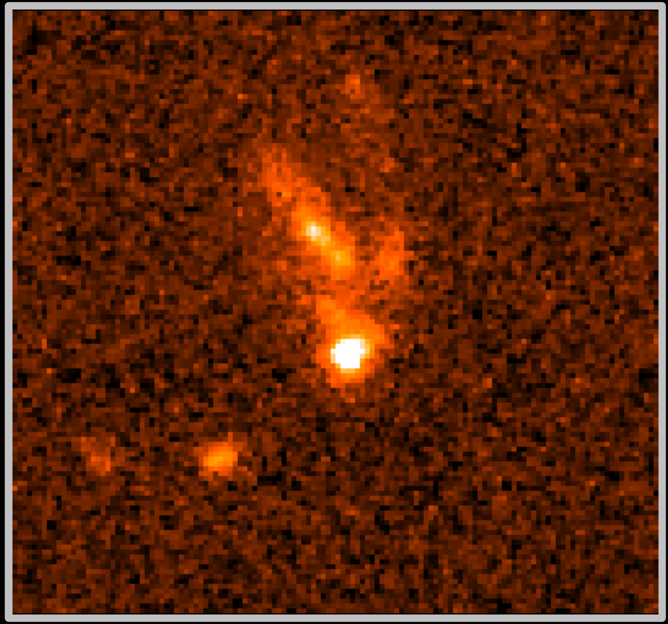
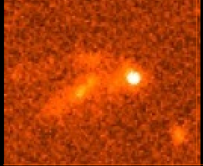
Gamma-Ray Bursts as Tracers of High-Redshift Star Formation

Promise and Peril

Daniel Perley
(Hubble Fellow, Caltech)

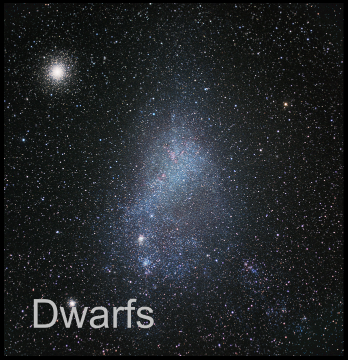


The afterglow and host of GRB990123 at z=1.6
(A. Fruchter)

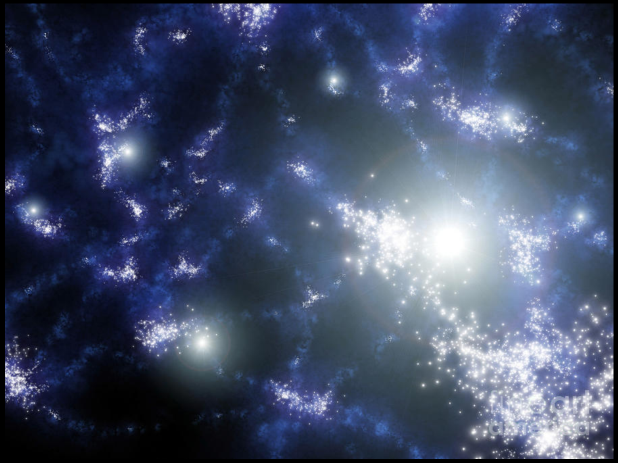


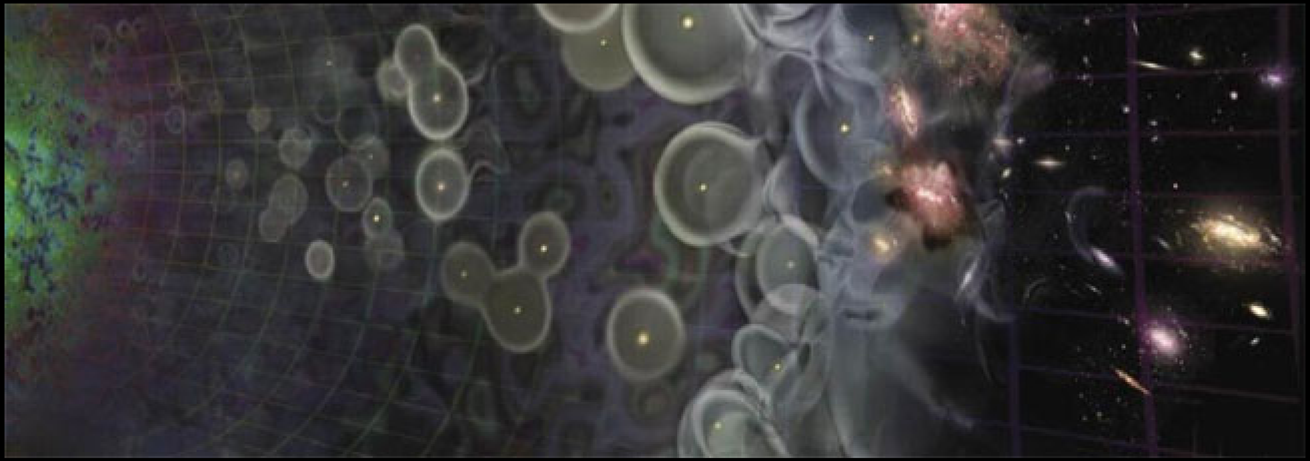
Star Formation in the Universe

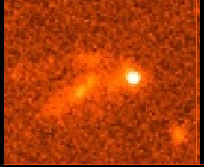
Where did the Universe's stars form?



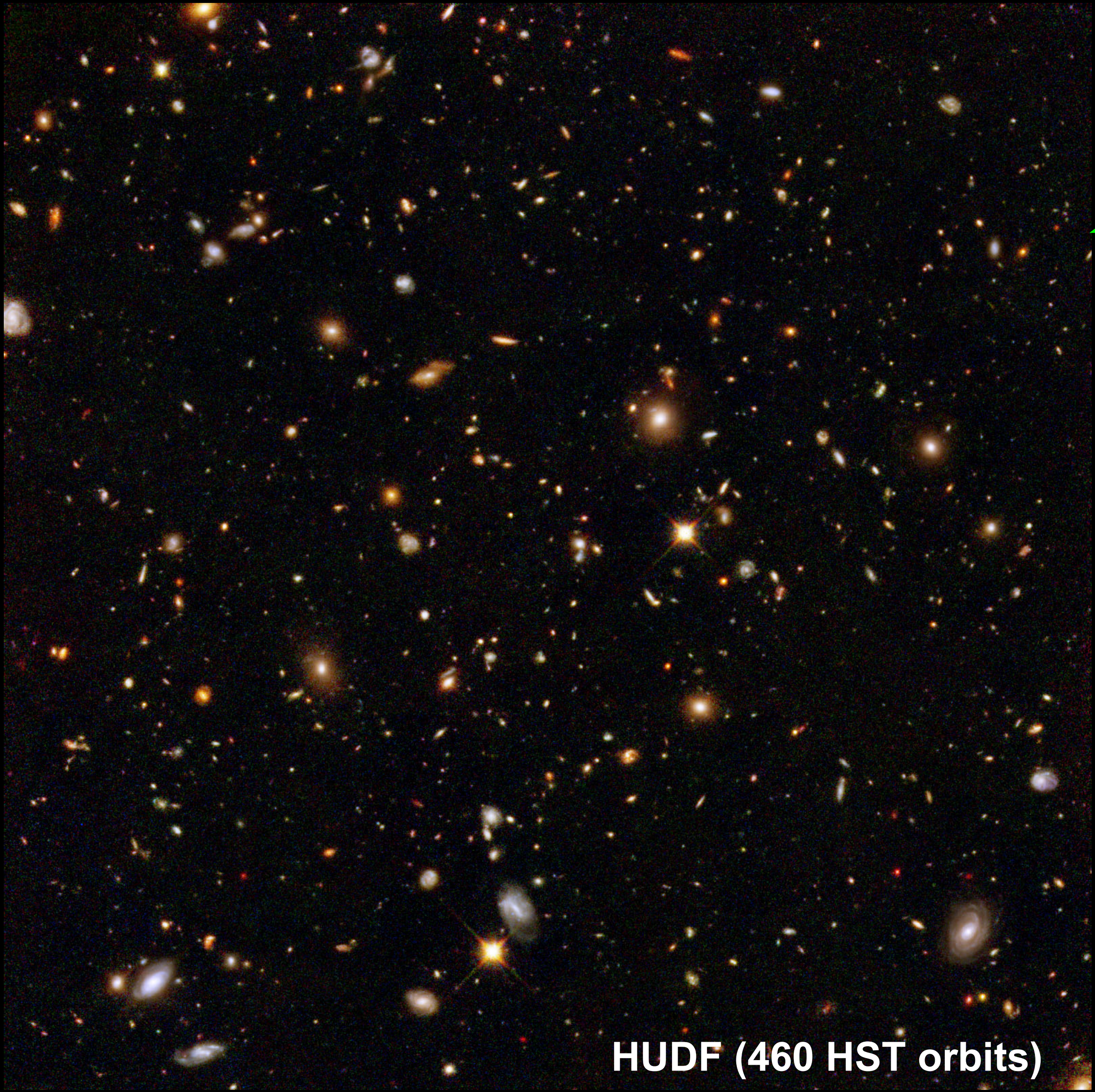
When did they form?

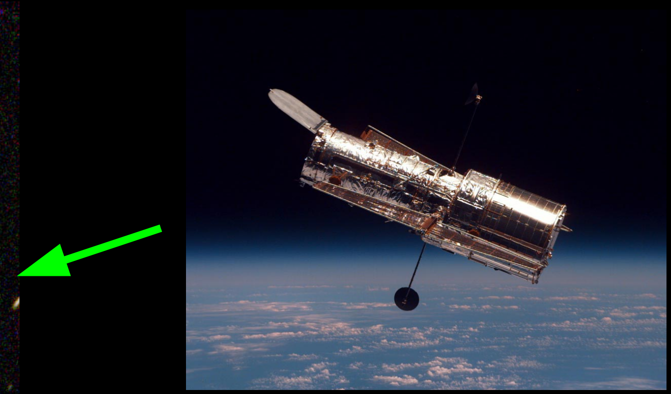


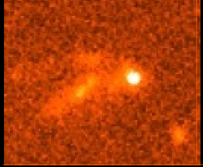




Quantifying Star Formation: Field Surveys







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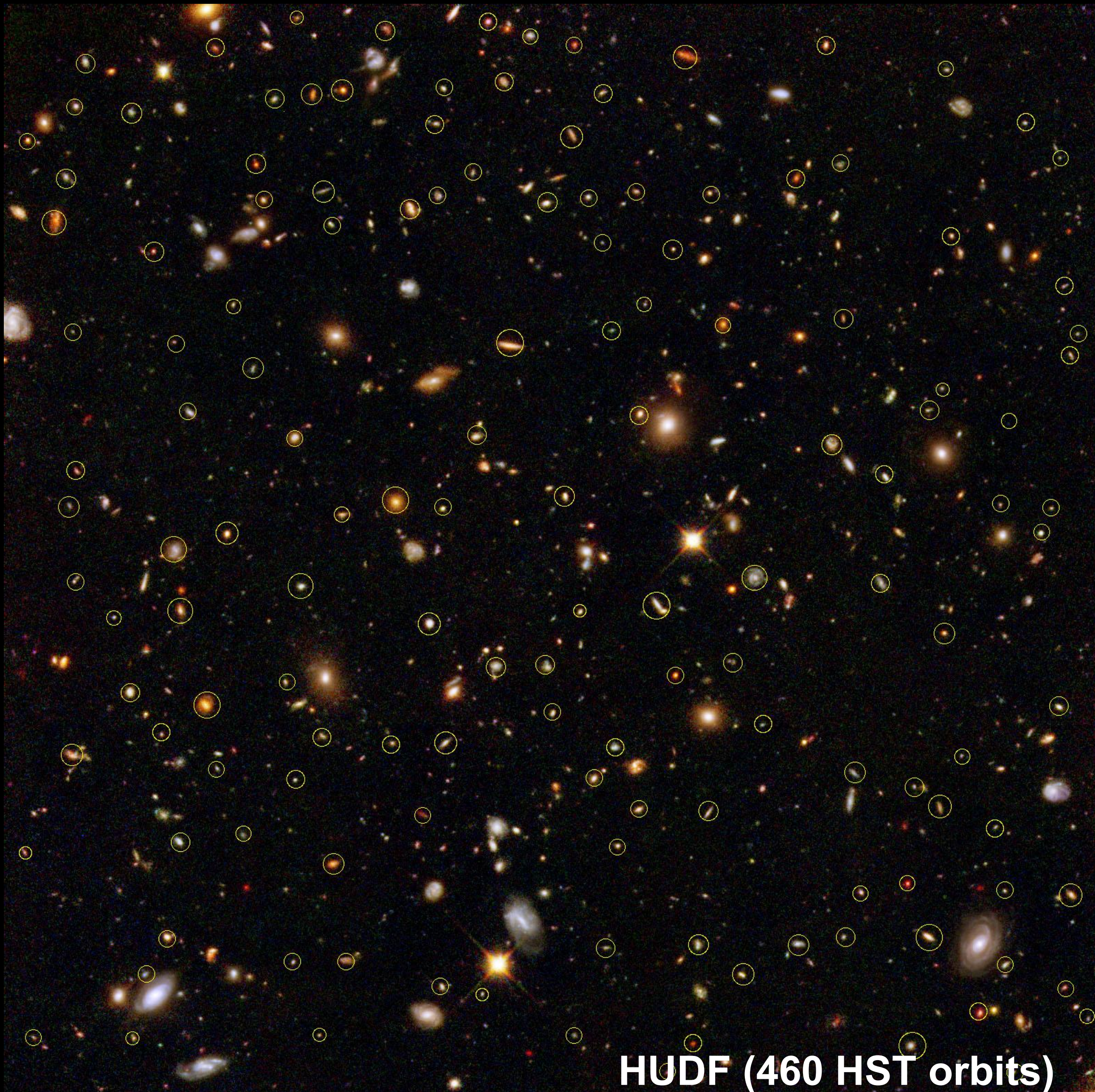

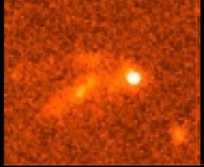

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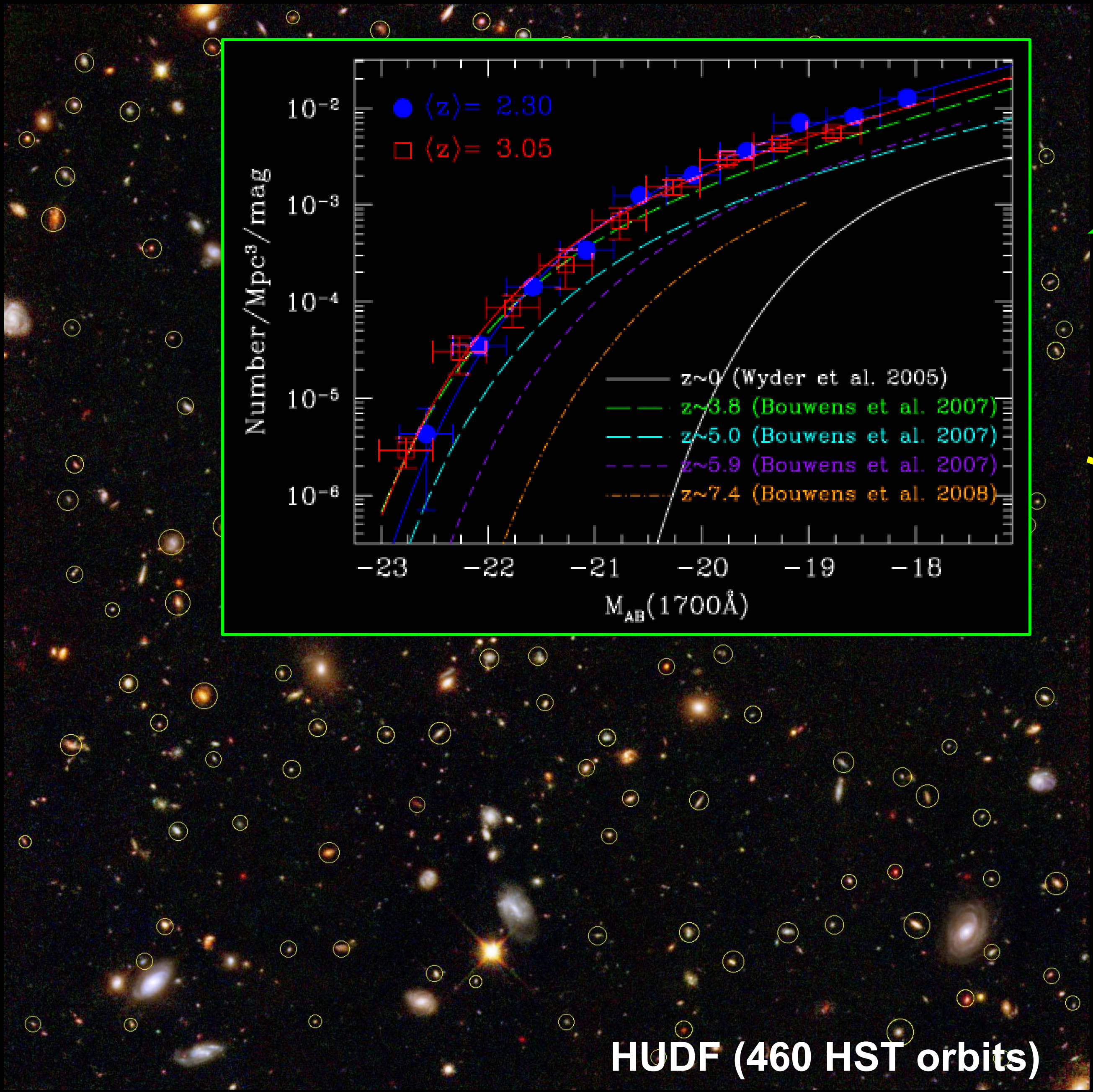
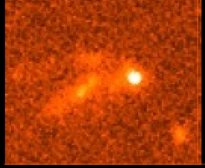
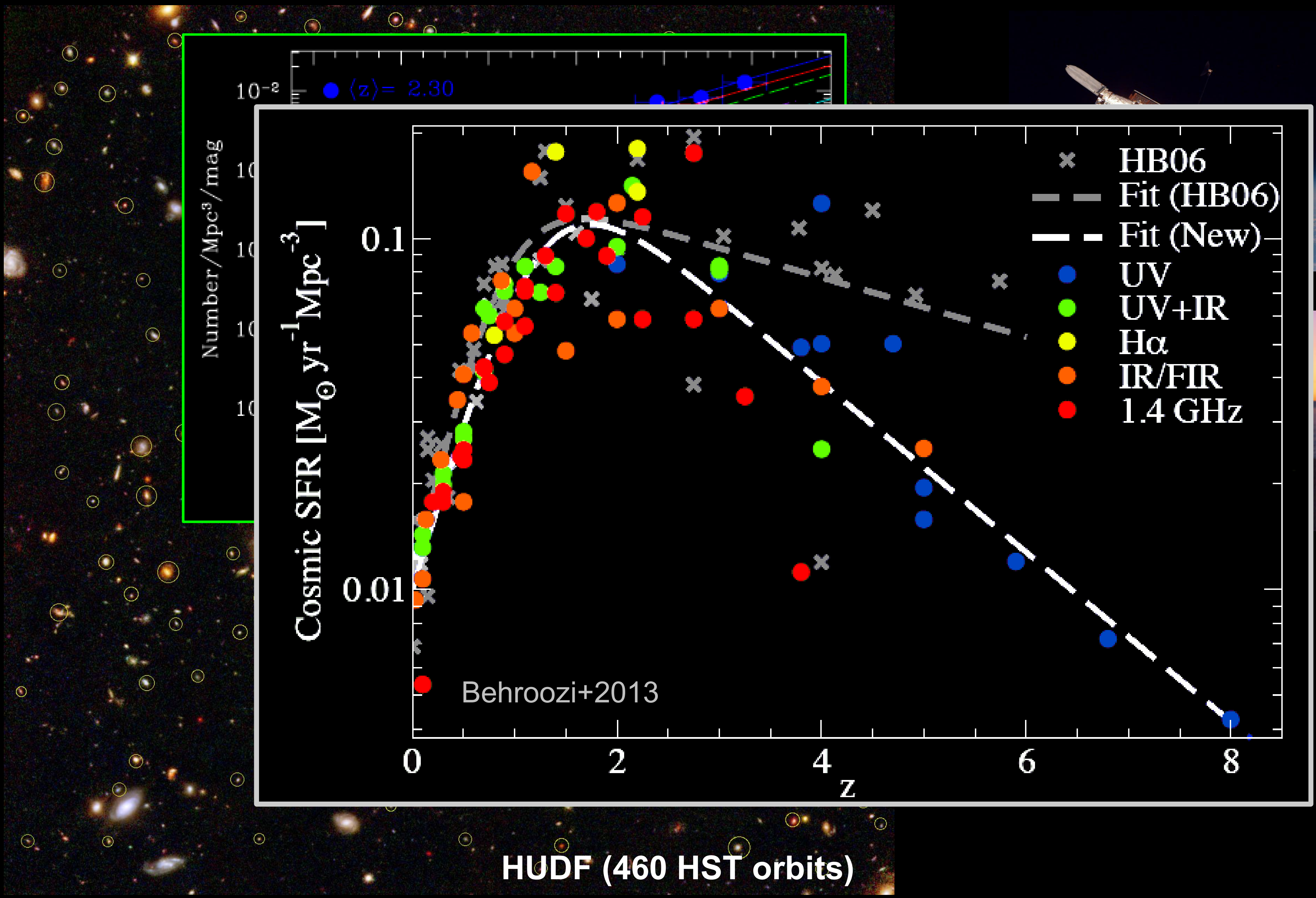
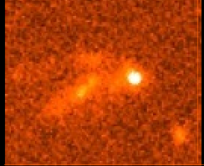




Quantifying Star Formation: Field Surveys





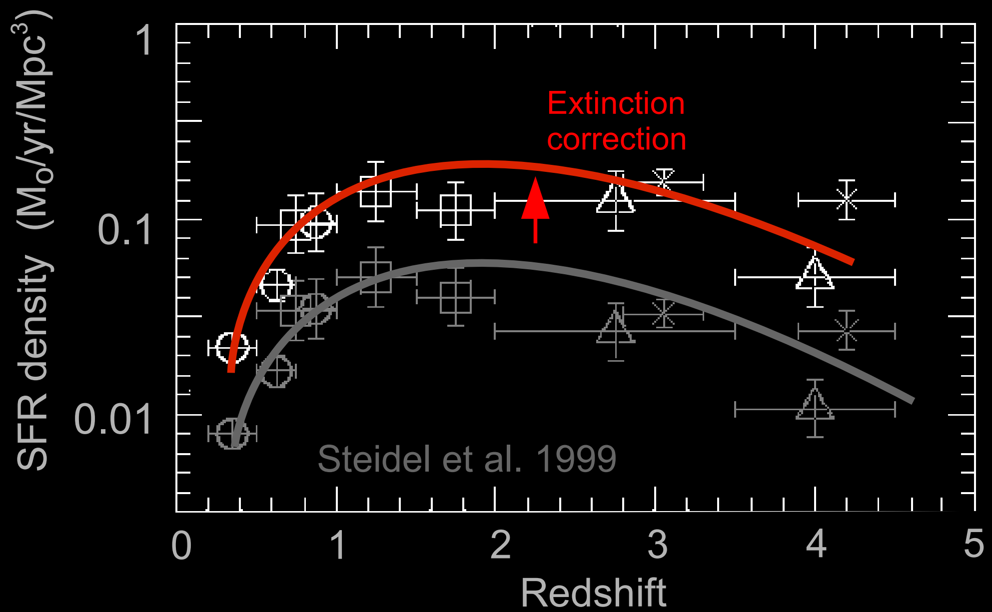
Limitations of Field Surveys

Dust Correction

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

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

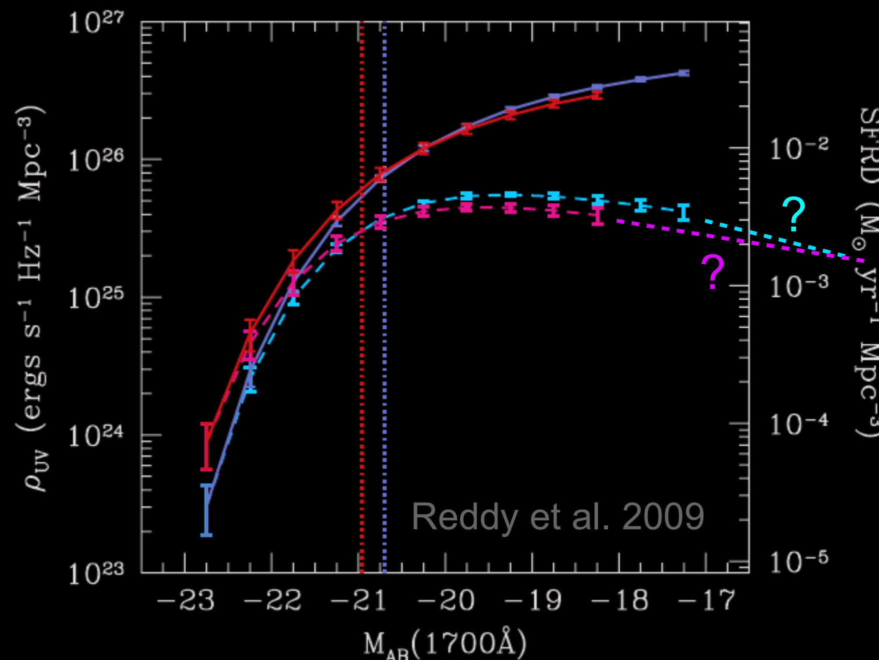
UV energy can be "recovered" at 8µm / FIR / submm, but these wavelengths have poor sensitivity to faint galaxies



Missing galaxies

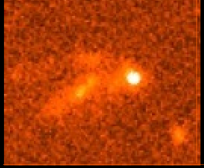
Faint galaxies (<0.1 L*) require extrapolation from bright end

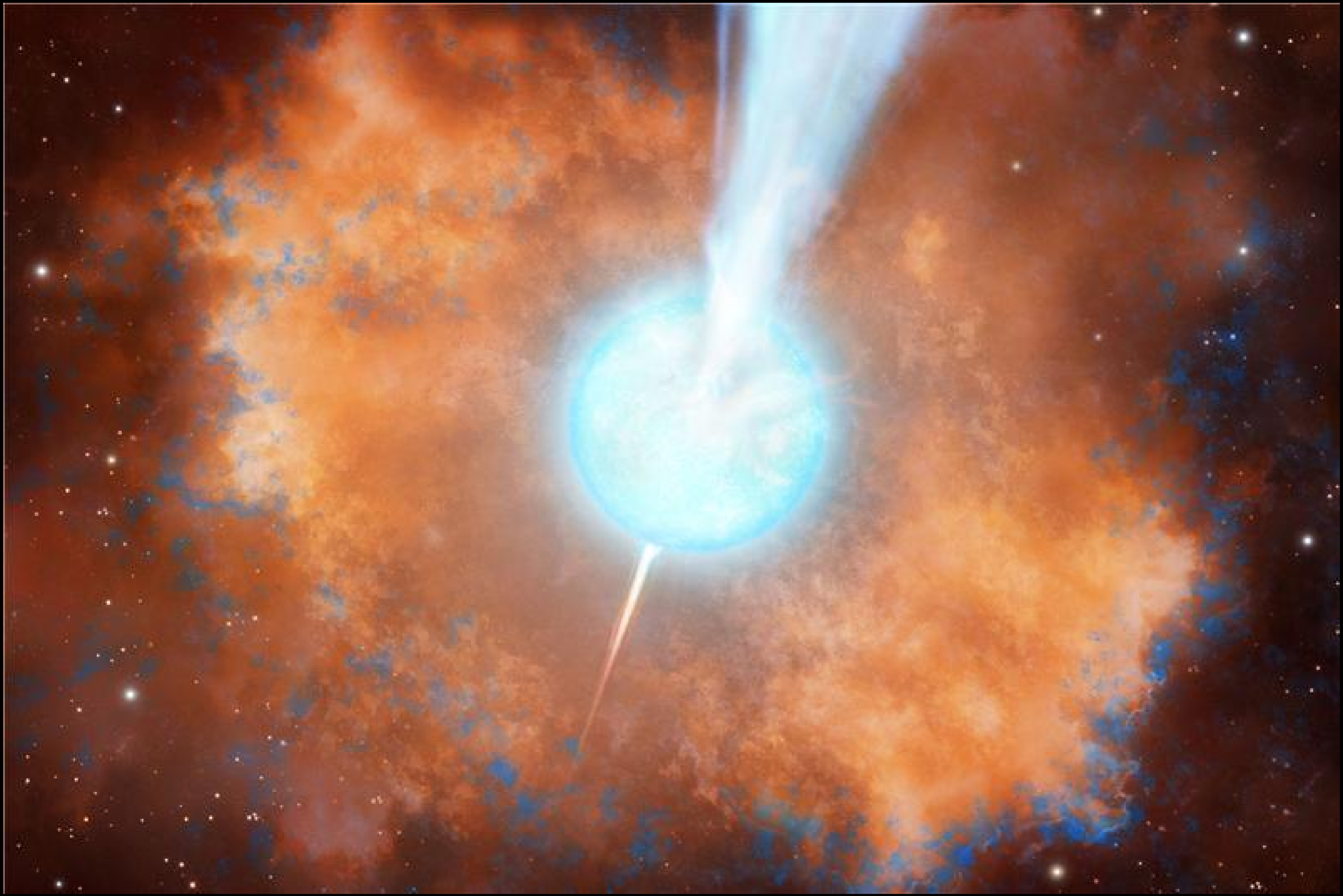
Redshift measurement imposes further biases



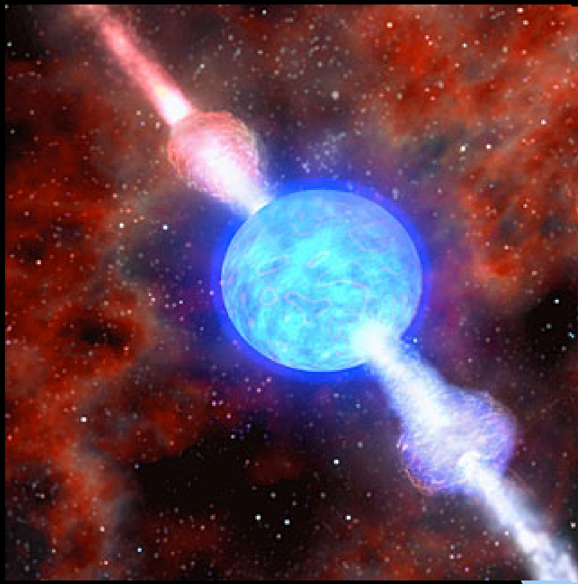
These problems are particularly limiting at z>3

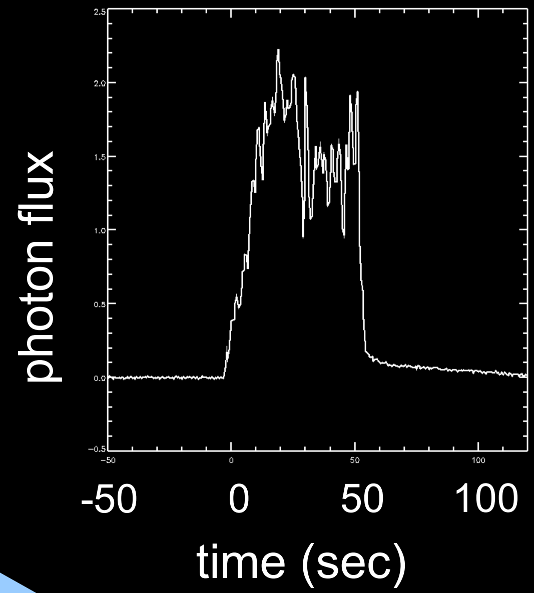
(Long) GRBs: Massive Stellar Core-Collapse

