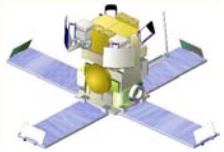
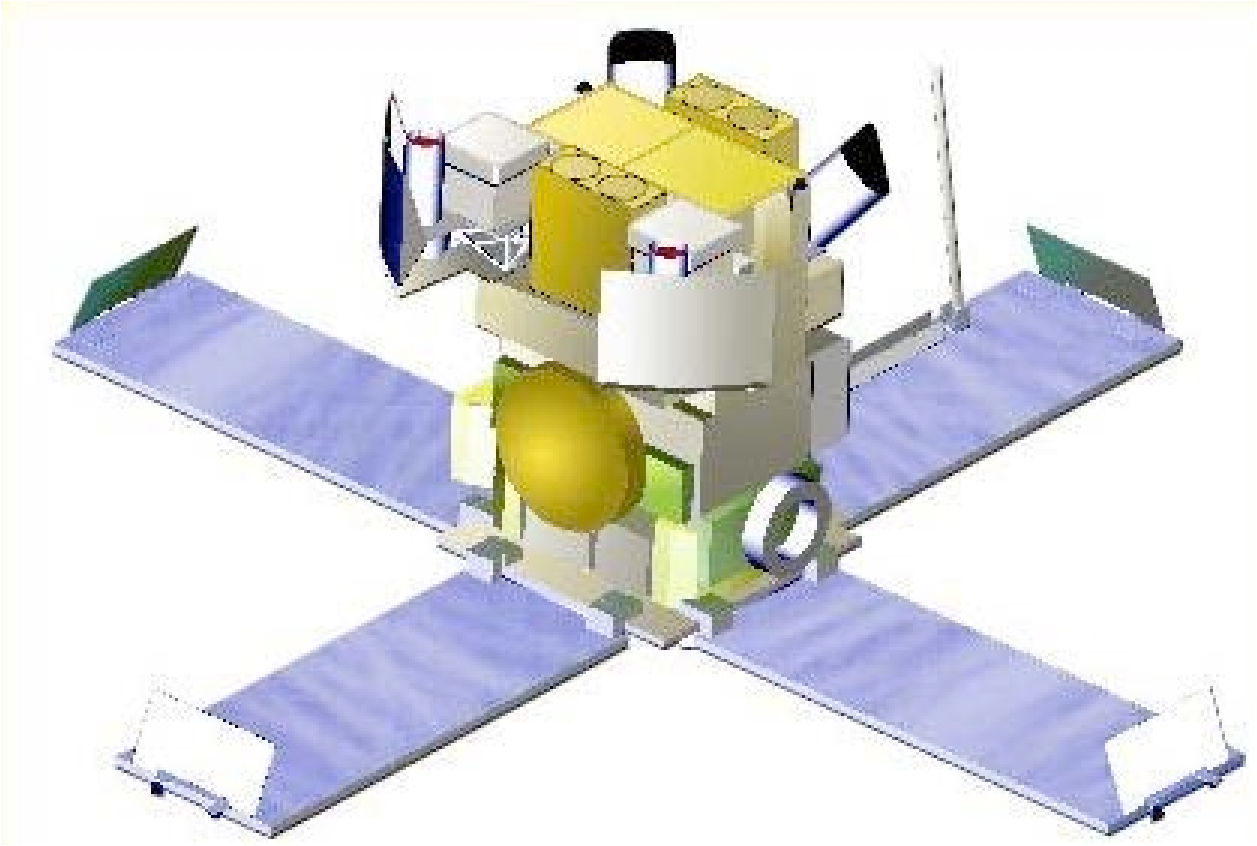
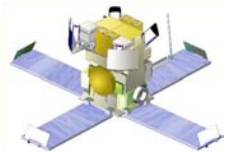


HETE-2 Science Highlights and Partnership w. *Swift*

D. Q. Lamb (U. Chicago)



Swift Workshop, New Orleans, LA
7 September 2004



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Brazil + India + Italy
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Stanford E. Woosley

National Aero & Space Administration
USA

Donald A.Kniffen
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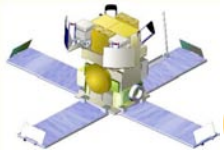
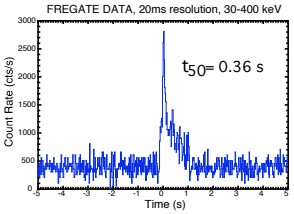
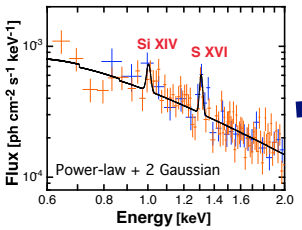
Scott D.Barthelmy
(GSFC Project Scientist)



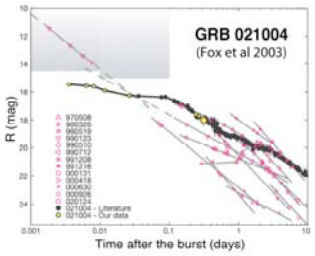
HETE Gamma-ray Bursts: 6 Major Scientific Insights in Past 1.5 Years



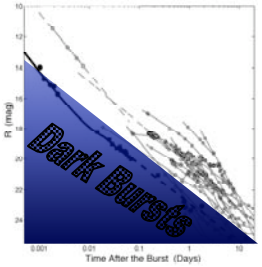
GRB020531:
First detection of short GRB with prompt optical/X-ray followup



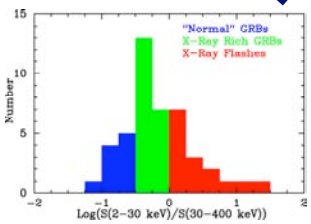
GRB020813:
X-ray lines from α particle nuclei (Chandra spectra)



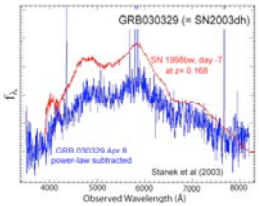
GRB021004:
Refreshed shock or inhomogeneous jet (NASA SSU)



GRB021211:
Insight into "Optically Dark" GRB Mystery

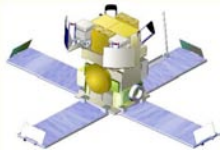


GRB020903:
Elucidation of "X-ray Flashes"

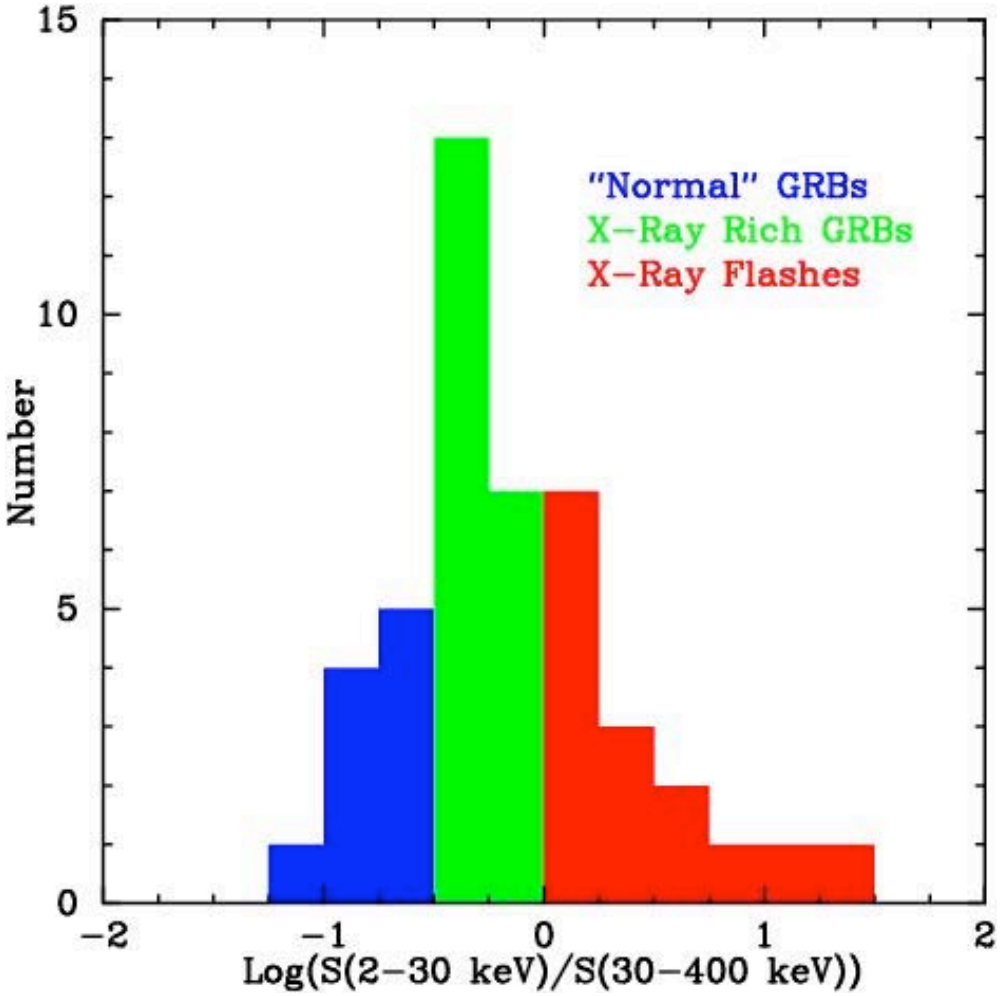


GRB030329:
GRB-SN Connection (SN2003dh; z=0.17)

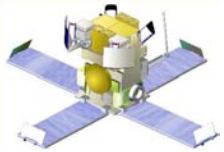
Courtesy G. R. Ricker



"X-Ray Flashes"

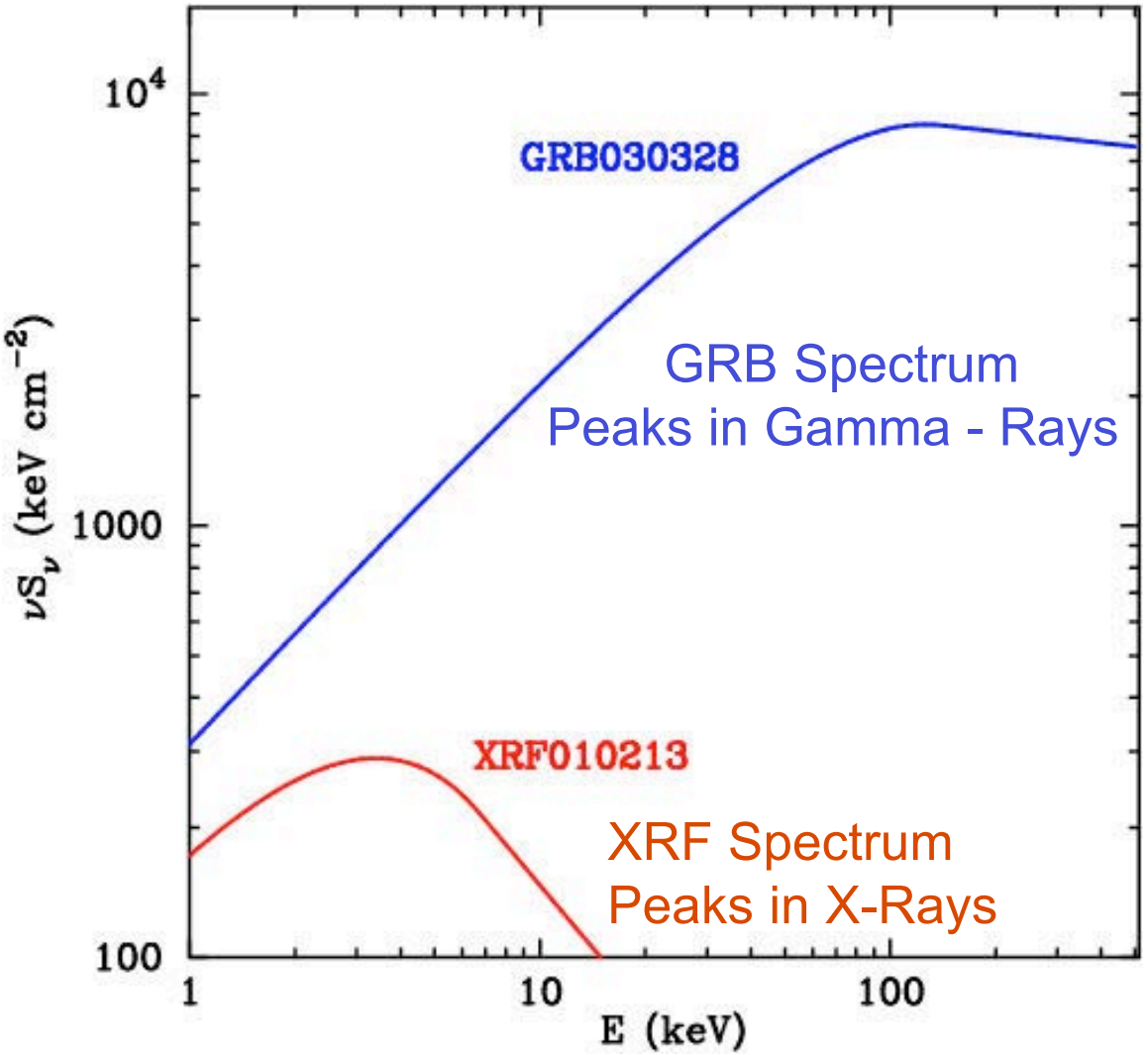


- Defining "X-ray flashes" (Heise et al. 2000) as bursts for which log (S_x/S_{gamma}) > 0 (i.e., > 30 times that for "normal" GRBs)
  - ~ **1/3** of bursts localized by HETE-2 are XRFs
  - ~ **1/3** are "X-ray-rich" GRBs
- Nature of XRFs is largely unknown
- XRFs may provide unique insights into
  - Structure of GRB jets
  - GRB rate
  - Nature of Type Ic supernovae



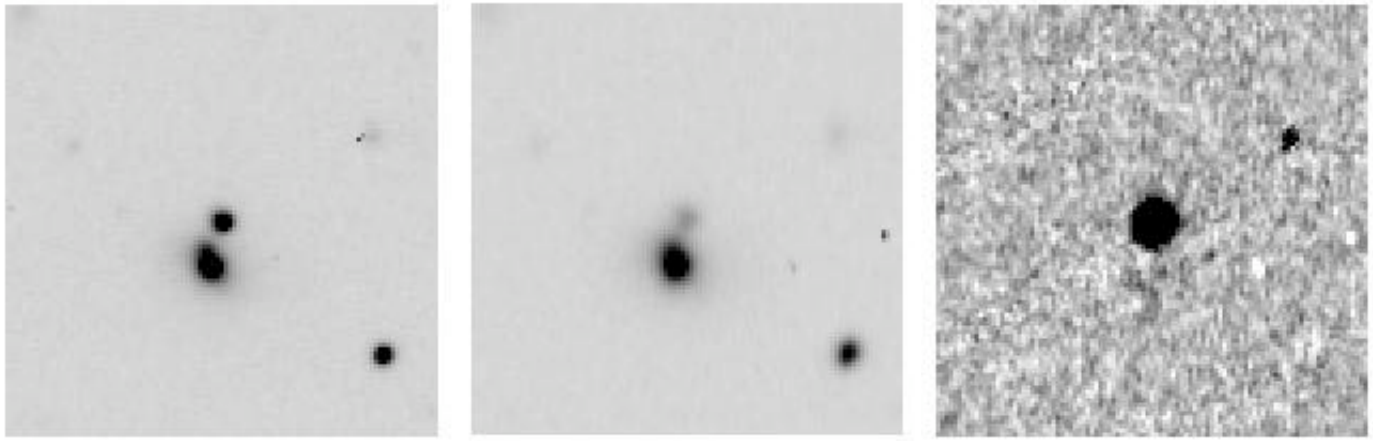
HETE-2 X-Ray Flashes vs. GRBs

Sakamoto et al. (2004)

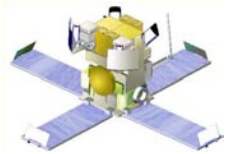


XRF 020903: Discovery of Optical Afterglow

Soderberg et al. (2002)

