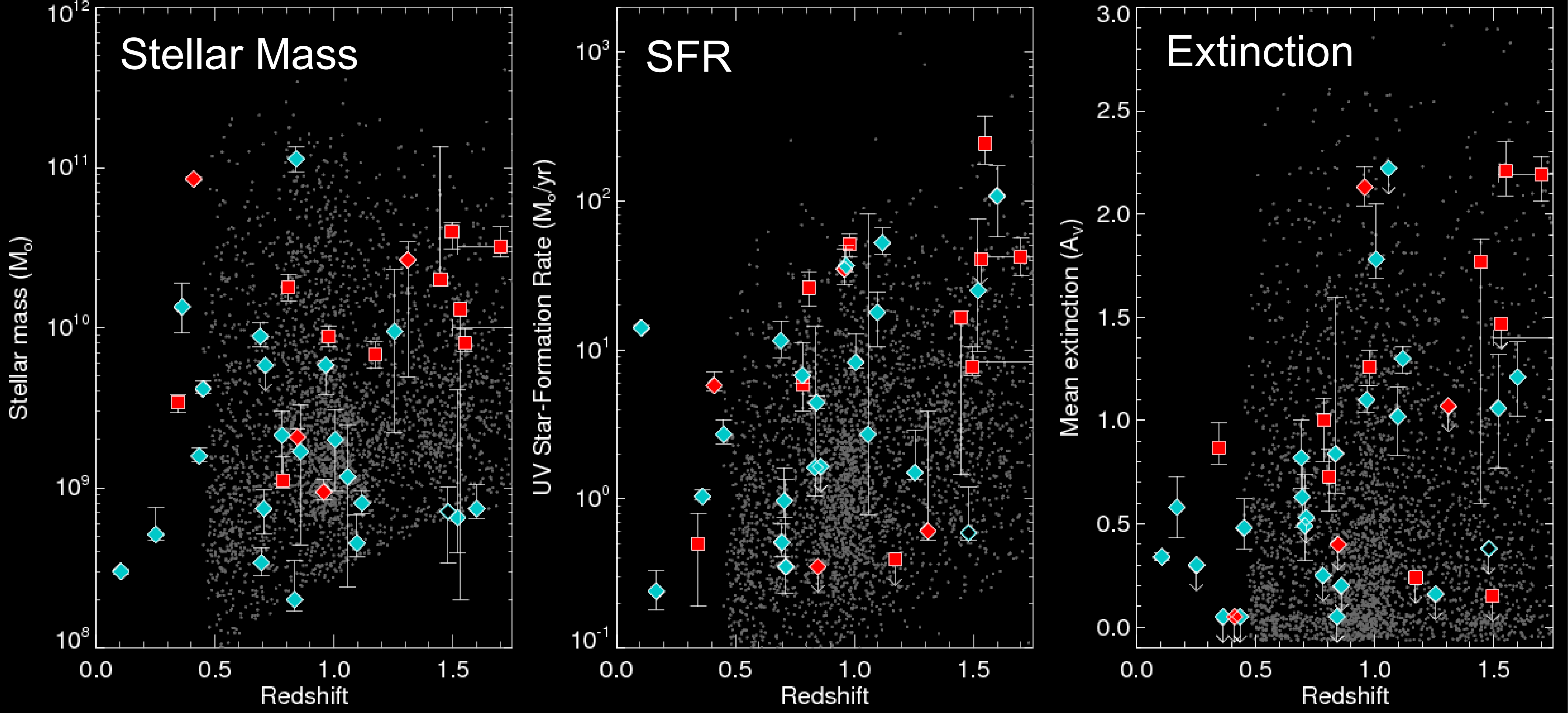
Comparisons vs. Field Galaxies at z~1



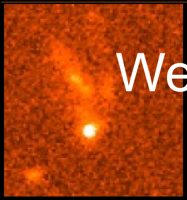
Looks “consistent” with field galaxy *number* distributions...

Combined sample versus field galaxies:

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



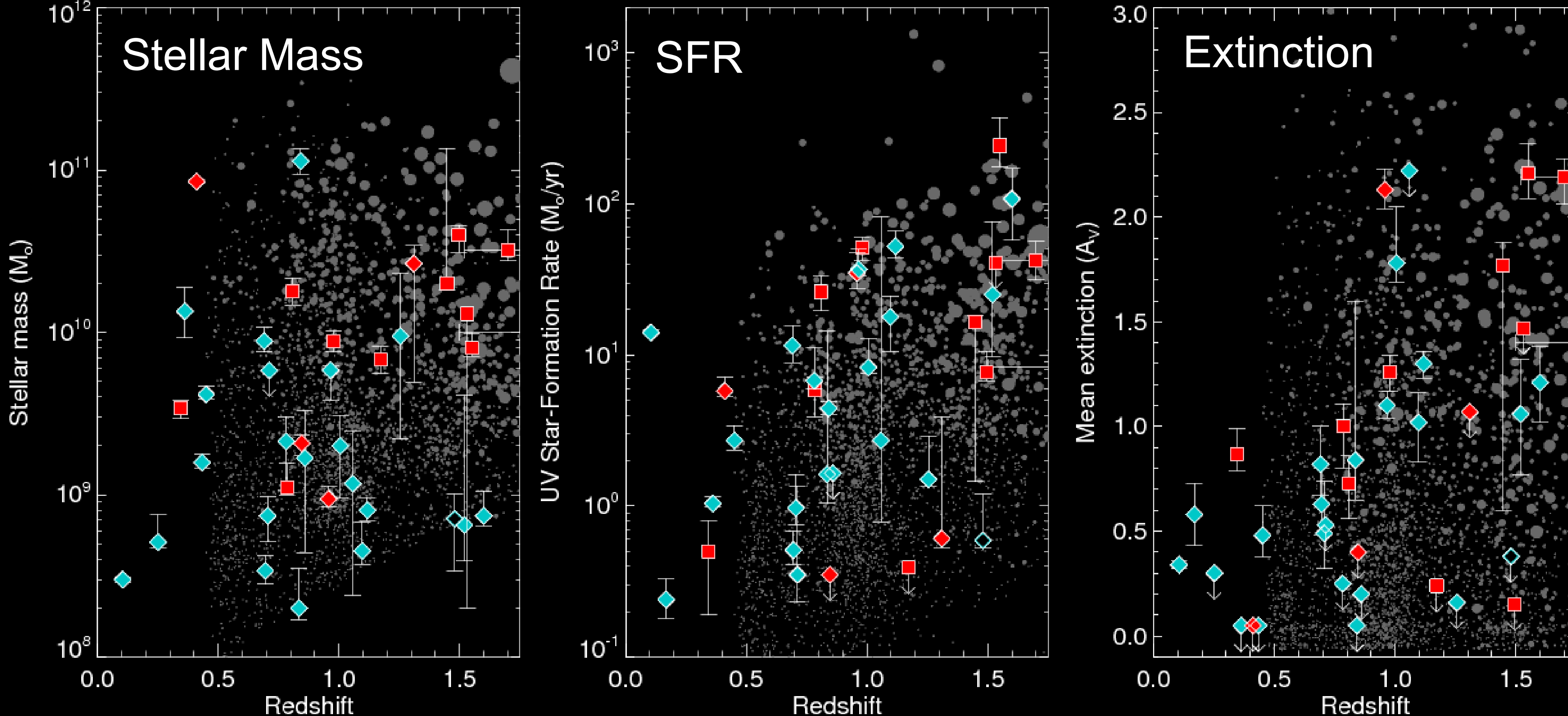
Comparisons vs. Field Galaxies at z~1



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



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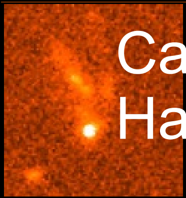

Calculate z-dependent median (mass,SFR,Av) of SFR-weighted population.
Half of GRBs should be above median, half below (if $R_{GRB} \propto SFR$)

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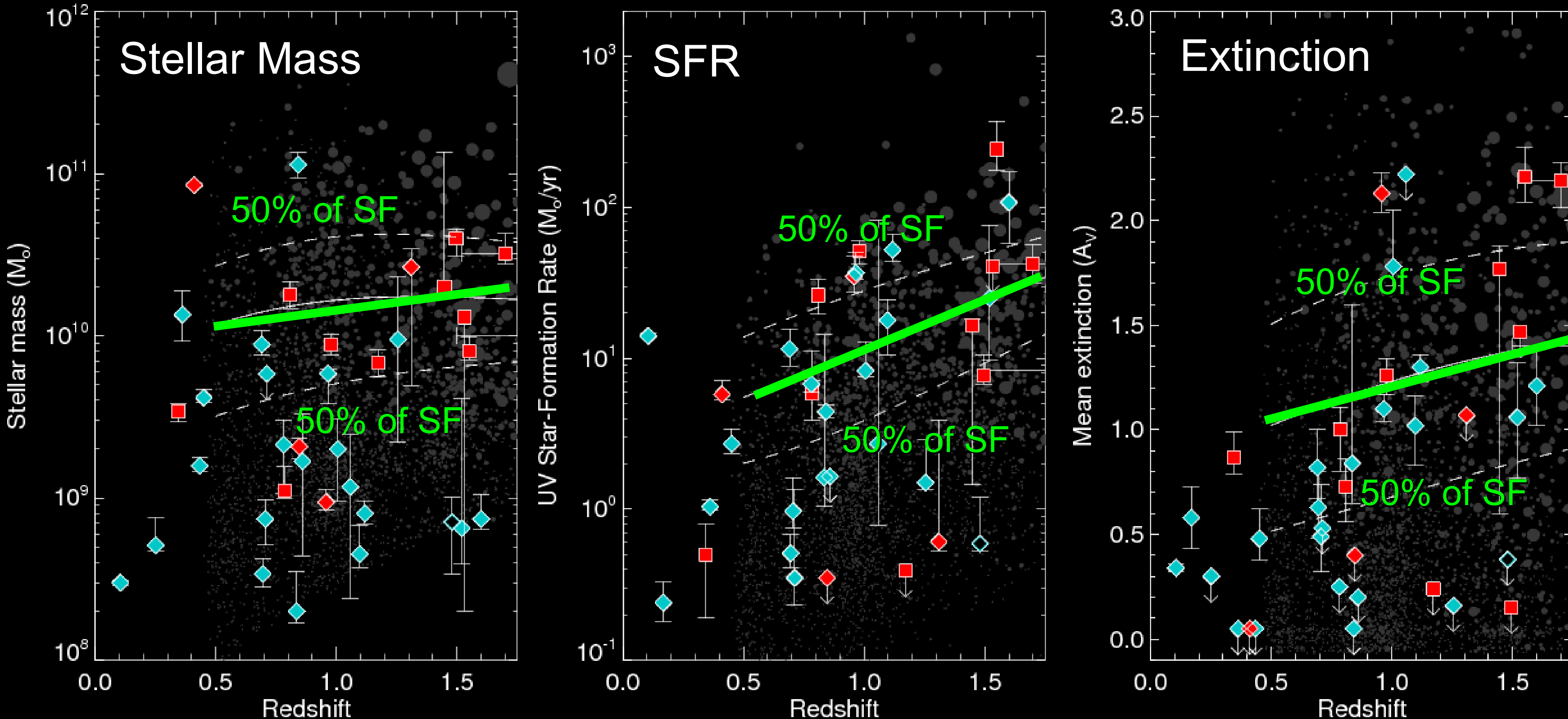

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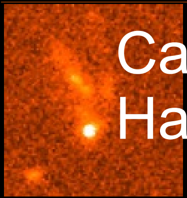