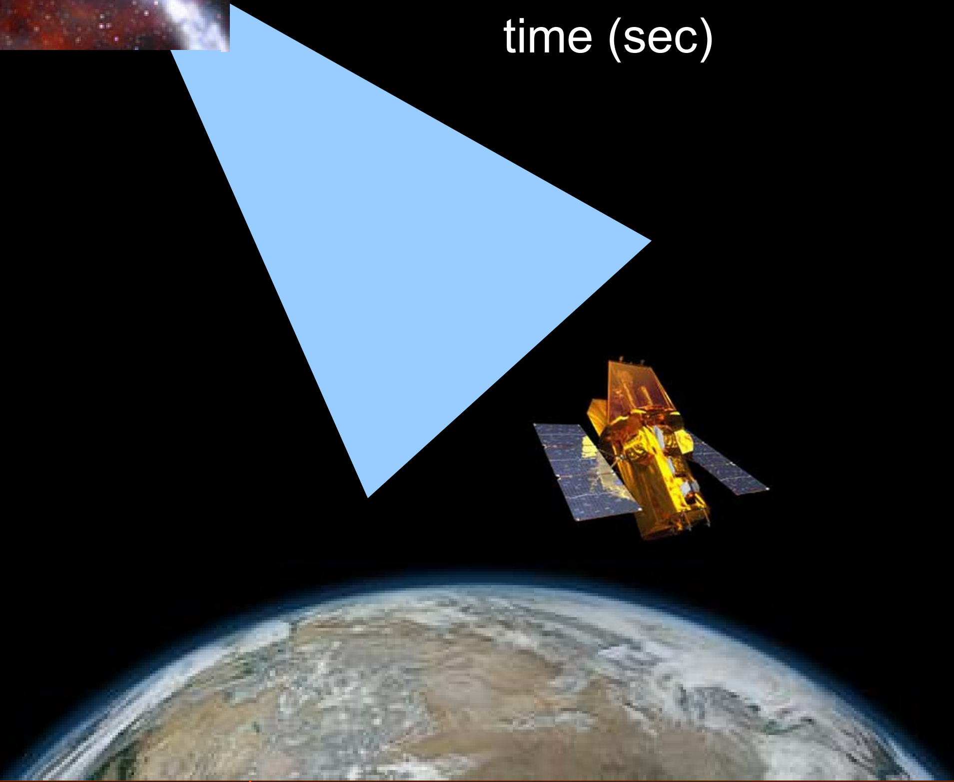


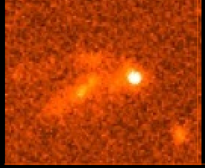


(Long-duration) Gamma-Ray Bursts

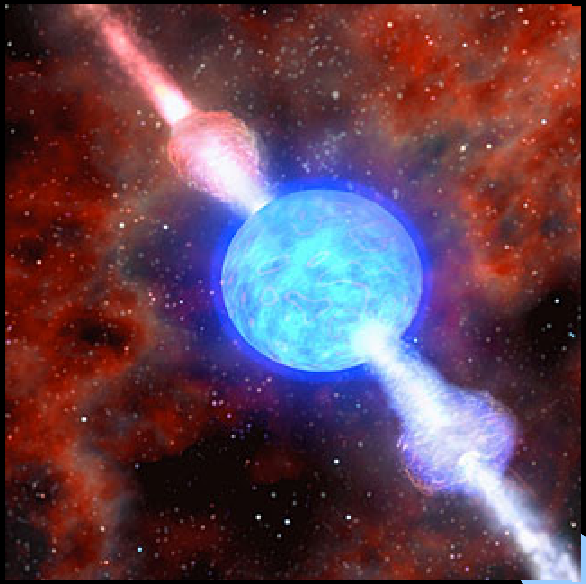


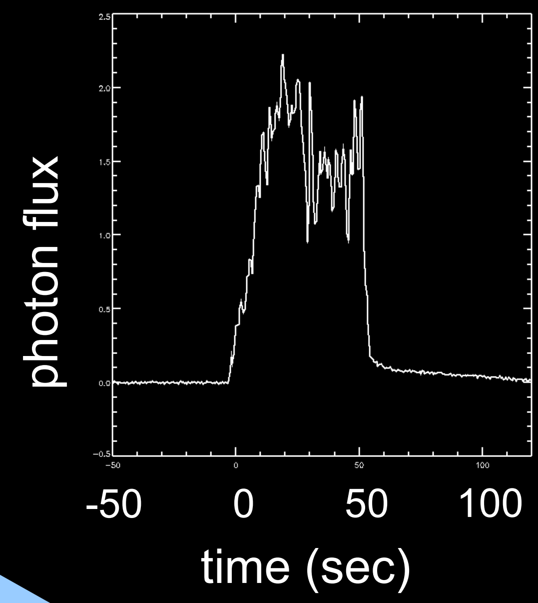


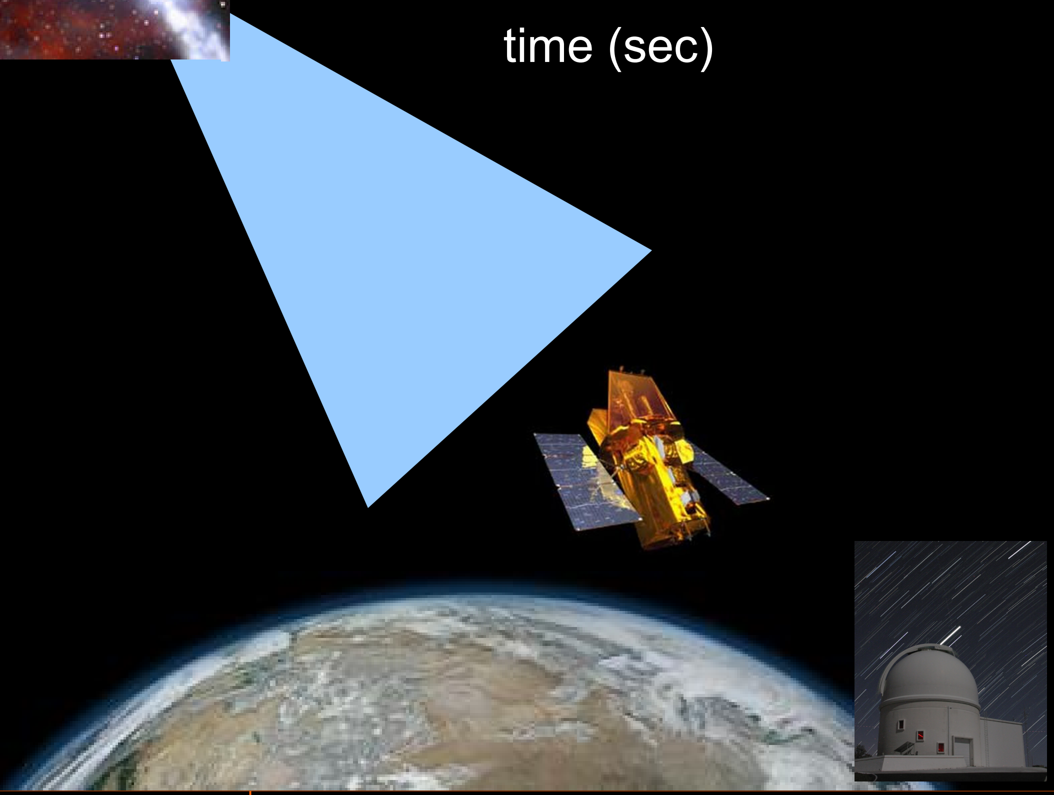




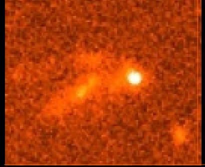
Gamma-Ray Bursts

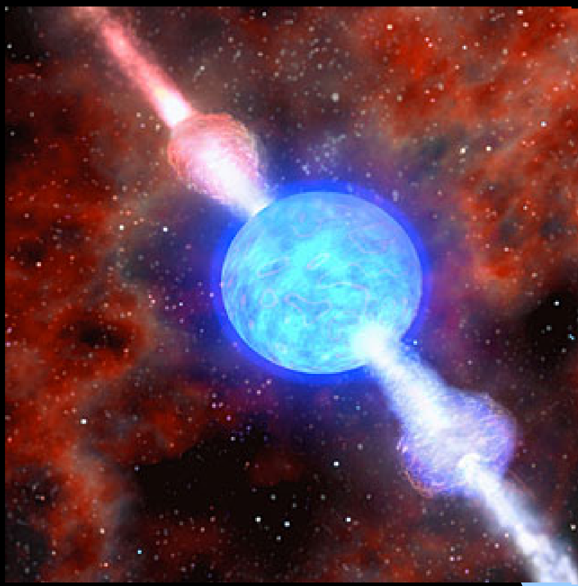


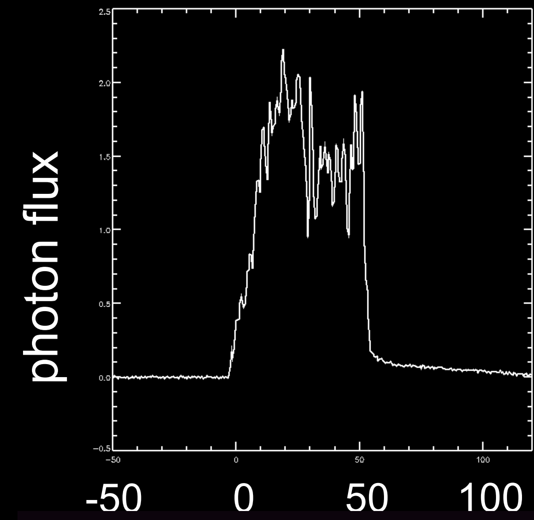


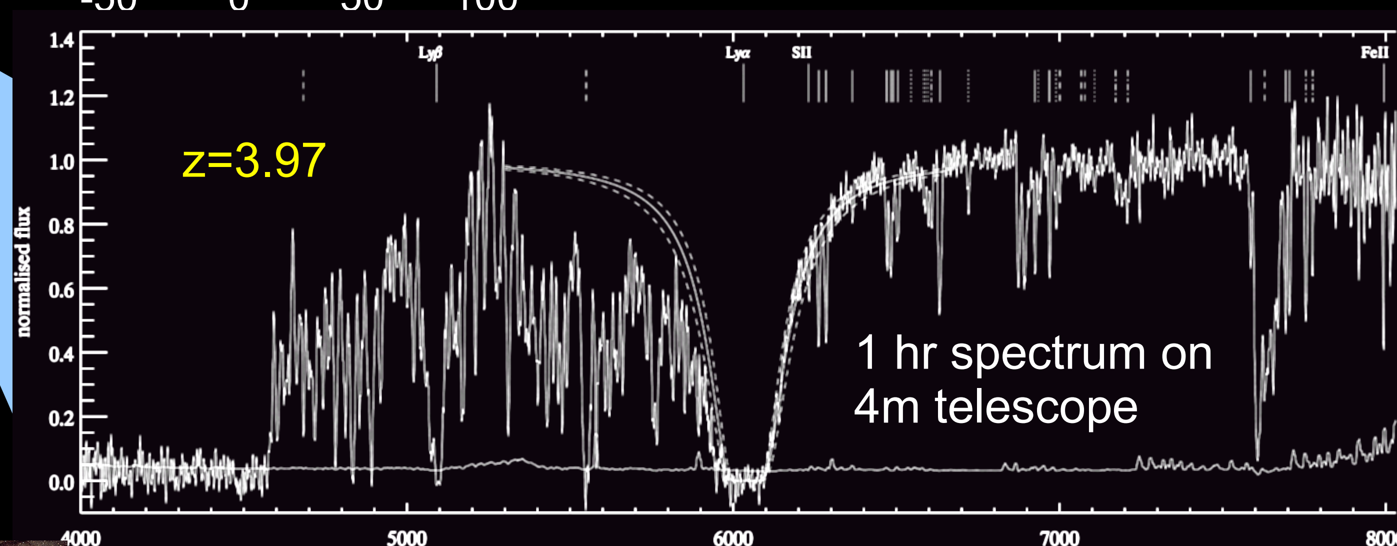


Gamma-Ray Bursts



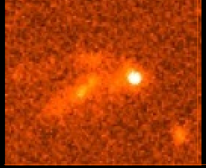


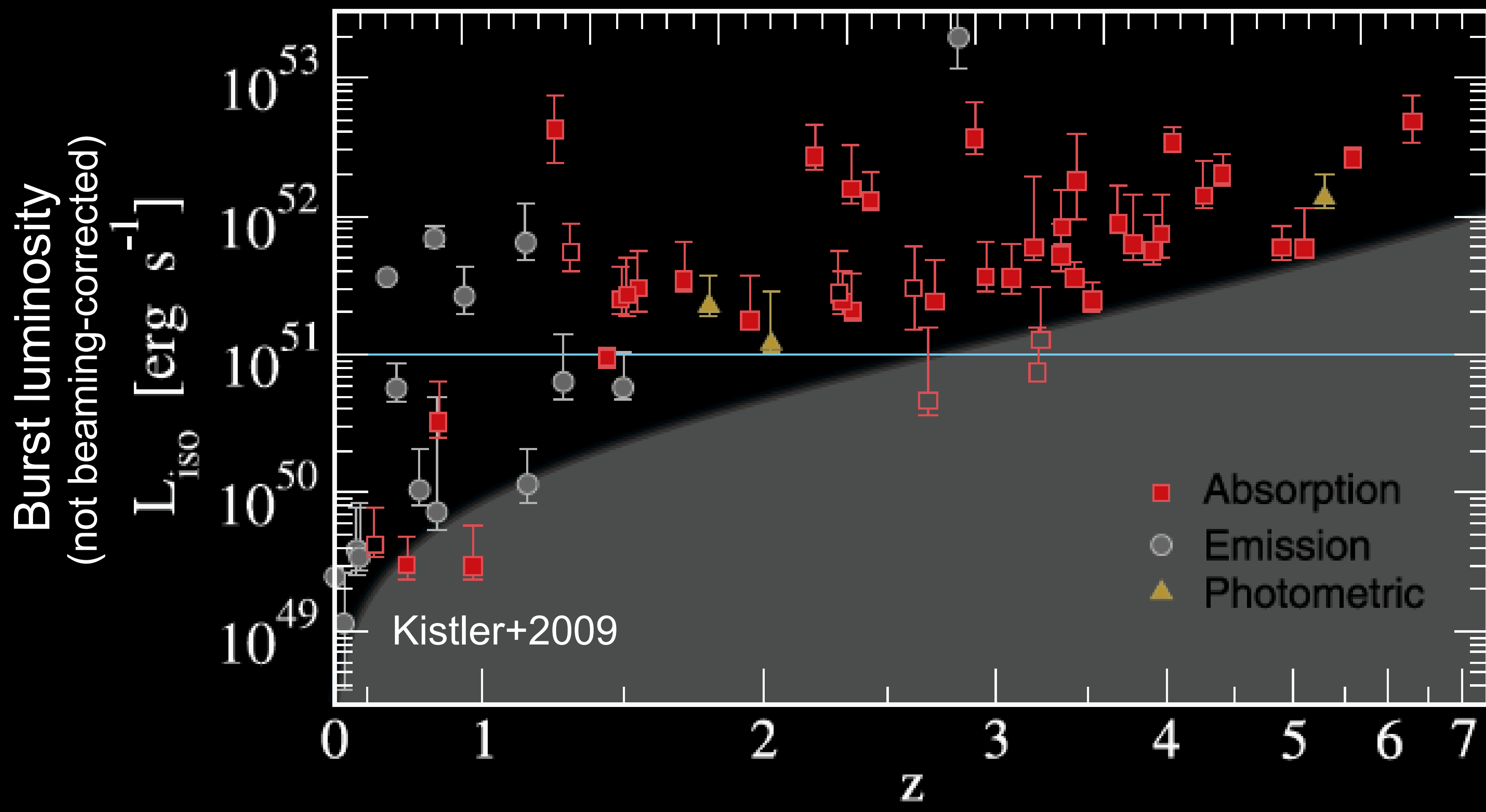


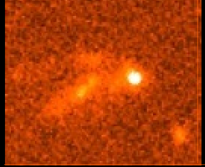


Starling+2005

Quantifying Star Formation with GRBs







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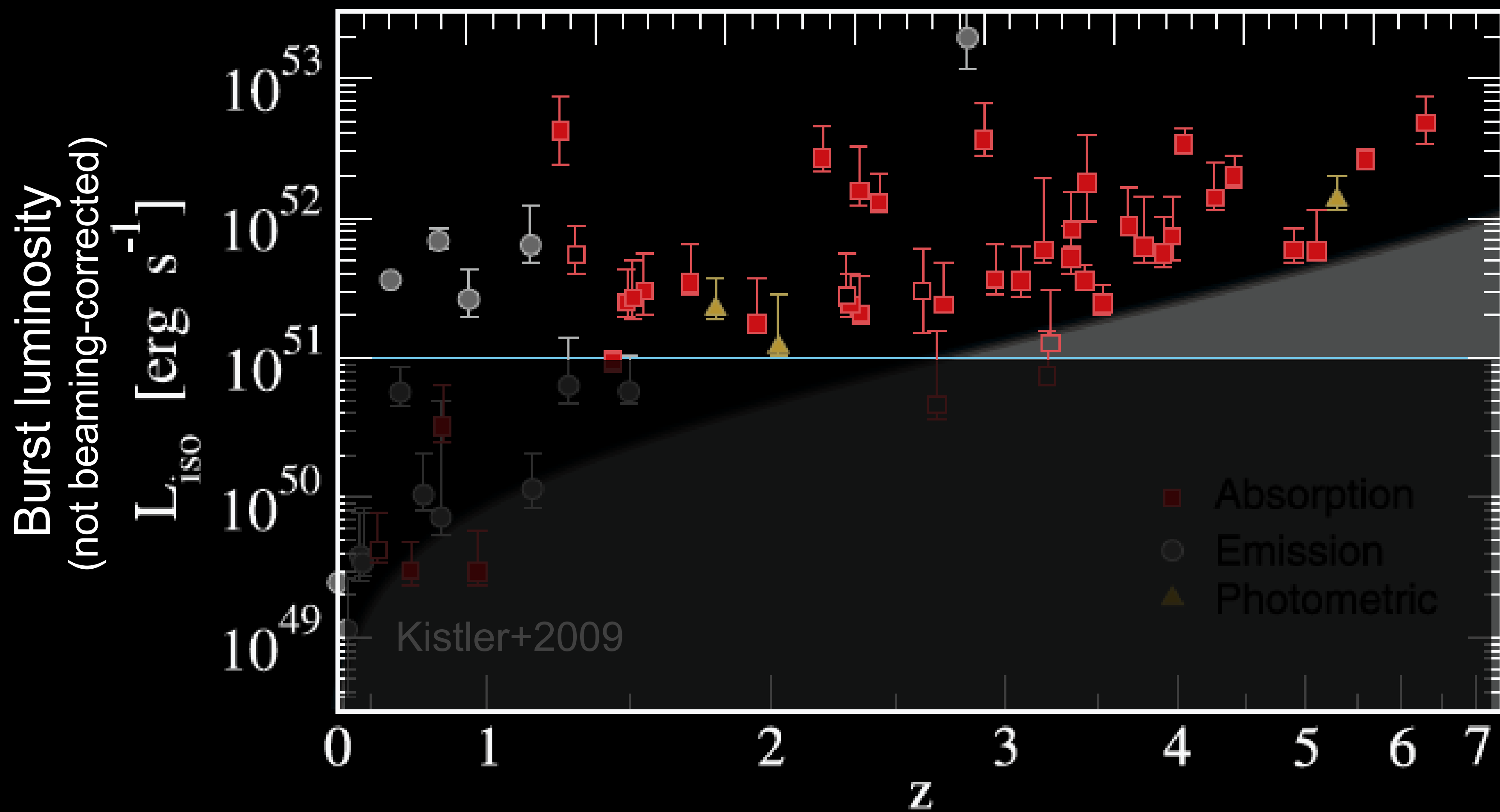
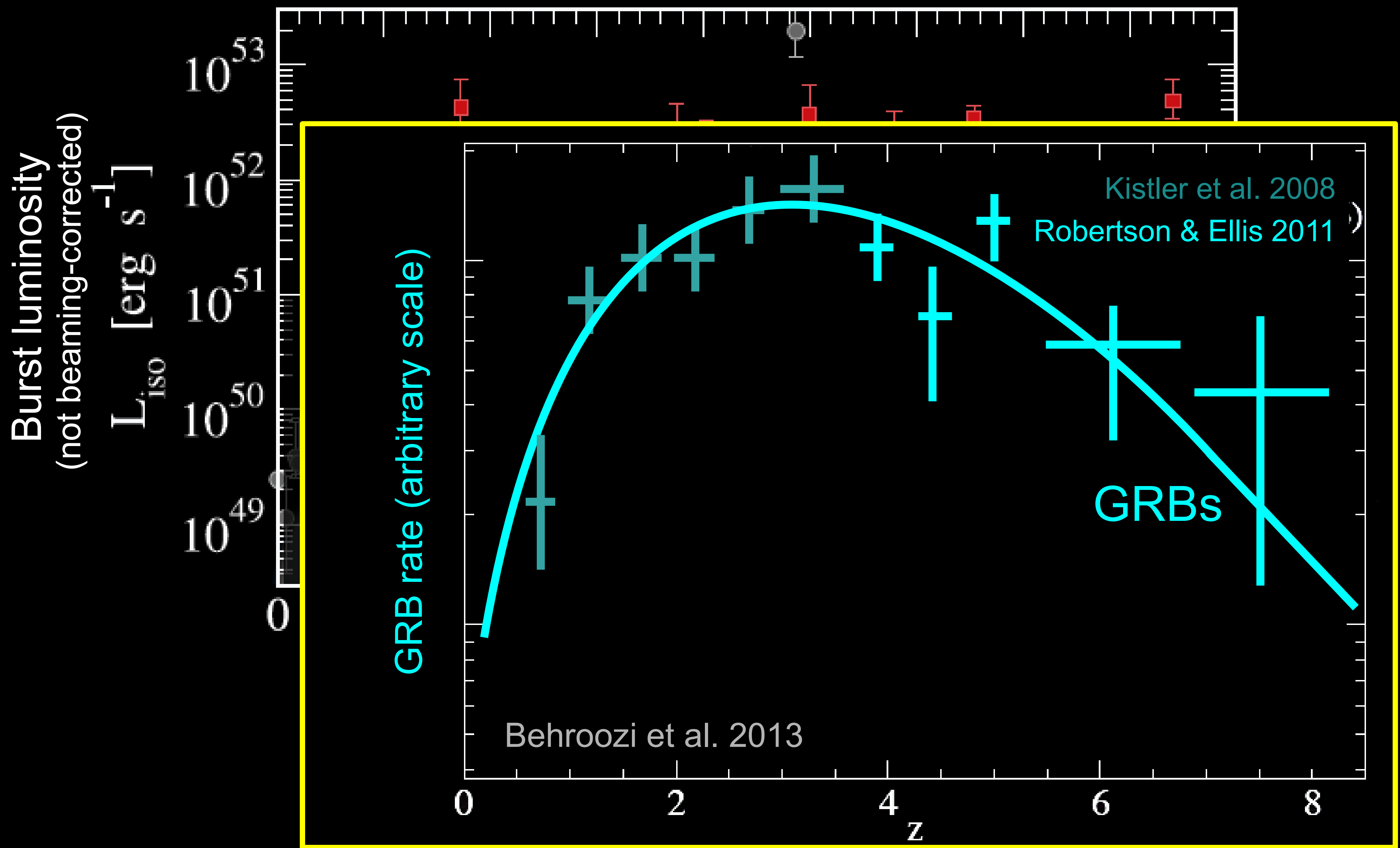
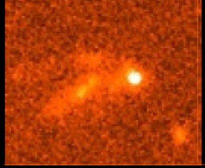
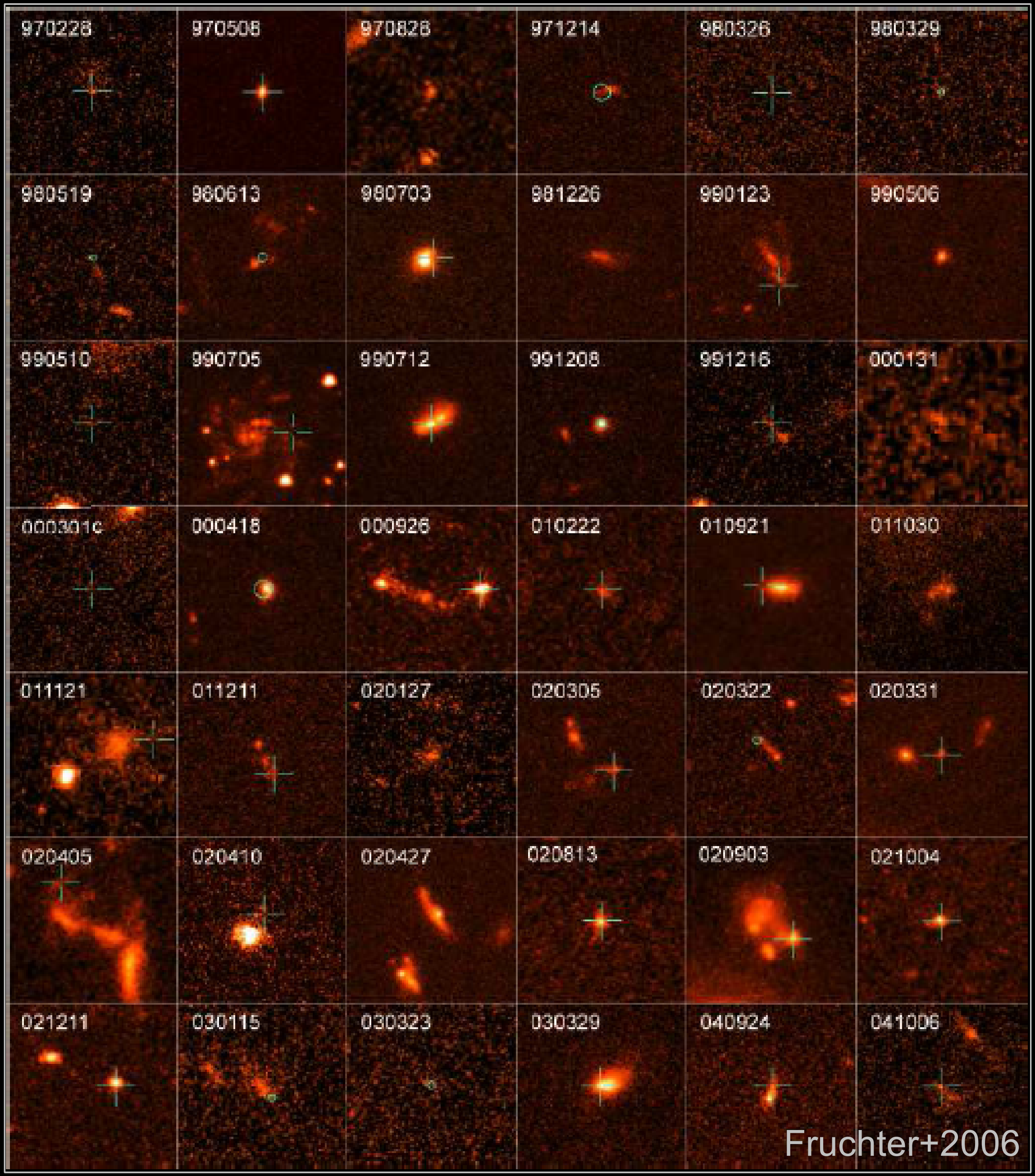


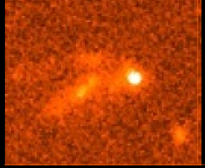
Quantifying Star Formation with GRBs



Quantifying Star Formation with GRBs

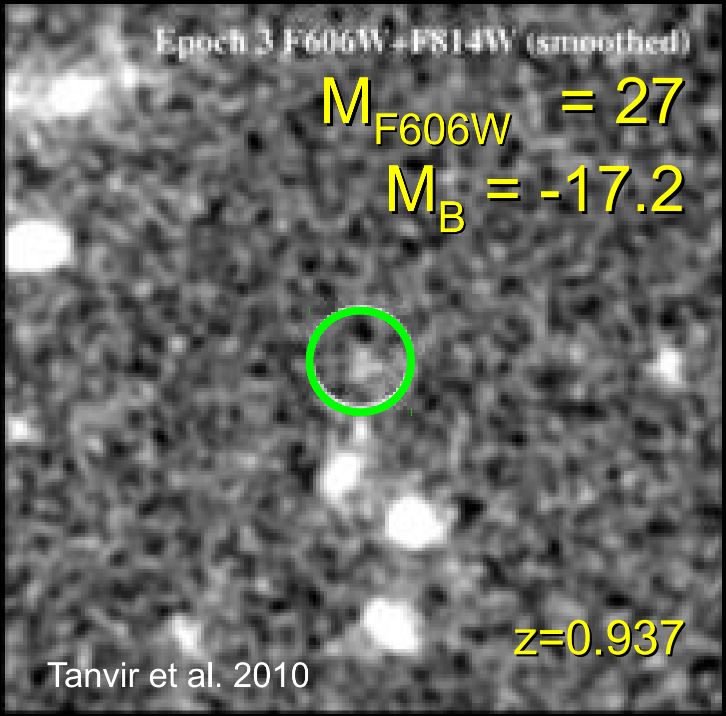




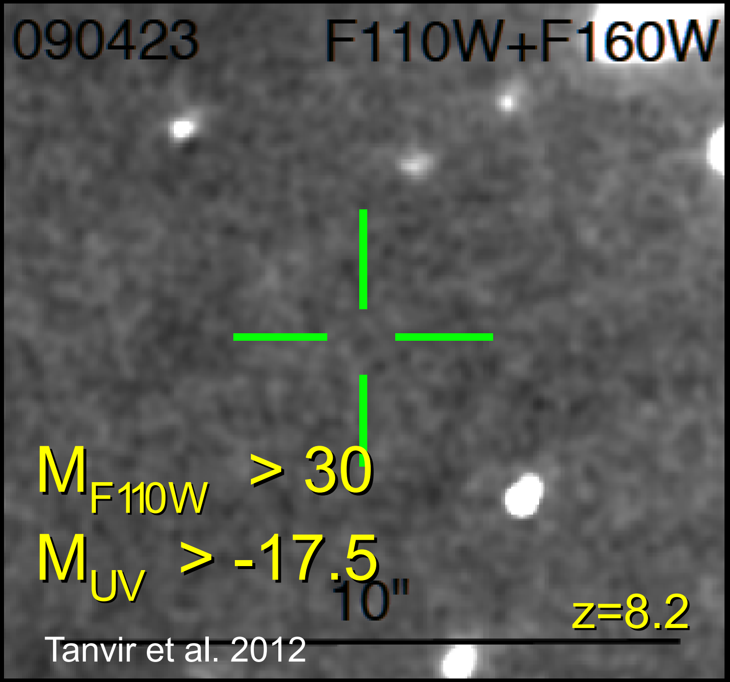


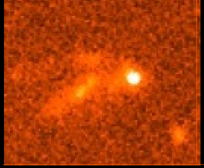
GRBs Can Probe the Faintest Galaxies

A sub-SMC galaxy at z~1

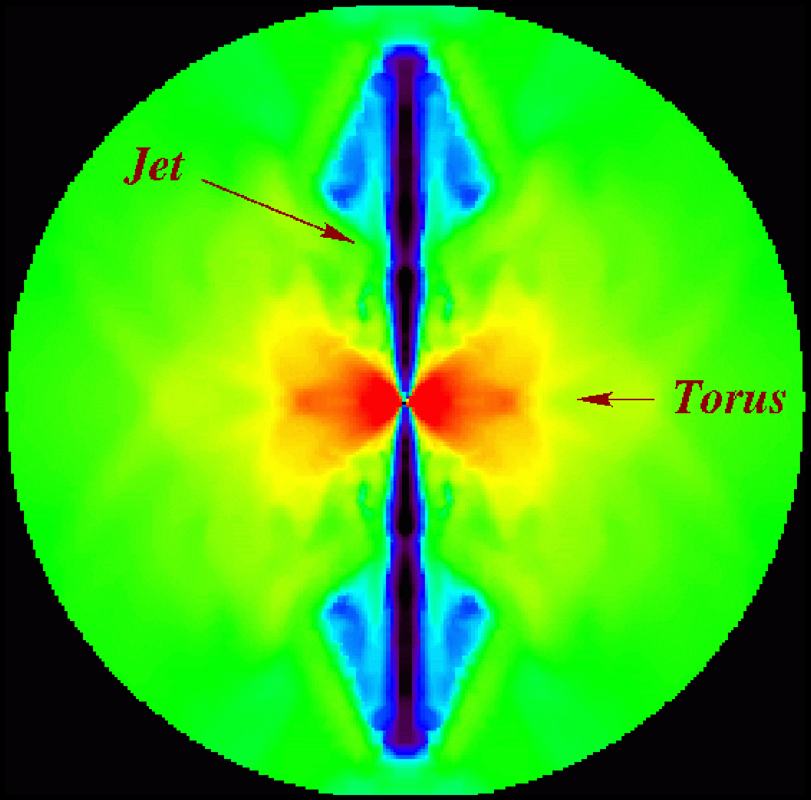


Extremely deep limits on a host at z=8.2





Collapsars: A Nonuniform Tracer?



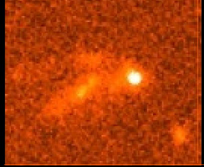
Only one per ~million SNe produces a gamma-ray burst.   The progenitor star must:

- Be very massive (>20 $M_\odot$)

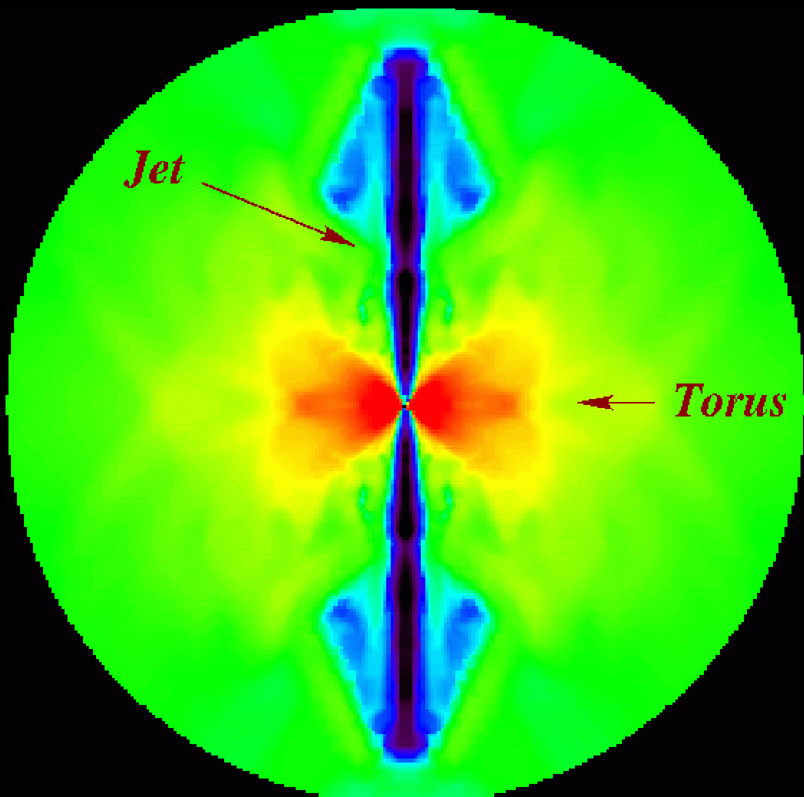
- Expel its hydrogen envelope (or convert it to heavy elements)

- Maintain very rapidly-rotating core (avoid losing ang. momentum)

The likelihood on these conditions may vary with galaxy type and redshift.



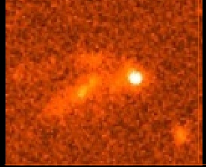
Collapsars: A Nonuniform Tracer?



Only one per ~million SNe produces a gamma-ray burst. The progenitor star must:

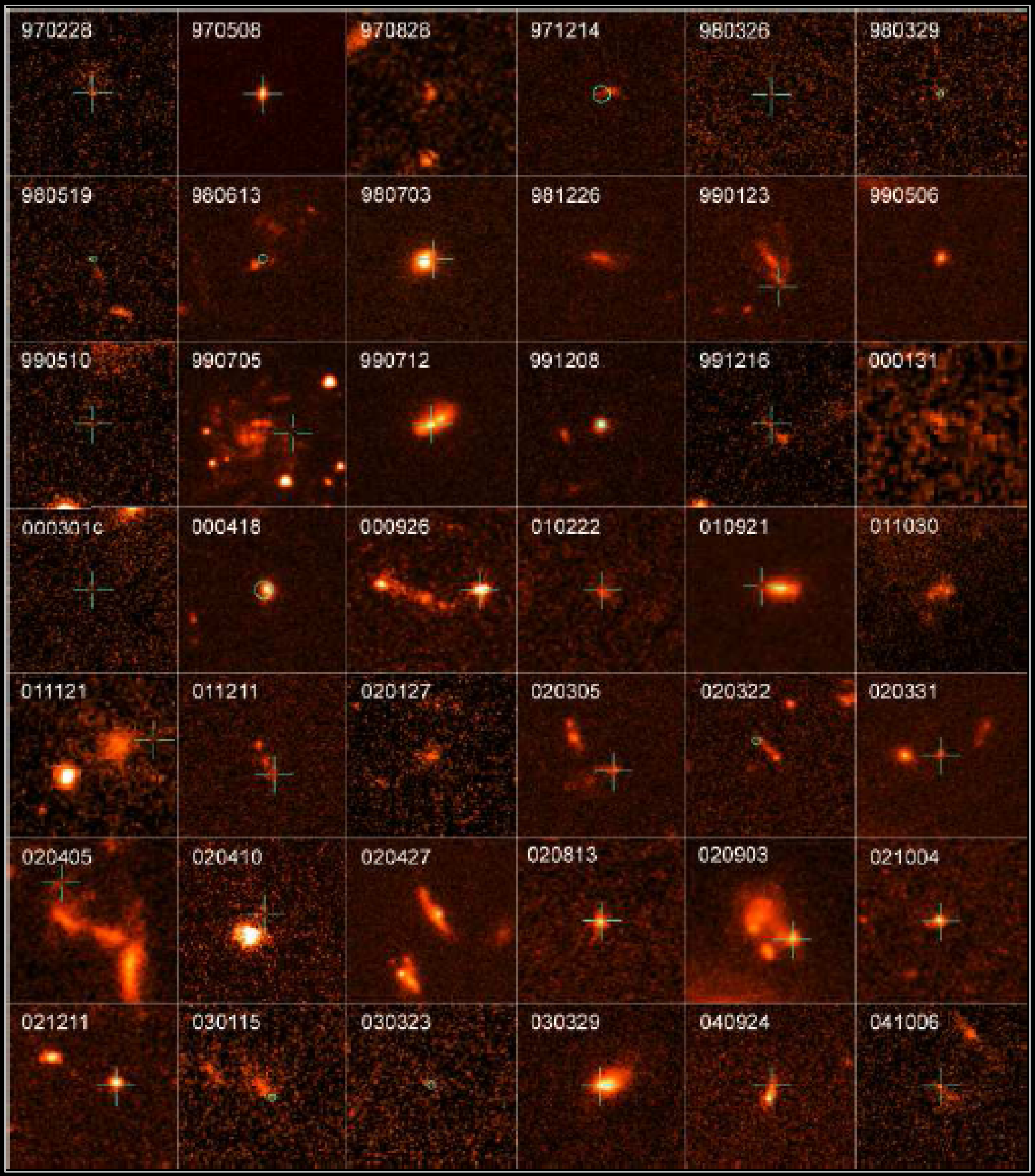
- Be very massive (>20 $M_\odot$)
  → Could depend on IMF?
- Expel its hydrogen envelope (or convert it to heavy elements)
  → Could require high metallicity?
- Maintain very rapidly-rotating core (avoid losing ang. momentum)
  → Could require low metallicity?

The likelihood on these conditions may vary with galaxy type and redshift.

