Transients in 10 Seconds or Less: Catching Gamma-Ray Bursts in the Act with ROTSE

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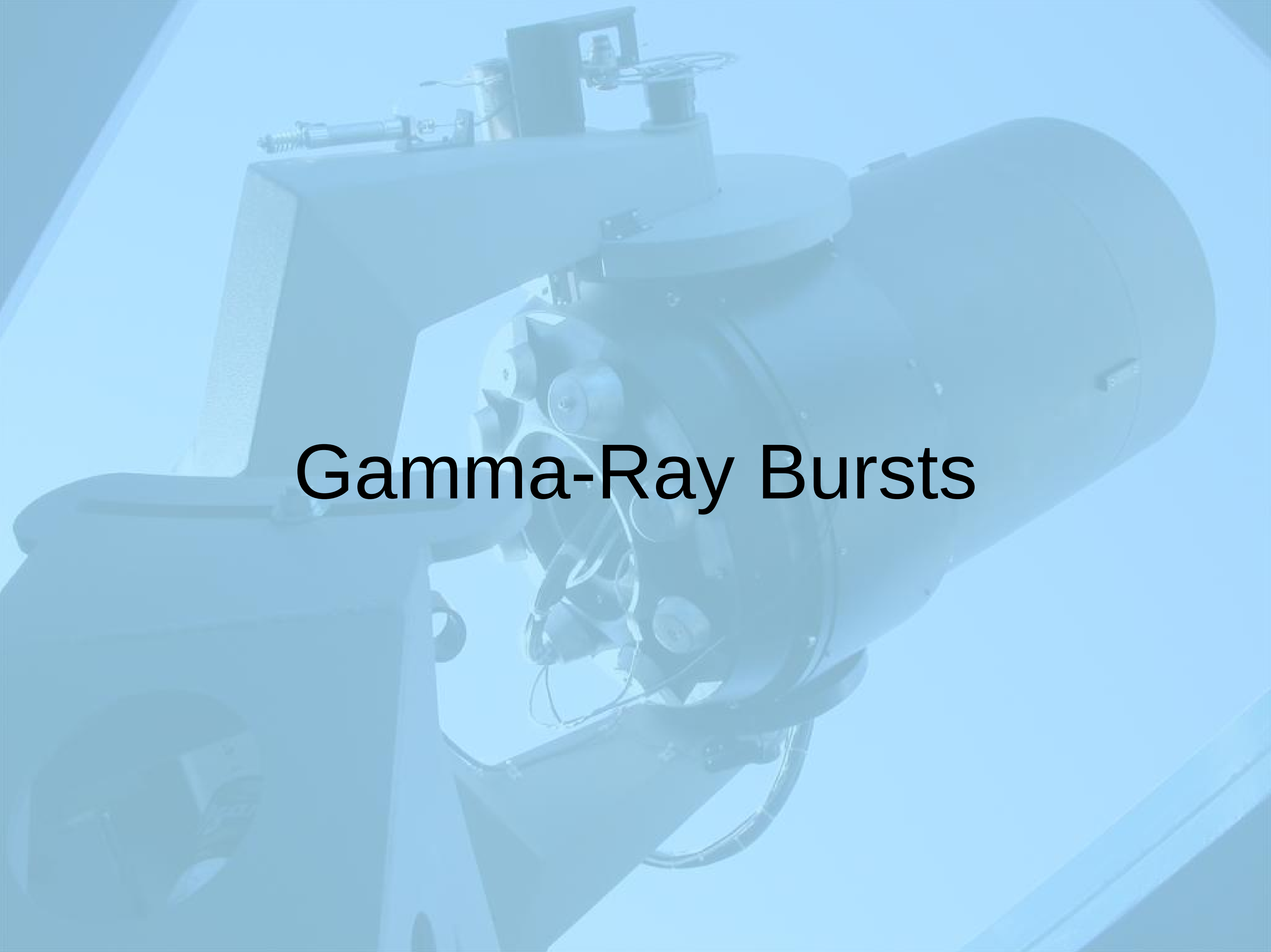
SLAC/KIPAC

Outline

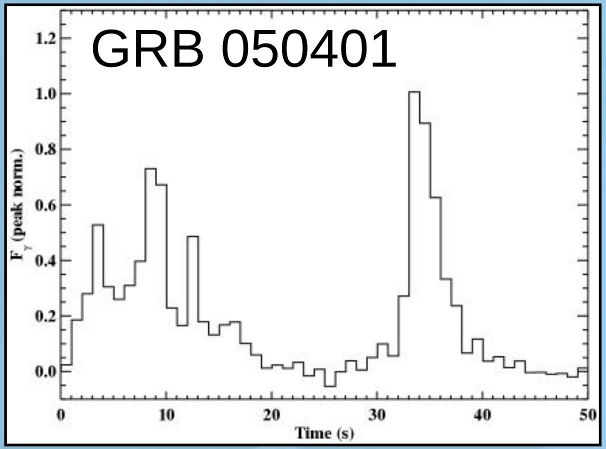
- Gamma-Ray Bursts
- Prompt Optical Emission from GRBs
- The ROTSE-III Telescope Array
- Recent Results
- The ROTSE-III Transient Search



Gamma-Ray Bursts

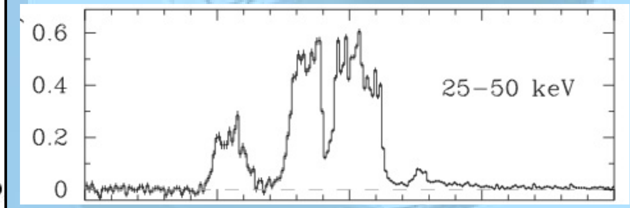
Gamma-Ray Bursts (GRBs)

- What are they?
  - Energetic explosions, releasing over 10^{51} ergs in γ-rays in 10s of seconds
  - Cosmological distances, z ~ 0.2-6+
  - Variable, diverse, and rare
    - About 2/day in the universe visible to Earth

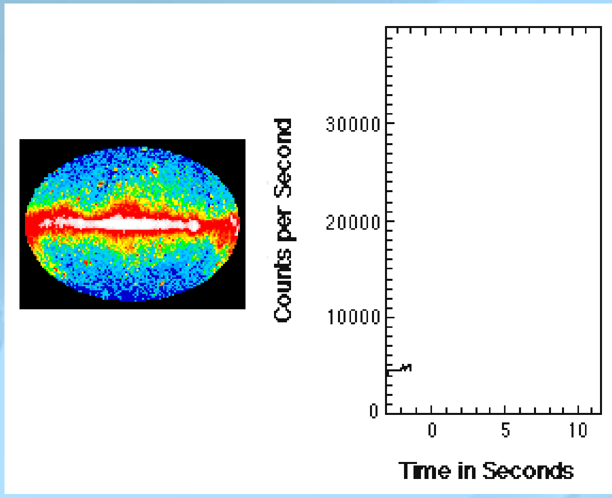


Rykoff et al., 2005

GRB 061007



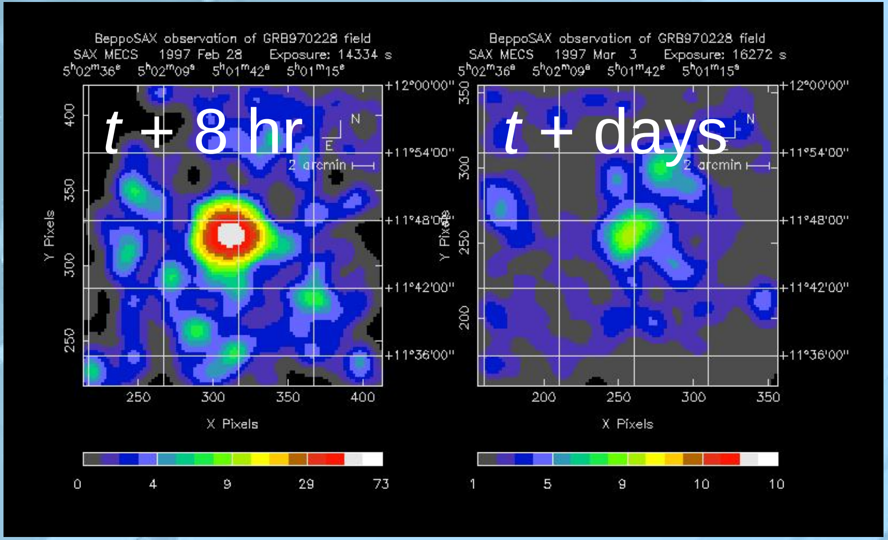
Schady, et al., 2006



GRB 990123 as seen by the Compton Gamma Ray Observatory (CGRO)

Gamma-Ray Bursts

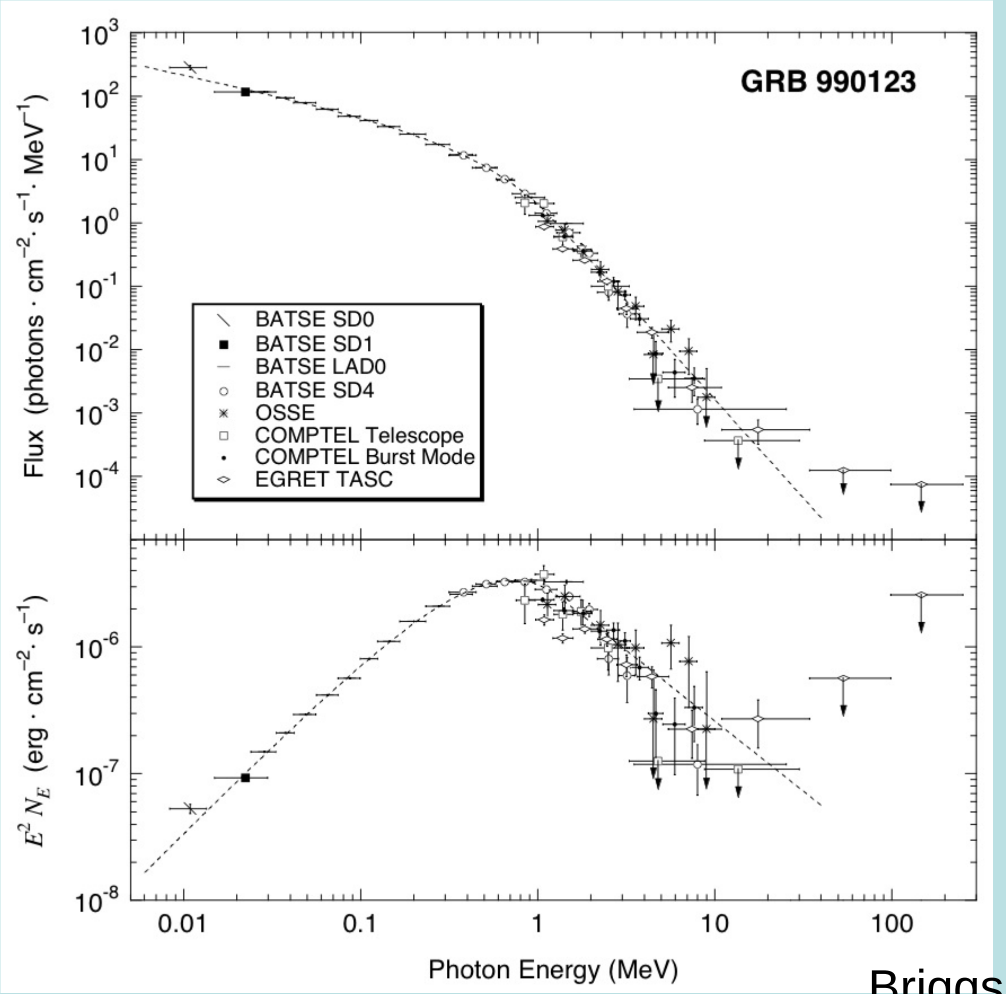
- Detected by satellites such as *Swift*
- Two types of GRBs: long and short
- Variability on millisecond timescales
- Bursts have "afterglows"
  - X-ray, optical, radio…
  - Only ~50% of bursts have detectable optical emission



