Multi-wavelength afterglow observations

A view of GRB energetics from the radio end of the spectrum

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

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Talk outline

1. A digression on radio afterglows
2. GRB energetics and the role of multi-wavelength observations
3. Revision of the GRB energy scale in the Swift Era
4. Alternate methods for measuring energy

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

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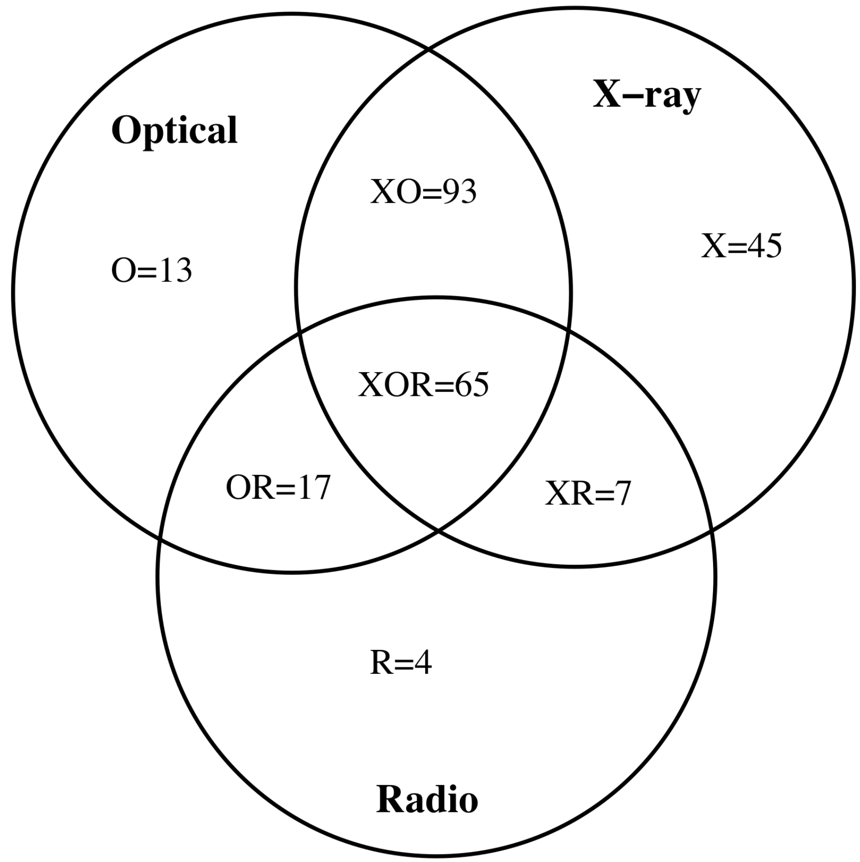
Radio Afterglow Statistics

- 1/3 of all GRBs seen as radio afterglows from 1997 to 2010
  - 93 of 244 events
  - No change Swift-era. Why?
- No strong redshift dependence
  - Equal above/below z=2
  - z<2=47/88. z>2=21/43.
- VLA is the 500 lb gorilla.
  - ATNF, WSRT, GMRT, SMA, CARMA, IRAM 30-m, PdBI
- EVLA (Berger: PI) and ALMA in 2011 will be 5000 lb gorillas

All 1997 to 2010 events



Preliminary

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Radio Afterglow Statistics

Swift-era events only

- 1/3 of all GRBs seen as radio afterglows in Swift-era
  - 46 of 149 events
  - No change Swift-era. Why?
- No strong redshift dependence
  - Equal above/below z=2
  - z<2=47/88.   z>2=21/43.
- VLA is the 500 lb gorilla.
  - ATNF, WSRT, GMRT, SMA, CARMA, IRAM 30-m, PdBI
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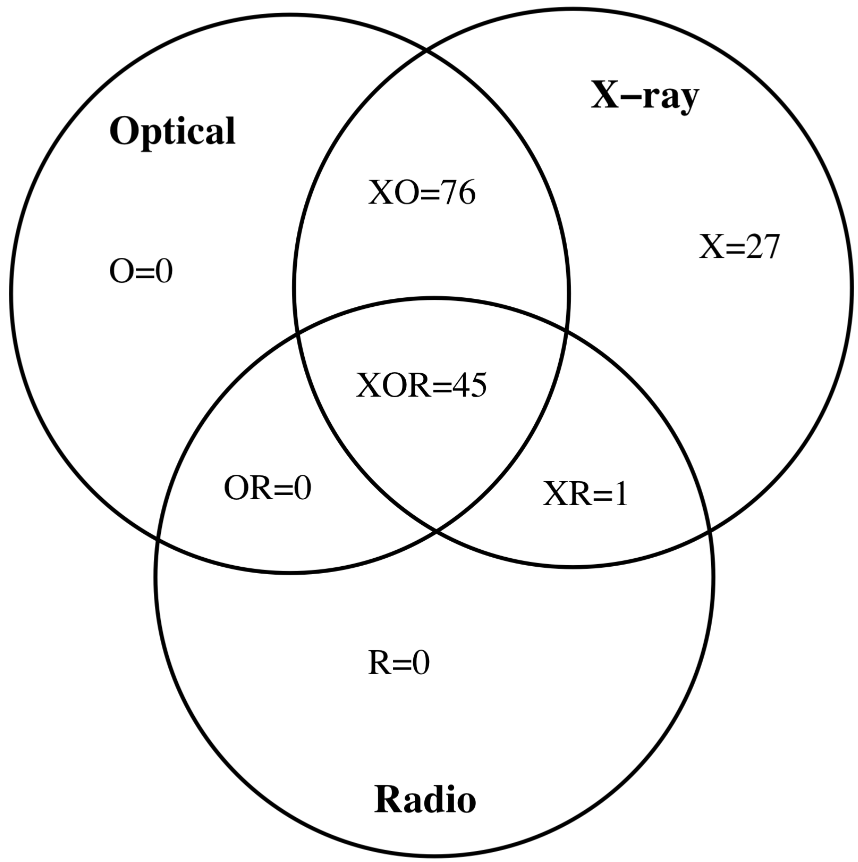

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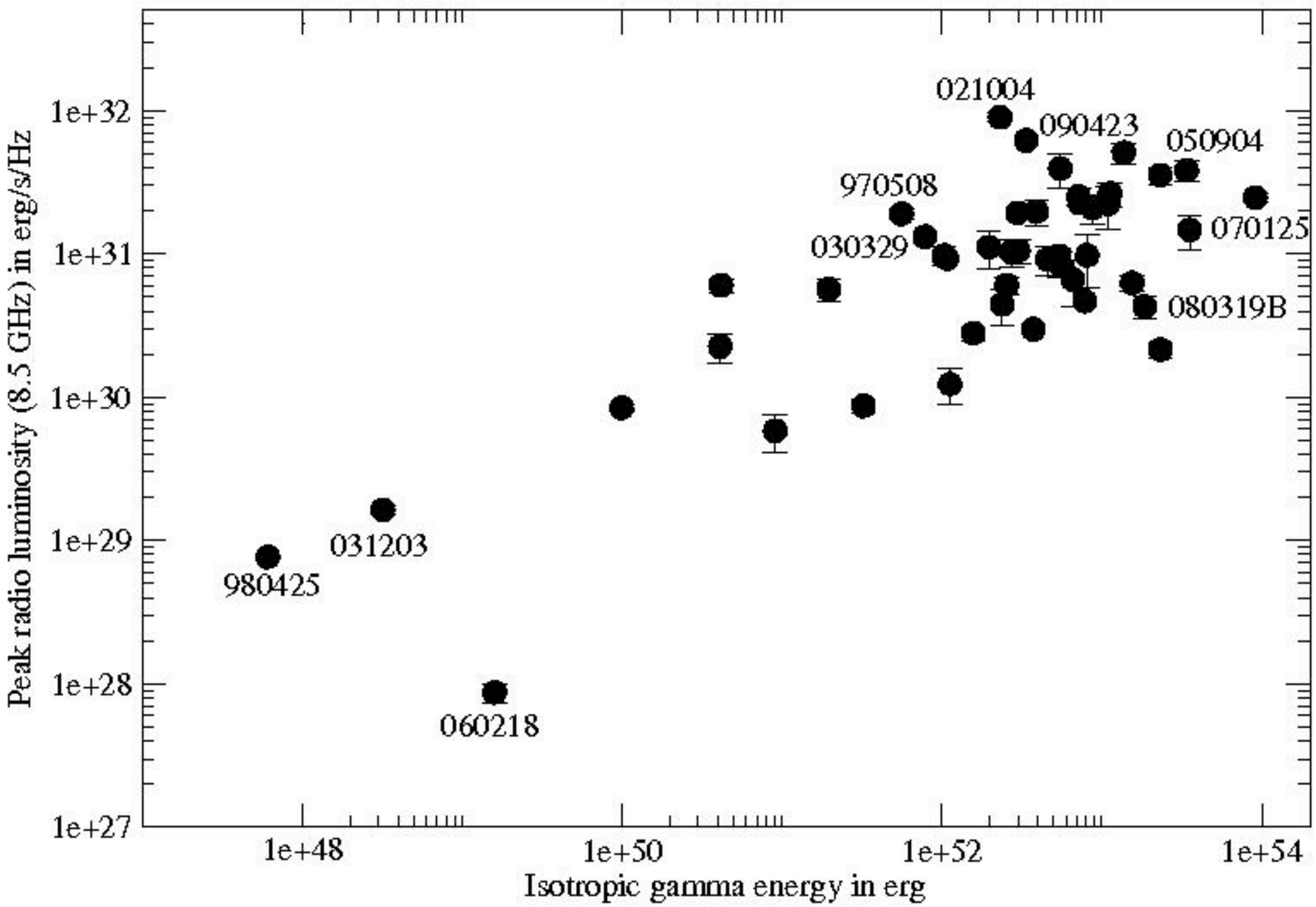
Radio Afterglow Correlations



