GRBs in the Era of Rapid Follow-up

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Collaborators

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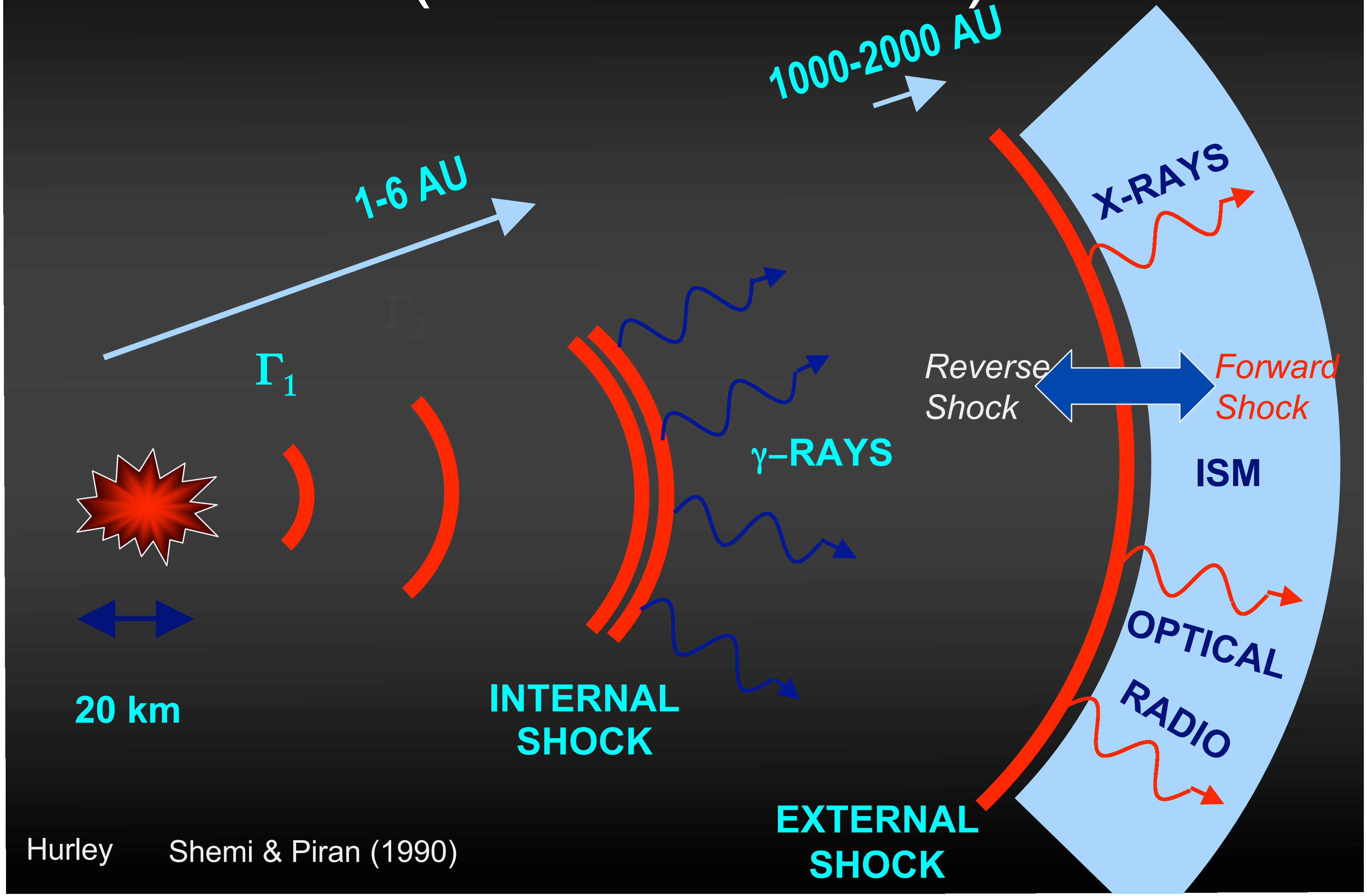
  - Andrea Melandri
  - Shiho Kobayashi
  - David Bersier
  - Iain Steele
  - Chris Mottram
  - Neil Clay
  - Robert Smith
  - Zach Cano
- External members:
  - Cristiano Guidorzi (INAF/Ferrara)
  - Andreja Gomboc (Uni. Ljubljana)
  - Alessandro Monfardini (CNRS-Grenoble)

Motivation

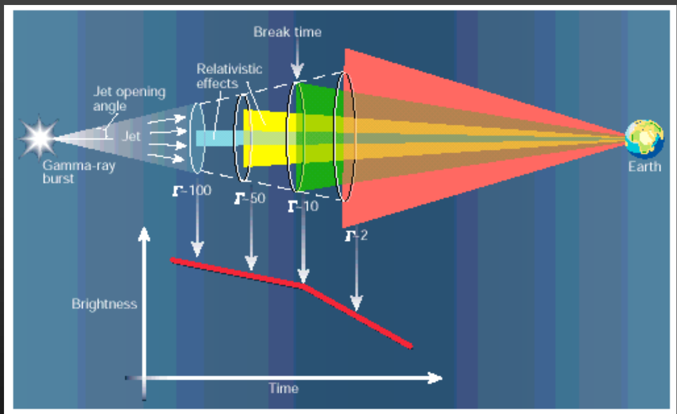
- Origin of Gamma Ray Bursts
  - core-collapse of massive stars
  - neutron star or neutron star - black hole mergers
- Access to regions of extreme physics
  - High Lorentz factors (>1000)
  - Strong gravity
  - Large magnetic fields
  - Fundamental physics
- Detectable to high redshift
- Short timescales need *real-time* observing
- Observationally and theoretically challenging

Fireball (Internal Shock) Model

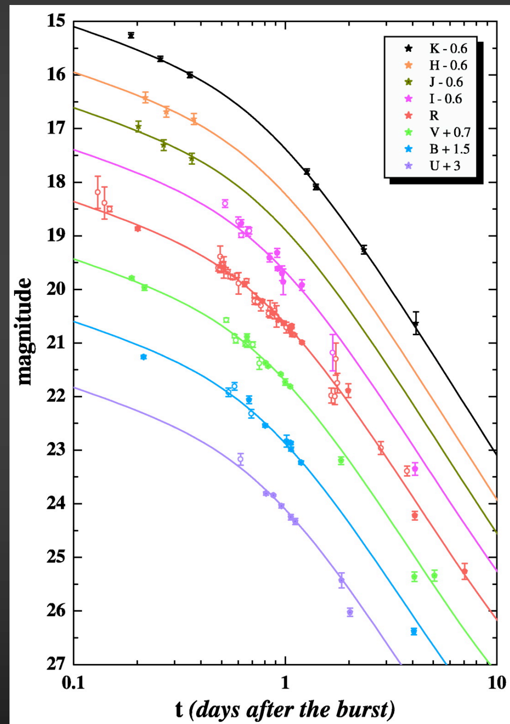


Afterglows and Jets

- Anisotropic emission (beaming) invoked
- Achromatic break in afterglow light curve
  - Jet 'break' $F_\nu \propto t^\alpha$; α steepens by $\Delta\alpha \sim 1$
  - For θ_j, jet radiates into $f_b = (1-\cos\theta_j) \sim \theta_j^2/2$
  - Break at t_j when $\Gamma < 1/\theta_j$; on seeing edge of jet



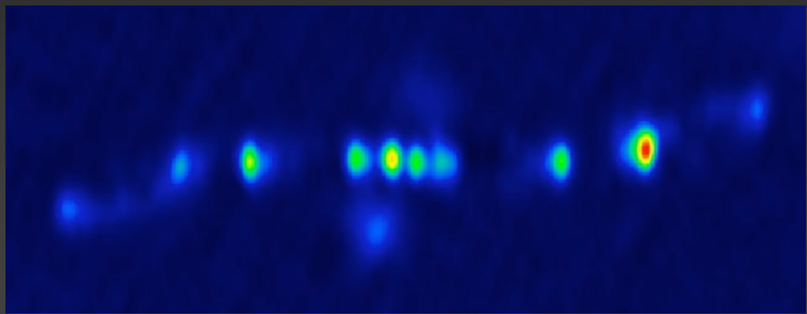
Woosley 2001



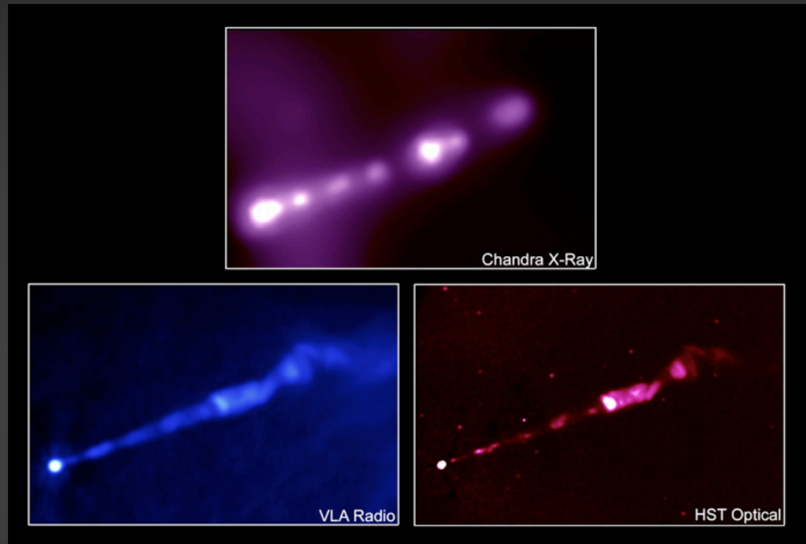
(e.g. Band et al. 2003; Klose et al. 2004)

