GRB ENERGETICS. Then and Now

Dale A. Frail
National Radio Astronomy Observatory

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

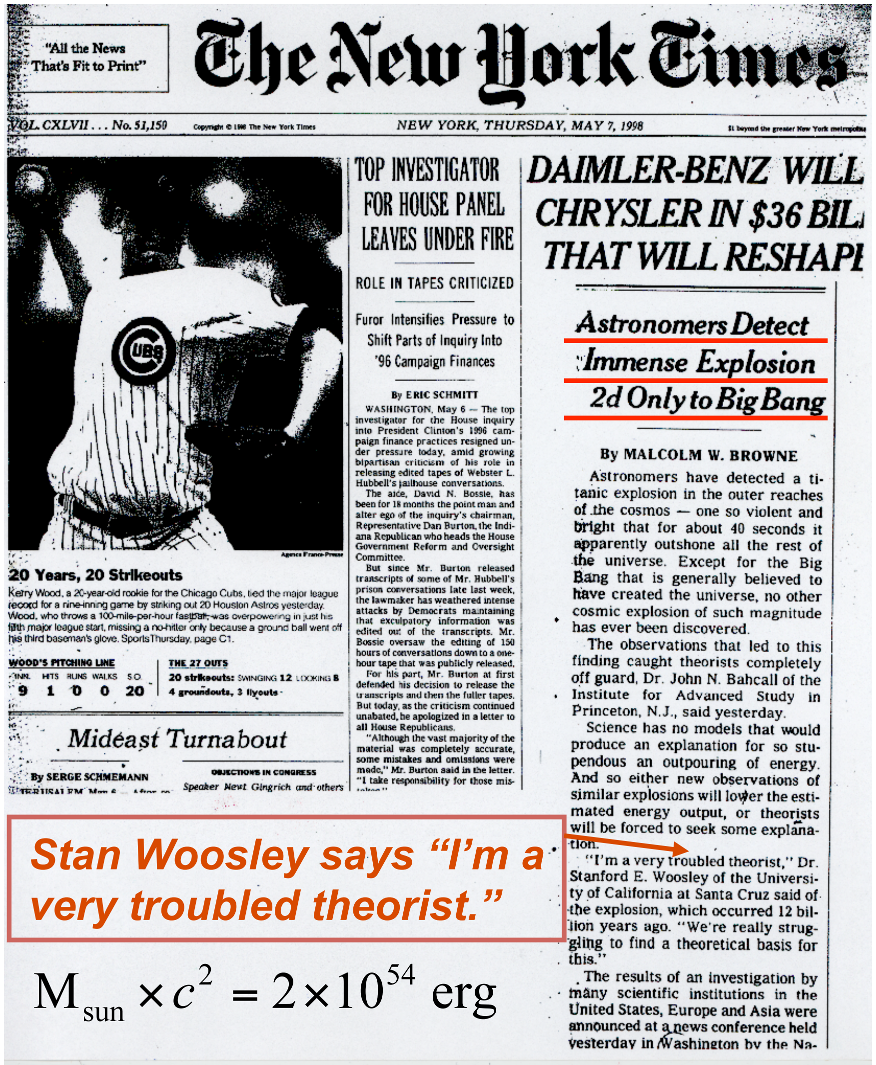
Talk outline

- What's past is prologue.
  - The energy crisis, jets and "standard reservoir" for central engines
- Recent developments.
  - Revision of the GRB energy scale in Swift Era
- The future.
  - GRBs in the EVLA Era

Recent work was done in collaboration with:

Brad Cenko, Poonam Chandra, Derek Fox, Shri Kulkarni, Fiona Harrison, Edo Berger, Eran Ofek, Douglas Bock & Mansi Kasliwal

The GRB Energy Crisis circa 1999



"All the News That's Fit to Print"

The New York Times

VOL. CXLVII . . . No. 51,159 — NEW YORK, THURSDAY, MAY 7, 1998

20 Years, 20 Strikeouts

Kerry Wood, a 20-year-old rookie for the Chicago Cubs, tied the major league record for a nine-inning game by striking out 20 Houston Astros yesterday. Wood, who throws a 100-mile-per-hour fastball, was overpowering in just his fifth major league start, missing a no-hitter only because a ground ball went off his third baseman's glove. SportsThursday, page C1.

WOOD'S PITCHING LINE

INN.	HITS	RUNS	WALKS	S.O.
9	1	0	0	20

THE 27 OUTS

20 strikeouts: SWINGING 12 LOOKING 8

4 groundouts, 3 flyouts

Mideast Turnabout

By SERGE SCHMEMANN

OBJECTIONS IN CONGRESS

Speaker Newt Gingrich and others

TOP INVESTIGATOR FOR HOUSE PANEL LEAVES UNDER FIRE

ROLE IN TAPES CRITICIZED

Furor Intensifies Pressure to Shift Parts of Inquiry Into '96 Campaign Finances

By ERIC SCHMITT

WASHINGTON, May 6 — The top investigator for the House inquiry into President Clinton's 1996 campaign finance practices resigned under pressure today, amid growing bipartisan criticism of his role in releasing edited tapes of Webster L. Hubbell's jailhouse conversations.

The aide, David N. Bossie, has been for 18 months the point man and alter ego of the inquiry's chairman, Representative Dan Burton, the Indiana Republican who heads the House Government Reform and Oversight Committee.

But since Mr. Burton released transcripts of some of Mr. Hubbell's prison conversations late last week, the lawmaker has weathered intense attacks by Democrats maintaining that exculpatory information was edited out of the transcripts. Mr. Bossie oversaw the editing of 150 hours of conversations down to a one-hour tape that was publicly released.

For his part, Mr. Burton at first defended his decision to release the transcripts and then the fuller tapes. But today, as the criticism continued unabated, he apologized in a letter to all House Republicans.

"Although the vast majority of the material was completely accurate, some mistakes and omissions were made," Mr. Burton said in the letter. "I take responsibility for those mis-

DAIMLER-BENZ WILL CHRYSLER IN $36 BIL THAT WILL RESHAPE

Astronomers Detect Immense Explosion 2d Only to Big Bang

By MALCOLM W. BROWNE

Astronomers have detected a titanic explosion in the outer reaches of the cosmos — one so violent and bright that for about 40 seconds it apparently outshone all the rest of the universe. Except for the Big Bang that is generally believed to have created the universe, no other cosmic explosion of such magnitude has ever been discovered.

The observations that led to this finding caught theorists completely off guard, Dr. John N. Bahcall of the Institute for Advanced Study in Princeton, N.J., said yesterday.

Science has no models that would produce an explanation for so stupendous an outpouring of energy. And so either new observations of similar explosions will lower the estimated energy output, or theorists will be forced to seek some explanation.

"I'm a very troubled theorist," Dr. Stanford E. Woosley of the University of California at Santa Cruz said of the explosion, which occurred 12 billion years ago. "We're really struggling to find a theoretical basis for this."

The results of an investigation by many scientific institutions in the United States, Europe and Asia were announced at a news conference held yesterday in Washington by the Na-

Stan Woosley says "I'm a very troubled theorist."

$$M_{sun} \times c^2 = 2 \times 10^{54}\ \text{erg}$$

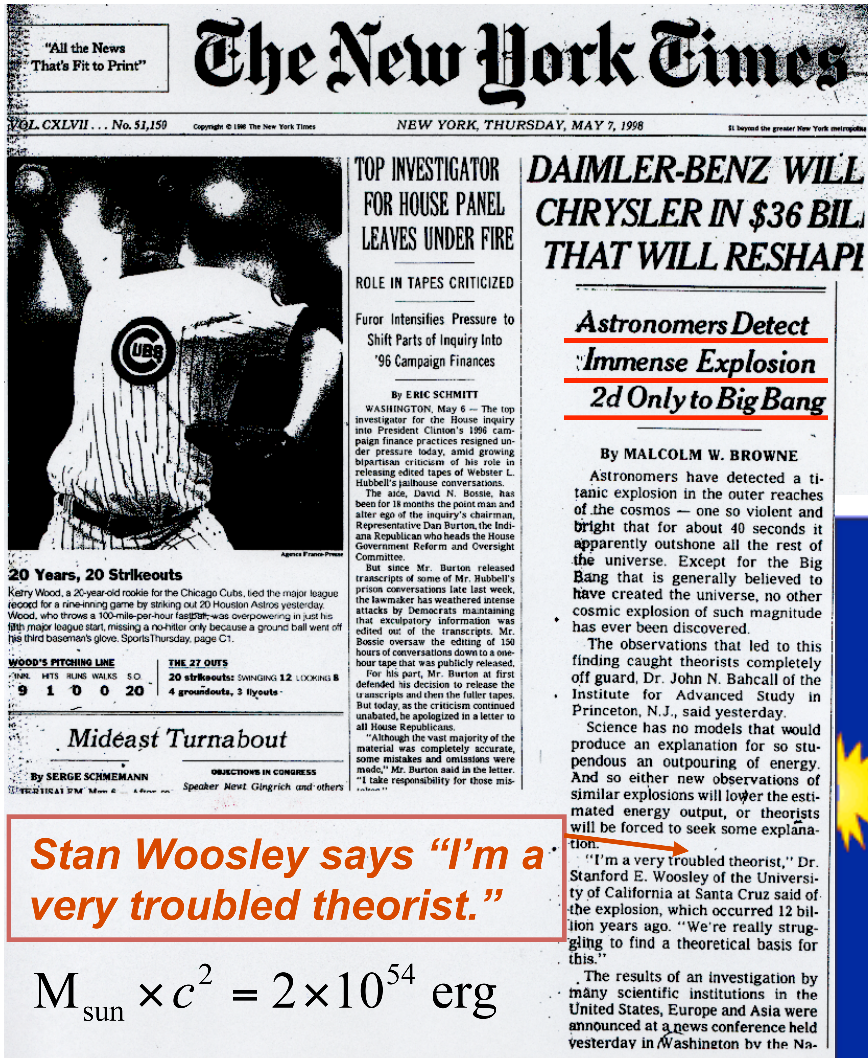
Assuming isotropy, the γ–ray energies spanned three orders of magnitude: 3×10^{51} to 3×10^{54} erg

Central Engine Energy Requirements

$$E_{rel} = E_{\gamma} + E_{inj} + E_{rad} + E_{k,ad}$$

- Magnetar
  - newly formed, rapidly rotating, high B (10^{15} G) NS
  - Erot= ½ I Ω^2=2x10^{52} erg. ε~10% (?) ➔2x10^{51} erg
- Collapsar
  - Newly formed BH + accretion disk, energy drawn from angular momentum of BH + torus system
  - Neutrino annihilation. ε~1% ➔10^{51} erg
  - MHD processes. ε~10%➔10^{53} erg

