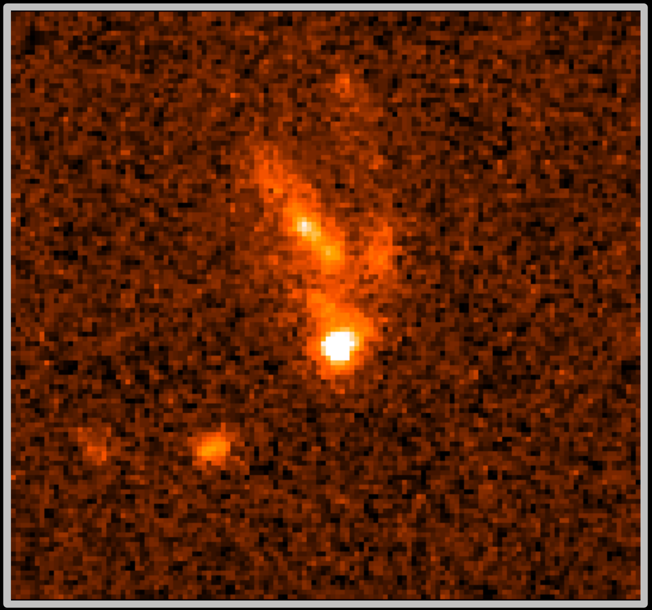
Gamma-Ray Bursts as Tracers of High-Redshift Star Formation: *Promises and Perils*

Daniel Perley
(Hubble Fellow, Caltech)



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Johan Fynbo
Daniele Malesani
Thomas Krühler
Andy Fruchter
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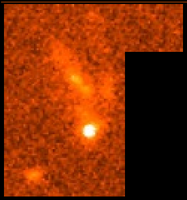
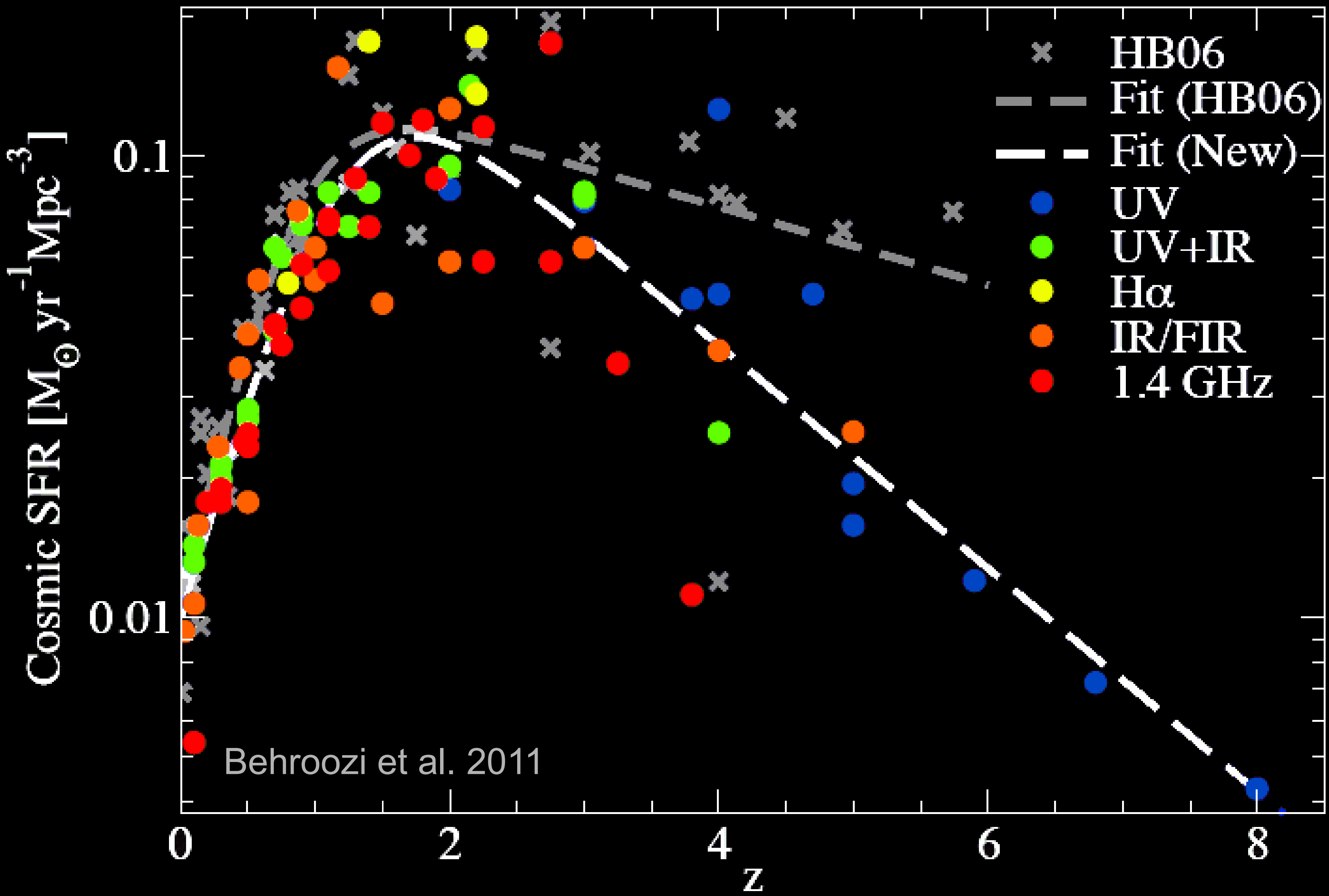
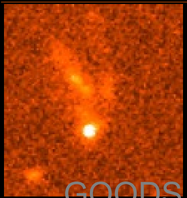
Cosmic Star-Formation History

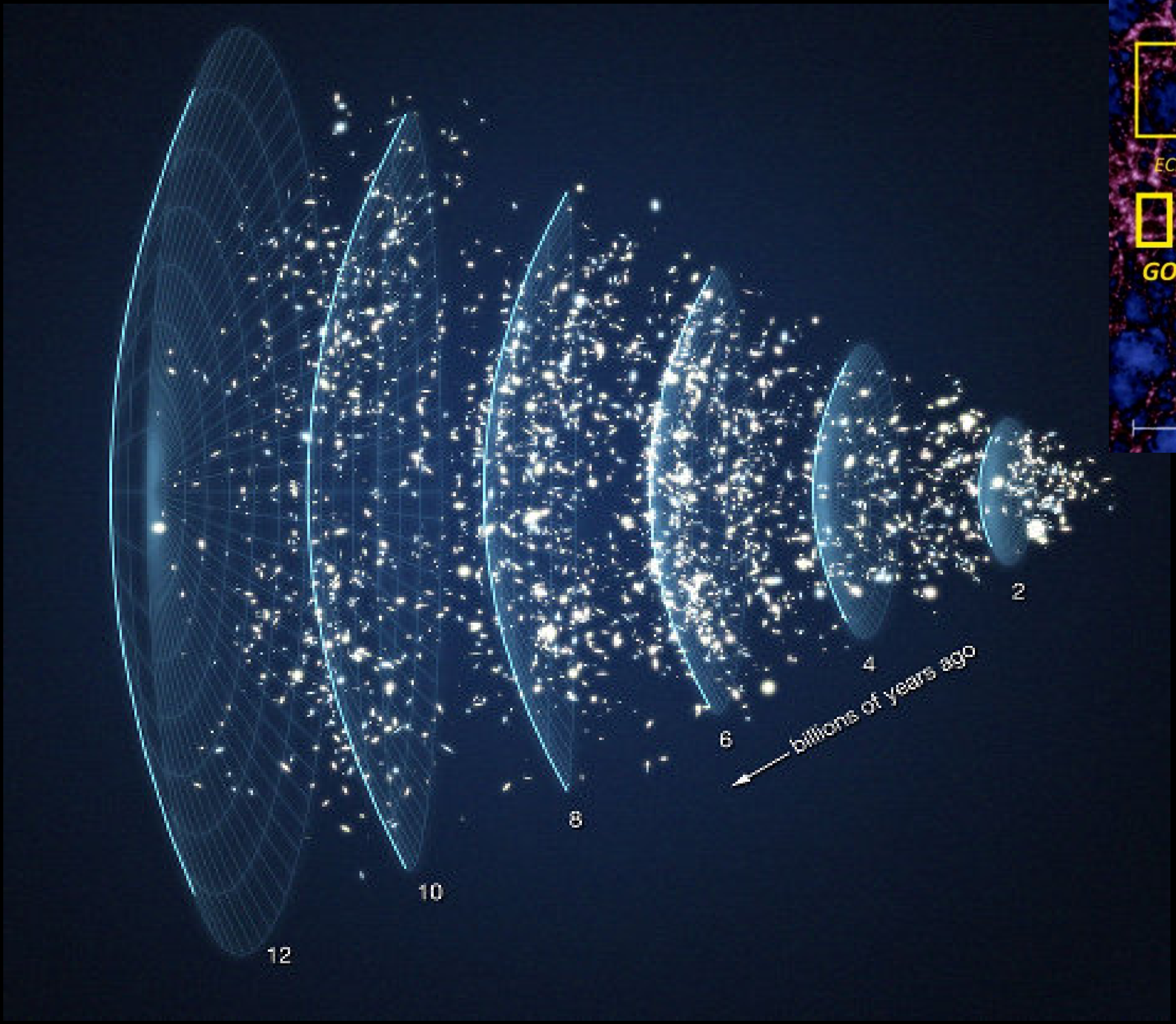


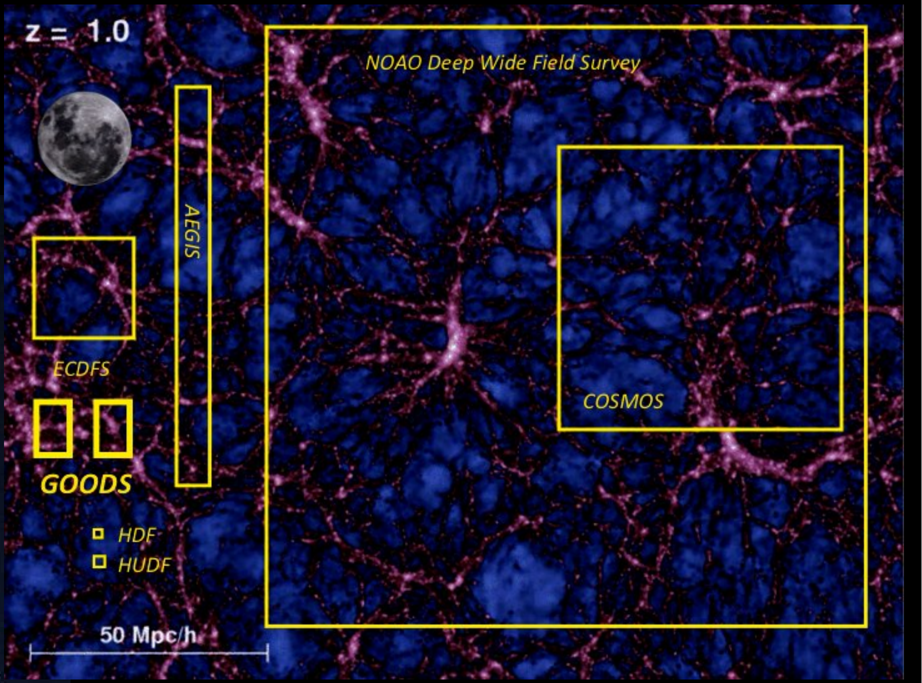


Field-Survey Strategy



GOODS visualization from ESO.org





from CANDELS blog

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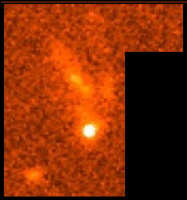
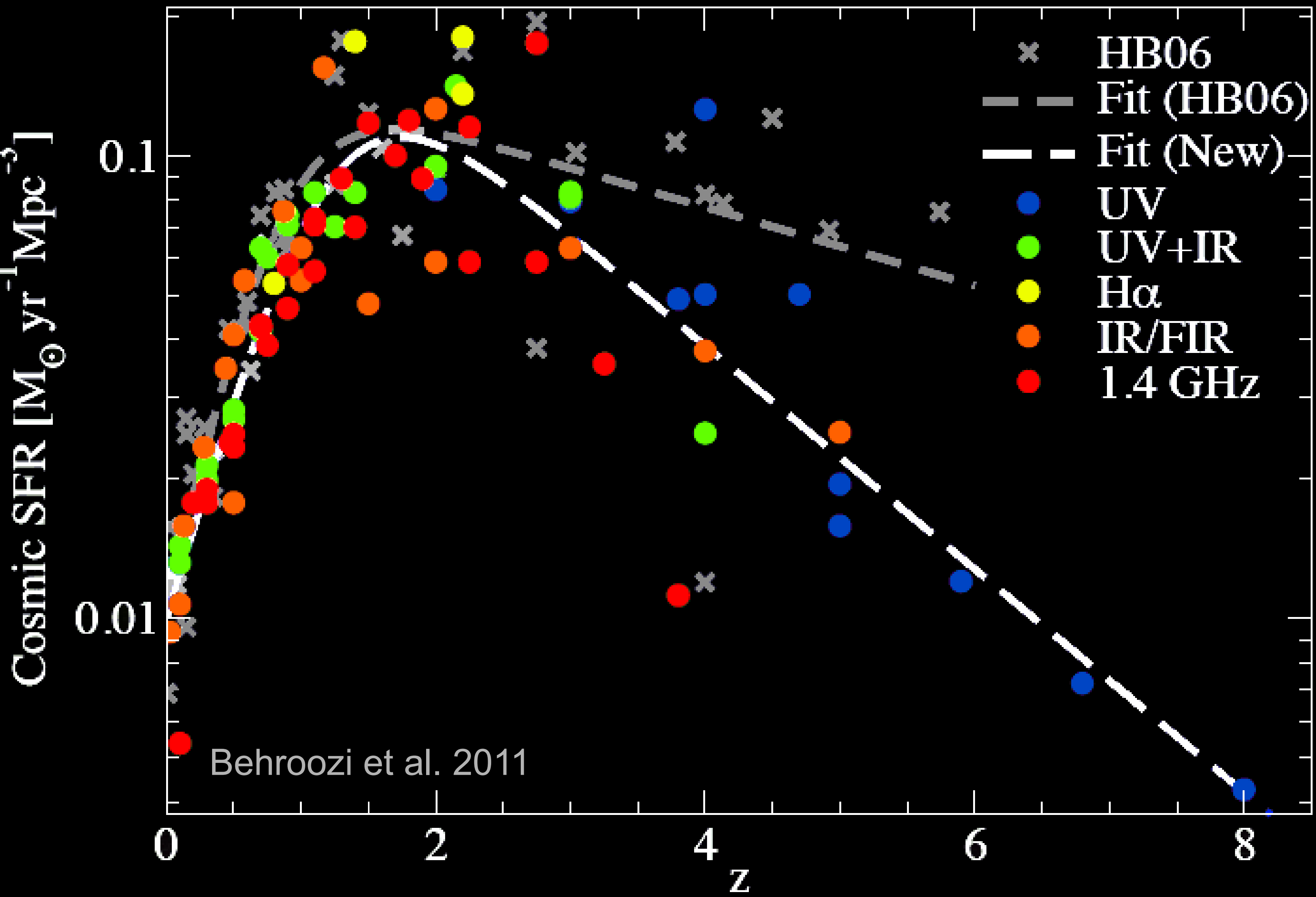




Limitations of Field Surveys

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.)

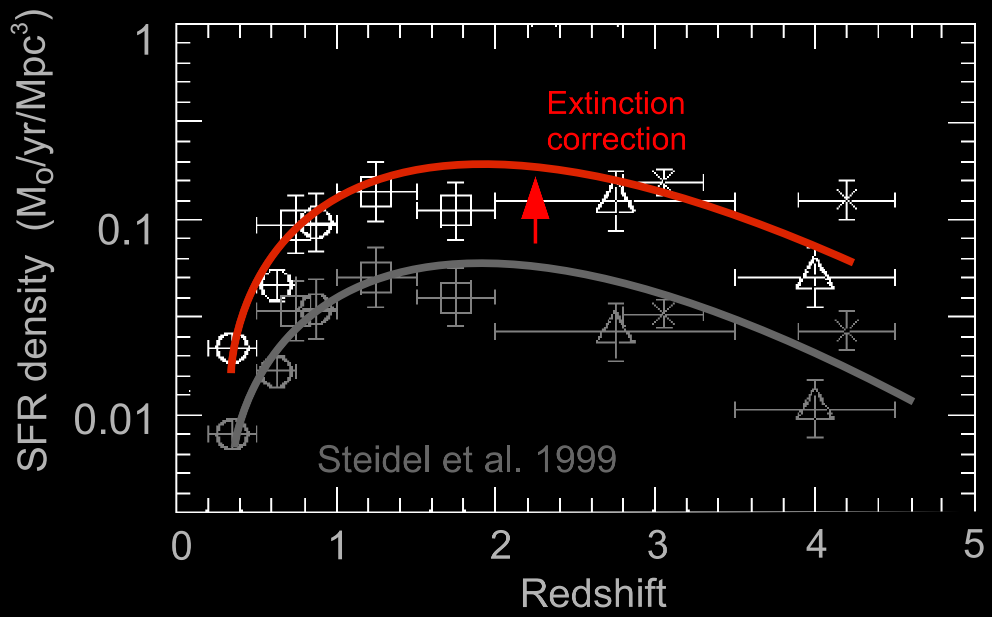
UV energy can be "recovered"
at 8μm / FIR / submm,
but these wavelengths have poor sensitivity to faint galaxies

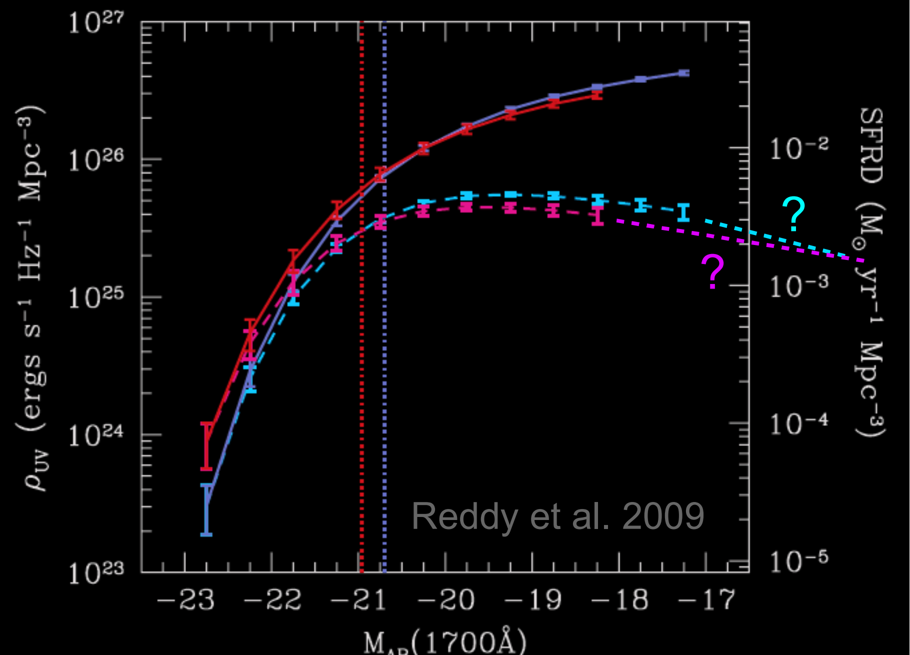
Missing galaxies

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

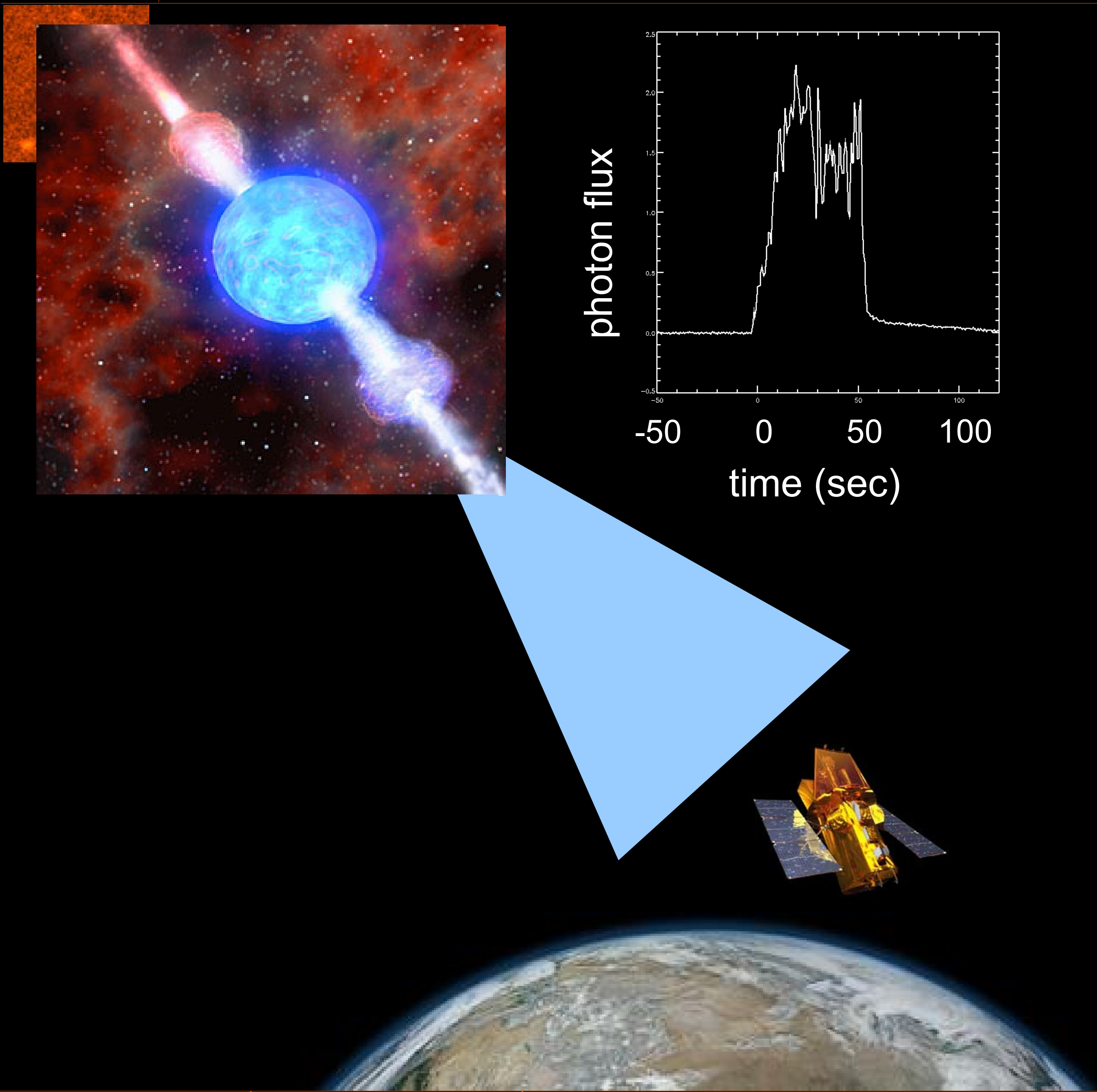
Redshift measurement imposes
further biases

These problems are particularly limiting at z>3

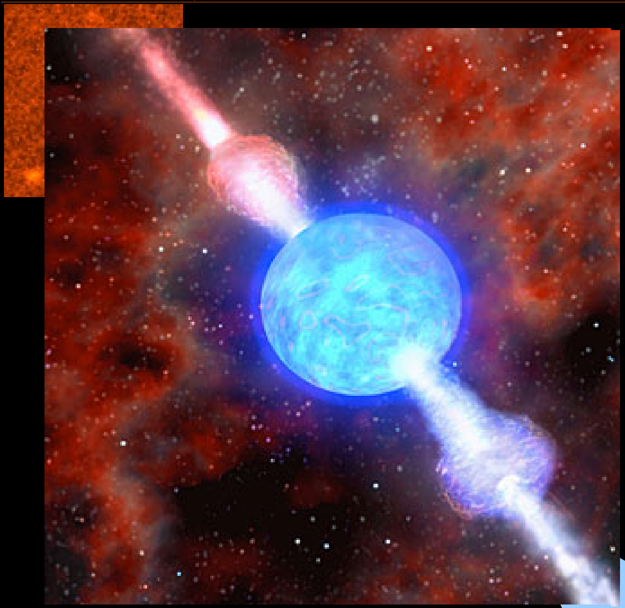


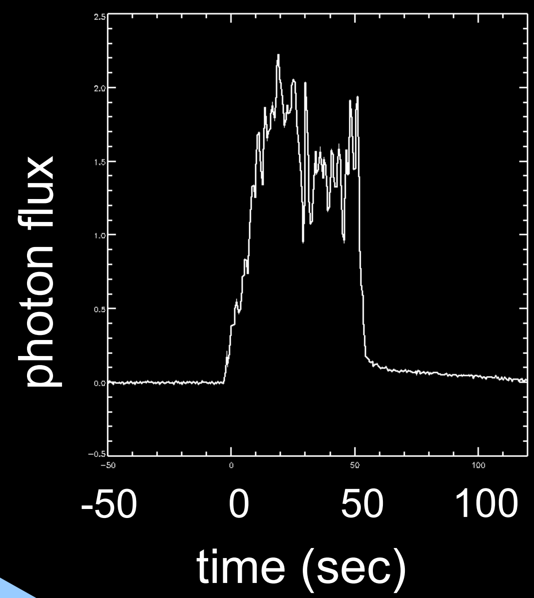


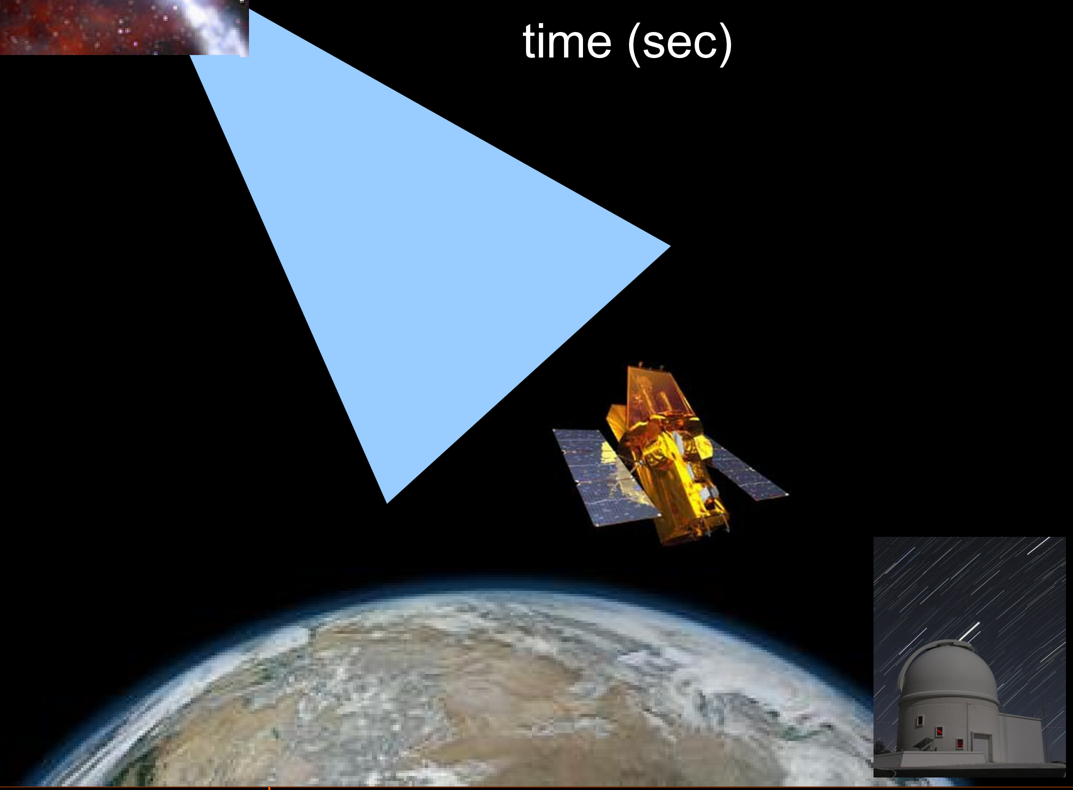
(Long-duration) Gamma-Ray Bursts



Gamma-Ray Bursts







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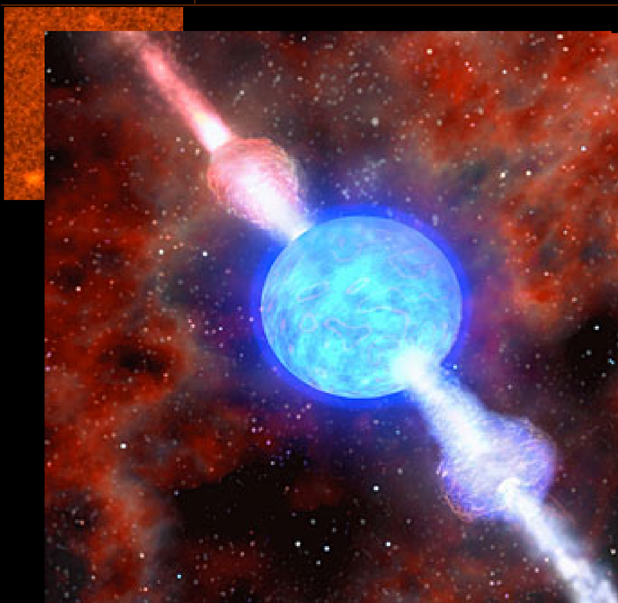
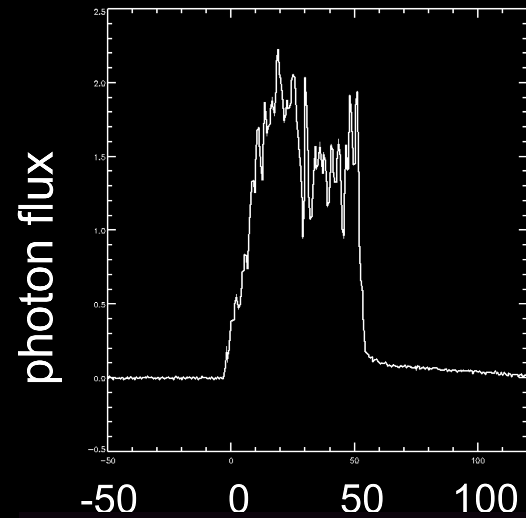
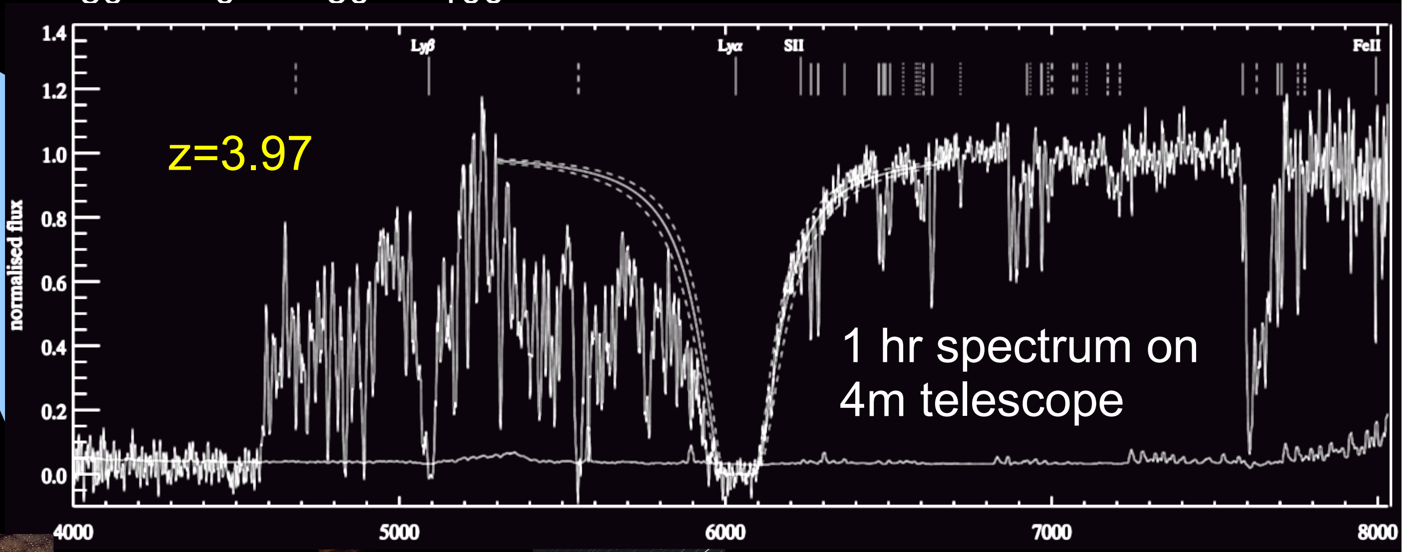
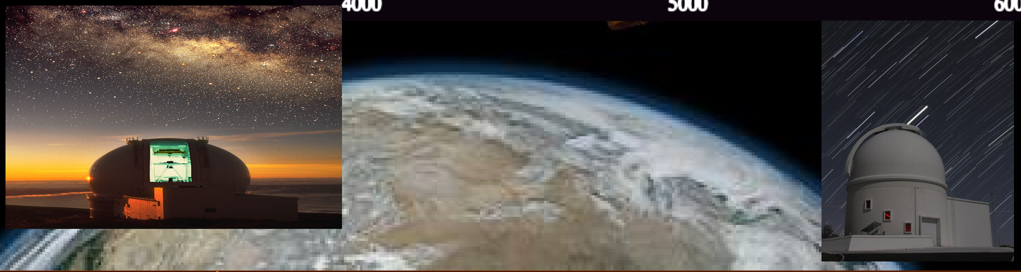






Starling+2005



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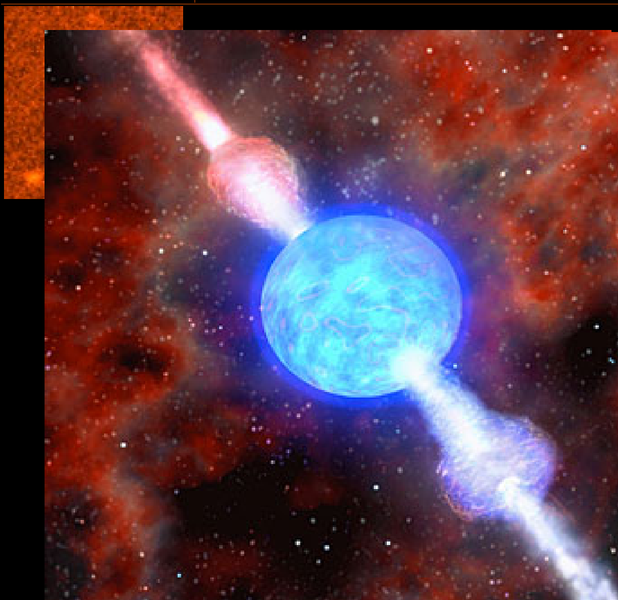

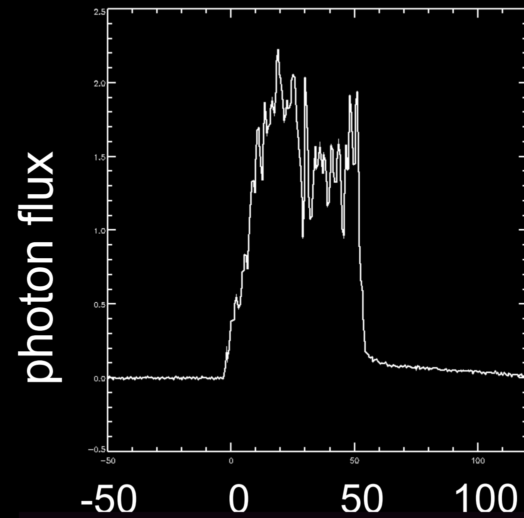

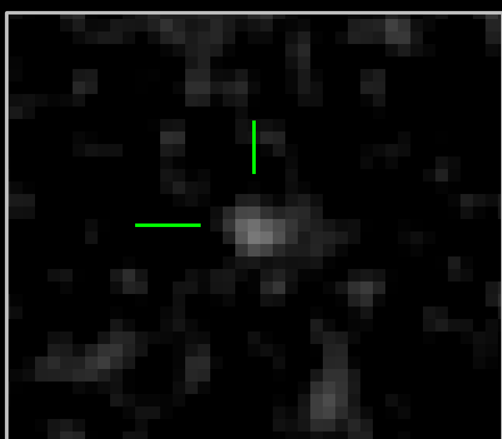

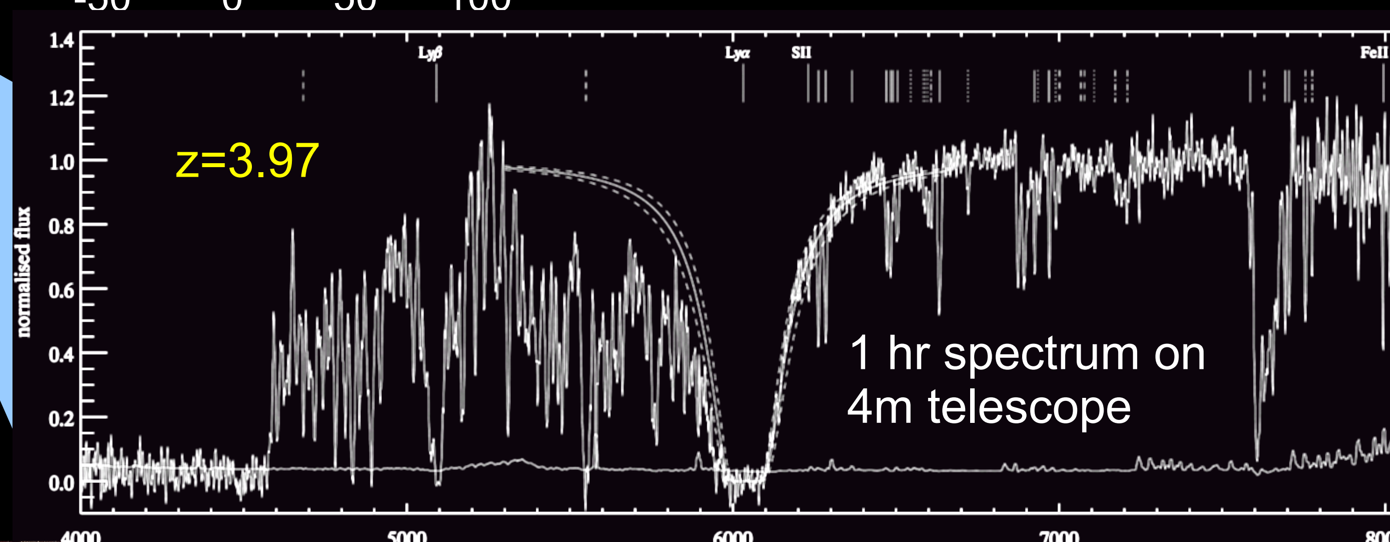

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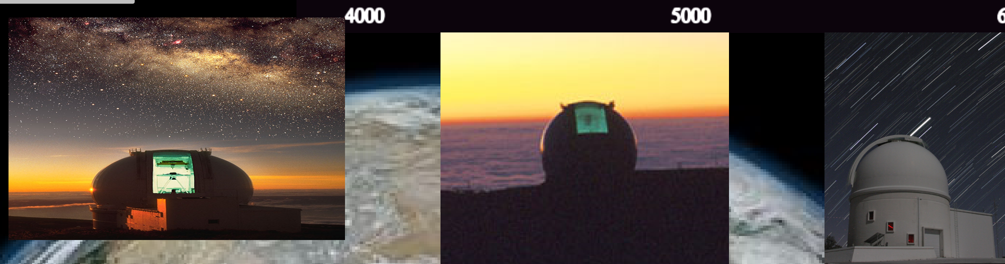
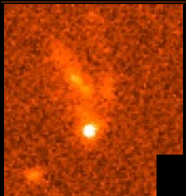
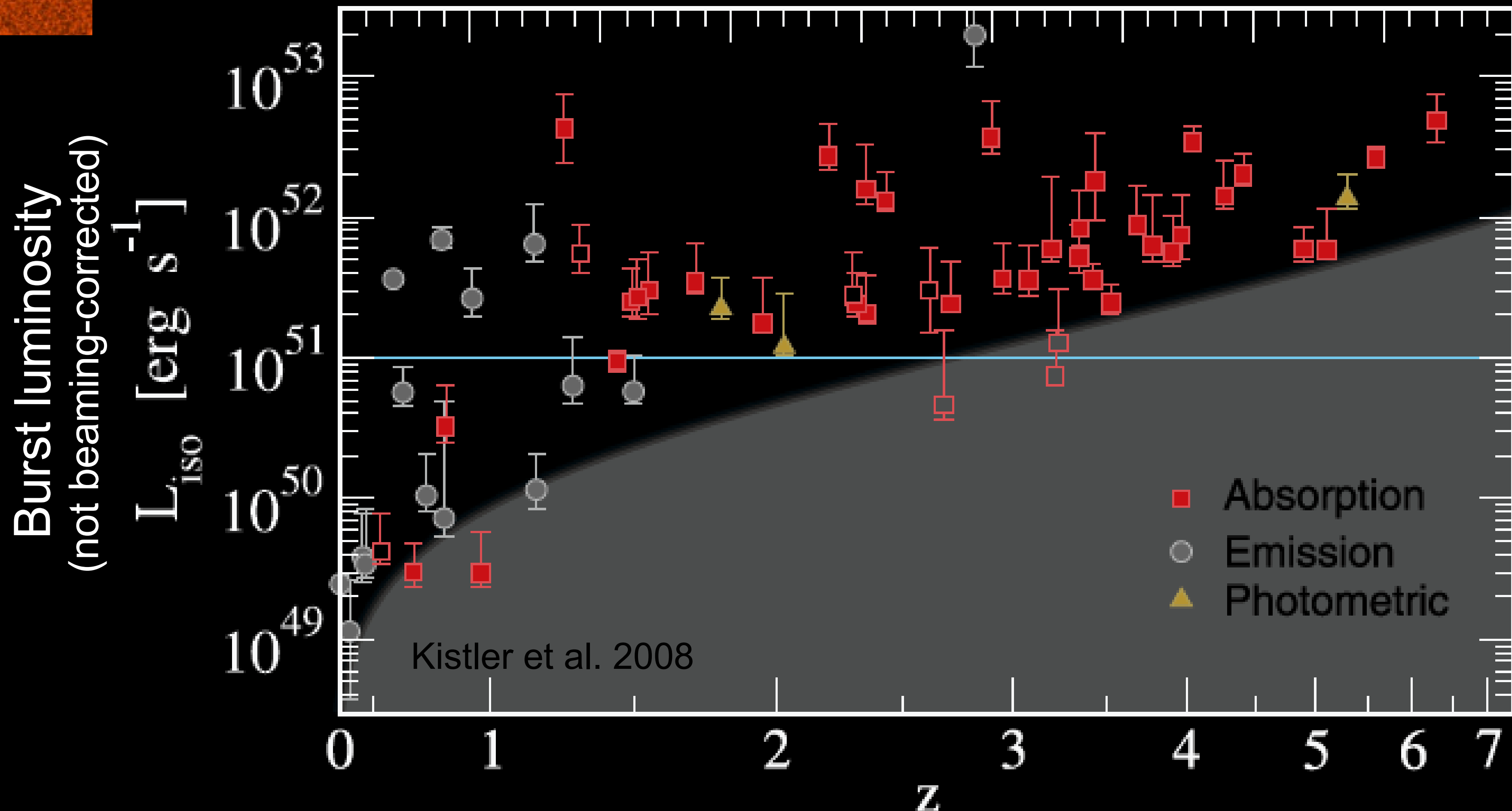
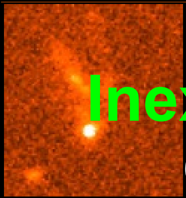


High-z SF History from GRBs





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

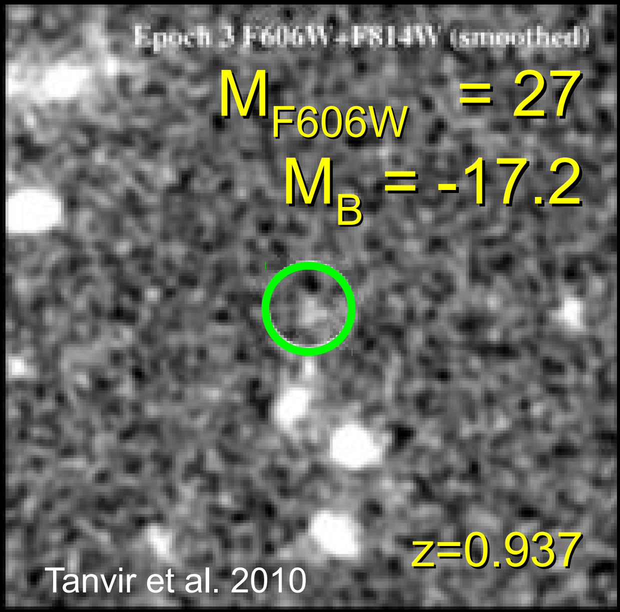
Sensitive to sub-threshold SFR

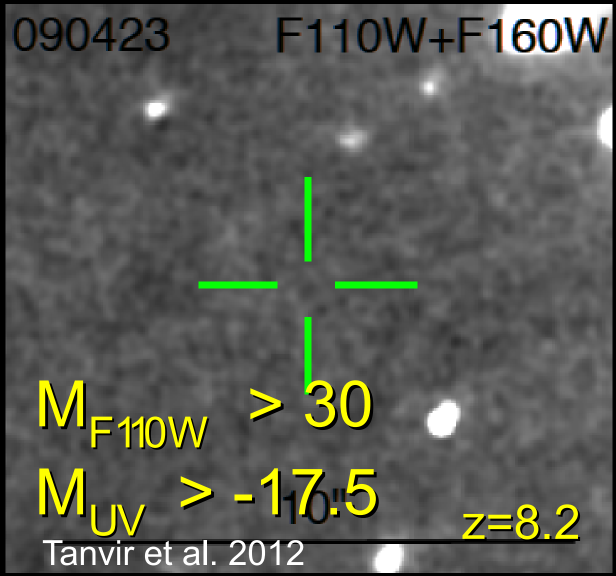
Host nondetections give a direct constraint on importance of undetectable galaxies