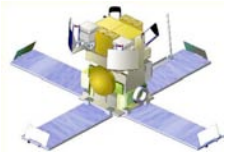


Palomar 48-inch Schmidt images: 2002 Sep 6 (left image), 2002 Sep 28 (middle image), subtracted image (right image)

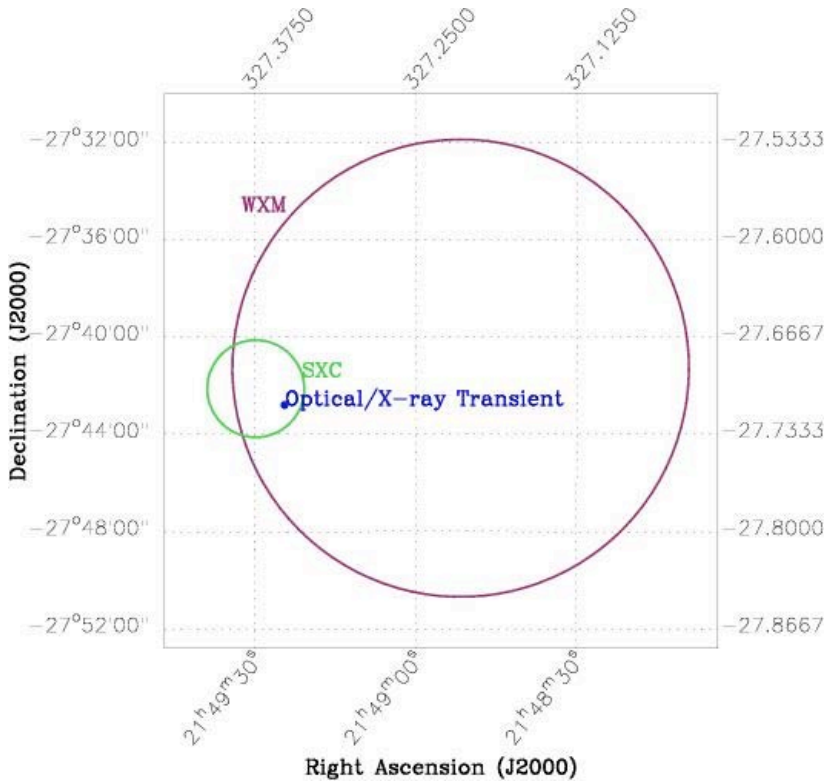


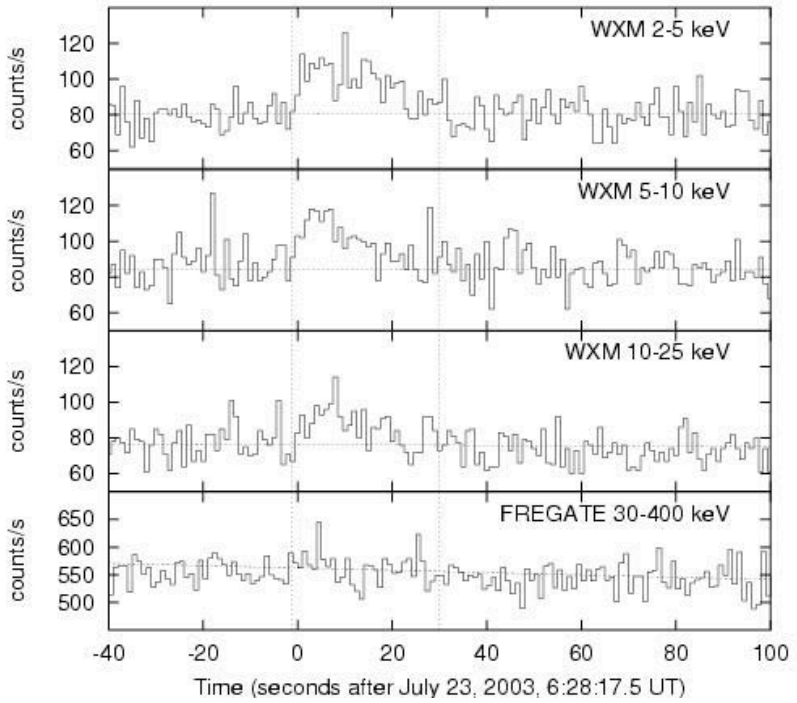
XRF 020903: Implications

- HETE-2 and optical follow-up observations of GRB020903 show that this XRF:
  - Lies on the extensions of the above distributions
  - Lies on an extension of the Amati et al. (2002) relation
  - Host galaxy is copiously producing stars, similar to those of GRBs
  - Host galaxy has a redshift z = 0.25, similar to those of GRBs
- These results provide evidence that GRBs, X-ray-rich GRBs, and X-Ray Flashes are closely related phenomena



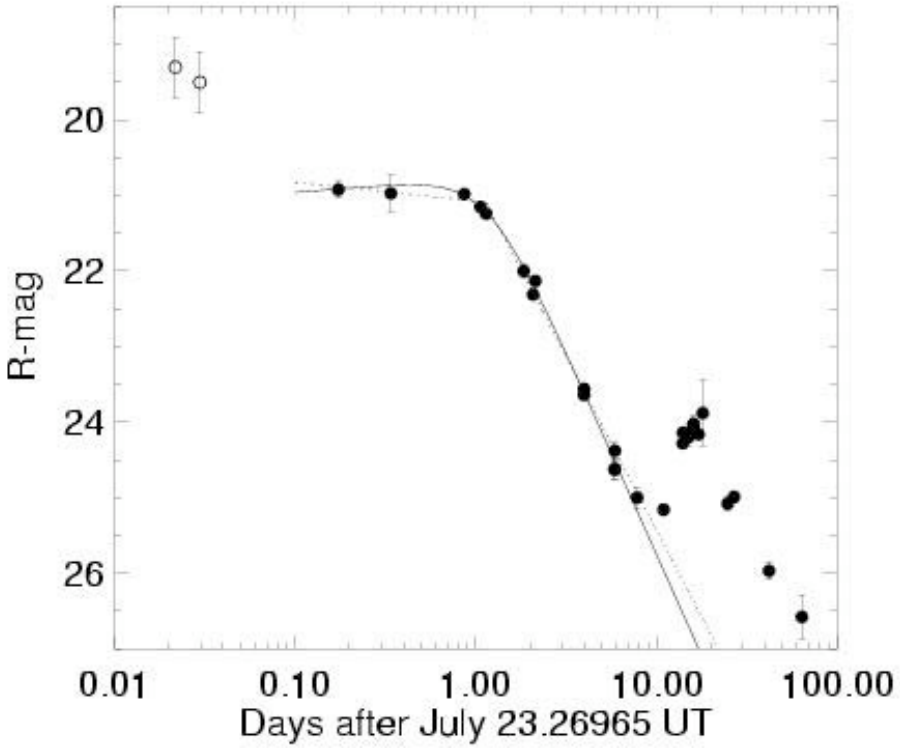
HETE-2 Observations of XRF 030723



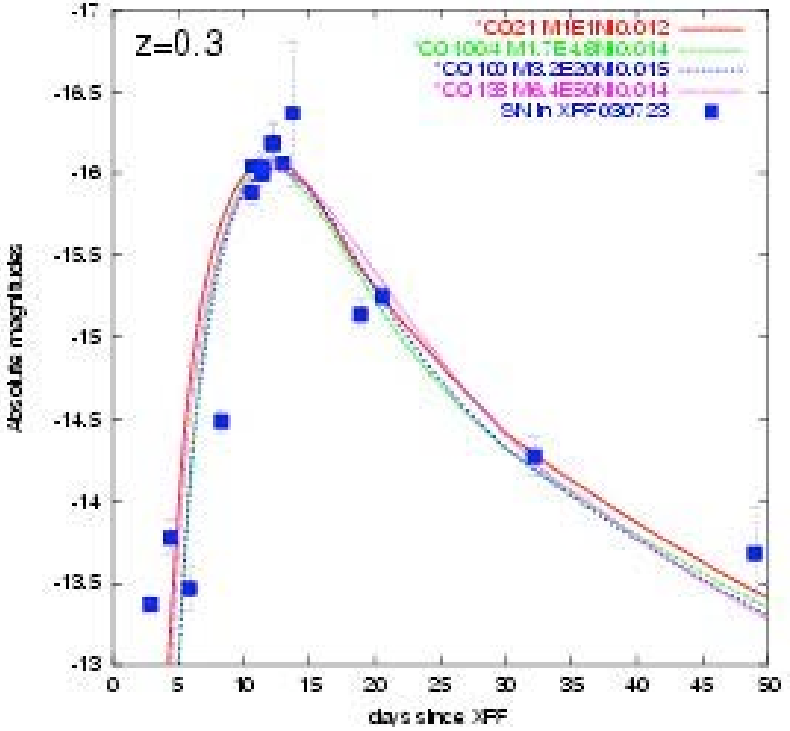


Butler et al. (2004)

XRF 030723: Optical Afterglow

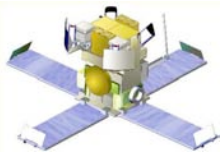


Fynbo et al. (2004)



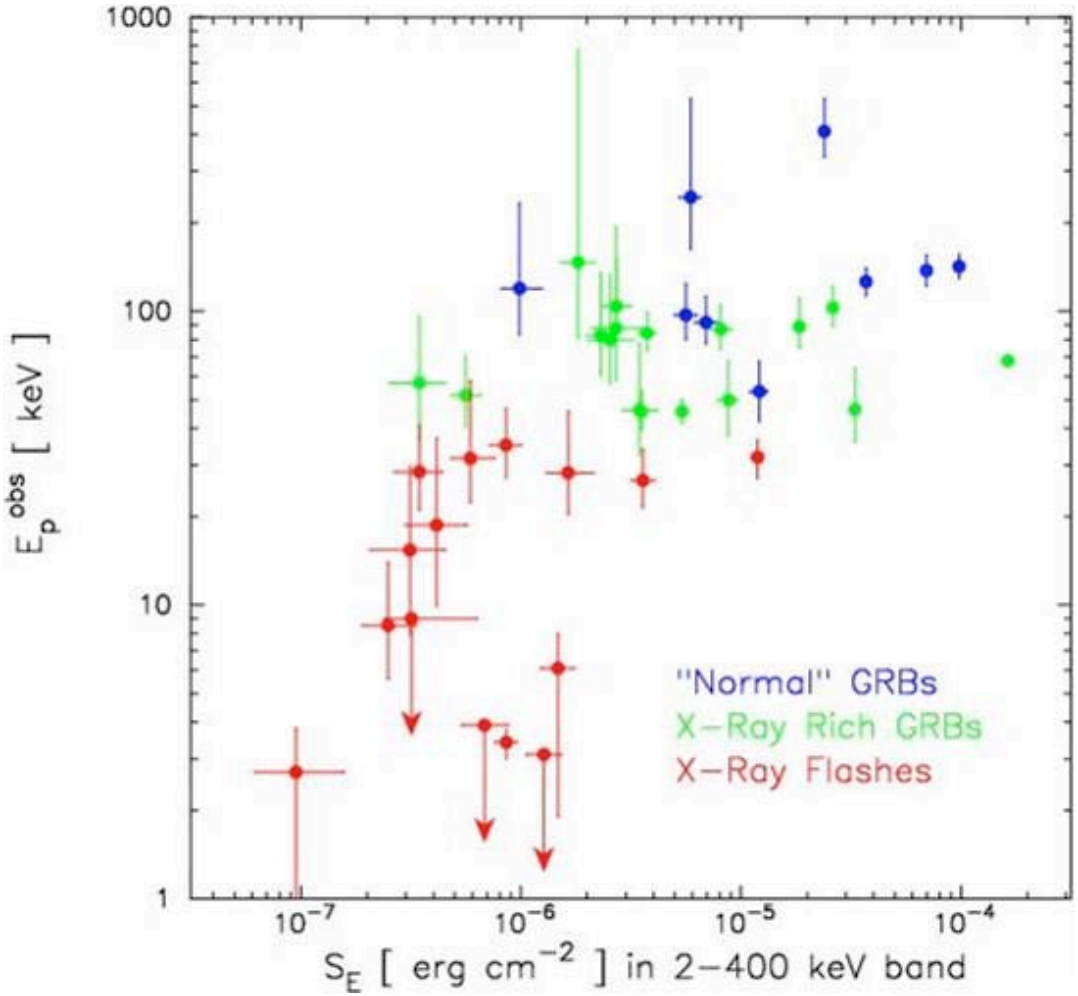
Tominaga et al. (2004)

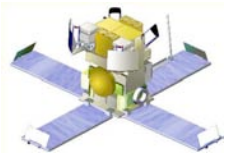
- Increase at ~ 15 days after burst might be due to SN component – or possibly, jet structure



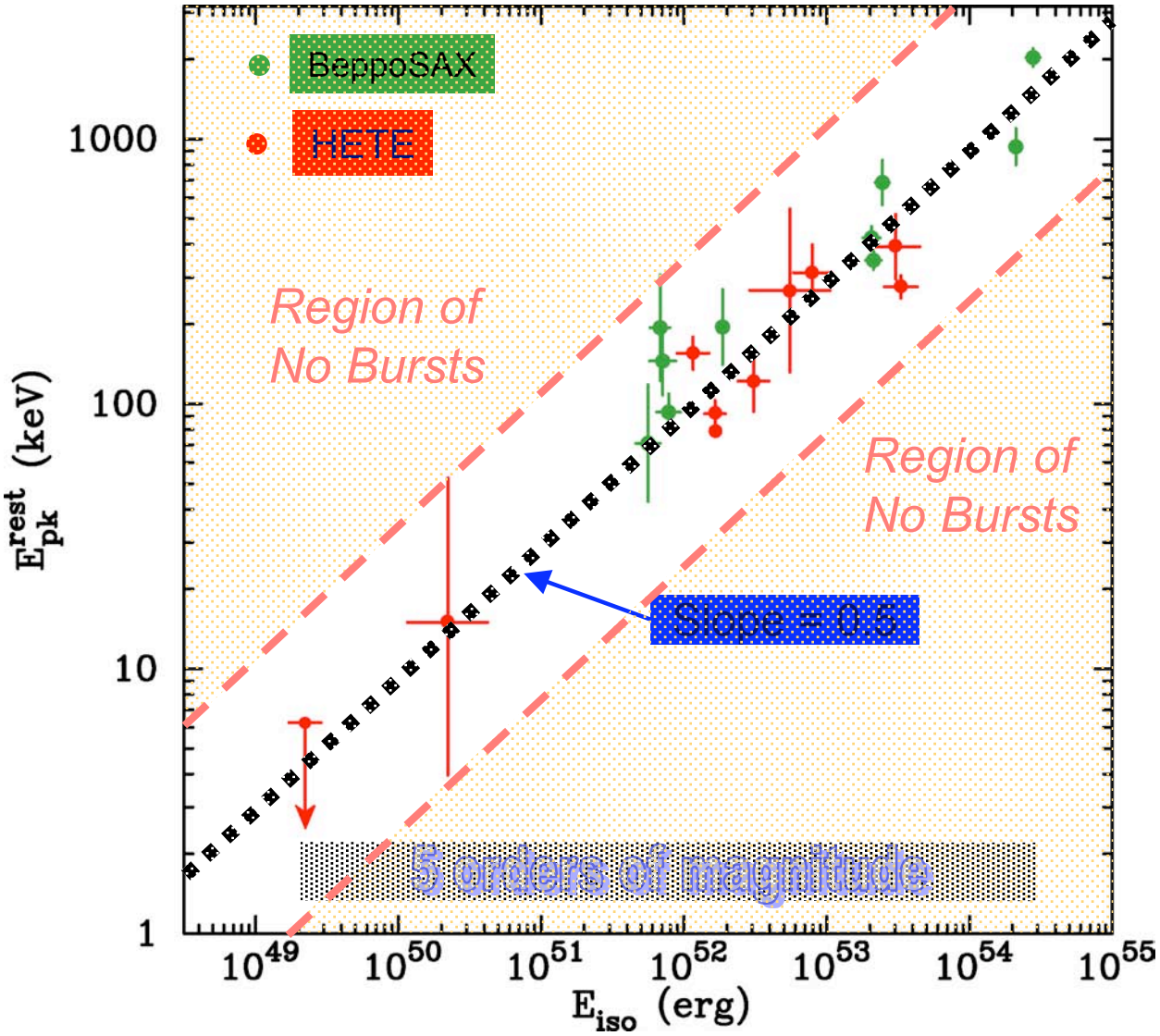
Density of HETE-2 Bursts in (S, E_{peak})-Plane