The GRB Energy Crisis circa 1999



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ApJ 519, L7, 1999

JETS IN GAMMA-RAY BURSTS

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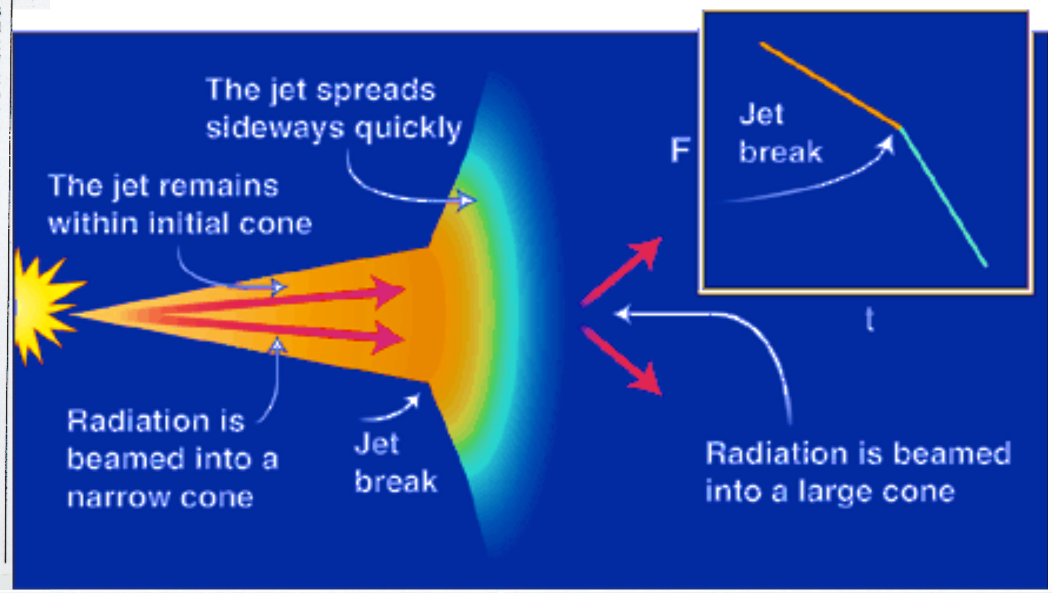
Received 1999 March 23; accepted 1999 May 3; published 1999 May 25

ABSTRACT

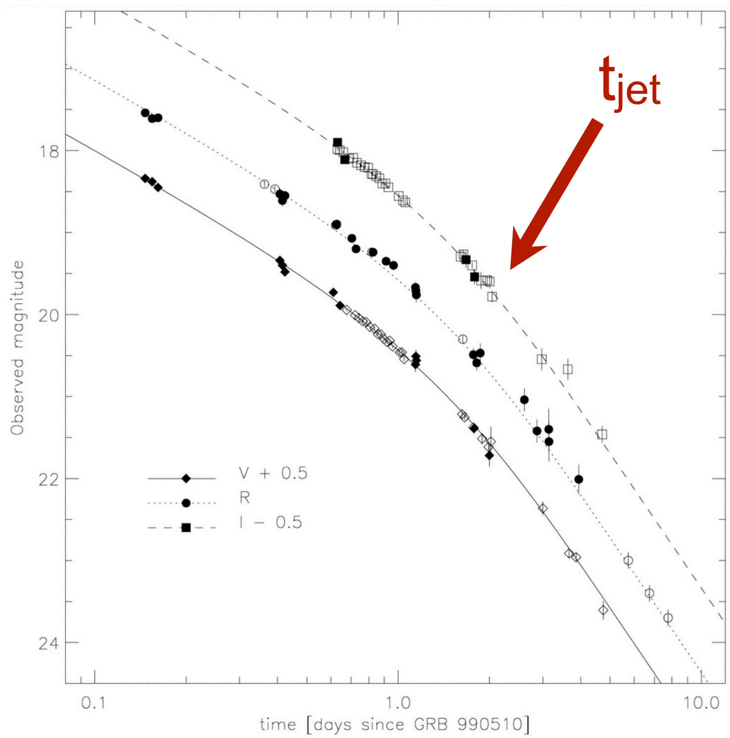
In the afterglows of several gamma-ray bursts (GRBs), rapid temporal decay, which is inconsistent with spherical (isotropic) blast-wave models, is observed. In particular, GRB 980519 had the most rapidly fading of the well-documented GRB afterglows, with $t^{-2.05 \pm 0.04}$ in optical as well as in X-rays. We show that such temporal decay is more consistent with the evolution of a jet after it slows down and spreads laterally, for which t^{-p} decay is expected (where p is the index of the electron energy distribution). Such a beaming model would relax the energy requirements on some of the more extreme GRBs by a factor of several hundred. It is likely that a large fraction of the weak- (or no-) afterglow observations are also due to the common occurrence of beaming in GRBs and that their jets have already transitioned to the spreading phase before the first afterglow observations were made. With this interpretation, a universal value of $p \simeq 2.4$ is consistent with all data.

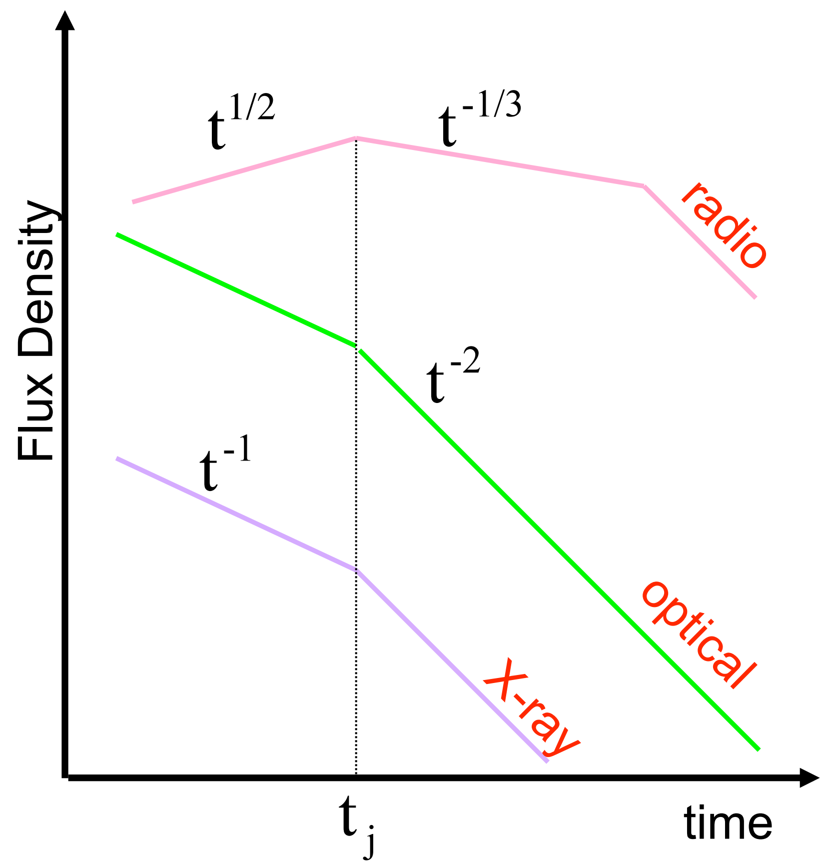
Subject headings: gamma rays: bursts — hydrodynamics — relativity — shock waves