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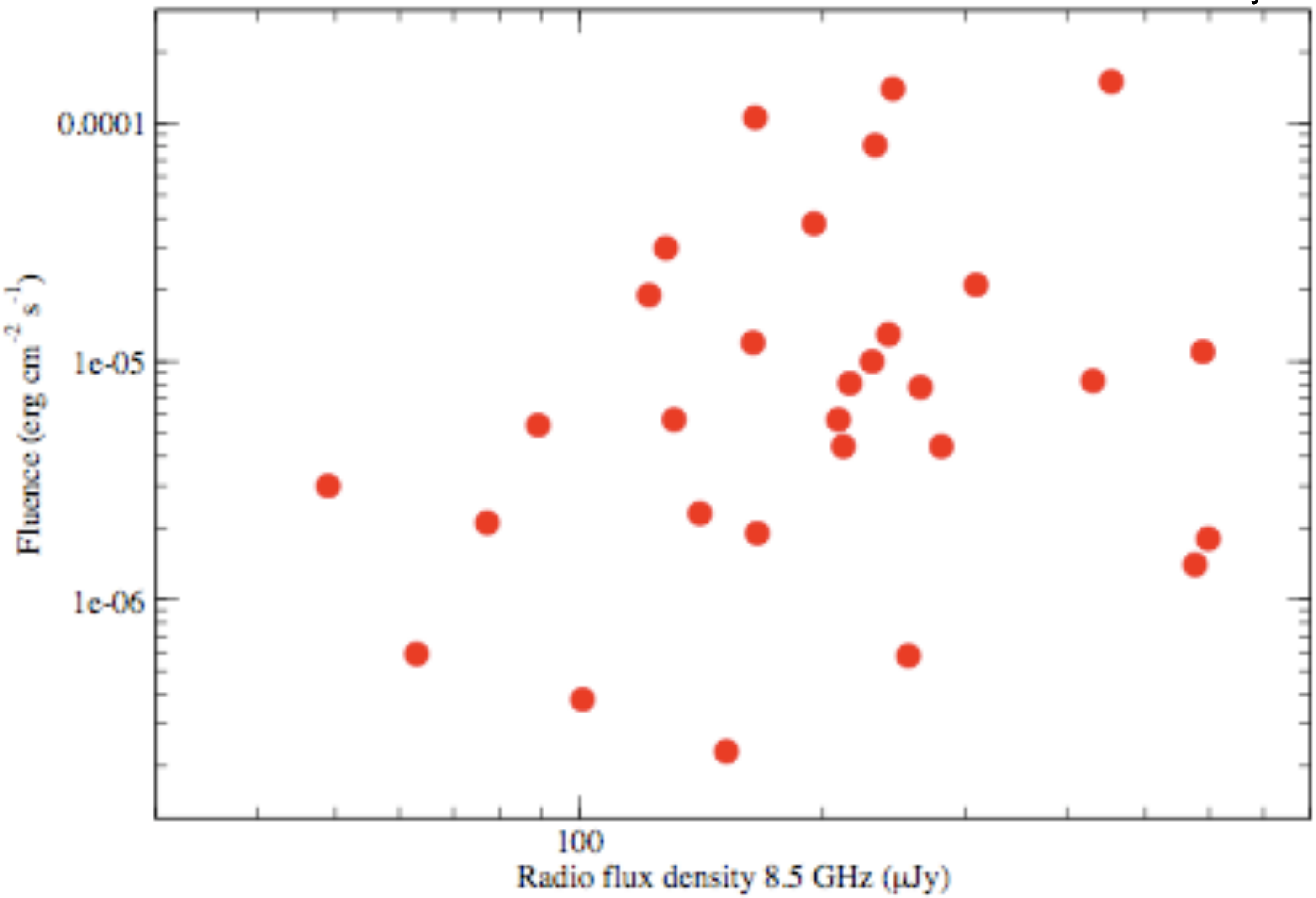
Radio Afterglow Correlations. FAIL!

z>0.4 and mean radio flux between 4 and 10 days.



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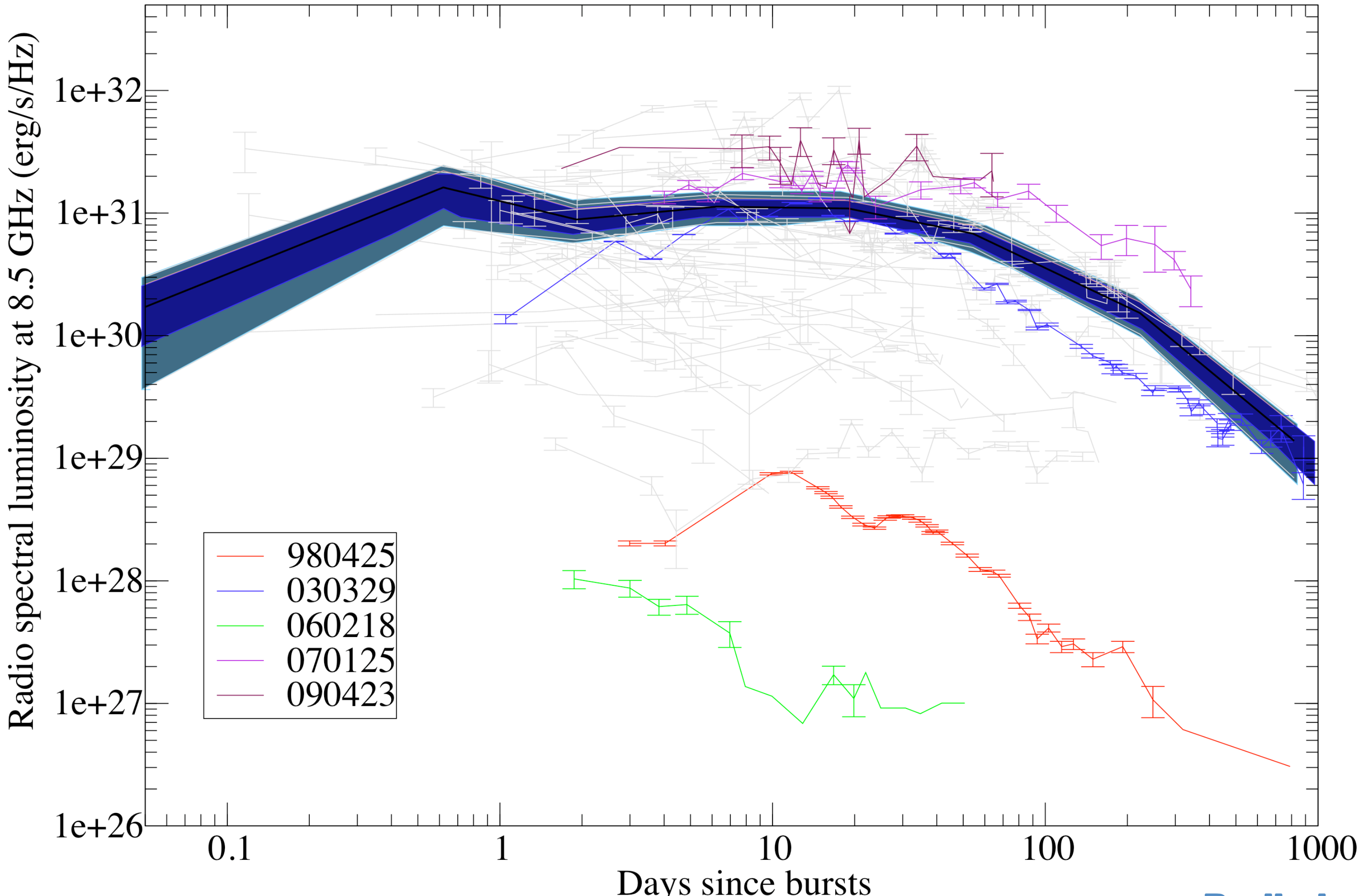
Canonical Radio Light Curve