"Global Properties of XRFs and X-Ray-Rich GRBs Observed by HETE-2," Sakamoto et al. (2004; astro-ph/0409128)





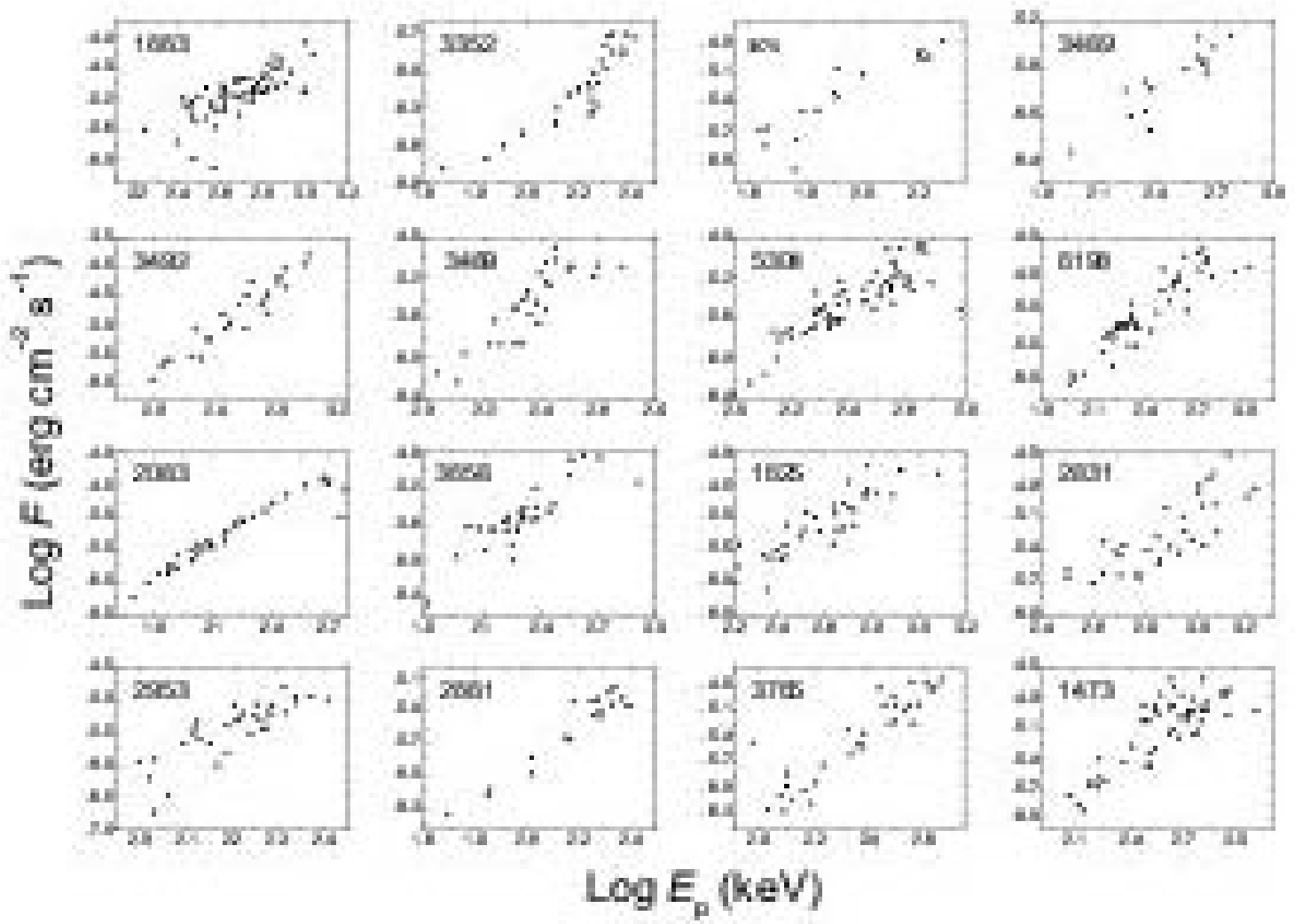
Dependence of GRB Peak Spectral Energy (E_{peak}) on Burst Isotropic Radiated Energy (E_{iso})



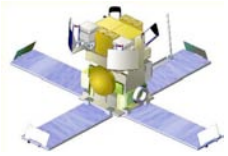
HETE-2 results confirm & extend the Amati et al. (2002) relation:

$E_{peak} \sim \{E_{iso}\}^{0.5}$

E_{iso}—E_{peak} Relation *Within* BATSE GRBs

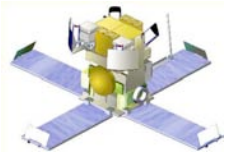


Liang & Dai (2004)



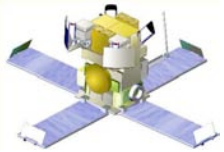
Implications of HETE-2 Observations of XRFs and X-Ray-Rich GRBs

- HETE-2 results, when combined with earlier results:
  - Provide strong evidence that properties of XRFs, X-ray-rich GRBs, and GRBs form a continuum
  - Key result: *approximately equal numbers of bursts per logrithmic interval* in all observed properties
  - Suggest that these three kinds of bursts are closely related phenomena



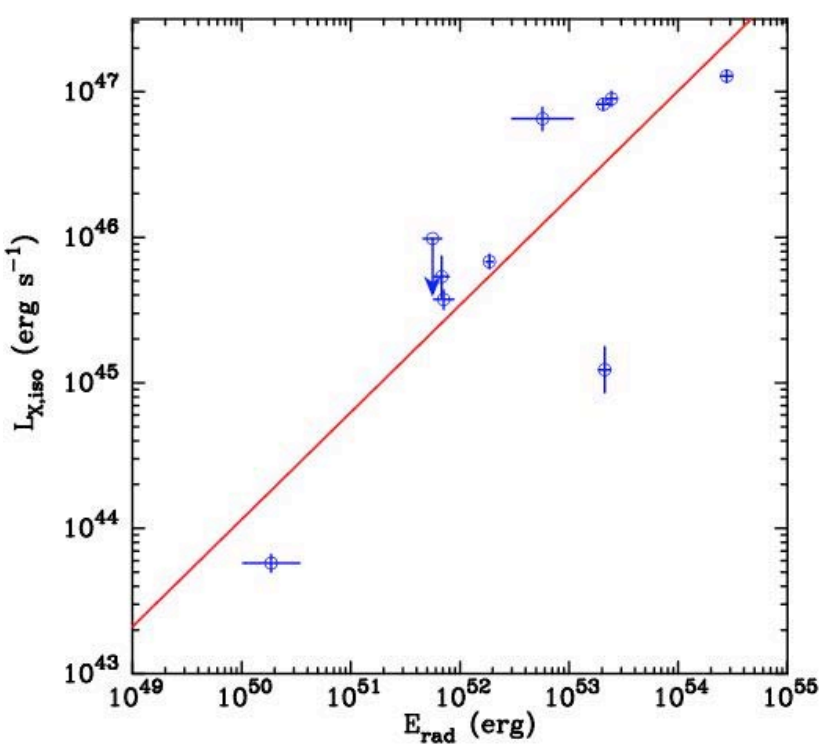
Observations of XRFs Are Stimulating New Theoretical Ideas

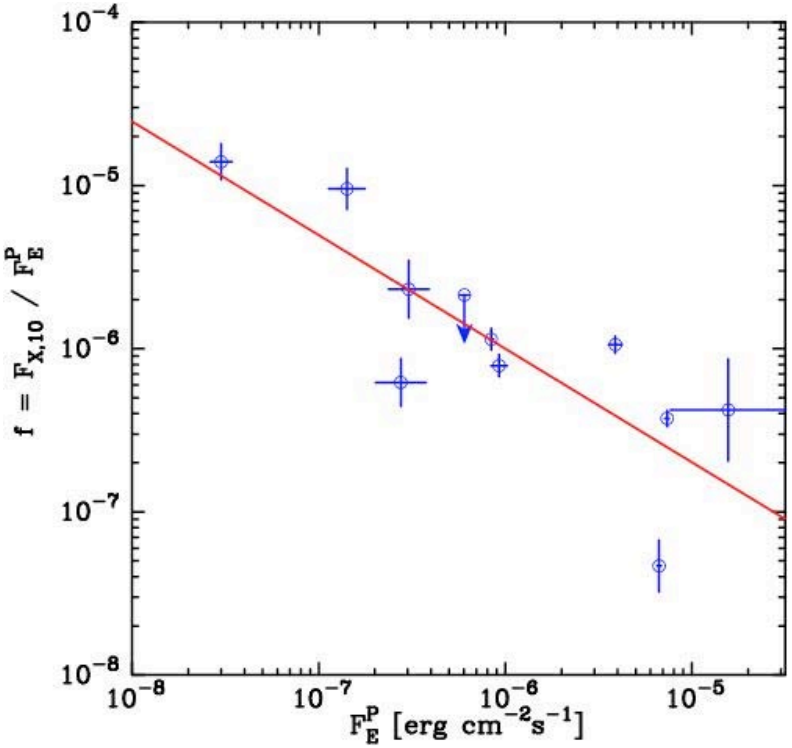
- XRF & GRB Jet Structure and Burst Rates
  - **A Unified Jet Model of XRFs, X-Ray-Rich GRBs, & GRBs (D. Q. Lamb, T. Q Donaghy & C. Graziani), New Astronomy Reviews,** 48, **459 (2004)**
  - **Quasi-Universal Gaussian Jets: A Unified Picture for GRBs & XRFs (B. Zhang, X. Dai, N. M. Lloyd-Ronning & P. Meszaros), ApJ,** 601, **L119 (2004)**
  - **XRF 030723: Evidence for a Two-Component Jet (Y. F. Huang, X. F. Wu, Z. G. Dai, H. T. Ma & T. Lu), ApJ,** 605, **300 (2004)**
  - **XRF 020903: Sub-Luminous & Evidence for A Two-Component Jet (A. Soderberg et al.), ApJ, 606, 994 (2004)**
  - **A Unified Jet Model of XRFs, X-Ray-Rich GRBs, & GRBs (D. Q. Lamb, T. Q Donaghy & C. Graziani, ApJ, in press (astro-ph/0312634) (2004)**
  - **Unified Model of XRFs, X-Ray-Rich GRBs & GRBs (R. Yamazaki, K. Ioka & T. Nakamura), ApJ, 607, 103 (2004)**
  - Gaussian Universal Jet Model of XRFs & GRBs (X. Dai & B. Zhang), ApJ, submitted (2004)
- XRF—SN Connection
  - **Possible SN in Afterglow of XRF 030723 (J. P. U. Fynbo et al.) ApJ, 609, 962 (2004)**
  - **Model of Possible SN in Afterglow of XRF 030723 (Tominaga, N., et al.), ApJ, 612,105 (2004)**
  - **XRFs & GRBs as a Laboratory for the Study of Type Ic SNe ((D. Q. Lamb, T. Q Donaghy & C. Graziani), New Astronomy Reviews, in press (2004)**
  - **GRB-SN Connection: GRB 030329 & XRF 030723 (J. P. U. Fynbo et al.), Santa Fe GRB Workshop Proceedings, in press (2004)**
- Relativistic Beaming and Off-Axis Viewing Models of XRFs
  - **Peak Energy-Isotropic Energy Relation in the Off-Axis GRB Model (R. Yamazaki, K. Ioka & T. Nakamura), ApJ, 606, L33 (2004)**
  - **Off-Axis Viewing as the Origin of XRFs (S. Ddo, A. Dr & A. De Rujula), A&A, in press (astro-ph/0308297) (2004)**
  - **XRFs from Off-Axis Non-Uniform Jets (Z. P. Jin & D. M. Wei), A&A, submitted (astro-ph/0308061) (2004)**



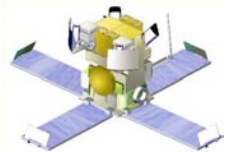
X-Ray and Optical Afterglows of XRFs Are *Also* Faint

Lamb, Donaghy & Graziani (2004)

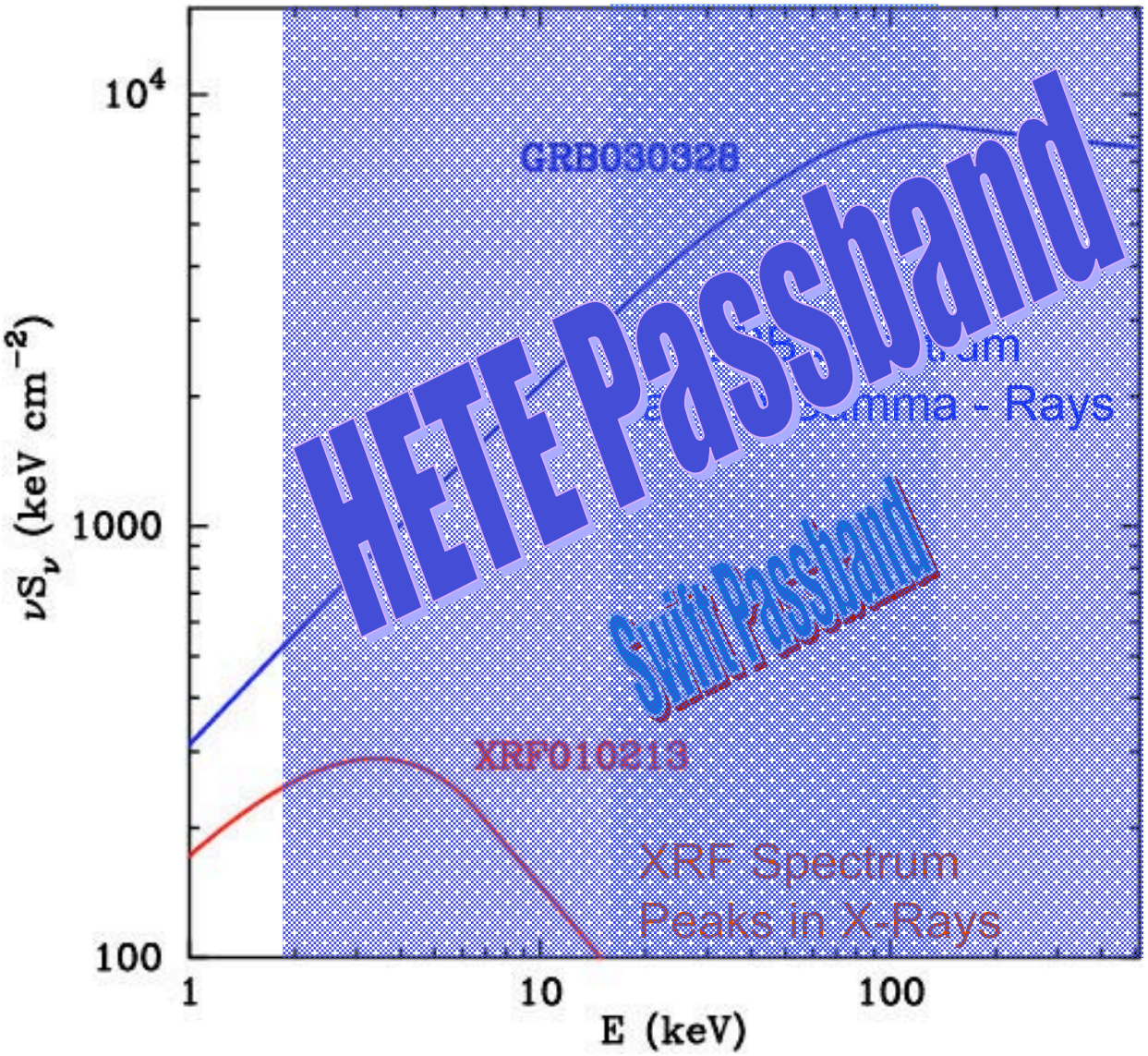




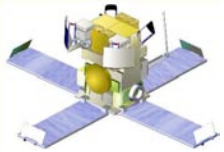
- X-ray and optical afterglows of XRFs are *much fainter* than those of GRBs
- Left panel: slope = 0.74 +/-0.17; right panel: slope = -0.70 +/- 0.15 (68% CL)
  => tantalizing evidence that efficiency of prompt emission is *much less* for XRFs than for GRBs (as expected from V ⇔ L estimator)