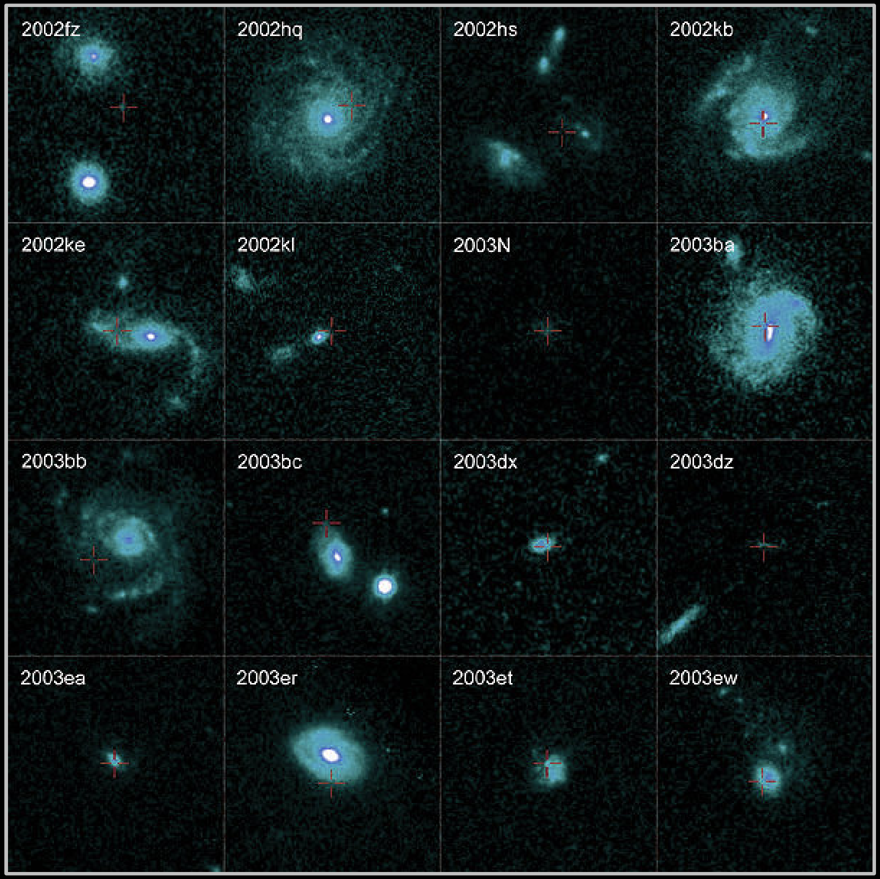


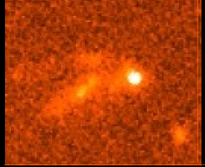
Different Host Morphologies

GRBs

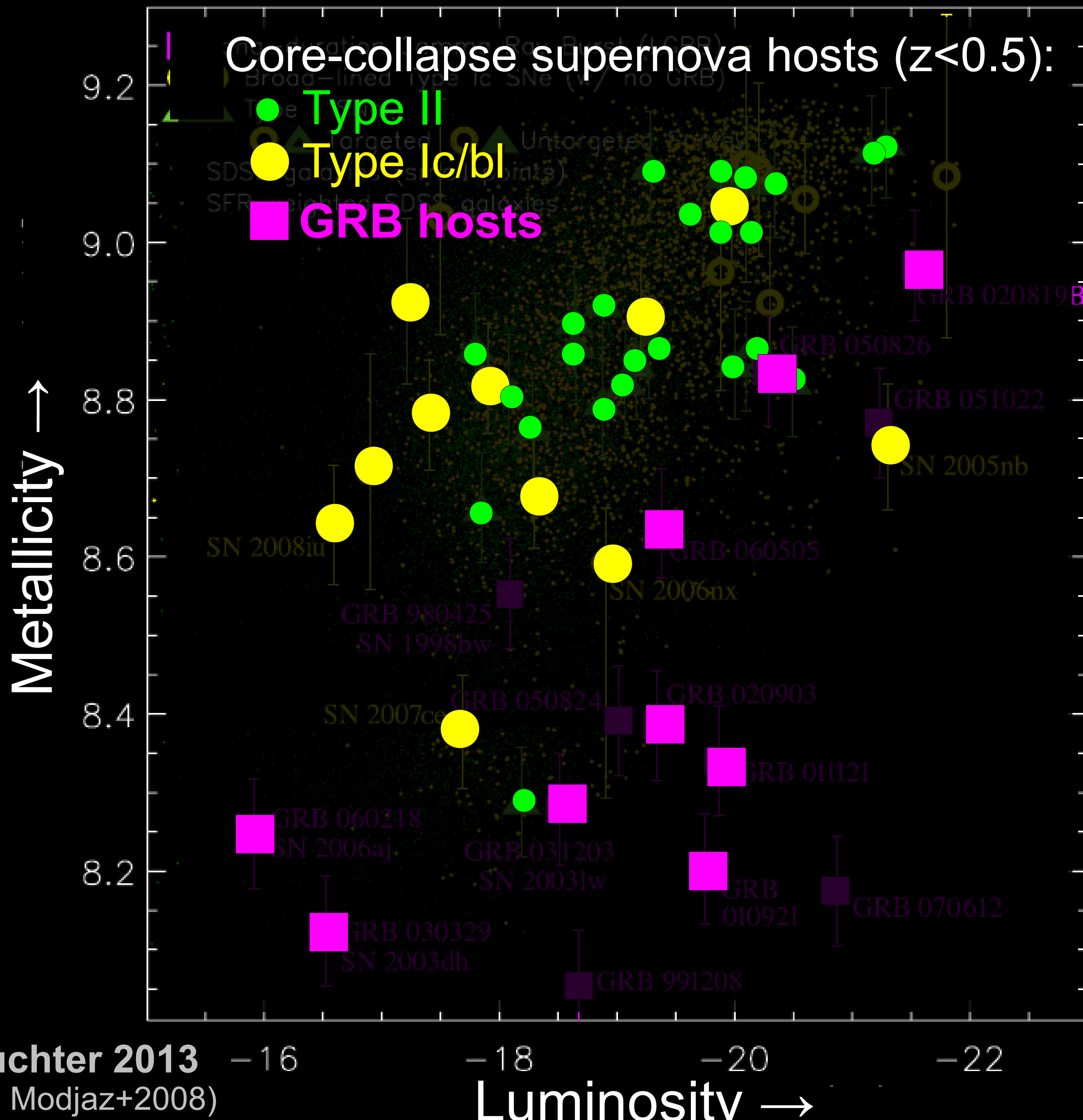


SNe

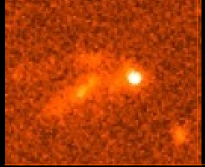




Lower Host Metallicities



Graham & Fruchter 2013
(Levesque+2010, Modjaz+2008)



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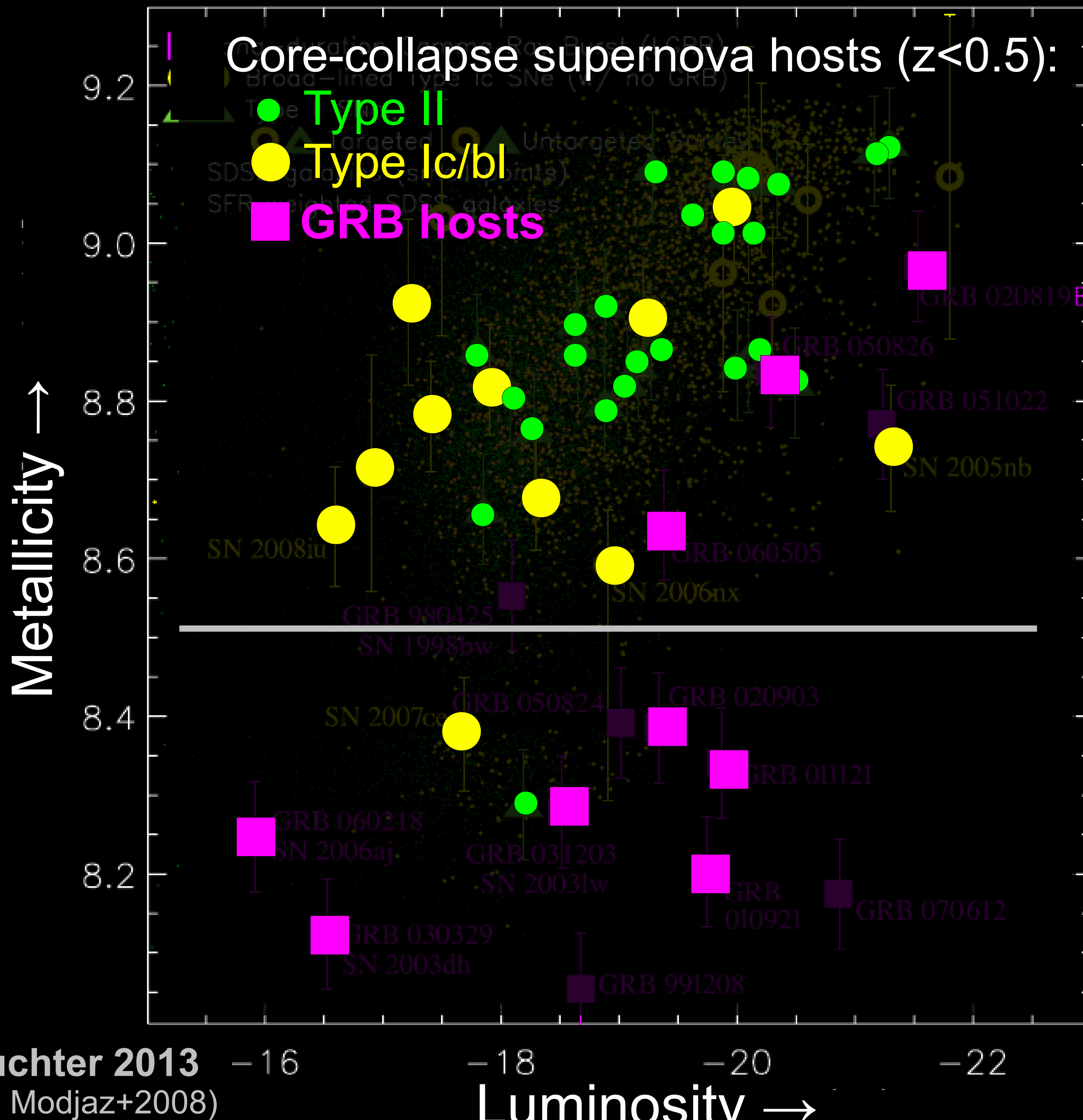
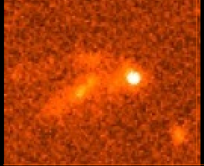


GRBs
rare
(~1 per 10^6 SN)

~0.7 $Z_\odot$

GRBs
"common"
(~1 per 10^5 SN)

Graham & Fruchter 2013
(Levesque+2010, Modjaz+2008)



Limitations of z~0 Comparisons

GRBs seem to prefer metal-poor, low-L galaxies at z~0, which would impact the use of GRBs to trace higher-z SFR. But...

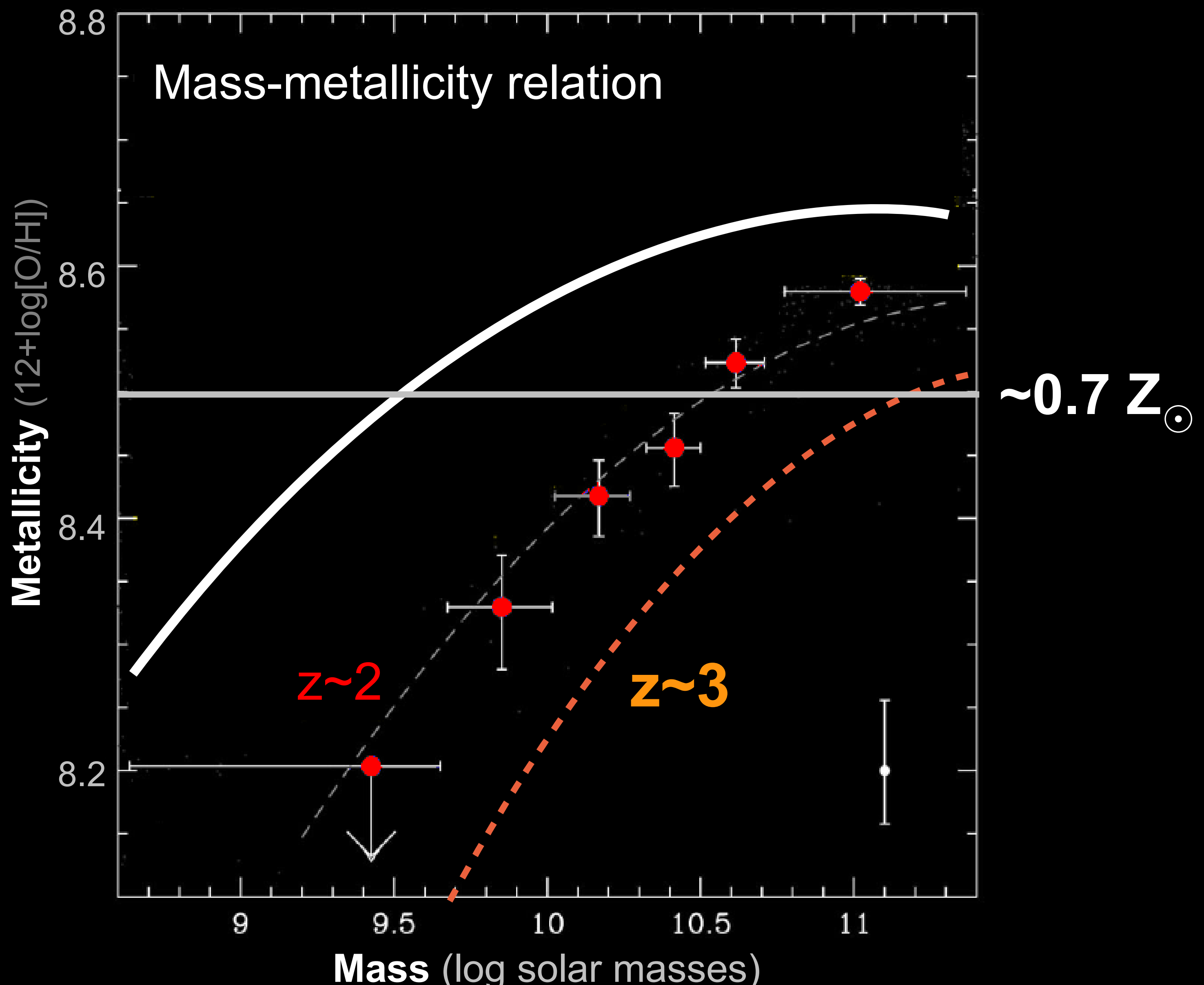
What is actually affecting the GRB rate? Metallicity, or another factor?

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

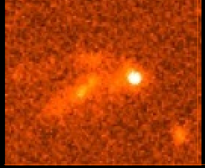
What effect does it actually have at higher redshift?

- Low-z GRBs are not much like high-z GRBs
  (with rare exceptions, orders of magnitude less energetic)
- High-z cosmic environments very different from today
  (higher SFR, lower mass, lower metallicity)

Cosmic Chemical Evolution



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



Objective

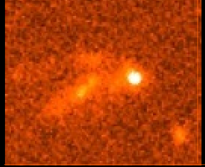
What is the GRB host population like beyond z>0.5, and how does it evolve with cosmic time?

What factors affect the GRB-to-SF rate ratio?

- Metallicity or some other factor (IMF?)
- Sharp transition at ~0.7 $Z_\odot$ or gradual rate dependence?

What can they teach us about early galaxies?

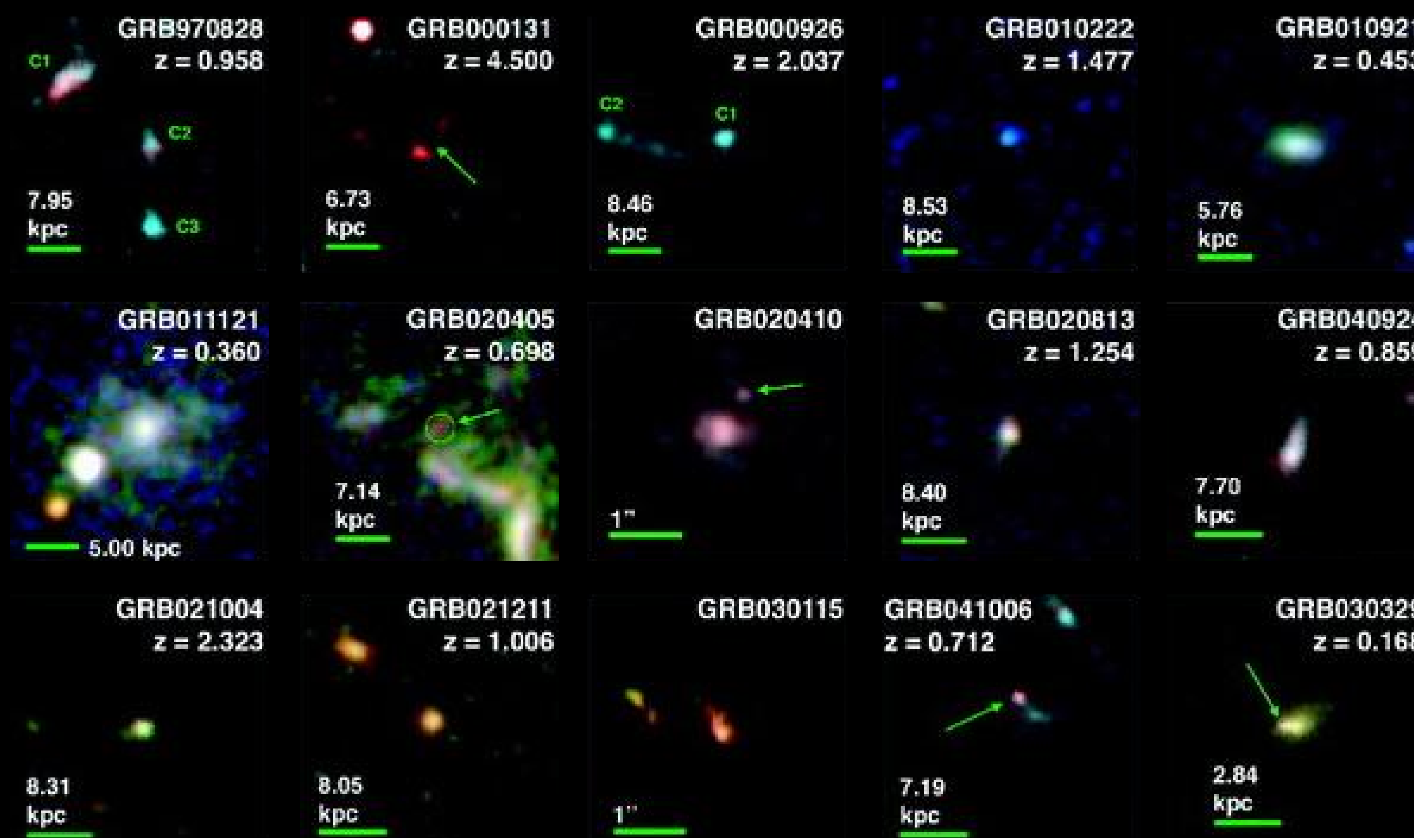
- Cosmic SFR density at very high redshifts
- The abundance and distribution of obscuring dust
- Constraints on the fraction of SFR in undetectable galaxies



Pre-Swift Hosts at z>0.5

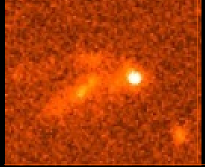
Most published, multi-band host galaxy photometry still originates from pre-*Swift* bursts (1997-2004)

Most at z=0.5-1.5 (satellite sensitivity)

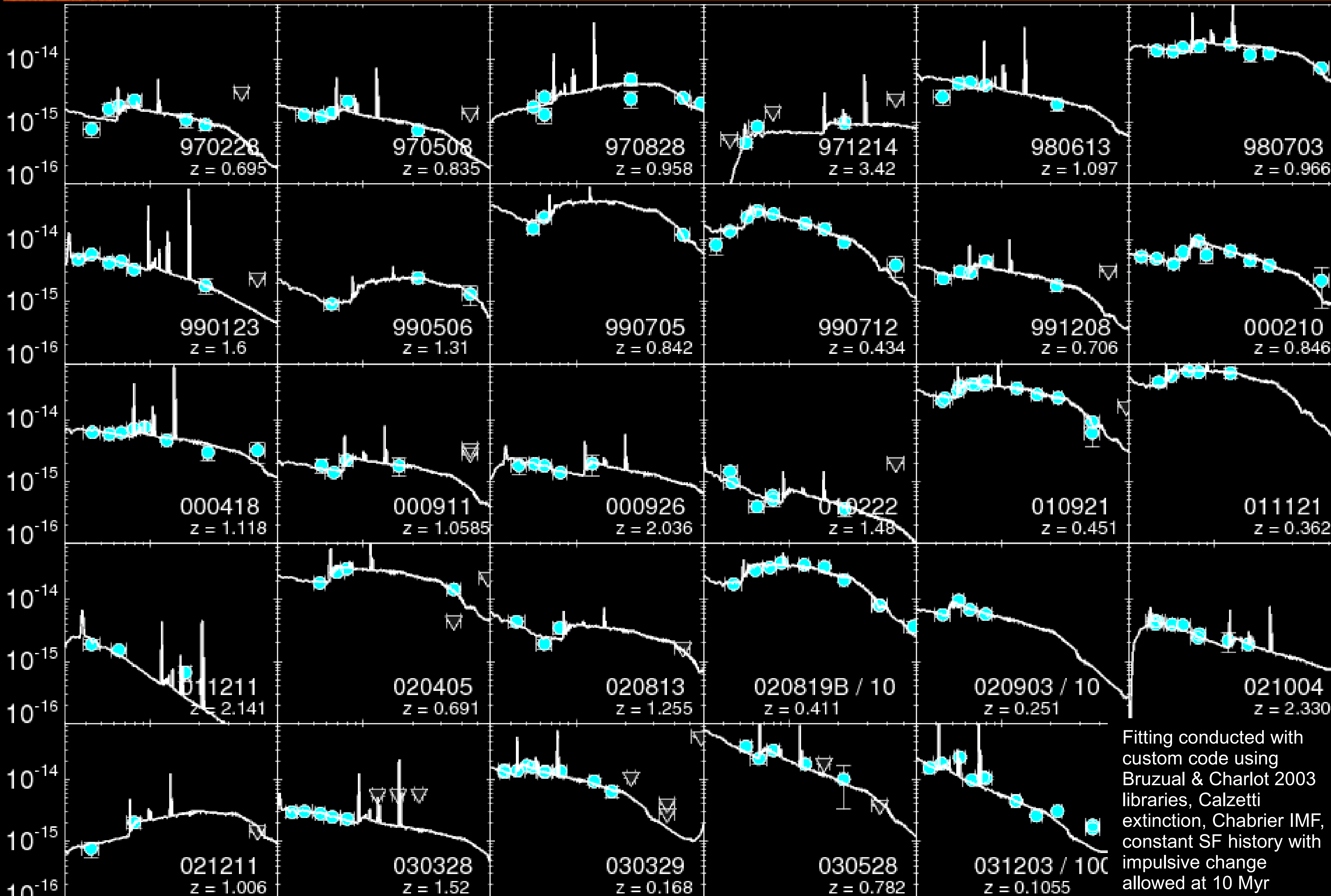


Photometry compiled from numerous sources via online database @ grbhosts.org (Savaglio et al. 2009)

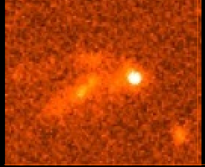
HST images from Wainwright et al. 2007



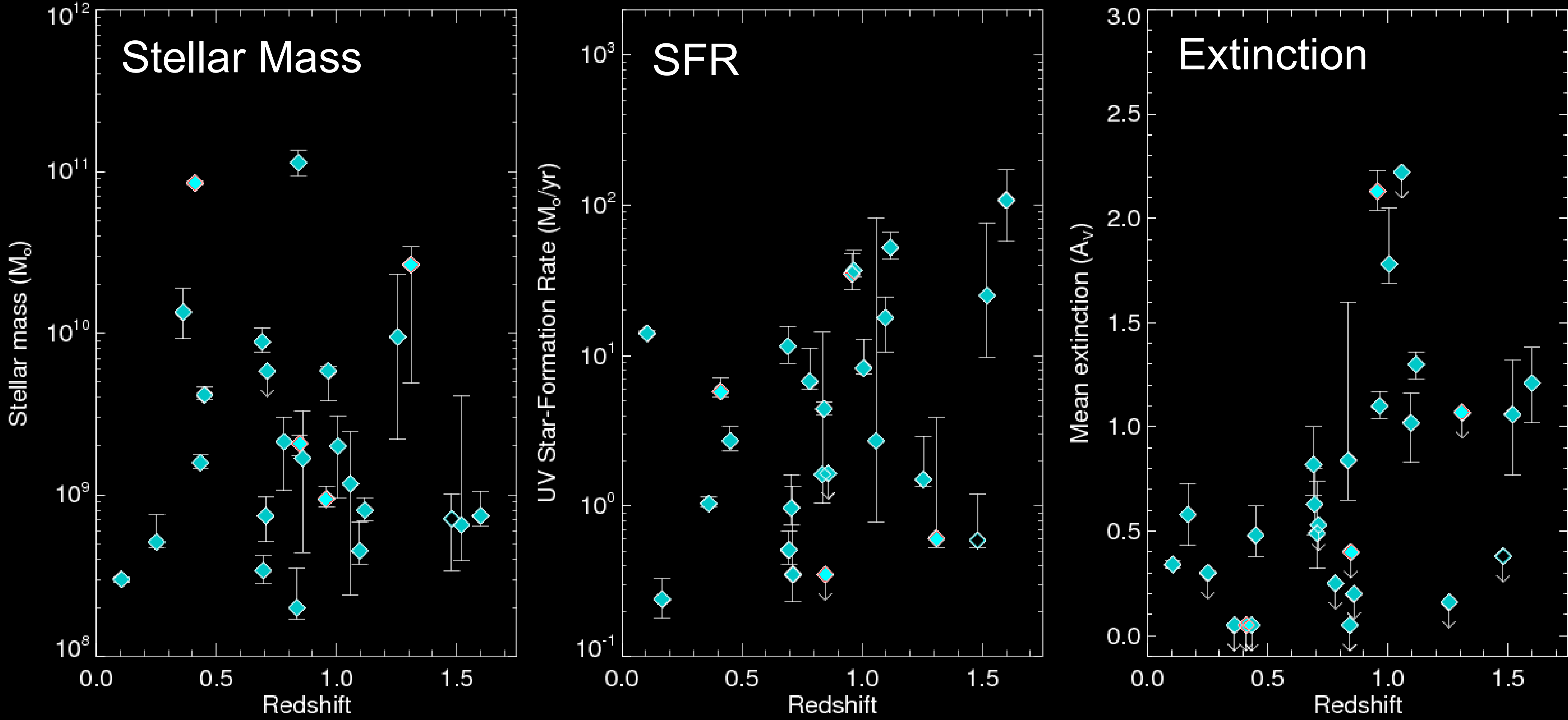
Pre-Swift Hosts at z~1

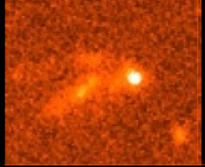


Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr



Pre-Swift GRB Host Properties





Dark GRBs

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

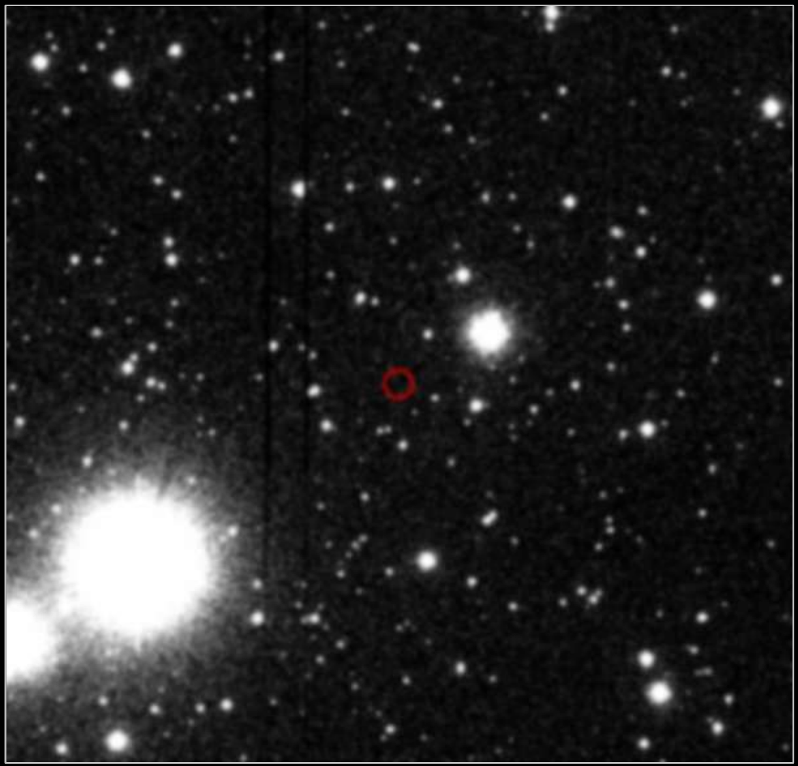
e.g,Groot+1998, Djorgovski+ 2001, Cenko+2009

No optical afterglow,
even with early follow-up.

Most are obscured by dust

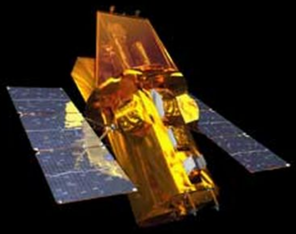
Perley+2009, Greiner+2011

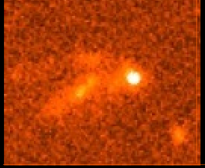
- Can't identify host without X-ray or radio follow-up.
- Can't measure redshift without finding the host (+expensive spectroscopy)



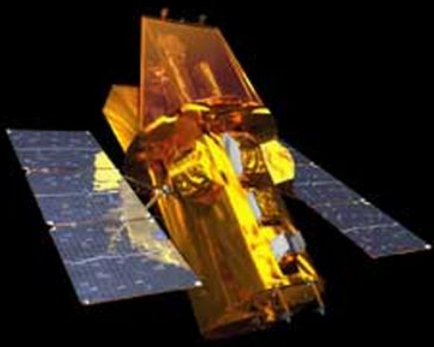
Palomar 60-inch follow-up of GRB 061222A
~10 minutes after burst

Omitting the hosts of dark bursts might have biased previous samples.
With *Swift*, we can now find and include them.





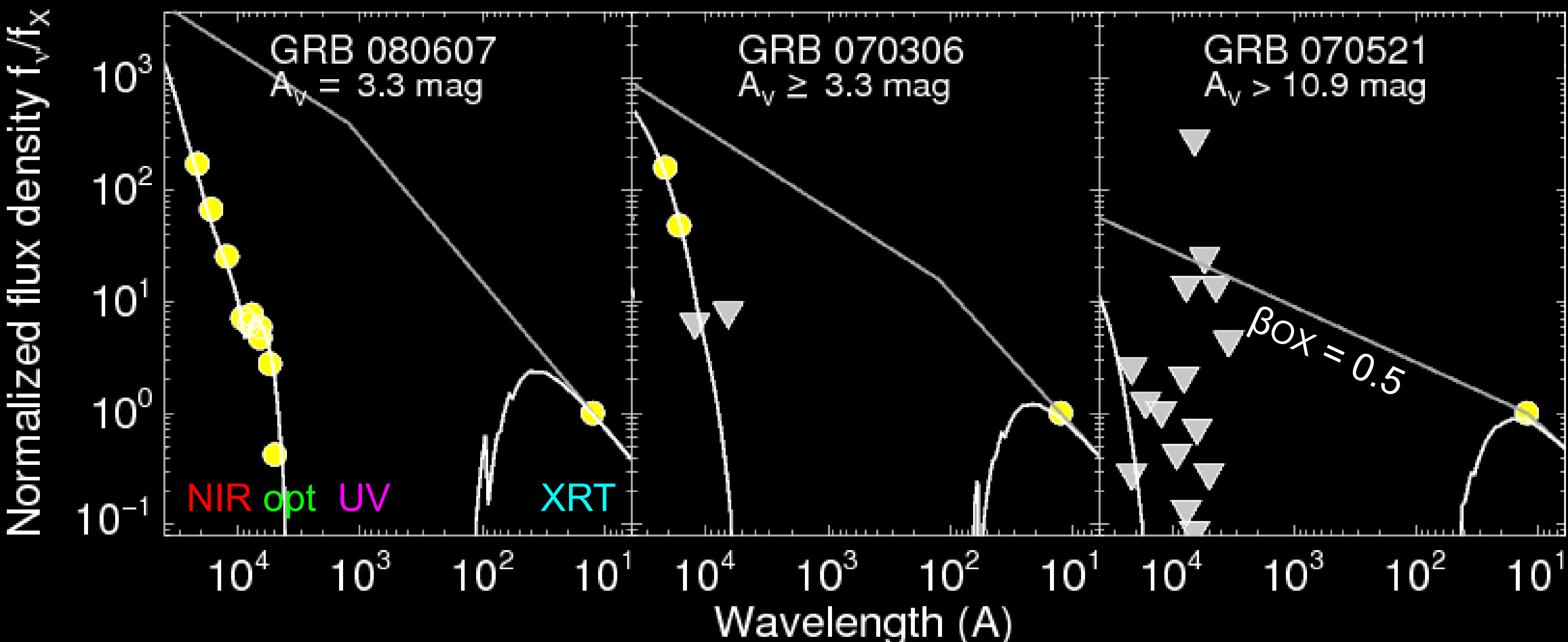
Selecting a Dusty-GRB Host Sample

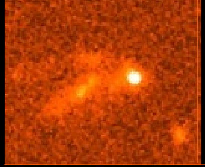


Selection: *Every* Swift-era burst with clear indication of Av > 1 mag

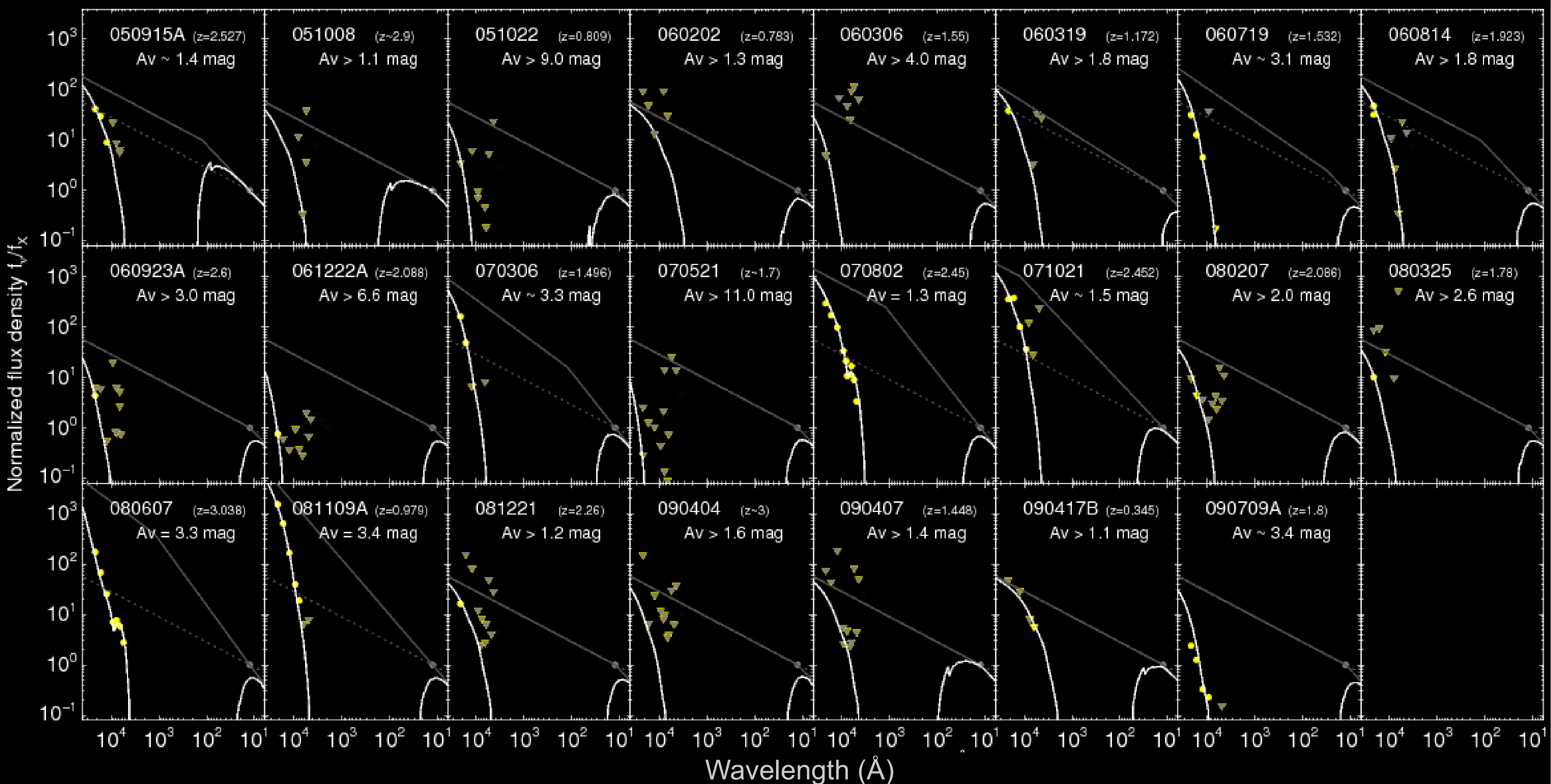
Compile all optical data, download all XRT data, construct co-eval SED, fit dust extinction...