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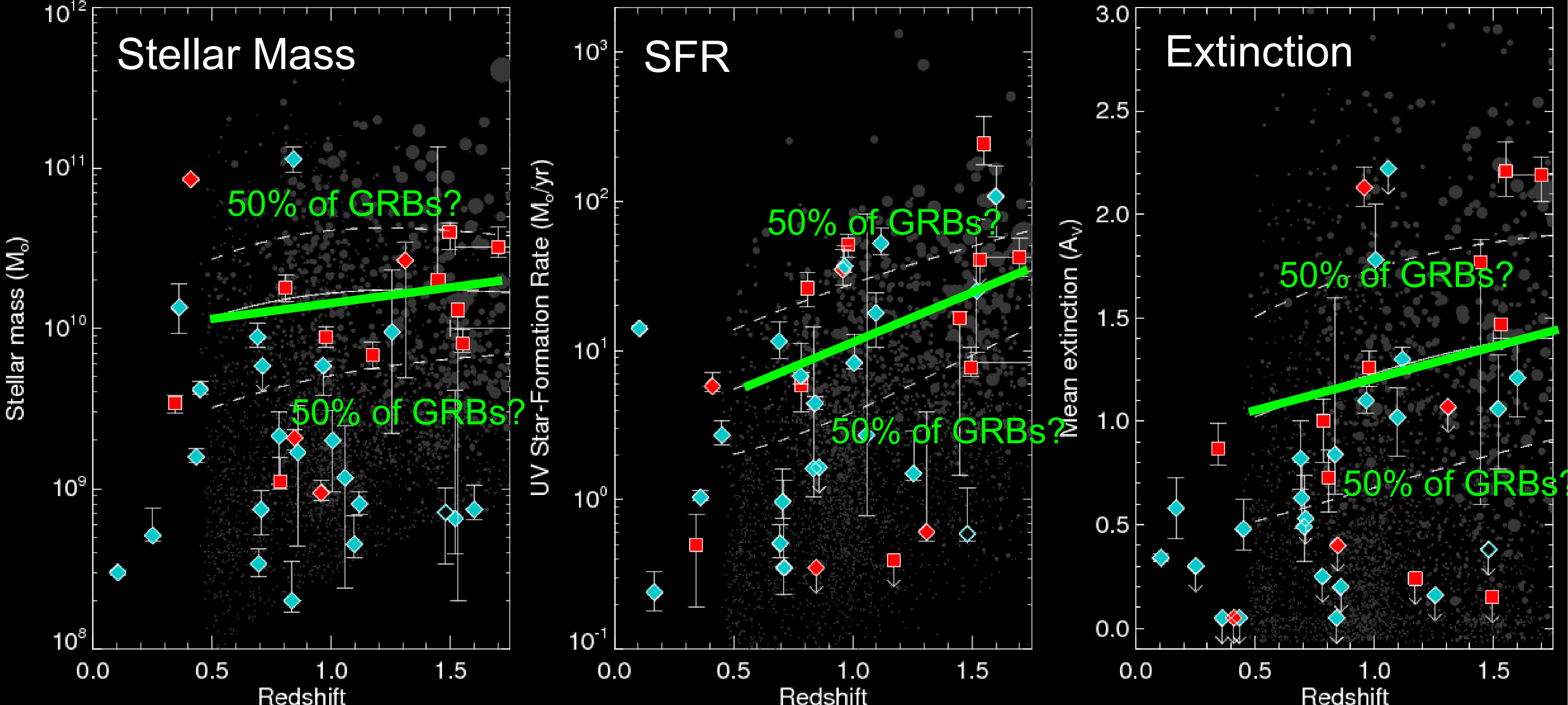

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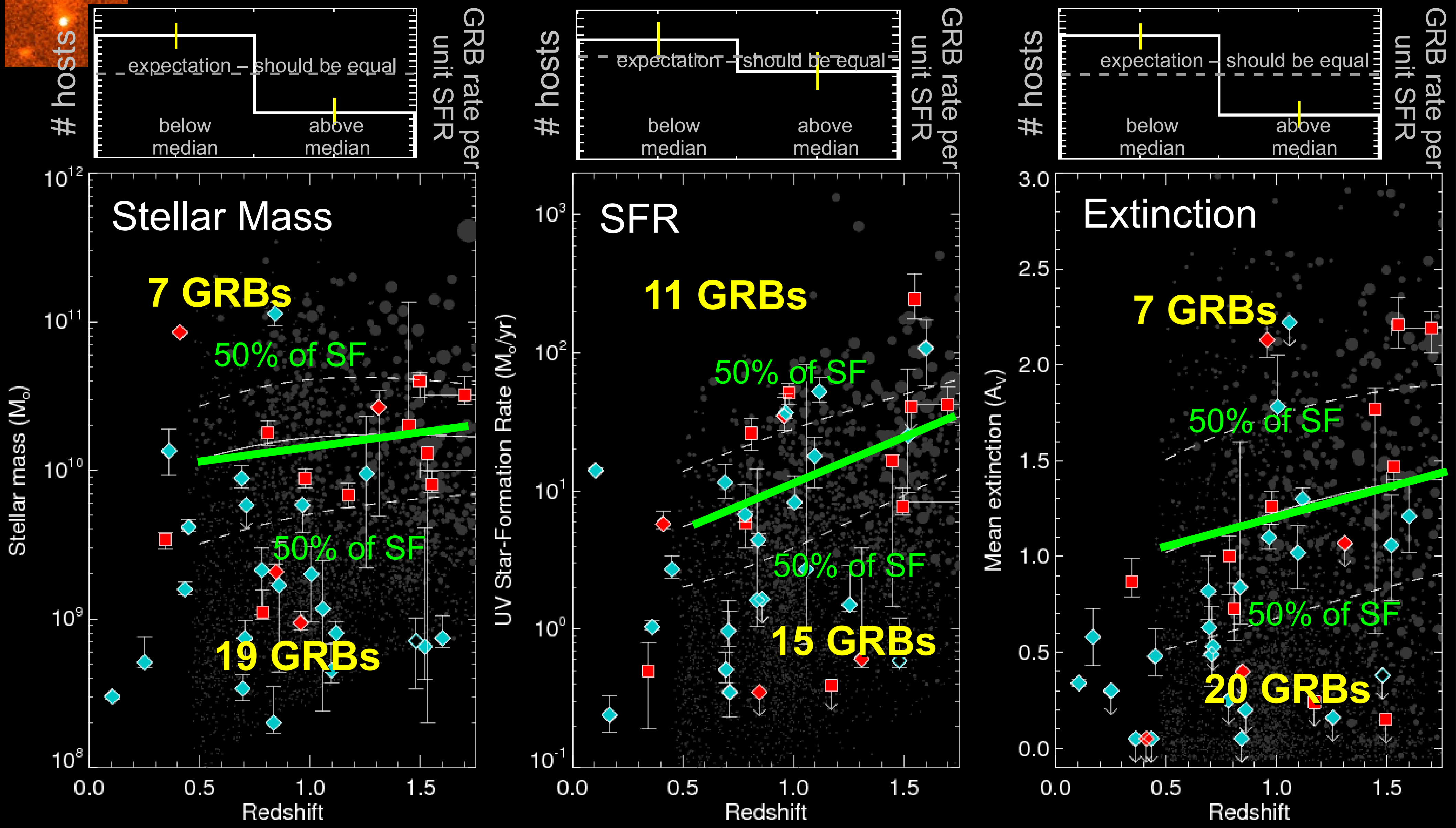
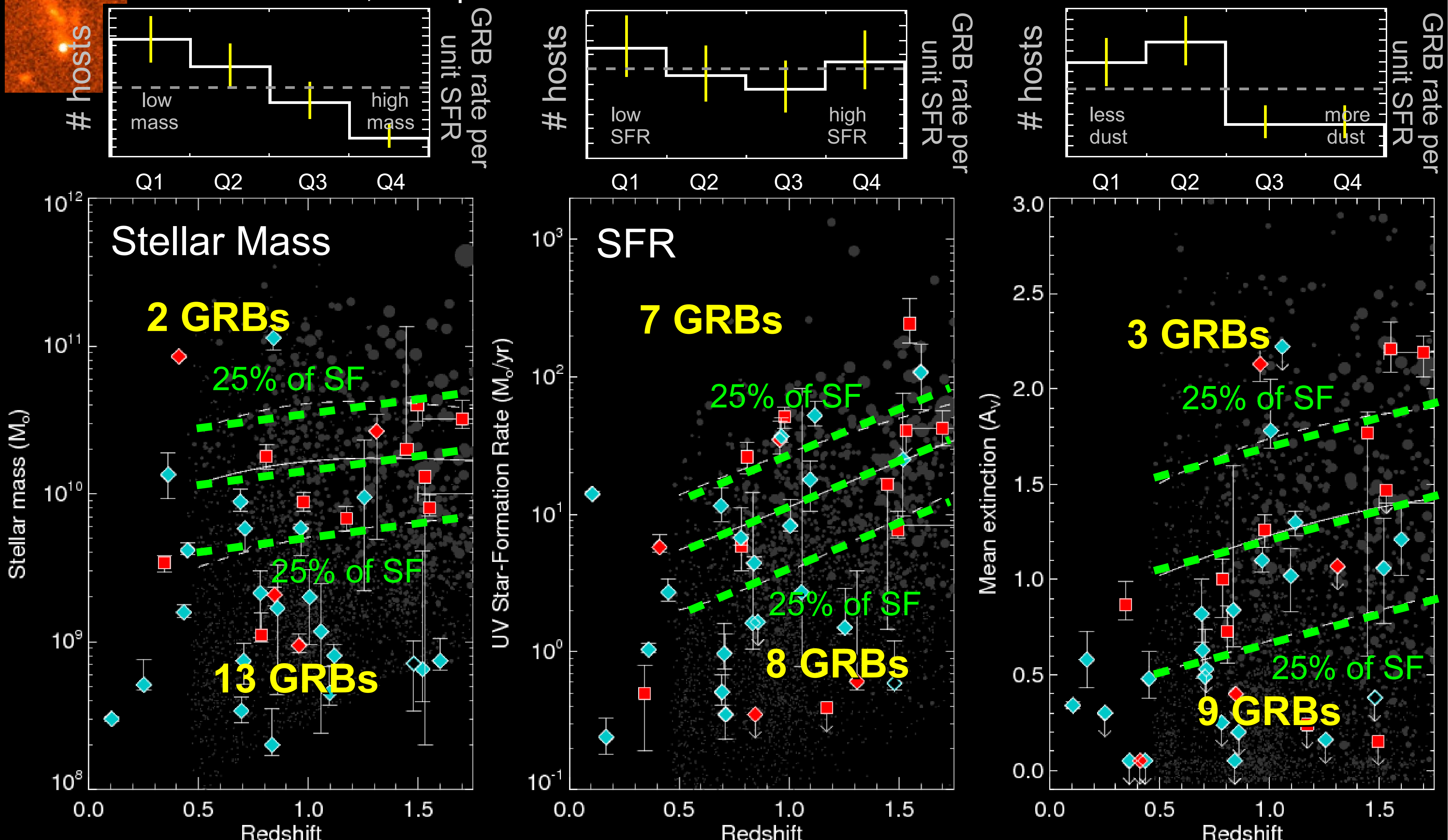


Comparisons vs. Field Galaxies at z~1

For more resolution, use quartiles:



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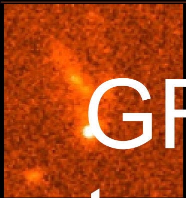

GRBs are poor tracers of star-formation at z~1,
even when dark GRBs are included.