Beppo-SAX X-Ray afterglow of GRB970228

Compactness Problem

- The γ-ray spectrum is *non-thermal*



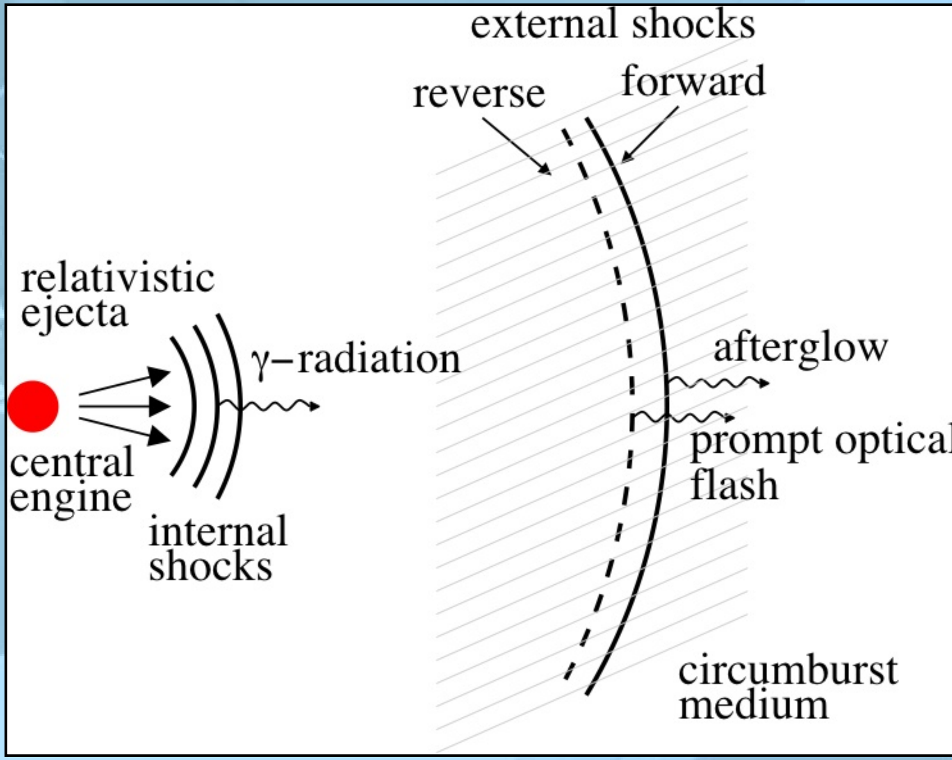
Briggs, et al, 1999

Ultrarelativistic Outflow

- Time dilation
  - The ejected material is travelling near the speed of light; it is right behind the emitted photons
  - The actual size of the GRB emission region is $\sim 2c\Gamma^2 t \sim 10^{14}$ cm (70 A.U.)
- Emitted light is blue-shifted into γ-rays
- Emitting region is optically thin if emitting material has Lorentz factor $\Gamma > 100$
  - Some of the fastest bulk flows in the Universe

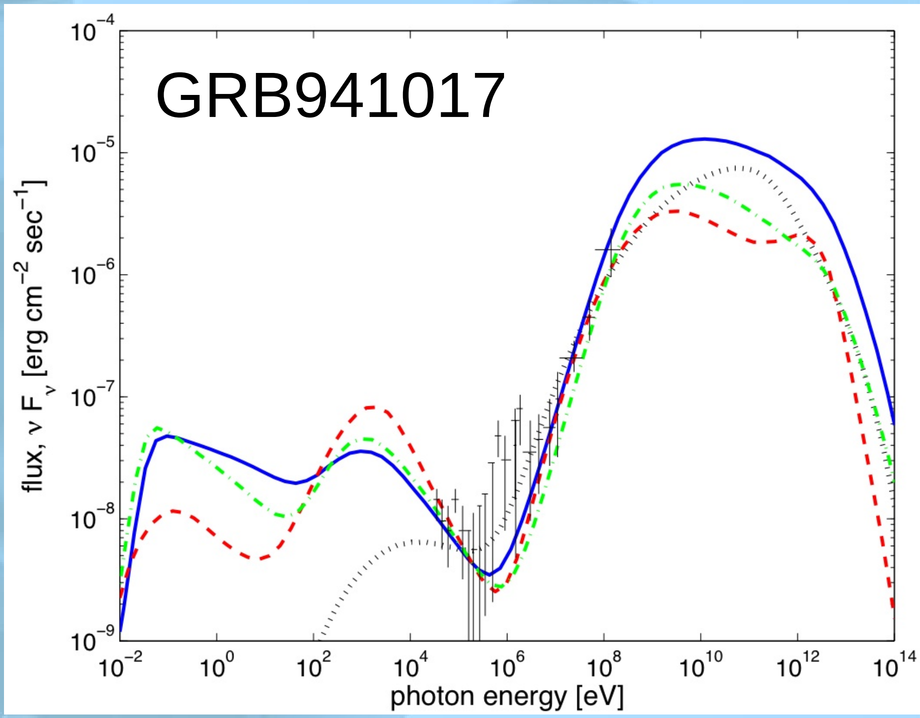
Fireball Model

- The Internal/External Shock model
- Synchrotron emission from shock-accelerated electrons
- Prompt γ-rays from internal shocks
- Afterglow from external forward shock in ambient environment
- Outflow is collimated
  - We look down the center of a jet

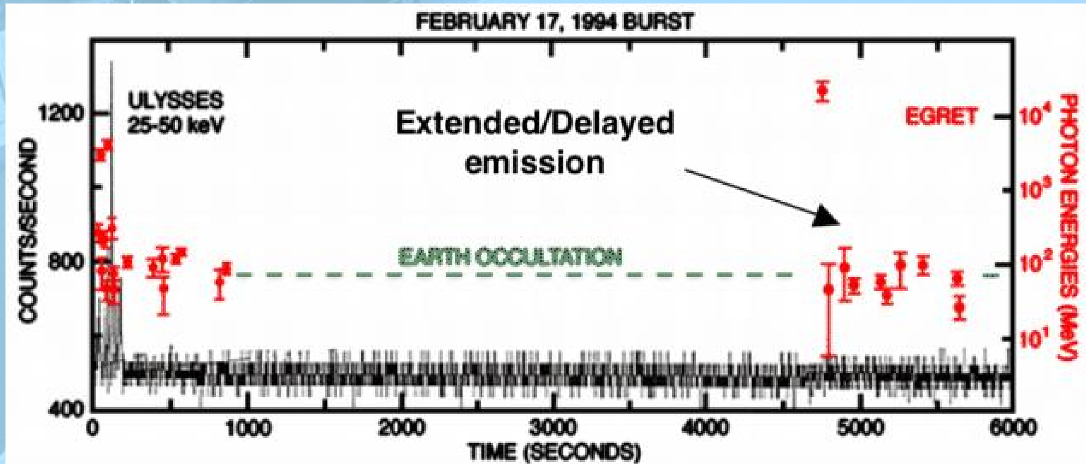


High Energy Emission from GRBs

- GRB emission has been seen to very high energies
- What is the true high energy profile?
  - Synchrotron + Inverse-Compton?



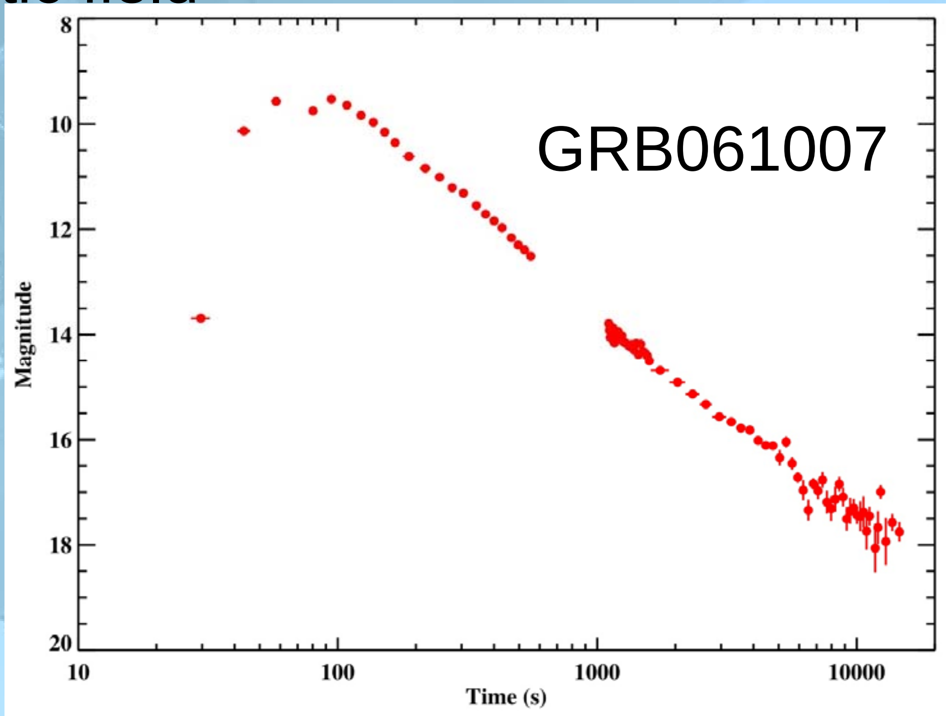
Pe’er & Waxman 2003, from Gonzalez, et al, 2003



