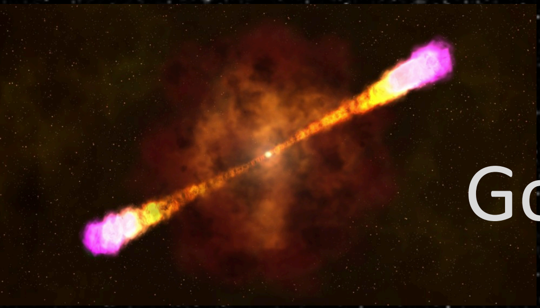
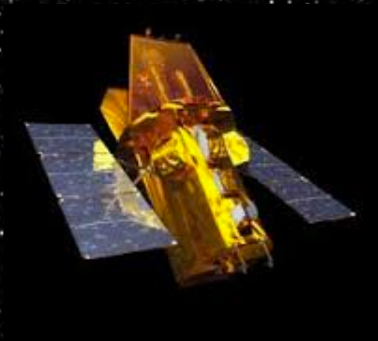
Gamma-ray Bursts from the *Swift* Burst Alert Telescope: Probing Intrinsic Distributions with Trigger Simulations



Amy Lien

Goddard Space Flight Center



CEA Saclay, 2015/09/15

Special Thanks to

- **Takanori Sakamoto (Aoyama Gakuin University)**
- **Scott Barthelmy (GSFC)**
- The *Swift*/BAT team:
  - Neil Gehrels (GSFC), **Craig Markwardt (GSFC)**, Jay Cummings (GSFC), **David Palmer (LANL)**, Hans Krimm (GSFC), Wayne Baumgartner (GSFC), Nicholas Collins (GSFC), Michael Stamatikos (OSU), Tilan Ukwatta (LANL)
- Nora Troja (GSFC), John Cannizzo (GSFC), Kevin Chen (Berkeley), Carlo Graziani (U Chicago)

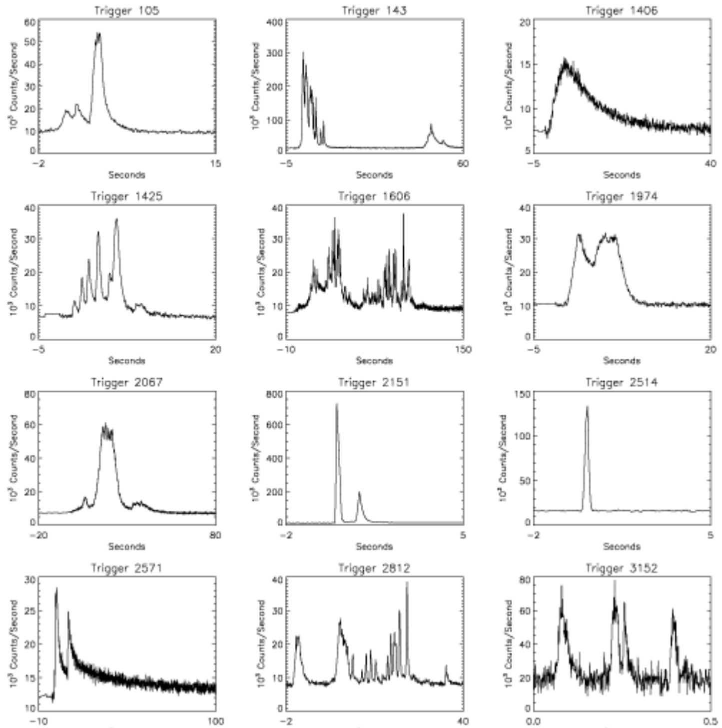
Outline

- Gamma-ray bursts (GRBs)
- Swift Burst Alert Telescope (BAT)
- Observed GRB distributions

  (The 3rd BAT GRB catalog)
- Probing intrinsic distribution
  - The BAT trigger simulator
- GRB rate
  - Implication on the high-redshift star-formation history
- Summary

What are gamma-ray bursts?

- Short pulses in gamma rays
  - Diverse light curve shapes
  - Afterglows in x rays, optical, and radio



What are gamma-ray bursts?

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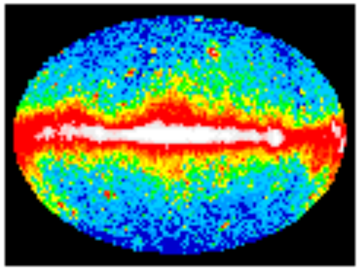
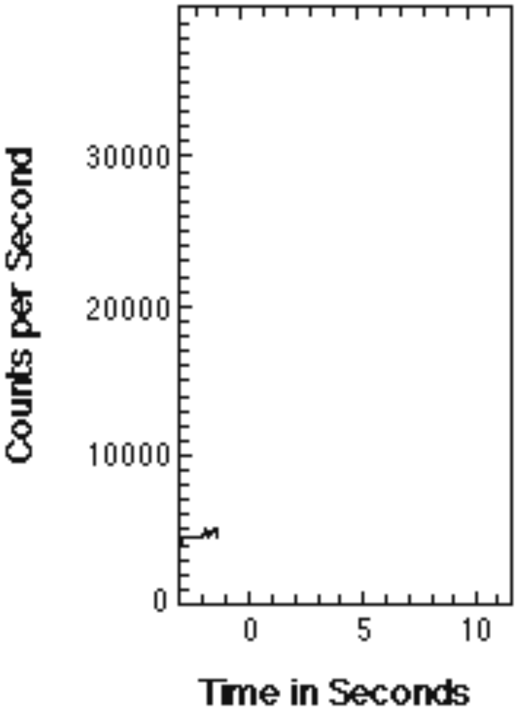
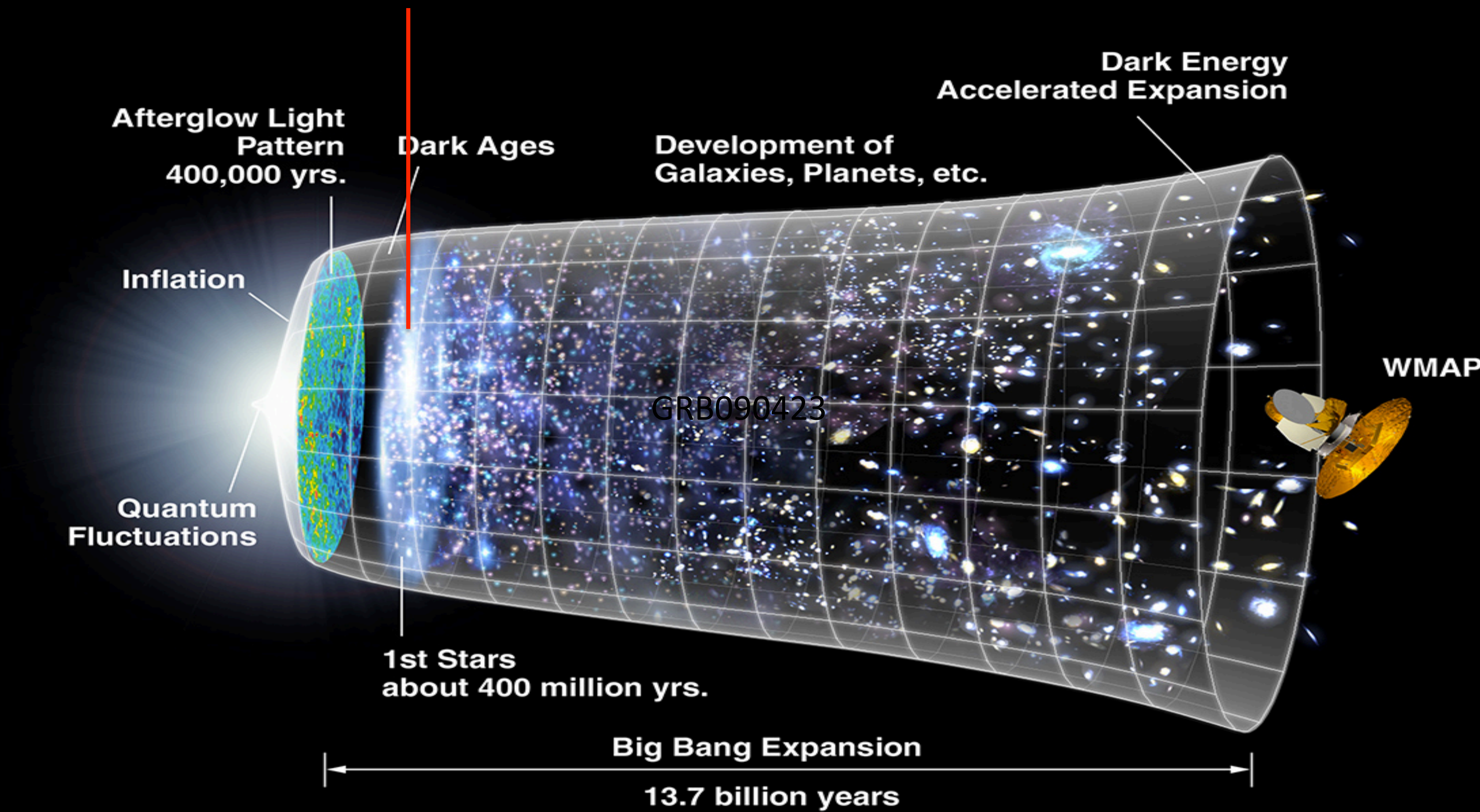
  - Diverse light curve shapes
  - Afterglows in x rays, optical, and radio
- Extremely bright
- Visible out to very high redshift
  - Redshift range:

    0.03 – 9.38





GRB090423 (z=8.2; 640 million years; Tanvir et al. 2009; Salvaterra et al. 200



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- Extremely bright
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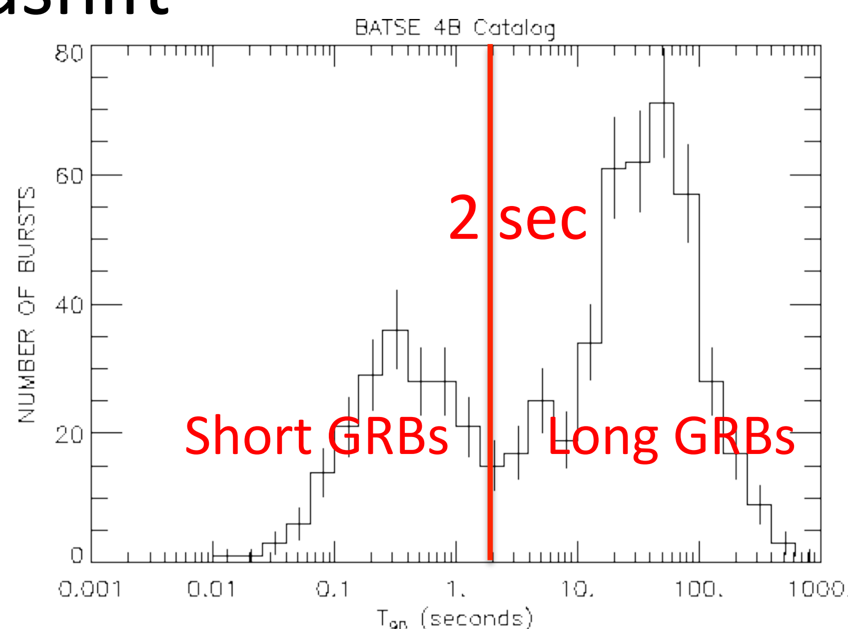
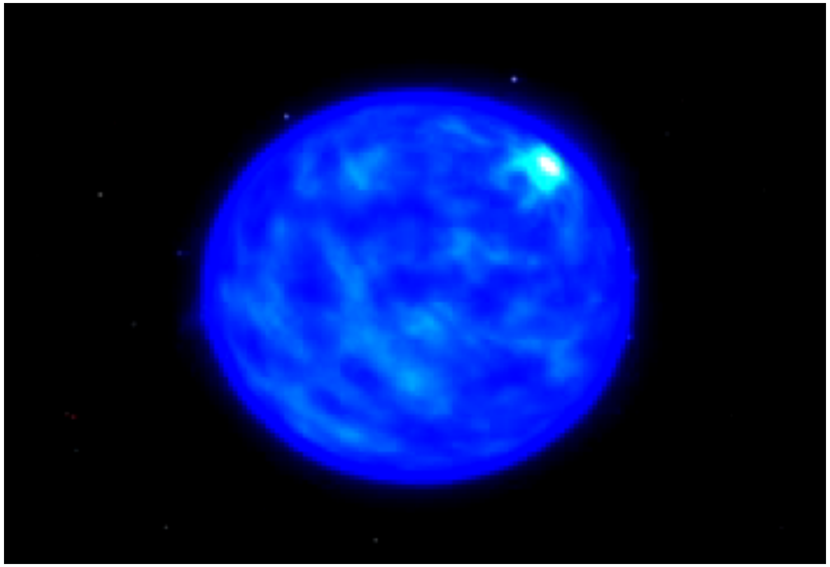
  - Redshift range: 0.03 – 9.38
- Long and Short bursts
  - Based on BATSE observations



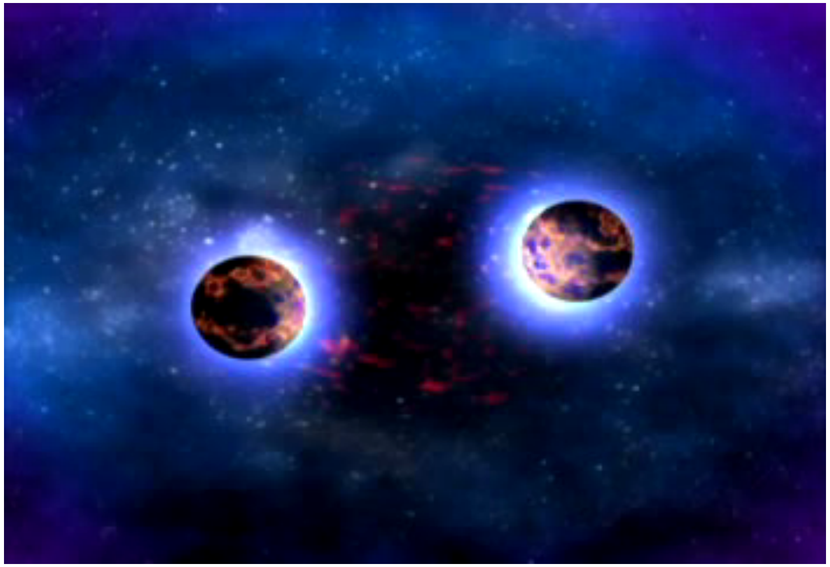
What are gamma-ray bursts?

Long GRBs



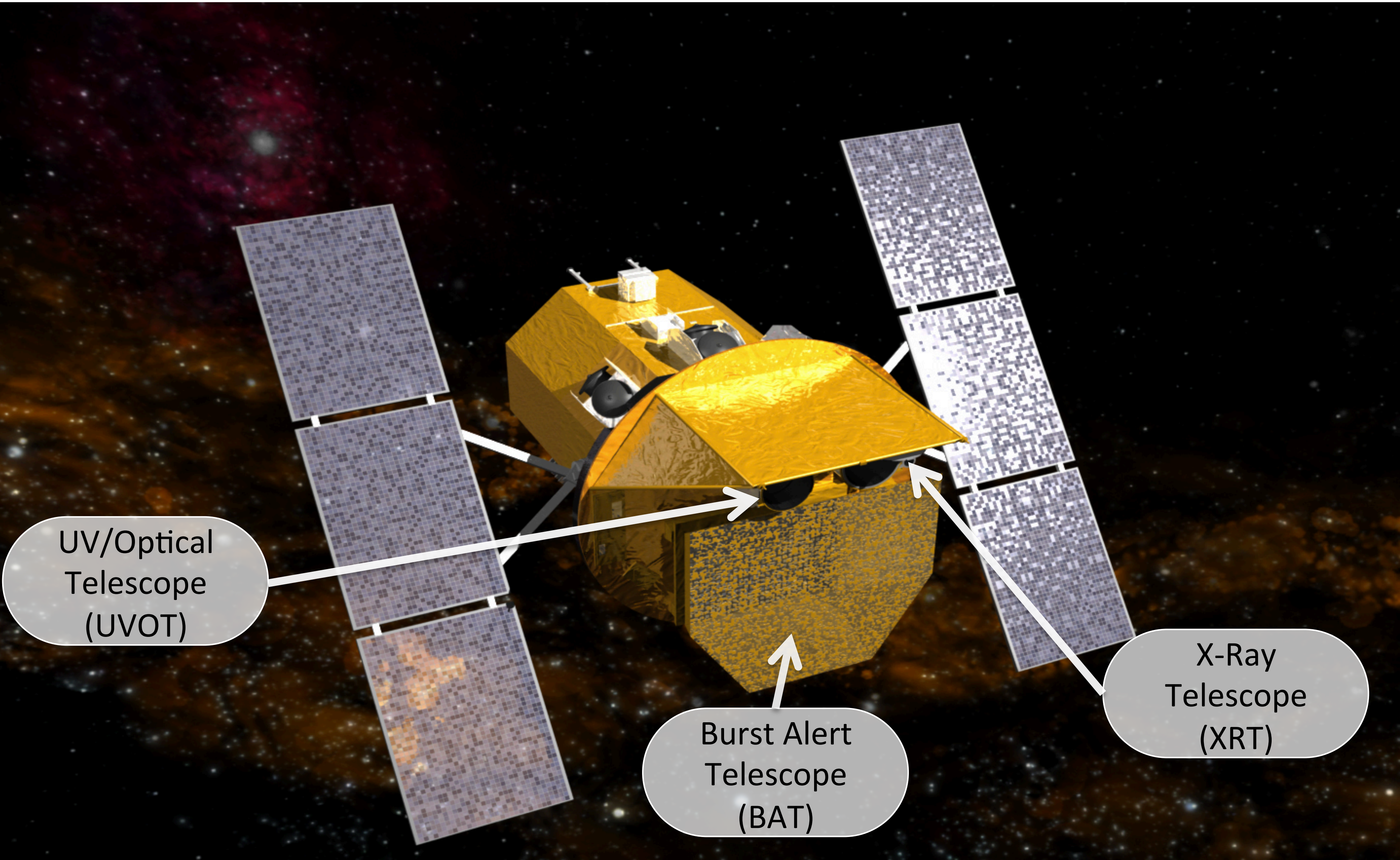
- Deaths of massive Stars
- Supernovae
- Black holes
- Acceleration of high-energy particles

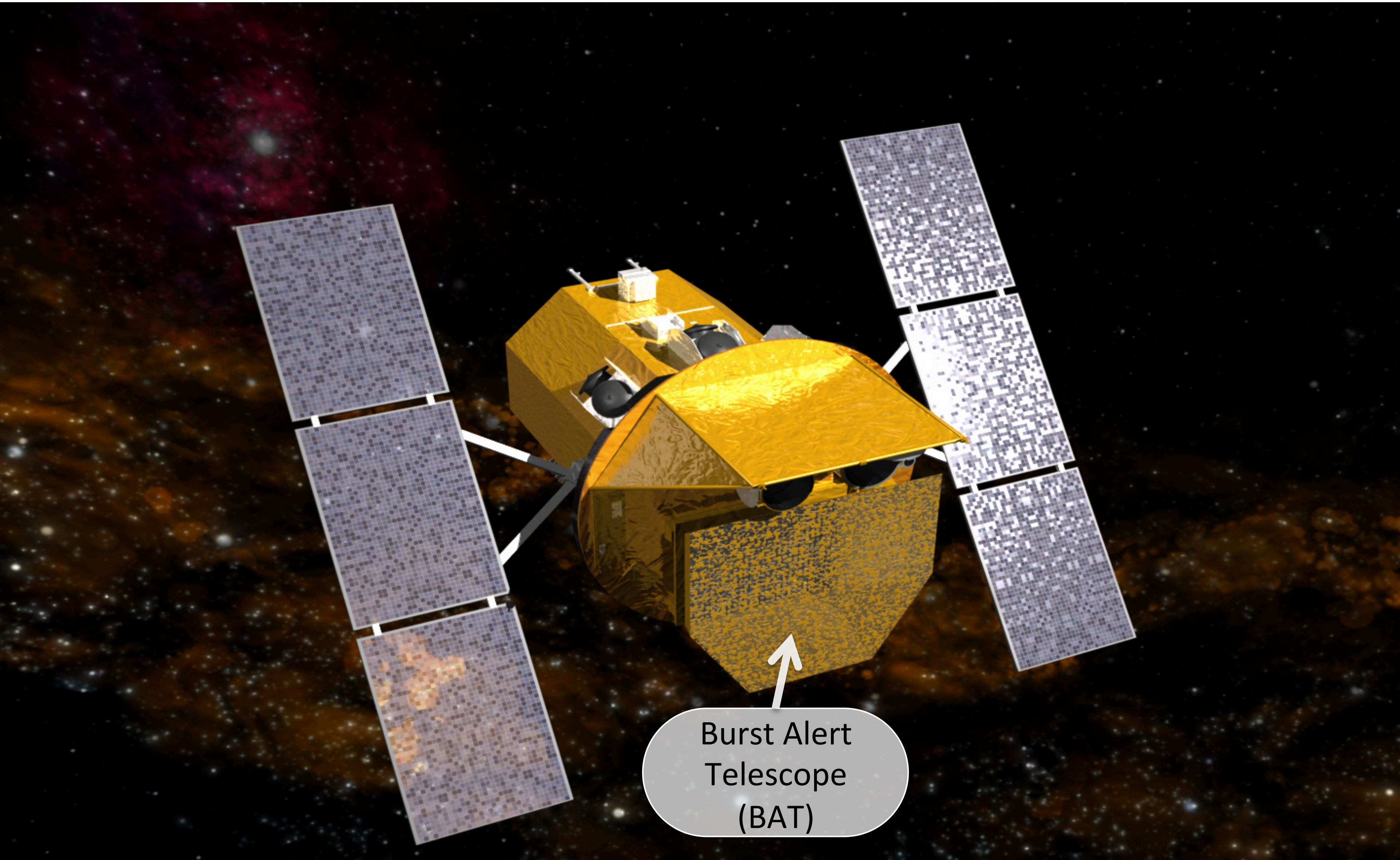
Short GRBs



- Compact-object mergers
  - Black holes
  - Neutron stars
- Gravitational wave

Figure Credit: NASA/Swift Mission Multimedia

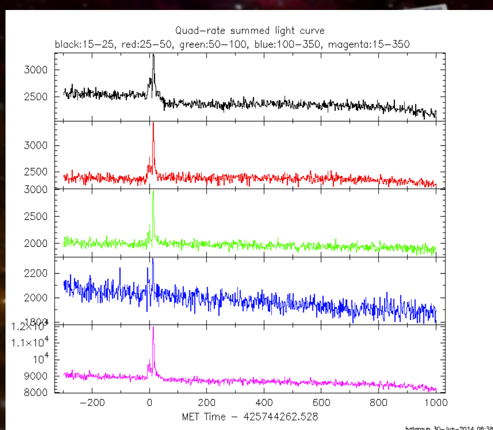

UV/Optical
Telescope
(UVOT)
Burst Alert
Telescope
(BAT)
X-Ray
Telescope
(XRT)

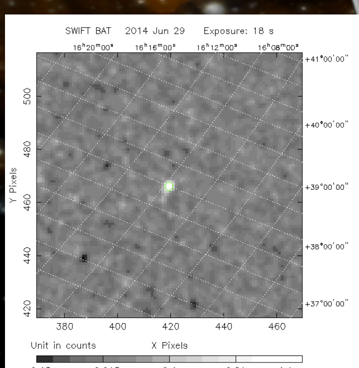

Burst Alert Telescope (BAT)

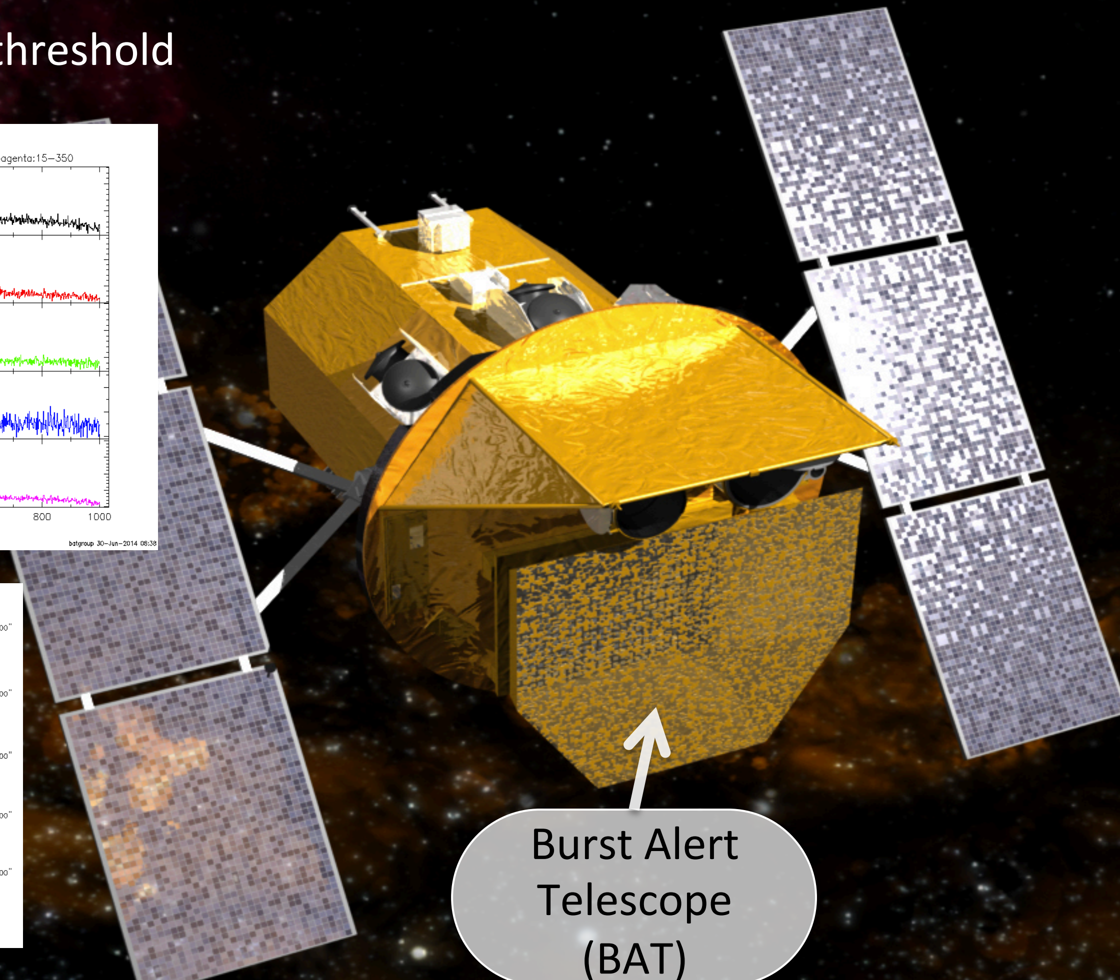
A. Rate trigger:

Stage 1: Rate trigger

Stage 2: Image threshold







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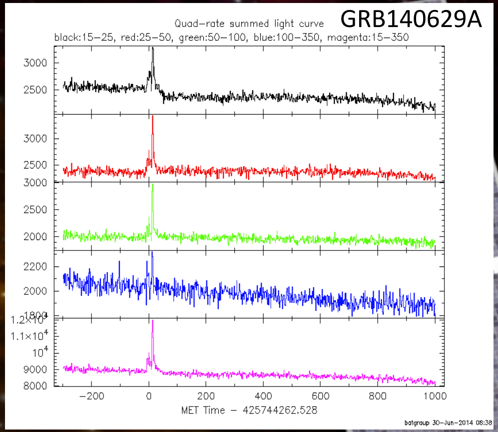

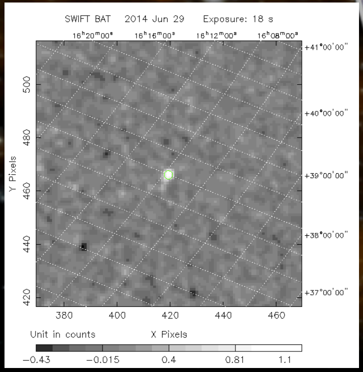

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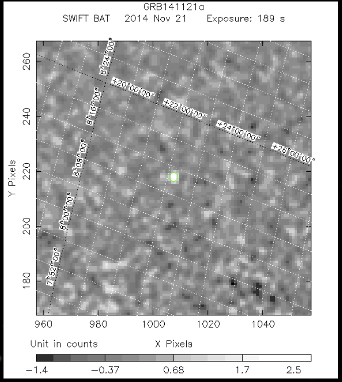

