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


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# Star Formation Tracers

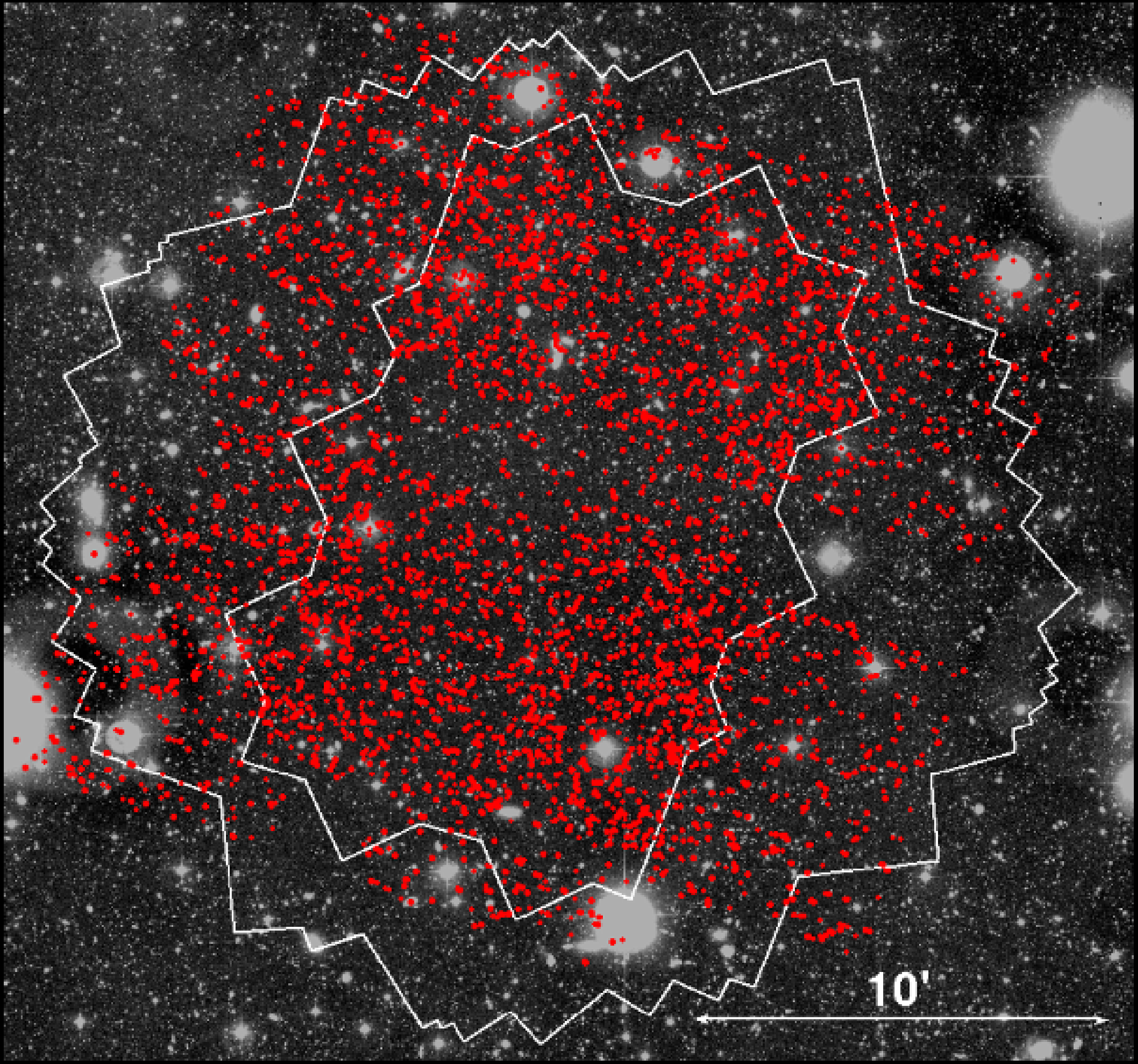
**When, where, and how did the stars in the Universe today form?**

→ *Find and quantify star formation as a function of environment and time.*

General idea:
Find an **observable** that scales roughly **linearly with star-formation rate**, independent of other factors.

**Ultraviolet emission**
(+reprocessed analogs: nebular lines, PAH lines, FIR)
from massive stars is the most common star-formation indicator.

# Field-Survey Strategy



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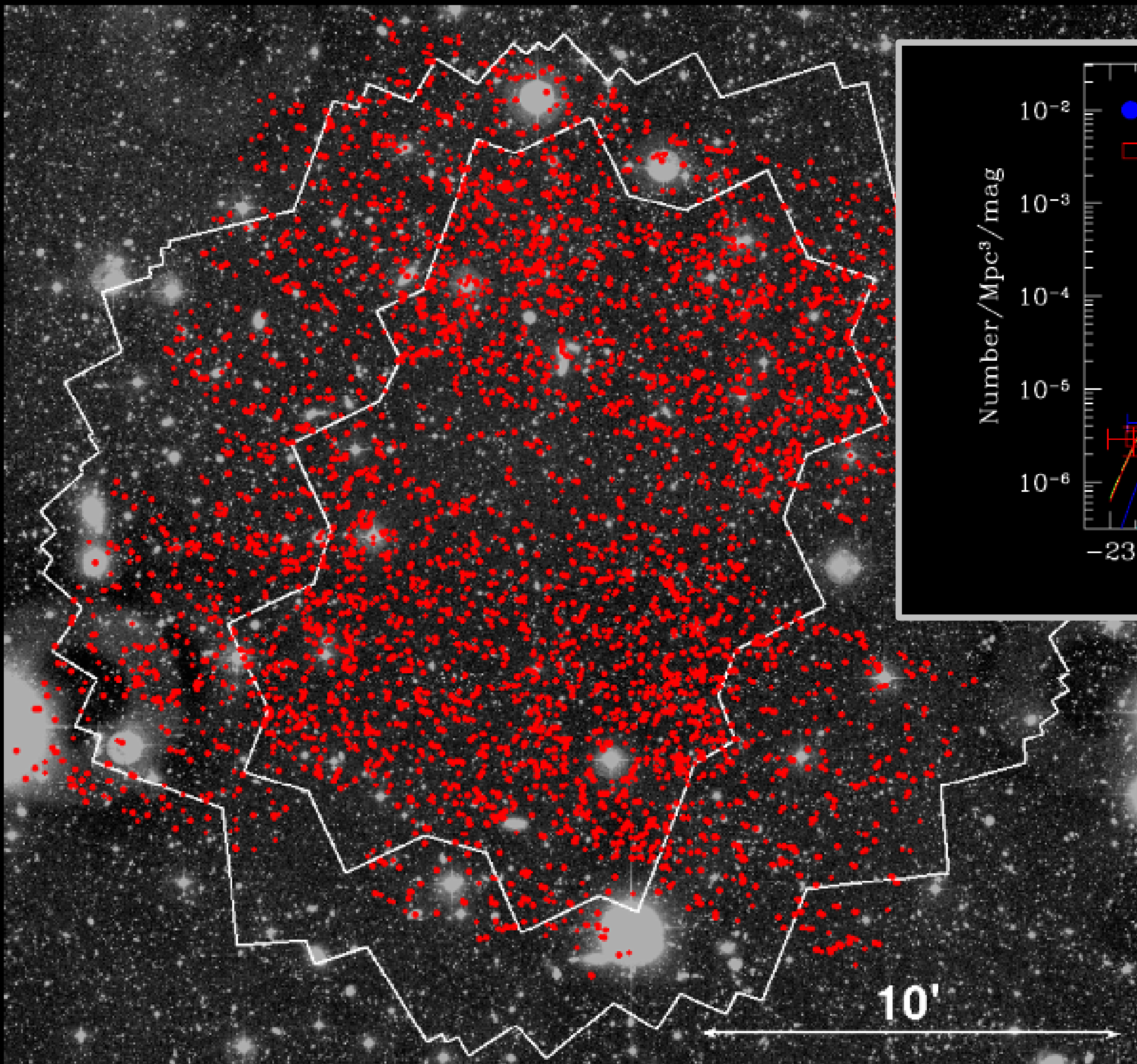
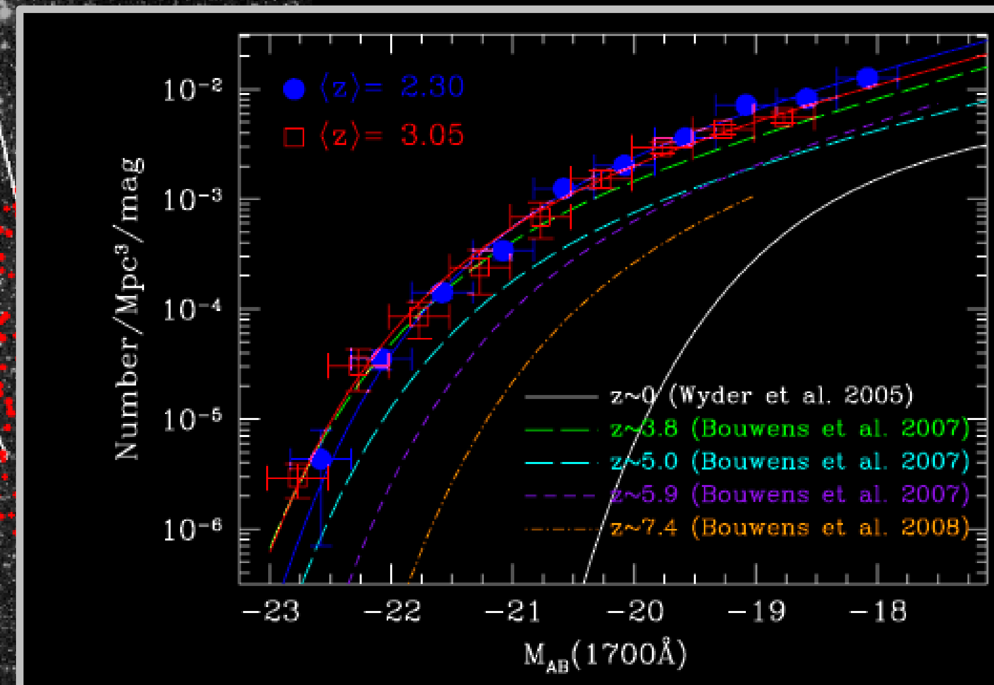
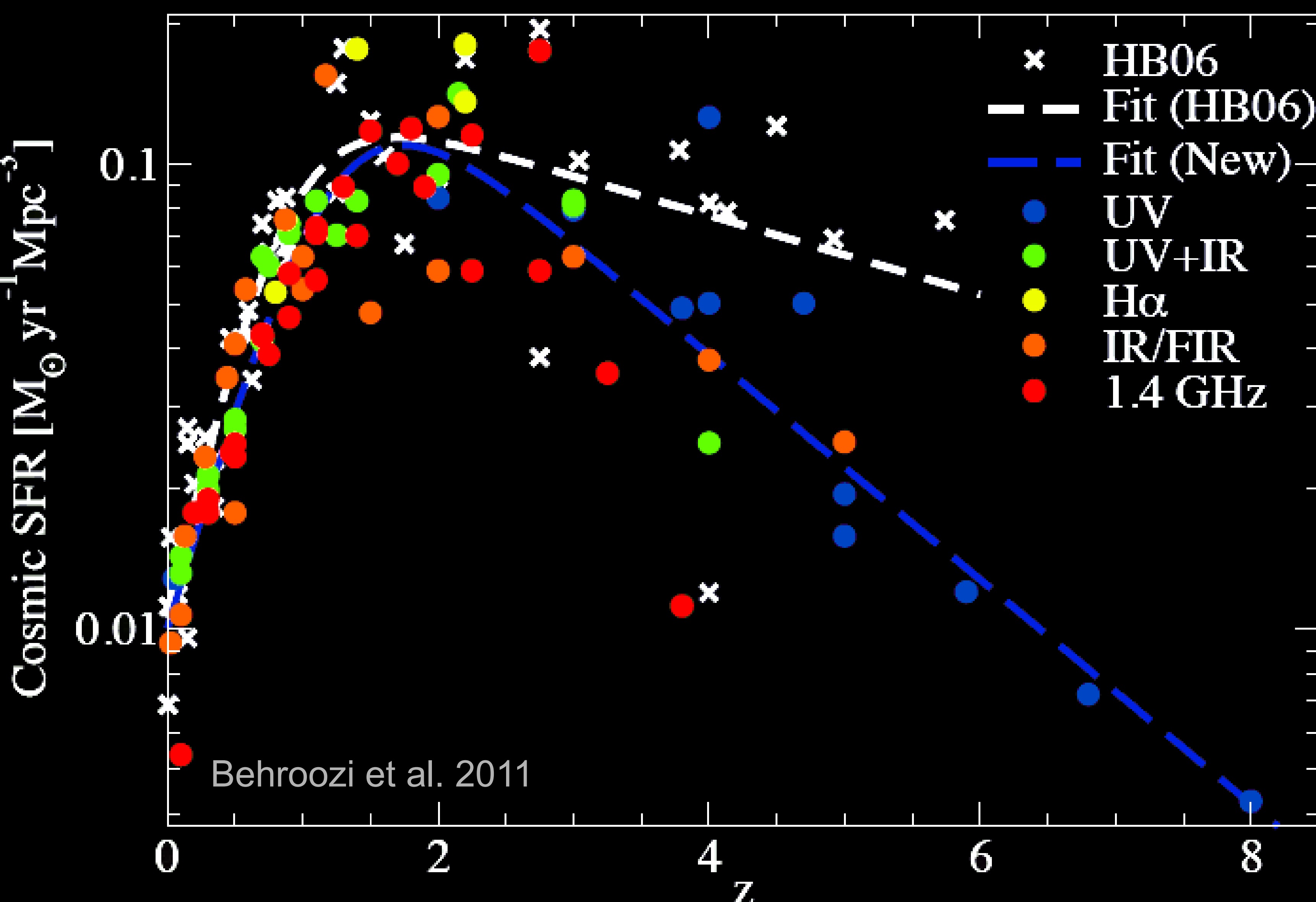



Reddy et al. 2009

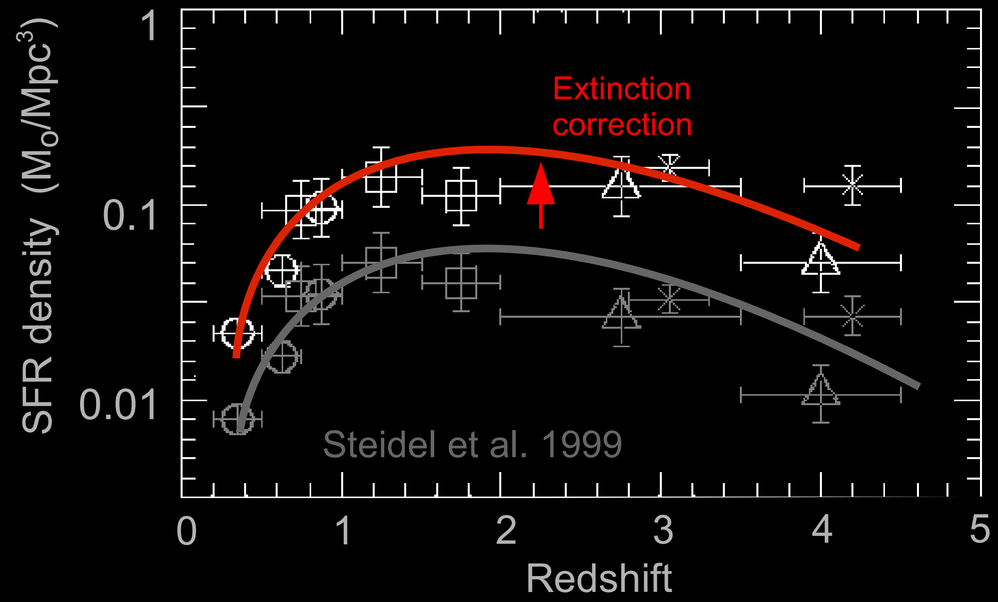
# Cosmic Star-Formation History



# Limitations of Field Surveys

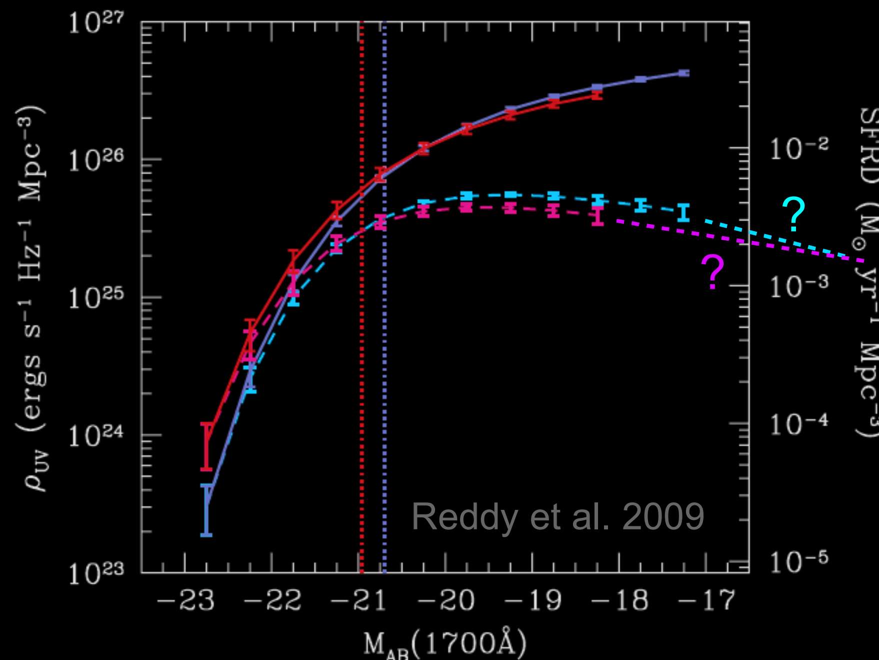
## Dust Correction

- **~80%** of UV light is absorbed by dust at z~2
- UV dust corrections are empirical (is Calzetti prescription universal? It fails for ULIRGs.)
- UV energy can be "recovered" at 8μm / FIR / submm, but these wavelengths have poor sensitivity to faint galaxies



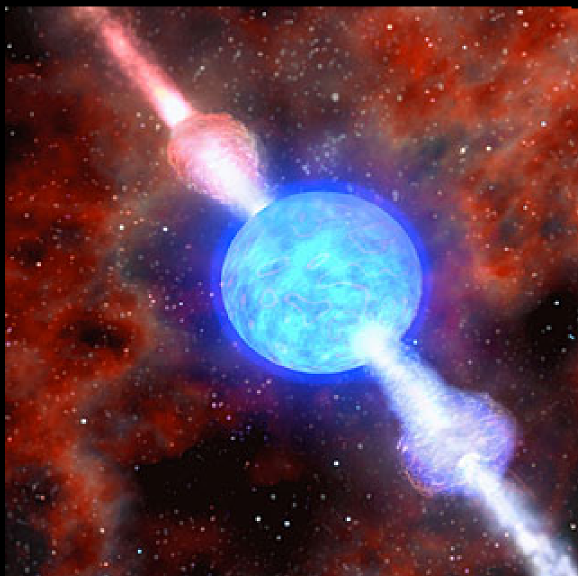

## Missing galaxies

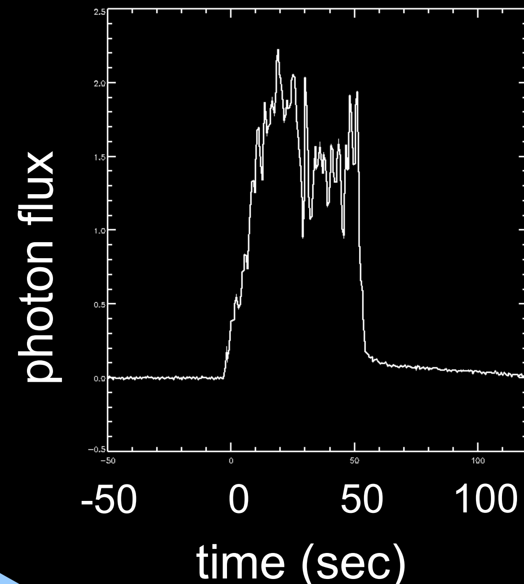
- Faint galaxies (<0.1 L*) require extrapolation from bright end
- Redshift measurement imposes further biases

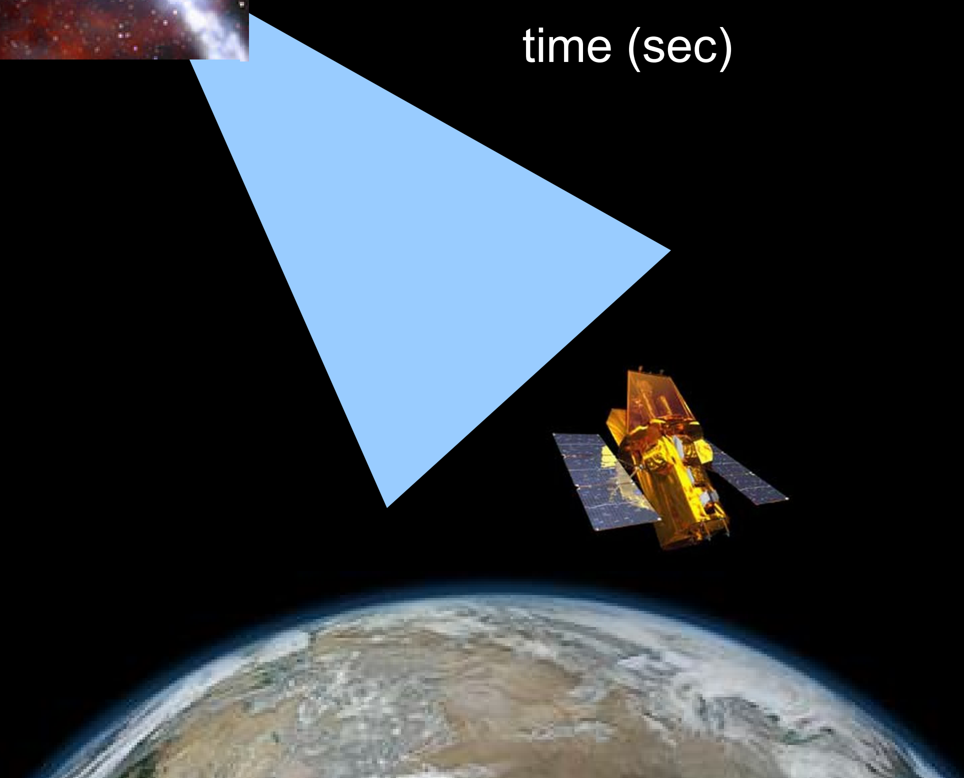



These problems are particularly limiting at z>3

# Gamma-Ray Bursts





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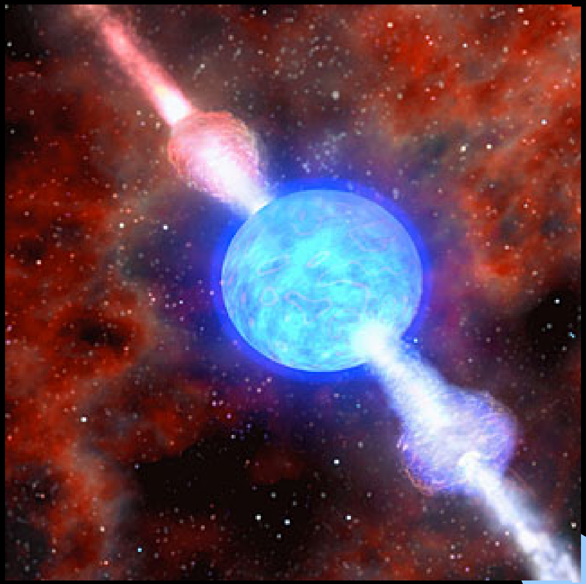

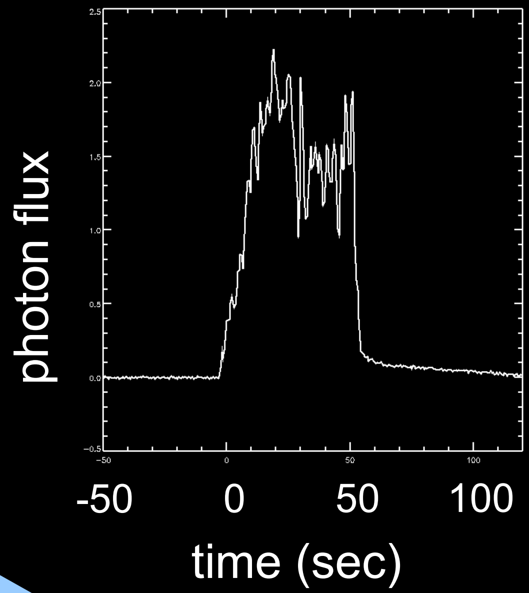


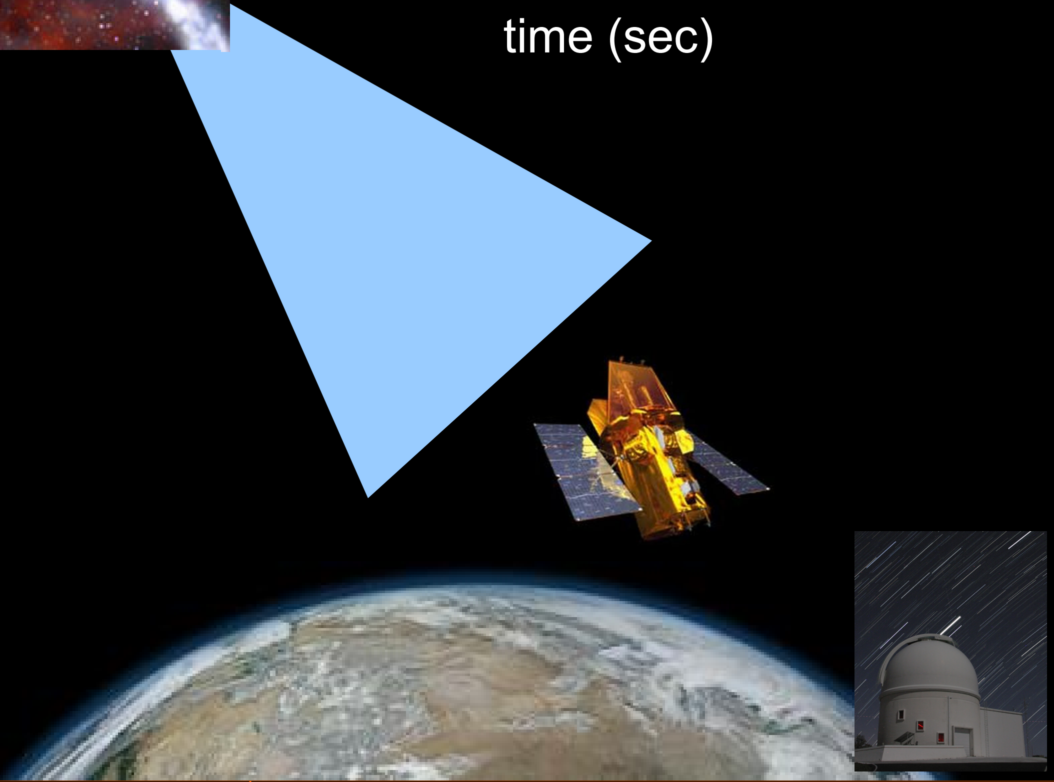

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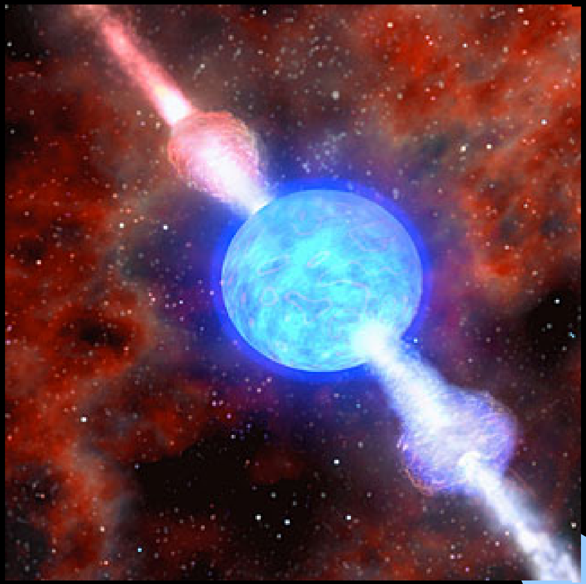