Pre-Swift Rapid optical response in 1997 ~10 hours post GRB

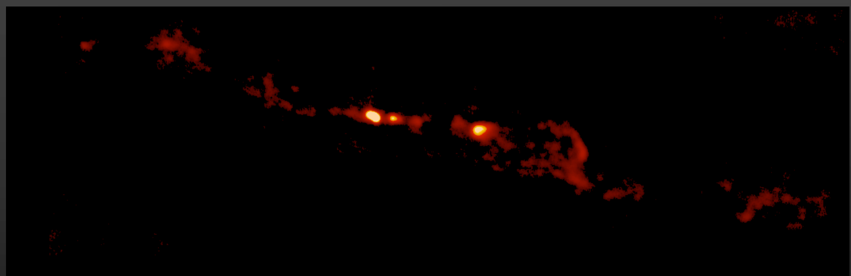
Ubiquitous Jets & Hindsight



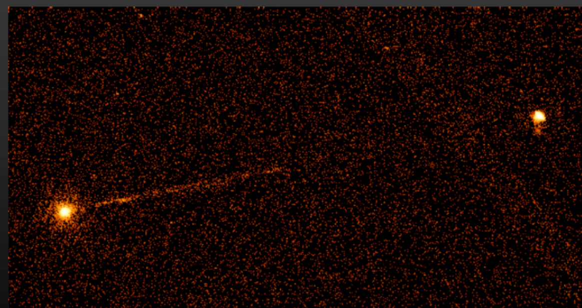
SS433 (Rupen et al.) $v_j \sim 0.26$ c



M87 (Biretta et al.) $v_{app} \sim 6$ c

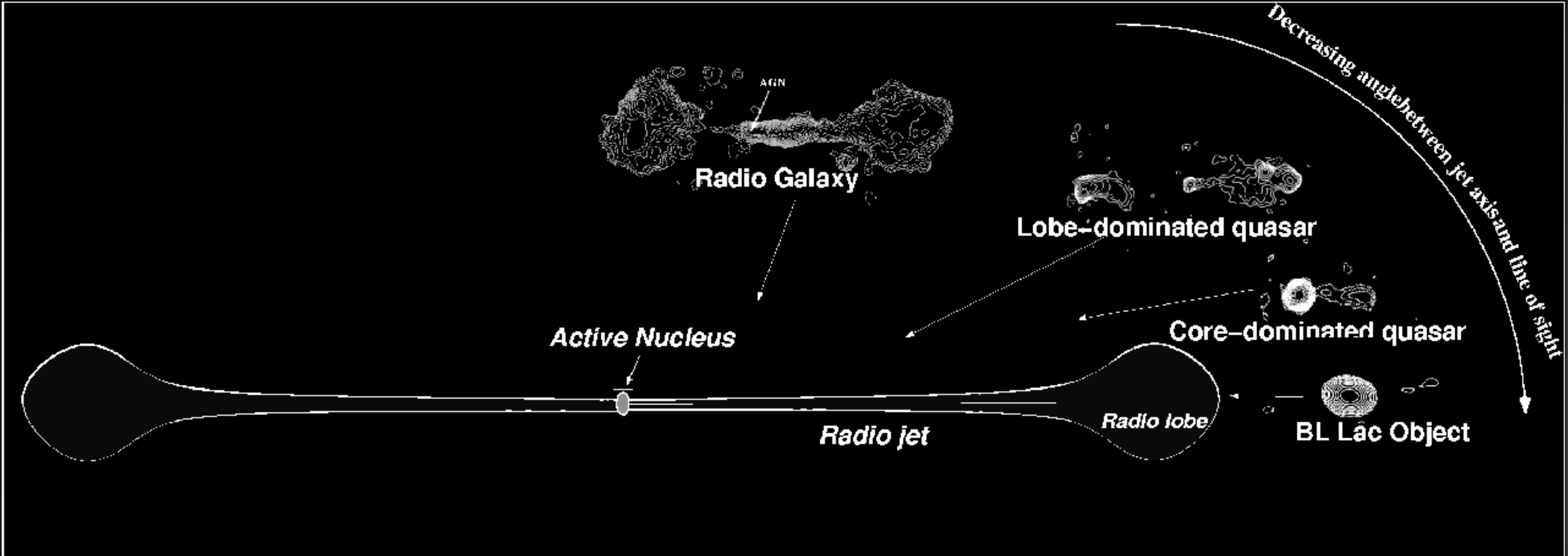


NGC 4151 (Mundell et al. 2003)
v < 12000 km/s



Pictor A (Wilson, Young & Shopbell 2001)

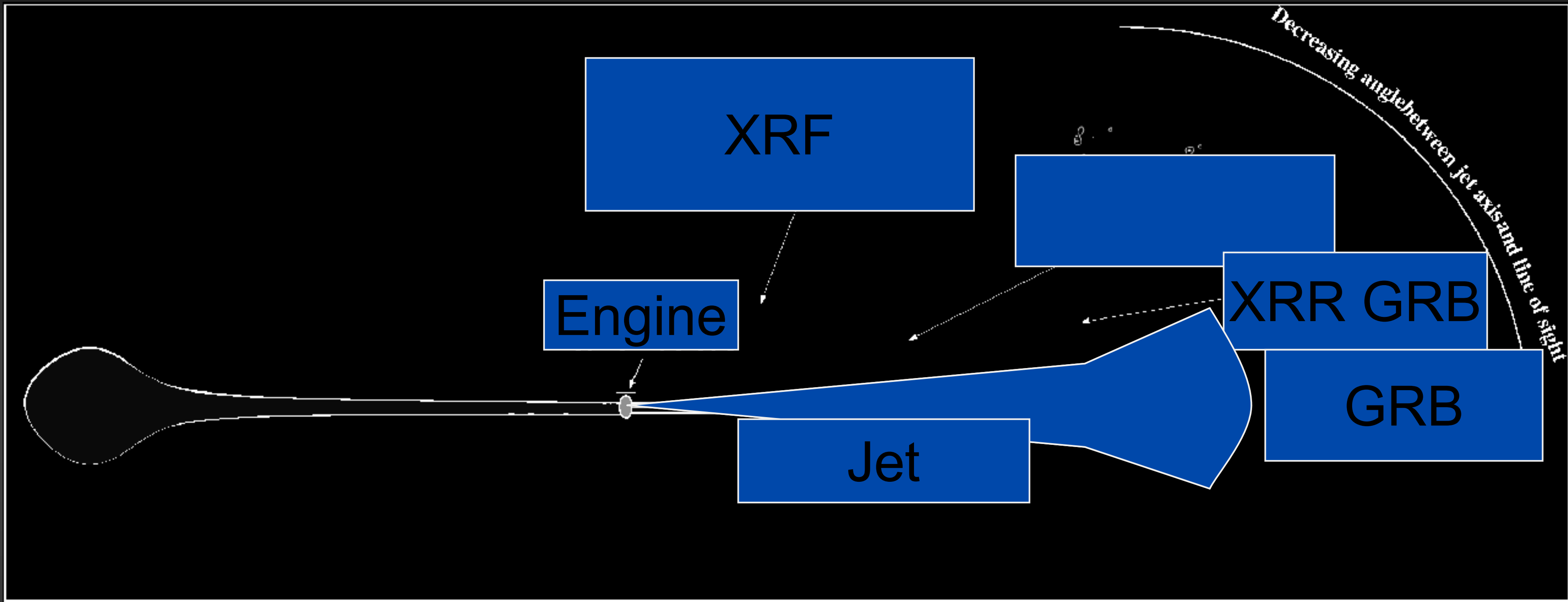
AGN Unification



Mundell et al. 2005, Advances in Science, ICP, p77

- Zoo of quasars - different observed properties explained by observer's perspective
  - Blazar ⇨ quasar ⇨ radio galaxy
  - Jet viewed head-on or side-on
  - Central engine driven by supermassive black hole

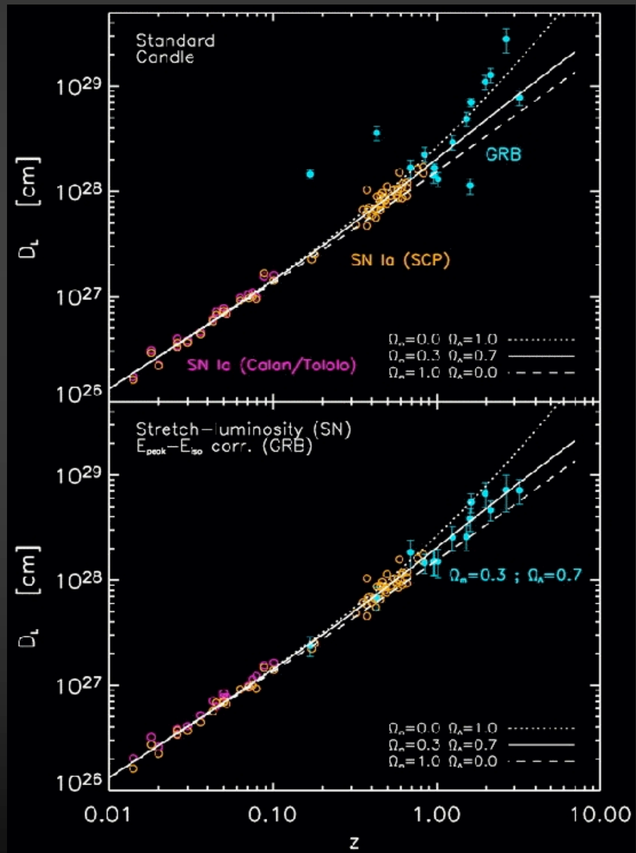
GRB Unification?