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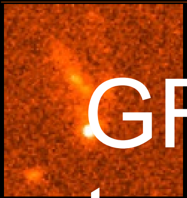

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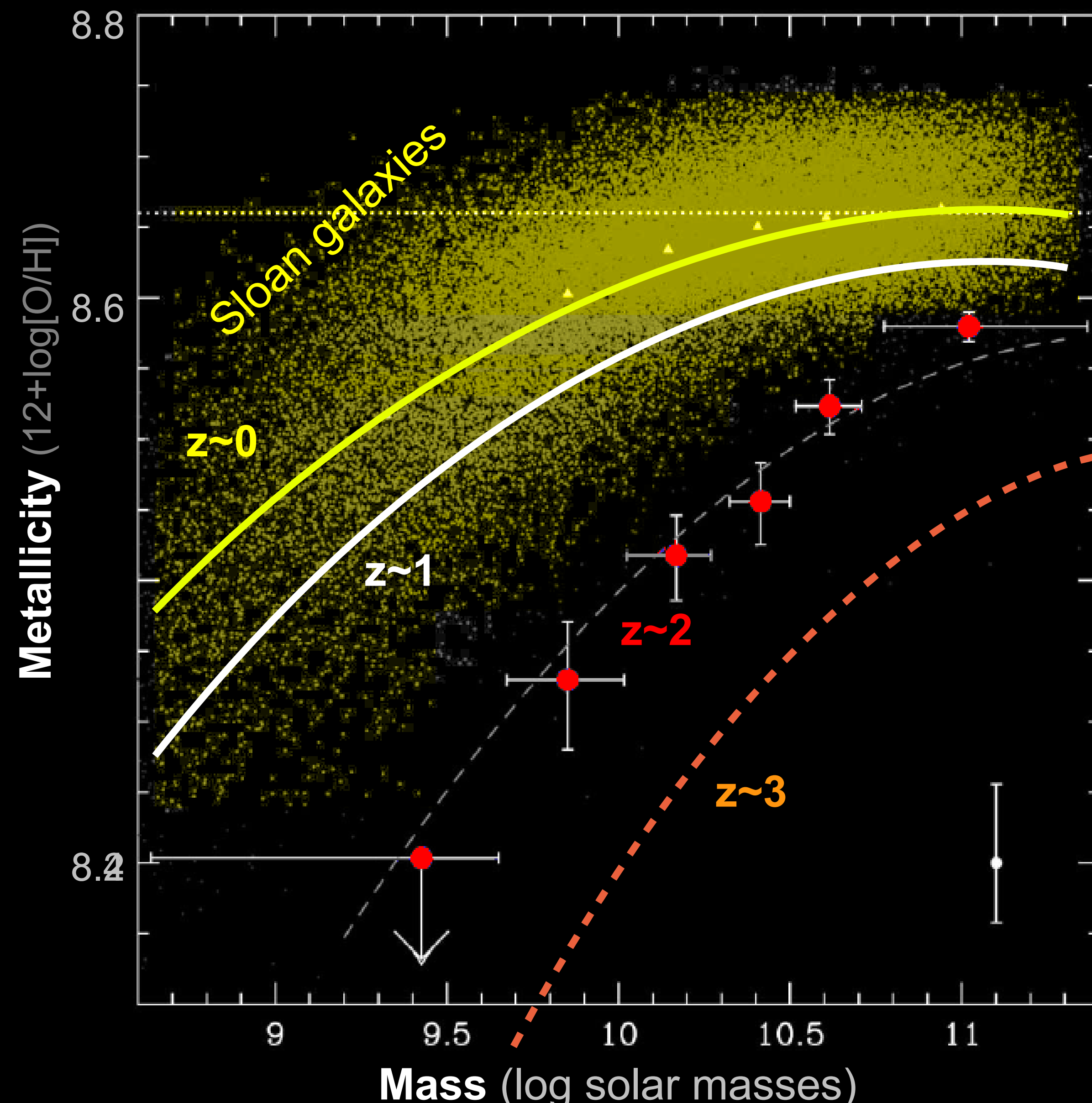
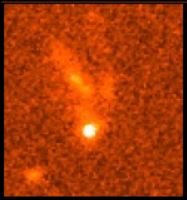
Not too surprising... but what about z ~ 2?



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

GRBs vs SFR at z~2



HST IR Snapshot program

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

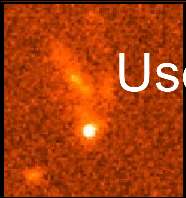
Tibbets-Harlow et al. in prep

VLT Optically Unbiased Host Project ("TOUGH")

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

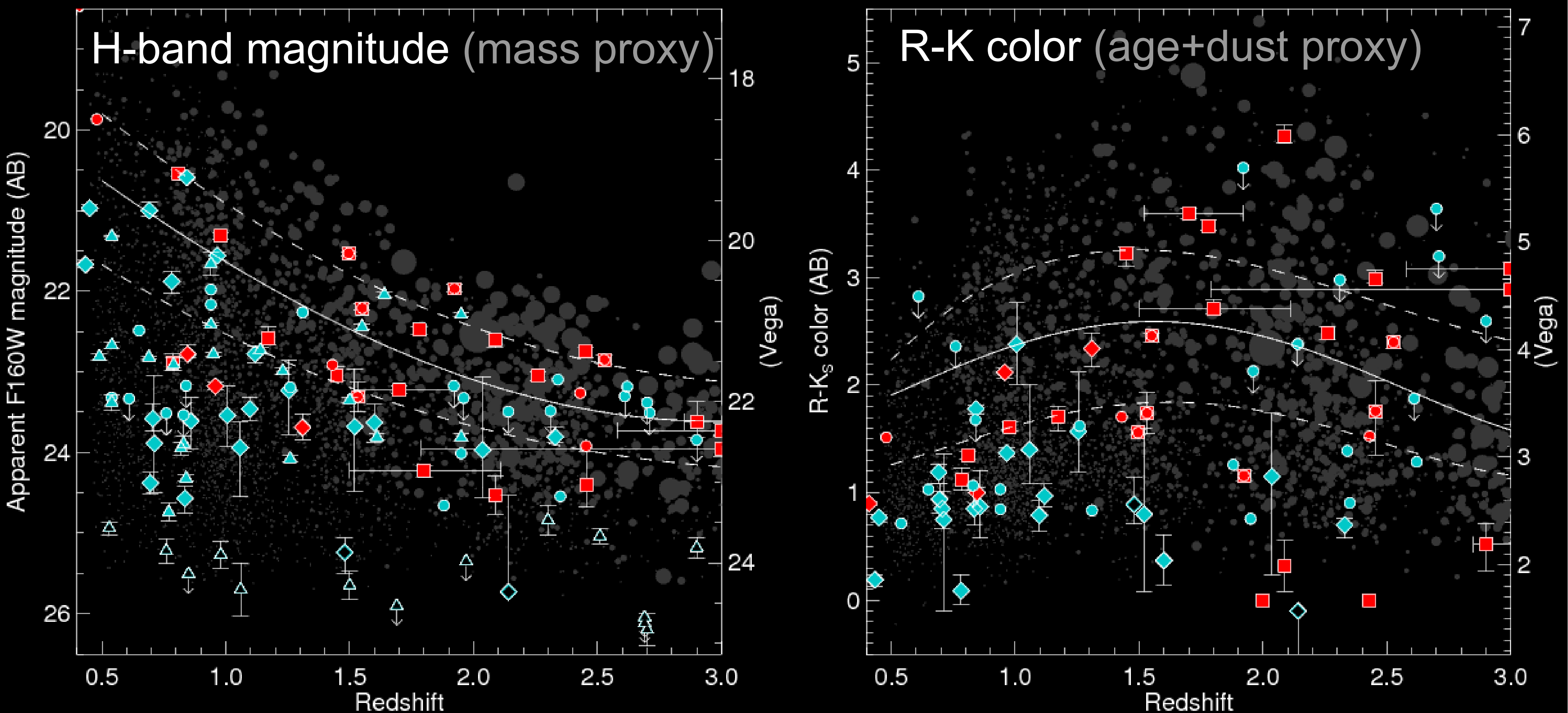
Hjorth et al. 2012
Malesani et al. in prep.
Jakobsson et al. 2012

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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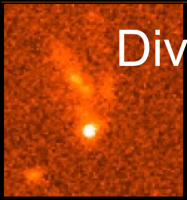
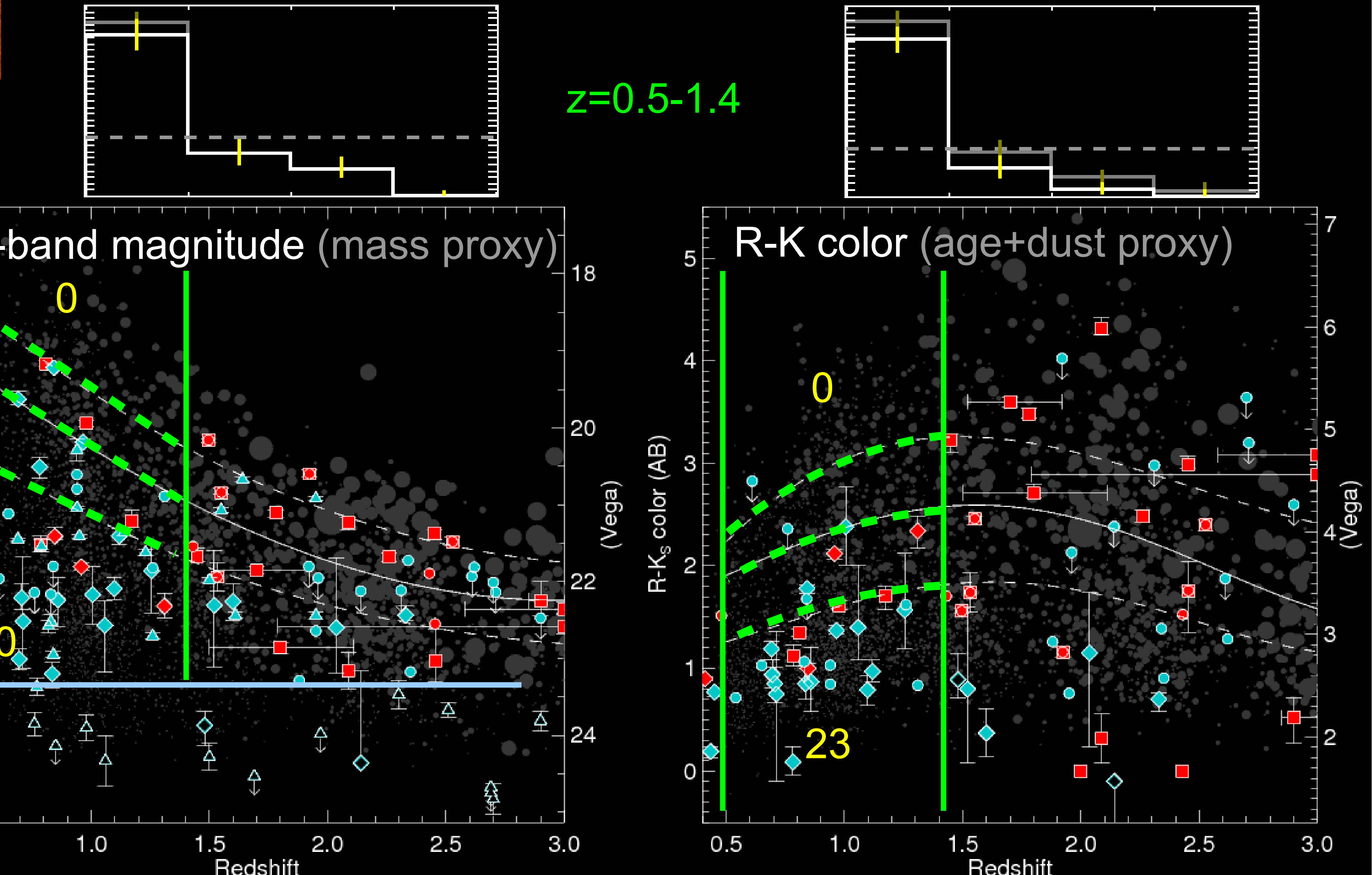
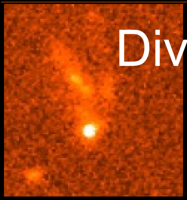


Divide by star-formation quartiles, repeating analysis at z~1 first:

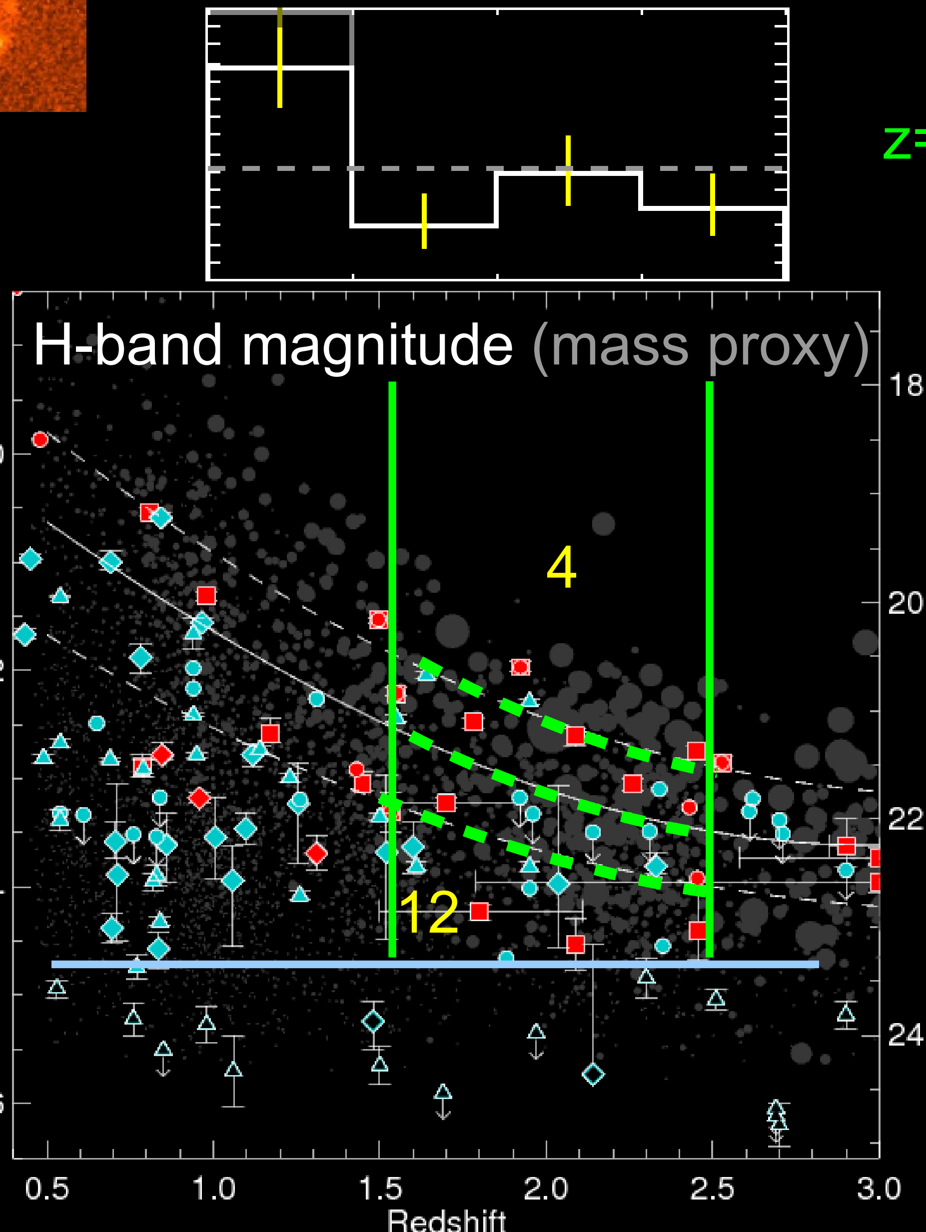


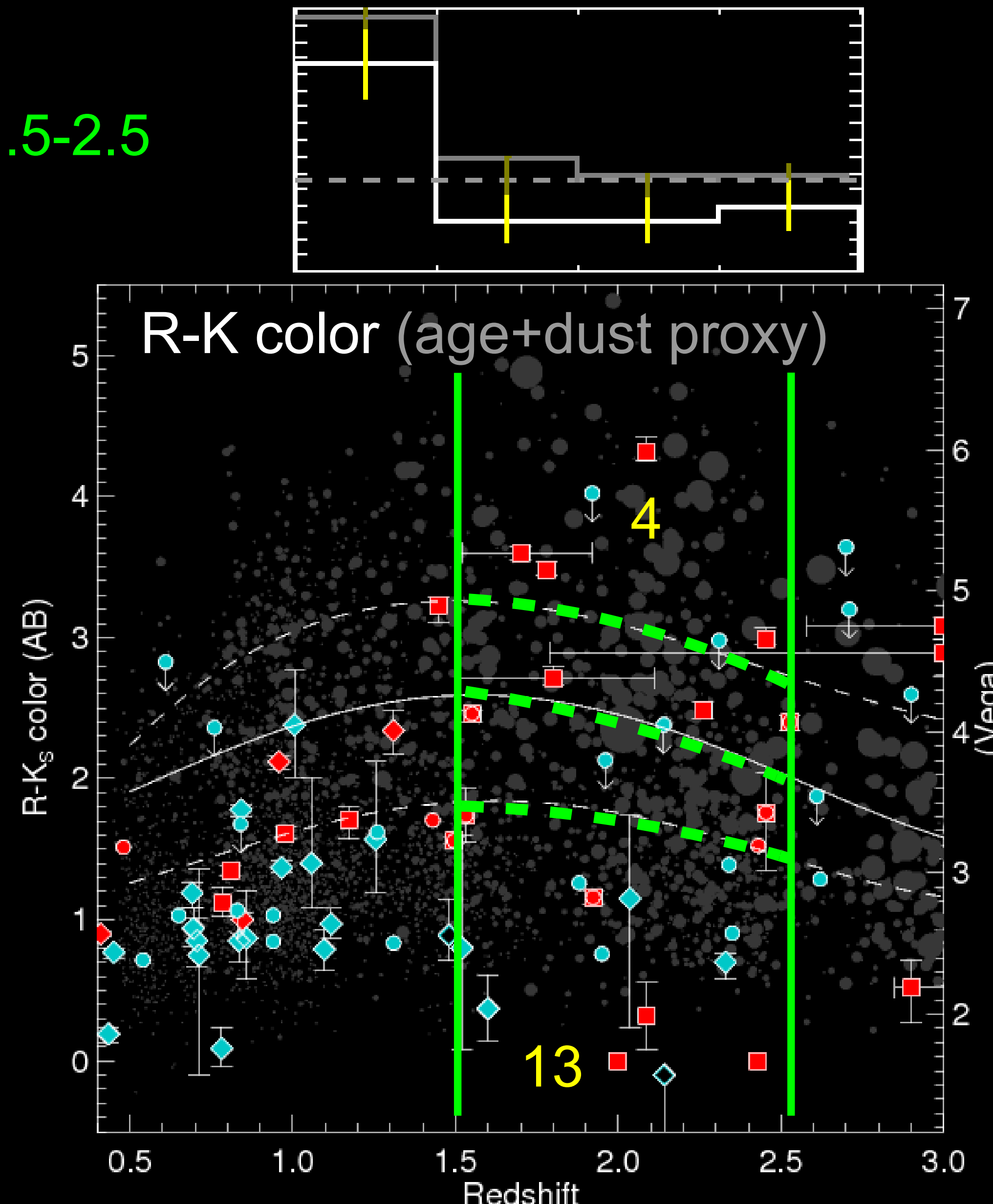
GRBs vs SFR at z~2



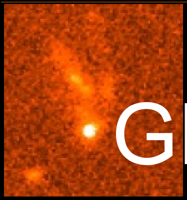
Divide by star-formation quartiles at z~2. Trend still present (but less pronounced)

z=1.5-2.5





Conclusion



GRBs are biased SFR tracers until at least z~2.

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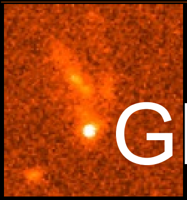

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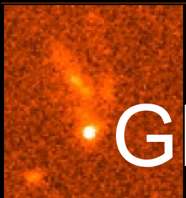

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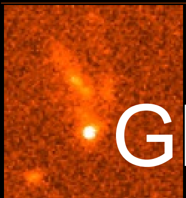

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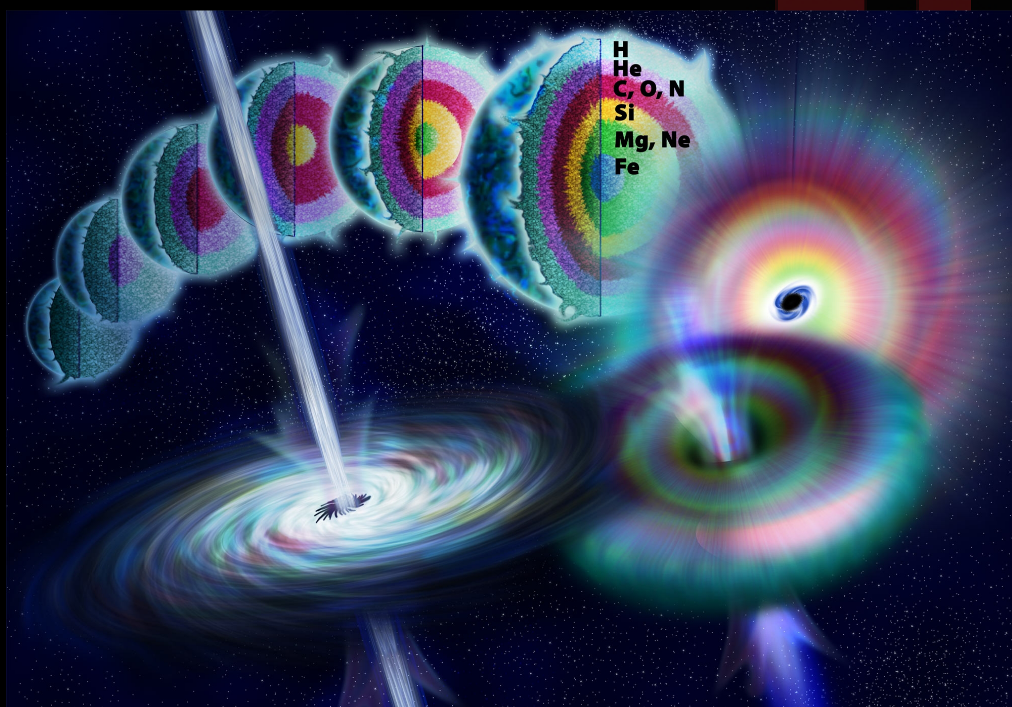

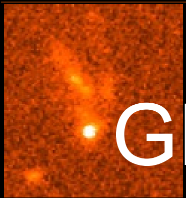

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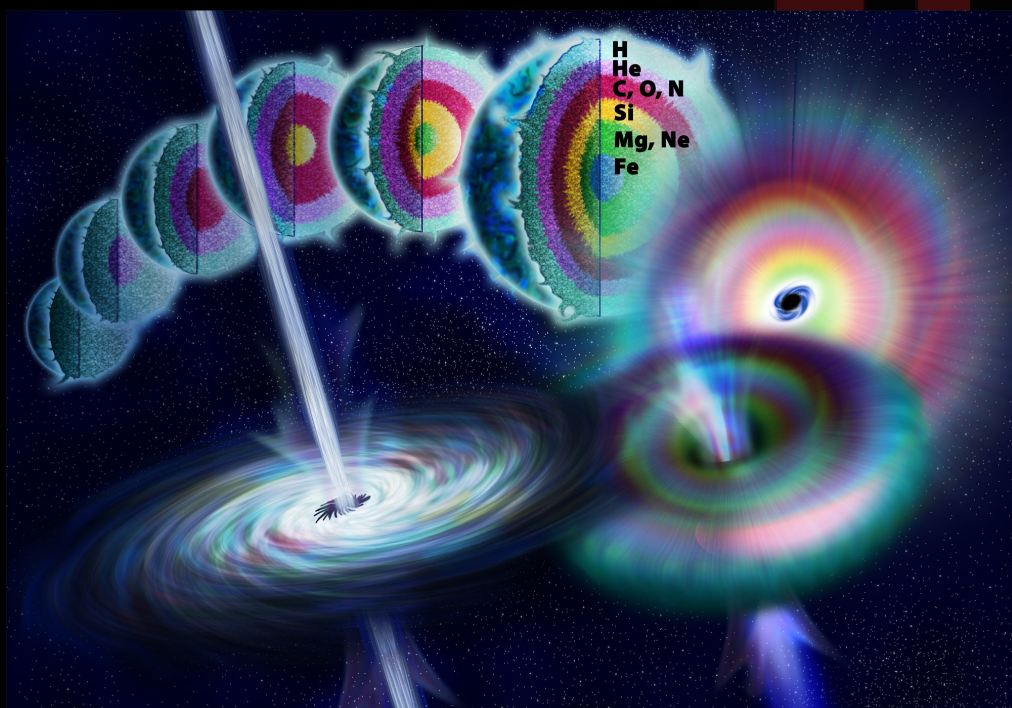
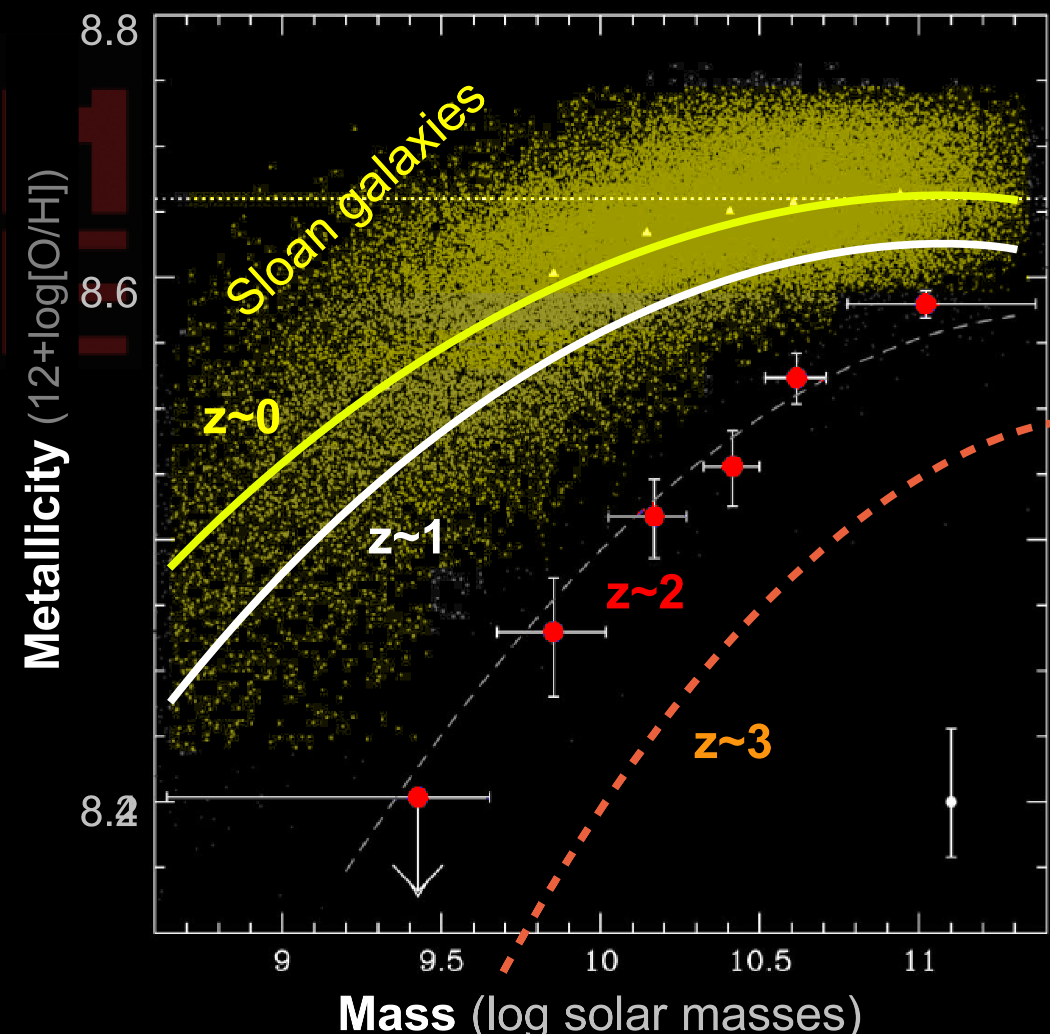
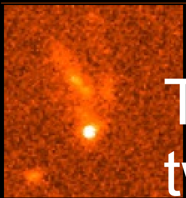