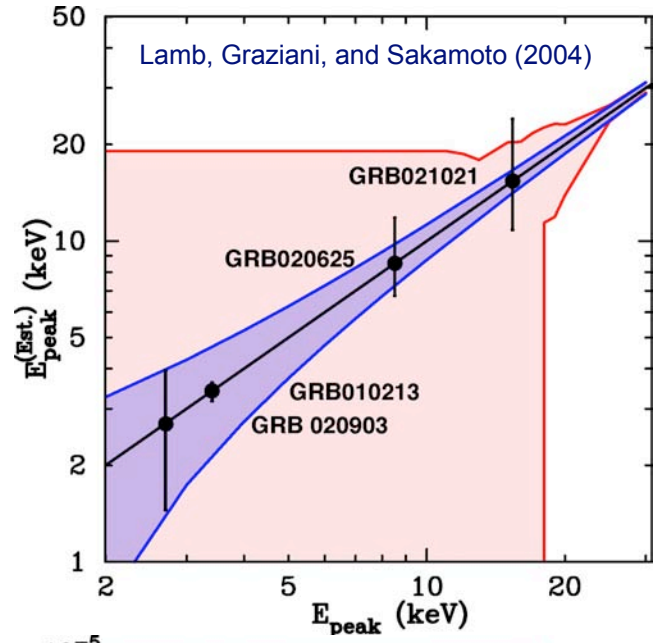
X-Ray Flashes vs. GRBs: HETE-2 and *Swift* (BAT)

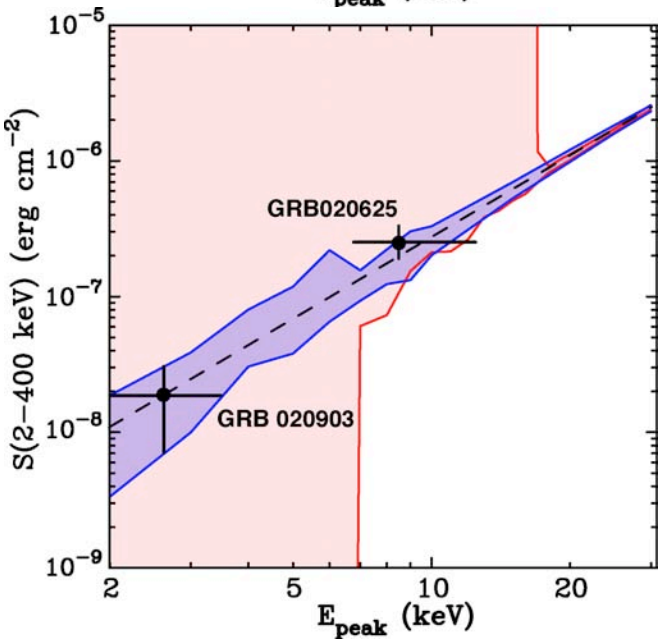


Even with the BAT's huge effective area (~2600 cm^2), only HETE-2 can determine the spectral properties of the most extreme half of XRFs.



Ability of HETE-2 and *Swift* to Measure E_{peak} and S_{bol} of XRFs



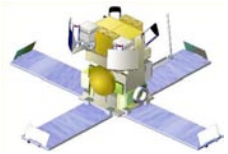


E_{peak}(estimated) vs. E_{peak}:

- Shaded areas are 68% confidence regions
- ***Swift*** (red):
  - *well-determined for E_{peak}> 20 keV*
  - *undetermined for E_{peak}< 20 keV*
- **HETE-2** (blue):
  - *well-determined down to E_{peak} ~ 3 keV*

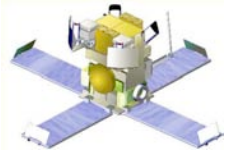
S_{bol}(estimated) vs. S_{bol}:

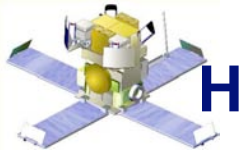
- Shaded areas are 68% confidence regions
- **Swift (red):**
  - *well-determined for E_{peak} > 20 keV*
  - *undetermined for E_{peak}< 20 keV*
- **HETE-2** (blue):
  - *well-determined down to E_{peak} ~ 3 keV*



Conclusions

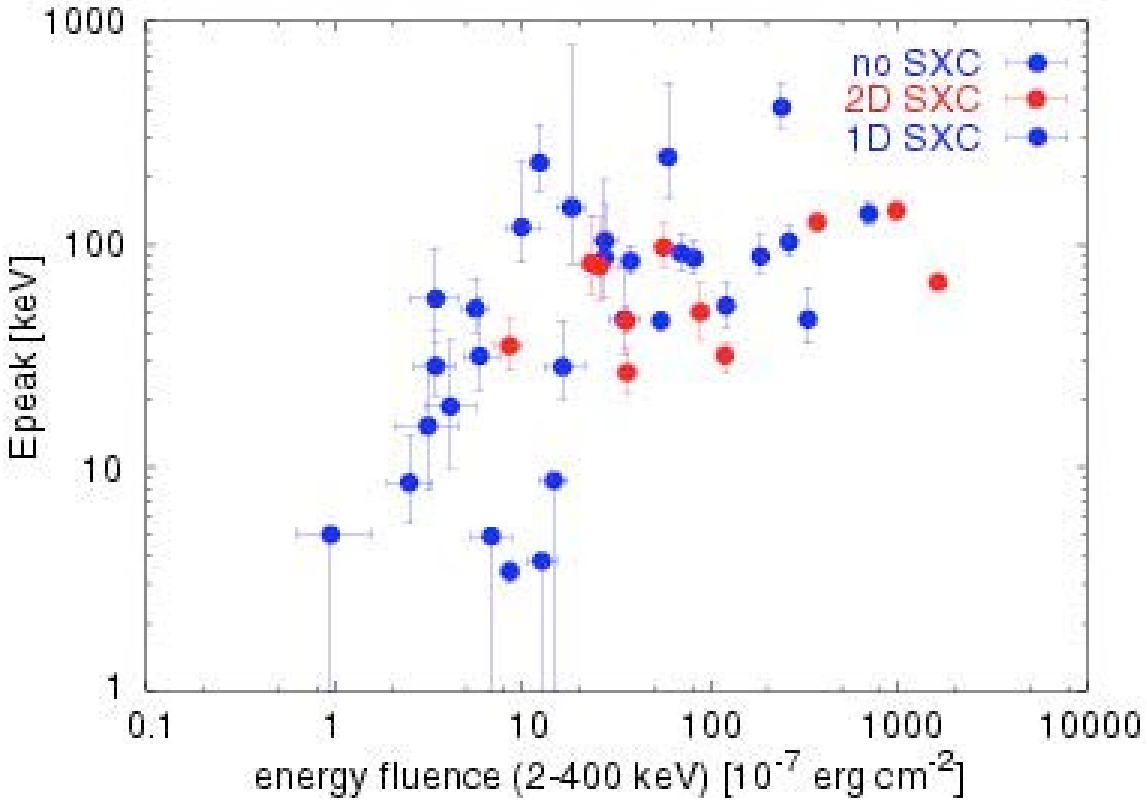
- HETE-2 has provided strong evidence that XRFs, "X-ray-rich" GRBs, and GRBs are closely related phenomena
- XRFs provide unique insights into
  - structure of GRB jets
  - GRB rate
  - nature of Type Ic SNe
- Confirmation will require *prompt*
  - localization of many XRFs
  - determination of E_{peak}
  - identification of X-ray and optical afterglows
  - determination of redshifts
- HETE-2 is ideally suited to do *the first two*, whereas *Swift* (with E_{min} ~ 15 keV) is not; *Swift* is ideally suited to do *the second two* whereas HETE-2 cannot
- **Prompt *Swift* XRT and UVOT observations of HETE-2 XRFs can therefore greatly advance our understanding of XRFs**

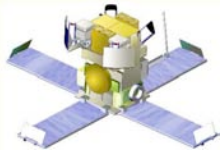




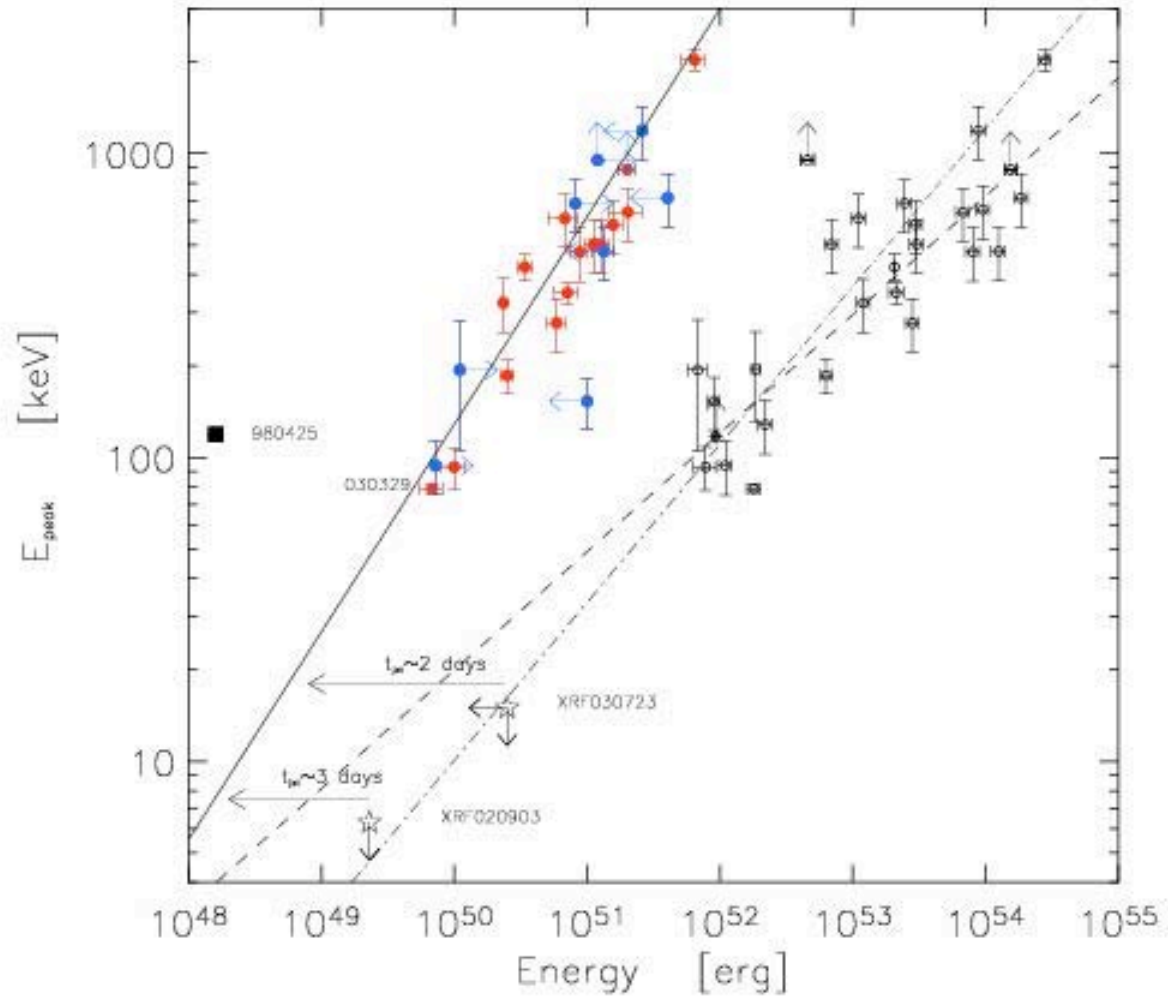
HETE is Solving Mystery of "Optically Dark" GRBs

- 13 of 15 HETE-2 SXC plus WXM localizations have led to ID of an optical/IR afterglow
- These bursts are a "fair sample" of all bursts localized by HETE-2 above SXC threshold
- WXM localizations are the key to XRF science

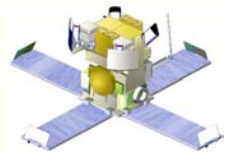




E_{gamma}—E_{peak} Relation

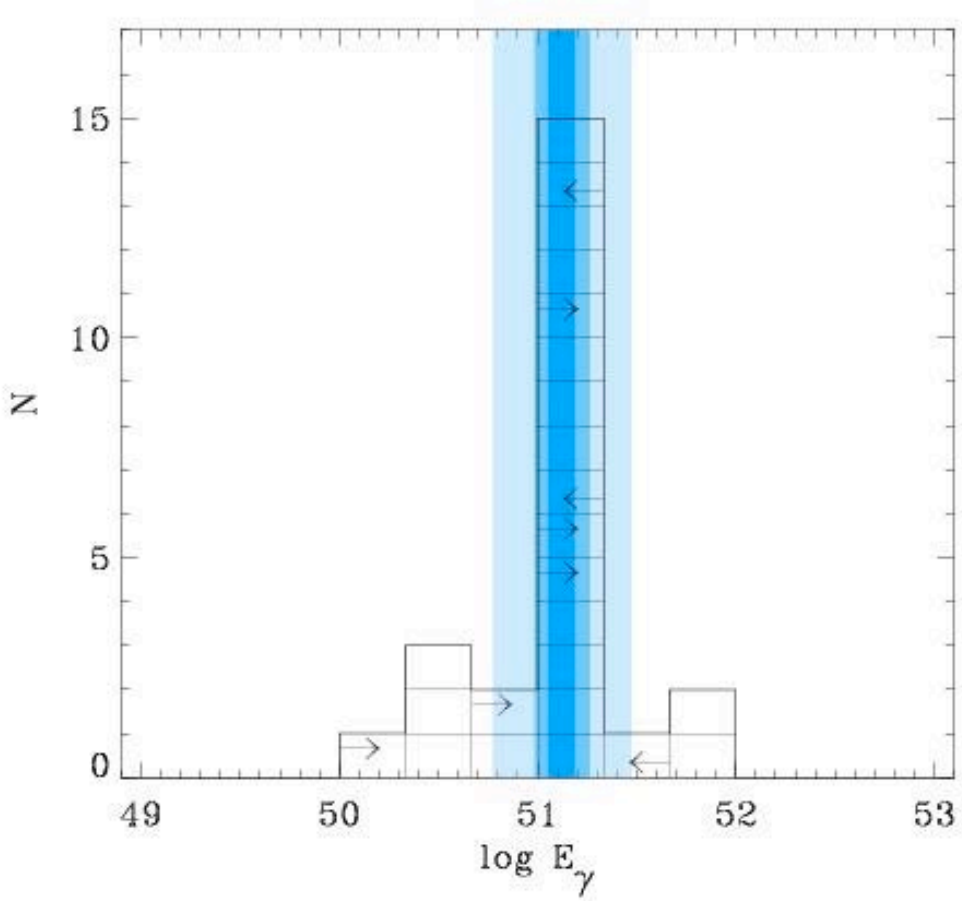


Ghirlanda et al. (2004)

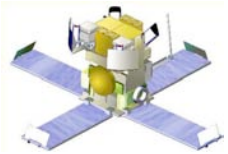


GRBs Have "Standard" Energies

Frail et al. (2001); Kumar and Panaitescu (2001)

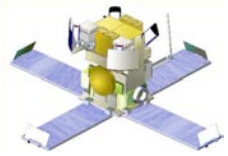


Bloom et al.(2003)



Power-Law Universal Jet Model

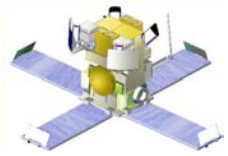
- E_{iso} (theta$_{view}$) ~ E_{gamma} (*theta*$_{view}$)$^{-2}$
- Exponent = -2 is necessary to recover the Frail et al. (2001) result (see, e.g., Rossi et al. 2002, Zhang & Meszaros 2002)
- Most viewing angles lie at ~ *theta*$_{max}$ or ~ 90^0 to jet axis (whichever is larger) because that is where most of solid angle is
- This implies that most bursts (and most bursts that we see) have large *theta*_view's, and therefore small E_{iso}'s, L_{gamma}'s, E_{peak}'s, etc. (Rossi et al. 2002, Zhang & Meszaros 2002, Perna et al. 2003)



Uniform Jet Model

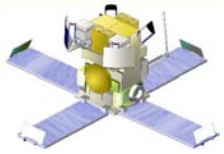
- Frail et al. (2000) result => $E_{iso} \sim E_{gamma}/Omega_{jet}$
- Amati et al. (2002) relation =>

  $E_{peak} \sim (E_{iso})^{1/2} \sim (E_{gamma}/Omega_{jet})^{1/2}$
- HETE-2 results show that E_{iso} spans ~ 5 decades!
- HETE-2 results imply $N(Omega_{jet}) \sim Omega_{jet}^{-2}$ =>
  - there are many more bursts w. *small* $Omega_{jet}$'s than large; however, we don't see most of them
  - we see ~ equal numbers of bursts per logarithmic decade in *all* properties ($Omega_{jet}$, E_{iso}, E_{peak}, L_{gamma}, L_x, L_R, etc.)!