- Zoo of GRBs - different observed properties explained by observer's perspective?
  - GRB ⇒ X-ray Rich GRB ⇒ X-ray Flash
  - Central engine driven by stellar-mass black hole

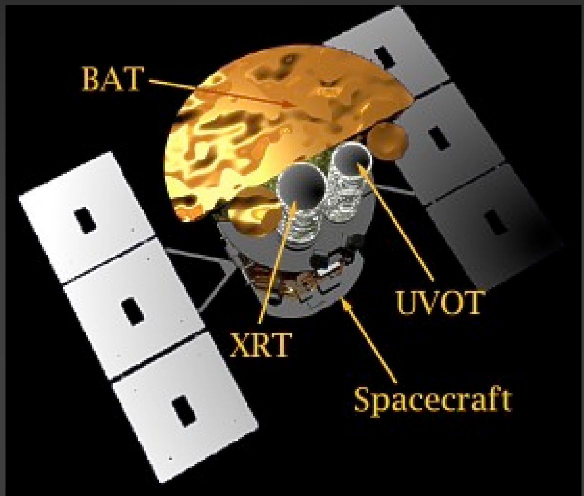
Standard Engine?

- Relativistic beaming + physical collimation?
- Opening angles ~few degrees
- Collimation-corrected E ~ 10^{51} erg
- Account for kinetic & non-EM?
  - Standard energy reservoir for long GRBs?
- If we can understand physics
  - Use as standard(izable) candles
  - Cosmological tools to high z environment
  - SF tracer?



e.g. Frail et al. 2001; Ghirlanda et al. 2004

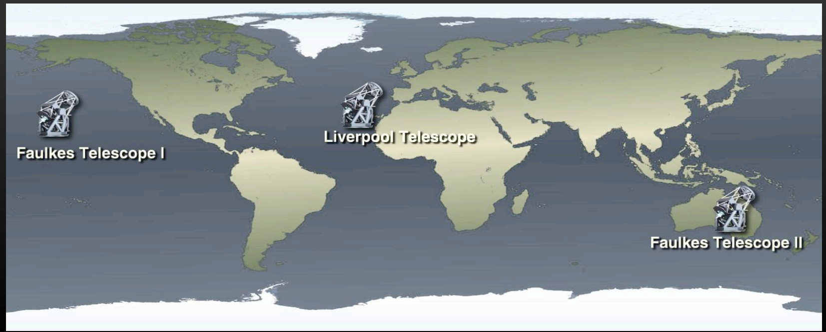
New Era of Rapid Followup



- Dedicated GRB satellite: SWIFT
  - Burst Alert Telescope (BAT): 15-150 keV
  - X Ray Telescope (XRT): 0.3-10 keV
  - Ultraviolet Optical Telescope (UVOT): 150-650 nm
- Real-time GRB sky map at: **http://grb.sonoma.edu/**

Large Robotic Telescopes

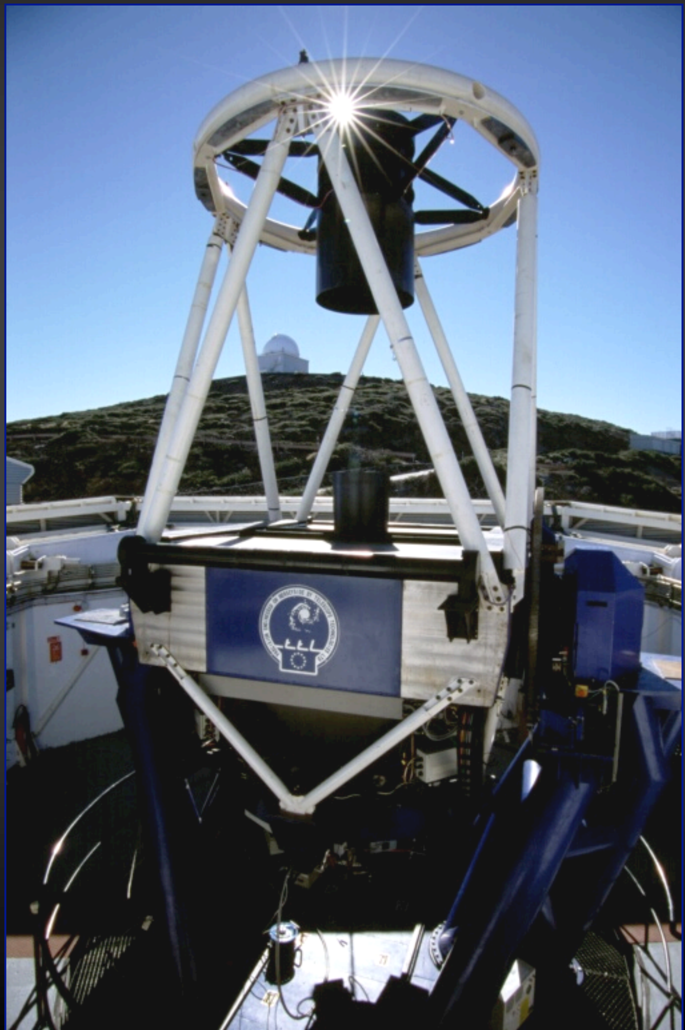
- Liverpool and Faulkes telescopes: world's largest (2-m) fully robotic optical telescopes (**http://telescope.livjm.ac.uk/**)
  - Fully-open enclosure (no dome seeing and fast slew), robotic operation, large aperture, comprehensive instrumentation
- Observations coordinated with other facilities, both ground-based and from space
- Condition-dependent observations
- Intelligent dispatch scheduler (*not* queue scheduled)
- Liverpool Telescope is *not* in Liverpool !



Liverpool Telescope Construction

(4 March 2002 - 20 Oct 2003)

Telescope Specifications

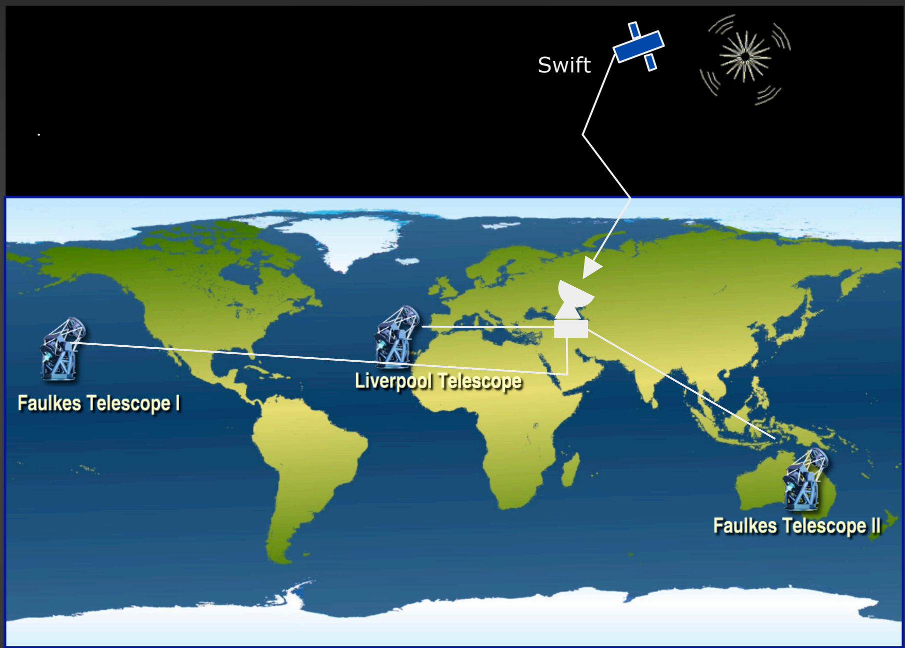


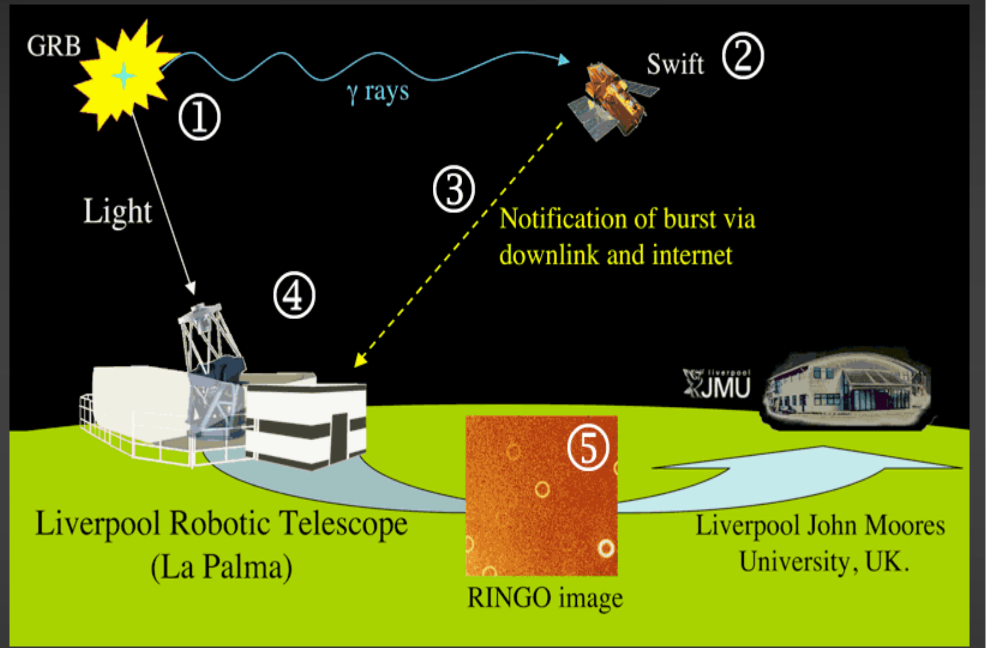
- Primary mirror diameter 2m
- Final focal ratio f/10
- Altitude-Azimuth design
- Image quality < 0.4" on axis
- Pointing < 2arcsec rms
- Rapid slew rate > 2º/sec
- Fully open enclosure
- Five instrument ports (4 folded and one straight- through) selected by deployable, rotating mirror in the A&G Box within 30 s
- Robotic (unmanned) operation with intelligent automated scheduler
- General user facility - not dedicated GRB telescope