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

Extra information

Afterglow spectrum can reveal galaxy metallicity, dust properties, kinematics





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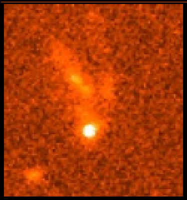

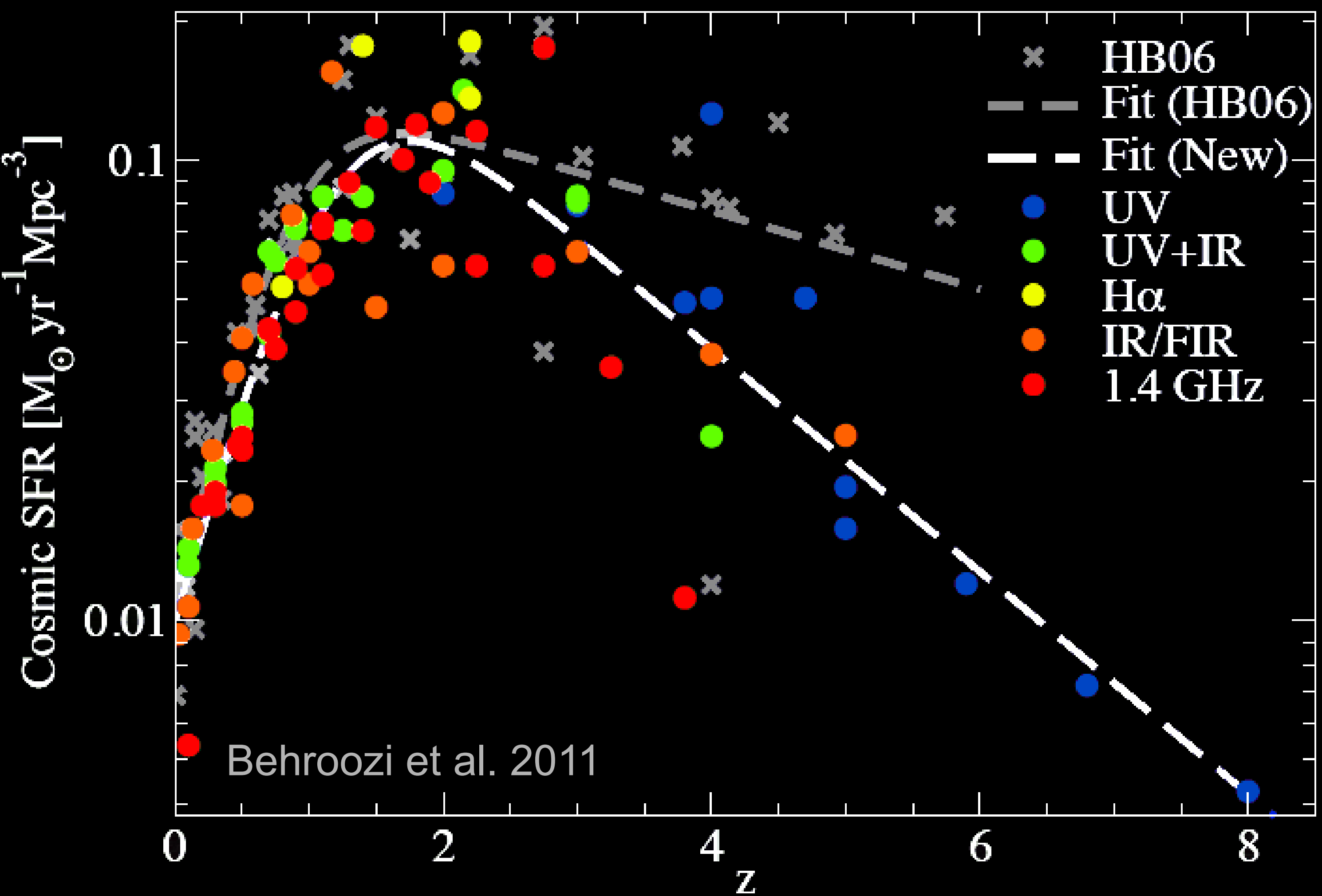

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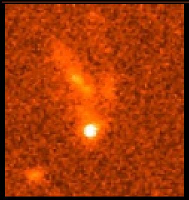

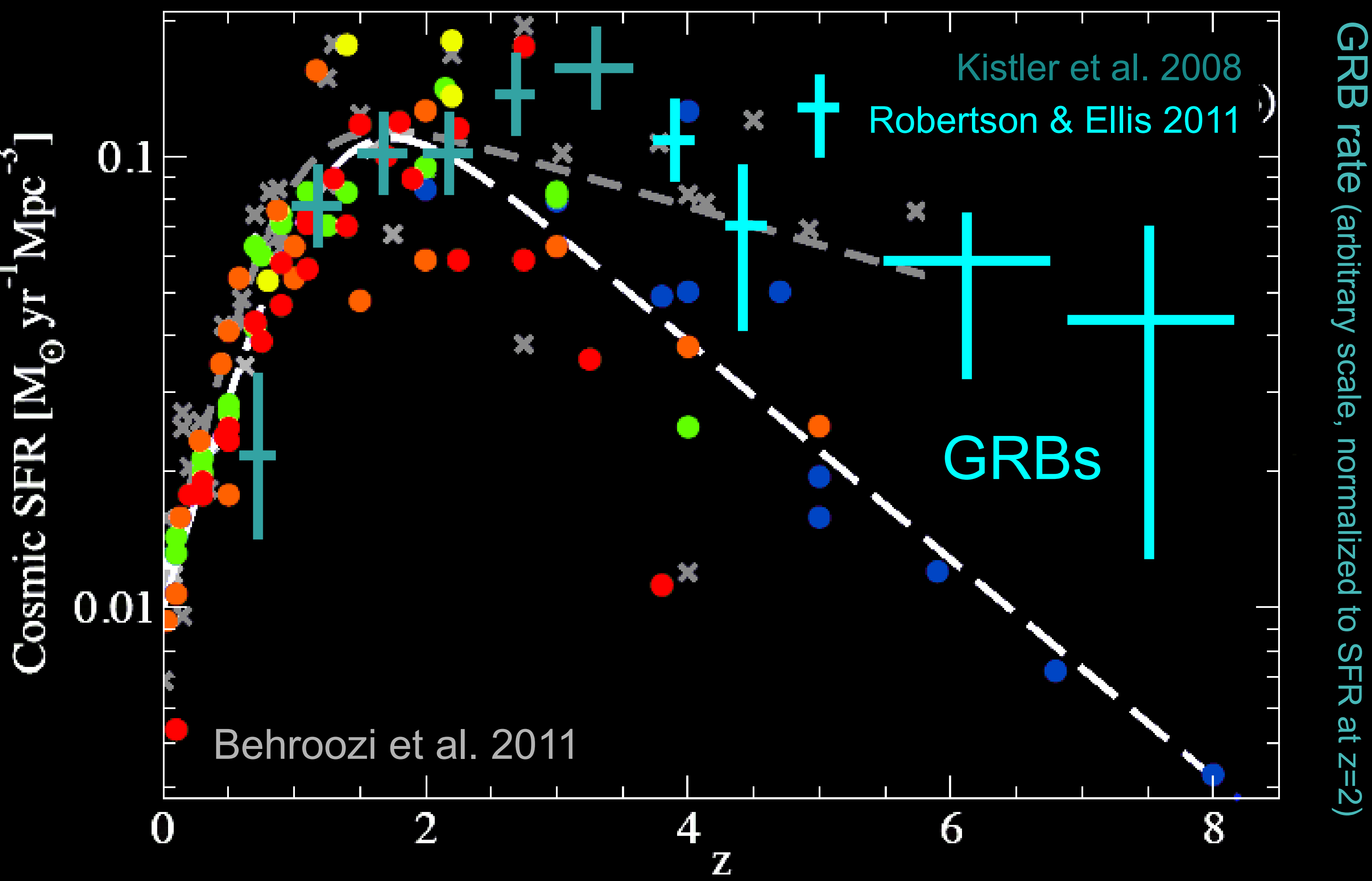

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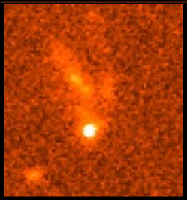

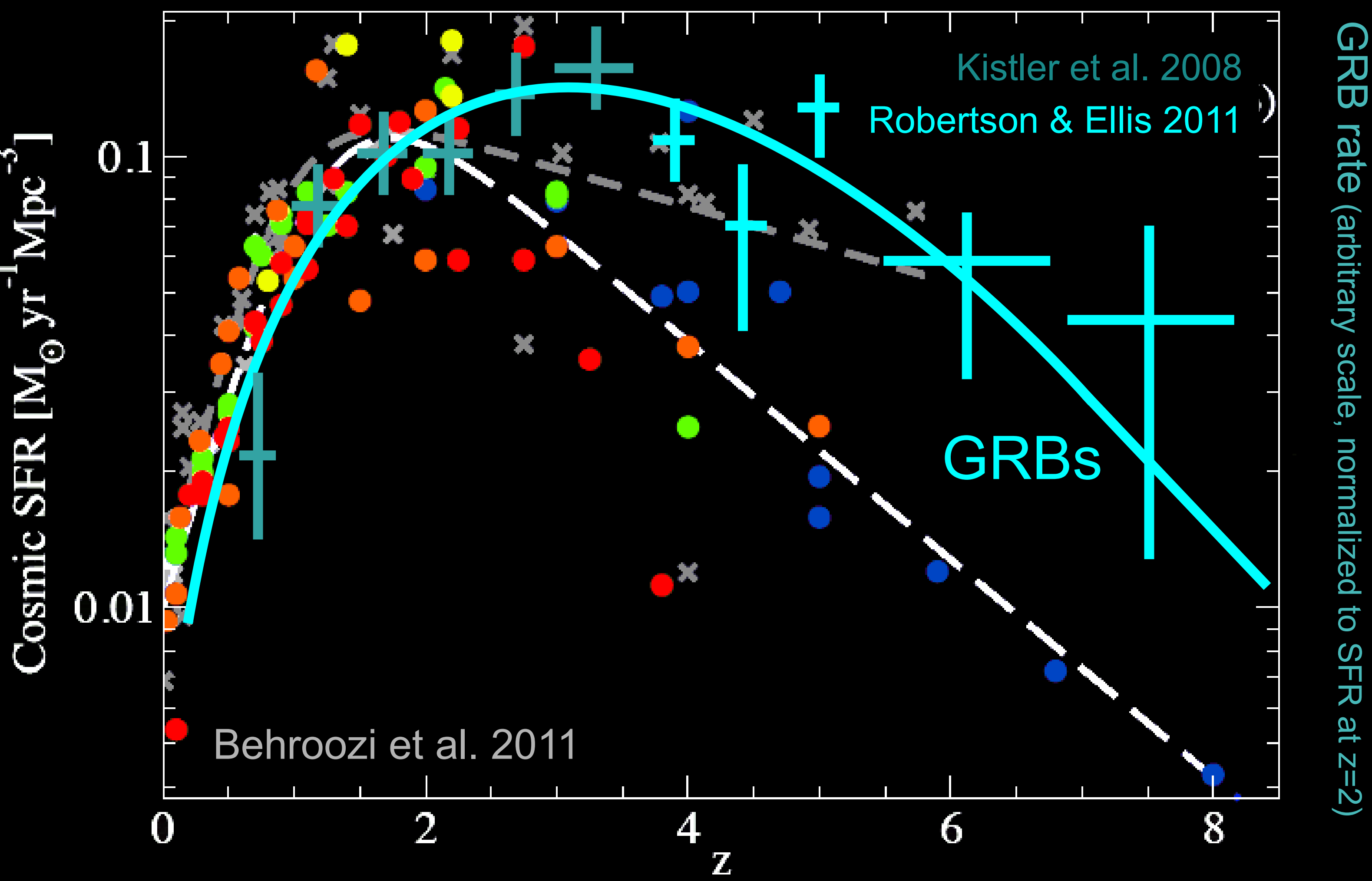

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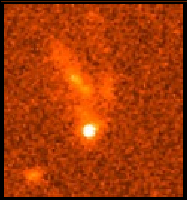
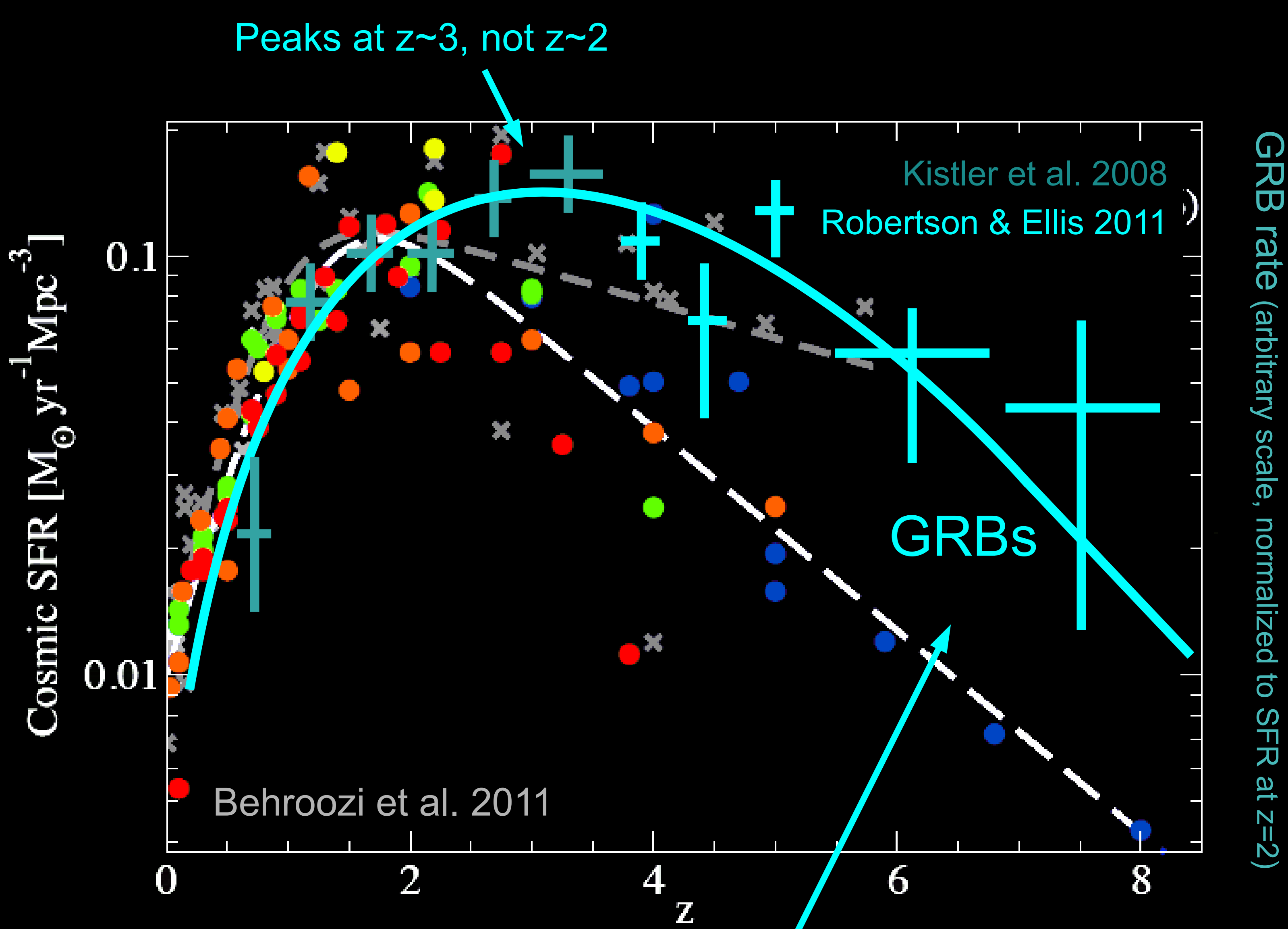
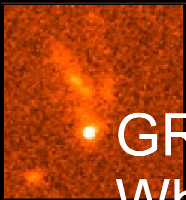




Successful high-z GRB detections imply large z>5 SFRD

Interpretations

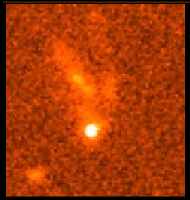


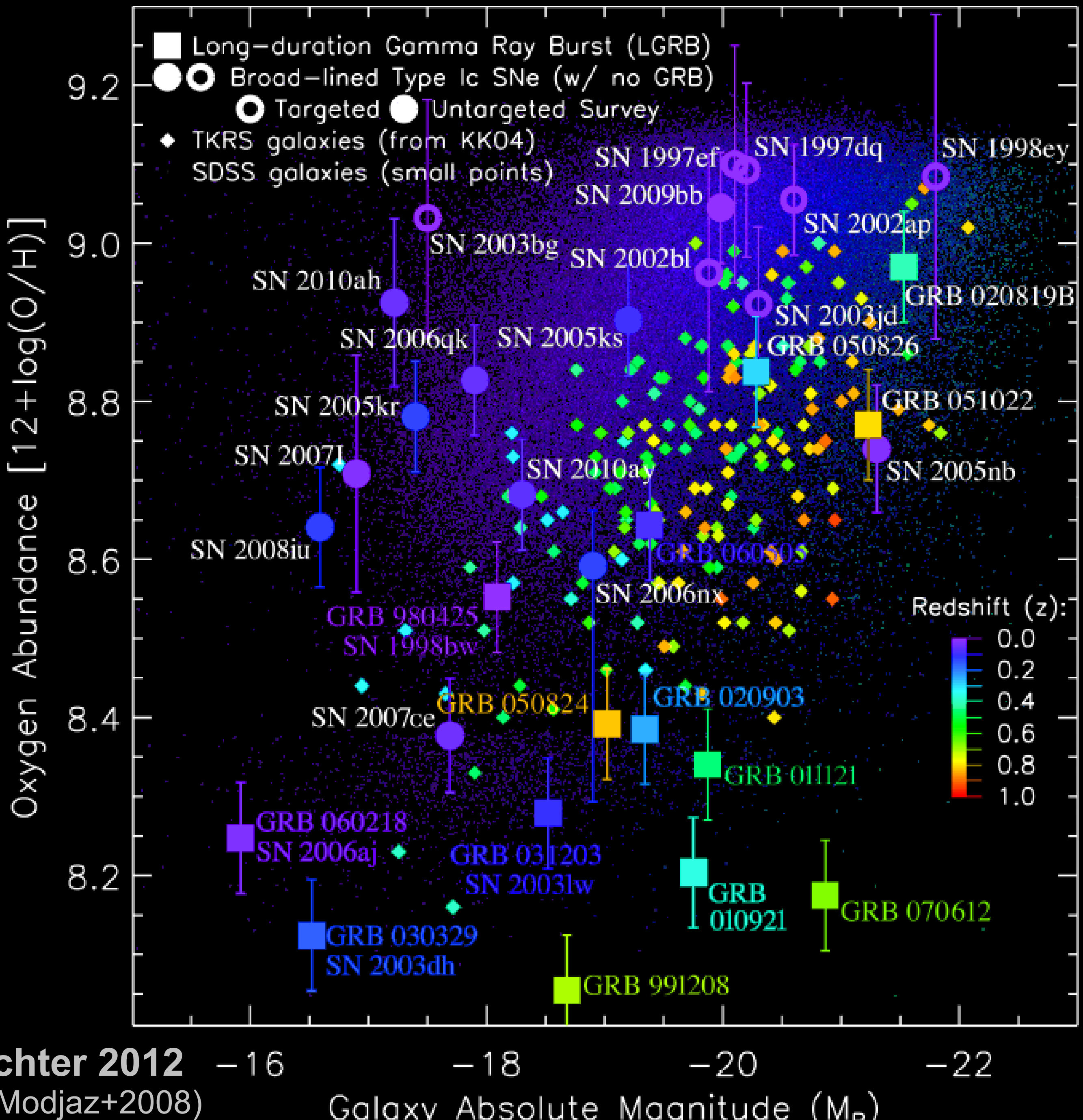
- GRB and field-survey measurements of the SFRD do not agree. Why not?

1. Field surveys systematically underestimate contributions from undetected, faint galaxies at high redshift, or undercorrect for dust.
   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, Graham & Fruchter 2013

Host Luminosity and Metallicity at z~0

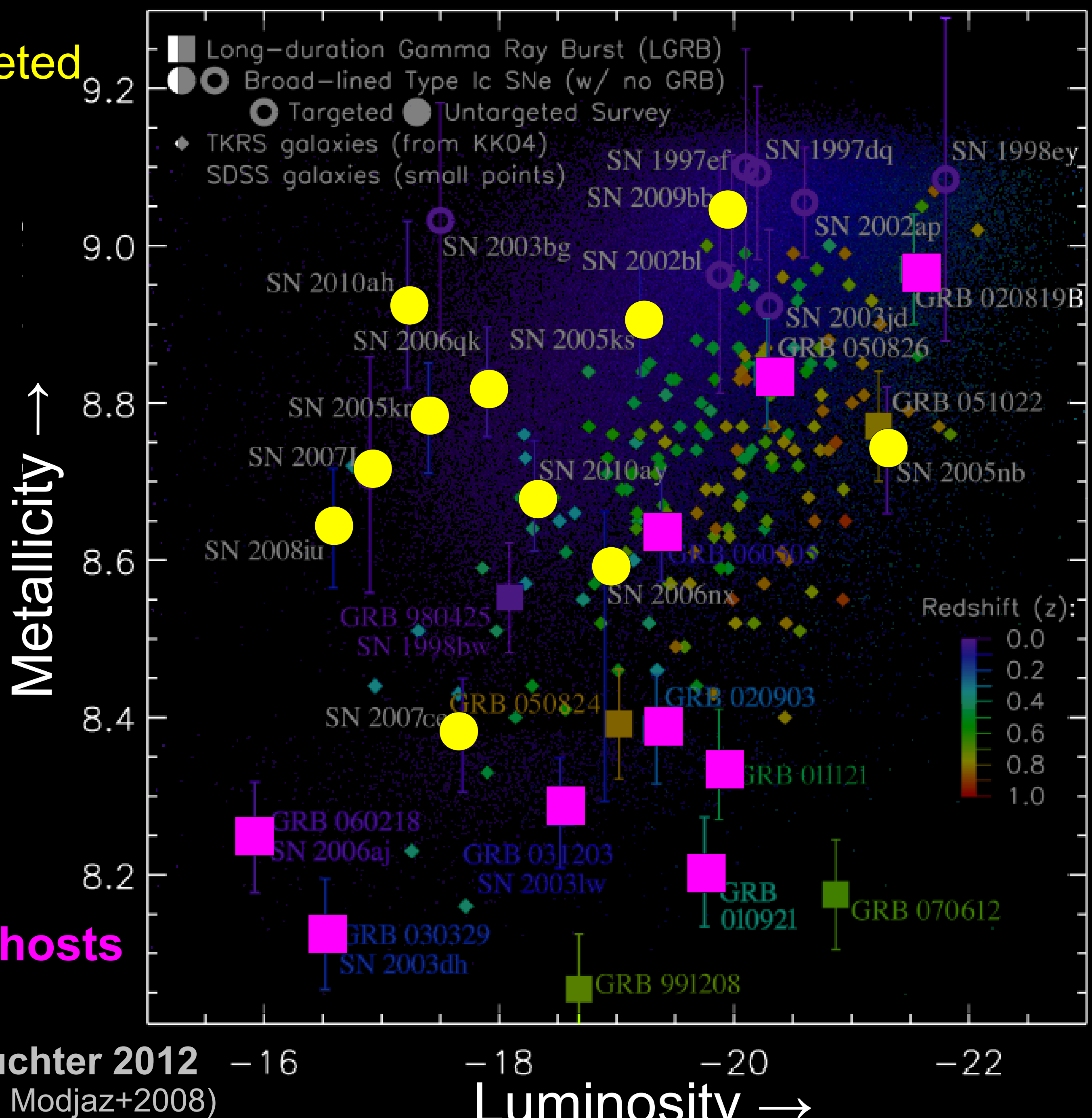




Graham & Fruchter 2012
(Levesque+2010, Modjaz+2008)

Host Luminosity and Metallicity at z~0

z~0 untargeted broad-lined Ic SNe



z<0.5 GRB hosts

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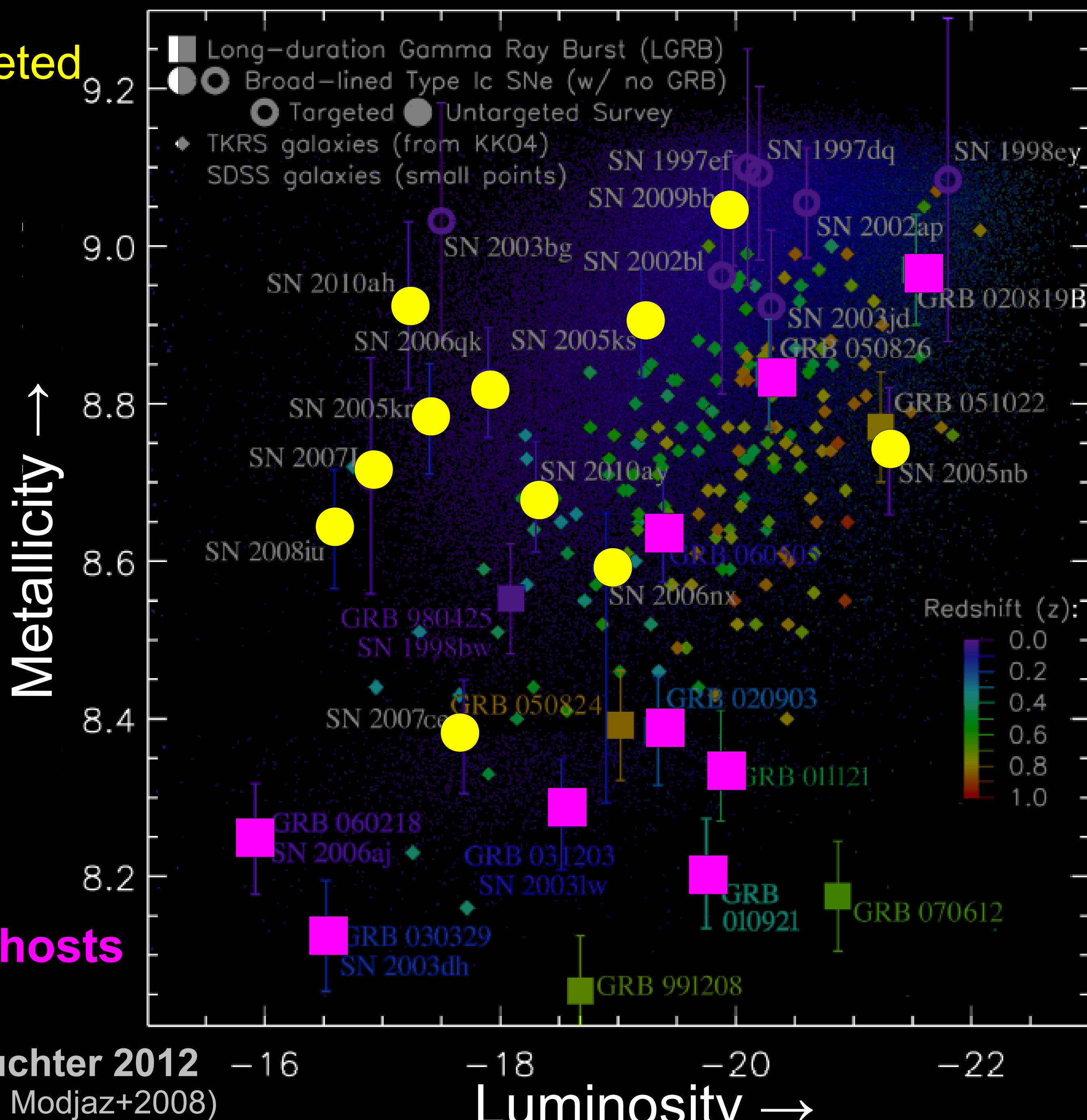

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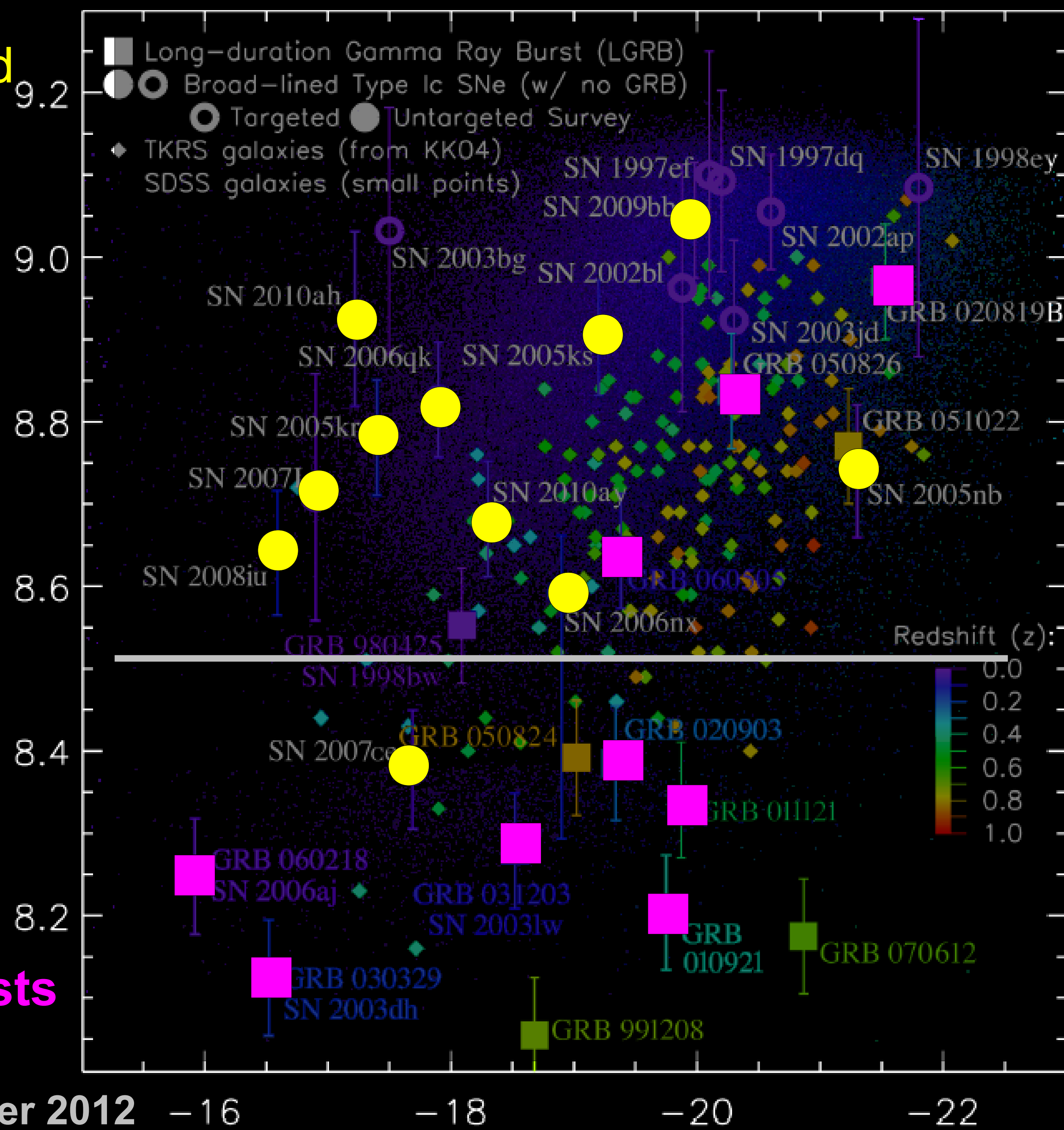

GRBs rare

~0.7 $Z_\odot$

GRBs "common"

z<0.5 GRB hosts

Graham & Fruchter 2012
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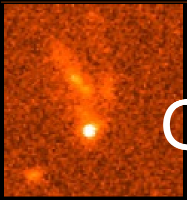
Limitations of z~0 comparisons



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)

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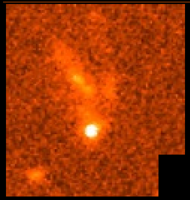

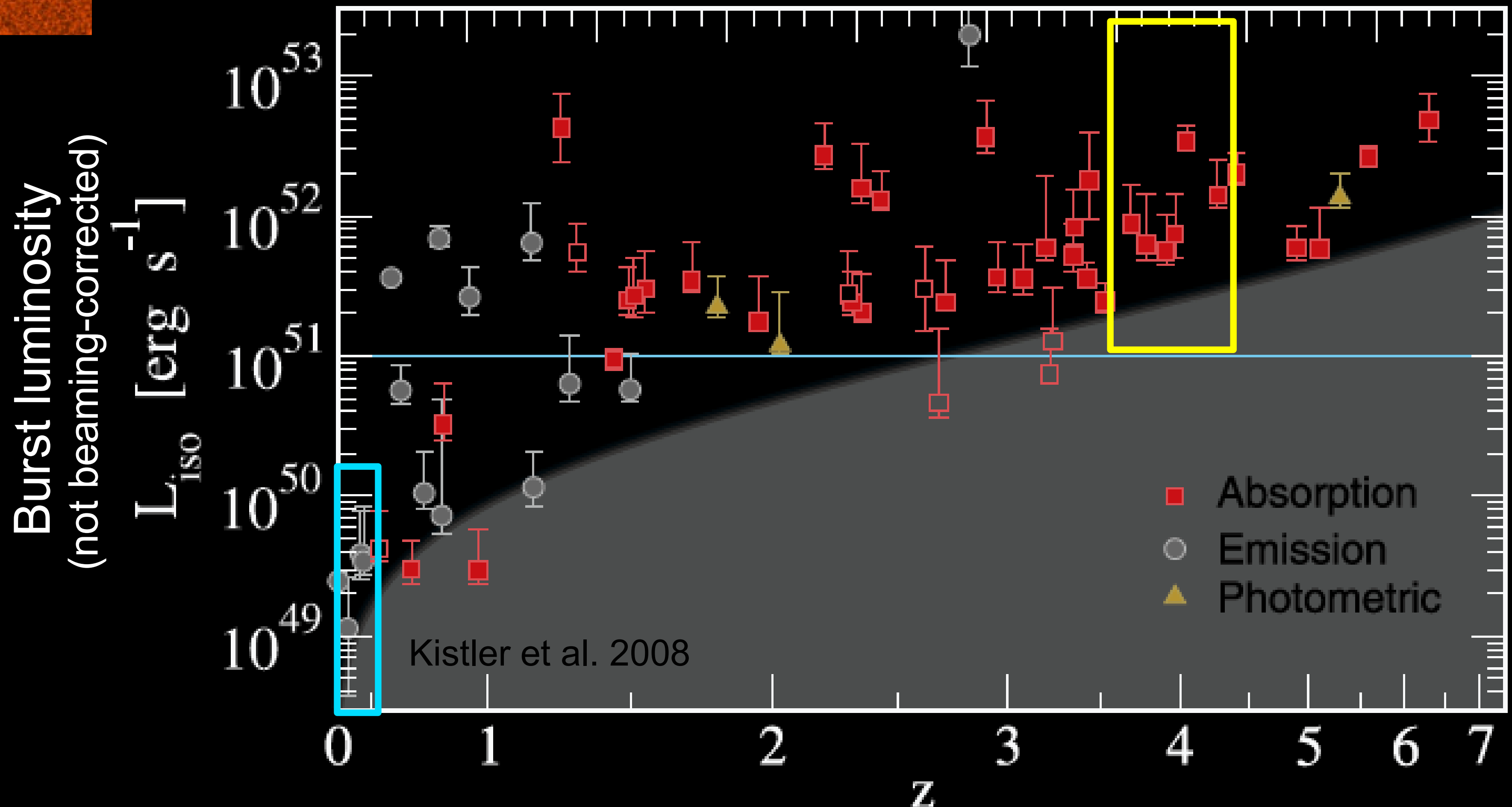

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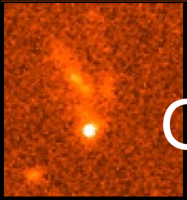

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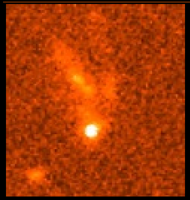

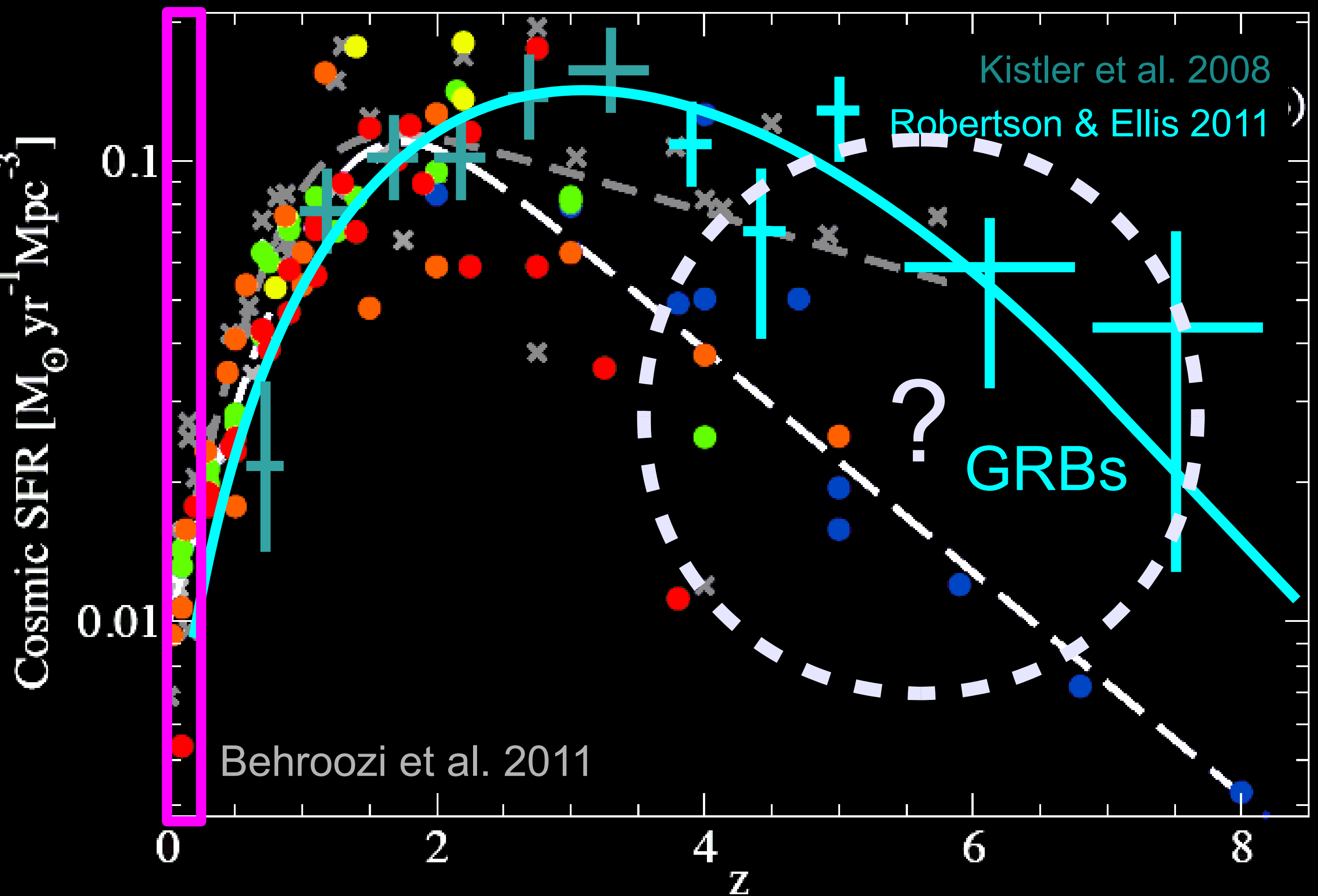

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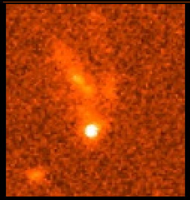
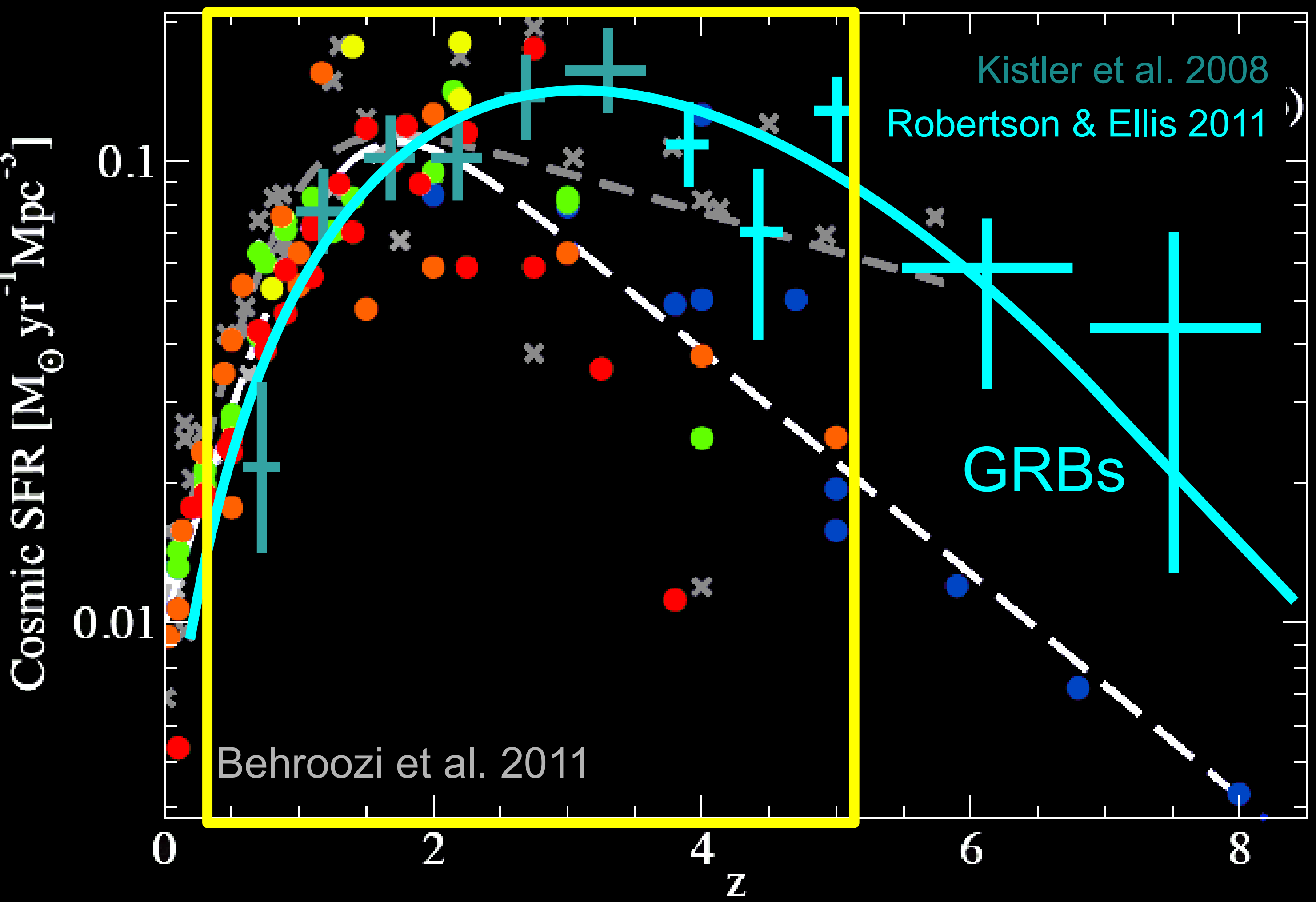
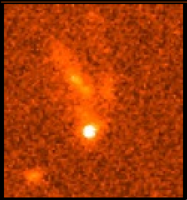




Designing a z>0.5 Host Survey



Go **BIG** – Observe a large number of systems to ensure good statistics, even if subdivided by redshift.

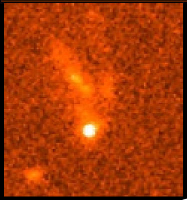
Go **DEEP** – Probe the entire host luminosity function down to deep-field depths (and beyond!)

Go **UNBIASED** – Avoid any risk of selection biases! Include dust-obscured GRBs and others with unknown-z.

Go **MULTIWAVELENGTH** – Use rest-frame NIR to measure masses. Use deep radio/submillimeter observations to identify obscured star-formation.

Direct metallicity measurement is observationally expensive, so focus on photometric comparisons.