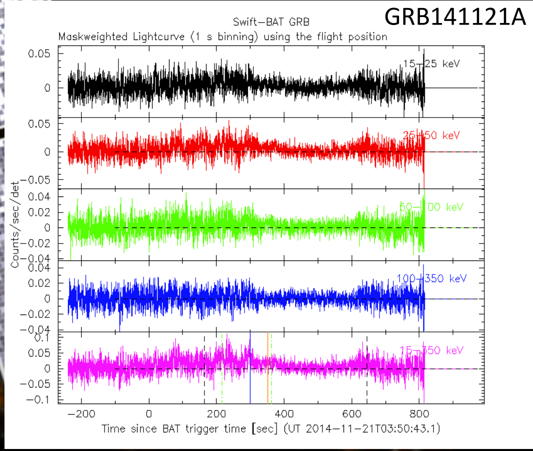

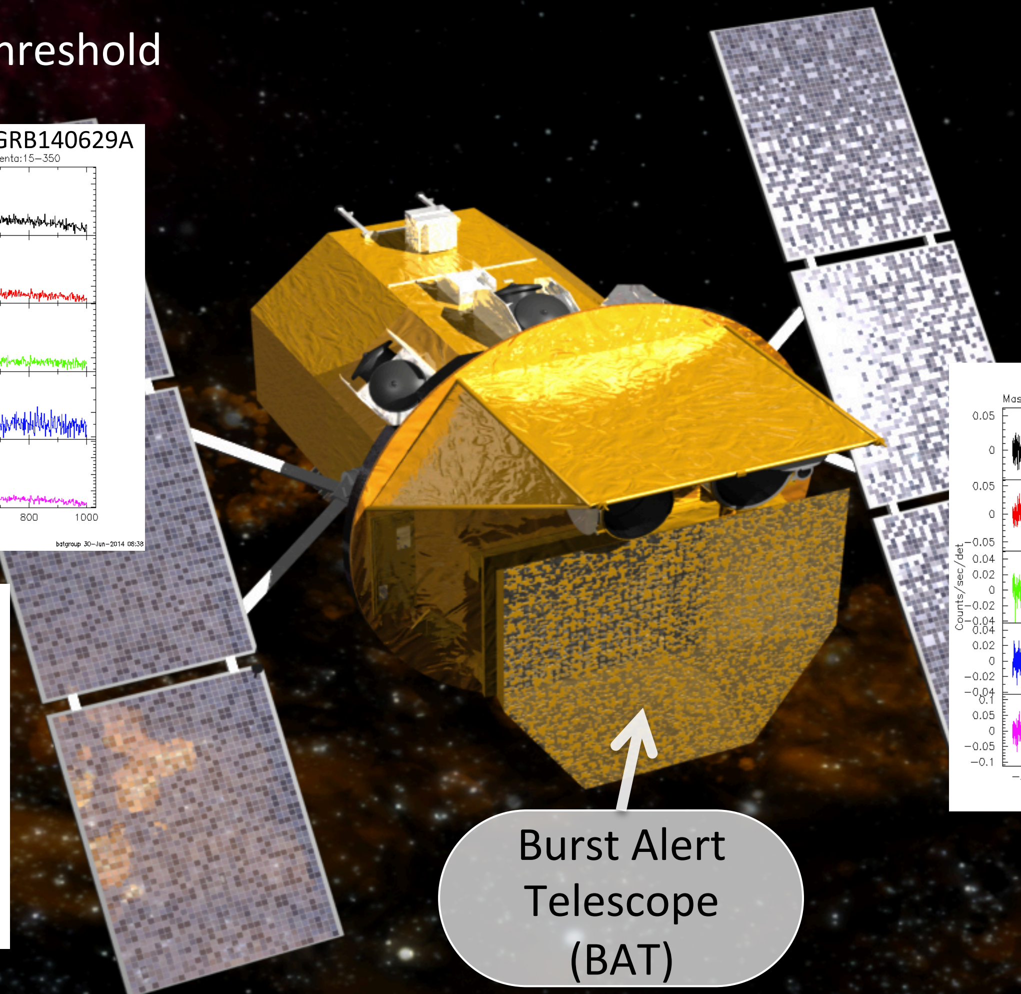

Swift

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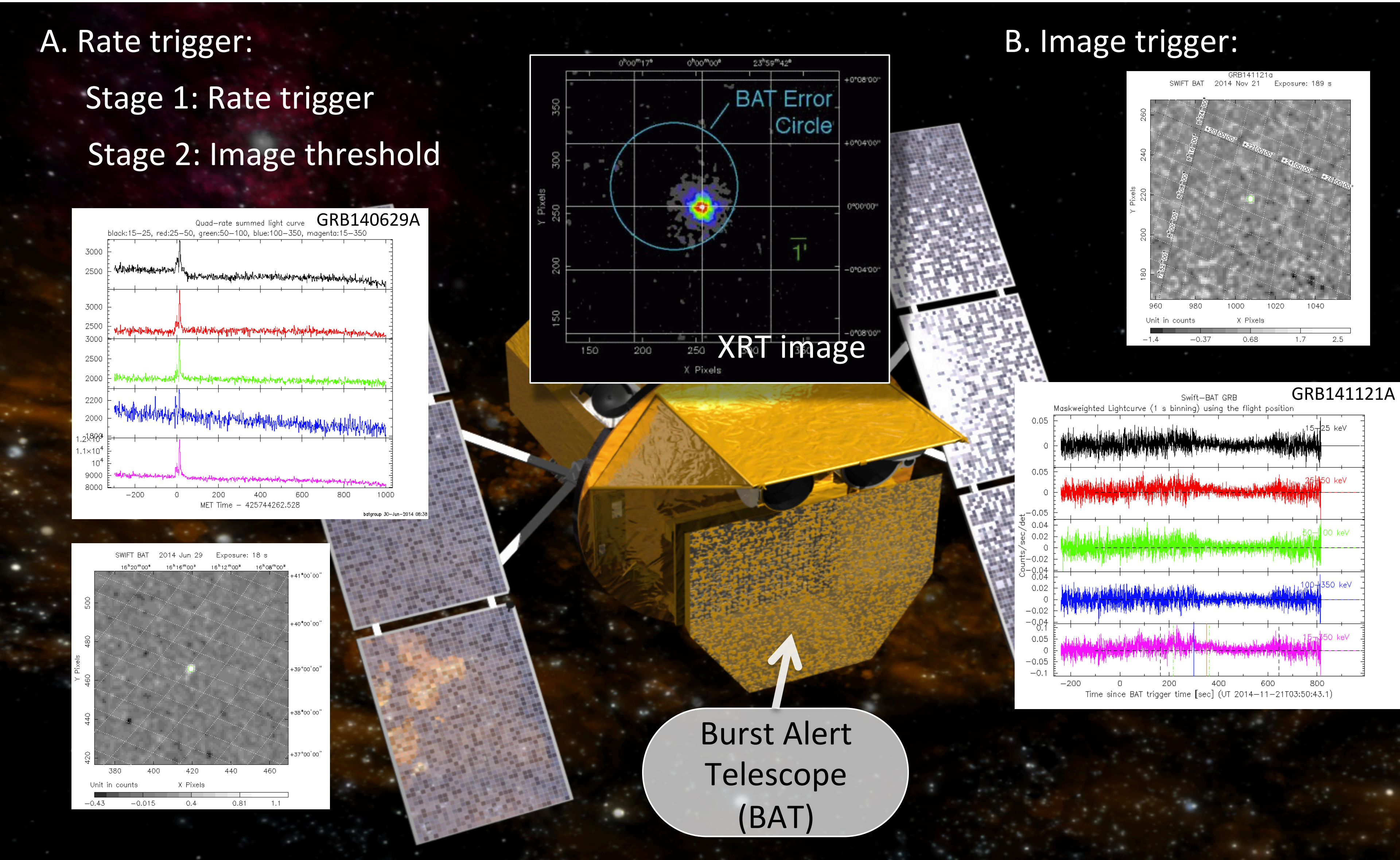
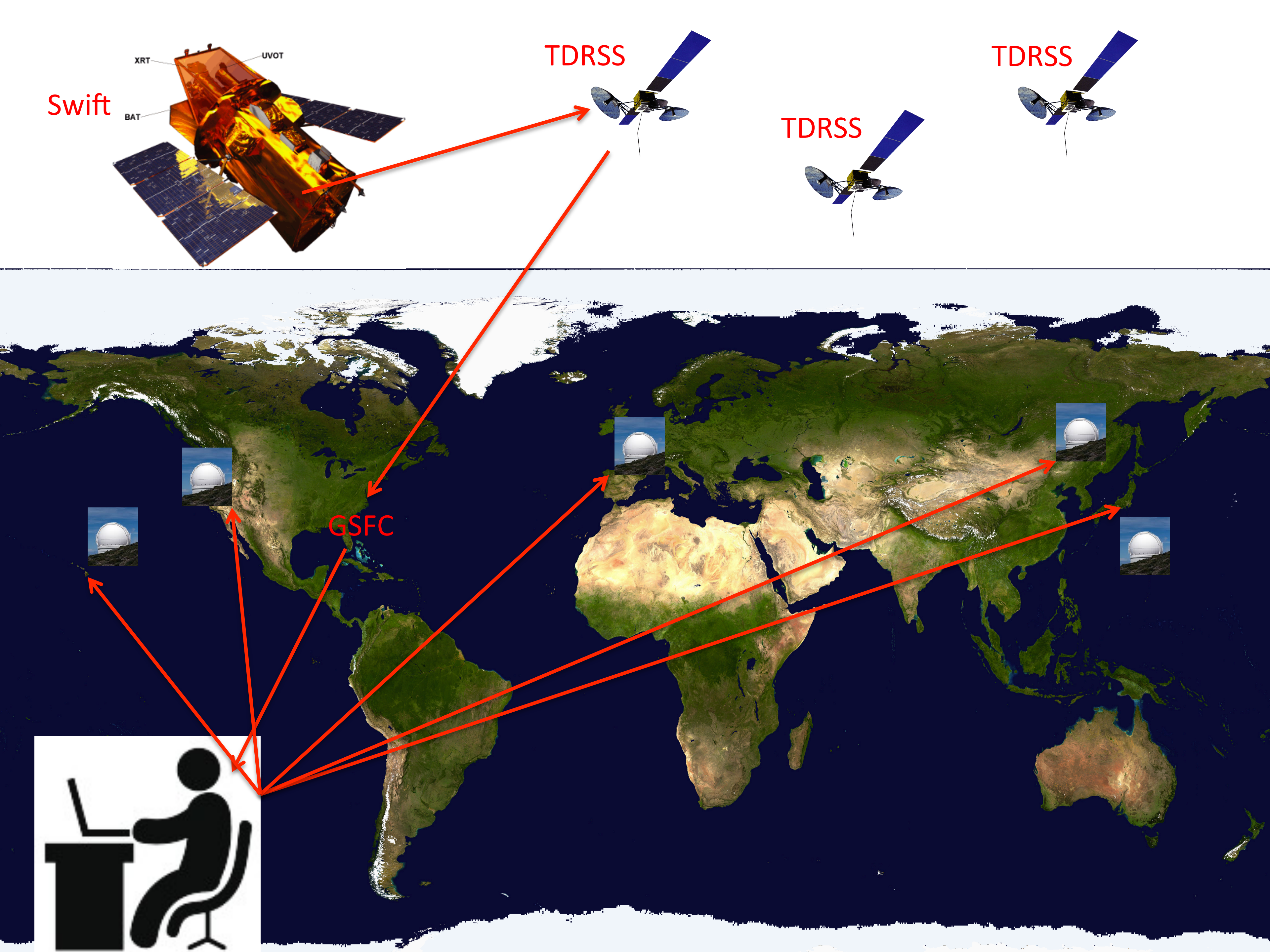




Swift
XRT
UVOT
BAT
TDRSS
TDRSS
TDRSS
GSFC

10 Years of *Swift*

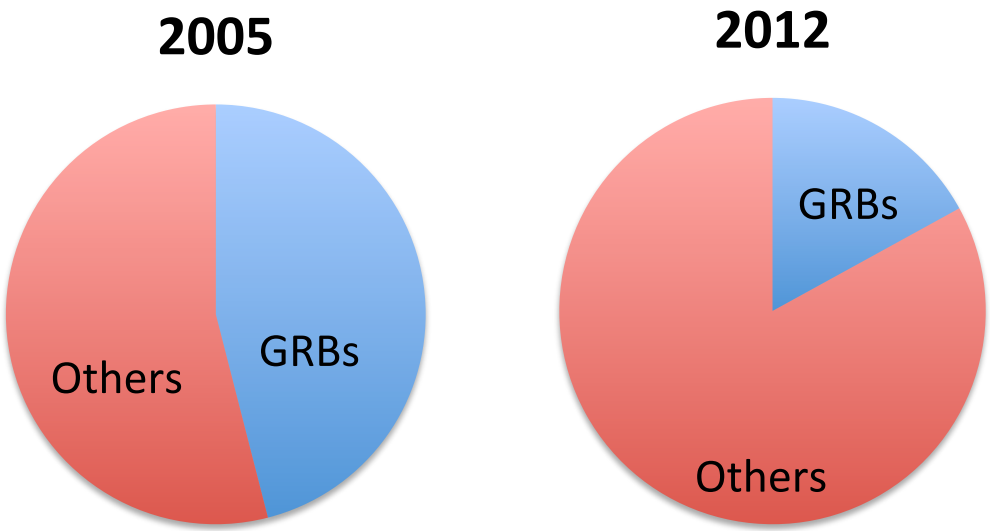
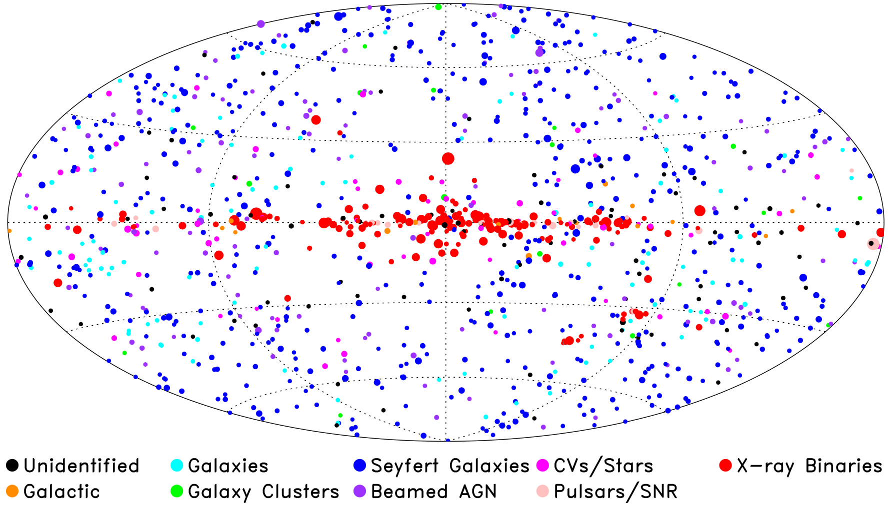


Chart Credit: Neil Gehrels' presentation

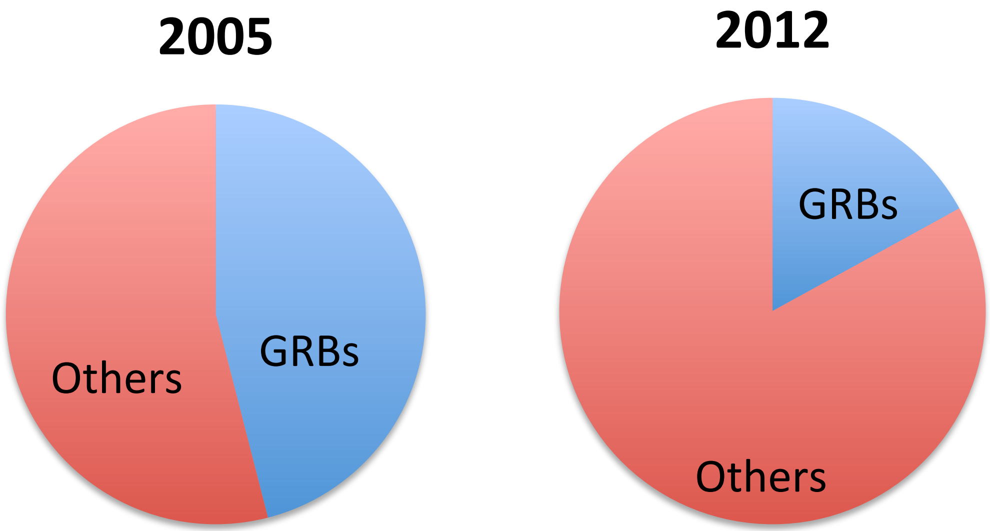
Figure credit: PSU webpage



Baumgartner et al. 2013

Cake Credit: Judith Racusin

~11 10 Years of *Swift*



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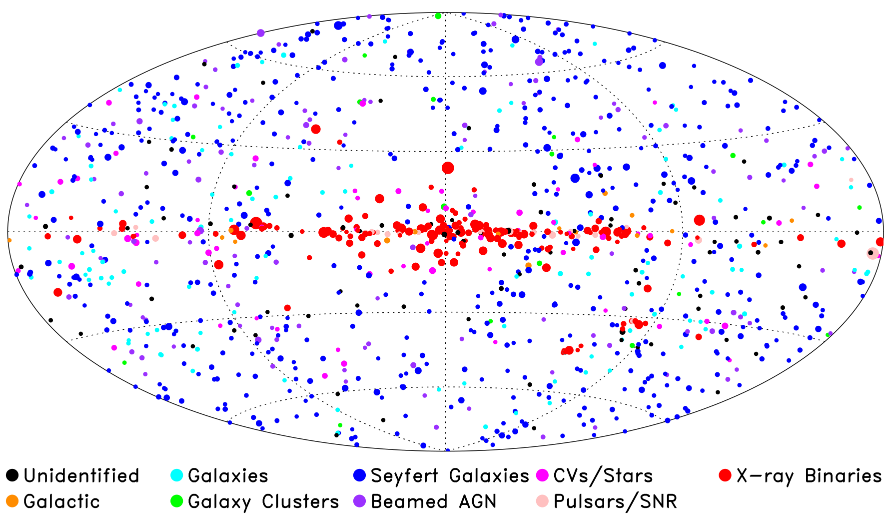

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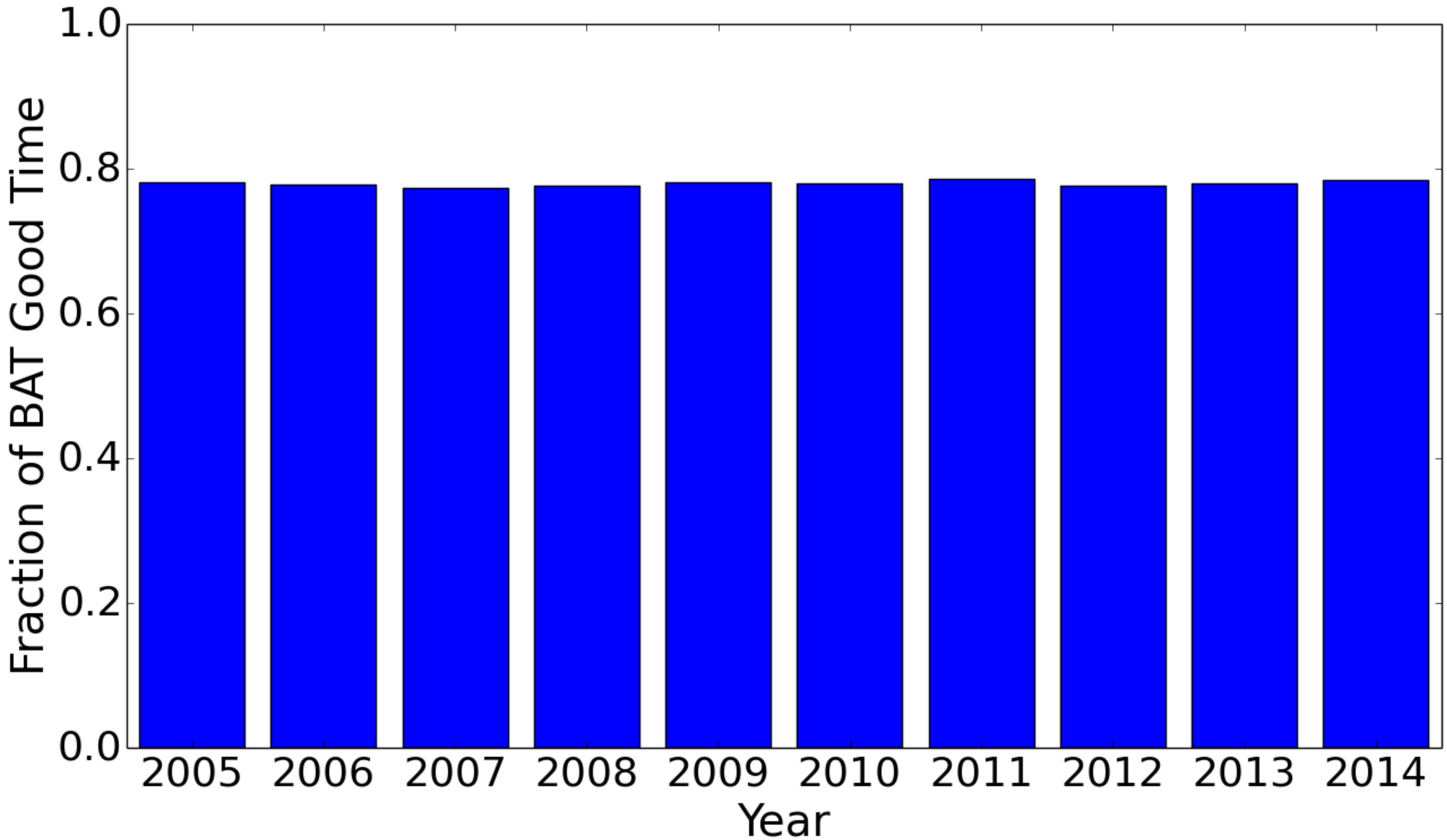
BAT Observing Time

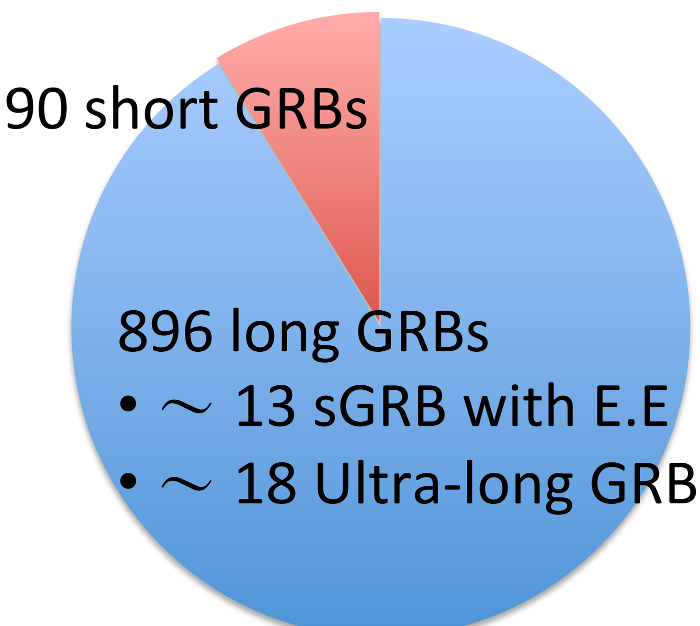
- ∼ 11+-1% deadtime for the South Atlantic Anomaly (SAA)
- ∼ 11+-1% due to slewing



Swift GRBs to date: ~ 11 Years after Launch

- 986 GRBs till now (GRB150911A)
  - About 2 GRBs per weak
- 326 GRBs have redshift measurements
- Complete results will be in the 3rd BAT GRB catalog

Figure credit: PSU webpage



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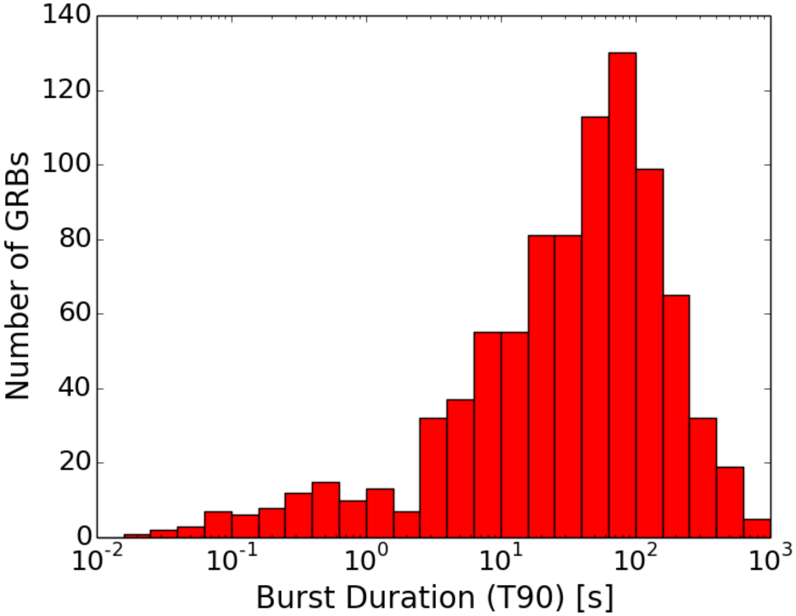
Burst Durations



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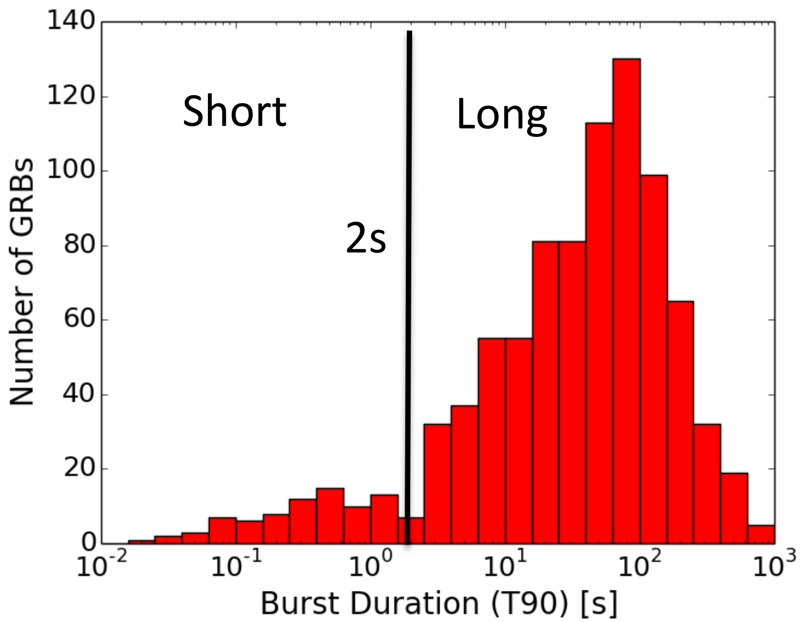

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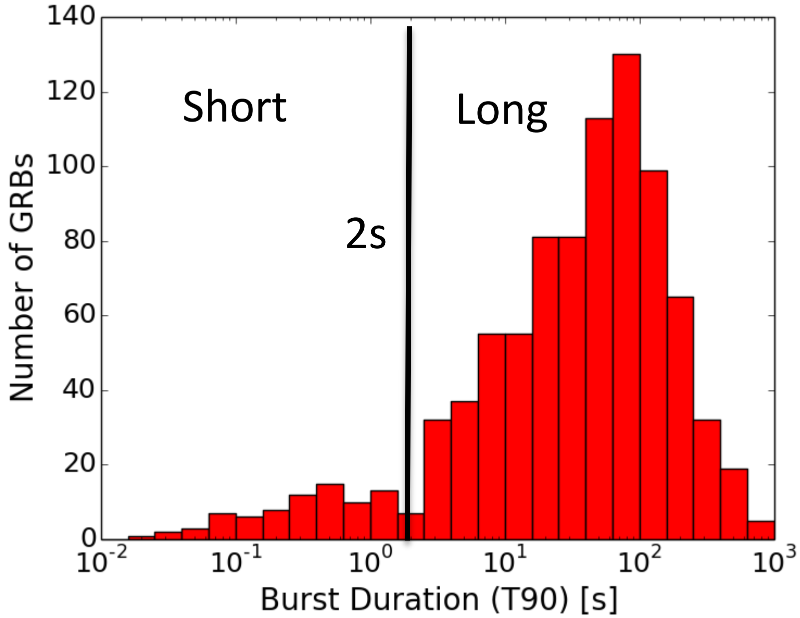