Instruments & Science Goals

Optical Camera (LT/FTN/FTS) ~5' FOV	• Early multicolour light curves • Shock physics/ISM • Later-time light curves/Jet breaks • GRB-Supernova connection
RINGO Polarimeter (LT only) ~5' FOV	• Early-time polarisation studies • 1% polarisation at r' > 15 mag • Fundamental tests of jet models
SupIRcam Infrared Camera (LT only) ~1' FOV	• High z 'naked' bursts vs • Low-z 'obscured' bursts
Spectrograph (FRODOSpec) (LT - April 09)	• Early time evolution of circumburst medium
STILT (LT- 2009/10) (FOV 1^o /20^o) RINGO2 (LT - 2010) IO (LT- 2011) (FOV 2^o)	•Bright bursts/neutrino counterparts •Polarisation to 17th mag •Deep simultaneous optical/IR

GRB Robotic Followup

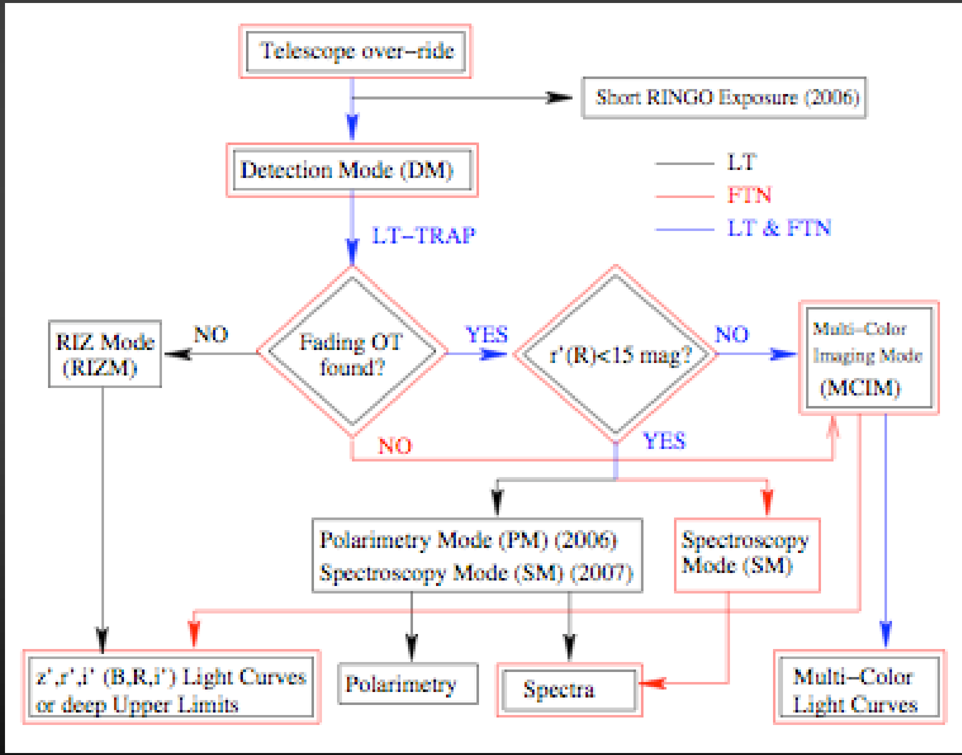




- Optimisation for GRB science goals:
  - Automatic response (over-ride), data analysis & interpretation strategy
  - No human intervention from receipt of alert ➜ observations ➜ automatic object ID ➜ choice and execution of subsequent observations

LT-TRAP ('Transient Rapid Analysis Pipeline')

- Sophisticated I.D. & decision making algorithm
- Over-ride mode starts on alert arrival
- Detection mode starts (n x 10s in r')
  - Astrometric fit, object extraction, cross-correlation with catalogues
  - Optical candidate?
  - Repeat for each image
  - Variability test (α>1)
  - Optical candidate I.D.?
  - Reports (16-bit) confidence level
- ***Auto-ID*** to R~19 mag in ~20s
- Subsequent strategy optimised and executed *automatically*
- GRB circular issued



Guidorzi et al. 2006, PASP ,118, 288

And it works ...

```
Date: Sun, 1 May 2005 22:16:30 -0400
From: Bacodine <vxw@capella.gsfc.nasa.gov>
To: ag@astro.livjm.ac.uk, grb@astro.livjm.ac.uk
Subject: GCN/INTEGRAL_POSITION

TITLE:          GCN/INTEGRAL NOTICE
NOTICE_DATE:    Mon 02 May 05 02:14:36 UT
NOTICE_TYPE:    INTEGRAL Wakeup
TRIGGER_NUM:    2484,    Sub_Num: 0
GRB_RA:         202.4403d {+13h 29m 46s} (J2000),
                202.4982d {+13h 29m 60s} (current),
                201.8971d {+13h 27m 35s} (1950)
GRB_DEC:        +42.6722d {+42d 40' 20"} (J2000),
                +42.6448d {+42d 38' 41"} (current),
                +42.9301d {+42d 55' 48"} (1950)
```

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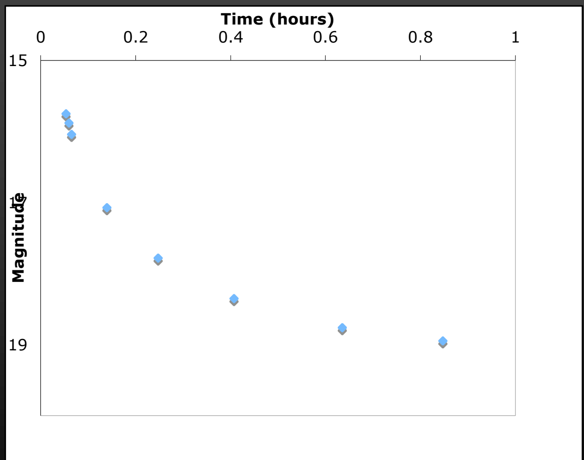
Date: Mon, 2 May 2005 03:18:40 +0100
From: Engineer account <eng@astro.livjm.ac.uk>
To: ag@astro.livjm.ac.uk, am@astro.livjm.ac.uk, cgm@astro.livjm.ac.uk,
     cjm@astro.livjm.ac.uk, crg@astro.livjm.ac.uk, grb@astro.livjm.ac.uk,
     grbgroup@star.herts.ac.uk, grbgroup@star.le.ac.uk, ias@astro.livjm.ac.uk,
     ltops@astro.livjm.ac.uk, mfb@astro.livjm.ac.uk, mjb@astro.livjm.ac.uk,
     rjs@astro.livjm.ac.uk
Subject: GRB Alert : LT : OT CANDIDATE