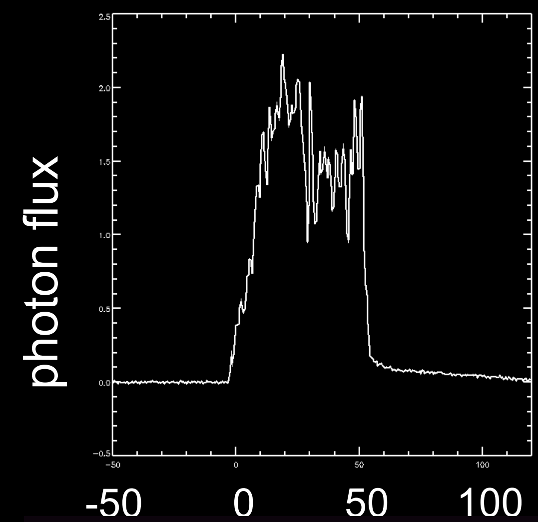


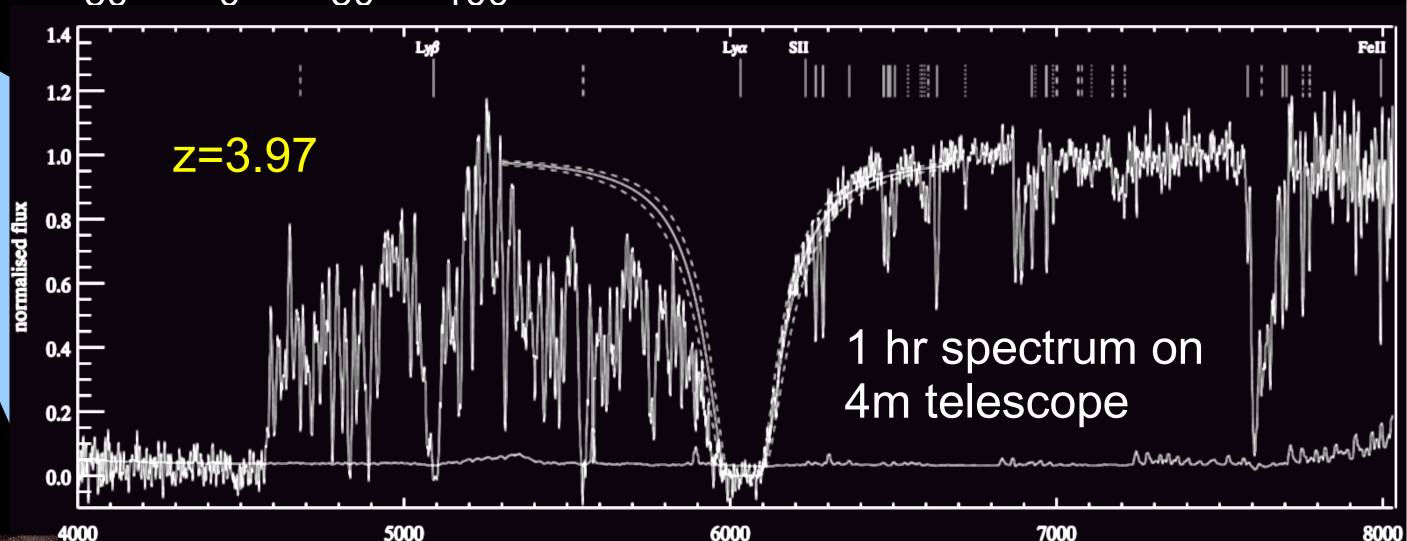


Starling+2005

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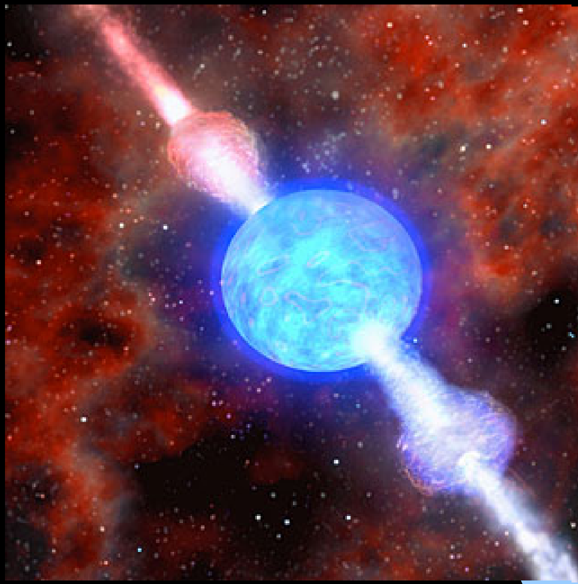
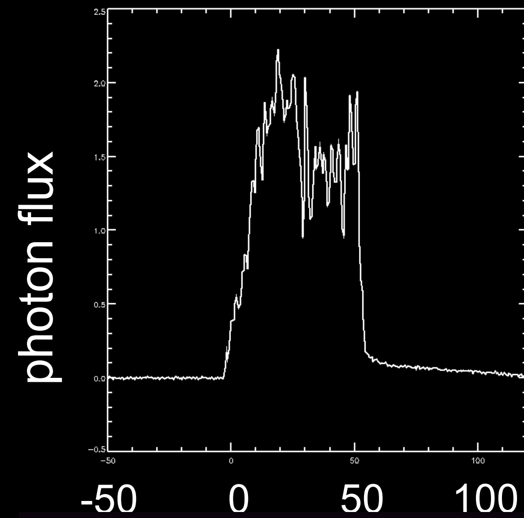
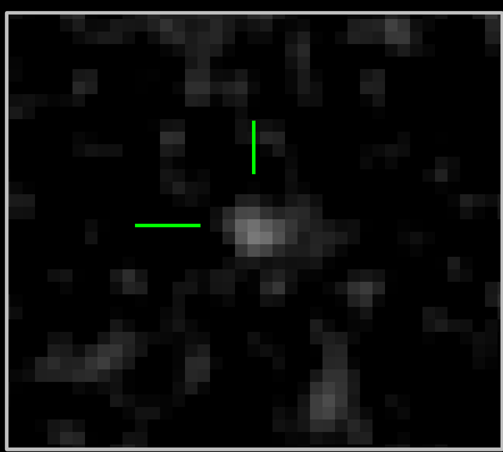
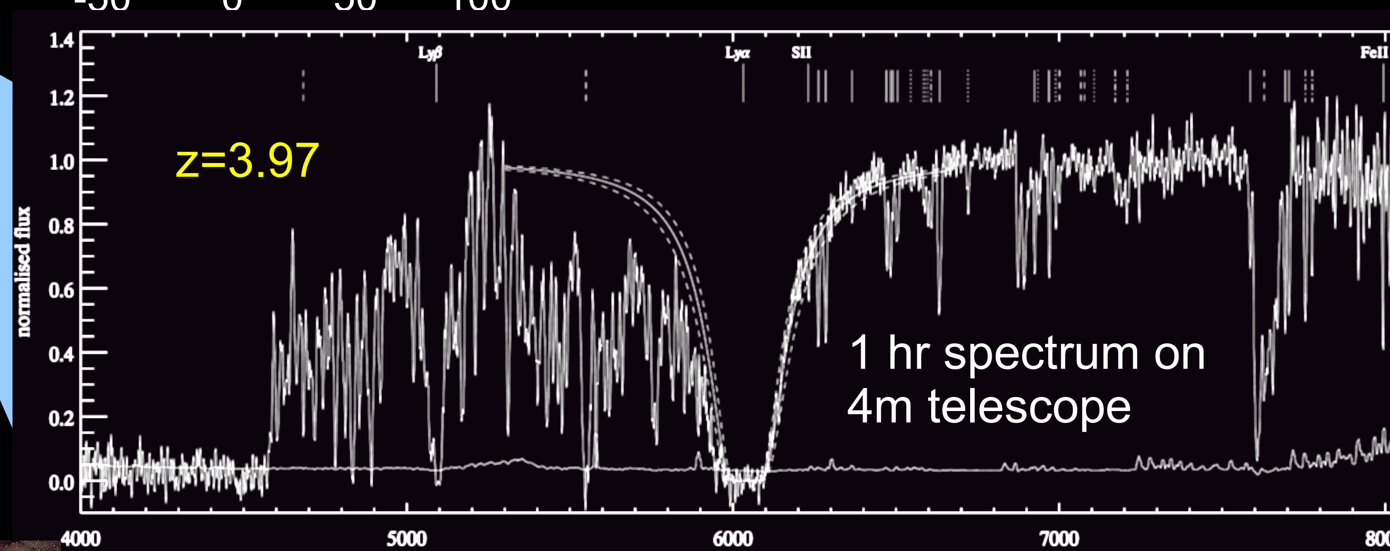







Starling+2005

# Advantages of GRB Selection

**Inexpensive**

Optical afterglow redshifts are cheap

(Host follow-up not as cheap, but still doable.)

**Dust-Unbiased**, in principle

Gamma-ray burst and X-ray/radio afterglows cut through dust

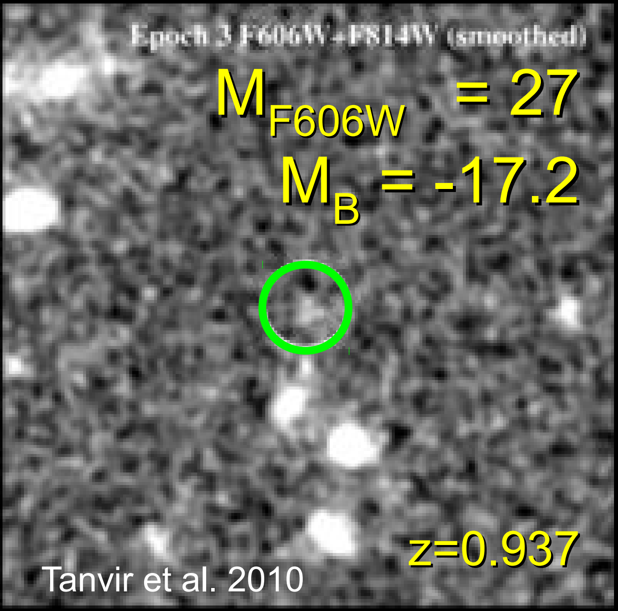
**Sensitive to sub-threshold SFR**

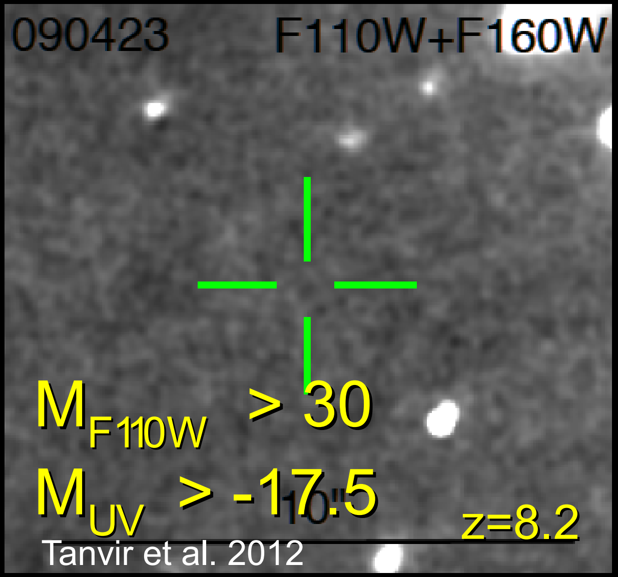
Host nondetections give a direct constraint on importance of in undetected galaxies

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

**No Cosmic Variance**

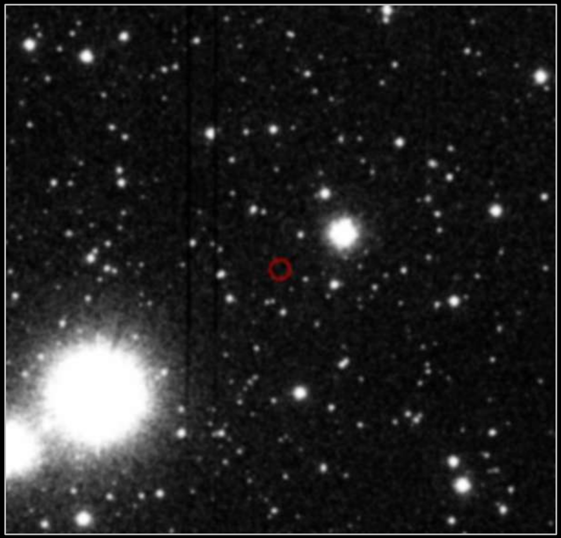
GRB satellites see (close to) the whole sky



# Disadvantages of GRB Selection

**Dust-biased**, in practice
- The "easy" redshift requires optical afterglow
  - (wiped out by dust)
- Host studies require a host position
  - (multiwavelength follow-up needed)

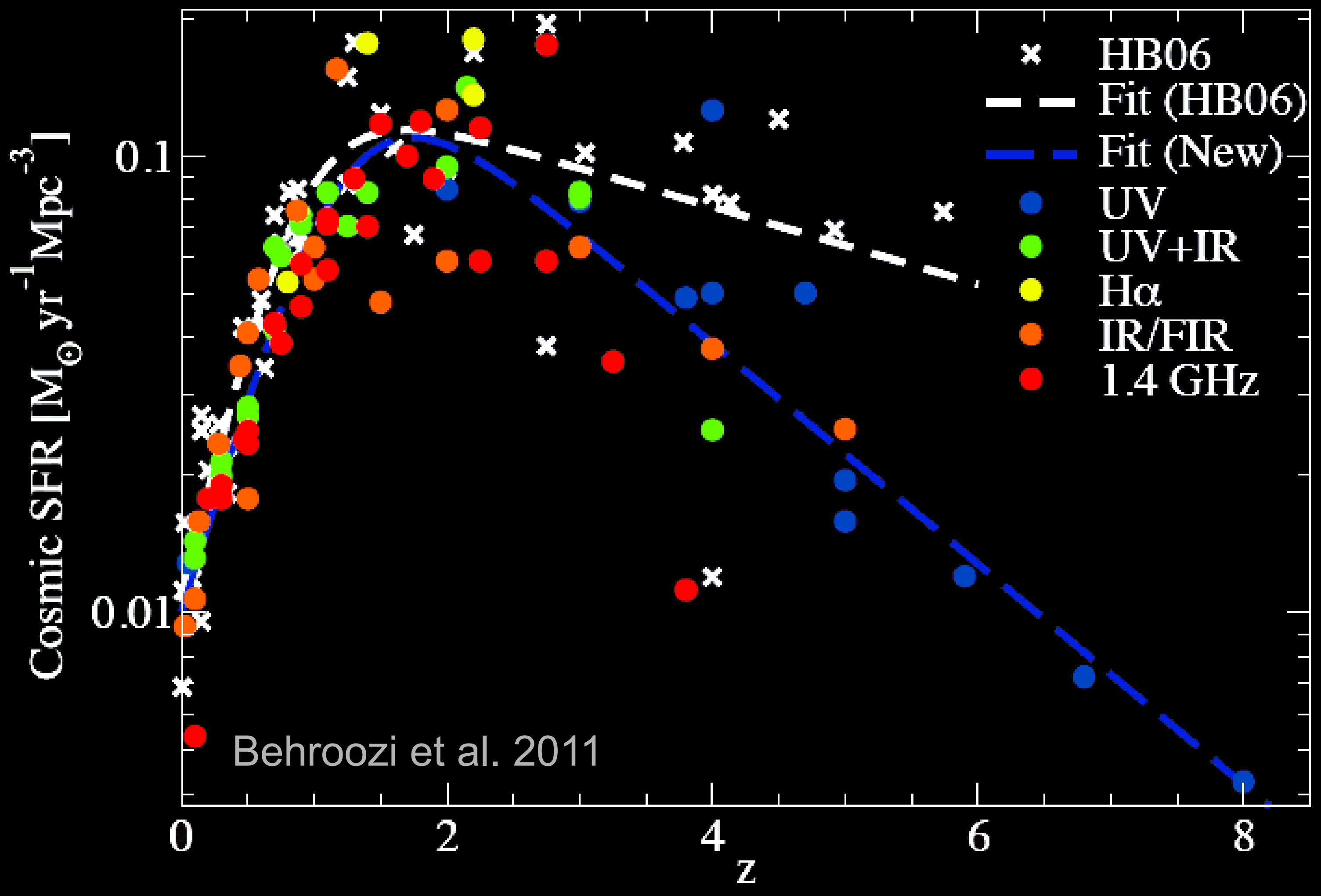


**Only 1 in ~1000 massive stars produces a GRB**
- Potential for strong sensitivity to additional variables
  - *other than SFR*!

# 200 Redshifts and Counting

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 120729A | 0.80 | 100418A | 0.6235 | 081008 | 1.967 | 071010A | 0.98 | 060605 | 3.78 |
| 120724A | 1.48 | 100316D | 0.059 | 081007A | 0.5295 | 071003 | 1.6043 | 060602A | 0.787 |
| 120714B | 0.3984 | 100302A | 4.813 | 080916A | 0.689 | 070810A | 2.17 | 060526 | 3.21 |
| 120712A | 4.1745 | 100219A | 4.6667 | 080913A | 6.7 | 070802 | 2.45 | 060522 | 5.11 |
| 120422A | 0.283 | 091208B | 1.0633 | 080906A | 2.0 | 070721B | 3.626 | 060512 | 2.1 |
| 120404A | 2.876 | 091127 | 0.490 | 080905B | 2.374 | 070612A | 0.617 | 060510B | 4.9 |
| 120401A | 4.5 | 091109A | 3.076 | 080810 | 3.35 | 070611 | 2.04 | 060505 | 0.089 |
| 120327A | 2.813 | 091029 | 2.752 | 080805 | 1.505 | 070529 | 2.4996 | 060502A | 1.51 |
| 120326A | 1.798 | 091024 | 1.092 | 080804 | 2.2045 | 070506 | 2.31 | 060418 | 1.49 |
| 120119A | 1.728 | 091020 | 1.71 | 080721 | 2.602 | 070419A | 0.97 | 060223A | 4.41 |
| 111229A | 1.3805 | 091018 | 0.971 | 080710 | 0.845 | 070411 | 2.954 | 060218 | 0.0331 |
| 111228A | 0.716 | 090927 | 1.37 | 080707 | 1.23 | 070318 | 0.840 | 060210 | 3.91 |
| 111209A | 0.677 | 090926B | 1.24 | 080607 | 3.036 | 070306 | 1.4959 | 060206 | 4.05 |
| 111107A | 2.893 | 090812 | 2.452 | 080605 | 1.6398 | 070208 | 1.165 | 060202 | 0.783 |
| 111008A | 4.9898 | 090809 | 2.737 | 080604 | 1.416 | 070110 | 2.352 | 060124 | 2.296 |
| 111005A | 0.0132 | 090726 | 2.71 | 080603B | 2.69 | 061222B | 3.355 | 060116 | 6.60 |
| 110818A | 3.36 | 090715B | 3.00 | 080520 | 1.545 | 061222A | 2.088 | 060115 | 3.53 |
| 110808A | 1.348 | 090618 | 0.54 | 080516 | 3.2 | 061126 | 1.159 | 060108 | 2.03 |
| 110801A | 1.858 | 090529 | 2.625 | 080430 | 0.767 | 061121 | 1.314 | 051111 | 1.55 |
| 110731A | 2.83 | 090519 | 3.85 | 080413B | 1.10 | 061110B | 3.44 | 051109B | 0.080 |
| 110715A | 0.82 | 090516A | 4.109 | 080413A | 2.433 | 061110A | 0.757 | 051109A | 2.346 |
| 110503A | 1.613 | 090426 | 2.609 | 080411 | 1.03 | 061021 | 0.3463 | 051016B | 0.9364 |
| 110422A | 1.770 | 090424 | 0.544 | 080330 | 1.51 | 061007 | 1.261 | 050922C | 2.199 |
| 110328A | 0.354 | 090423 | 8.2 | 080319C | 1.95 | 060927 | 5.467 | 050908 | 3.35 |
| 110213A | 1.46 | 090418A | 1.608 | 080319B | 0.937 | 060926 | 3.20 | 050904 | 6.29 |
| 110205A | 2.22 | 090313 | 3.375 | 080310 | 2.4266 | 060912A | 0.937 | 050826 | 0.296 |
| 110128A | 2.339 | 090205 | 4.6497 | 080210 | 2.641 | 060908 | 1.8836 | 050824 | 0.83 |
| 101219B | 0.5519 | 090102 | 1.547 | 080129 | 4.349 | 060906 | 3.685 | 050820A | 2.6147 |
| 100906A | 1.727 | 081228 | 3.8 | 080109 | 0.0064 | 060904B | 0.703 | 050814 | 5.3 |
| 100901A | 1.408 | 081222 | 2.77 | 071122 | 1.14 | 060814A | 0.84 | 050802 | 1.71 |
| 100816A | 0.804 | 081203A | 2.1 | 071117 | 1.331 | 060729 | 0.54 | 050801 | 1.56 |
| 100814A | 1.44 | 081121 | 2.512 | 071112C | 0.8230 | 060714 | 2.71 | 050730 | 3.969 |
| 100728B | 2.106 | 081118A | 2.58 | 071031 | 2.692 | 060708 | 1.92 | 050603 | 2.821 |
| 100621A | 0.542 | 081109A | 0.9787 | 071025 | 5.2 | 060707 | 3.43 | 050525A | 0.606 |
| 100513A | 4.8 | 081029 | 3.8479 | 071020 | 2.145 | 060614 | 0.125 | 050505 | 4.27 |
| 100425A | 1.755 | 081028A | 3.038 | 071010B | 0.947 | 060607A | 3.082 | 050416A | 0.6535 |

# High-z SF History from GRBs



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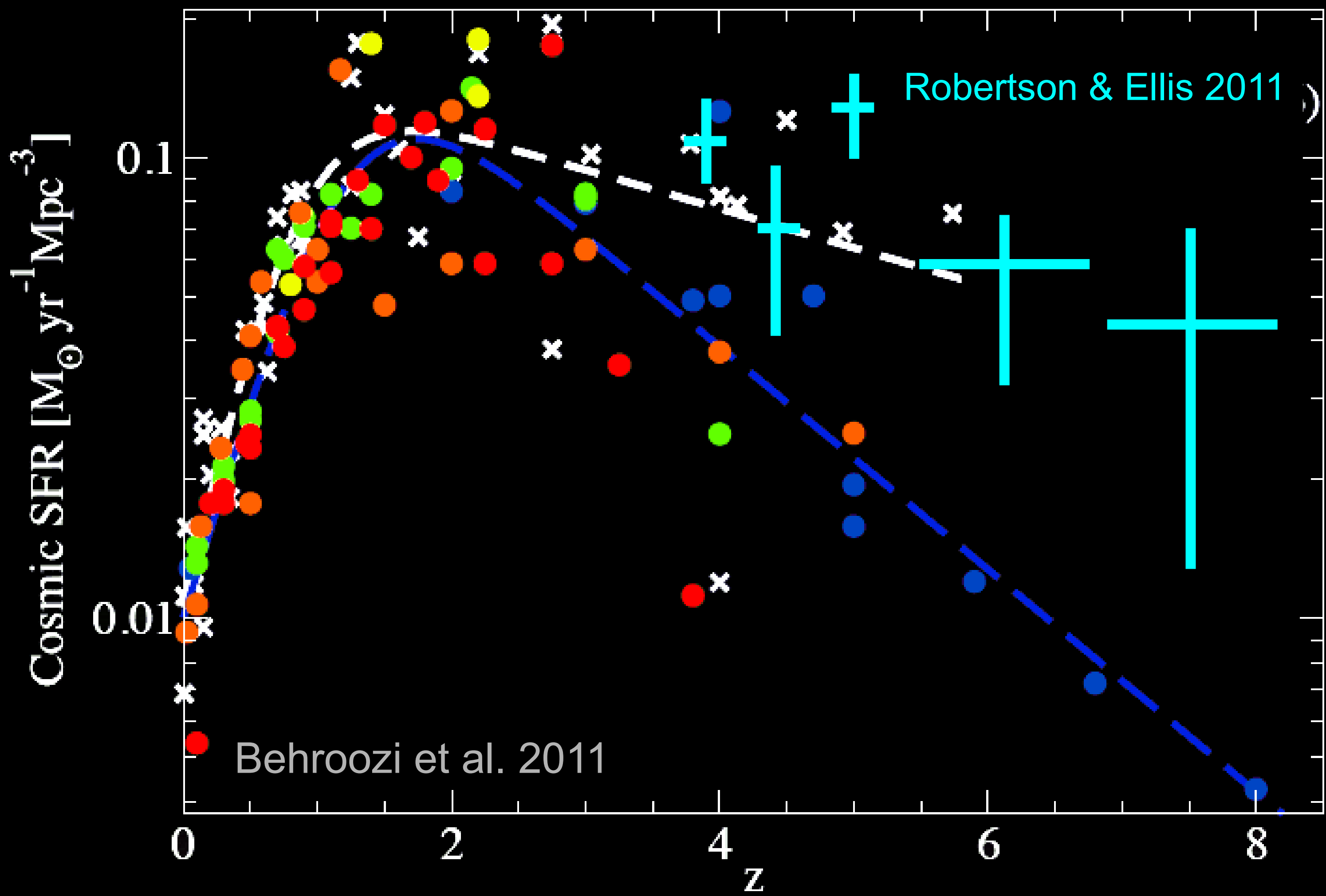