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Central Engine Energy Requirements

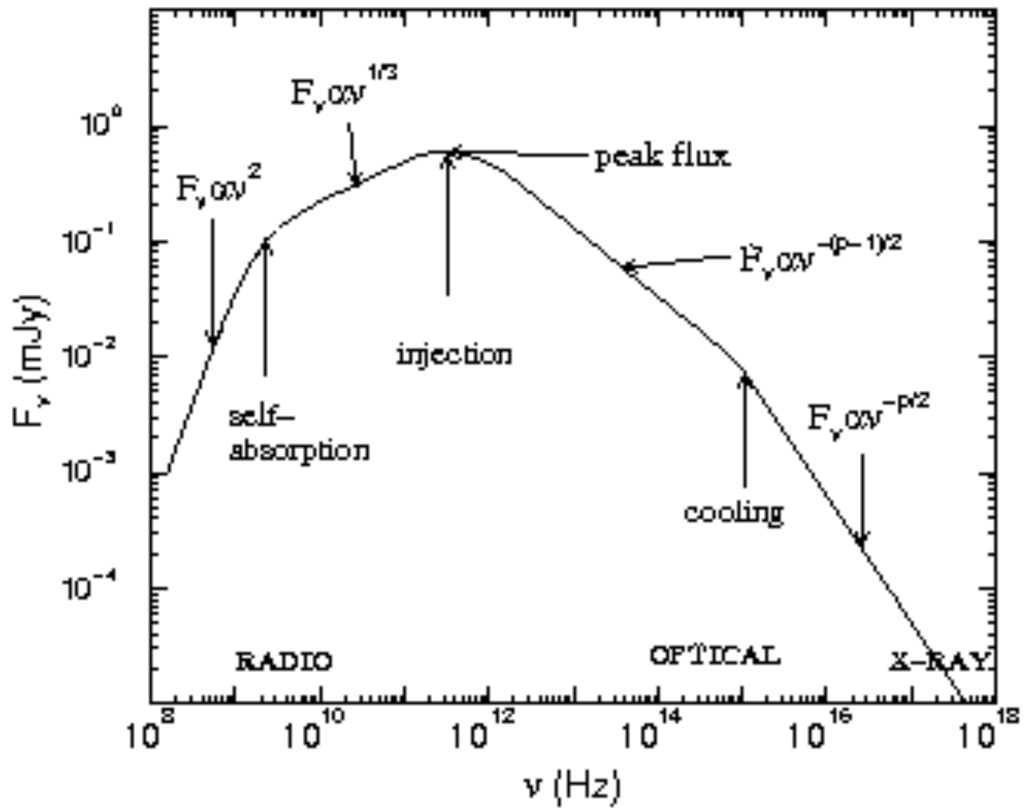
$$E_{rel} = E_{\gamma} + E_{inj} + E_{rad} + E_{k,ad}$$

- 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 Multi-wavelength Afterglow

- Long-lived emission at X-ray, optical and radio wavelengths
- Power-law decays
- Spectrum broadly consistent with synchrotron emission
- Polarization detected
- Relativistic expansion measured



Measure: F_m, ν_m, ν_c, ν_a, t_{jet} ➔ Infer: E_k, $n(r)$, ε_e, ε_B, θ_{jet}

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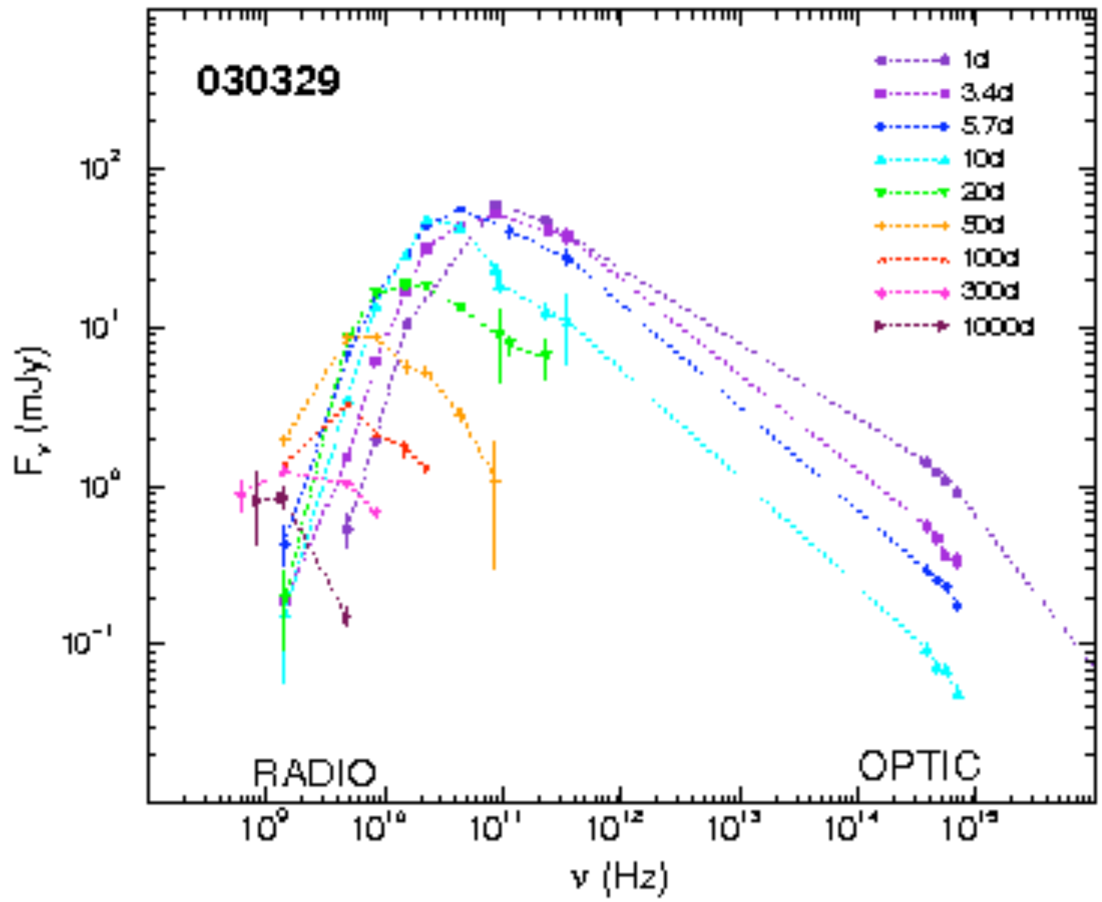
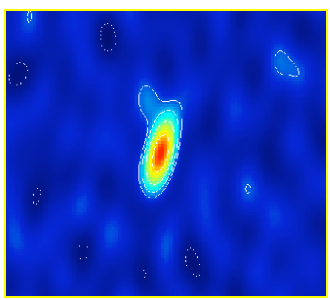
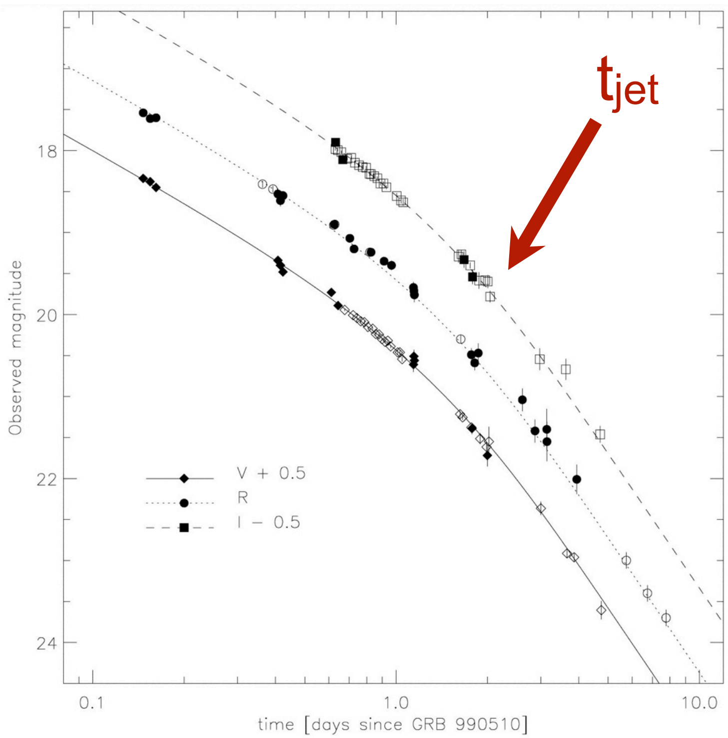
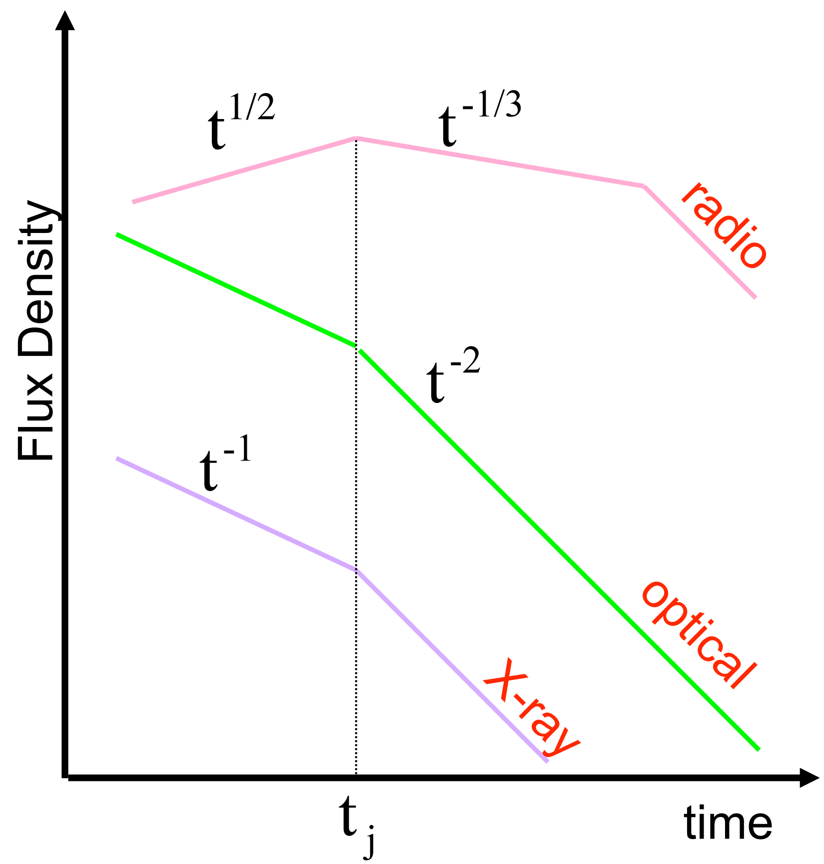




