Gamma-Ray Bursts and Host Galaxies at High Redshift

Daniel Perley (Caltech)

Andrew Levan
Nial Tanvir
Steve Schulze
Antonino Cucchiara

The High-Redshift Frontiers

The early Universe was an exciting time:

- First stars
- First galaxies
- First quasars
- First metals
- Reionization of IGM
- Growth of structure

Observational gap between z~1000 (CMB)
and z~9 (Lyman-break galaxies)
/ z~7 (spectroscopically-confirmed galaxies/quasars)

Observing the High-z Universe

In **emission**:

How much star-formation?
(Enough to produce reionization?)

In what kinds of galaxies?
  Bright, faint?
  Any dust?

What stellar populations?
  Pop III stars?

In **absorption**:

History of chemical enrichment:

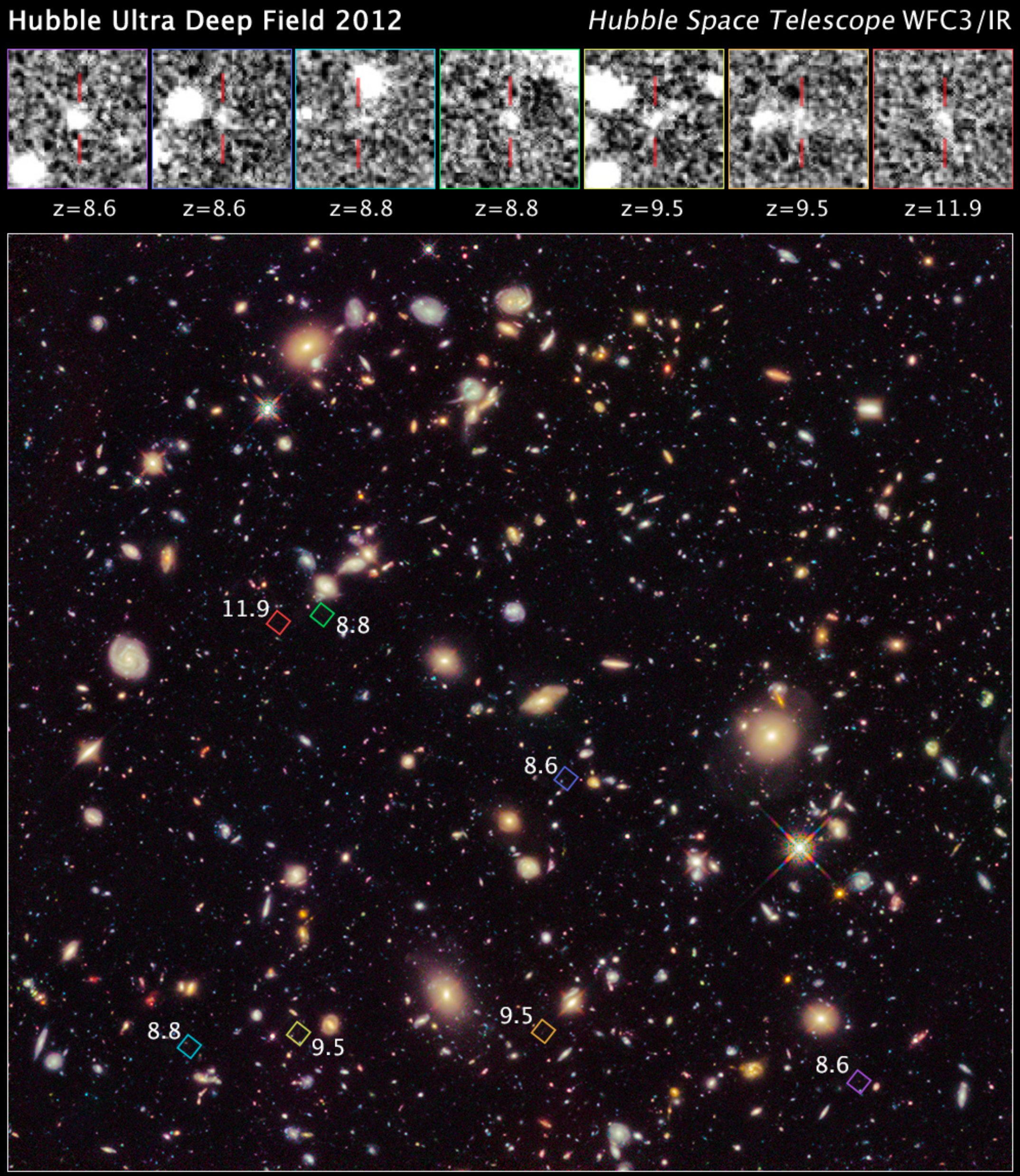
How fast did metals form?

Relative abundances; signatures of early SNe?

Early dust formation?

When did reionization come to an end?

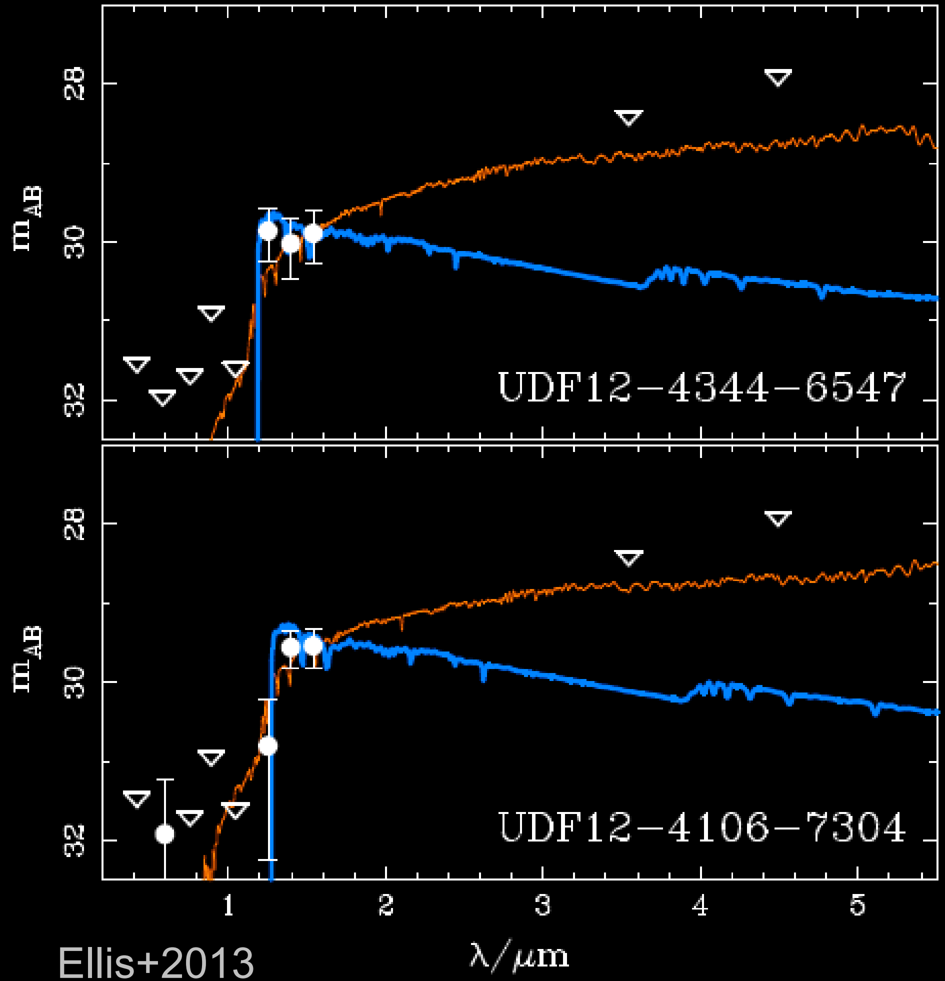
High-z Universe in Emission: LBGs



NASA and ESA

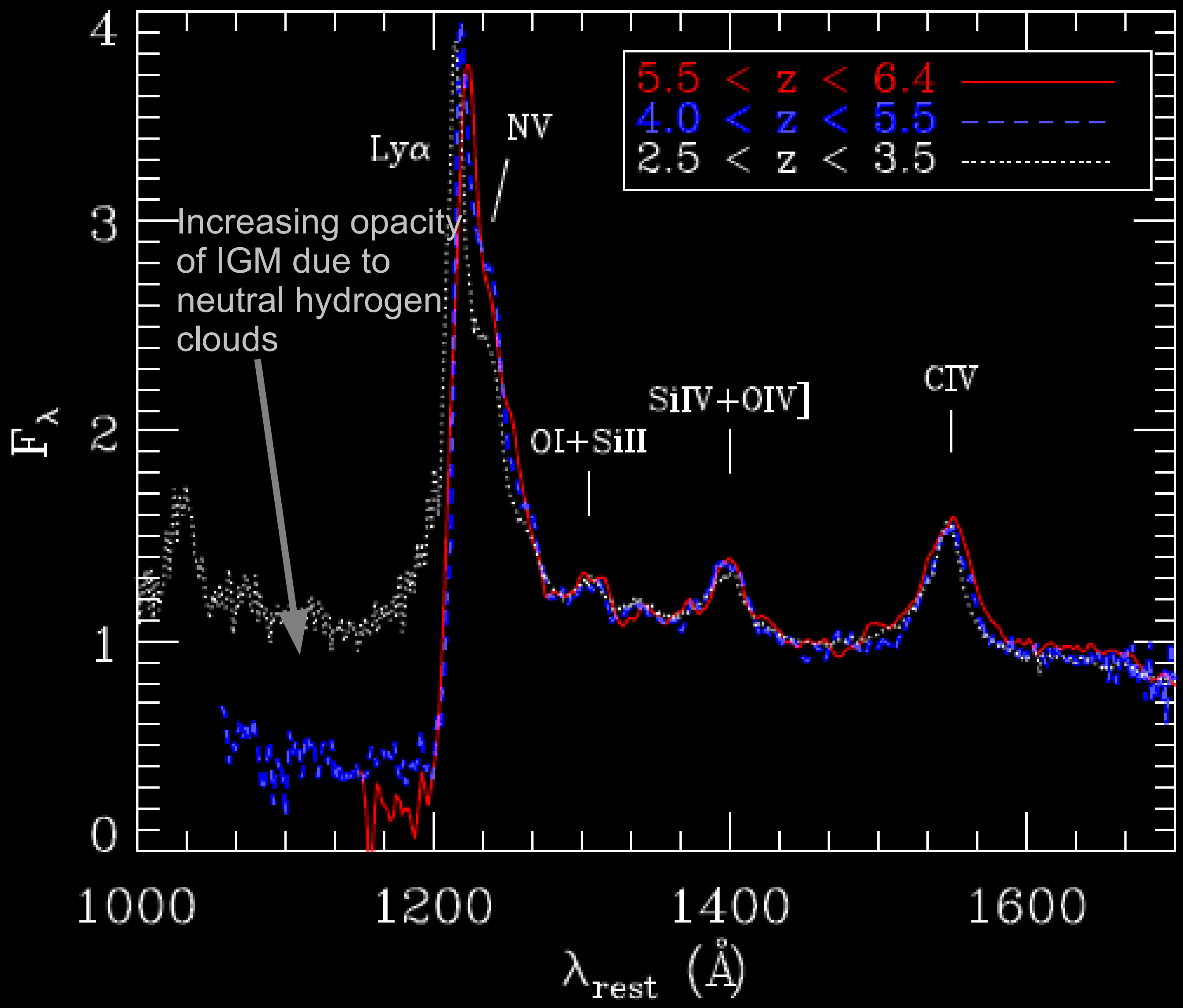
STScI-PRC12-48a

Lots of z~5-7 and a handful of z>8 galaxies now known from HST (at a cost of 1000s of orbits; no spectroscopic information)