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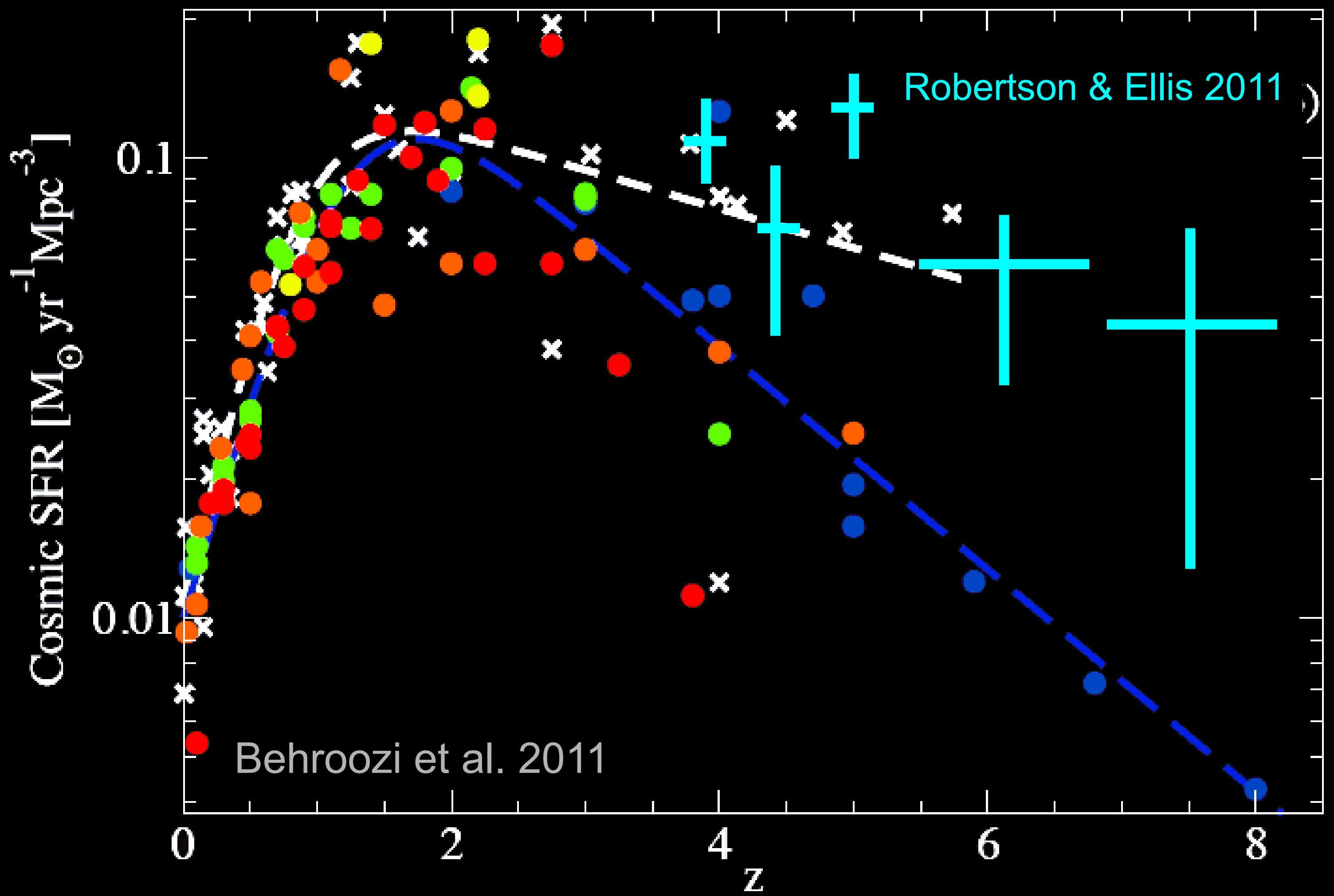


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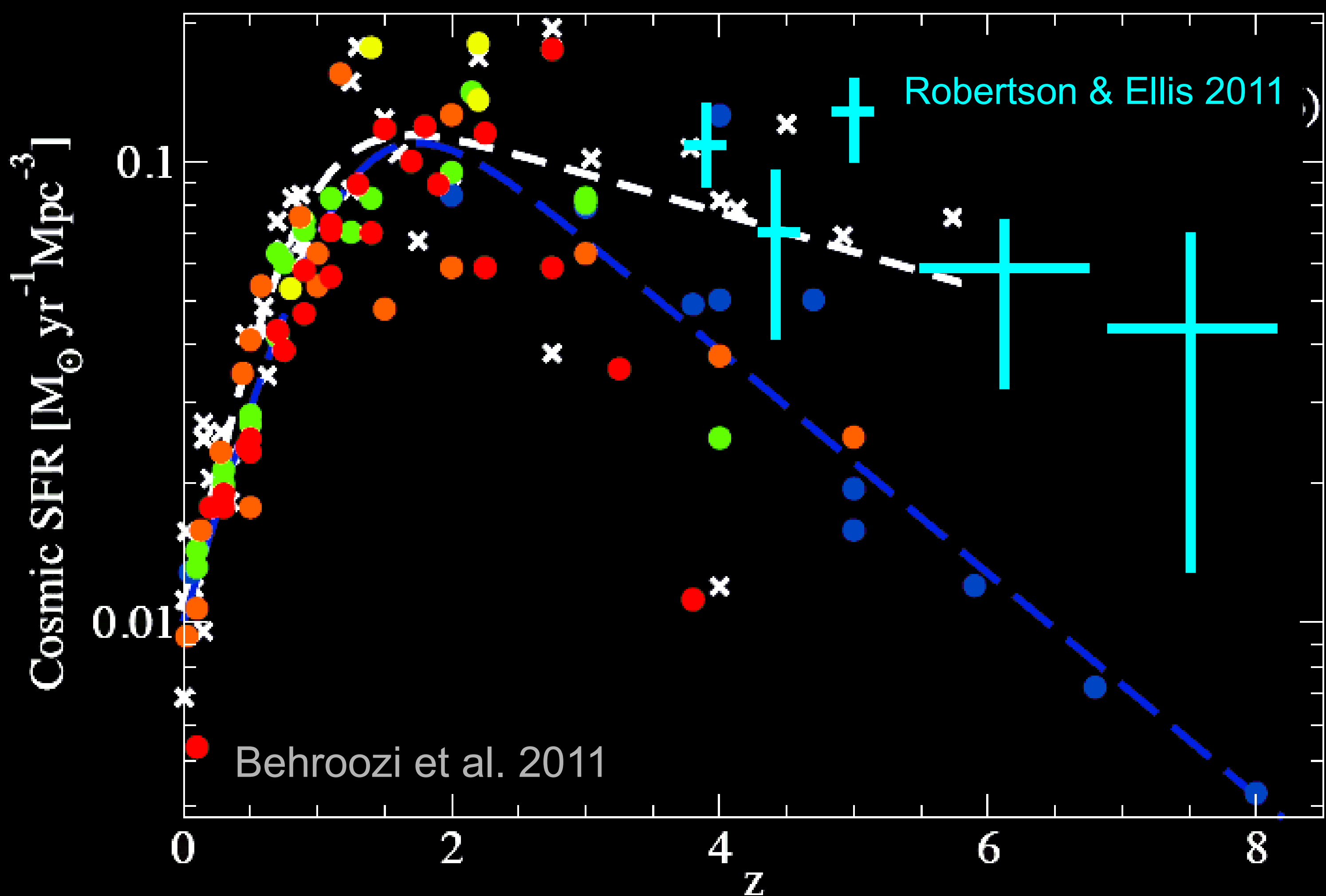



1. Much more star-formation in high redshift systems than field surveys are indicating

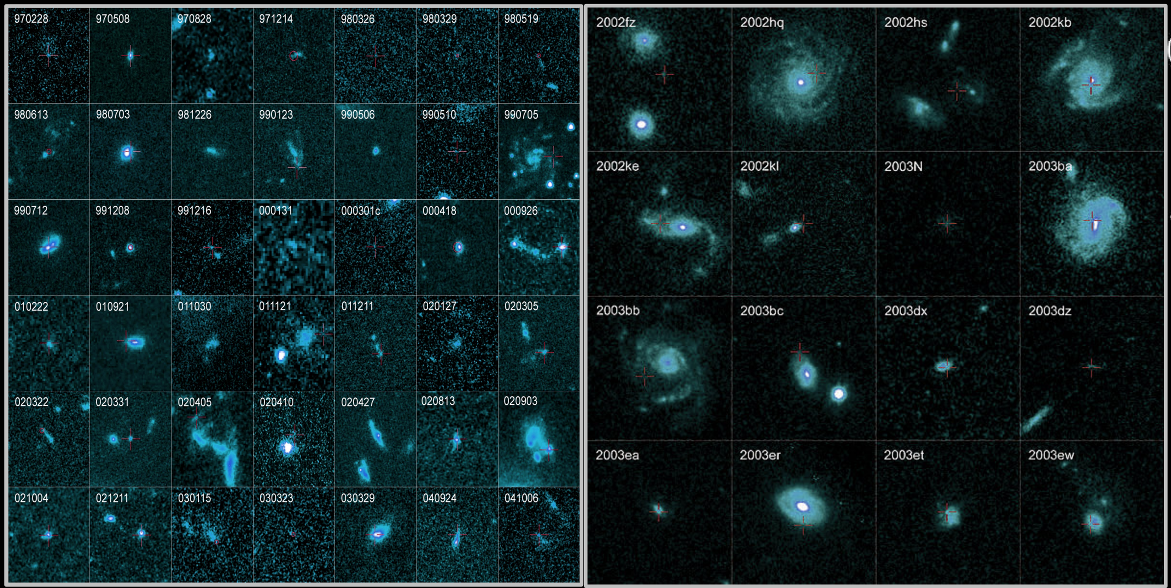
2. Many GRBs missed due to dust.

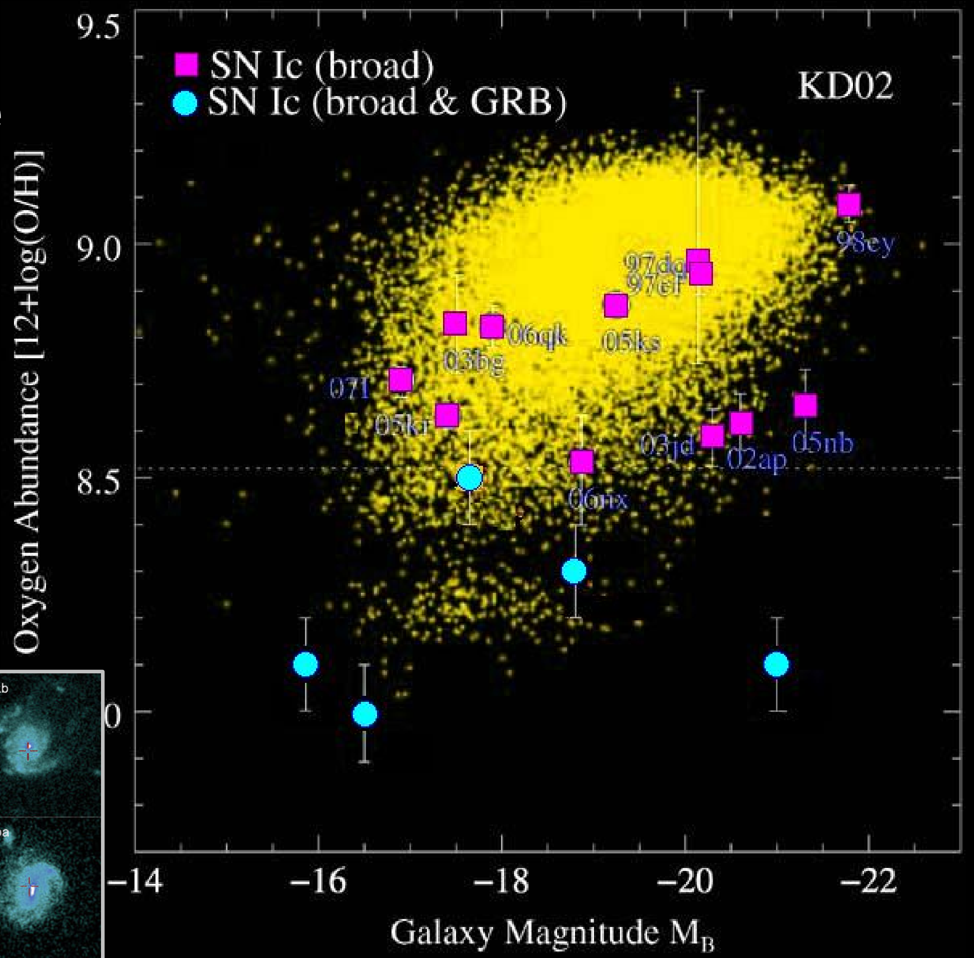
3. GRBs are imperfect SFR tracers.

# Differences Persist at z~0.5

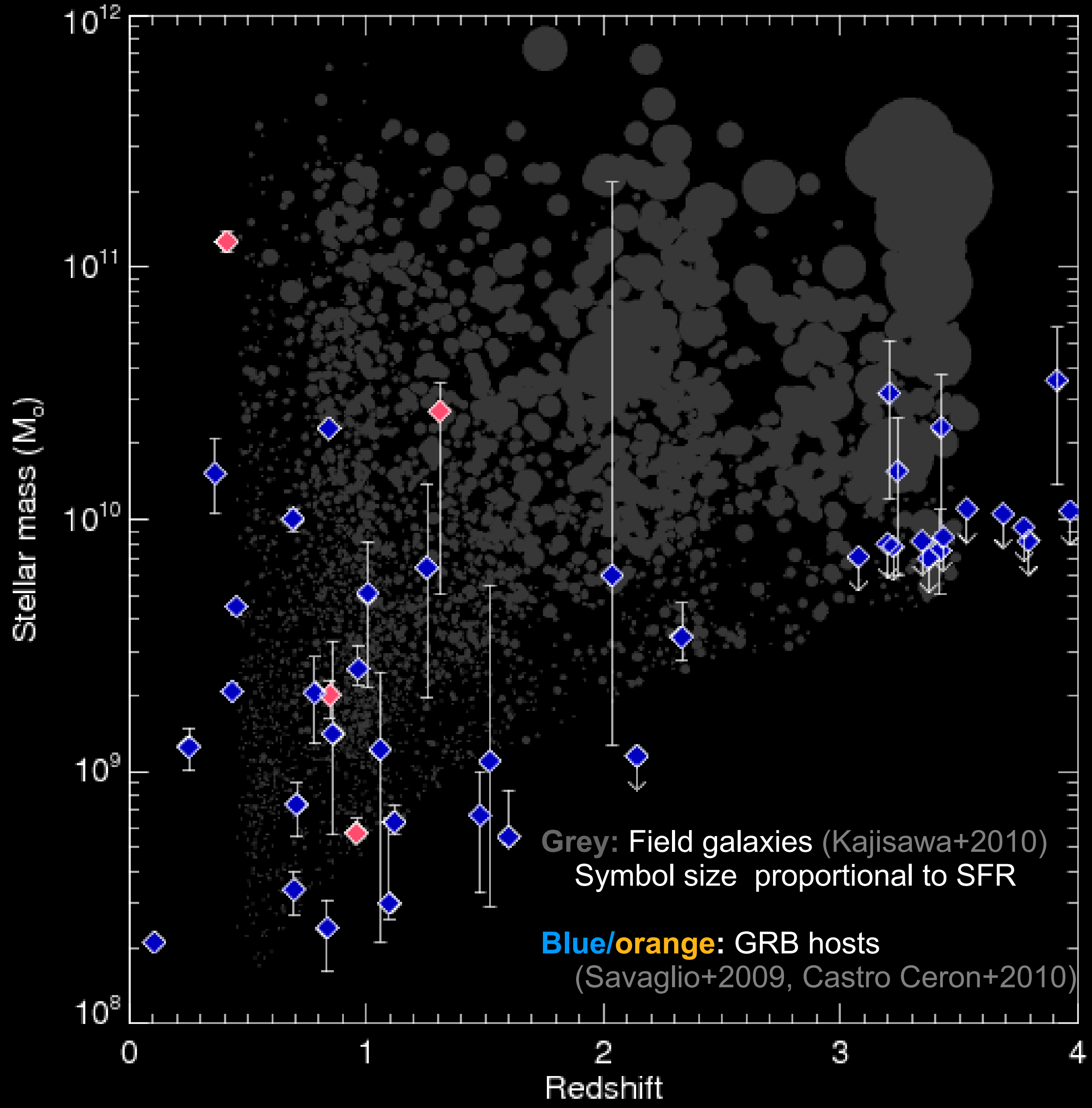
Low-z GRB hosts have lower metallicitities than Ic supernovae
Modjaz et al. 2008

Low-z GRB hosts are more irregular than Ib supernova hosts
Fruchter et al. 2006



# Differences Persist at z~1-3



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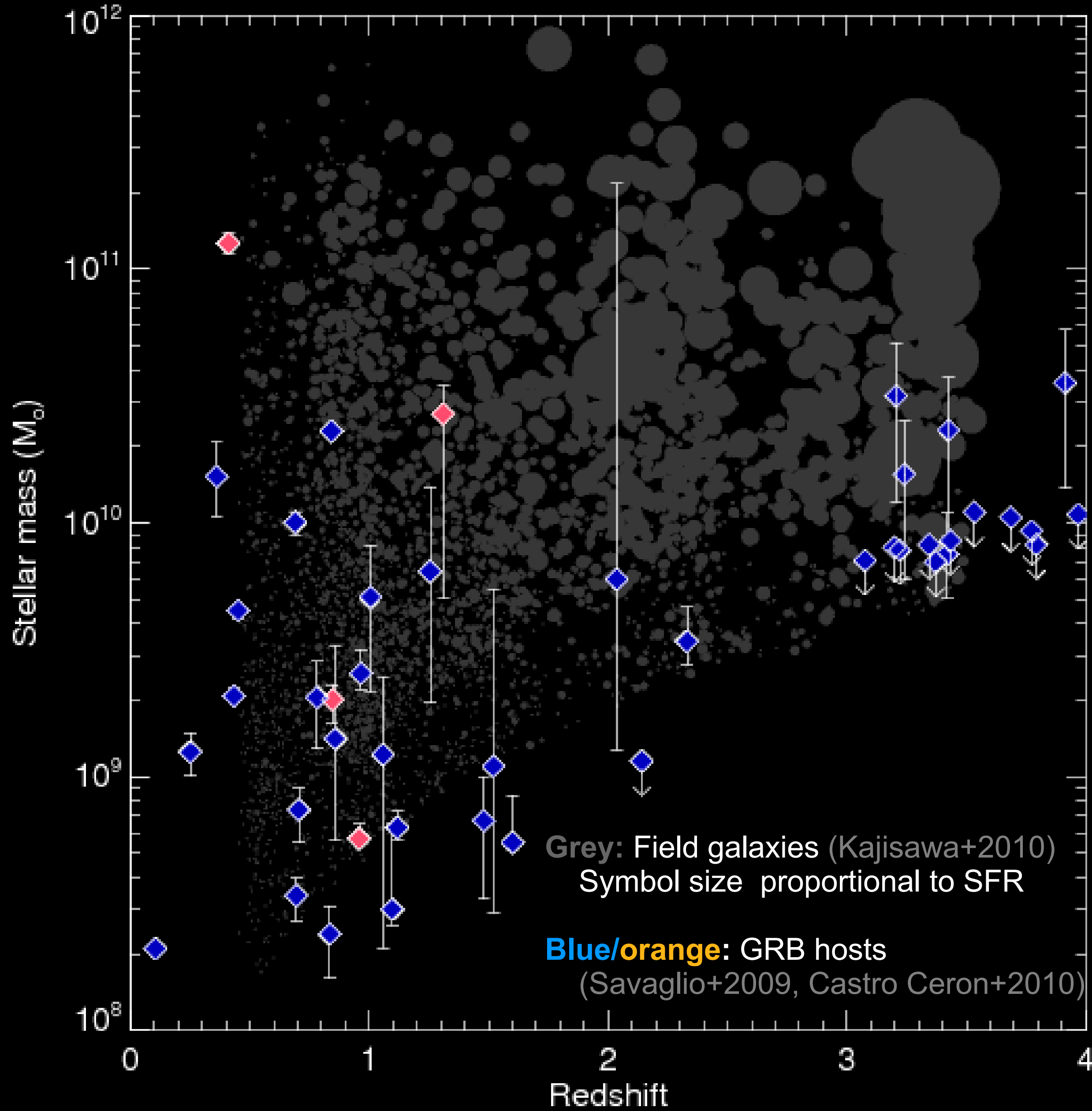


Median mass of z~1 hosts only ~$10^9$ $M_o$;
very few above >$10^{10}$ $M_o$

Castro Ceron+2010

Similar dearth of high-SFR, dusty galaxies (LIRGs/ULIRGs)

Le Floch+2006

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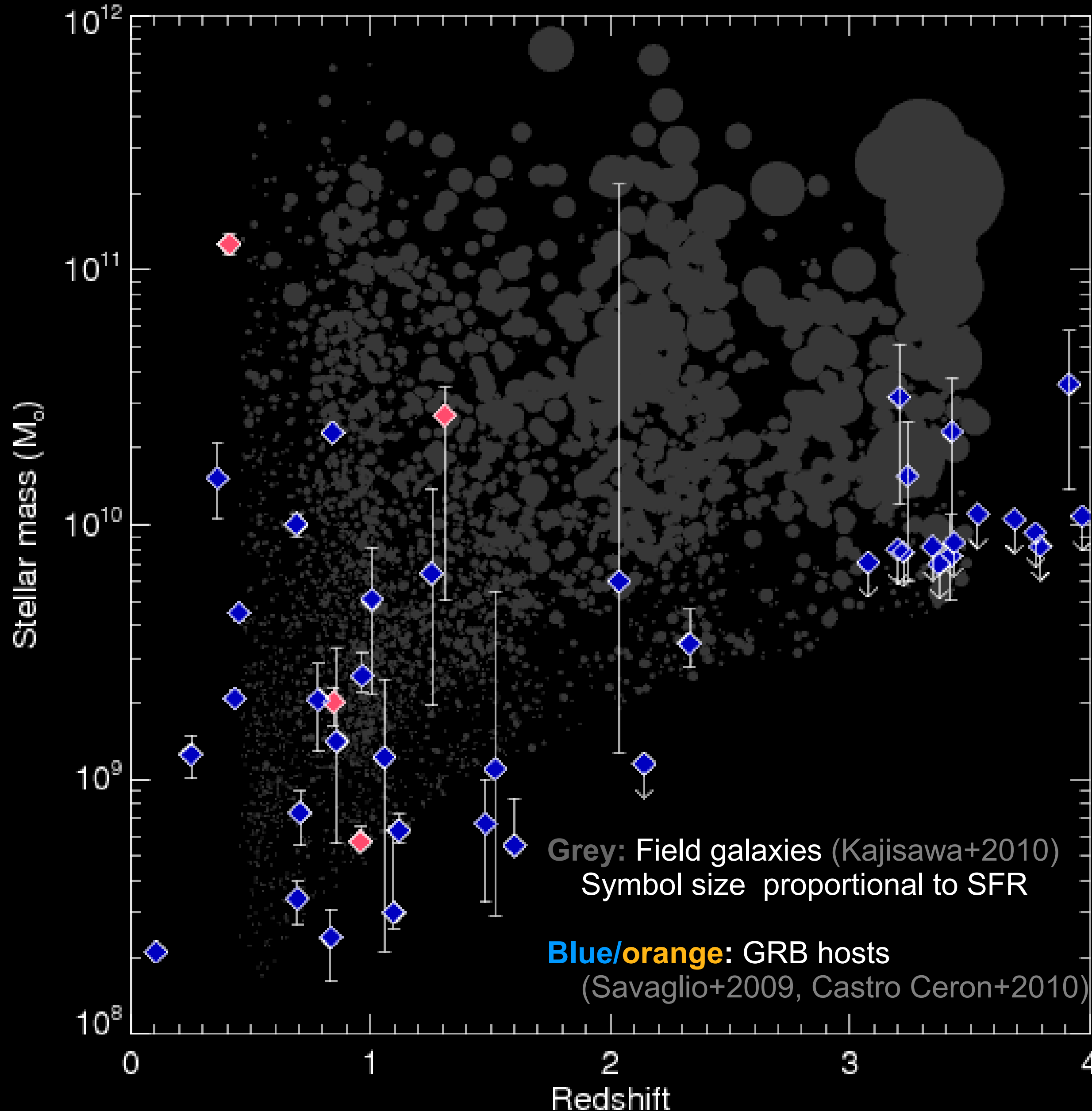


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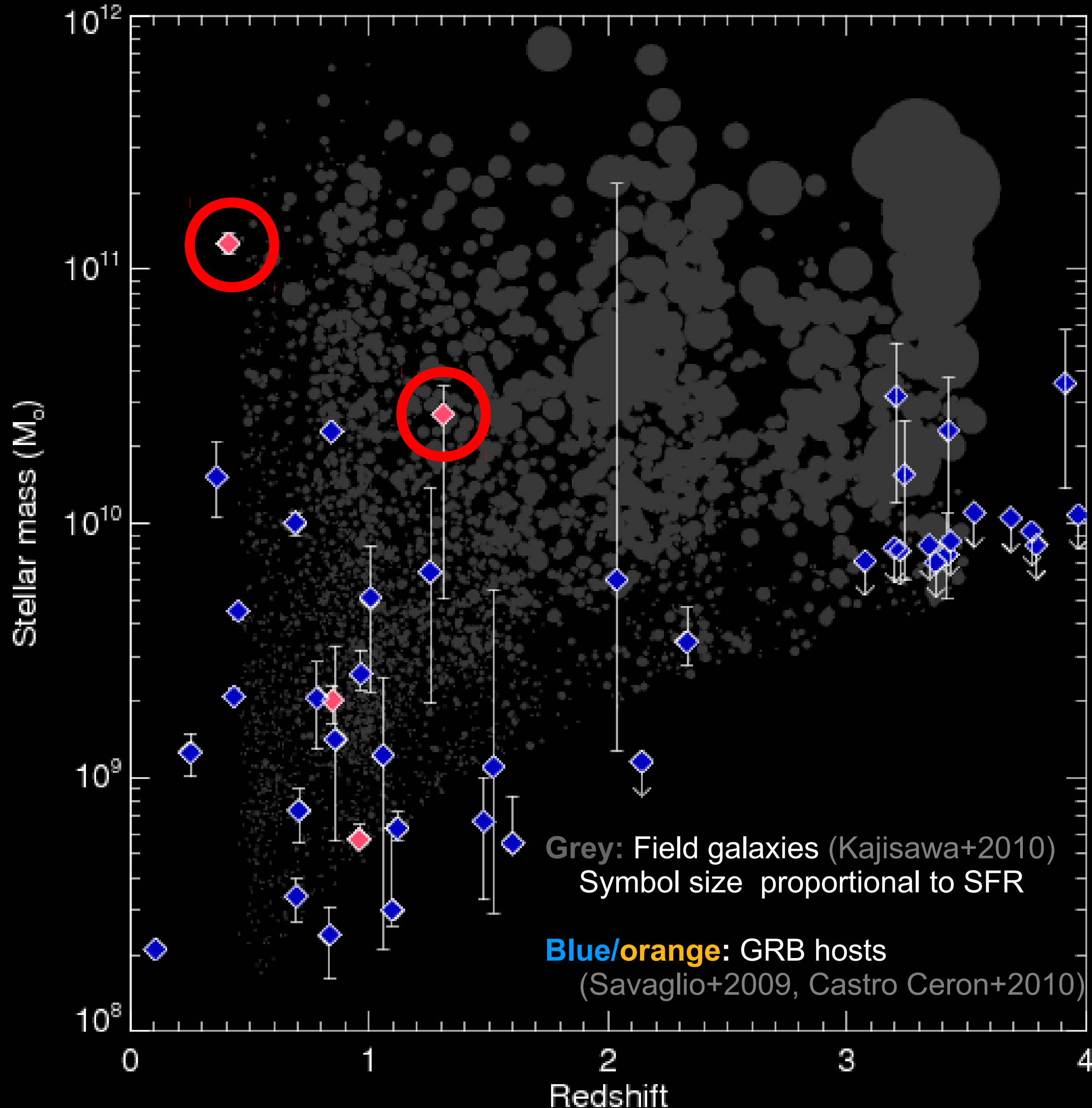