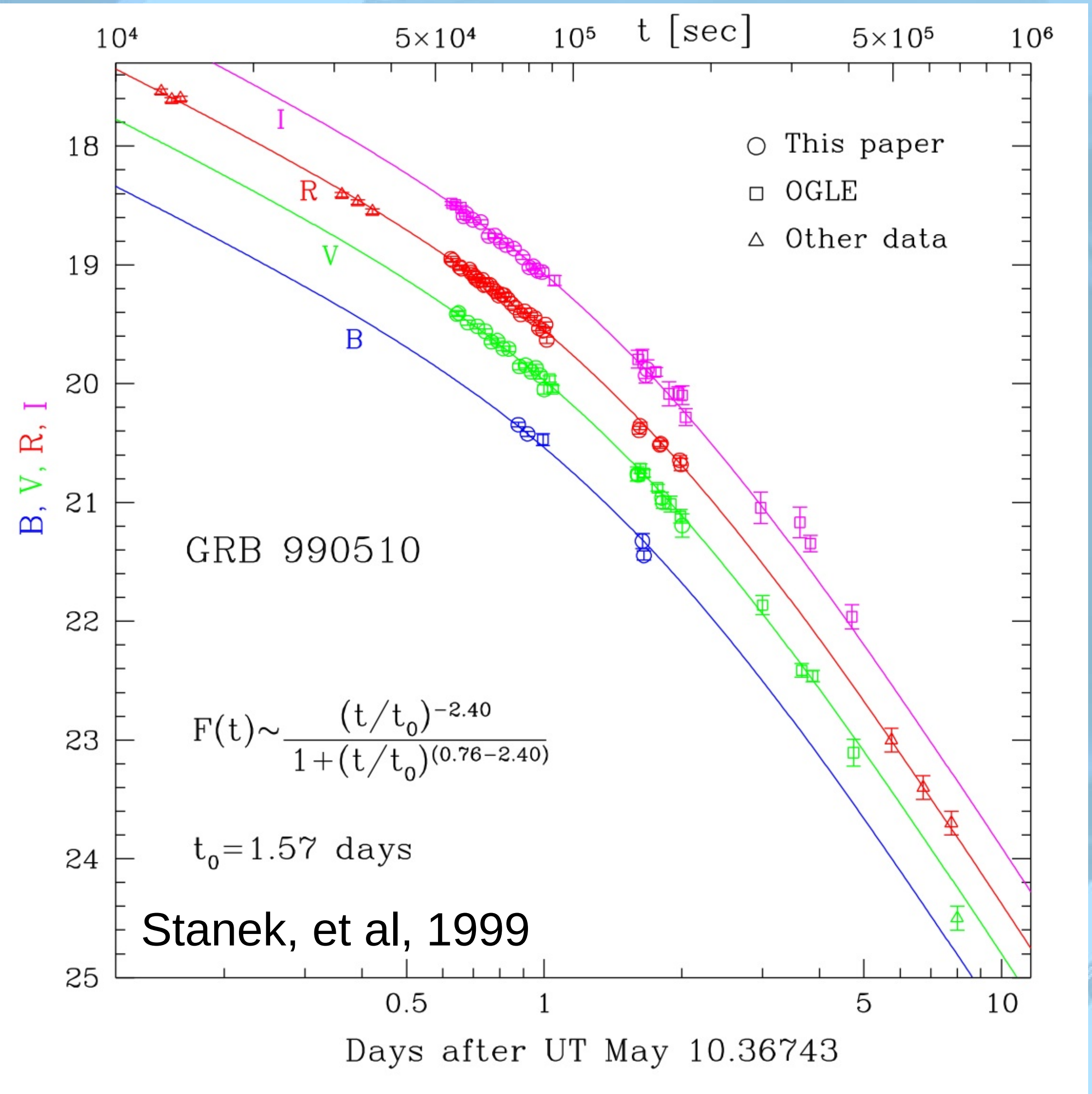
Hurley, et al., 1994

Optical Afterglows

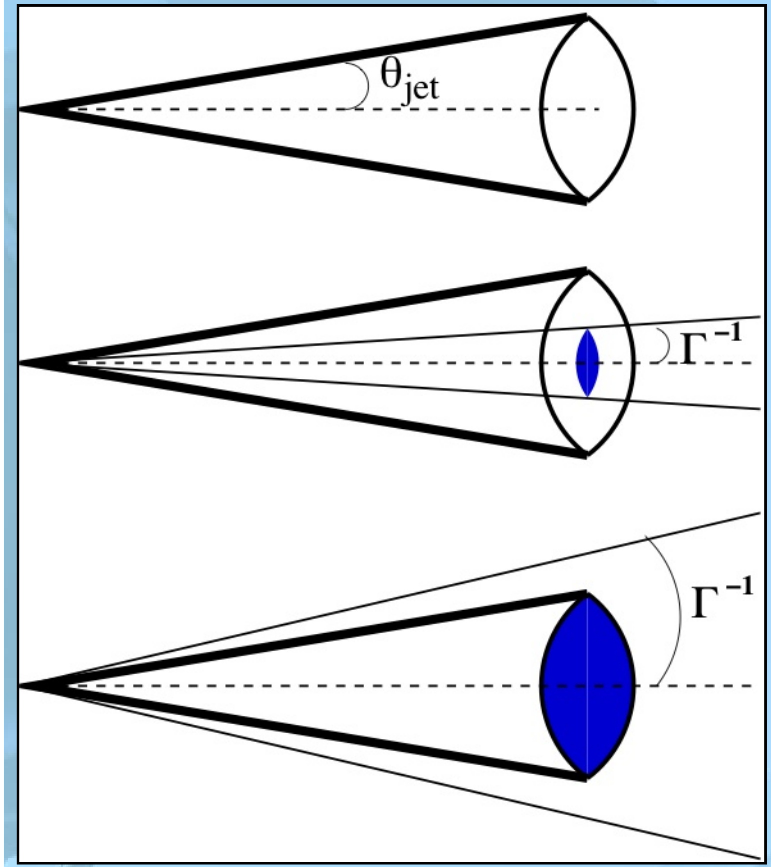
- Forward external shock accelerates electrons with a power-law spectral energy distribution
- Relativistic electrons emit synchrotron emission
  - Requires ambient magnetic field
- Ejecta decelerates into ambient medium, and afterglow fades as a power-law



Collimated Outflow: GRB Jets

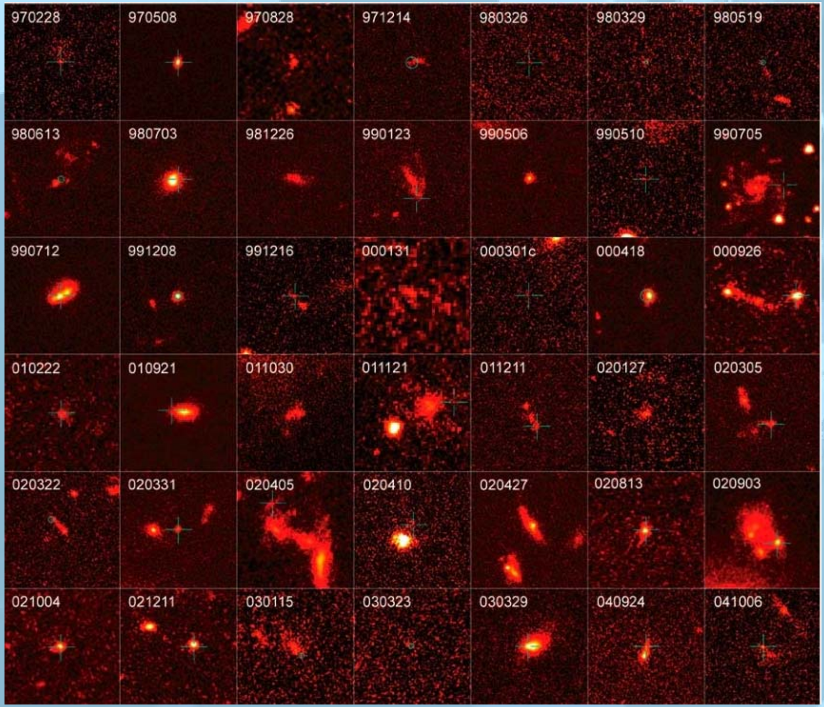


Stanek, et al, 1999

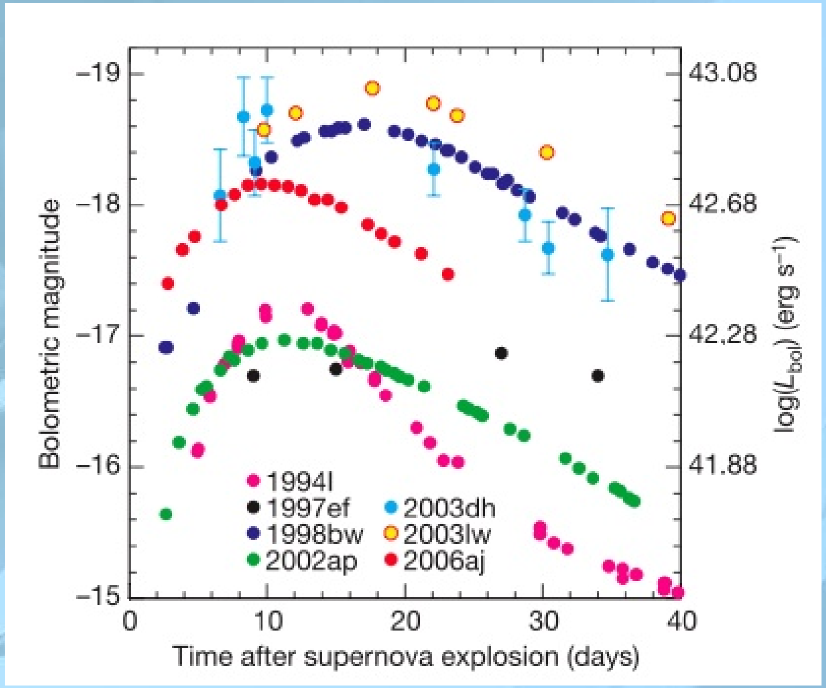


GRB Progenitors

- Clues to long burst origins:
  - Associated with star-forming regions & host galaxies (Bloom et al, 2002)
  - Some bursts associated with core-collapse Supernovae (eg, GRB 030329) (Hjorth, et al, 2003)