I have completed detection mode.
The best optical transient I could find has a position of 13:29:46.25 ,
+42:40:27.50 (J2000).
Thats at (approximate) pixel position (760.260010,567.530029) on the detection
mode images.
It has a magnitude of 15.575000 (vs USNOB1) and counts 13166.900391.
The astrometric fit has a residual of 0.160000 arc-seconds.
The confidence level is 1.000000.
I am confident that I have found an genuine OT.
I am now changing to lt_ot_imaging mode.
```



Guidorzi et al. 2005, ApJ, 630, L121

- LT began observing <u>3.1 min</u> after GRB onset.
- *Automatic I.D.* within 1 minute (**r'~15.8** & rapid fade)
- Multi-colour imaging sequence **auto-triggered**
- First early-time *multi-colour* light curve of afterglow.

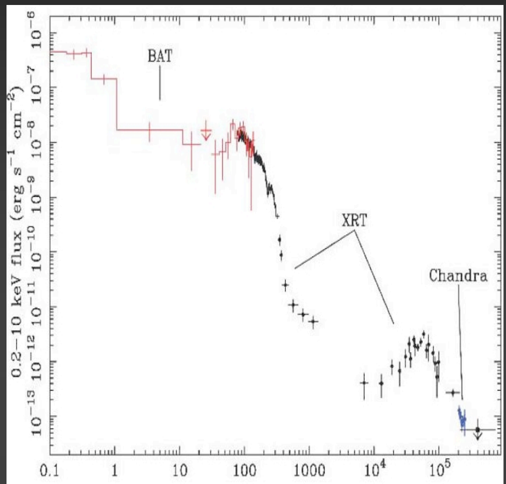
Pre-Swift/Fermi Predictions

- Optical counterparts to most GRBs
- Many bright optical flashes at early time
- Smooth light curves - jet breaks easy to spot
- High-energy spectral turnover
- High z GRBs easily identified
- Short bursts understood
- Look for new jobs….

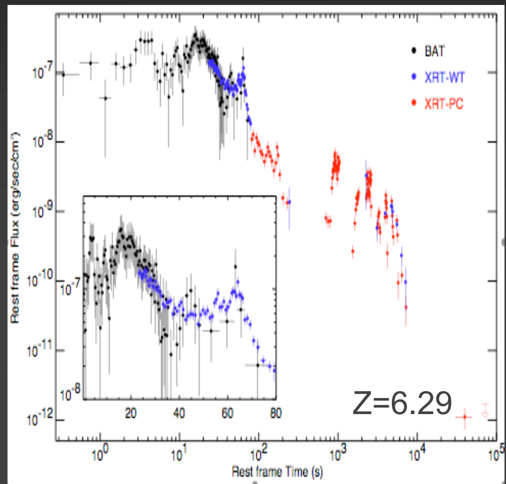
Swift/Fermi Outcomes

- ~50% of GRBs remain optically dark
- Lack of bright reverse-shock optical flashes
- Complex light curves in all bands
- Band function to high energies
- First z=8.2 GRB identified only this year
- Short bursts still challenging
- Astronomers busier than ever...

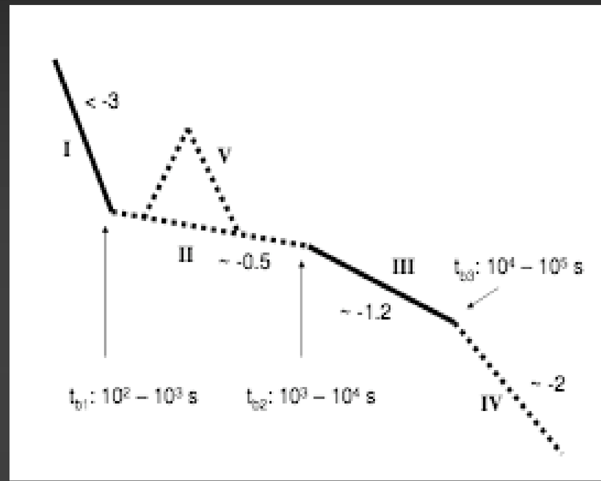
Early-Time Light Curves



GRB050724 - (Barthelmy et al. 2005)



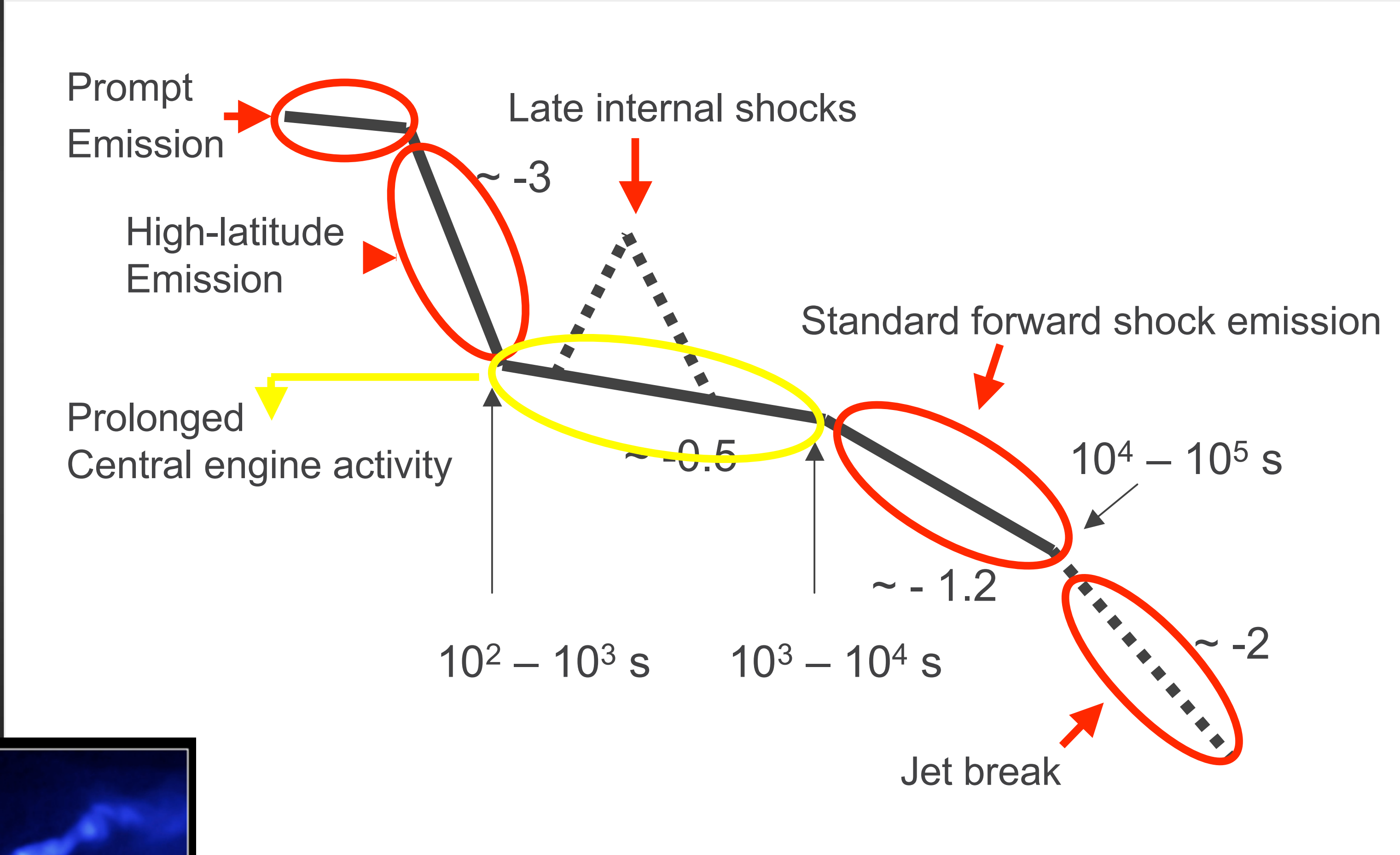
GRB 050904 (Cusumano et al. 2005)

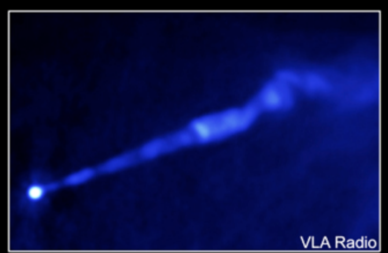


Zhang et al 2006.

- Swift γ/X-ray light curves surprisingly complex
  - 50 % with X-ray flares (late-time internal shocks - Kocevski et al. 07)
  - Simple power law inadequate
- Long-lived central engine activity - canonical?
- Common origin for prompt & afterglow emission?