Designing a z>0.5 Host Survey



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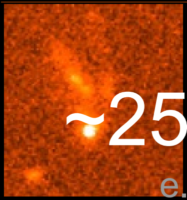
Dark GRBs



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

e.g,Groot+1998, Djorgovski+ 2001, Cenko+2009

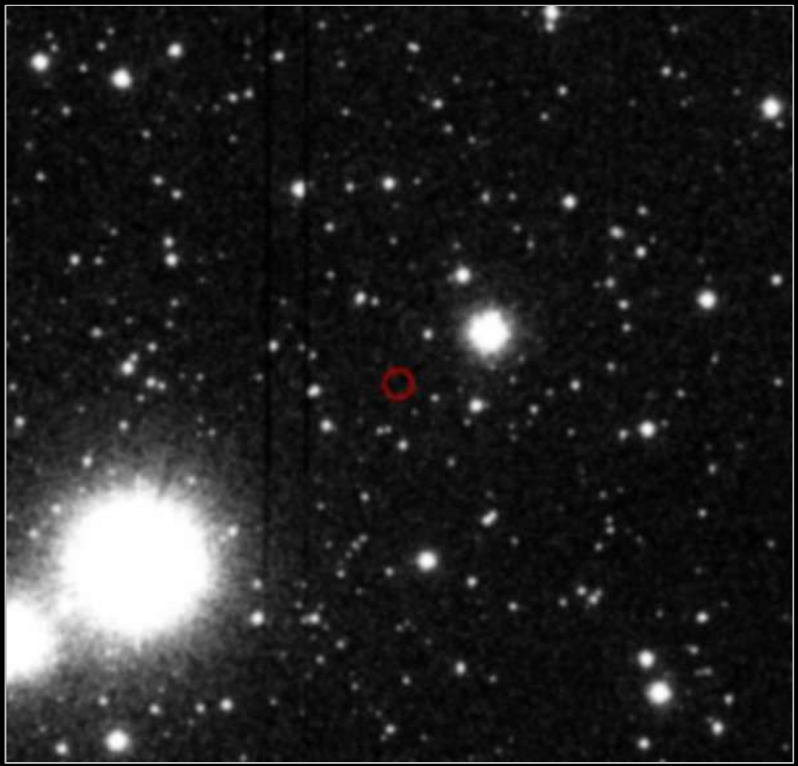
No optical afterglow,
even with early follow-up.

Most are obscured by dust

Perley+2009, Greiner+2011

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

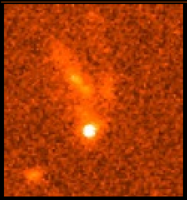
- Can't measure redshift without finding the host (+expensive spectroscopy)

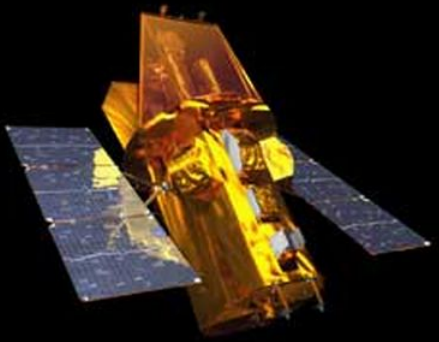


Palomar 60-inch follow-up of GRB 061222A
~10 minutes after burst

If dust-obscured events probe a different host population, these galaxies must be identified and included in our samples!

Dark GRBs in the *Swift* Era





Before *Swift:*

~10 GRBs per year

Localized to ~10 arcmin in a few hours

No on-board follow-up; have to manually trigger Chandra, VLA, etc. after many hours to get a position

Hard to distinguish obscured events from events with faint afterglows

Swift:

~100 GRBs per year

Localized to ~2 arcmin in ~30 seconds

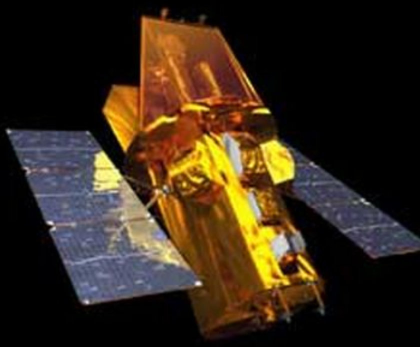
Automated X-ray followup:
~2 arcsec error circle distributed within a few minutes for every burst
(unless Sun/Moon-constrained)

Can also trigger NIR/radio follow up when the burst is still very bright

Excellent X-ray light curves – can easily distinguish bright, obscured GRBs from intrinsically faint afterglows

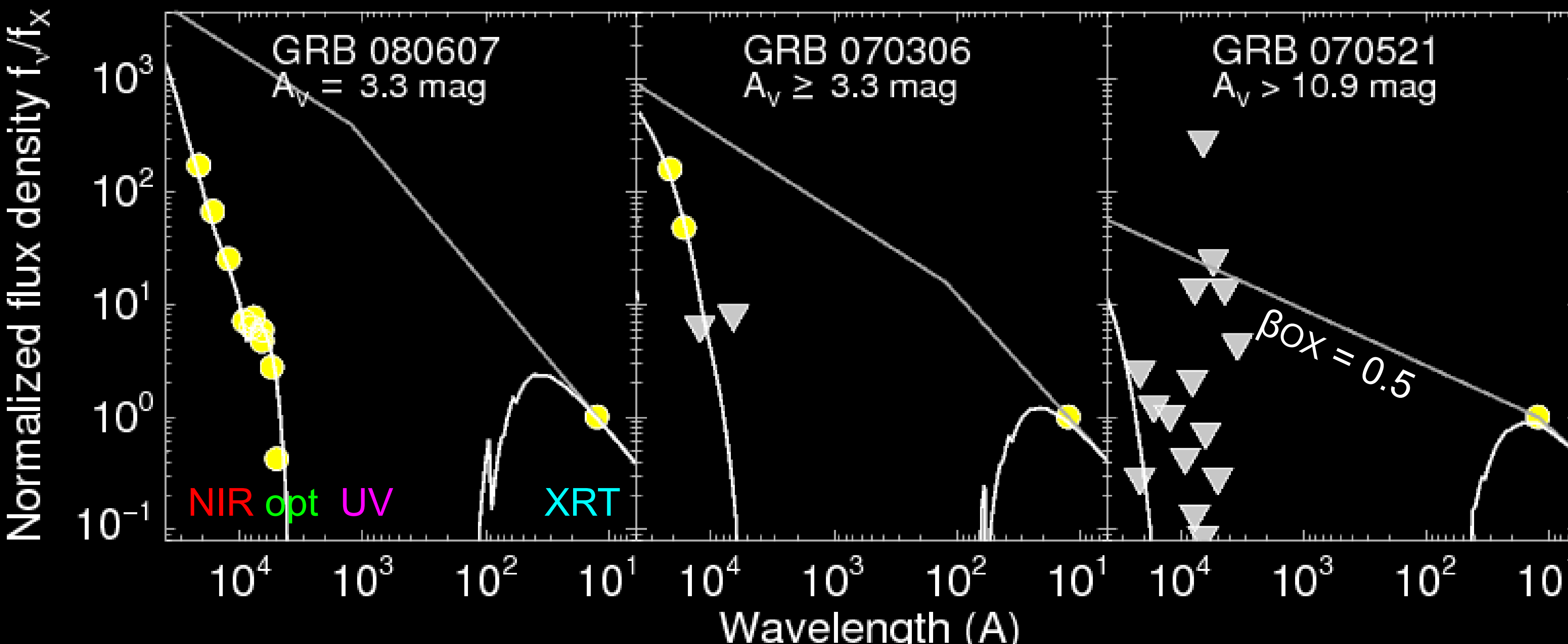
Selecting a Dusty-GRB Host Sample

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:



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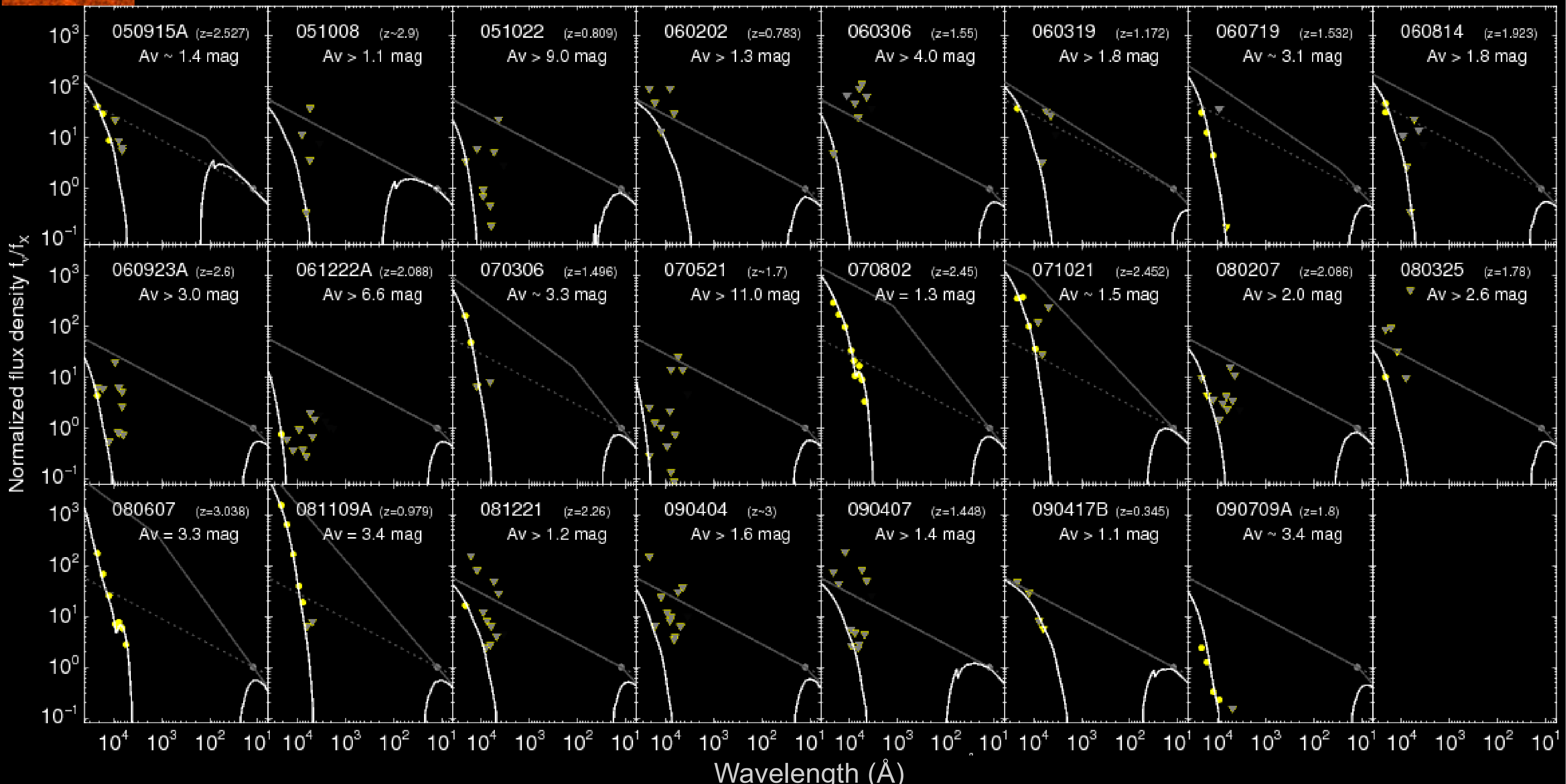
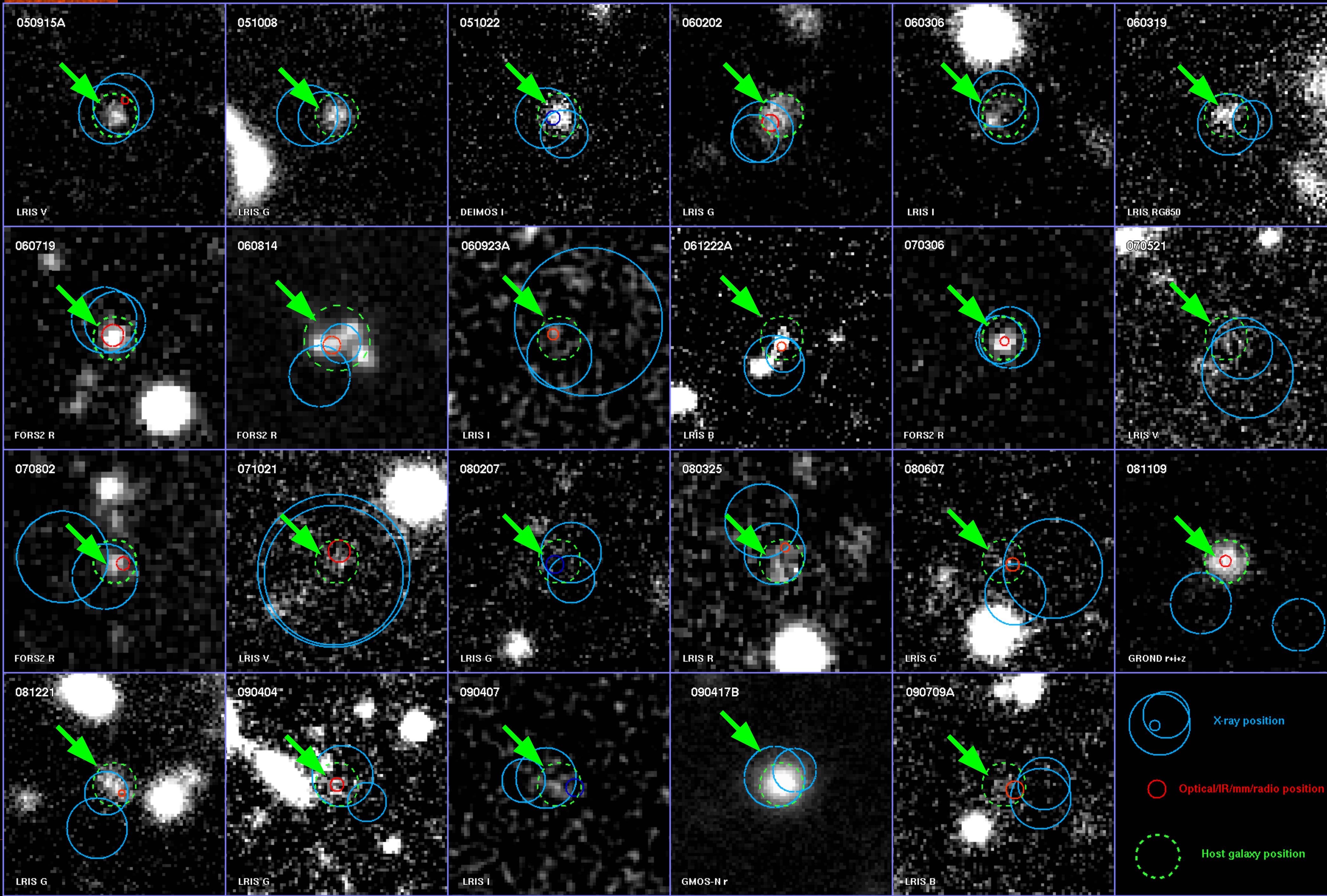


23 events from 2005-2009

2 with optical afterglow redshift

Optical Host Mosaic

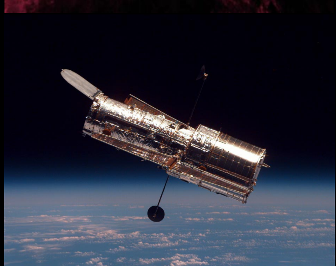


Observing a Dusty-GRB Host Sample

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

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

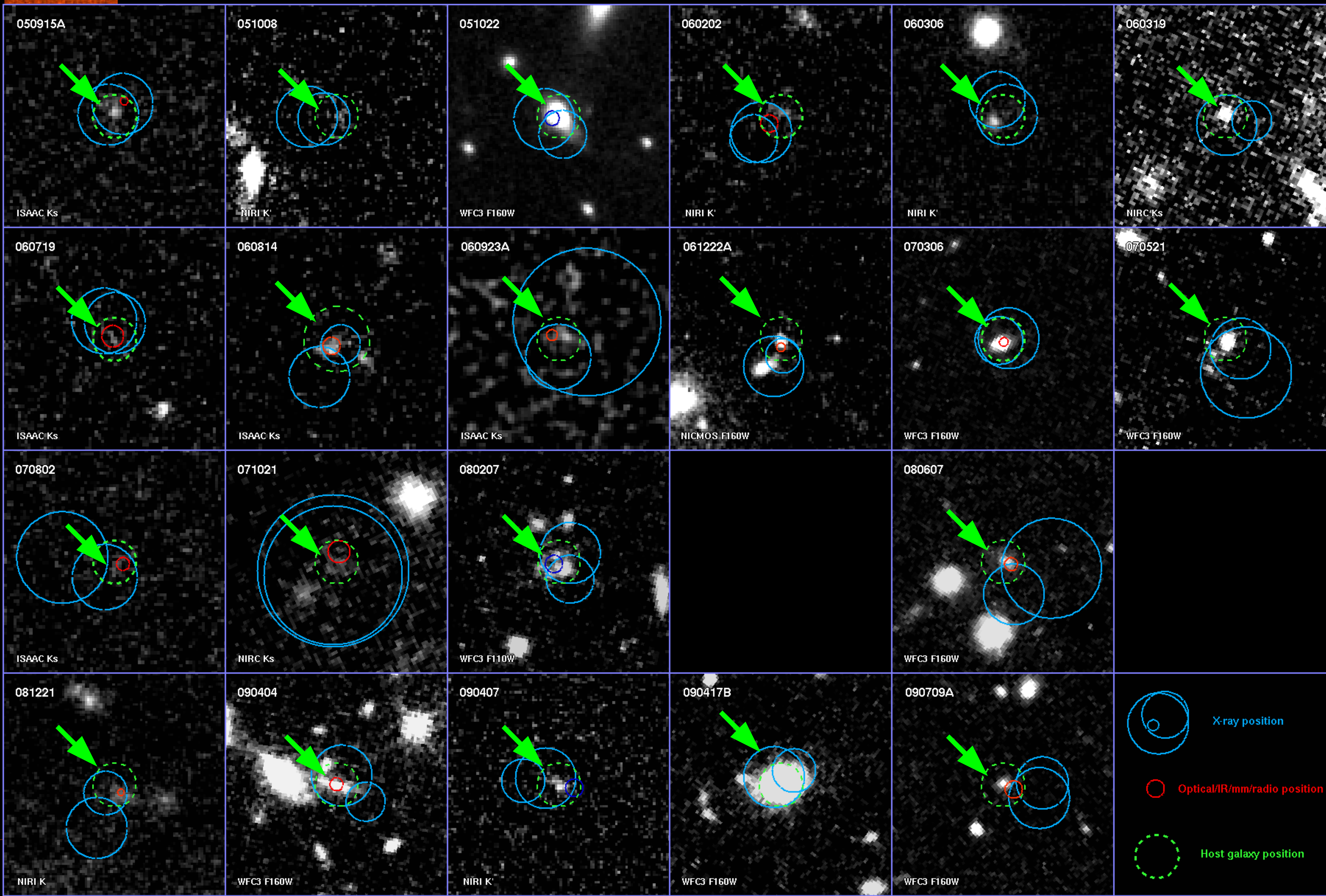
Spitzer: Rest-frame NIR photometry for stellar masses.



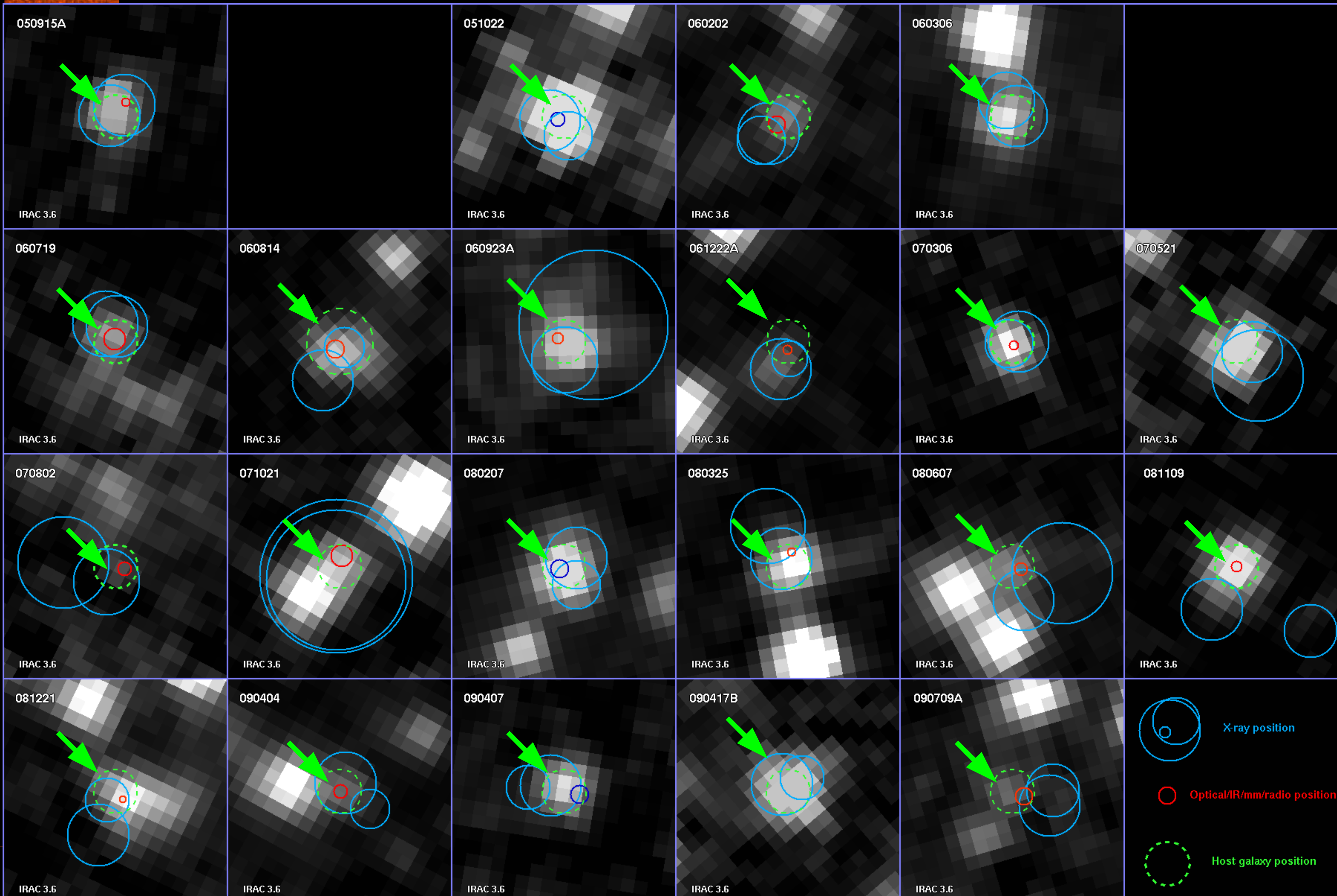
HST: NIR photometry, especially of faint targets.

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

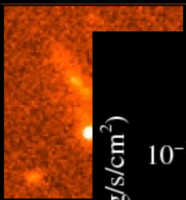
Near-IR Host Mosaic

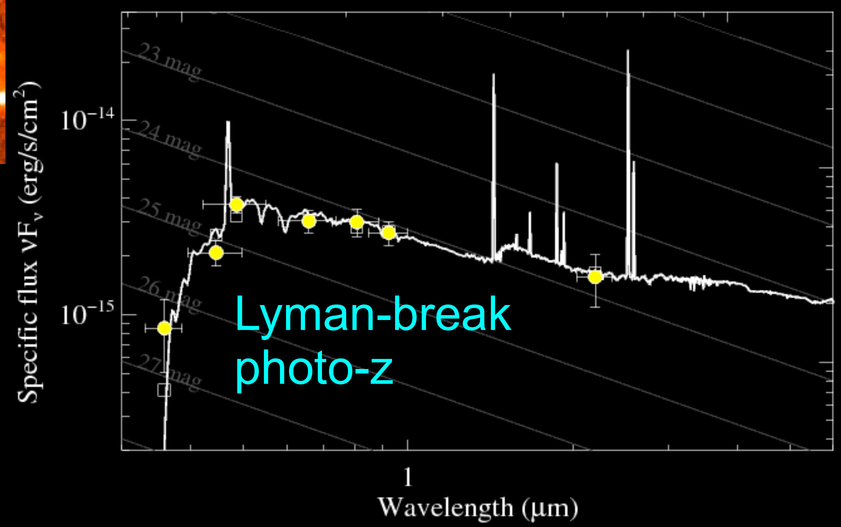


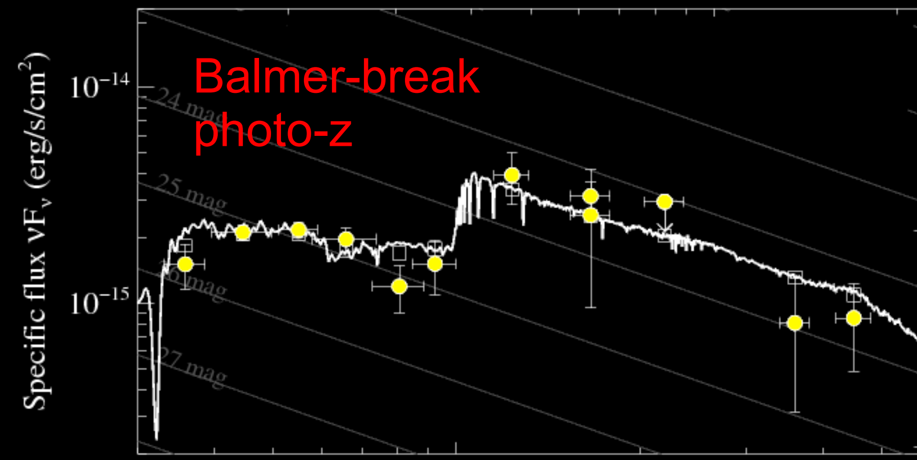
Spitzer Host Mosaic

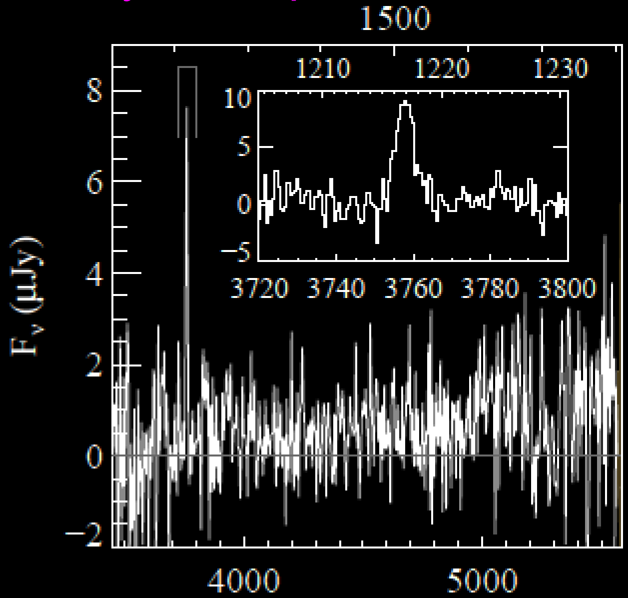


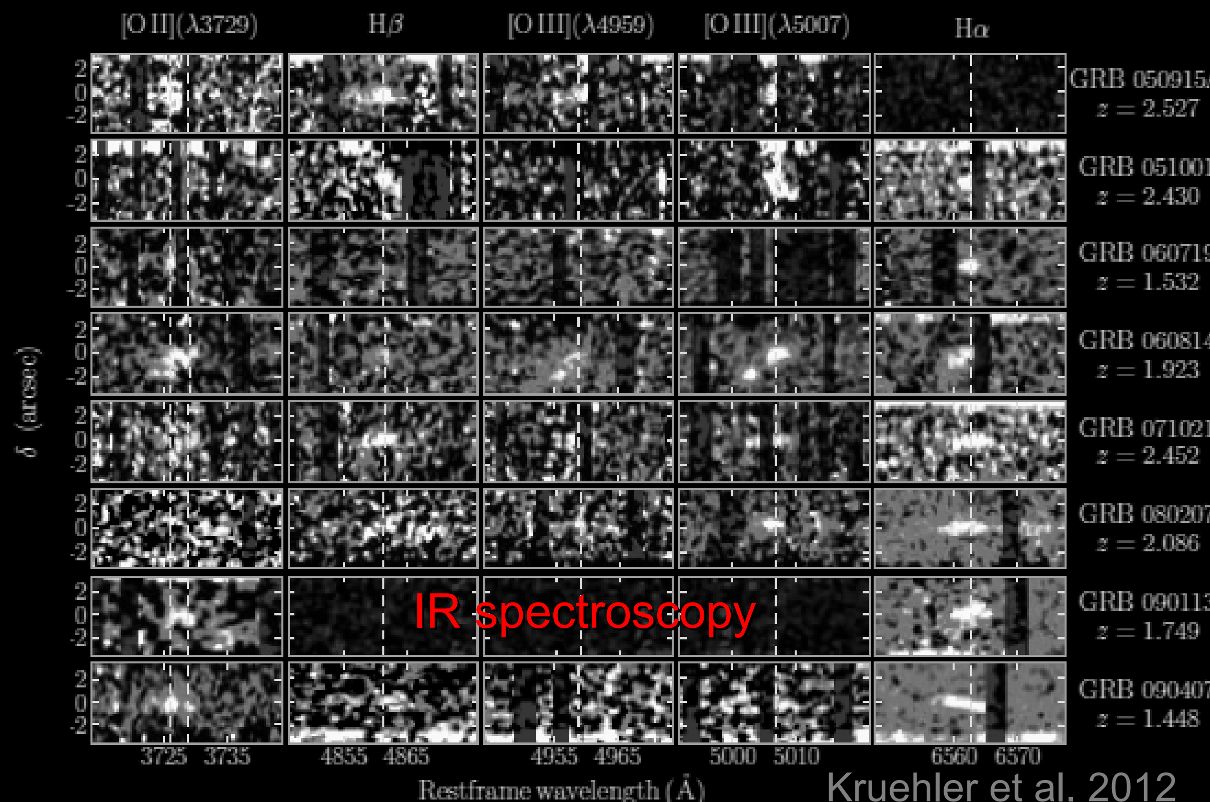
Redshift Measurement





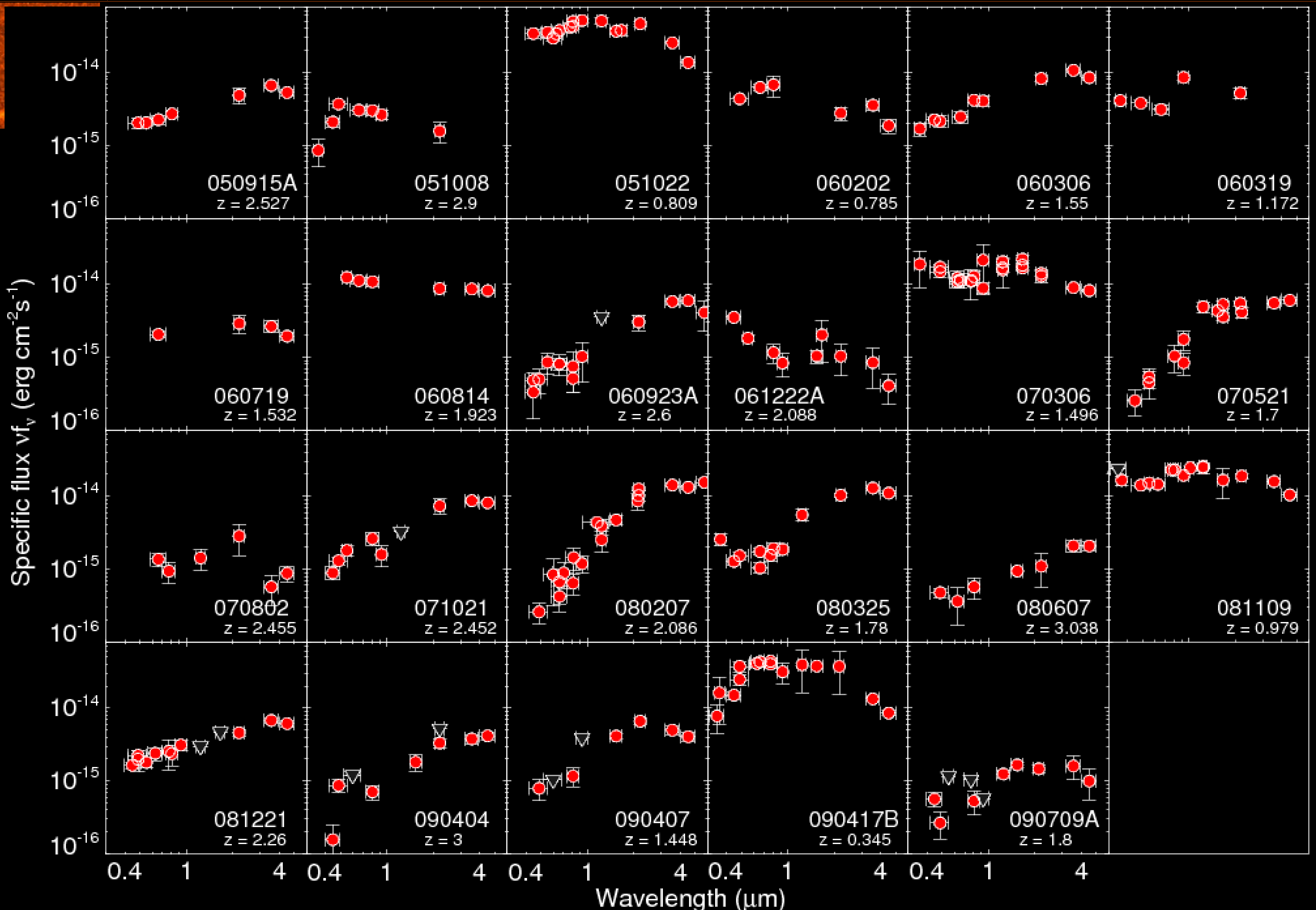




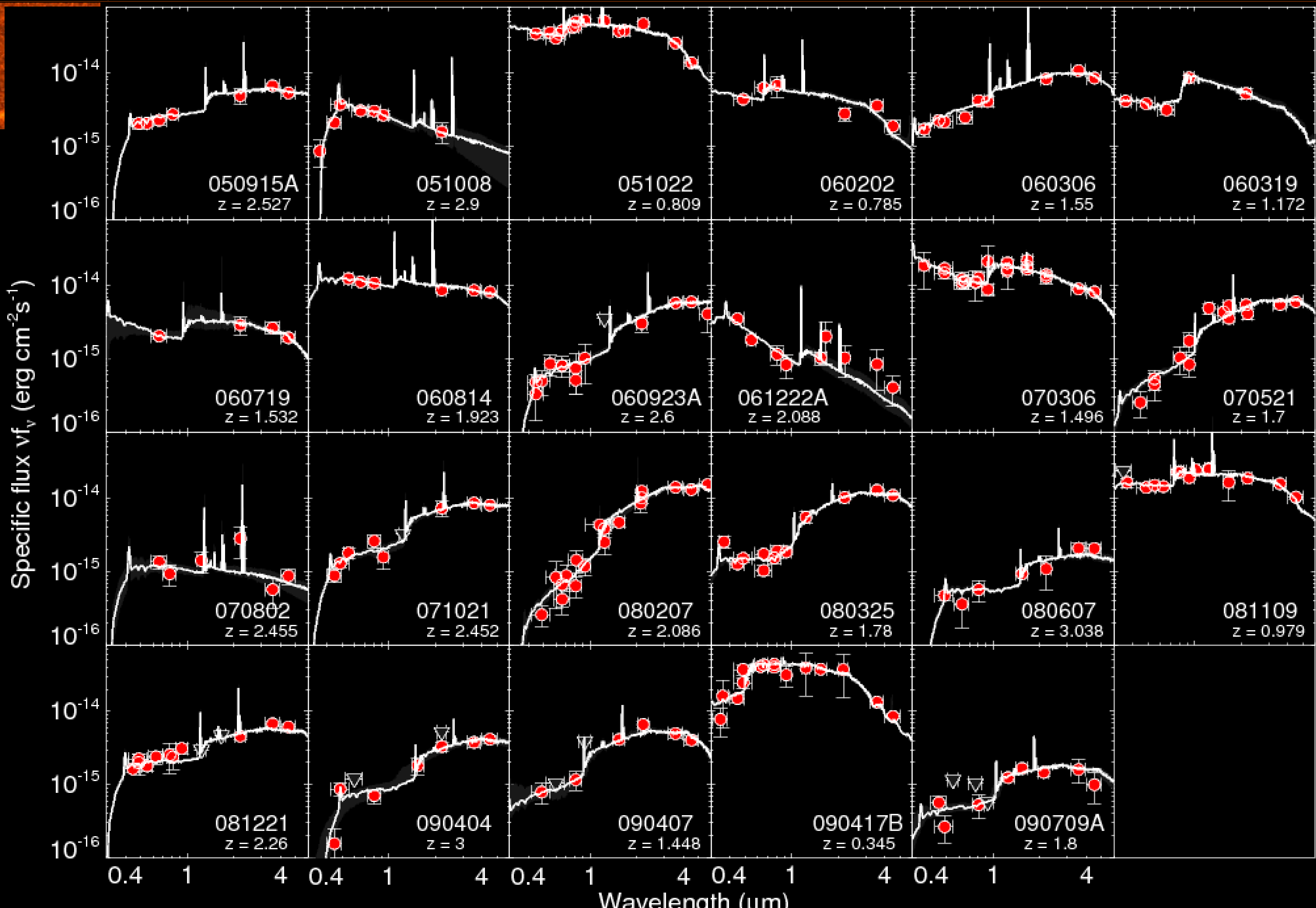


Kruehler et al. 2012

SED Fitting

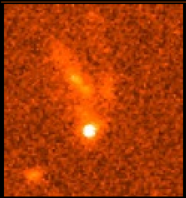

Specific flux νf$_ν$ (erg cm^{-2}s^{-1})
10^{-14}
10^{-15}
10^{-16}
050915A
z = 2.527
051008
z = 2.9
051022
z = 0.809
060202
z = 0.785
060306
z = 1.55
060319
z = 1.172
060719
z = 1.532
060814
z = 1.923
060923A
z = 2.6
061222A
z = 2.088
070306
z = 1.496
070521
z = 1.7
070802
z = 2.455
071021
z = 2.452
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
0.4
1
4
Wavelength (μm)

SED Fitting



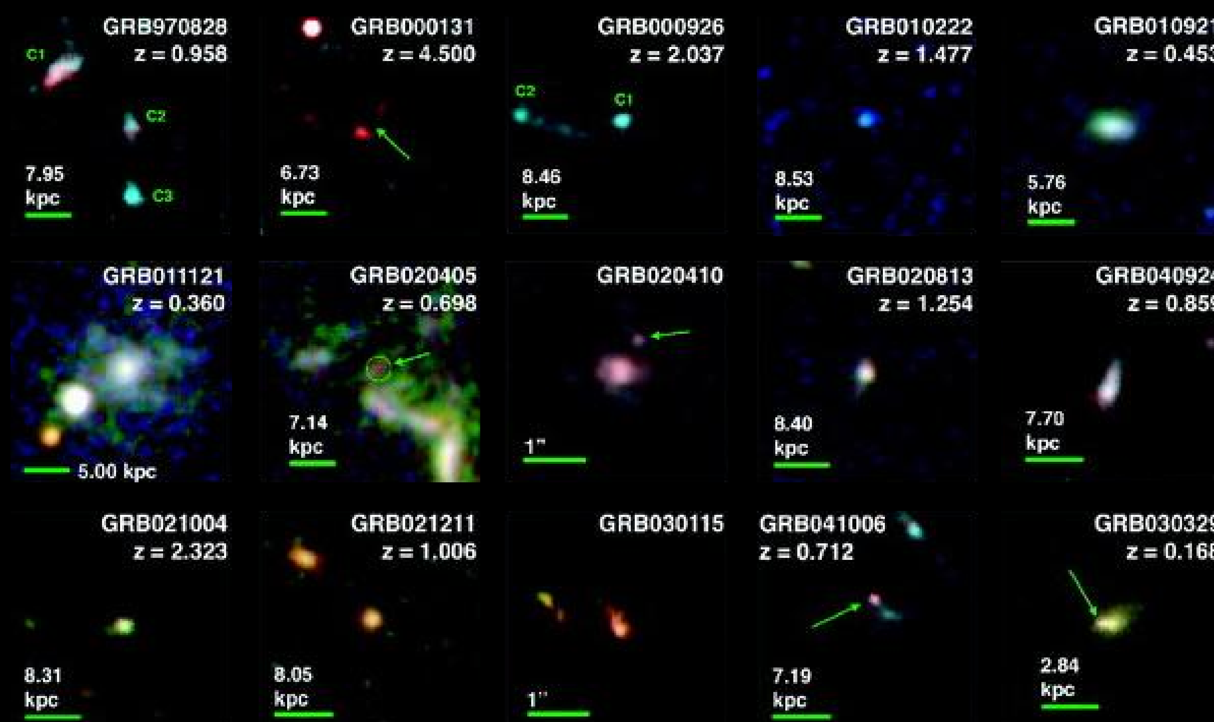
Specific flux νf_ν (erg cm^-2 s^-1)
Wavelength (μm)
050915A z = 2.527
051008 z = 2.9
051022 z = 0.809
060202 z = 0.785
060306 z = 1.55
060319 z = 1.172
060719 z = 1.532
060814 z = 1.923
060923A z = 2.6
061222A z = 2.088
070306 z = 1.496
070521 z = 1.7
070802 z = 2.455
071021 z = 2.452
080207 z = 2.086
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

Pre-Swift Control Sample



Pre-Swift: dark GRBs hard to localize, but rate of GRBs was slow enough for community efforts to to “keep up” with: most (>65%) have published host photometry in the literature.

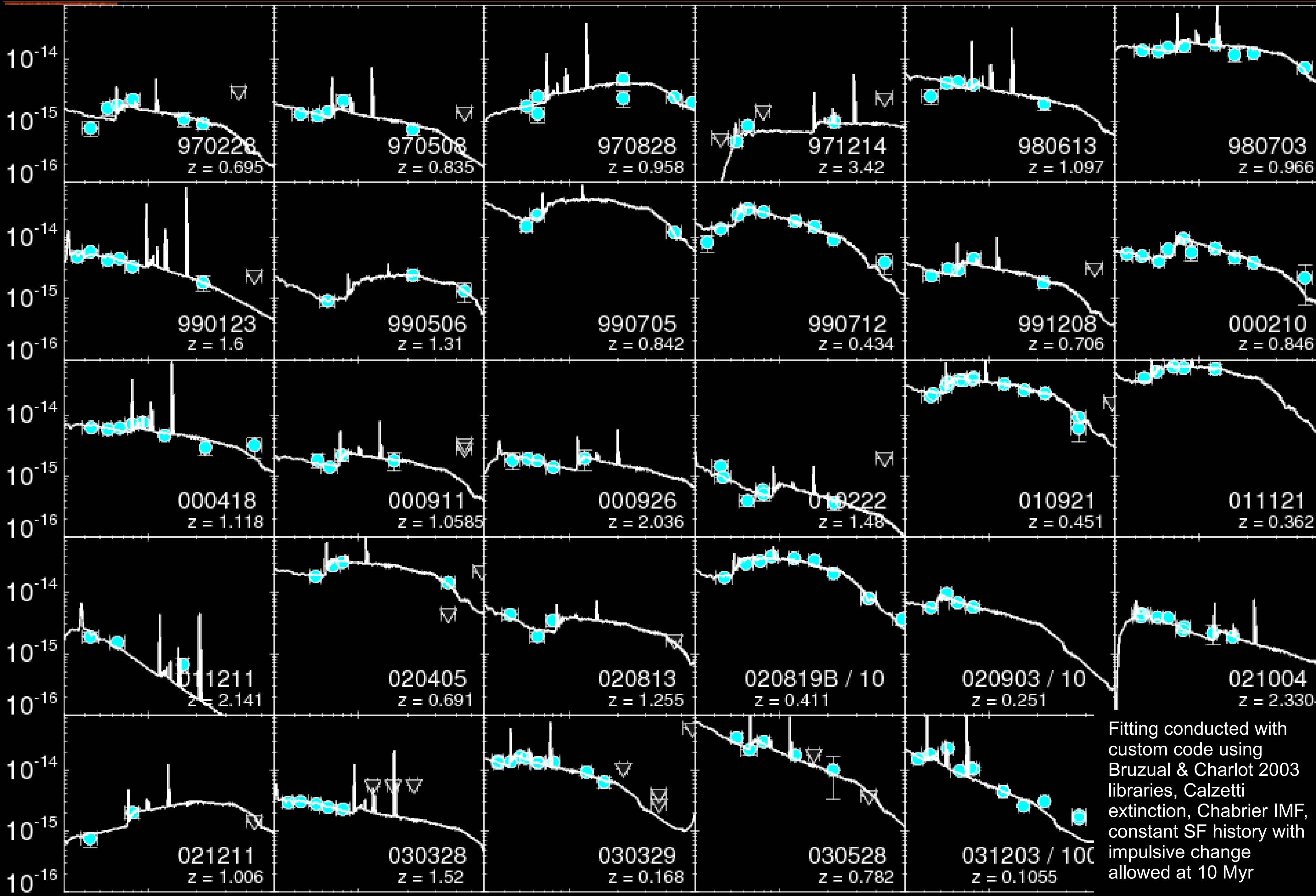
Nearly all are at z<1.5 – early satellites saw only bright, nearby GRBs.