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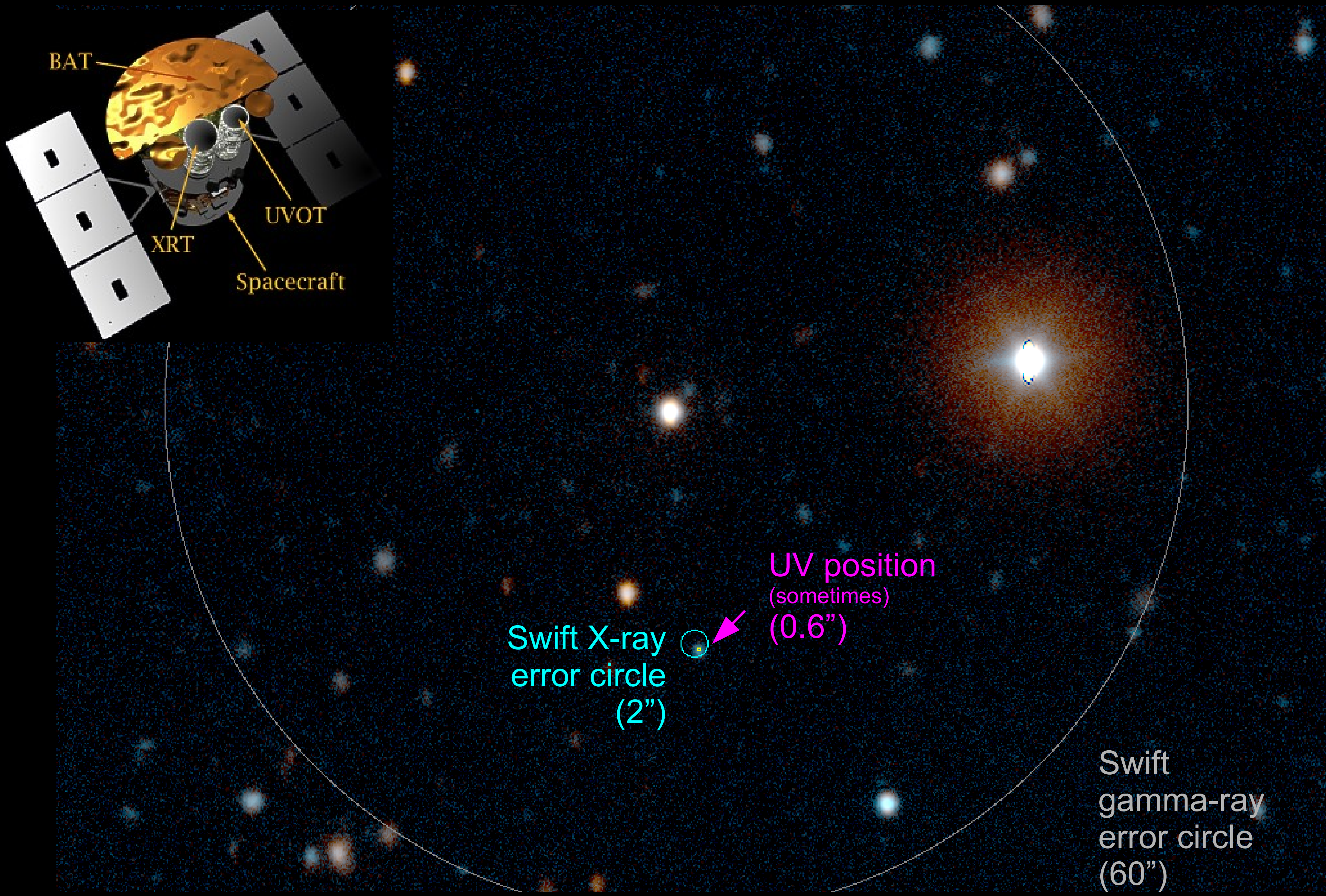
# Follow-up with Swift



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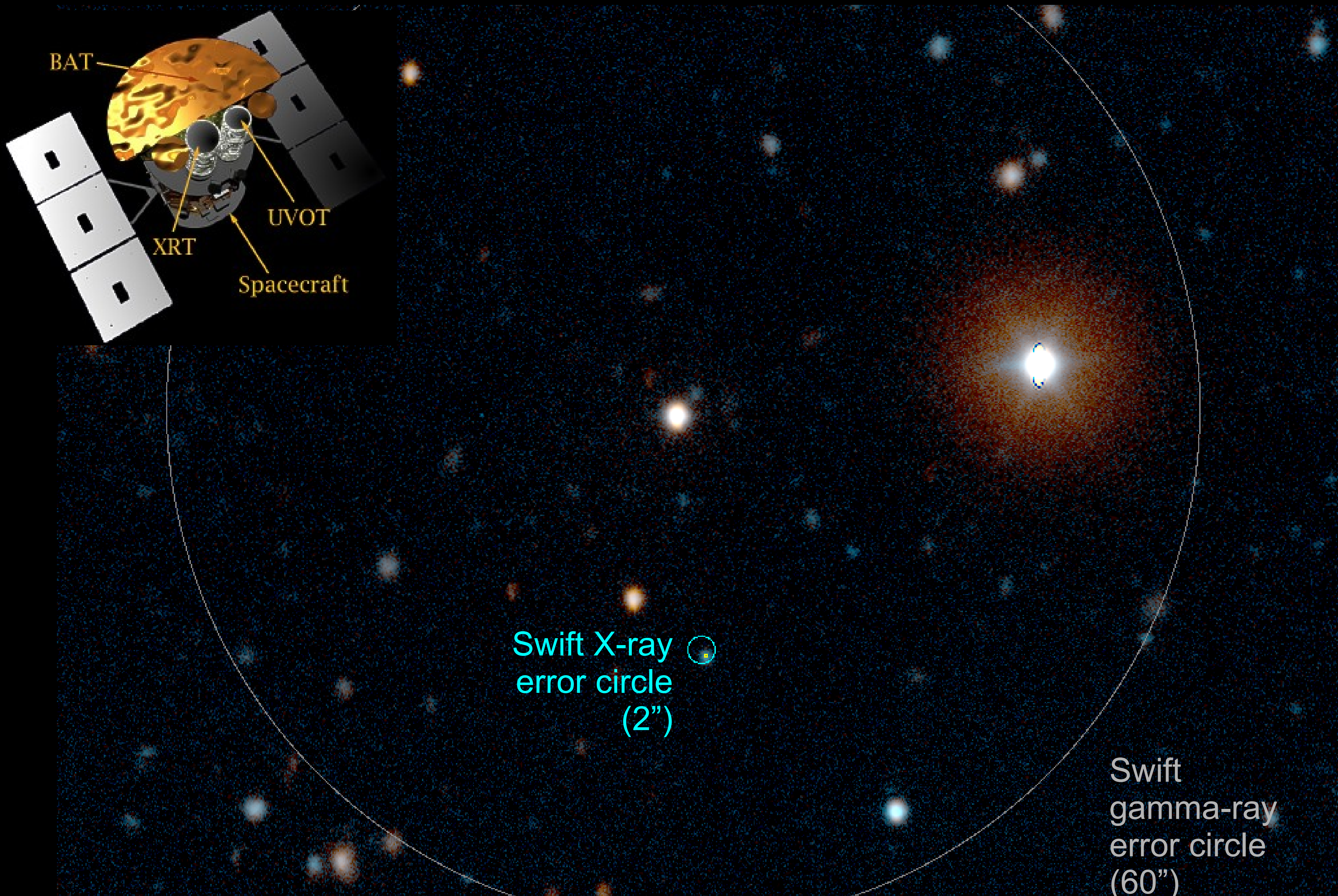
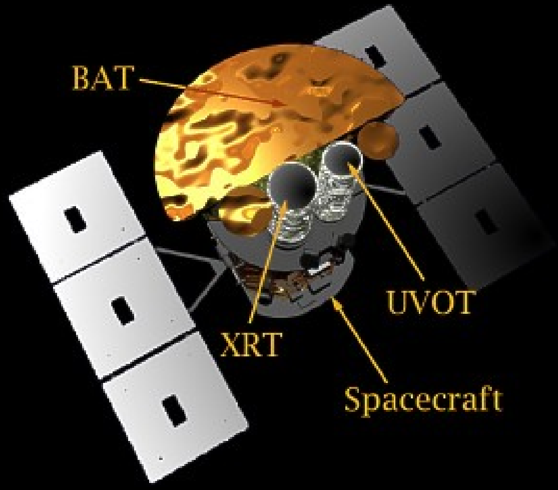
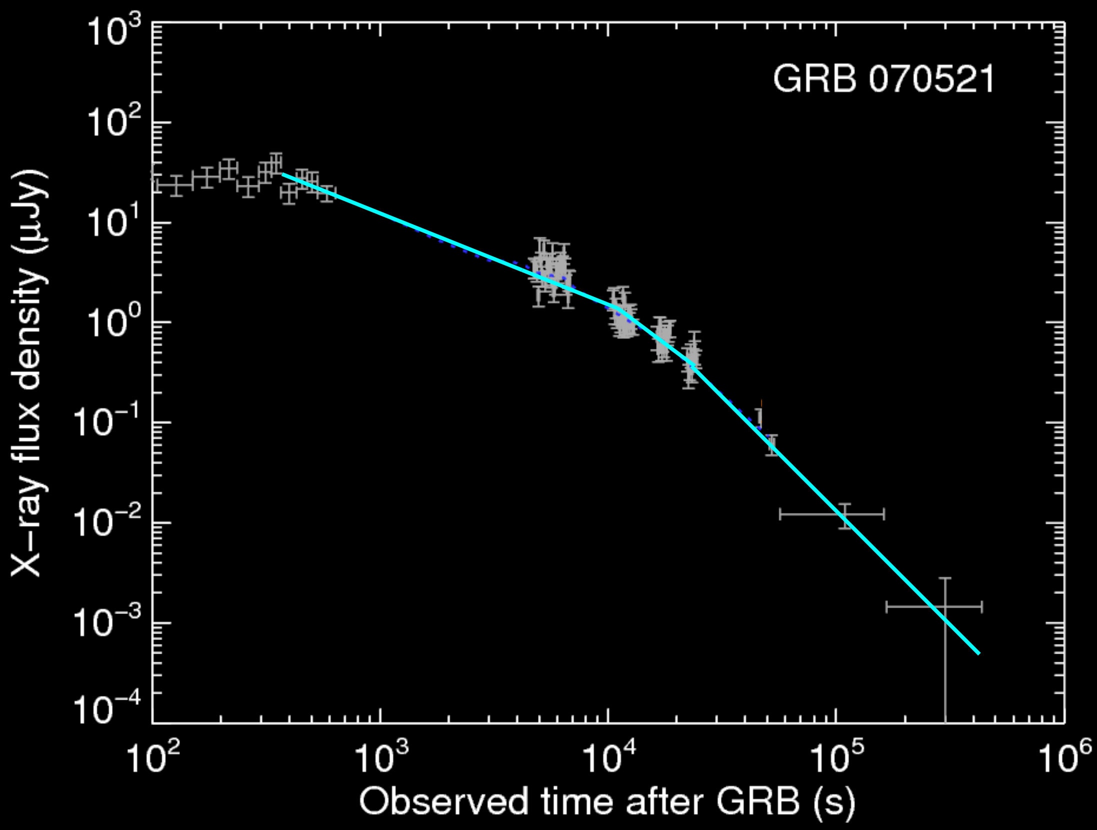


# Recognizing Dusty Events with XRT



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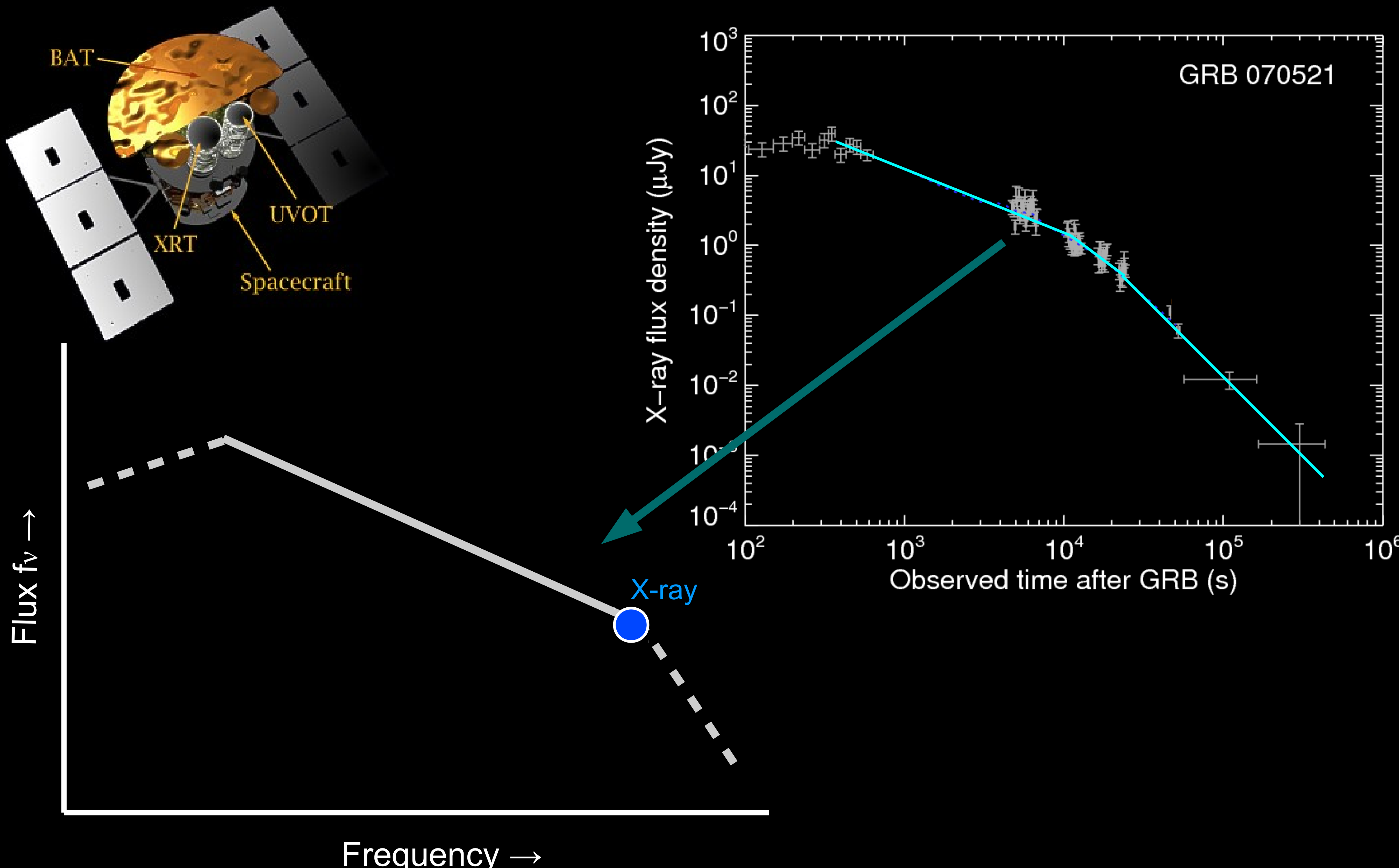

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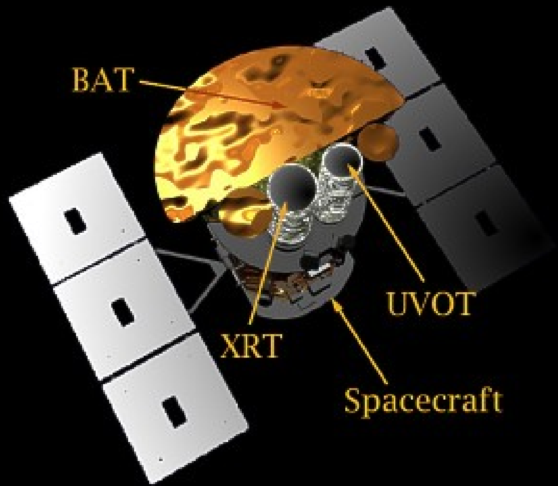


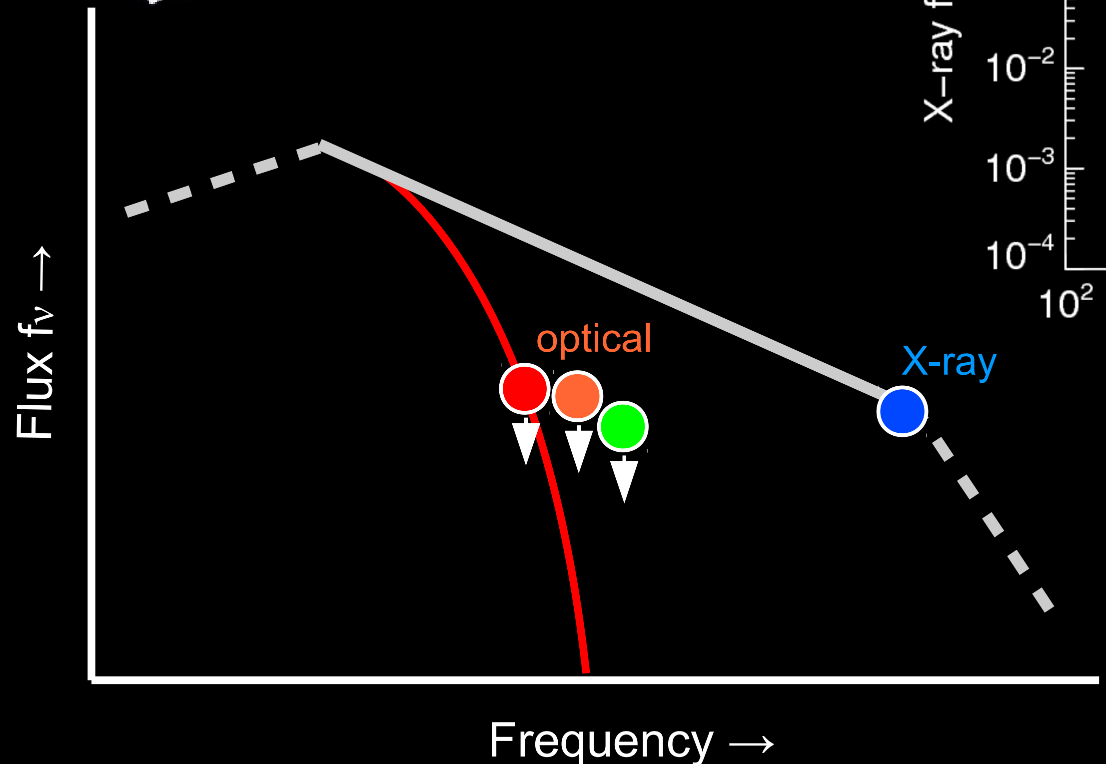


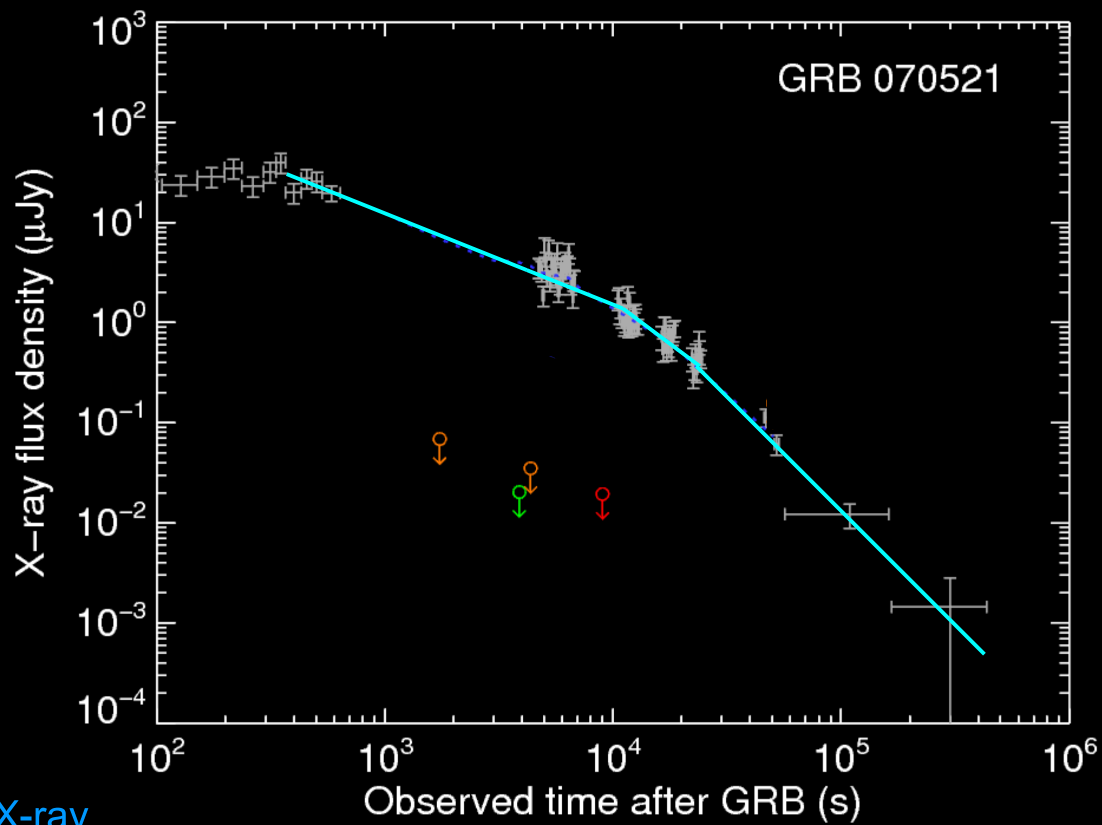

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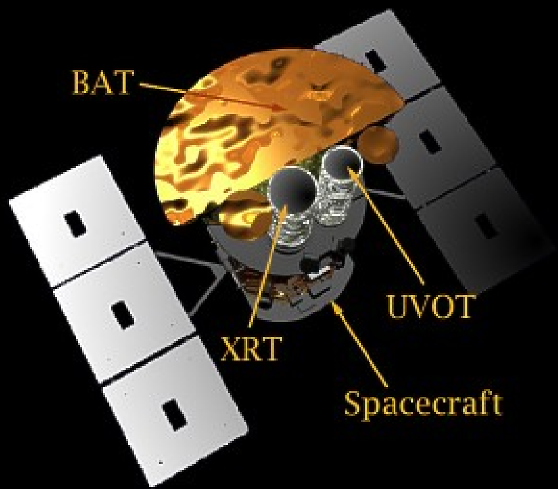
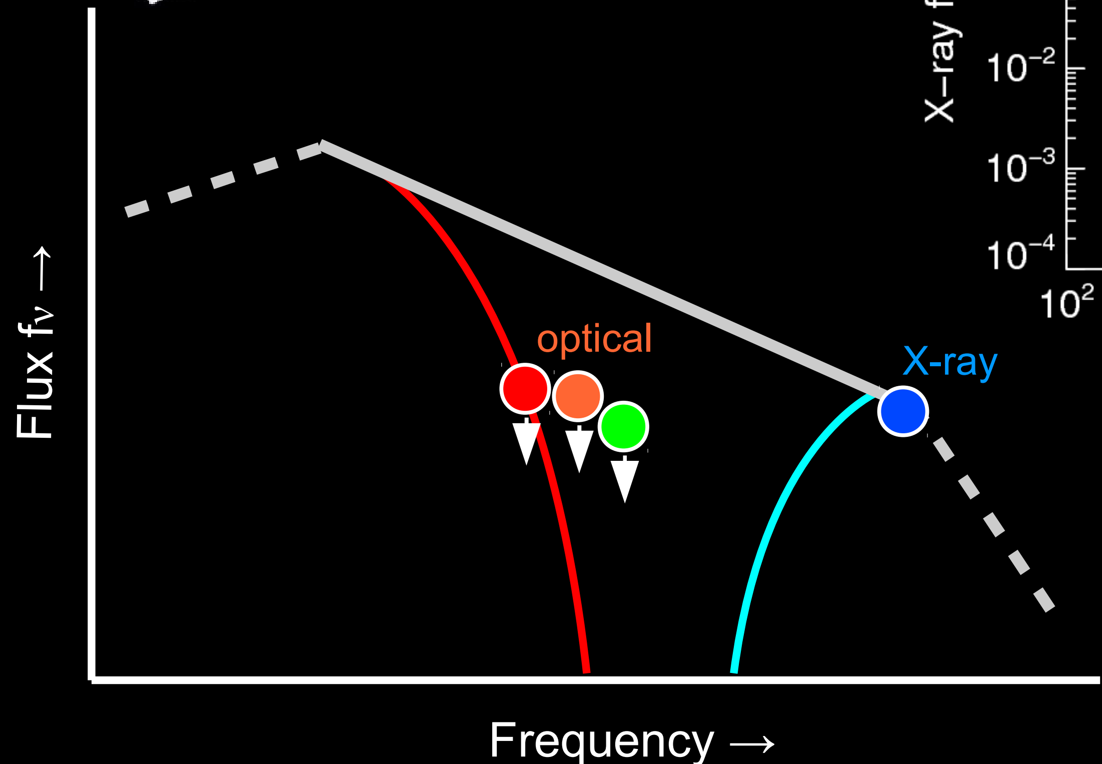
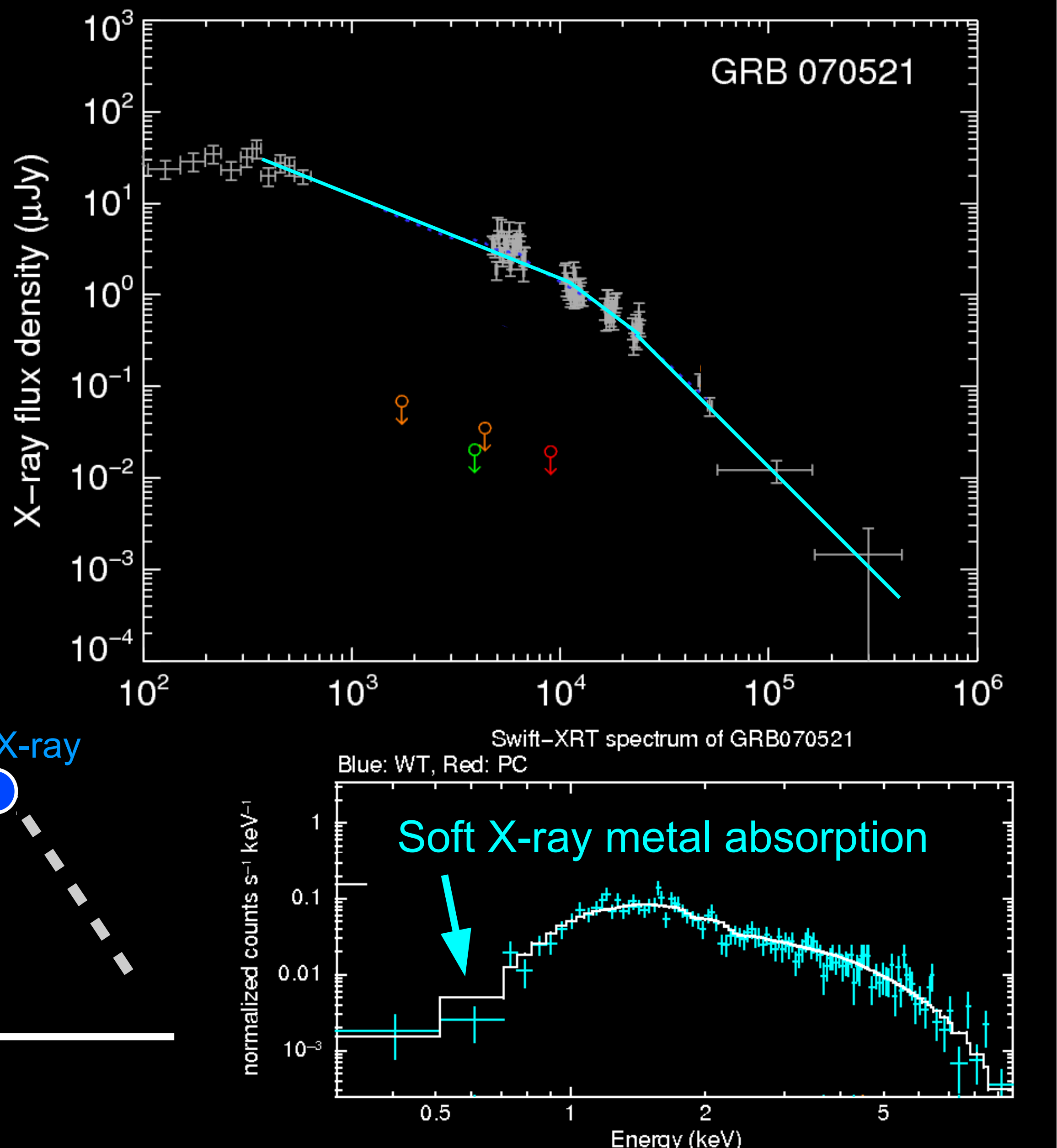