Origins of GRB Rate Variations



The number of GRBs per unit SFR can depend on (at least) two classes of variables.

- ISM **chemical** properties
(affect stellar evolution):
    Metallicity

- ISM **physical** properties
(affect star formation & IMF):
    UV radiation field.
    Gas density.

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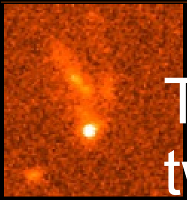

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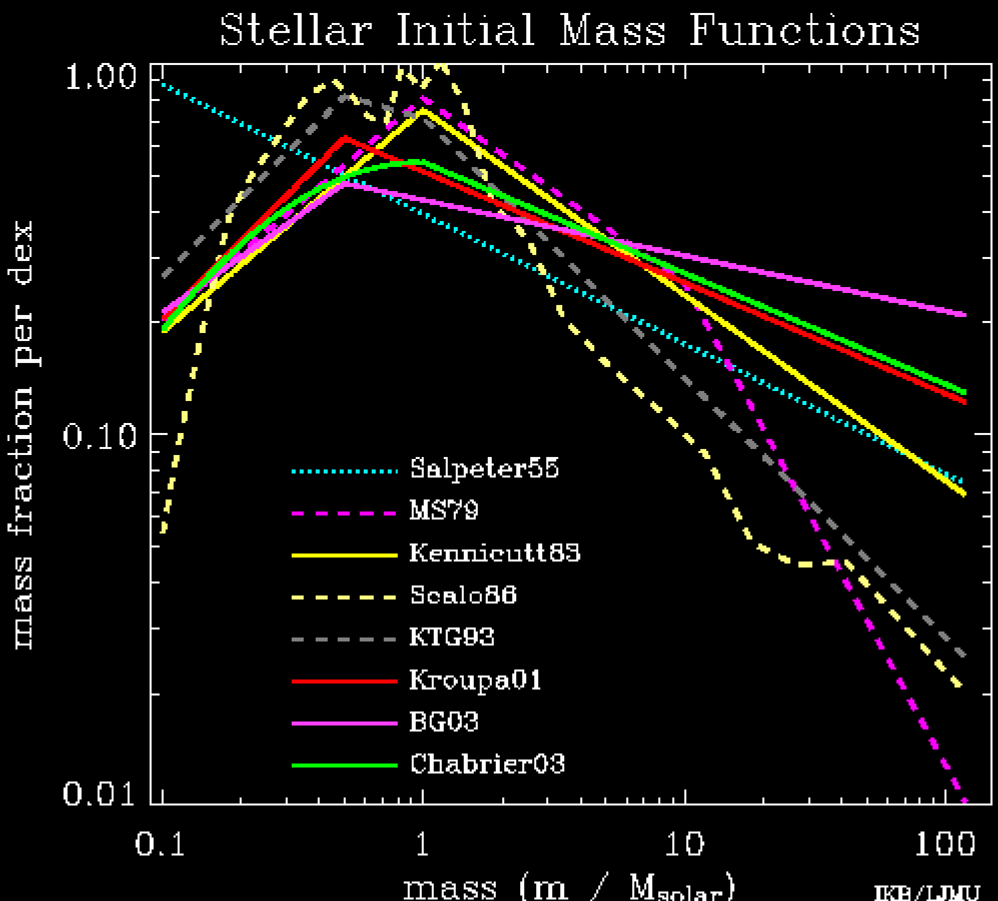

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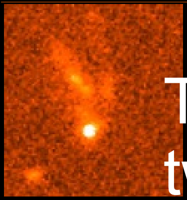

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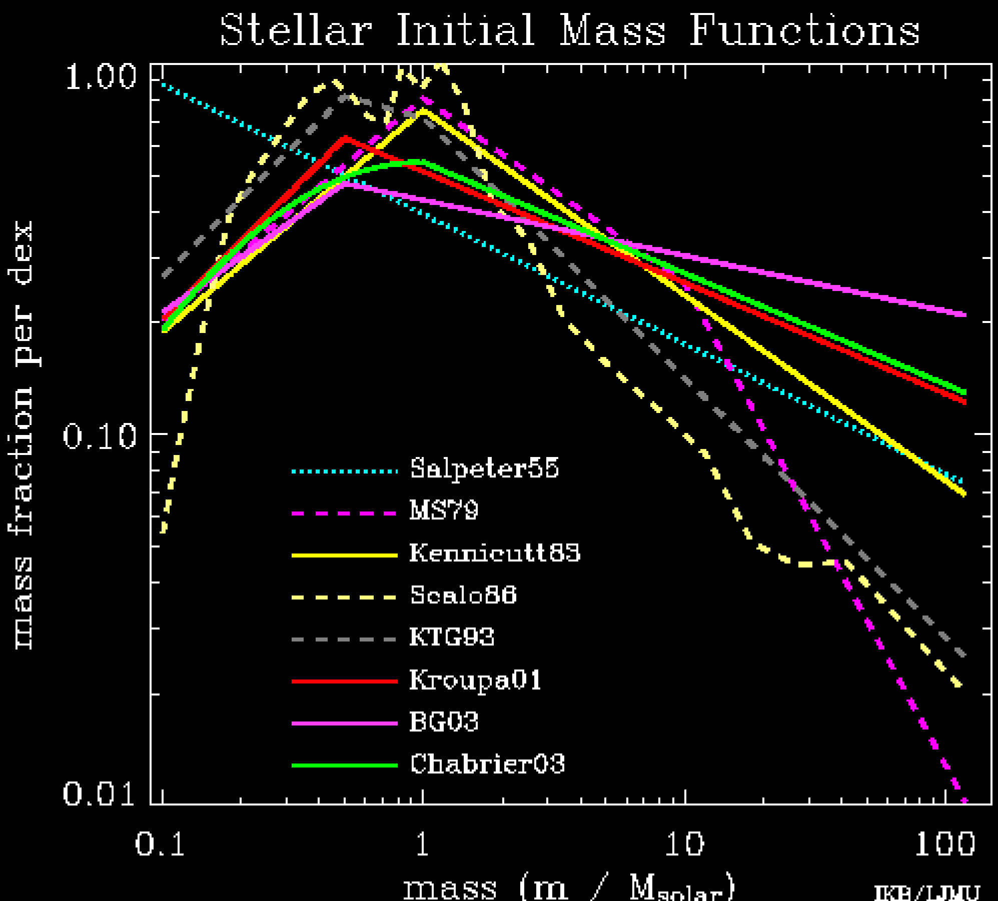

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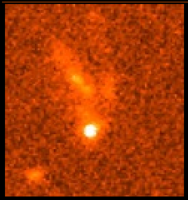

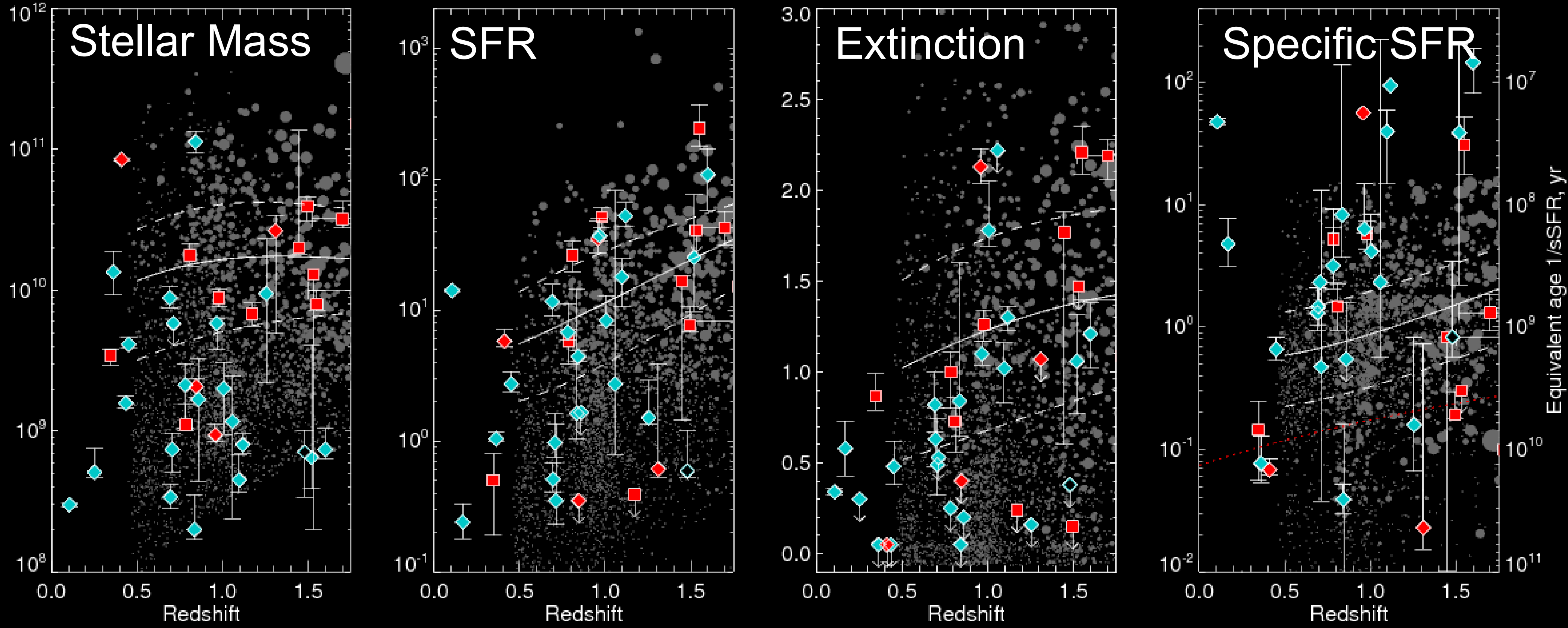

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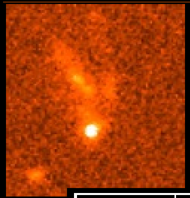