Afterglow SEDs:



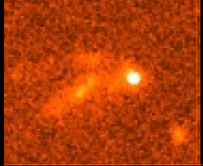


Selecting a Dusty-GRB Host Sample



23 events from 2005-2009

2 with optical afterglow redshift



Observing a Dusty-GRB Host Sample

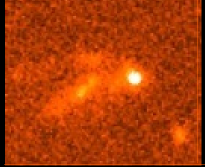
Keck: Optical photometry & UV star-formation rates.
Photometric & spectroscopic redshifts.

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

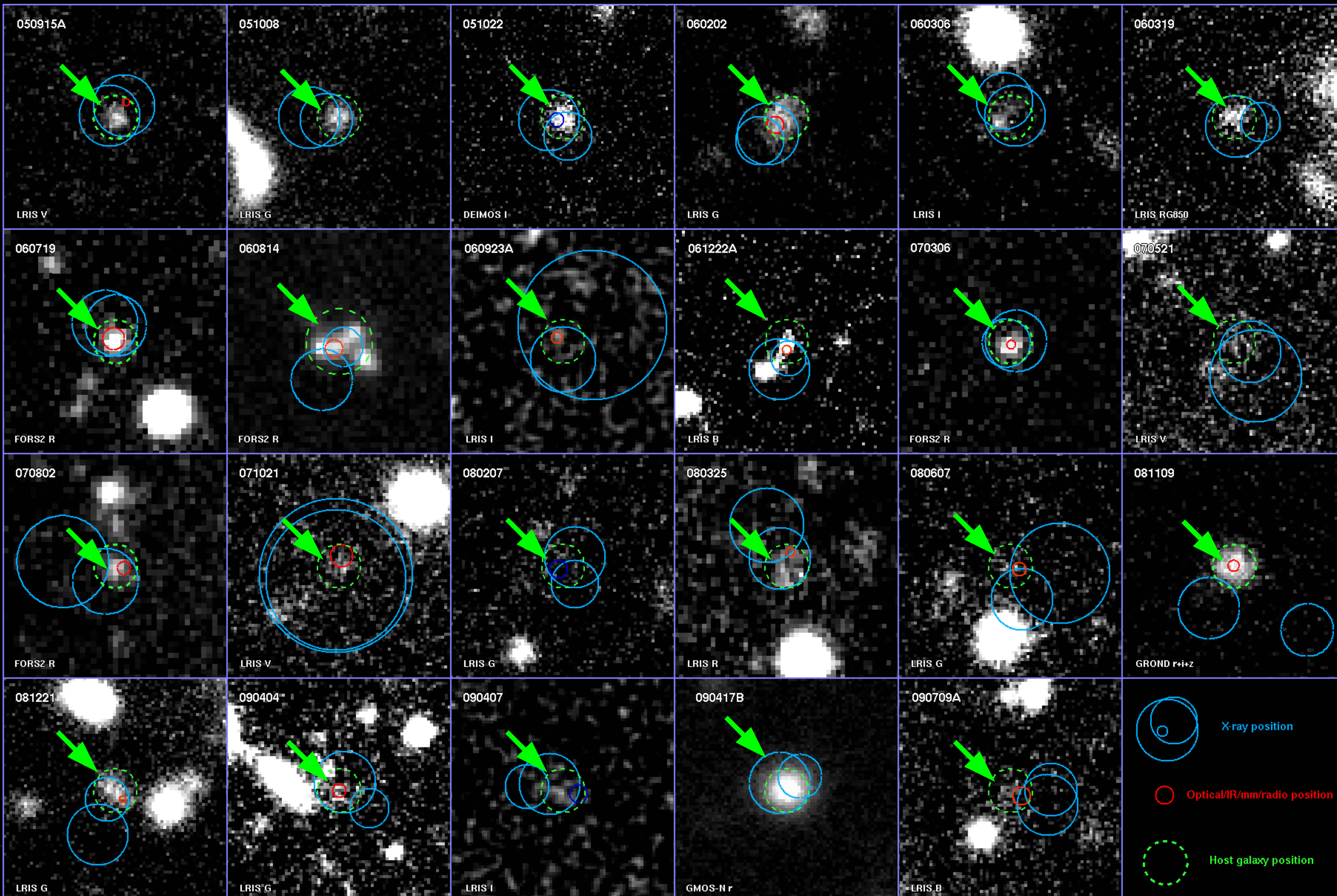
Spitzer: Rest-frame NIR photometry for stellar masses.

HST: NIR photometry, especially of faint targets.

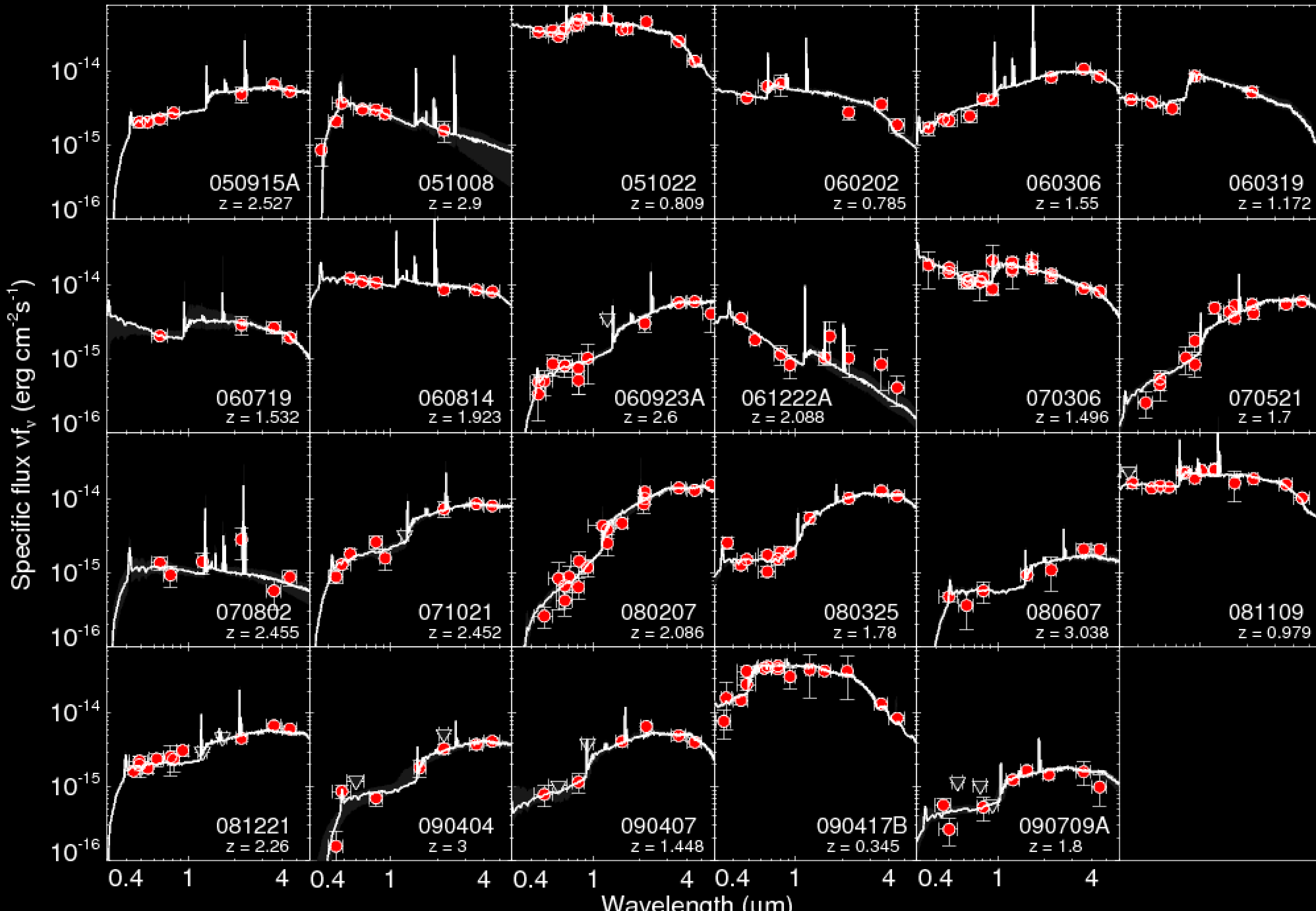
VLT: R- and K-band photometry, spectroscopic redshifts



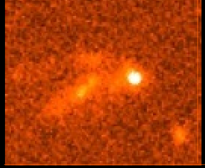
Finding Dark GRB Hosts



SED Fitting



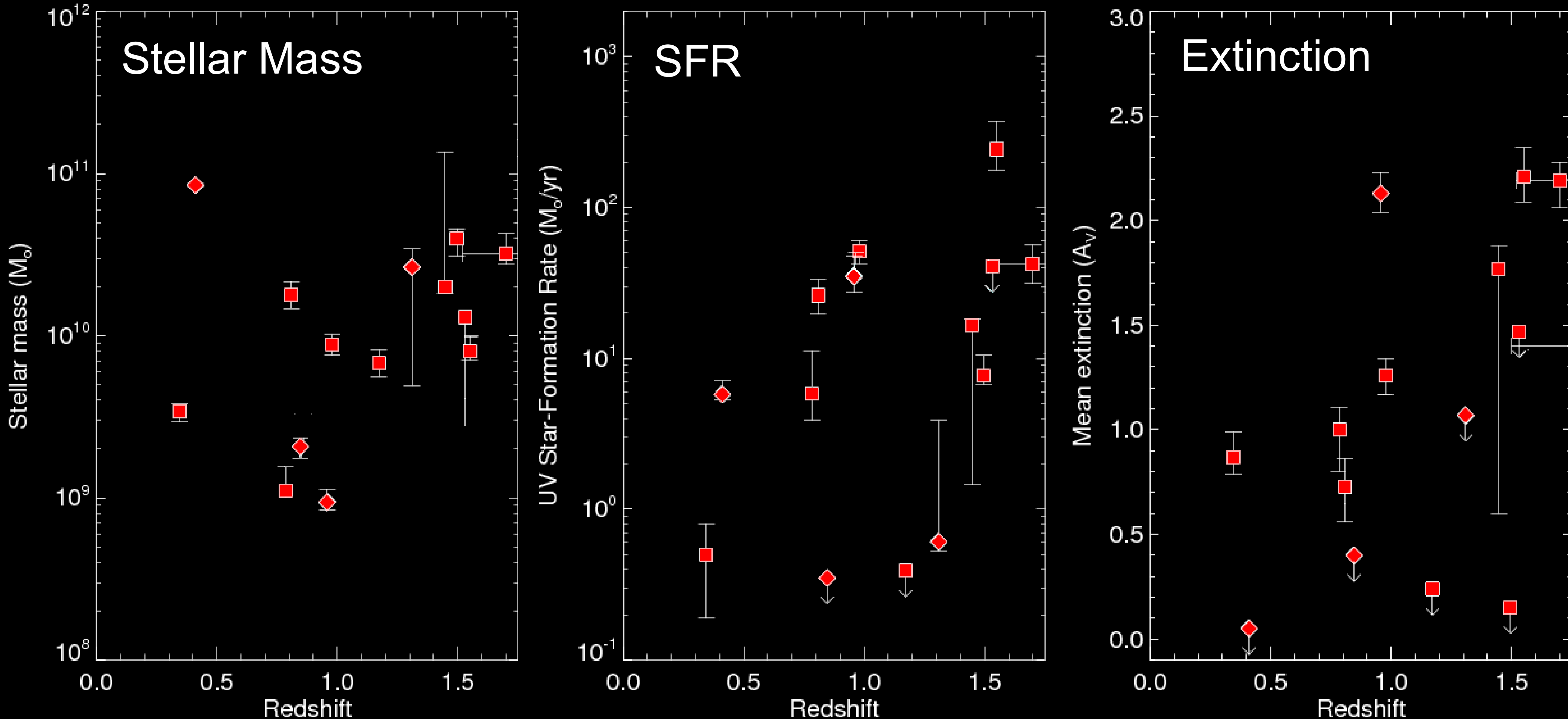
050915A
z = 2.527
051008
z = 2.9
051022
z = 0.809
060202
z = 0.785
060306
z = 1.55
060319
z = 1.172
060719
z = 1.532
060814
z = 1.923
060923A
z = 2.6
061222A
z = 2.088
070306
z = 1.496
070521
z = 1.7
070802
z = 2.455
071021
z = 2.452
080207
z = 2.086
080325
z = 1.78
080607
z = 3.038
081109
z = 0.979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

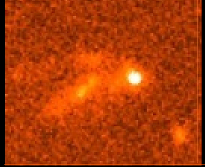


GRB Hosts at z~1

Dark sample (z=0-1.7):

Red = obscured GRB.

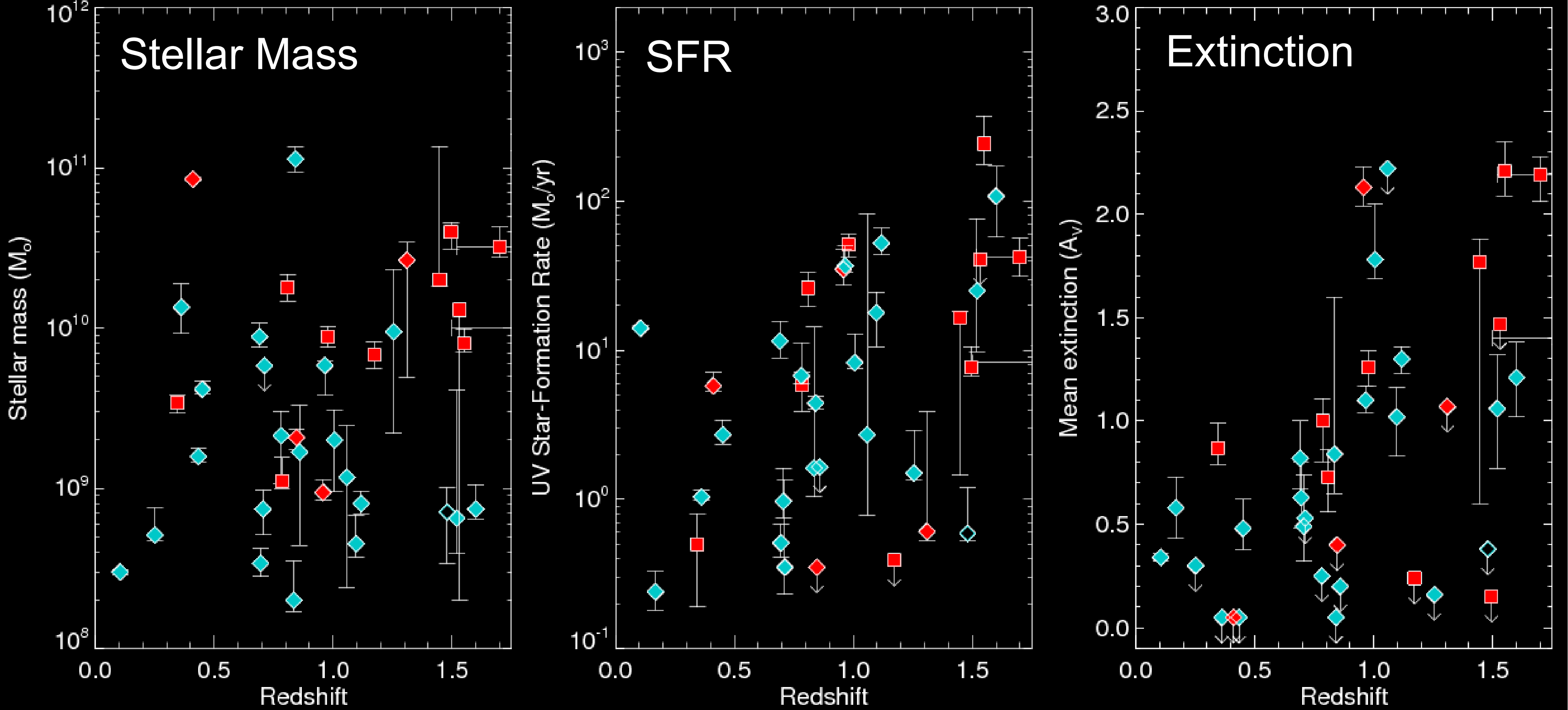


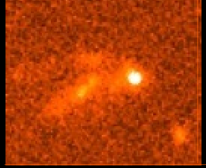


GRB Hosts at z~1

"pseudo-complete", pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.





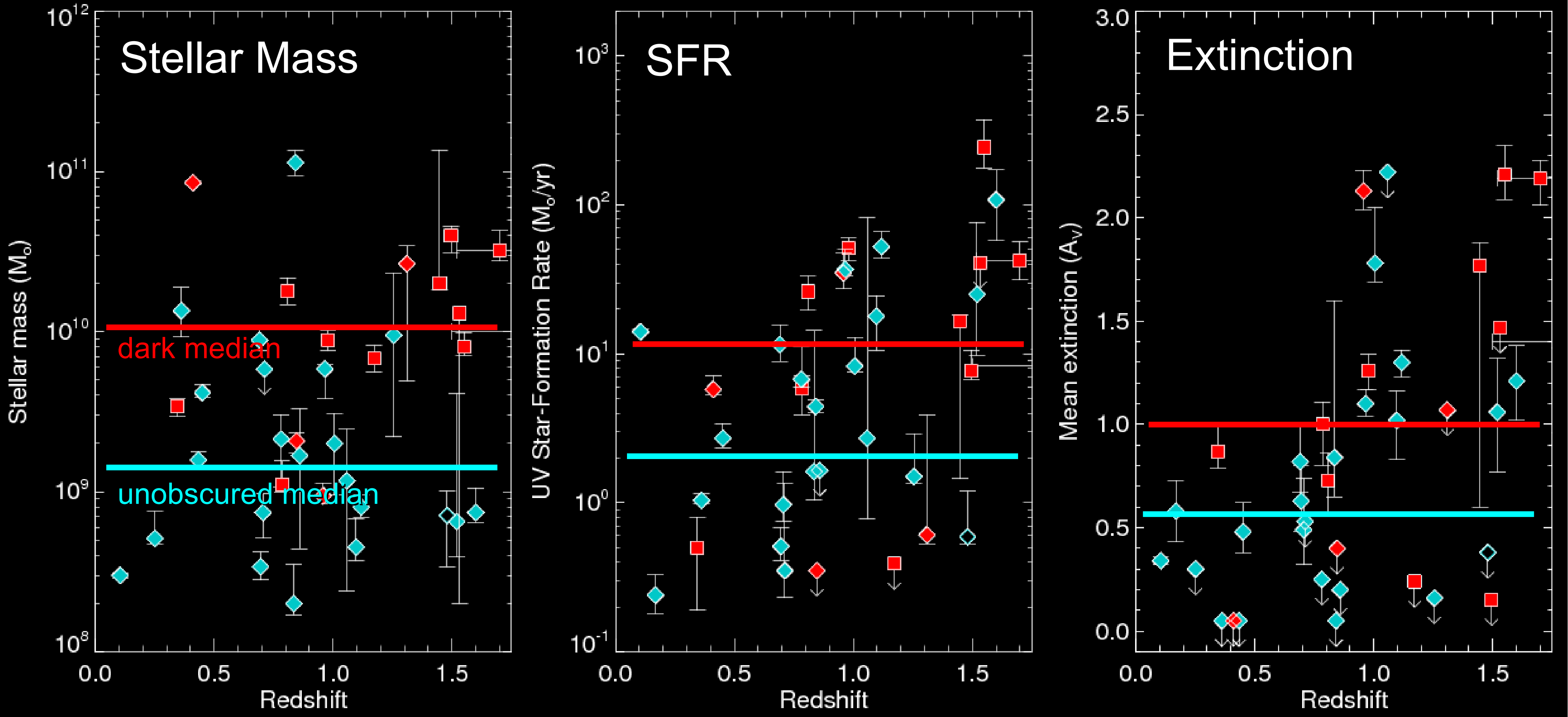
GRB Hosts at z~1

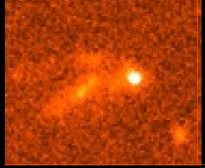
"Darkness" matters.

Obscured GRBs are in more obscured, massive, star-forming hosts.

"pseudo-complete", pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



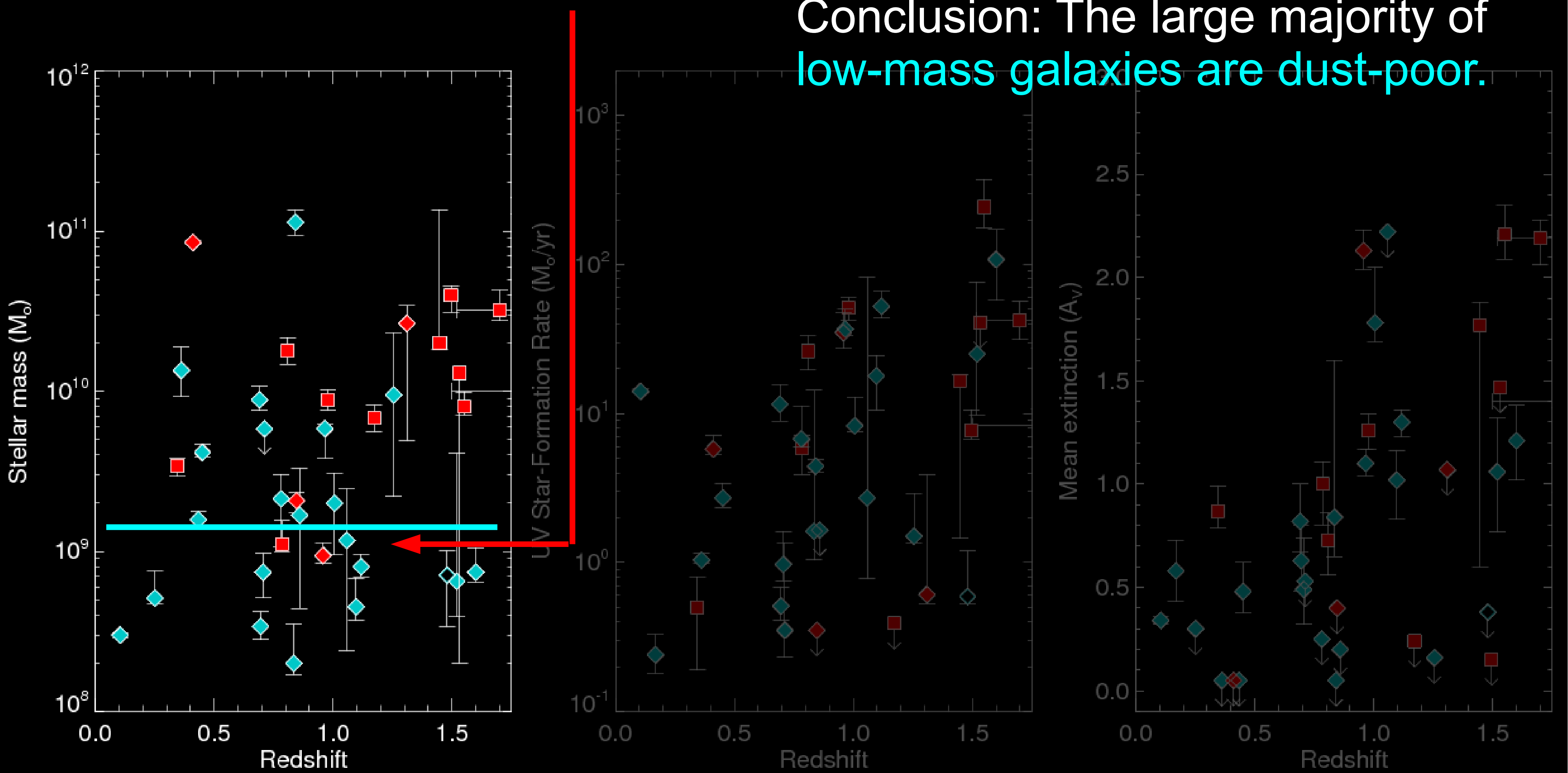


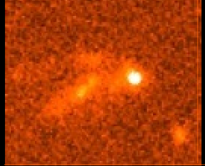
Dust in the Universe

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.

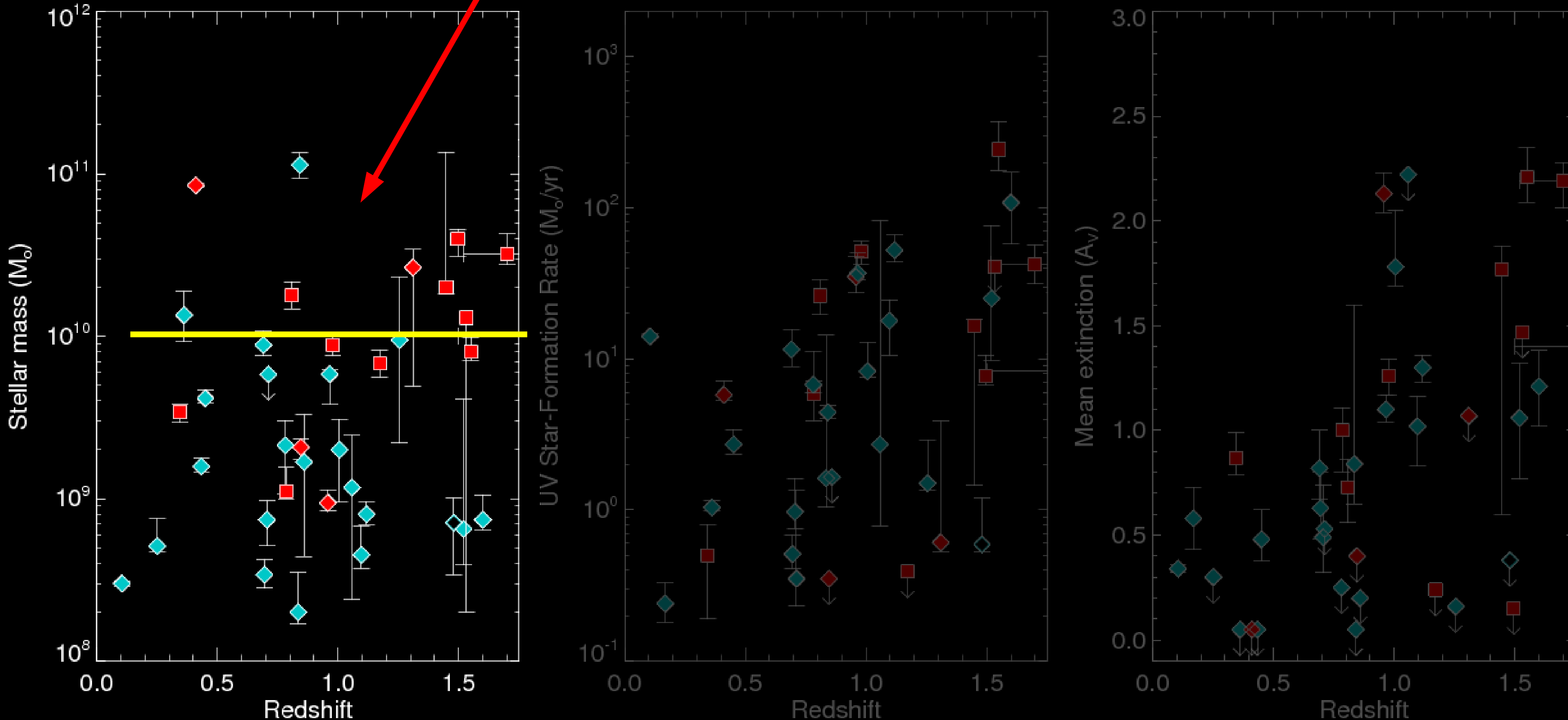




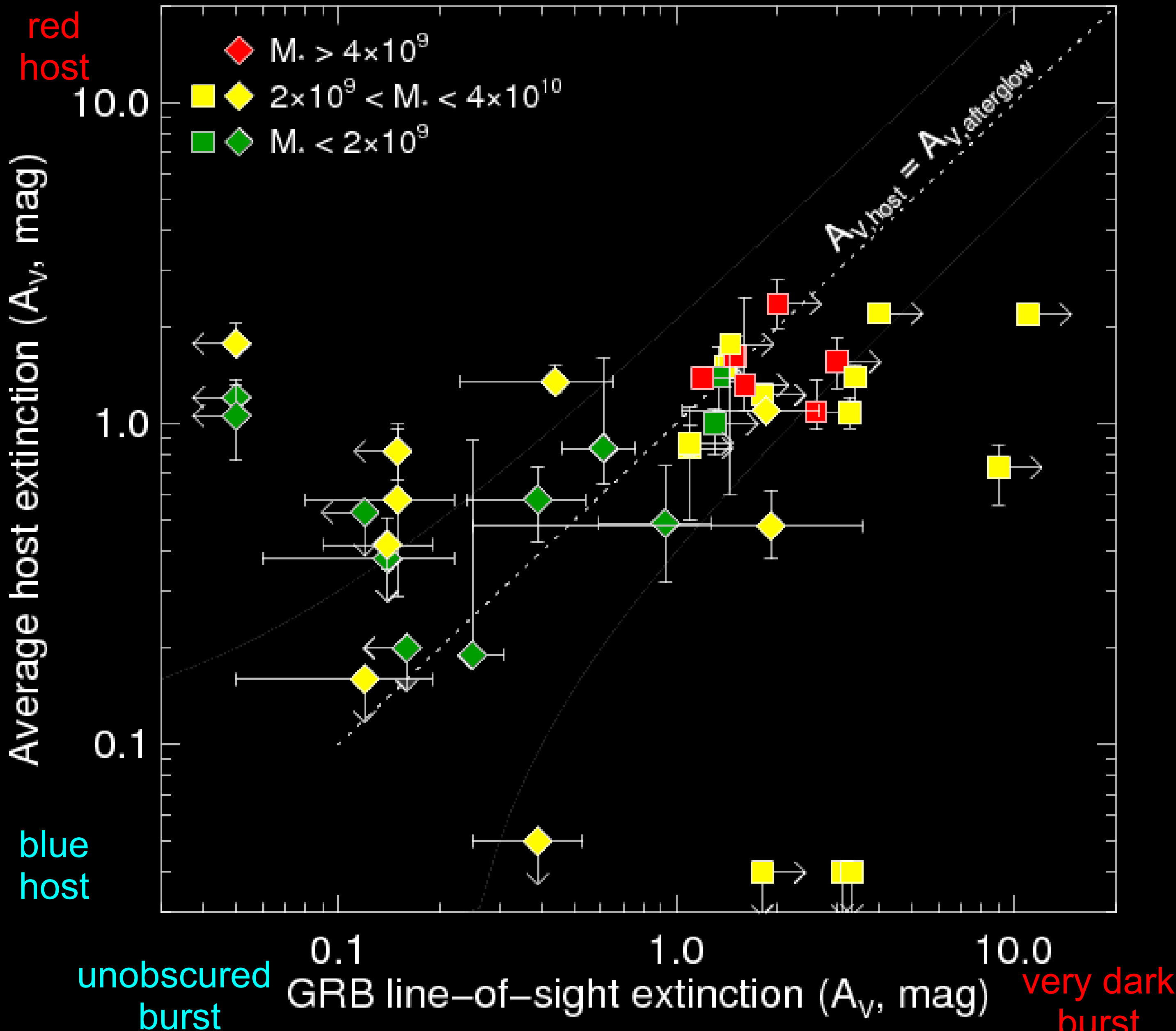
Dust in the Universe

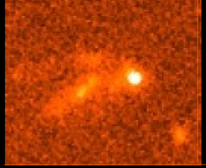
Among GRBs in galaxies **above 10^{10} M_o**,
7 out of 9 are **heavily extinguished**.