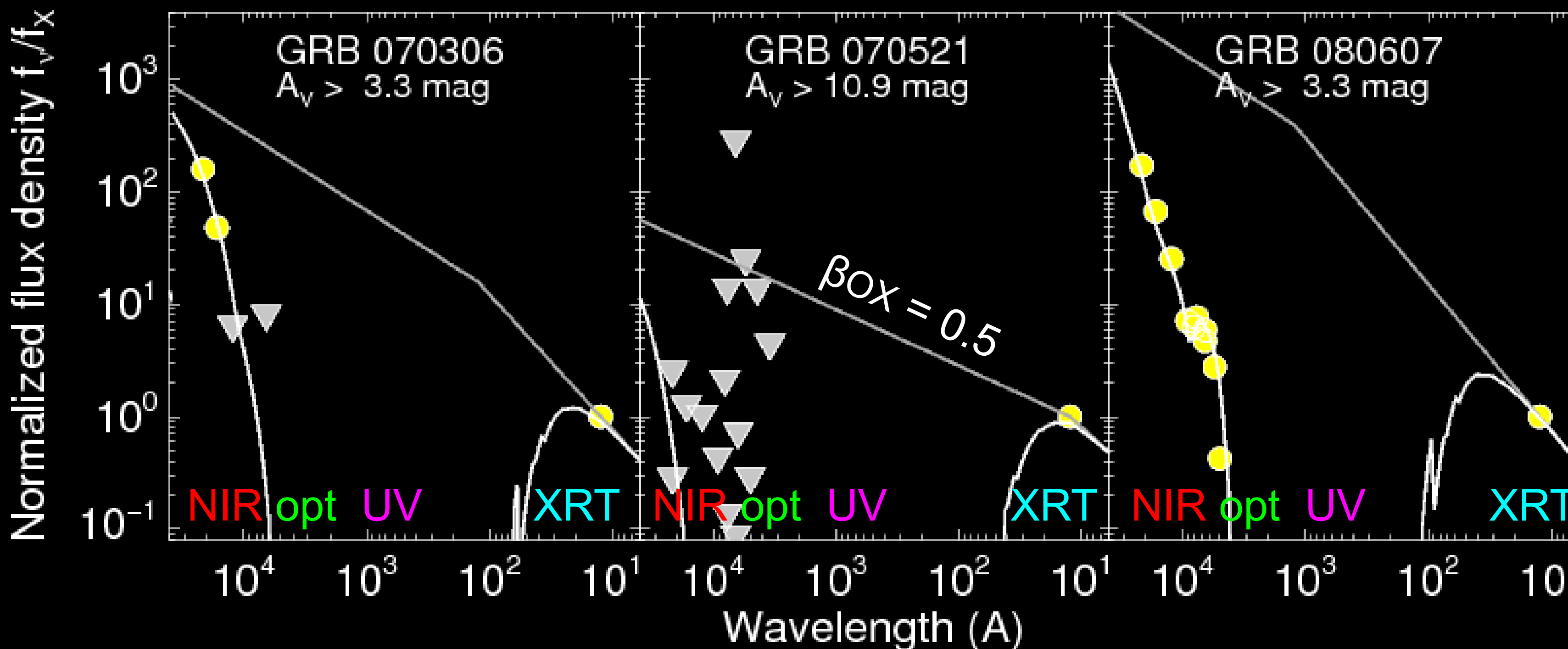



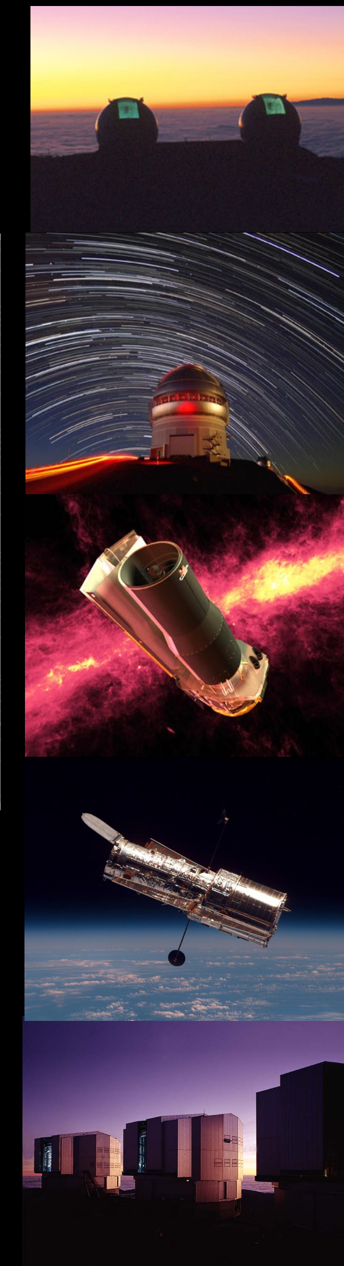



# Selecting a Dusty-GRB Host Sample

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

**Afterglow** SEDs:



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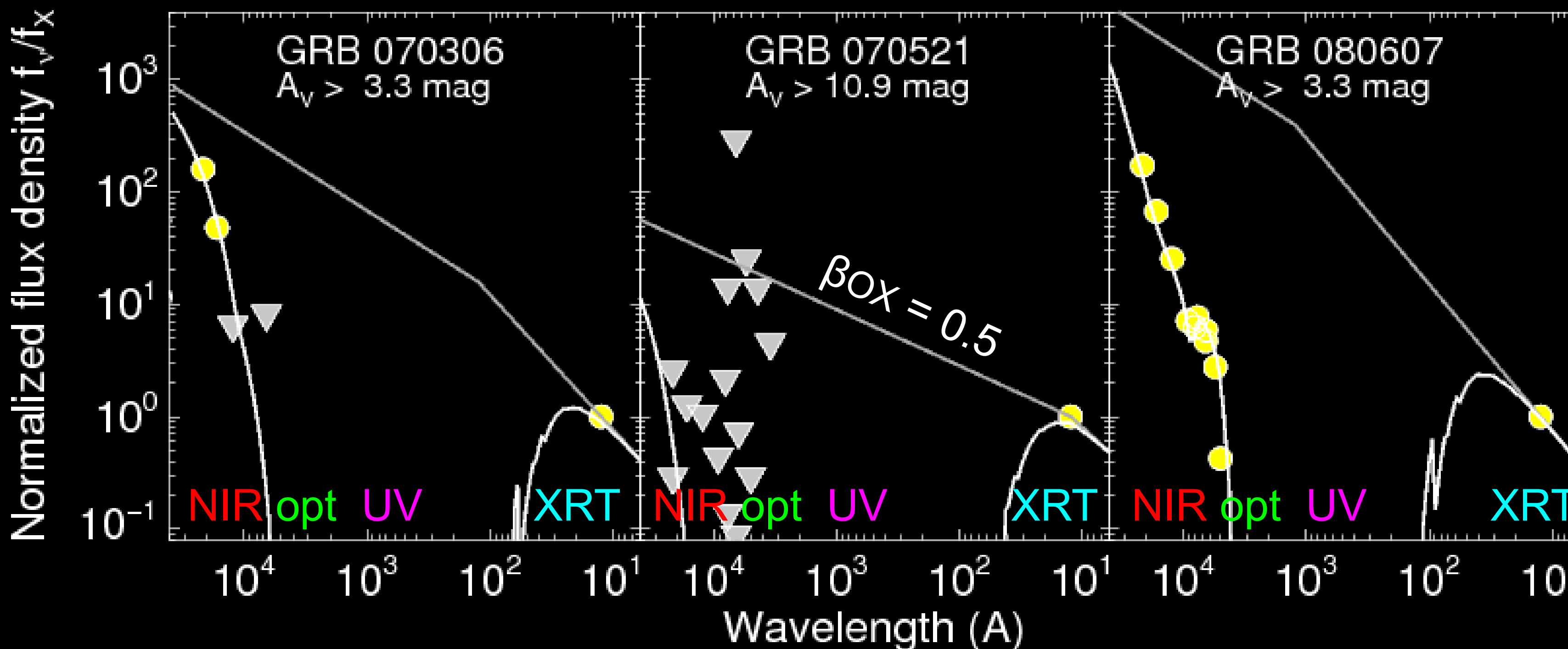
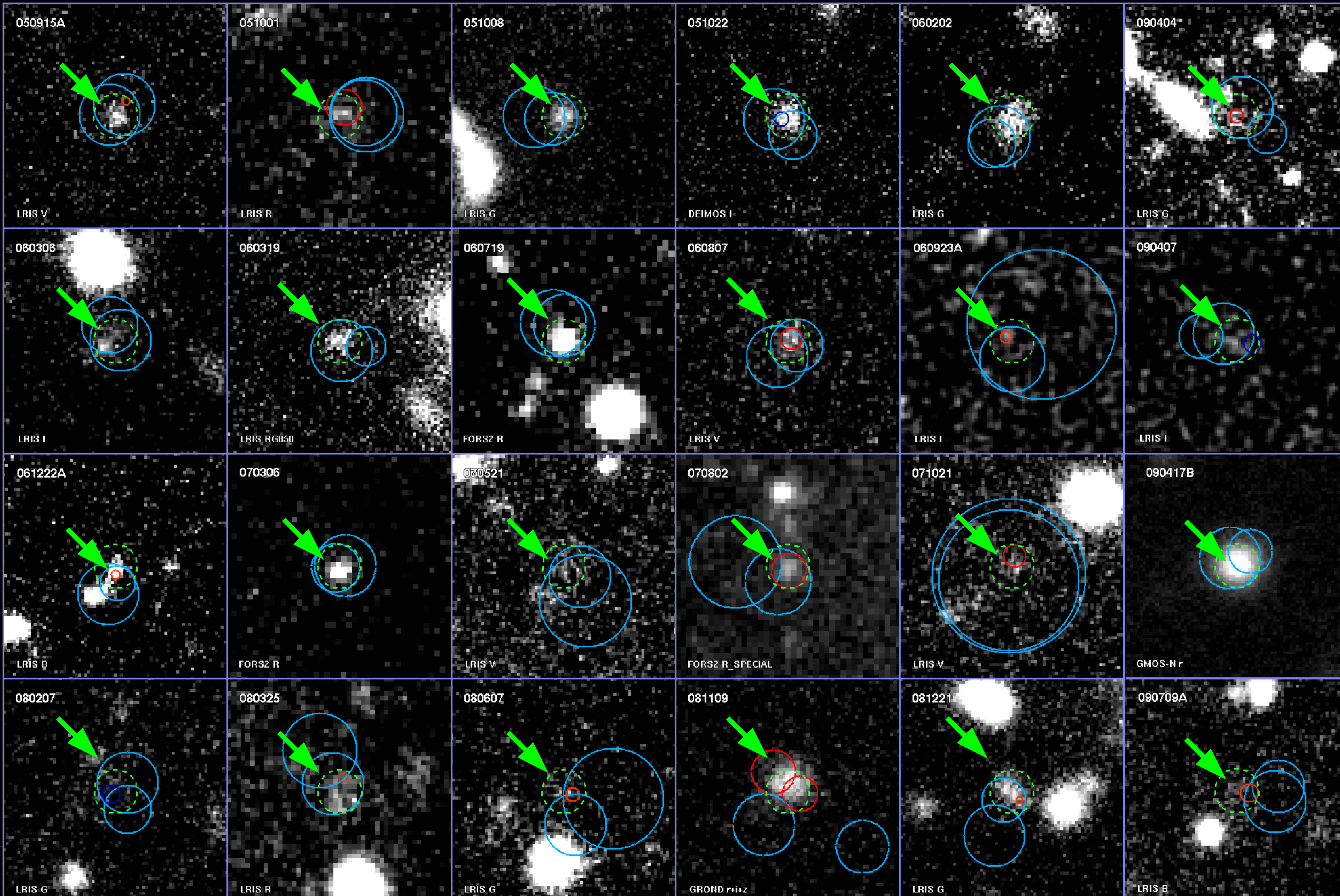
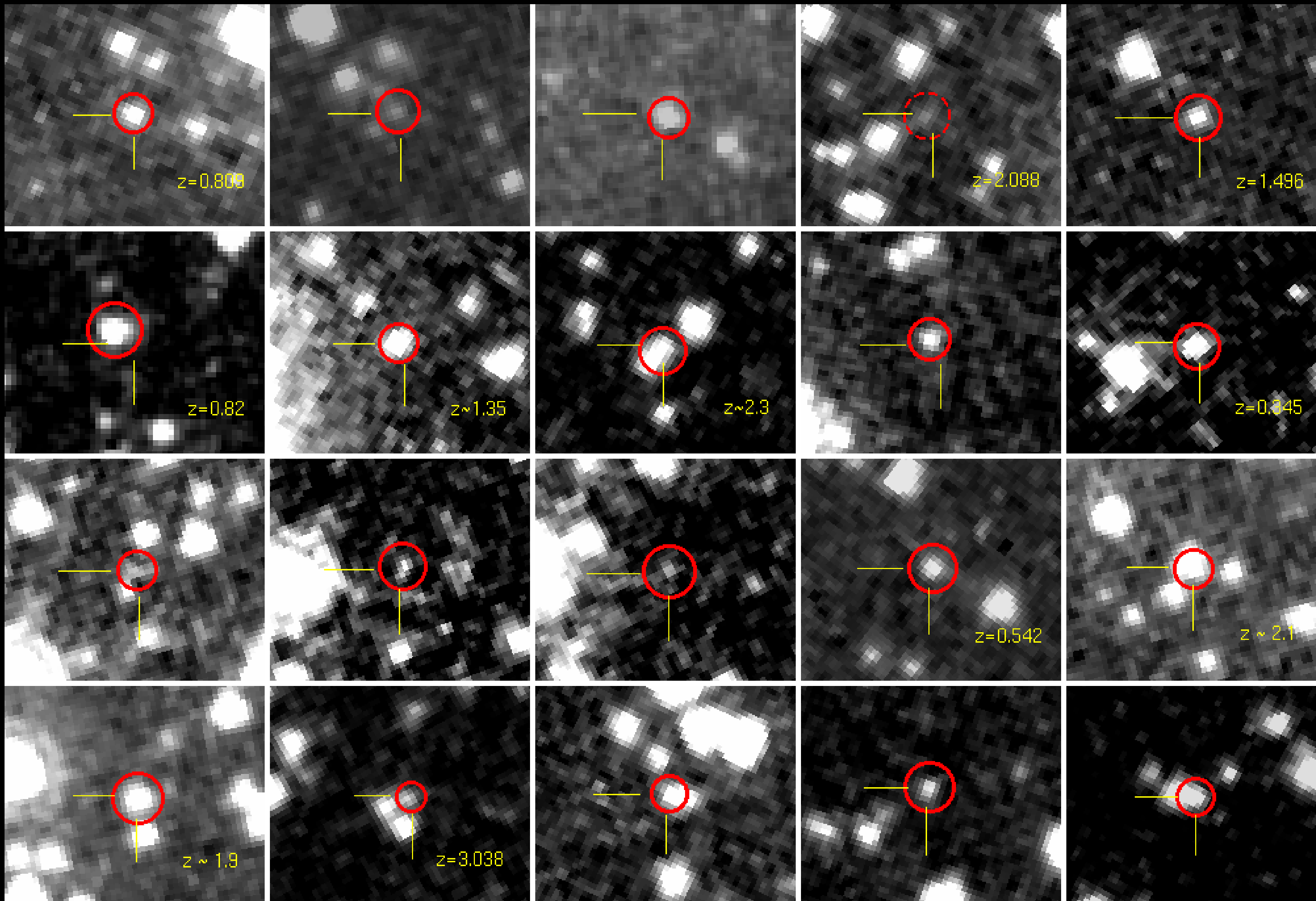