Fruchter, et al., 2006



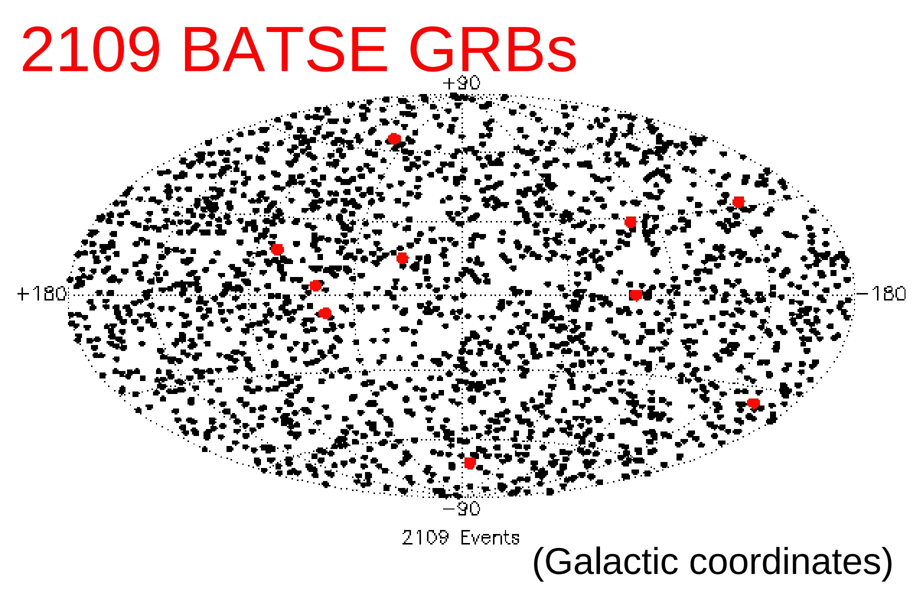
Pian, et al., 2006

The Collapsar Model

- Very massive (> 20 $M_\odot$) rapidly rotating star
- Core collapses into a black hole
- Stellar material (~ 0.1 $M_\odot$) accretes onto the black hole, with jets out the poles
- Simultaneous supernova
  - This peaks after 1-2 weeks

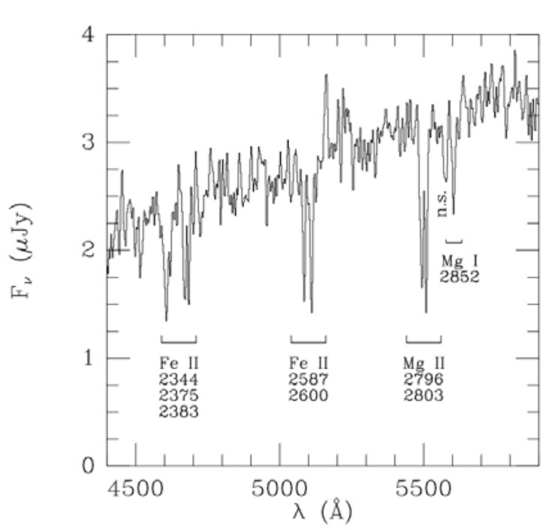
NASA/Skyworks Digital

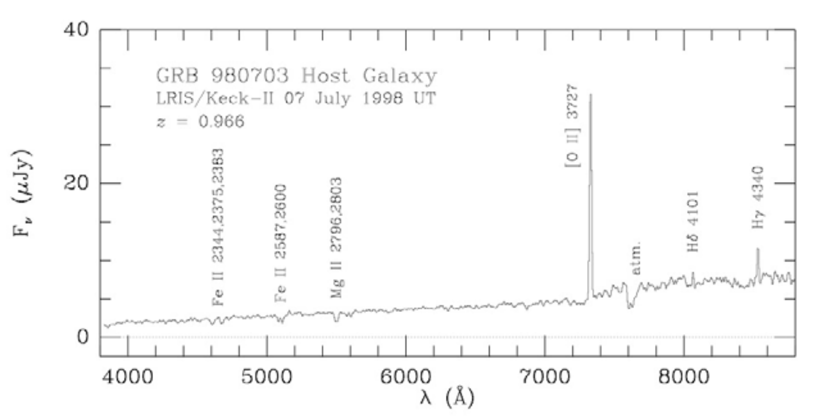
GRBs at Cosmological Distances



- BATSE GRBs were isotropic on the sky
- Absorption features in afterglows + host galaxy emission lines give distance to GRB

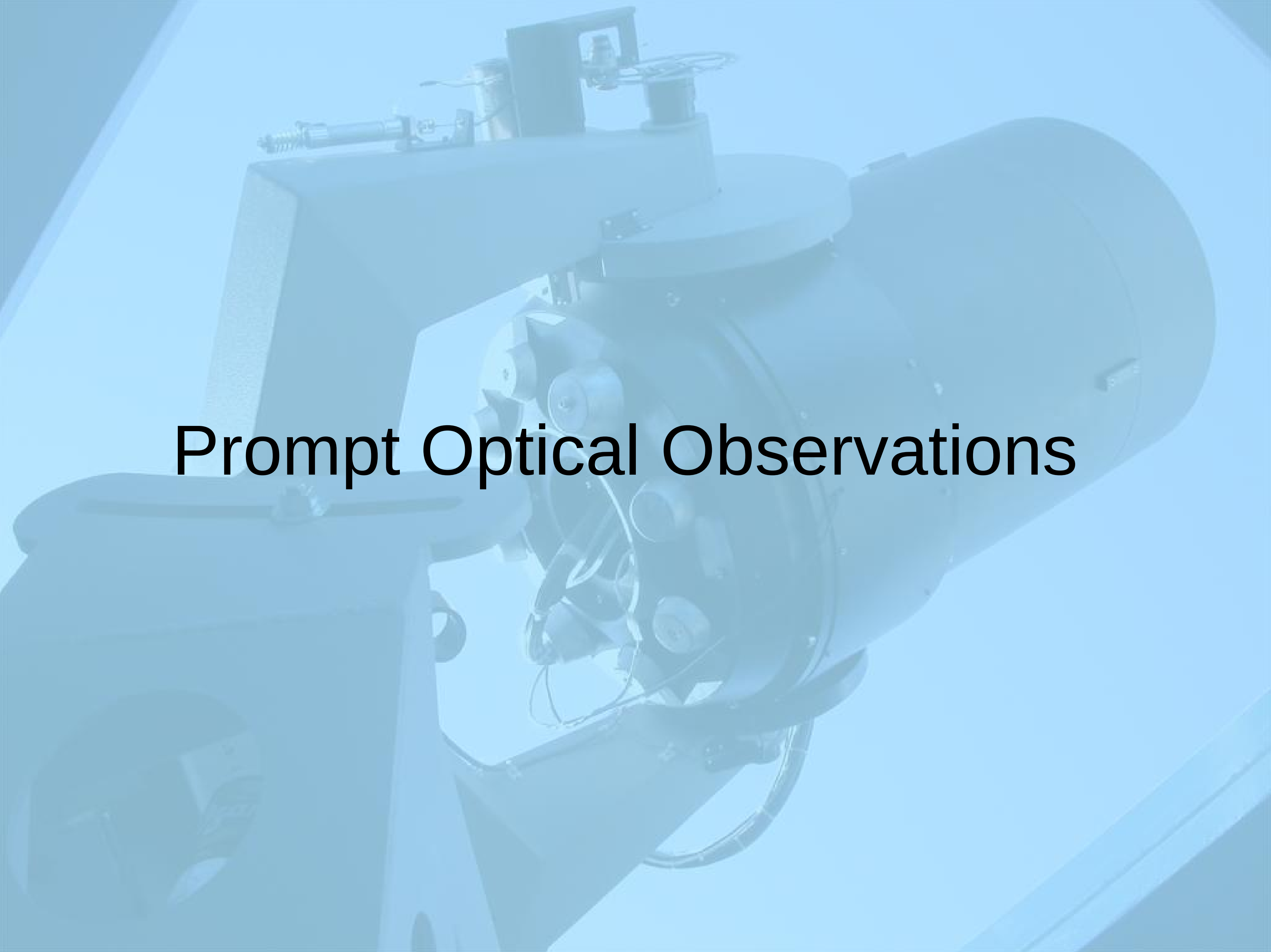
GRB980703





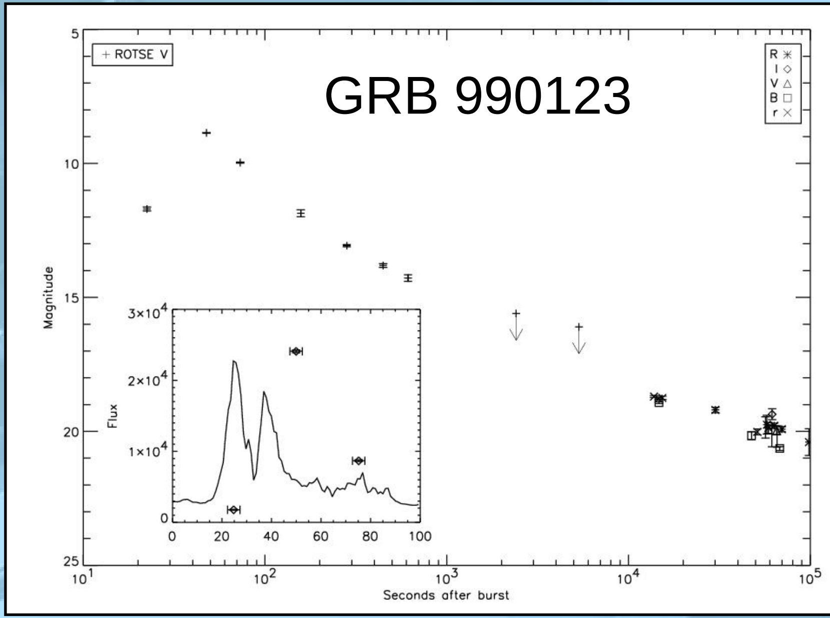
Djorgovski, et al, 1998

Prompt Optical Observations



Prompt Optical Emission & Early Afterglows

- Late afterglow tells us about the environment, not the central engine
  - At 10 s post-burst, probing 10^{15} cm (200 AU)
- Early observations more directly measure conditions in explosion
- Prompt flash from reverse shock predicted
- Through 1999, only one afterglow imaged early