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

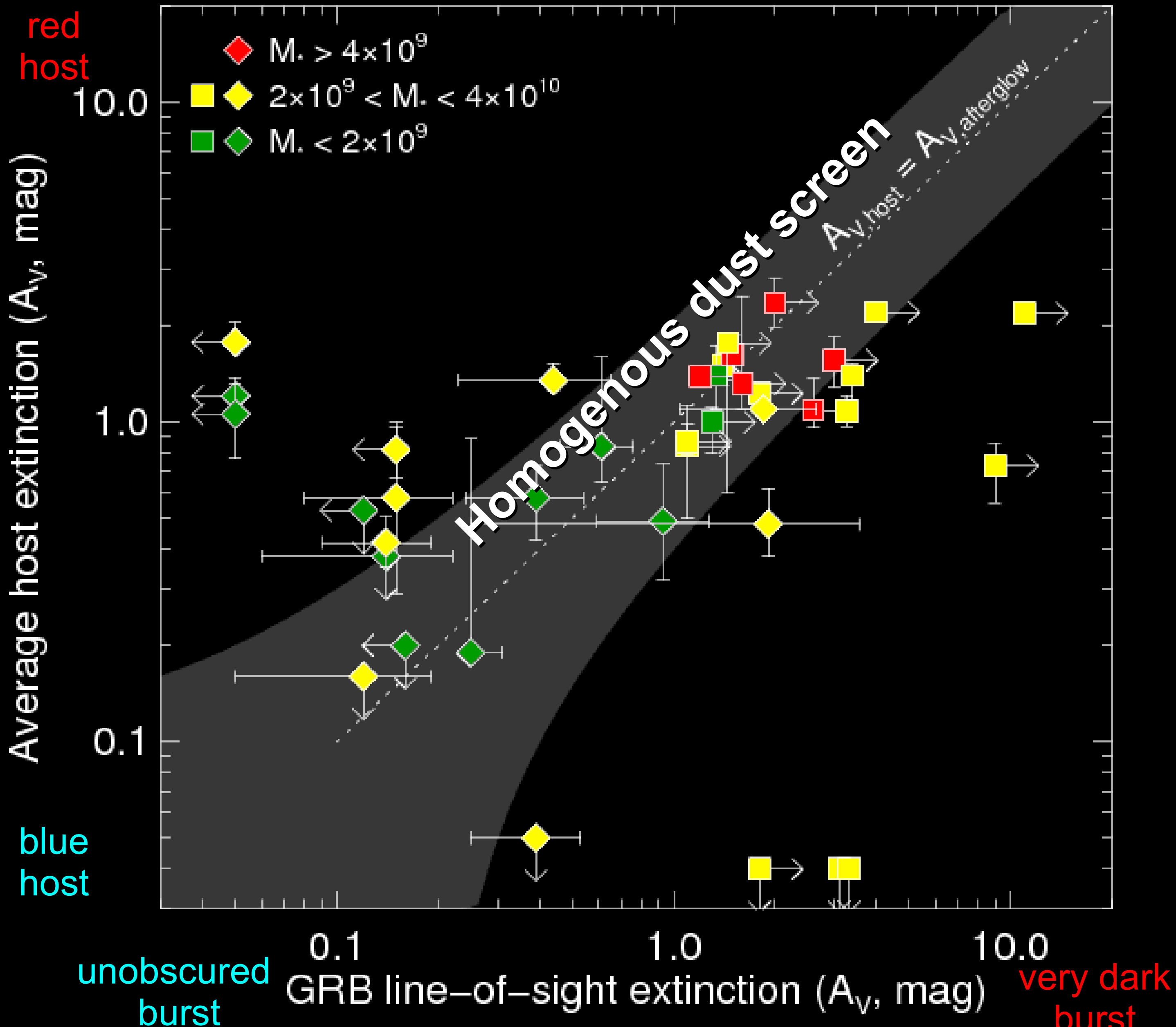


Dust Distribution Within Galaxies



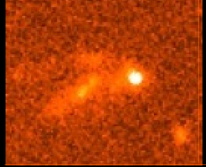


Dust Distribution Within Galaxies

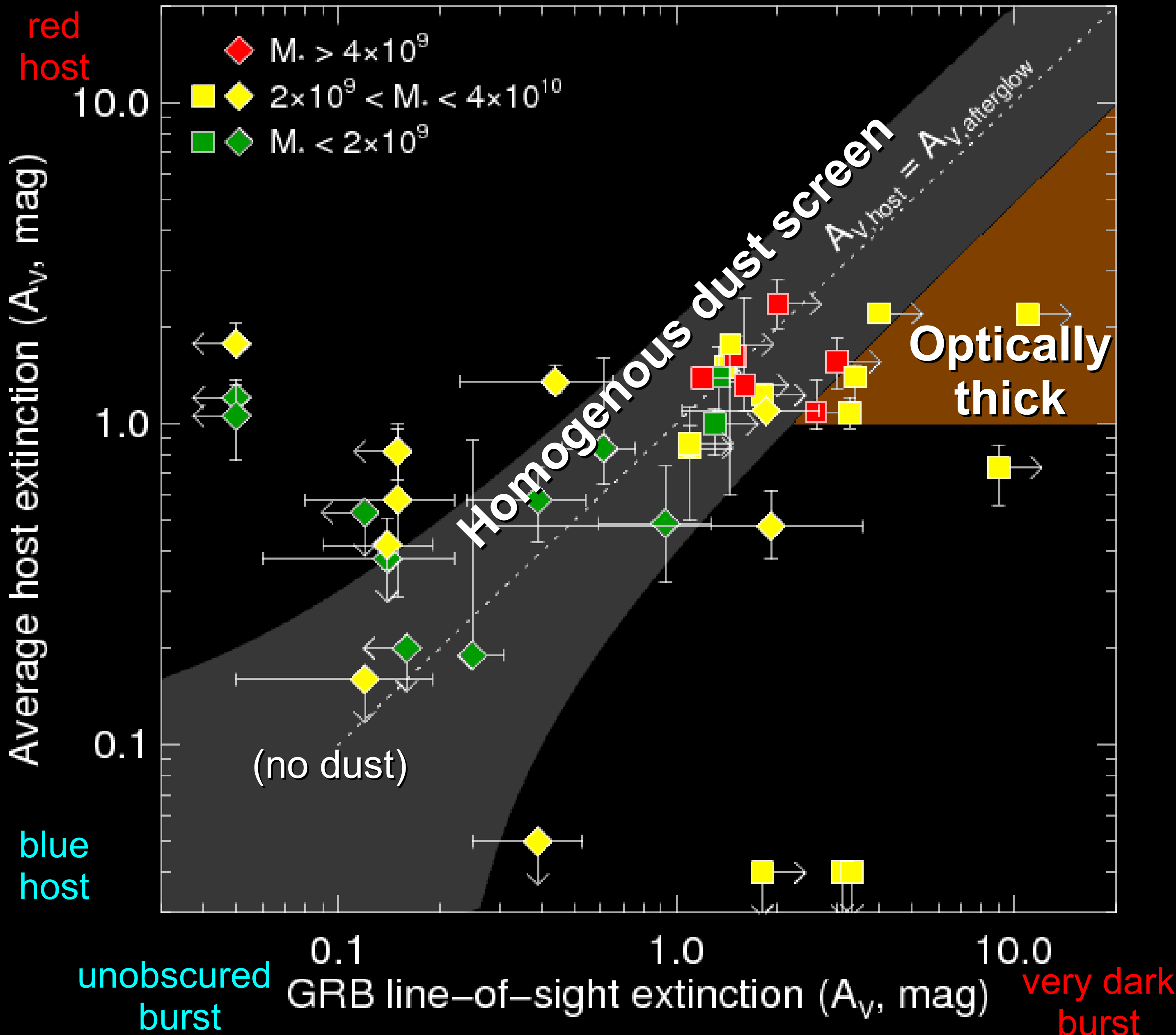


Dusty sightline (usually) implies a dusty, massive galaxy:

High-z galaxies are relatively dust-homogeneous.



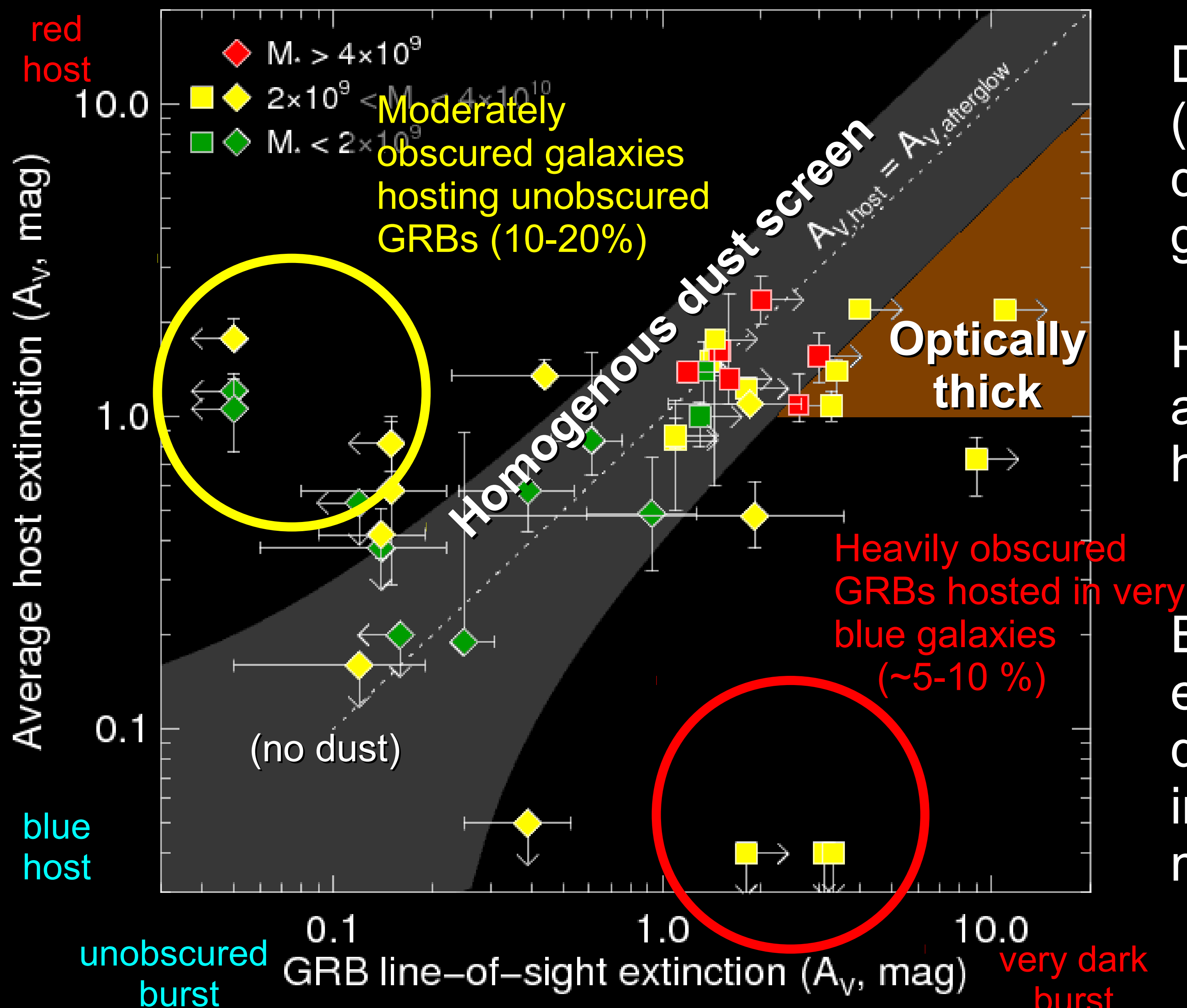
Dust Distribution Within Galaxies



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

High-z galaxies are relatively dust-homogeneous.

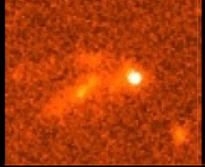
Dust Distribution Within Galaxies



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

High-z galaxies are relatively dust-homogeneous.

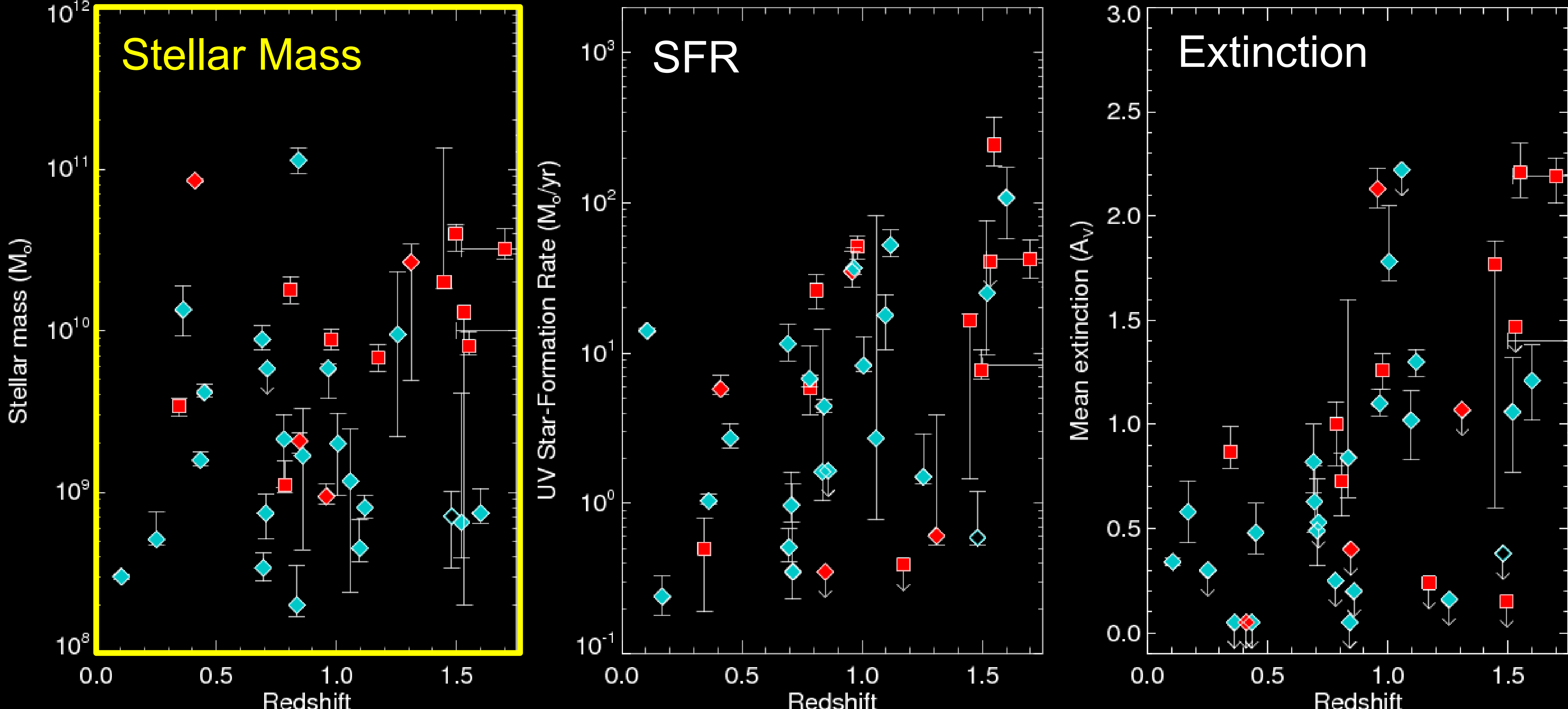
Exceptions do exist in both directions, mostly in intermediate-mass galaxies.

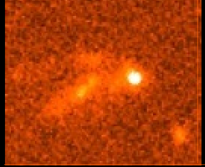


GRB Hosts vs. Field Galaxies at z~1

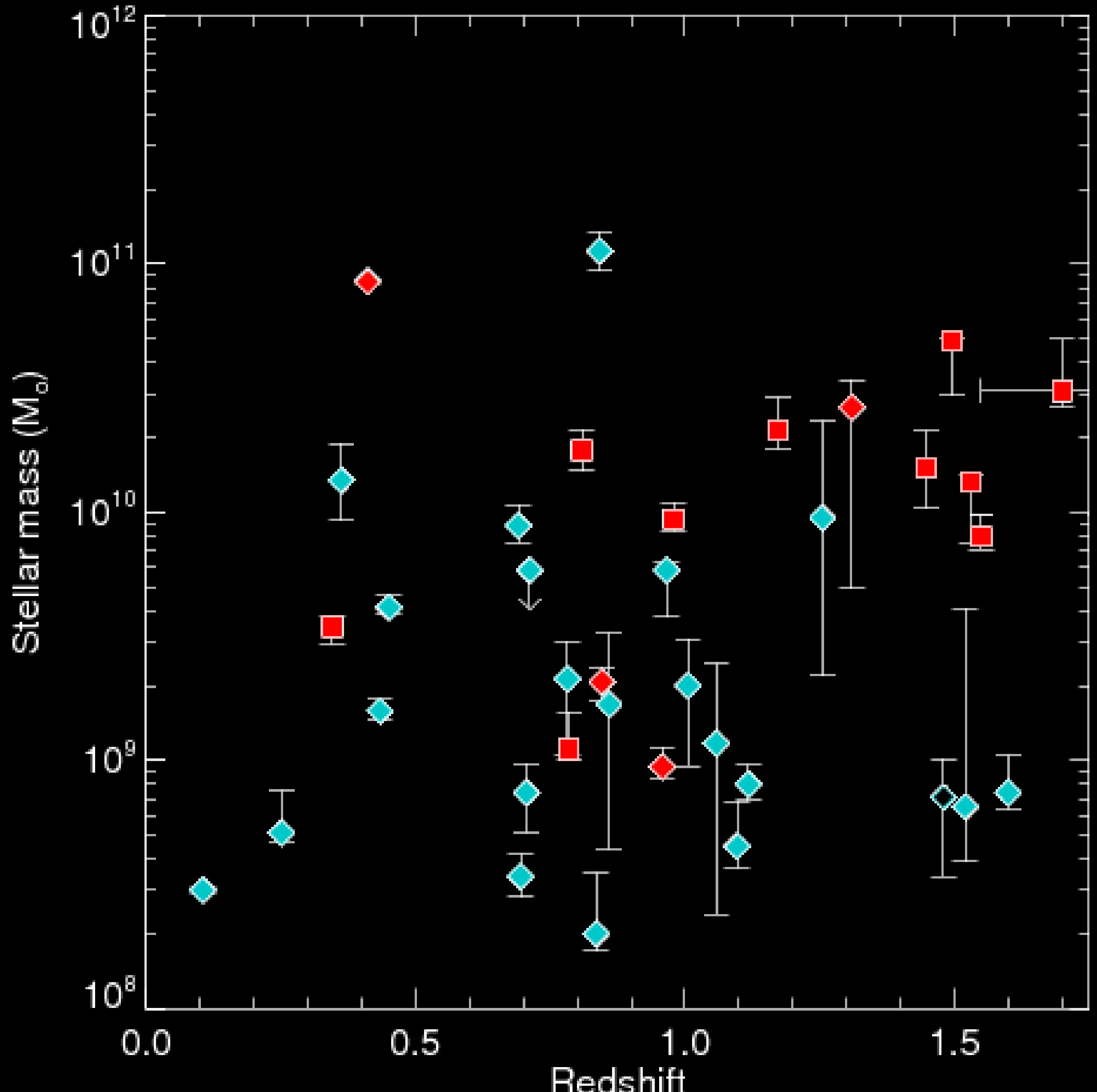
Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

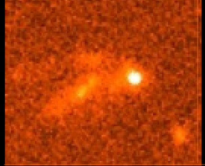




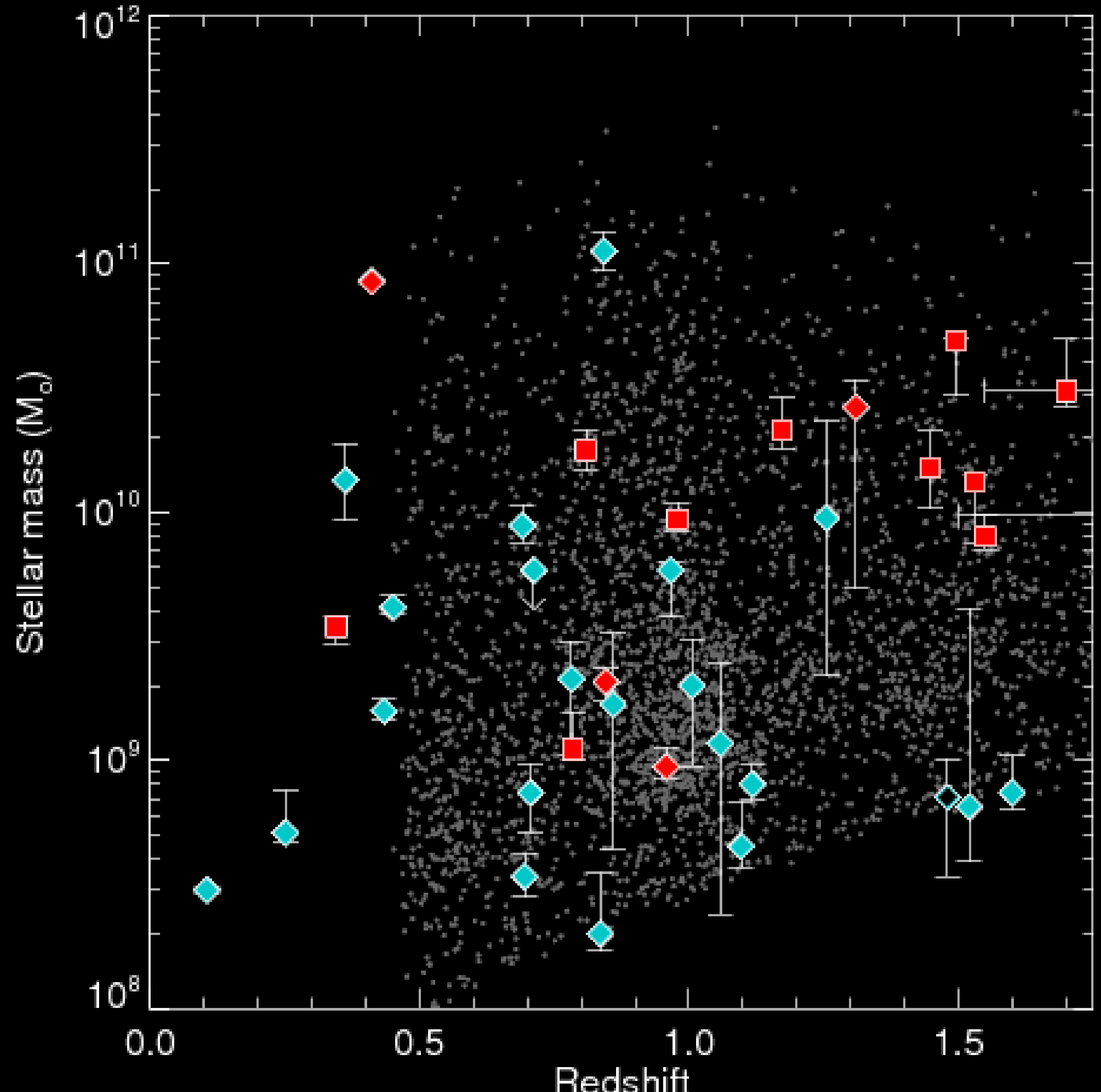
GRB Hosts vs. Field Galaxies at z~1



Blue=unobscured GRB
Red = obscured GRB

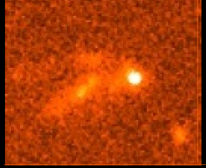


GRB Hosts vs. Field Galaxies at z~1

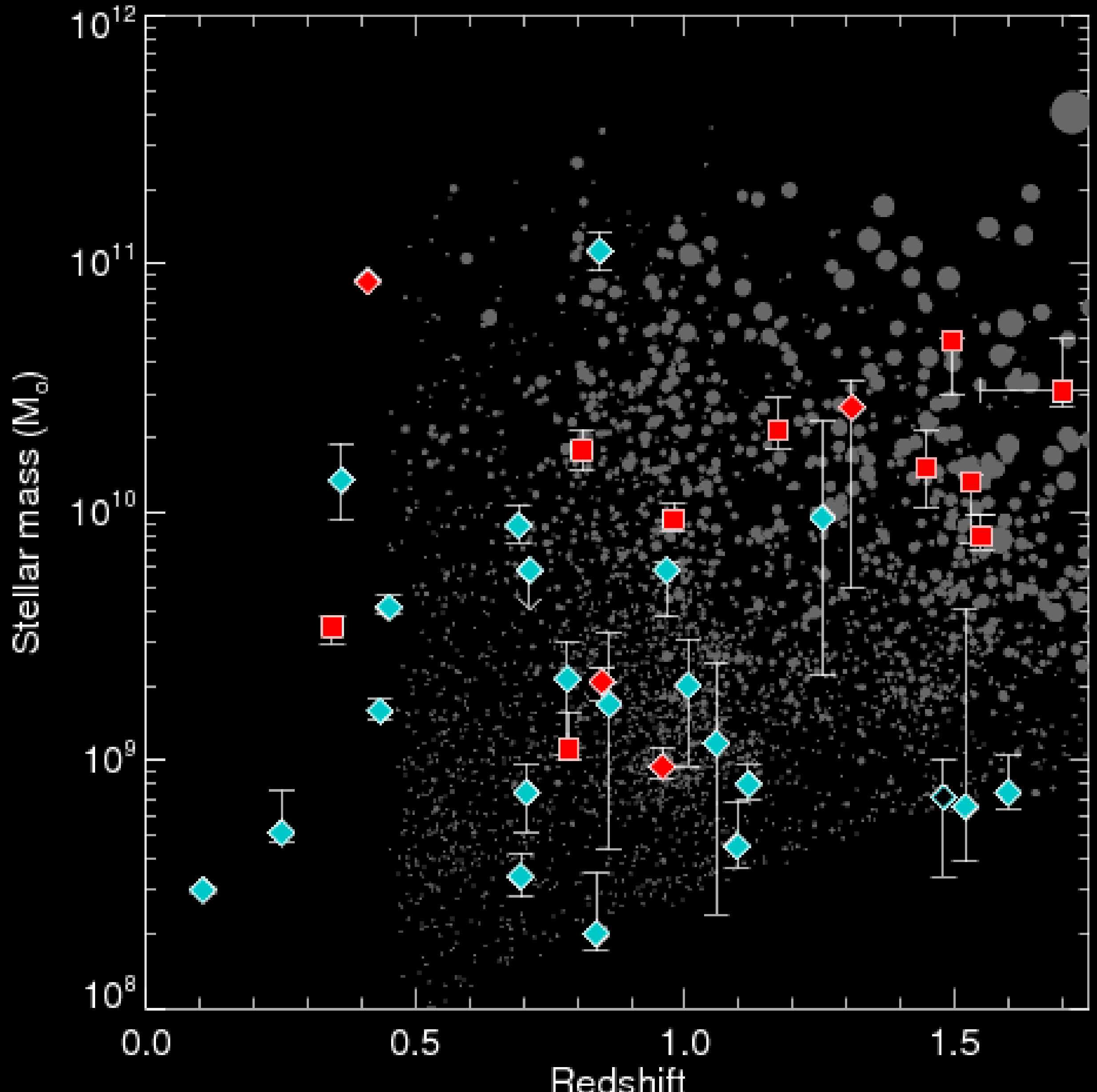


Blue=unobscured GRB
Red = obscured GRB

Gray – mass-selected field galaxies from GOODS-North
(Kajisawa+2011)

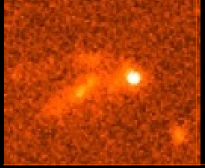


GRB Hosts vs. Field Galaxies at z~1

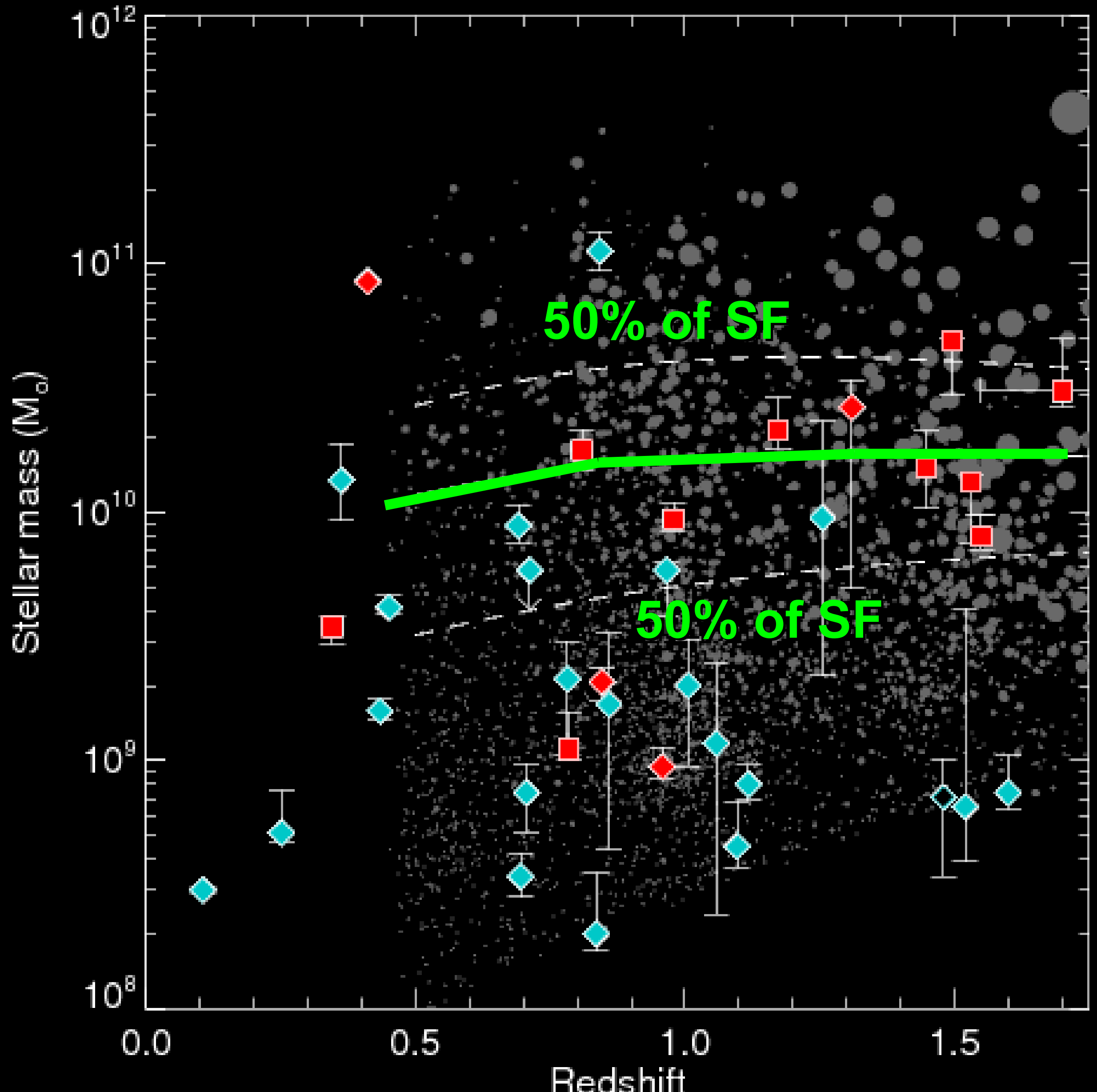


Blue=unobscured GRB
Red = obscured GRB

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



GRB Hosts vs. Field Galaxies at z~1

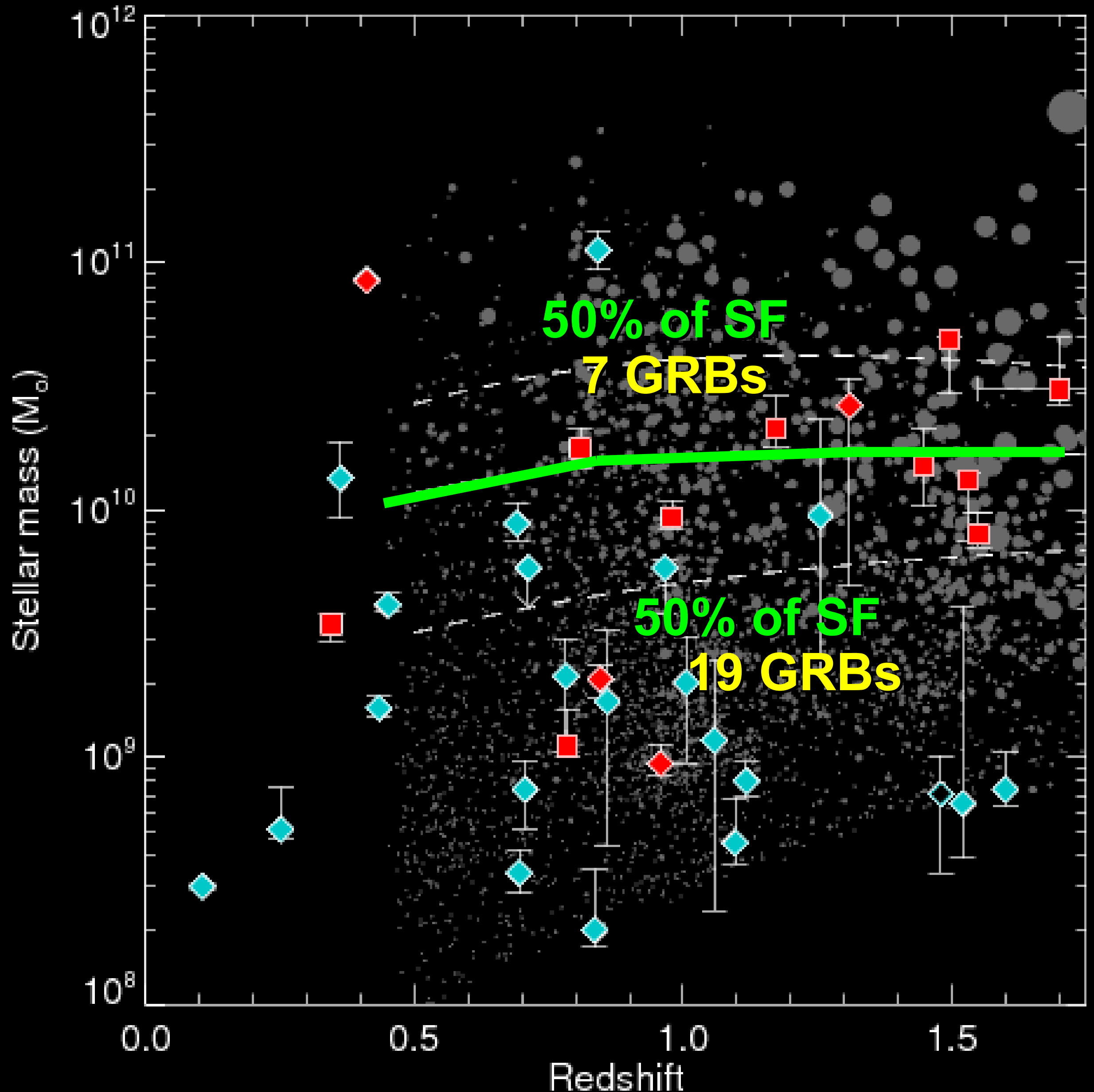


Blue=unobscured GRB
Red = obscured GRB

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

Median mass of cosmic star-formation

GRB Hosts vs. Field Galaxies at z~1



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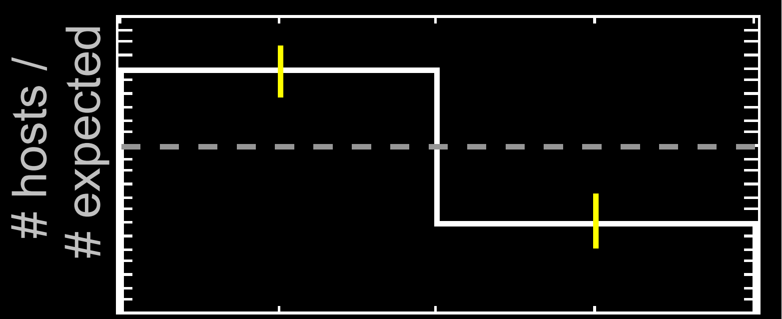
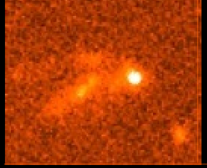
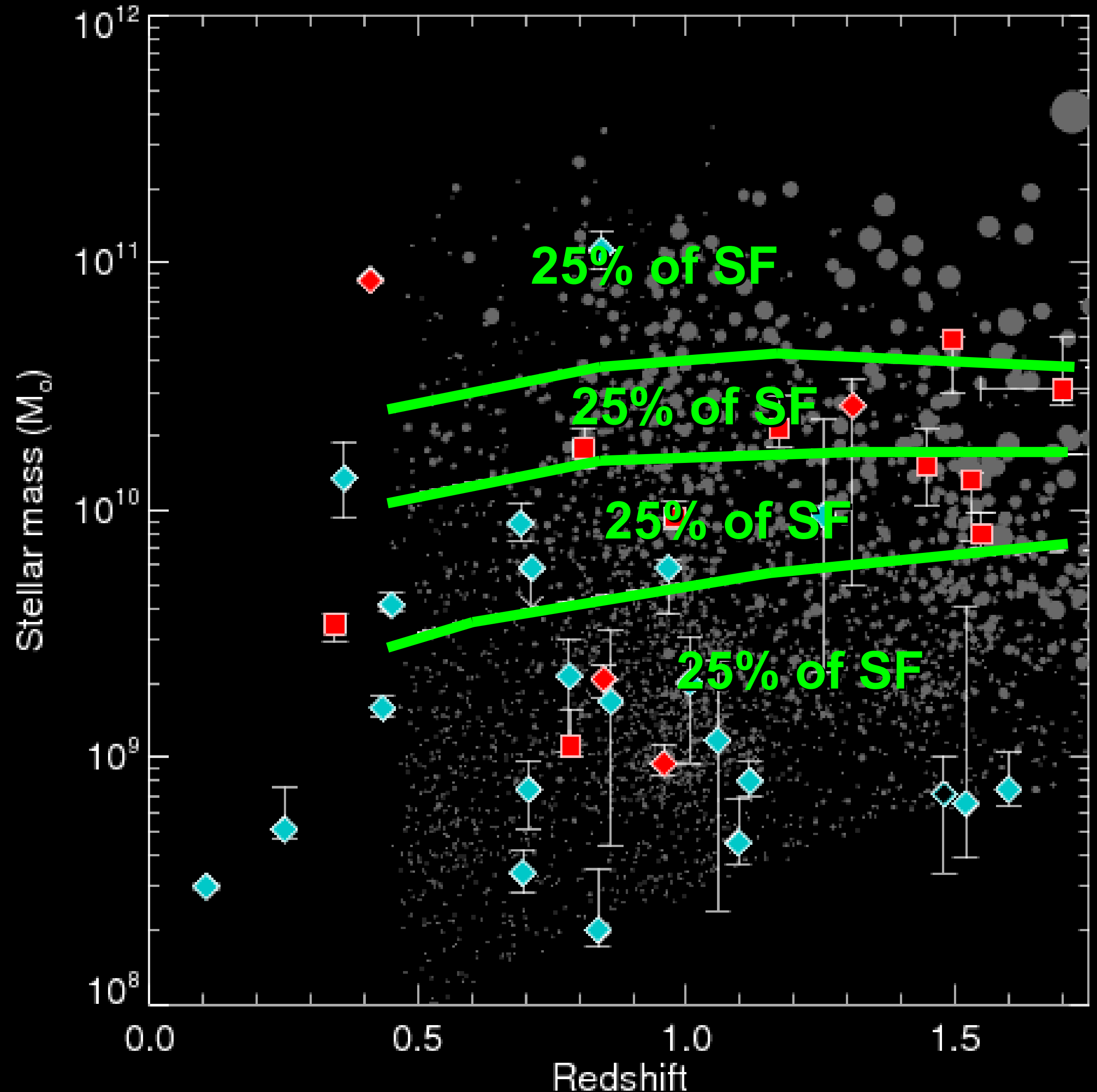
Gray – mass-selected field galaxies from GOODS-North (Kajisawa+2011)
Area scaled by star formation rate