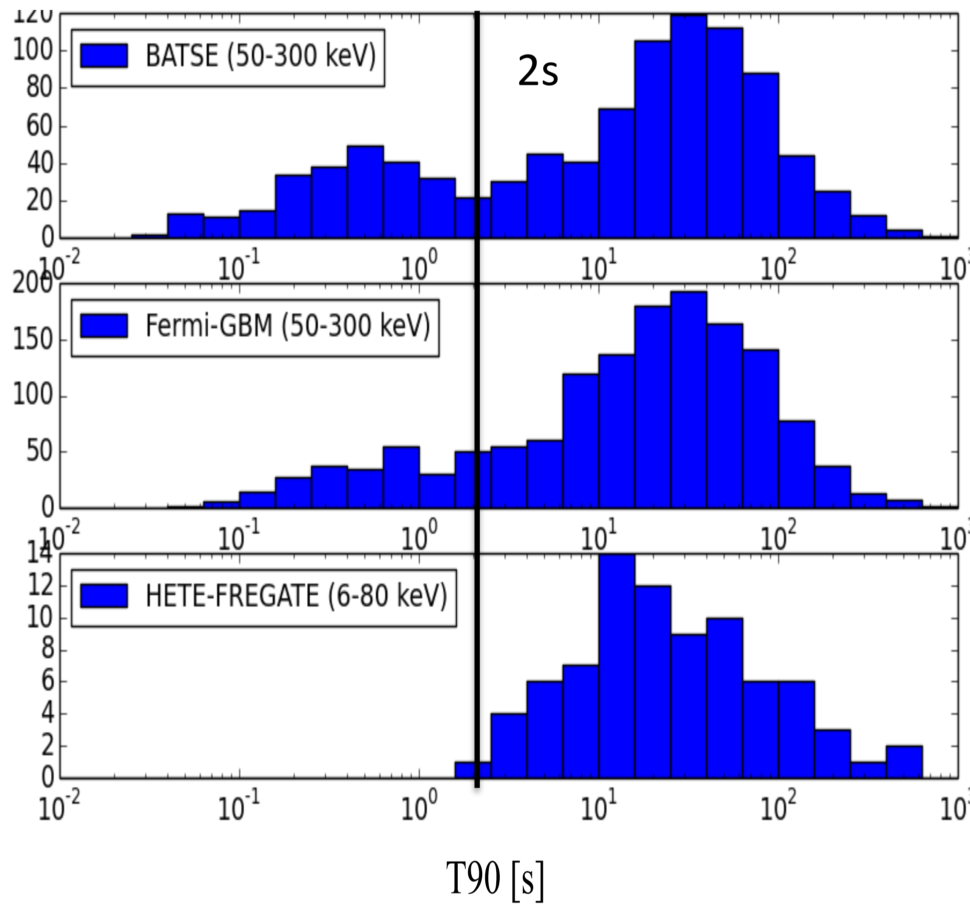

Fig credit: Taka's presentation

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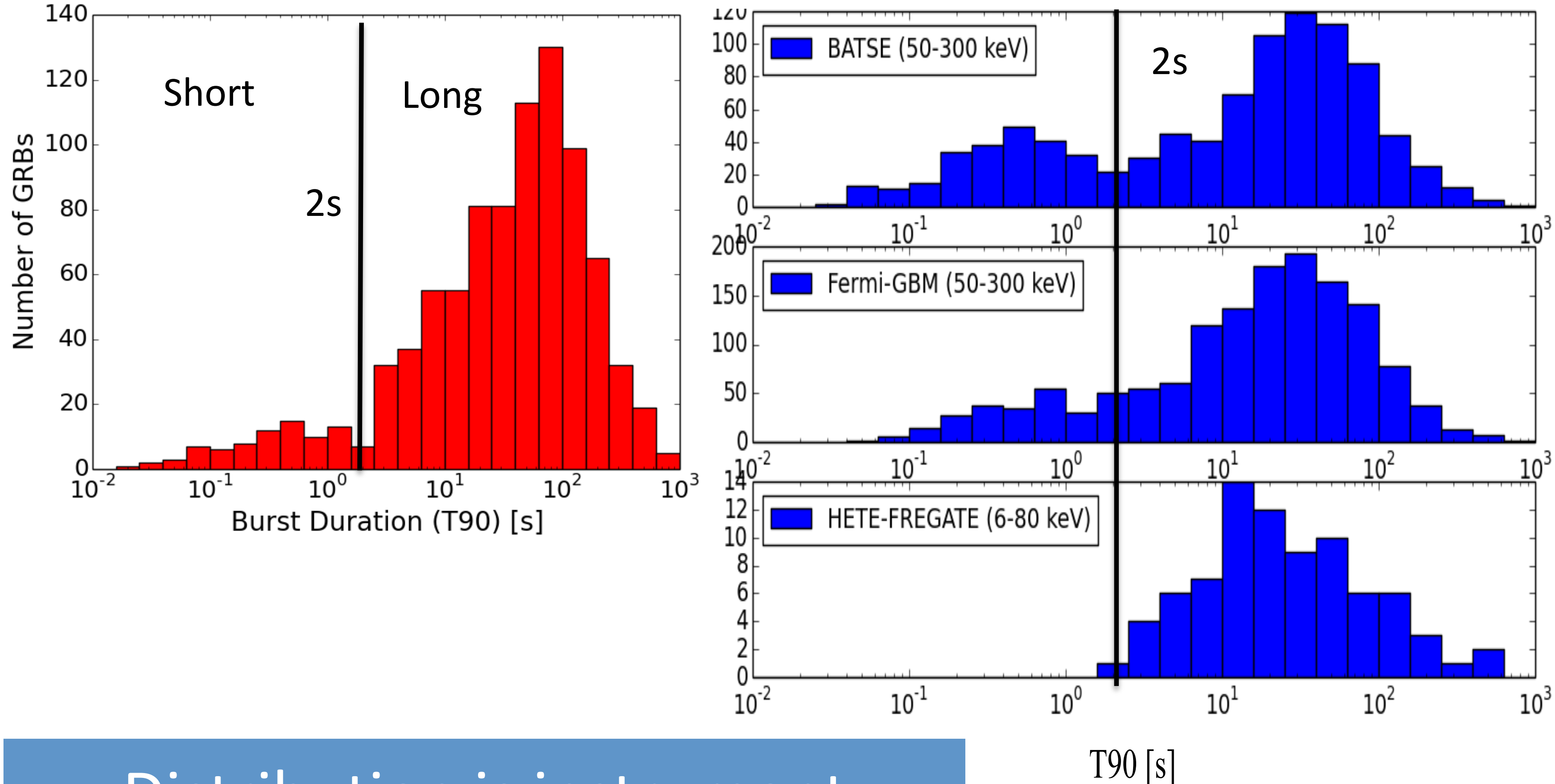
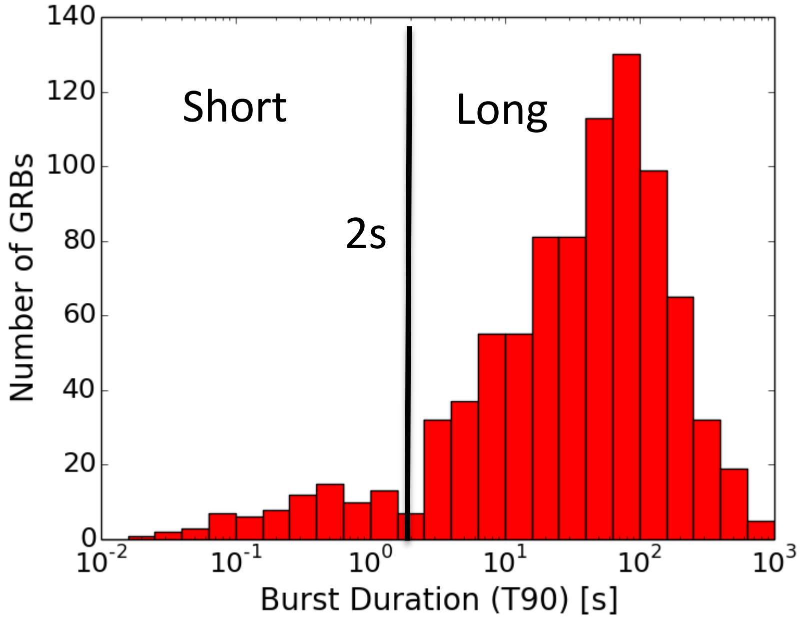
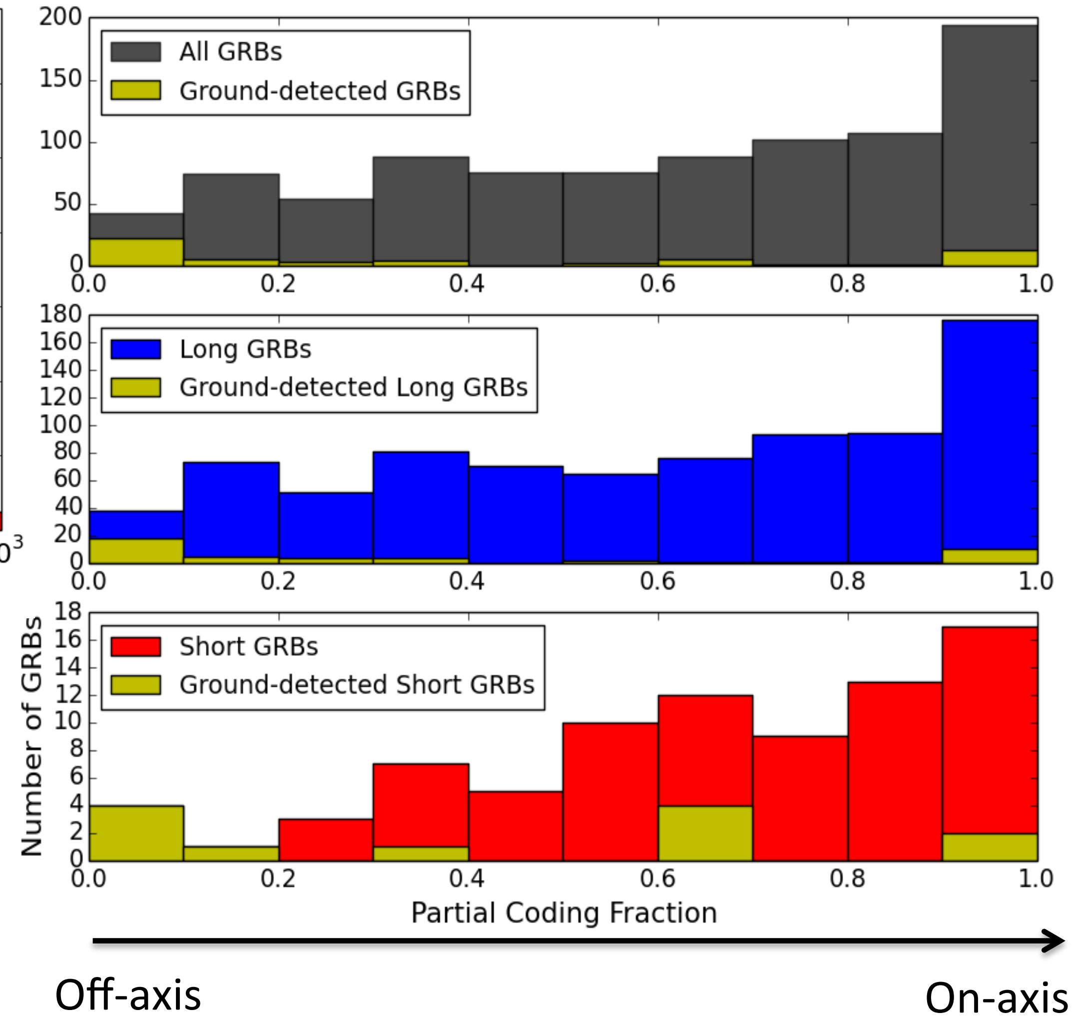


Distribution is instrument dependent

Fig credit: Taka's presentation

Burst Durations





- Short GRBs are less-likely to be detected off-axis
- Some off-axis short GRBs are found in ground analyses

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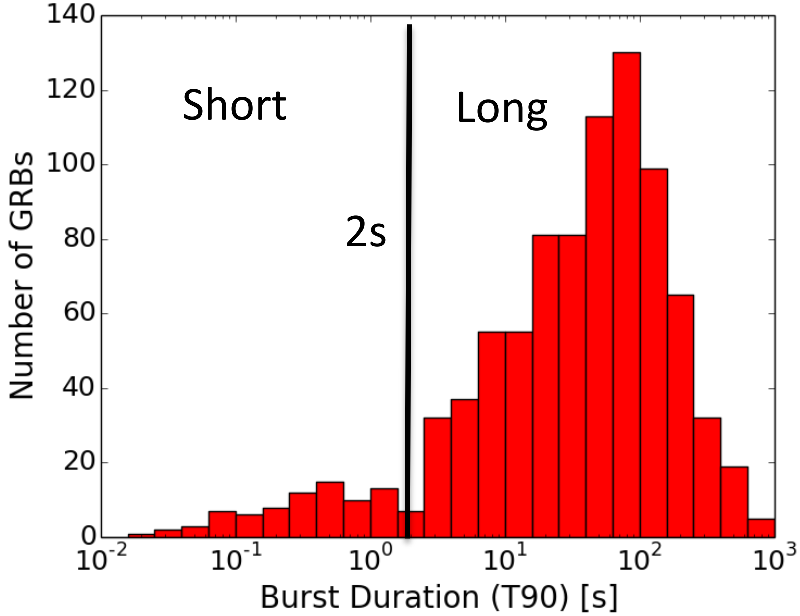

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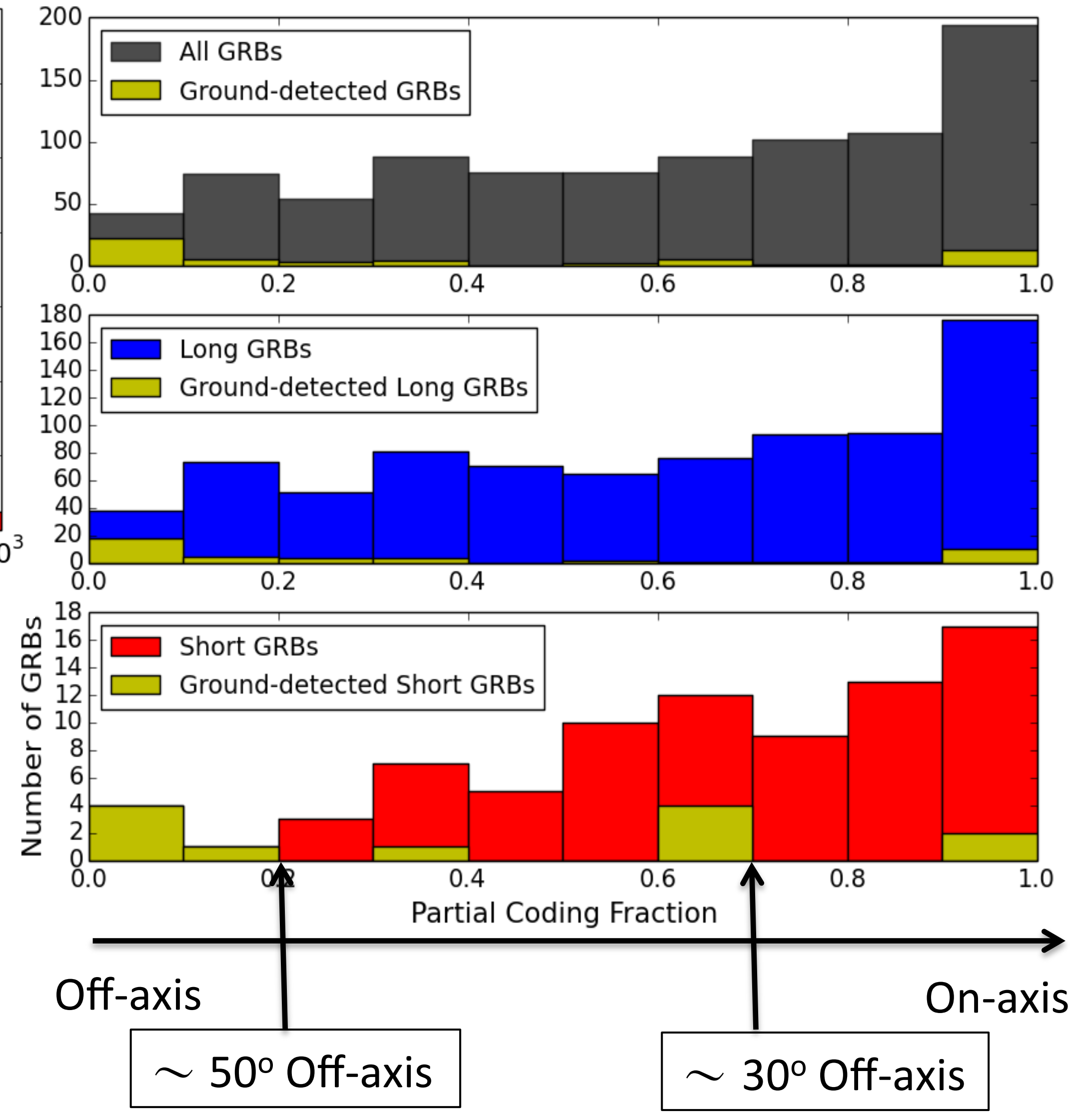
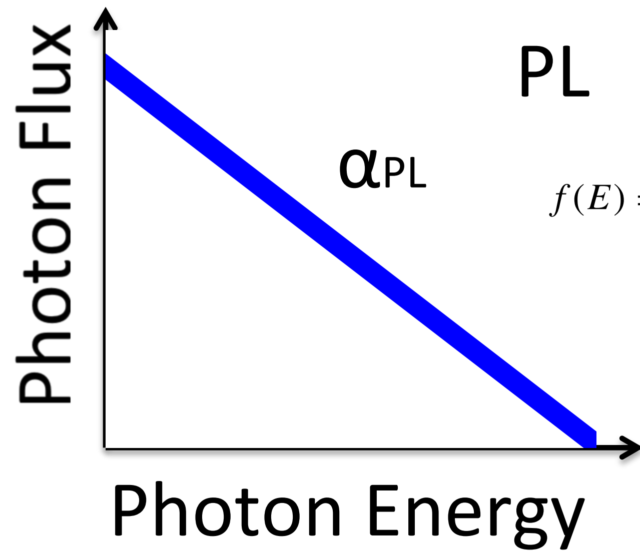


Spectral Fits

- Following the 2nd BAT GRB catalog (Sakamoto et al. 2011)
- (a) simple power law (PL)

  (b) cutoff power law (CPL)
- Choose CPL If $\Delta\chi^2 > 6$
- Additional criteria for an acceptable spectral fit

$$f(E) = K_{50}^{\rm CPL}\left(\frac{E}{50\ {\rm keV}}\right)^{\alpha^{\rm CPL}} \exp\left(\frac{-E(2+\alpha^{\rm CPL})}{E_{\rm peak}}\right)$$



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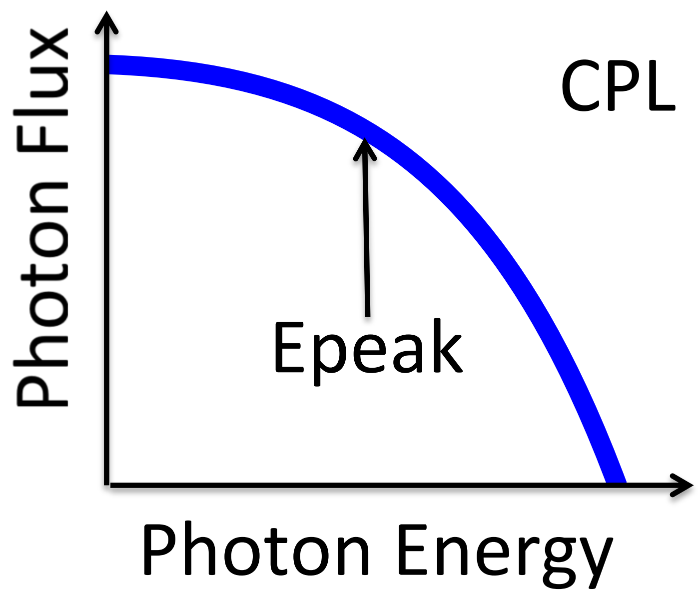

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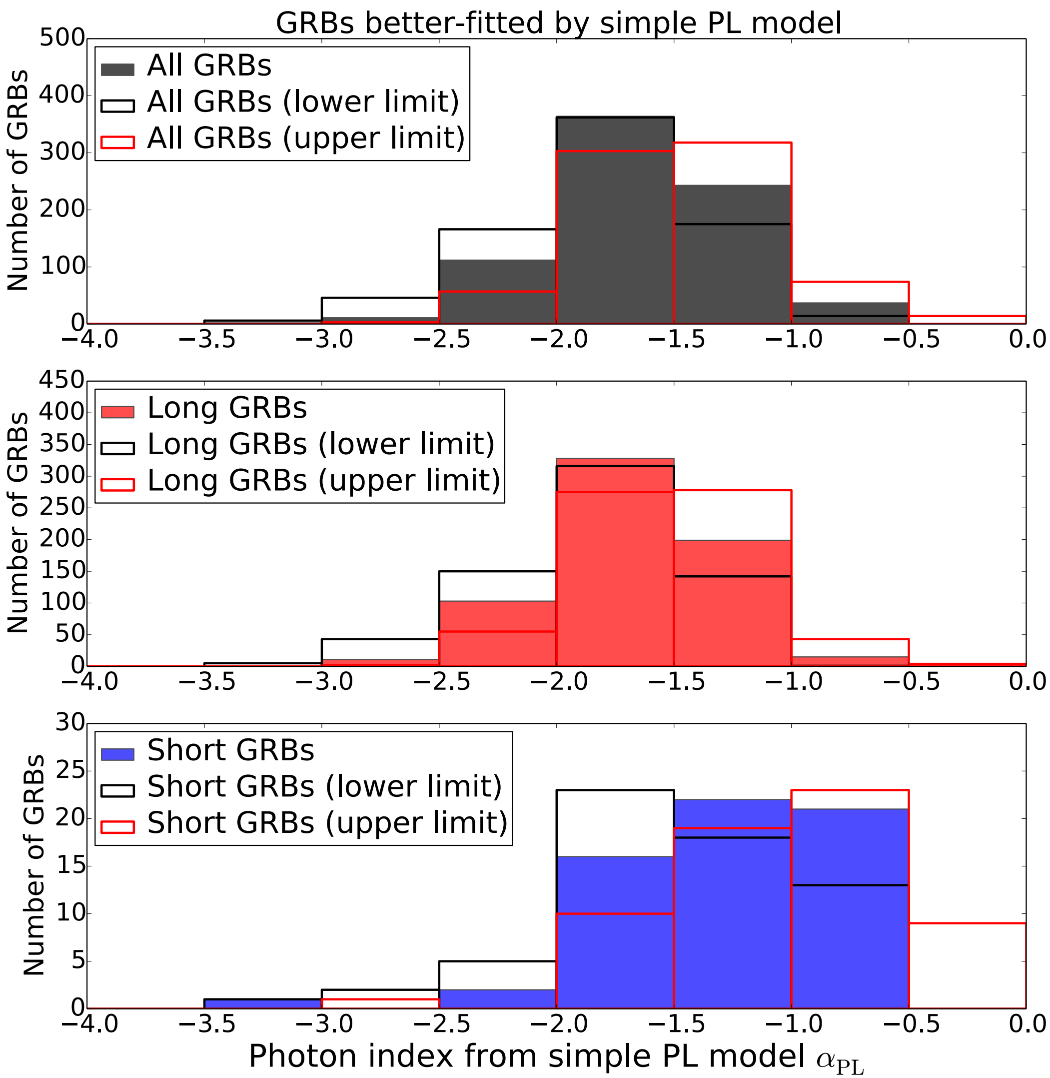

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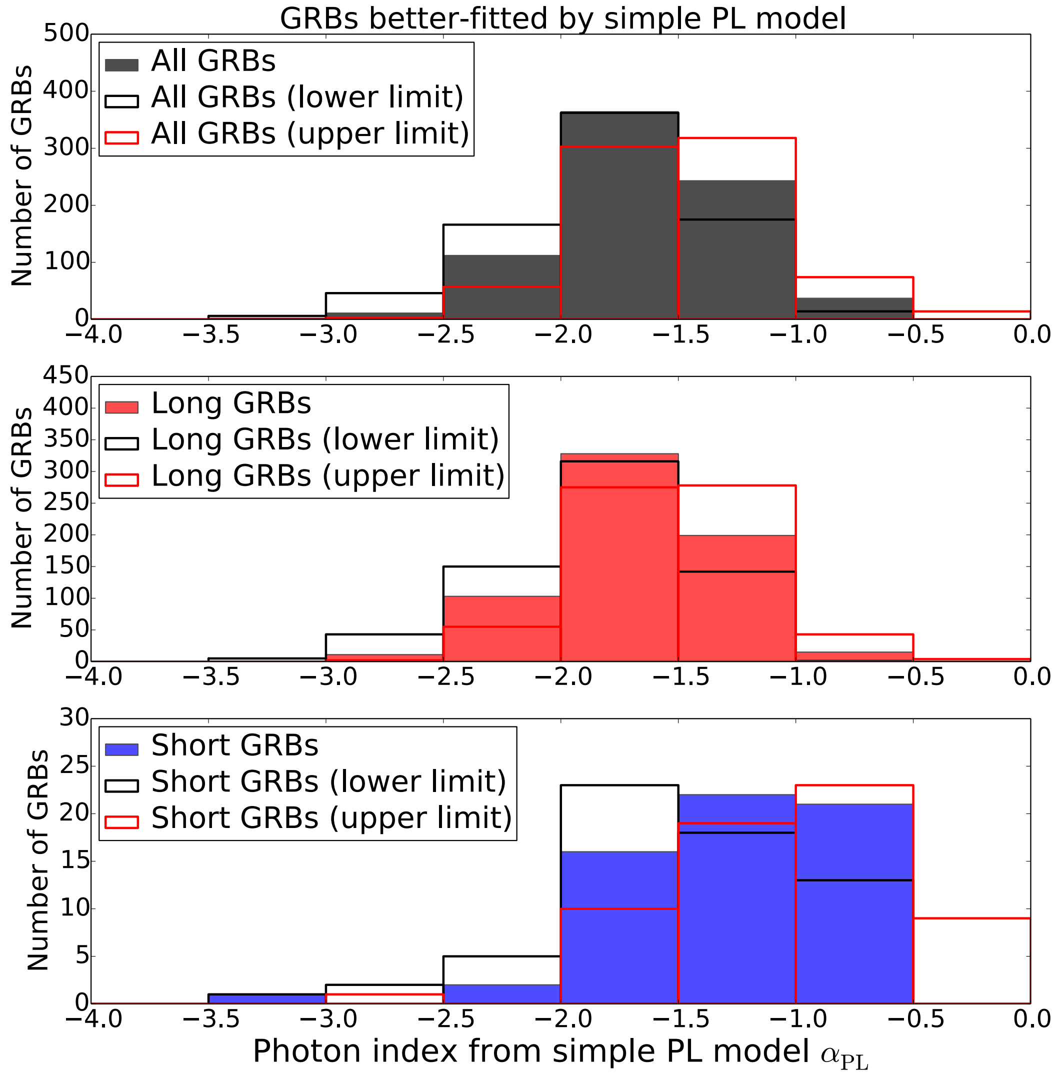
In BAT sample, short GRBs are only slightly harder than long GRBs.



Spectral Fits – Cutoff Power Law

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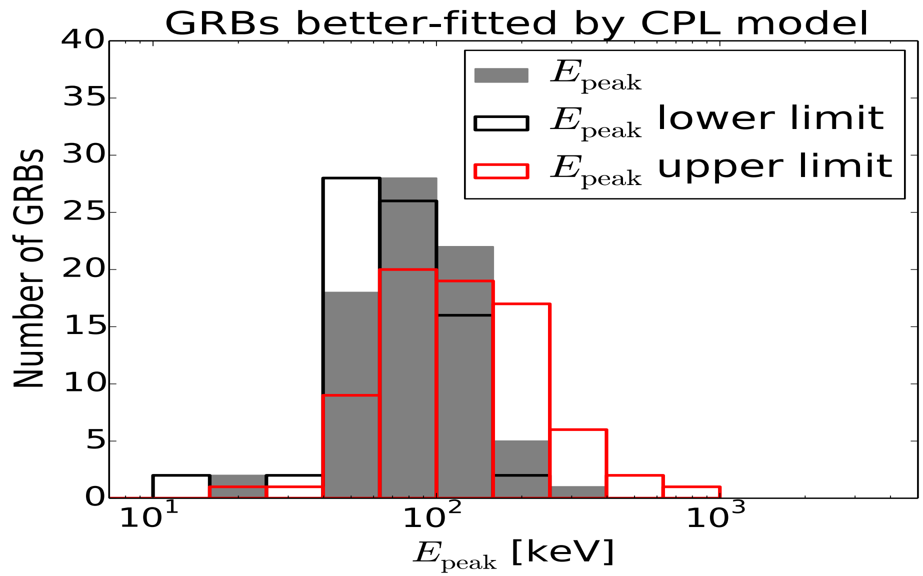
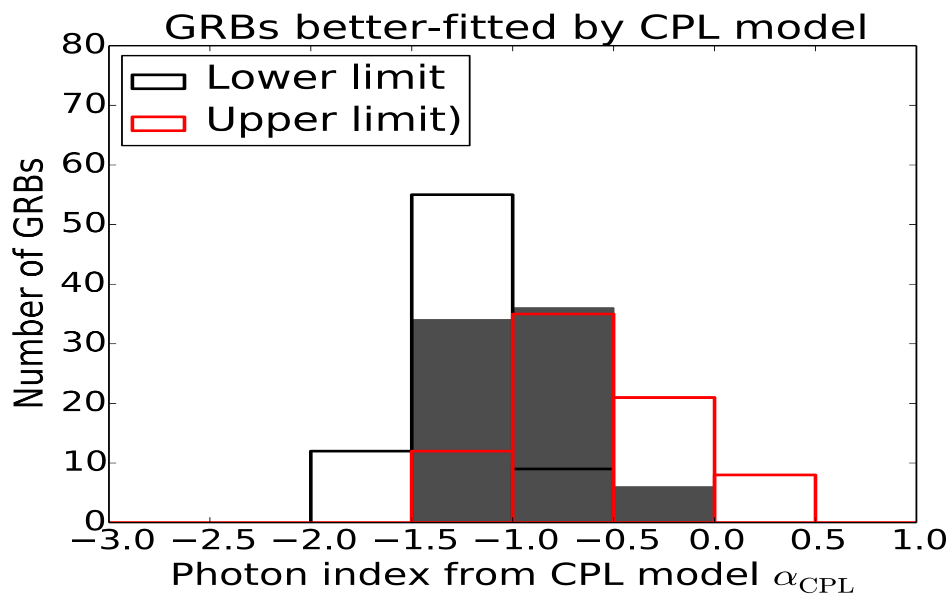
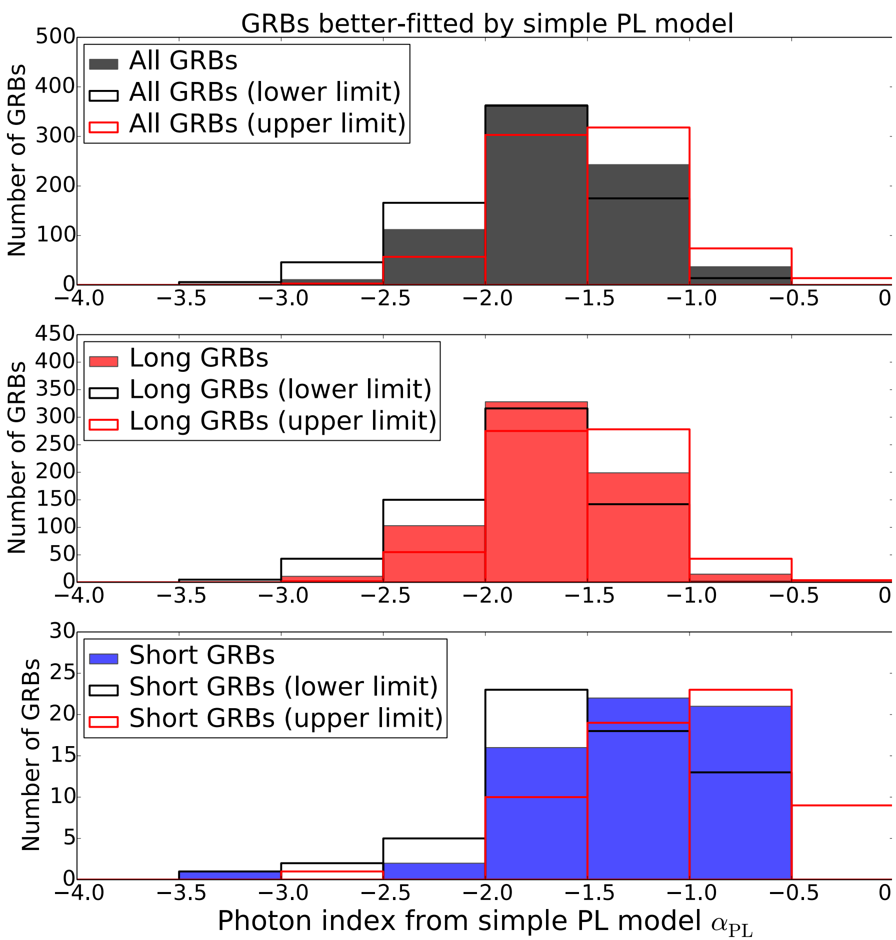
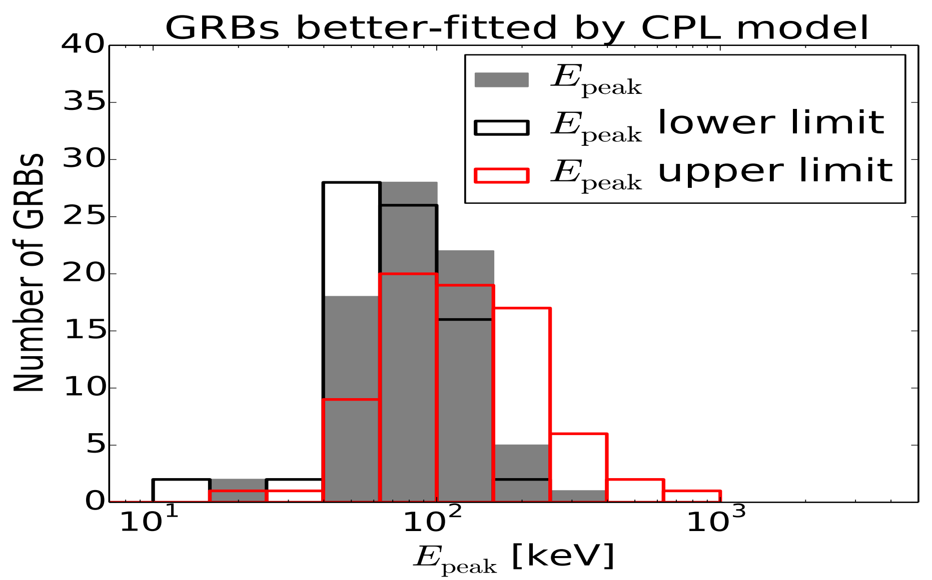
  (all long GRBs)