- Internal vs external shocks?
- *Early-time* multi-λ observations key

Early-Time Light Curves

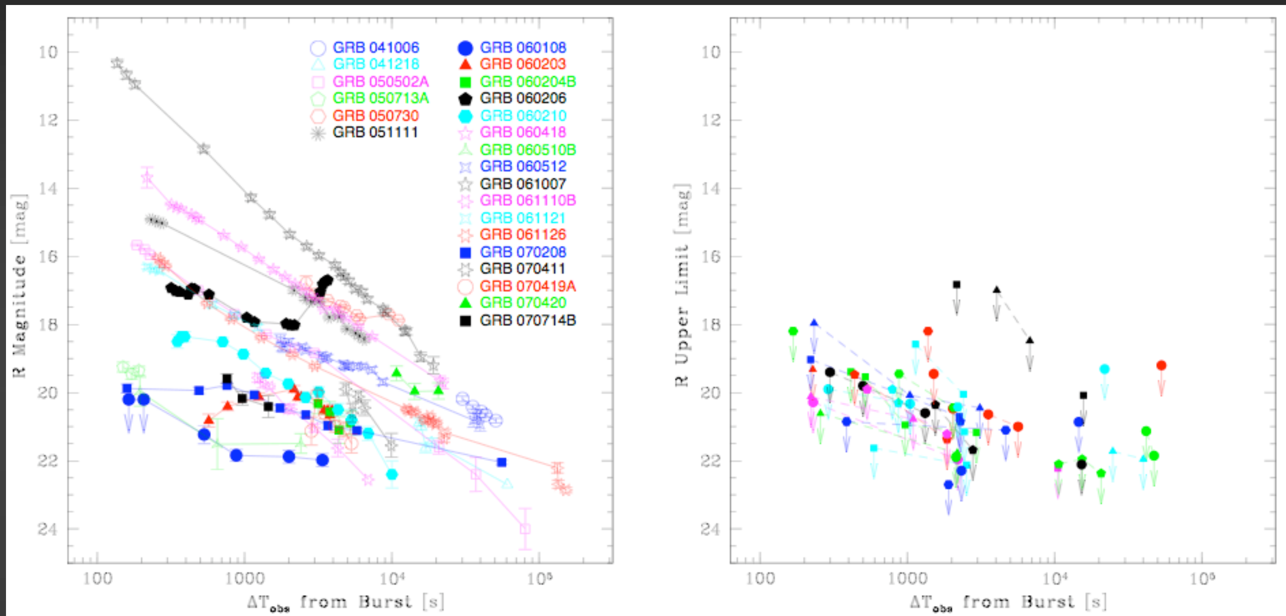




Optical/X-ray rebrightening

Zhang et al 2006.

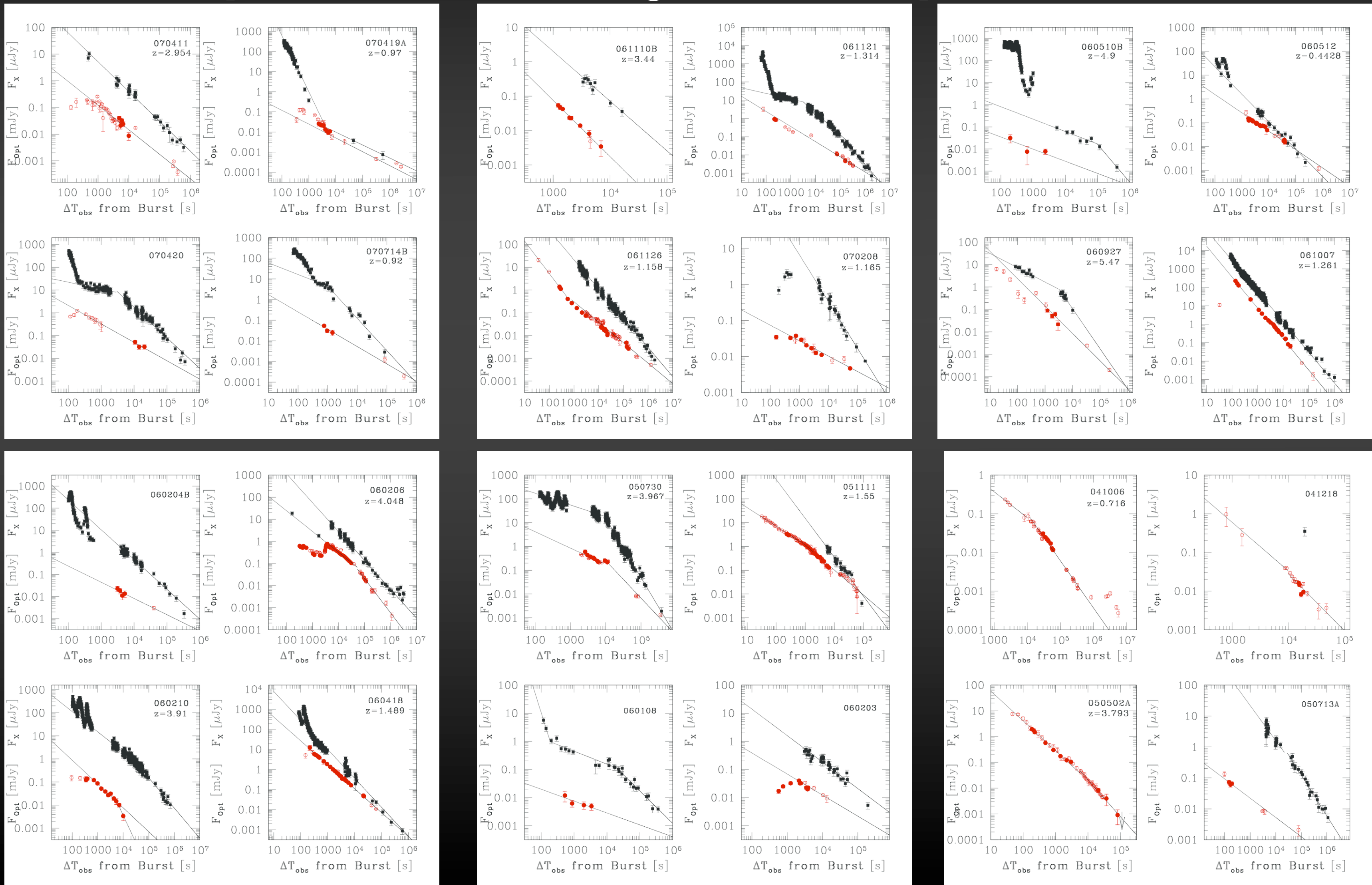
Optical Light Curves



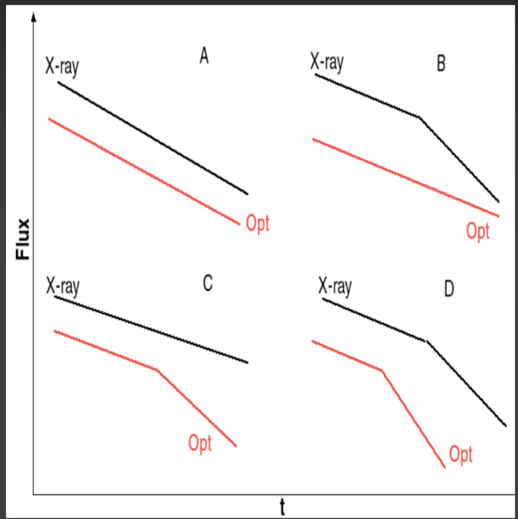
Melandri et al. 2008, ApJ, 686, 1209

- Wide range of observed brightness
- Deep, fast observations vital
- Probe properties of ambient medium
- ~50% of optical afterglows remain undetected

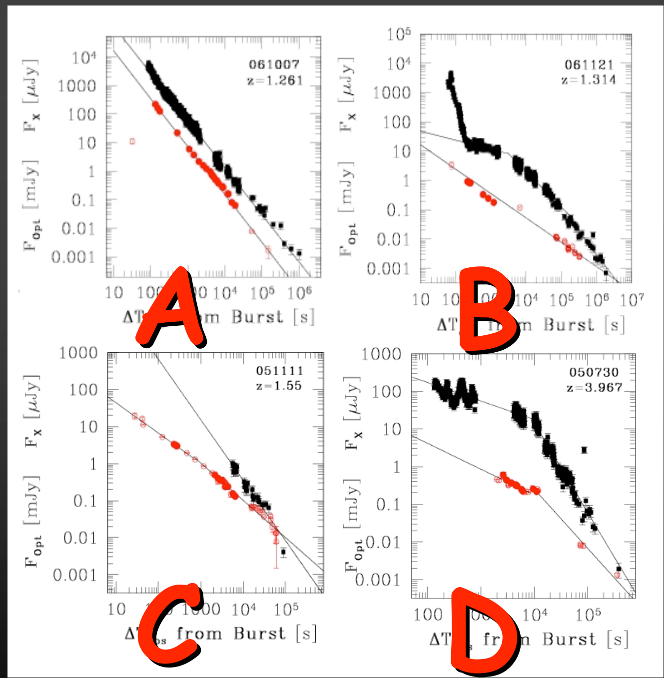
Optical:X-ray Comparisons



Standard Fireball Model



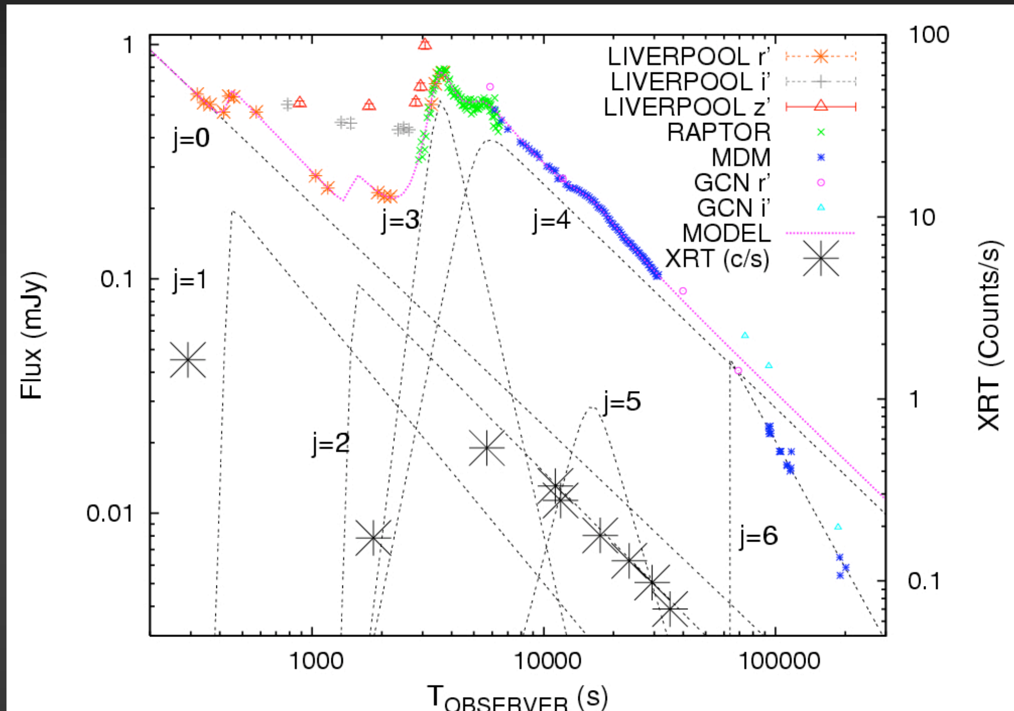
X-ray + optical classification scheme



- **A** : no break in optical or X-ray
  ⇒ ν_C above/between bands
- **B** : break in X-ray, not in optical
  ⇒ ν_C passes through X-ray band
- **C** : break in optical, not in X-ray
  ⇒ ν_C passes through optical band
- **D** : break in optical & X-ray bands
  ⇒ energy injection stops or jet break

Melandri et al. 2008, ApJ, 686, 1209

Optical Flares: GRB 060206



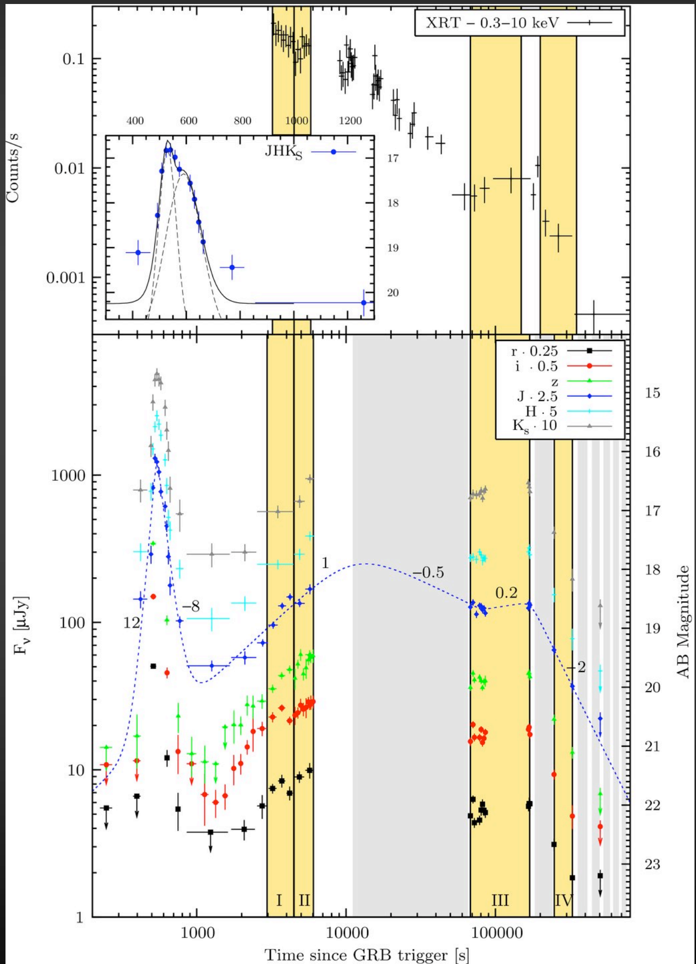
z=4.05

Monfardini et al. 2006, ApJ, 648, 1126; (see also Wozniak et al. 2006, Stanek et al. 2006)

$$F_\nu(t) = \sum_j F_j \cdot \sqrt[n]{\frac{2}{(t/t_j)^{-\alpha_{1_j} \cdot n} + (t/t_j)^{-\alpha_{2_j} \cdot n}}}$$

- Multiple bumps - smooth broken power laws
- High-z time dilation helps
- Rapid variability at t~440s (Δt_{rest}< 4s <<t) - ongoing internal-engine activity
- Major rebrightening at t~3000s - energy injection ($\nu_{opt} < \nu_c < \nu_X$)
- Optical break between 3 x 10^4 s & 9 x 10^4 s; not seen in X ray - **not due to jet break**
- **Simultaneous** optical /X-ray light curves vital to infer jet properties and GRB energetics

Optical Flares: GRB 080129

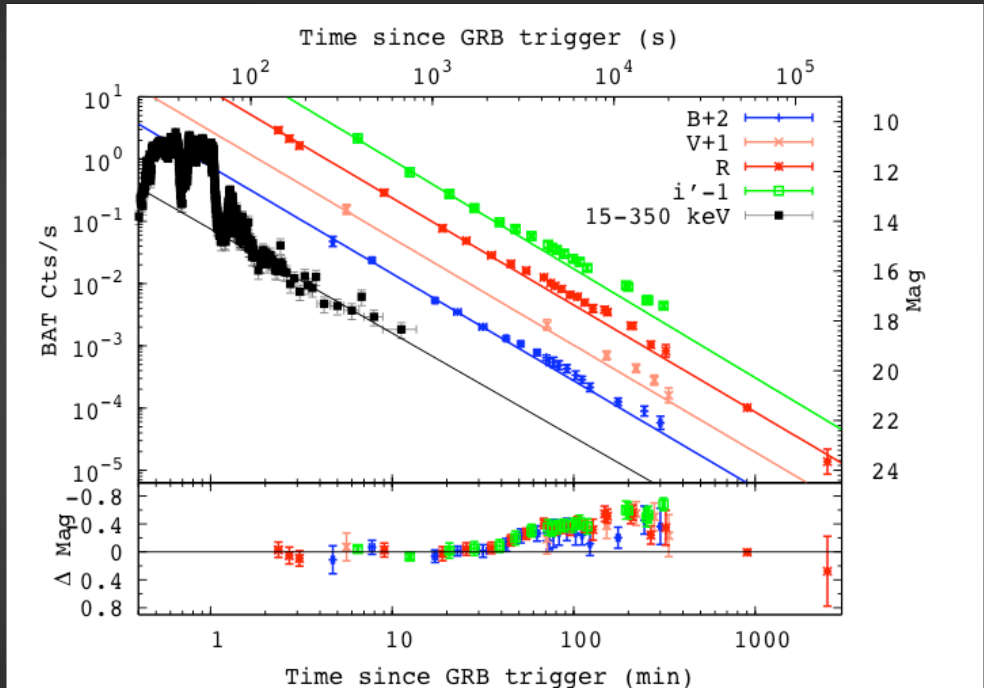


- GRB 080129: z = 4.349 (Greiner et al. 2009, ApJ, 693,1912)
- Later bump is emerging afterglow