Ellis+2013

High-z Universe in Absorption: Quasars



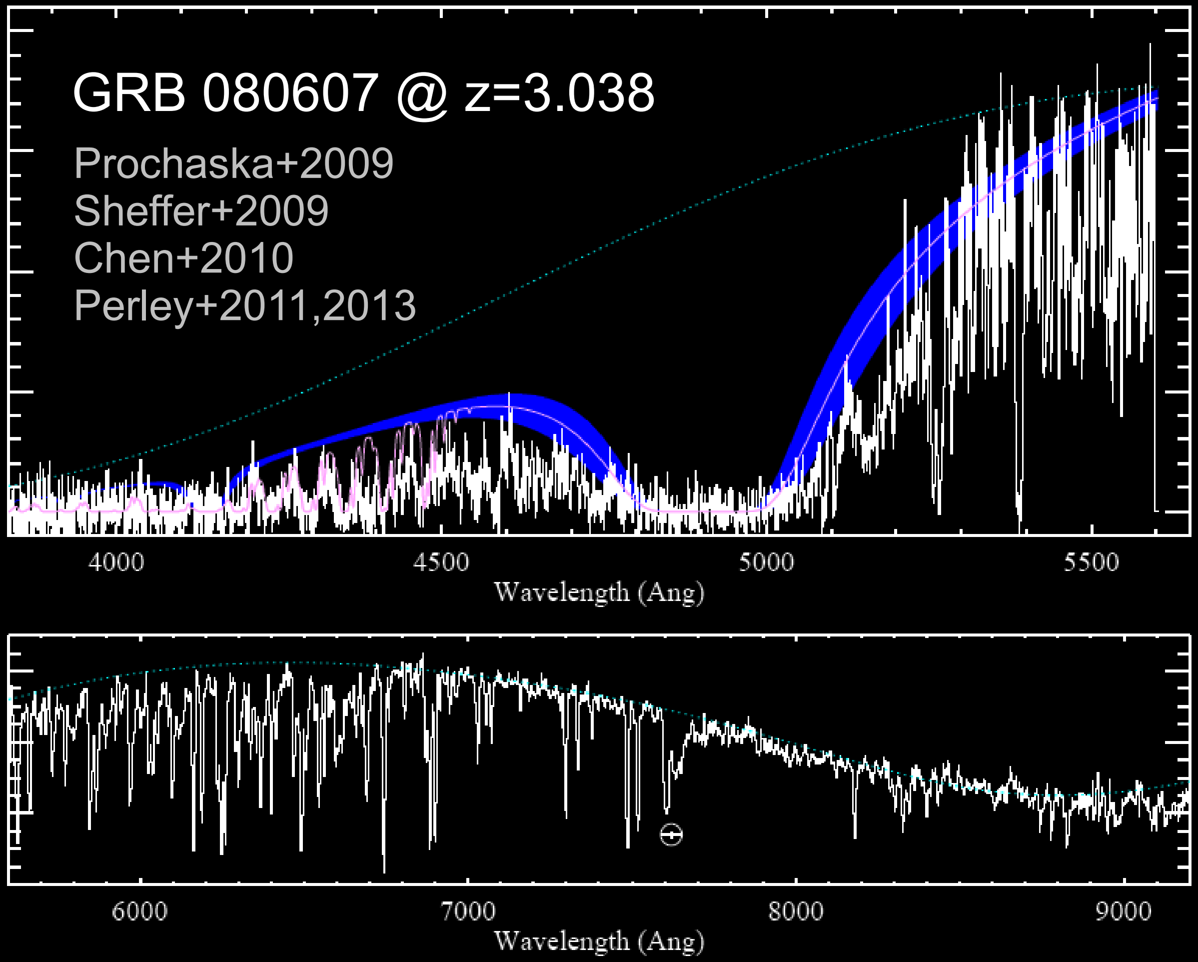
Increasing opacity of IGM due to neutral hydrogen clouds

Juarez+2009

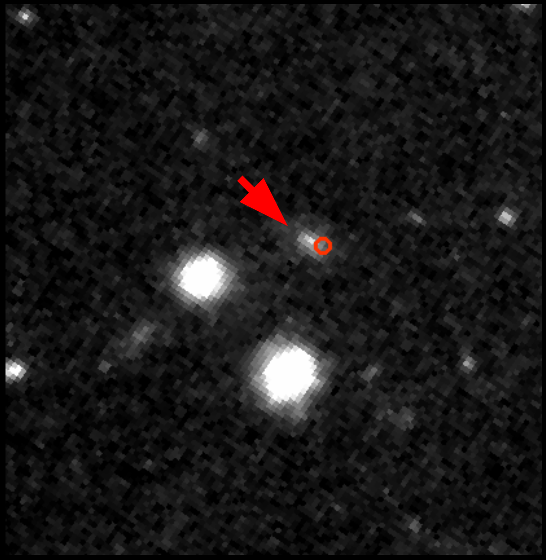
Quasars are bright enough for spectroscopy (with some effort!), but probe exotic environments – and effectively vanish beyond z>7

GRBs: Probes of High-z Universe

Far more luminous than QSO's, and easier to find
Probe (“typical?”) star-forming galaxies
Fade away to *also* allow deep host observations
Originate from star-formation; numbers may probe cosmic SFR

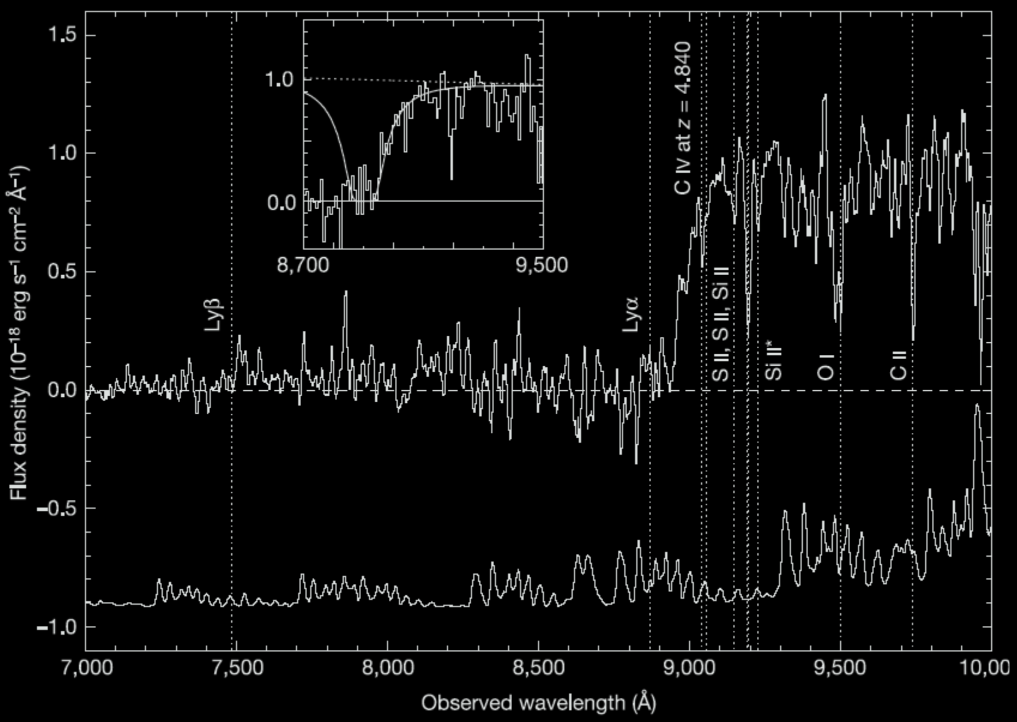

GRB 080607 @ z=3.038
Prochaska+2009
Sheffer+2009
Chen+2010
Perley+2011,2013

A GRB probing a metal-enriched molecular cloud
Metal-enriched molecular cloud in a moderately massive, red galaxy



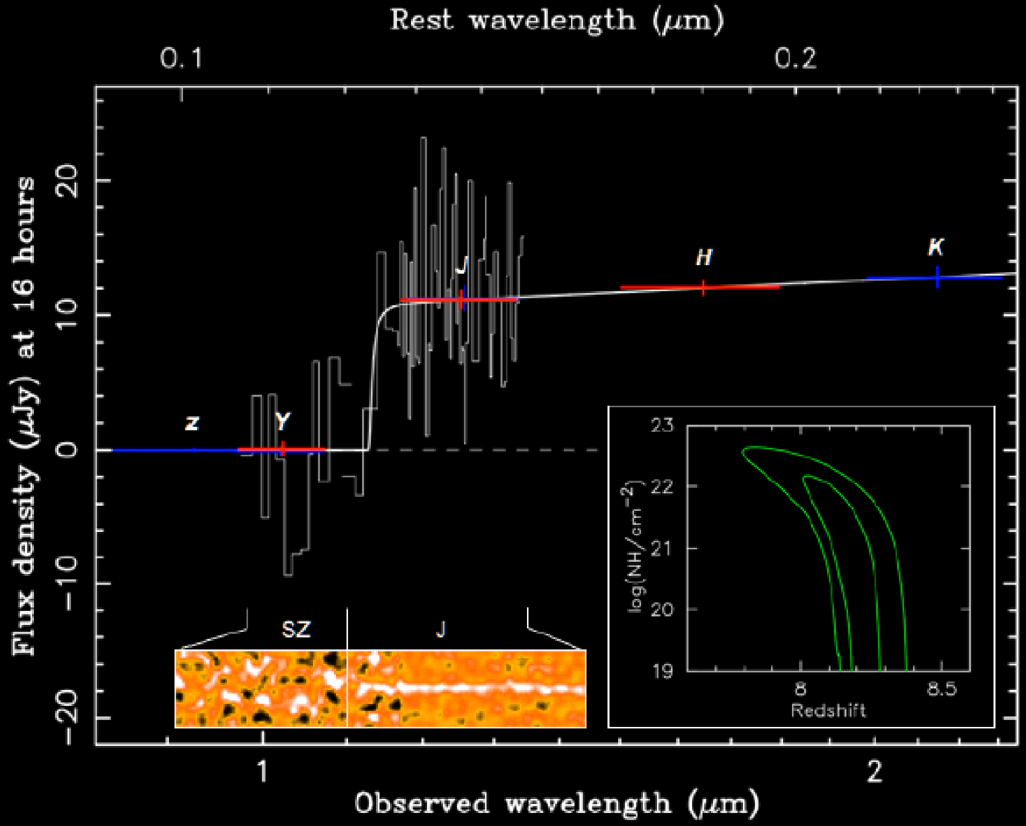
High-z GRBs

GRB 050904 (z=6.295)