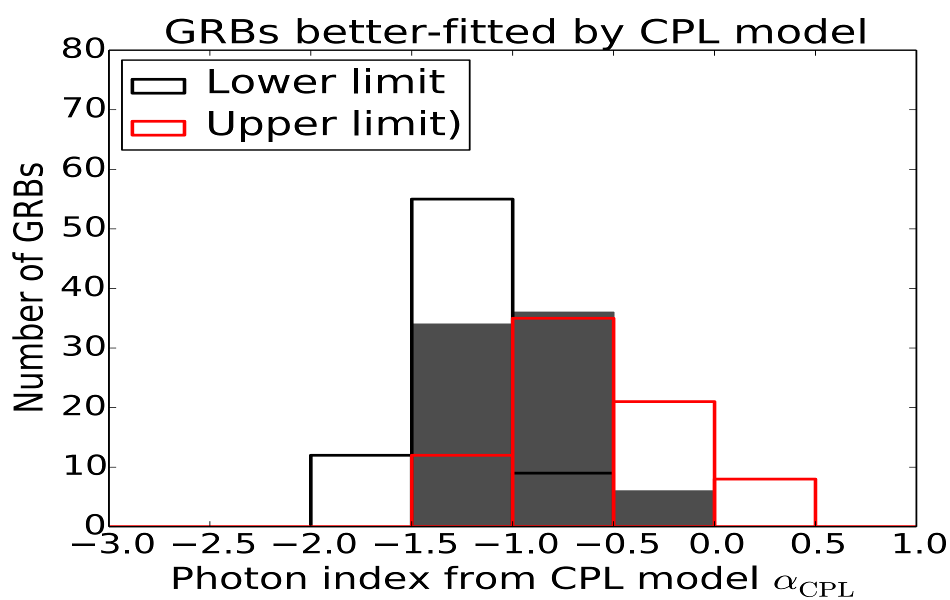




Spectral Fits – Cutoff Power Law







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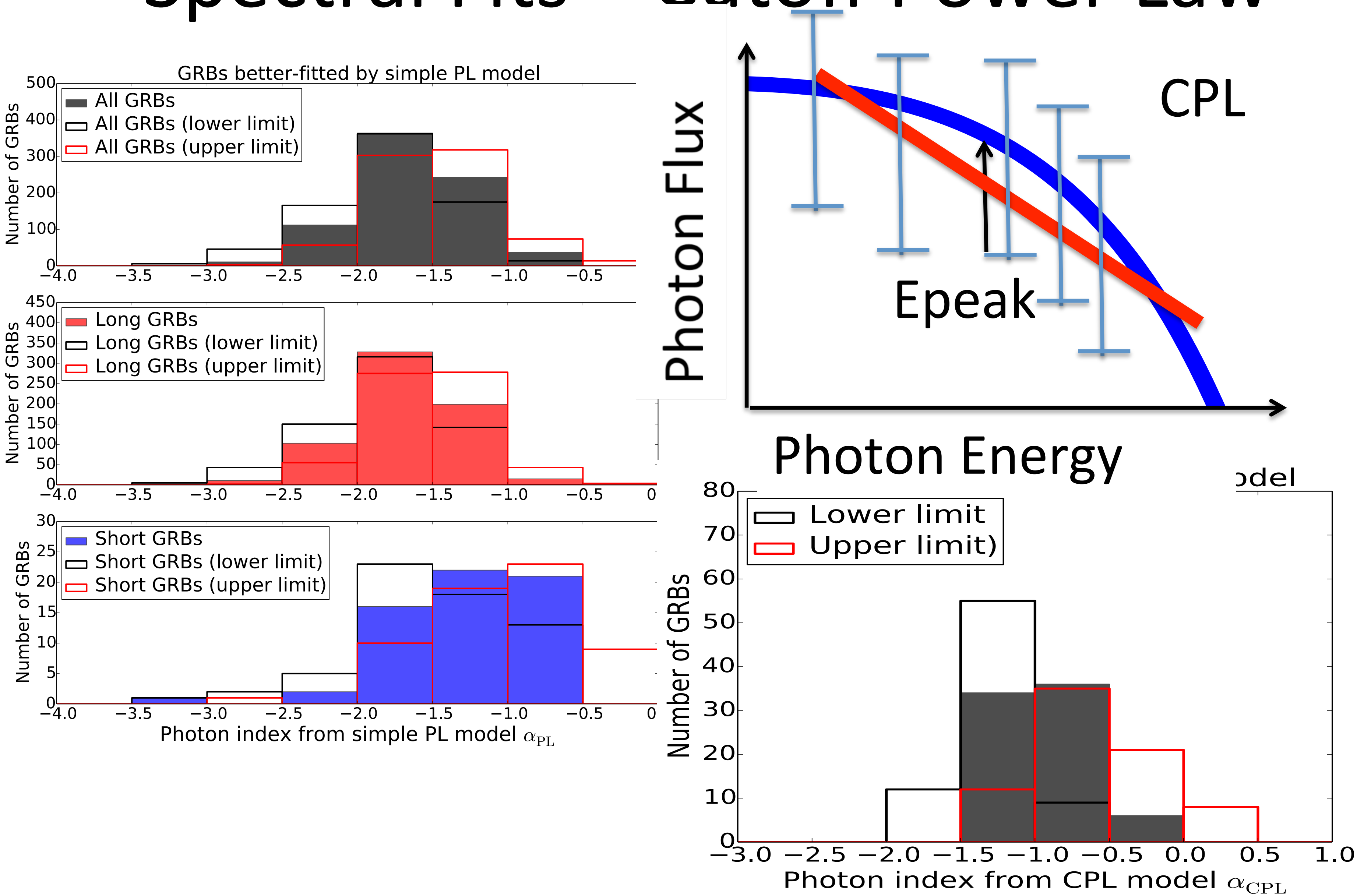

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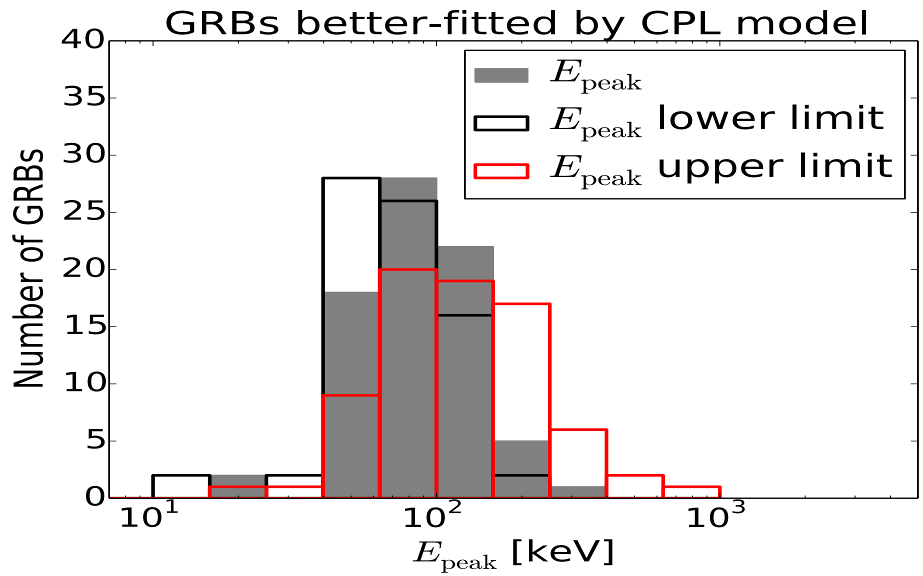

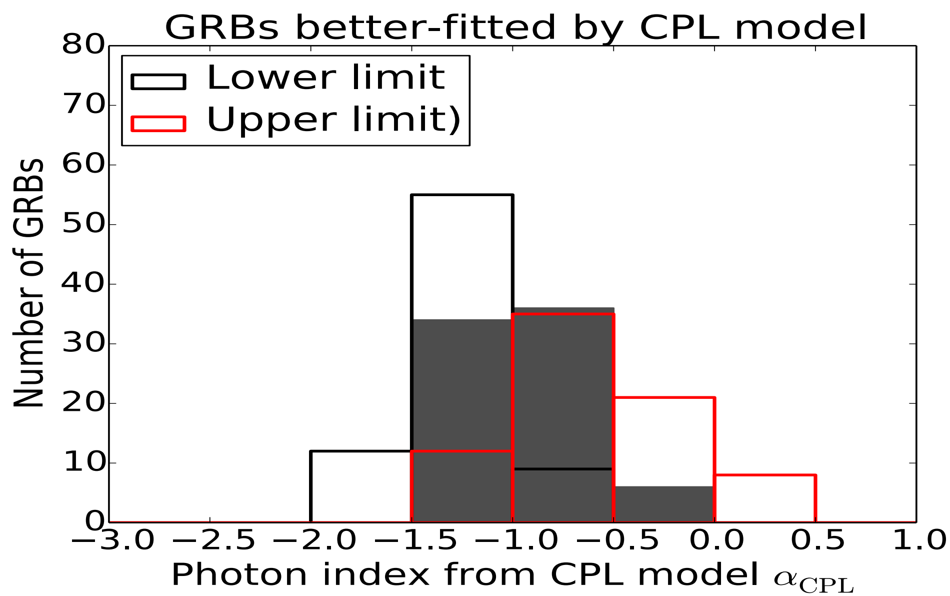

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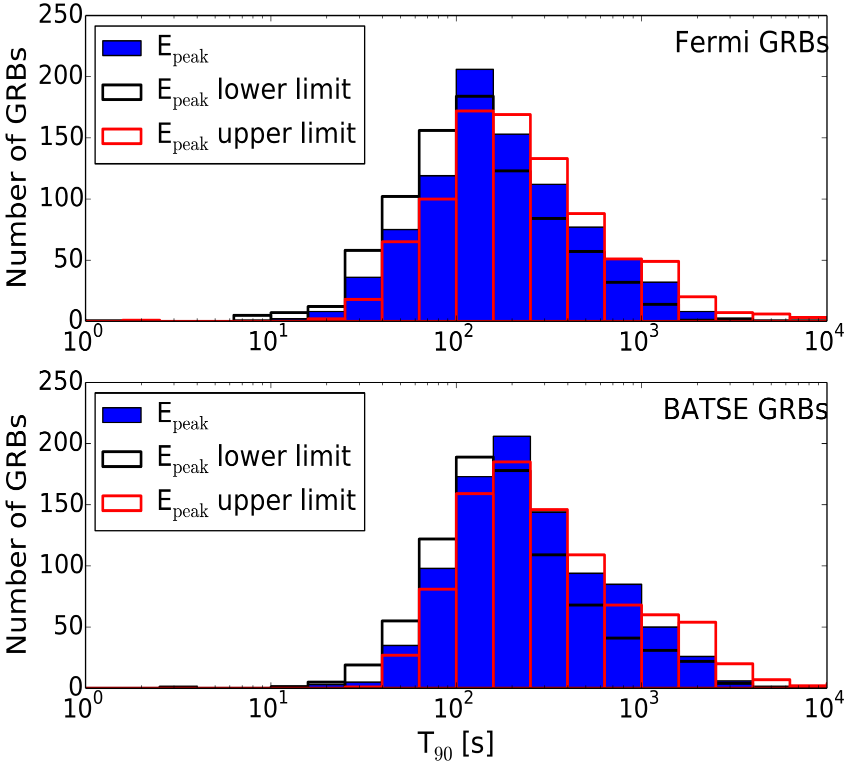

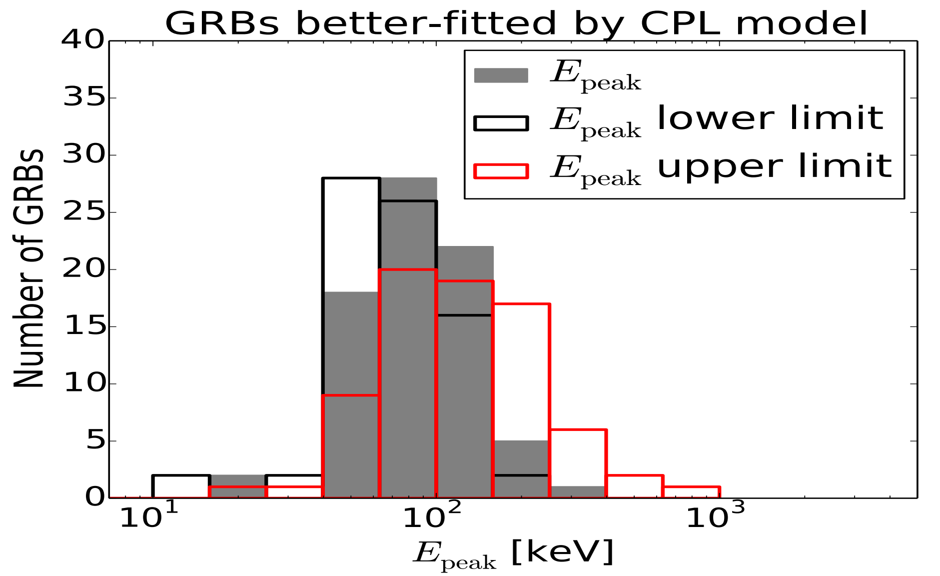

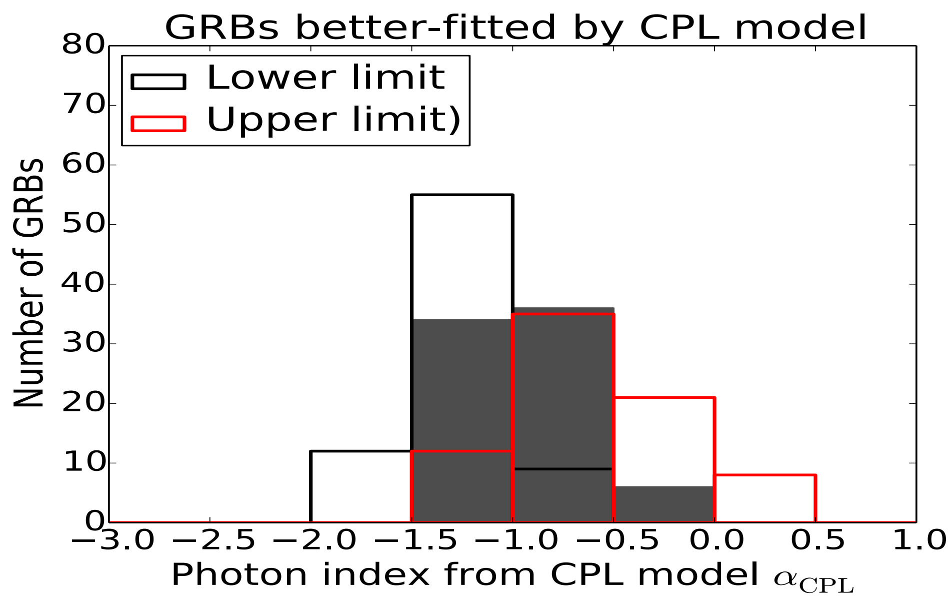

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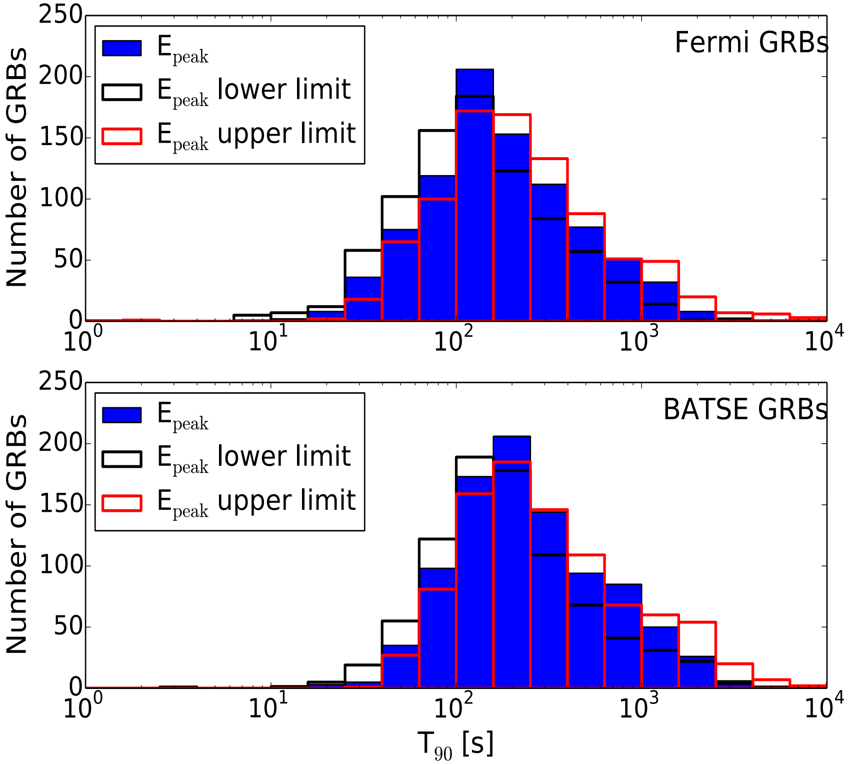
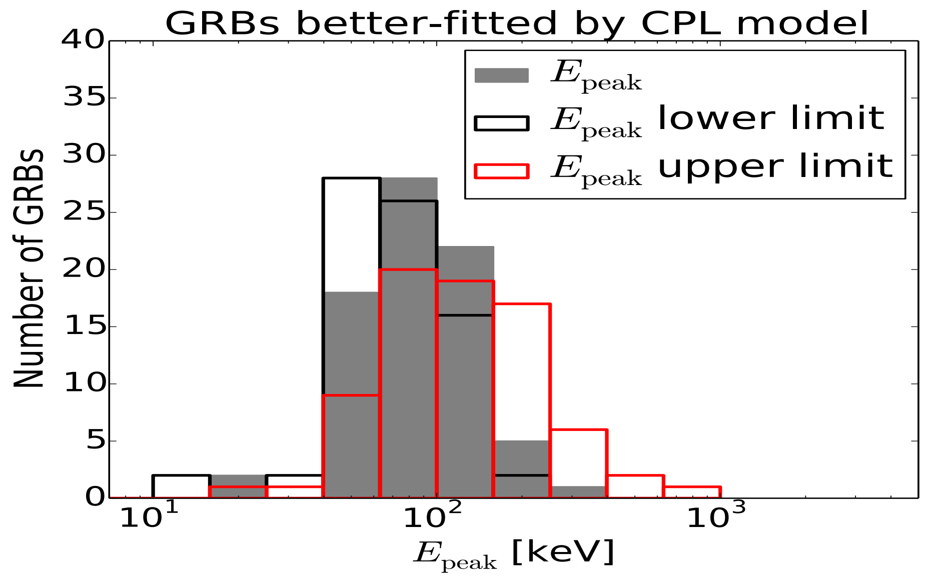
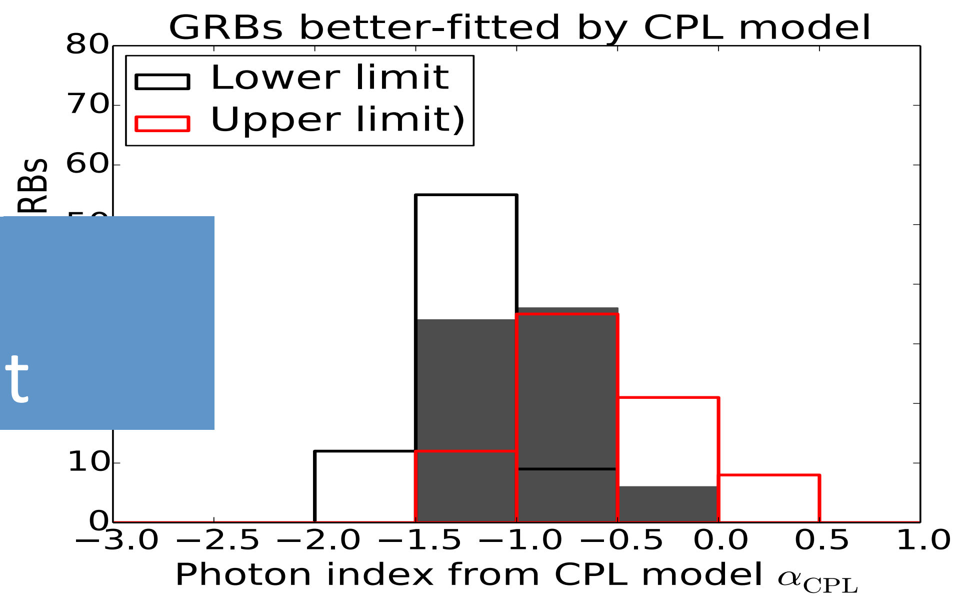
Spectral Fits – Cutoff Power Law