- Flare unexplained
  - Rise too steep for reverse shock
  - Uncorrelated with γ rays
  - X-ray flare?
  - Residual shocks?
  - Hot spot in Poynting flux?
- Polarization prediction

Greiner et al. 2009, ApJ, 693, 1912

Light-Curve Studies

Deep Multi-Colour Photometry



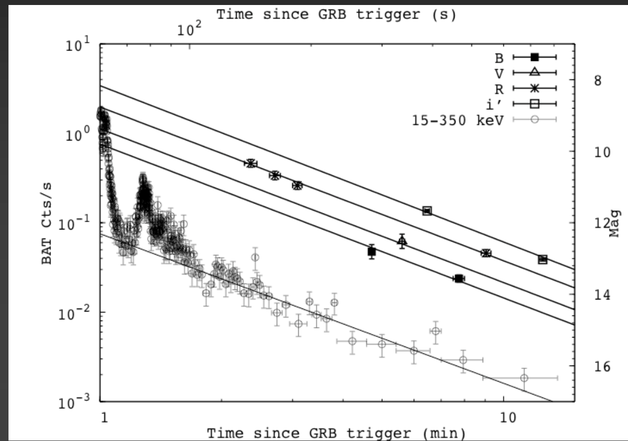
- One of the brightest (R~10 mag): FTS/VLT/Magellan - GRB 061007
- *Simple* light curves: t = 137 sec to 2 days

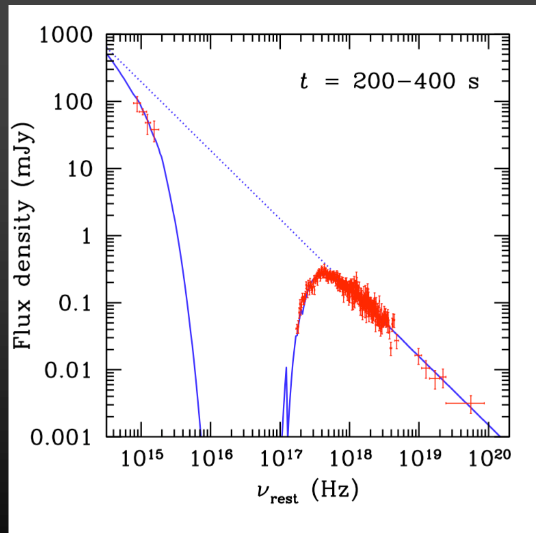
Mundell et al. 2007, ApJ, 660, 489

Bright, but no flash

GRB 061007

- Bright γ, X, optical afterglow
- Reverse-shock optical flash ruled-out
- SED modelling:
  - $\beta_{ox\gamma}$ =1.02+/-0.05,
  - A_V (rest)=0.48 (SMC profile)
- Microphysics explains lack of *Swift* optical flashes
  - Flash predicted in radio/IR at 137s
- E_{iso} = 10^{54} erg
- Jet θ> 4.7^o Eγ > 3.4 x 10^{51} erg
- No jet break before 10^6 s ⇨ spectral correlation outlier





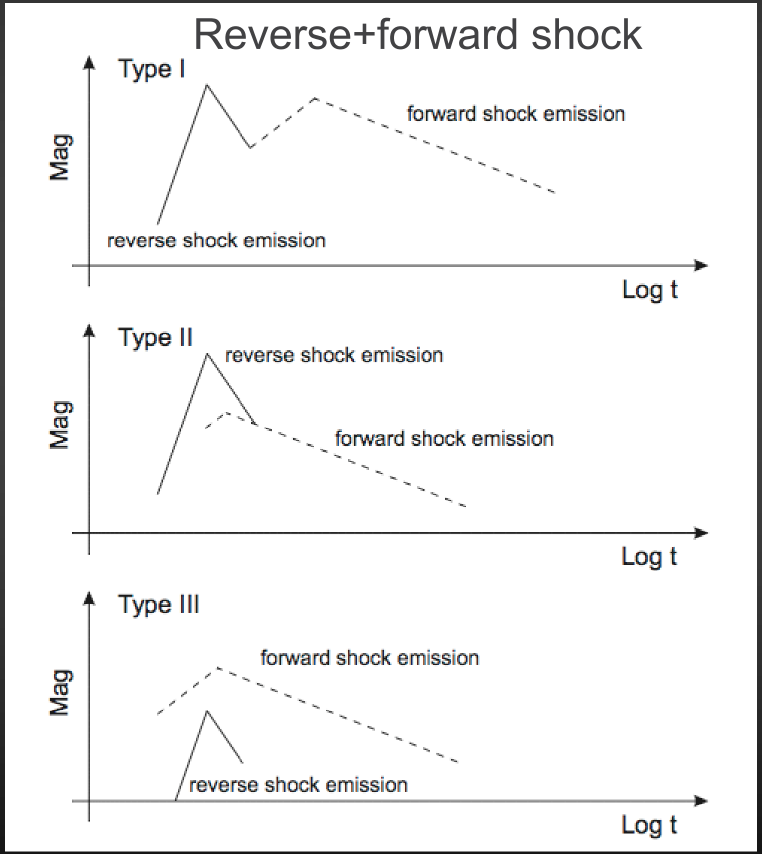
Mundell et al. 2007, ApJ, 660, 489

Fireball Magnetization

- Standard (internal shock) synchrotron model
  - Baryon-dominated jet creates tangled B-field in shock layer
  - Prompt γ-ray variability (internal shocks)
  - Inefficient conversion of bulk:radiated energy
- Alternative: Poynting flow
  - Large-scale ordered magnetic fields advected outwards
  - Powerful acceleration and collimation
- Origin of magnetic fields unknown
  - Energy dissipation/deposition key for explosion energetics
  - Dissipation through magnetic reconnection?
  - Energy transfer details still unknown

Fireball Magnetization

- Indirect diagnostics
  - Bright optical flashes predicted from reverse shocks
  - Bright forward shock emission *only* e.g. GRB 061007, 060418
  - Typical synchrotron frequency below optical band (Mundell et al. 2007)
  - Magnetized, but baryon-dominated fireball in few GRBs with optical reverse shock emission (GRB061126 - Gomboc et al. 2008, ApJ, 687, 443; Gomboc et al. 2009)