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

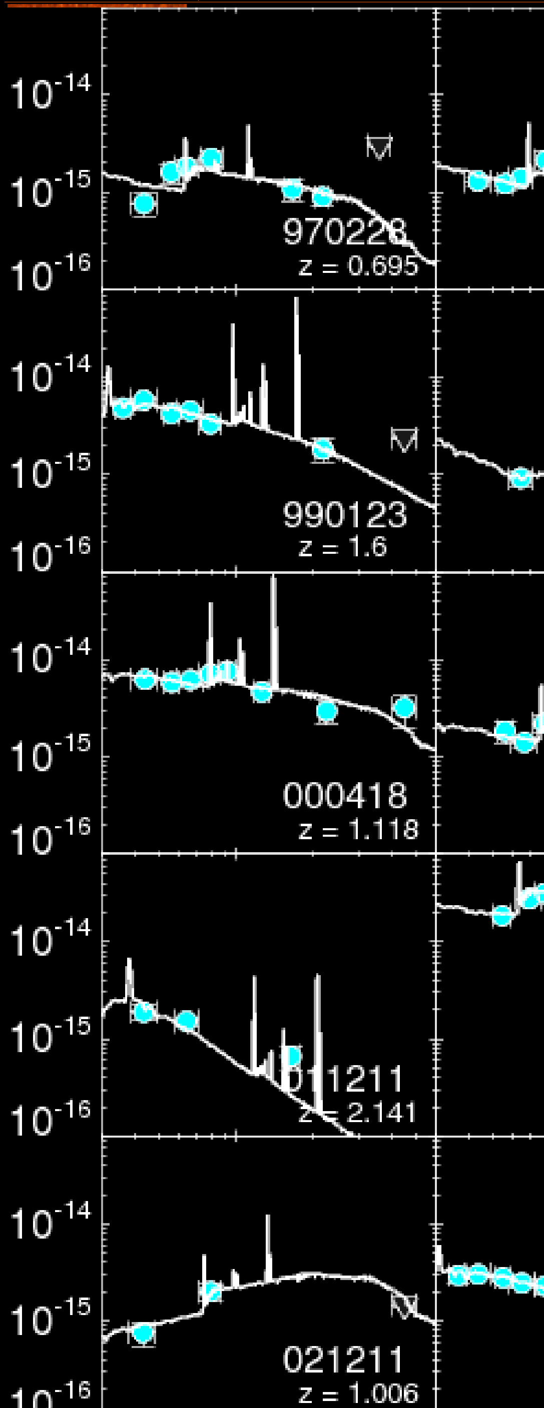
HST images from Wainwright et al. 2007

Pre-Swift Control Sample

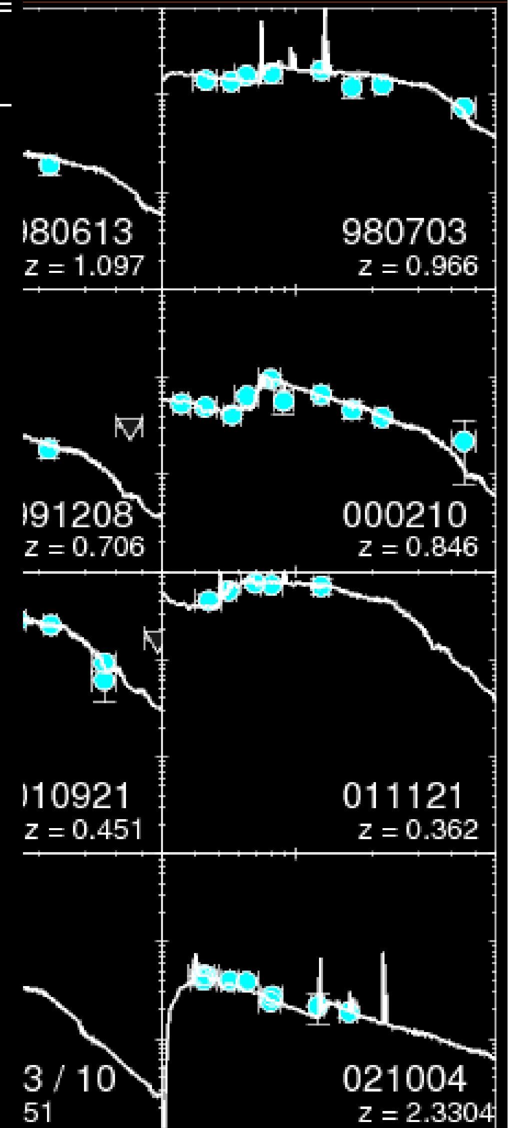


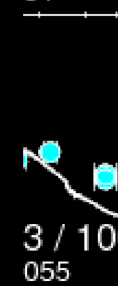
Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr

Pre-Swift Control Sample



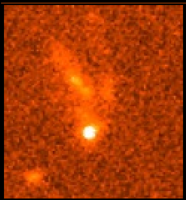
GRB[a]	z[b]	SFR[c] $M_\odot\ yr^{-1}$	M_*[d] $10^9\ M_\odot$	A_V[e] mag	χ^2/dof
970228	0.69	$0.5^{+0.2}_{-0.1}$	$0.3^{+0.1}_{-0.1}$	$0.63^{+0.17}_{-0.15}$	11.3/4
970508	0.83	$1.6^{+12.7}_{-0.6}$	$0.2^{+0.2}_{-0.0}$	$0.84^{+0.76}_{-0.19}$	8.3/3
970828	0.96	$35.0^{+12.6}_{-7.6}$	$0.9^{+0.2}_{-0.1}$	$2.13^{+0.10}_{-0.09}$	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





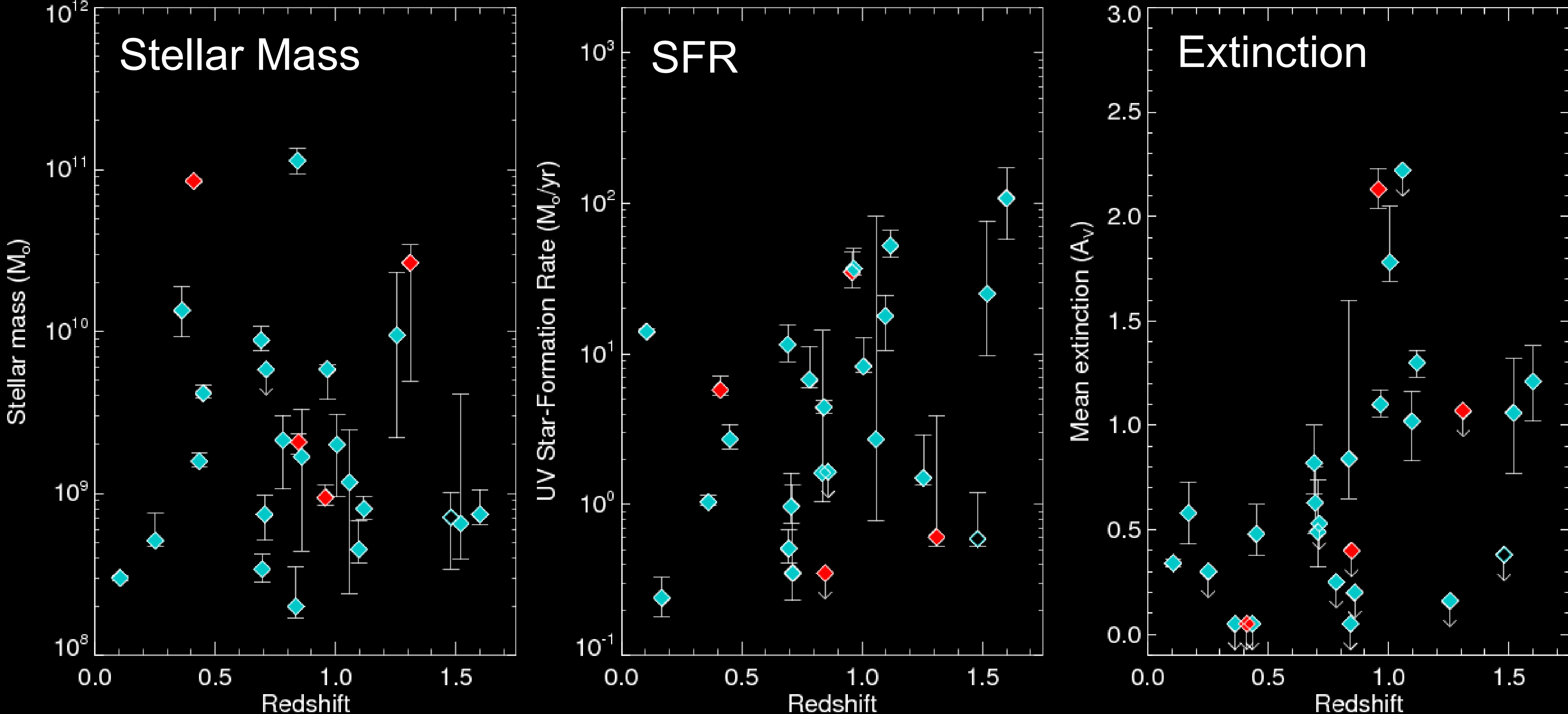
Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr

Comparisons at z~1

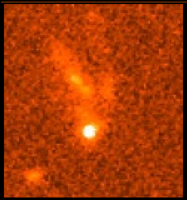


Pre-Swift events only:

Blue=unobscured GRB, Red = obscured GRB.

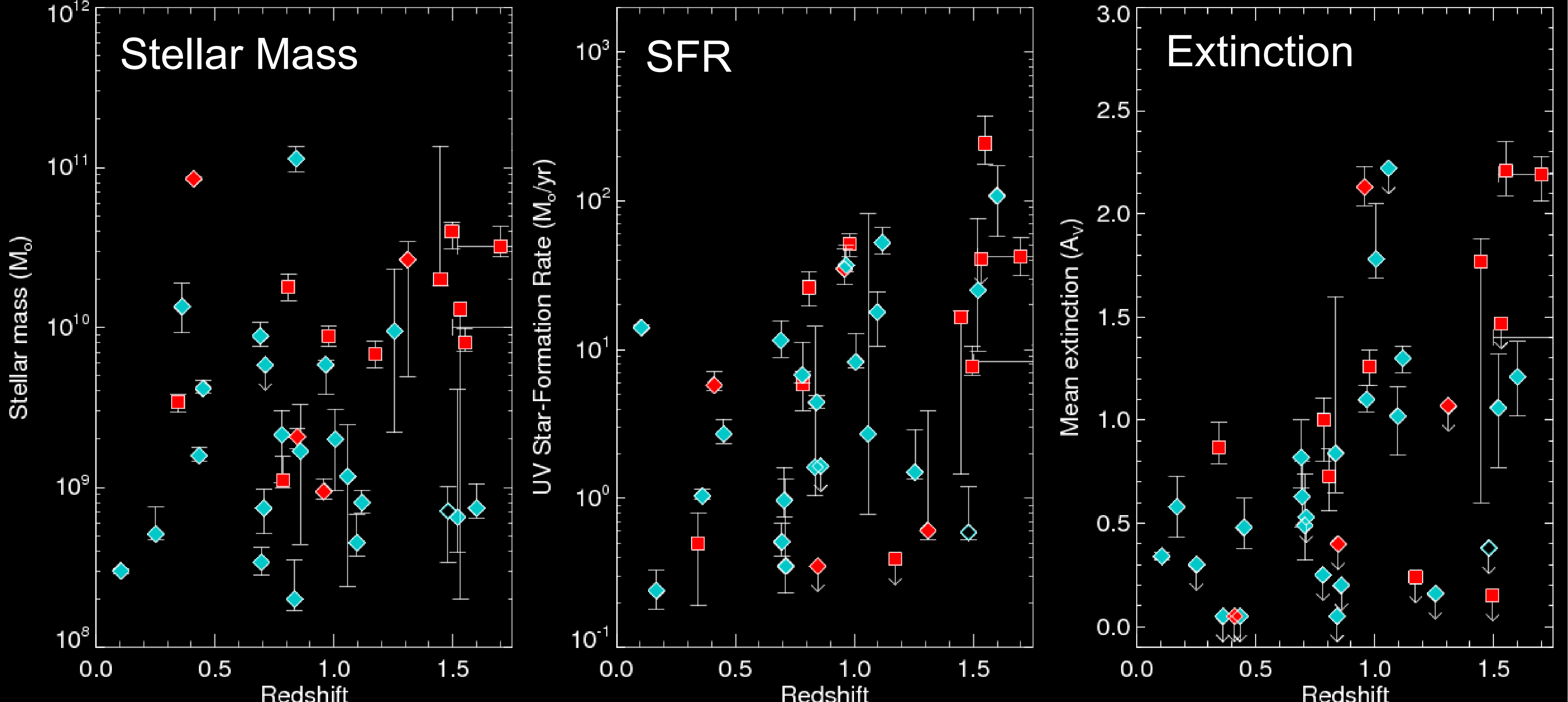


Comparisons at z~1



Combined pre-Swift + dark sample:

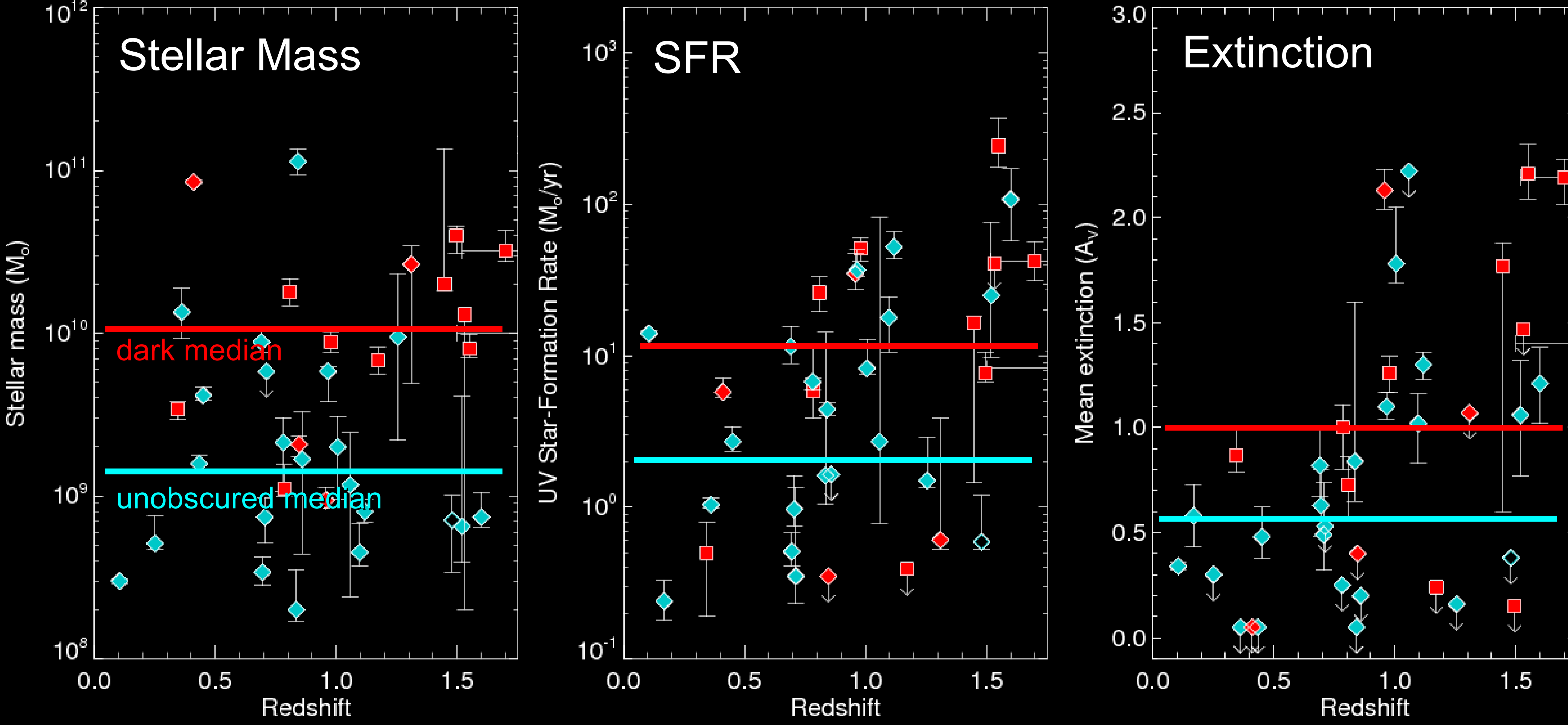
Blue=unobscured GRB, Red = obscured GRB.



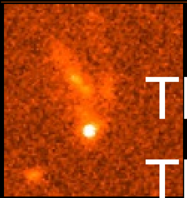
Comparisons at z~1

"Darkness" matters!
Obscured GRBs are in more obscured, massive, star-forming hosts.

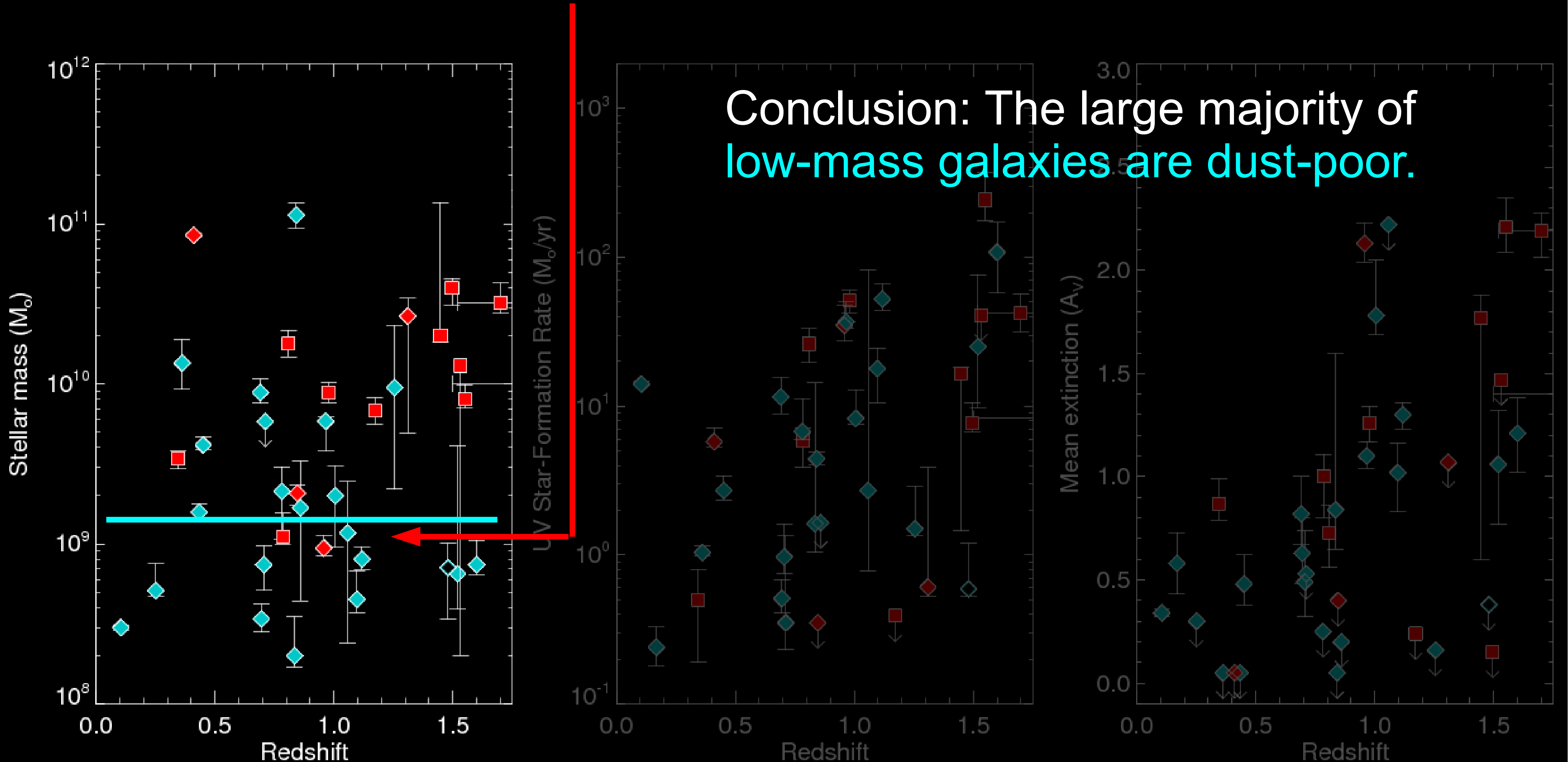
Combined pre-Swift + dark sample: Blue=unobscured GRB, Red = obscured GRB.



Dust in The Universe

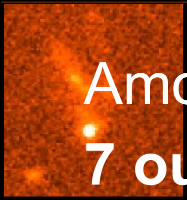


The ***least massive*** host of _any_ obscured GRB is M ~ 10^9 M_o (LMC-like)
The ***median mass*** host of the unobscured GRBs is also ~ 10^9 M_o



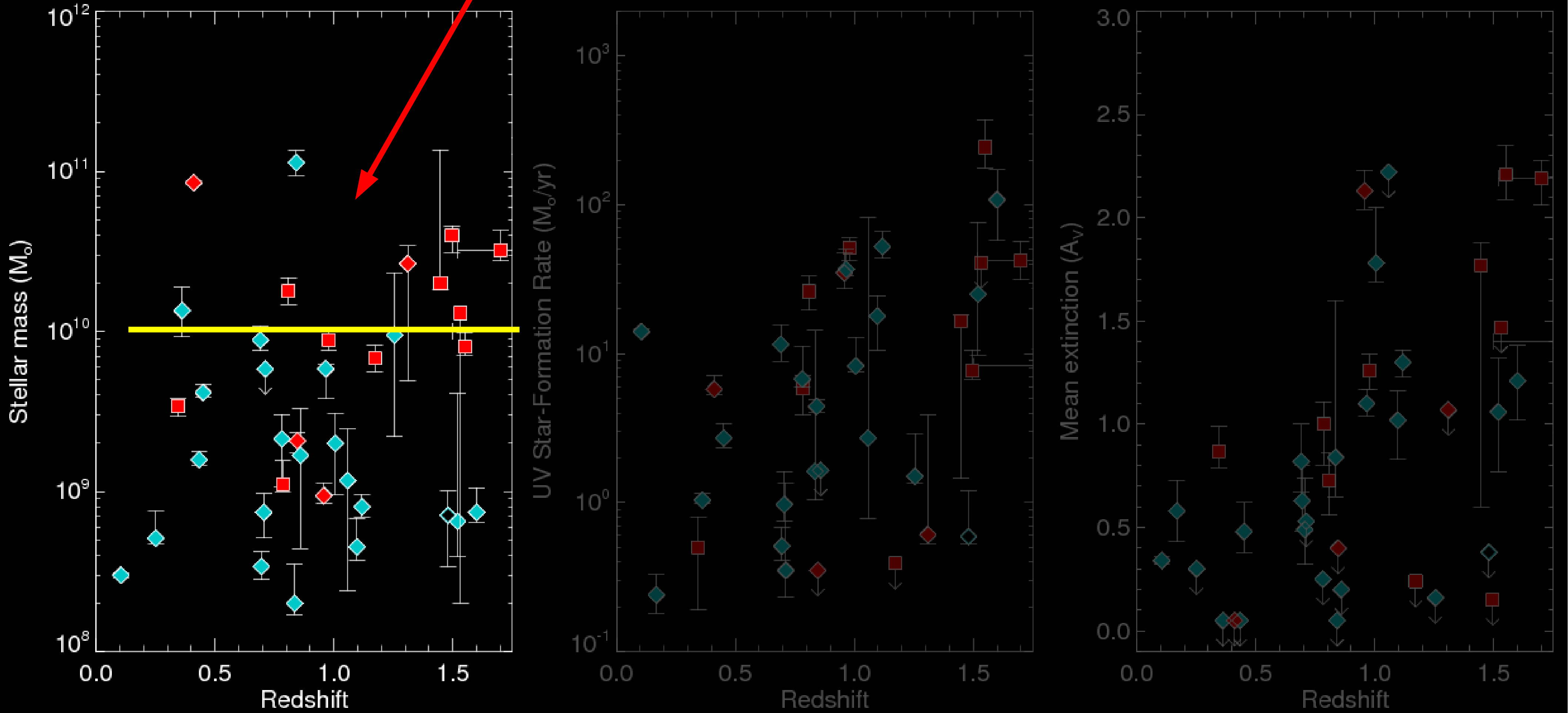
Conclusion: The large majority of low-mass galaxies are dust-poor.

Dust in The Universe

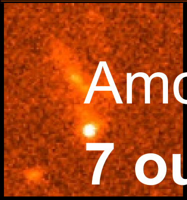


Among GRBs in galaxies **above 10^{10} M_o**, **7 out of 9** are **heavily extinguished**.

Conclusion: Most sightlines to star-forming regions in high-mass galaxies are opaque.



Dust Distribution Within Galaxies



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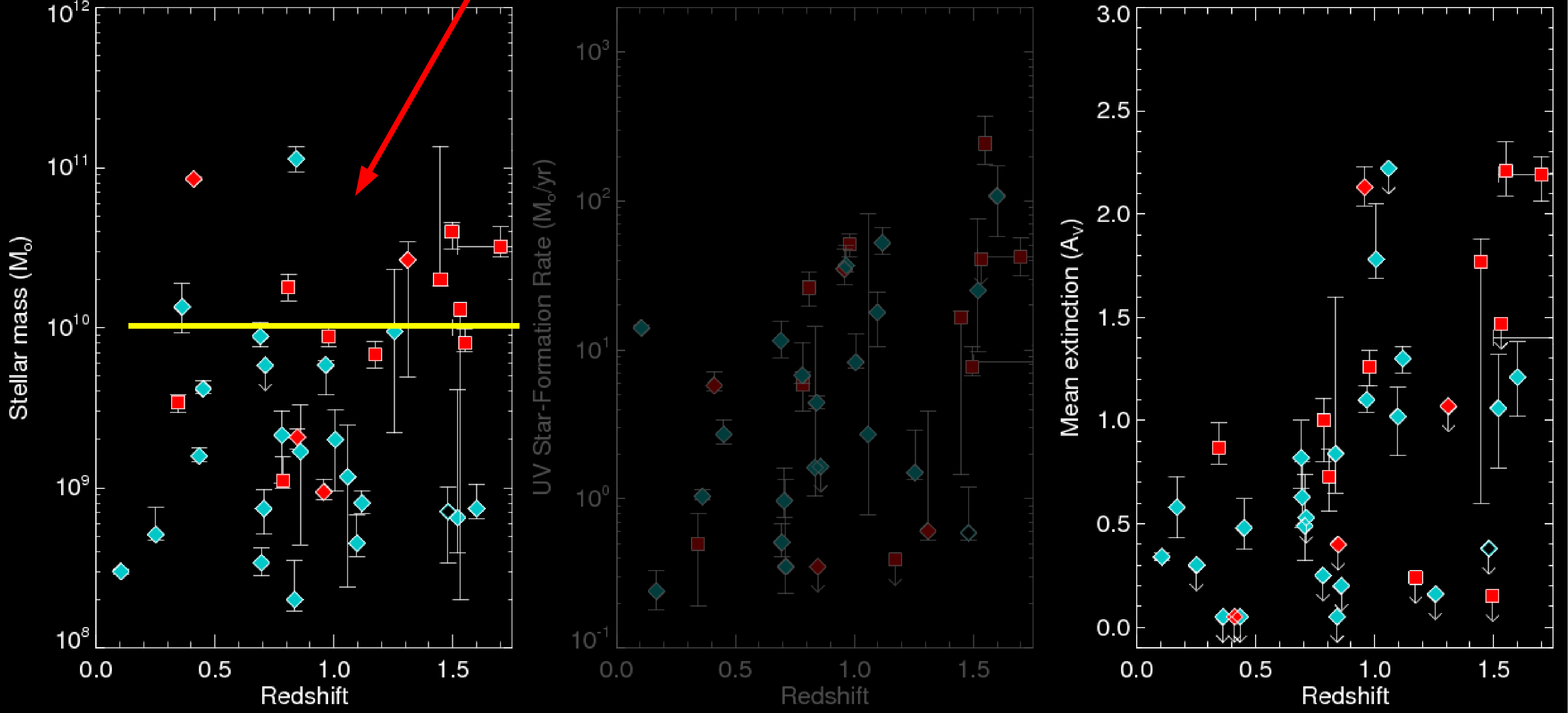

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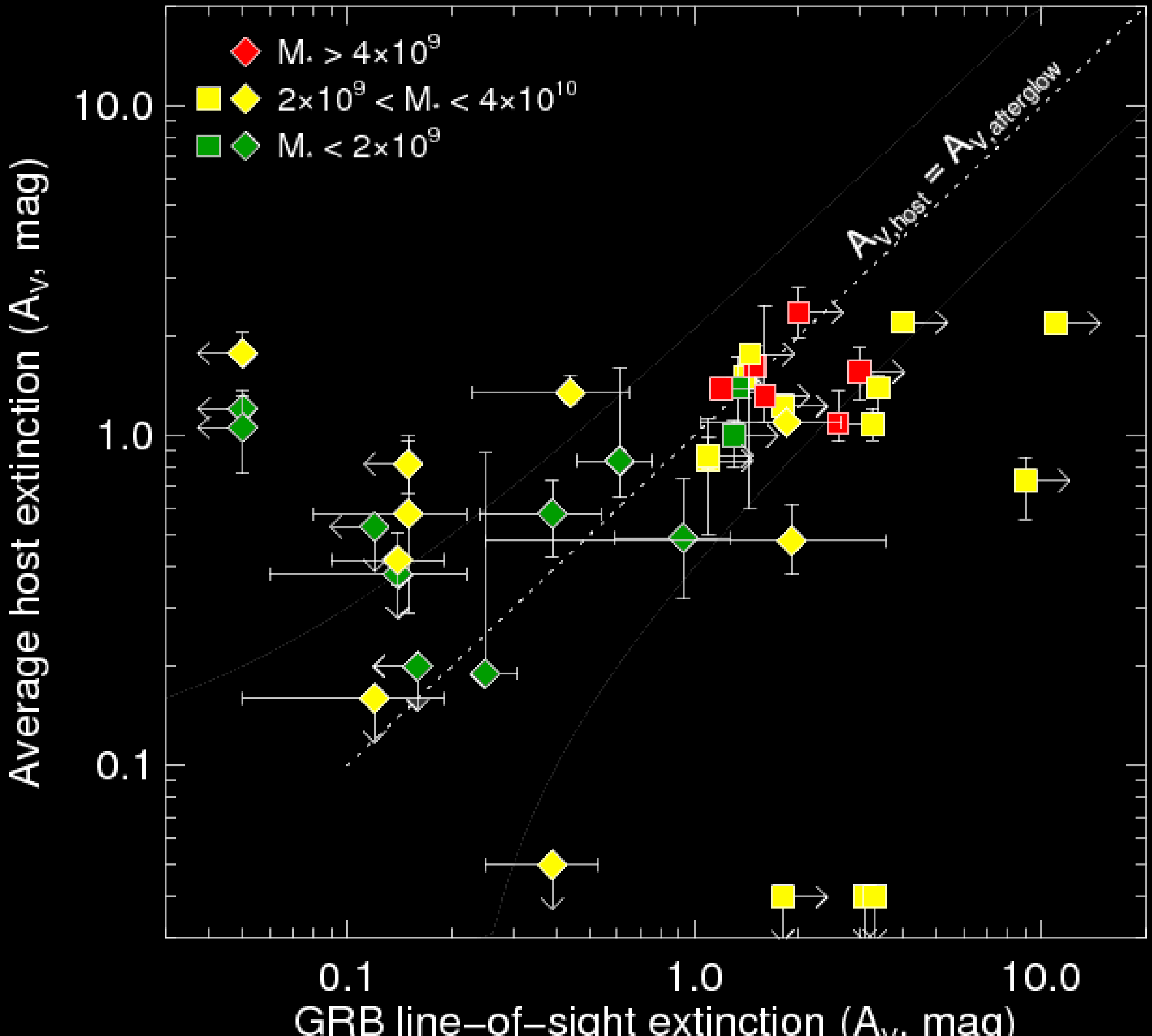
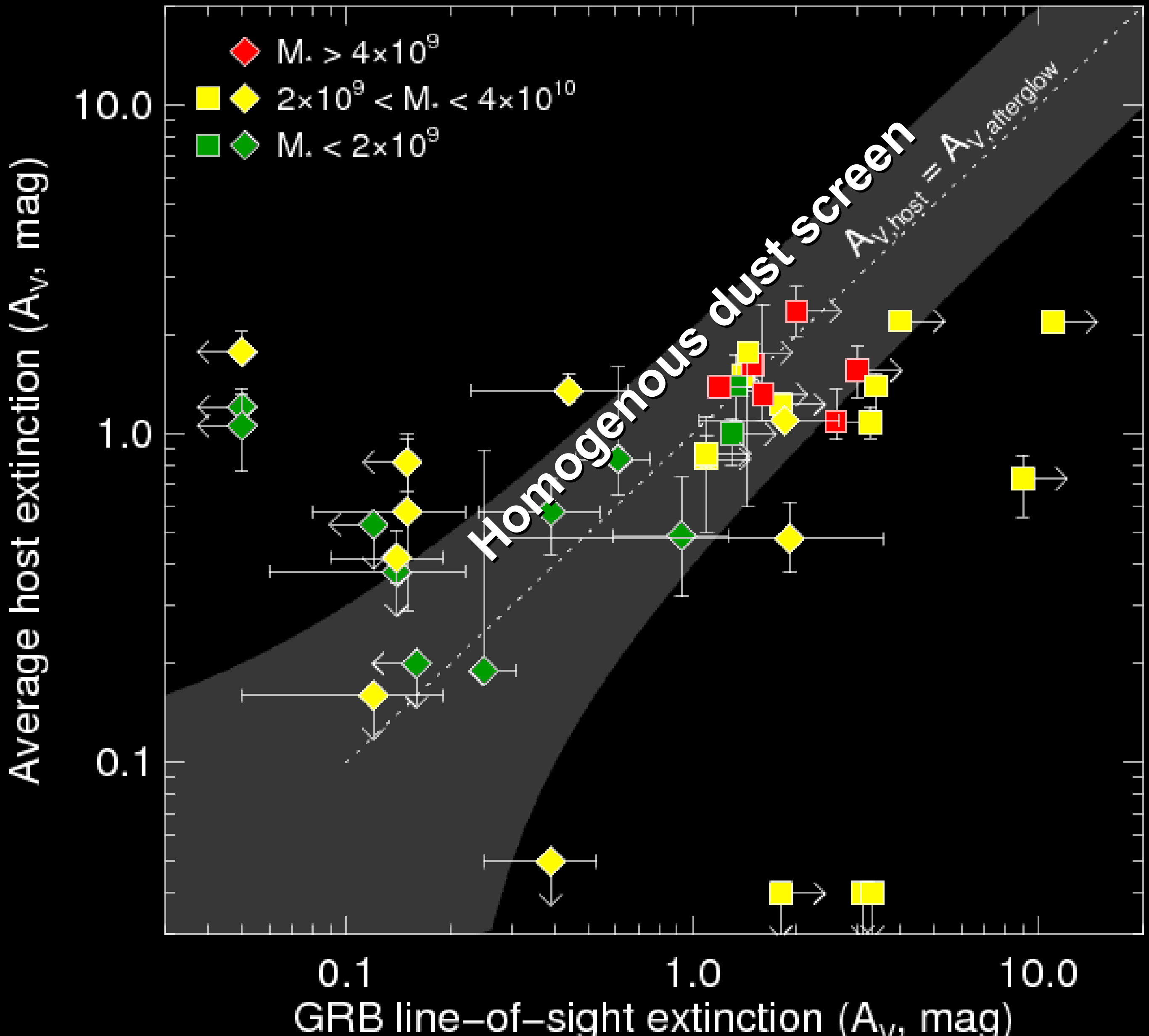


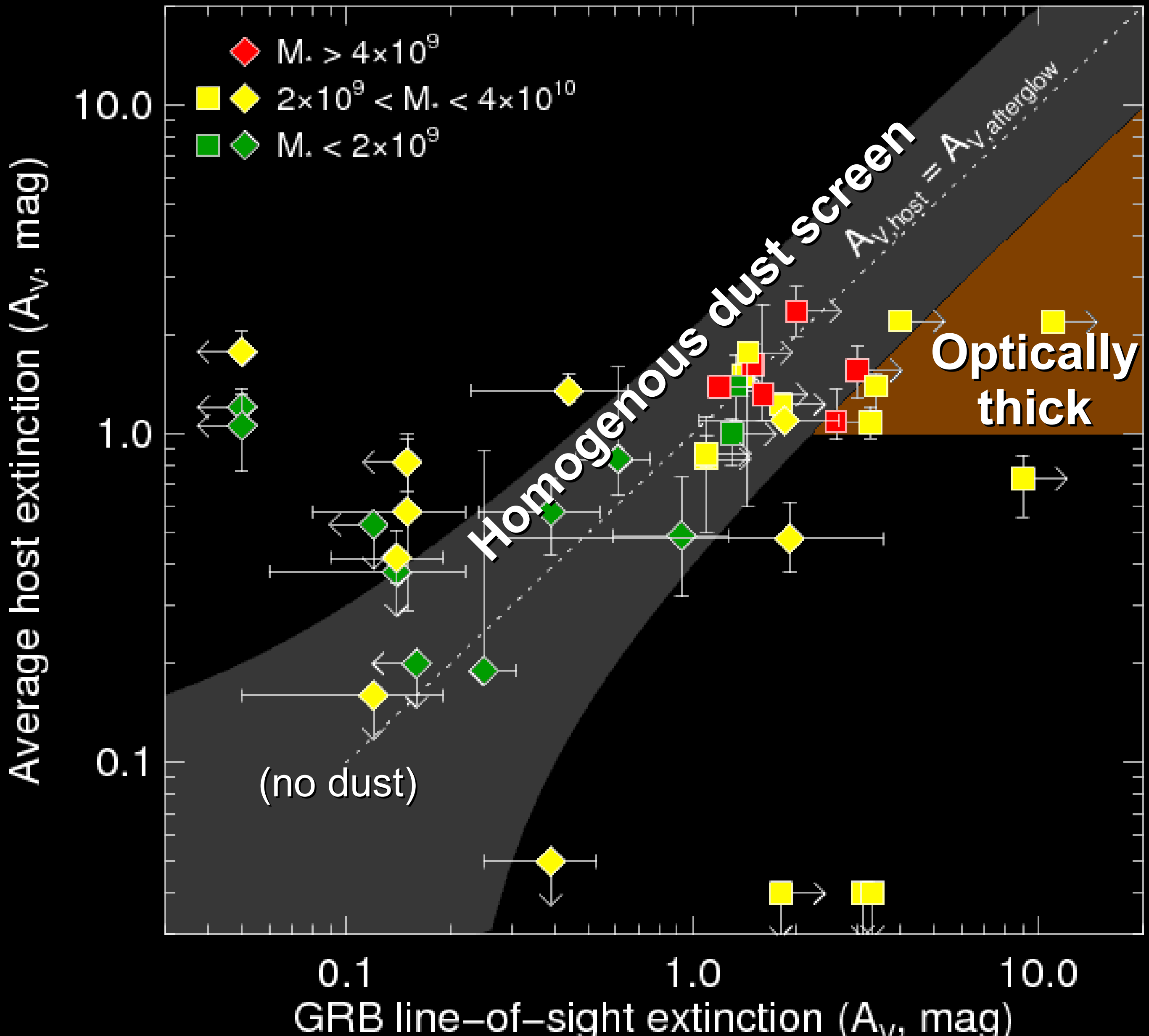
Dust Distribution Within Galaxies



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

High-z galaxies are relatively dust-homogeneous.

Dust Distribution Within Galaxies



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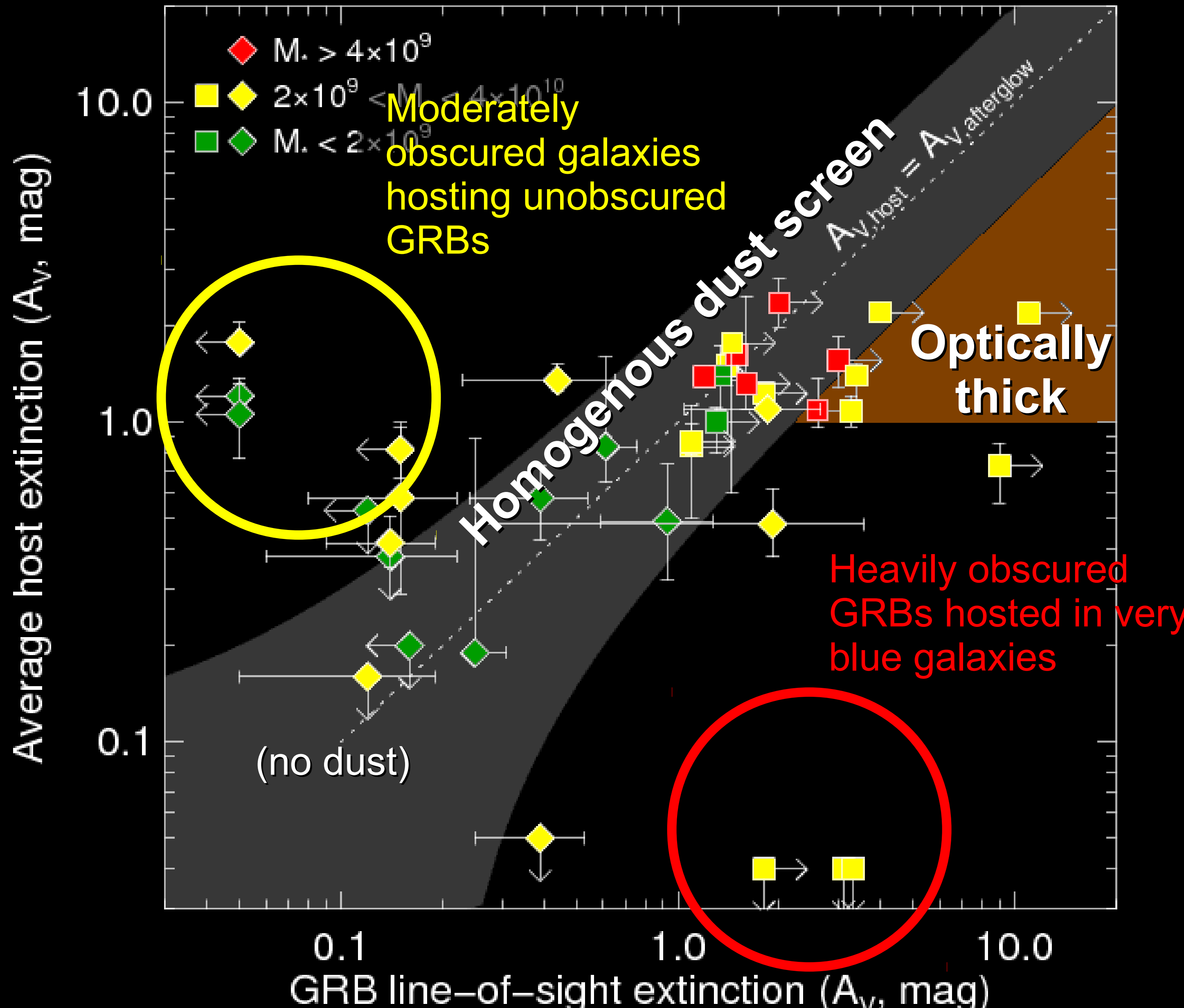
Dust Distribution Within Galaxies

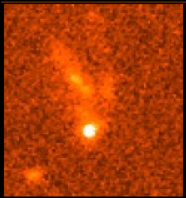


Dusty sightline (usually) implies a dusty, massive galaxy:

High-z galaxies are relatively dust-homogeneous.

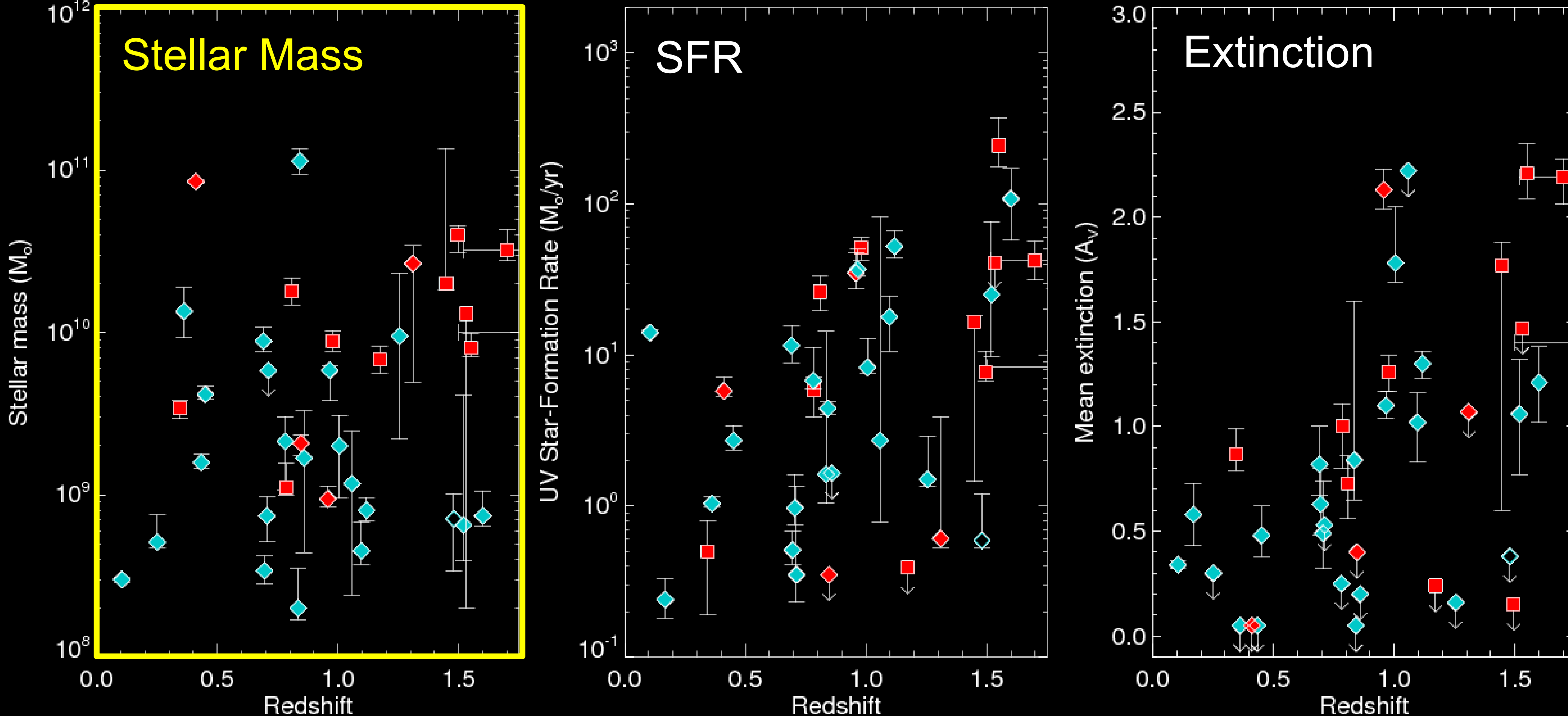
Exceptions do exist in both directions, mostly in intermediate-mass galaxies.