Piran, Science, 08 Feb 2002

Jet Signatures





Harrison et al. 1999

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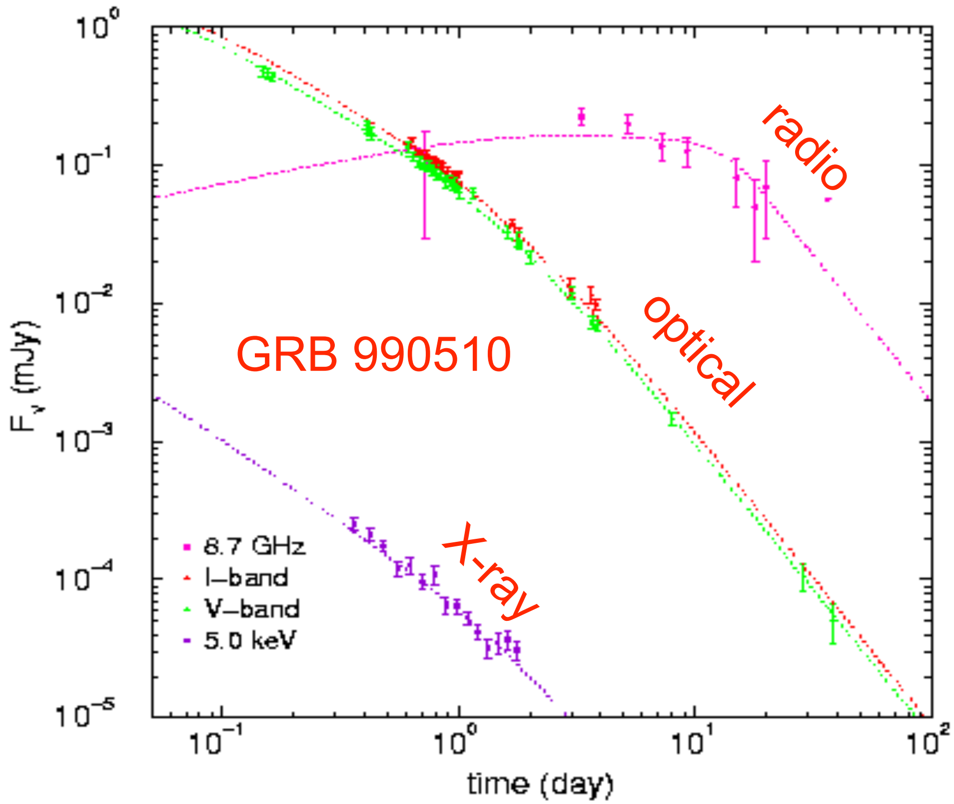
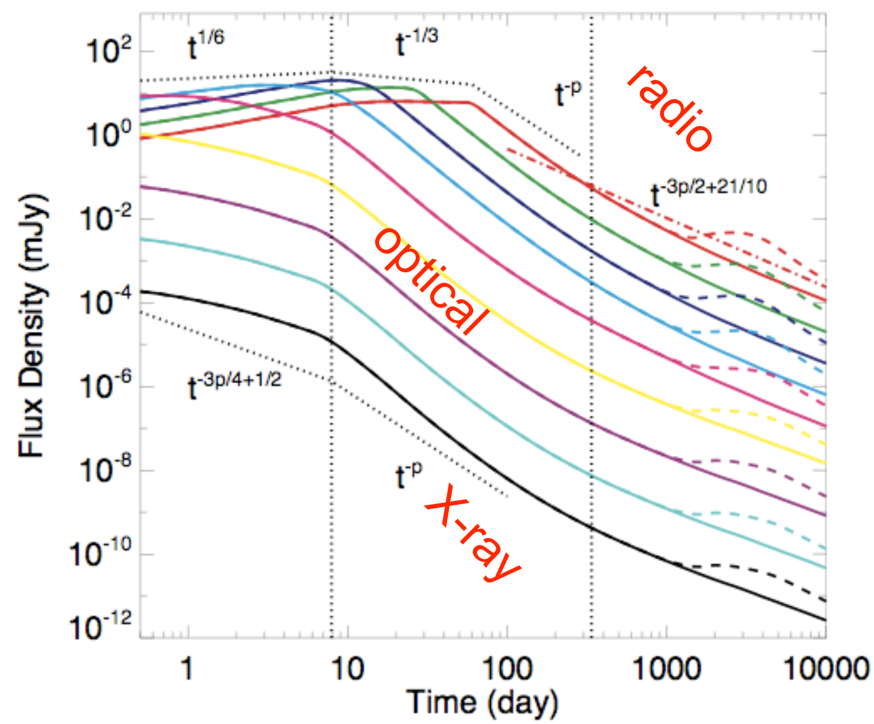
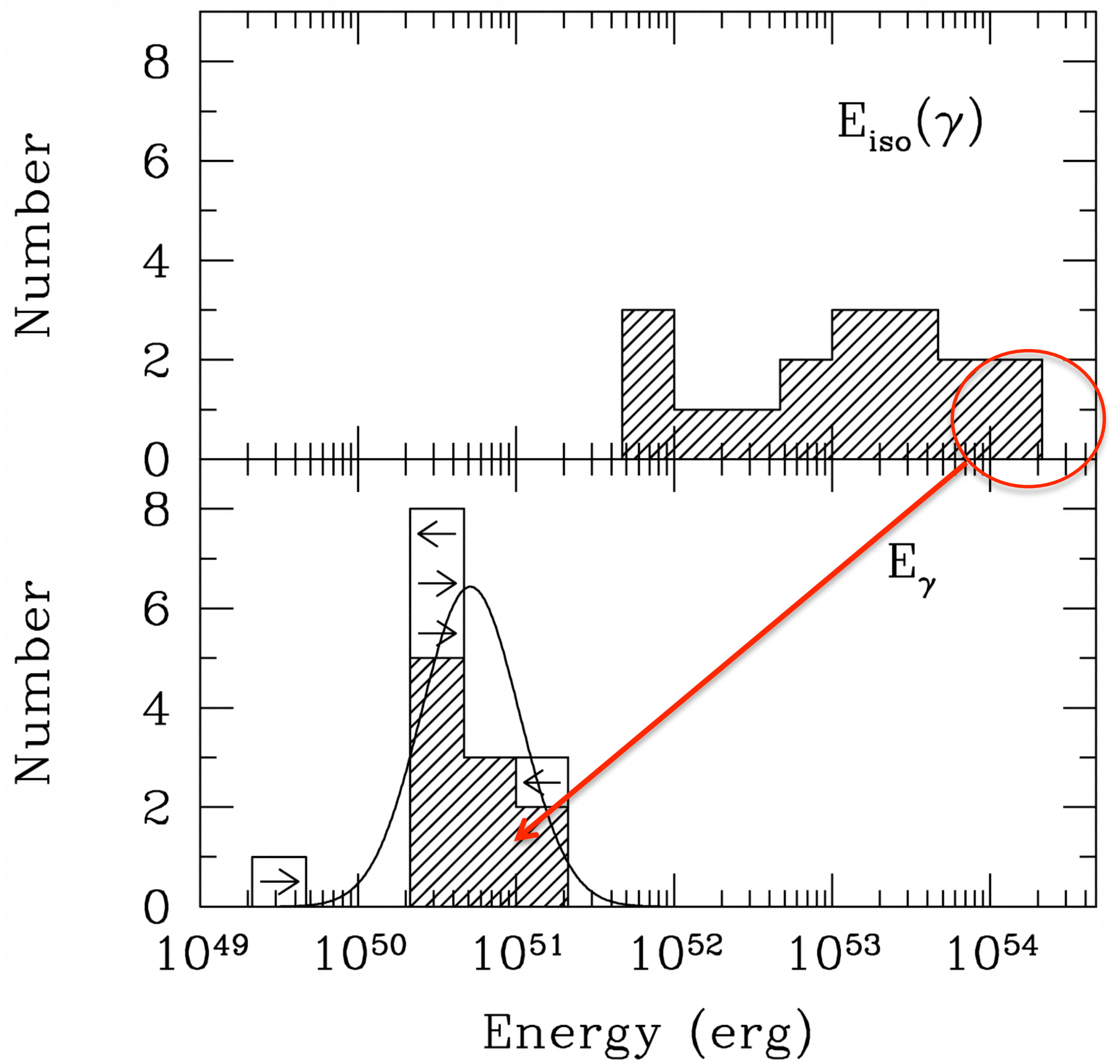


Panaitescu and Kumar (2001)



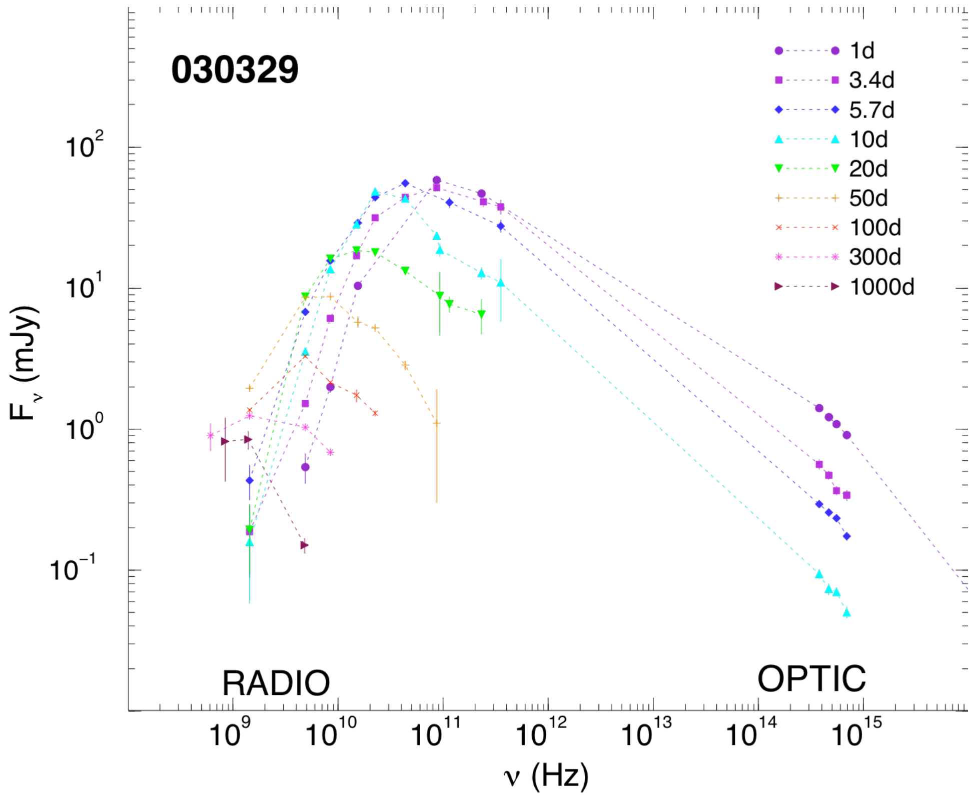
Zhang & MacFadyen (2009).
See also Granot et al. (2001) and
Van Eerten et al. (2009)

The GRB Energy Crisis Resolved

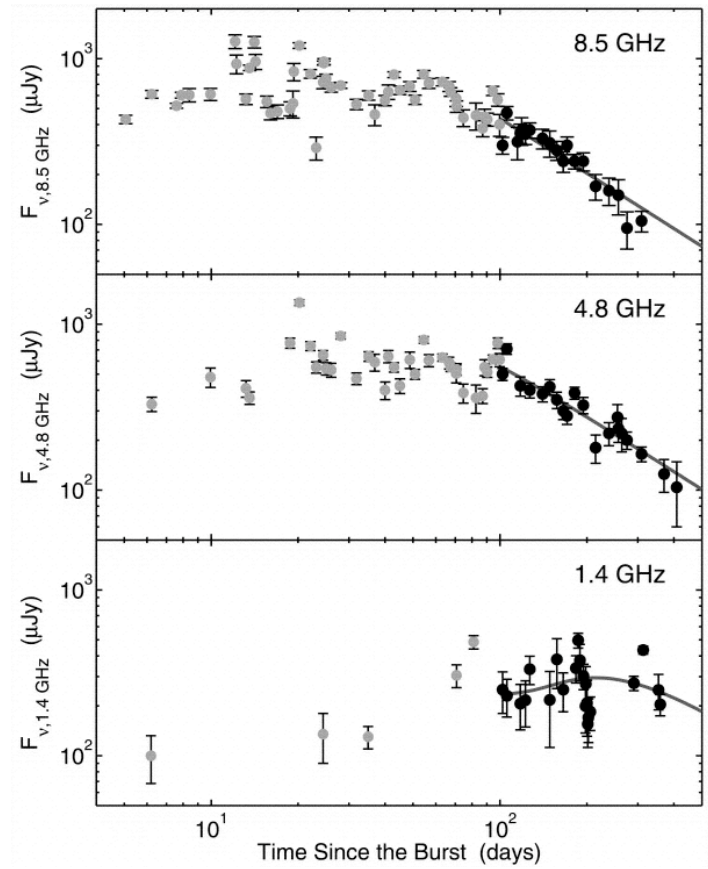


Frail et al (2001)

Other Methods of Estimating Energy



Panaitescu (2009)



Berger et al. (2004)