Kawai+2006

GRB 090423 (z=8.2)



Tanvir+2012
Salvaterra+2012

High-z GRBs

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060522	**5.11**	**spectroscopic**	Cenko+2006
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060927	**5.467**	**spectroscopic**	Ruiz-Velasco+2007
080320	6	photometric	Perley+2009
120521C	6	photometric	in prep.
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120923A	**8.5**	**spectroscopic**	Tanvir, this conference
090429B	**9.4**	photometric	Cucchiara+2011

All *Swift* bursts, out of 760 in mission (270 with measured redshifts)

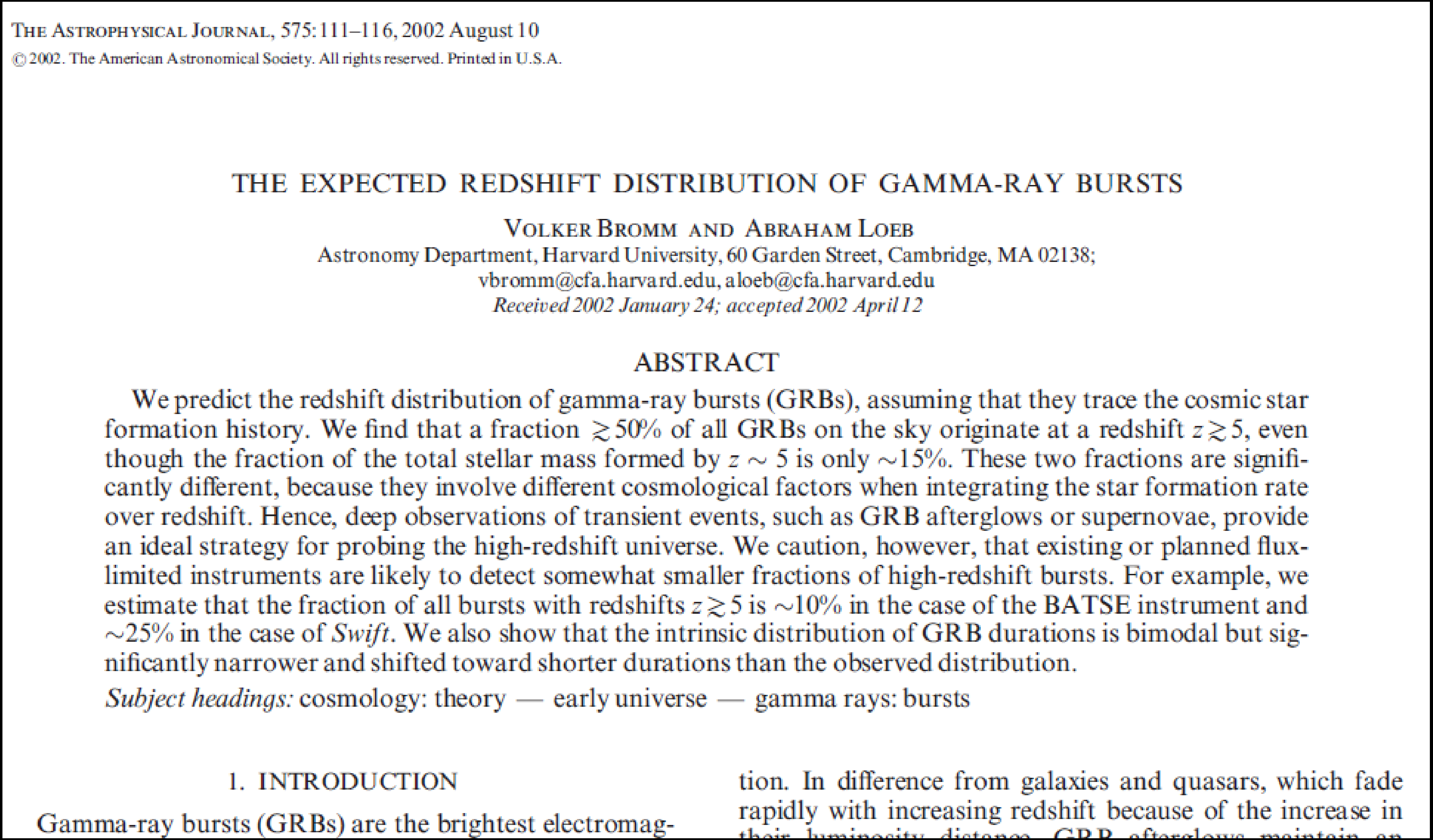
Outline

The **rates** of high-z events
- Observationally
  - How many are we missing?
  - Can we do better?
- Intrinsically
  - GRB rate at high-z

The **environments** of high-z events
  - Host galaxy constraints

Observed Rates

Some early predictions



The Astrophysical Journal, 575:111–116, 2002 August 10

THE EXPECTED REDSHIFT DISTRIBUTION OF GAMMA-RAY BURSTS

Volker Bromm and Abraham Loeb
Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138;
vbromm@cfa.harvard.edu, aloeb@cfa.harvard.edu

Received 2002 January 24; accepted 2002 April 12

ABSTRACT

We predict the redshift distribution of gamma-ray bursts (GRBs), assuming that they trace the cosmic star formation history. We find that a fraction $\gtrsim 50\%$ of all GRBs on the sky originate at a redshift $z \gtrsim 5$, even though the fraction of the total stellar mass formed by $z \sim 5$ is only $\sim 15\%$. These two fractions are significantly different, because they involve different cosmological factors when integrating the star formation rate over redshift. Hence, deep observations of transient events, such as GRB afterglows or supernovae, provide an ideal strategy for probing the high-redshift universe. We caution, however, that existing or planned flux-limited instruments are likely to detect somewhat smaller fractions of high-redshift bursts. For example, we estimate that the fraction of all bursts with redshifts $z \gtrsim 5$ is $\sim 10\%$ in the case of the BATSE instrument and $\sim 25\%$ in the case of *Swift*. We also show that the intrinsic distribution of GRB durations is bimodal but significantly narrower and shifted toward shorter durations than the observed distribution.

Subject headings: cosmology: theory — early universe — gamma rays: bursts

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the brightest electromag-

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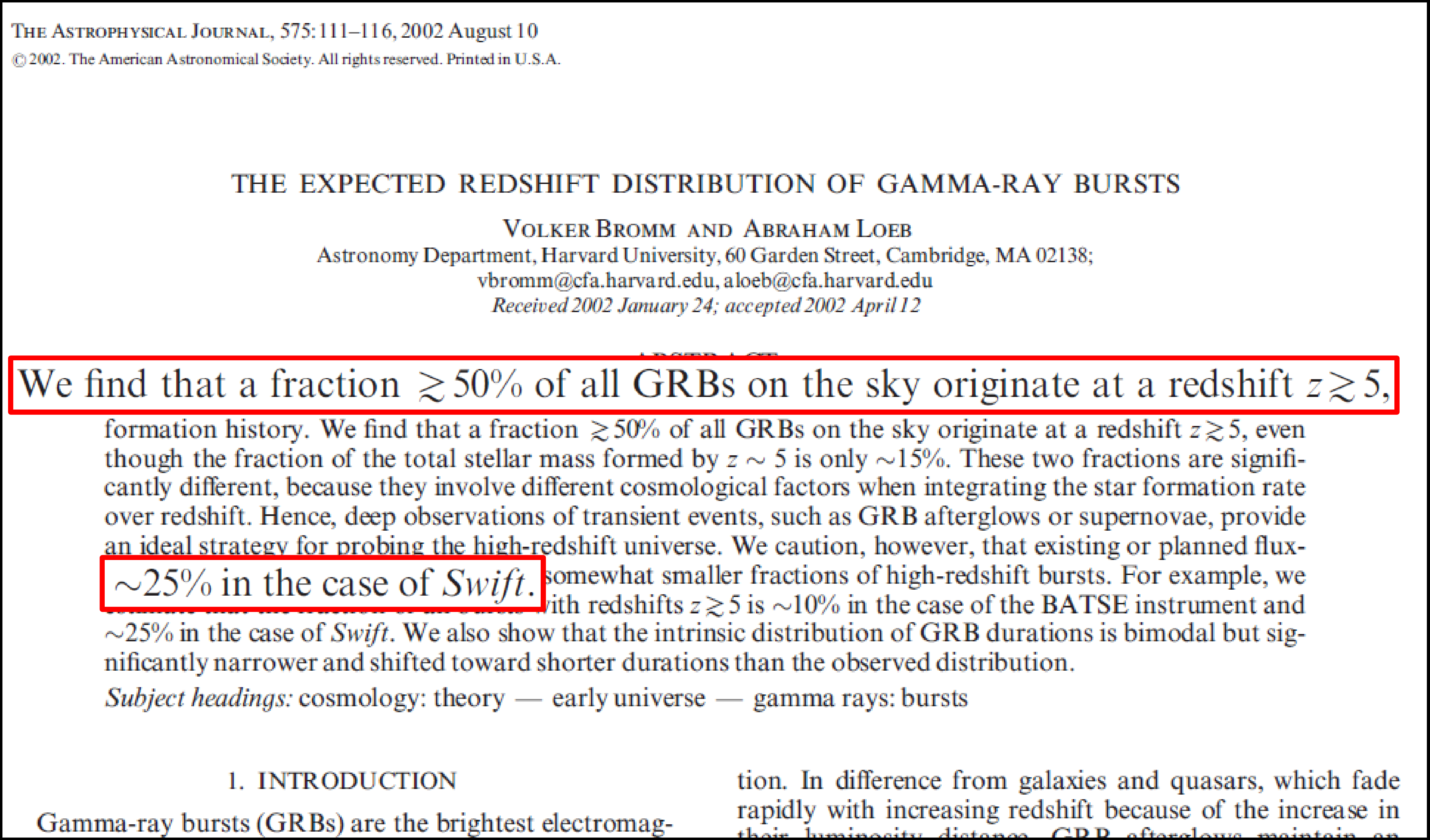
Some early predictions



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How Frequent?