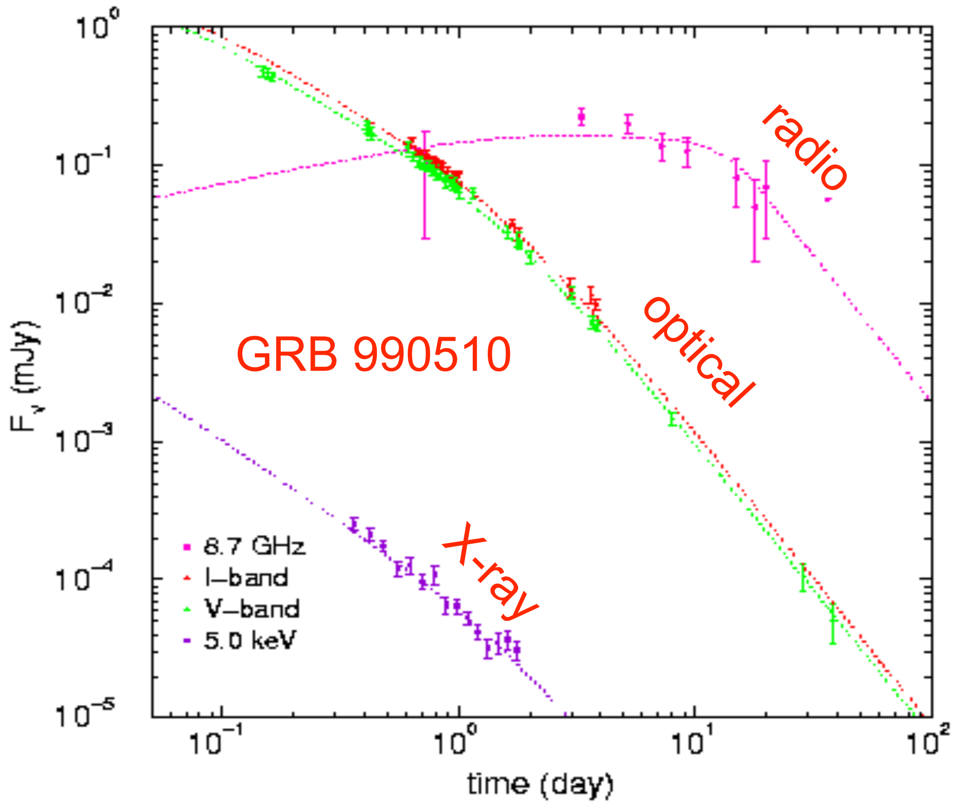
Jet Signatures circa 2000



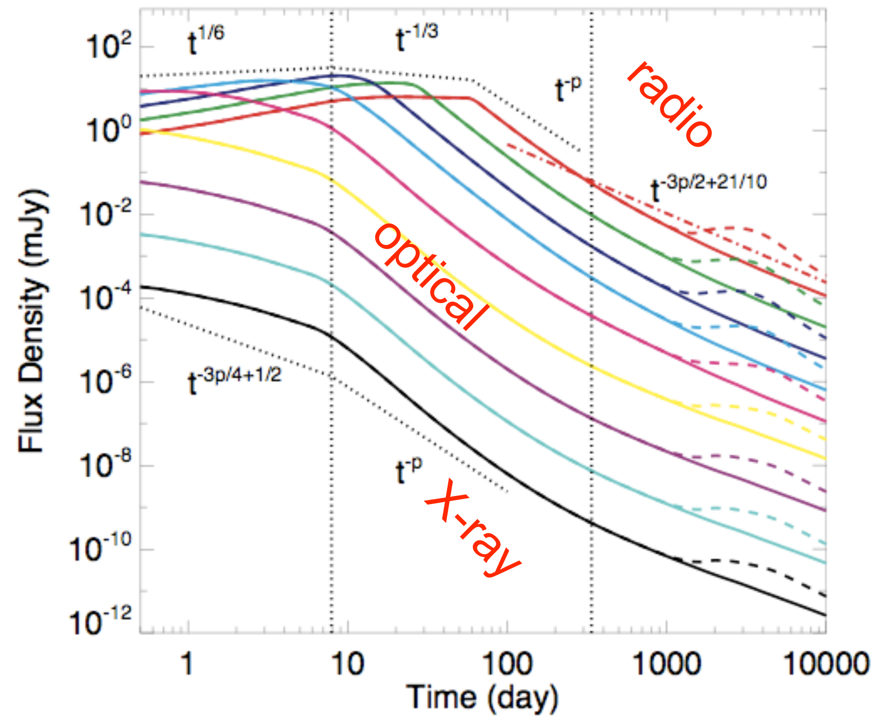


Harrison et al. 1999

Jet Signatures circa 2010

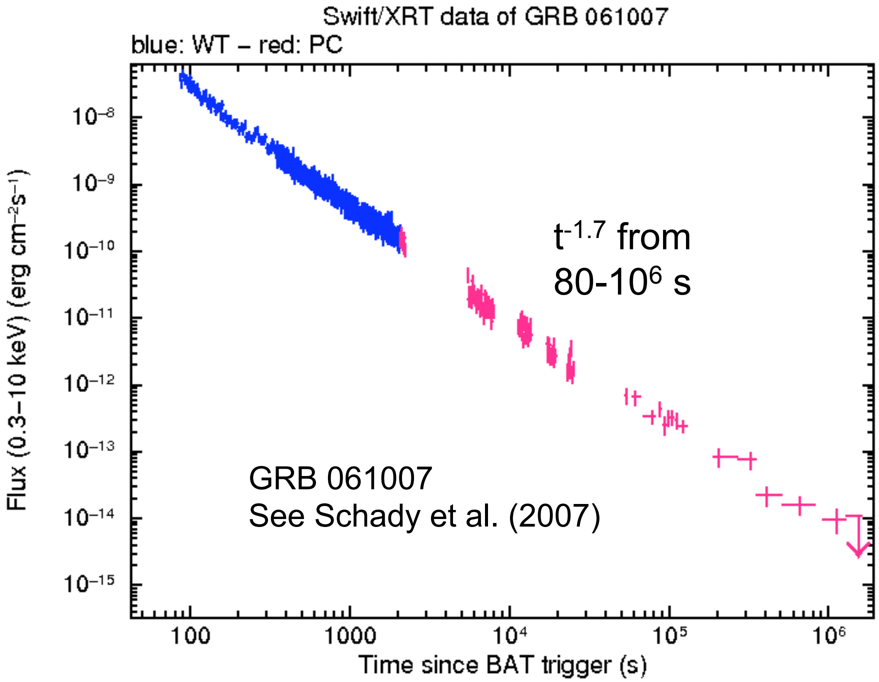


Panaitescu and Kumar (2001)