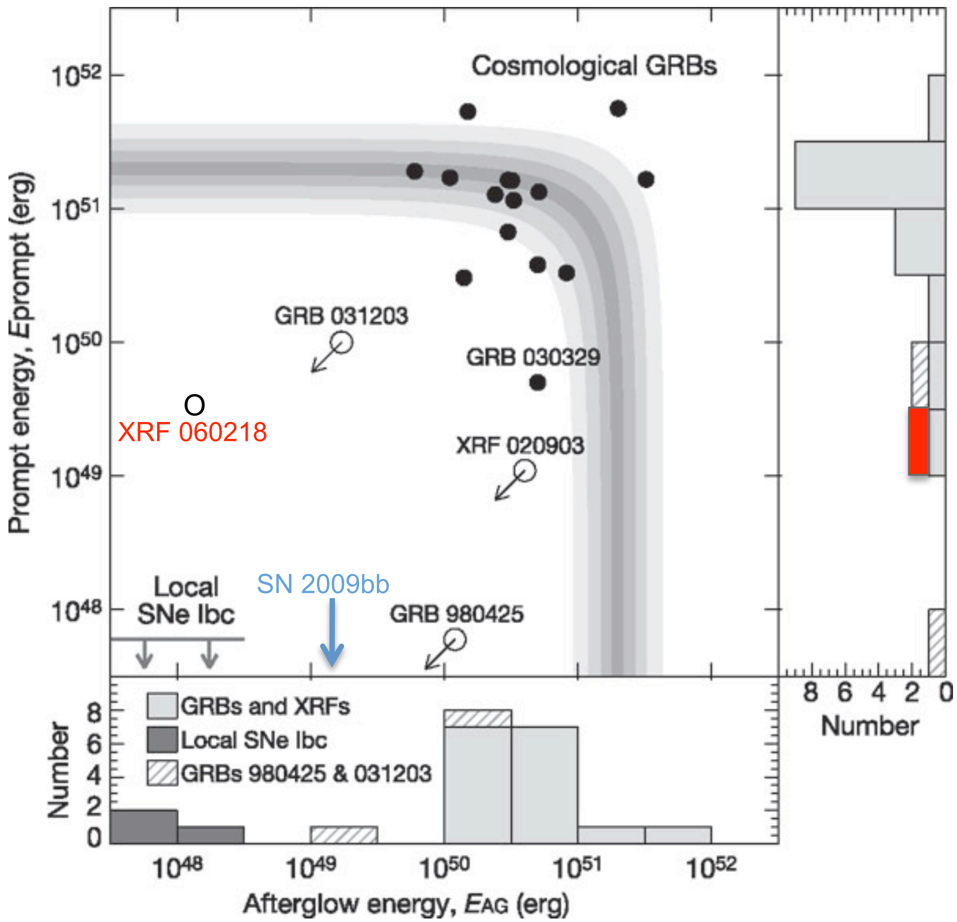
That was then…

- The GRB energy crisis was resolved
- GRB outflows are highly beamed (θ ~ 1-10 degrees)
- Geometry measured from jet break signature in light curves
- Beaming-corrected radiated energies are narrowly distributed around a "standard" value of $\sim 10^{51}$ erg
- A host of other measurements (X-ray afterglows, broadband modeling, calorimetry) support this energy scale
- This energy scale is consistent with models of GRB central engines

This is now…

1. The established class of sub-energetic gamma-ray bursts.
2. The mystery of the missing jets in the Swift era.
3. The emerging population of hyper-energetic events.

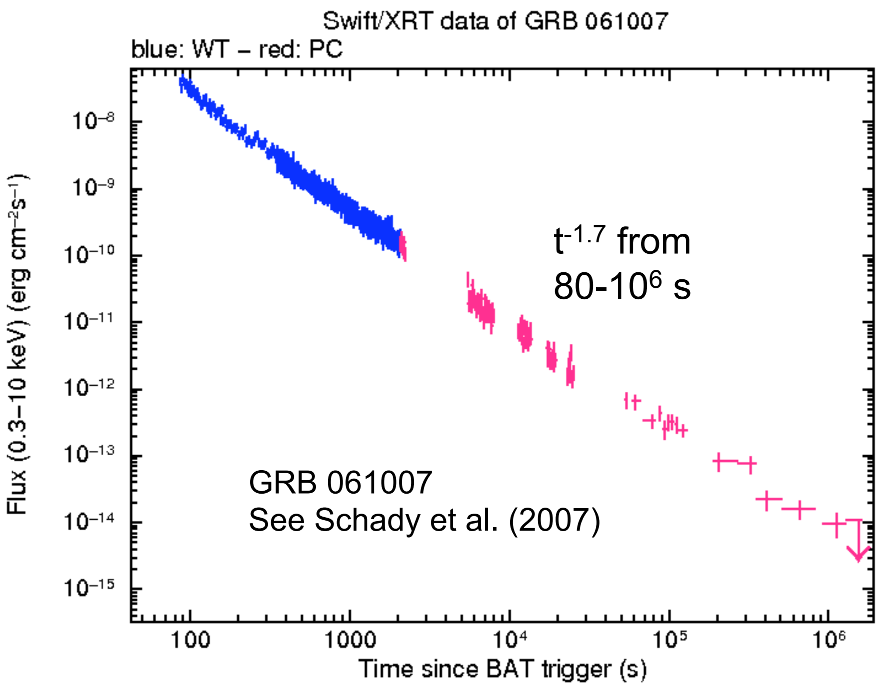
The Class of Sub-Energetic GRBs



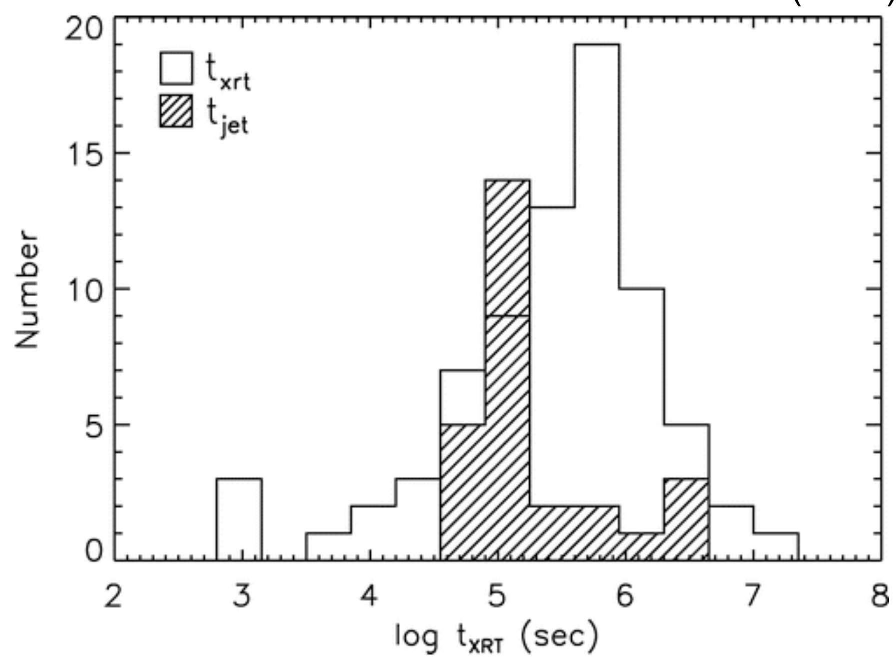
Soderberg et al. (2004)

- Low luminosity (10^{47} erg/s) gamma-ray emission (smooth l.c.)
- Quasi-isotropic, mildly relativistic ejecta. Radio traces rel. ejecta.
- 100X less relativistic energy
- >10X more common (by volume)
- CC SNe ➔ LL GRBs ➔ HL GRBs viewed as sequence of greater efficiency of conversion of total energy into relativistic ejecta energy
- LL GRBs a distinct central engine or variation of SNe explosion?

GRB Energetics in Swift Era. Missing Jets?



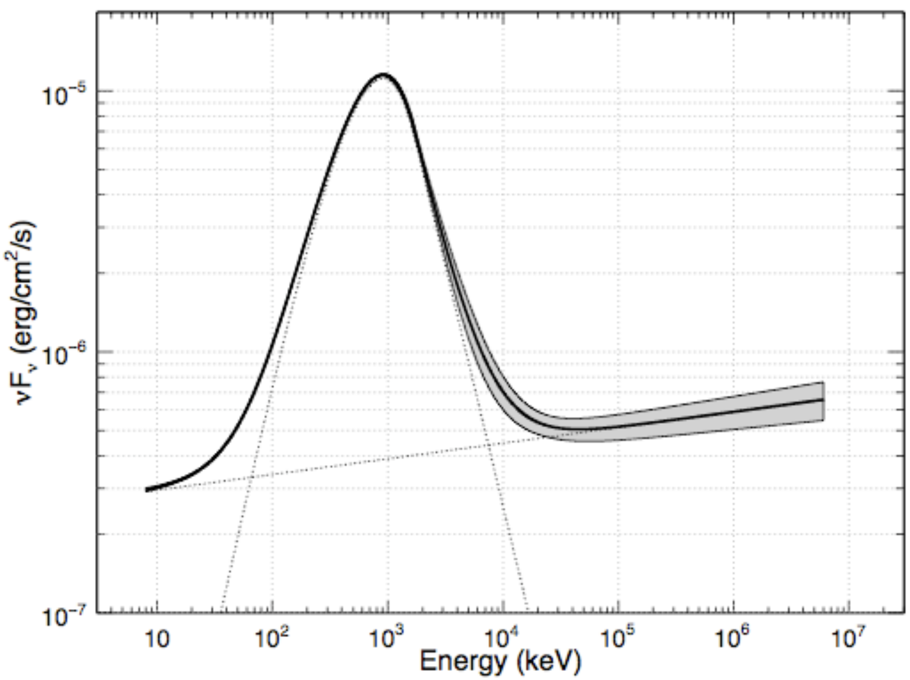
Koceveski & Butler (2008)



Fewer than 10% of all *Swift* X-ray light curves show breaks consistent with a jet-like outflow.

Swift Complications: Soft Energy Response

GRB 090902B



Abdo et al., 2009

- 15-350 keV BAT bandpass provides limited spectral coverage
- Often miss E_{peak}
- Leads to large uncertainties in $E_{\gamma,iso}$

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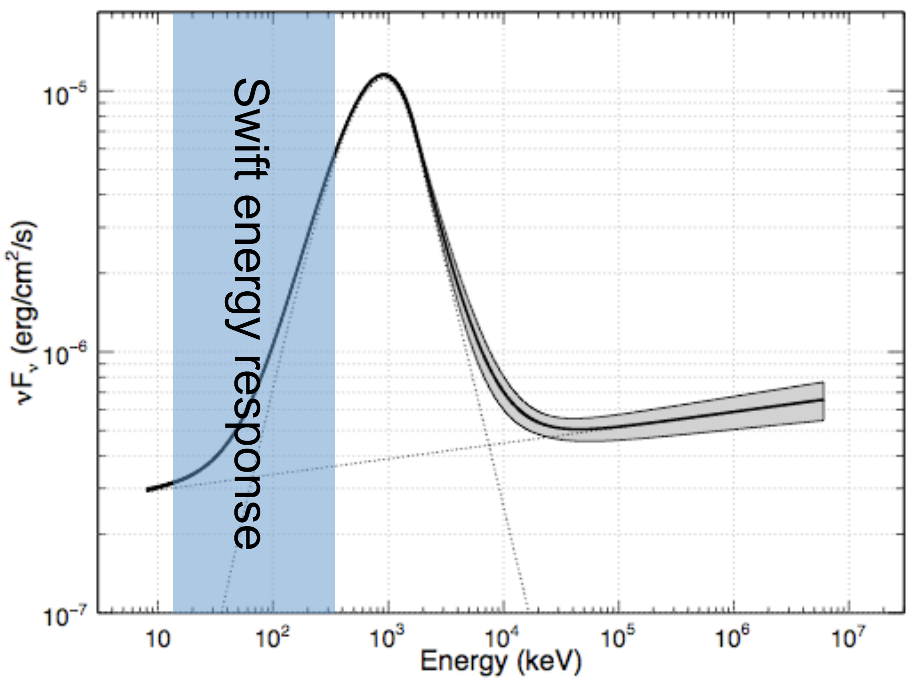