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All Swift bursts (760 to date):

13/760 = 1.7% at z>5
8/760 = 1.0% at z>5.5
3/760 = 0.4% at z>8
1/760 = 0.1% at z>9

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All Swift bursts *with redshifts* (270 to date):

13/270 = 4.8% at z>5
8/270 = 3.0% at z>5.5
3/270 = 1.1% at z>8
1/270 = 0.4% at z>9

Biases against (and for!) high-z GRBs

Determining the redshift of a z>6 GRB is unlike a z<5 GRB because

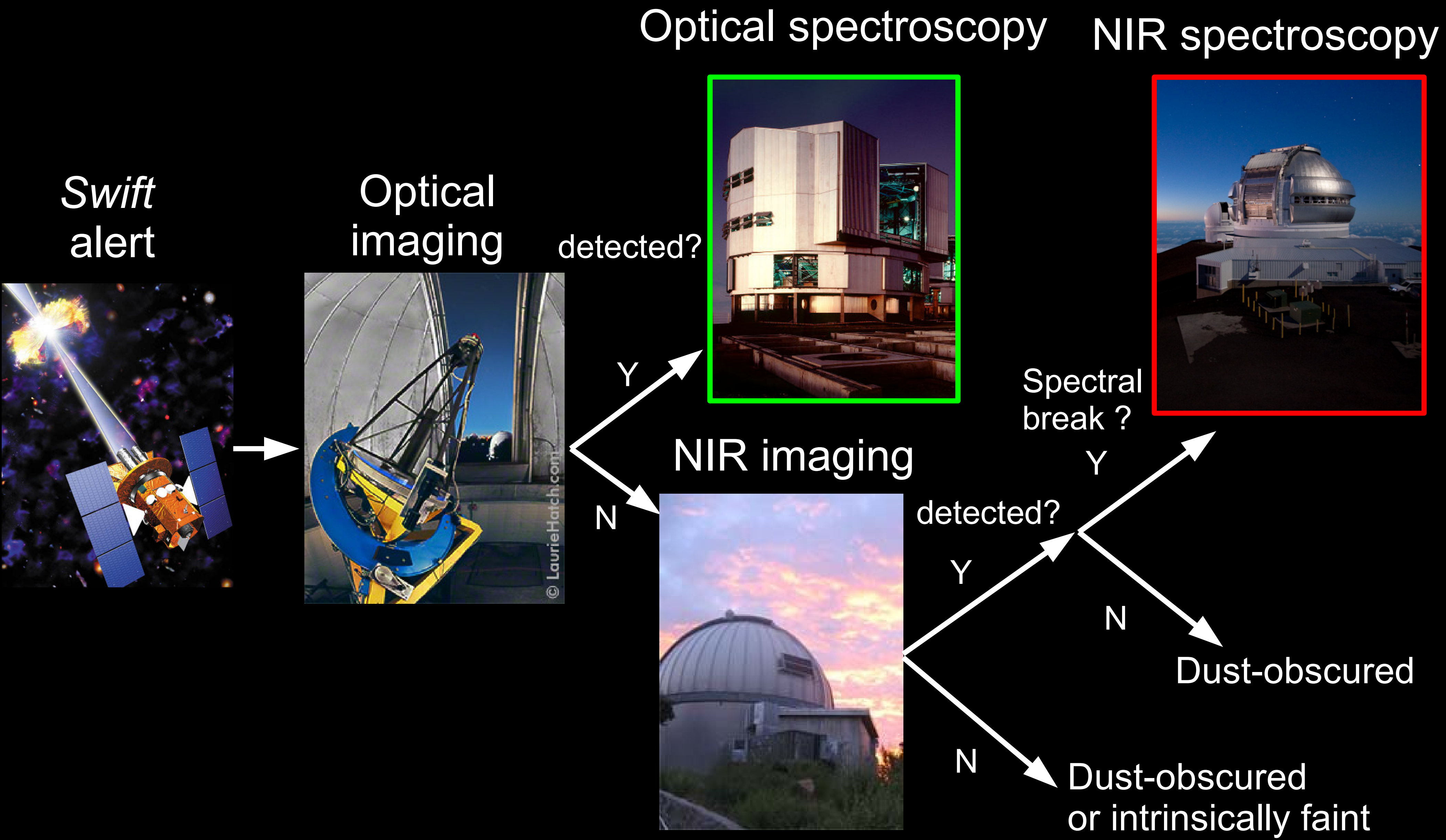
– : **Infrared follow-up is necessary**
   - No optical afterglow
   - IR imagers much less ubiquitous than optical to localize AG
   - IR spectrographs often unavailable than optical (and are less sensitive in general)

– : Afterglows are never very bright

+ : **Significant community interest**
   - Optical nondetection + IR detection: Observers ”pull out all the stops”

+ : Photometric redshift often practical

The Path to a Redshift



Swift alert

Optical imaging

detected?

Y

Optical spectroscopy

N

NIR imaging

detected?

Y

Spectral break ?

Y

NIR spectroscopy

N

Dust-obscured

N

Dust-obscured or intrinsically faint

Biases against (and for!) high-z GRBs

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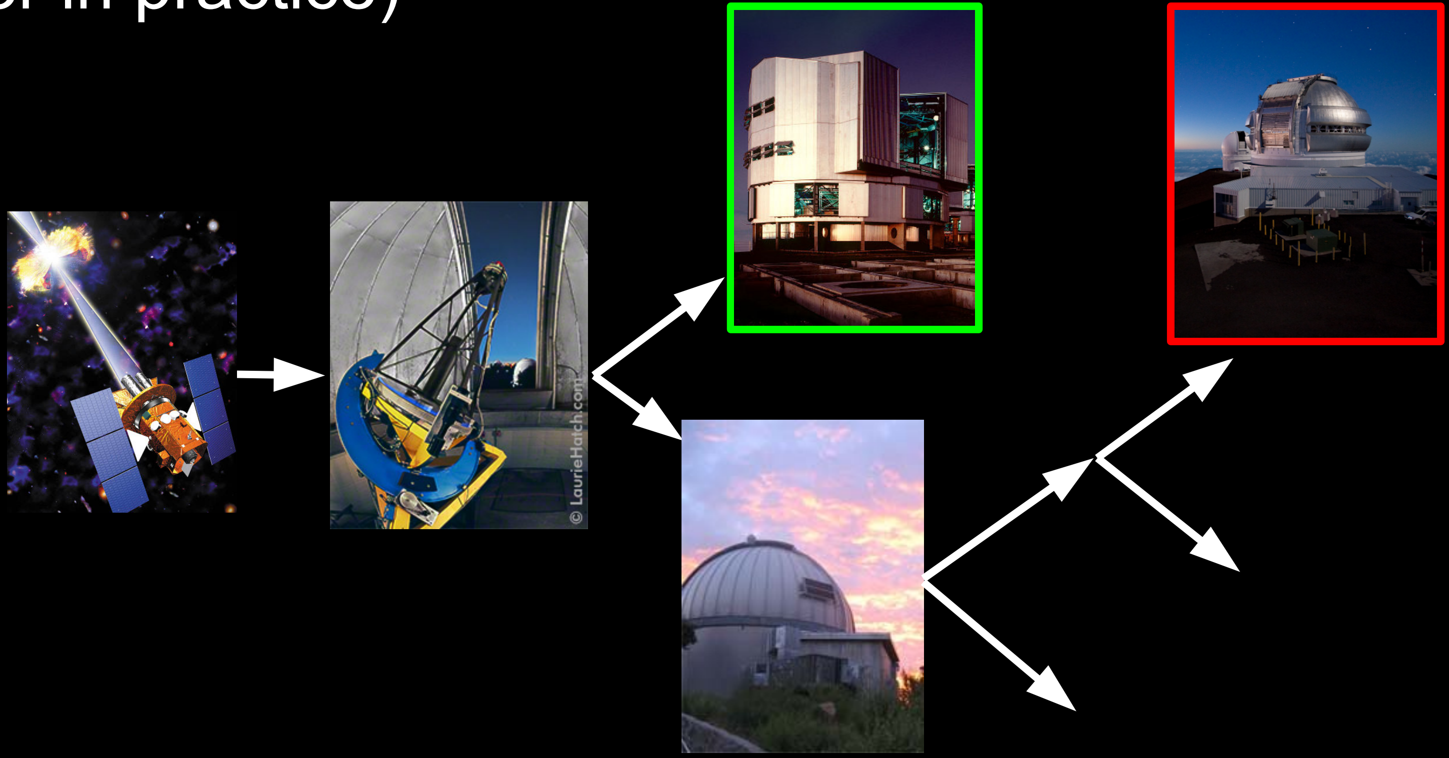
Photometric redshift often practical

Reliable rates using “complete” samples

Delimit a sample on the basis of good observability
(in principle or in practice)

1. Each step is more likely to succeed

2. Even without spectroscopy, optical/NIR detections carry redshift information



Some examples:

P60 sample – Cenko et al. 2009, Perley et al. 2009
GROND sample – Greiner et al. 2011
TOUGH sample – Hjorth et al. 2012, Jakobsson et al. 2012
BAT6 sample – Salvaterra et al. 2011

Three highly complete samples

Bursts automatically followed by the **P60** telescope

griz observations, often complimented by other western US / Hawaii telescopes

55 events (through 2012)
44 optical detections

Of remaining 11,
9 host detections

2 at high-z (z>5.5)

Bursts quickly followed by **GROND**

grizJHK simultaneous!

39 events (through 2011)
34 optical detections

NIR observations to check for breaks directly – no need for hosts!

Of five undetected events, two probably dust-obscured or faint;

1 to **3** at high-z (z>5.5)

Bursts well-located on sky for Southern-hemisphere follow-up

Afterglow data variable, but all have **deep host observations**

69 events (through 2011)
34 optical detections

(Of the remaining five: two definitely at high-z, one possibly at high-z)

0 to 1 at high-z (z>5.5)

Three highly complete samples

Bursts automatically followed by the **P60** telescope

griz observations, often complimented by other western US / Hawaii telescopes

55 events (through 2012)
44 optical detections

2 / 55:

4^{+5}_{-3} %

Of remaining 11,
9 host detections

2 at high-z (z>5.5)

Bursts quickly followed by **GROND**

grizJHK simultaneous!

39 events (through 2011)
34 optical detections

NIR observations to check for breaks directly – no need for hosts!