Median mass of cosmic star-formation





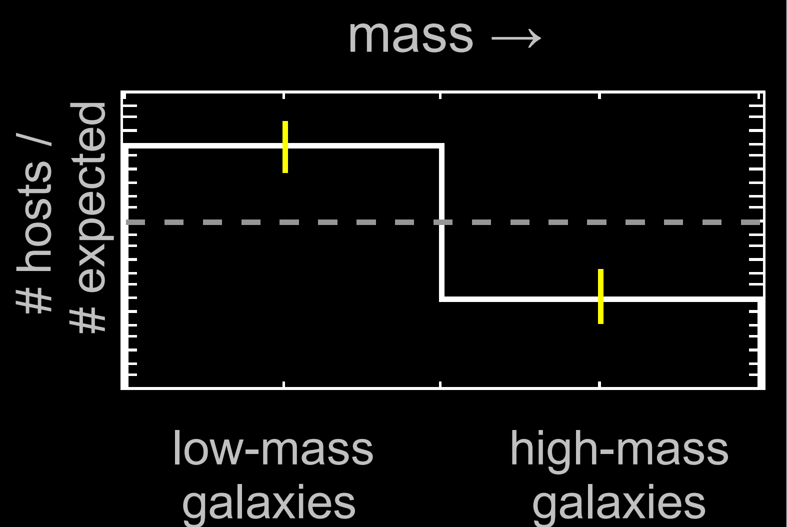
GRB Hosts vs. Field Galaxies at z~1

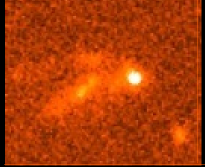


Blue=unobscured GRB
Red = obscured GRB

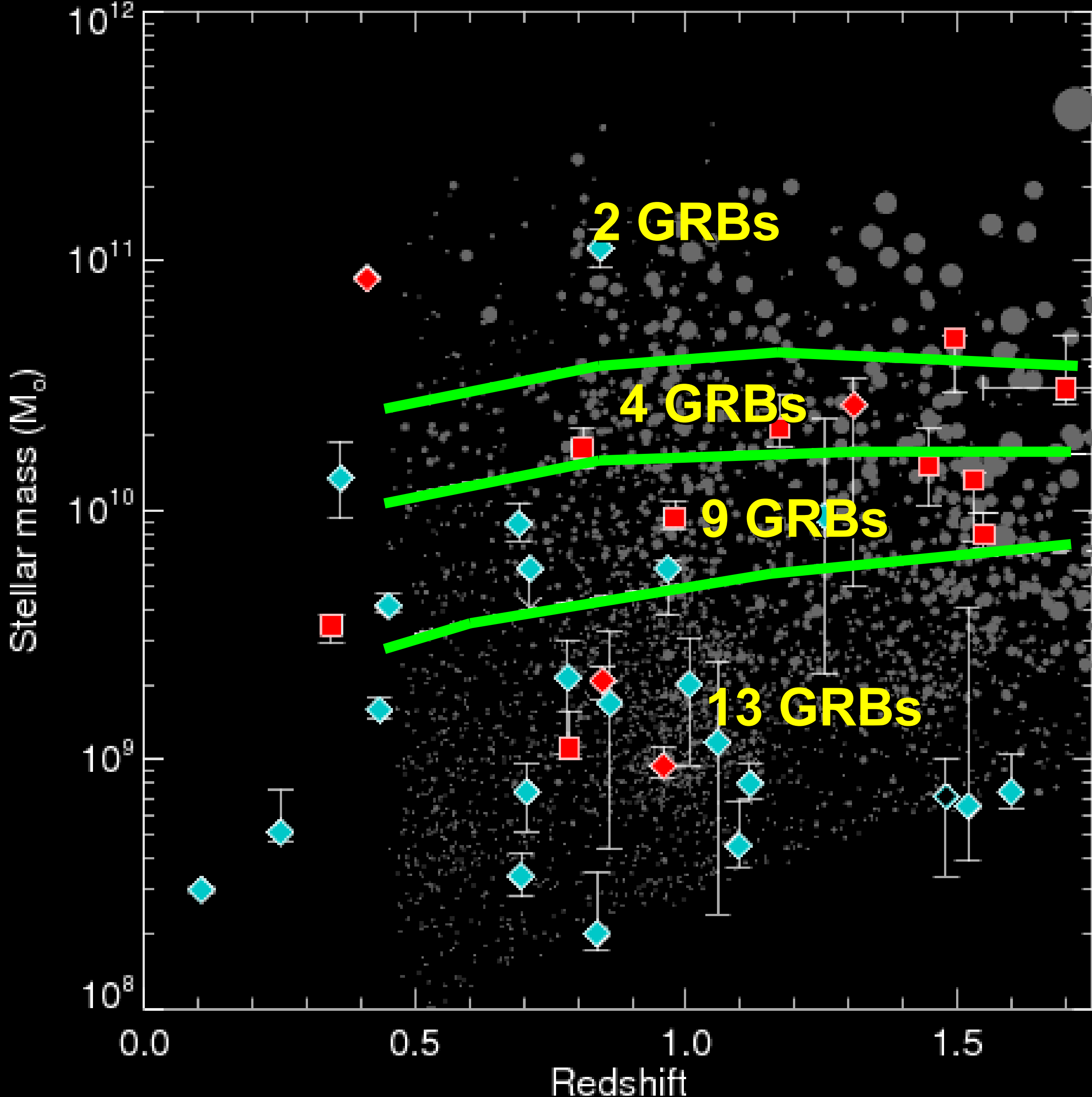
Gray – mass-selected field galaxies from GOODS-North (Kajisawa+2011)
Area scaled by star formation rate

Cosmic star-formation quartile boundaries





GRB Hosts vs. Field Galaxies at z~1



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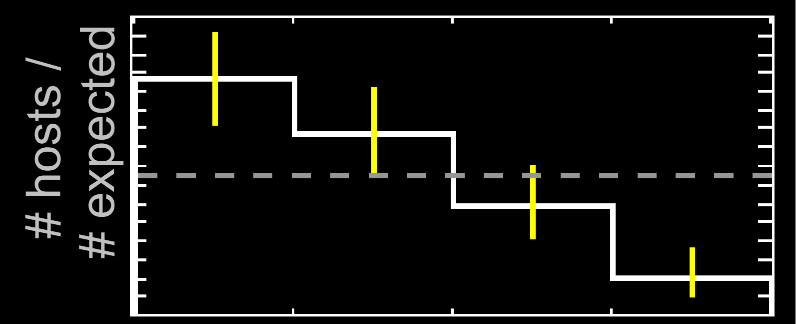
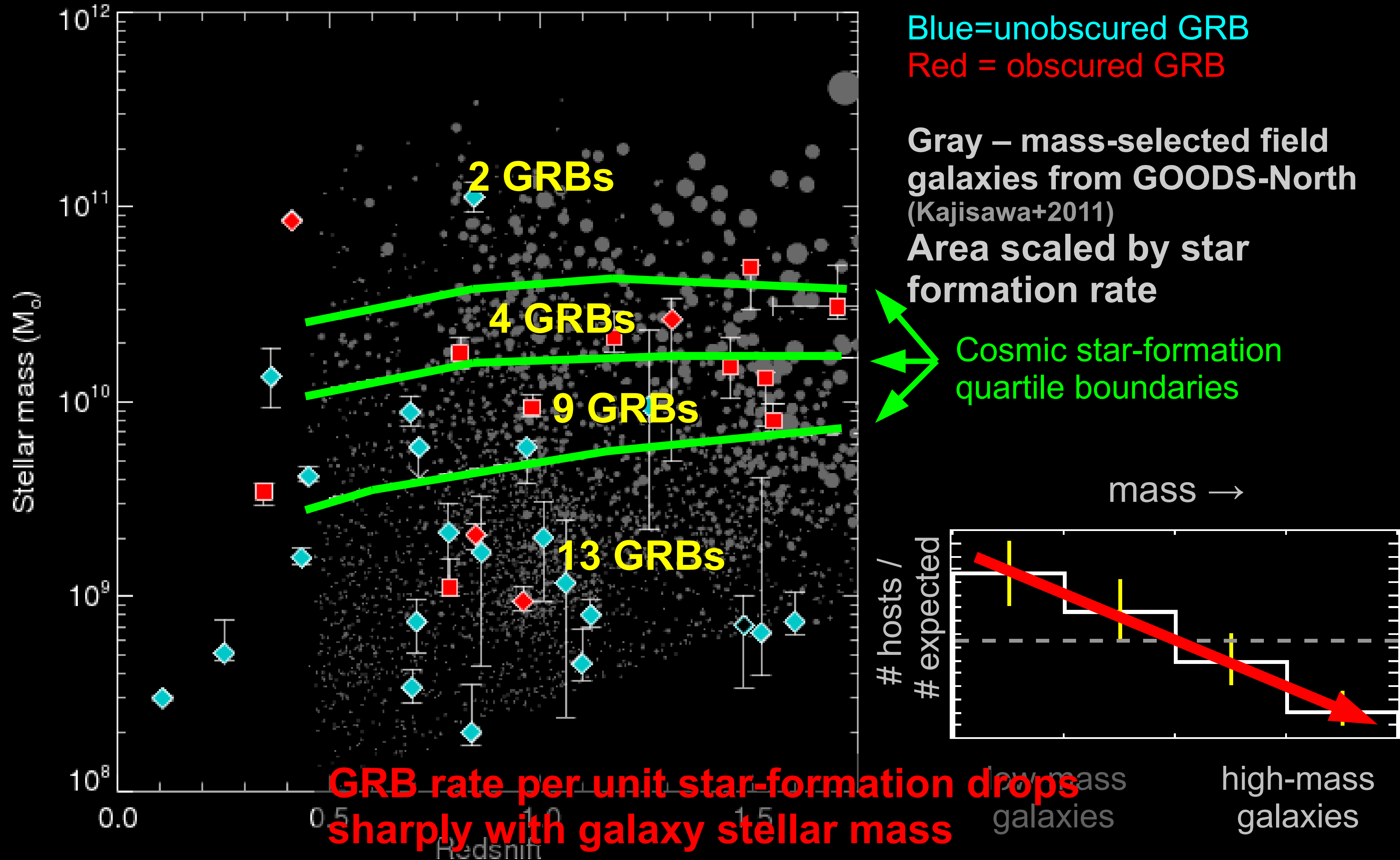
Gray – mass-selected field galaxies from GOODS-North
(Kajisawa+2011)
Area scaled by star formation rate

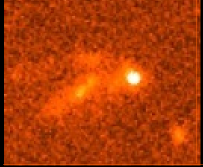
Cosmic star-formation quartile boundaries



GRB Hosts vs. Field Galaxies at z~1



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 of its host. What might it care about?

ISM chemical properties:

Metallicity (affects stellar evolution)

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

ISM physical properties:

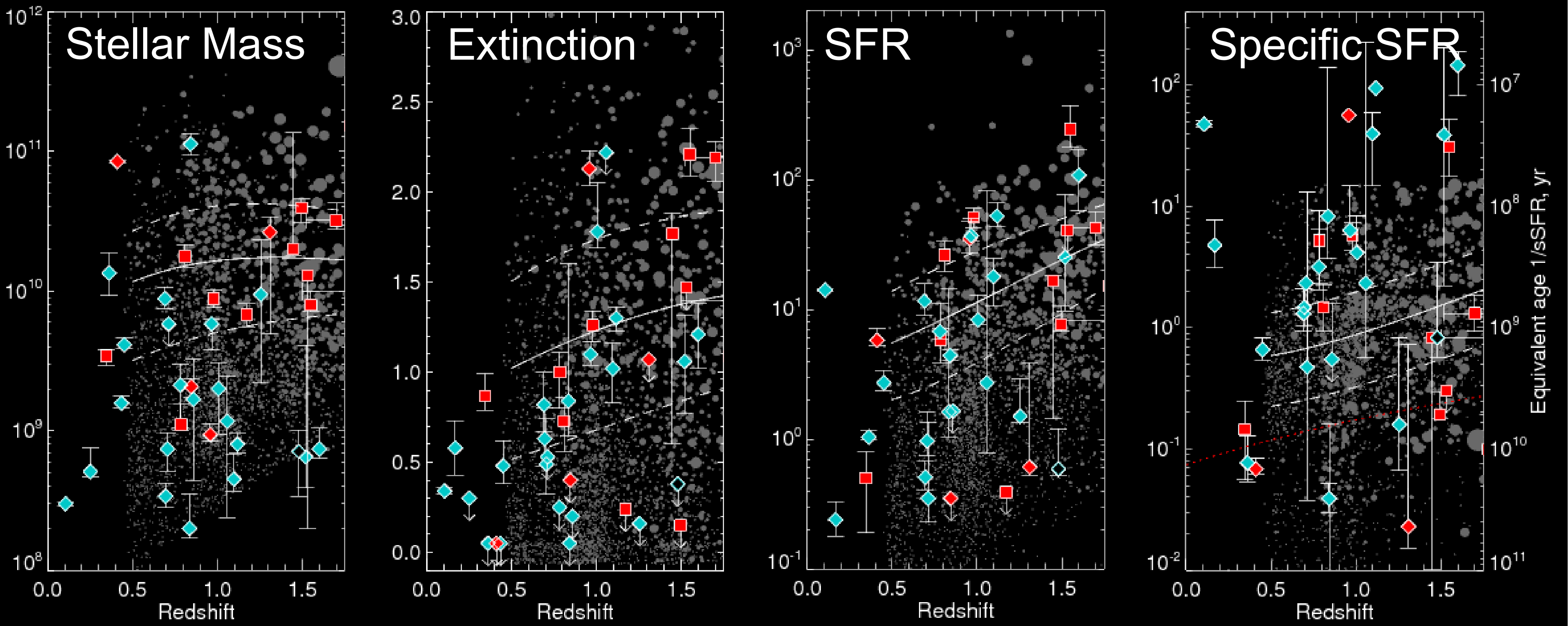
UV radiation field.

Gas density.

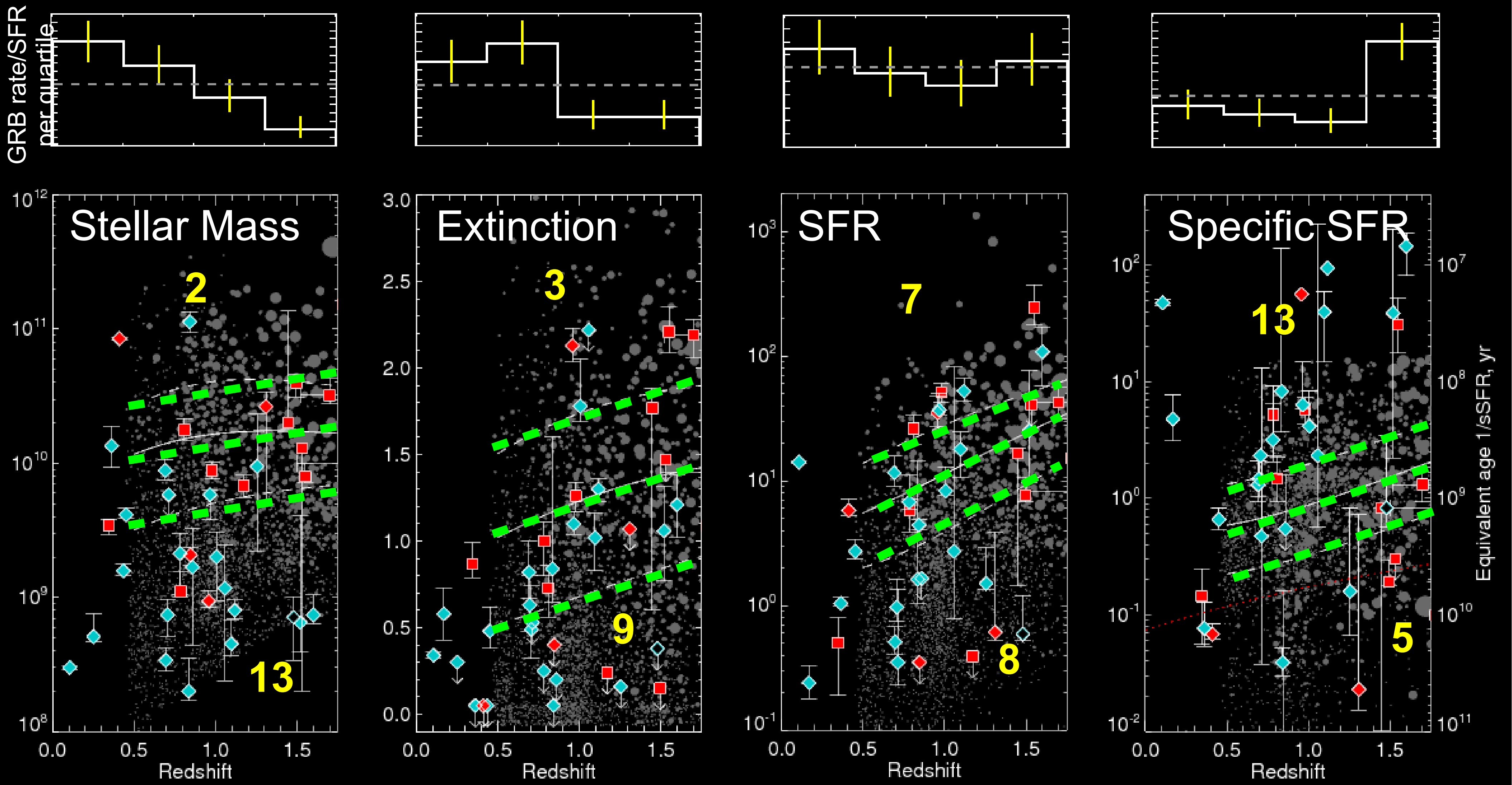
most strongly correlated with **SFR**/**sSFR**.

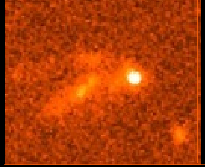
(could affect IMF, initial binarity properties, stellar interactions/collisions, etc.)

Metallicity, or something else?



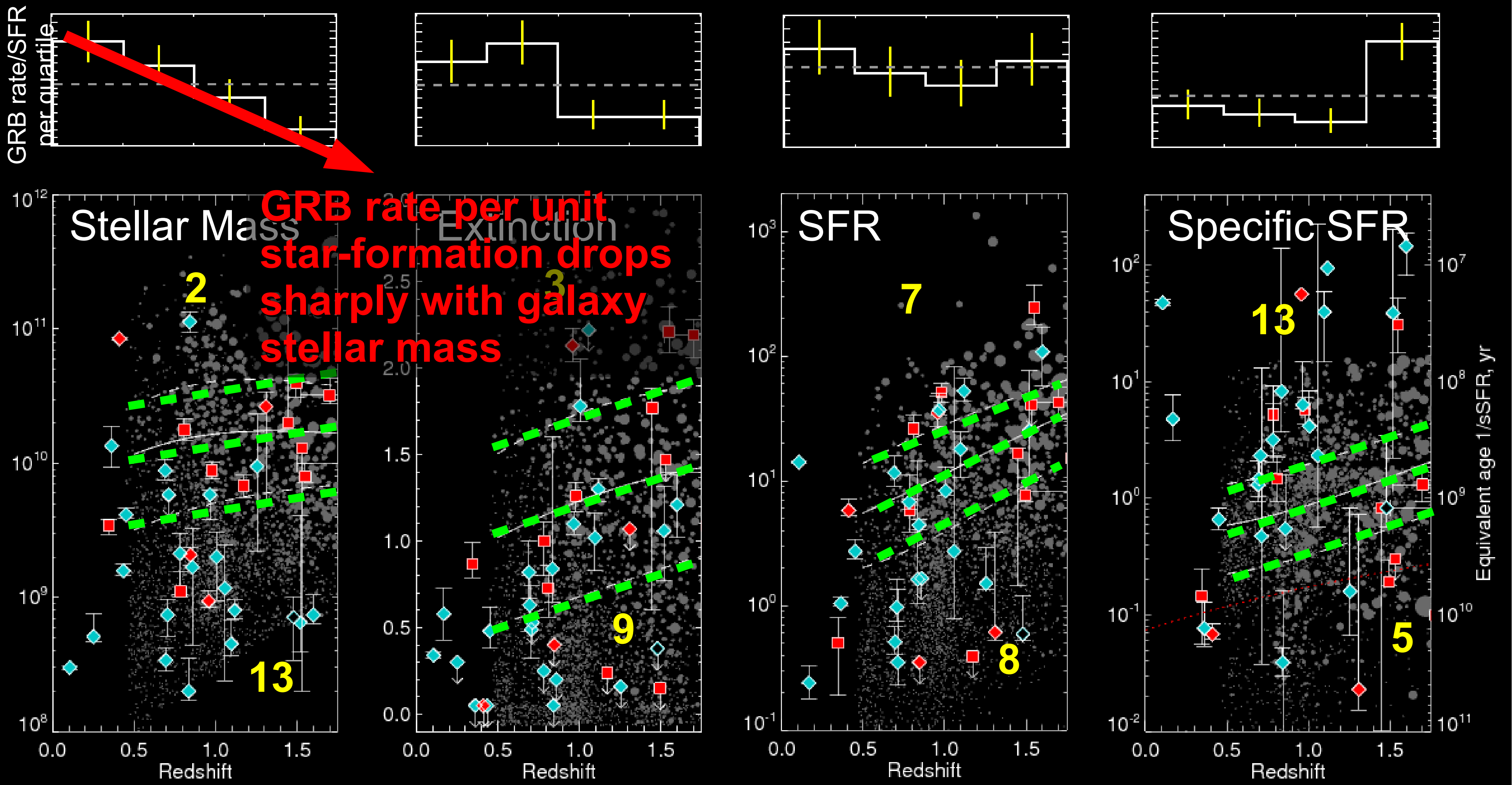
Metallicity, or something else?

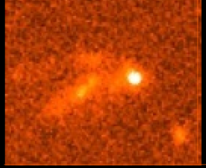




Metallicity, or something else?

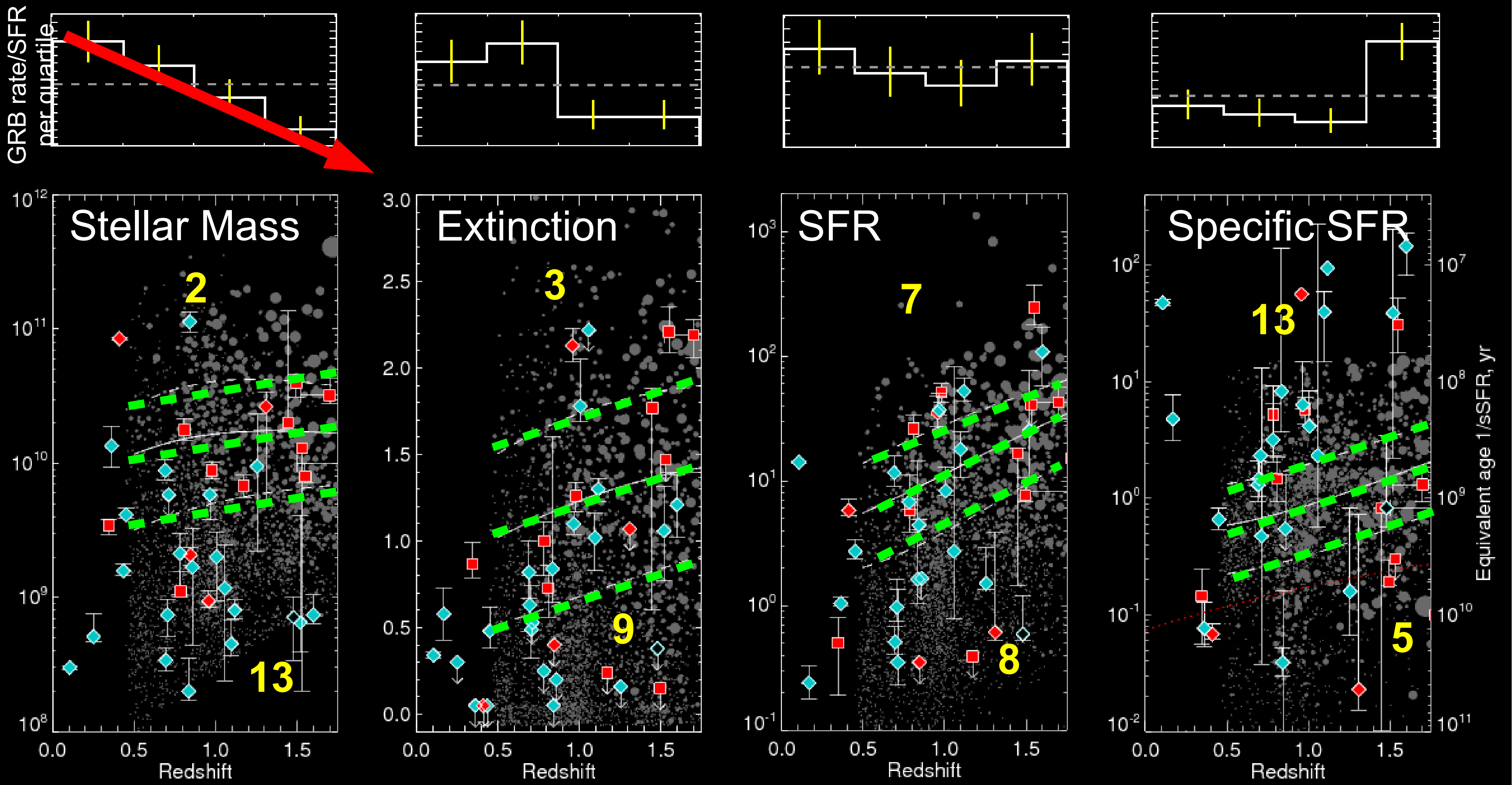
strong effect

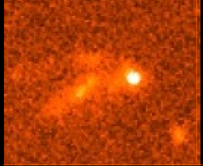




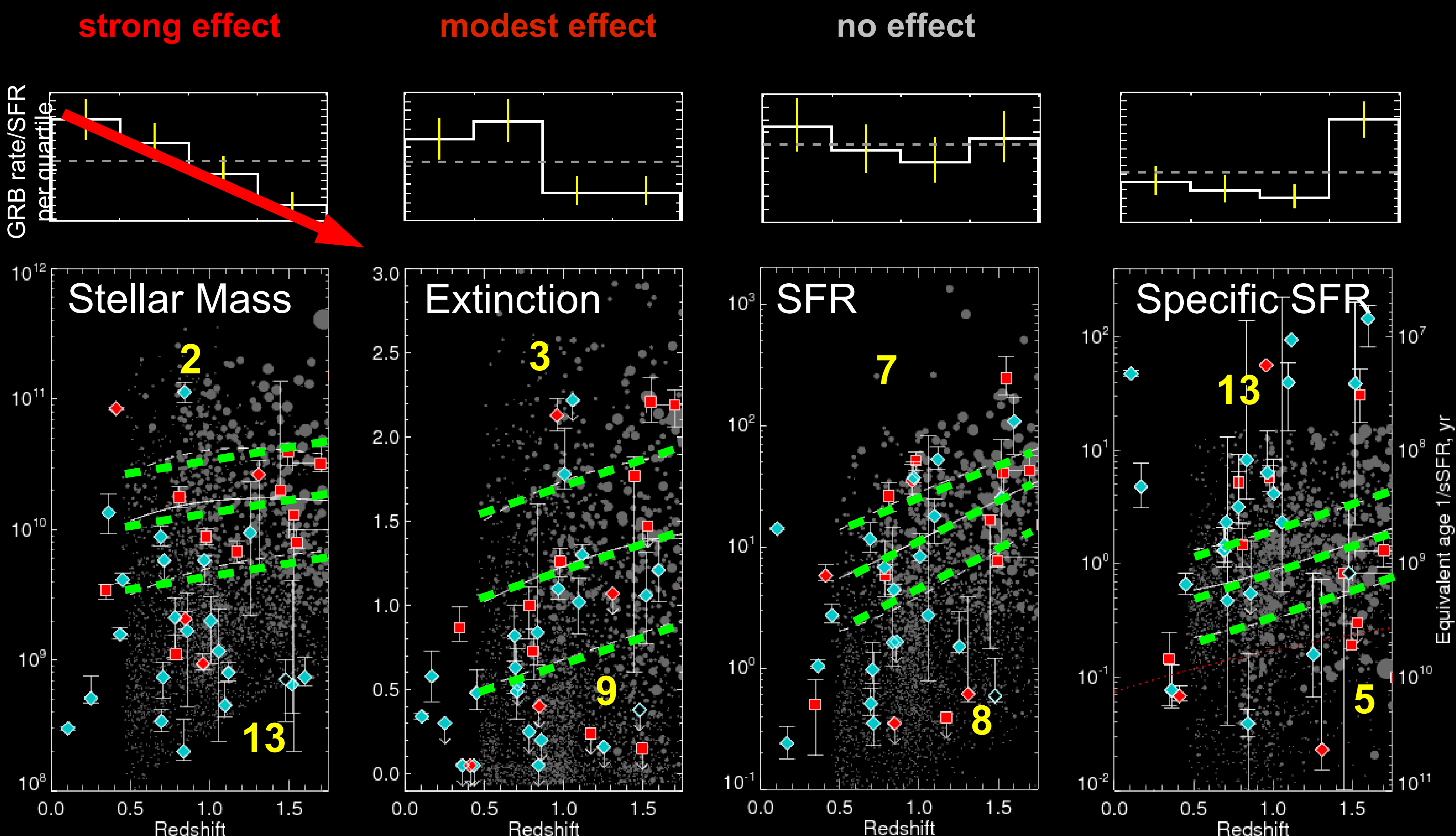
Metallicity, or something else?

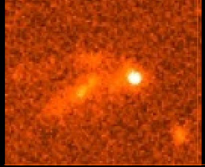
strong effect **modest effect**



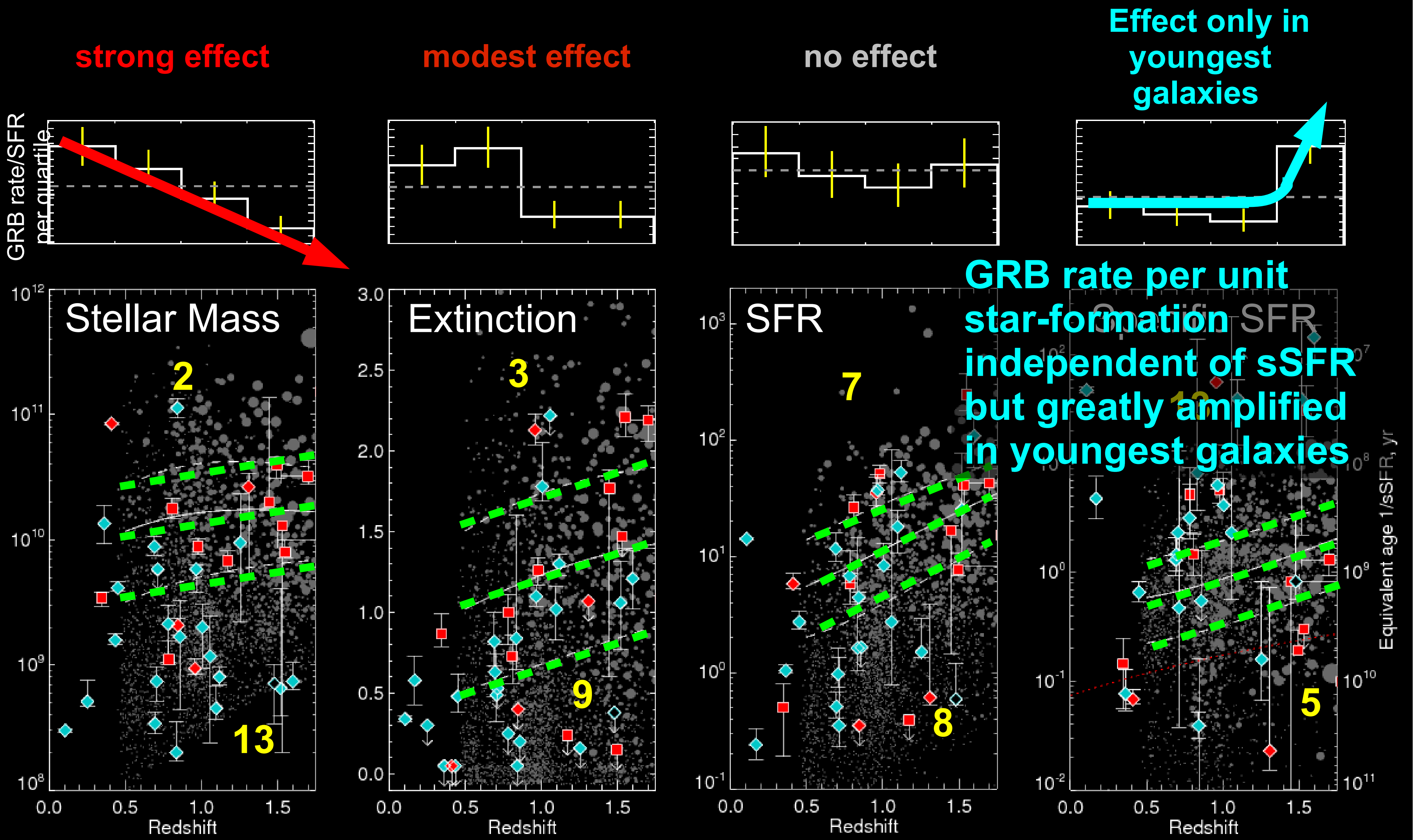


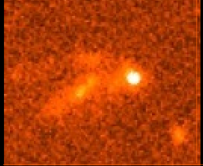
Metallicity, or something else?





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.

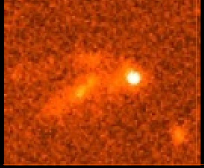
Gas density.

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

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

May play a secondary role in youngest galaxies?

But, needs to be separated from metallicity-sSFR trend (Mannucci et al. 2011)
May be related to potential preference for compact galaxies (Kelly et al. 2014)



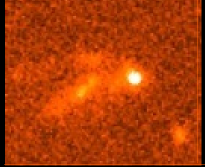
Moving Beyond z>1.7

Swift detects plenty of GRBs at high-z!

(Median afterglow redshift ~2; Jakobsson+2012)

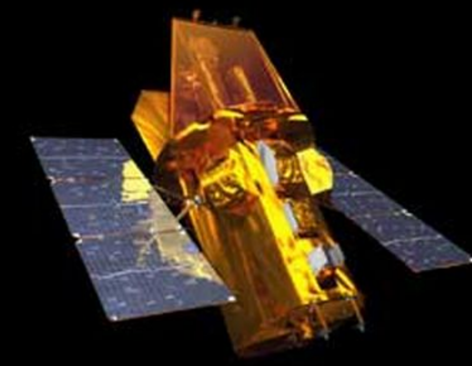
Can we recover the mass distribution of their hosts to check this directly?