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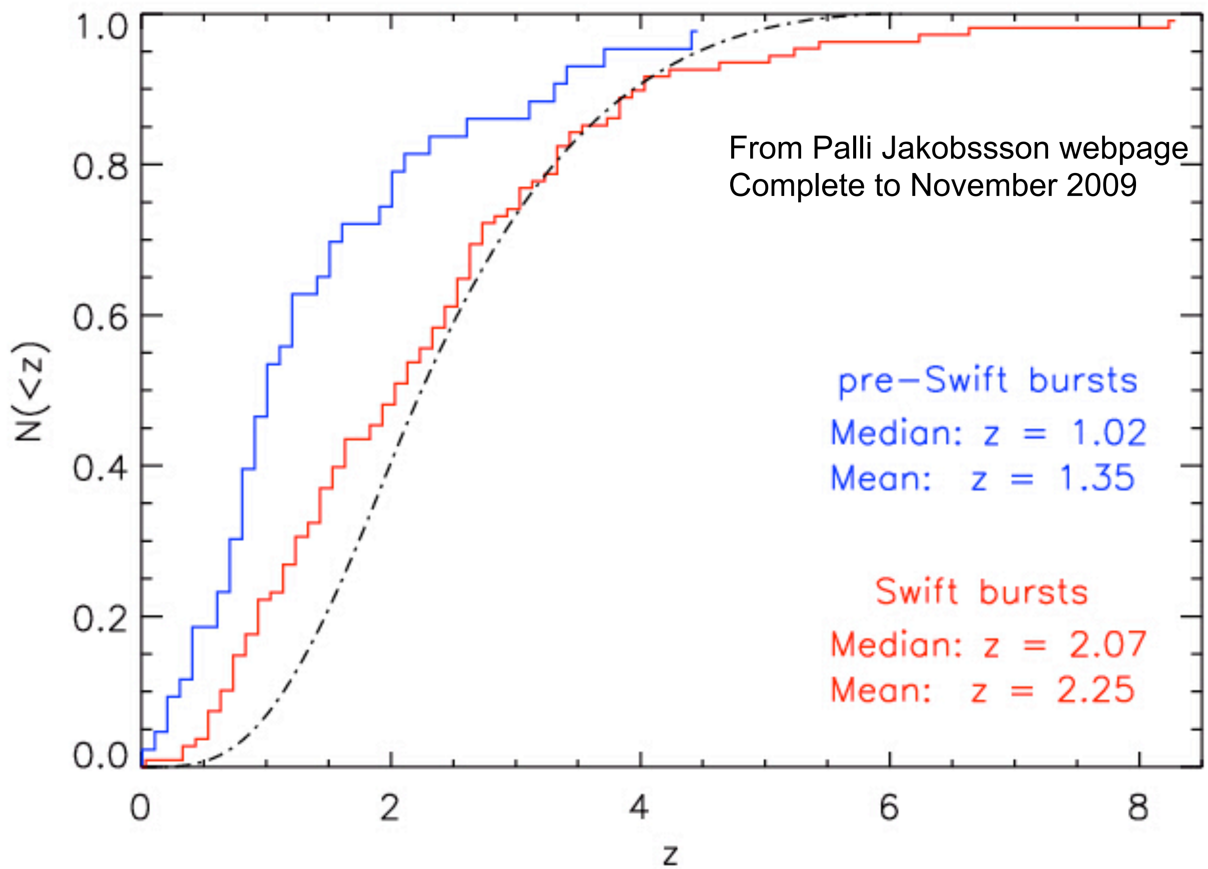
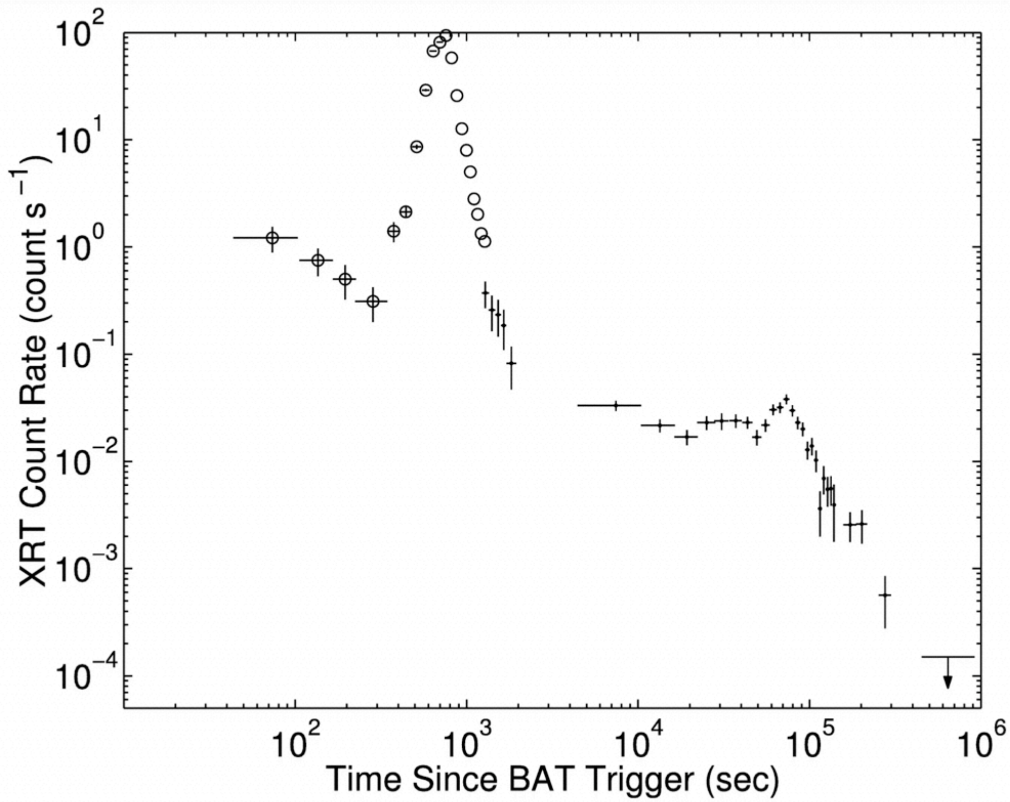
Swift Complications: Redshift



Median Swift redshift 2X higher. Shifts t_{jet} to later times.

Swift Complications: Energy Injection

- Bright flares and long-lived plateau phases in X-ray afterglows
- Can inject significant amount of energy into forward shock (Ek)



Falcone et al. 2005

The Jets Mystery - Summarized

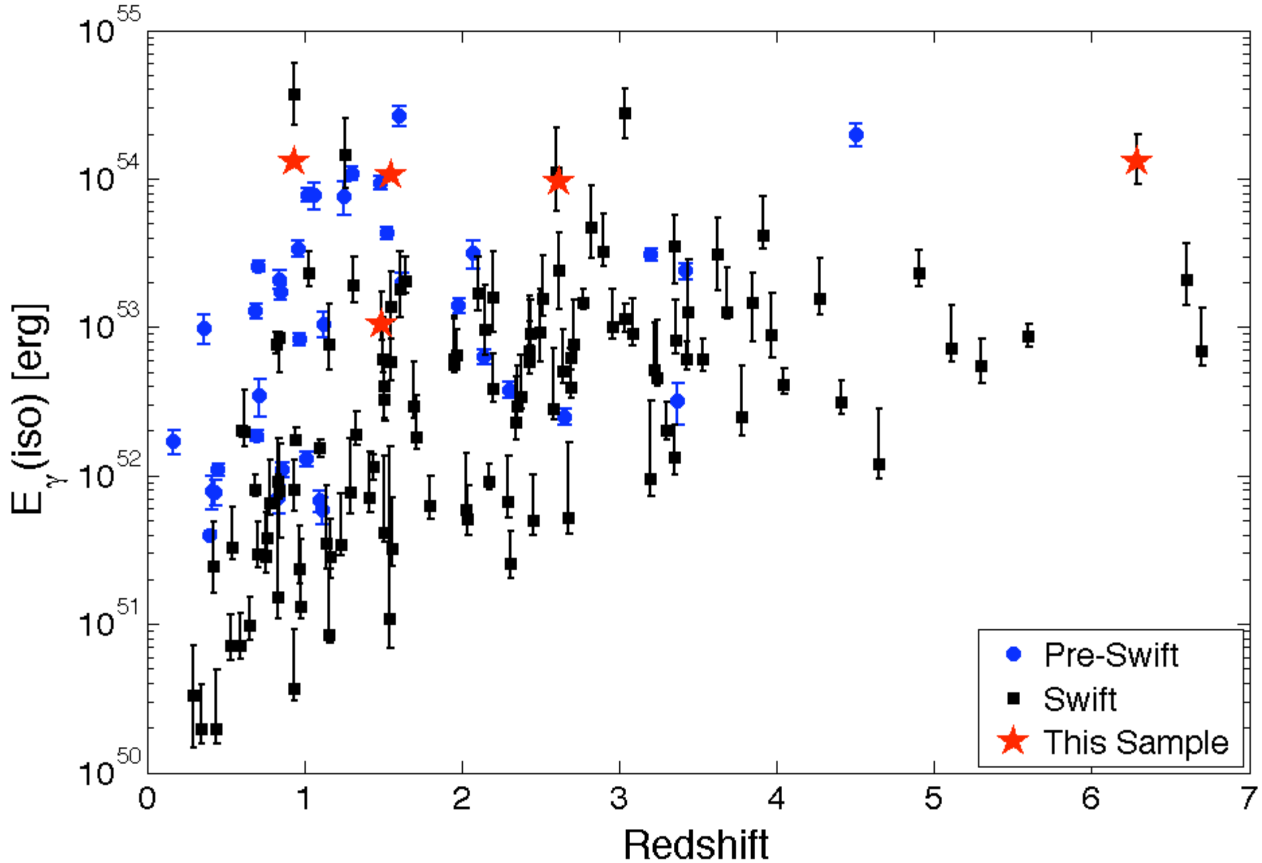
- *Swift* is more sensitive but has a softer energy response
- Median redshift higher. Shifts t_{jet} to later times.
  - Perna et al. predicted shift to larger t_{jet} & θ_{jet} pre-launch
  - Panaitescu notes that AG flux and t_{jet} anti-correlated

$$F_\nu \propto dE/d\Omega \propto \vartheta_{jet}^{-2} \propto t_{jet}^{-1} \quad (E_{jet} = const)$$

- Lack of breaks in X-ray light curves masked by other effects
  - Ongoing-energy injection (central engine and refreshed shocks), inverse Compton contribution, multiple-emission components, etc

Mystery? Not really. Jets are real. Harder to identify.