Comparisons vs. Field Galaxies at z~1



Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



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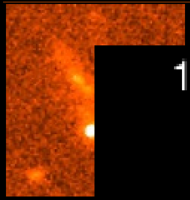

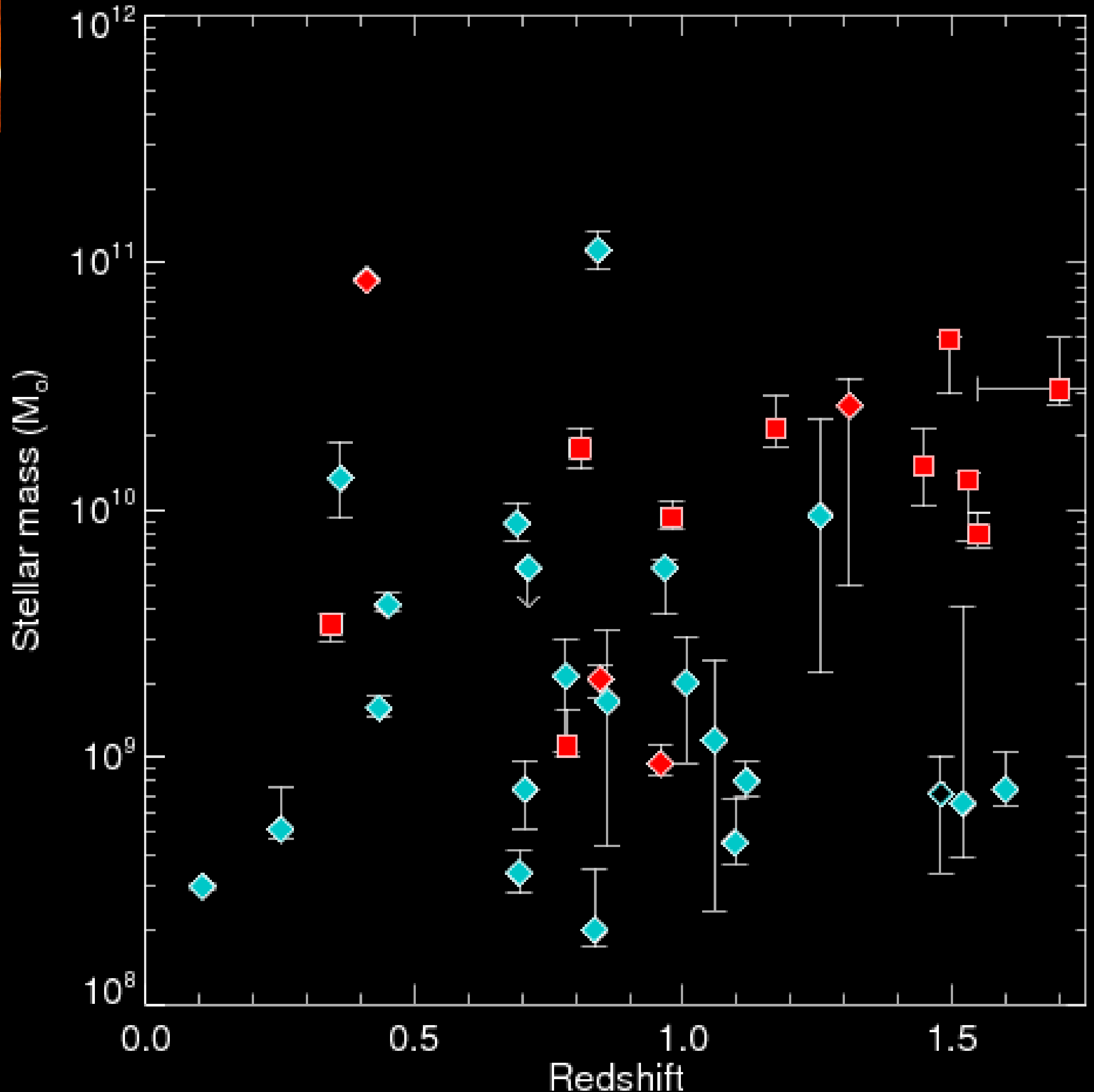

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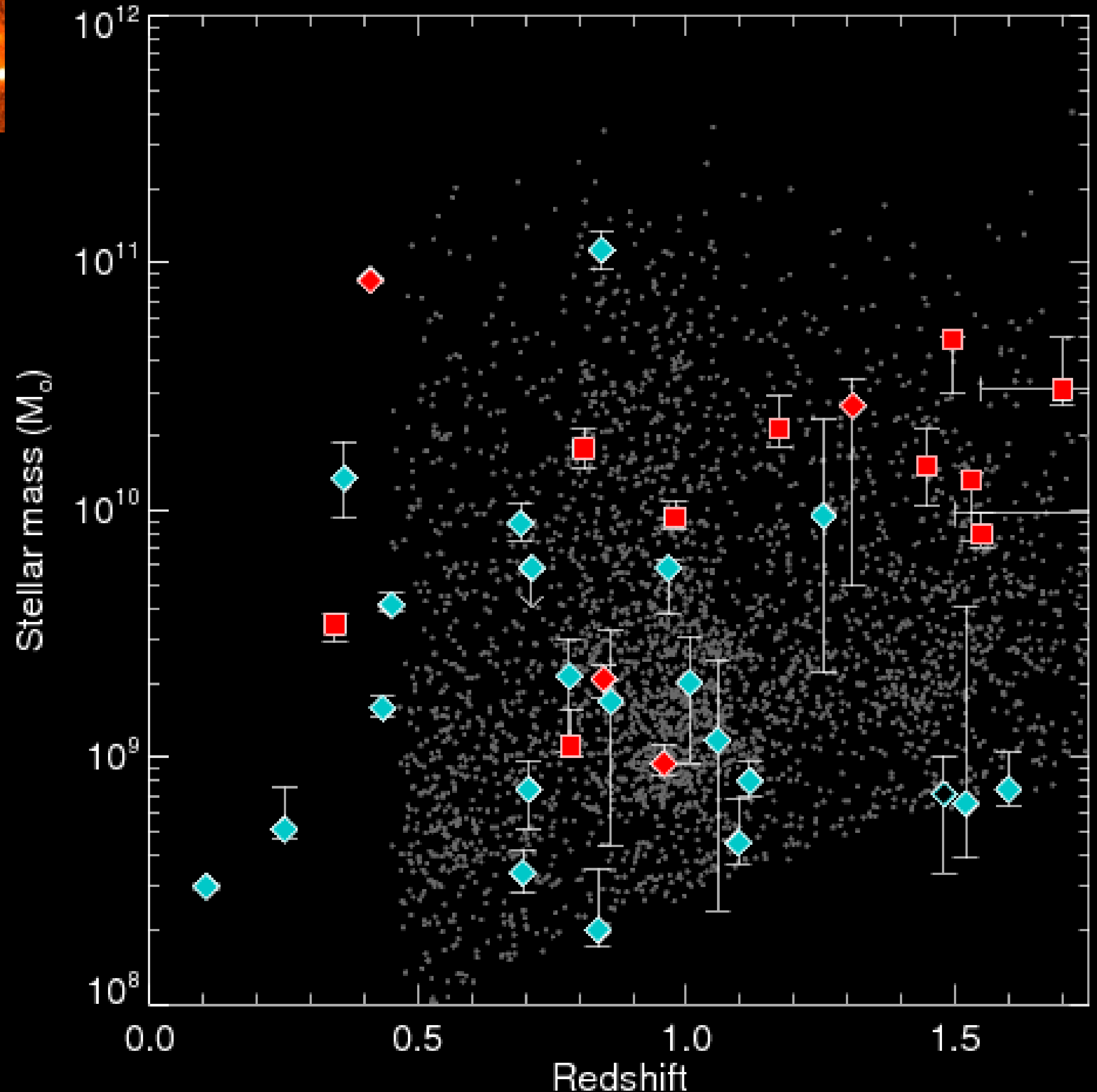
Comparisons vs. Field Galaxies at z~1



Blue=unobscured GRB
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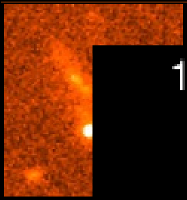
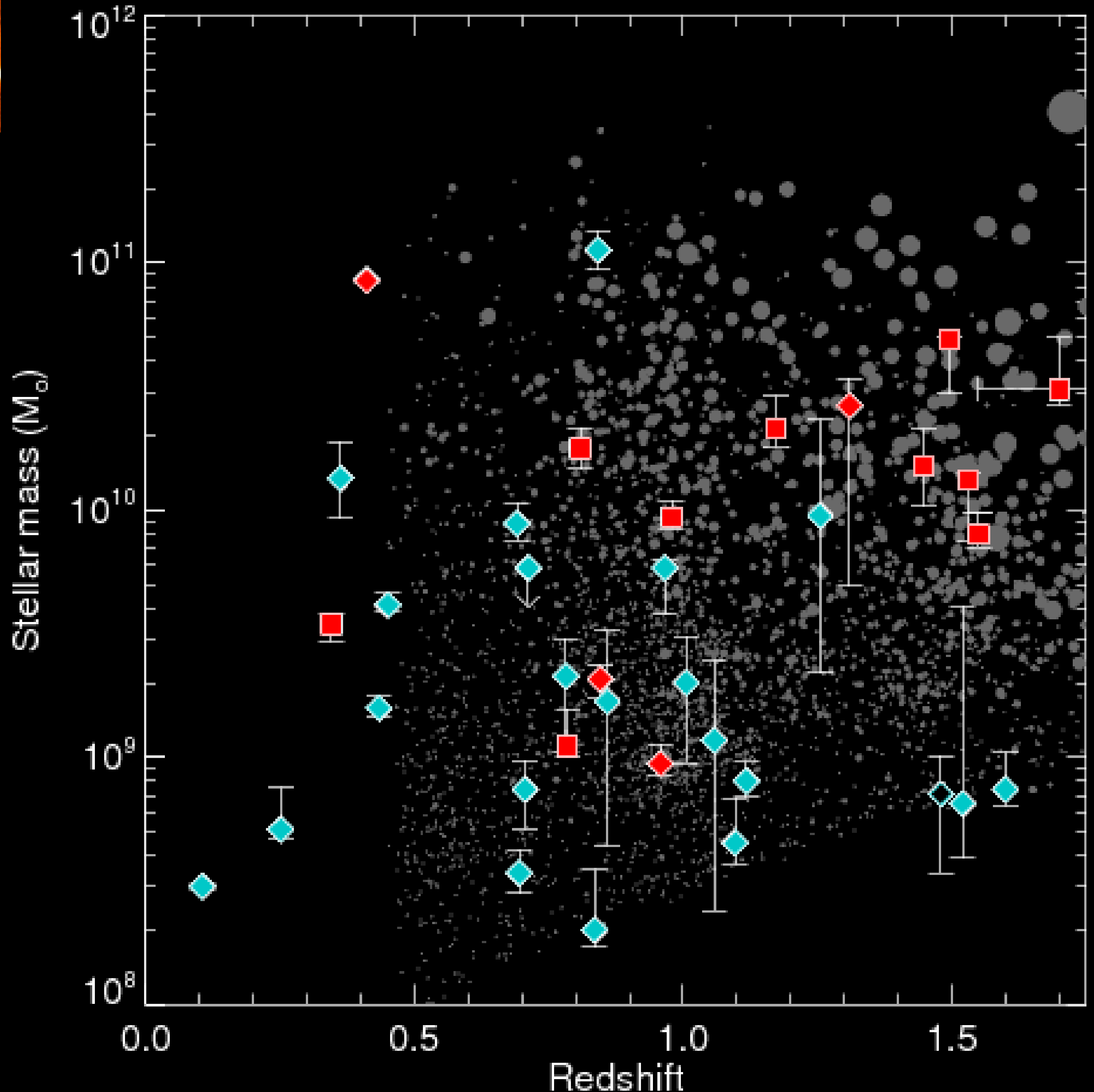
Gray – mass-selected field galaxies from GOODS-North
(Kajisawa+2011)

Comparisons vs. Field Galaxies at z~1





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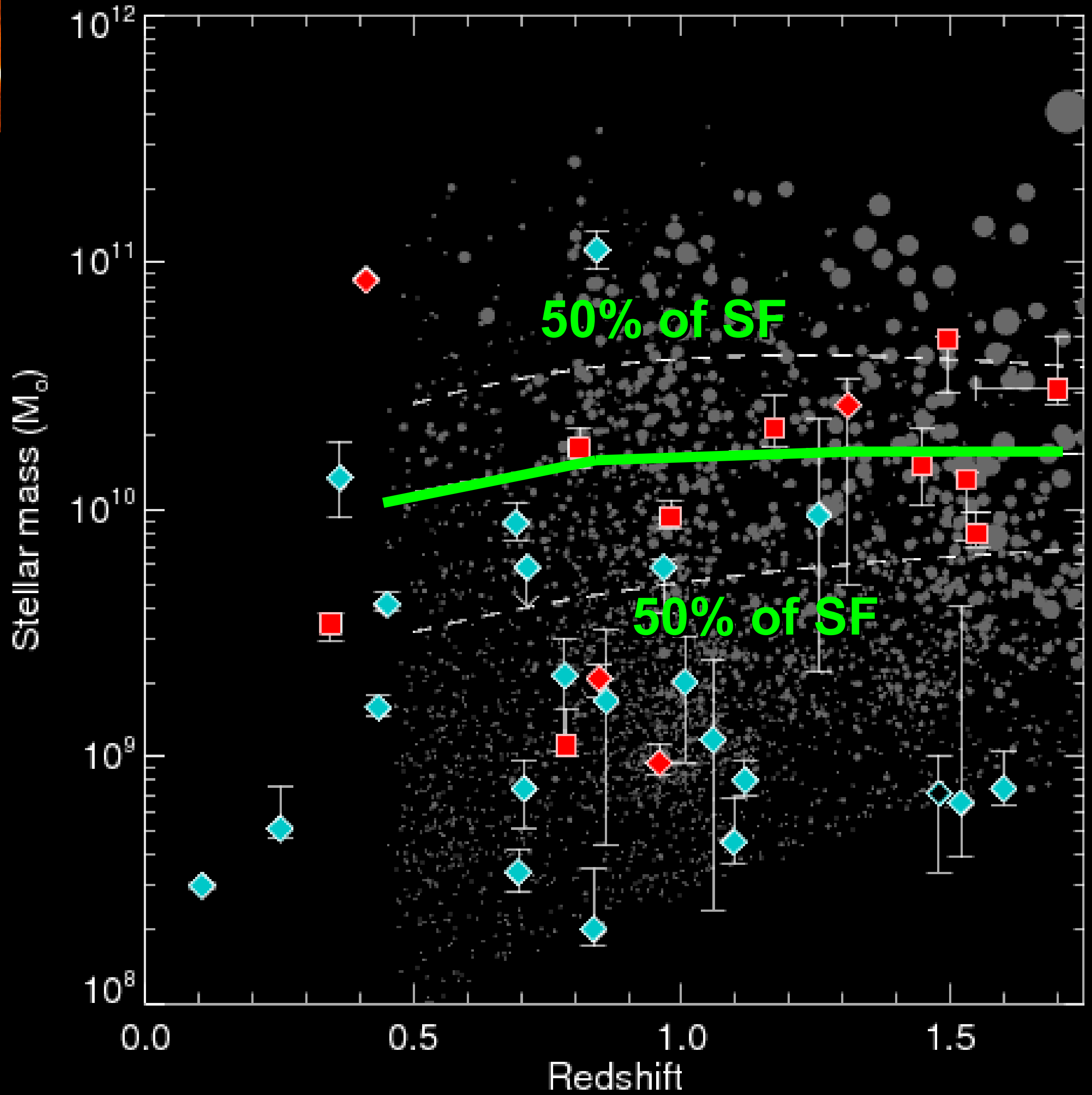
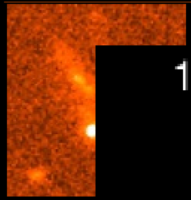
Gray – mass-selected field galaxies from GOODS-North
(Kajisawa+2011)
Area scaled by star formation rate

Comparisons vs. Field Galaxies at z~1





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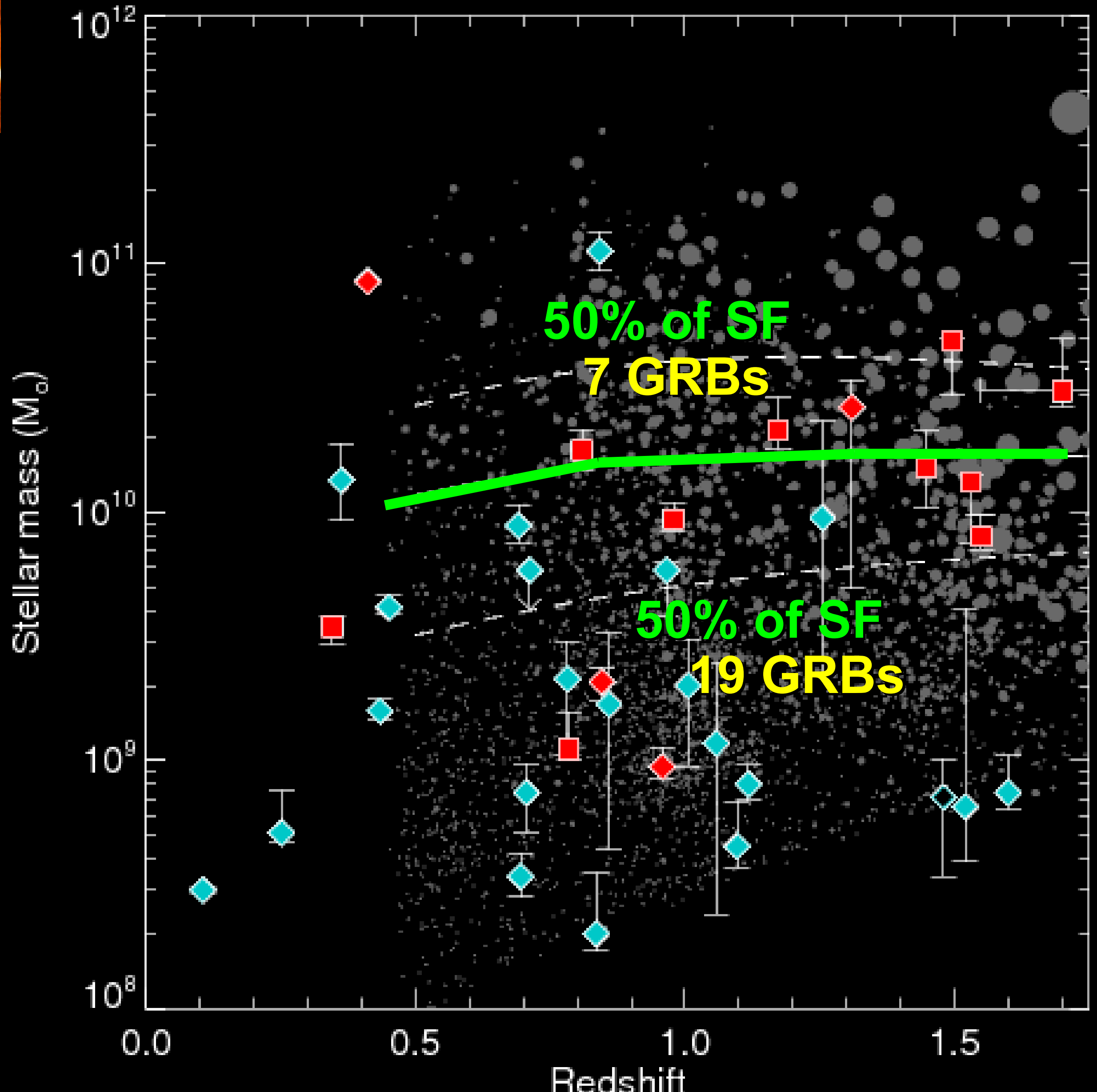
Area scaled by star formation rate

Median mass of cosmic star-formation

Comparisons vs. Field Galaxies at z~1



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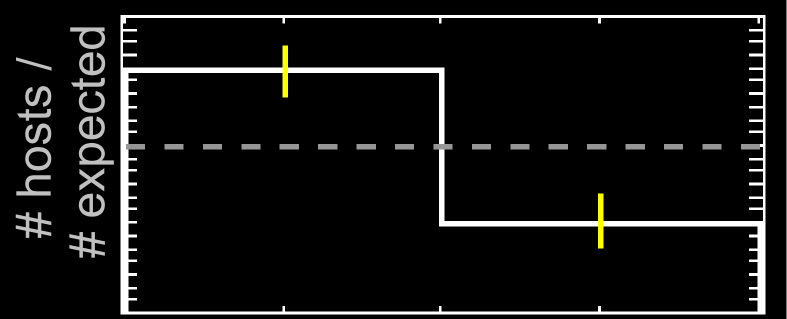
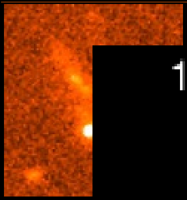
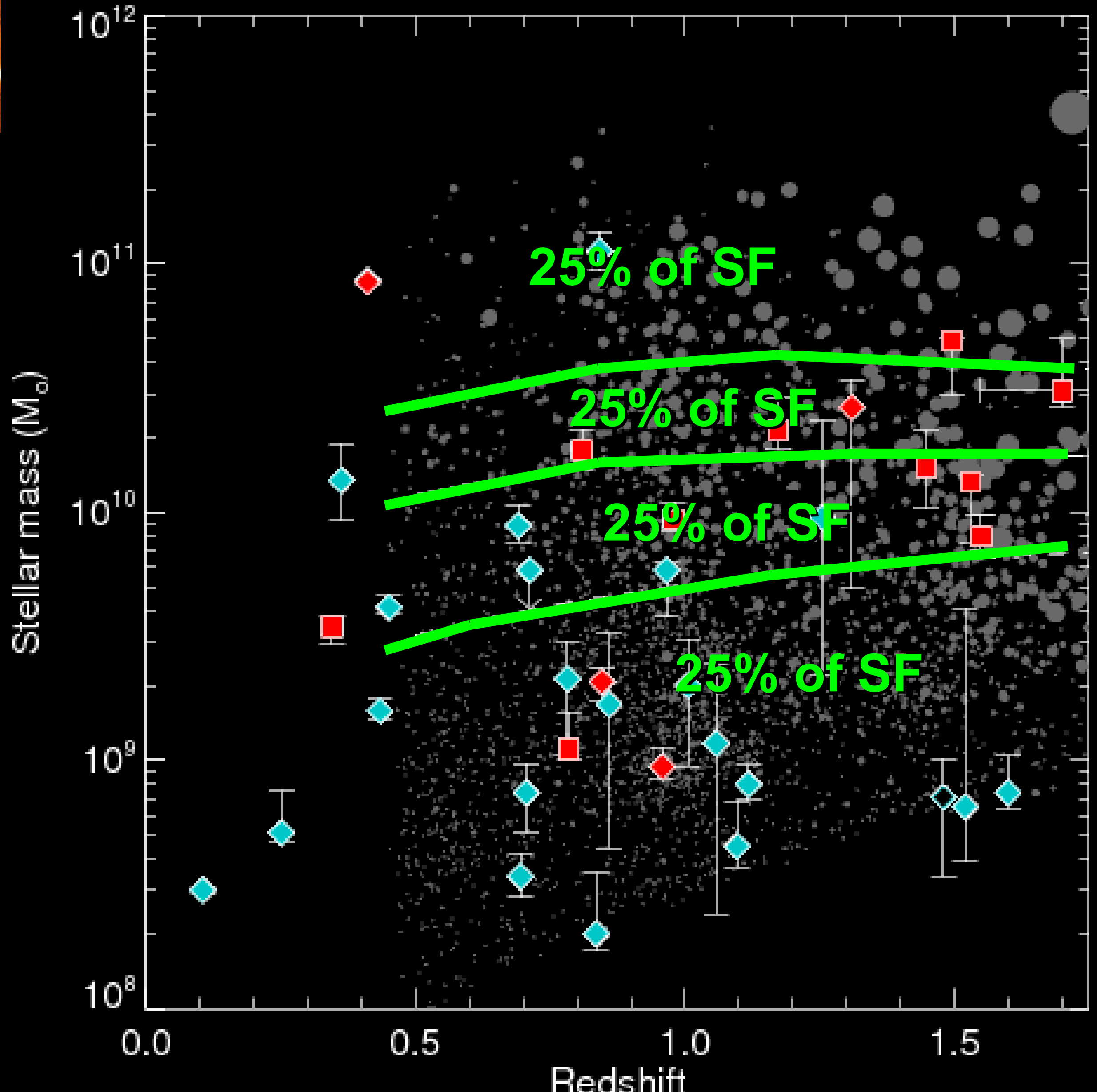


Comparisons vs. Field Galaxies at z~1

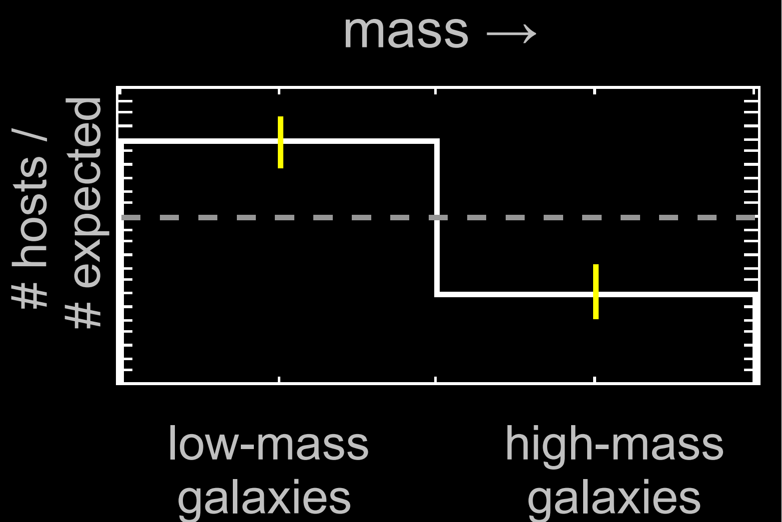




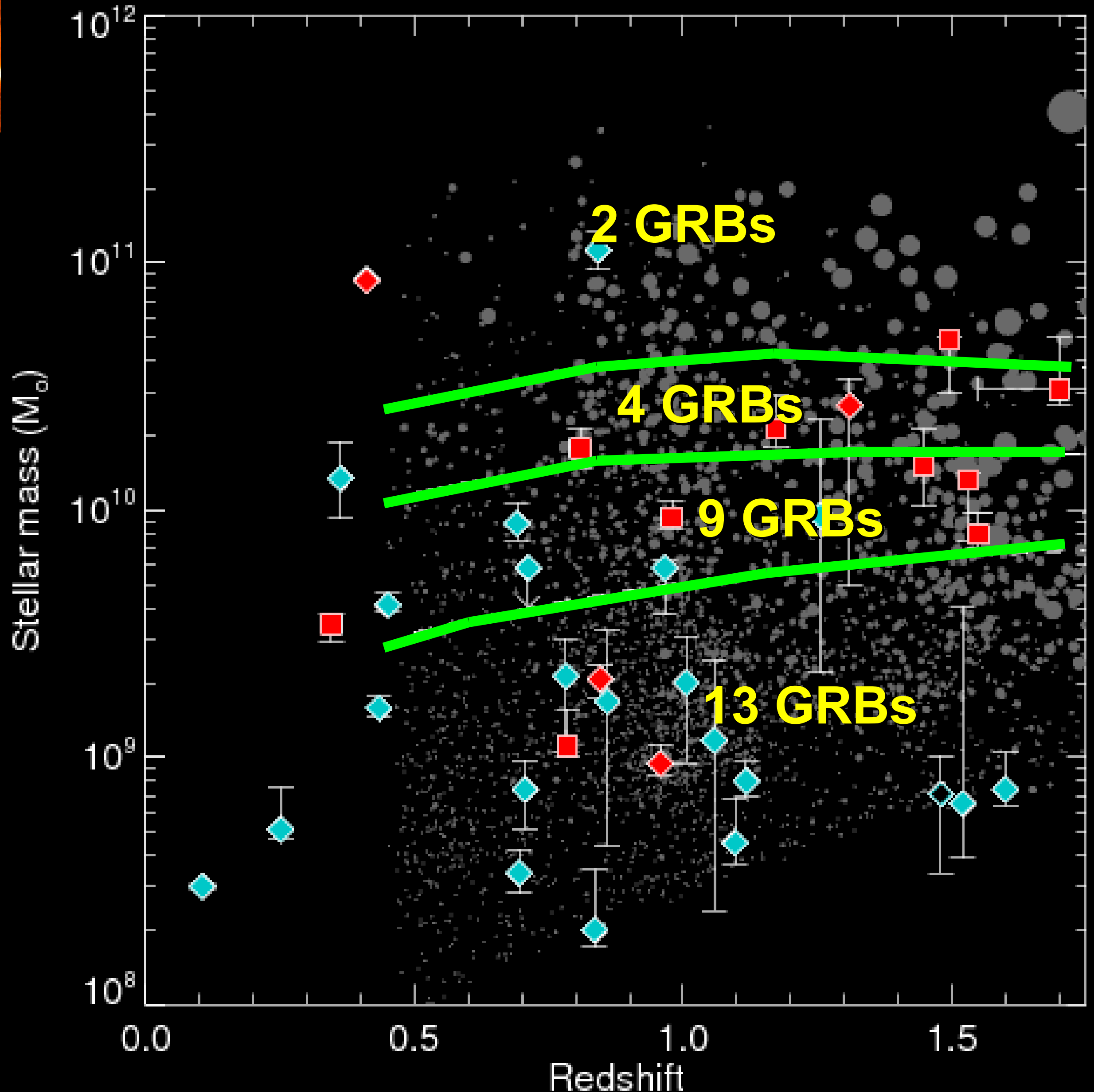
Blue=unobscured GRB
Red = obscured GRB

Gray – mass-selected field galaxies from GOODS-North
(Kajisawa+2011)
Area scaled by star formation rate

Cosmic star-formation quartile boundaries



Comparisons vs. Field Galaxies at z~1



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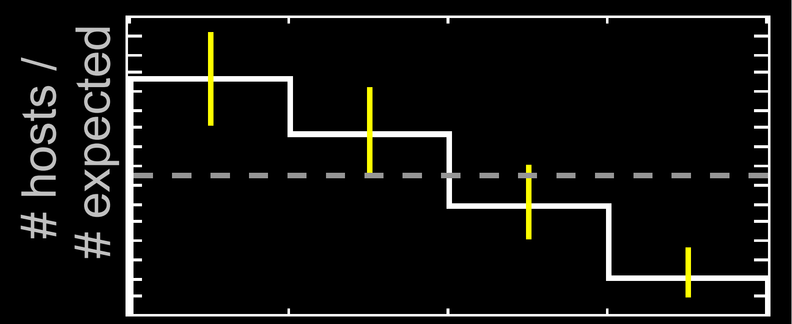
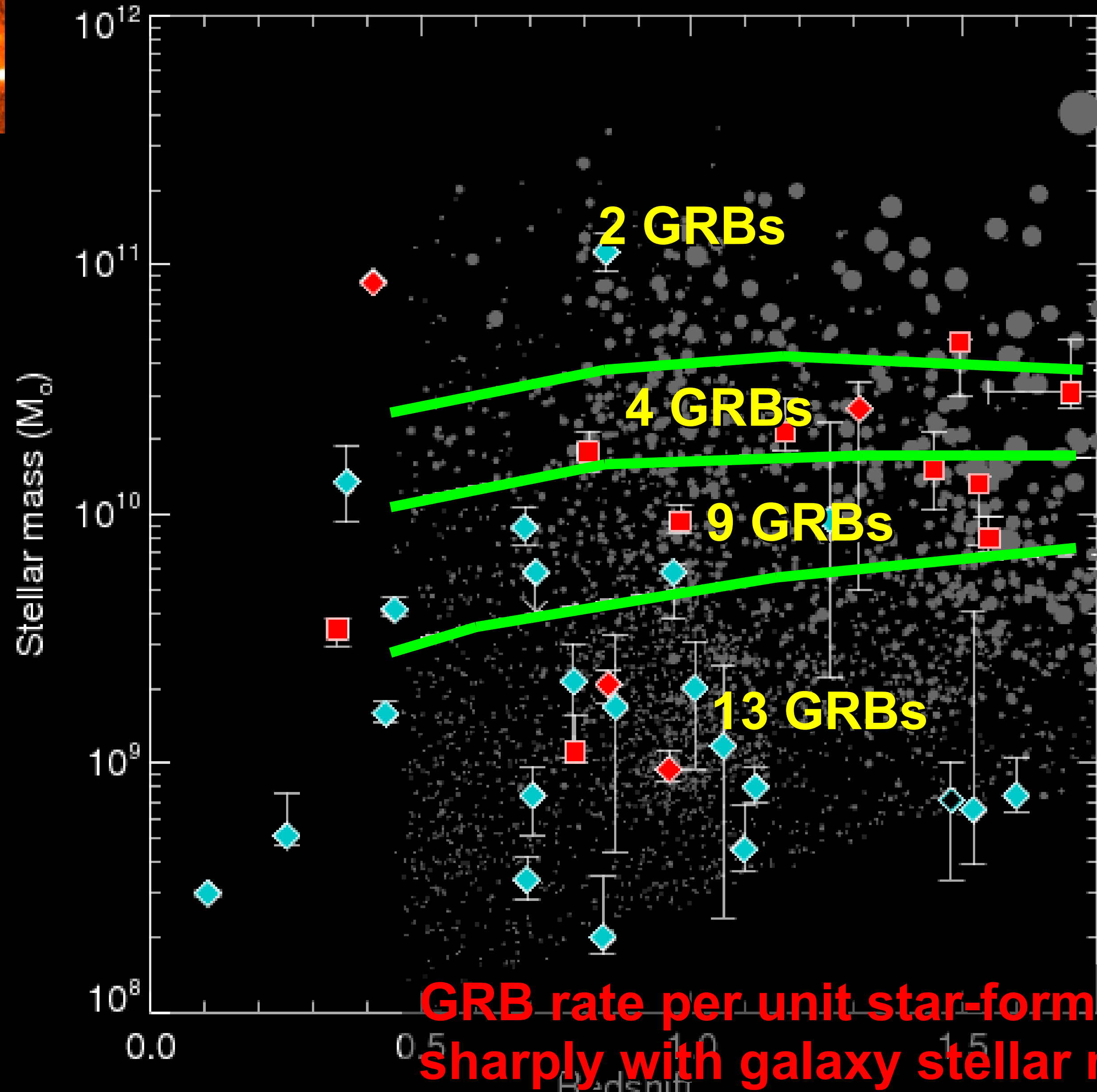


Comparisons vs. Field Galaxies at z~1



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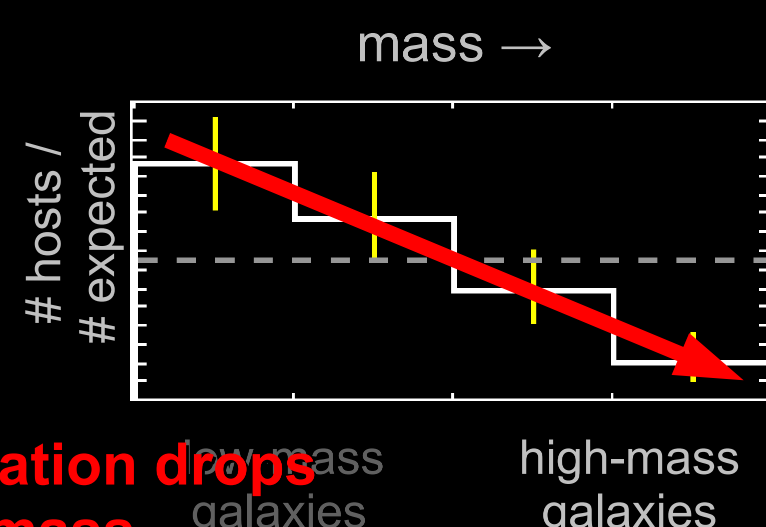
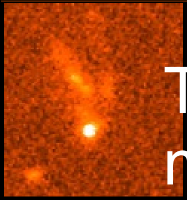


GRB rate per unit star-formation drops sharply with galaxy stellar mass

Metallicity, or something else?



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:

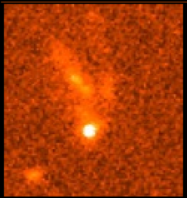
UV radiation field.

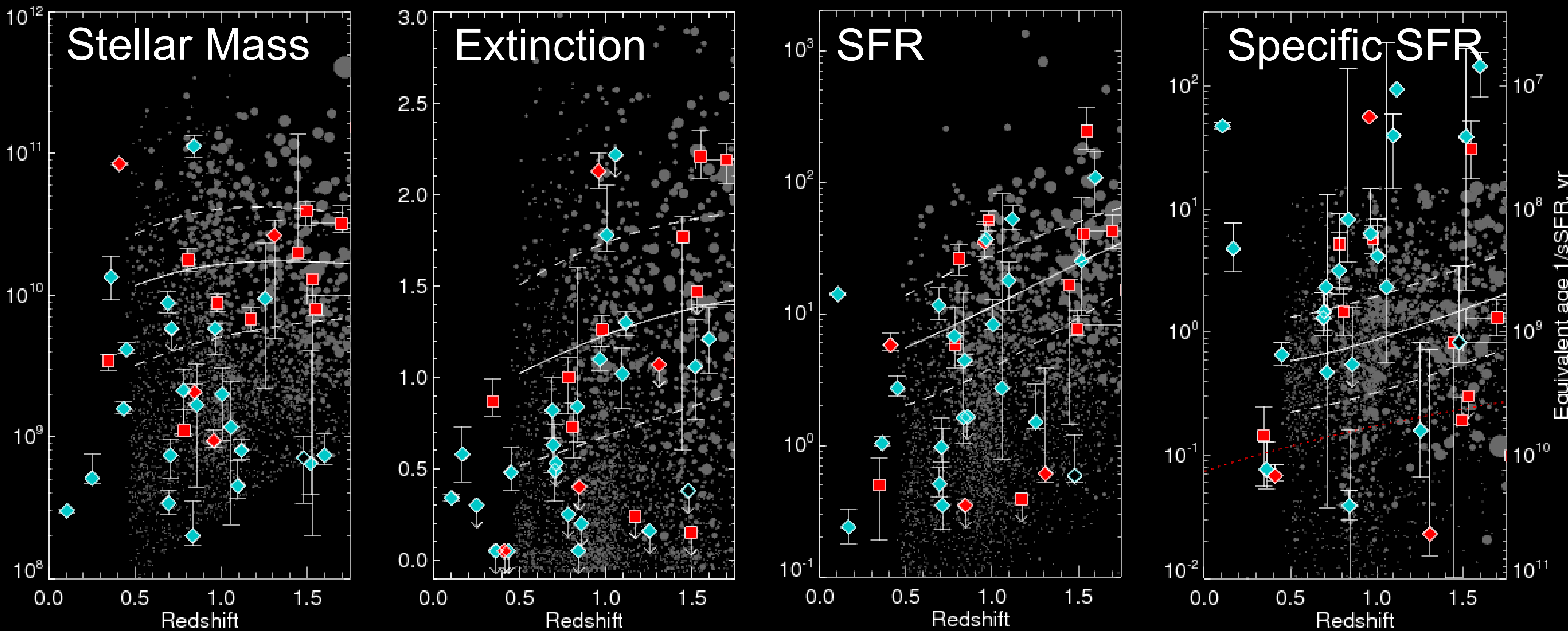
Gas density.

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

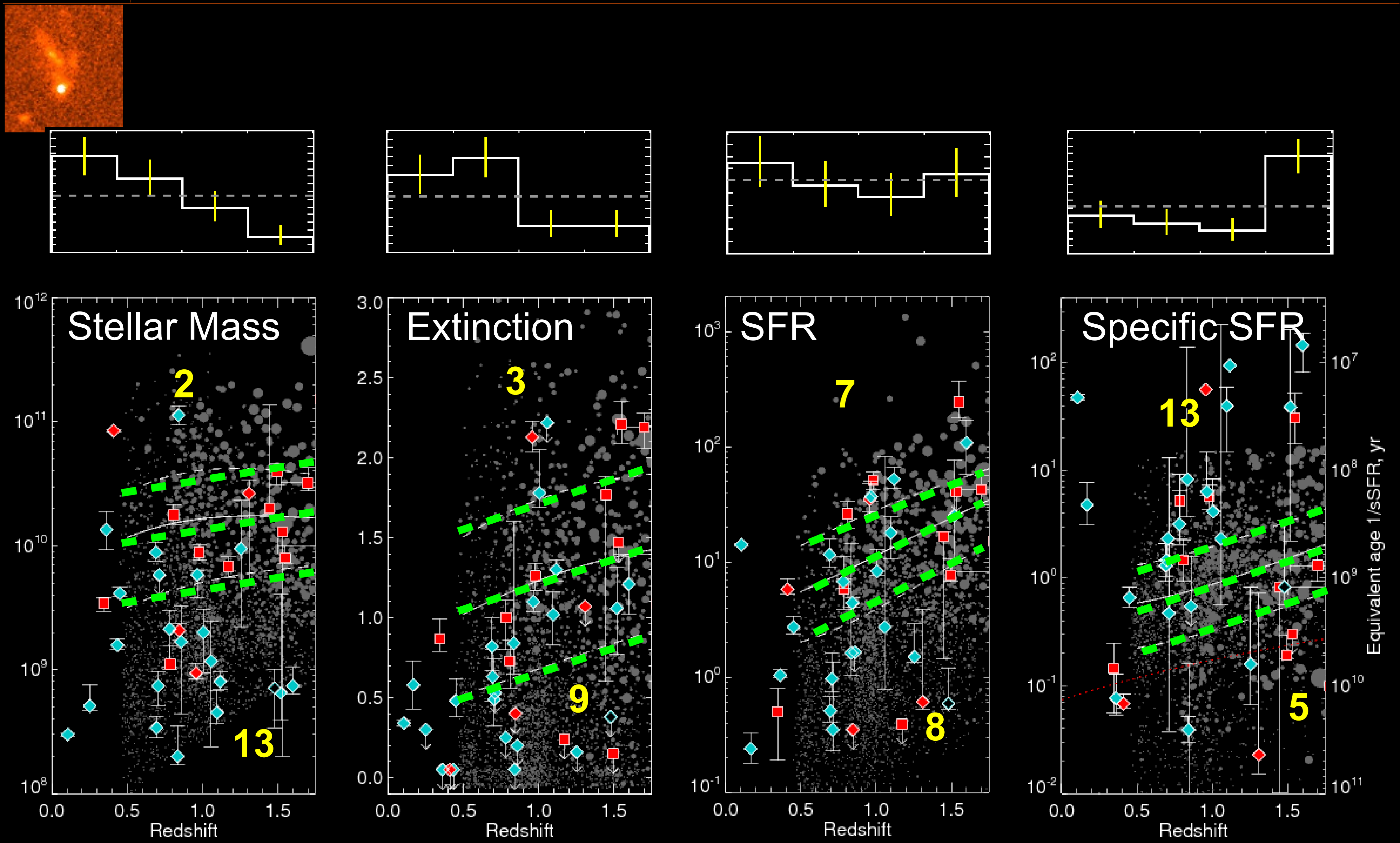
(could affect IMF, initial binarity properties, stellar interactions/collisions, etc.)

Metallicity, or something else?