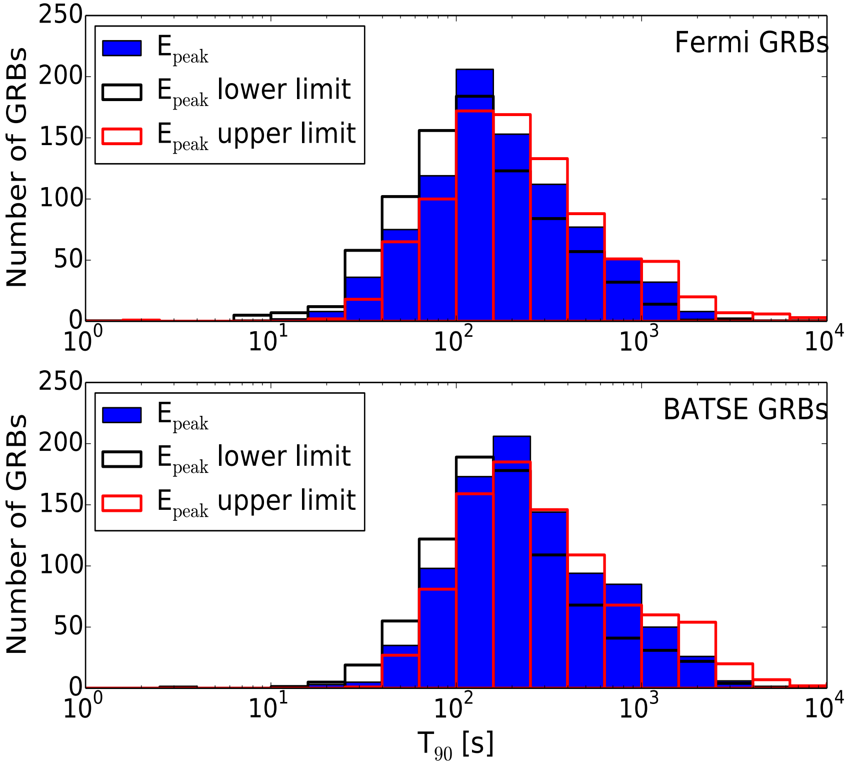


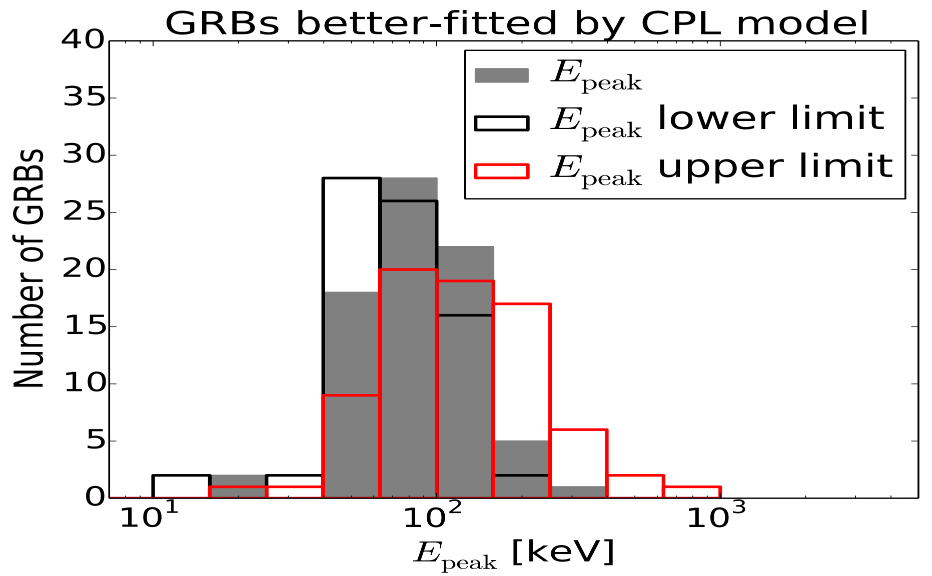


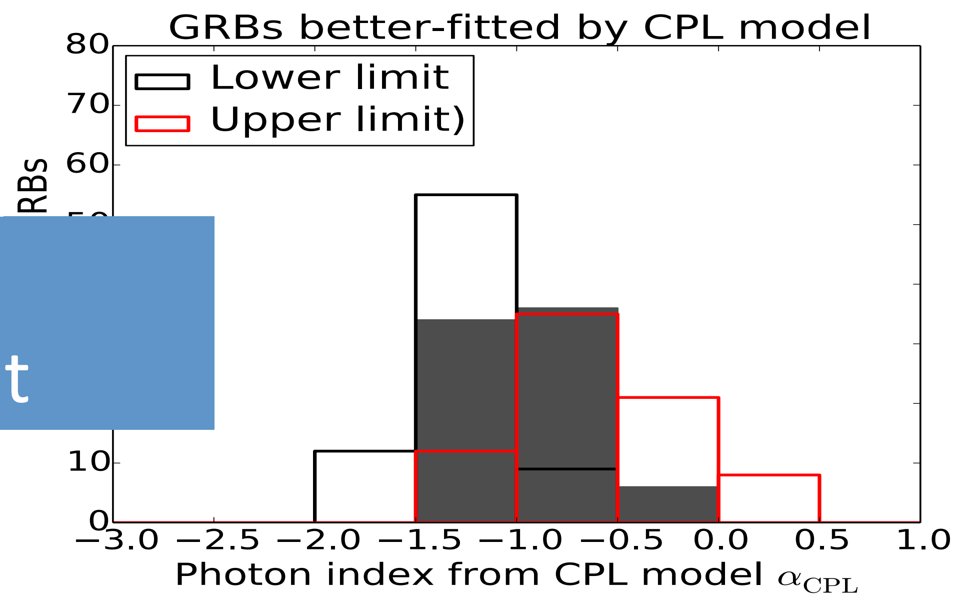


Epeak distribution is instrument dependent

Spectral Fits – Cutoff Power Law







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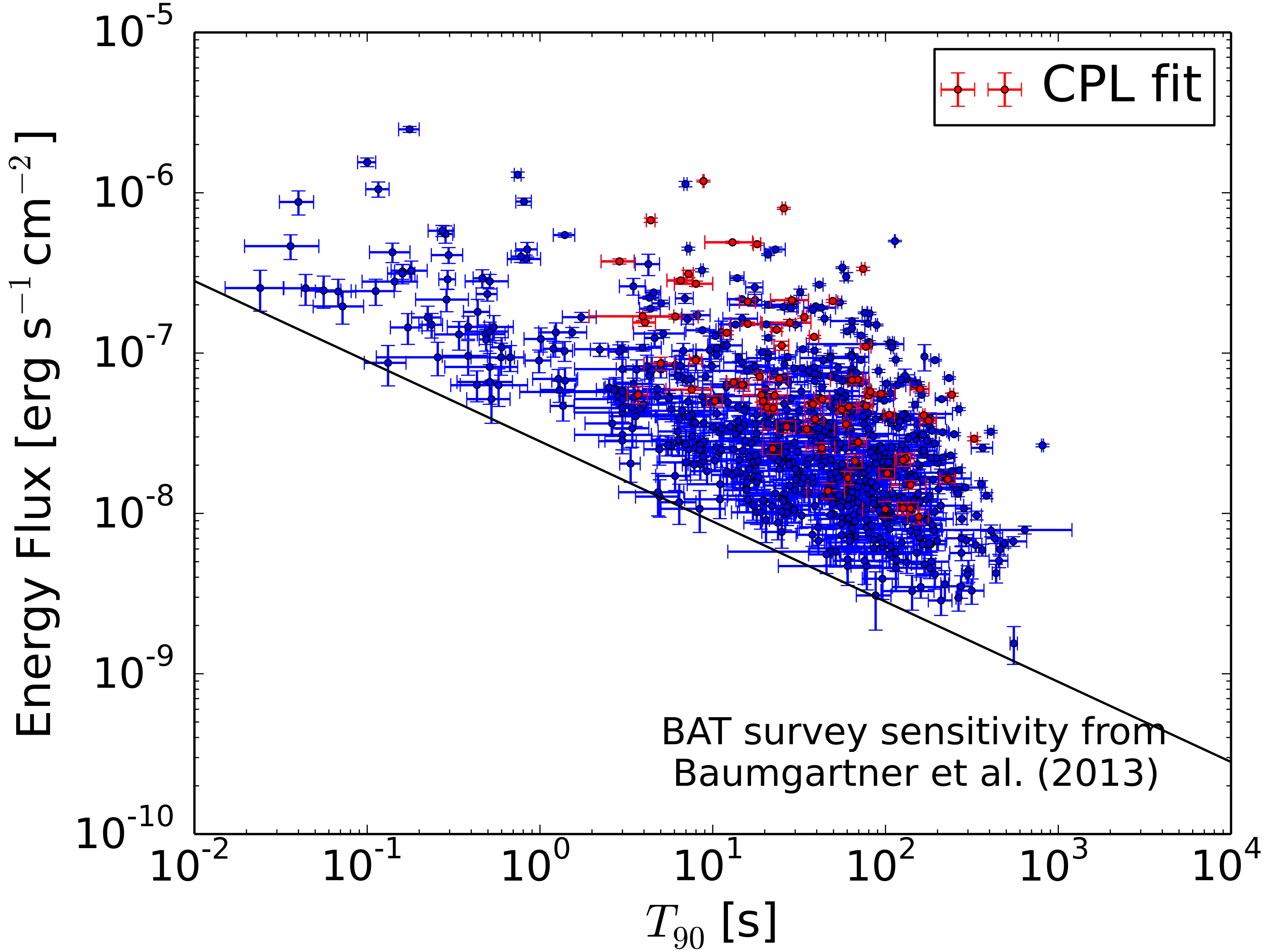
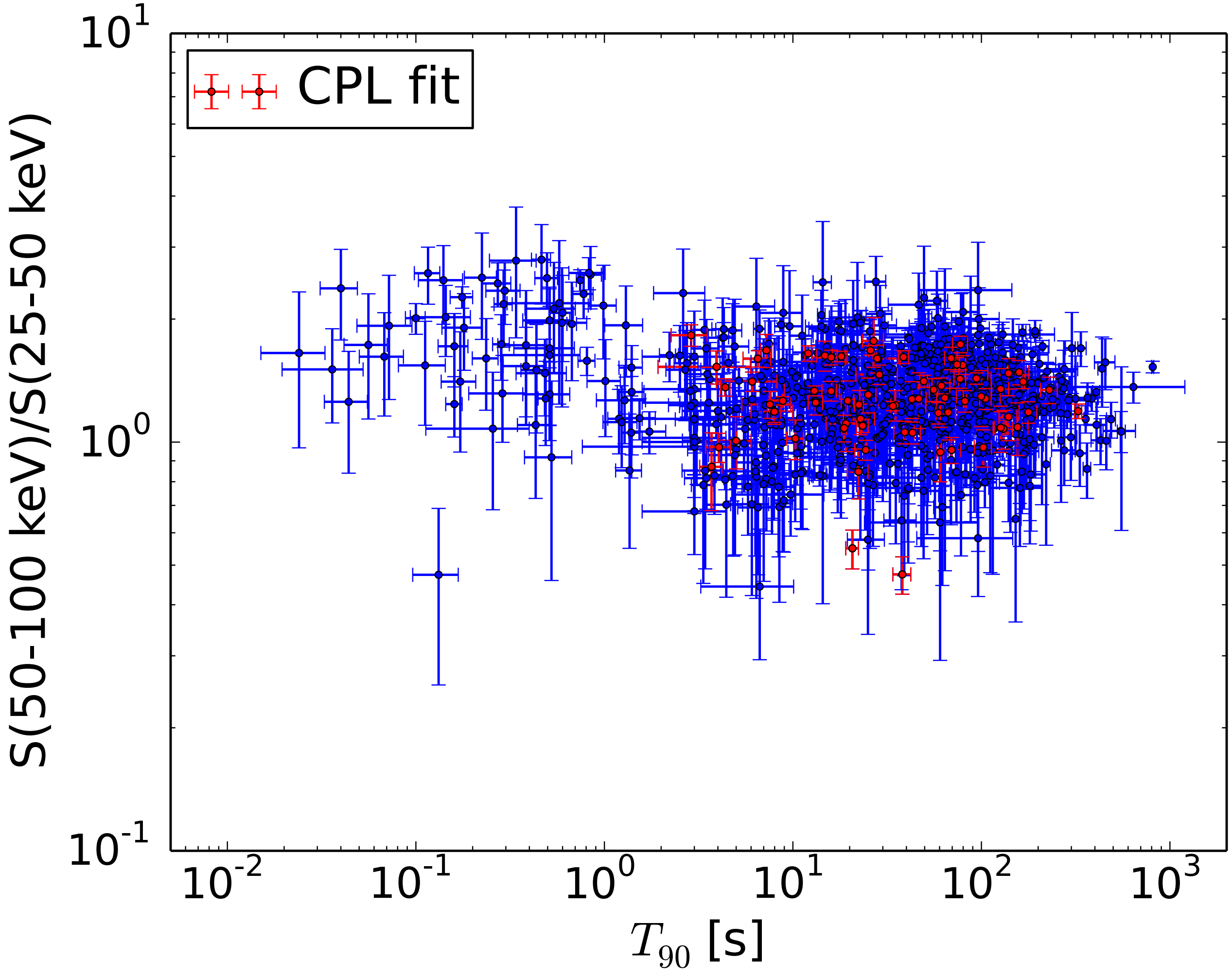
BAT Sensitivity on GRB detections

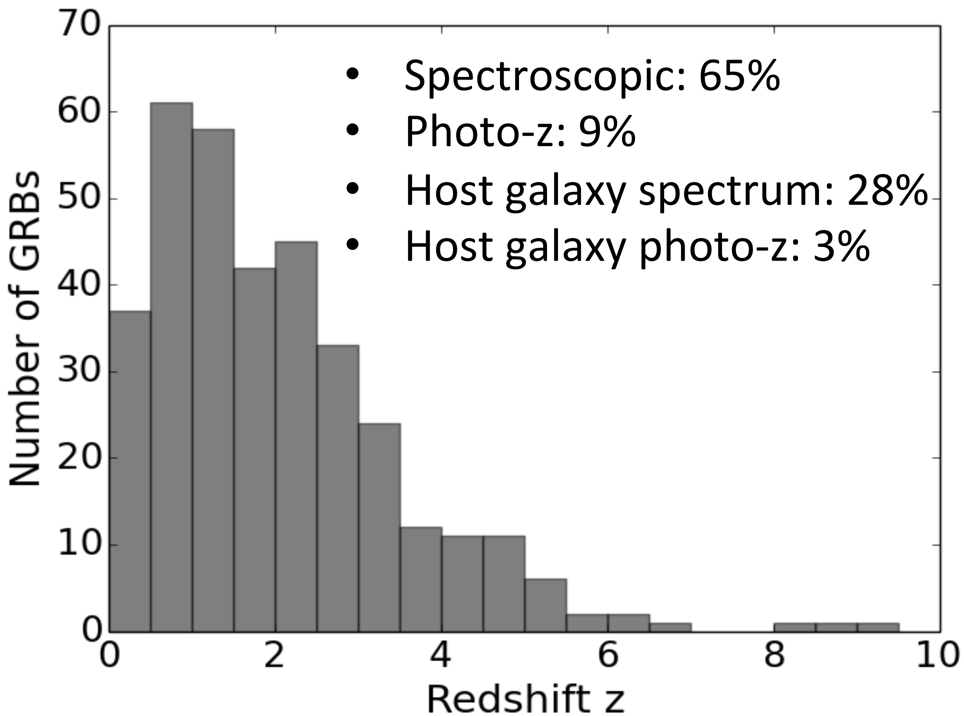


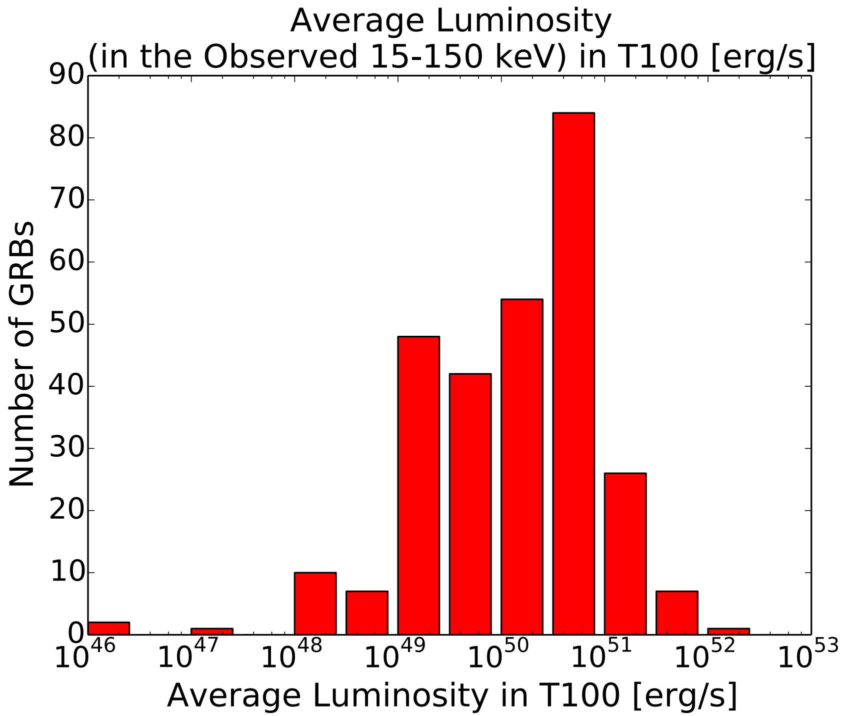
Short-hard vs long-soft?



Redshift and Luminosity Distribution

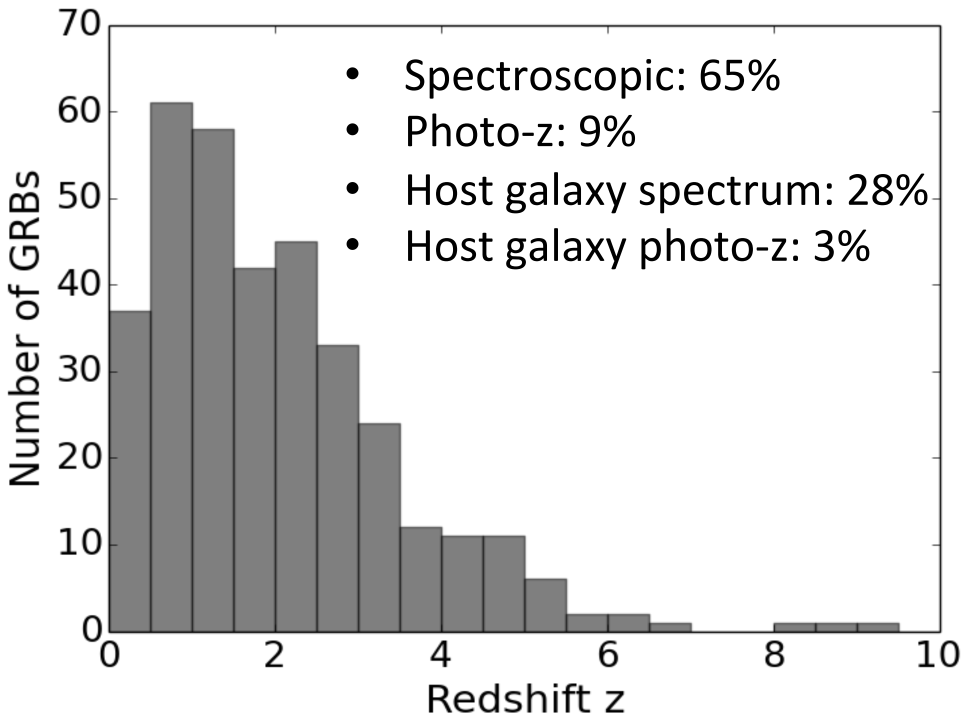
- Thanks to the ground-based follow-up campaign
- Redshift list compiled by Kevin Chen (U of California, Berkeley)
    - Info from papers, GCNs, online lists (e.g., GRBOX by Dan Perley)

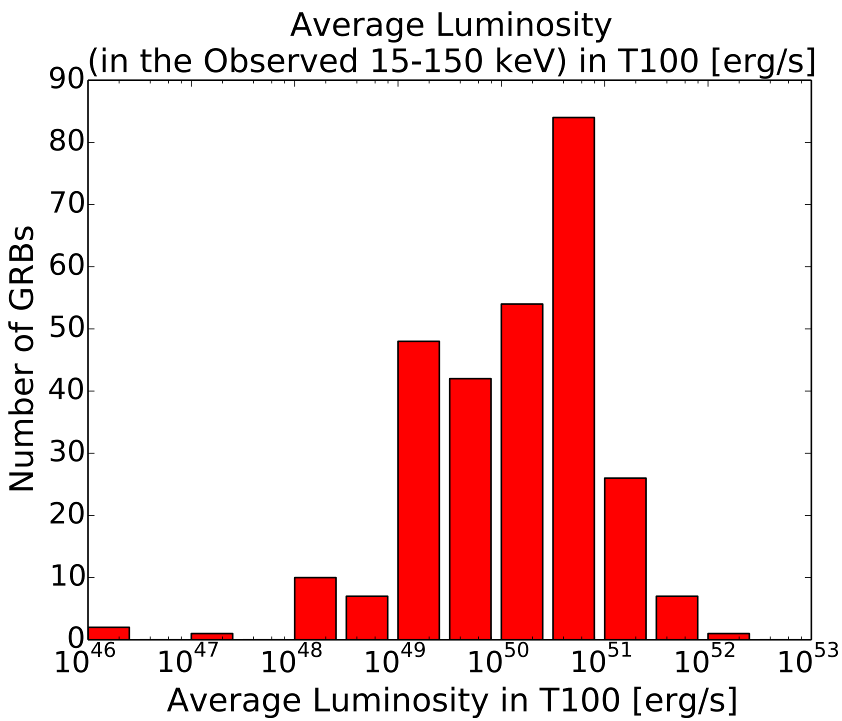




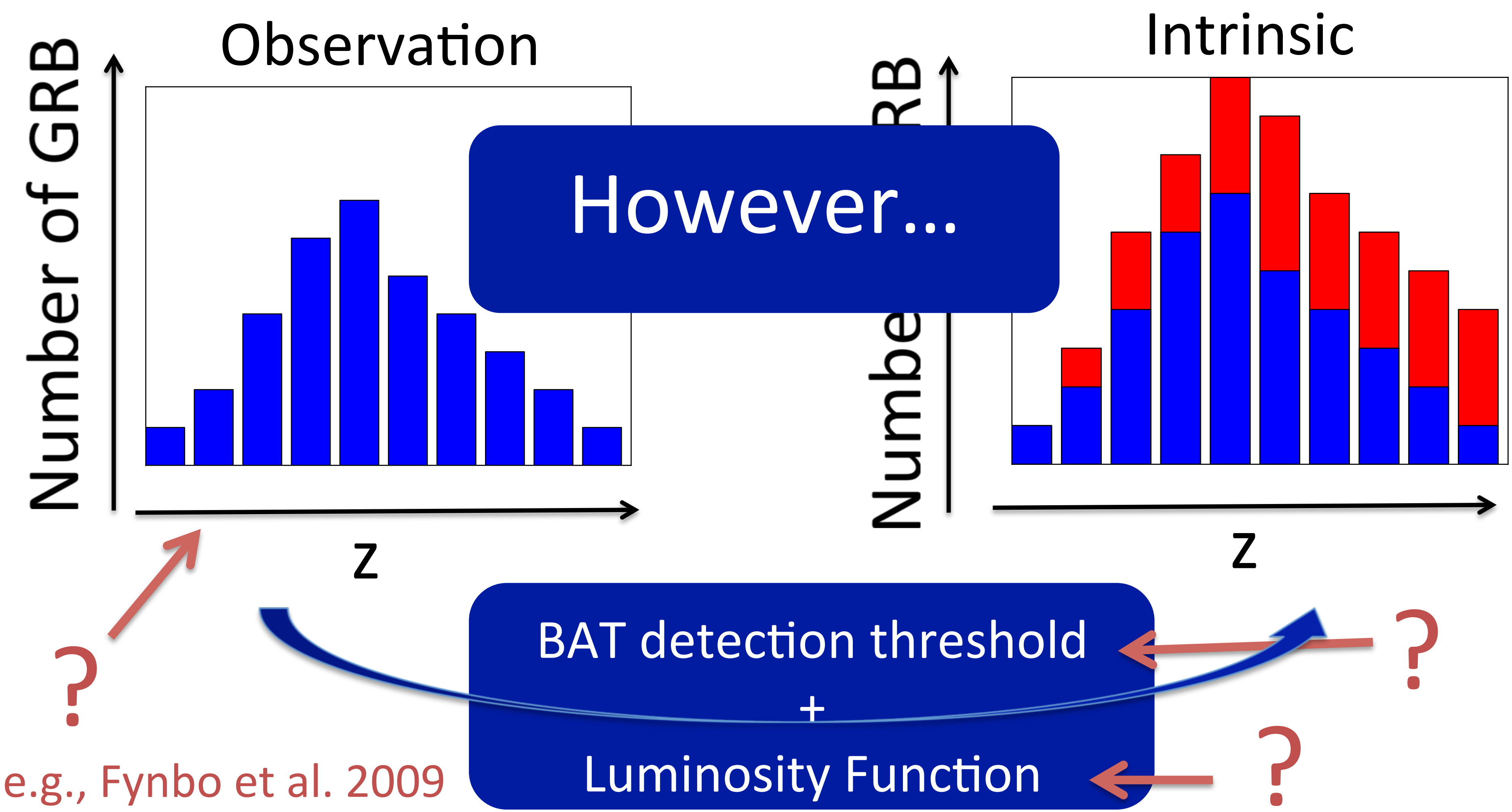
Redshift and Luminosity Distribution

Do we have all we need to find GRB rate?



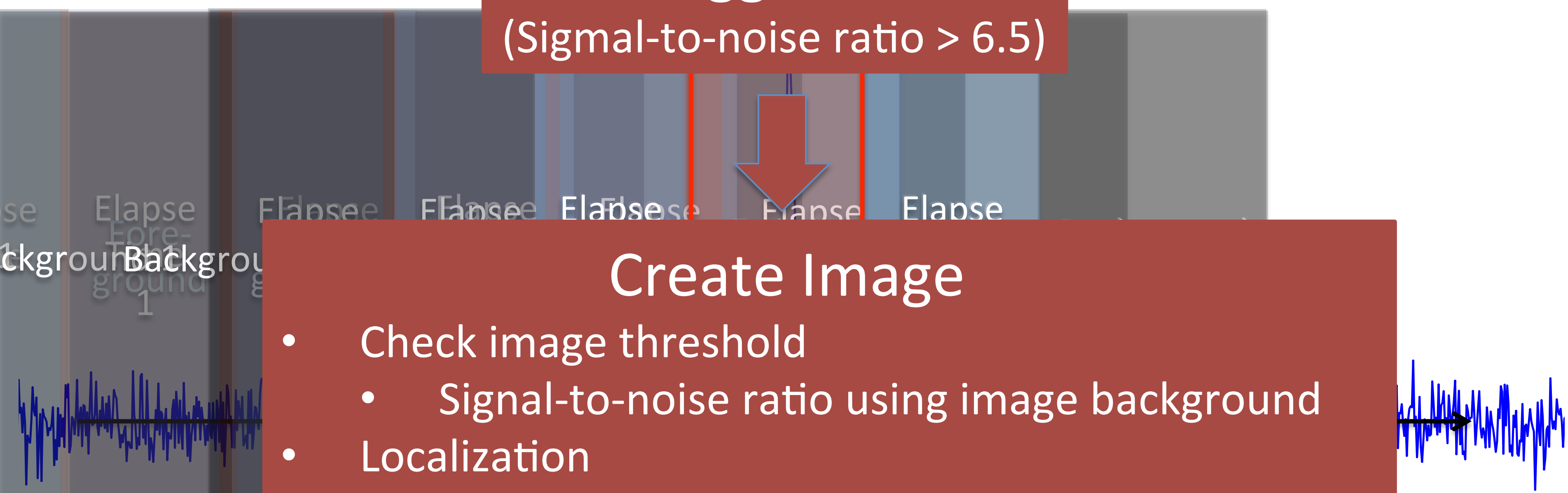


Finding intrinsic GRB rate: A naïve theorist approach…..



Trigger Algorithm of the BAT

1. Rate trigger followed by image threshold:
   - > 500 different trigger criteria
   - Each trigger criterion has different
     - energy bands, time periods, signal-to-noise thresholds, etc
   - Image threshold: lization



Triggered!
(Signal-to-noise ratio > 6.5)

Create Image
- Check image threshold
  - Signal-to-noise ratio using image background
- Localization
  - Known souce? Check with on-board sky catalog

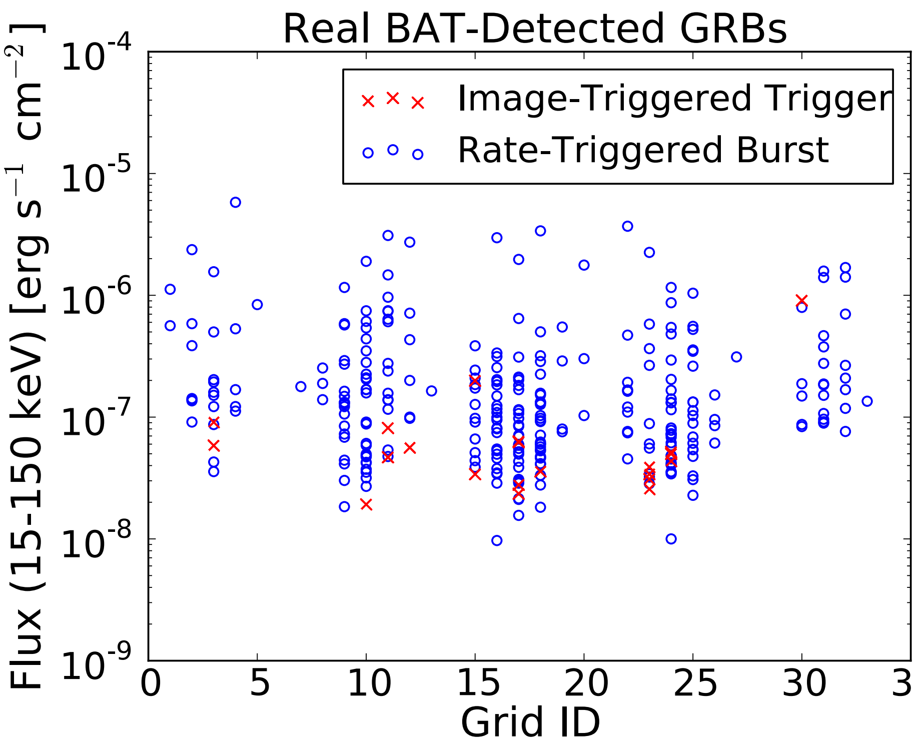
2. Image trigger: Creating images every ～ min to look for bursts

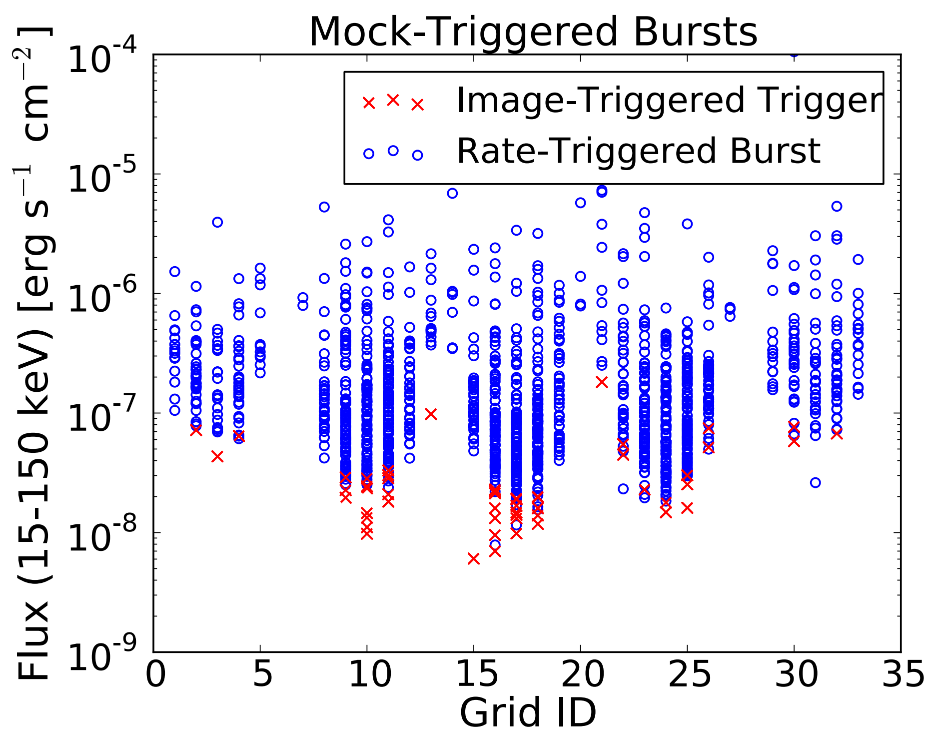
Using Swift's Data to Probe The Intrinsic GRB Rate

- Difficulties of reconstructing the intrinsic rate from the observed rate:
  - Swift is not a single-threshold telescope
  - The selection bias from observations
- Goal of this work:
  - Search for the intrinsic rate by simulating the complex Swift trigger algorithm
  - Trigger simulator: Generally follows the same process as the actual BAT trigger algorithm

Sensitivity Comparisons

- Grid ID: ID name on the detector's plane, related to incoming angle





Real BAT-detected GRBs (Sakamoto et al. 2009):
- Total triggered bursts: 324
- 303 rate trigger
- 21 image trigger

Our simulations:
- Total triggered bursts: 1400
- 1347 rate trigger
- 53 image trigger

General Approach: A Semi-Monte-Carlo Simulation

Initial guess of GRB properties → Create simulated lightcurves → Run through all *Swift* trigger criteria → Match with actual *Swift* detected GRB sample

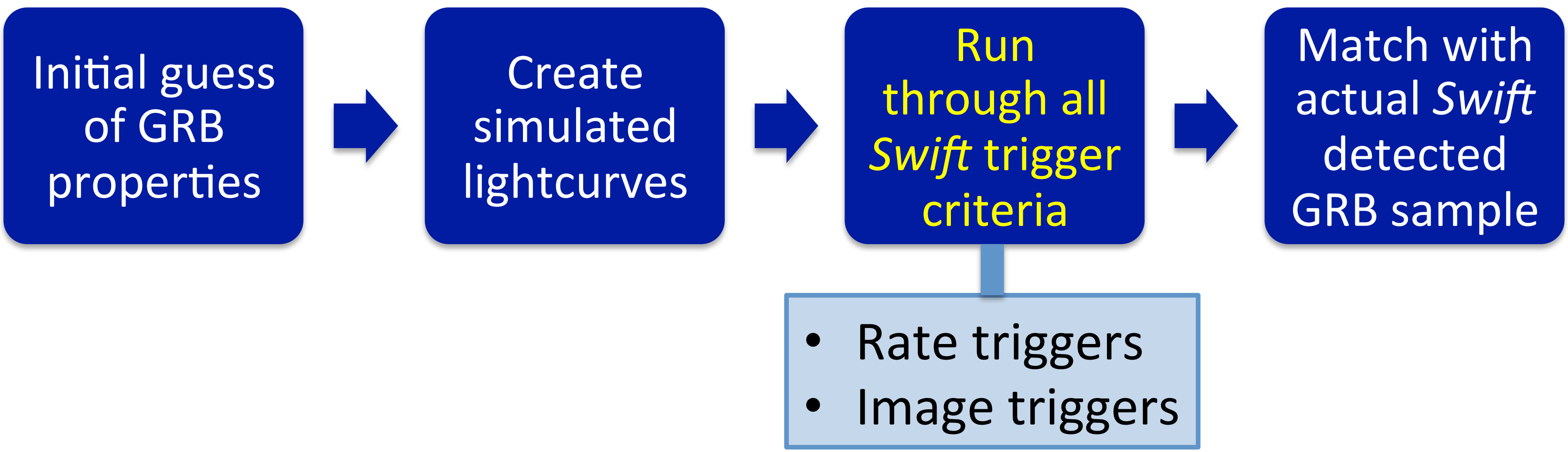
- Redshift and Luminosity distributions (functional form from Wanderman et al. 2010)
- Spectral distribution (Epeak, alpha, beta of the BAND function)
- Pulse shapes (from real Swift observations)