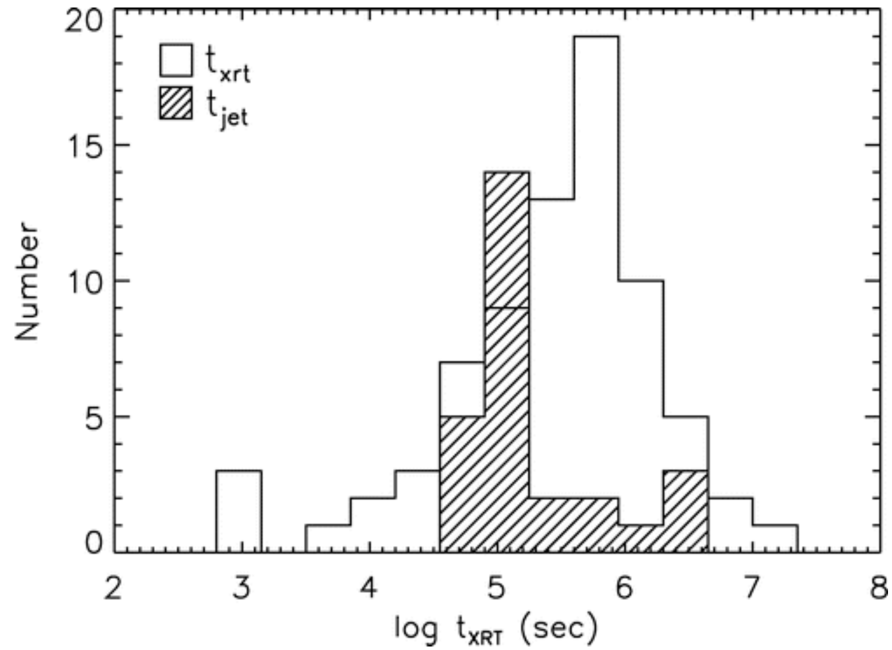


Zhang & MacFadyen (2009).
See also Granot et al. (2001) and
Van Eerten et al. (2009)

GRB Energetics in Swift Era. Missing Jets?



Koceveski & Butler (2008)



See also Racusin et al. 2009

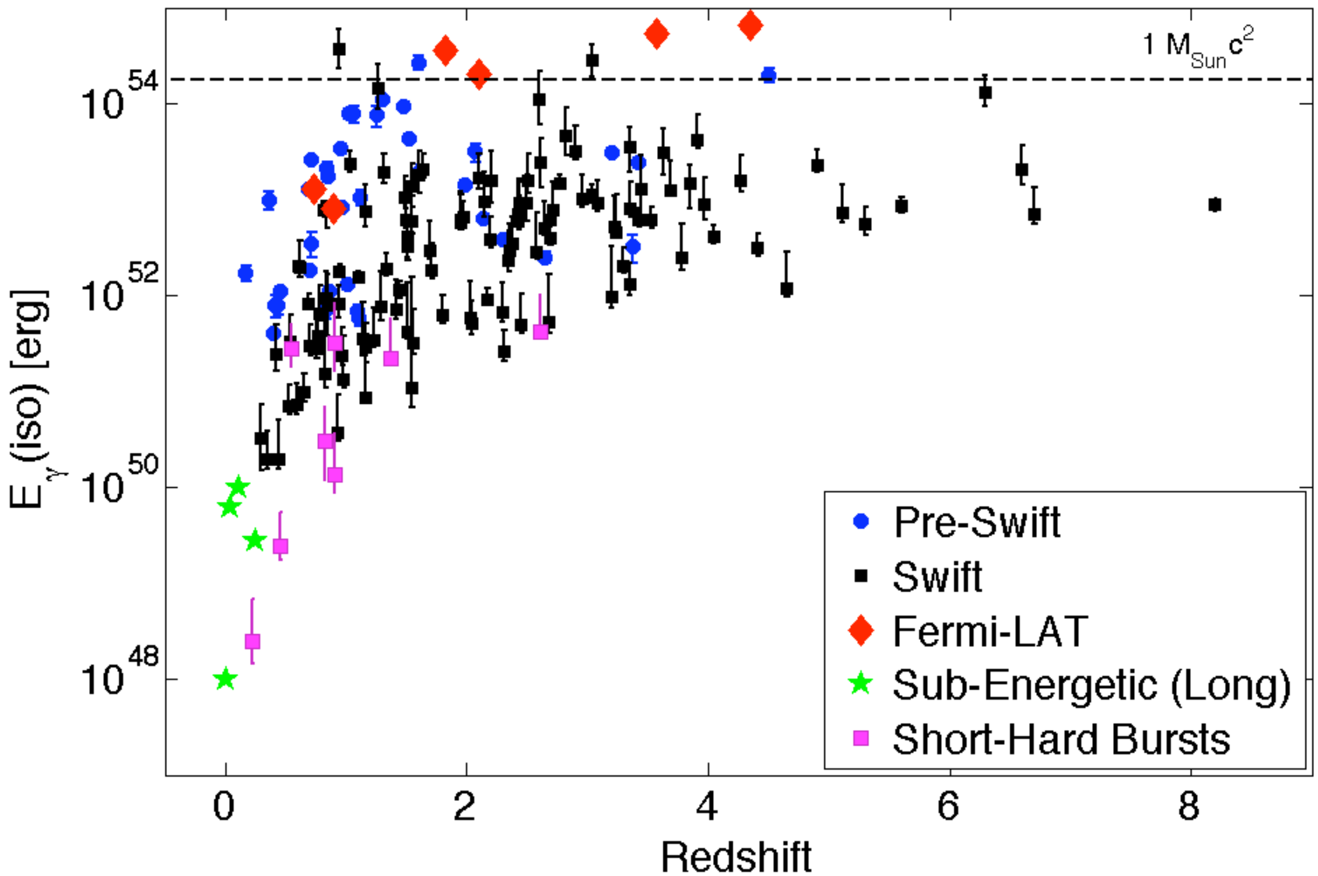
Fewer than 10% of all *Swift* X-ray light curves show breaks consistent with a jet-like outflow.

The Jets Mystery - Summarized

- *Swift* is more sensitive but has a softer energy response
- Median redshift higher. Shifts t_{jet} to later times
  - Fainter afterglows. Costly telescope time to follow-up
- 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
- Orientation effects increase break time (van Eerten et al. 2010)

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 $z=2.615$

$E_{\gamma,iso}=9.7\times10^{53}$ erg

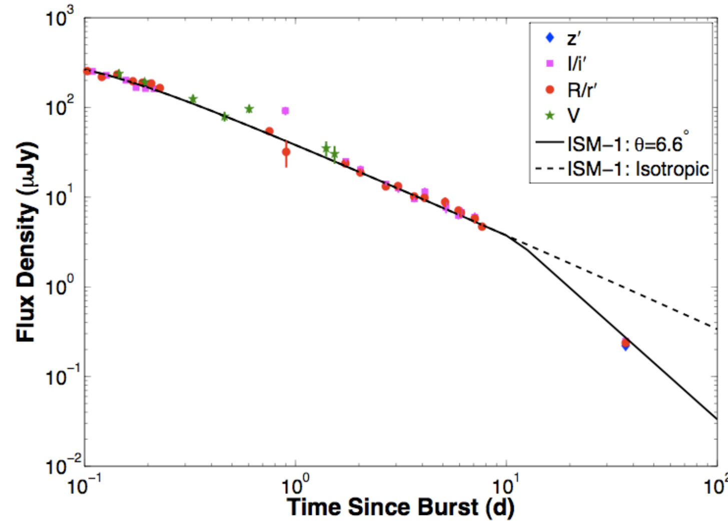
Achromatic jet break at $t_{jet}=11.1$ d