Approx **30** events from 2005-2009
2 with optical afterglow redshift

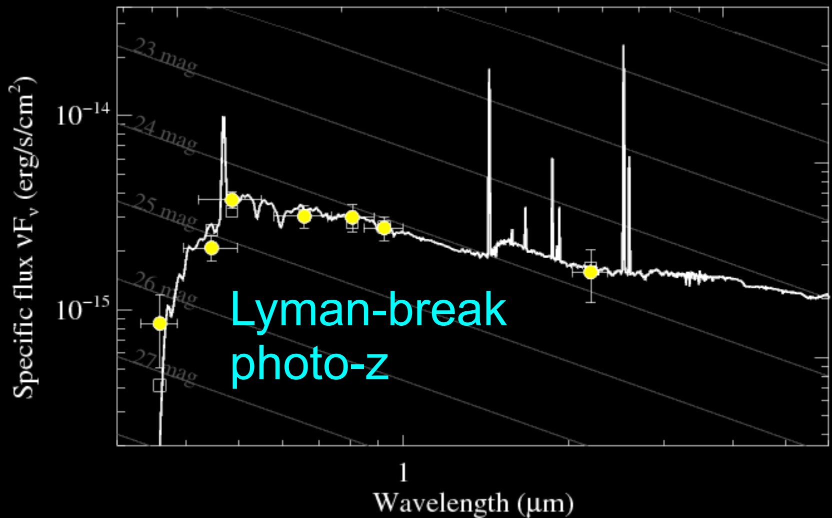
# Optical Host Mosaic

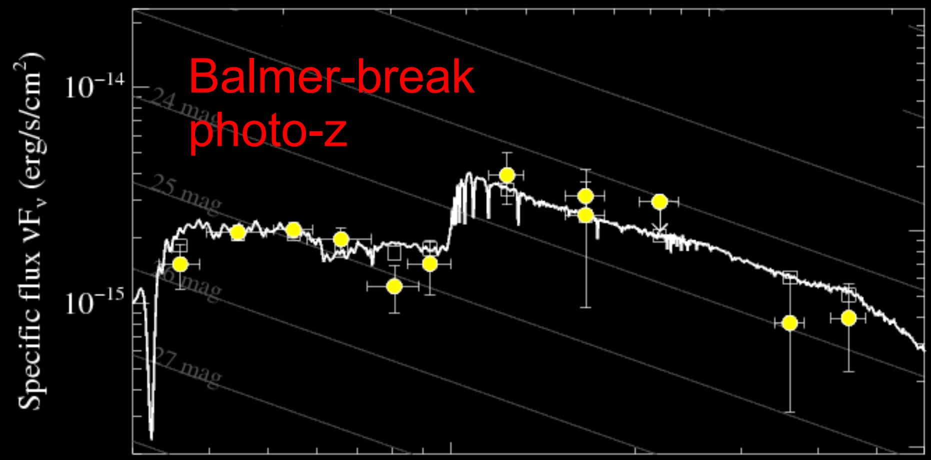


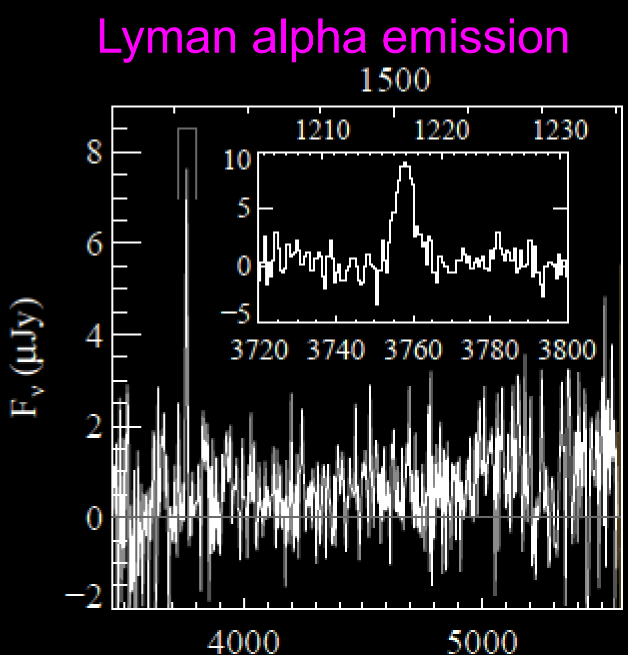
# Spitzer/IRAC Host Mosaic

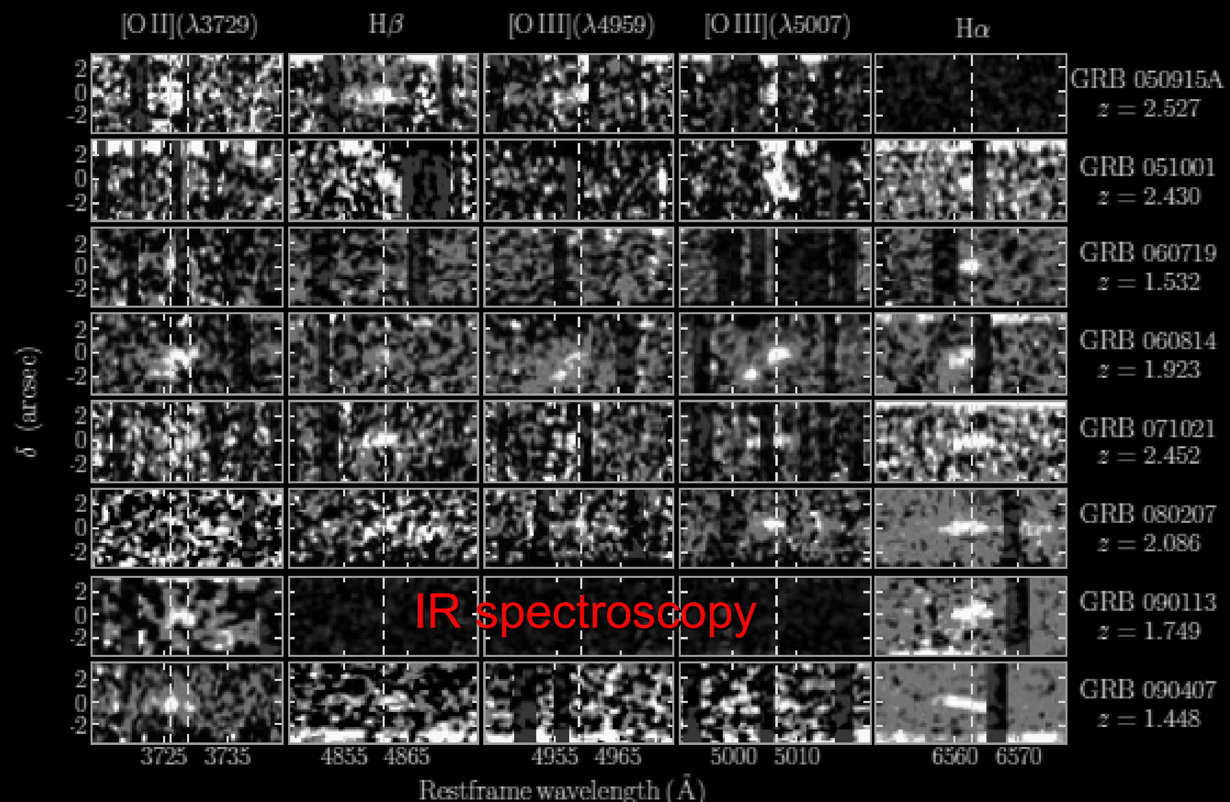


# Redshift Measurement

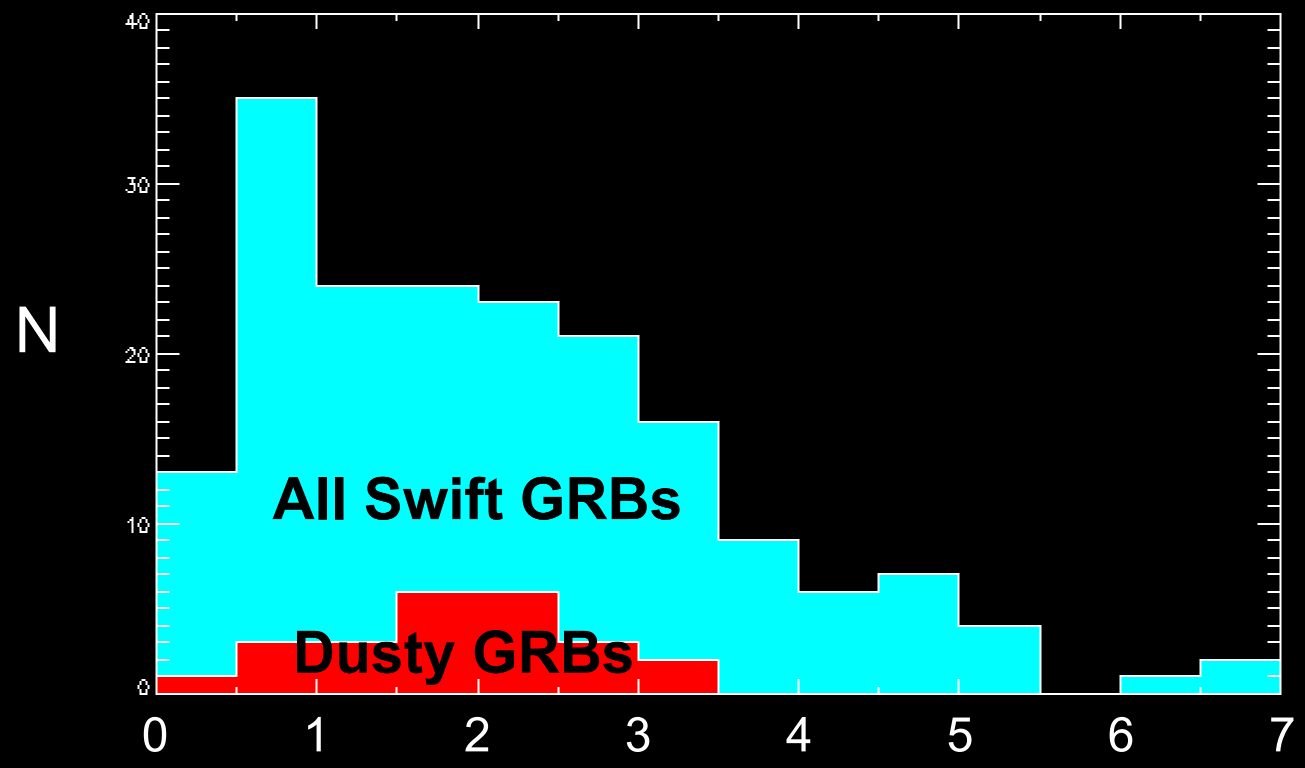


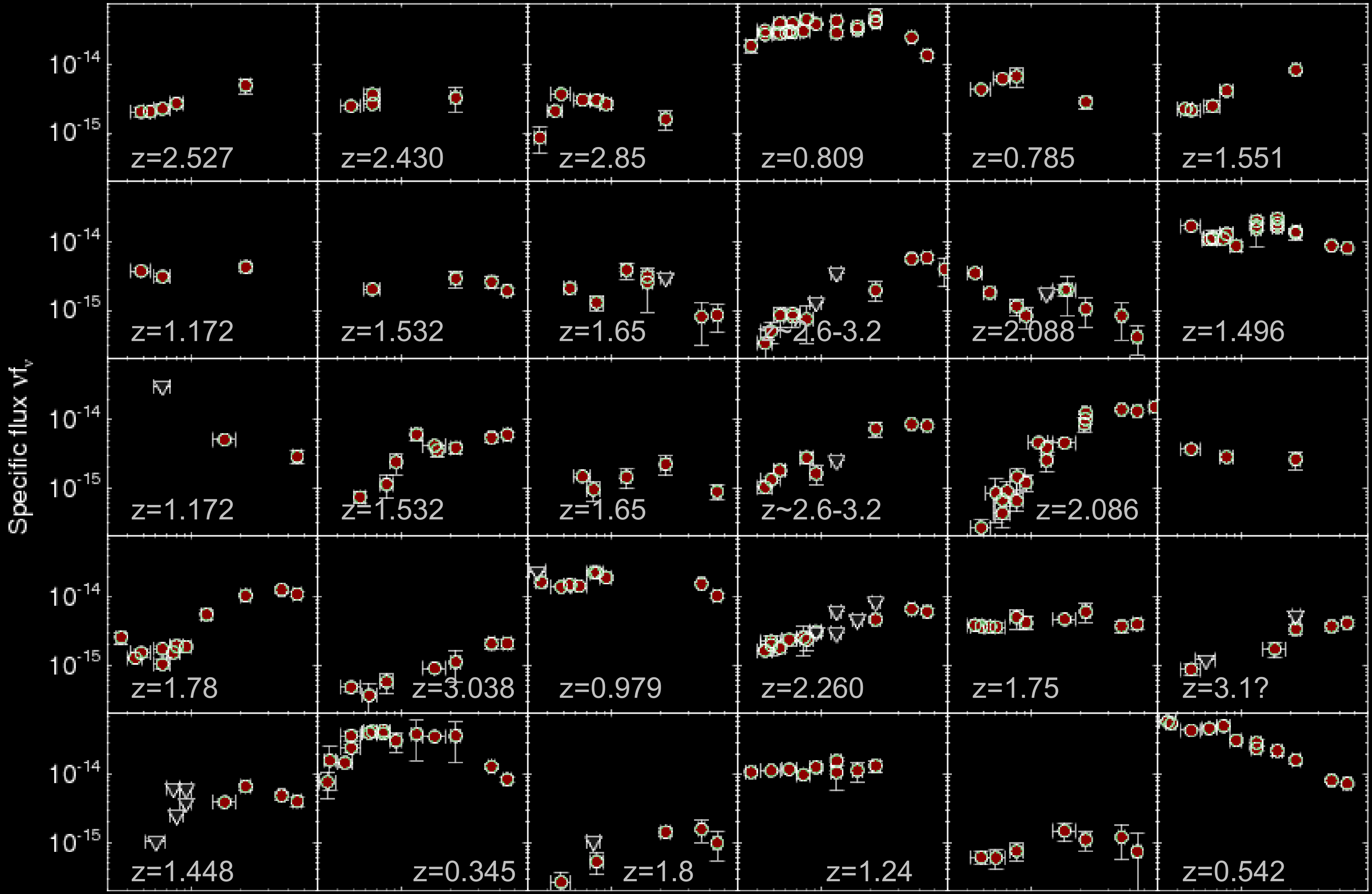



# Redshift Distribution

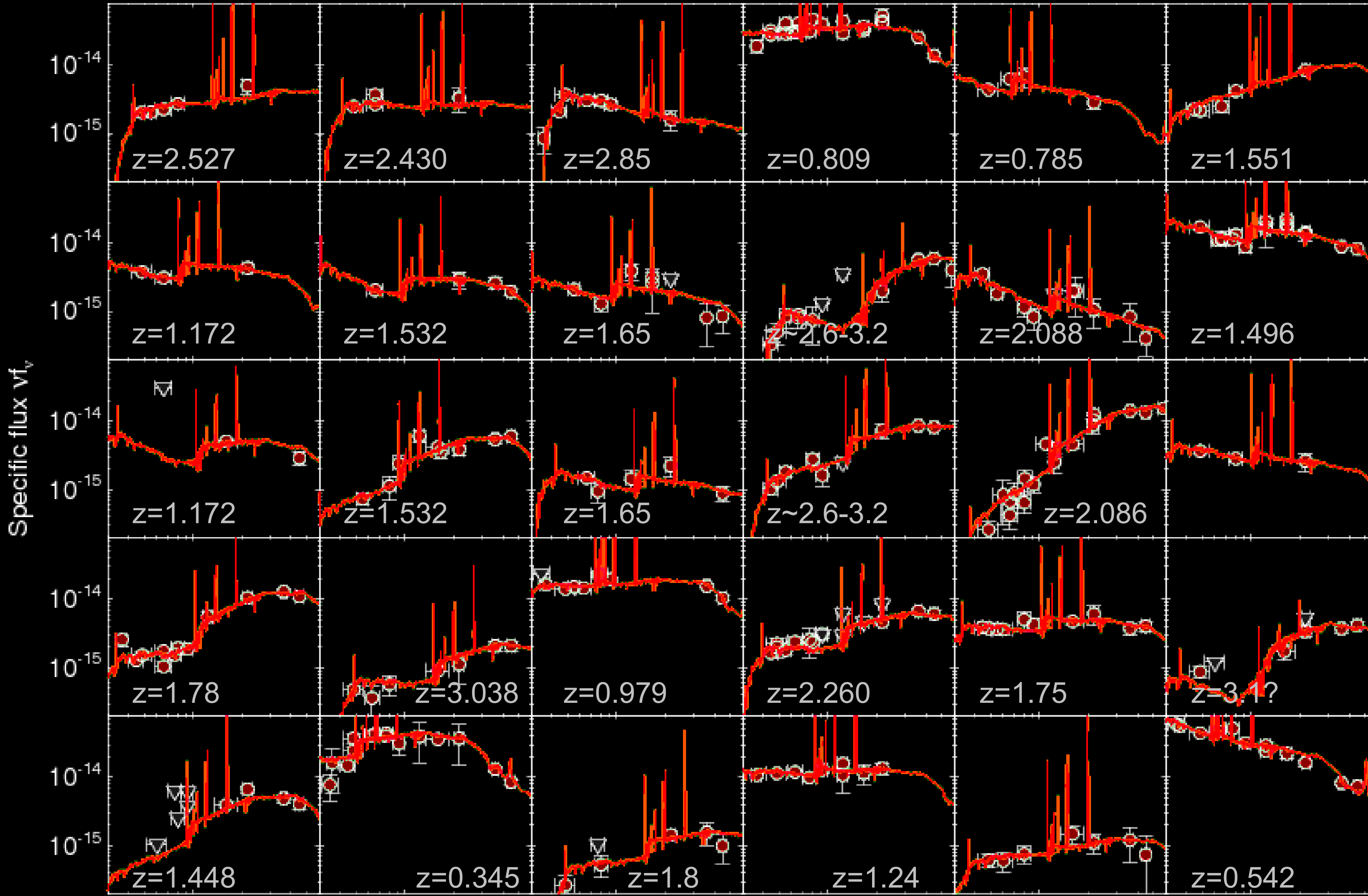



Broadly similar to overall redshift distribution
(possibly more strongly concentrated at z~2)

# SED Fitting


Specific flux $\nu f_\nu$
$10^{-14}$
$10^{-15}$
z=2.527
z=2.430
z=2.85
z=0.809
z=0.785
z=1.551
z=1.172
z=1.532
z=1.65
z~2.6-3.2
z=2.088
z=1.496
z=1.172
z=1.532
z=1.65
z~2.6-3.2
z=2.086
z=1.78
z=3.038
z=0.979
z=2.260
z=1.75
z=3.1?
z=1.448
z=0.345
z=1.8
z=1.24
z=0.542

# SED Fitting



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z=3.1?
z=1.448
z=0.345
z=1.8
z=1.24
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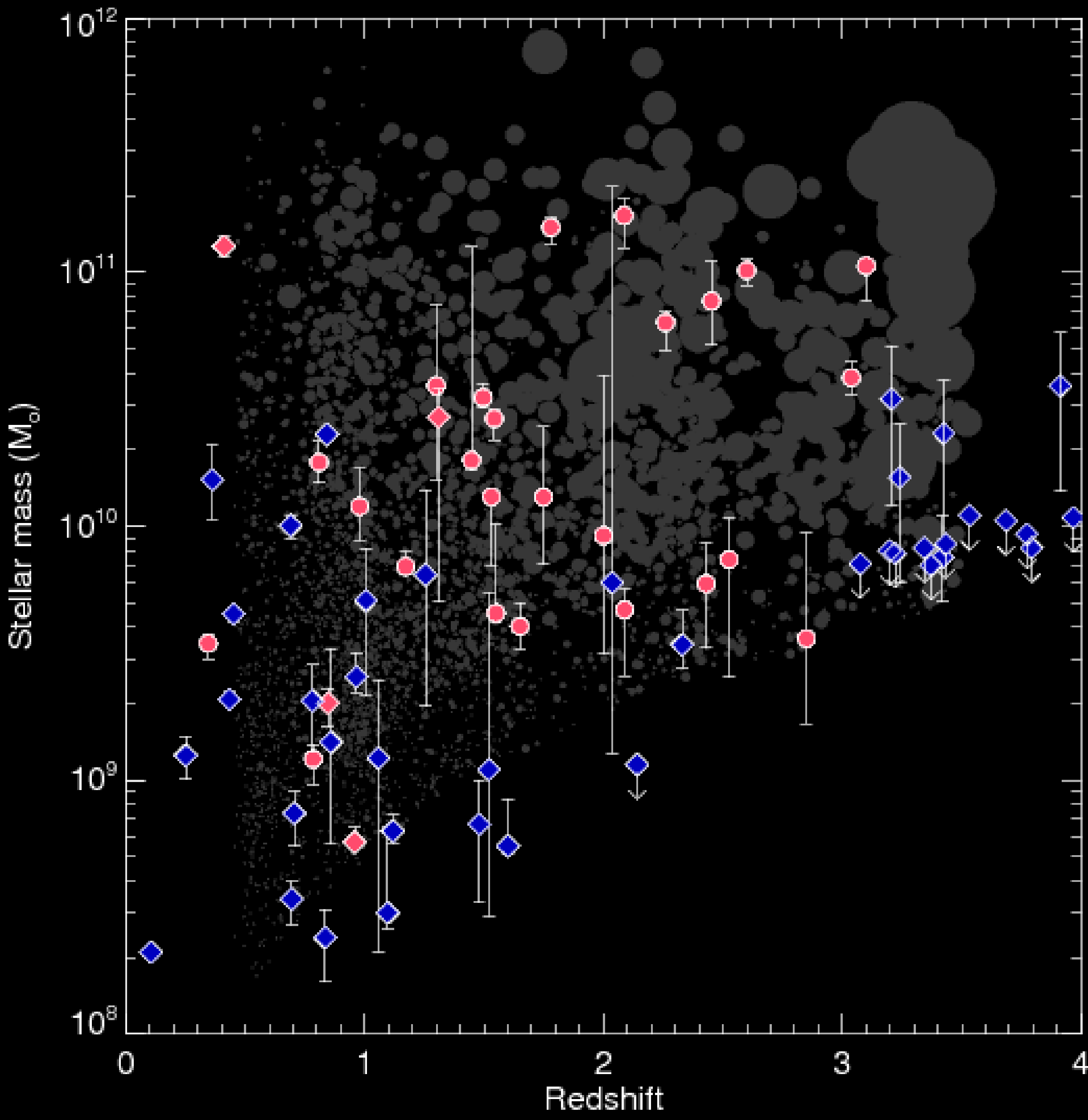
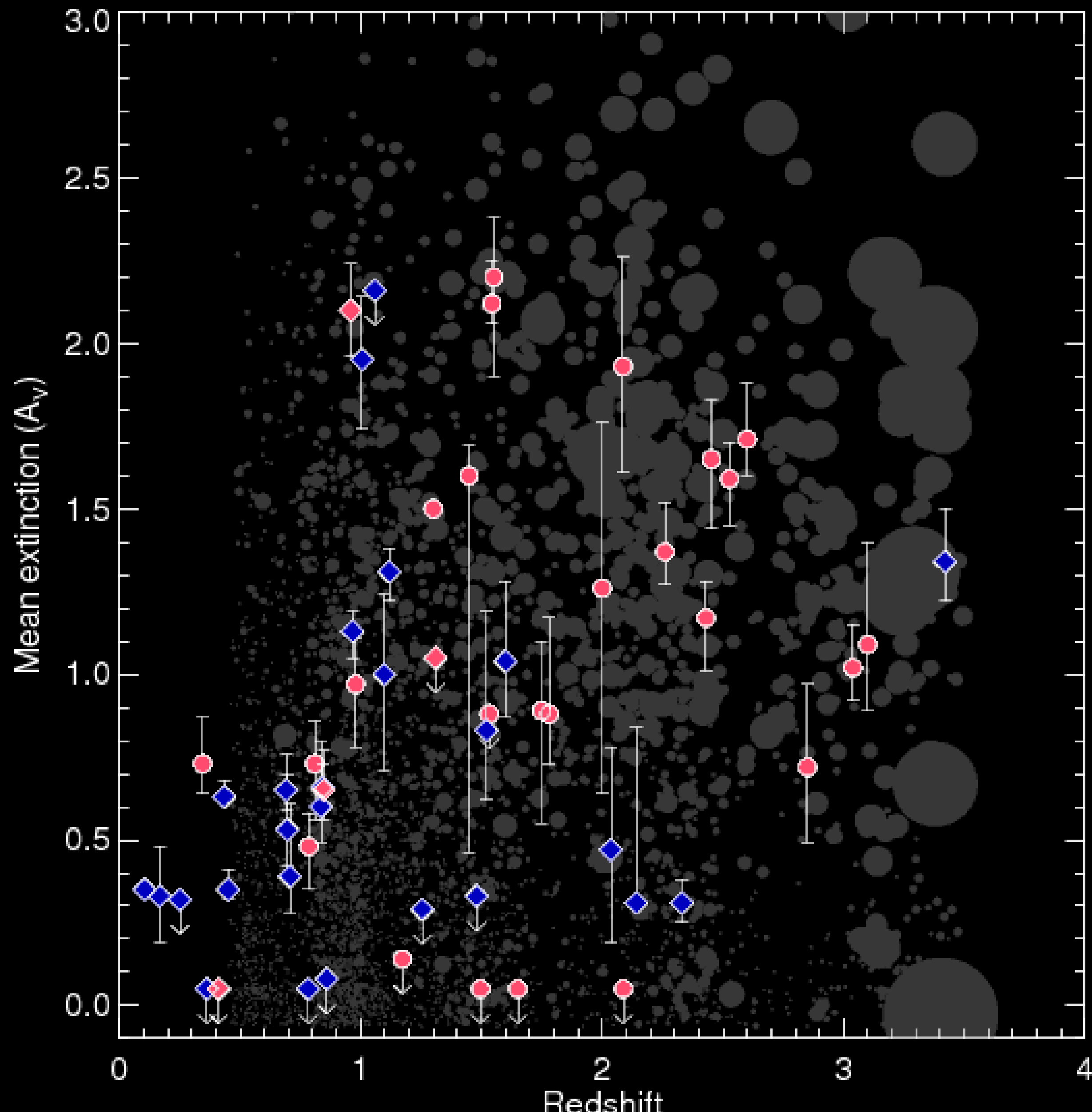
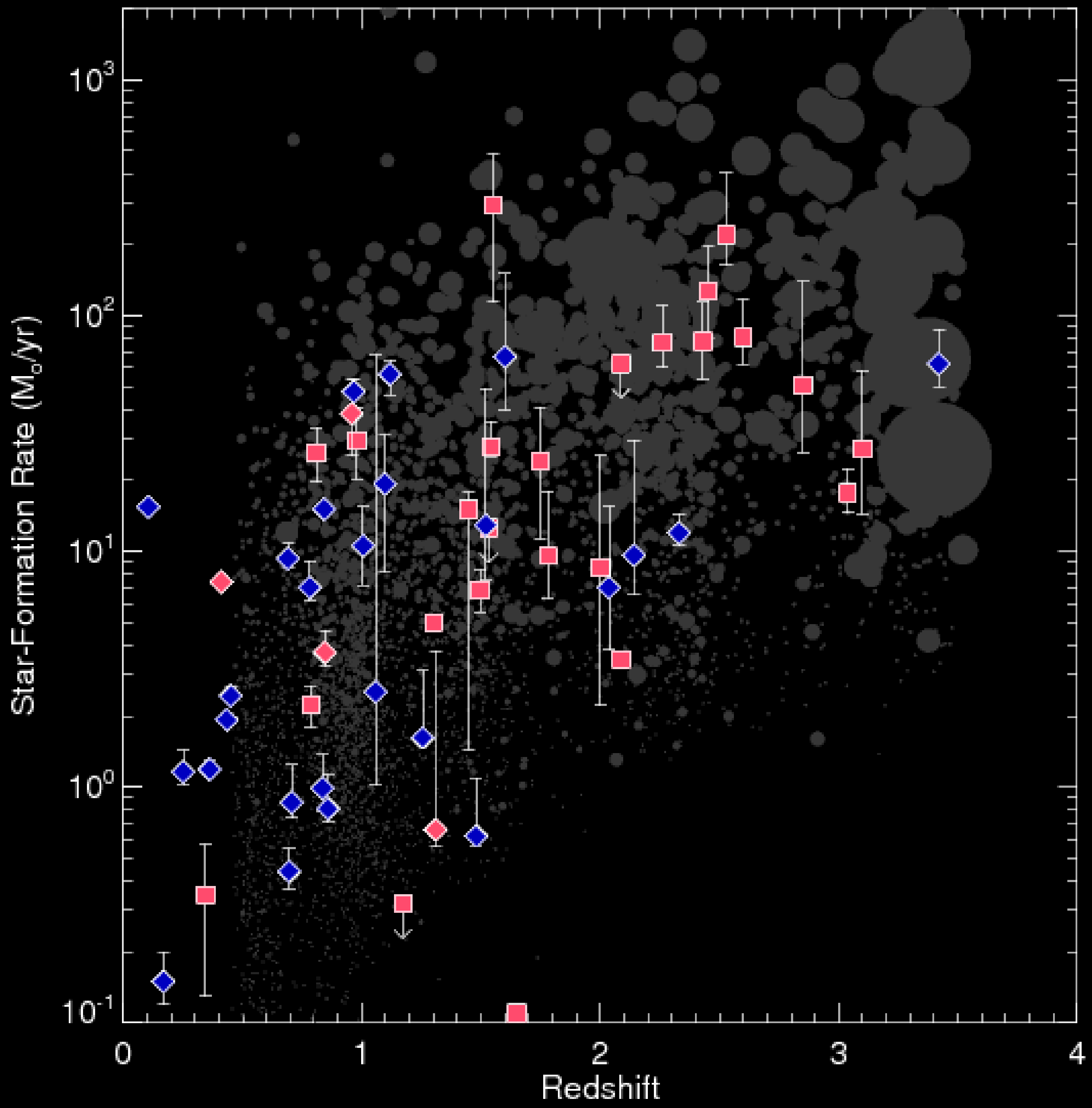
# Stellar Mass versus Redshift