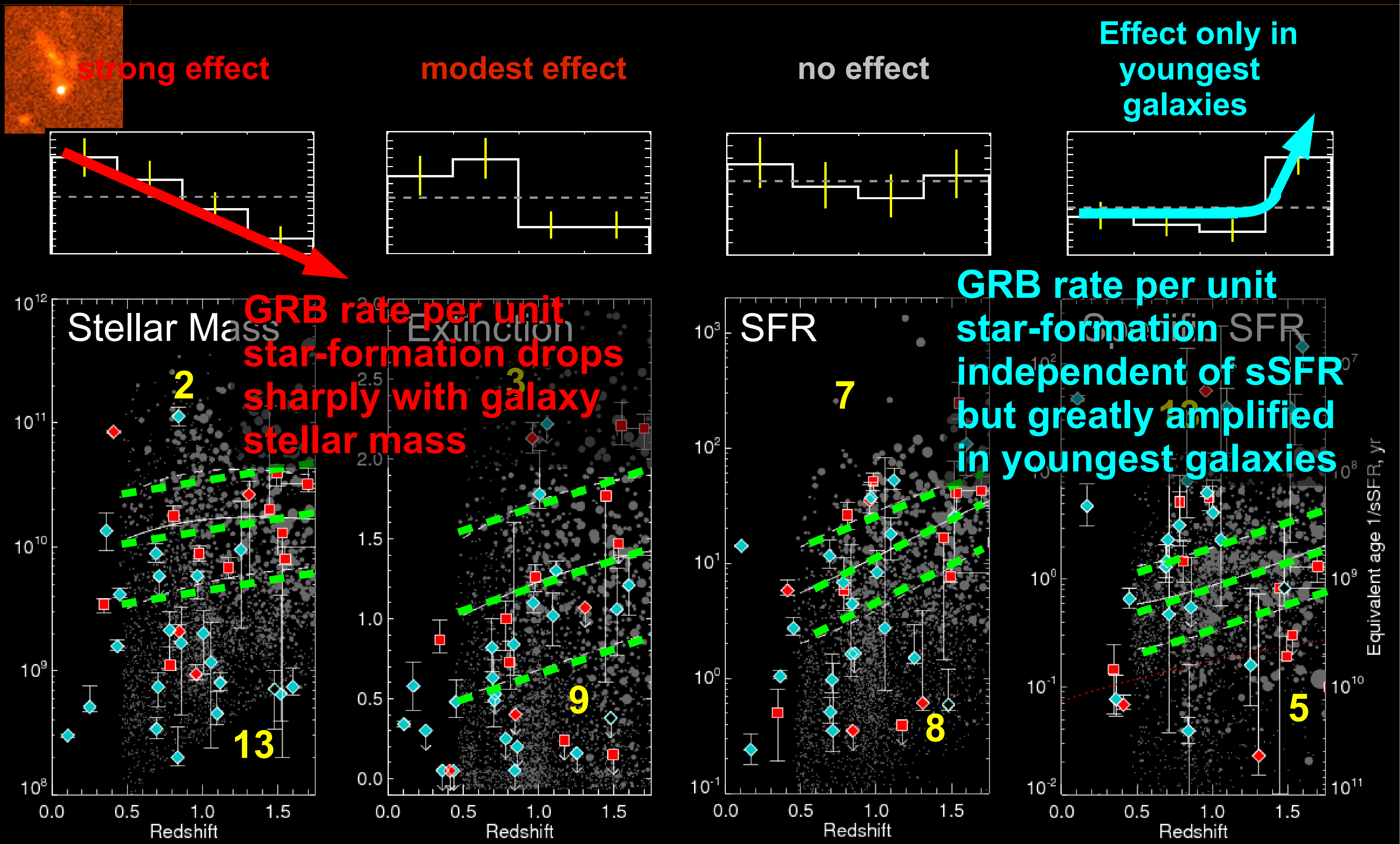




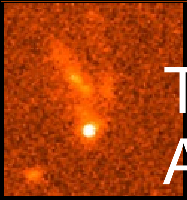
Metallicity, or something else?



Metallicity, or something else?



Metallicity, or something else?



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)

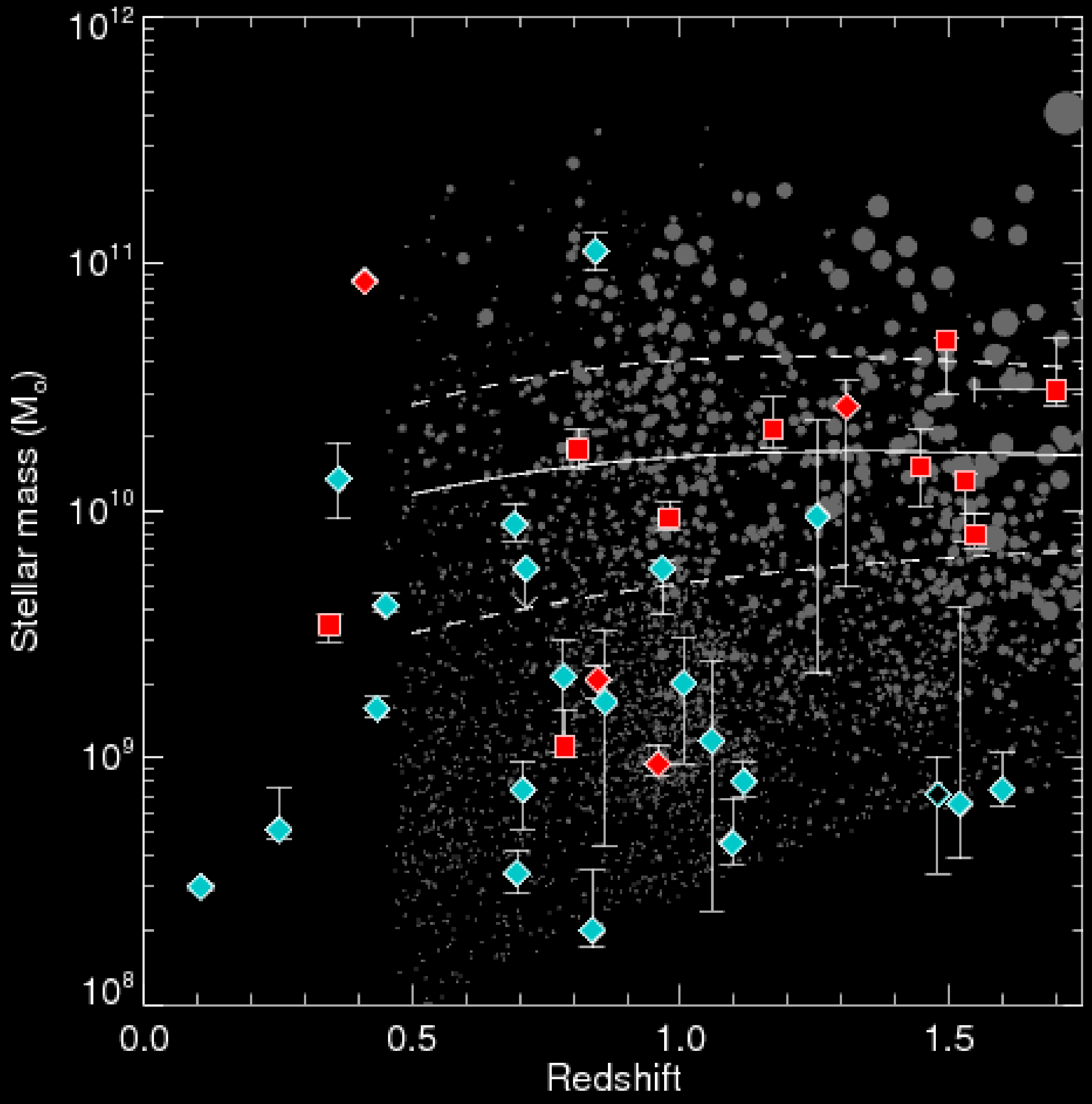
ISM physical properties:

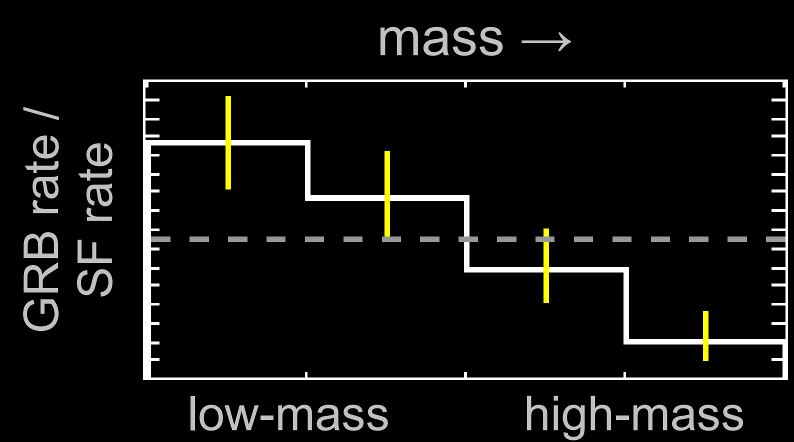
- *UV radiation field.*
- *Gas density.*

(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])

How Metal-Poor is Necessary?





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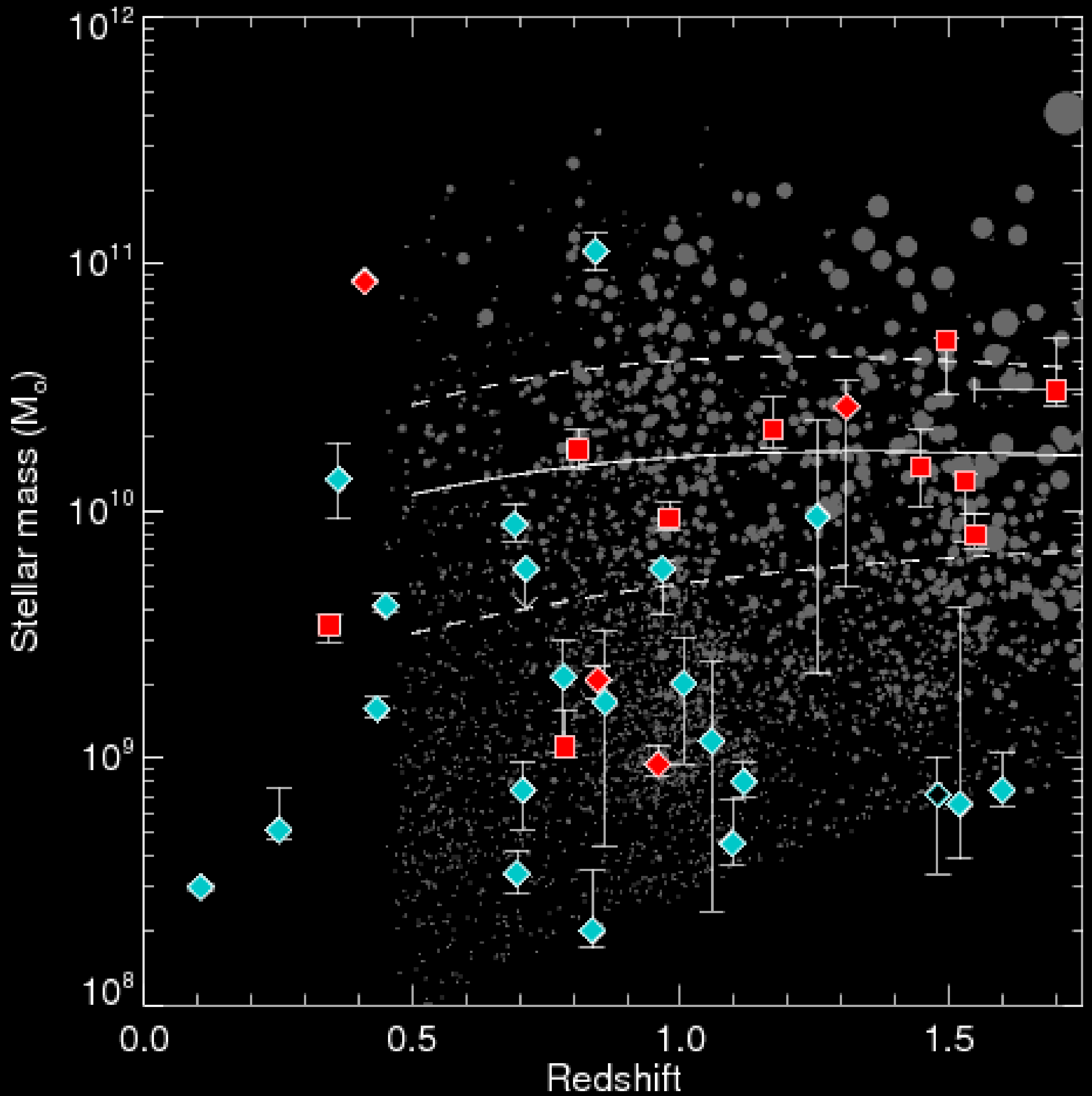

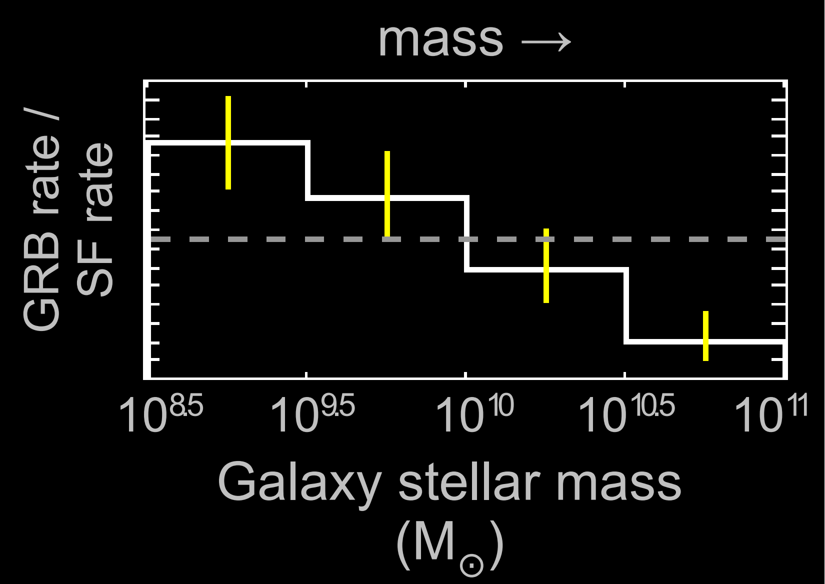

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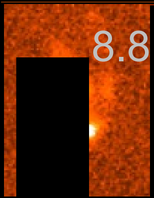
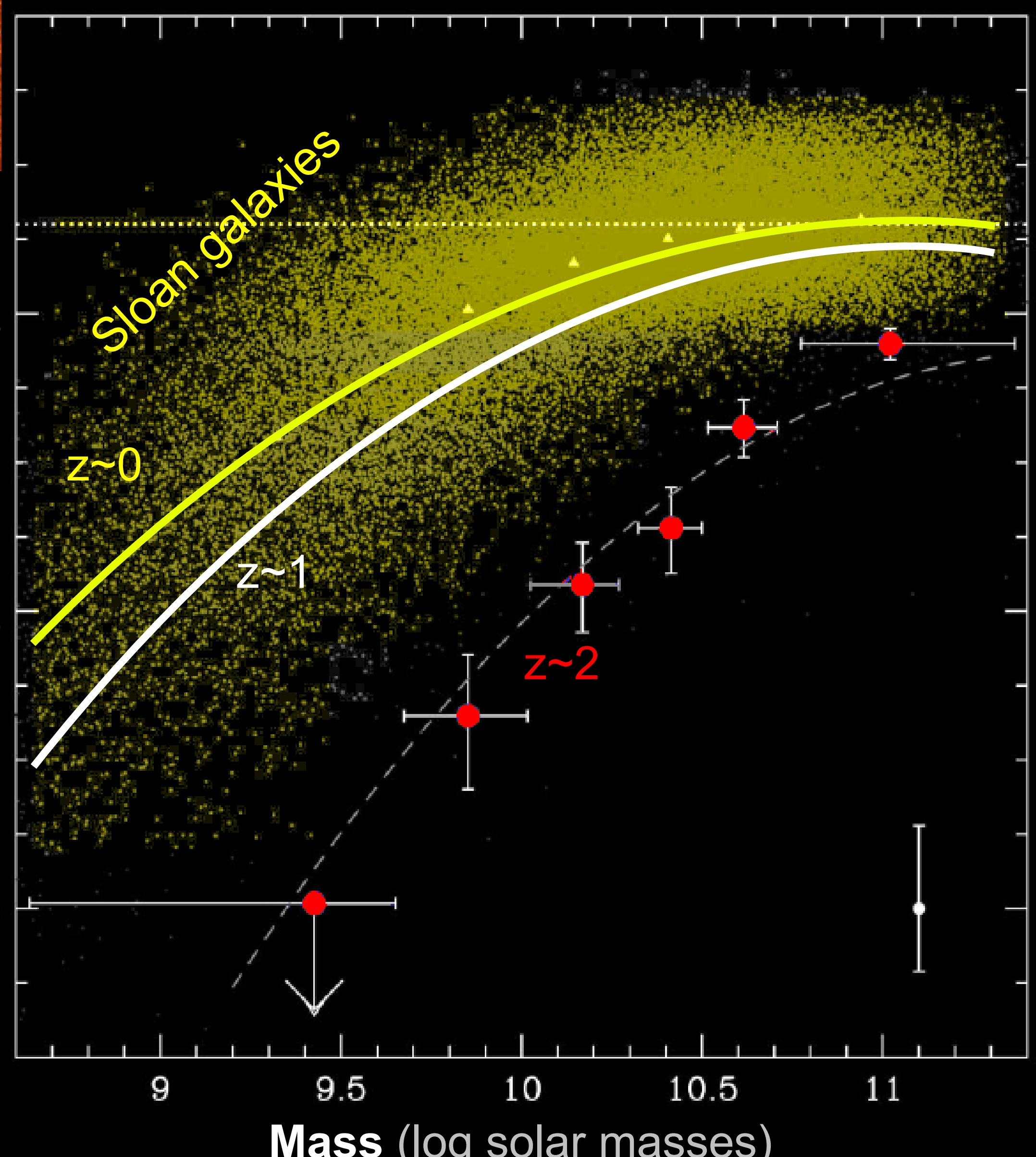
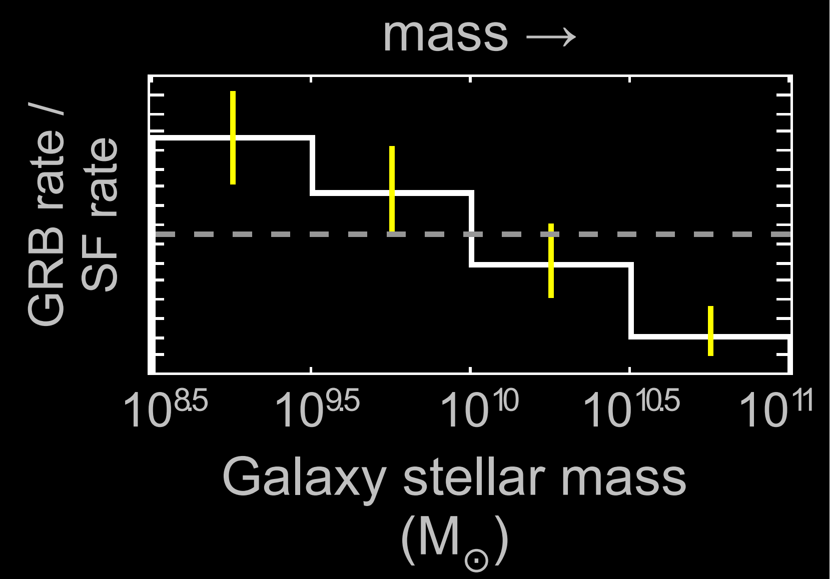




Kewley et al. 2008, Savaglio et al. 2005,, Erb et al. 2006, Maiolino et al. 2008,2009



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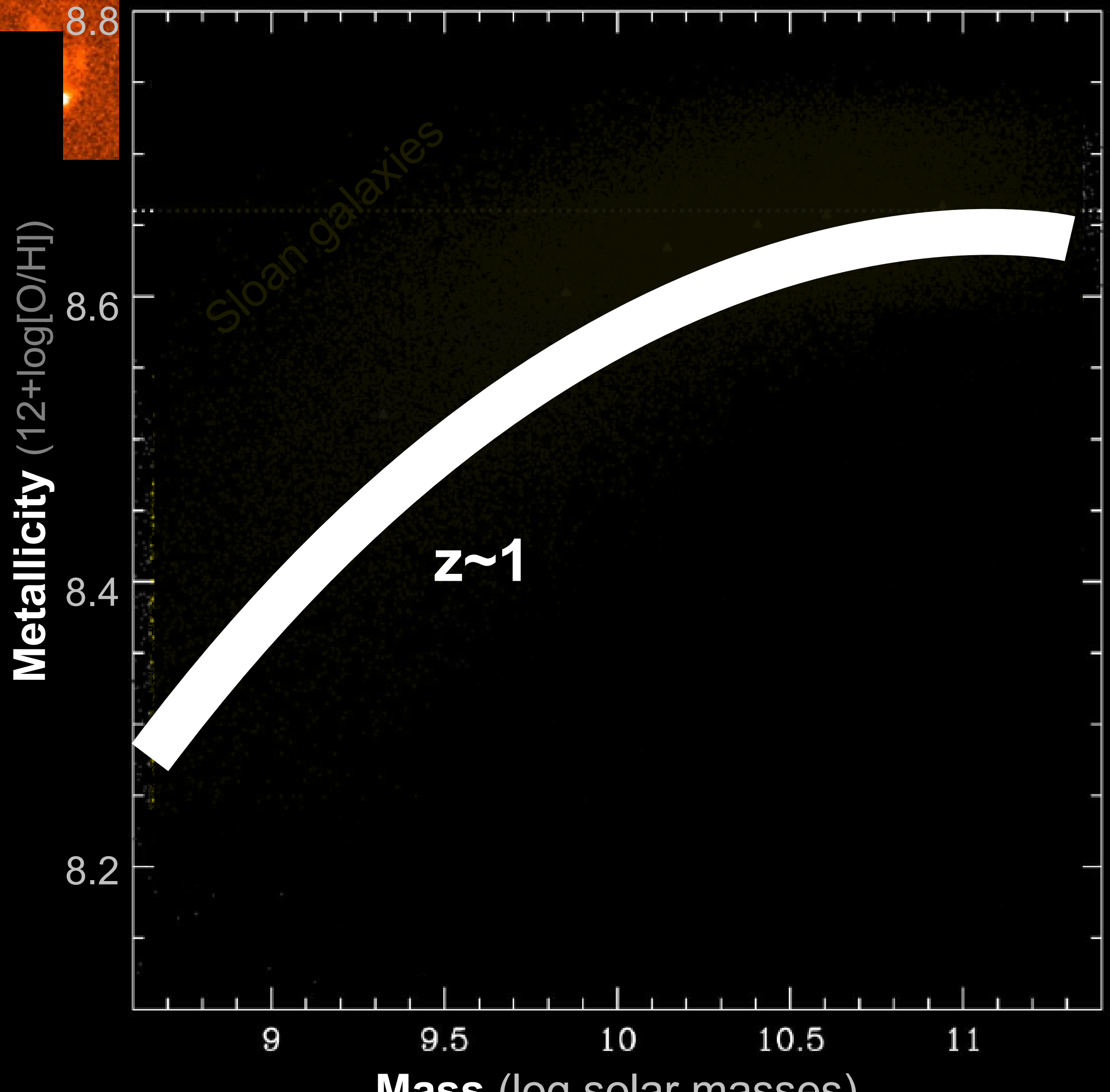

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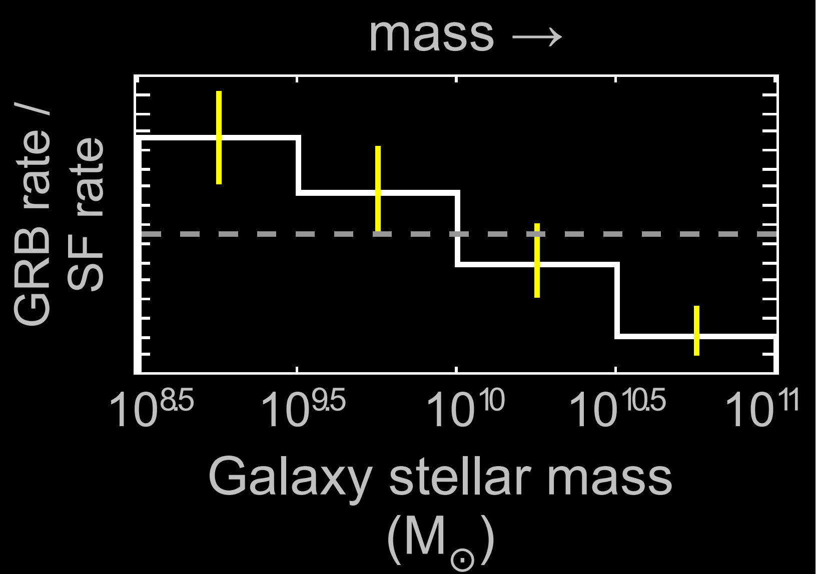

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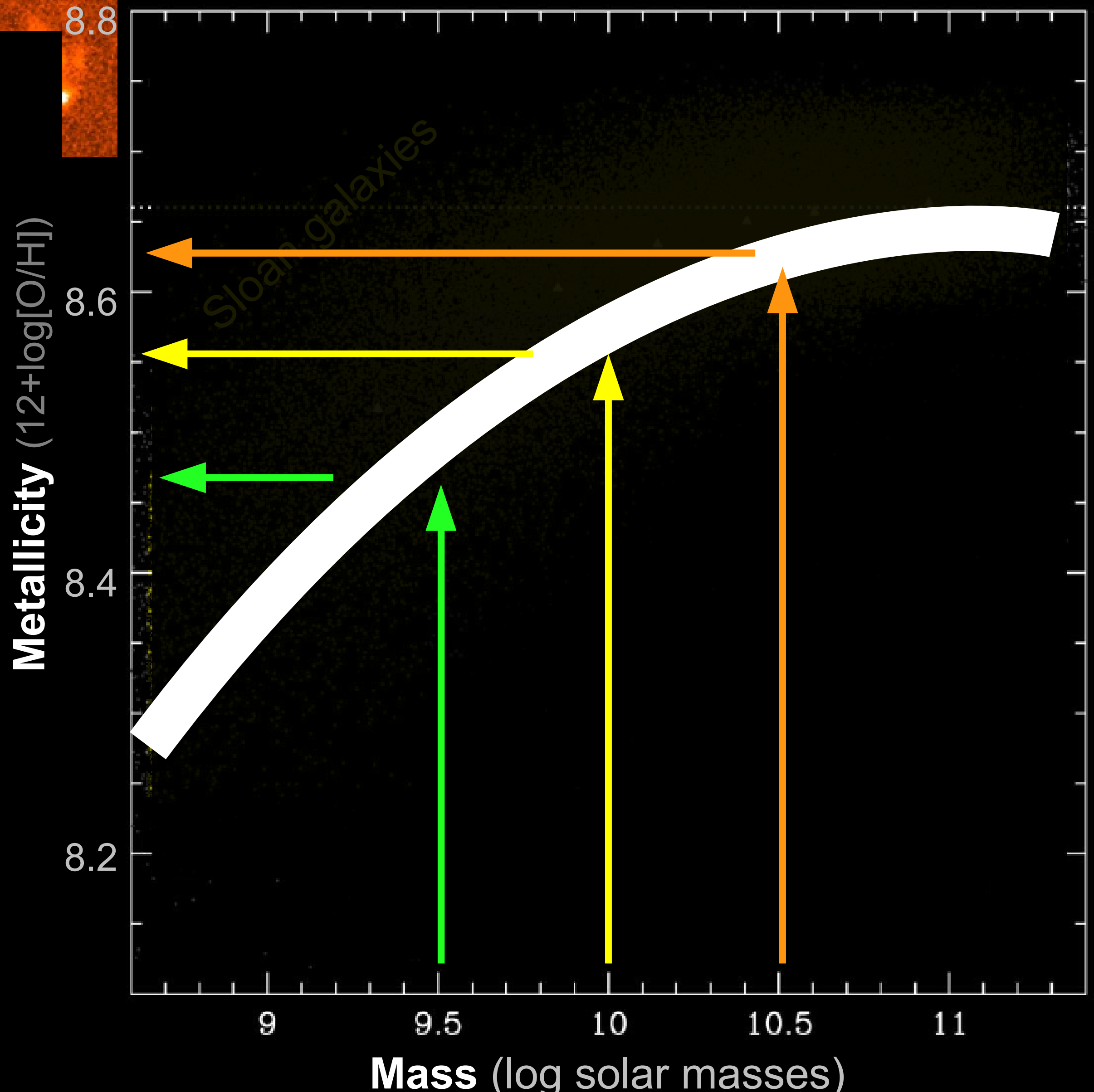

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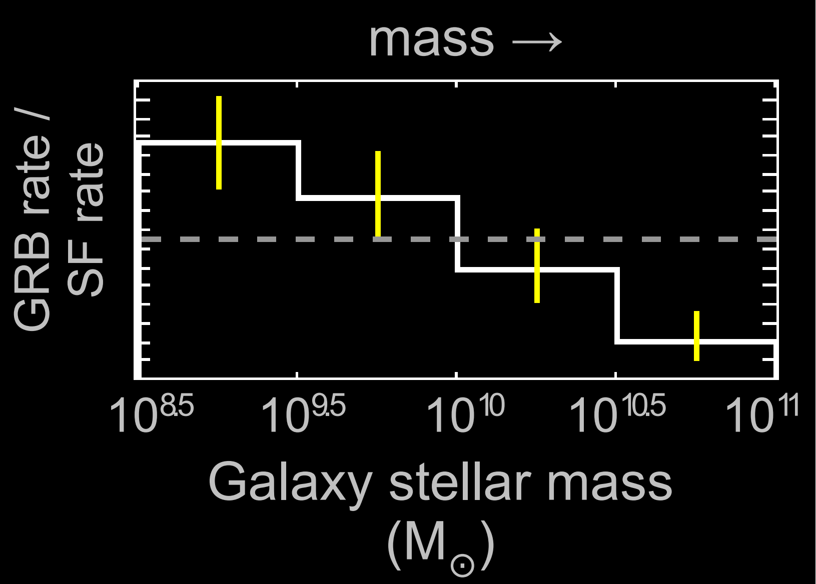

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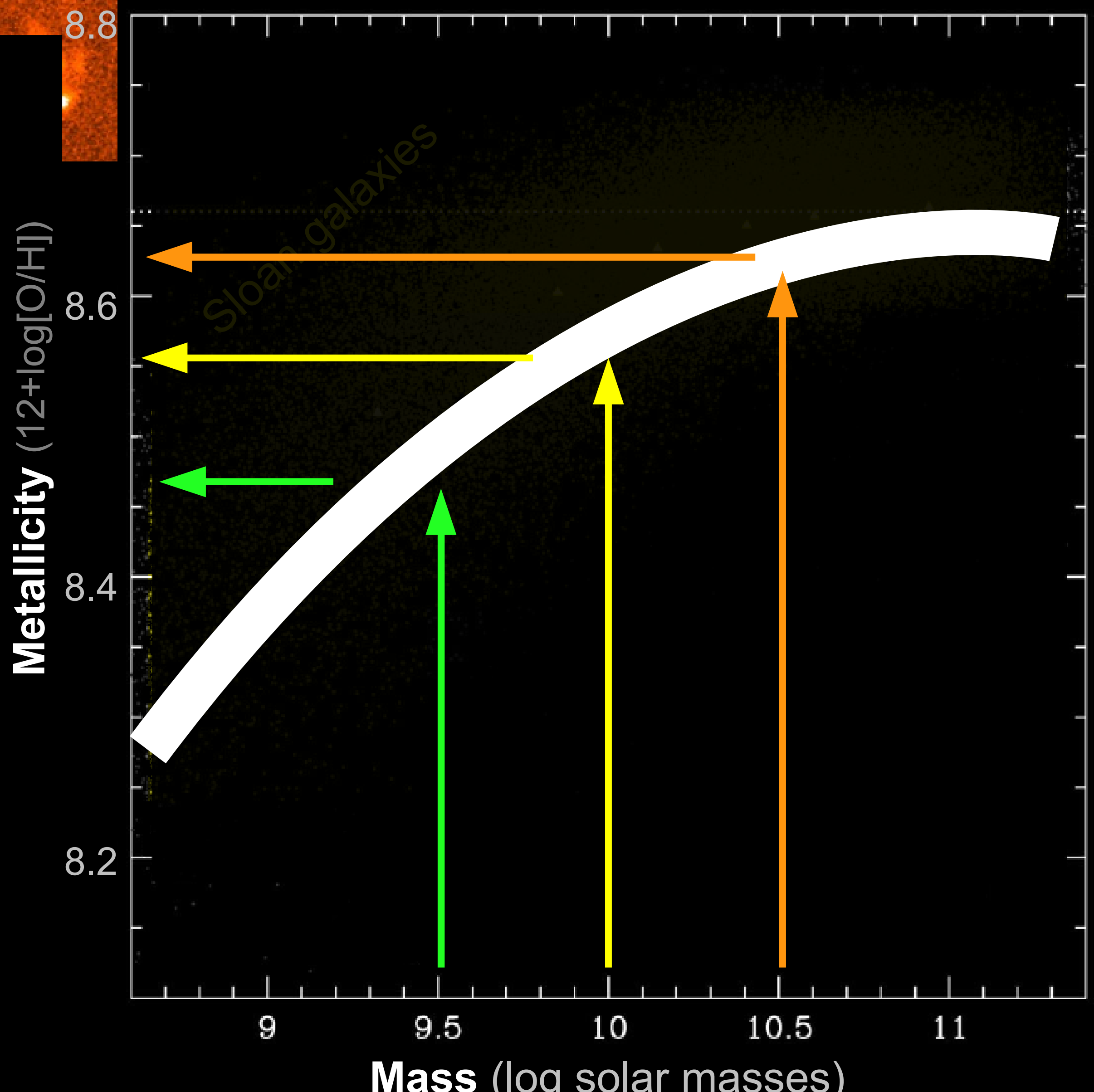

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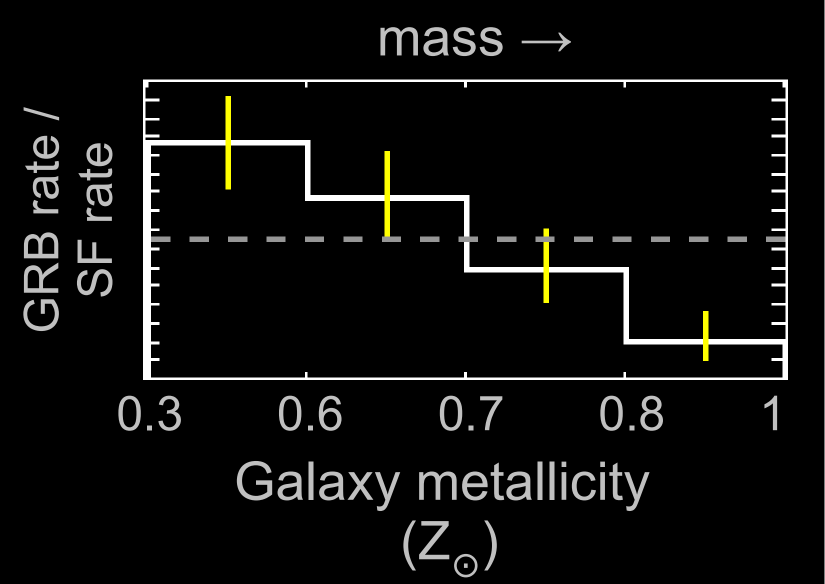

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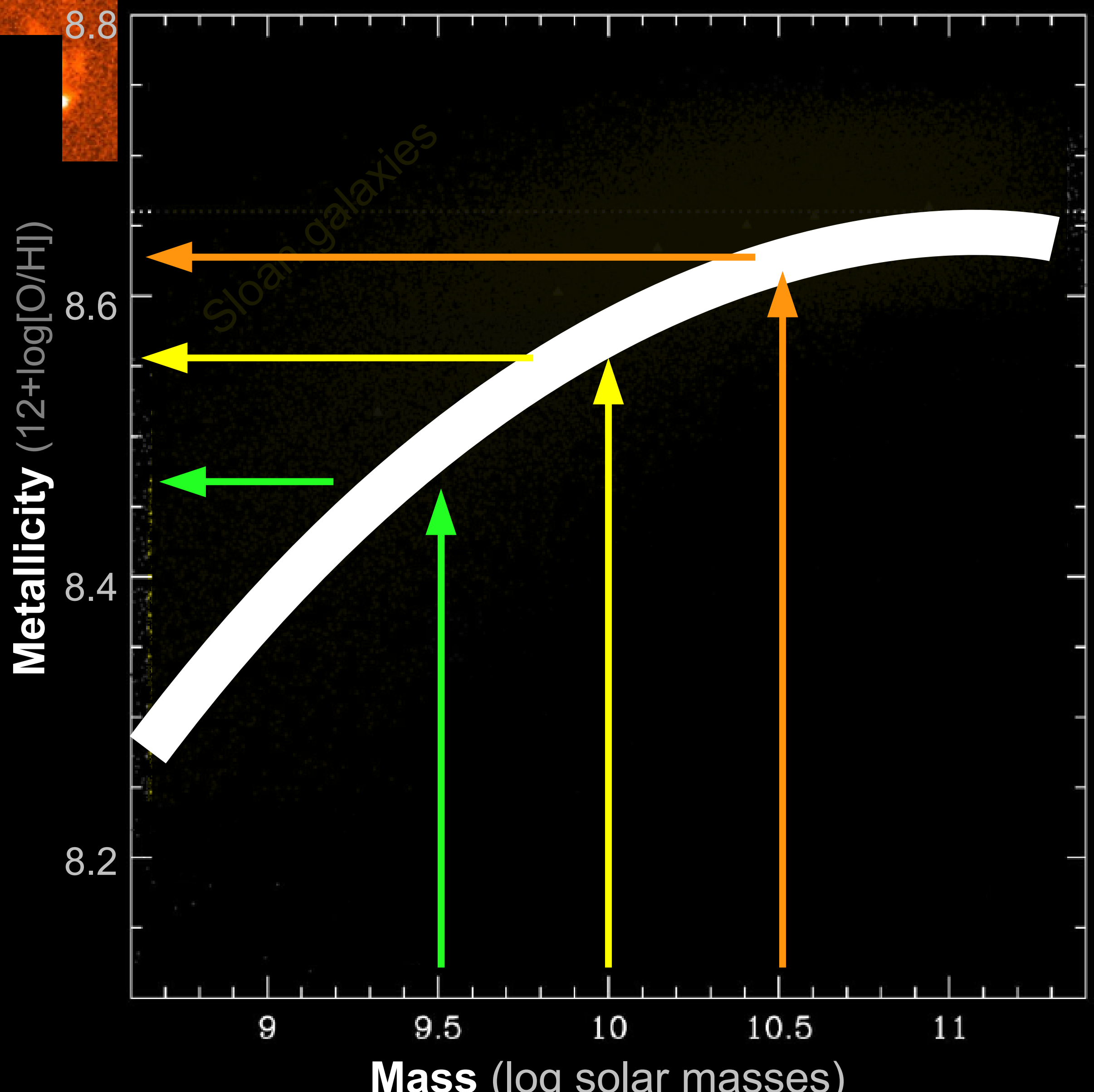

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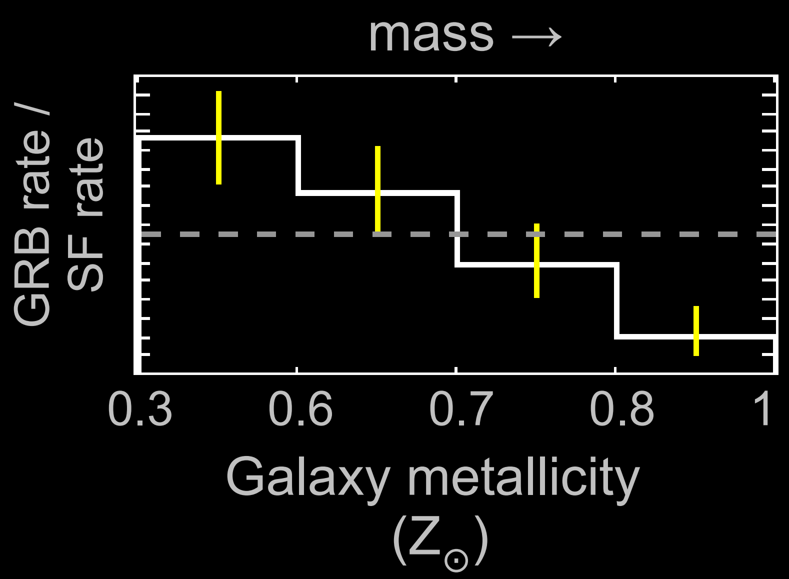
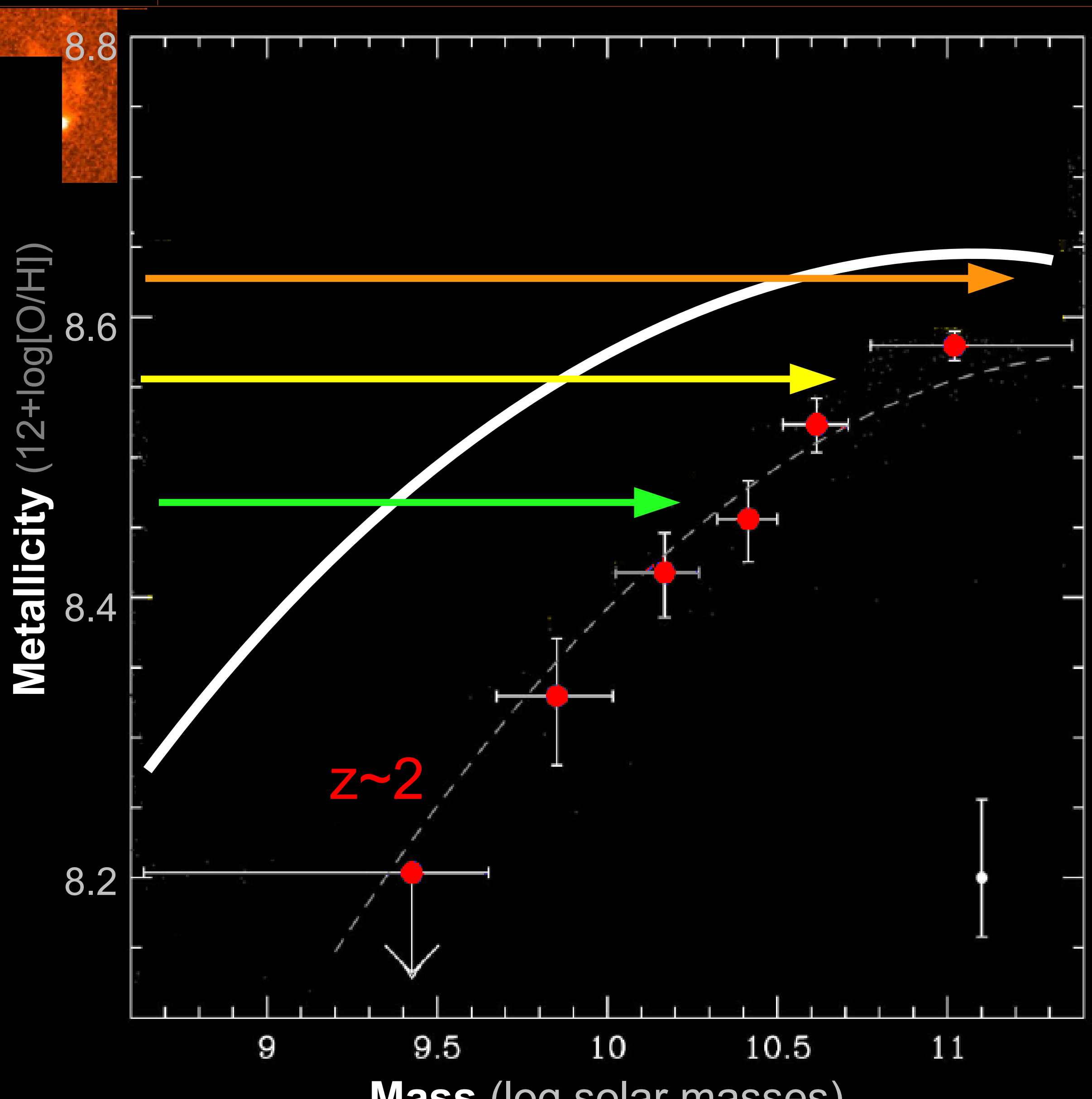


Sharp decline in GRB production rate at ~0.7 $Z_\odot$

Consistent with spectroscopic metallicity threshold from nearby hosts.

(Also, no further large rise below <0.3$Z_\odot$ – not shown here)

How Metal-Poor is Necessary?