General Approach: A Semi-Monte-Carlo Simulation

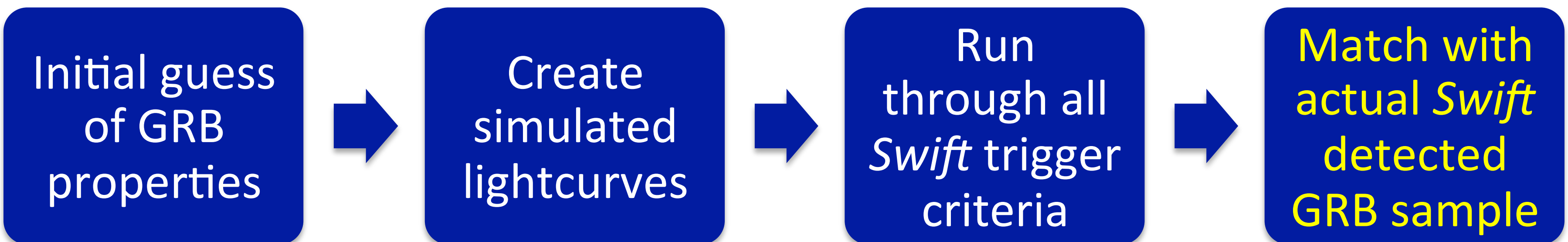
Initial guess of GRB properties → Create simulated lightcurves → Run through all *Swift* trigger criteria → Match with actual *Swift* detected GRB sample

- Different burst incident angles
- Different background levels
- Option of including spectral (E_{peak}) evolution

General Approach: A Semi-Monte-Carlo Simulation

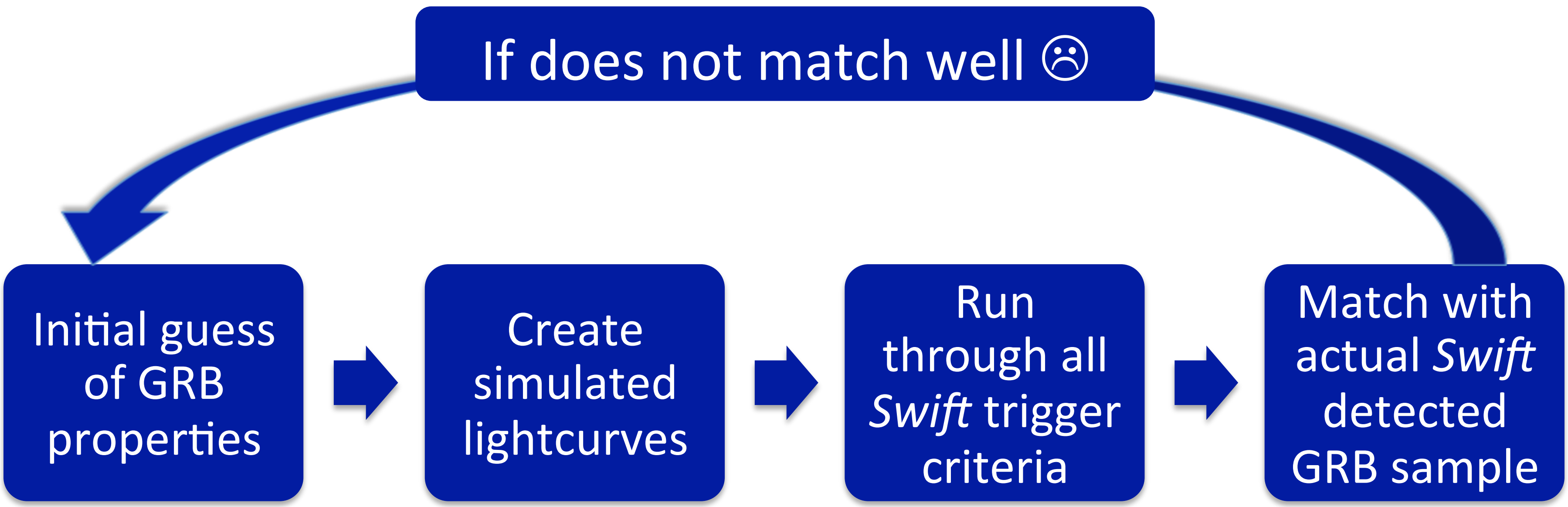


General Approach: A Semi-Monte-Carlo Simulation

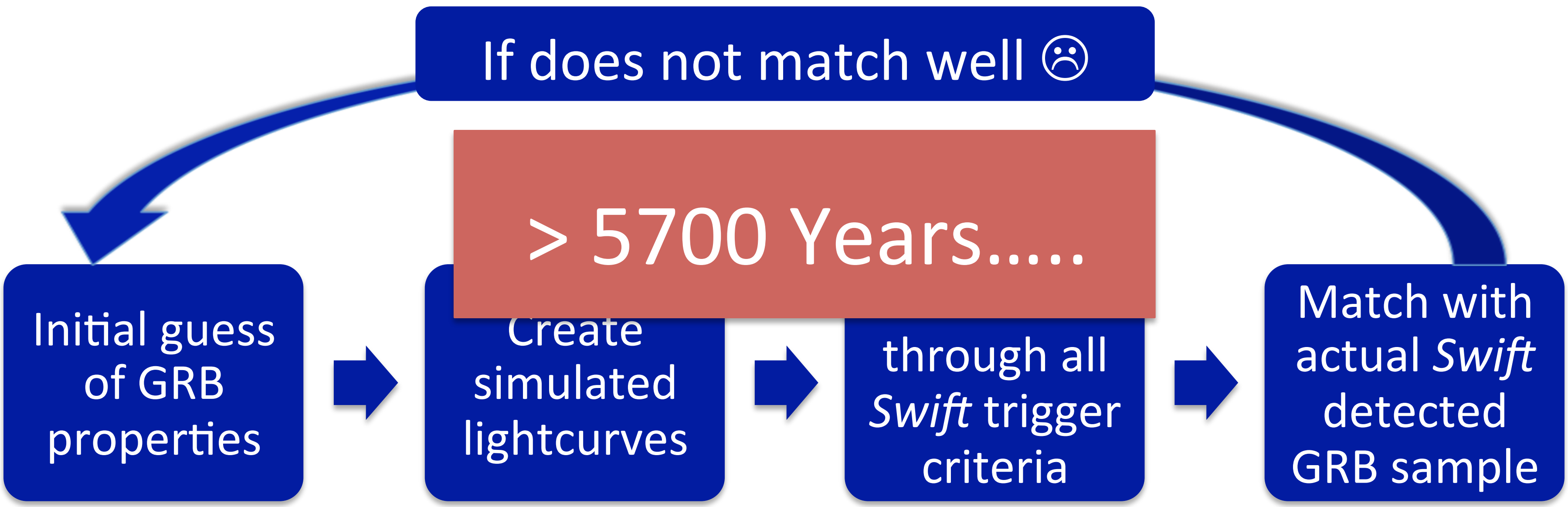


- Redshift sample (Fynbo et al. 2009)
- Peak-flux sample (Sakamoto et al. 2011)
- Swift's detection per year (e.g., Gehrels et al. 2012)
- E_{peak}, E_{iso} (e.g., Butler et al. 2007, 2010)

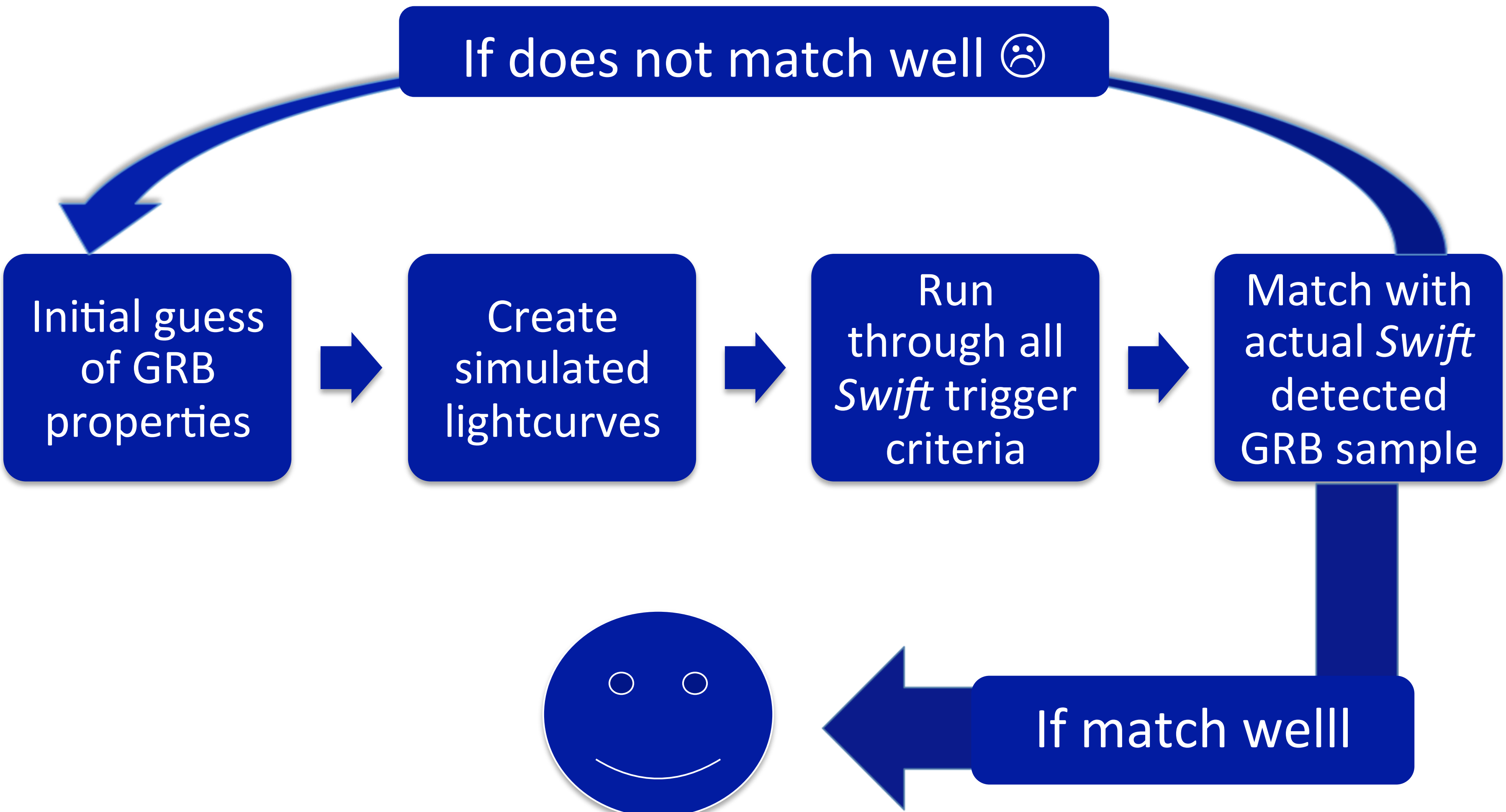
General Approach: A Semi-Monte-Carlo Simulation



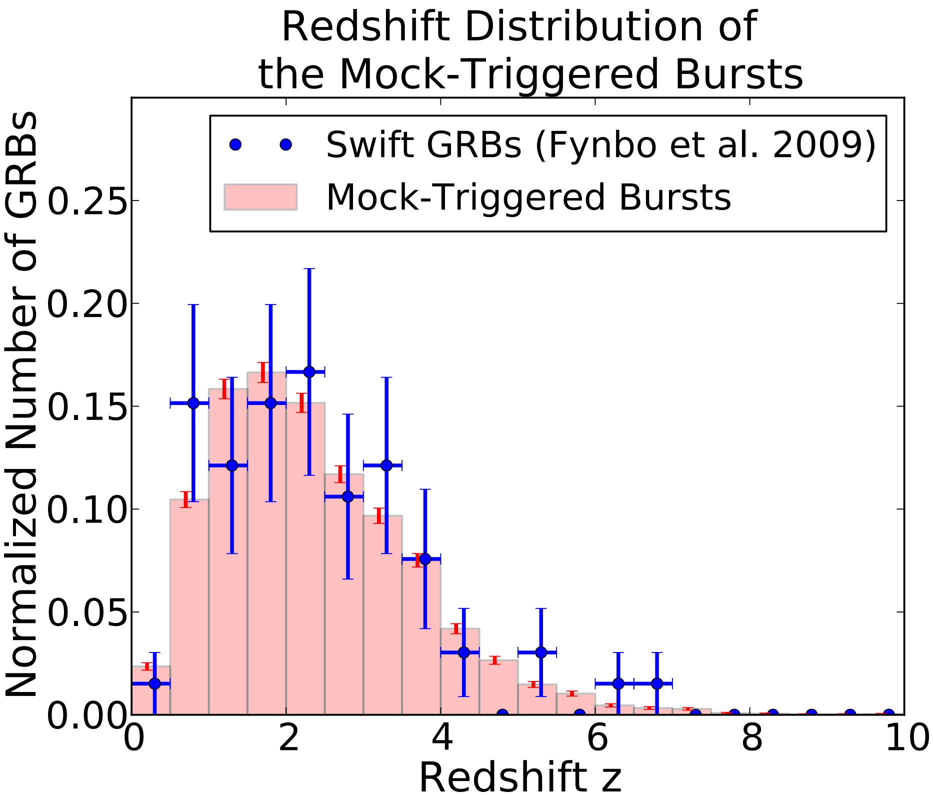
General Approach:
A Semi-Monte-Carlo Simulation

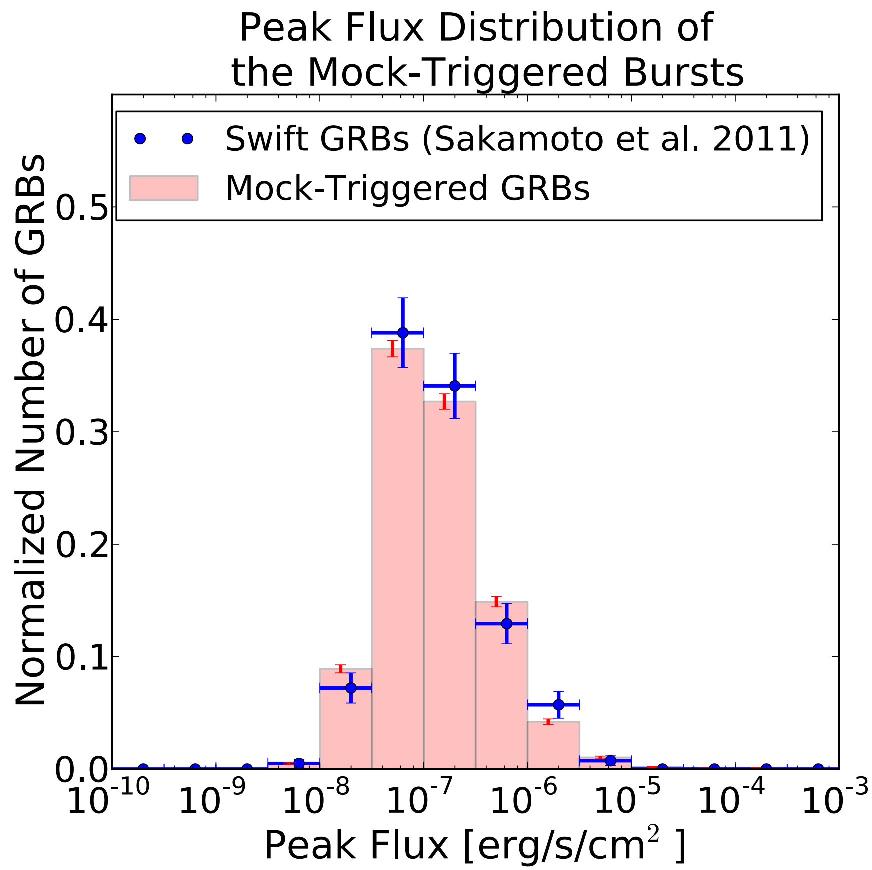


General Approach: A Semi-Monte-Carlo Simulation



Results from the Best-Fit Sample: The Redshift and Peak-flux Distributions



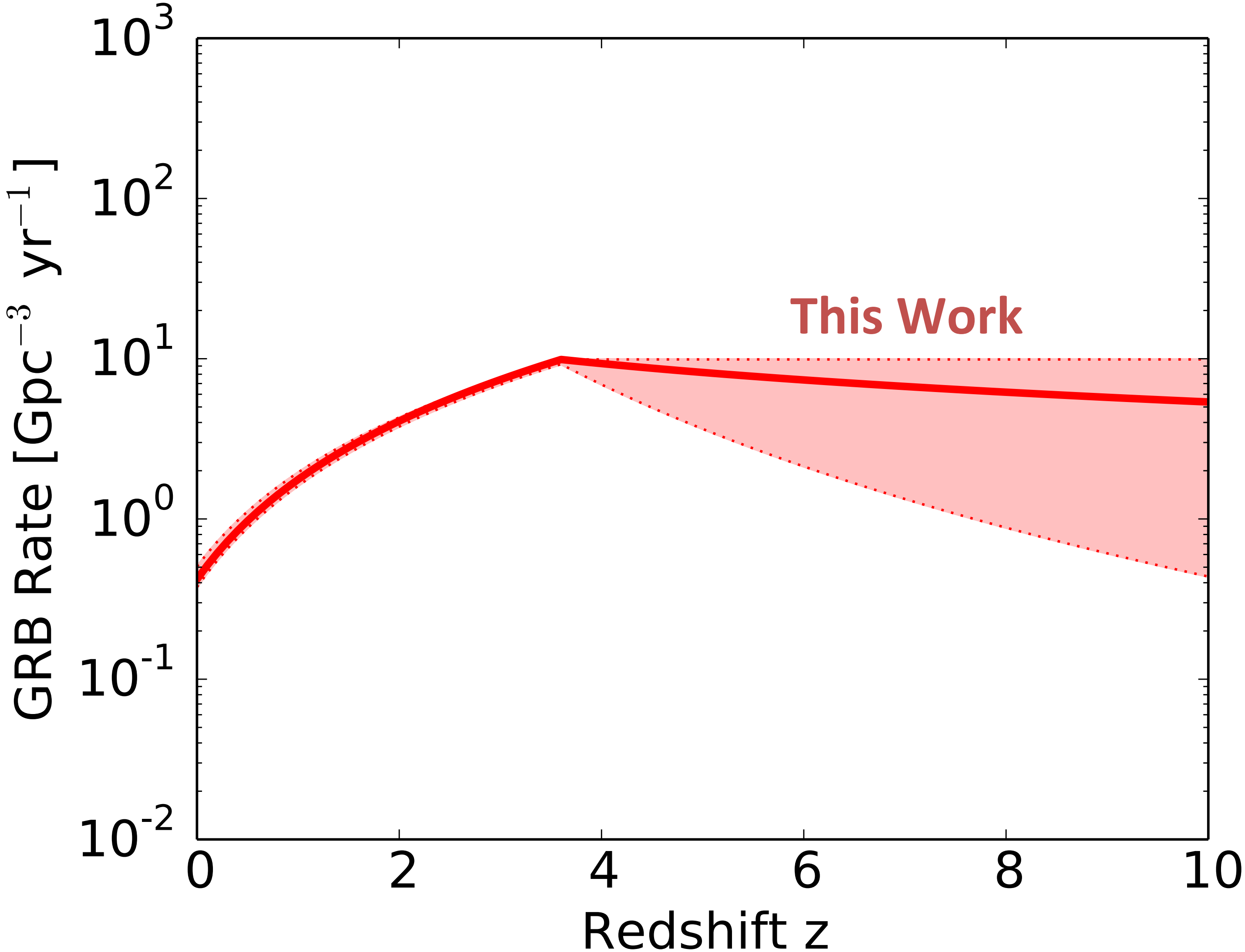


KS-test significance: 99.79%

KS-test significance: $85.59^{+14.10}_{-81.93}\%$

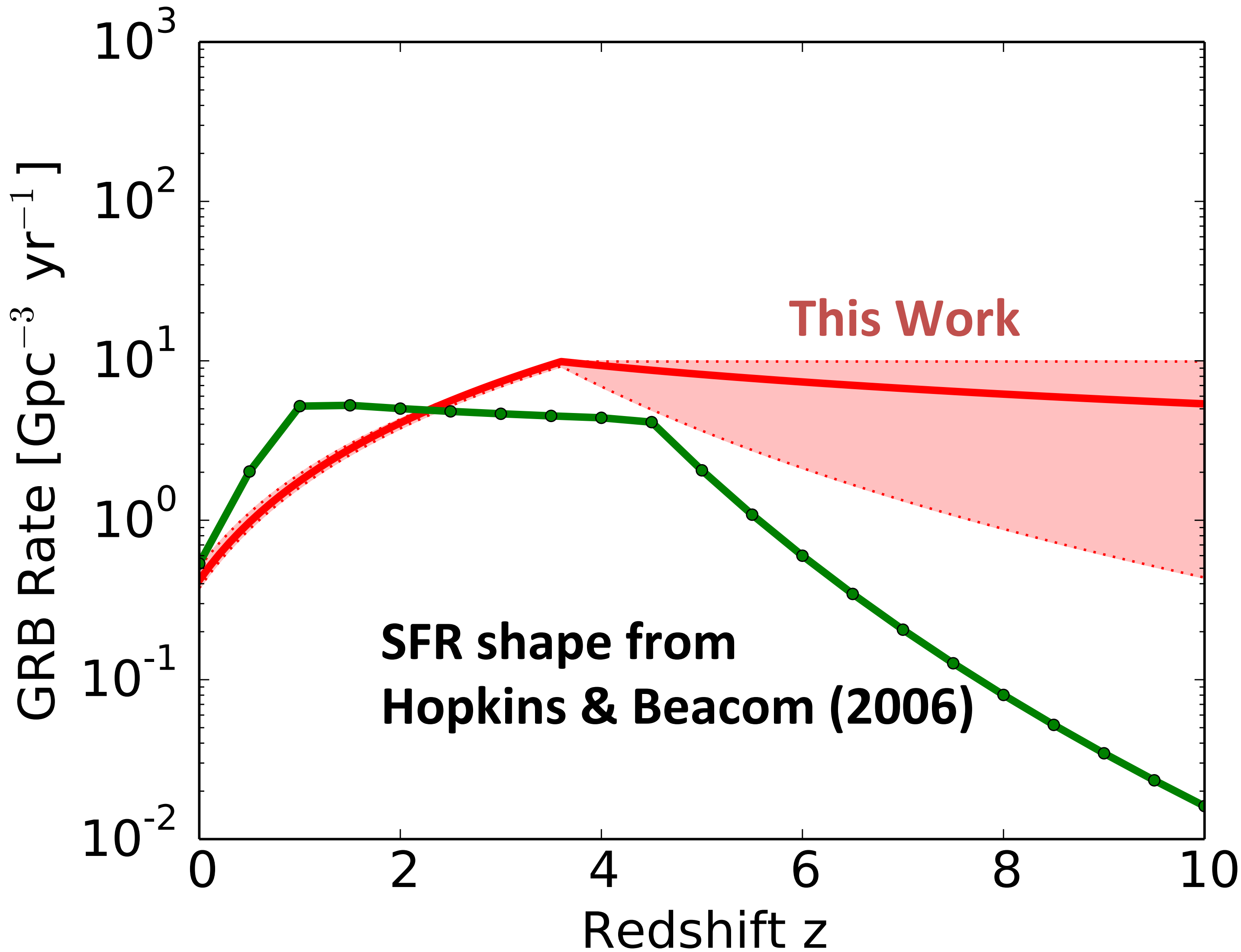
Prediction for Swift: $\sim$ 96 bursts per year

The GRB Rate



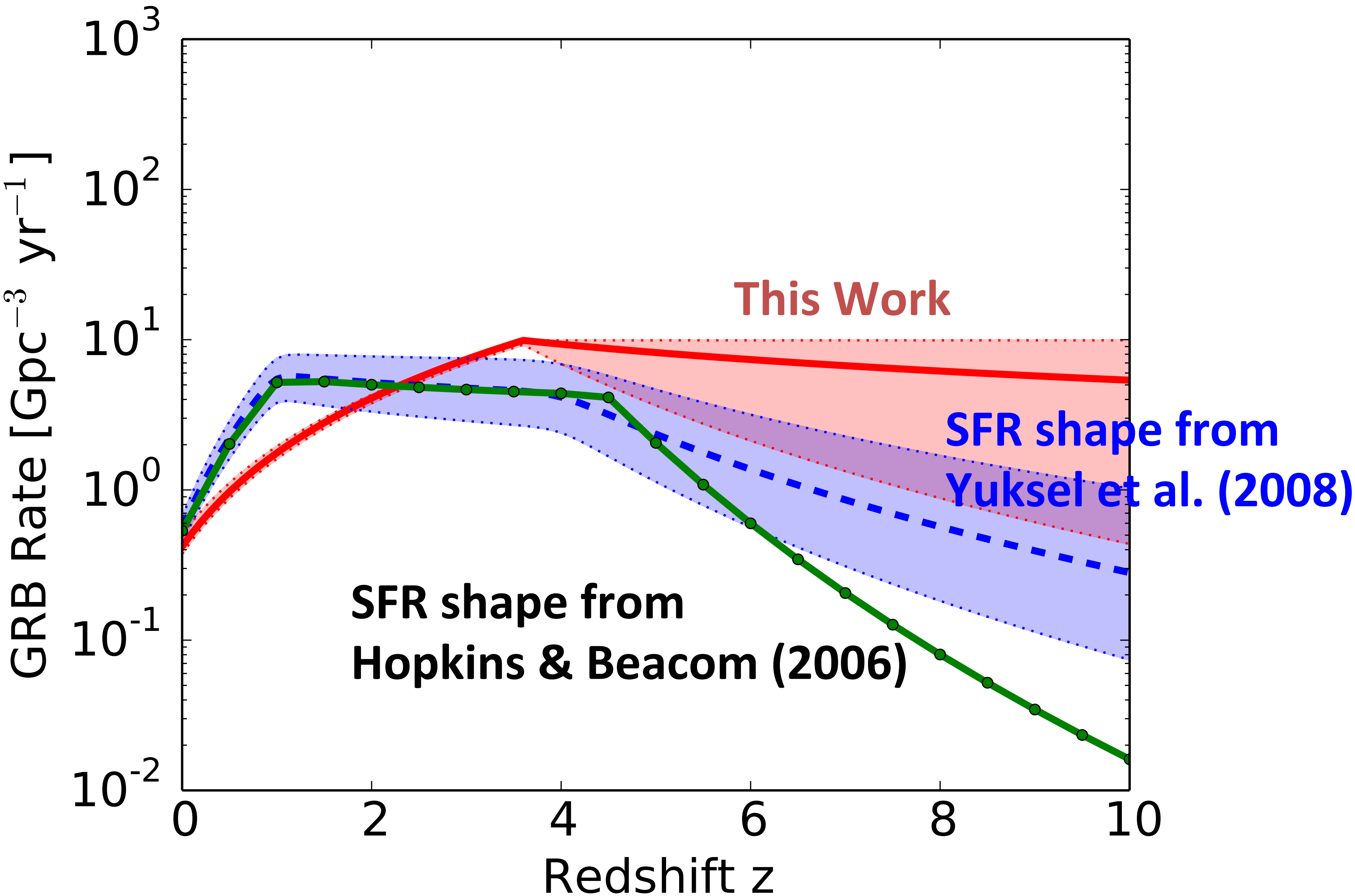
Lien et al. (2014)

The GRB Rate



Lien et al. (2014)

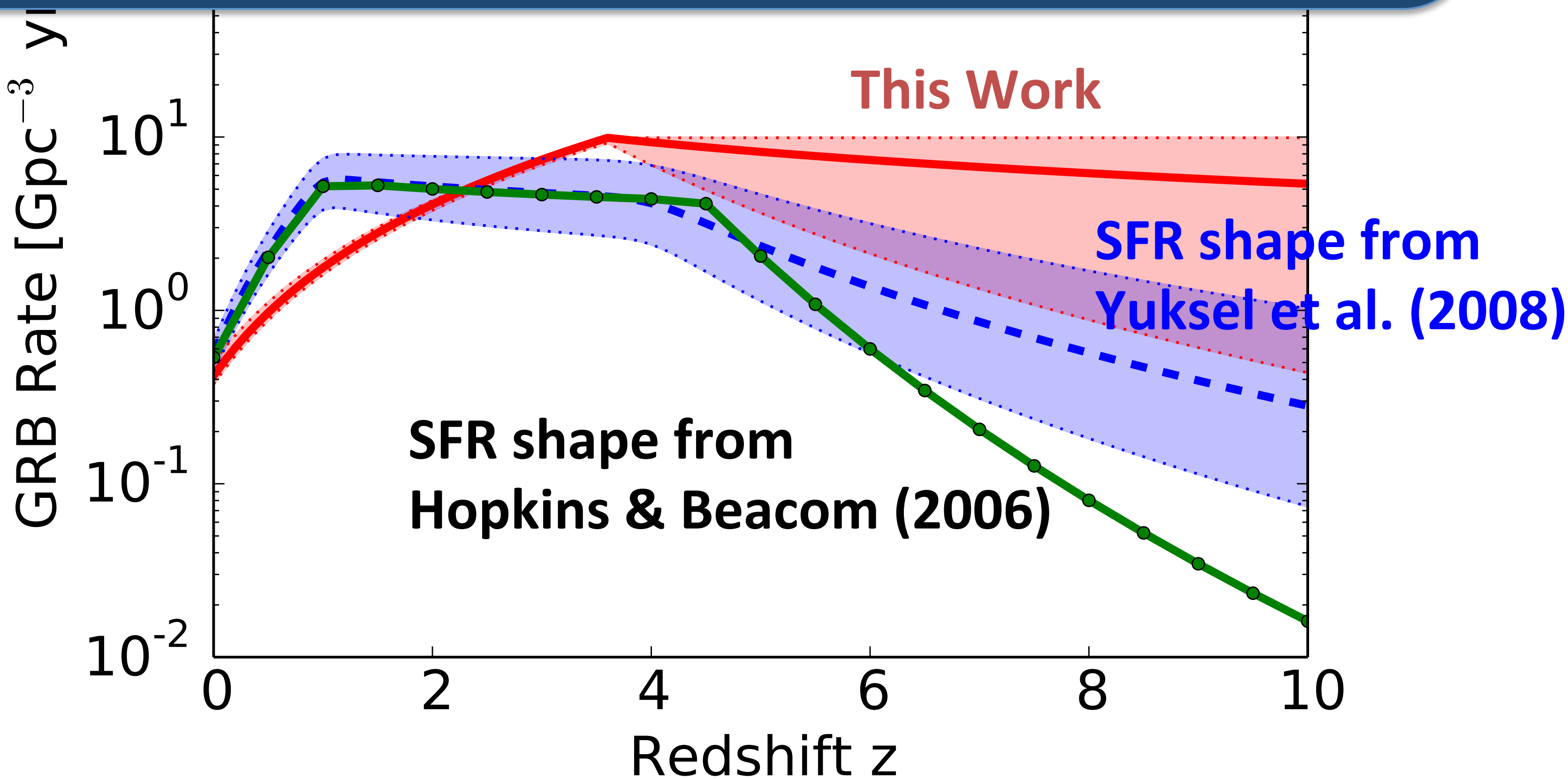
The GRB Rate



Lien et al. (2014)