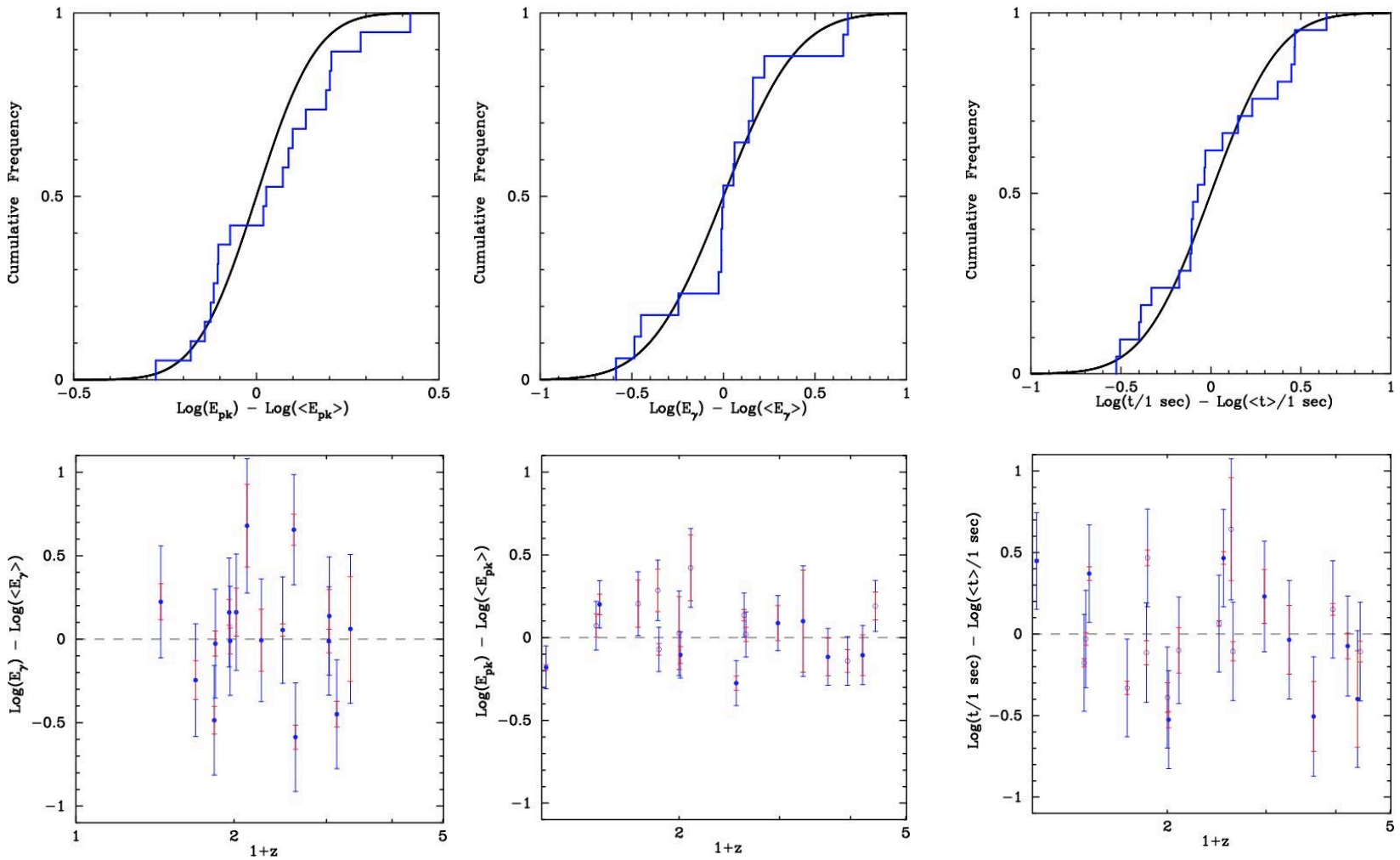


Simulations of Observed GRBs

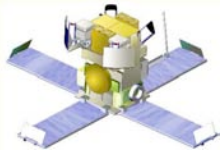
- Our approach is the following:
  - We first model the bursts in the source frame
  - We then propagate the bursts from the source frame to the Earth, using the cosmology that we have adopted
  - We determine which bursts are observed, using the properties of the instruments that observe them
- We execute our simulations as follows:
  - For each burst, we obtain a redshift *z* and a jet opening solid angle $Omega_{jet}$ by drawing from specific distributions
  - We introduce three Gaussian smearing functions to generate
    - Spread in jet energy (E_{gamma})
    - Spread in Epeak around the Amati et al. (2002) relation
    - Spread in the timescale T that converts fluence to flux
  - Using these five quantities, we calculate various rest-frame quantities (E_{iso}, E_{peak}, etc.)
  - Finally, we construct a Band function for each burst and transform it to the observer frame, which allows us to
    - Calculate fluences and peak fluxes
    - Determine if the burst would be detected by various instruments



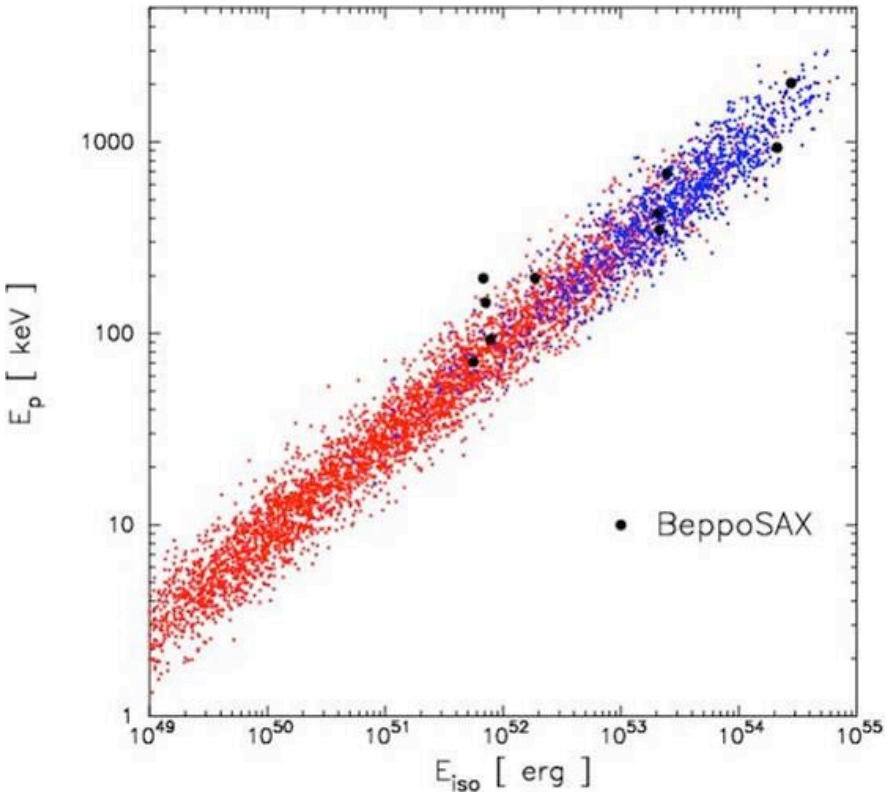
Gaussian Smearing Functions



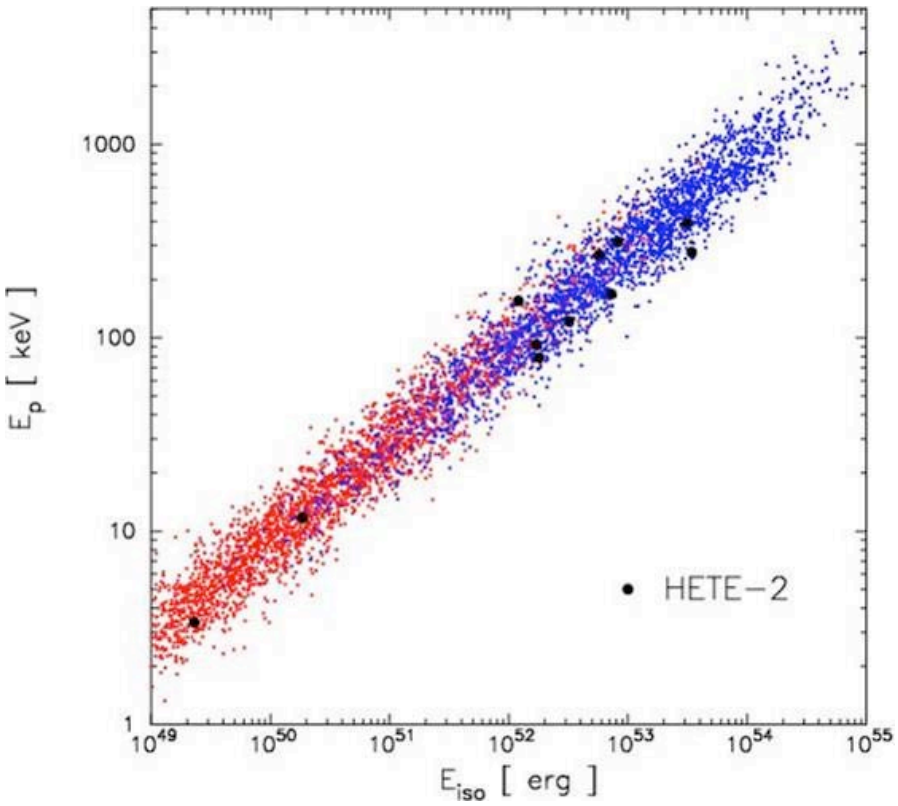
- Observed distributions are well-fit by narrow Gaussians
- No evidence for evolution of any of Gaussians w. redshift *z*