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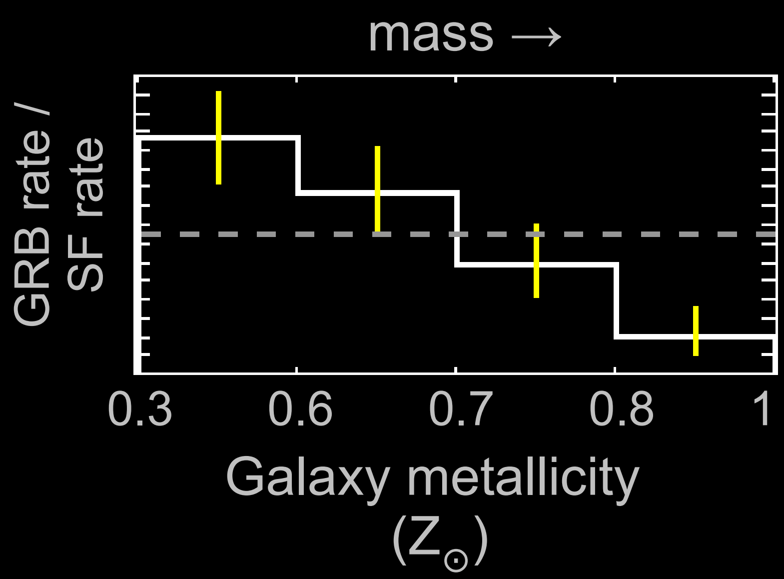

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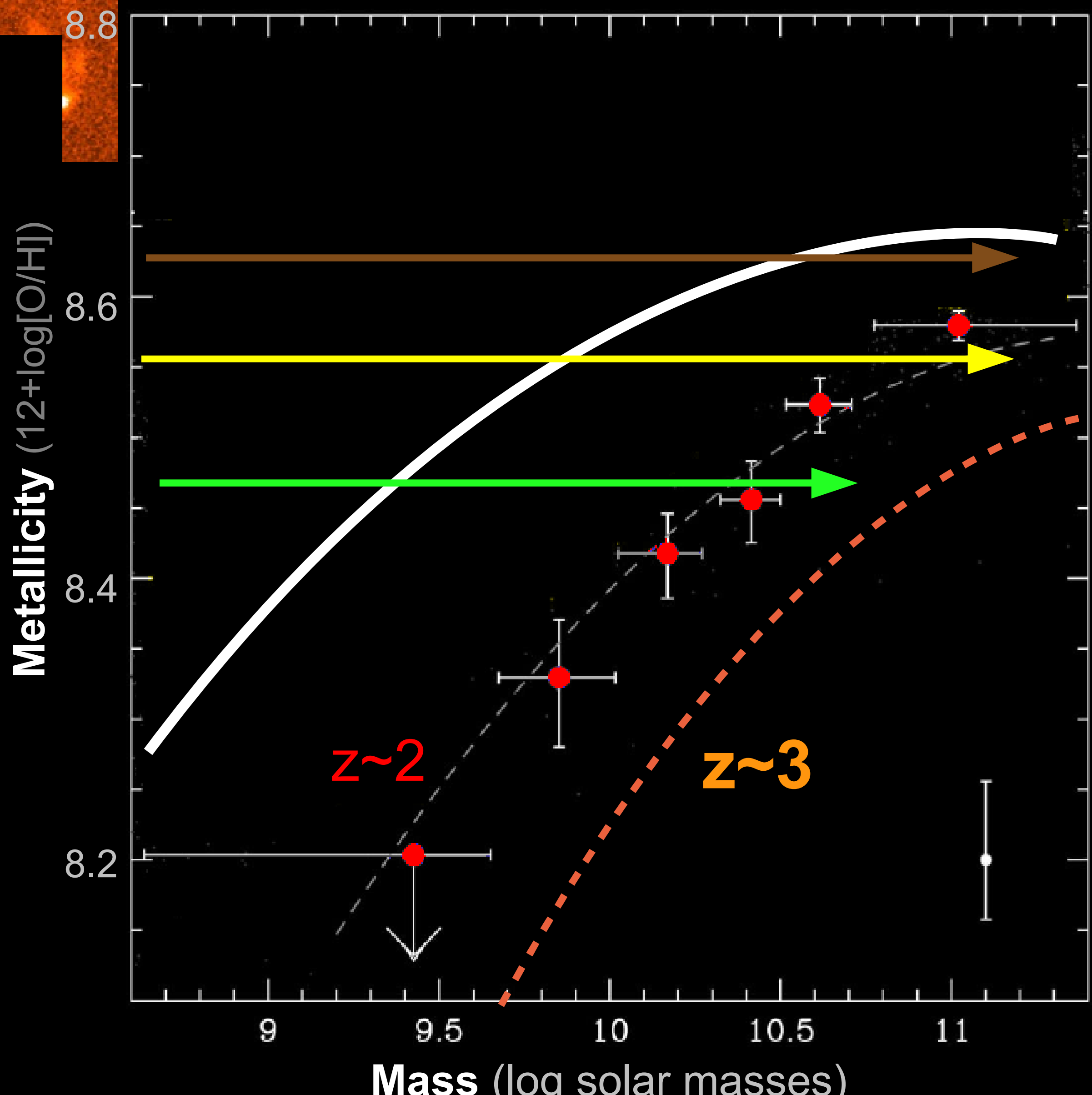

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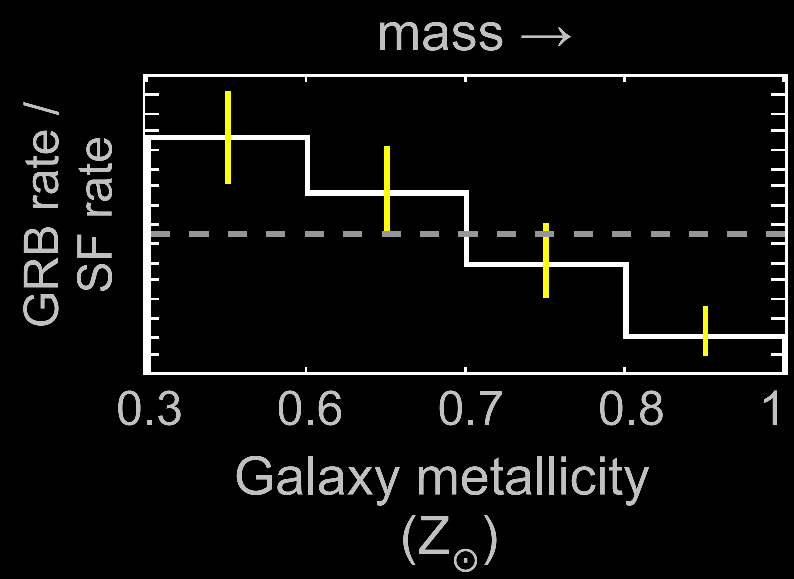

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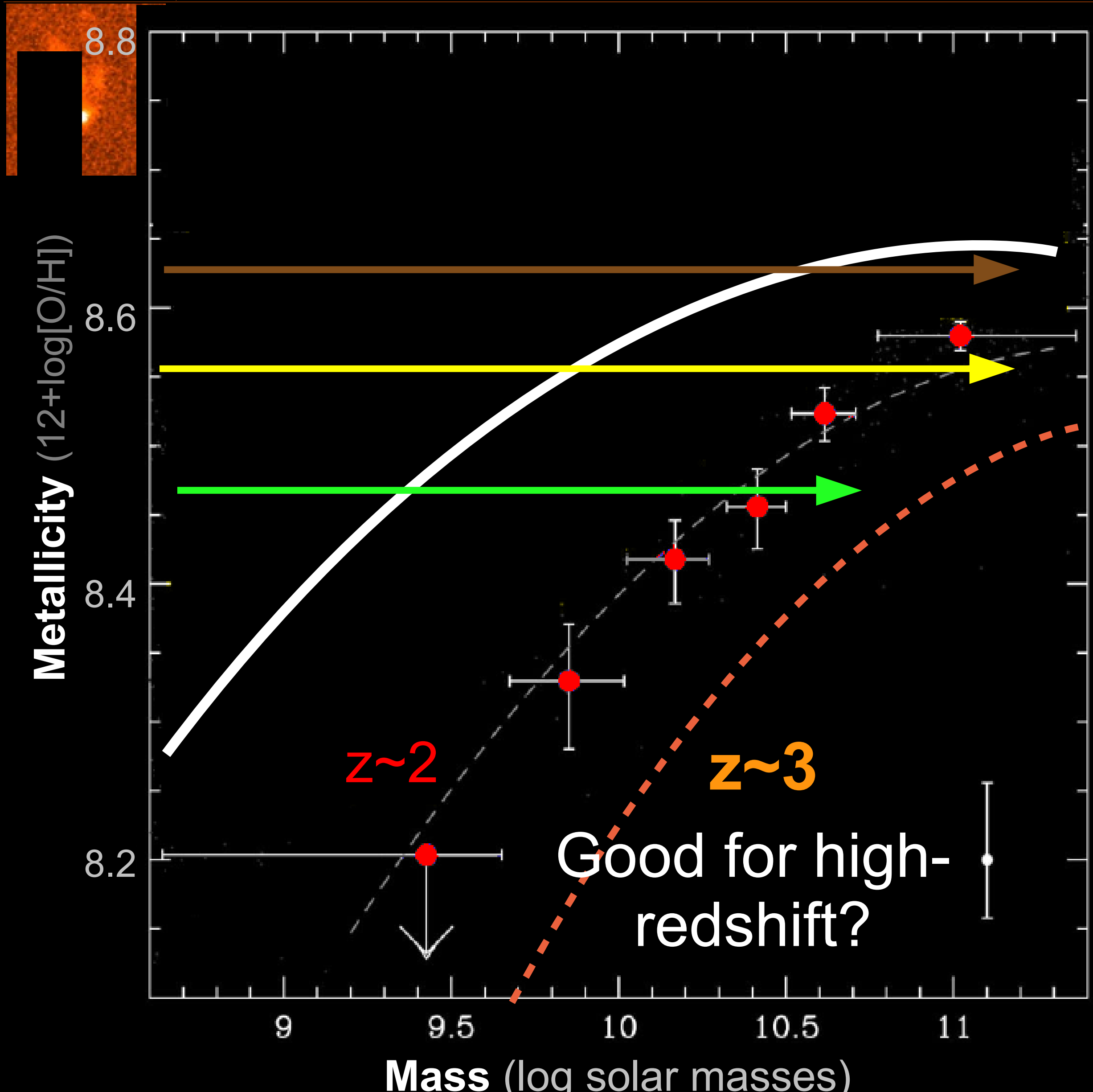

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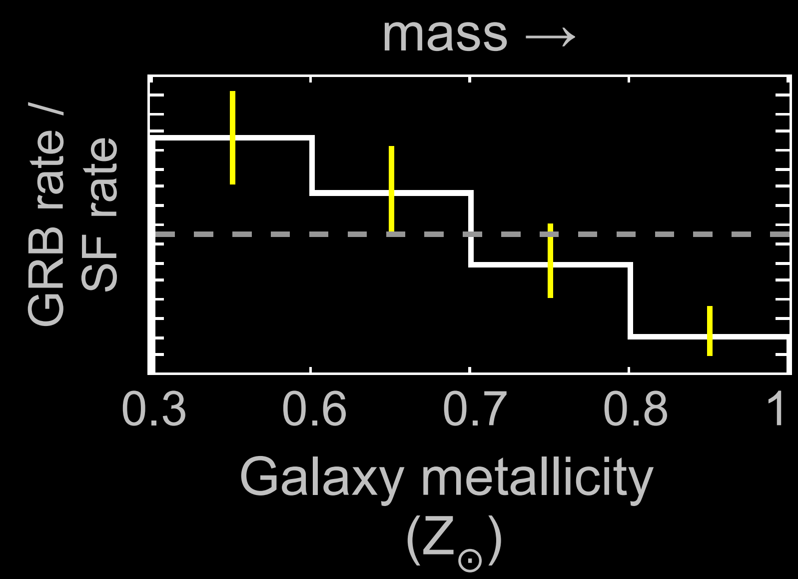

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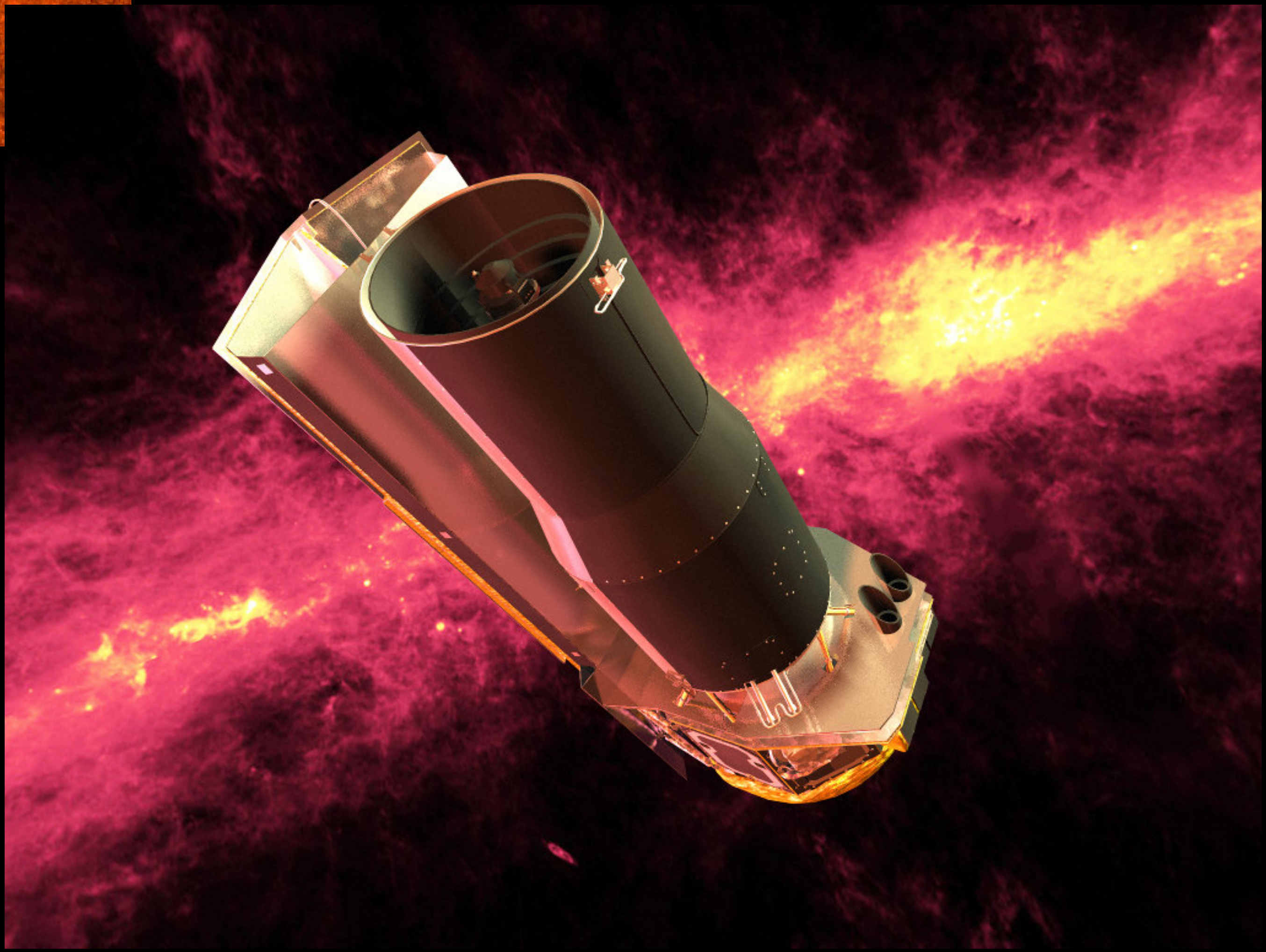
Spitzer Large Program

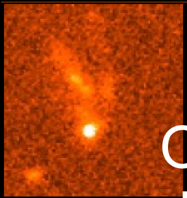


IRAC lives on!

3.6 μm imaging to 25th AB magnitude in 1 hour exposure

Stellar mass machine – easily detect 10^{10} $M_{\odot}$ galaxies to z~5

Spitzer Large Program



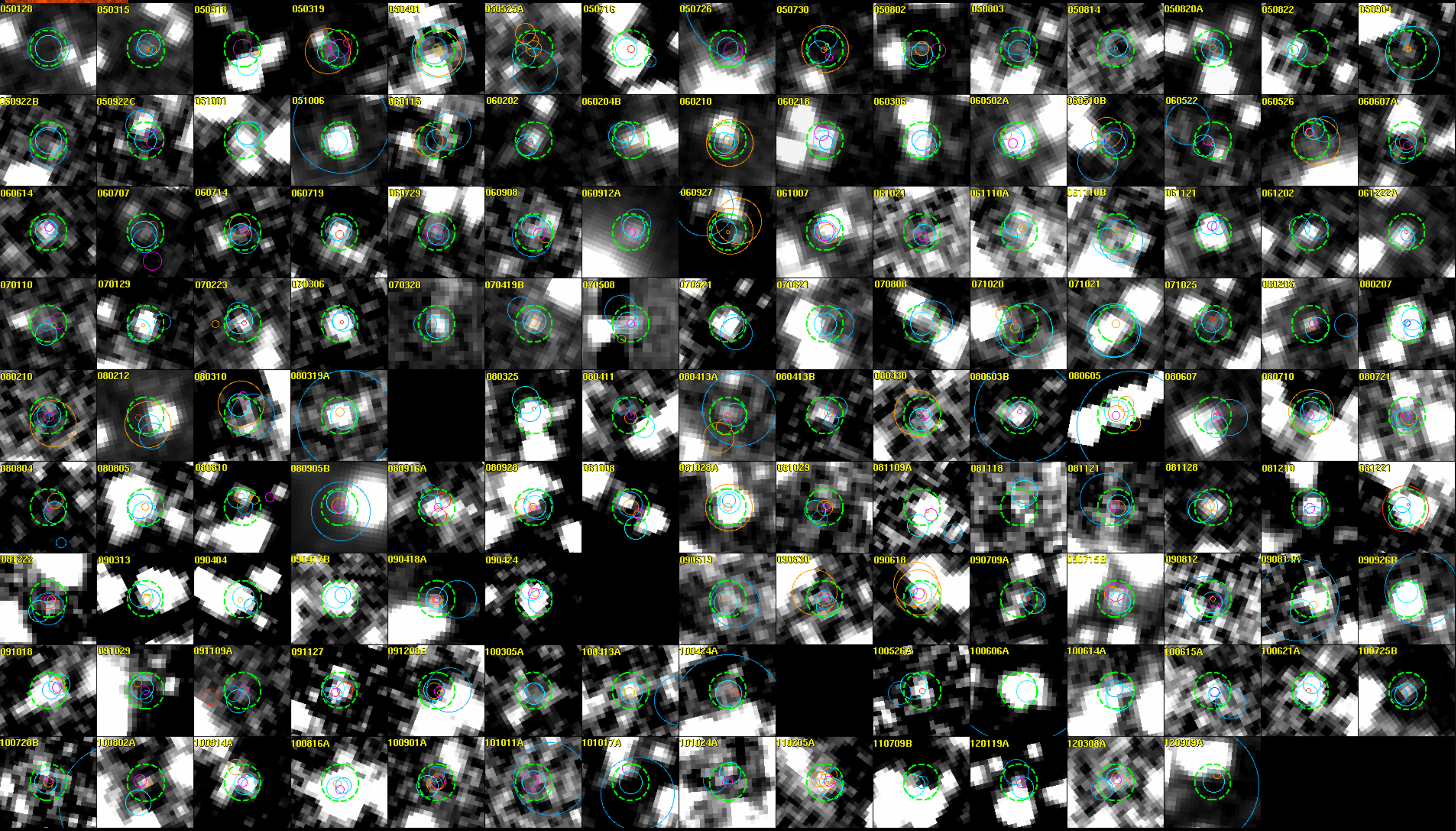
Observe a sample of **130** *Swift* GRB positions, selected based on pre-determined, **unbiased** cuts:

- Burst was brighter than average in gamma-rays
- Swift slewed immediately to the position
- Favorable sky location at time of explosion for observing
- Low Milky Way foreground extinction
- No nearby bright stars
- Localized within 2” (very slight bias)

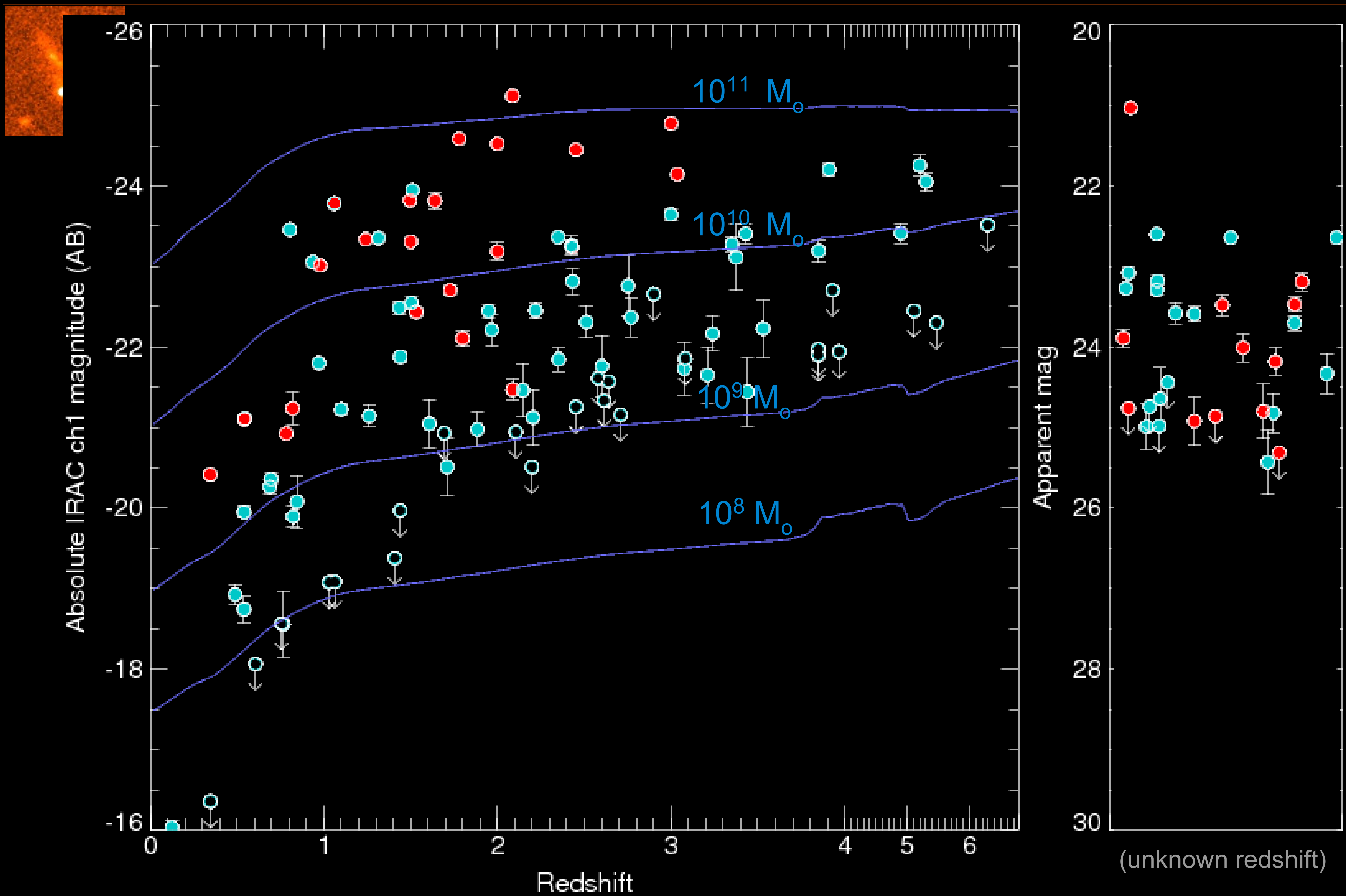
(Similar procedure to VLT R/K-band host survey; Hjorth+2012)

75% have predetermined redshift (usually from afterglow.)
(Will have to get the remaining 25% from the host if possible.)

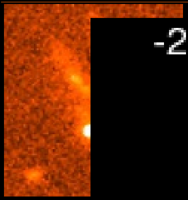
Spitzer Large Project Imaging

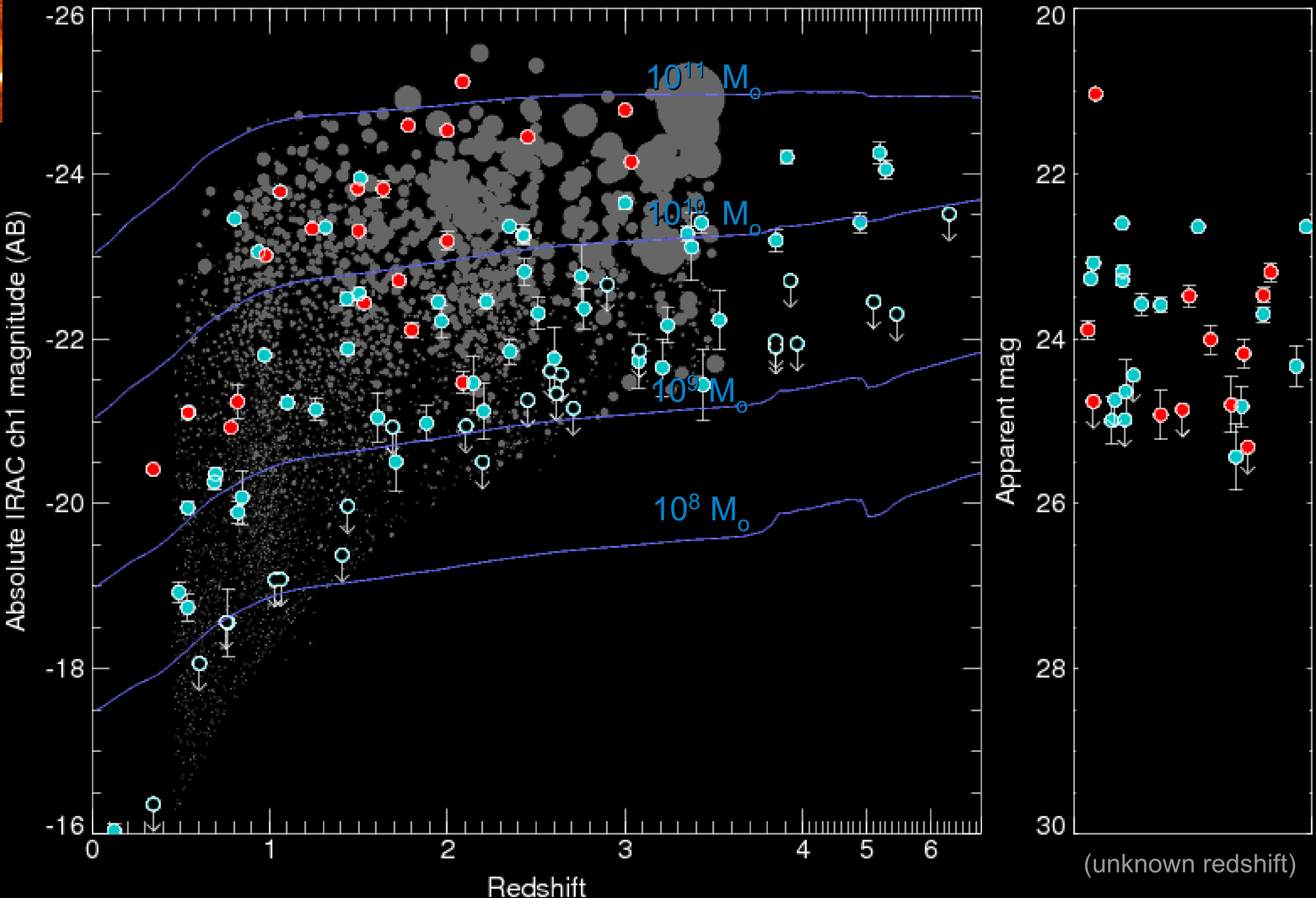


GRB NIR luminosities to z~7

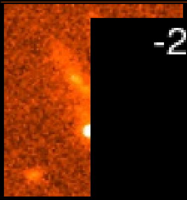


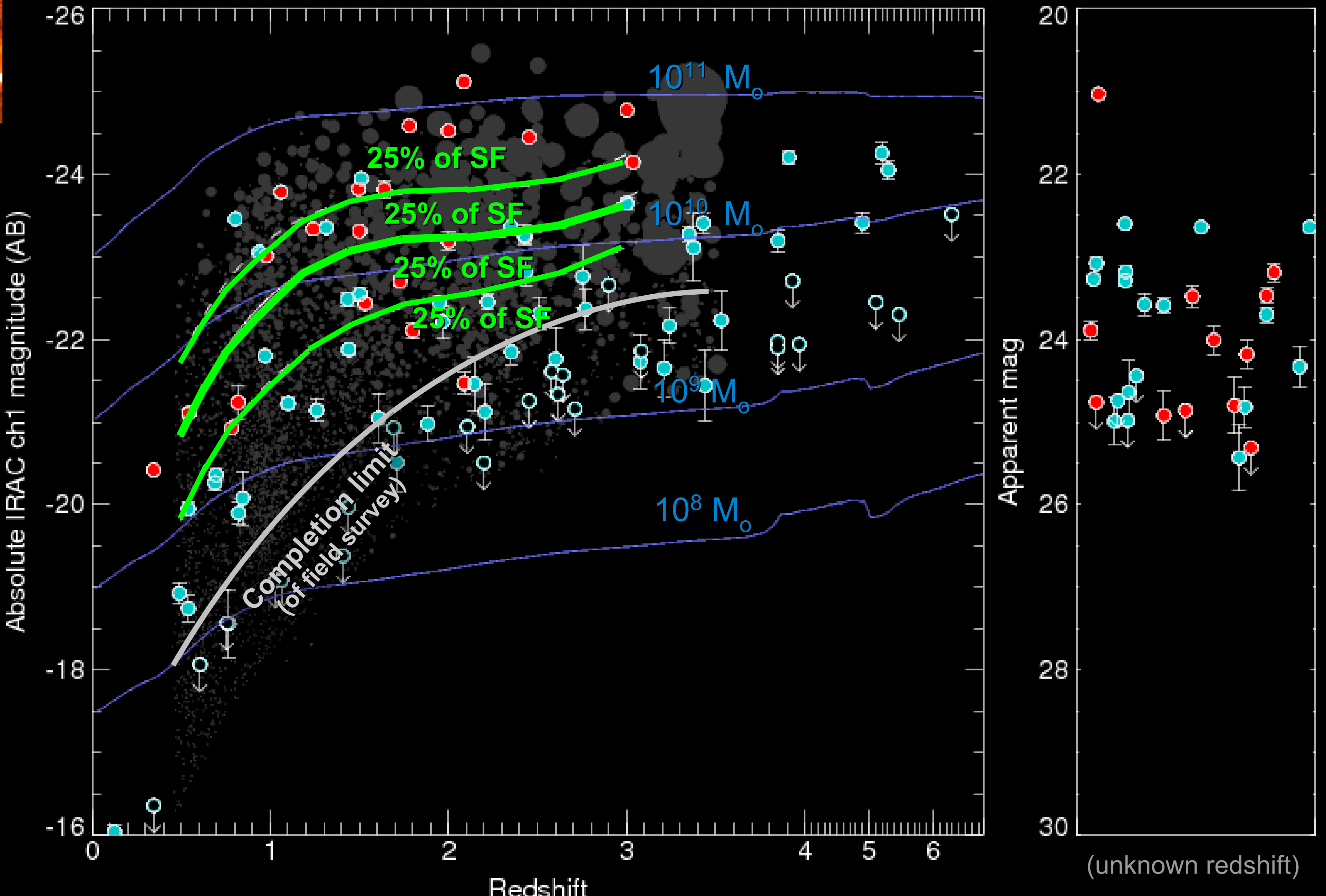
GRBs vs. Galaxies



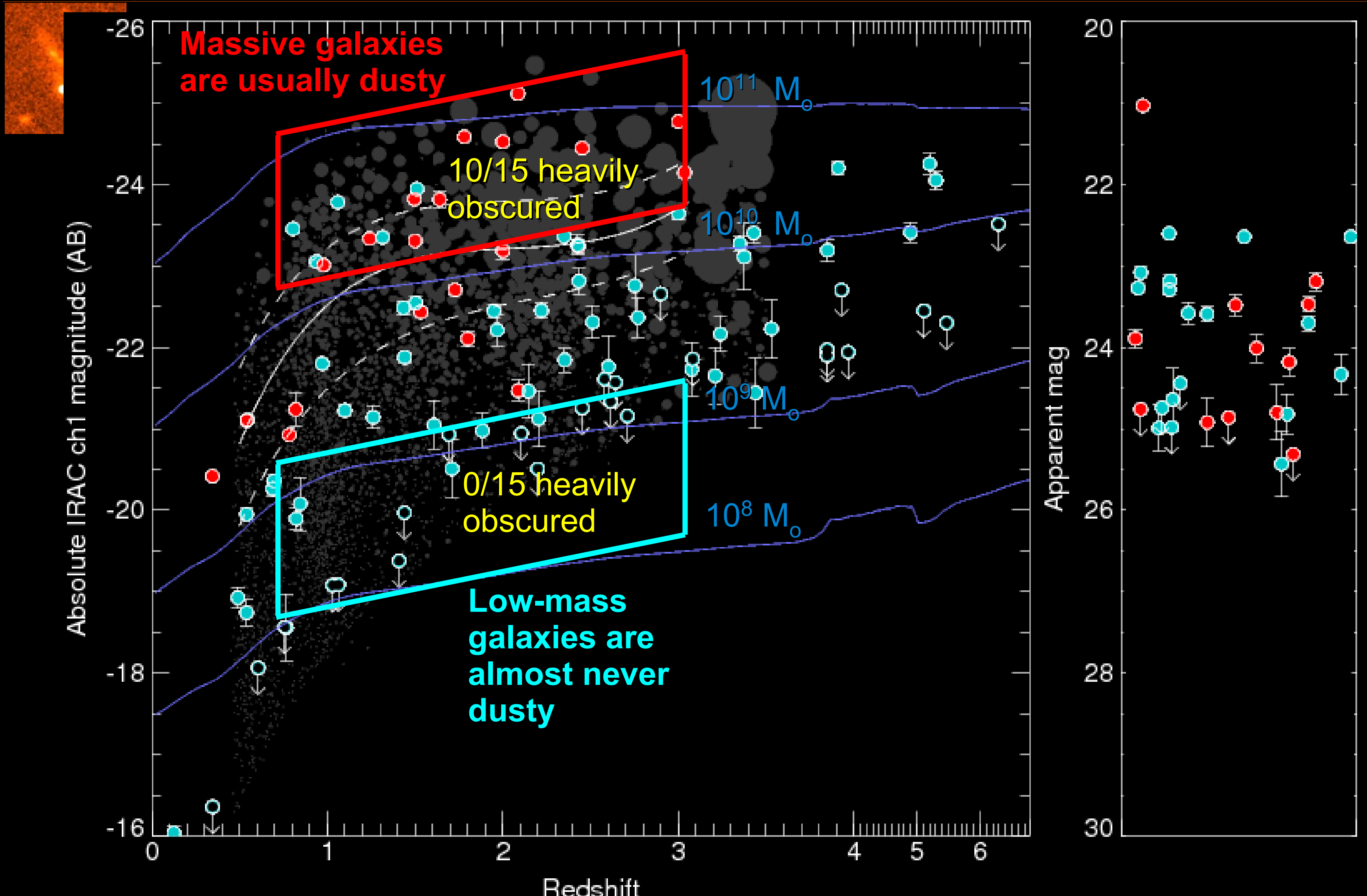


GRBs vs. Star Formation



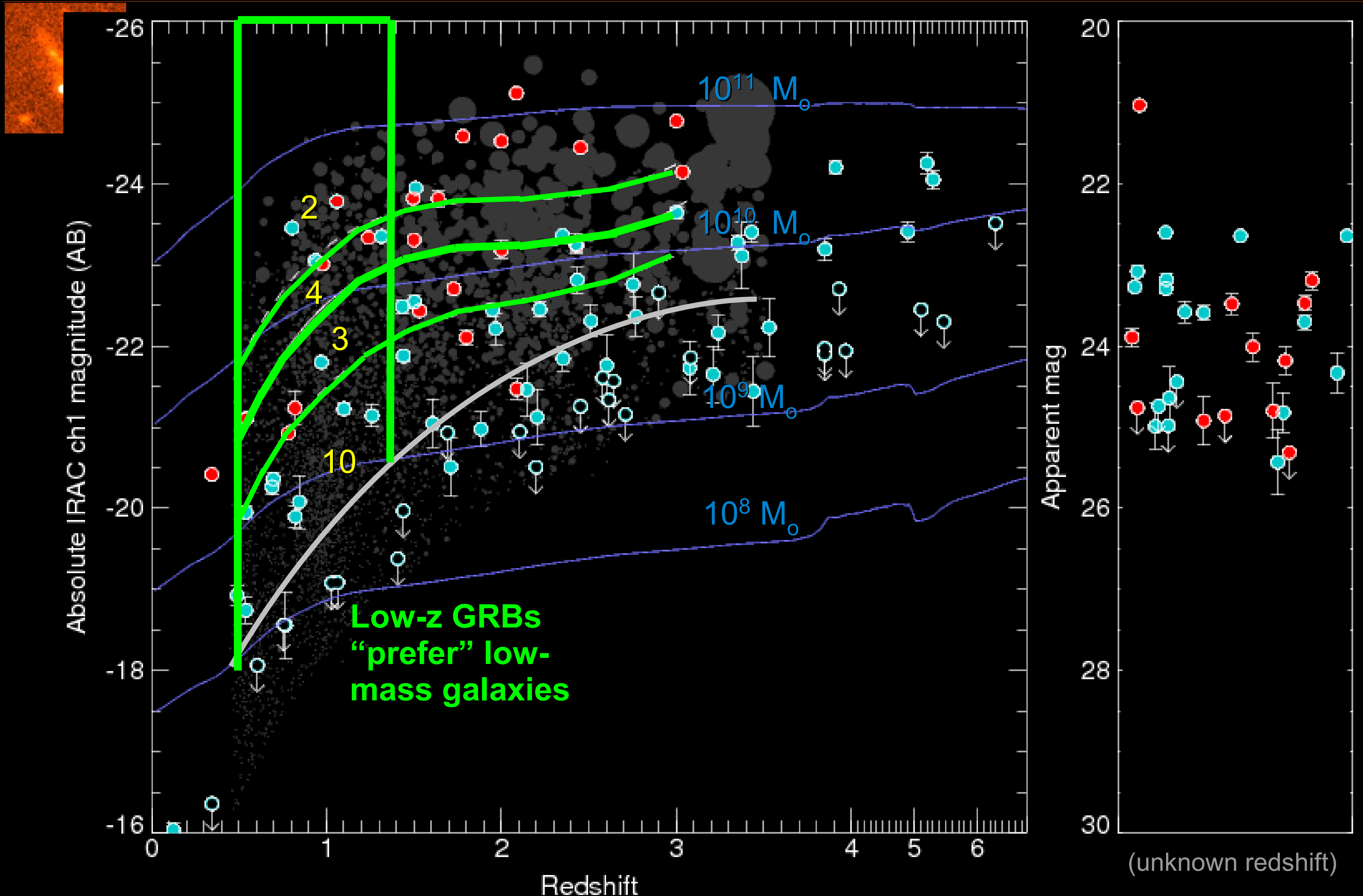


GRBs vs. Dust



Massive galaxies are usually dusty
10/15 heavily obscured
0/15 heavily obscured
Low-mass galaxies are almost never dusty
10^{11} M_o
10^{10} M_o
10^{9} M_o
10^{8} M_o
Absolute IRAC ch1 magnitude (AB)
Redshift
Apparent mag
-26
-24
-22
-20
-18
-16
0
1
2
3
4
5
6
20
22
24
26
28
30

GRBs vs. Star Formation



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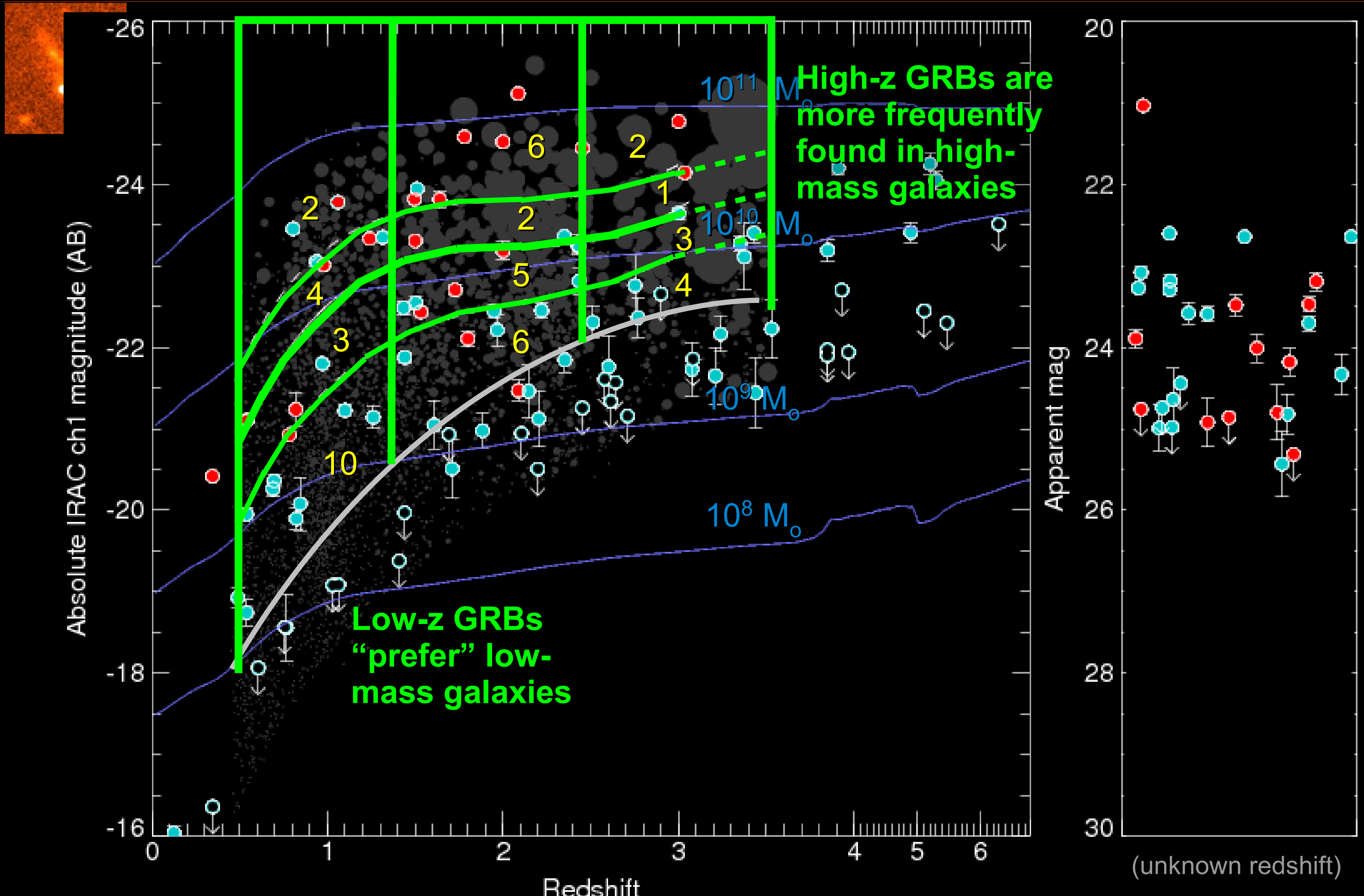

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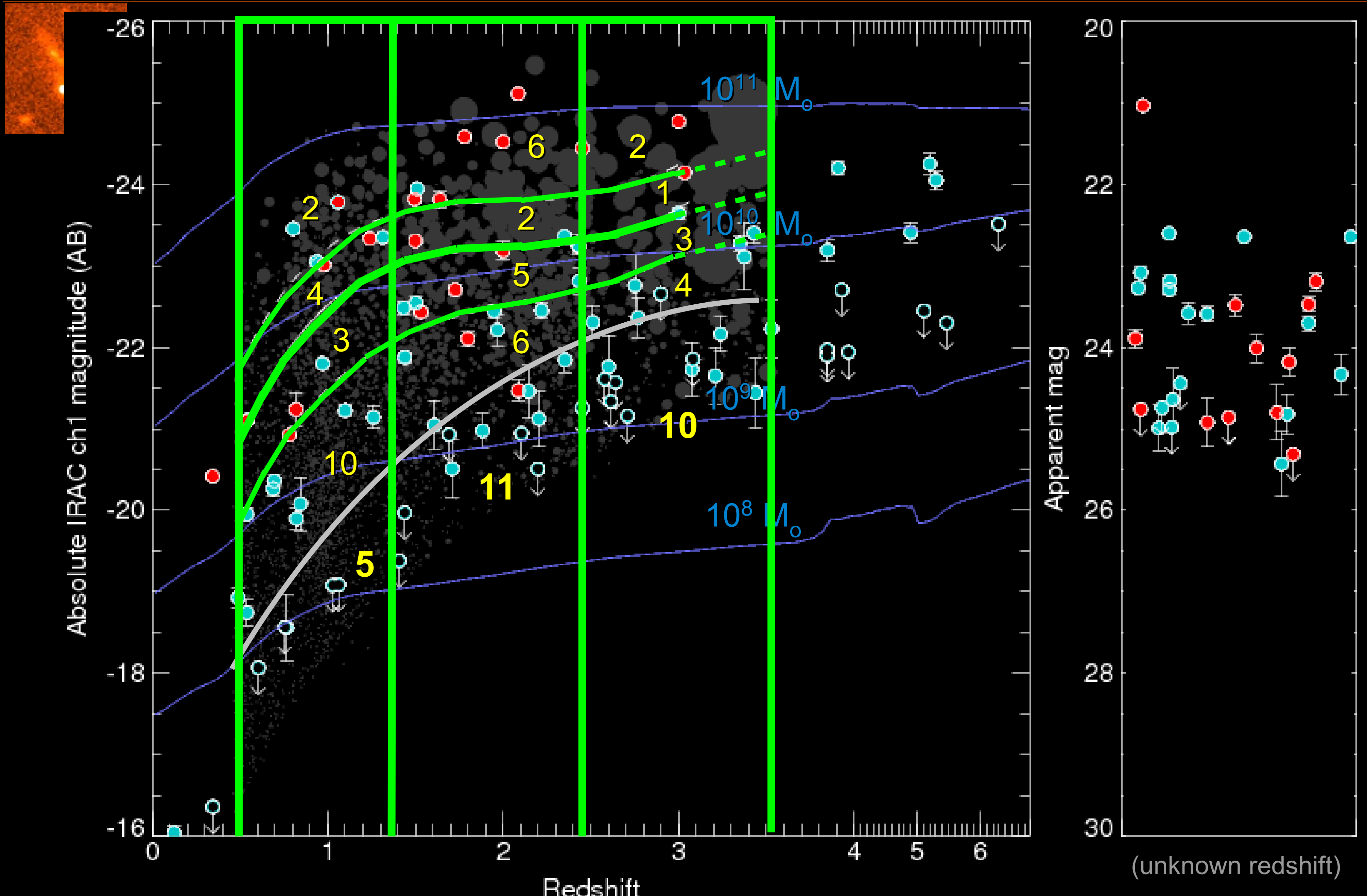