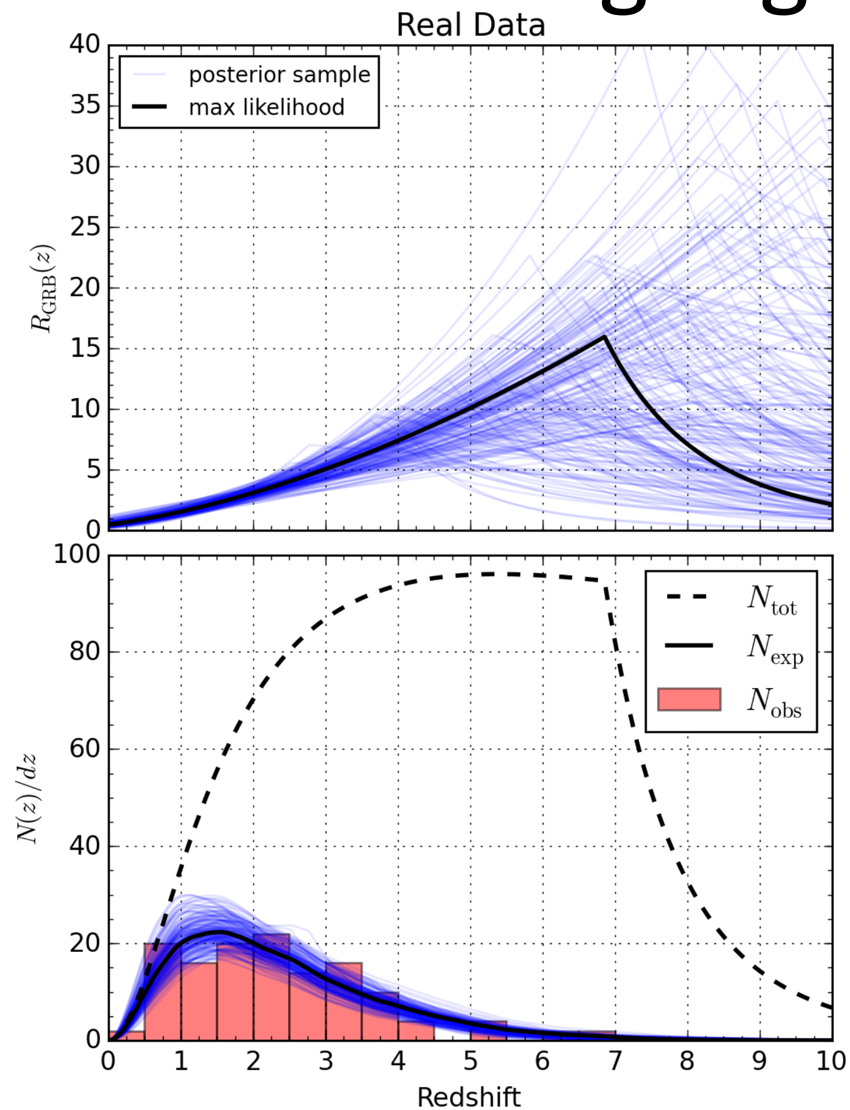
Possibilities:

1. Higher star-formation rate in the early universe
2. The ratio of GRB/SN evolves (e.g., Woosley & Heger 2012)
3. Luminosity evolution (e.g., Virgili et al. 2011)



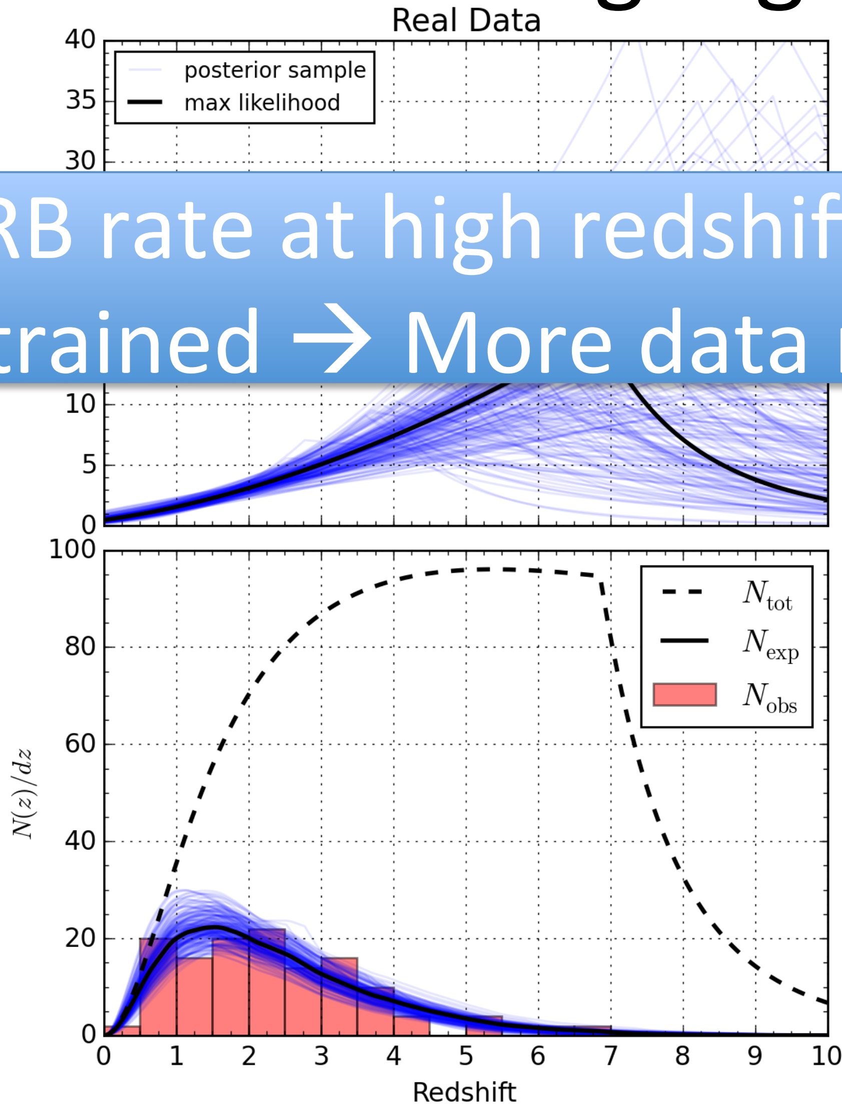
Lien et al. (2014)

Exploring Uncertainties with Machine-Learning Algorithm



Graff et al. (2015)

Exploring Uncertainties with Machine-Learning Algorithm



GRB rate at high redshift is unconstrained → More data needed!

Graff et al. (2015)

Summary

- GRBs are important in many aspects of astrophysics and cosmology:
  - Star-formation history, Stellar evolution, supernovae, black holes, gravitational waves, high-energy particle accelerations
- Understanding instrumental biases is important for probing intrinsic GRB characteristics.
- Measurements of GRB redshift (particularly at high redshift) and broadband spectra are crucial.

Summary

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- Measurements of GRB redshift (particularly at high redshift) and broadband spectra are crucial.

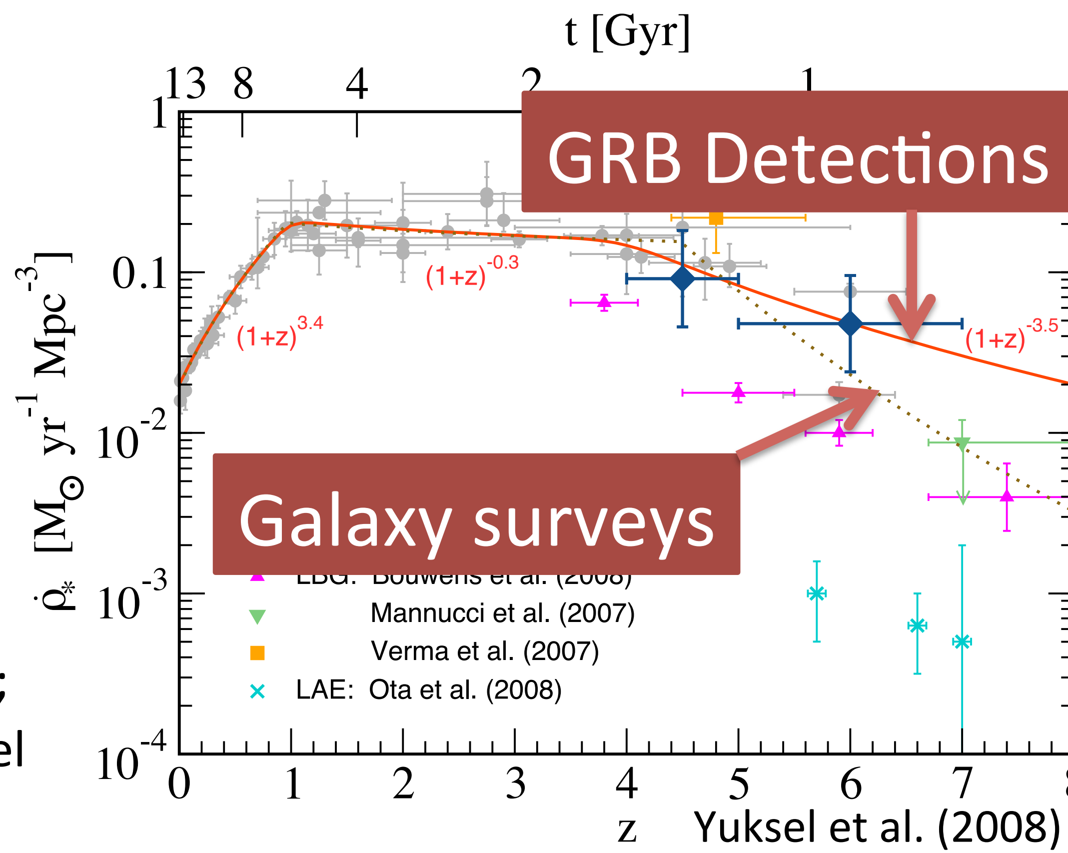

SVOM

Thank You!

Back-up slides

GRBs, Supernovae, and Star Formation

- Long GRBs (T90 > 2 sec)
  - Related to core-collapse supernovae (Type Ibc)
  - Related to the death of massive stars
- Long GRBs as probes of star formation
  - Particularly crucial at high redshift (e.g., Ciardi & Leob 2000, Tanvir et al. 2012)
- Important to measure long GRB rate (e.g., Butler et al. 2010; Wanderman et al. 2010; Yuksel et al. 2008)

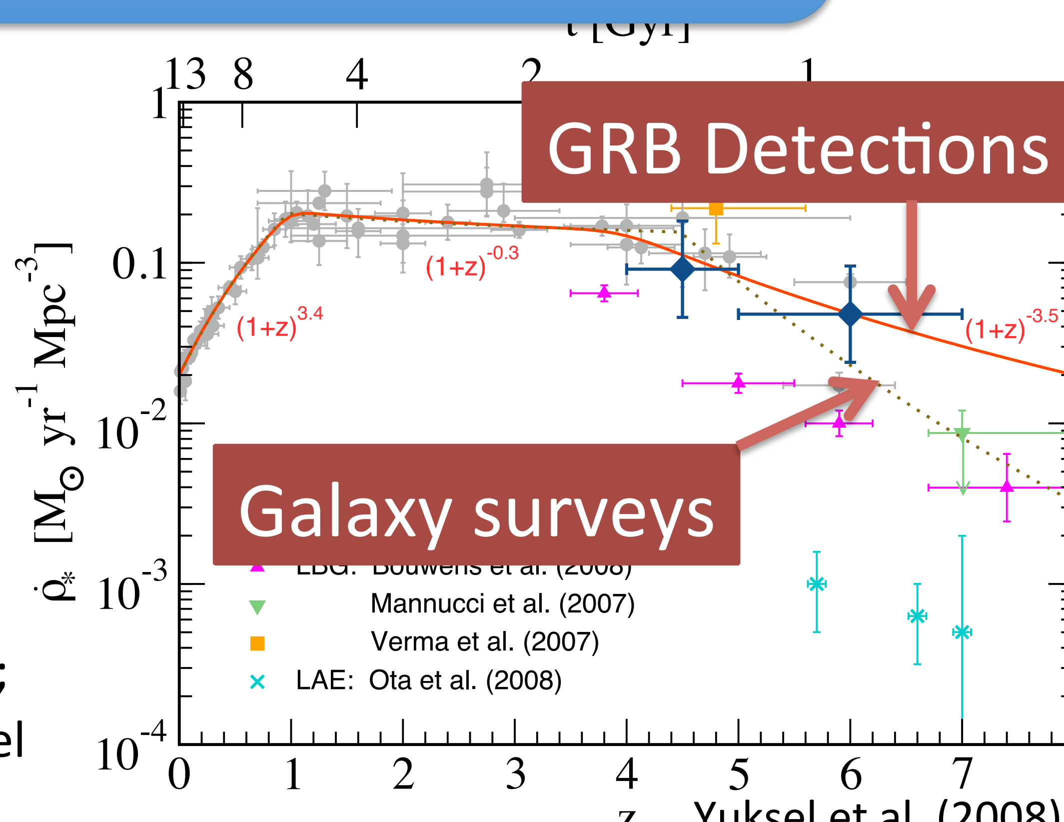


Yuksel et al. (2008)

GRBs, Supernovae, and Star Formation

- Long G
  - Rela
  - Rela
- Long G
  of star formation
  - Particularly crucial at high redshift (e.g., Ciardi & Leob 2000, Tanvir et al. 2012)
- Important to measure long GRB rate (e.g., Butler et al. 2010; Wanderman et al. 2010; Yuksel et al. 2008)

Do we have enough information?

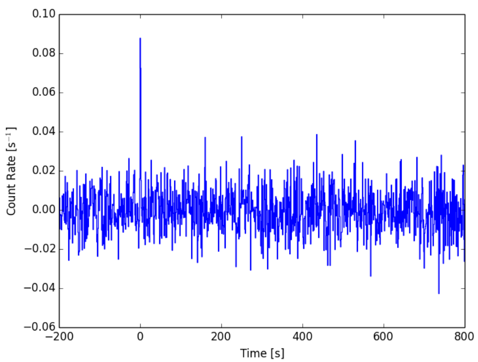


Yuksel et al. (2008)

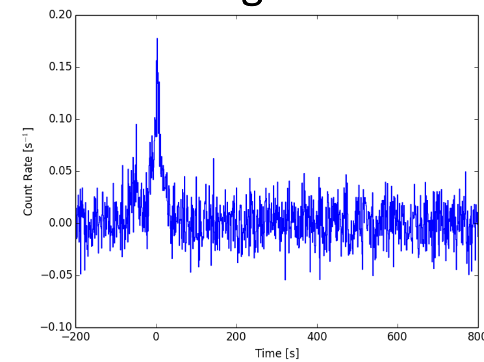
Swift GRBs to date

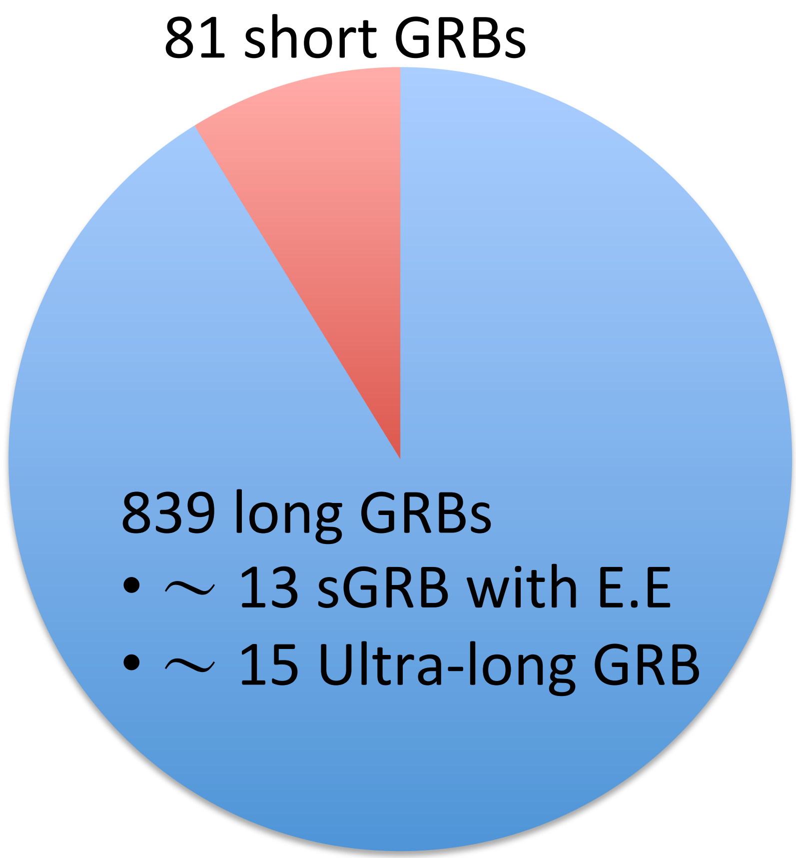
- 926 GRBs till now.
- In this presentation: 919 GRBs till GRB141109B
- 314 have redshift measurements

Short GRB

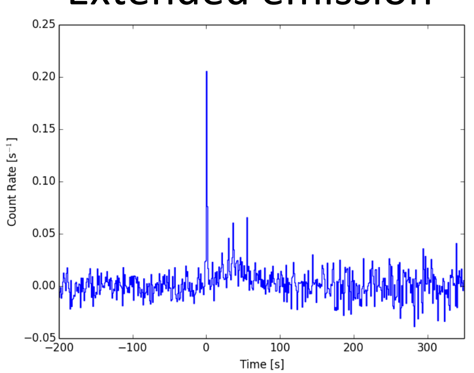


Long GRB

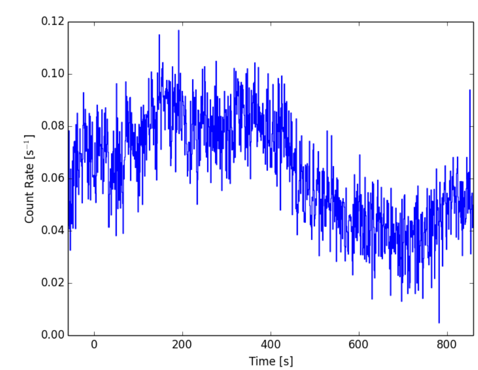




Short GRB with Extended emission



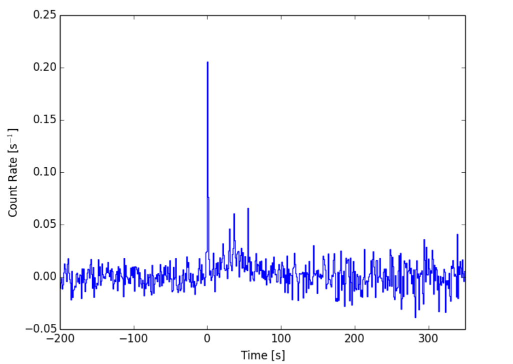
Ultra-Long GRB

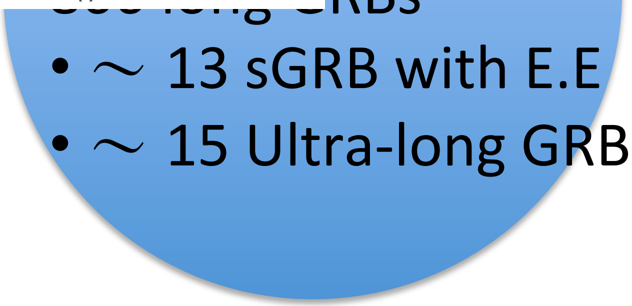


Swift GRBs to date: 10 Years after Launch

- 926 GRBs till now
  - About 2 GRBs per weak
- 314 GRBs have redshift measurements
- Complete results will be in the 3rd BAT GRB catalog

Figure credit: PSU webpage





Cake Credit: Judith Racusin

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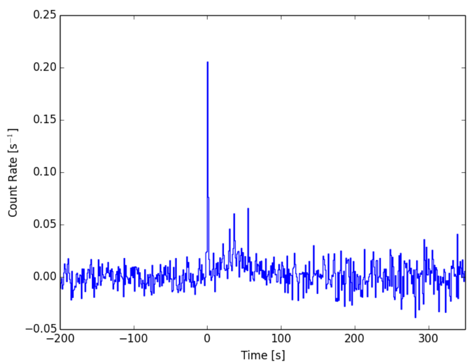
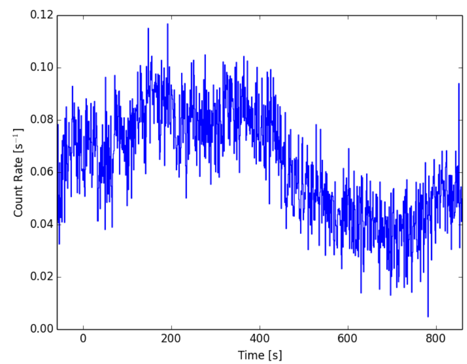


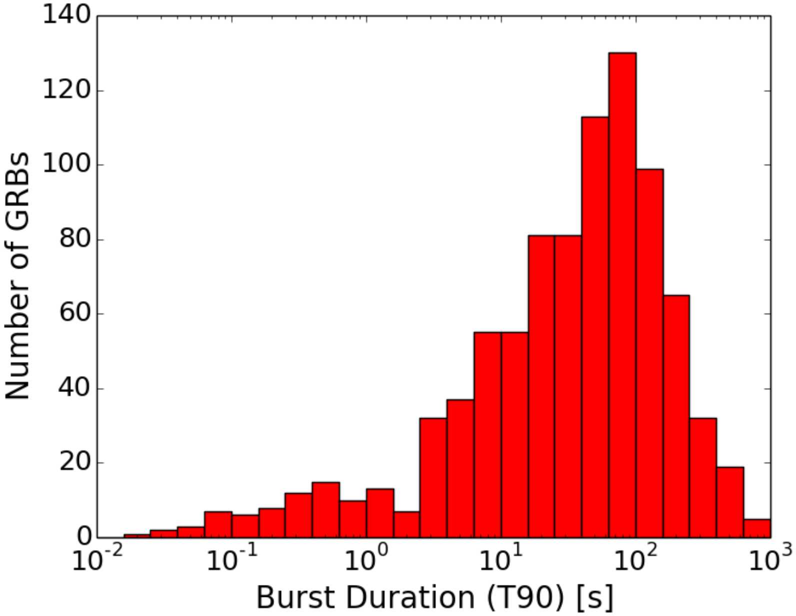


- ∼ 13 sGRB with E.E
- ∼ 15 Ultra-long GRB

Figure credit: PSU webpage

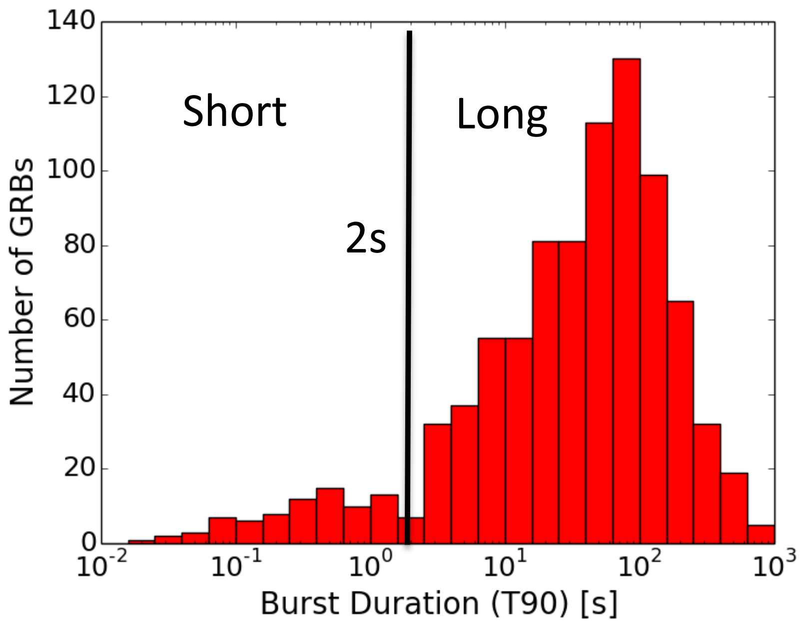
Cake Credit: Judith Racusin

Burst Durations



T90: A duration encloses 90% of GRB photons

Burst Durations



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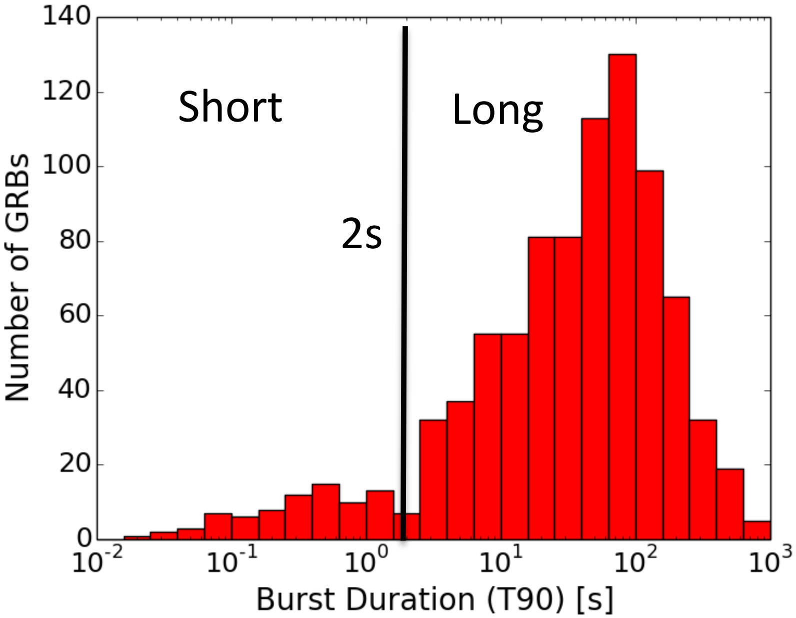

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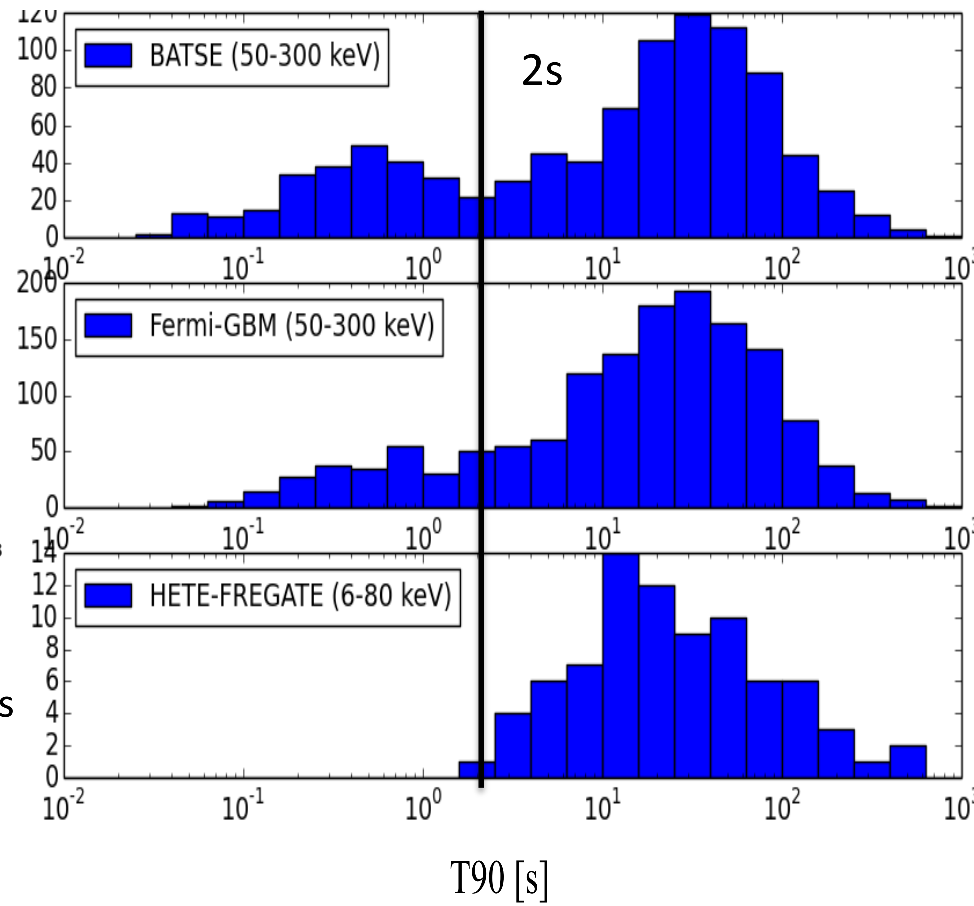
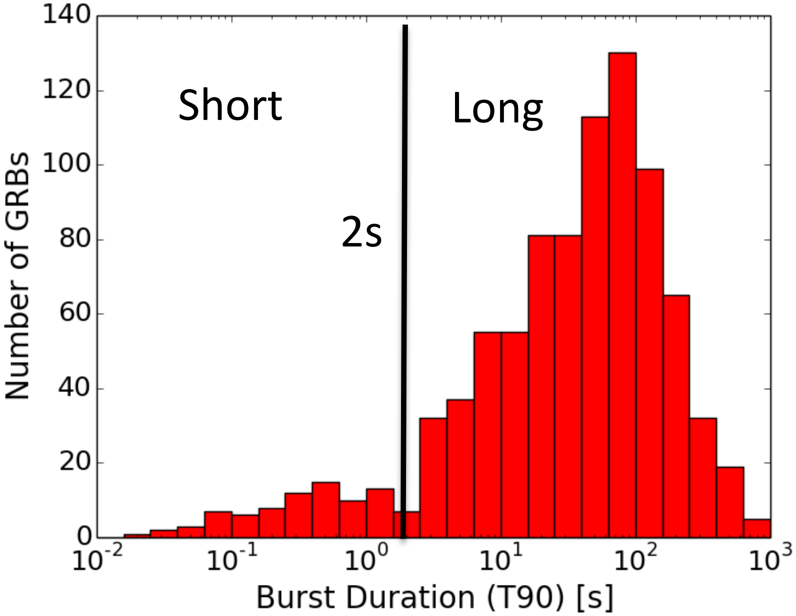
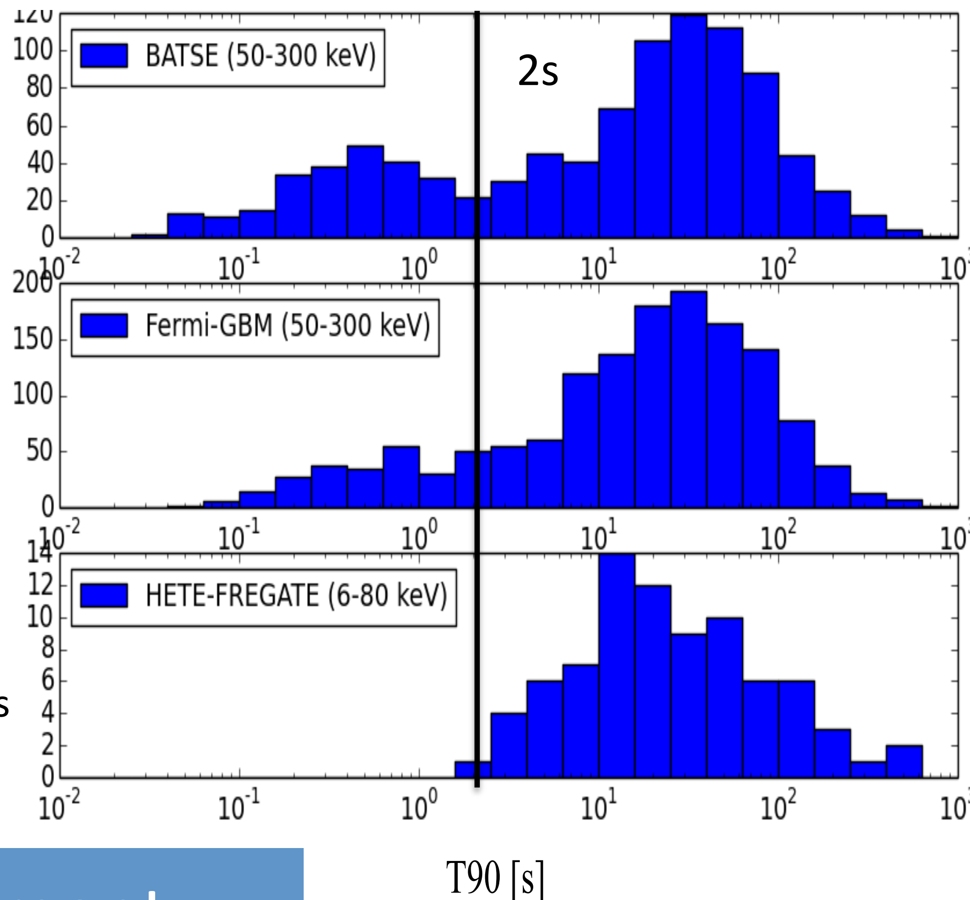