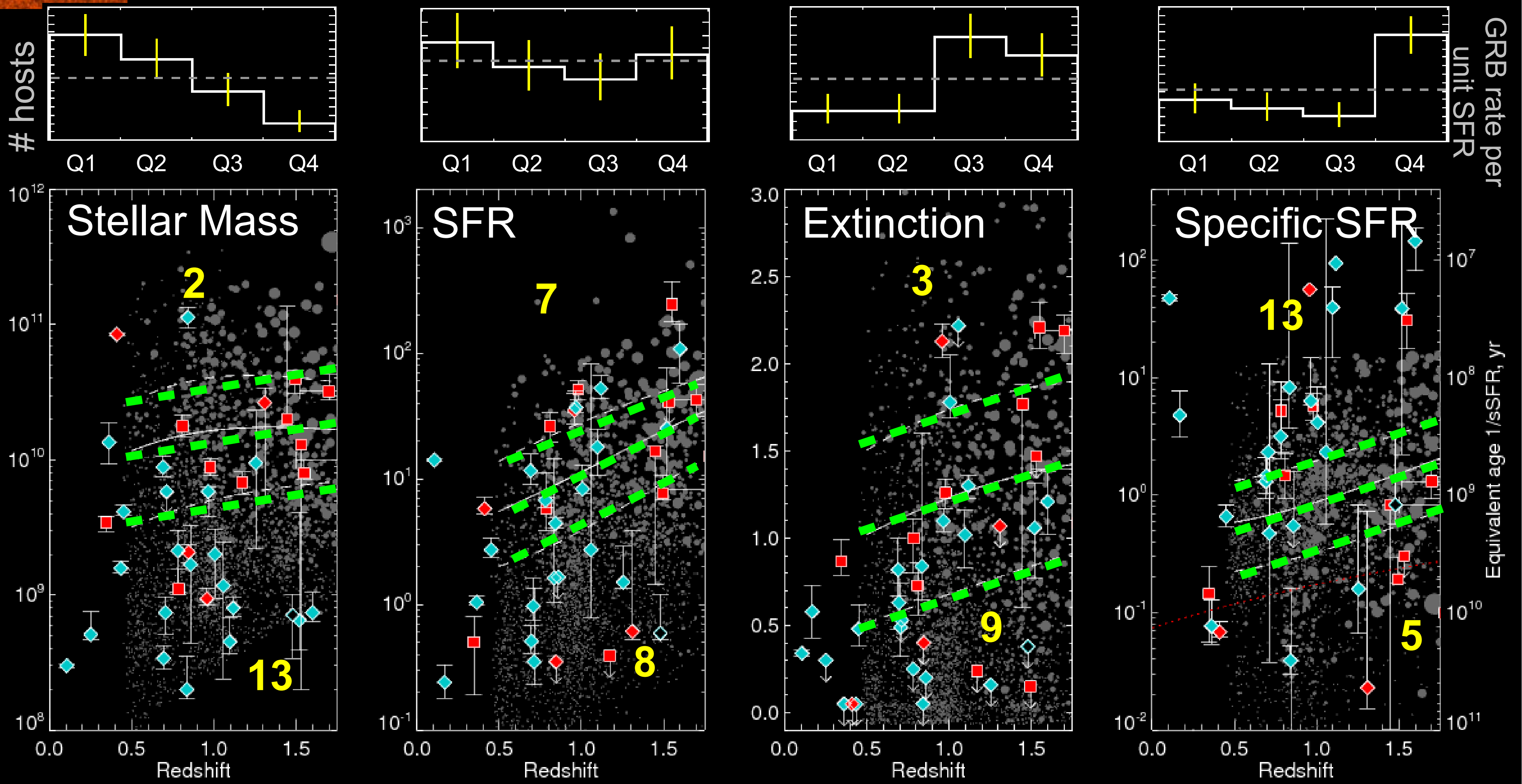

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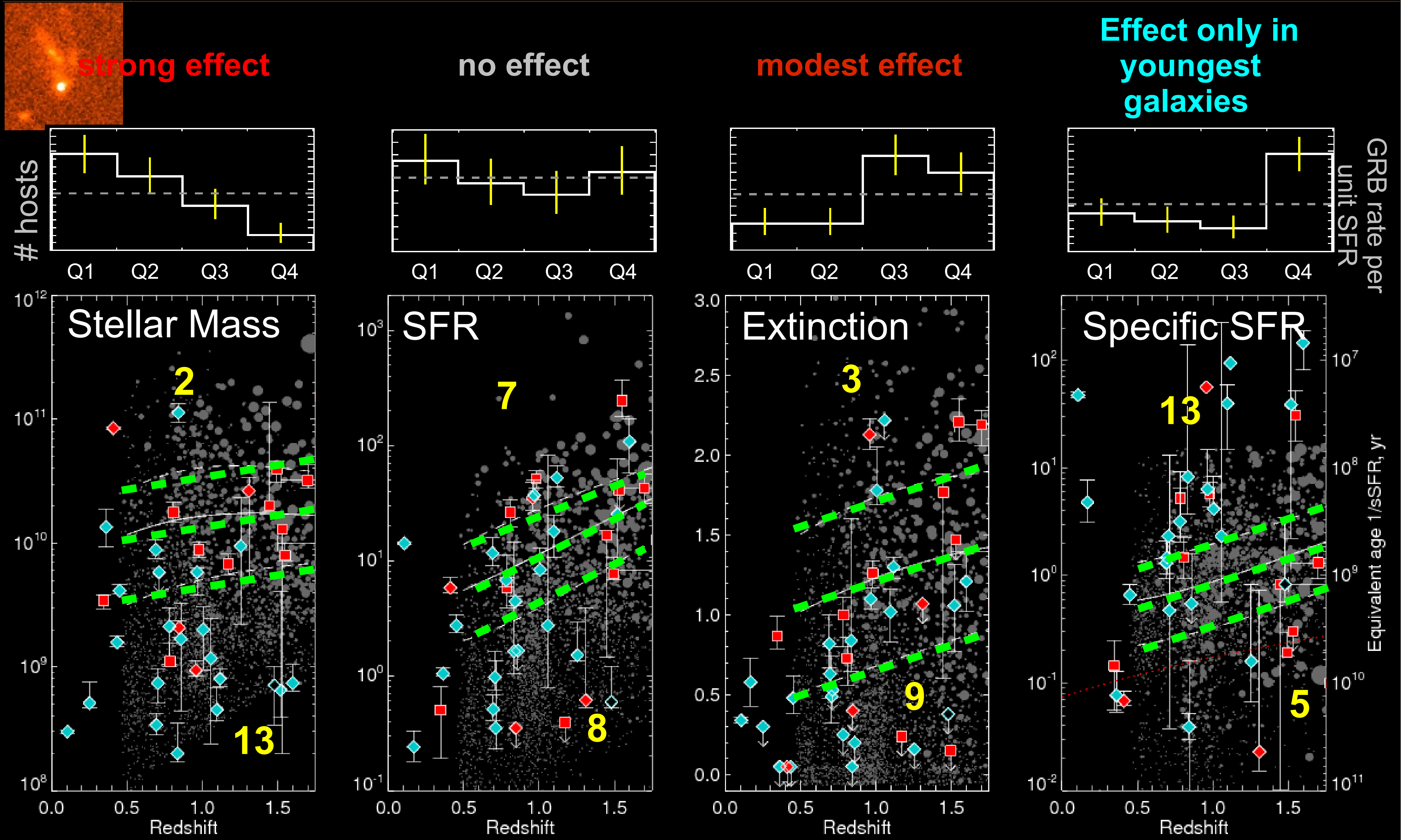

GRBs in submillimeter galaxies?

Densest, most rapidly star-forming galaxies in the Universe are the dusty cores of SMGs. Do we find GRBs there?

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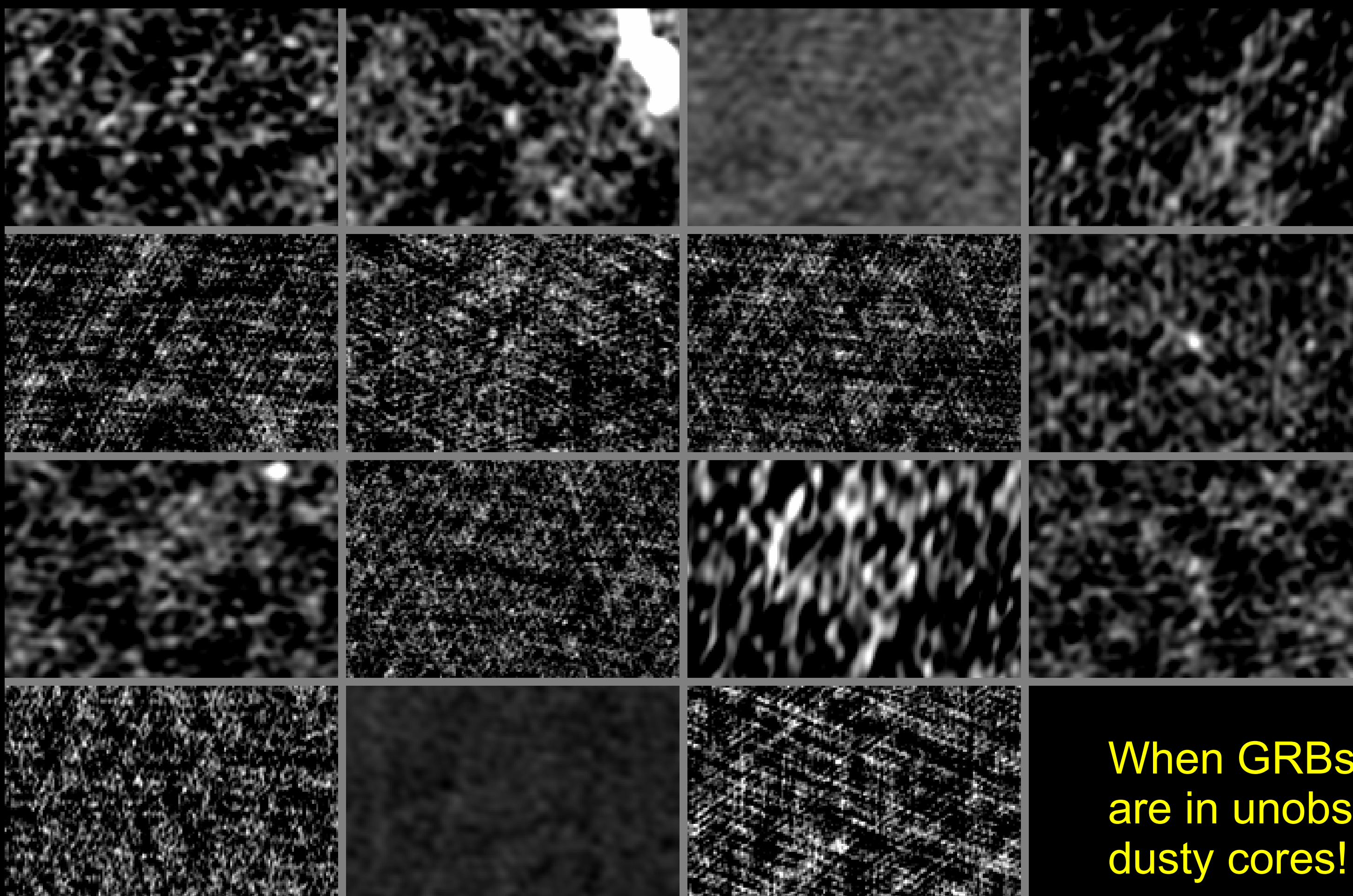
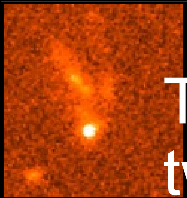


Perley & Perley 2013: Few JVLA radio detections among dark GRB hosts – these are *not* luminous SMGs

When GRBs *are* found in SMGs they are in unobscured regions, not the dusty cores! (e.g. Michalowski+2009)