Akerlof et al., 1999

The ROTSE Project

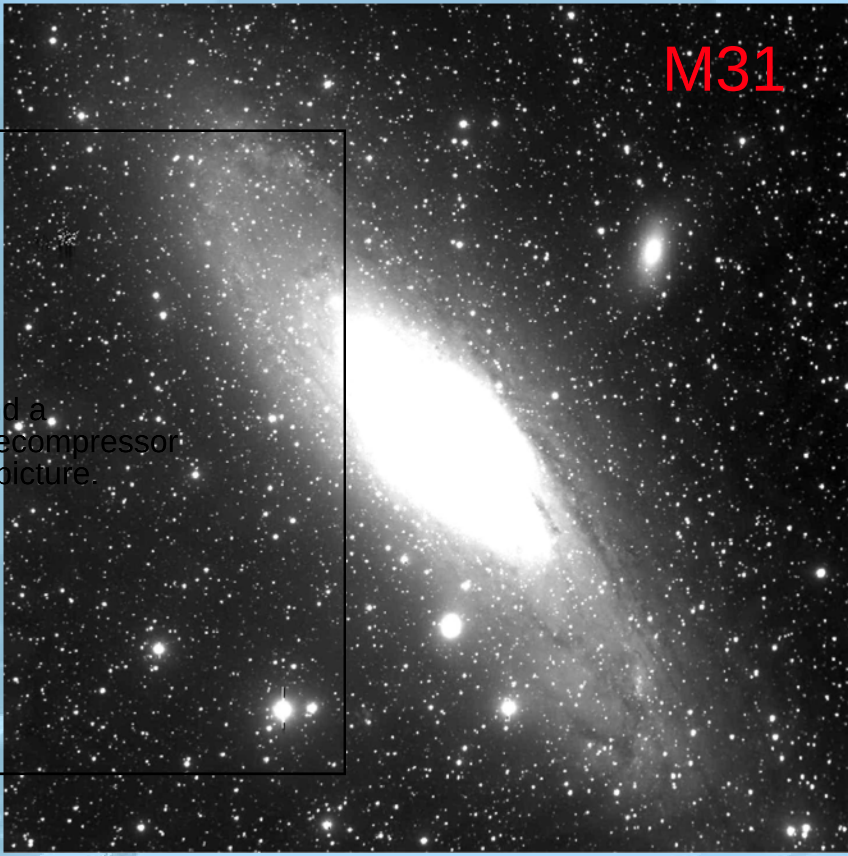
- The Robotic Optical Transient Search Experiment (ROTSE-III) telescopes
  - Successors to ROTSE-I telephoto array
  - Rapid response to GRB triggers
  - Simple optical and mechanical design
  - Global distribution
- Worldwide collaboration
  - U-Mich, LANL, UNSW, U-Texas, MPIK, several Turkish institutions, GSFC

What happens in the first mi

ROTSE-III Specifications

- 0.45 m telescopes
- 1.85° x 1.85° field (f/1.9)
- Unfiltered 2k x 2k CCD
- Fast (6 s) readout
- ~ 40 deg/s max. slew speed
- All automated, no people in the loop
- Built for *rapid* response to GRB triggers
- Median GRB alert response time is 7 seconds
- 17th mag for short (5s) exposures; 18.5 for 60s exp.

QuickTime™ and a
Motion JPEG OpenDML decompressor
are needed to see this picture.

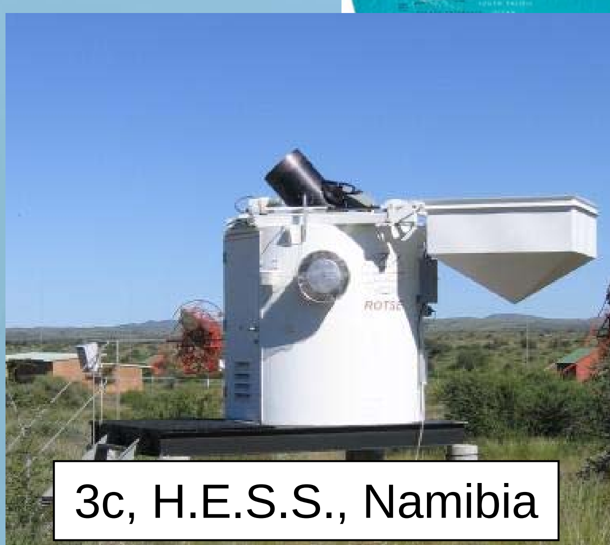


ROTSE-III Worldwide


3b, McDonald, Texas


3d, TUG, Turkey

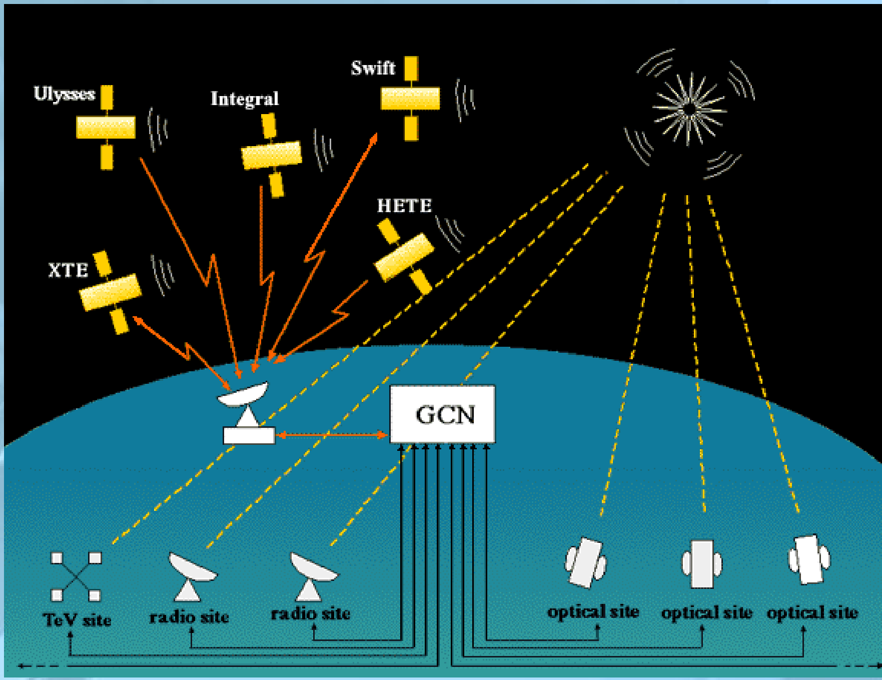
The Sun Never Rises on the ROTSE Empire


3c, H.E.S.S., Namibia


3a, SSO, Australia

The GRB Coordinates Network

- The GRB Coordinates Network (GCN) makes prompt follow-up possible
- A satellite detects a GRB, sends the position down in real-time to GSFC
- A message is sent over the Internet to robotic telescopes
- Grad students are woken up at inconvenient times