Fig credit: Taka's presentation

Burst Durations



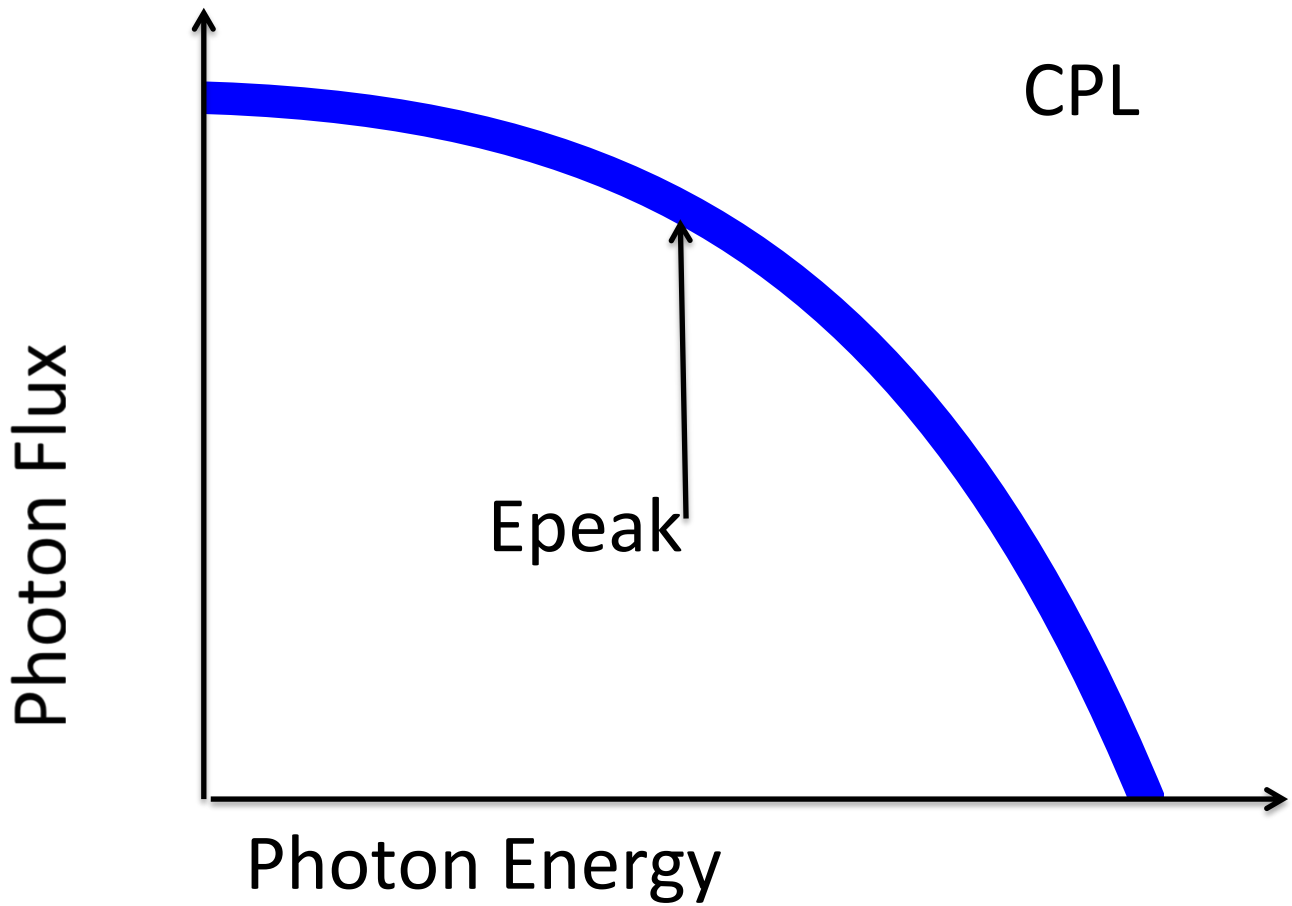


T90: A duration encloses 90% of GRB photons

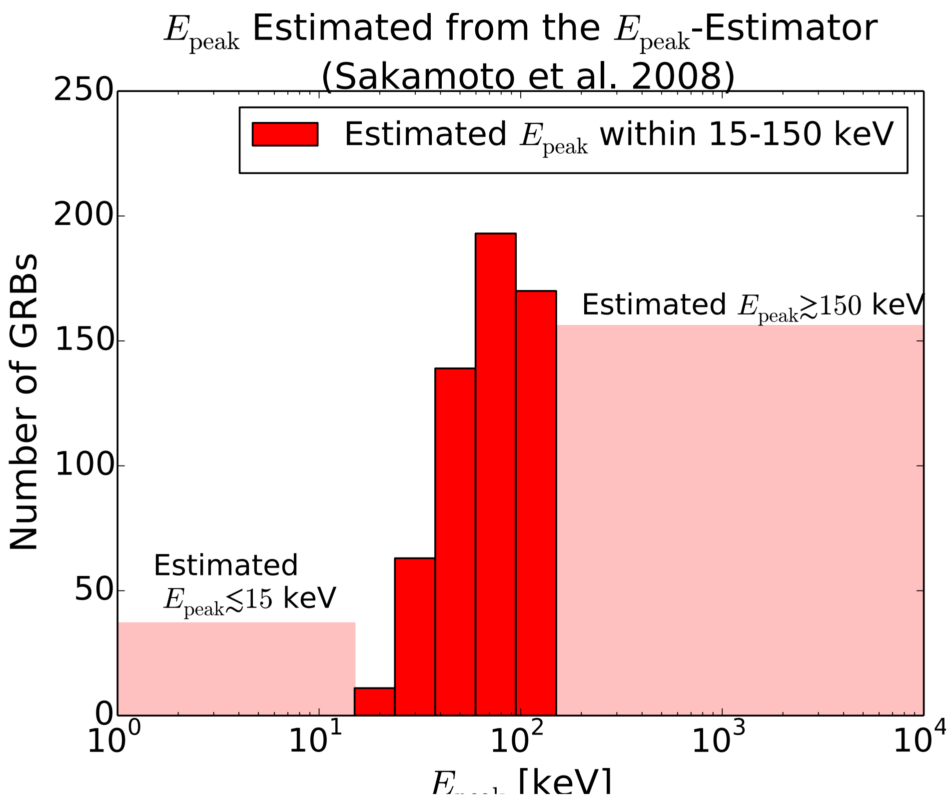
Fig credit: Taka's presentation

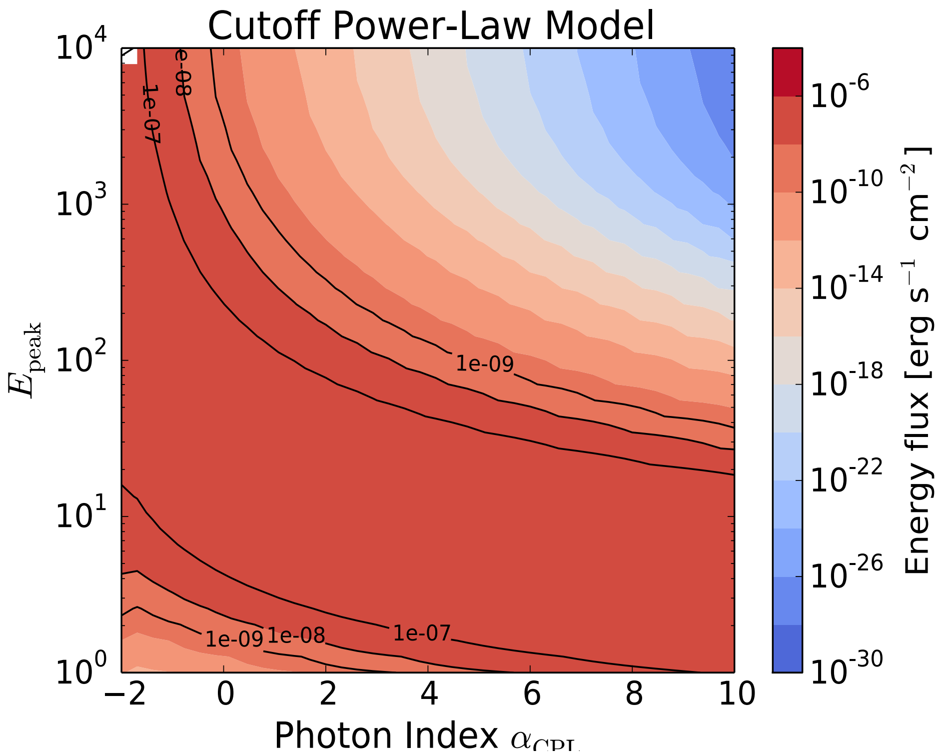
Distribution is instrument dependent

BAT selection effect on GRB spectra

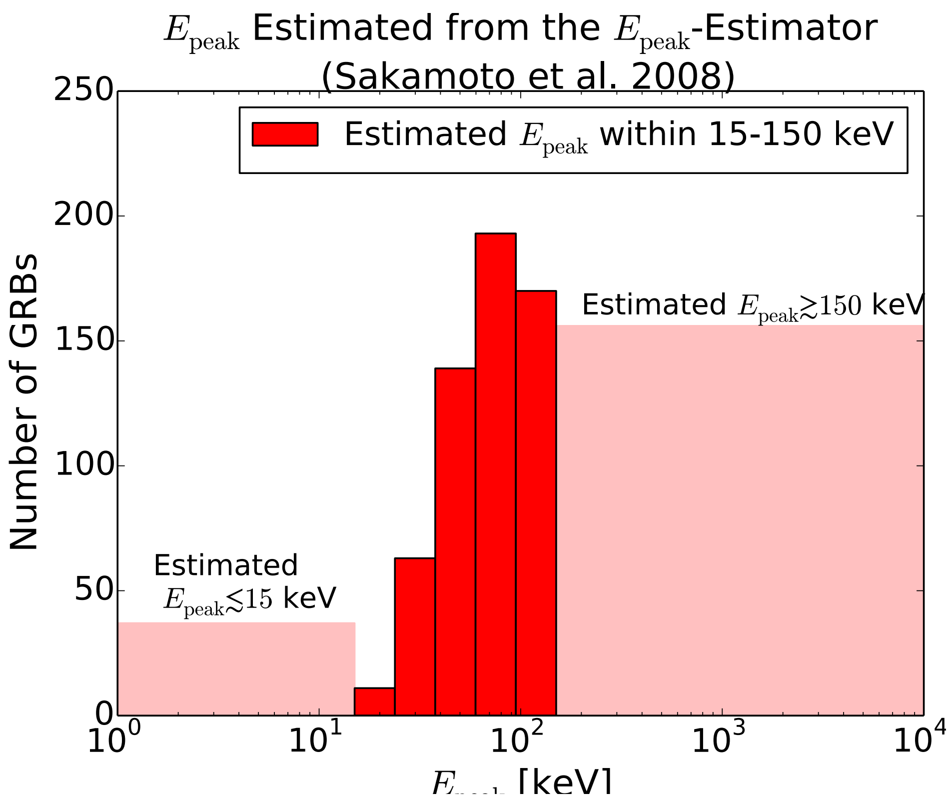


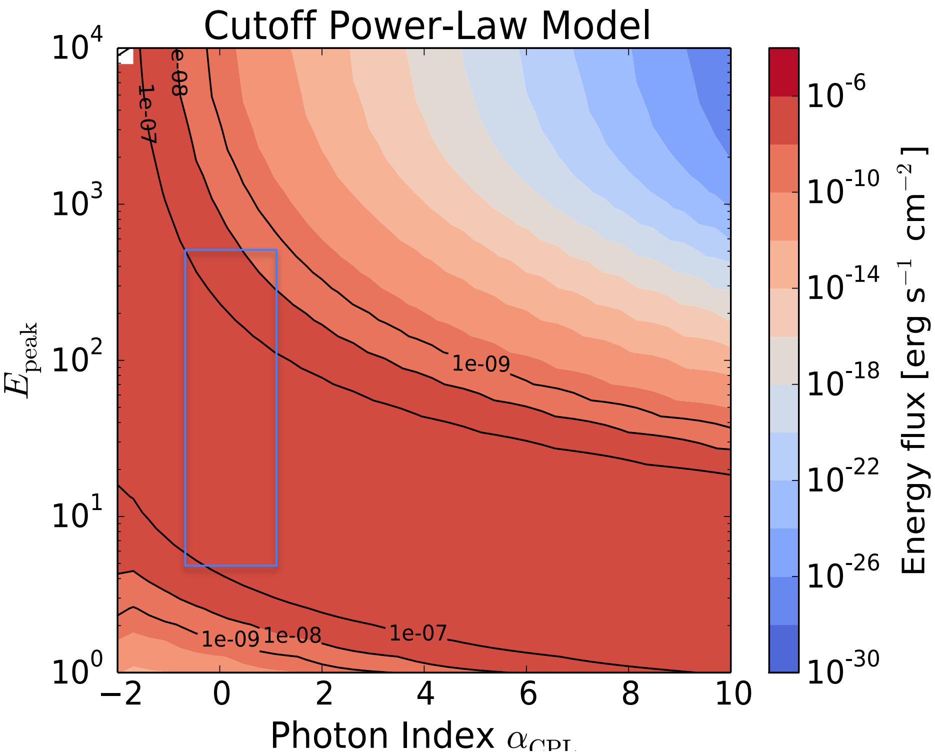
BAT selection effect on GRB spectra



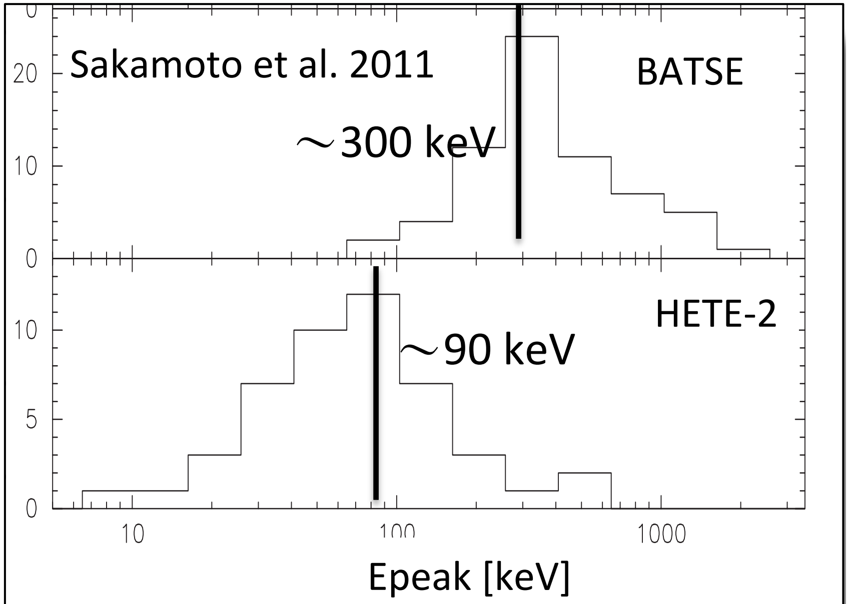


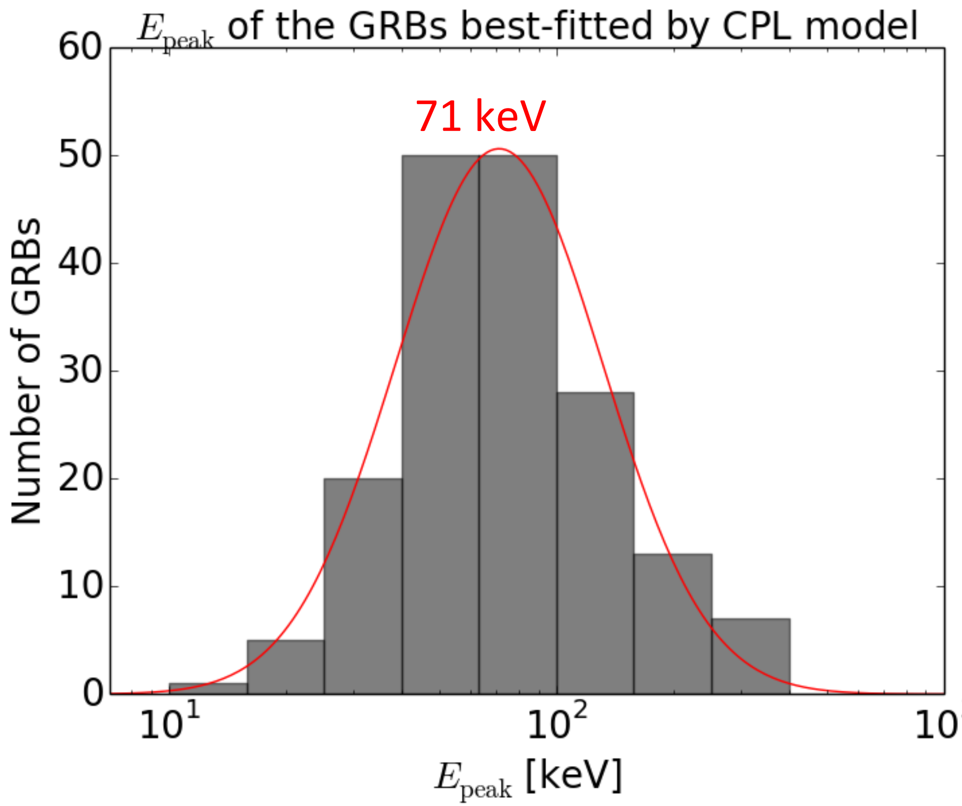
BAT selection effect on GRB spectra





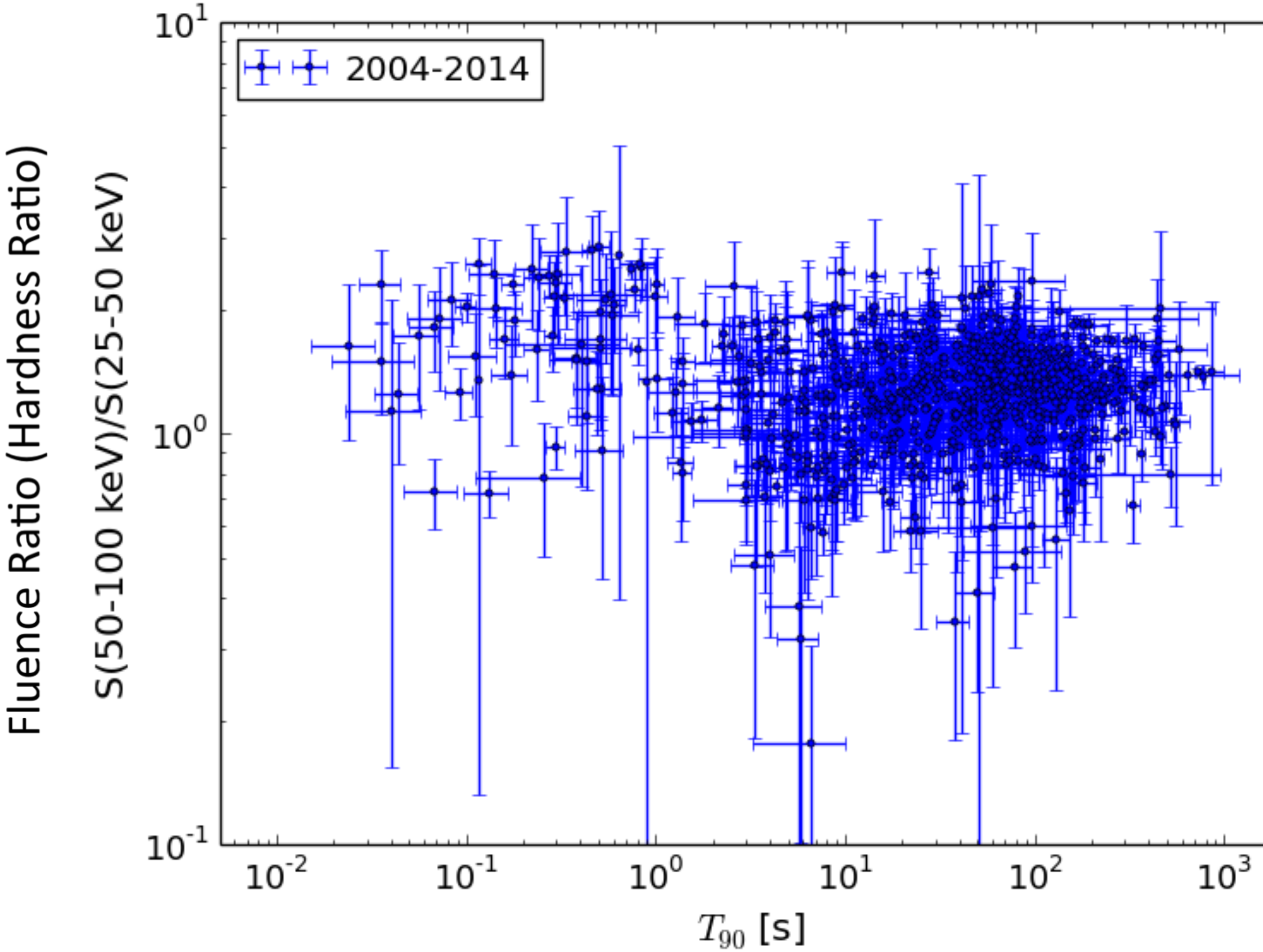
Spectral Fits





- 175 GRBs are fitted better with cutoff power law
  - Epeak are likely to be in the BAT-energy range.

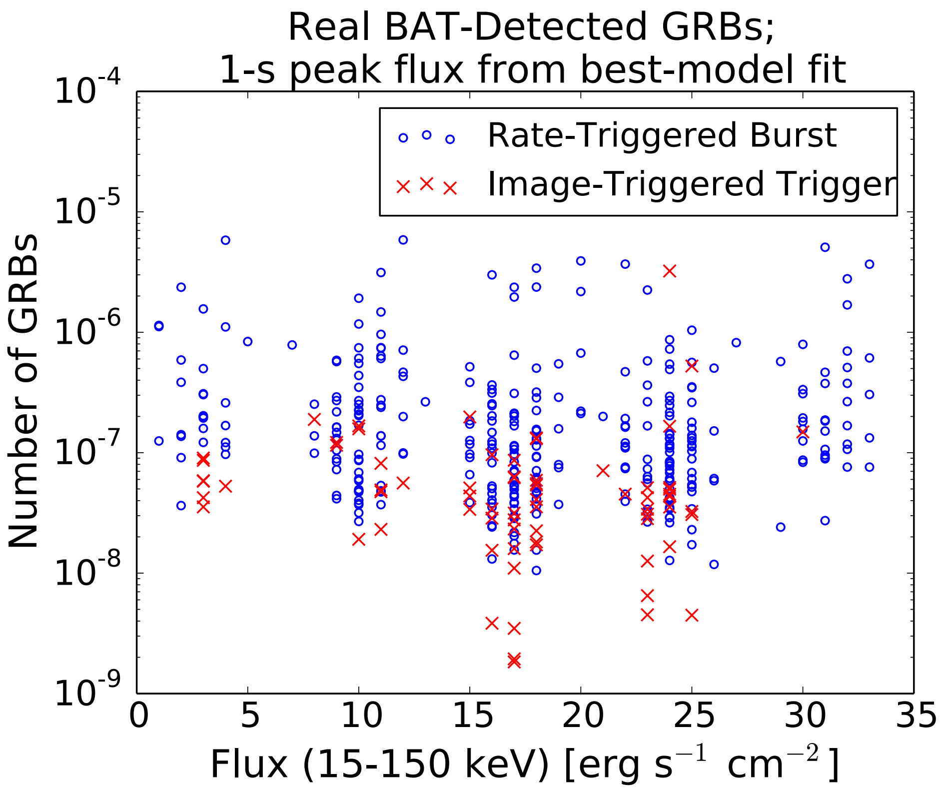
Burst Duration vs Spectrum

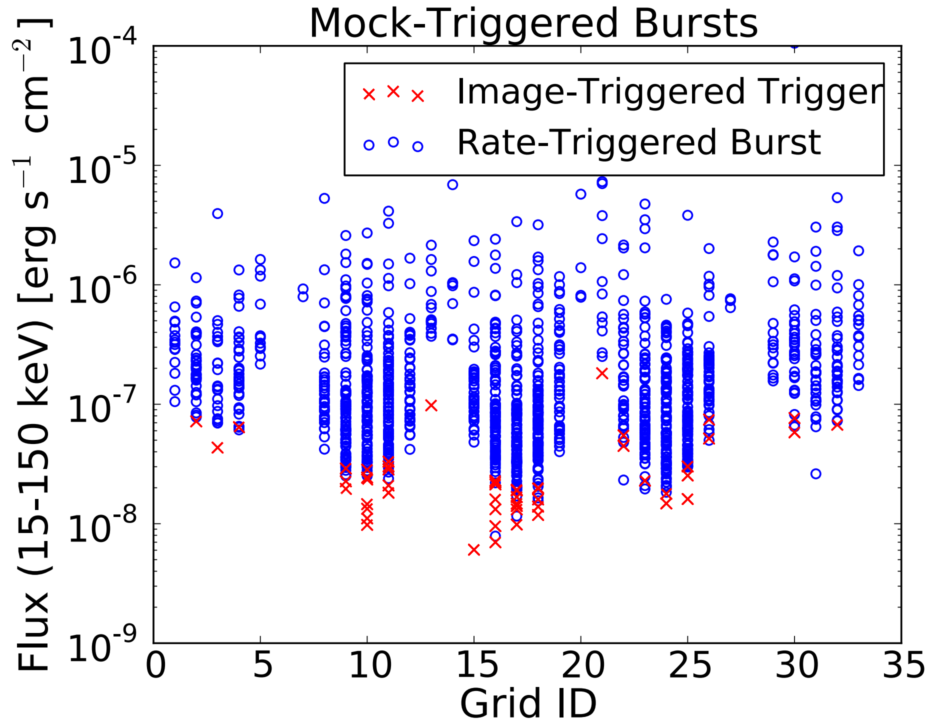


Burst Duration

Sensitivity Comparisons

- Grid ID: ID name on the detector's plane, related to incoming angle





Real BAT-detected GRBs (2005-2009):
- Total triggered bursts: 409
- 338 rate trigger
- 71 image trigger

Our simulations:
- Total triggered bursts: 1400
- 1347 rate trigger
- 53 image trigger

Summary

- Adopting the complex BAT-trigger algorithm improve the sensitivity and hence more dim (low-flux) bursts are needed in the intrinsic sample.
- Need more bursts from high redshift to create a good match with the observations.
- Very high GRB rate at large redshift, unless luminosity evolution is considered.
- It seems like some kind of relation between bursts' energy output (e.g., L_{peak}) and spectral parameters (e.g., E_{peak}) is needed to generate good match with the observations.
- The 3rd BAT GRB catalog is coming soon! Suggestions welcome!