2±1 / 39:

5^{+7}_{-3} %

Of five undetected events, two probably dust-obscured or faint;

1 to **3** at high-z (z>5.5)

Bursts well-located on sky for Southern-hemisphere follow-up

Afterglow data variable, but all have **deep host observations**

69 events (through 2011)
34 optical detections

0.5±0.5/69:

1^{+4}_{-1} %

(Of the remaining five: two definitely at high-z, one possibly at high-z)

0 to 1 at high-z (z>5.5)

Combining Forces

+

+

Combine all three samples: **146 total GRBs**

136 of these have optical detections of AG or host

Remaining 10:
- 060522 z=5.11
- 050502B z=5.2
- 060927 z=5.46
- 080320 z~6
- 050904 z=6.3
- 090423 z=8.2
- 090429B z=9.2
- 080915 z=??
- 100205A z=??
- 061004 z=??

Only Three are Uncertain

080915: Faint burst with an extremely X-ray faint afterglow, though early GROND nondetection still requires some attenuation. No host constraint. (More likely low-z than high-z.)

100205A: Afterglow detected in H and K-band only; red. But no host to extremely deep limits. Either dust-obscured in a very faint host (much fainter than any host in Perley+2013) OR z~11.

061004: Deep VLT limits at 0.5 days; fairly ordinary X-ray afterglow. Could be either low-z or high-z.

All show no X-ray column excess (large X-ray column rules out high-z.)

080915 z=??
100205A z=??
061004 z=??

Combining Forces


P60

\+


GROND

\+


TOUGH

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z>5.5 : 4-7 / 146 (2 - 8%)
z>8 : 2-5 / 146 (1 - 6%)
z>10 : 0-3 / 146 (< 5%)

80% confidence
range from
Poisson statistics

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z>5.5 : 4-6 / 146 (2 - 7%)
z>8 : 2-4 / 146 (0.4 - 5%)
z>10 : 0-2 / 146 (< 3%)

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All events with redshifts (surprisingly consistent!)

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8/270 = 3.0% at z>5.5
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1/270 = 0.4% at z>9

Room for Improvement?

At 95 Swift bursts per year...

Swift detects **2 to 7** z>5.5 bursts per year

of these:

- **0.5**/year has opt+IR photometry, no spectroscopy
- **0.5**/year actually gets a spectroscopic redshift
- remainder (**1-6**/year) are missed

Swift detects **0.4 to 5** z>8 bursts per year

- **0.1**/year has a photometric redshift
- **0.2**/year has a spectroscopic redshift
- remainder are missed

Similar success rate as for optical (selection effects cancel out!), but this is not high – 30% or less.

The Leaky Pipeline

5 high-z GRBs per year

~35% Close to Sun or in Galactic plane.

4

~20% Good position but no >1m observations (weather, technical failures)

4

~30% No NIR imaging available to identify NIR counterpart

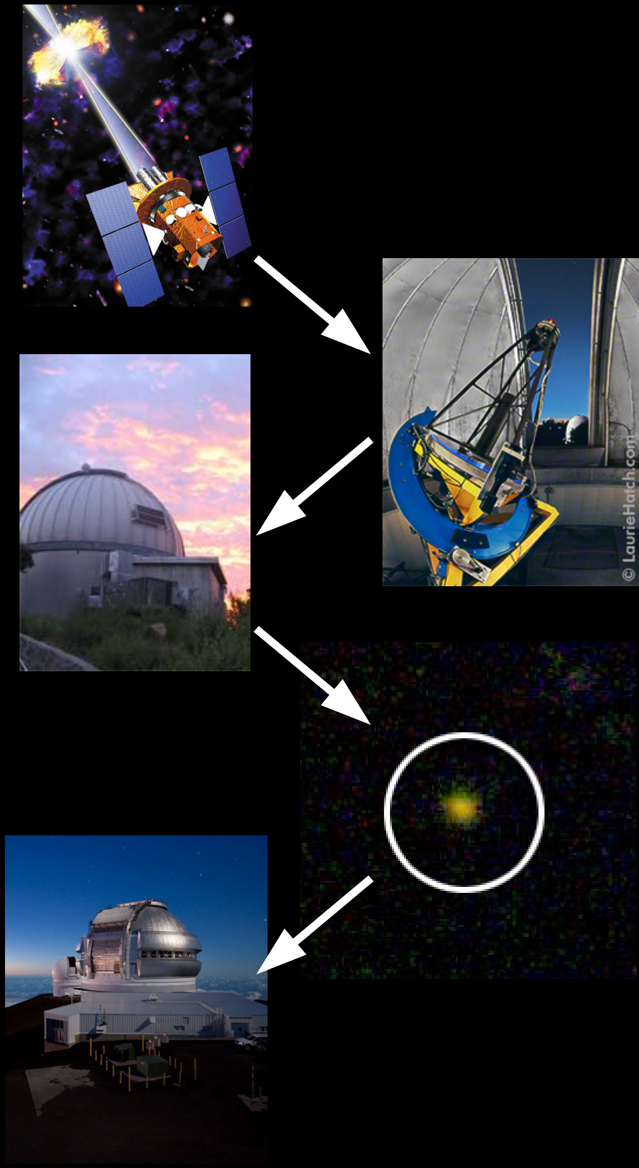
3

~30 % Not detected in NIR either – nothing to take spectrum of

2

~30% No NIR spectrograph mounted or large telescopes weathered out

1



The Leaky Pipeline

5 high-z GRBs per year

~35% Close to Sun or in Galactic plane.

Observe fewer plane or near-Sun non-GRB targets (but, other communities to serve, XRT cooling)

4

~20% Good position but no >1m observations (weather, technical failures)

Need more fast-responding mid-sized facilities (with quick circulars!)

4

~30% No NIR imaging available to identify NIR counterpart

Need more NIR facilities (especially simultaneous optical+NIR: GROND, RATIR)

3

~30 % Not detected in NIR either – nothing to take spectrum of

No easy solution!

2

~30% No NIR spectrograph mounted or large telescopes weathered out

No easy solution!

1

Swift real-time indicators (from fluence, NH, etc. - Morgan et al. 2012) also help, but will always need NIR follow-up!

Intrinsic Rates

Intrinsic rates

Observed R(z)

z>5.5	**2 - 7%**
z>8	**0.4 - 5%**
z>10	**< 3%**

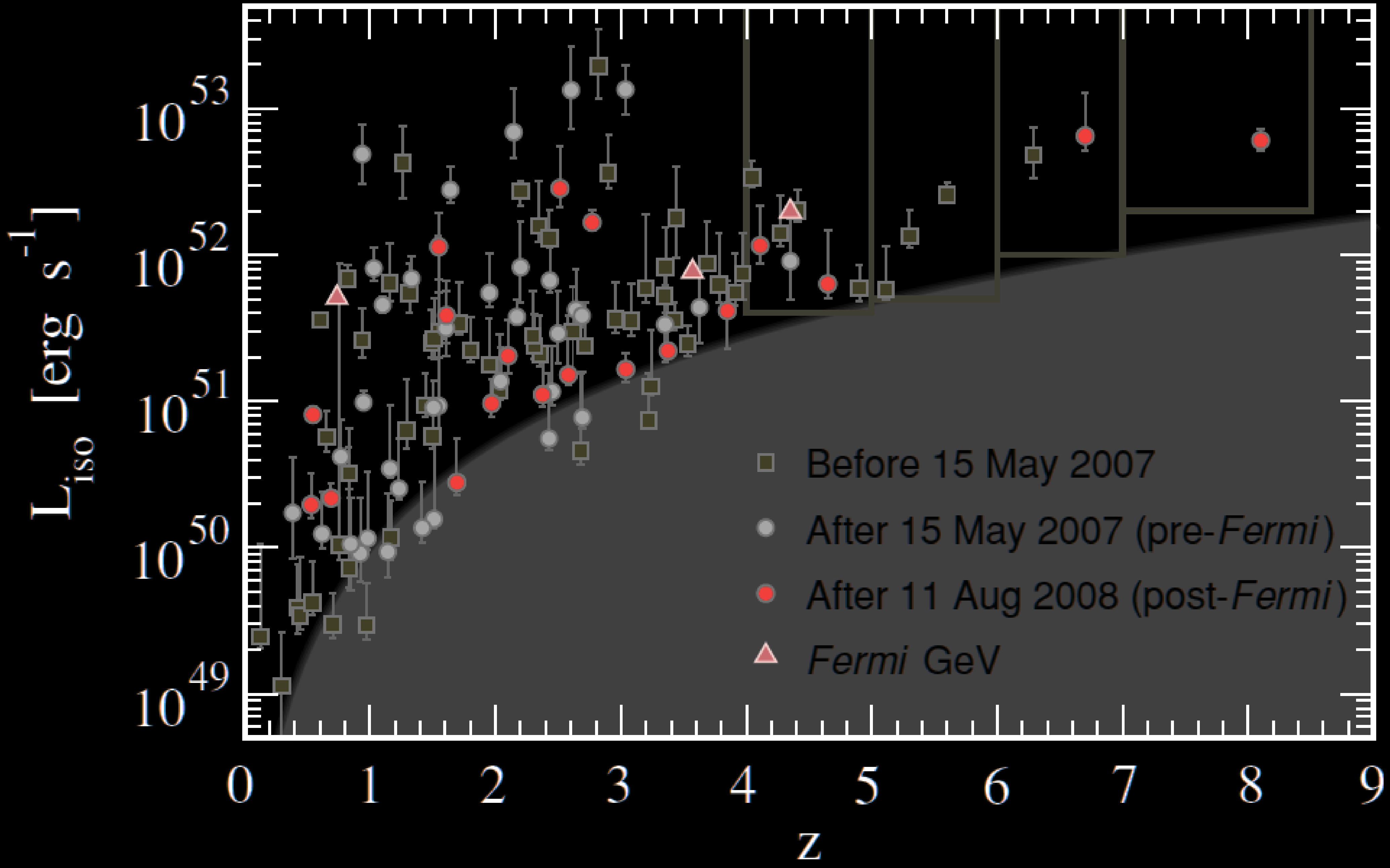
Correct for detector threshold (high-z bursts are harder to find)

Detector-corrected R(z)