(Have to go deep on a large number of targets...)



A New, Fully Unbiased Host Survey

Design and execute a *large, deep, unbiased* multiwavelength survey to include all host galaxies of all types at all redshifts!

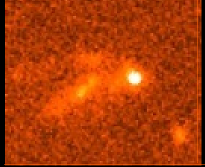


Selection criteria:

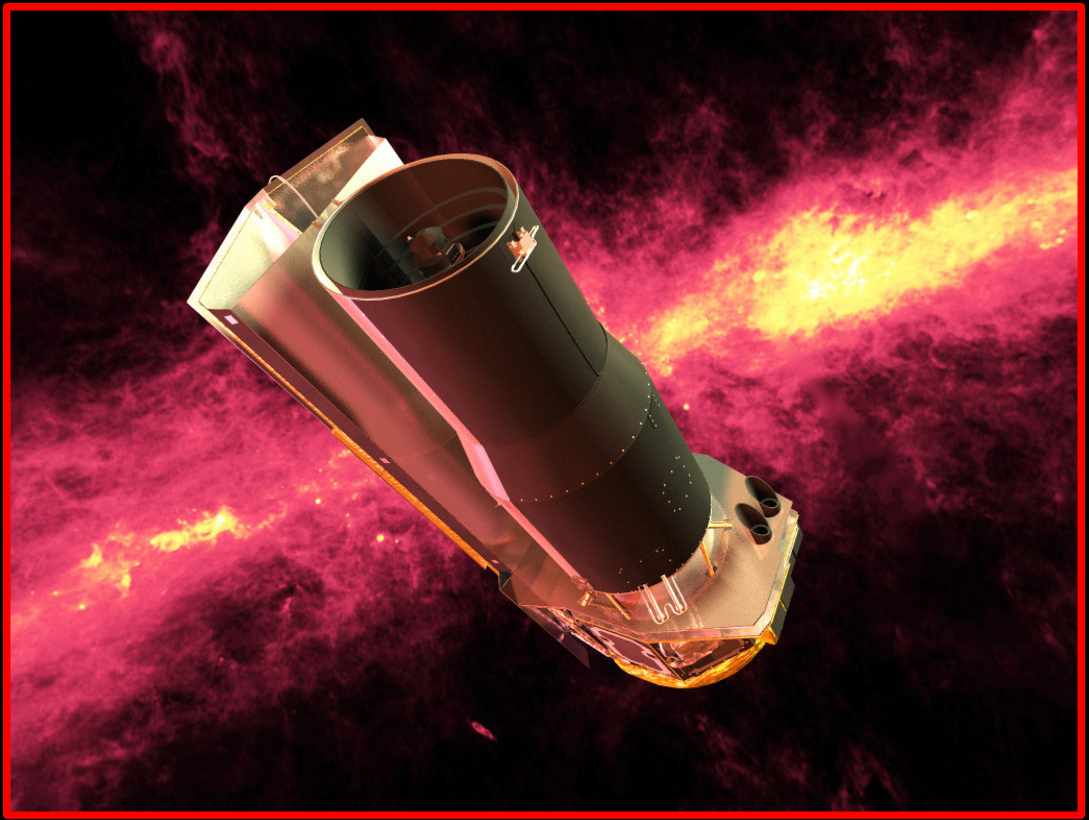
- *Swift* detected; gamma-ray fluence > 10^{-6} erg/cm^2
- *Swift* slewed immediately to the position
- Far from the Sun at time of explosion (afterglow easily observable)
- Low Milky Way foreground extinction
- No nearby bright stars
- Localized within 2” (very slight bias)

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

→ **130** *Swift* GRBs (out of ~1000 to date),
75% with predetermined redshift (usually from afterglow.)
(Will have to get the remaining 25% from the host if possible.)



A New, Fully Unbiased Host Survey



Spitzer (3.6 μm imaging):

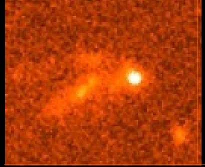
- Good **stellar mass** proxy (even with no color information);
- Sensitive to 10^{10} $M_\odot$ galaxies to z~5
- 230-hour large program to observe all 130 targets

VLA (3 GHz continuum):

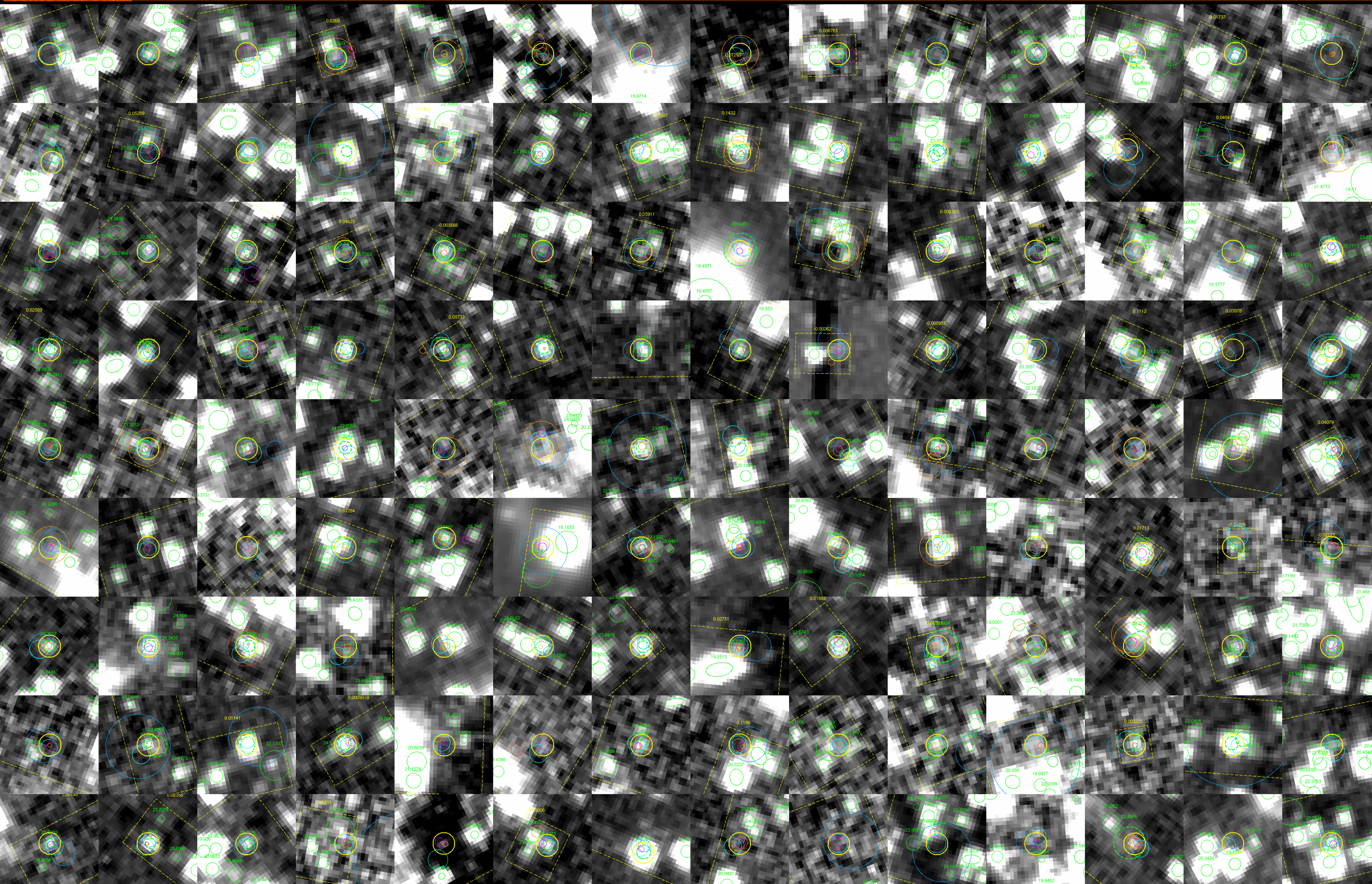
- Dust-unbiased **SFRs**
- 90 hours to observe 29 targets

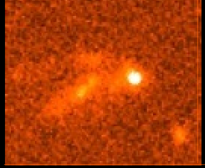
Keck, Gemini, VLT, GTC

- Optical/NIR imaging for full SED modeling (age, extinction, improved stellar masses)
- Spectroscopy to complete redshift distribution
- Numerous programs ongoing

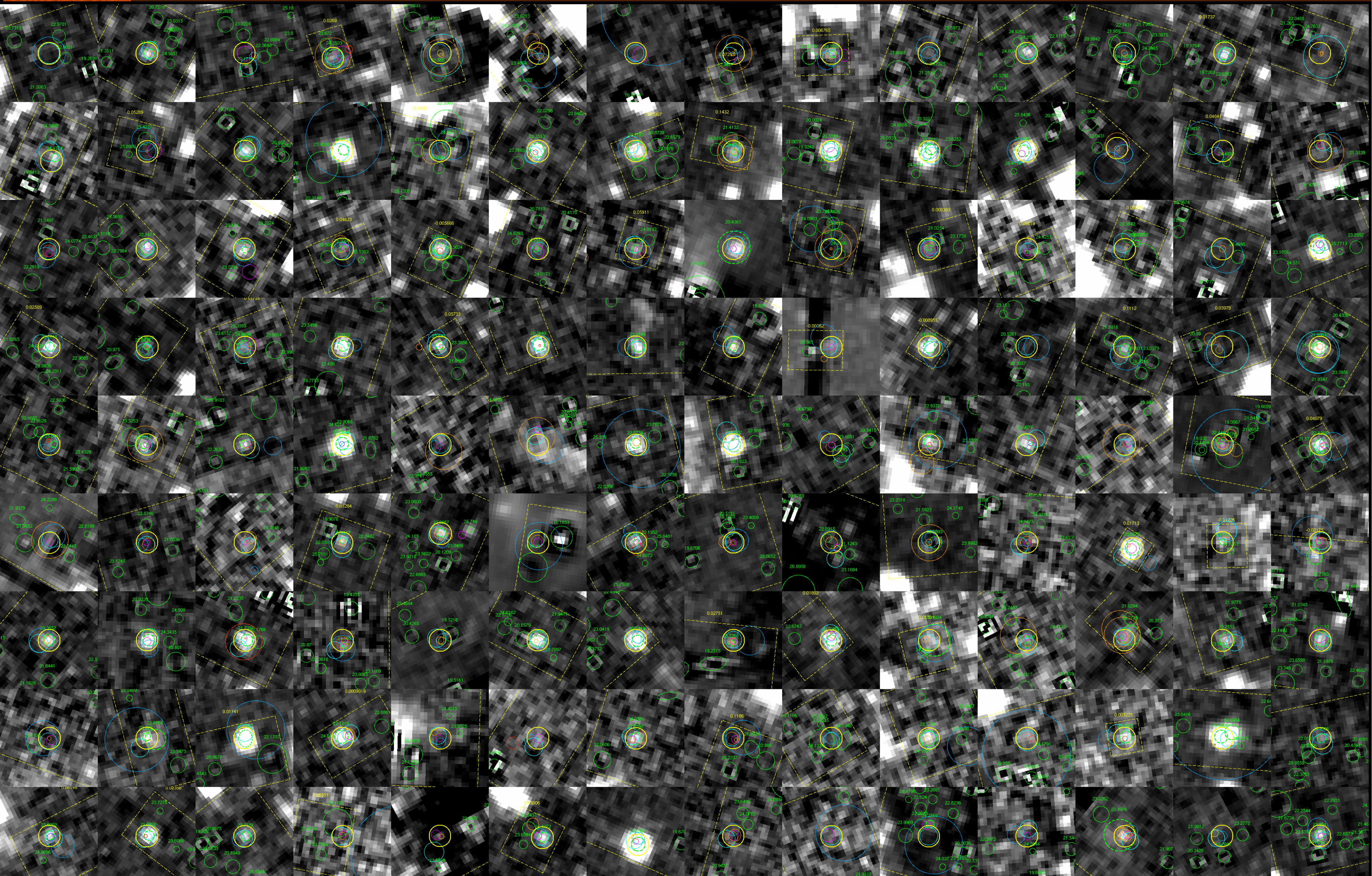


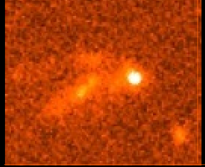
130 GRB Host Galaxies from Spitzer



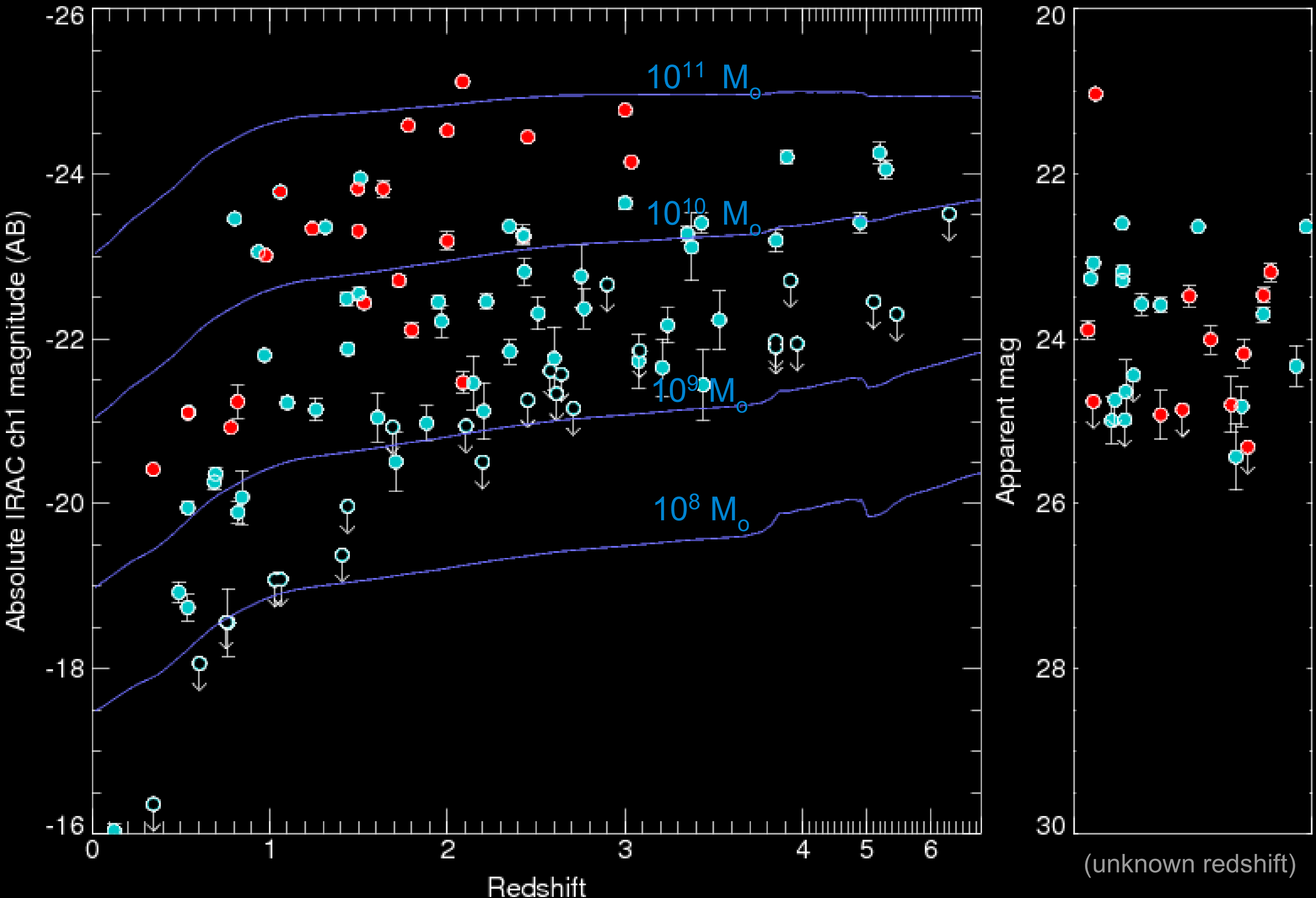


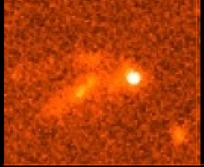
130 GRB Host Galaxies from Spitzer



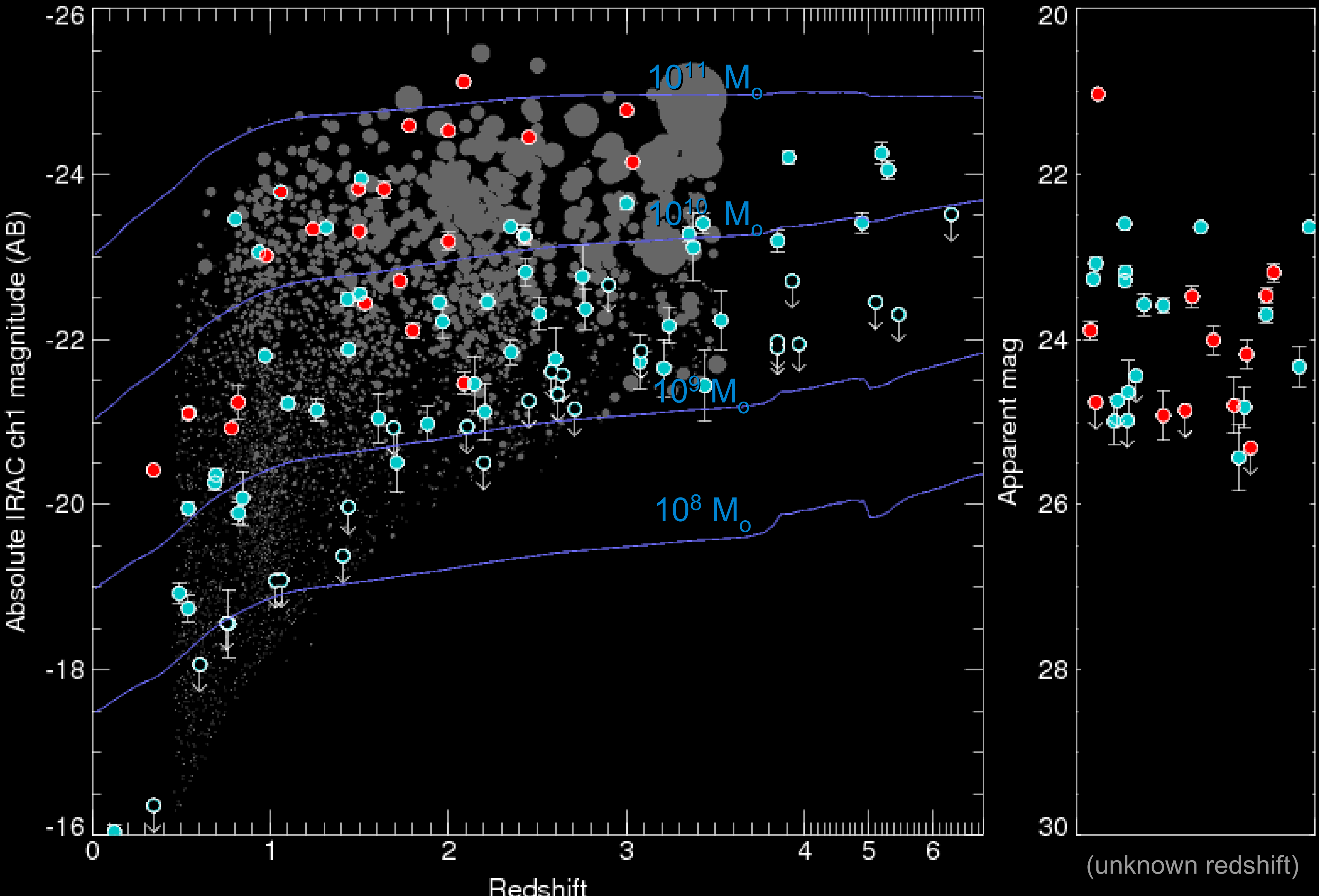


GRB NIR luminosities to z~7

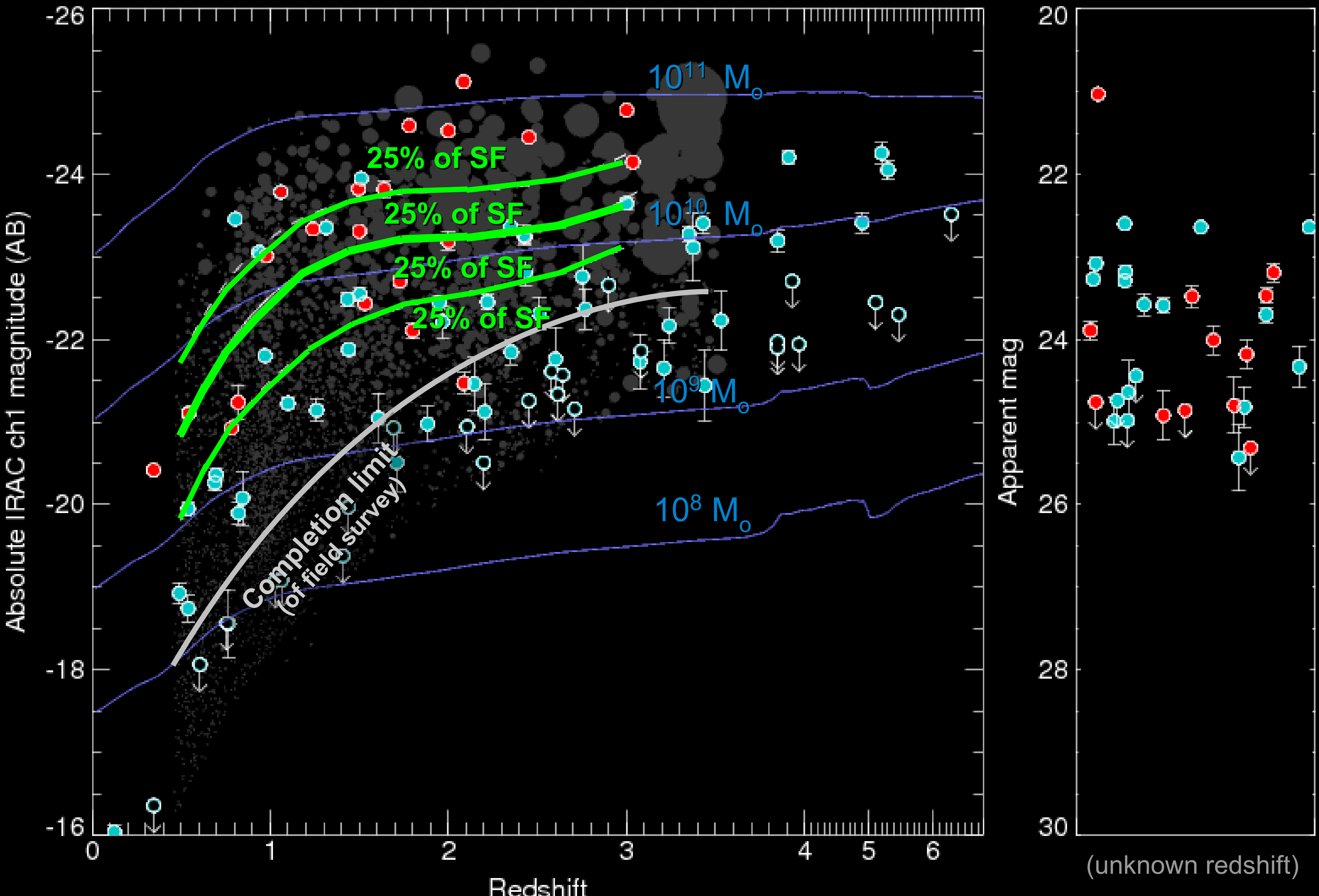




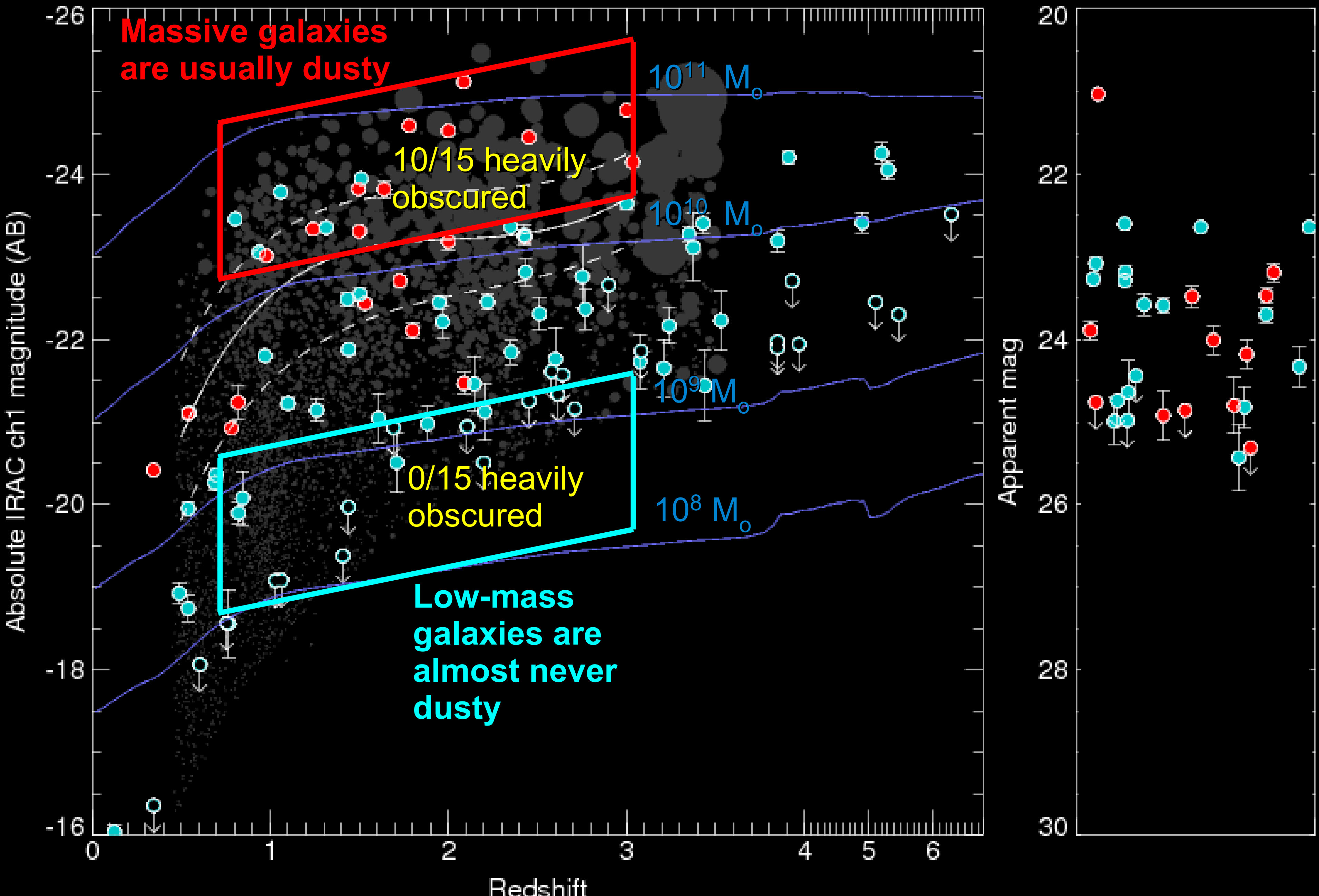
GRBs vs. Galaxies



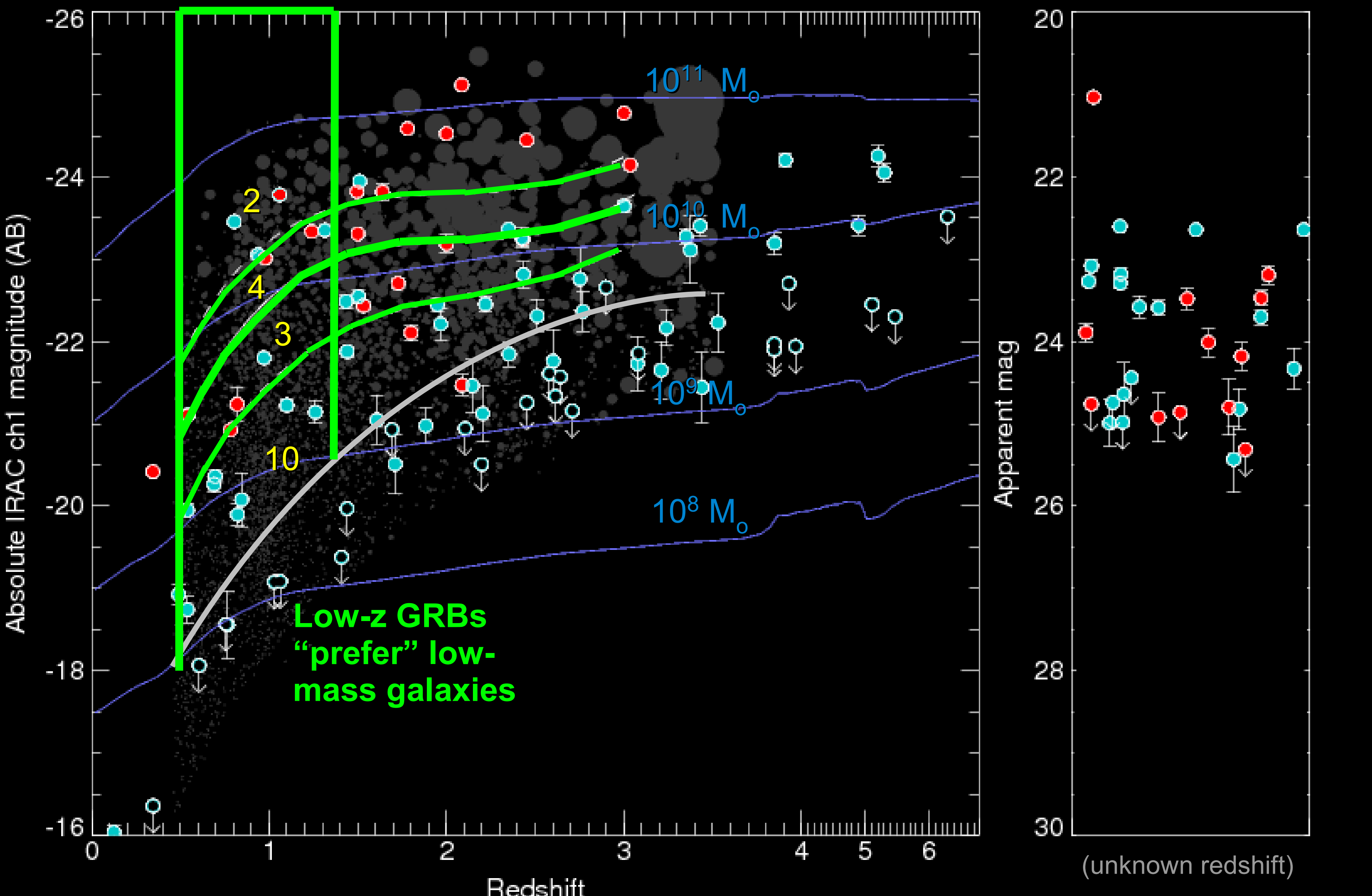
GRBs vs. Star Formation

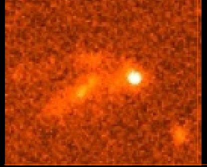


GRBs vs. Dust

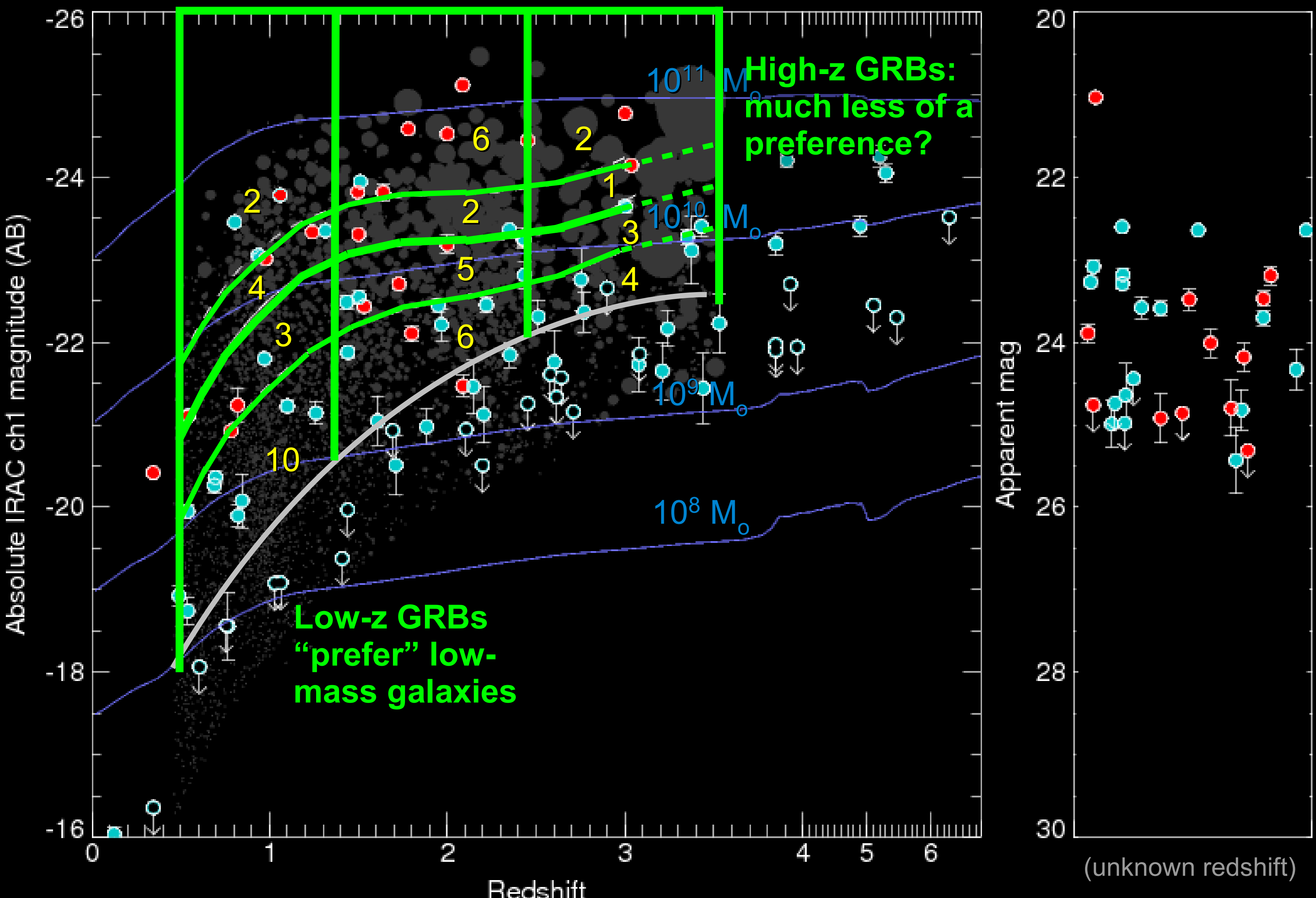

Massive galaxies are usually dusty
10/15 heavily obscured
0/15 heavily obscured
Low-mass galaxies are almost never dusty
10¹¹ M☉
10¹⁰ M☉
10⁹ M☉
10⁸ M☉
Absolute IRAC ch1 magnitude (AB)
-26
-24
-22
-20
-18
-16
0
1
2
3
4
5
6
Redshift
Apparent mag
20
22
24
26
28
30