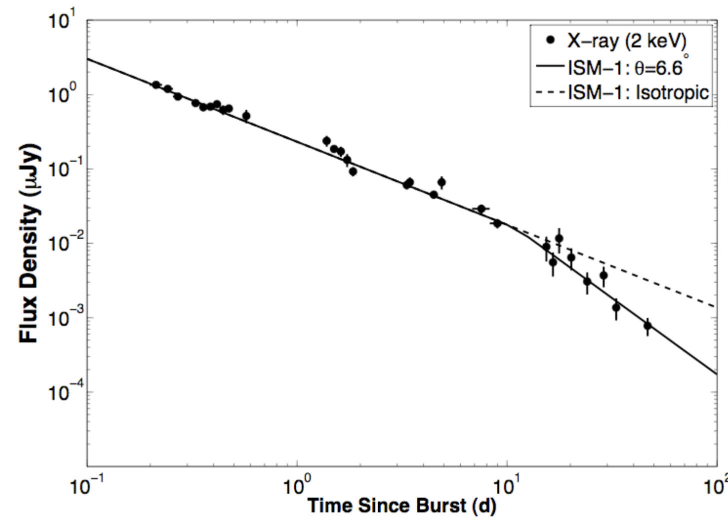
$E_{\gamma}=6.4\times10^{51}$ erg

Multi-wavelength afterglow fit:

$\Theta_{jet}=6.6$ deg

$E_{k}=35.6\times10^{51}$ erg





Cenko et al. 2009

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GRB 070125

Redshift z=1.547

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

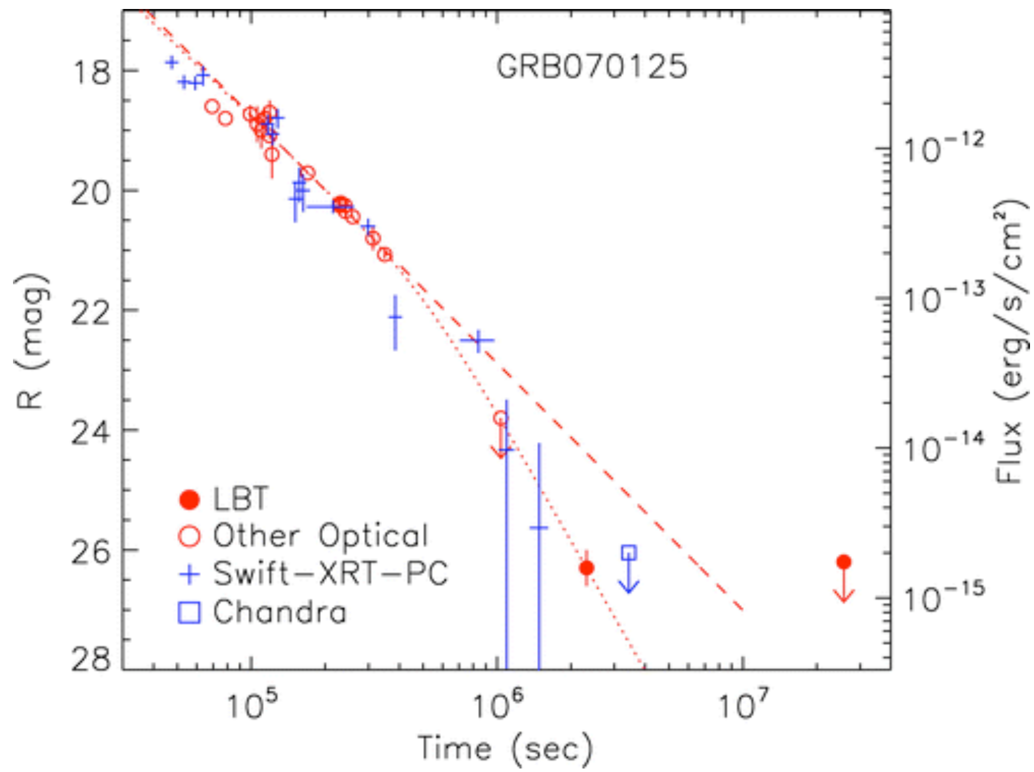
Achromatic jet break at t_{jet}=3.7 d

E_{γ}=25.3x10^{51} erg

Multi-wavelength afterglow fit:

Θ_{jet}=13.2 deg

E_k=1.7x10^{51} erg



Dai et al. 2008

See also Chandra et al. 2008

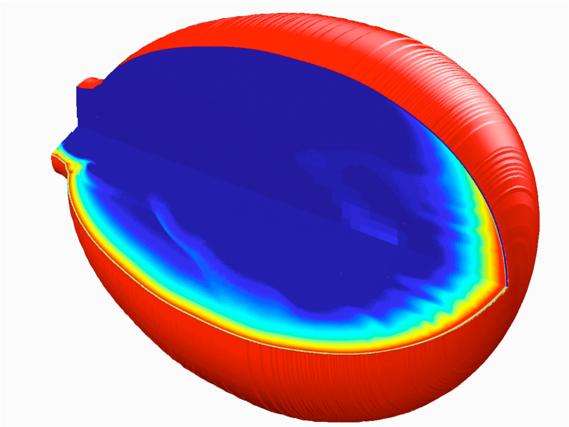
Energetics from multi-wavelength data

- GRB outflows are highly beamed (θ ~ 1-10 degrees)
- Jets still exist but they need the right set of measurements.
- GRB energy scale appears to be broader than pre-*Swift* era
  - "Average" cosmological GRB has $E_k \sim E_\gamma \sim 10^{51}$ erg
  - 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)*

(*See Brad Cenko's talk)

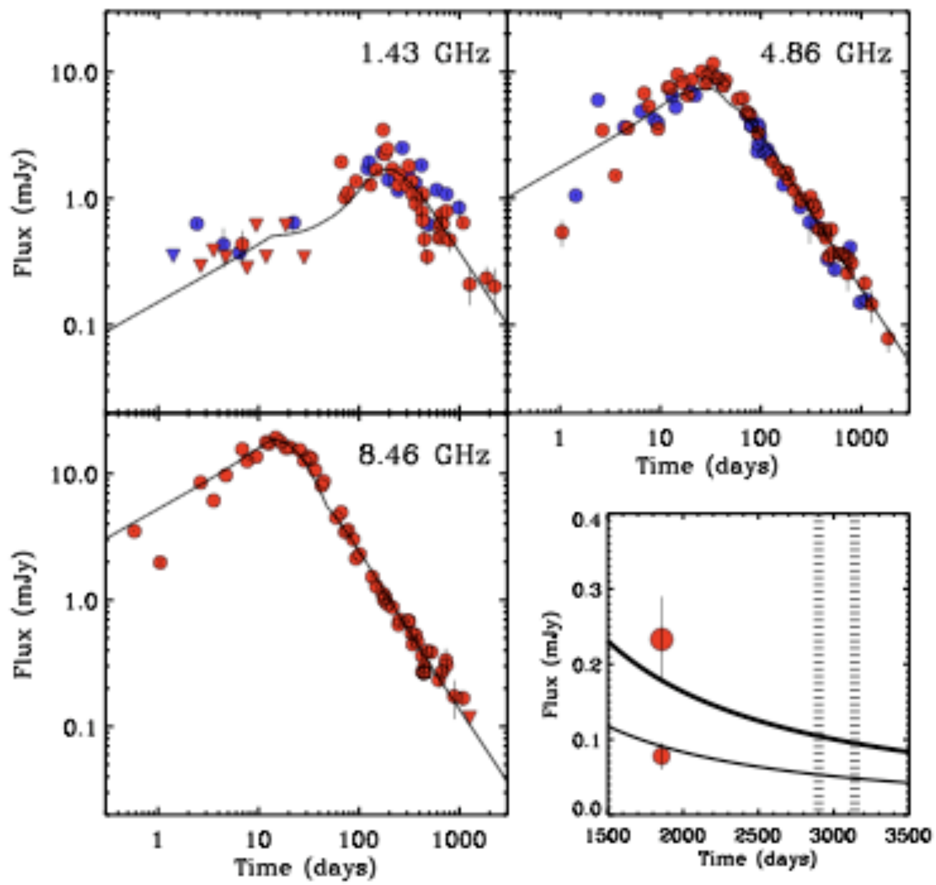
Other Methods of Estimating Energy

- These energy (and geometry) estimates are ultimately model dependent and require high quality, late-time afterglow data
- Late-time (>10^6 s) X-ray and optical AG data is expensive
- Need an alternate method that is independent of
  - (a) early central engine activity,
  - (b) outflow geometry and
  - (c) specific afterglow models