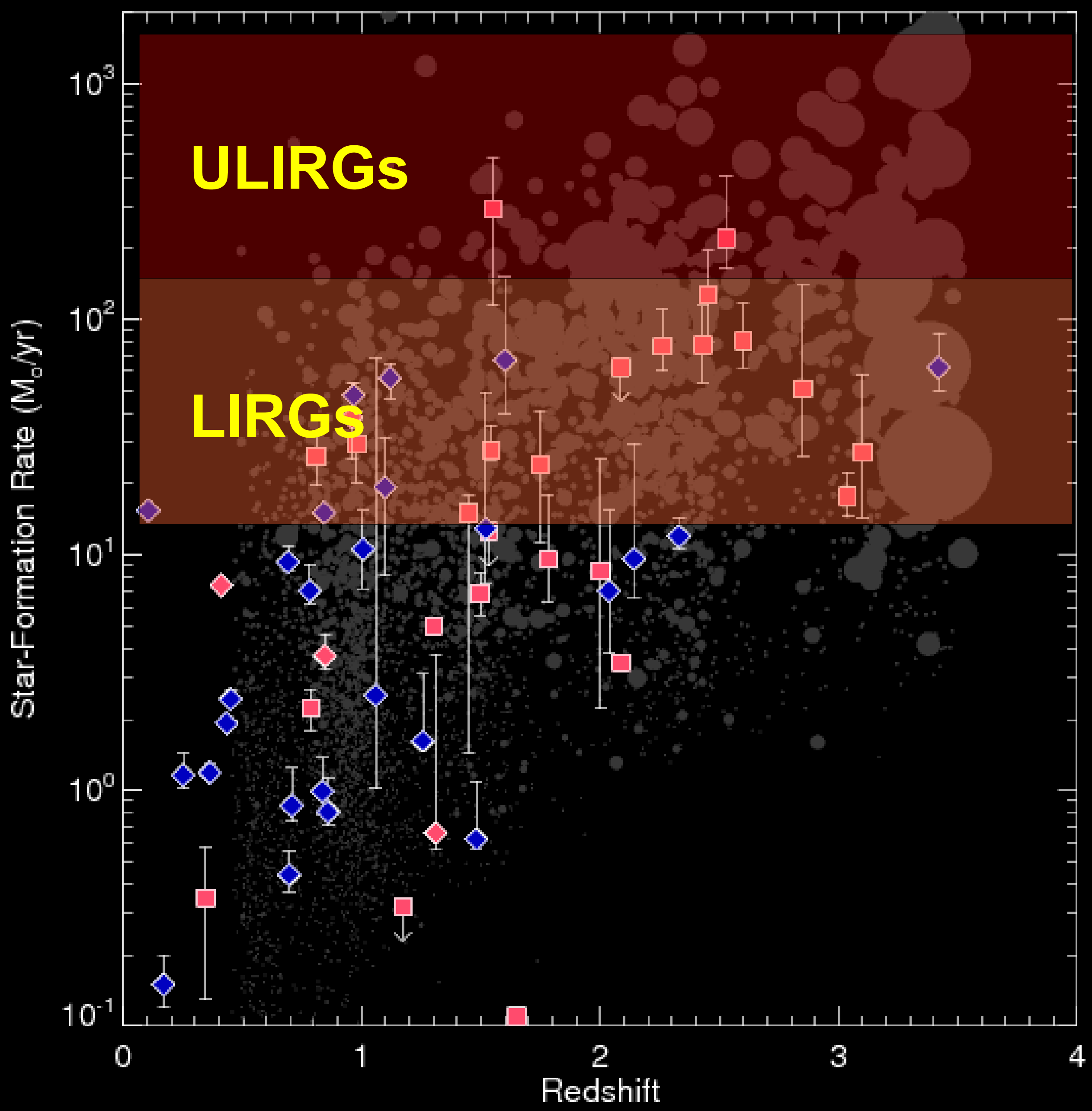
# Host Extinction versus Redshift



# (Corrected) UV SFR versus Redshift

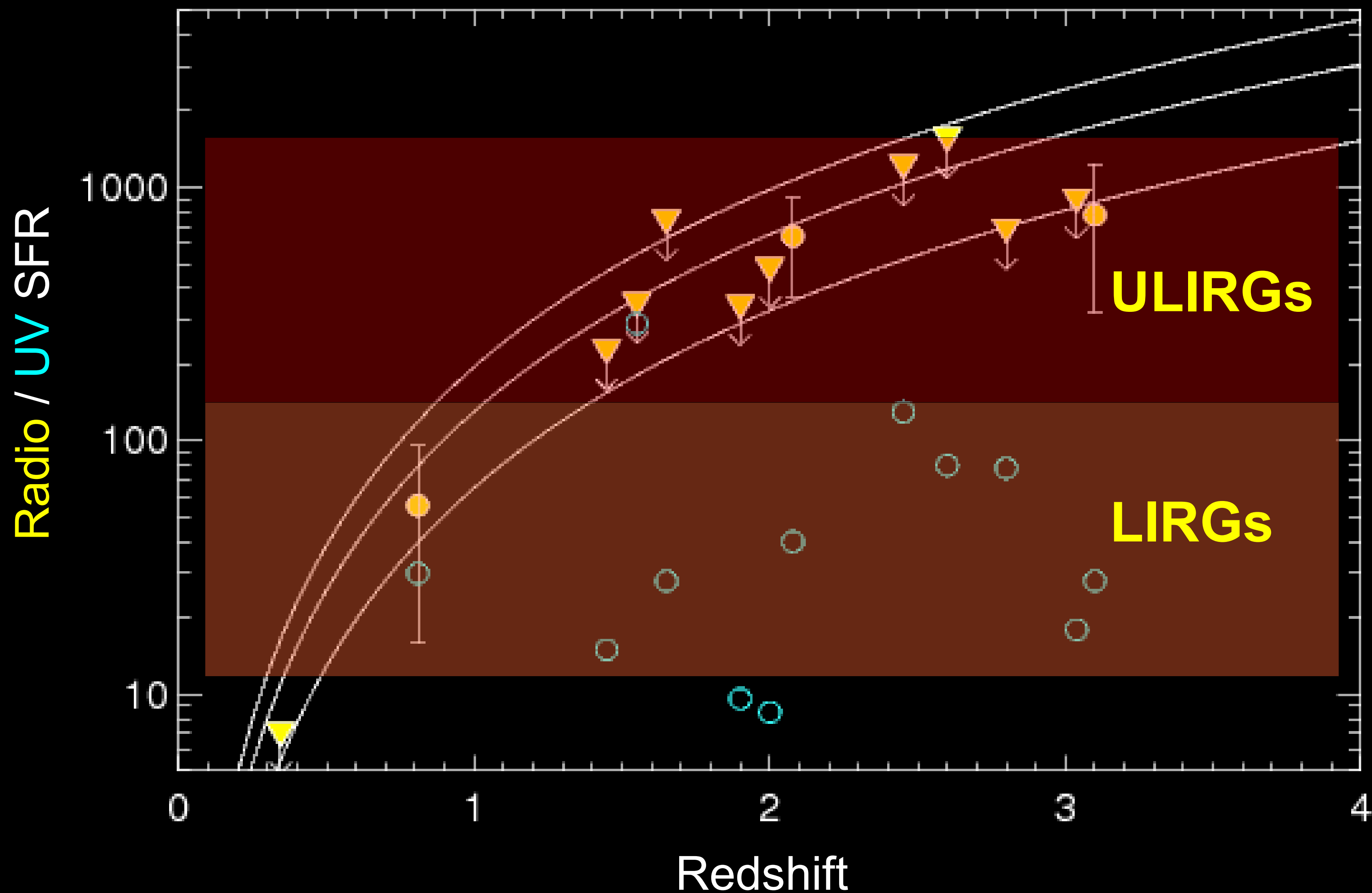


# (Corrected) UV SFR versus Redshift

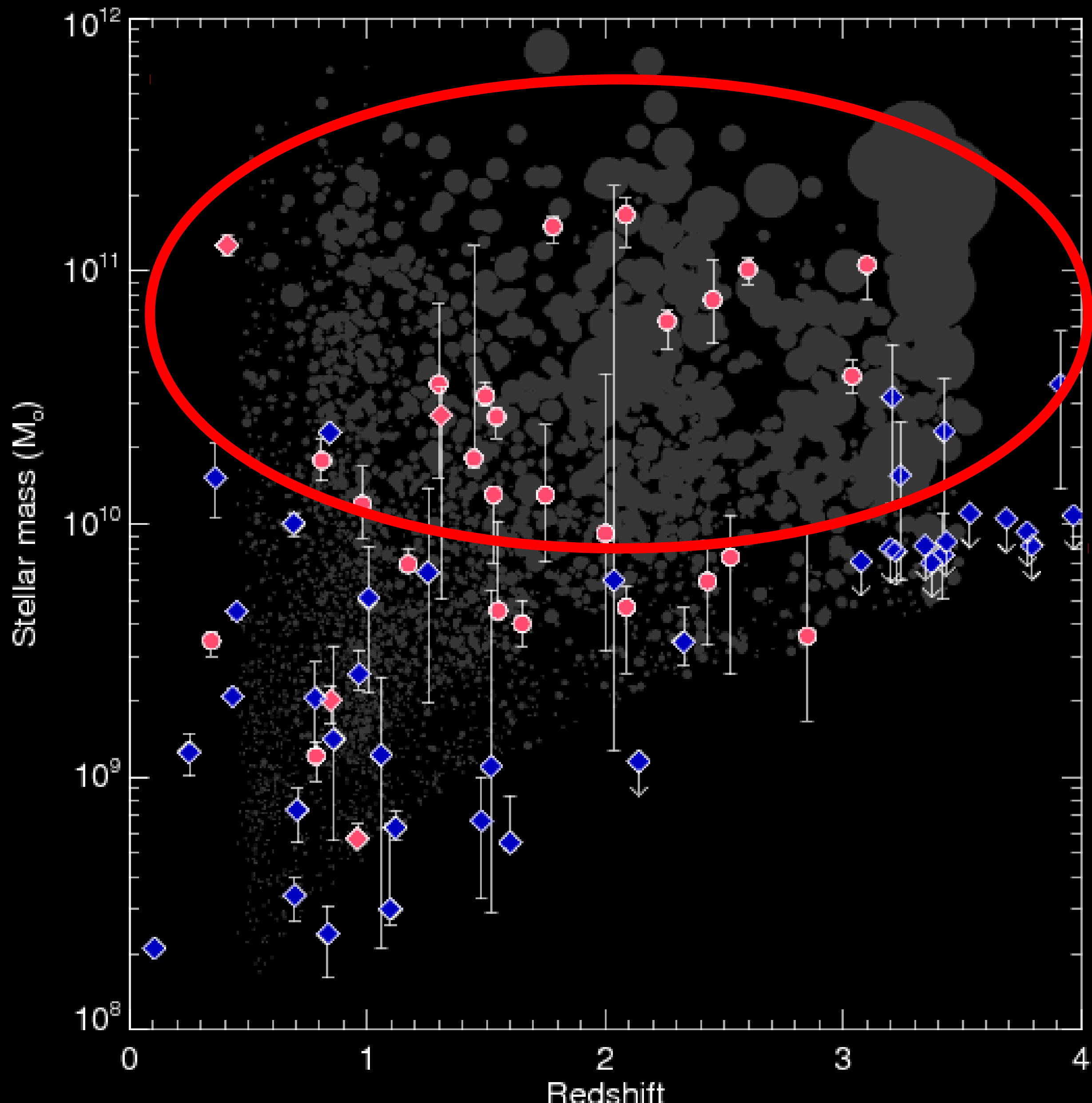


# Radio SFR versus Redshift

3 / 14 detected with EVLA (to 10 μJy): very high SFRs

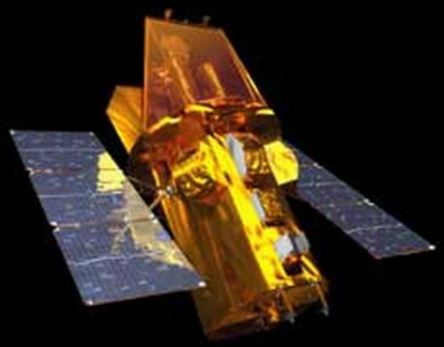


# Good Star Formation Tracers After All?



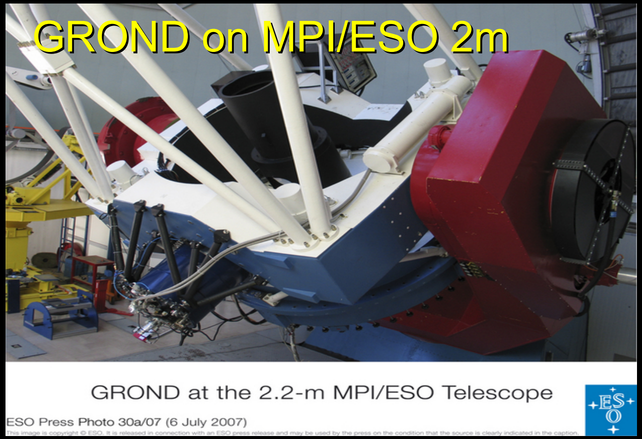

GRBs do occur in massive, luminous galaxies. But are there enough of them?

# Swift Extinction Distribution



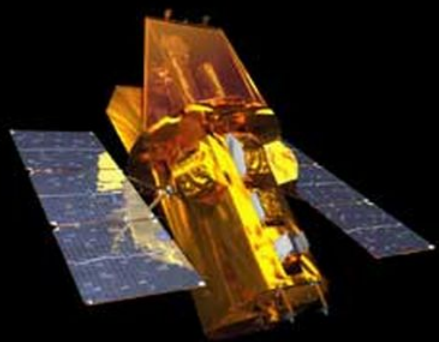
+


Cenko+2009
Perley+2009




Greiner+2011
Kruehler+2012

# Swift Extinction Distribution



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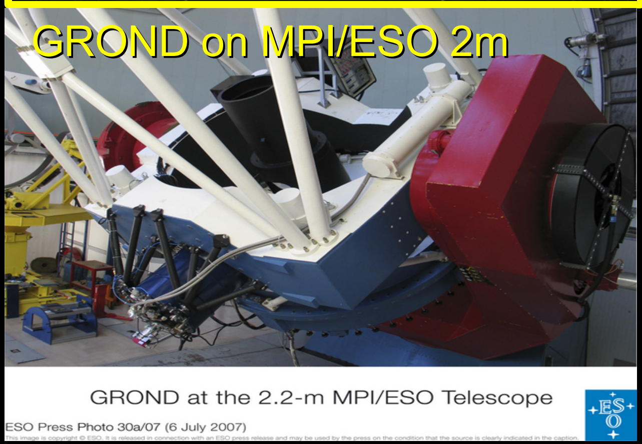


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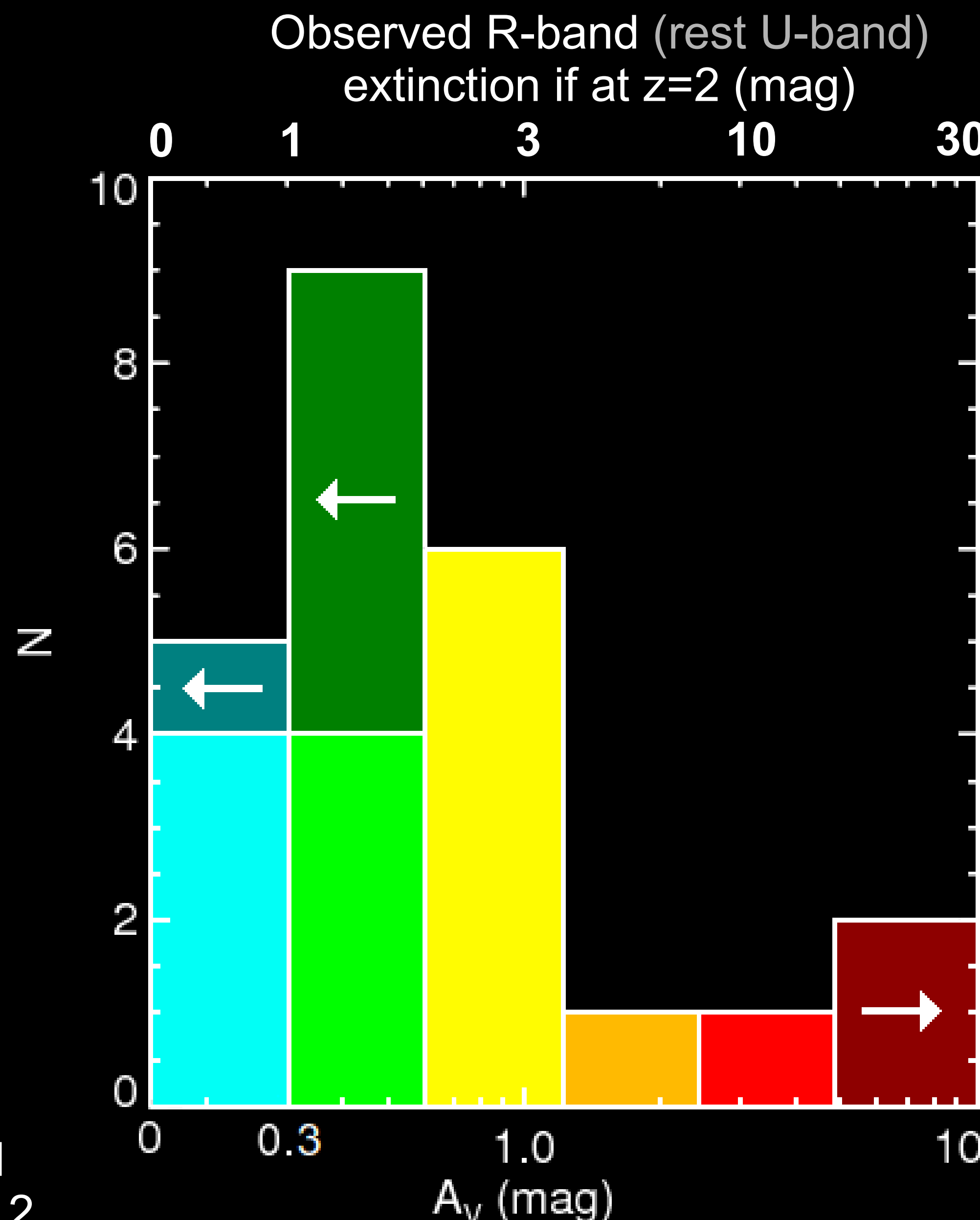

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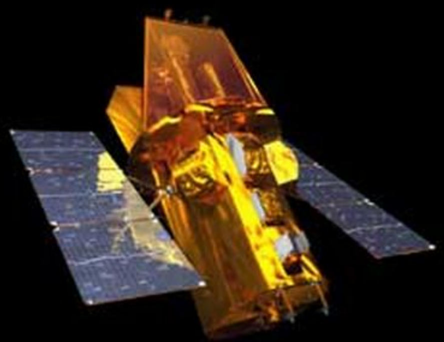
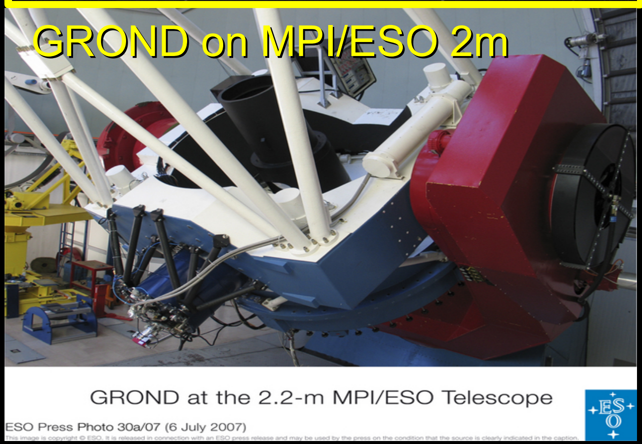


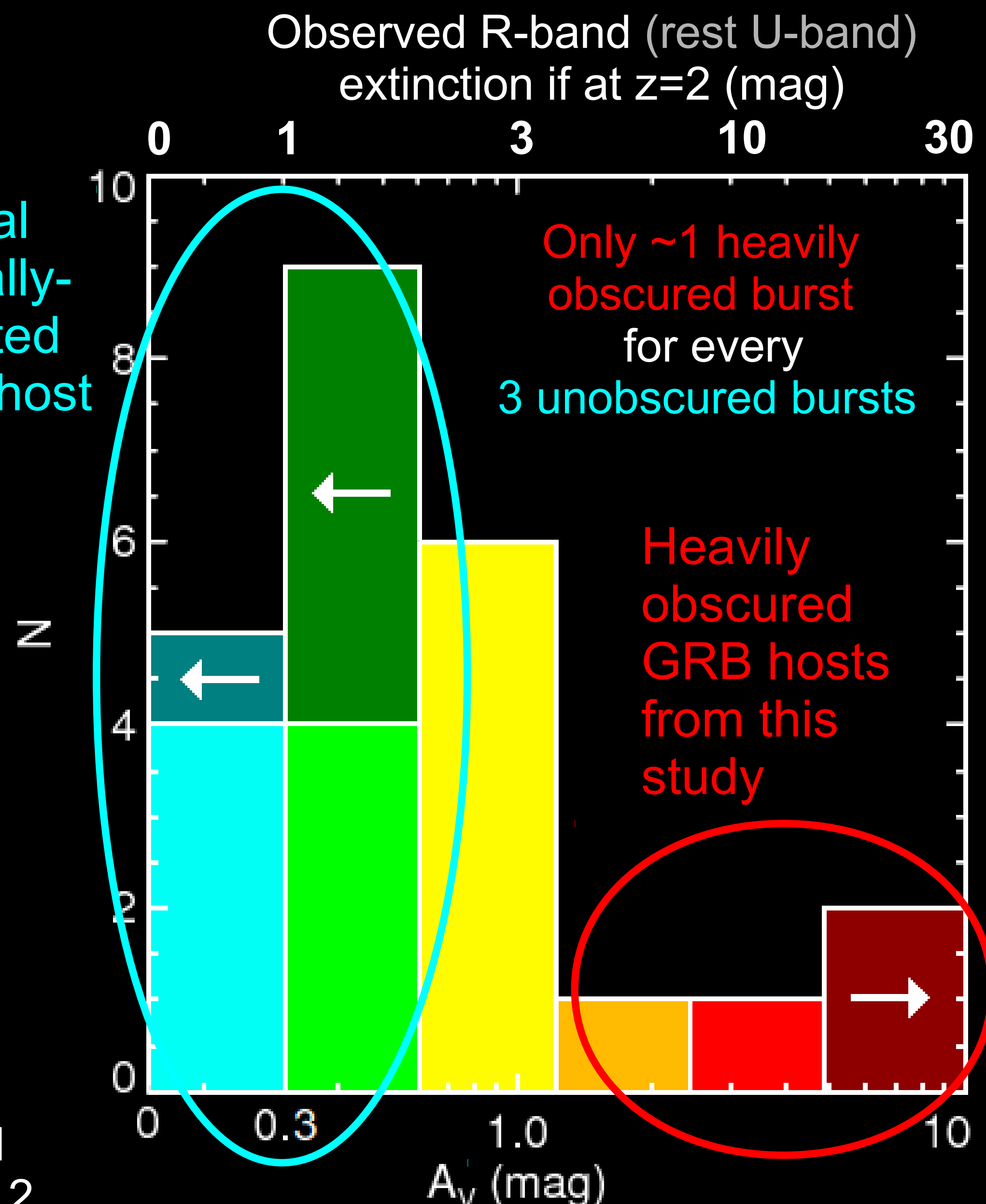
+

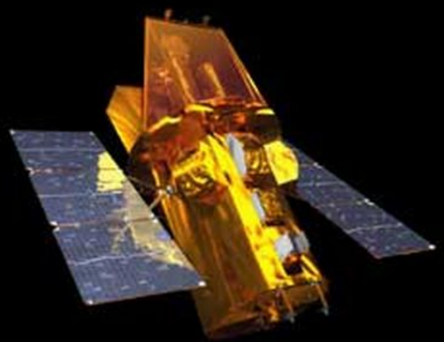

Cenko+2009
Perley+2009

Greiner+2011
Kruehler+2012

Typical optically-selected GRB host



# Swift Extinction Distribution



\+


Cenko+2009
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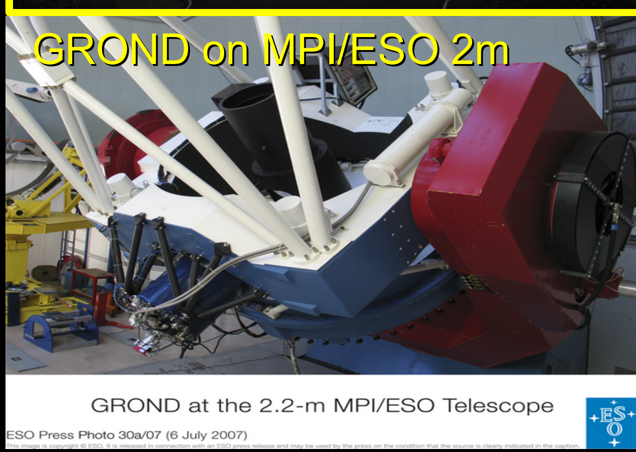


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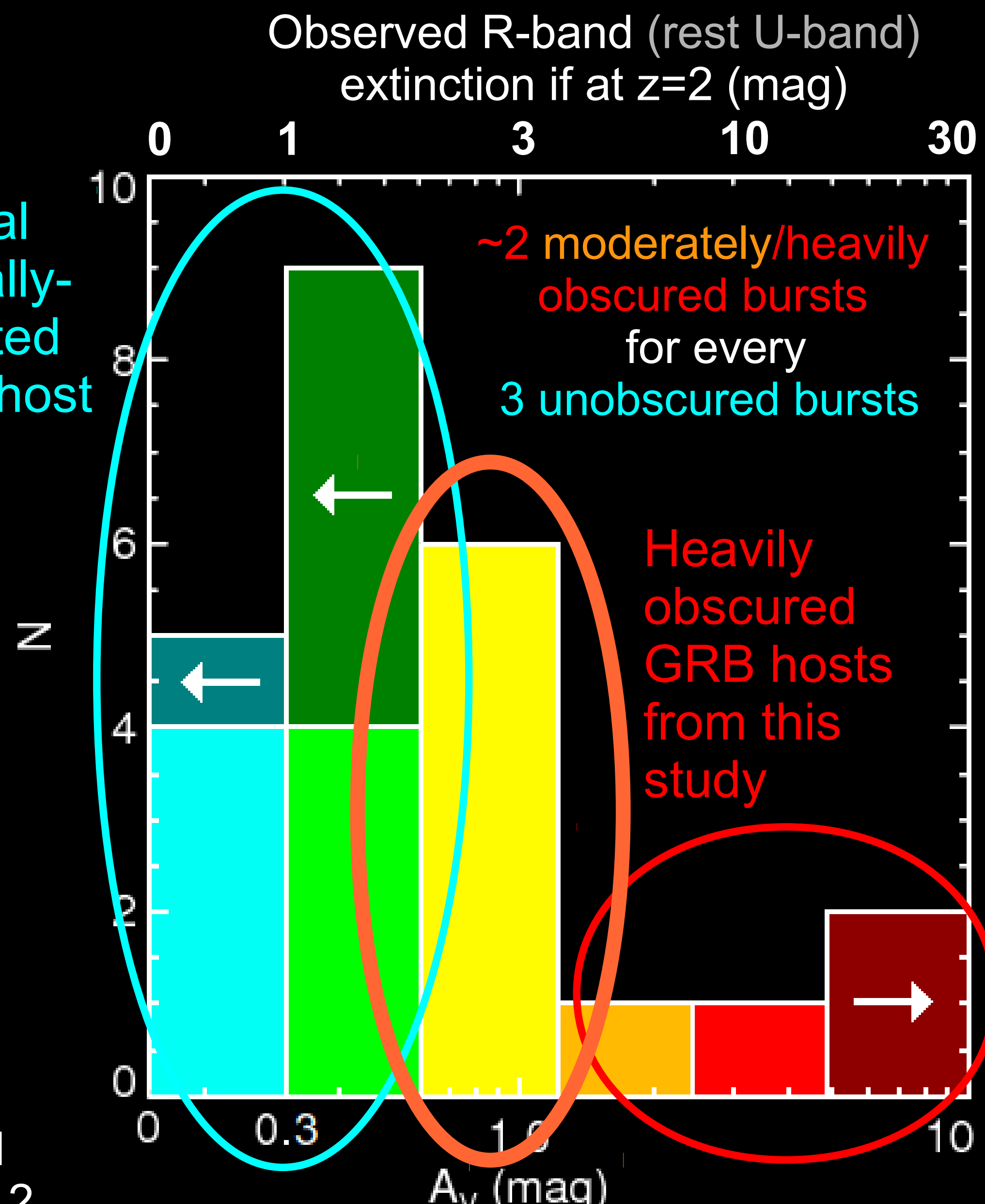
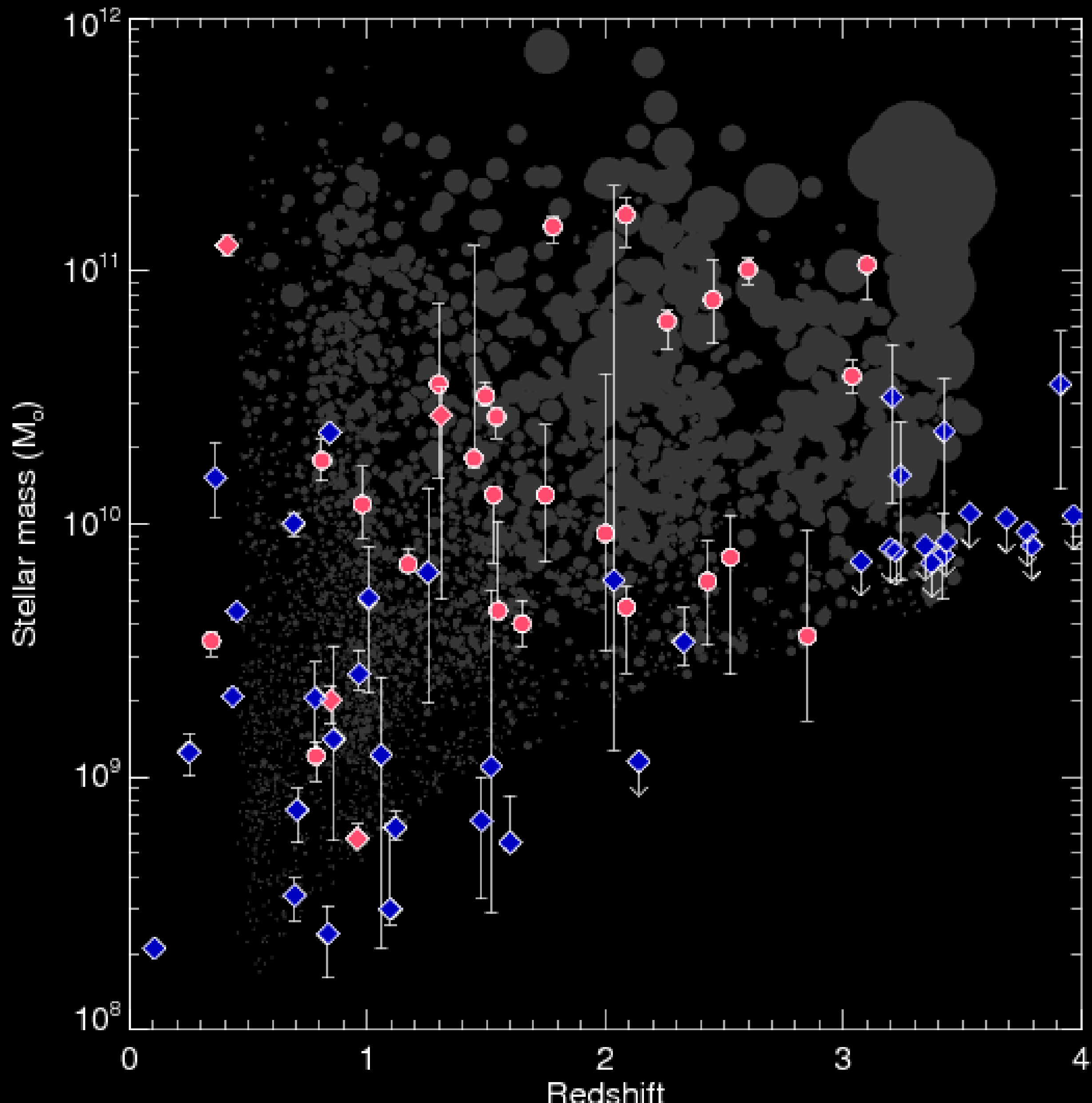
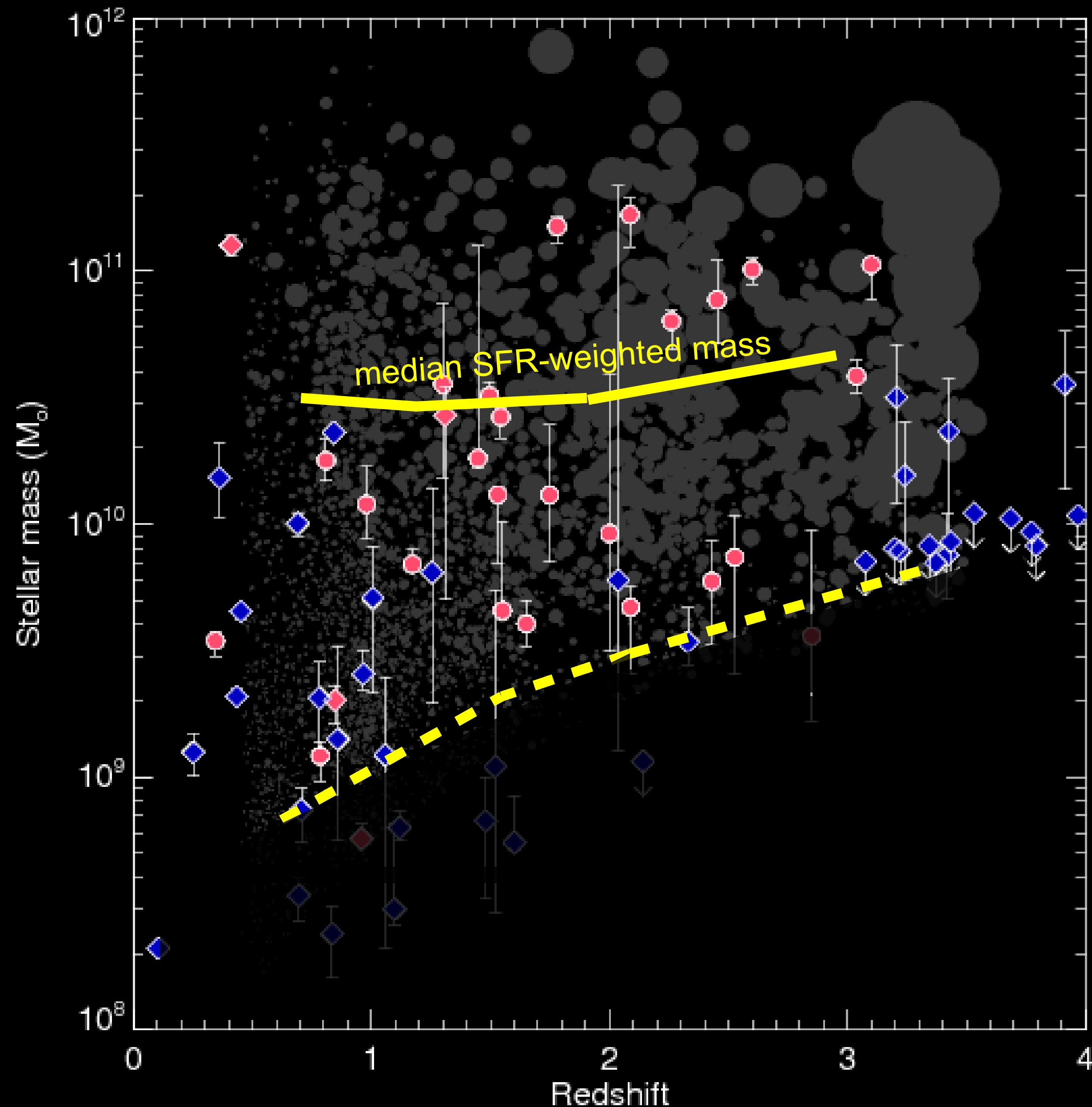


# Good Star Formation Tracers After All?




GRBs do occur in massive, luminous galaxies. But are there enough of them?