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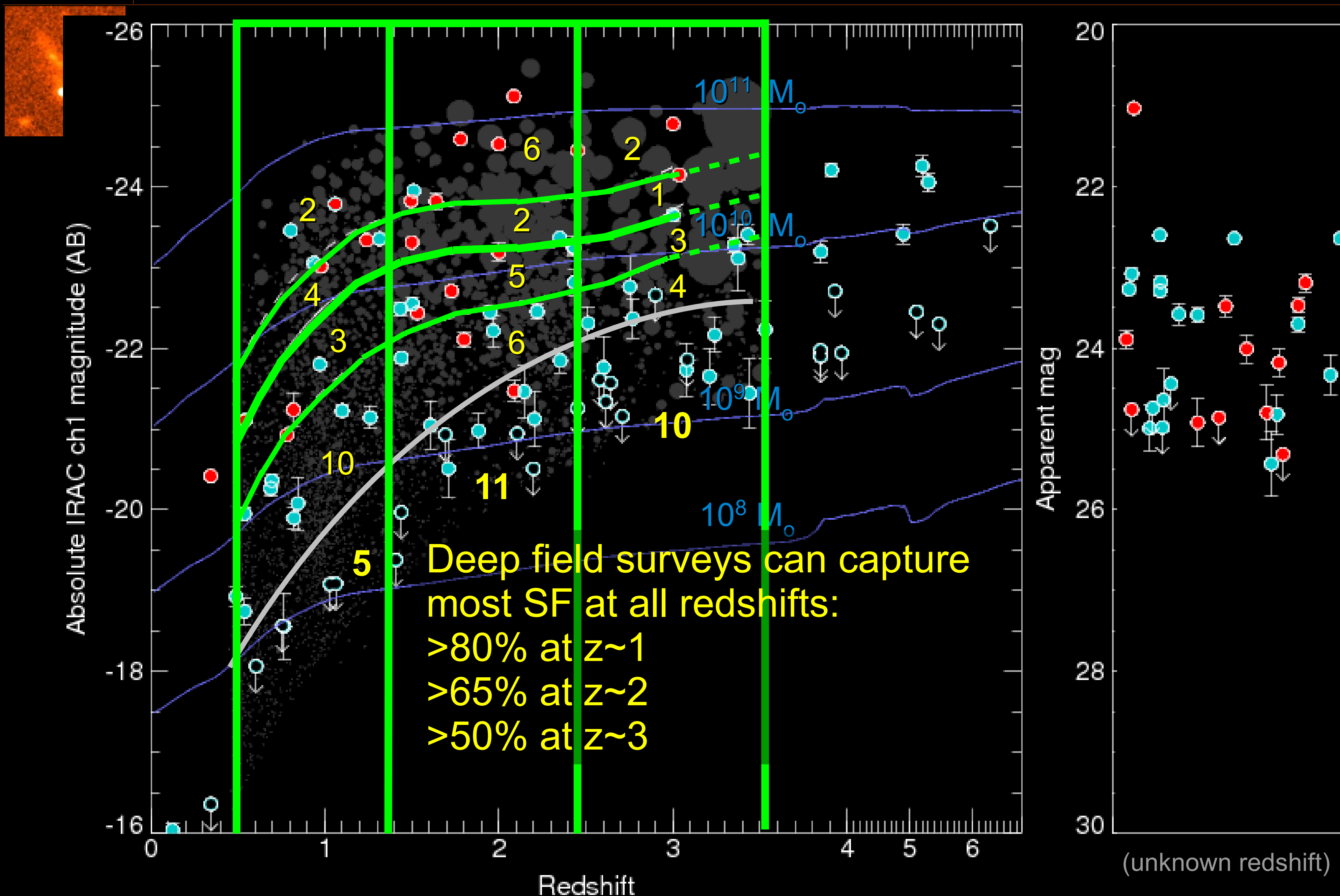
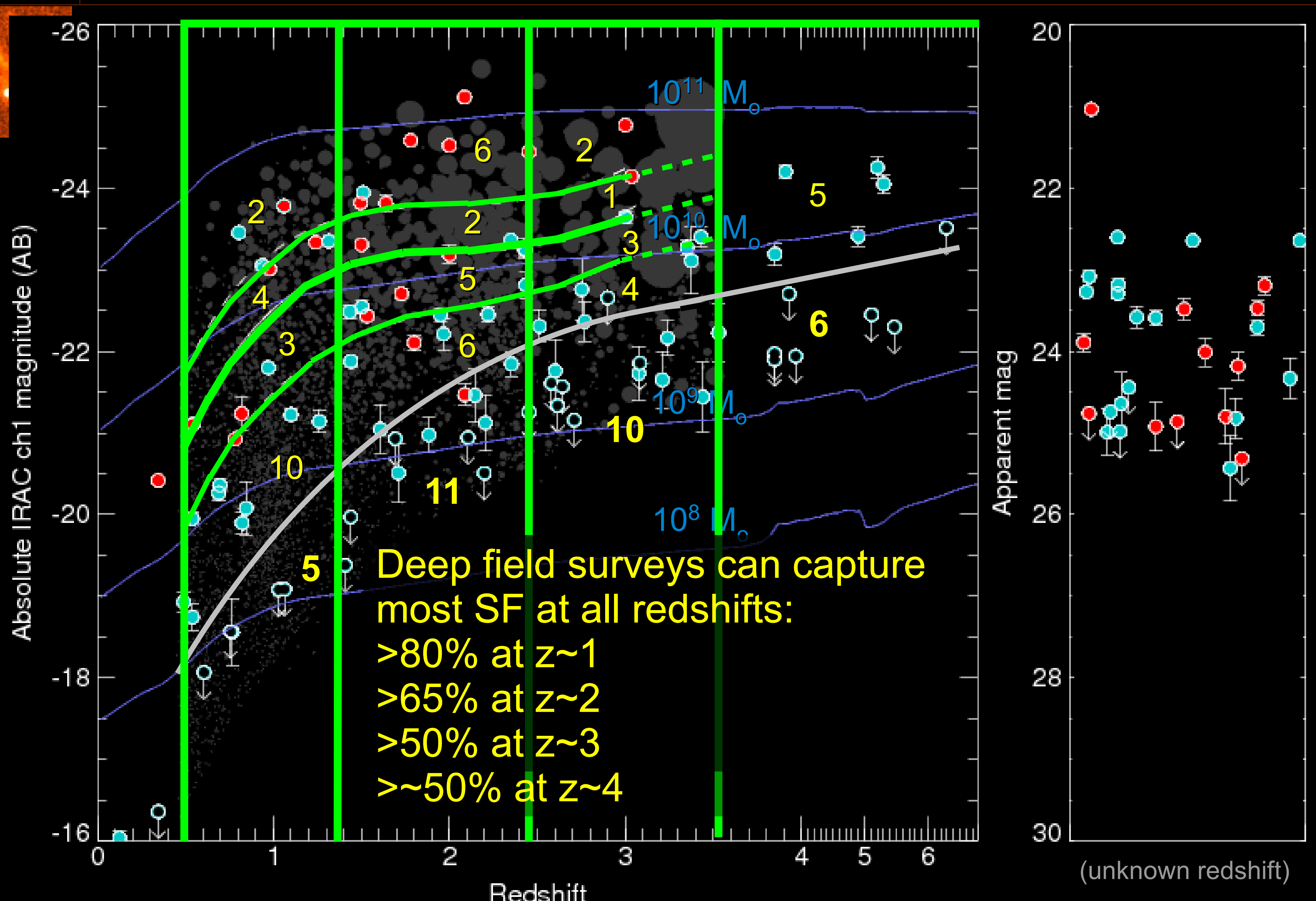
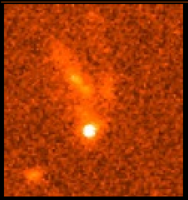


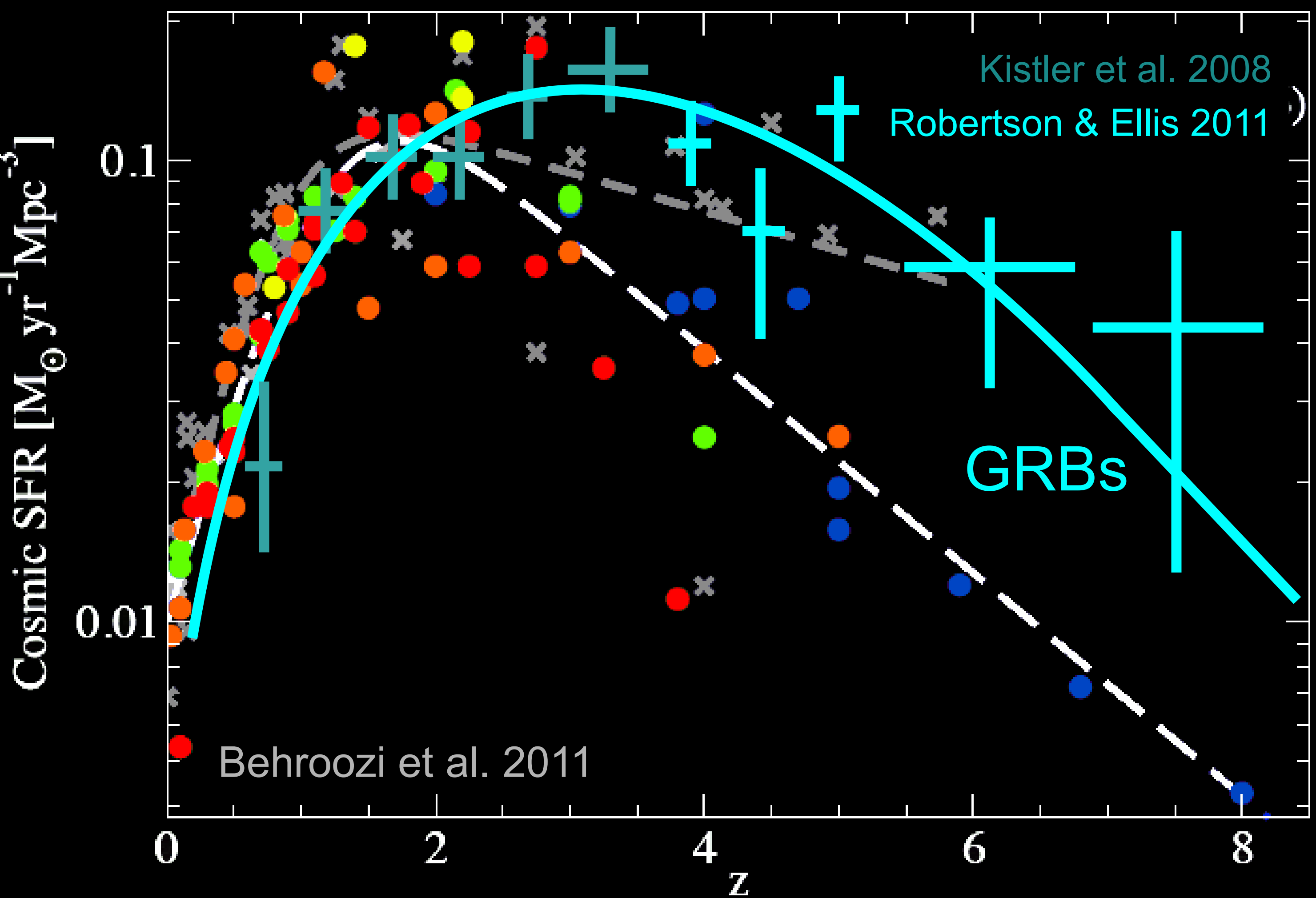
Deep field surveys can capture most SF at all redshifts:
>80% at z~1
>65% at z~2
>50% at z~3

GRBs vs. Star Formation



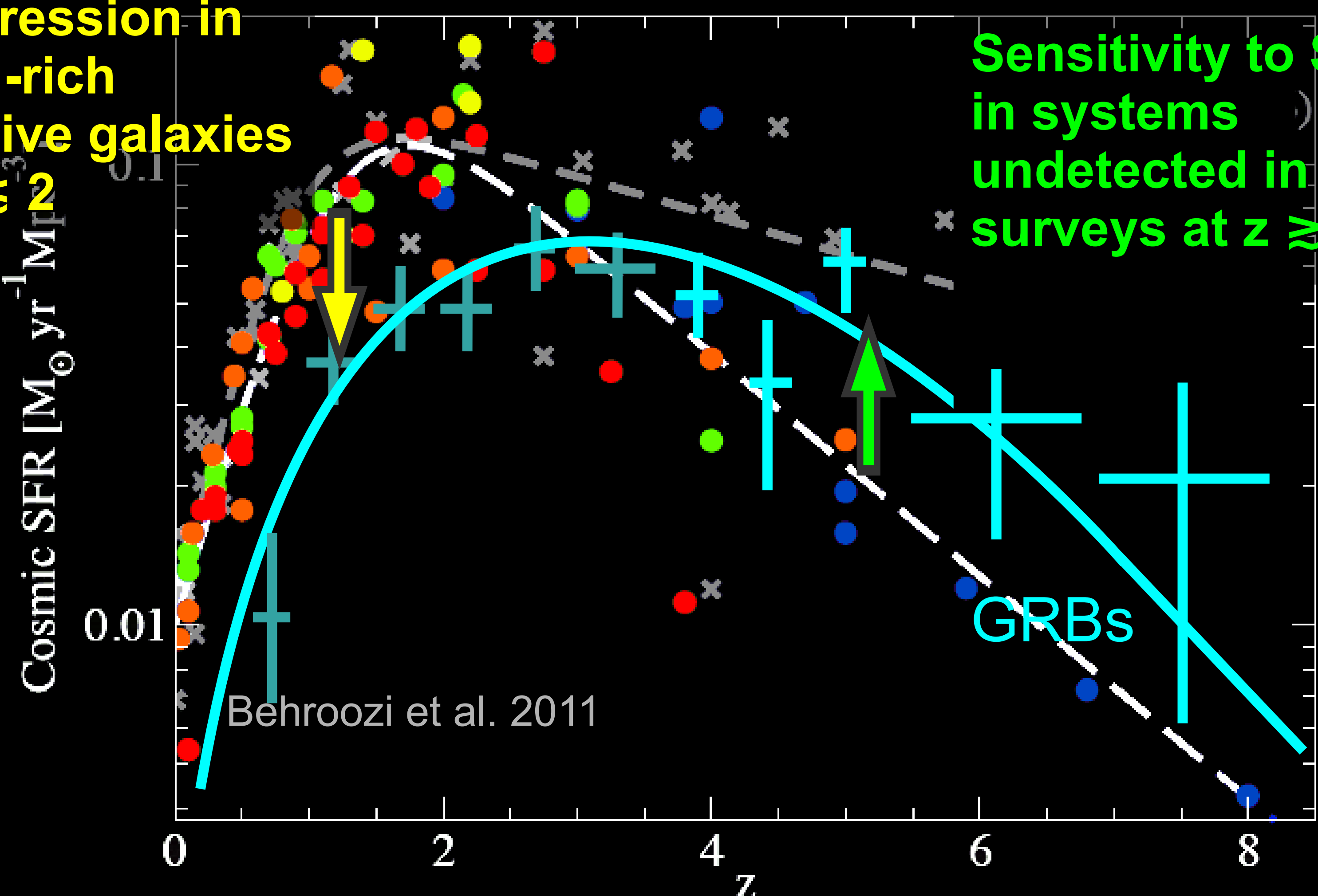
High-z SF History from GRBs





High-z SF History from GRBs

Re-normalize at z~3



Conclusions

Gamma-ray bursts are a powerful (but non-uniform and not yet fully-calibrated) **tracer of star formation in distant galaxies.**

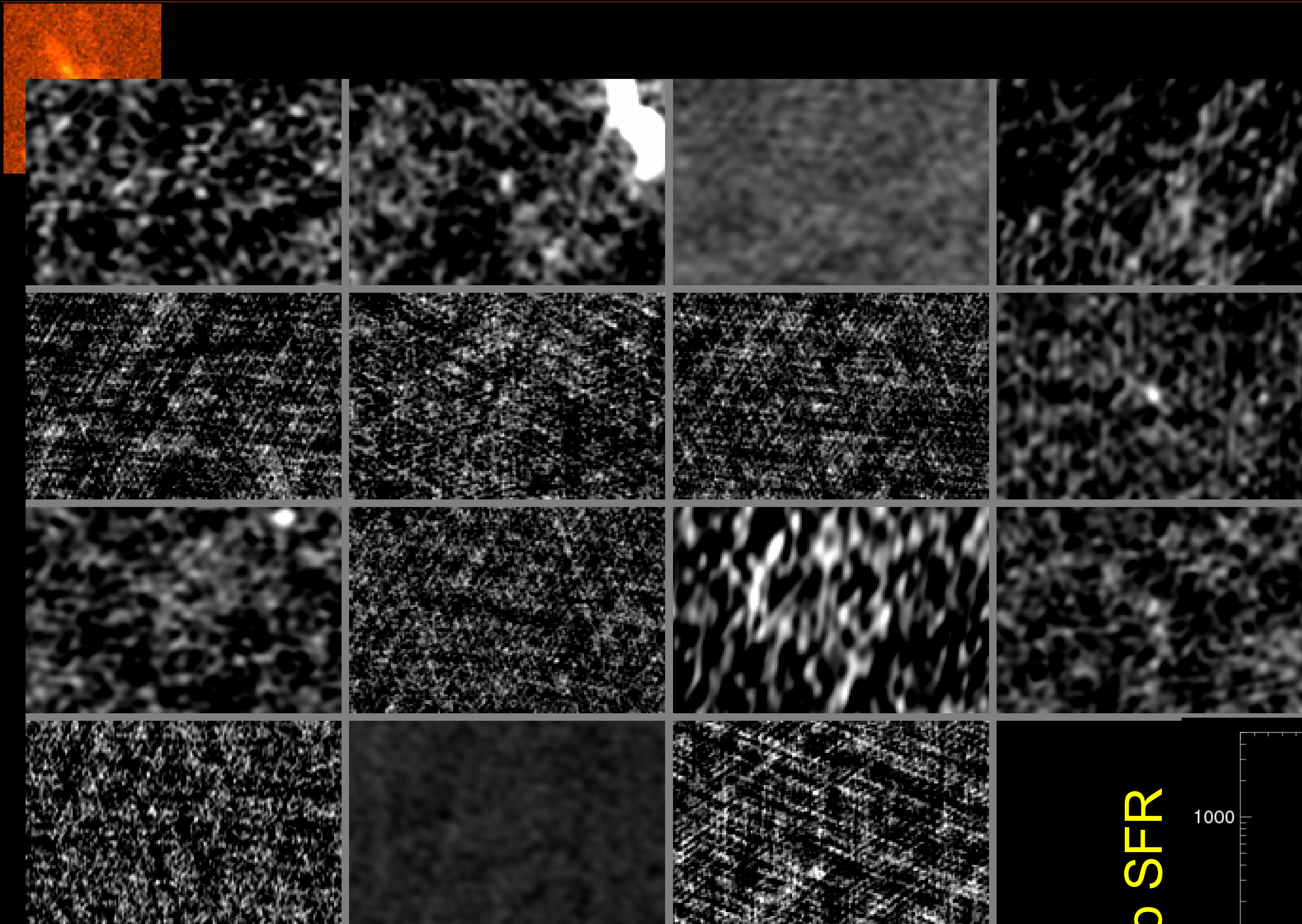
GRBs at z~1 do not trace the star formation rate exactly.

- They prefer **low-mass** galaxies but do not care about galaxy SFR.
  - But a very high sSFR seems to help – deserves further study
- Driving factor in GRB production is probably **metallicity.**
  - (Consistent with "classical" theory wind-driven momentum loss)
- Low (~0.1-0.5 $Z_\odot$), but not extreme, metallicity is adequate.
- May trace chemical evolution + SFR (still interesting!)

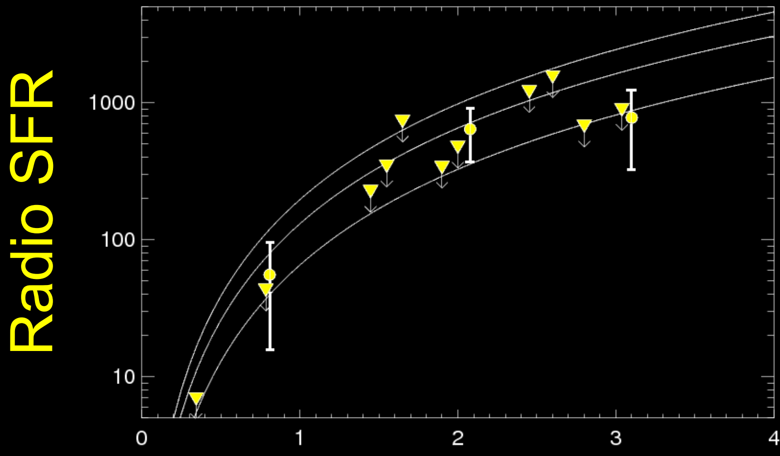
GRBs already place interesting constraints on star-formation and high-z galaxy properties.

- Low-mass galaxies contain very little dust and are optically thin.
- High-mass galaxies have lots of dust and a high covering fraction.
- Deep mass-selected surveys see most cosmic SFR out to z~6!
- GRBs support a falling cosmic SFRD above z>4
  - and may soon provide constraints on high-z SFR in very faint galaxies

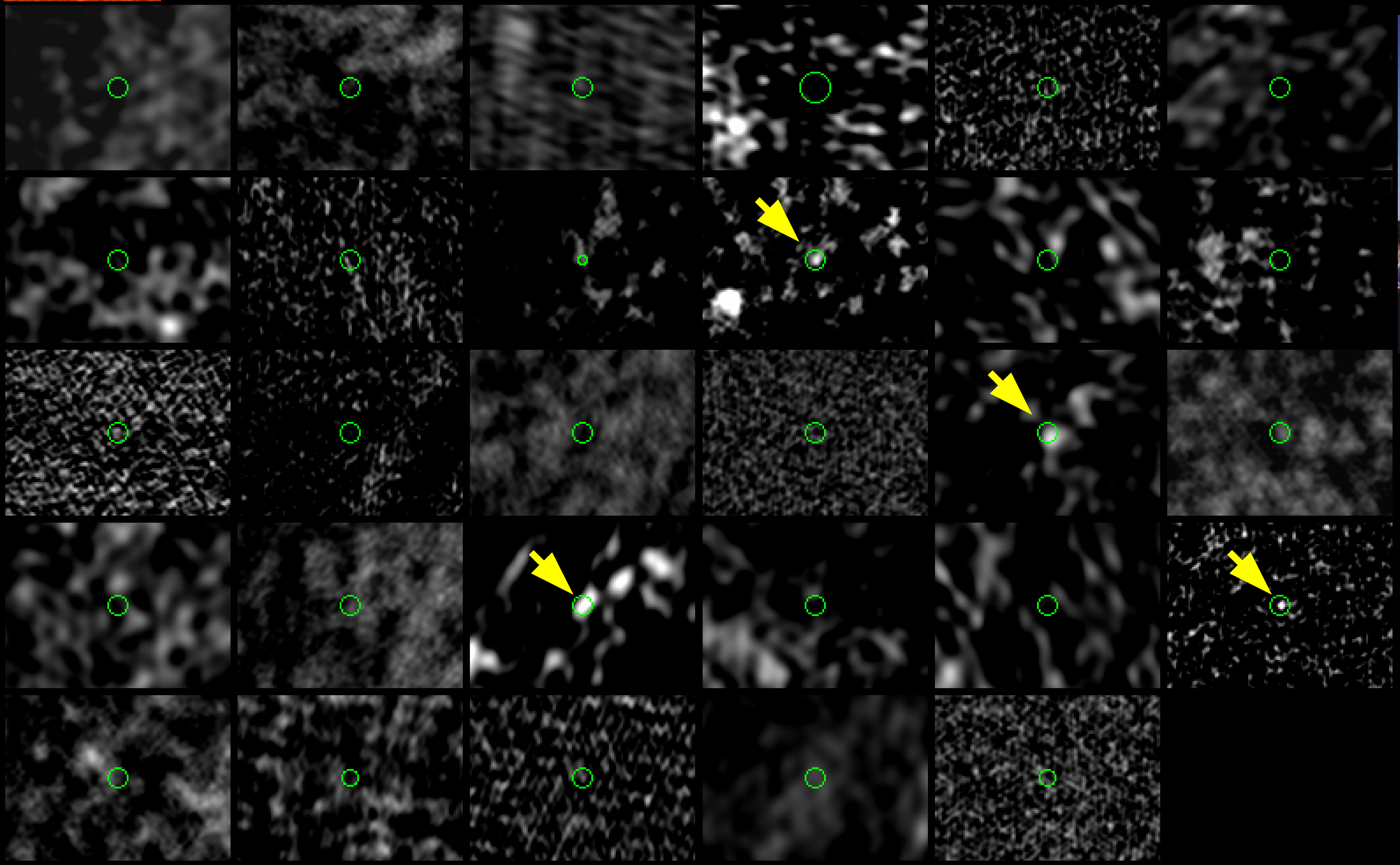
Few GRB hosts are SMGs



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

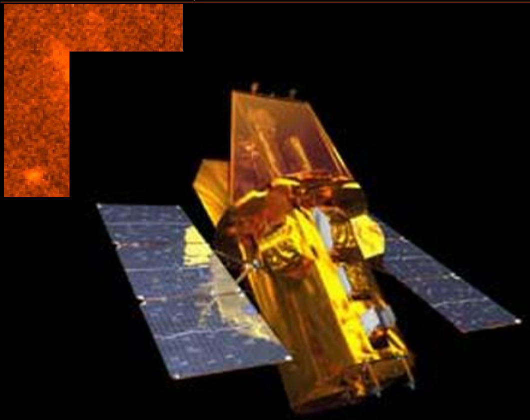


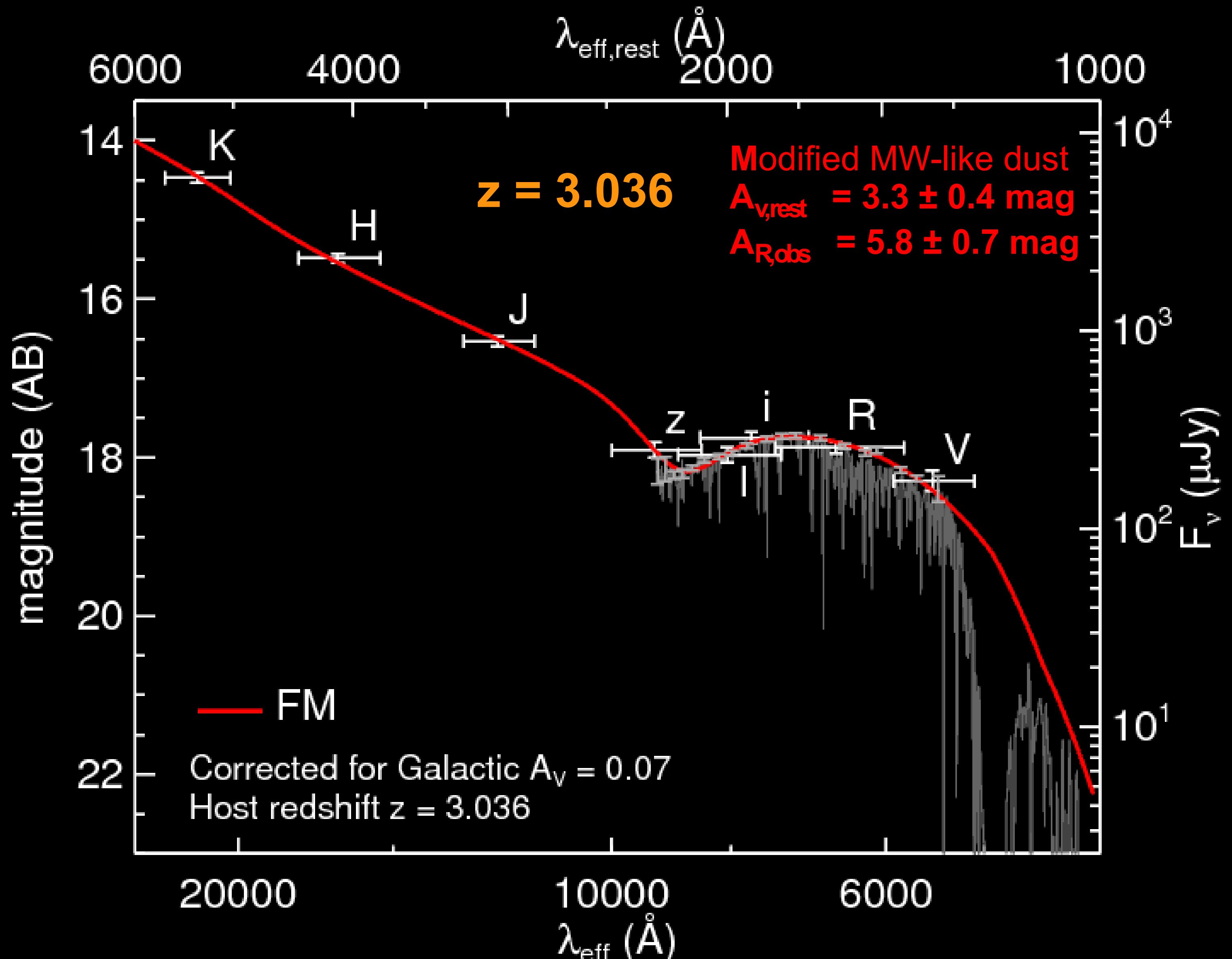
GRB host submillimeter-galaxy fraction



"Unbiased" sample:
4/29 detections with VLA to 10 microJansky ($z<2.5$ GRBs)

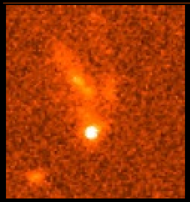
The Exceptionally Luminous GRB 080607

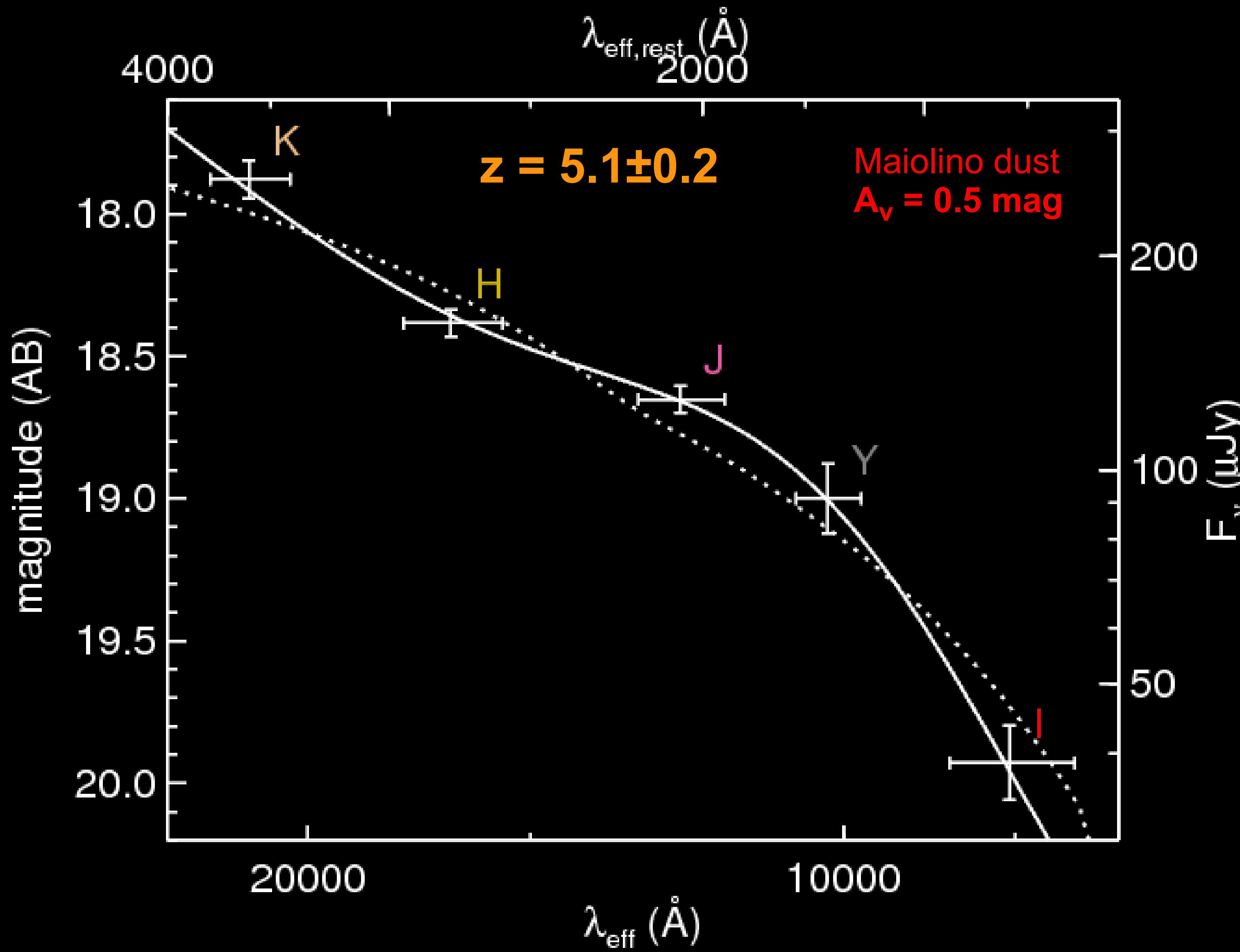




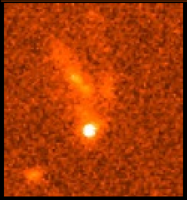
Perley et al. 2010b

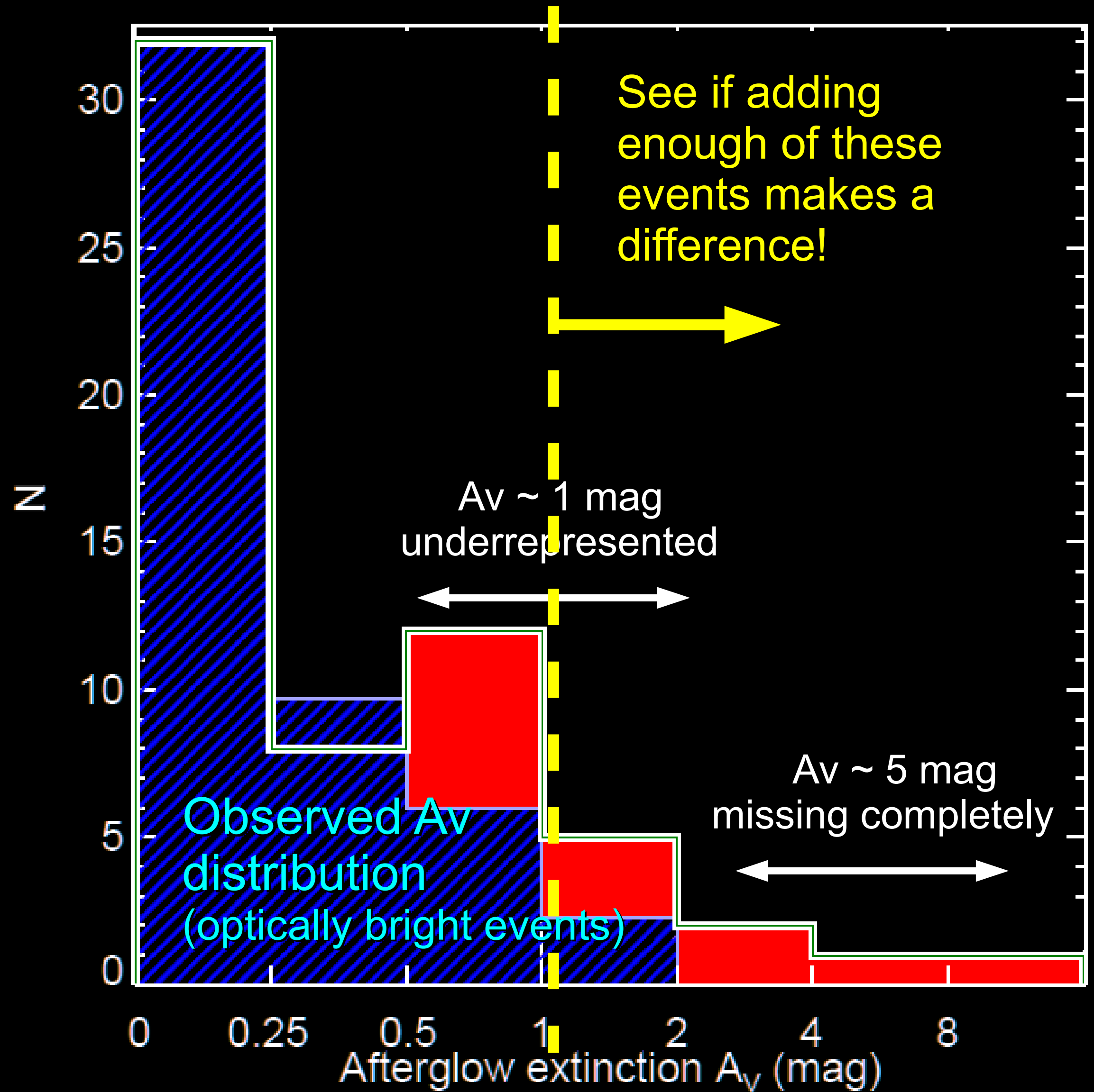
Exotic dust at z~5 from GRB 071025





Dust and Selection Bias

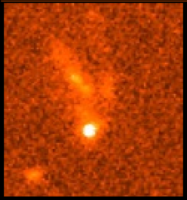


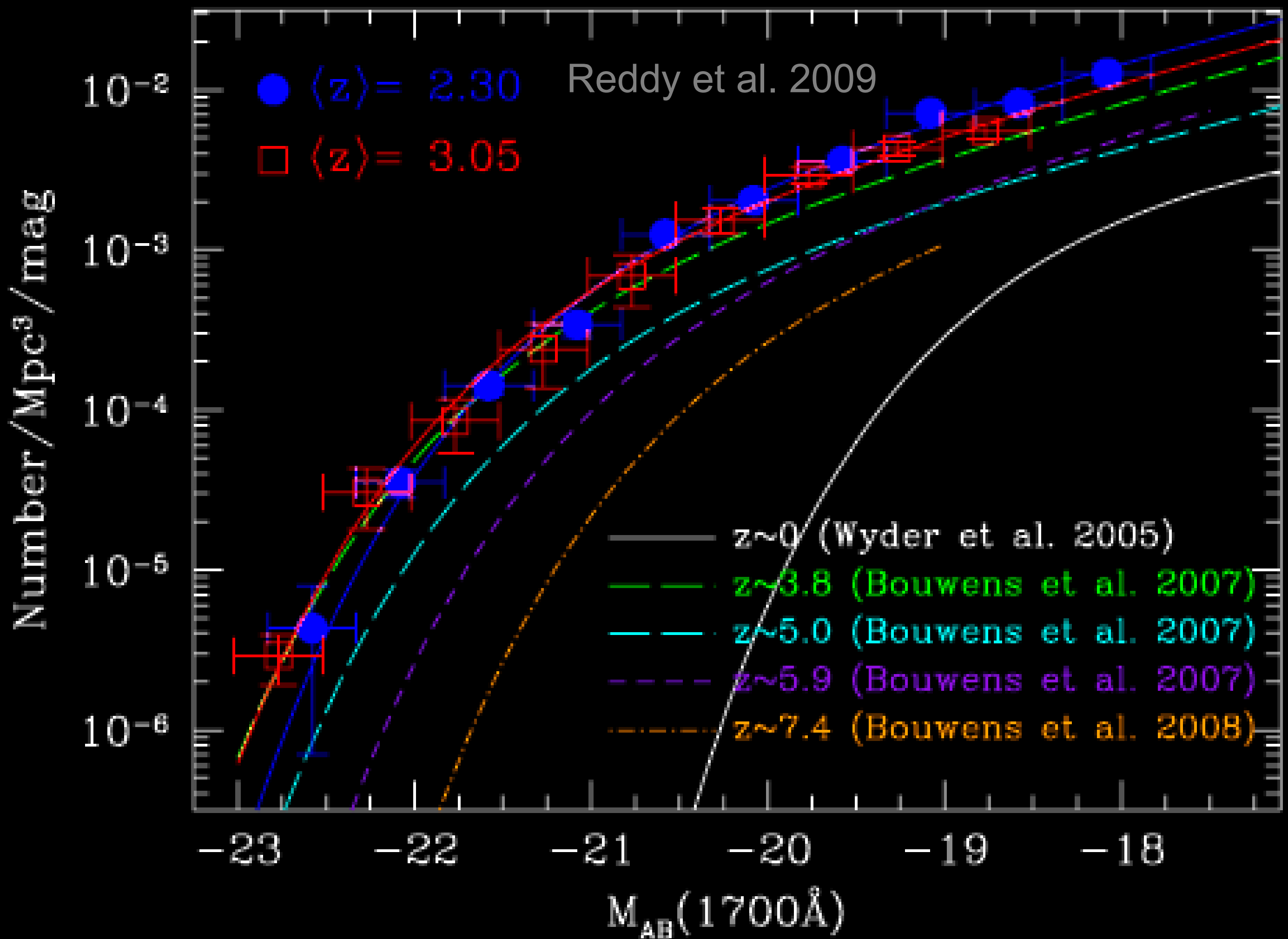


~20% of GRBs are systematically missing from optical afterglow searches as a result of dust.

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

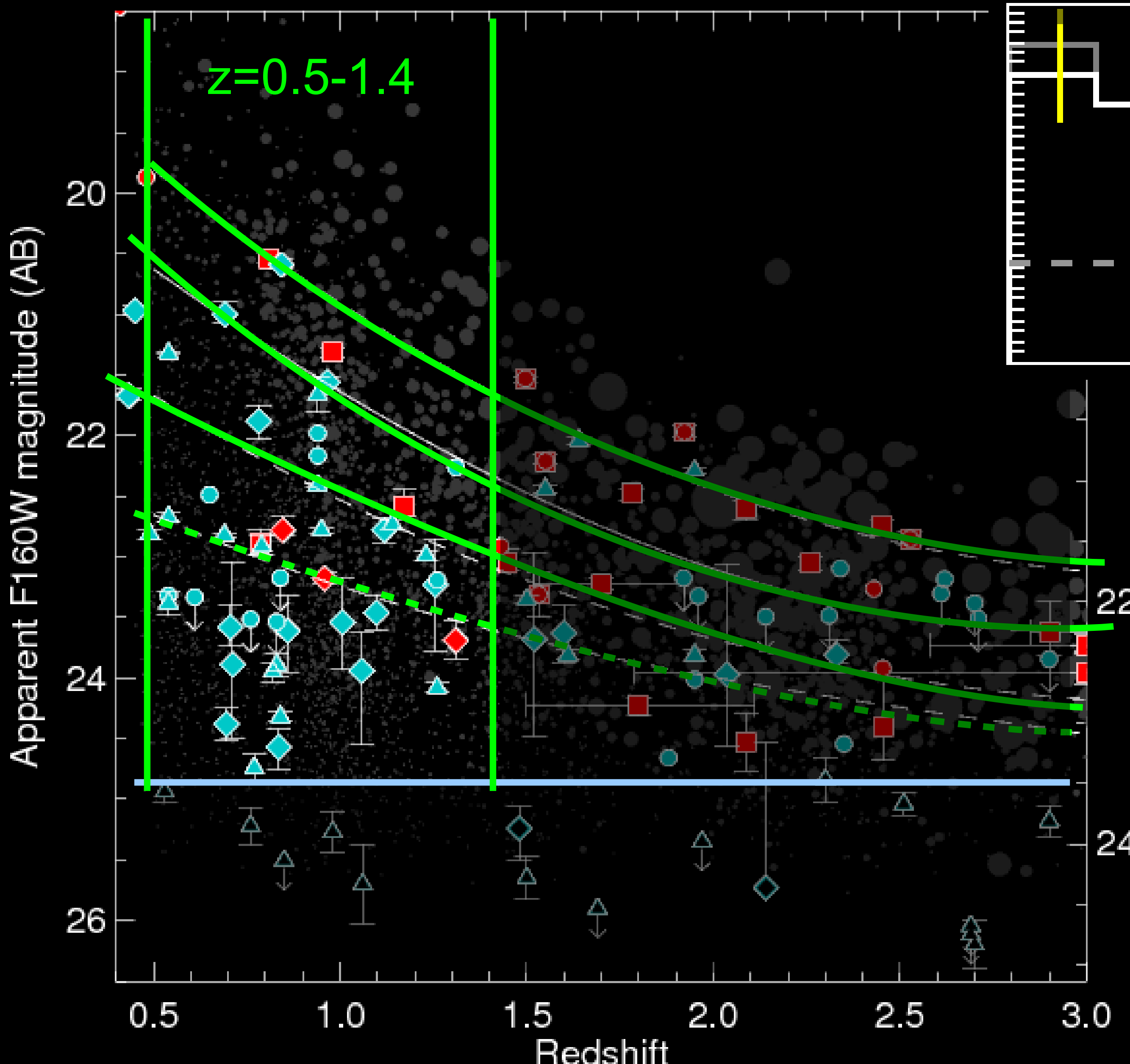
Faint-End Slope

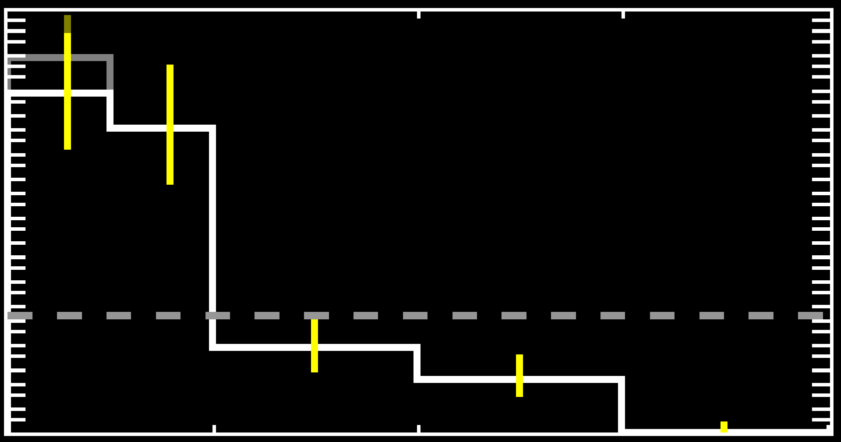




← Ultraviolet Luminosity

Does metal dependence level out?





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

No further variation seen.