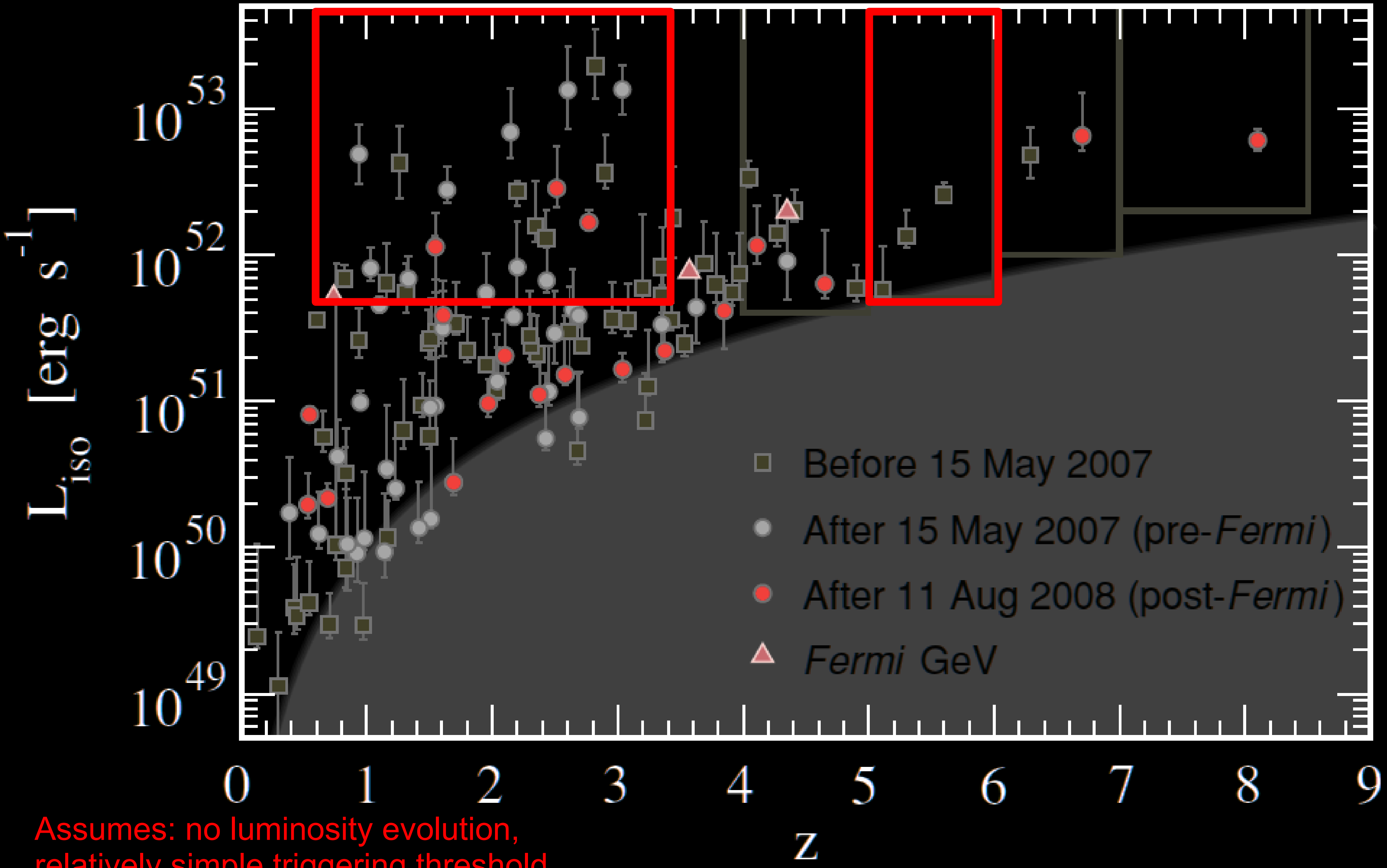
Correct for cosmology (light cone effects, time dilation)

Intrinsic R(z)

Detector thresholds



Detector thresholds



Assumes: no luminosity evolution,
relatively simple triggering threshold

Intrinsic rates

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Correct for detector threshold (high-z bursts are harder to find)

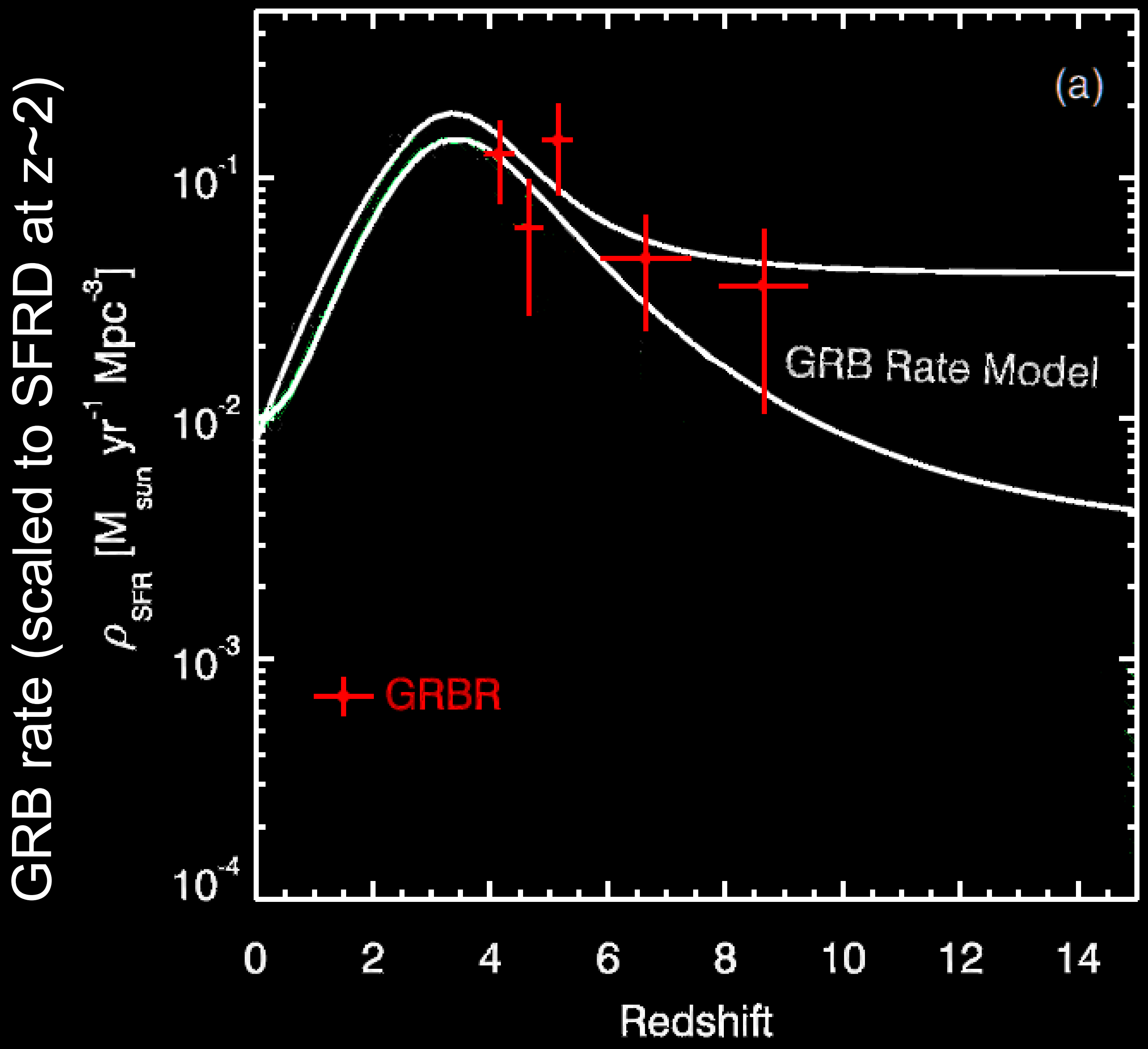
Detector-corrected R(z)

Correct for cosmology (light cone effects, time dilation)

Intrinsic R(z)

Results from:
Kistler+2009
Butler+2009
Robertson & Ellis 2012
They used “all GRBs”, but this turns out to be close to unbiased.
(earlier analysis and Jakobsson+2012)

Intrinsic Rate



Robertson & Ellis 2012

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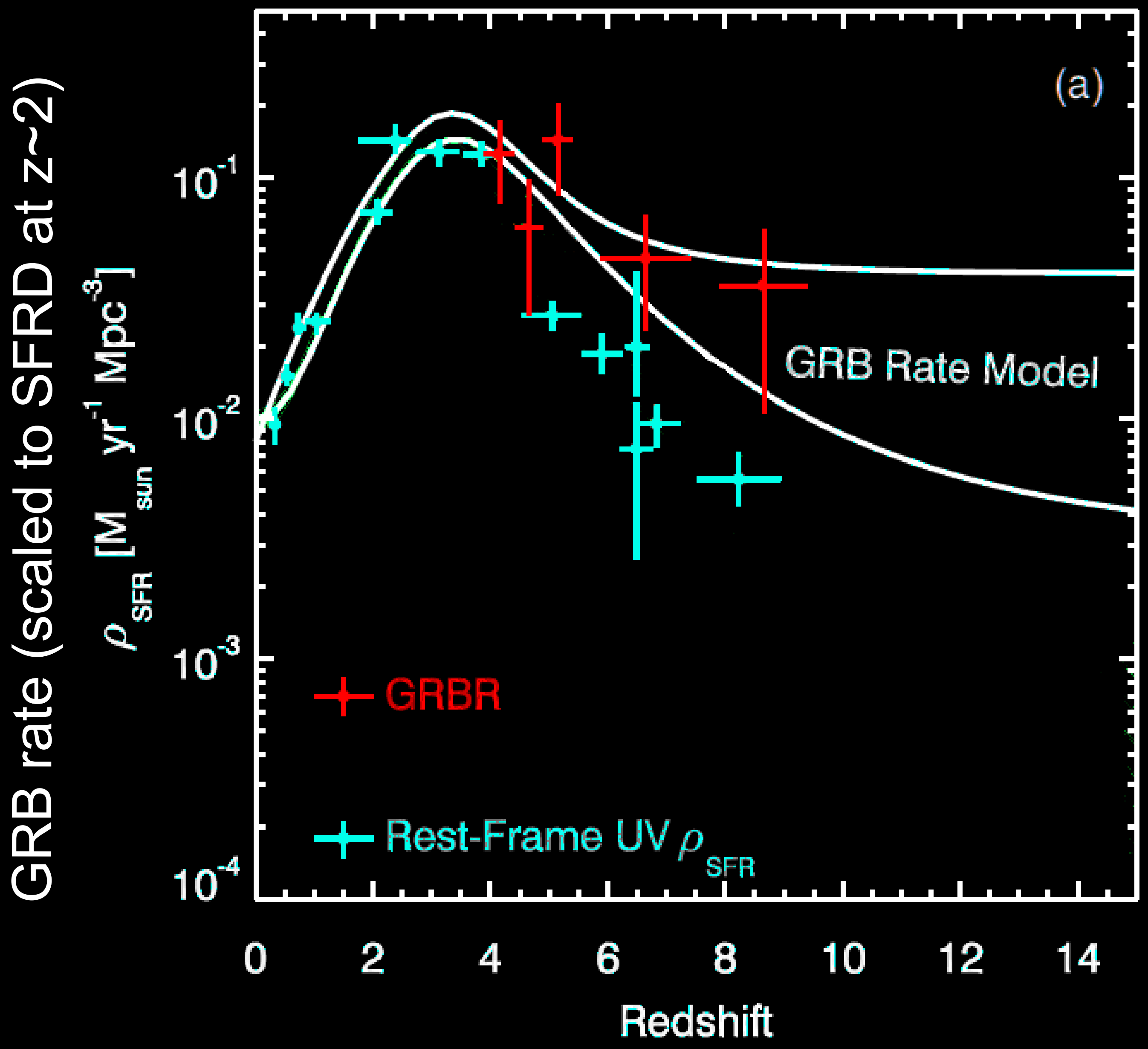