The Bright *Swift* GRB Sample



Cenko et al. 2009

The tightest constraints on GRB central engine models come from outliers at the high end of the energy distribution

GRB 050820A

Redshift z=2.615

$E_{\gamma,iso}$=9.7x10^{53} erg

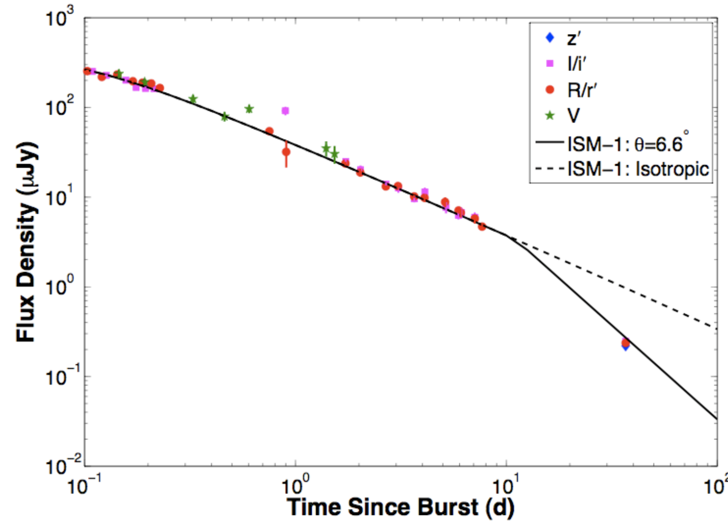
Achromatic jet break at t_{jet}=11.1 d

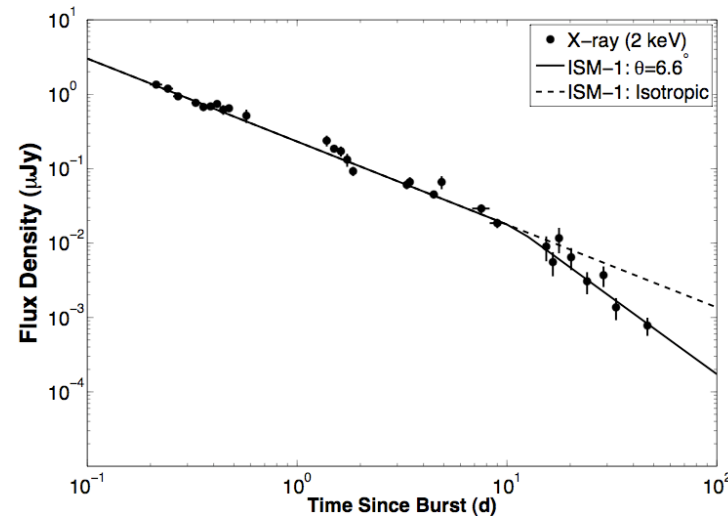
E_{γ}=6.4x10^{51} erg

Multi-wavelength afterglow fit:

Θ_{jet}=6.6 deg

E_k=35.6x10^{51} erg





Cenko et al. 2009

GRB 070125

Redshift z=1.547

$E_{\gamma,iso}$=1.1x10^{54} erg

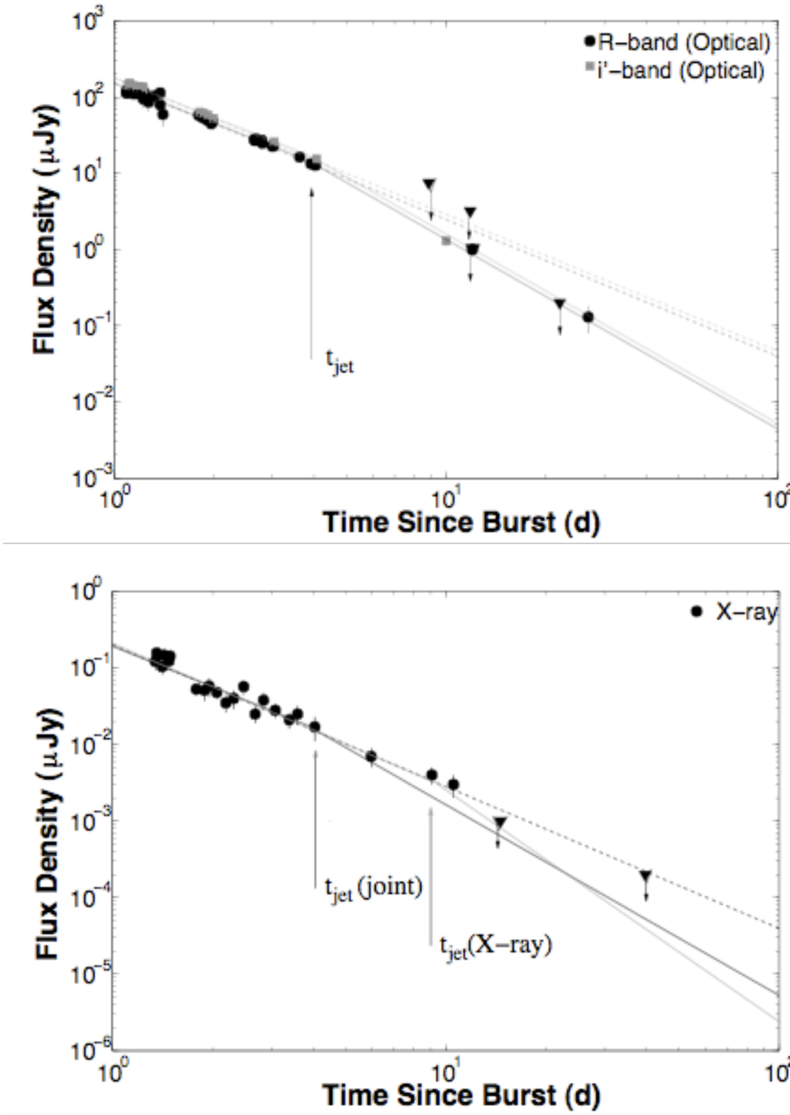
Achromatic jet break at t_{jet}=3.7 d

E_{γ}=25.3x10^{51} erg

Multi-wavelength afterglow fit:

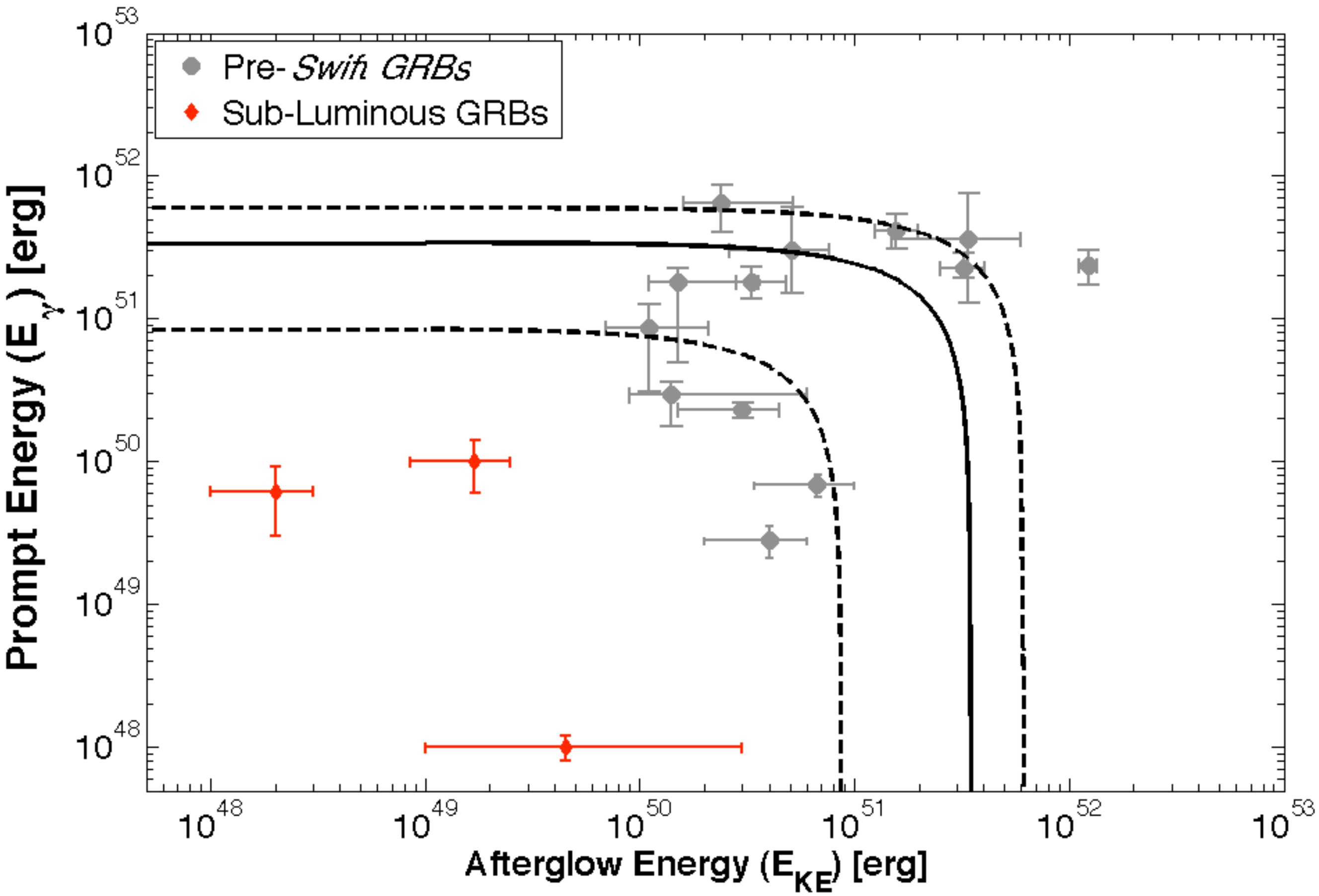
Θ_{jet}=13.2 deg

E_k=1.7x10^{51} erg



Chandra et al. 2008

Swift Energetics Results



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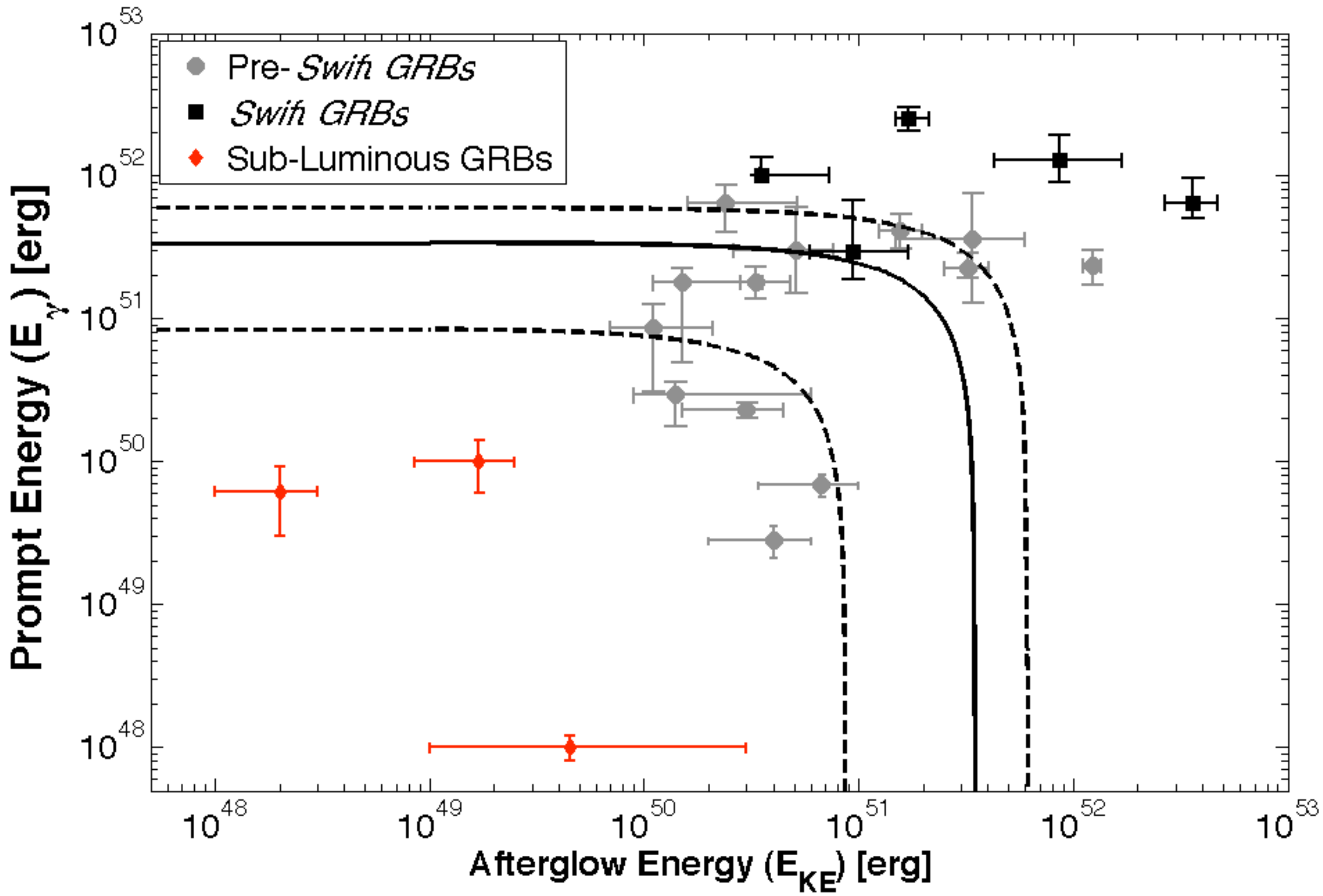
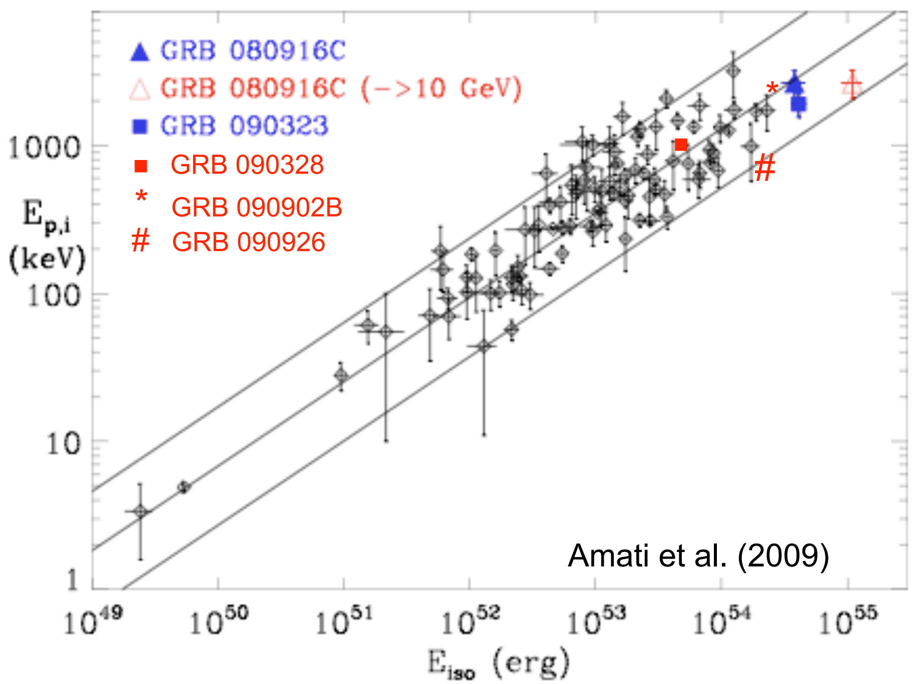
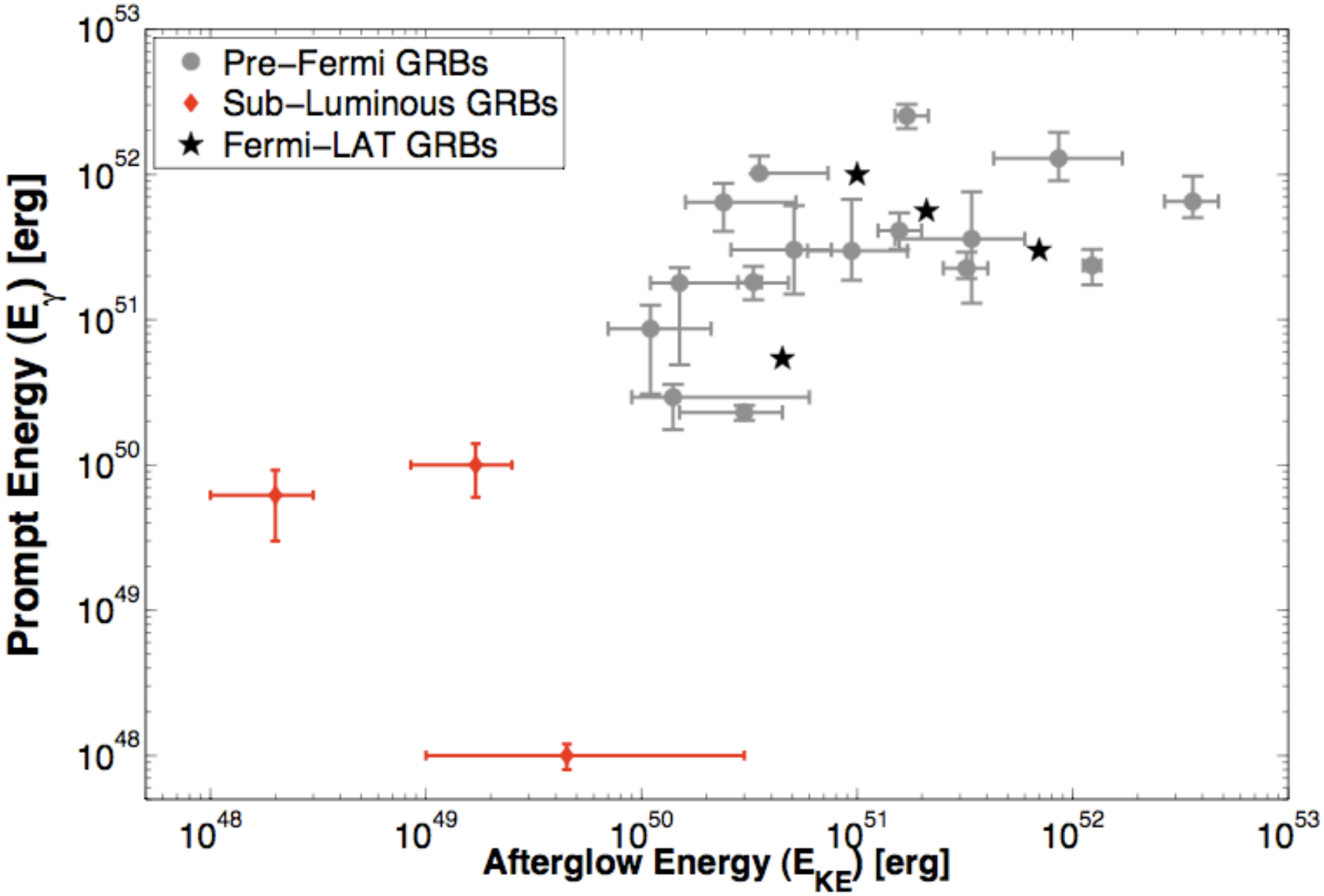


Fermi. The next step.



- GBM + LAT (8 keV-300 GeV) versus *Swift* BAT (15-350 keV)
- *Fermi*'s response self-selects high E_{iso} events
  - *Brighter* afterglows
- *Fermi* sensitive additional GeV spectral components
- Cycle 1. Broadband follow up of 4 LAT long duration GRBs with known redshift

Fermi Energetics Results (Preliminary)



GRB 090323, GRB 090328, GRB 090902B, GRB 090926

Hyper-Energetic Events

- Several GRBs with high beaming-corrected energies for which we have multi-wavelength afterglow datasets with measured jet breaks. Recent examples include -
  - GRB 090323 $z=3.57$ $E_{iso}=4.1\times10^{54}$ erg $\theta_{jet}=10$ deg
  - GRB 090424 $z=8.26$ $E_{iso}=1.0\times10^{53}$ erg $\theta_{jet}>12$ deg
- High E_{iso} events with X-ray or optical/NIR afterglow data that shows no jet breaks. Examples include –
  - GRB 061007 $z=1.26$ $E_{iso}=1.0\times10^{54}$ erg
  - GRB 080916C $z=4.35$ $E_{iso}=8.8\times10^{54}$ erg
  - Interesting but less secure limits on E_γ and E_k
  - Could be either *narrowly beamed* canonical GRBs or wide-angle, *hyper-energetic* events.