# Good Star Formation Tracers After All?



# Good Star Formation Tracers After All?

No. (at least, not at z~1)

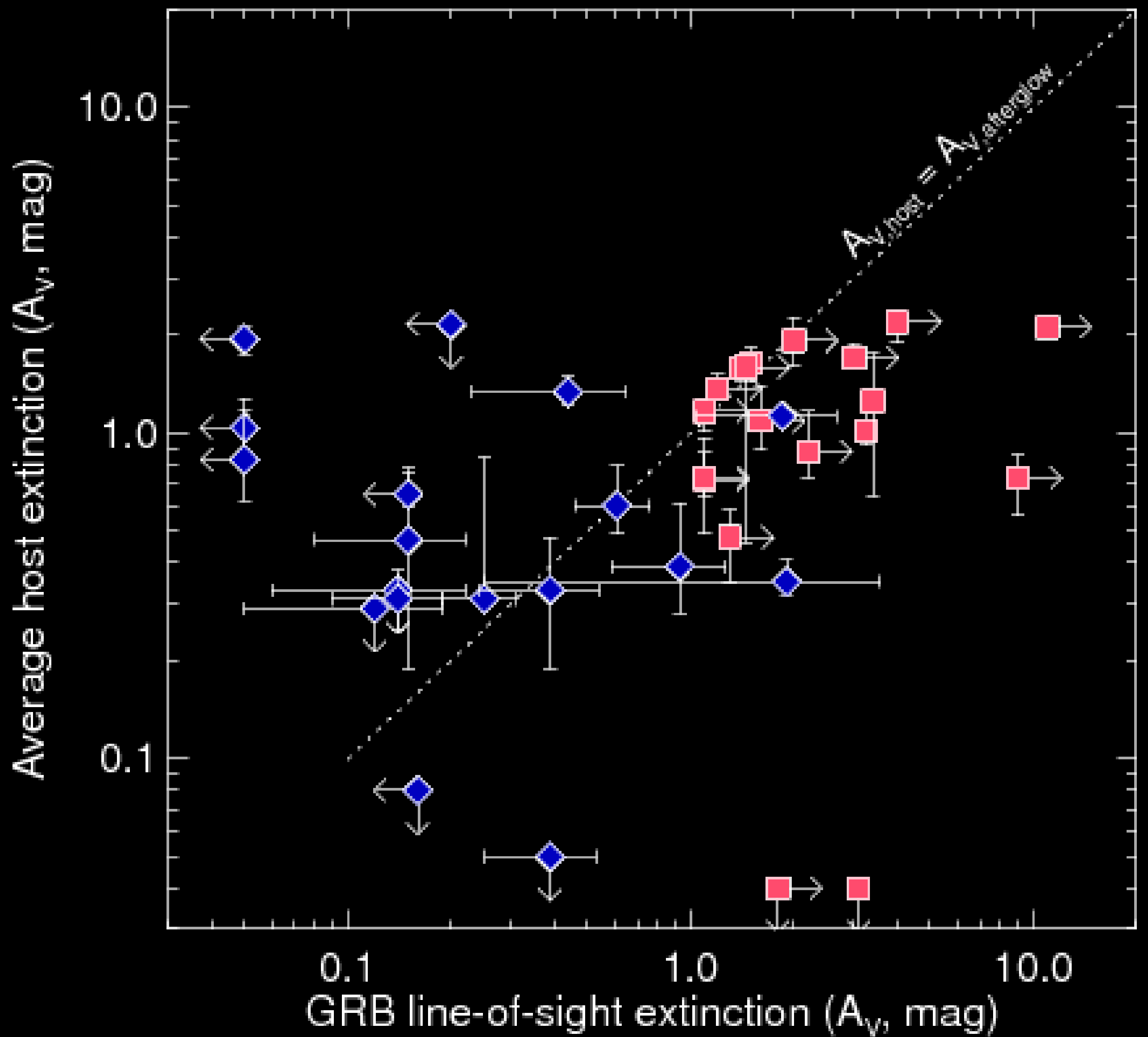
Relative to the SFR(mass) distributions in MOIRCS deep survey...

GRBs remain highly biased tracers of SFR at
z~0.5-1.5, *even including dust-obscured bursts.*

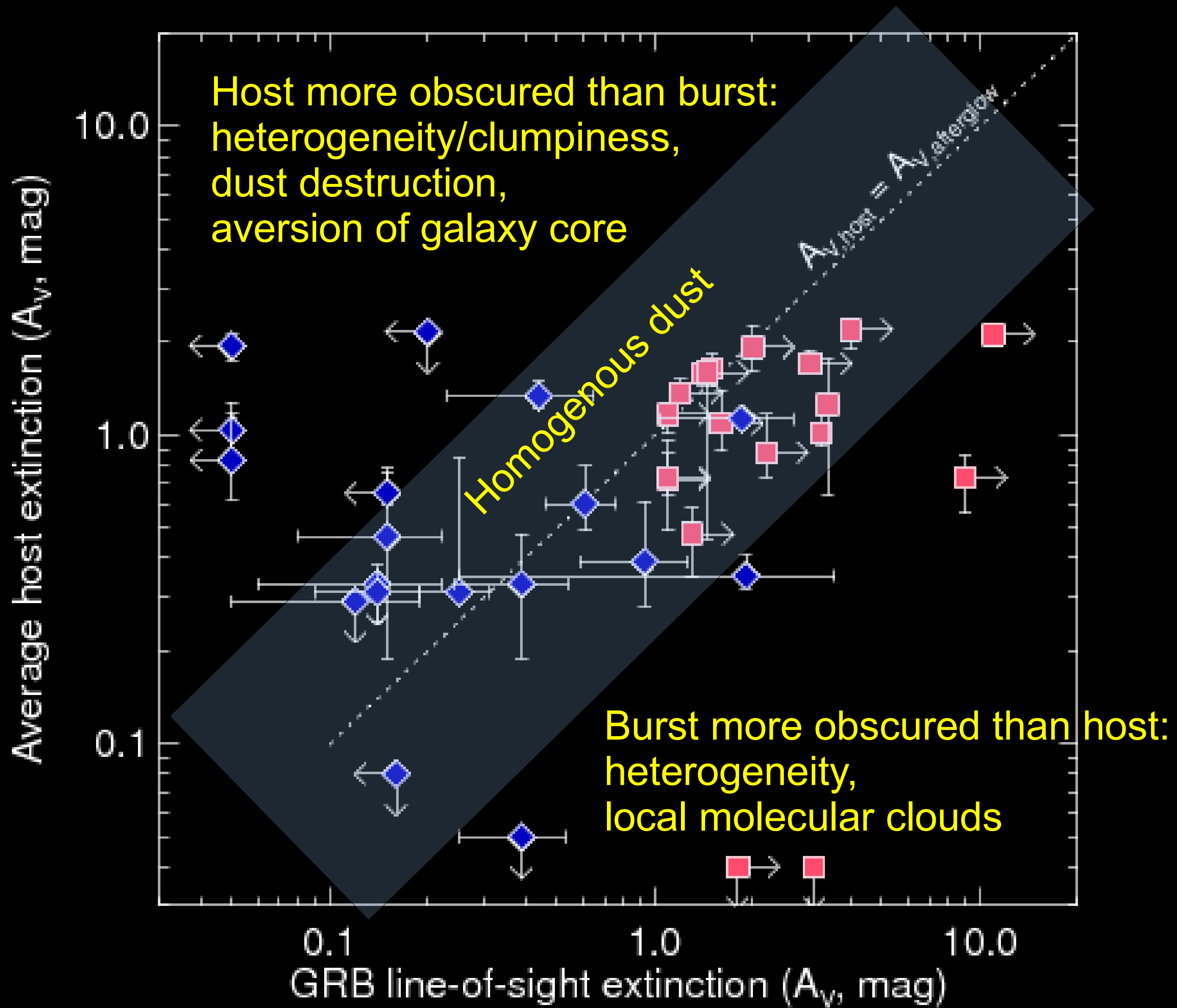
Rate suppression is at least a factor of >5 for
$M > \text{few} \times 10^{10}\ M_{\odot}$ galaxies versus
$M \sim \text{few} \times 10^{9}$ galaxies

Consistency may improve at higher-z, but extreme caution is warranted!

# Where is the dust?

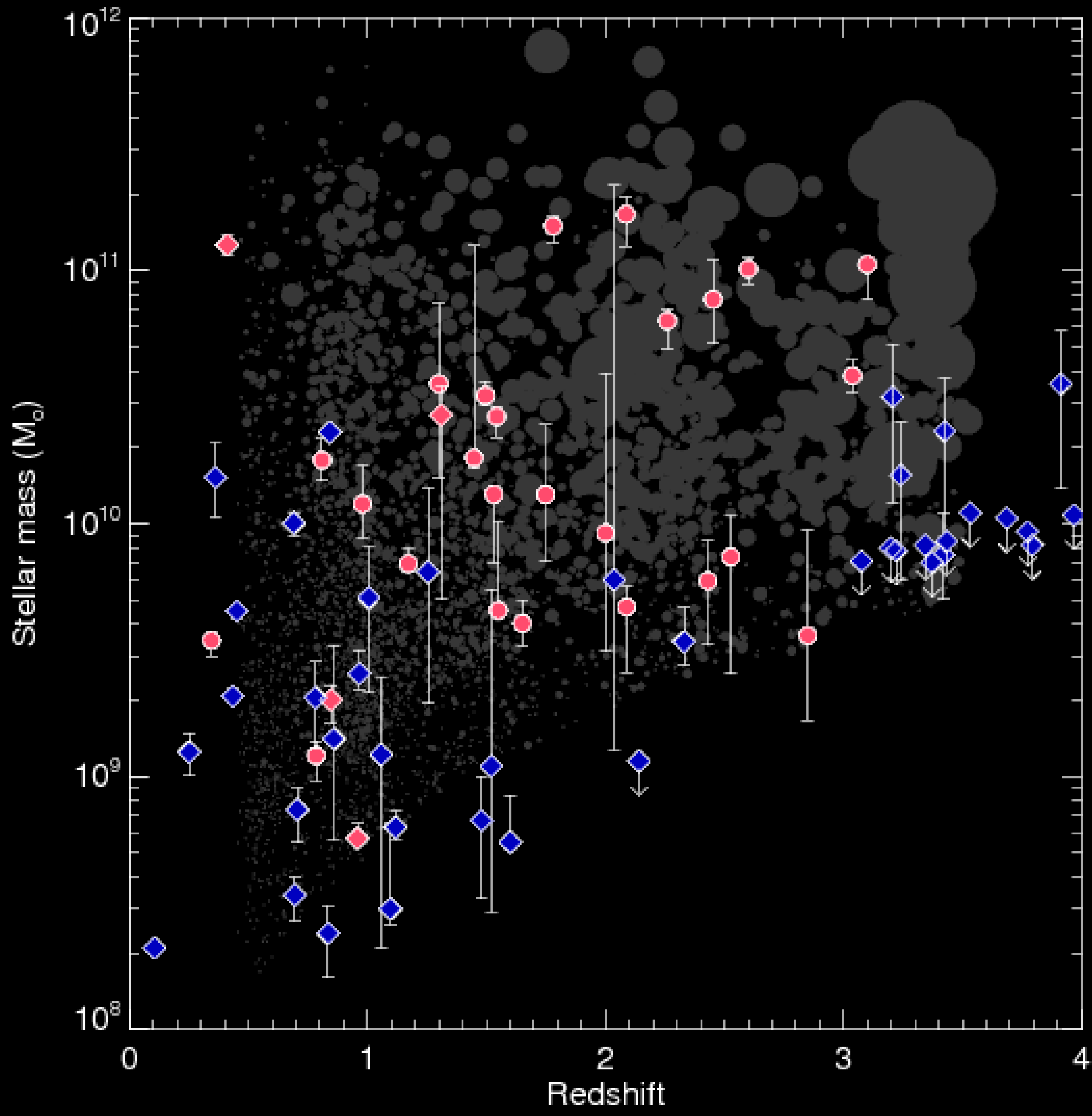


# Where is the dust?




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

# Extinction-Mass Correlation



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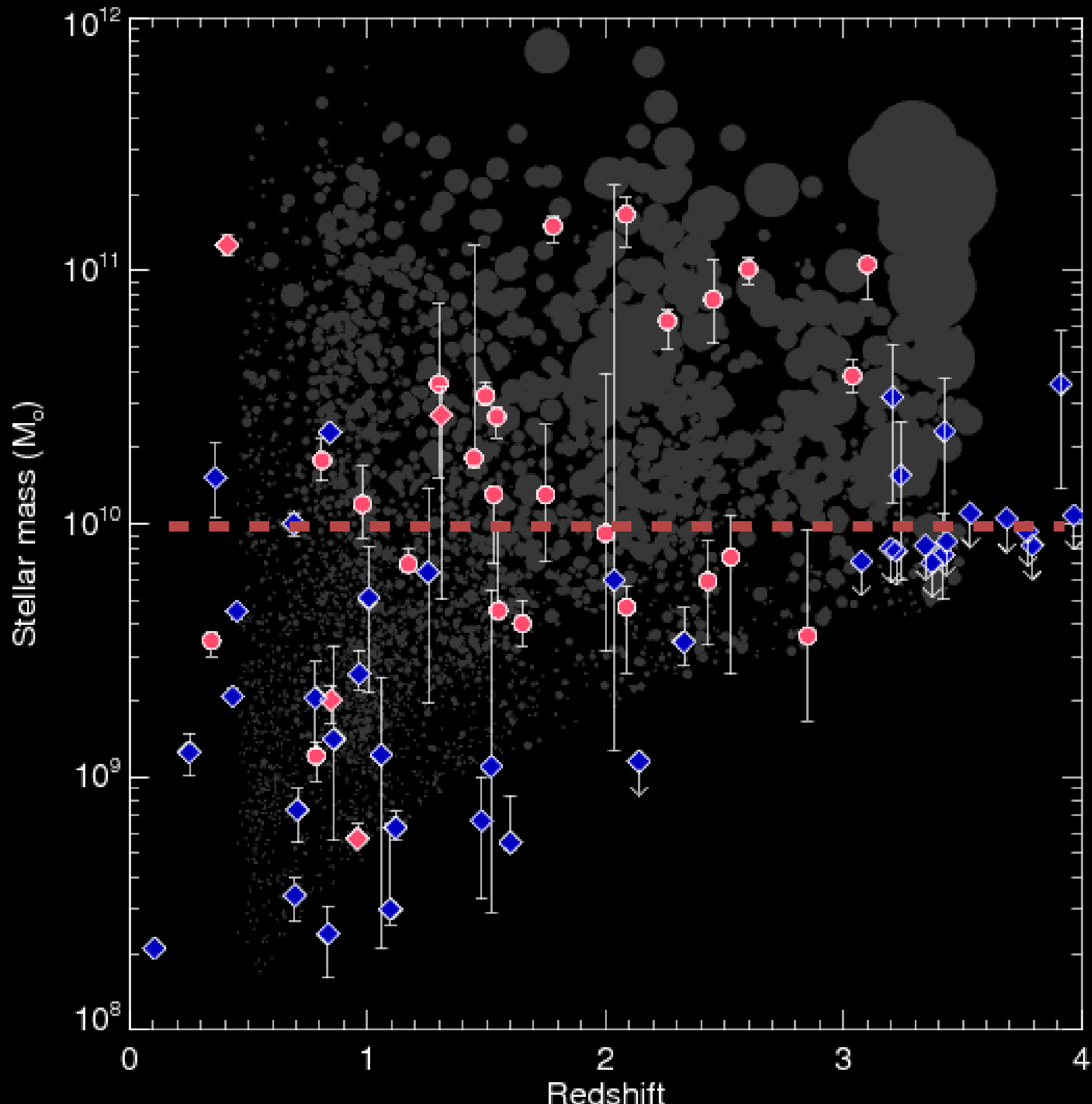
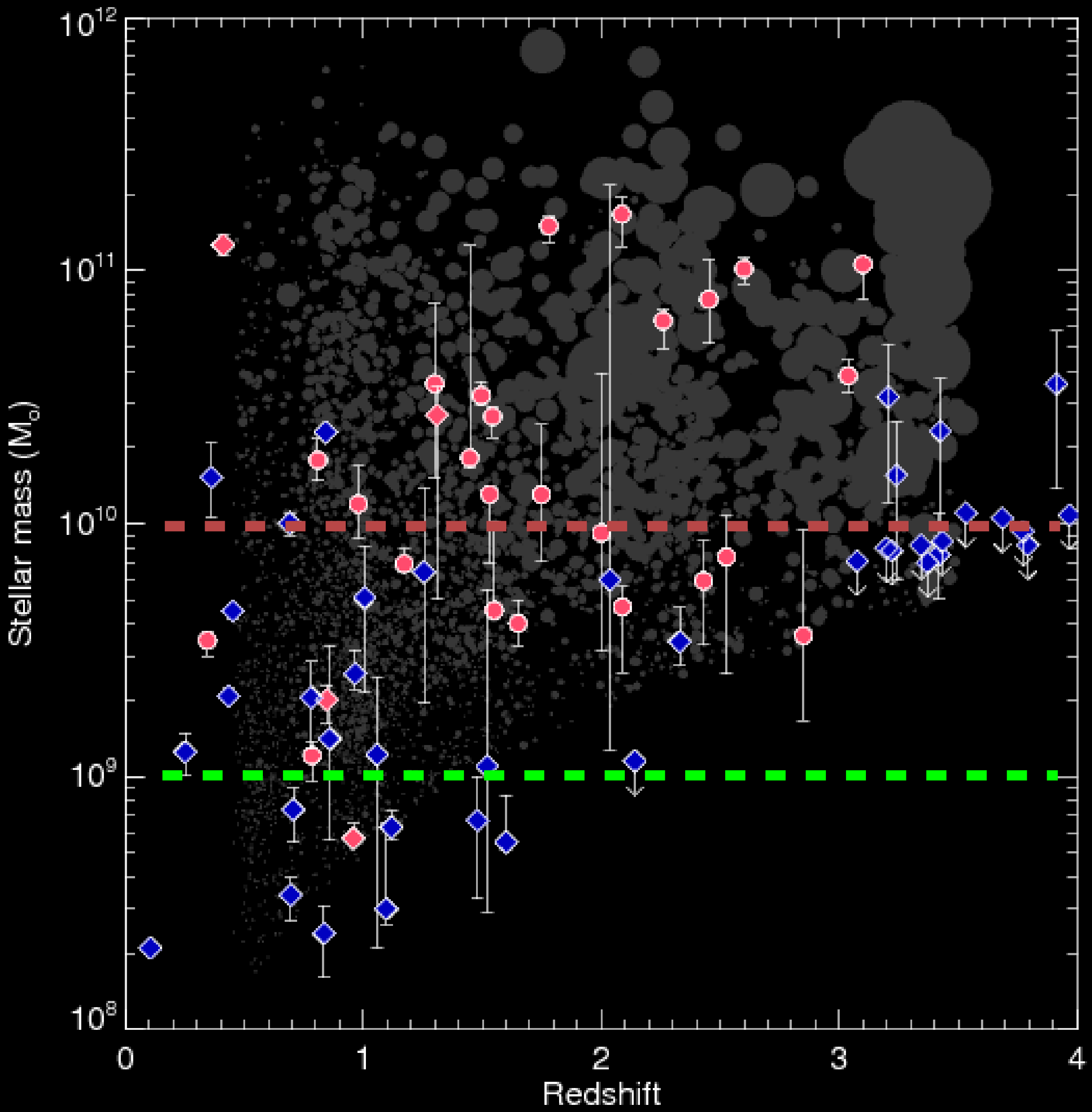



Massive, luminous galaxies are heavily obscured.

(well-known)

# Extinction-Mass Correlation




Massive, luminous galaxies are heavily obscured.

(well-known)

Low-mass galaxies are rarely obscured.

(assumed, but hard to prove by other means!)

# Conclusions

**GRBs occur in all types of high-z star-forming galaxies.**

High-mass and low-mass, dwarf to ULIRG/SMGs

No strict cutoff/aversion of any large-scale environment.

**GRBs at z~1 are not unbiased tracers of star-formation.**

Factor of ~5-10 suppression above $\sim 3 \times 10^{10}$ $M_o$.

Metallicity effect?   Clue to the nature of the progenitor.

Relation above z>1.5 or at lower masses unclear.

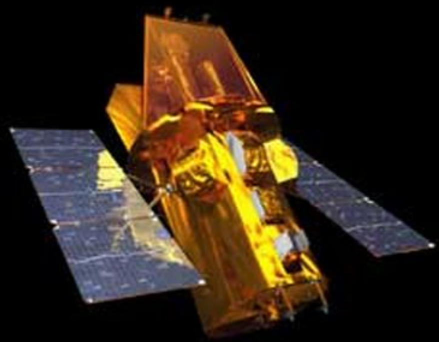
(Still usable as a limited SFR tracer in some regimes?)

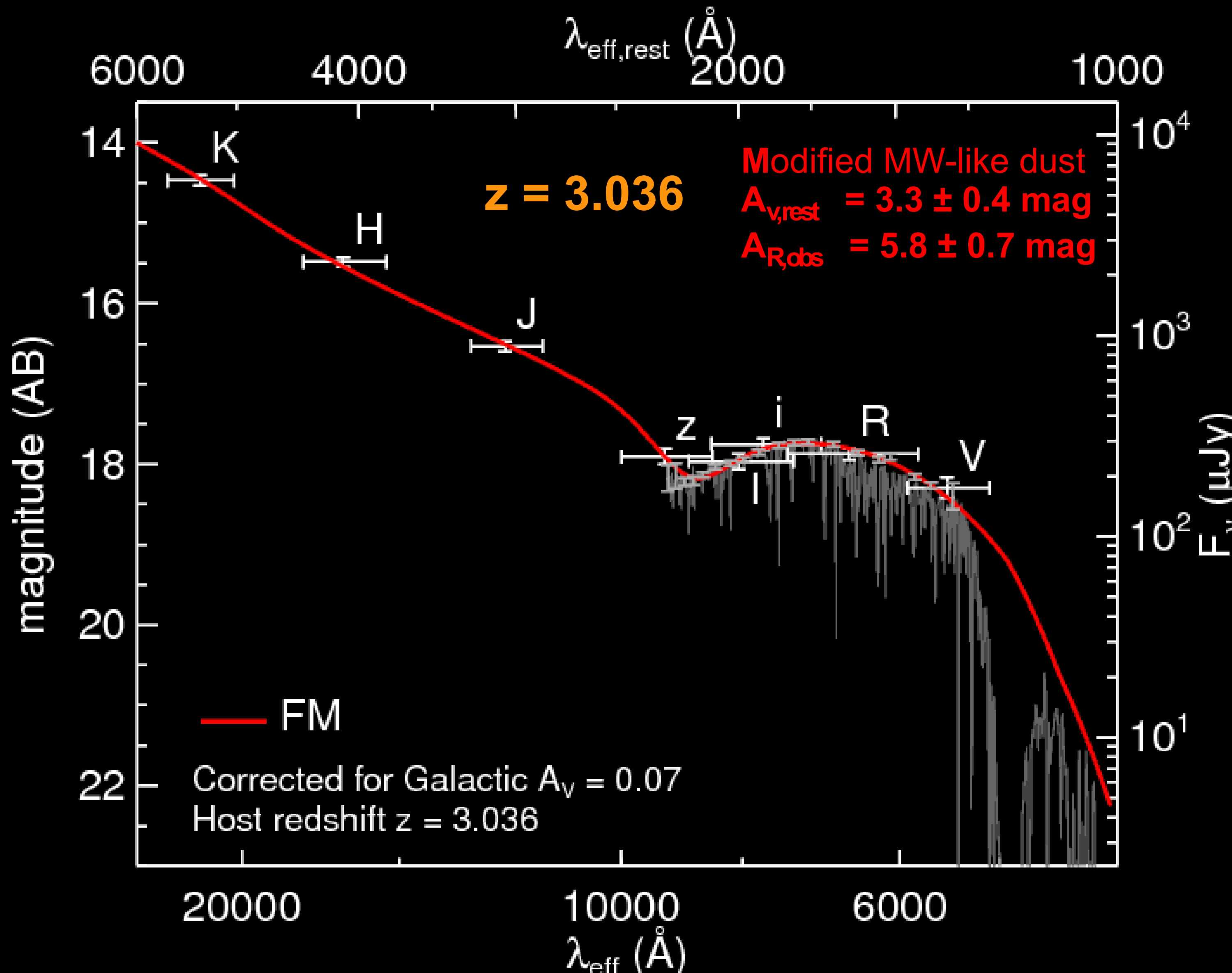
**Nevetheless, GRBs confirm that:**

Dust correction is not a major concern in low-mass galaxies

Dust in high-z galaxies is relatively homogeneous, with exceptions

# The Exceptionally Luminous GRB 080607






Perley et al. 2010b