Robertson & Ellis 2012

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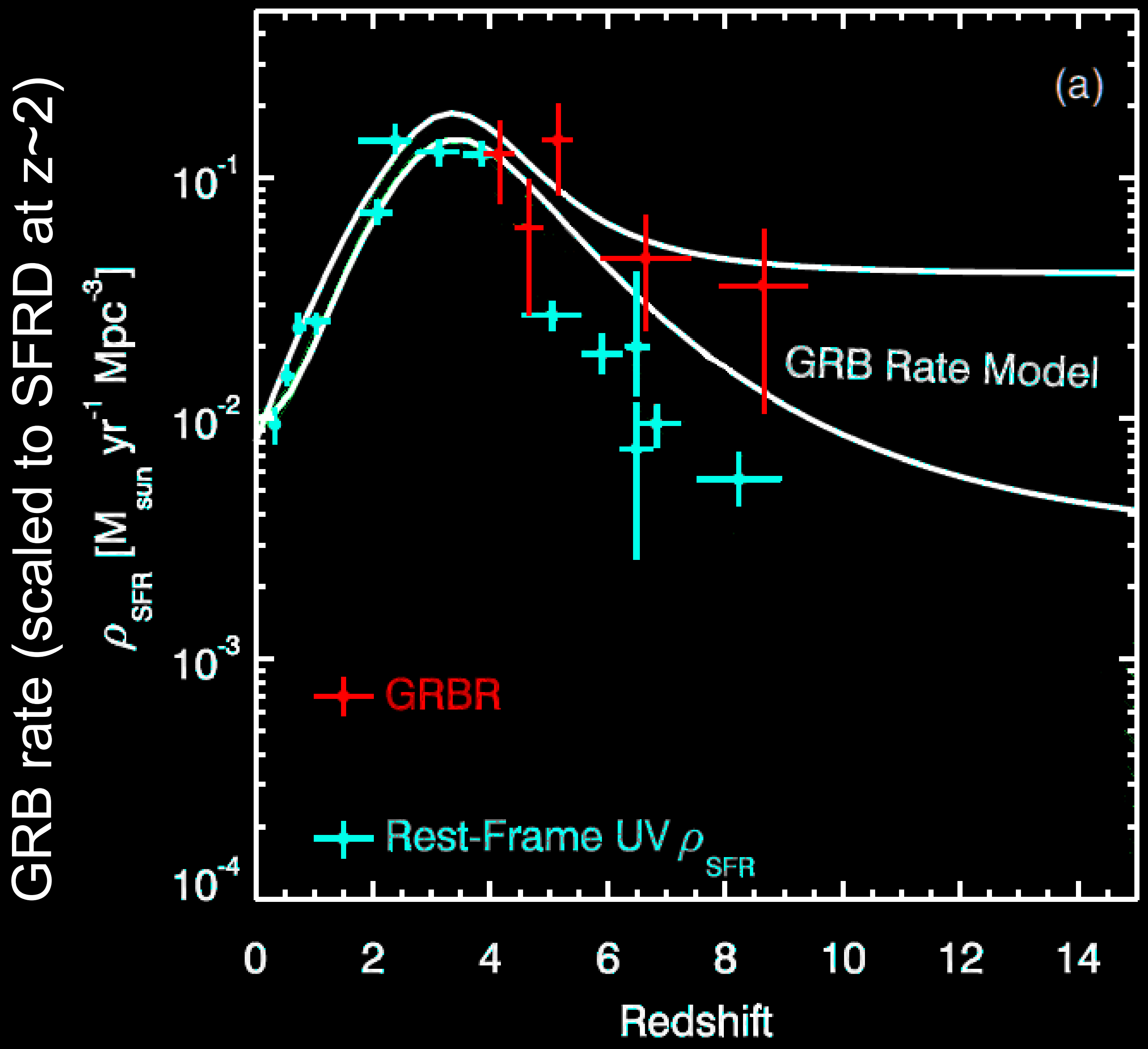


GRB rate *too high* compared to star formation beyond z>3 (by an order of magnitude at z~8!)

LBG SFRD's "predict" ~1/10 high-z GRB rate that is currently seen (i.e, 0.2%)

Robertson & Ellis 2012

GRBs vs. LBGs: who is right?

LBG rates are not entirely secure either

(Revised *down* by 1 order of magnitude due to change in dust correction procedure during past few years, and LBGs extrapolate from tip of luminosity function)

But, increasing evidence that z<2 GRBs are not good star-formation tracers either

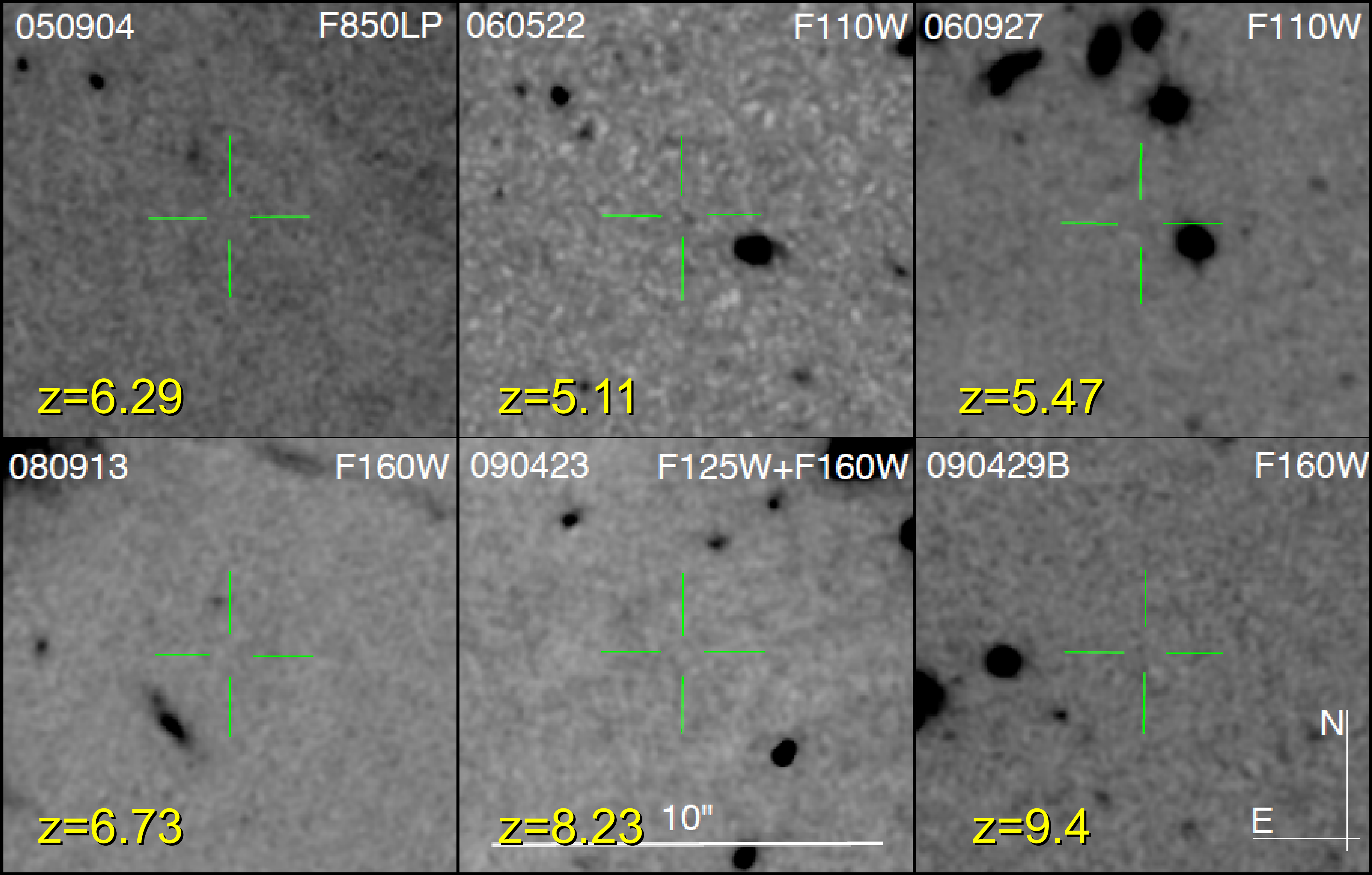
(Graham & Fruchter 2012, Perley+2013)

Metallicity bias? (Explored by Robertson & Ellis; may work but not perfect fit either – metallicity is low in most galaxies at z>3 already.)

Need more events (and more complete+homogeneous studies!)