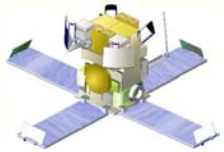
Predicted E_{ios}-E_{peak} Relation



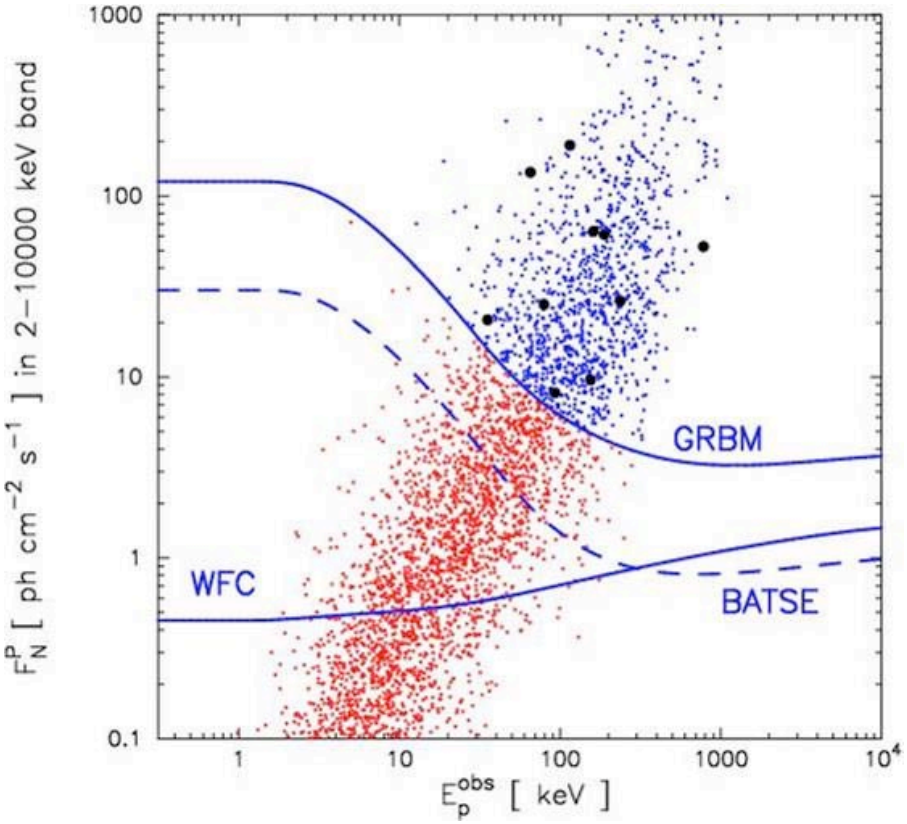
BeppoSAX bursts



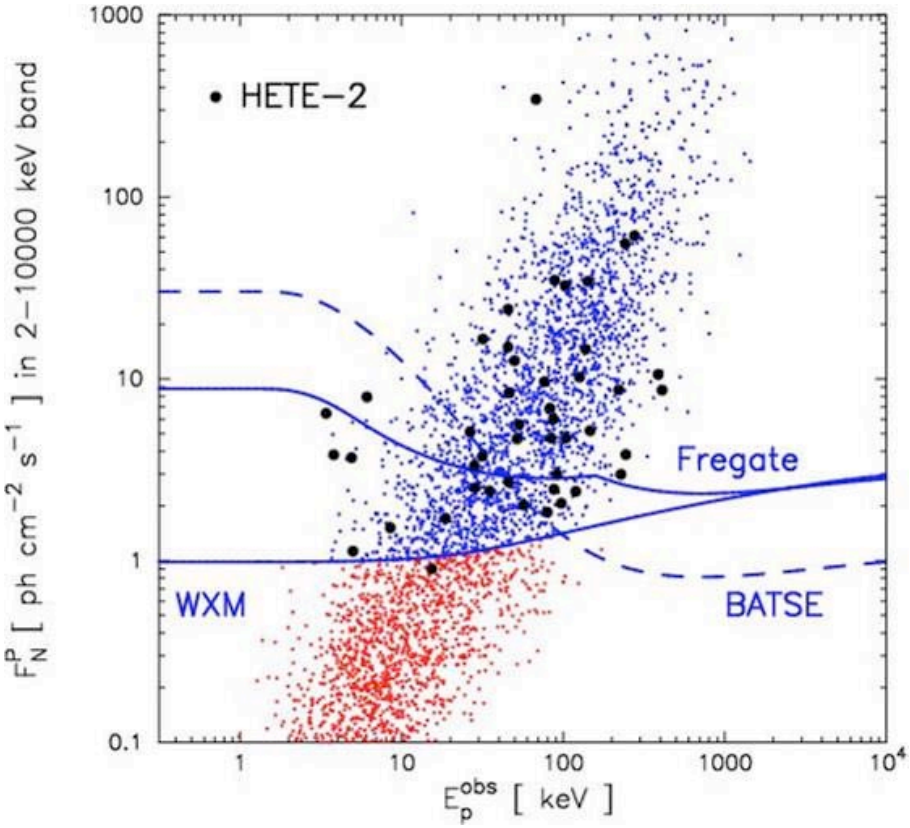
HETE-2 bursts



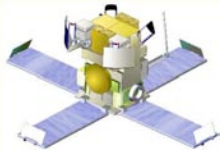
Determining If Bursts are Detected



BeppoSAX bursts

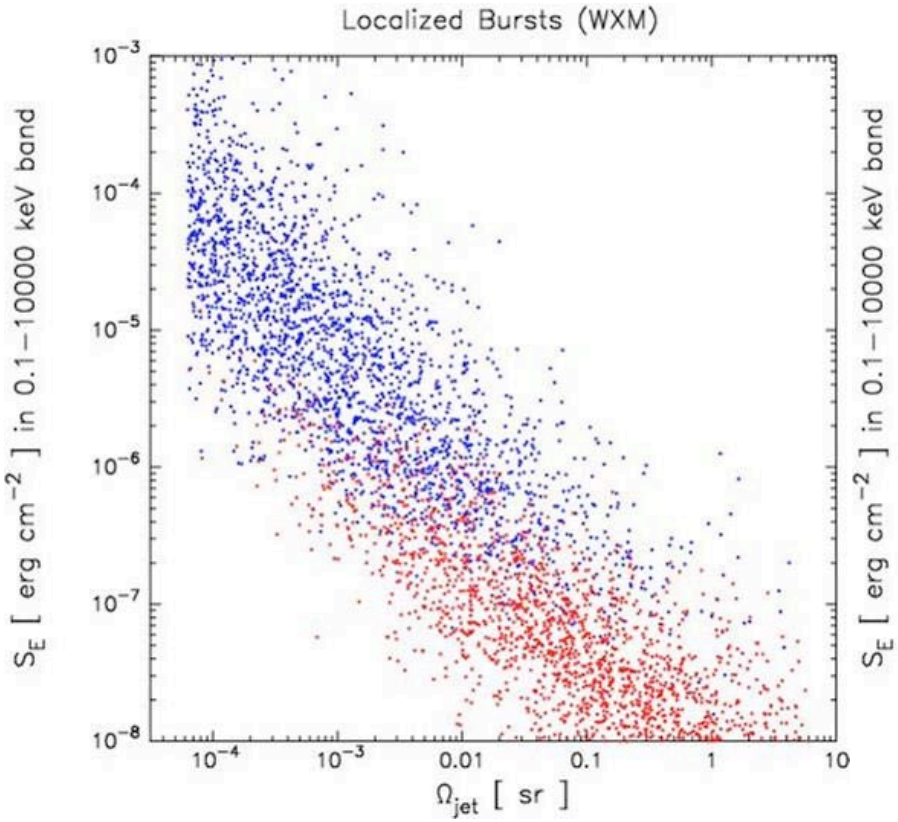


HETE-2 bursts

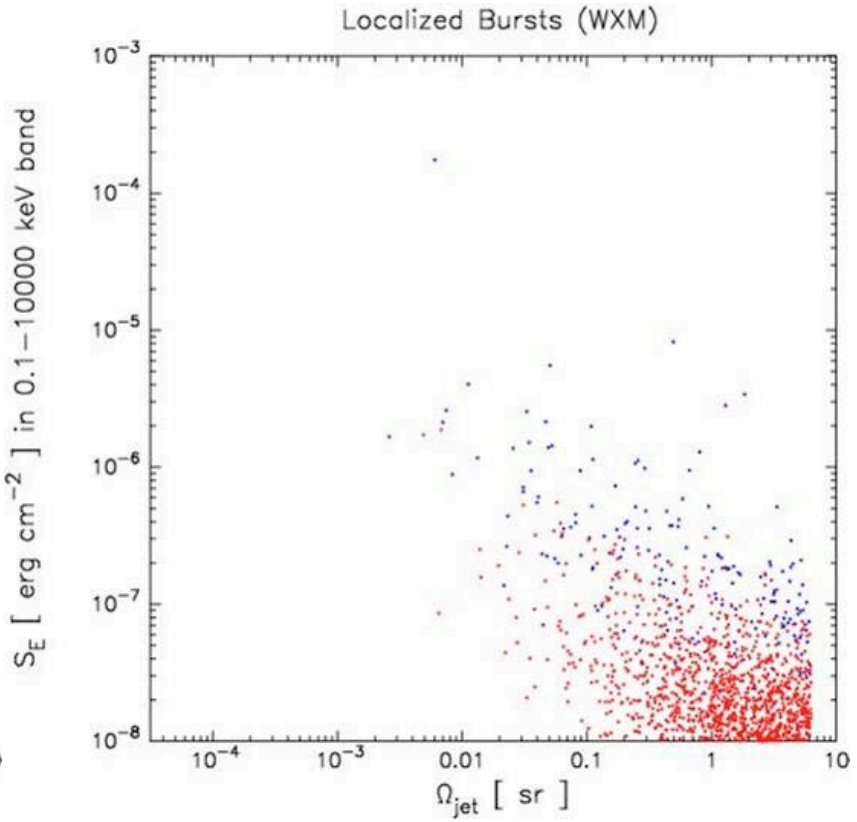


Comparison of Uniform Jet and Universal Jet Models

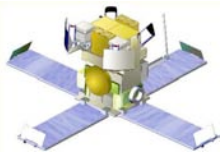
Lamb, Donaghy, and Graziani (2003)



Uniform Jet Model

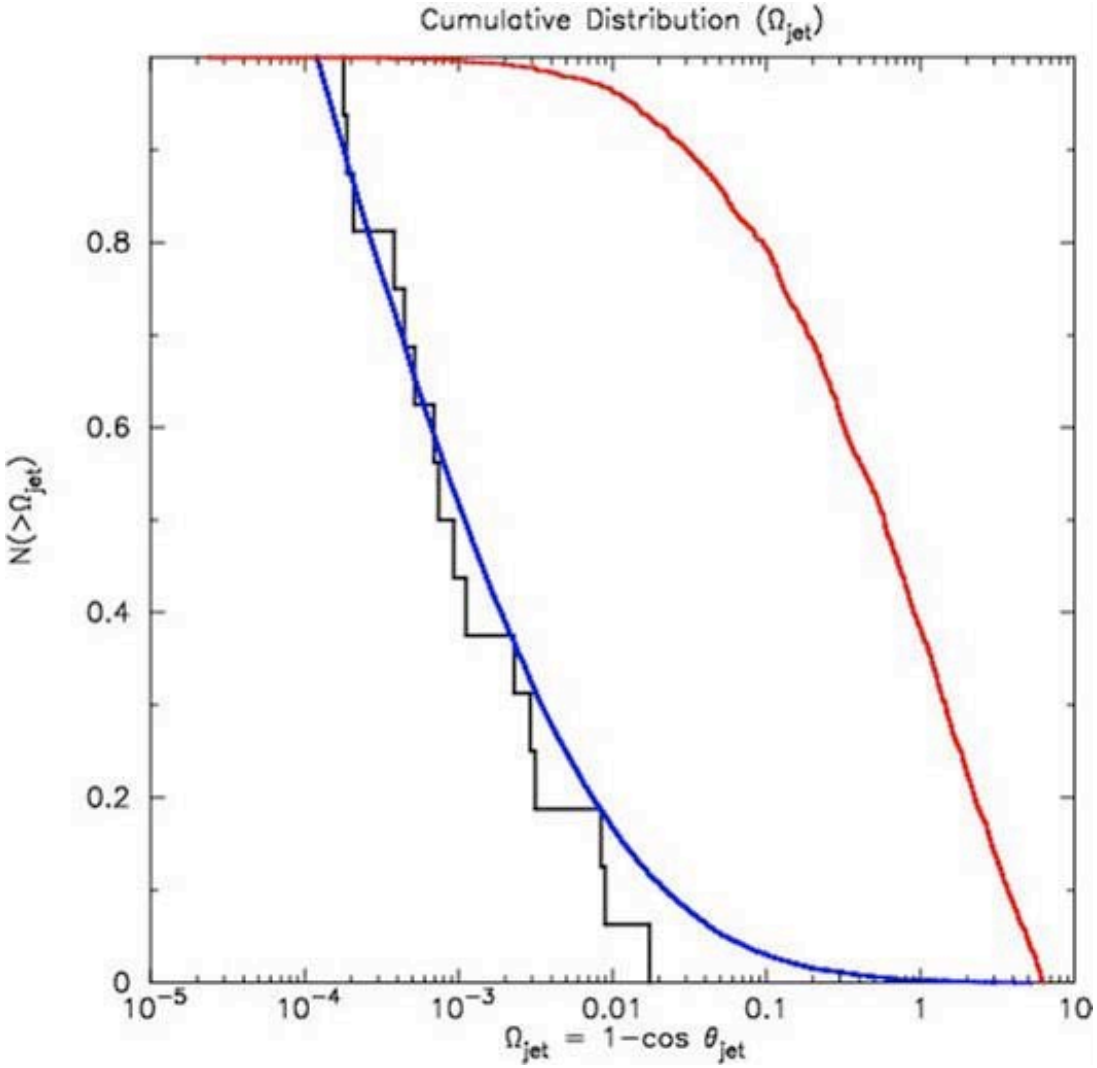


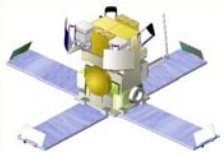
Power-Law Universal Jet Model



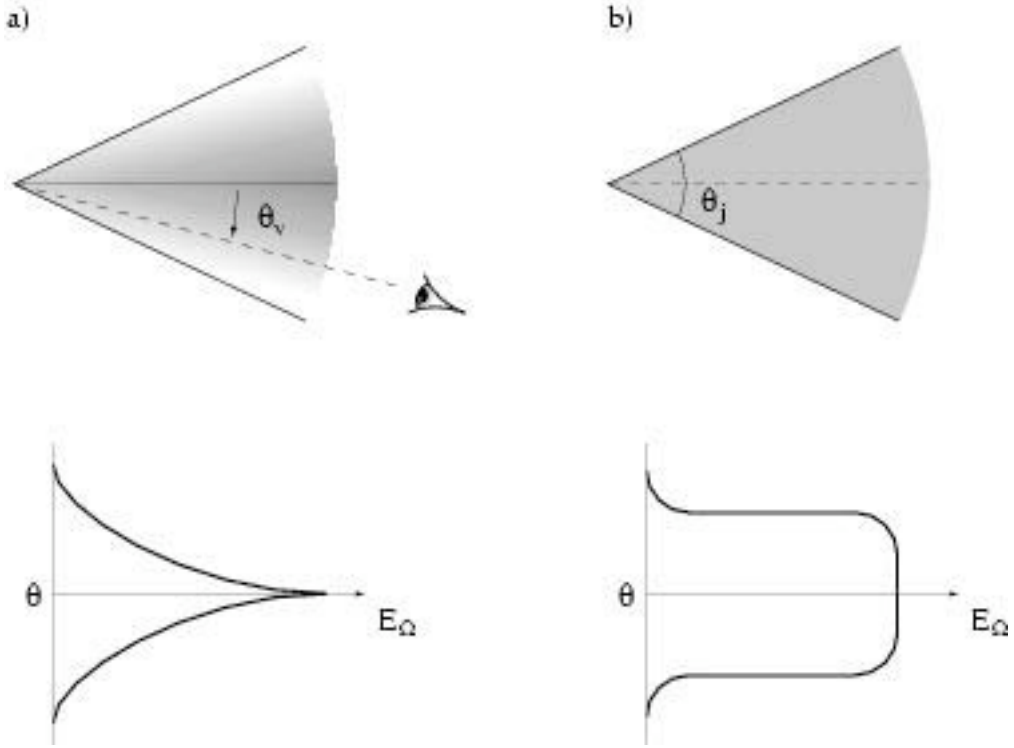
Comparison of $Omega_{jet}$ ($Omega_{view}$) w. Observations

Lamb, Donaghy, and Graziani (2003)



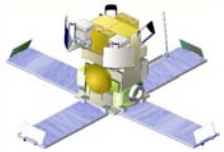


Universal Jet vs. Uniform Jet Models



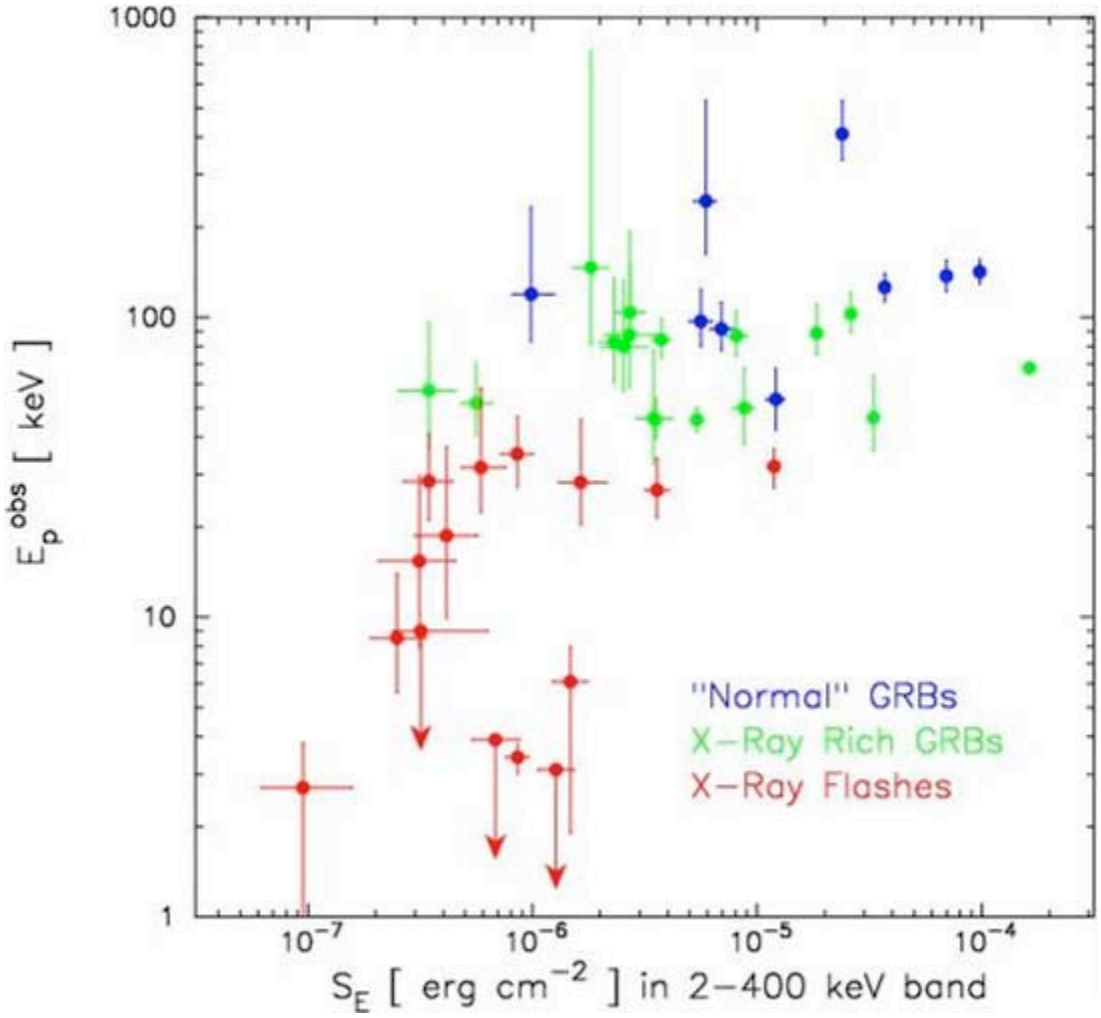
Universal Jet Model Uniform Jet Model

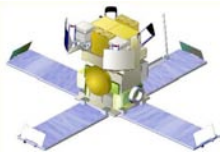
(Diagram from Lloyd-Ronning and Ramirez-Ruiz 2002)