Automated Detection of Afterglows

Calibrate Images → Stack Images

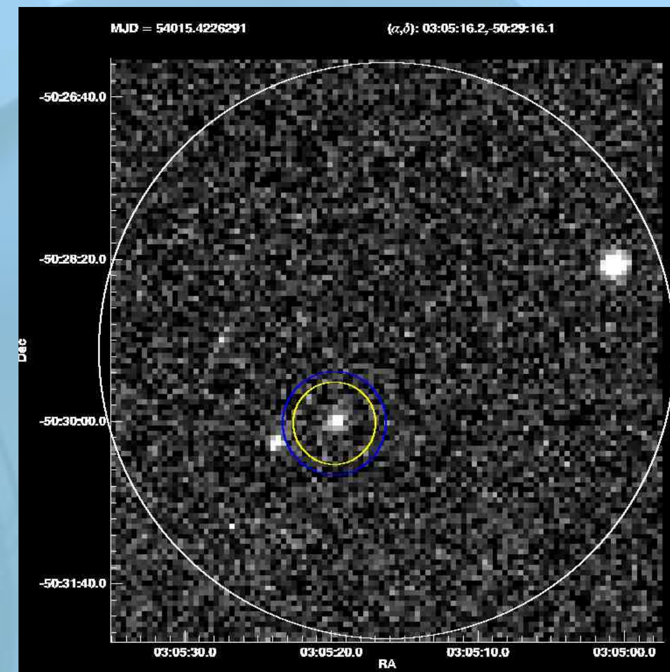
Calibrate Images: ~ 10 s /image

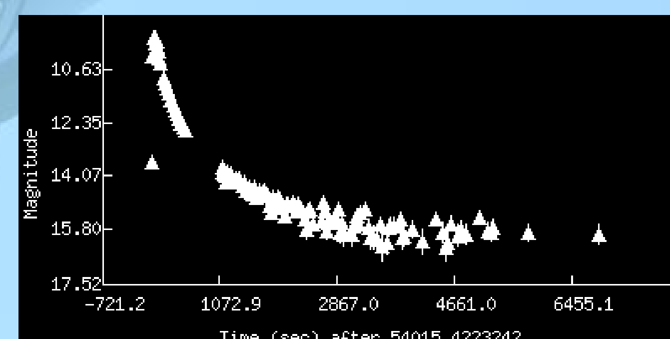
Stack Images: 1 m - 10 m

Search For New/Variable Objects

Candidates Put On Web Page

~1 m - 5 m



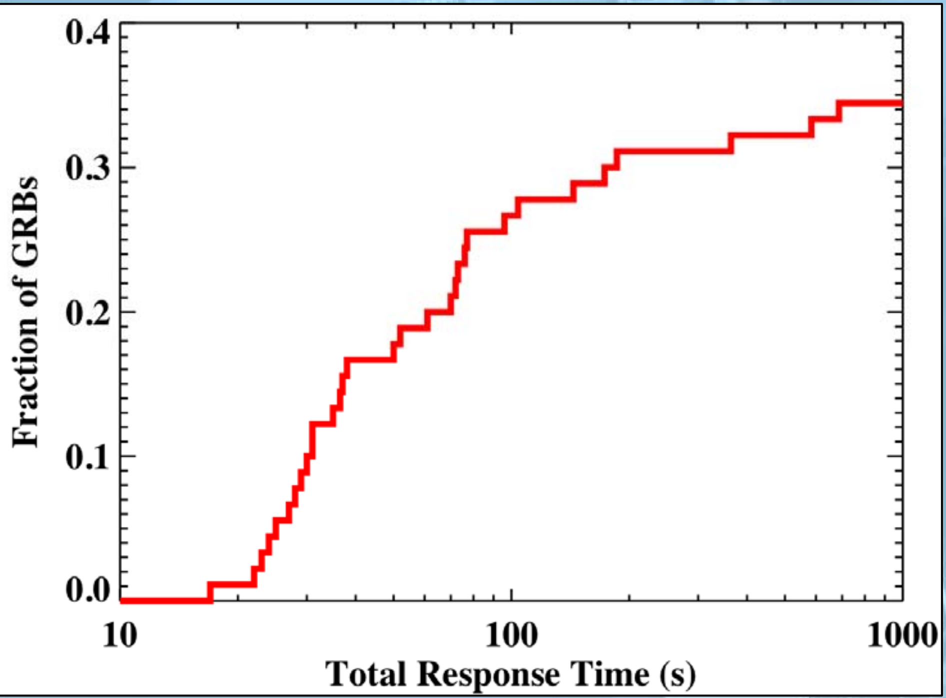


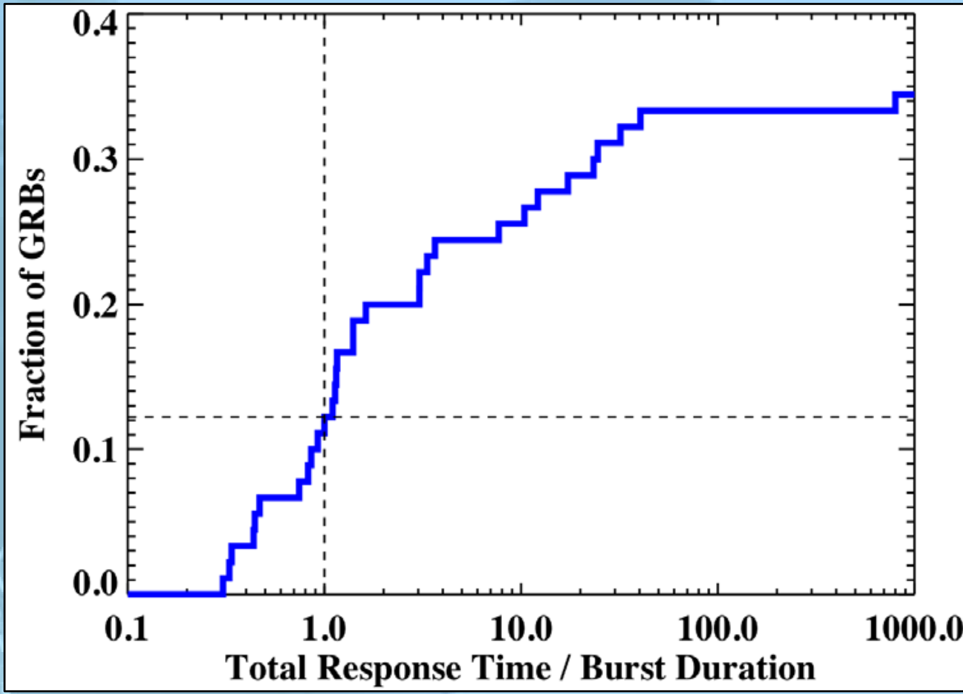
GRB 061007

Automated Detection

- We have announced optical counterparts in as little as 4 minutes from the start of γ-ray emission
- Until November, 2006 we required a person to confirm a counterpart
- New system that can announce counterparts automatically within ~ 30 s of the GRB
  - Expect 3-5 per year that can be identified in this way

Prompt Observations





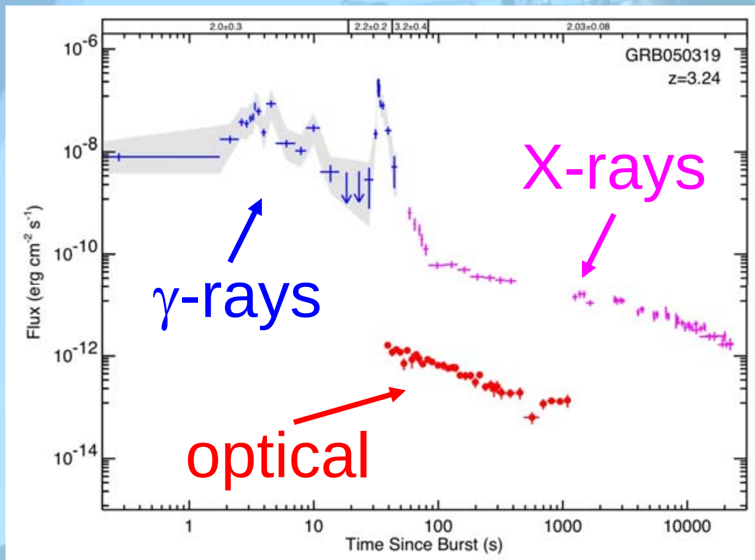
- Respond “rapidly” to ~ 1/3 of GRB triggers from *Swift*
- First exposure is contemporaneous with γ-ray emission for over 10% of all Swift bursts

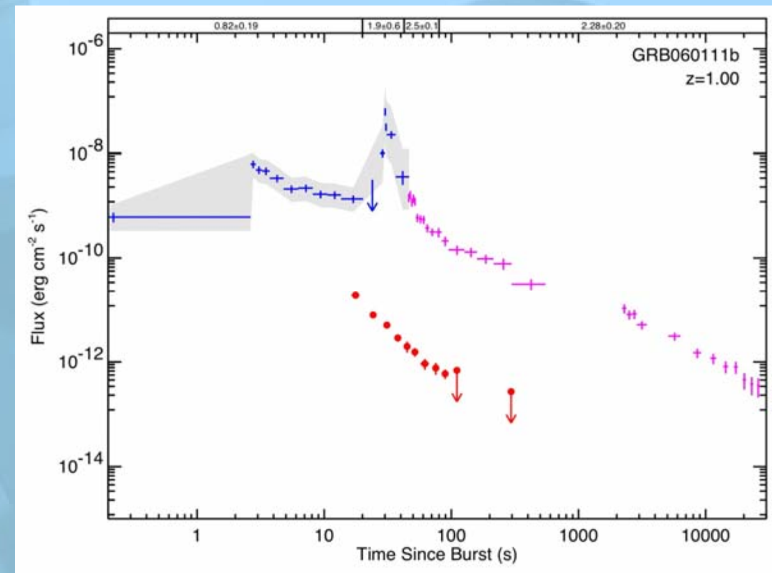
Technical Challenges

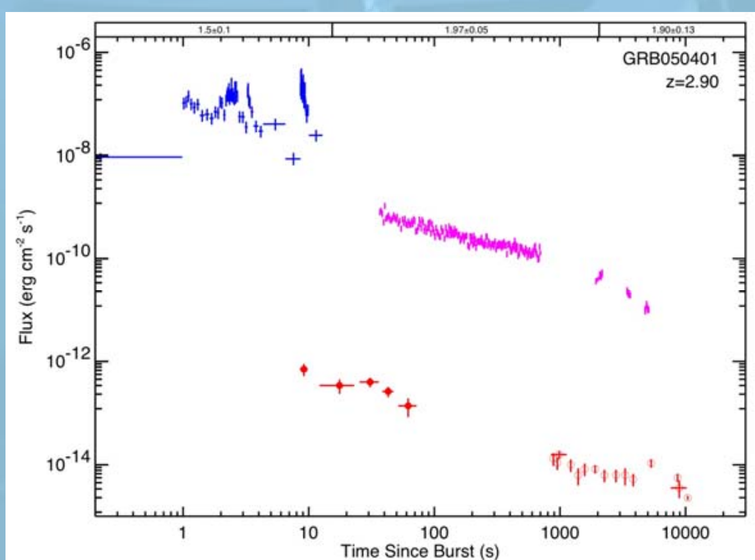
- Remote locations with limited bandwidth
- Temperature range from 0ºF - 110ºF
- Wind speeds up to 110 mph
- Rain, snow, sleet, hail…
- Troubleshooting must be done remotely, with limited diagnostics