Host Galaxies

No secure detections above z>5 yet



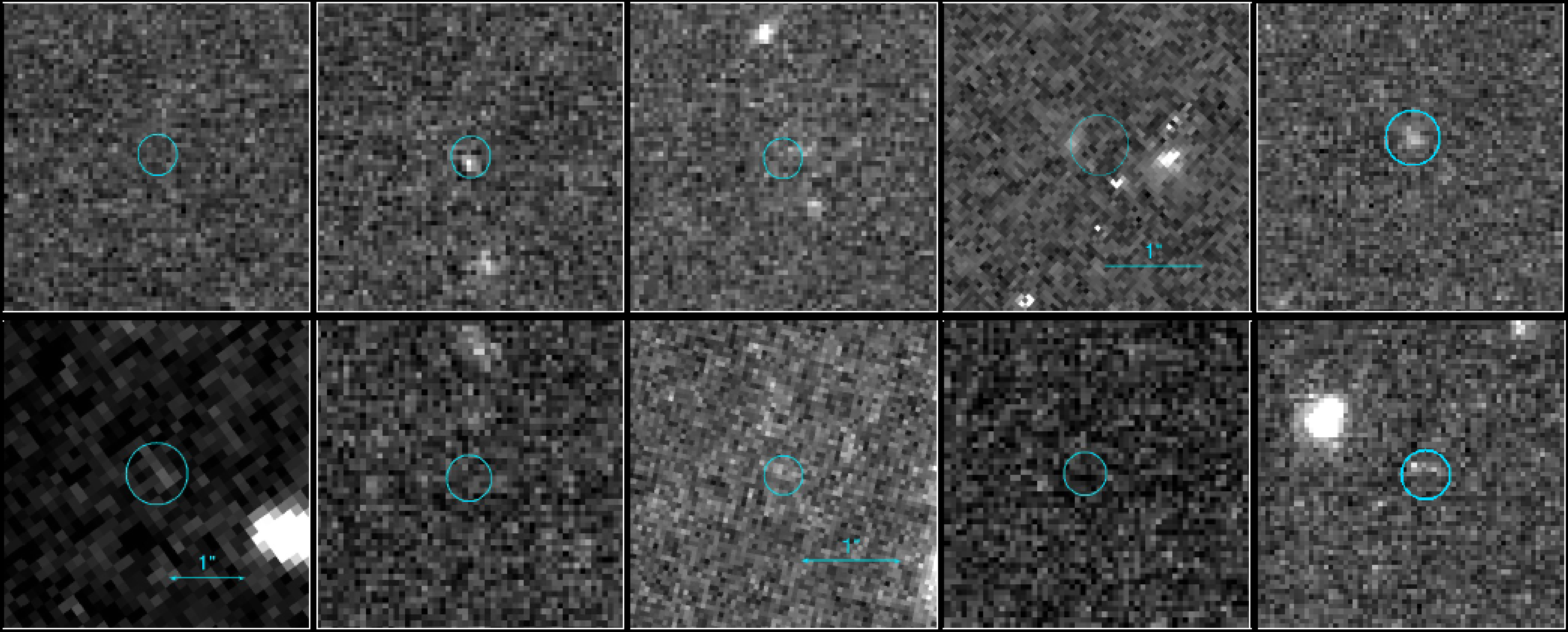
Tanvir et al. 2012

No secure detections above z>5 yet

Consistent with GRB rate following SF rate beyond z>4 *if* faint-end slope of galaxy UV luminosity function is steep (but consistent with LBG expectations.)

GRB hosts at z~3-4

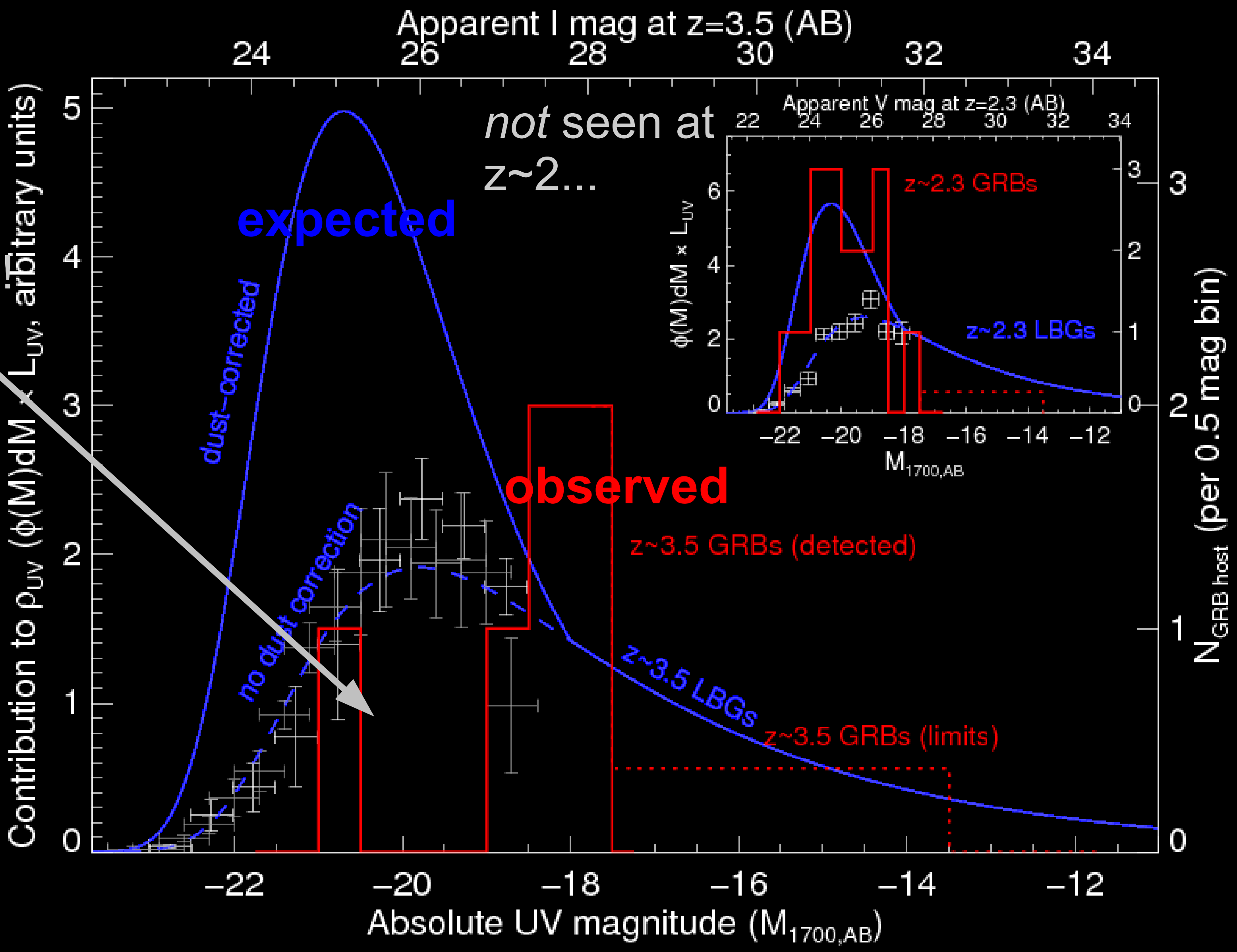
HST imaging of z>3 GRB hosts in TOUGH



Schulze et al. in prep.

GRB hosts at z~3-4

Curious absence of bright LBGs!



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GRB hosts at z~3-4

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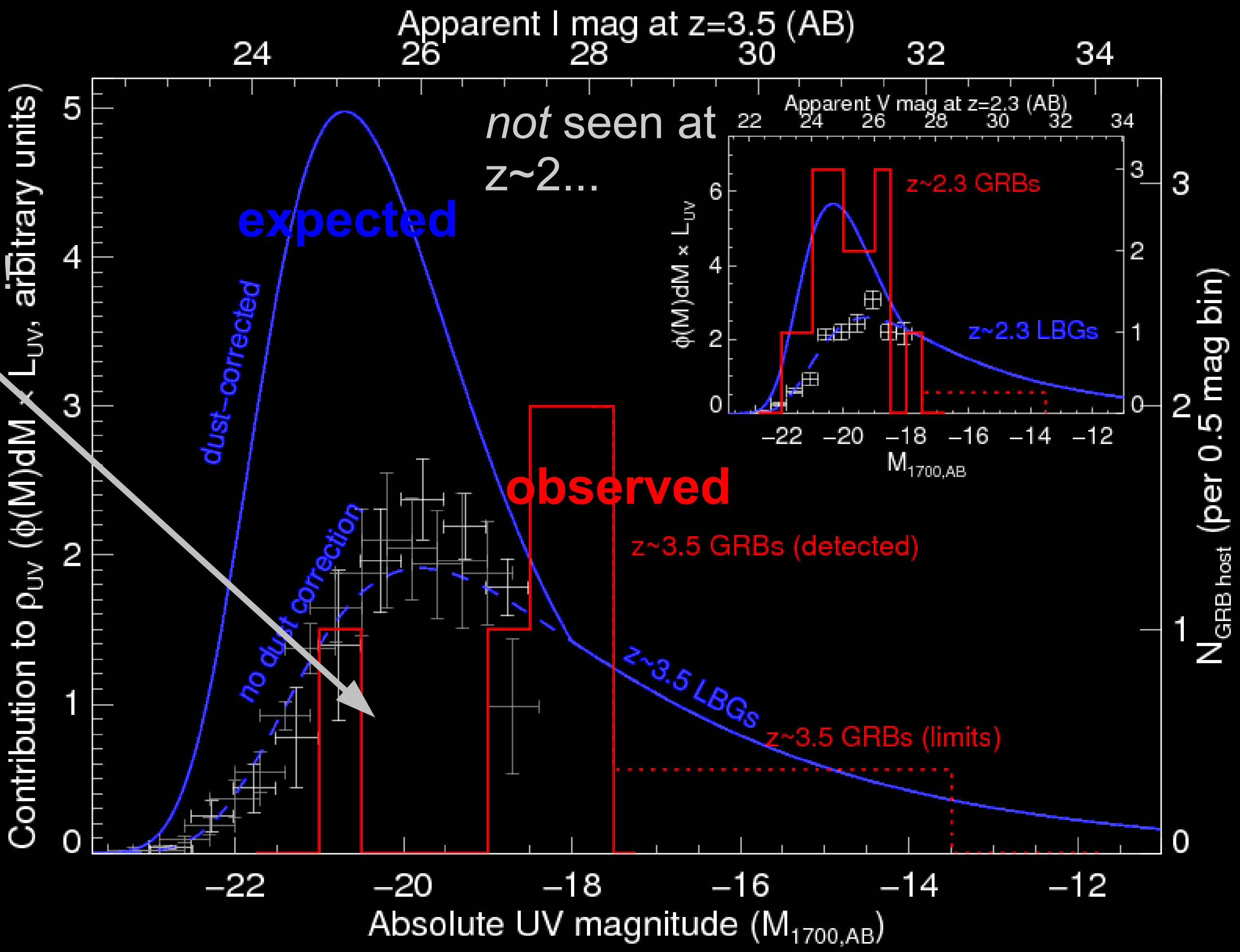

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Conclusions

The **rates** of high-z events

Observationally 5% at z>5.5, 0.5-3% at z>8

How many are we missing? Most! 50+%

Can we do better? Some improvement possible; challenging...

Intrinsically Peaks at z~3, similar at z~0 and z~8

GRB rate at high-z x10 higher than expected from LBGs?

The **environments** of high-z events

Host galaxy constraints

Faint galaxies at z>3 (surprisingly few LBGs);
no detections yet at z>5

*** Populations of z>6 events remain sparing (and precious!) and will probably remain so.**

*** Larger, more uniform studies of intermediate-z events (z=3-5) will help in interpreting results at high-z.**