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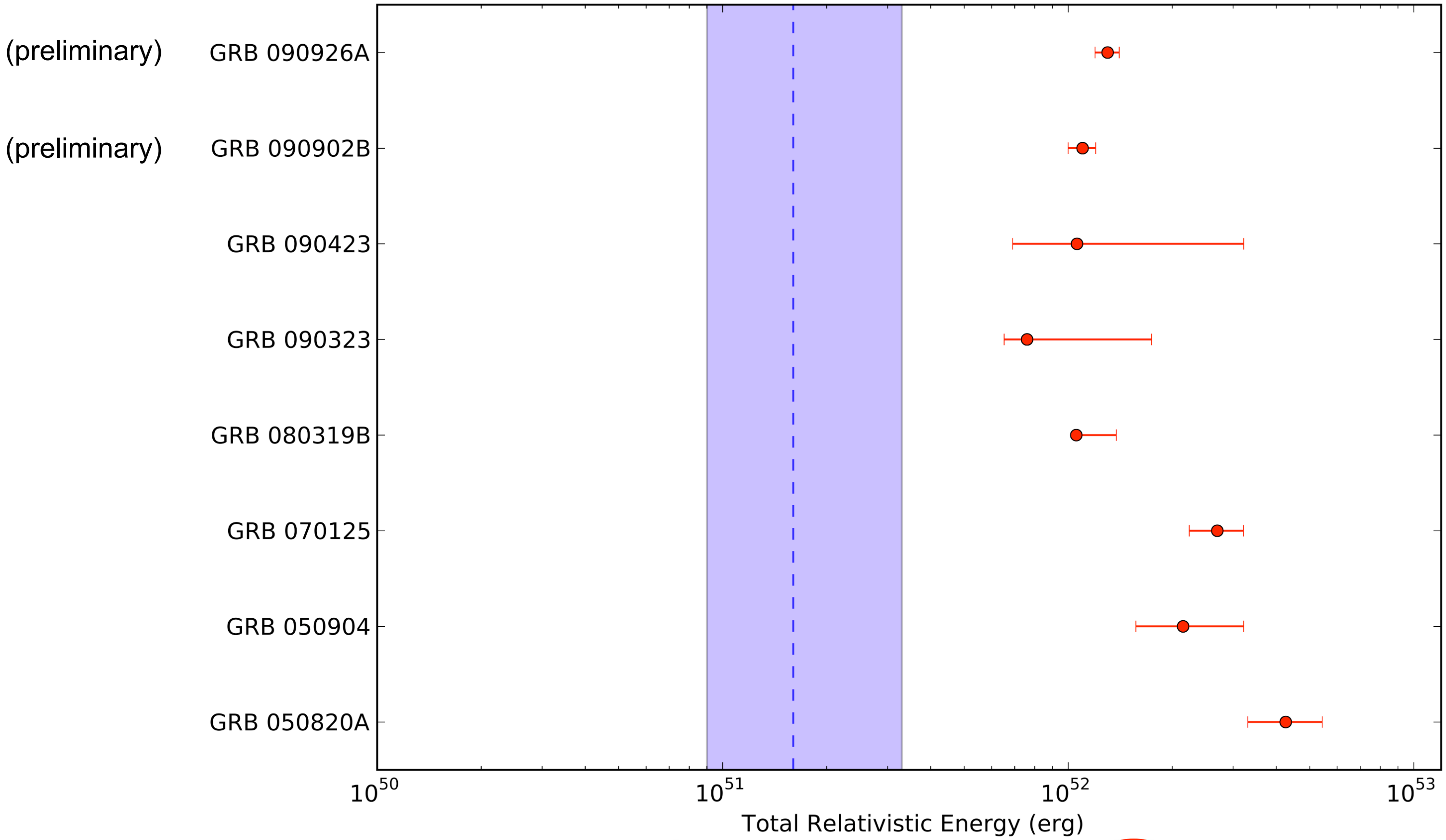
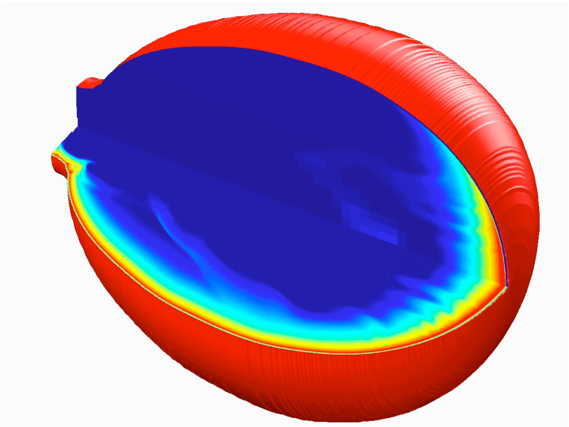
Fermi Energetics Results (Preliminary)



$$E_{rel} = E_{\gamma} + E_{inj} + E_{rad} + E_{k,ad}$$

An Emerging Population. Hype or Hyper?

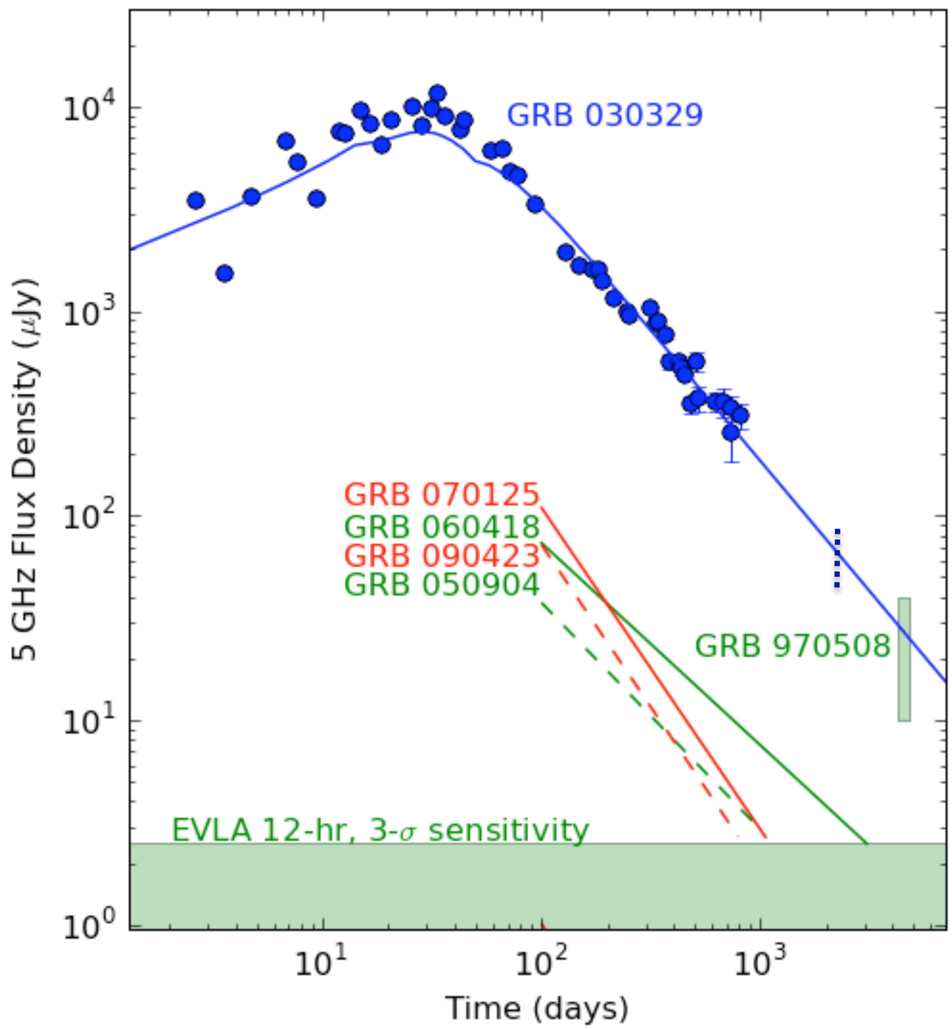
- These energy (and geometry) estimates are ultimately model dependent and require high quality afterglow data
- Need an alternate method that is independent of
  - (a) early central engine activity,
  - (b) outflow geometry and
  - (c) specific afterglow models



An Emerging Population. Hype or Hyper?

- Late-time (radio) Calorimetry
  - Fireball becomes non-relativistic, quasi-spherical
  - Outflow described by robust Sedov-Taylor formulation
  - Recent relativistic hydrodynamics simulations show that the transition to Sedov-Taylor slower than analytic predictions
  - Method has been limited to bright GRBs (970508, 980703 and 030329). EVLA can study hyper-energetic GRBs

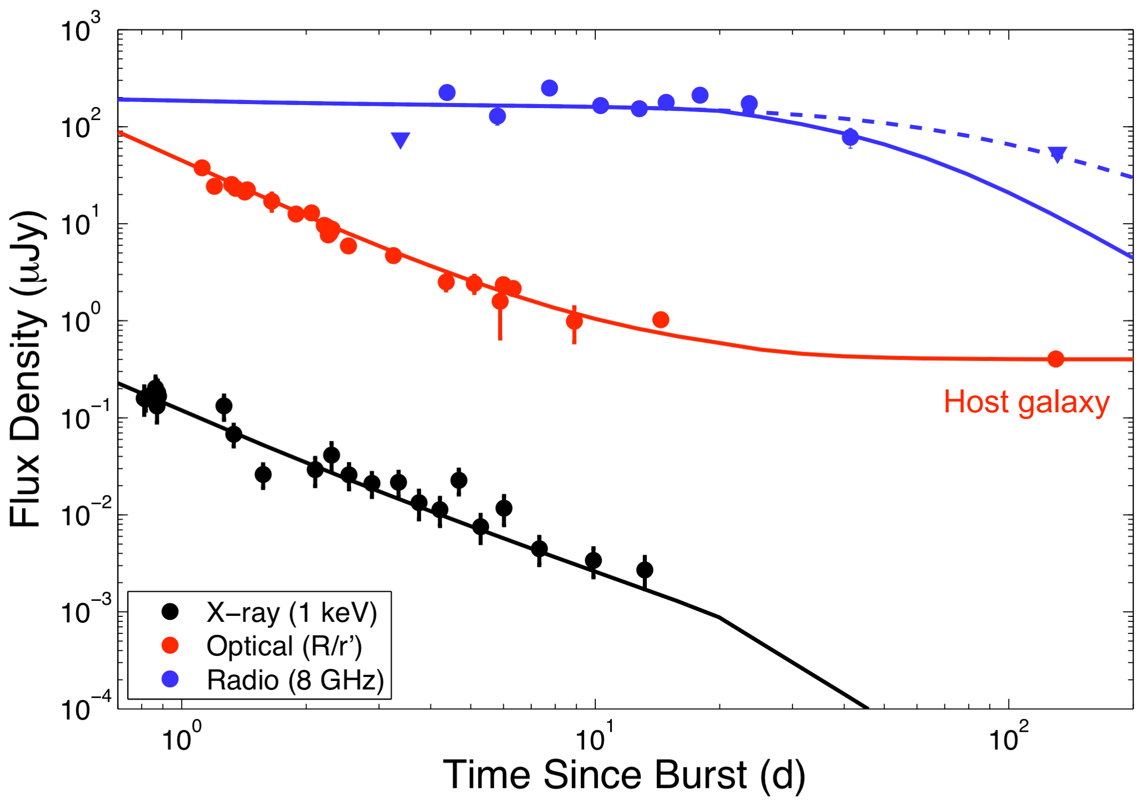
EVLA Calorimetry of Hyper-Energetic GRBS



Summary

- GRB energetics remains an important clue to understanding the relation of long-duration GRBs with CC SNe, and for constraining central engine models
- Jets still exist but they need the right set of measurements.
- GRB energy scale appears to be broader than pre-*Swift* era
  – Strong evidence for a distinct class of under-energetic events linking CC SNe and cosmological GRBs
  – Growing case to be made for a population of hyper-energetic events ($E_{rel}>10^{52}$ erg)
- Better calorimetry needed to verify energy distribution

Hyper-energetic Fermi burst



Cenko et al. in prep (2009)

GRB 090323 at z=3.27

Preliminary modeling

Multi-wavelength afterglow fit by a hyper-energetic explosion with wide-angle jet-like outflow

θ_{jet}=10 deg

E_k=3.2x10^{51} erg

E_γ=66x10^{51} erg

(A*=2.1 ε_e=0.28, ε_B=0.01%, p=2.59)