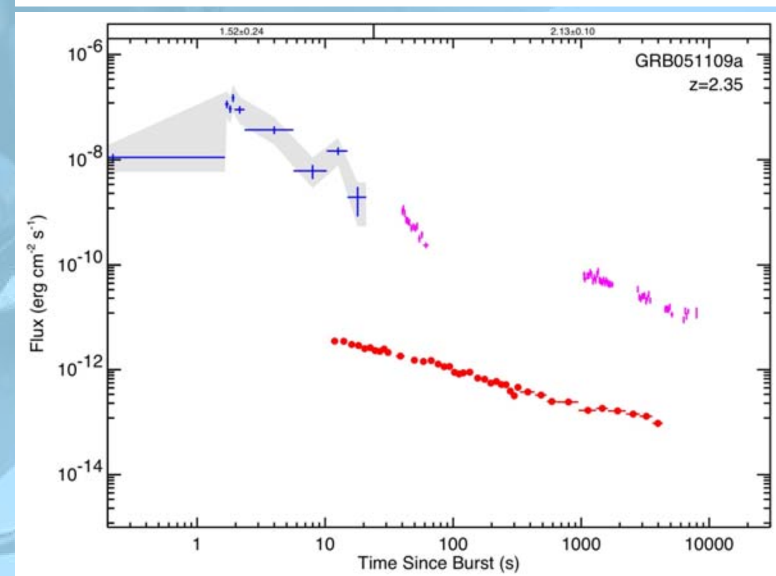
Prompt Counterparts

Fading Afterglows



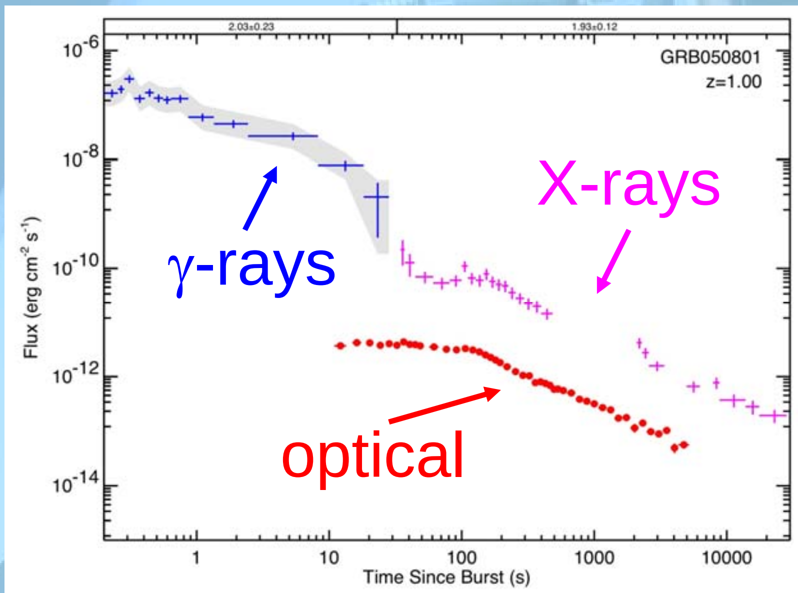


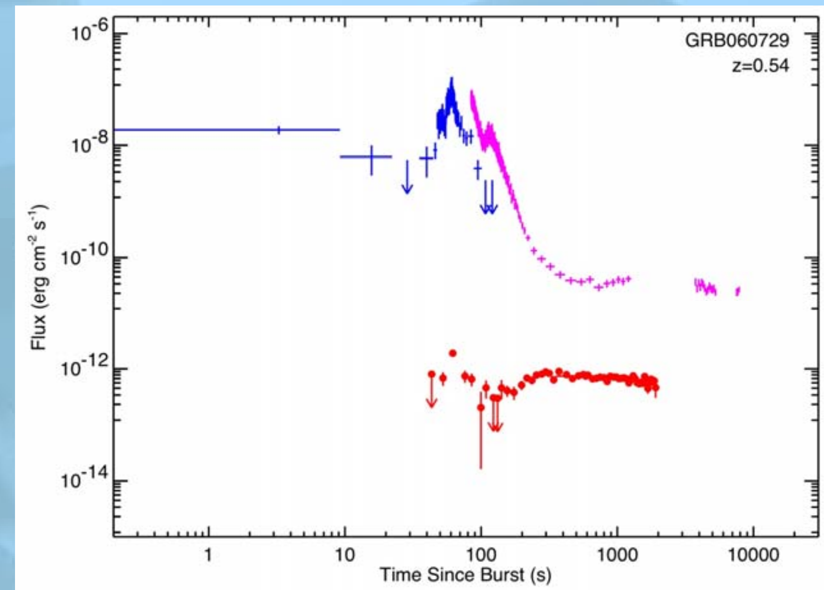


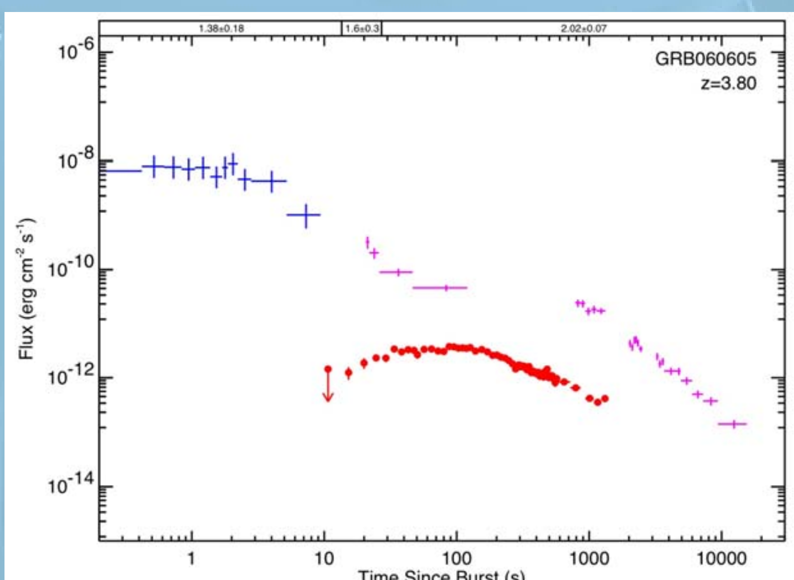


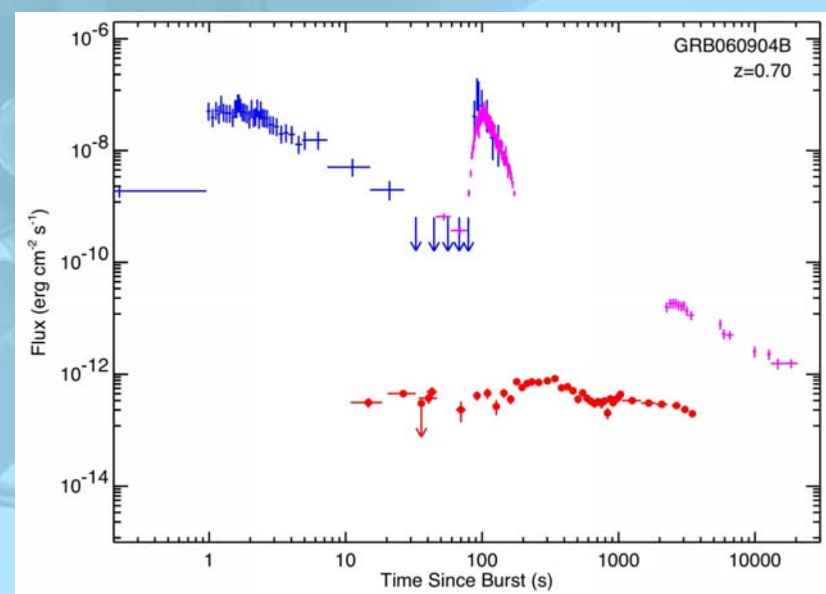
Blue: BAT, Magenta: XRT, Red: ROTSE-III (Optical)