Density of HETE-2 Bursts in (S, E_{peak})-Plane

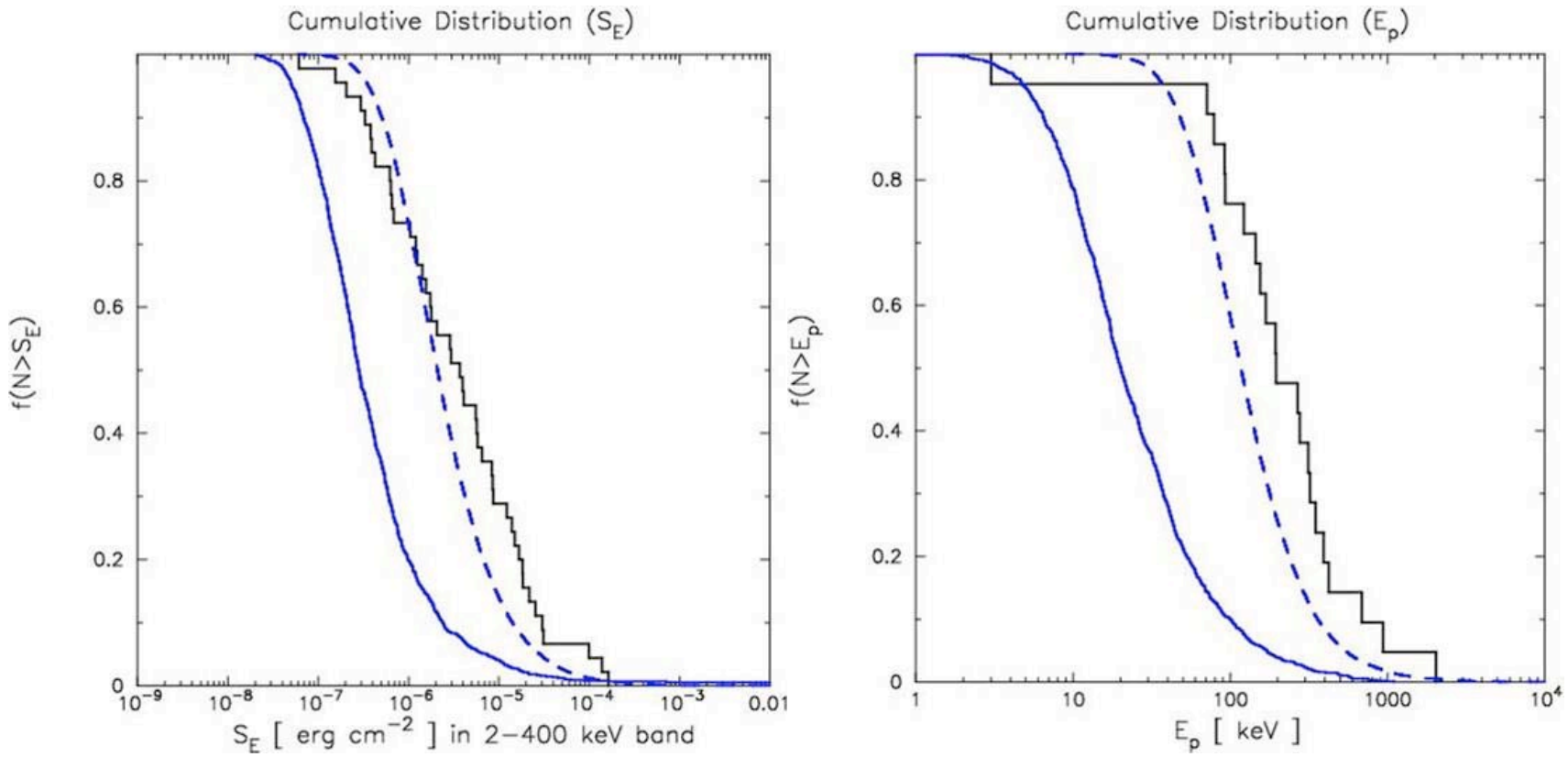
Sakamoto et al. (2004)



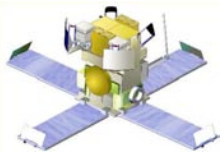


Comparison of Predicted and Observed HETE-2 Fluence and E_{peak} Distributions

Lamb, Donaghy & Graziani (2003)



Power-Law Universal Jet Model



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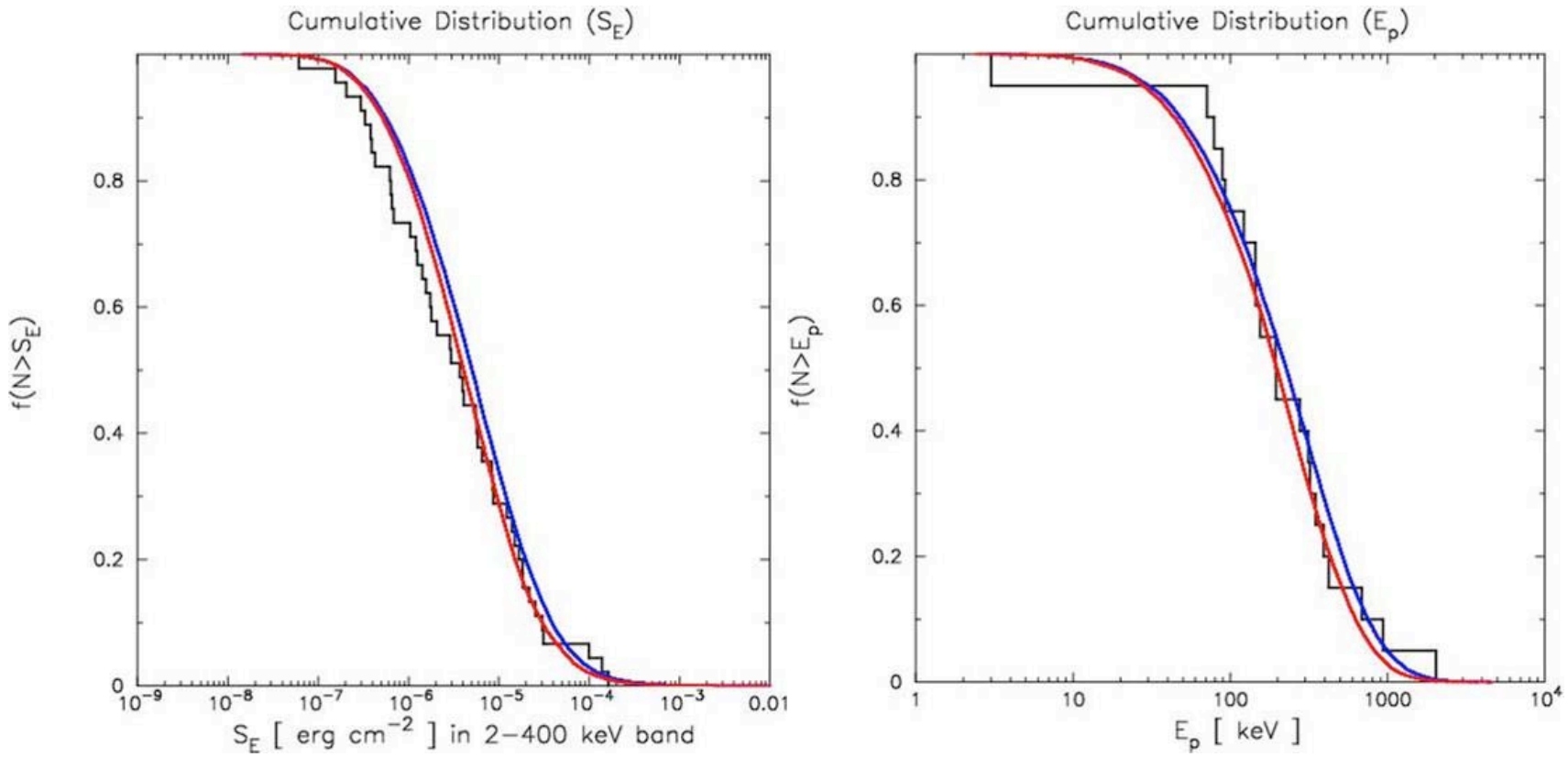
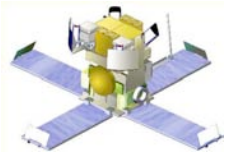
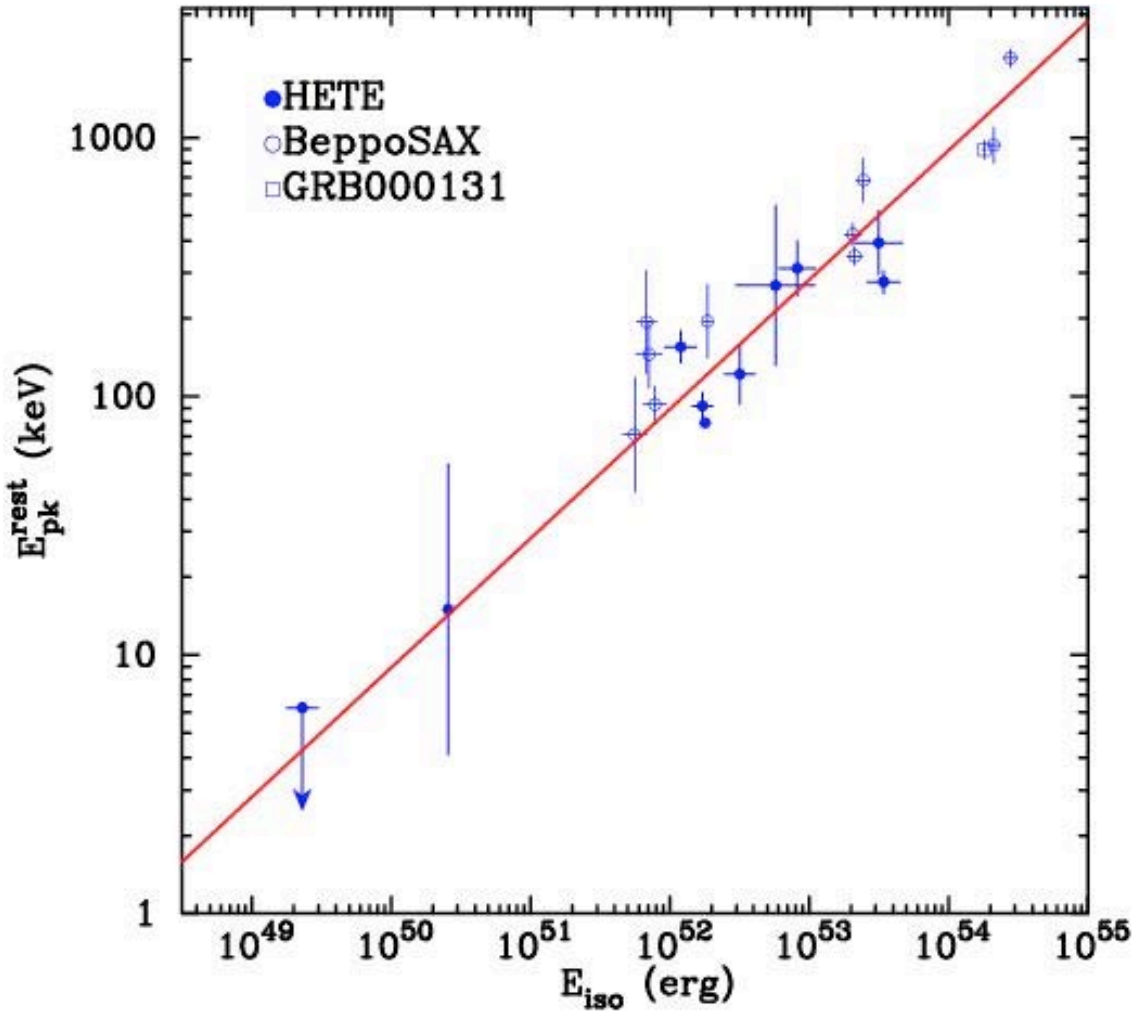


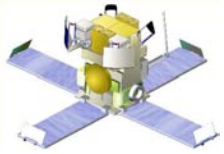
Uniform Jet Model



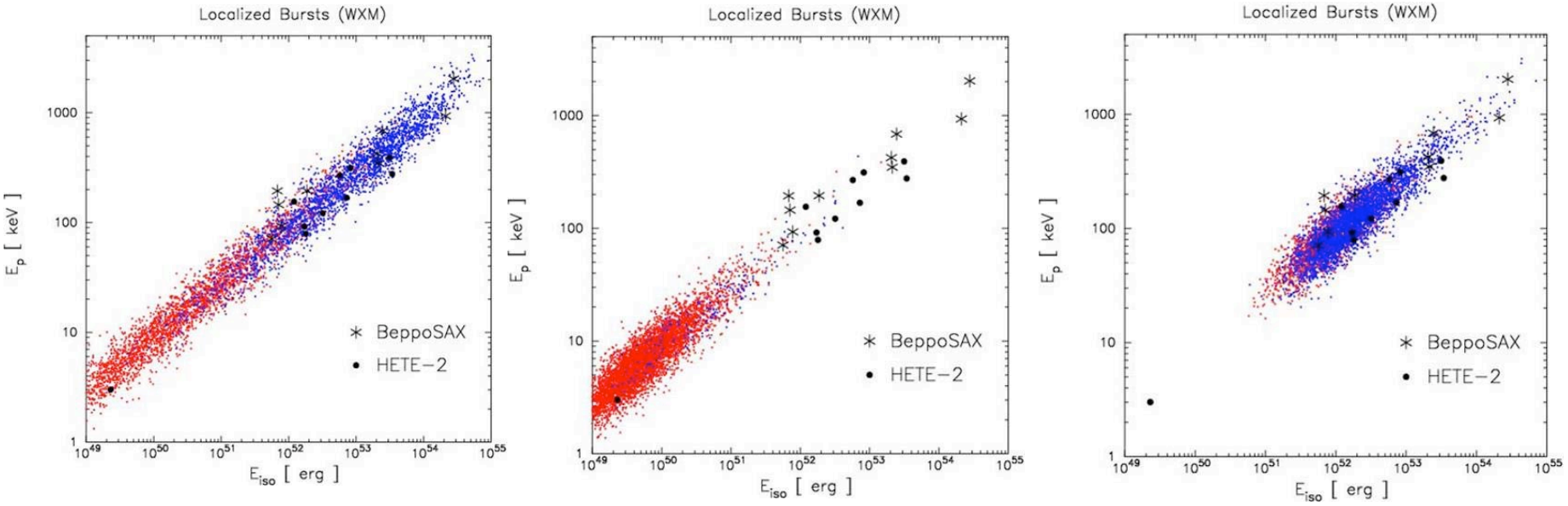
$E_{iso} - E_{peak}$ Relation



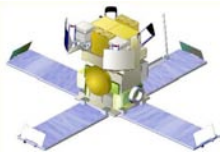
Lloyd-Ronning, Petrosian & Mallozzi (2000); Amati et al. (2002); Lamb et al. (2003)