Origins of GRB Rate Variations



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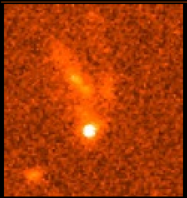
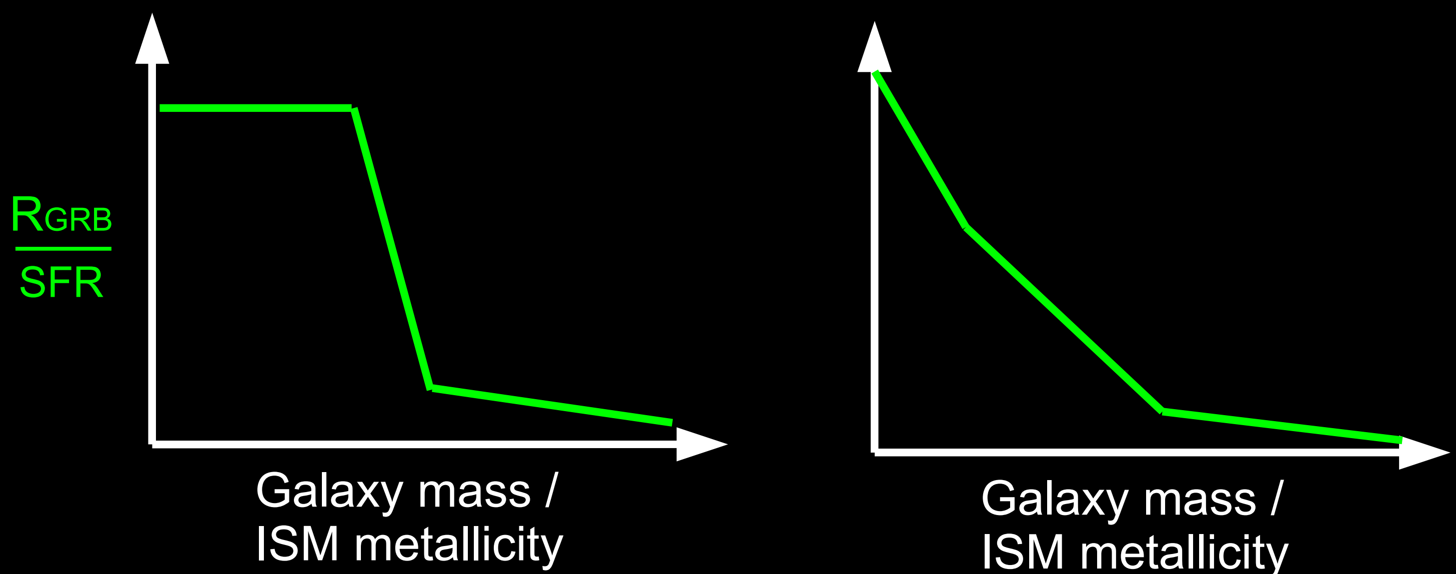
Quantifying metal dependence



Is there a regime where GRB rate variations (due to e.g. metallicity) can be ignored?



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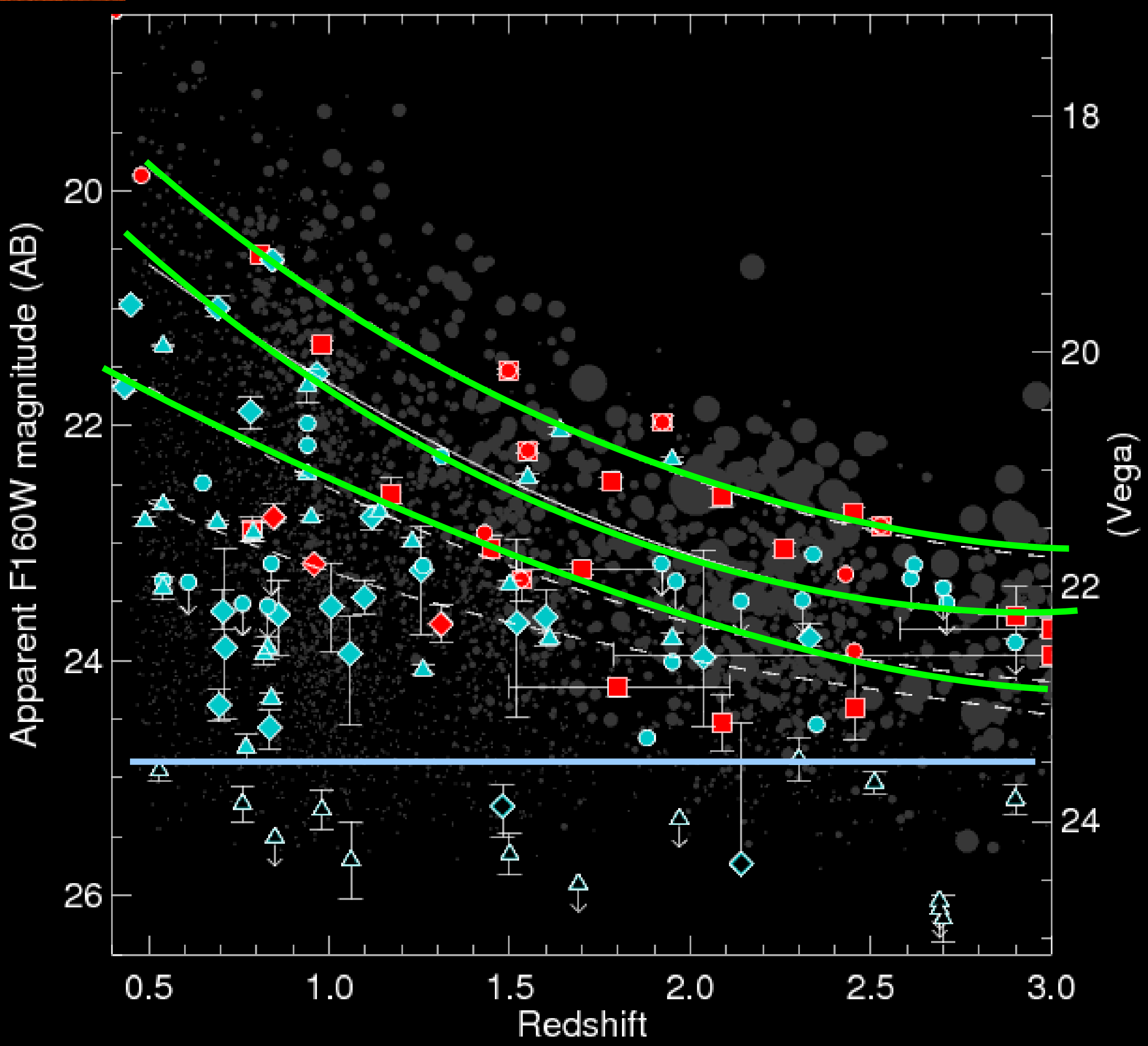

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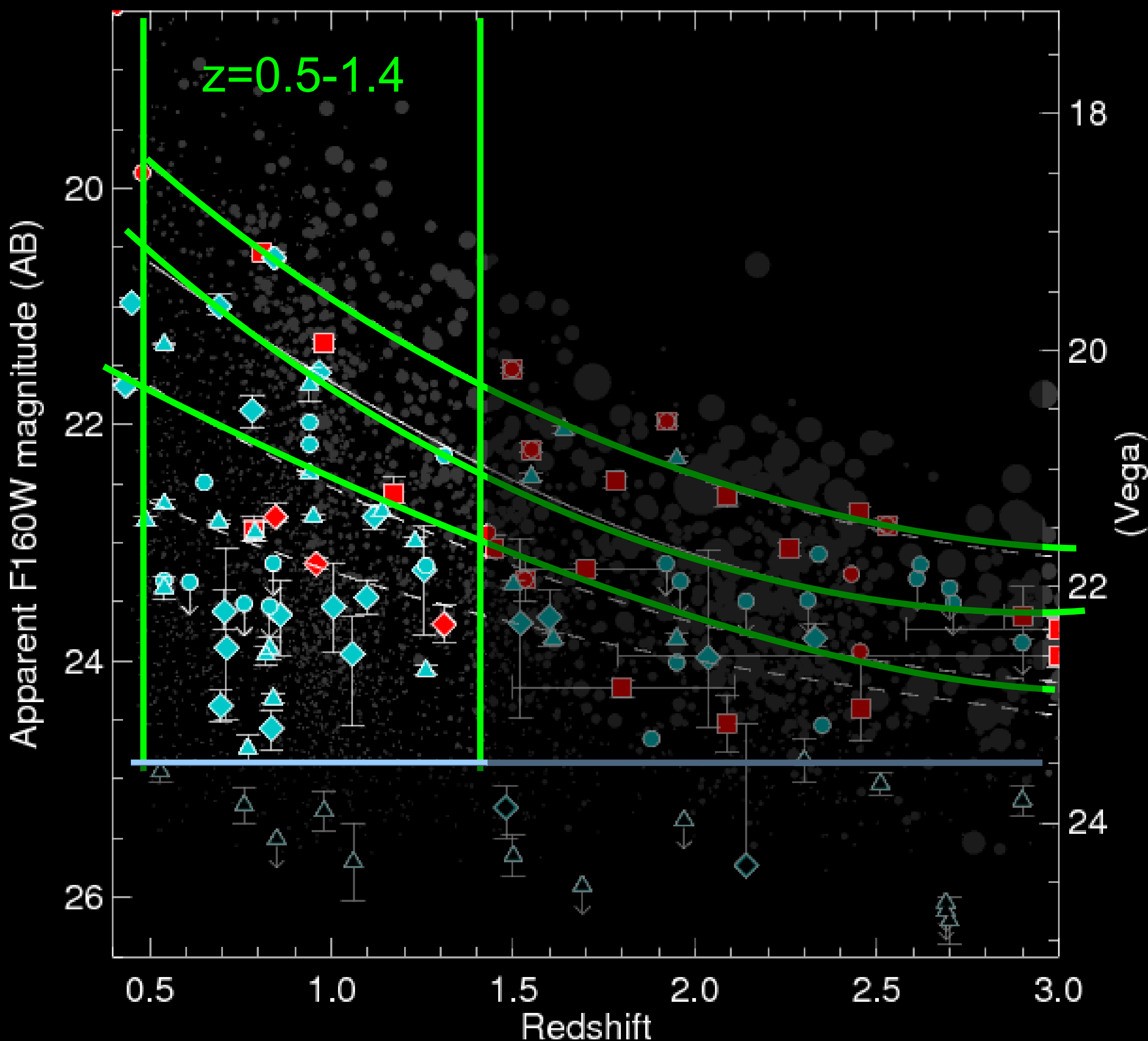

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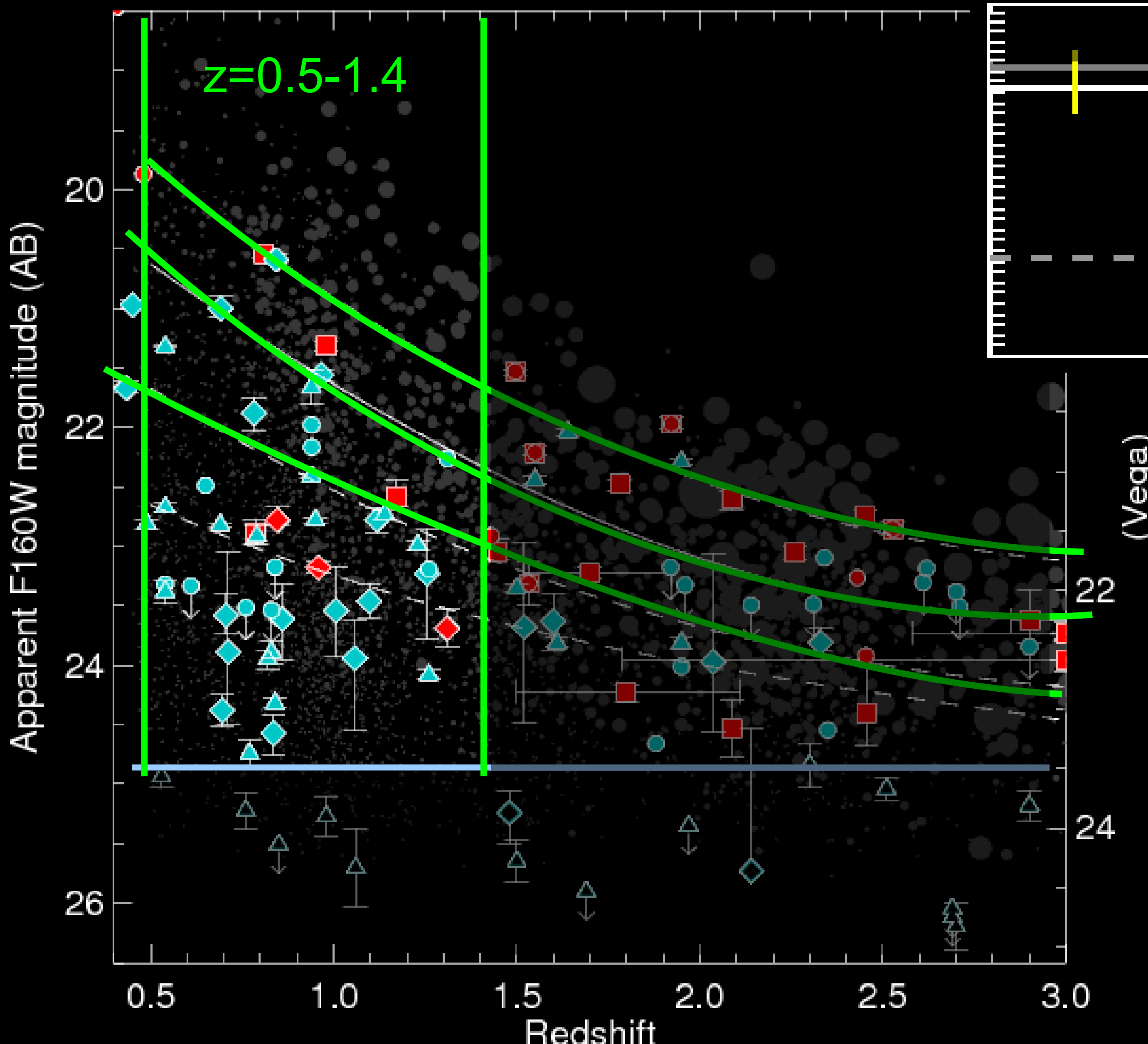