Late-time (radio) calorimetry

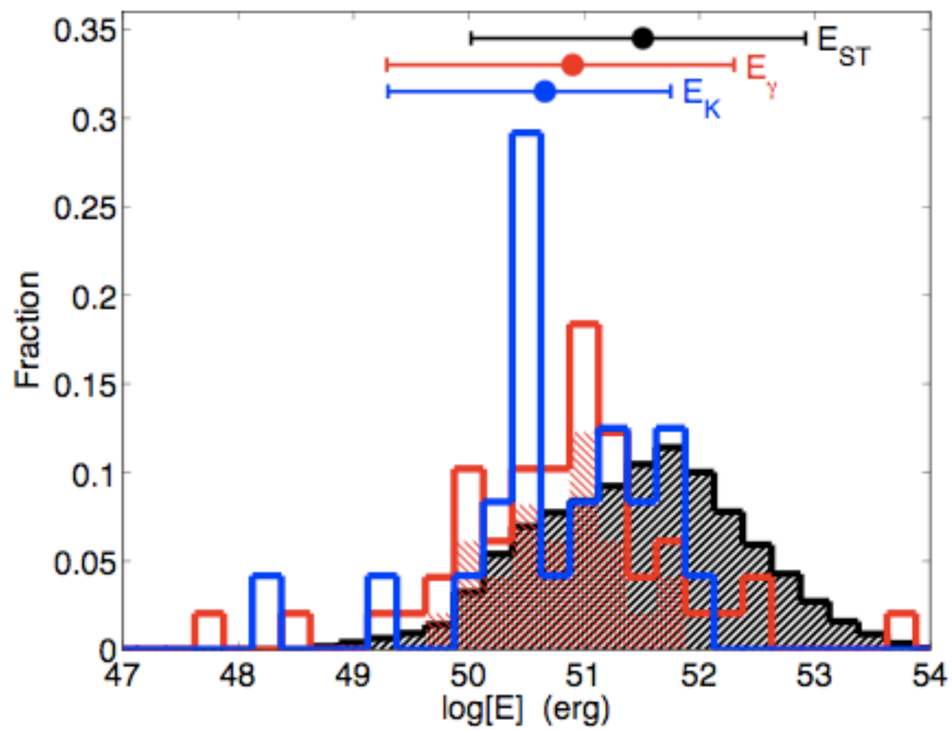
- Fireball becomes non-relativistic, quasi-spherical
- Outflow described by robust Sedov-Taylor formulation
- Recent relativistic hydrodynamics simulations show that the transition to Sedov-Taylor slower than analytic predictions
- Full method has been limited to bright GRBs (970508, 980703 and 030329)



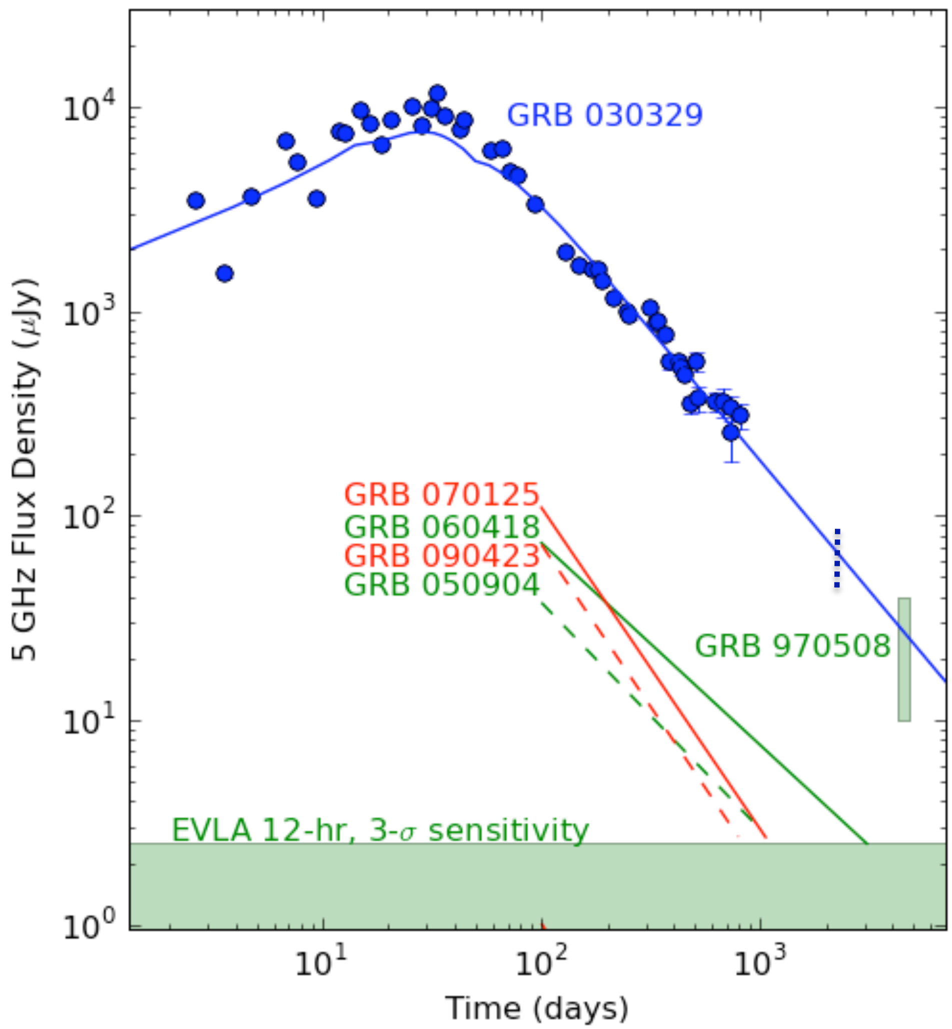
Soderberg et al. (2011) see also van der Horst et al. (2008)

Late-time (radio) calorimetry

- Shivers & Berger (2011) show that energy solutions may also be possible with partial data
- 20 GRBs, some with single-frequency light curves and upper limits at late times t>100d.
- Median energy (2-3)x10^{51} erg
- 90% confidence < 80x10^{51} erg
- Rules out large energy reservoir of slow ejecta (Γβ~1)
- Great potential for a small investment of telescope time



EVLA Calorimetry of Hyper-Energetic GRBS



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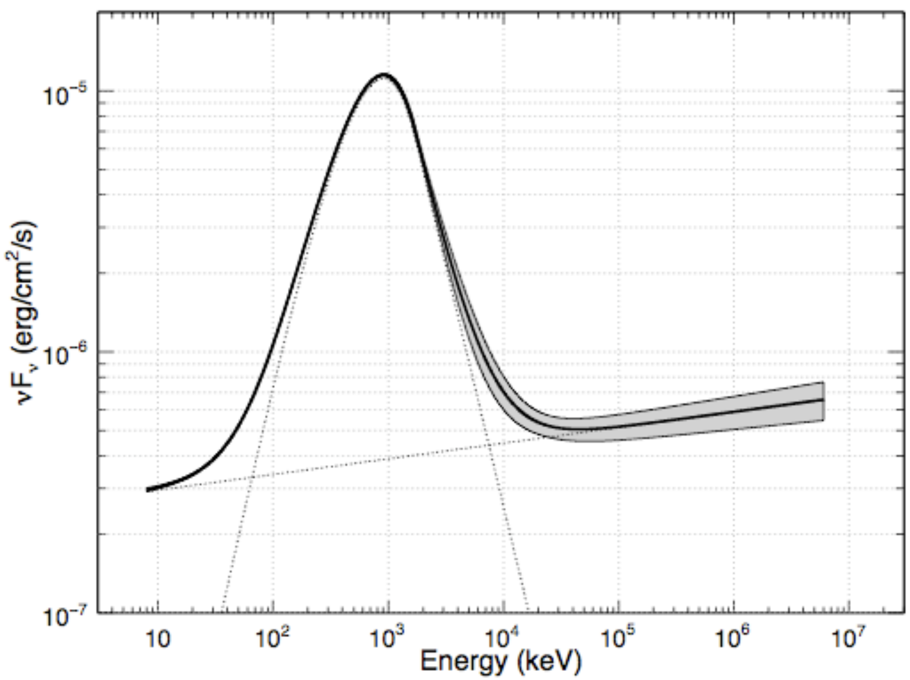
Summary