Rising Afterglows

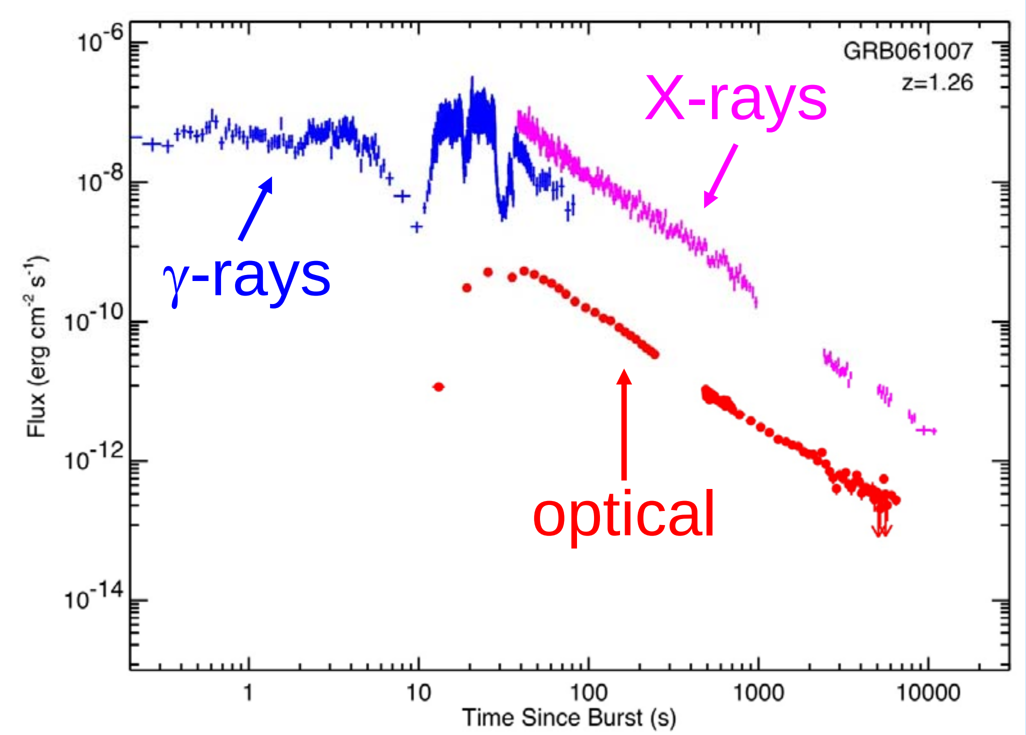








GRB 061007

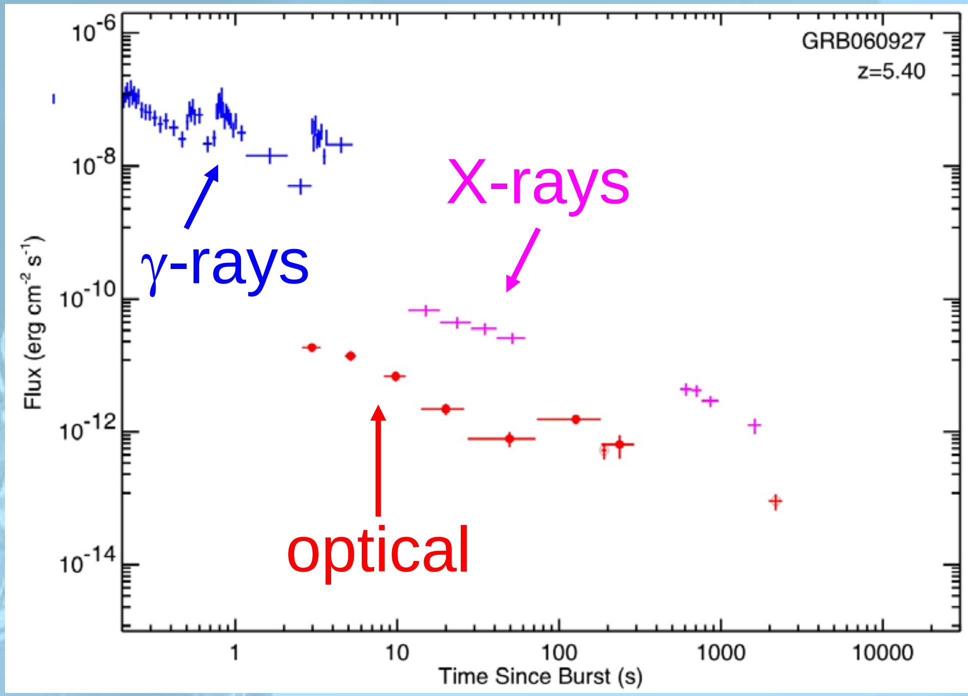


QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

- Brighter by a factor of 50 in < 5 seconds
- Afterglow does not fit the models

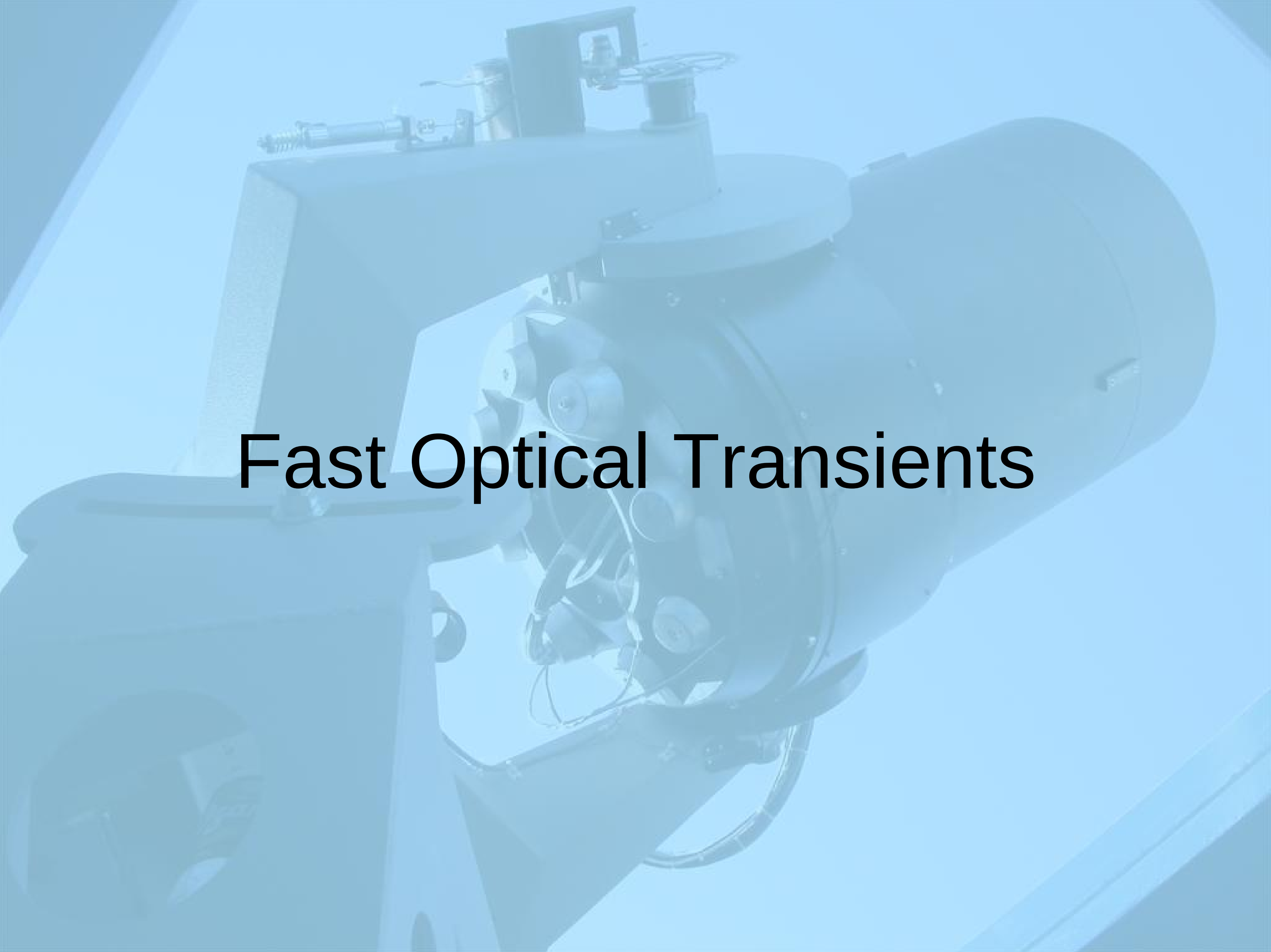
GRB 060927

- High redshift event: z=5.4
- Extremely bright
- Rapid response by ROTSE-IIIa
- Optical afterglow already fading < 3 s after the start of the burst!



Other ROTSE Science

- ROTSE-III telescopes always taking images
  - Fast optical transient search (eg, Rykoff, et al, 2005)
  - Microquasar & X-ray Binary optical monitoring (eg, Baykal, et al, 2006)
  - Supernova searches (eg, Quimby, PhdT, 2006)
  - Blazar Monitoring (eg, Aharonian, et al., 2006)



Fast Optical Transients

Untriggered GRB Afterglows

- Untriggered GRBs
  - Even if a satellite doesn't detect it, there are ~ 2 GRBs/day visible to the earth
  - Advantage: We know what these optical afterglows look like
  - Disadvantage: Rare
- Orphan GRB Afterglows
  - After the jet break, afterglows should be visible off axis
  - Advantage: Rate might be > 200/day
  - Disadvantage: We don't know what they look like

Untriggered GRBs

- Search designed to look for untriggered GRBs
  - We know what we’re looking for
- How much coverage is required?
  - 2 GRBs/day visible to earth (from BATSE)
  - ~ 50% with visible afterglows
  - 1/day/40000 $deg^2 \rightarrow$
  - ~ 110 $deg^2 \cdot yr$ effective coverage required
- Search strategy to have as much coverage as possible

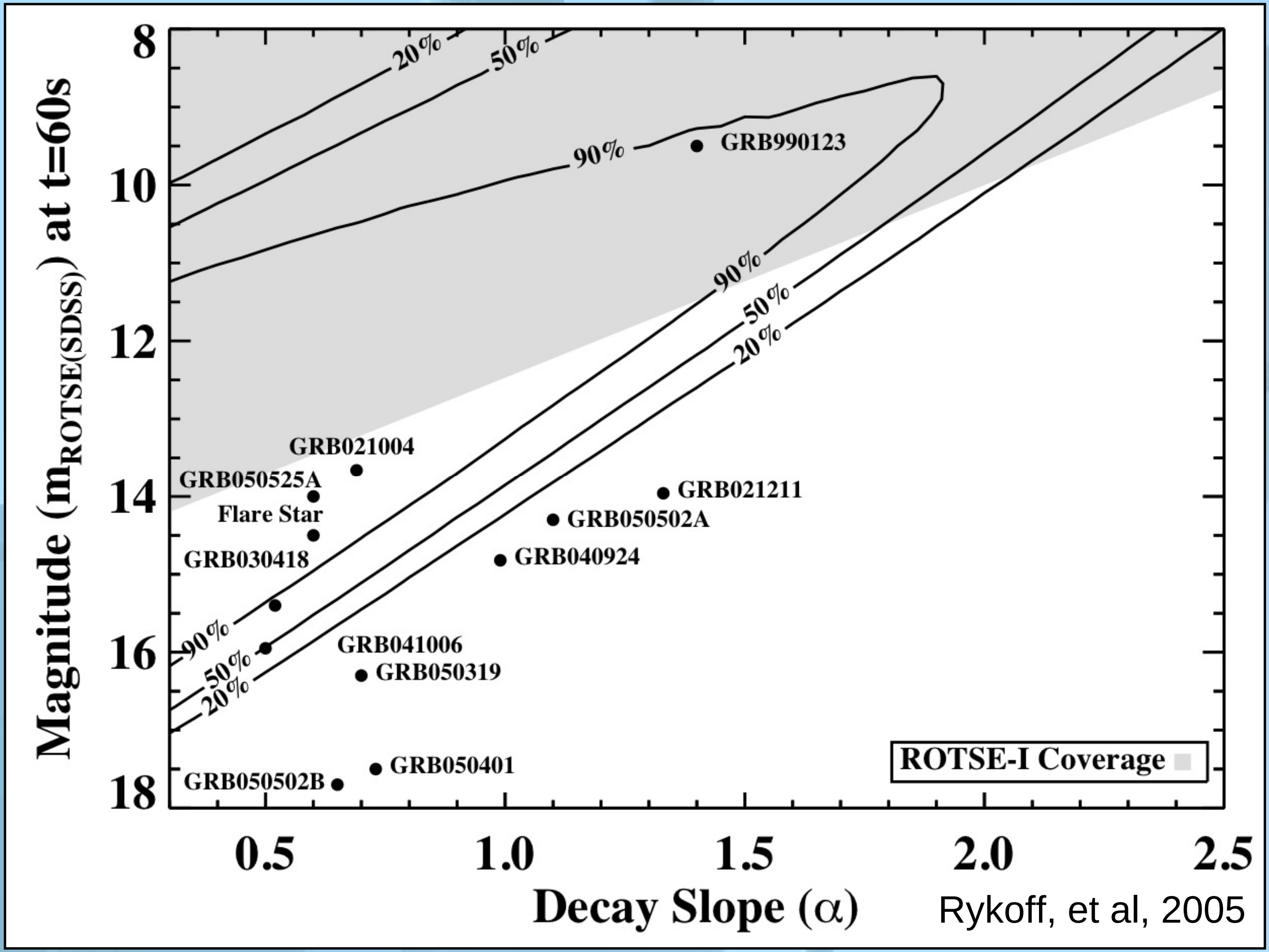
Search Strategy

- Search equatorial stripe covered by SDSS
  - Deep, 5 band images to identify hosts, quiescent counterparts
  - Equatorial region visible from North and South
- Require rapid identification for follow-up
- Take pairs of images, each pair separated by 30 minutes
  - Require transient in 4 consecutive images
  - Effective coverage time is 30 minutes, assuming a typical transient is brighter than our limiting magnitude for 1+ hour

Results

- Through March 2005, covered 1.74 $\text{deg}^2 \cdot \text{yr}$ with limiting magnitudes better than 17.5
  - Four telescopes operational from May 2004
  - Search is ongoing - now around ~ 4 $\text{deg}^2 \cdot \text{yr}$
- Found
  - Many new cataclysmic variables
  - Several m-dwarf flares
  - Two supernovae from dwarf galaxies (2005cg, 2005ch)
  - No unidentified transients
  - And many asteroids
    - All are known

Results



- Sensitive to ~ 50% of typical afterglows

Conclusion□□

- GRBs probe extreme physics
  - High energies, high luminosities, fast variability
- Early optical & multiwavelength observations provide constraints on models
  - Onset of the afterglow is not well understood
- Rapid, automated optical afterglow localizations are possible
- Optical transient searches are possible, but finding “orphan afterglows” is difficult