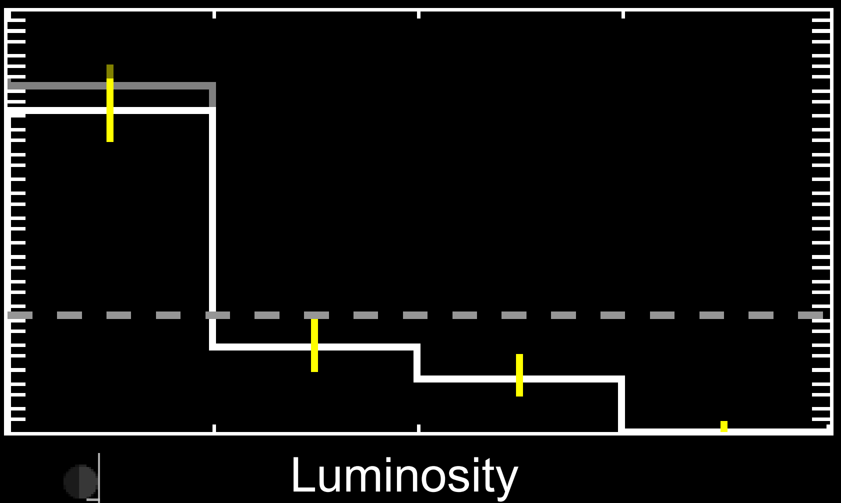

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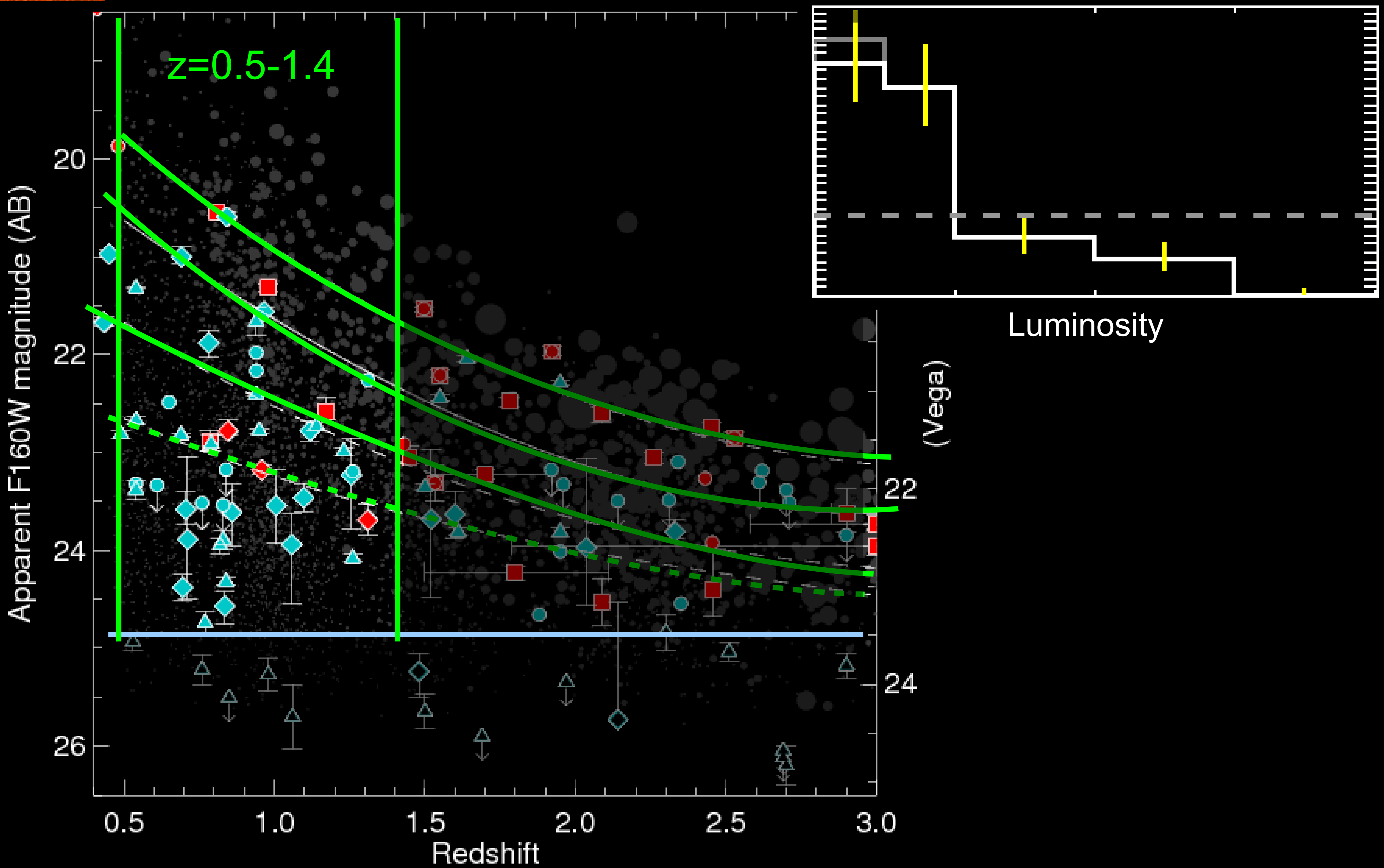
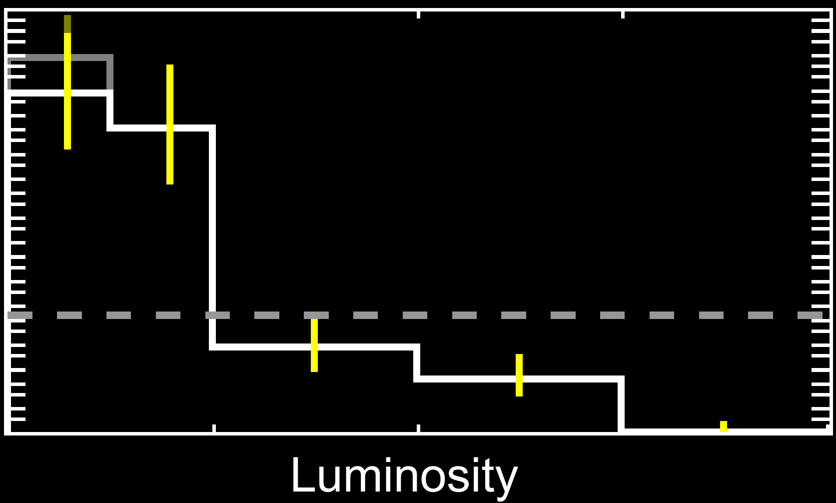
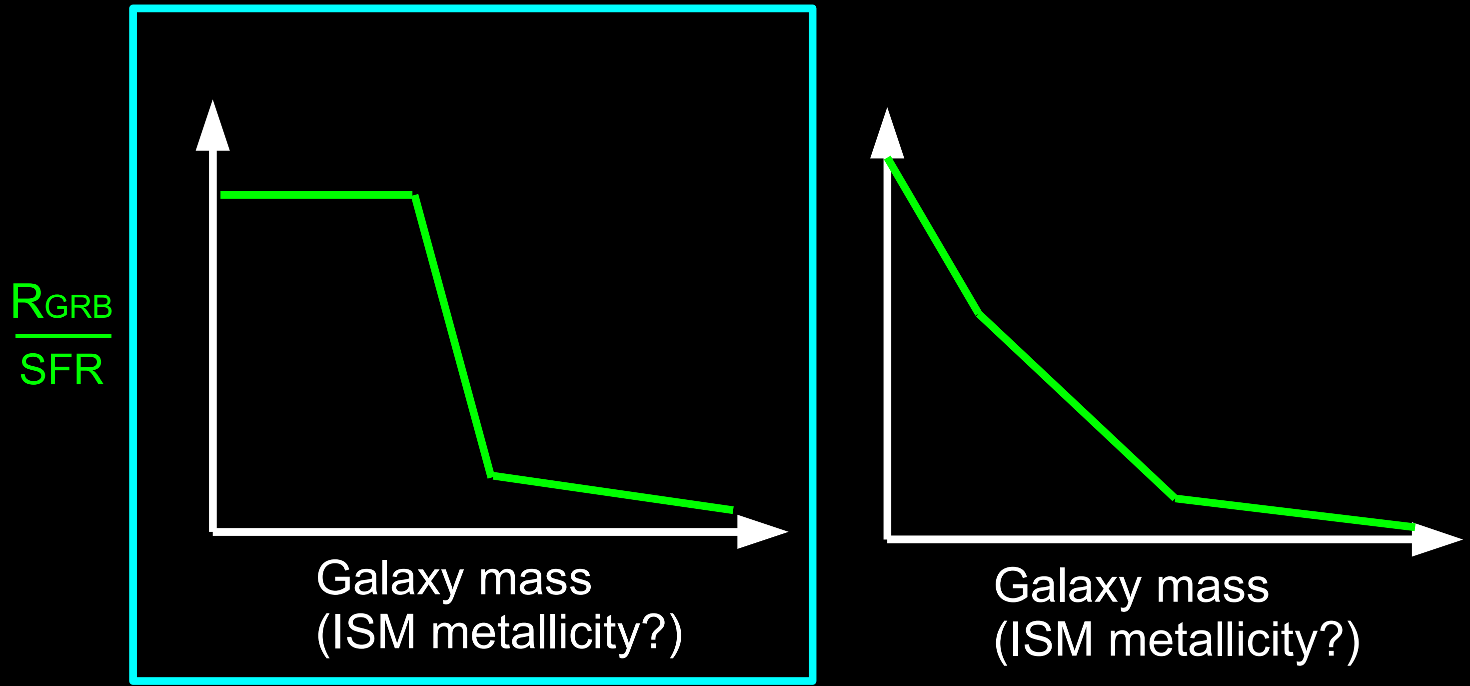


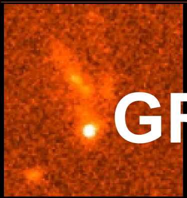
Quantifying metal dependence

No significant luminosity dependence below $M < 10^{9.5}\ M_\odot$ observed so far – consistent with a ~1/2 $Z_\odot$ “threshold”.





Conclusions



- **GRBs at z<2 are not unbiased tracers of star-formation.**
    - Consistent with metallicity dependence.
        - Possible secondary amplification of GRB rate in high-sSFR galaxies?
    - Rate variation levels off at low-mass end
        - No further variation below $<10^9 M_\odot$ @ z~1
        - Metallicity "threshold" at $\sim 0.5 Z_\odot$ may be real
        - Still viable tracers for low masses, z>3? Maybe...

Dark burst hosts are very different from unobscured hosts.

Including both unobscured and obscured bursts in correct proportion is *critical* for statistical analysis and further progress!