- 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

Swift Complications: Soft Energy Response

GRB 090902B

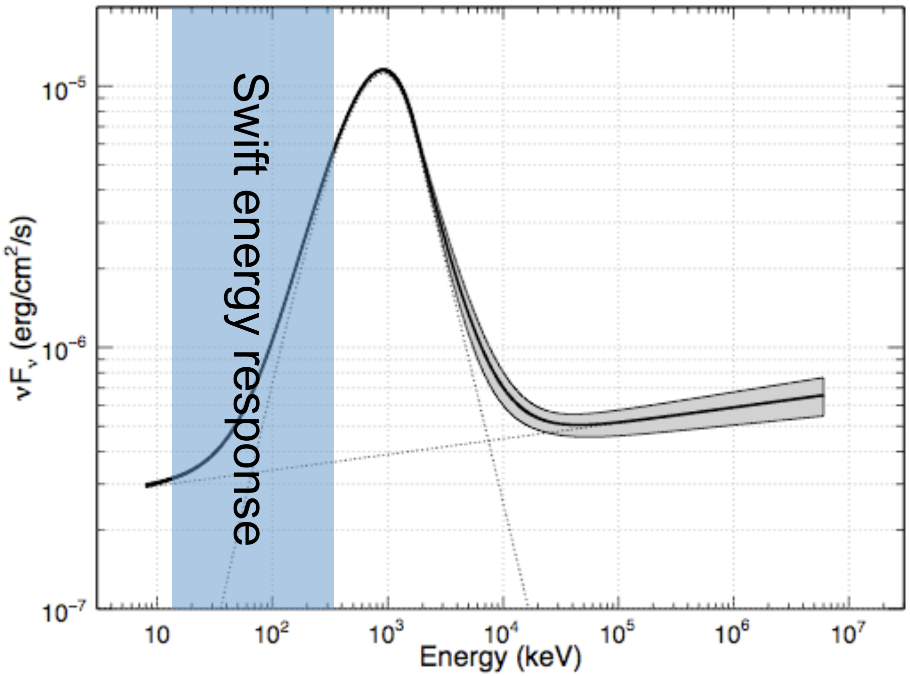


Abdo et al., 2009

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

Swift Complications: Soft Energy Response

GRB 090902B



Abdo et al., 2009

- 15-350 keV BAT bandpass provides limited spectral coverage
- Often miss E_{peak}
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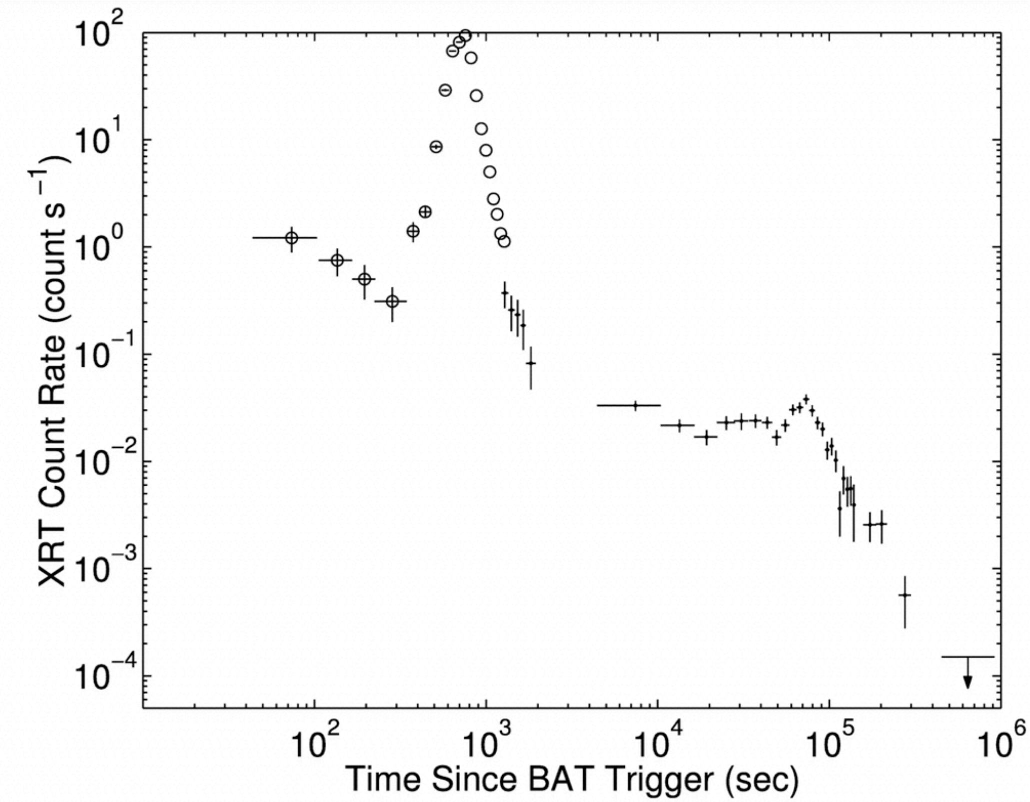
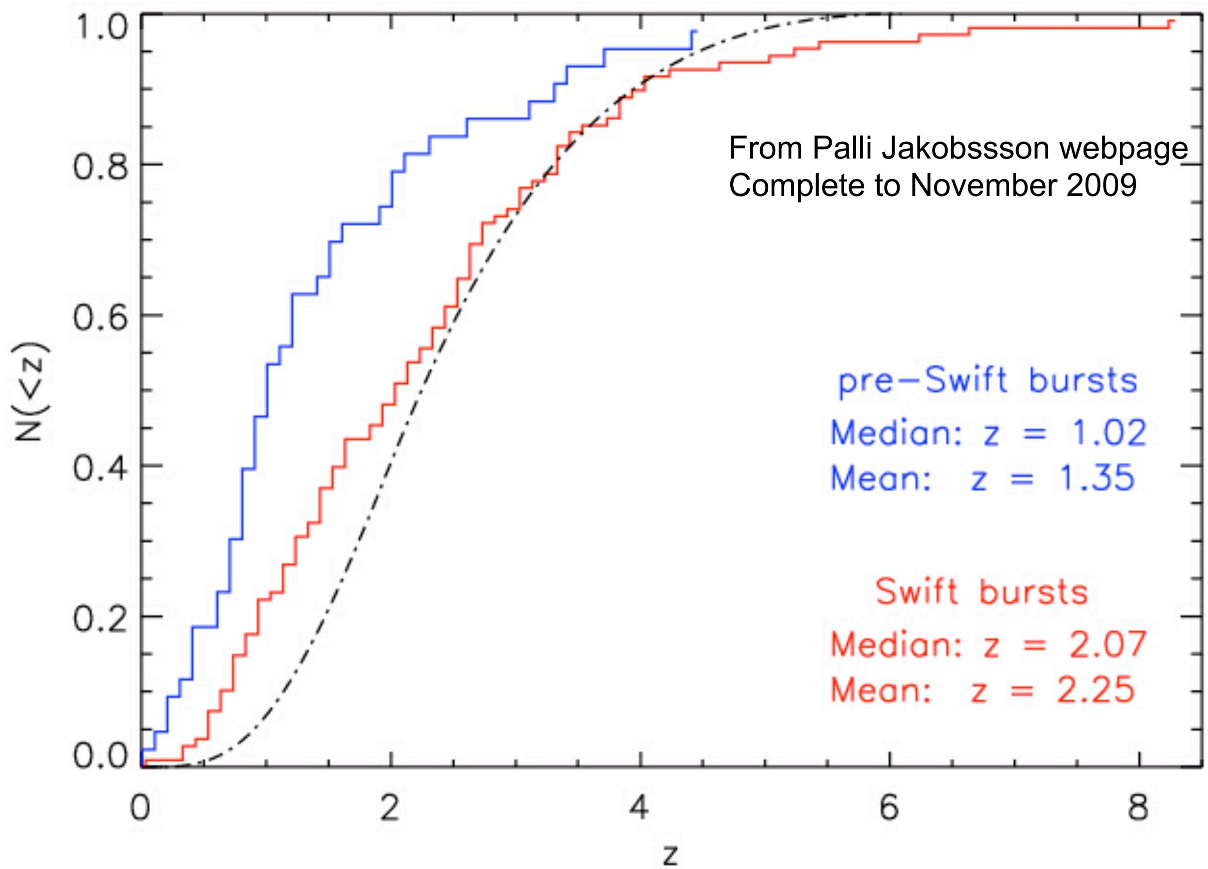
Swift Complications: Energy Injection

- 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

Swift Complications: Redshift



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