GRBs vs. Star Formation





GRBs vs. Star Formation



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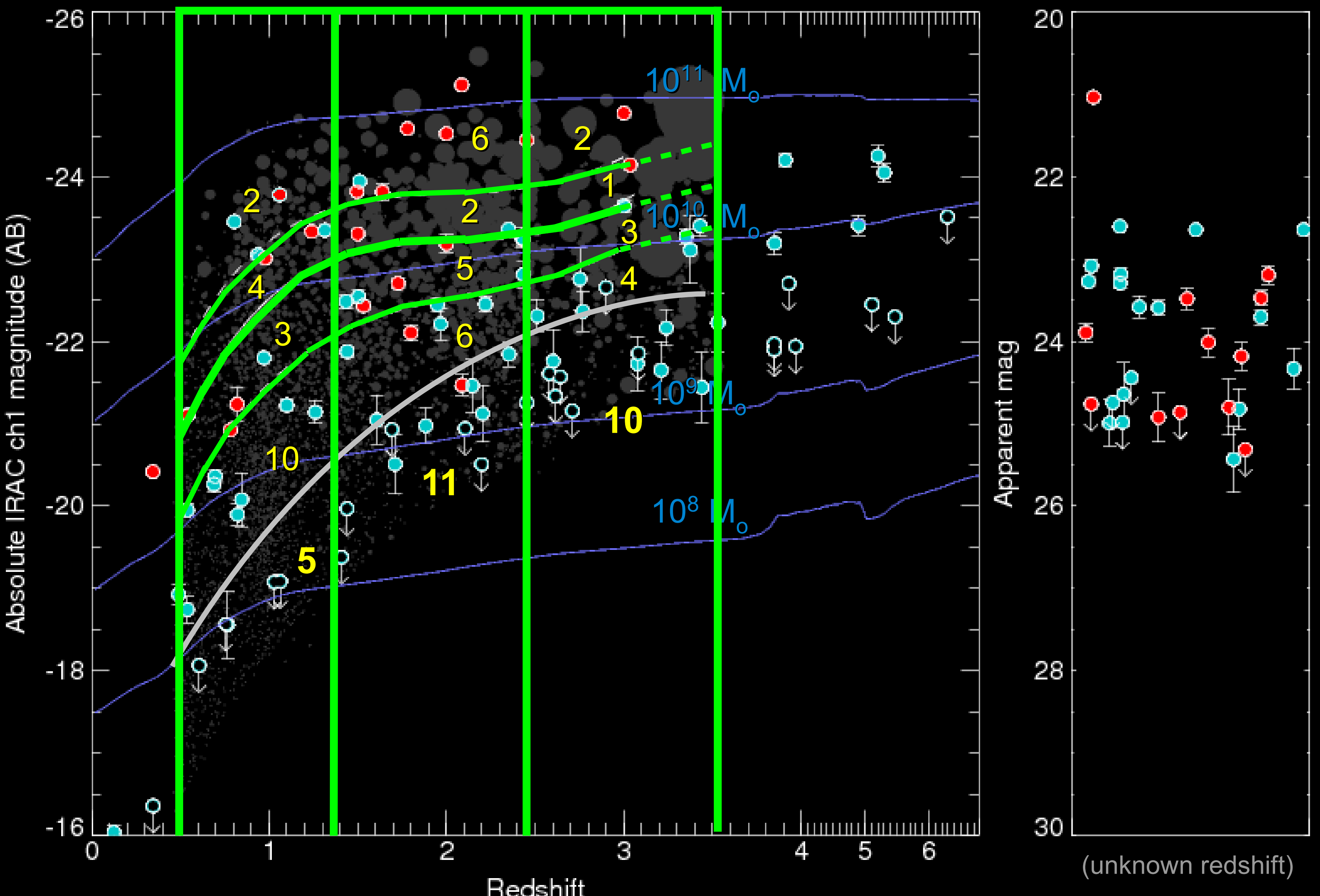

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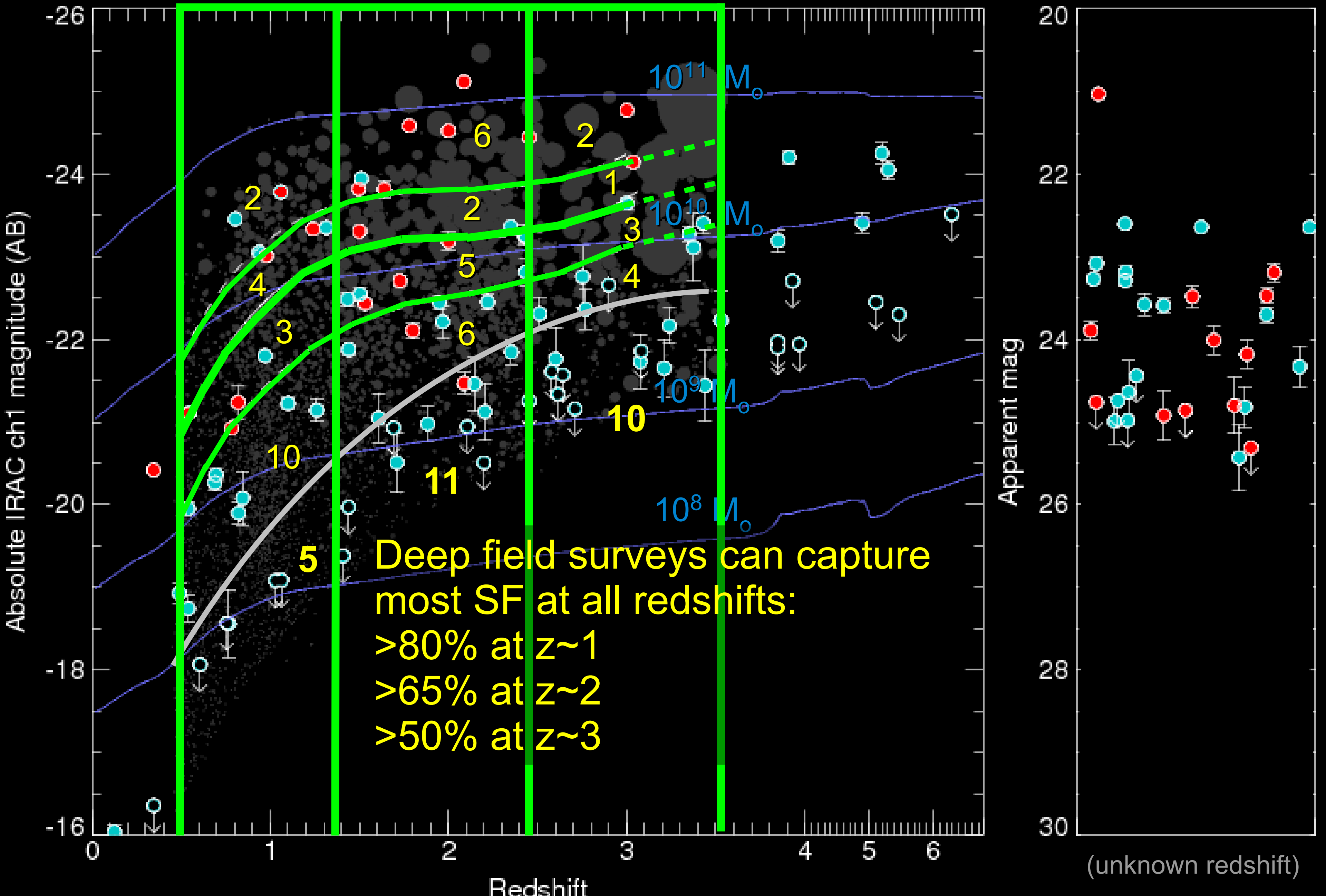

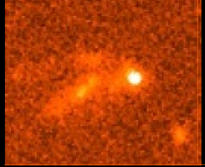

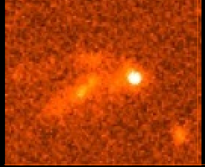

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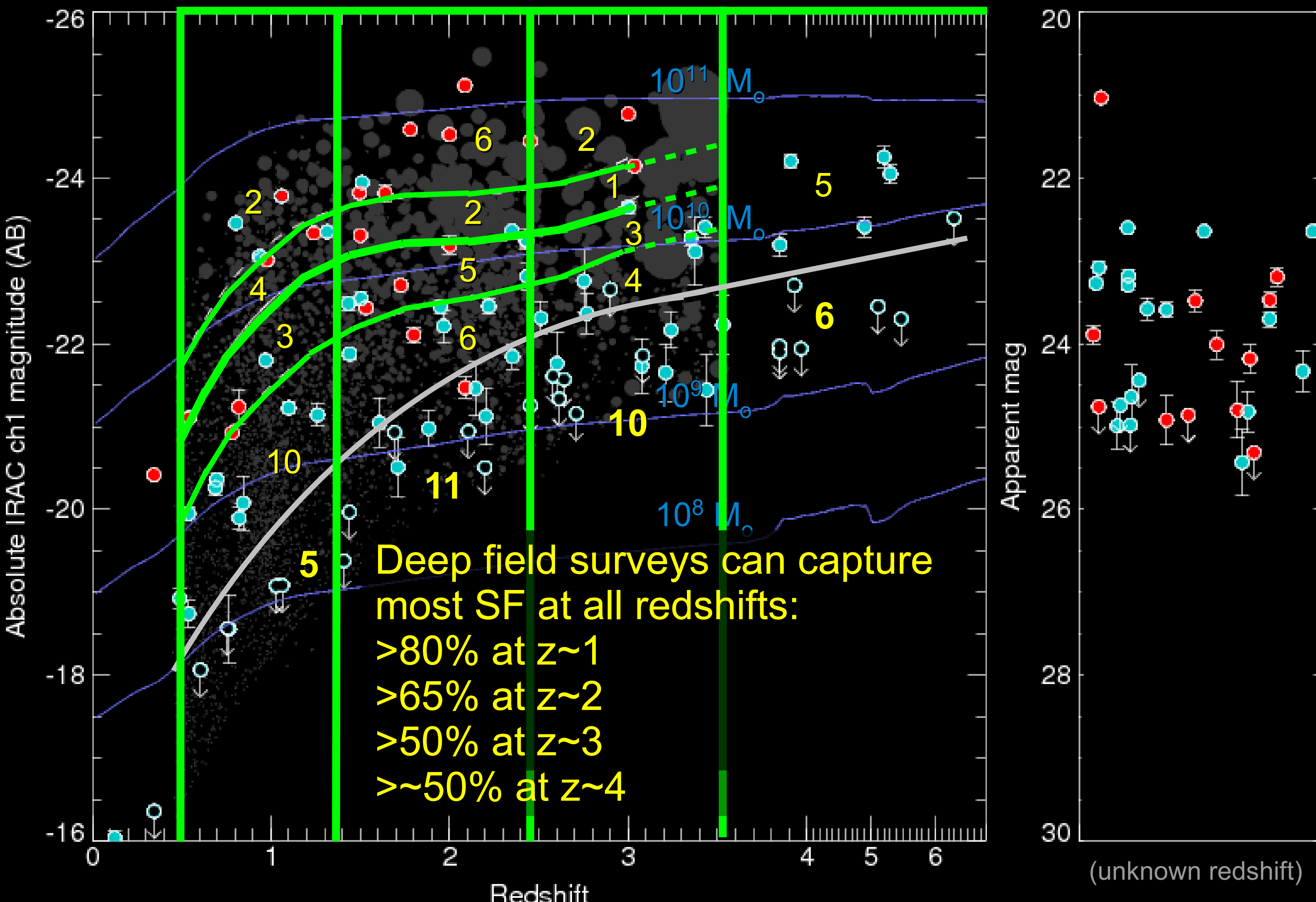
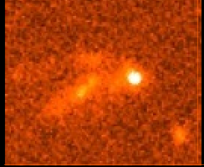




Conclusions from Spitzer Survey

Dark GRBs (still) originate from more massive galaxies

~10^{11} $M_\odot$ galaxies obscure nearly all their star-formation;

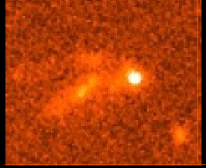
~10^{9} $M_\odot$ galaxies obscure almost none.

GRBs (still) strongly avoid high-mass galaxies at z~1

Trend weakens (but still present) out to z~2 and probably z~3.

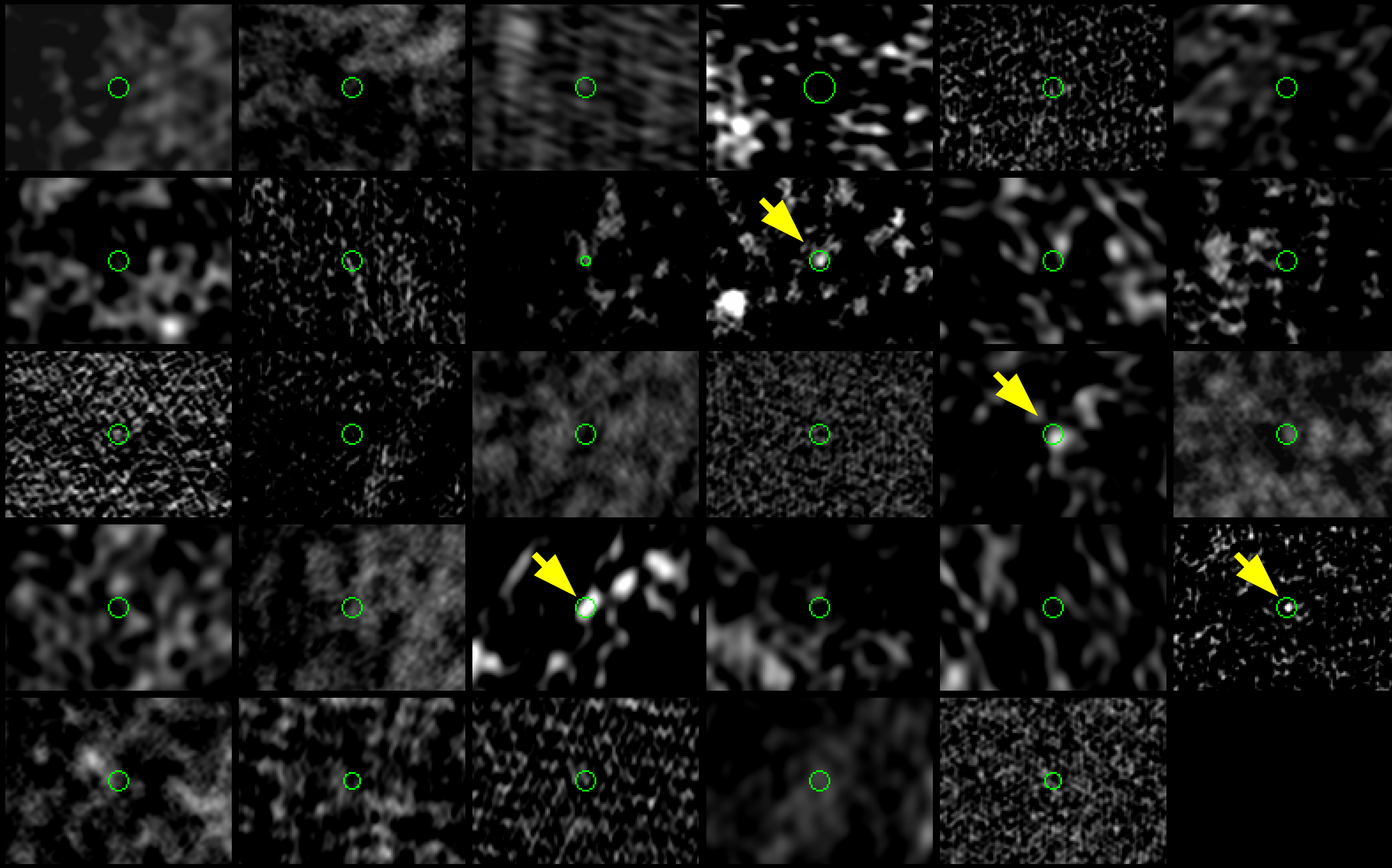
→ Consistent with a metallicity-dependent GRB rate with a sharp transition close to ~0.7 $Z_\odot$

Deep, mass-selected field surveys see most star formation even out to z~5.



Host Star-Formation Rates from VLA

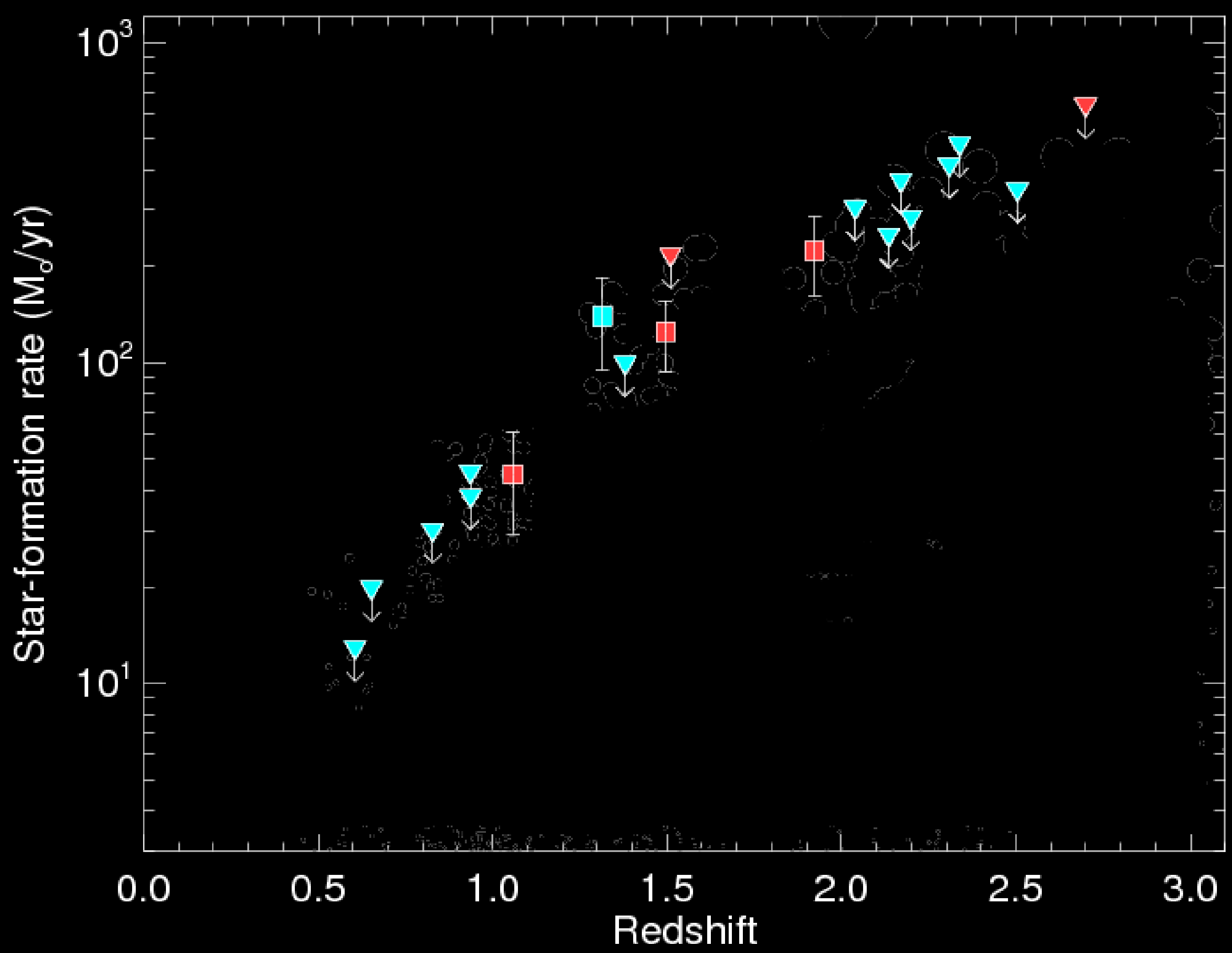
Use **radio** observations (fully dust-unbiased) of a subsample to constrain *star-formation rates*

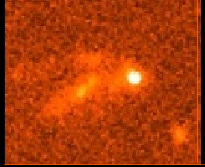


4/29 detections with VLA to 10 microJansky ($z<2.5$ GRBs)

Host Star-Formation Rates from VLA

Four radio host detections (very luminous hosts – LIRGs/ULIRGs)





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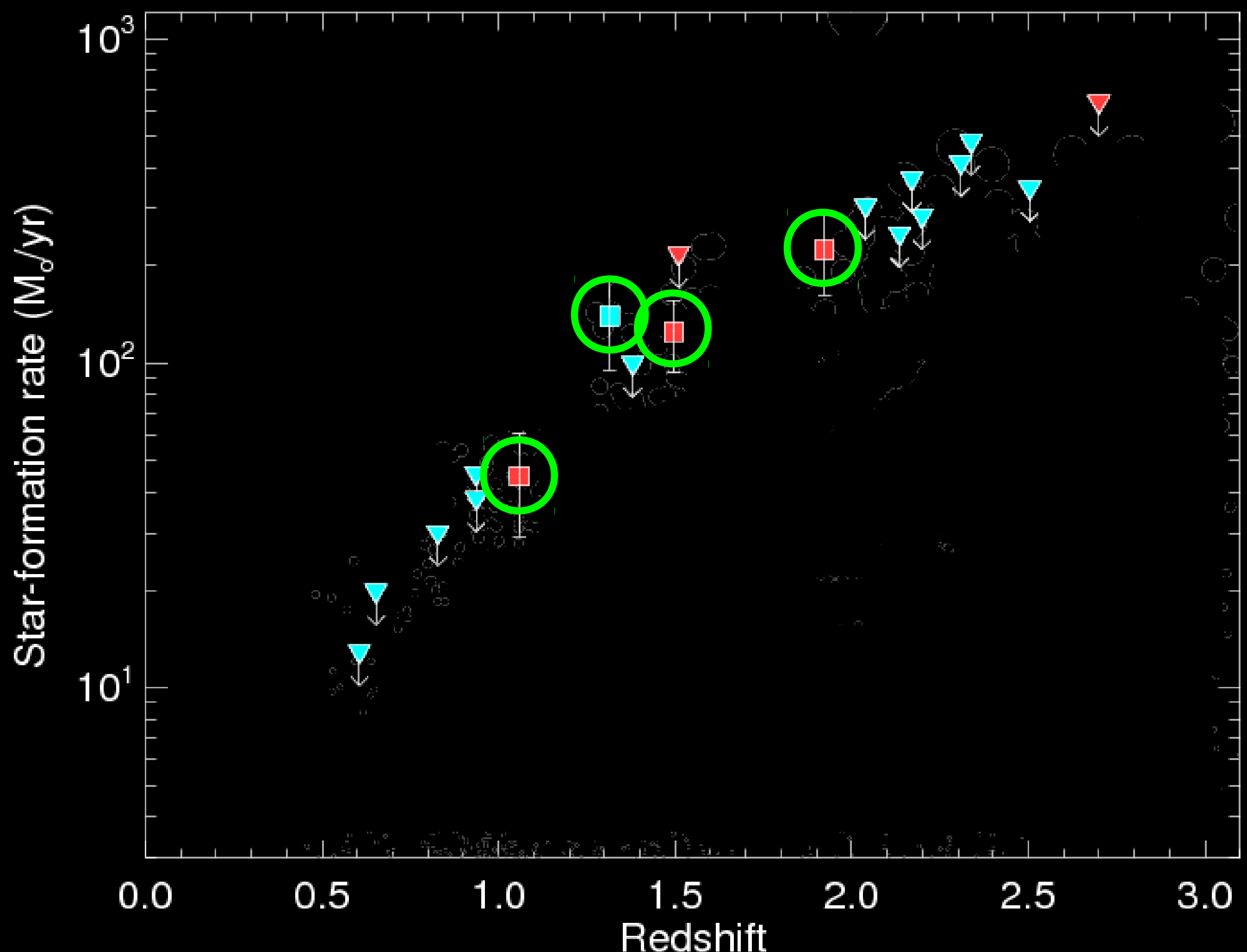

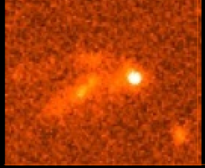

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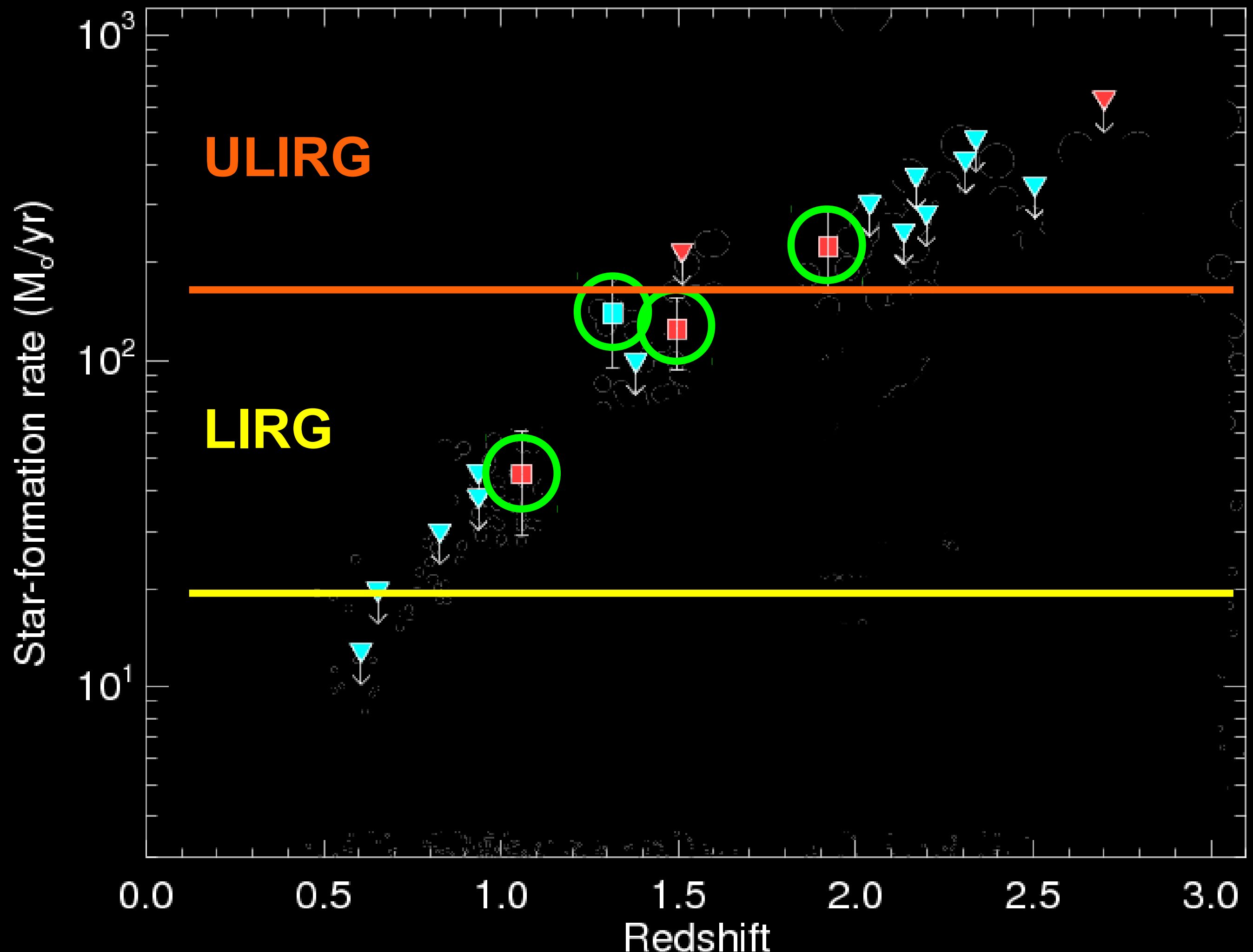
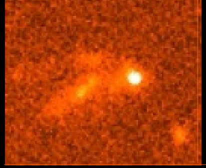
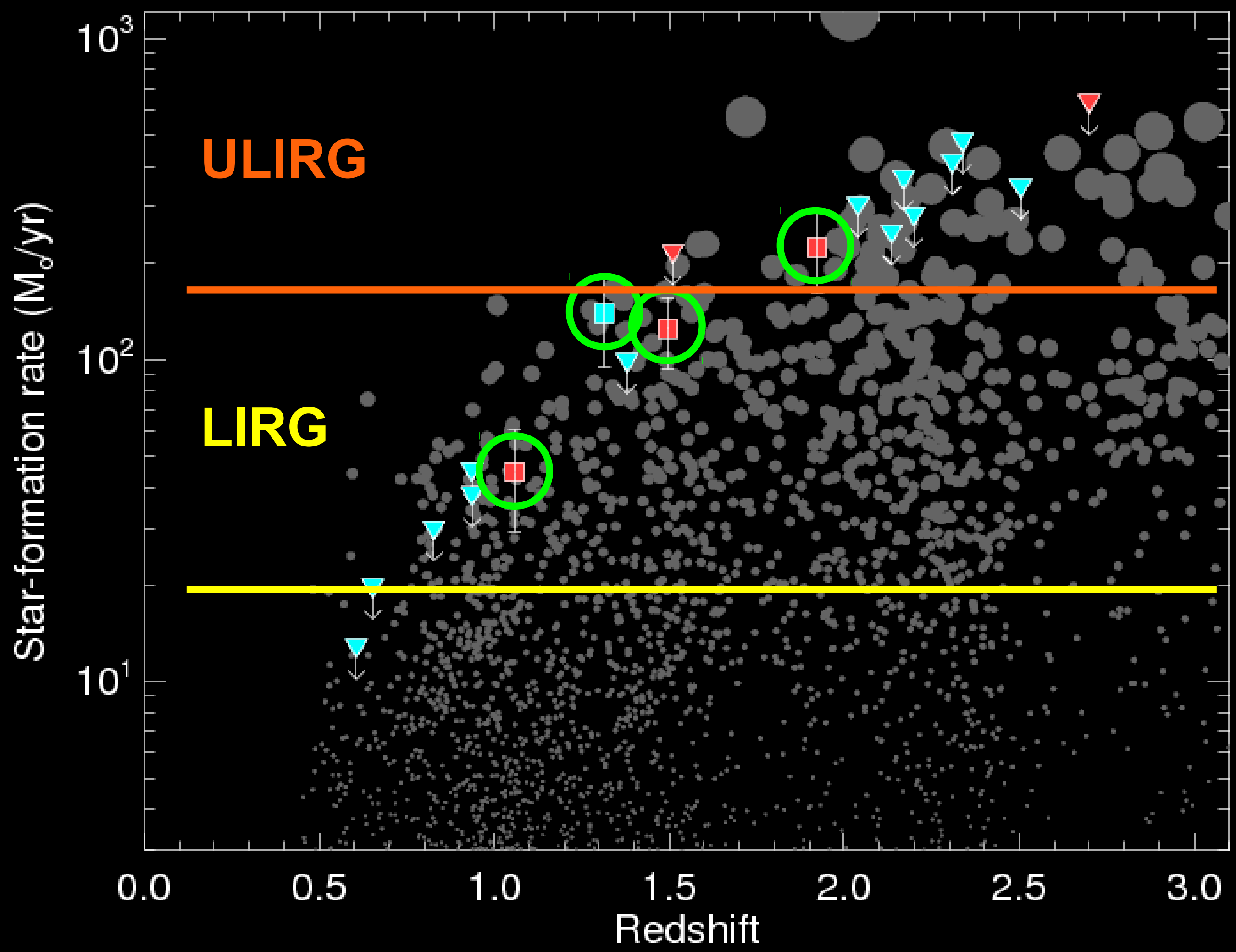
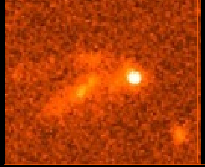




Host Star-Formation Rates from VLA

Four radio host detections (very luminous hosts – LIRGs/ULIRGs)
Consistent with expectations (~10% of high-z SFR in ULIRGs; ~40% in LIRGs.)





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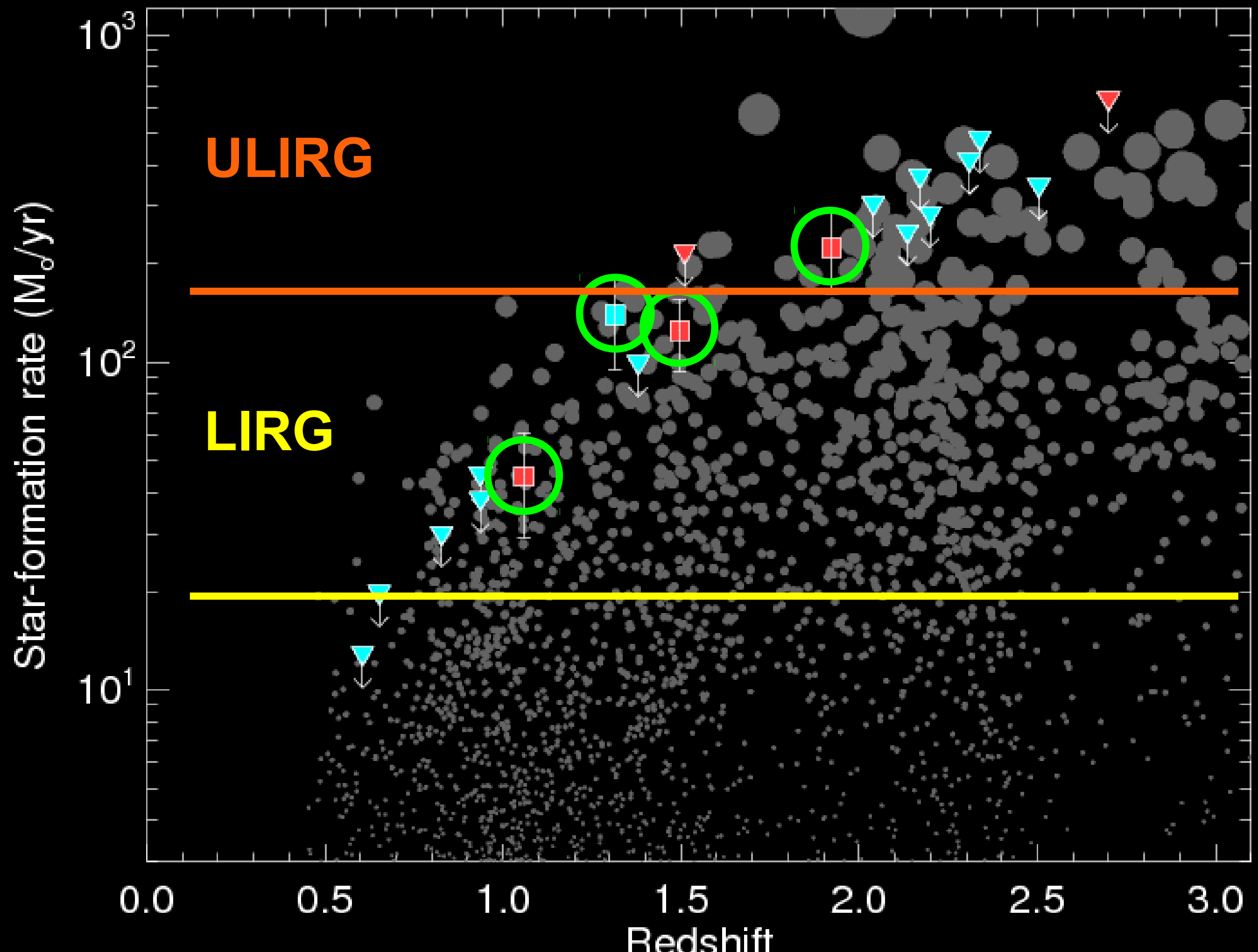
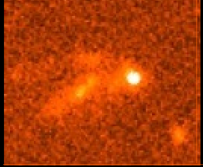


3/4 of detected hosts are from dark bursts!

(LIRGs/ULIRGs are dusty!)



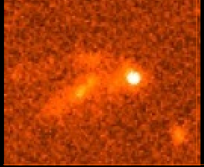
Conclusions from VLA Survey

GRBs do *not* strongly avoid or prefer extremely high-SFR galaxies at z~1 (LIRGs/ULIRGs)

If GRBs are heavily suppressed by metallicity, either:

- ULIRGs are not metal-rich
- Some other dependance (sSFR?) compensates

(Larger radio sample, ALMA, UV SFRs, etc. will tell us much more.)



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 of wind-driven momentum loss)
- Low ($<0.7\ Z_{\odot}$), 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
- ULIRGs *may* not be very metal-rich
- GRBs support a falling cosmic SFRD above z>4