Comparison of Universal and Uniform Jet Models

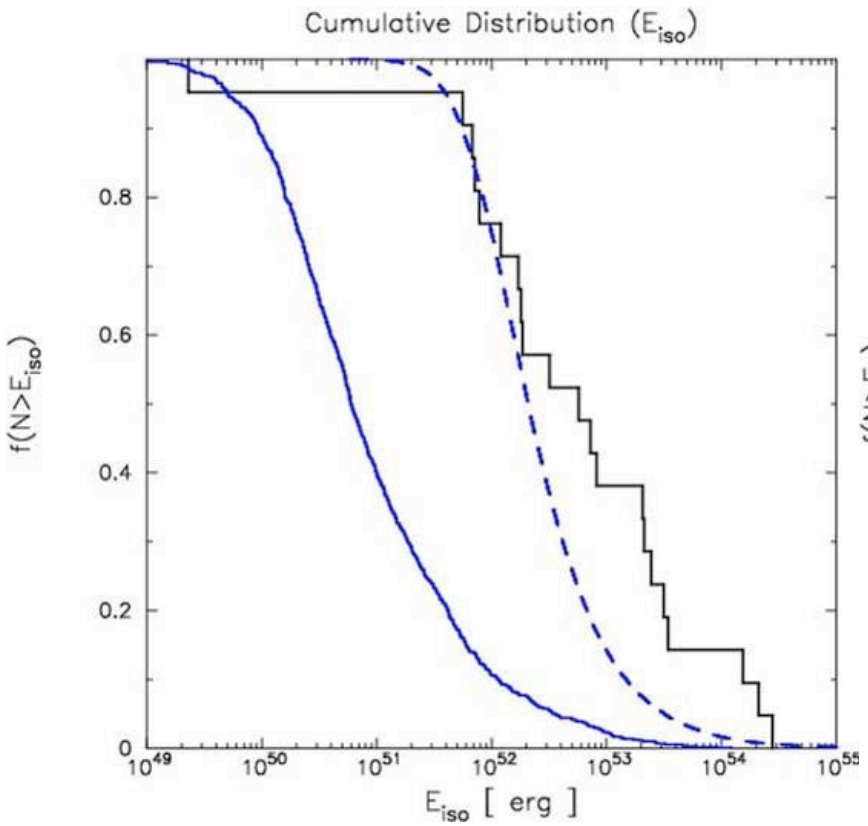


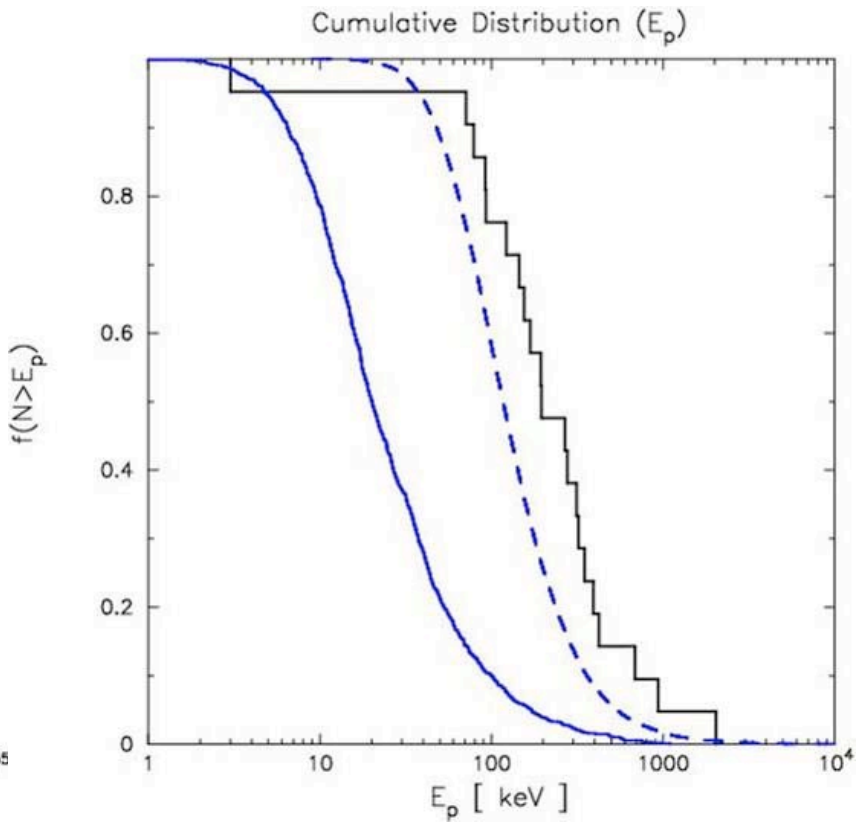
- Uniform jet model can account for *both* XRFs and GRBs
- Power-law universal jet model can account for GRBs, but not *both* XRFs and GRBs



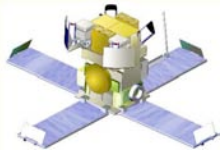
Comparison of Predicted and Observed E_{iso} and E_{peak} Distributions

Lamb , Donaghy, and Graziani (2003)





Power-Law Universal Jet Model



Comparison of Predicted and Observed E_{iso} and E_{peak} Distributions

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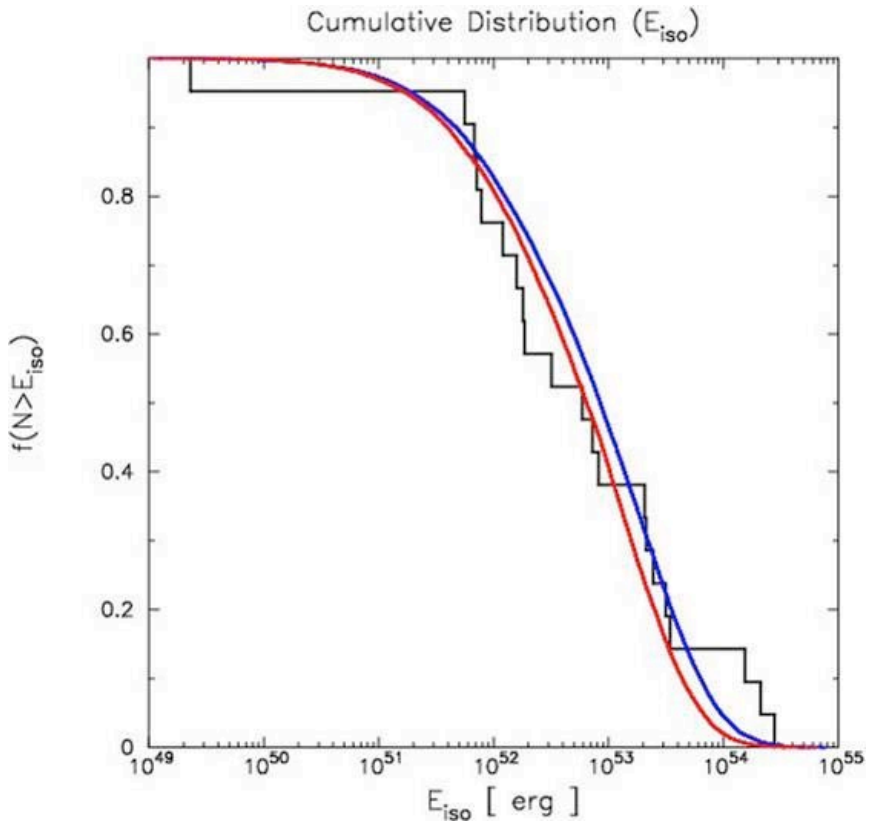
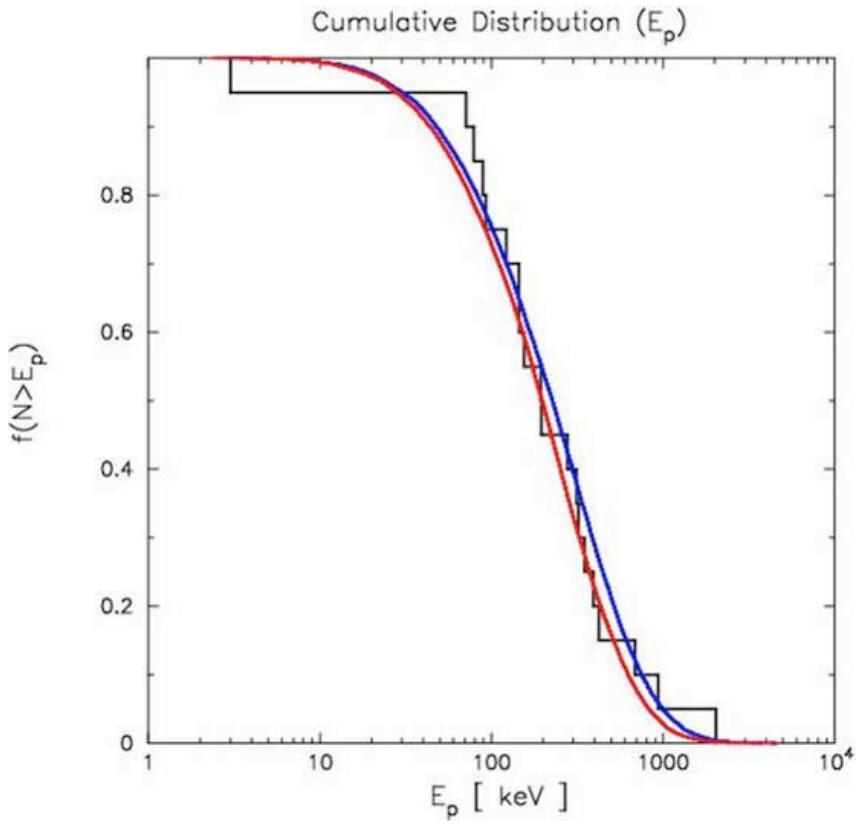
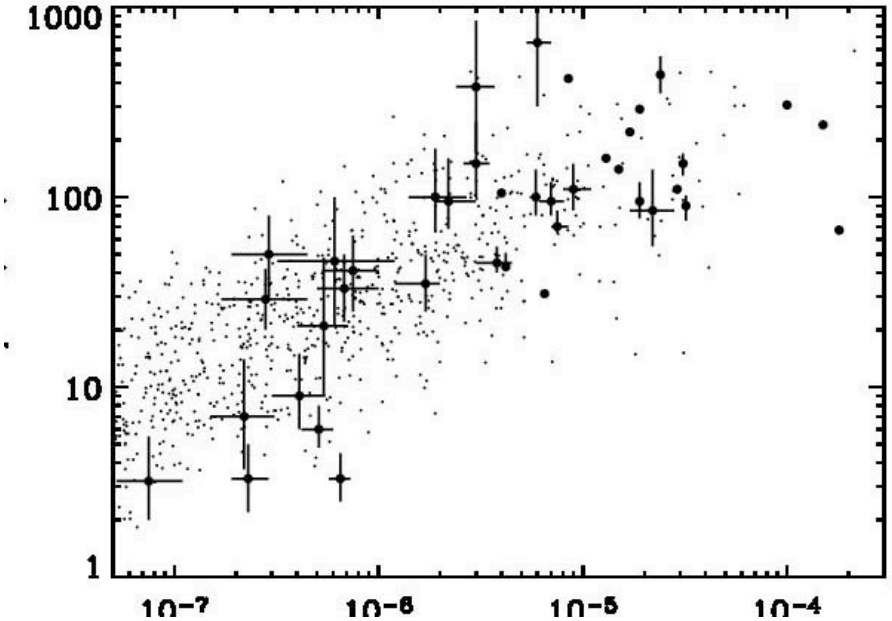
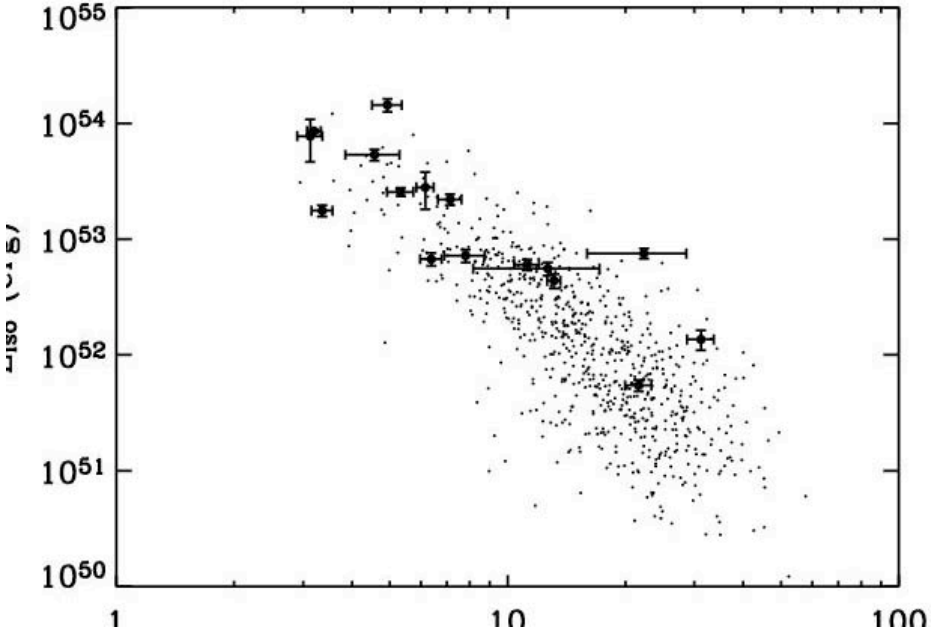




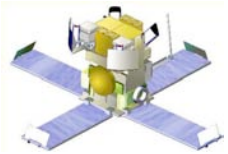
Uniform Jet Model

Gaussian Universal Jet Model



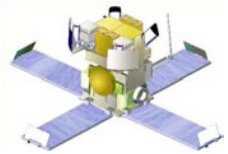


Zhang et al. (2004)



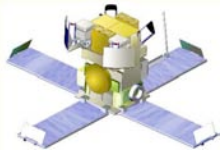
Implications of the Uniform Jet Model

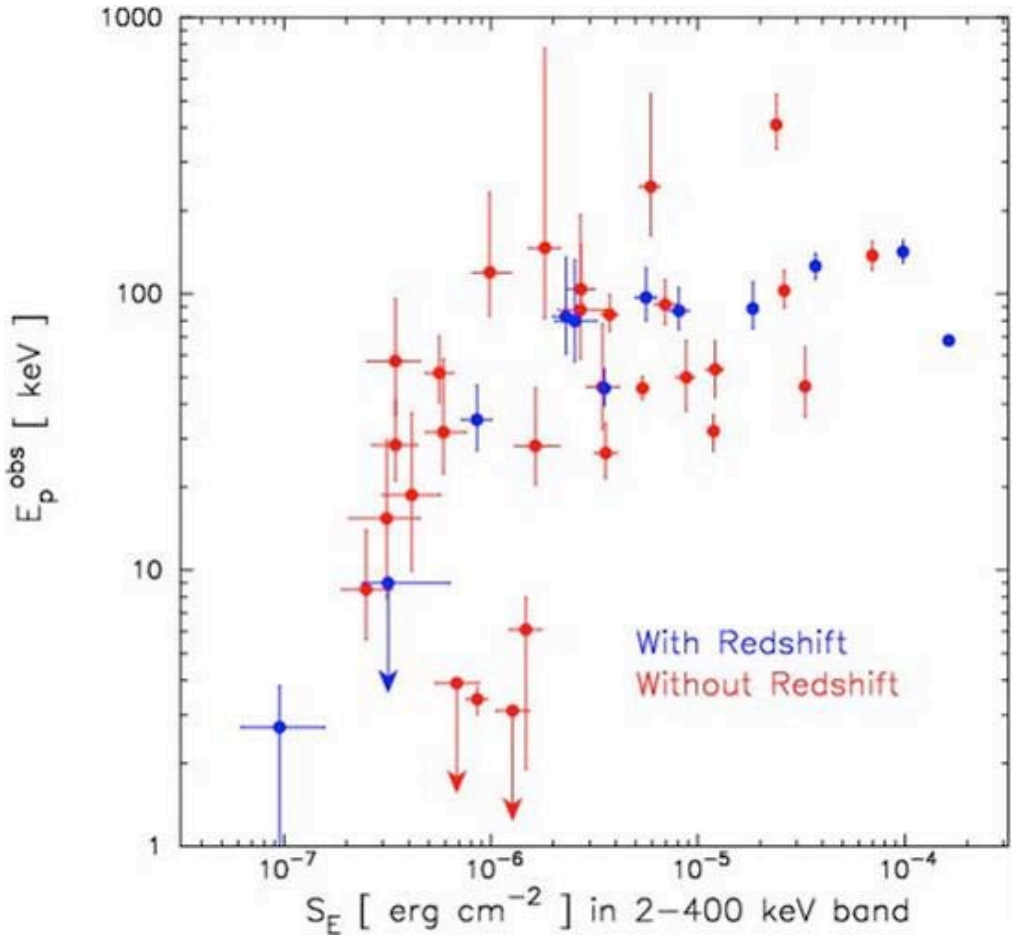
- Model provides unified picture of XRFs, “X-ray-rich GRBs,” and GRBs
- Extra parameter (distribution of jet opening solid angles $\mathrm{Omega}_{\mathrm{jet}}$) enables it to account for key result: *approximately equal numbers of bursts per logarithmic interval*
- Model implies that E_{jet} and E_{gamma} may be ~ 30 times smaller than has been thought
- It will be important to determine whether bursts with much smaller values of E_{iso} and L_{iso} than the “standard” value are outliers, or are a sign that jet structure is more complicated
- This is particularly true in the case of XRFs, which may have considerably smaller values of E_{iso} and L_{iso}



Further Implications of Uniform Jet Model

- Model implies most bursts have small $Omega_{jet}$ (these bursts are the hardest and most luminous bursts); however, we see very few of these bursts
- Range in E_{iso} of five decades => *minimum* range for $Omega_{jet}$ is ~ 6 x 10^-4 < $Omega_{jet}$ < 6
- Unified jet model therefore implies that there are ~ 10^5 more bursts with small $Omega_{jet}$'s for every such burst we see => if so, R_{GRB} may be comparable to R_{SN}
- However, efficiency in conversion of E_{gamma} (E_{jet}) to E_{iso} may be less for XRFs



HETE-2 Bursts in (S, E_{peak})-Plane

Sakamoto et al. (2004)