  - Magnetic suppression of reverse shocks in others?

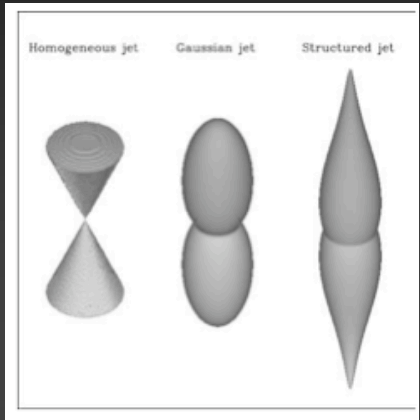


GRBs 990123, 021211, 060111B, 060117, 061126, 080319B (Gomboc et al. 2009)

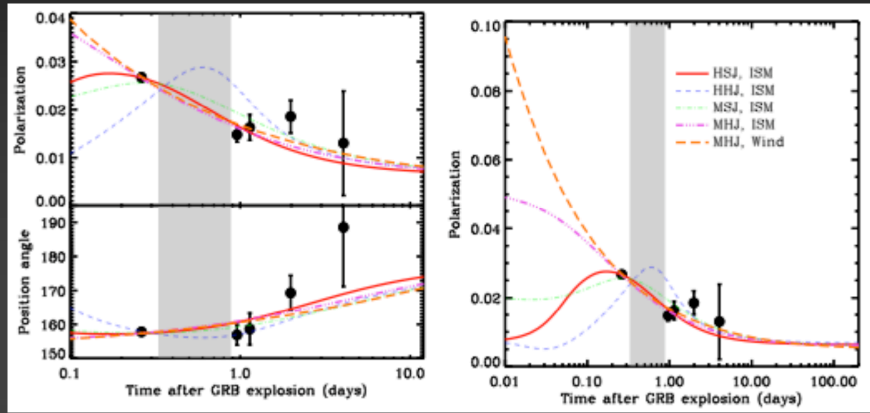
Fireball Magnetization

- Direct diagnostics
  - Sychrotron emission ➜ intrinsic polarization
  - Significant γ-ray polarization (controversial P~ 0 or 70-80% GRB021206 - Coburn & Boggs 2003 vs Rutledge & Fox 2003/ Wigger et al. 2003)
  - GRB 041219A - prompt γ-ray 4%➜ 43 ± 25% (Gotz et al. 2009)
  - Fast-fading signal and spatially unresolved
  - Model light curves ambiguous
  - *Early-time* optical polarisation powerful

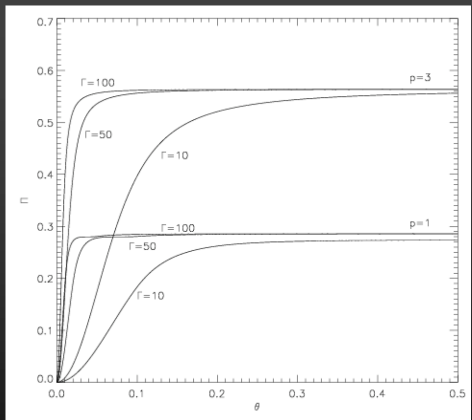
Early Polarisation Diagnostics



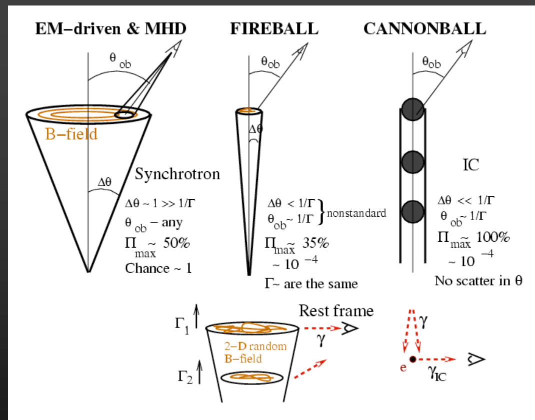
Energy per unit solid angle (log-scaled)



Polarisation predictions; GRB 020813 data



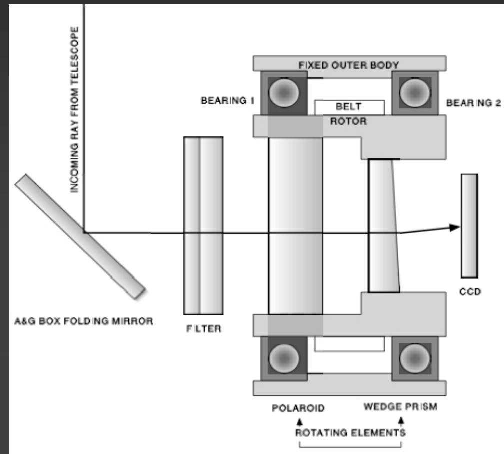
Polarisation fraction vs viewing angle for Γ = 10, 50 100 (isotropic expansion & power-law particle distribution)

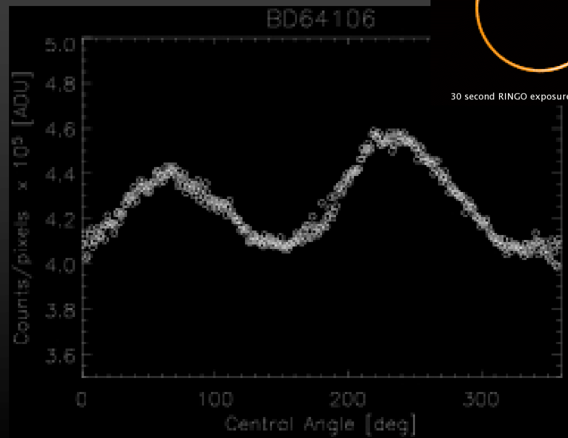


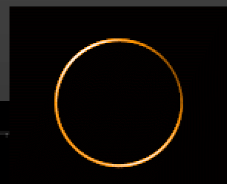
Prompt emission predictions (one rules out internal shock model if >20% detected early)

RINGO Polarimeter

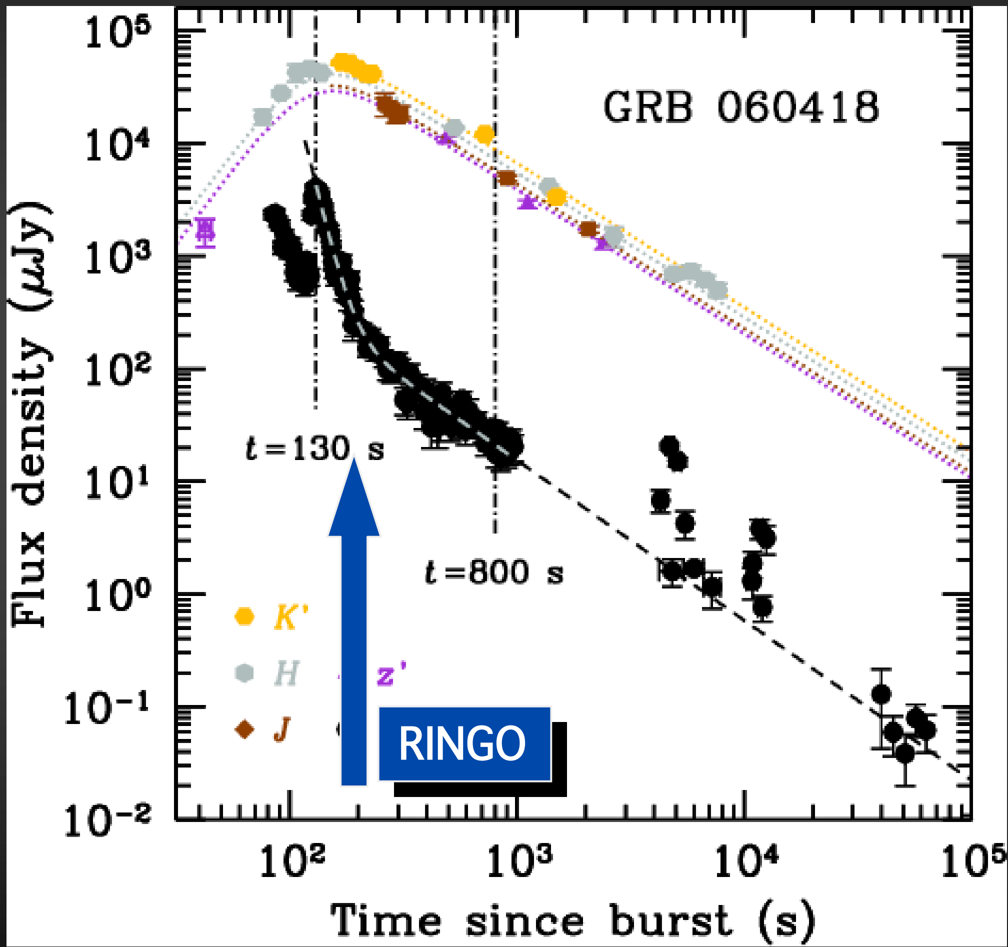
- Novel design (D. Clarke): rotating polaroid (500rpm) in telescope beam
- CCD field of view ~5 arcmin
- Variable signal for polarised sources
- Time variable signal ➜ spatial signal by small angle wedge prism rotating with polaroid
- Signal recorded on CCD
- Each point source is a ring
- Polarisation signal mapped twice around ring
  - Correct for instrumental effects
  - Small variation: polarisation signal out of phase with instrument signal
  - Recover correct signal
- ~0.1% purity on 15 mag star
- First light on BD64106 (5% polarised)






30 second RINGO exposure of BD +64 106

GRB 060418

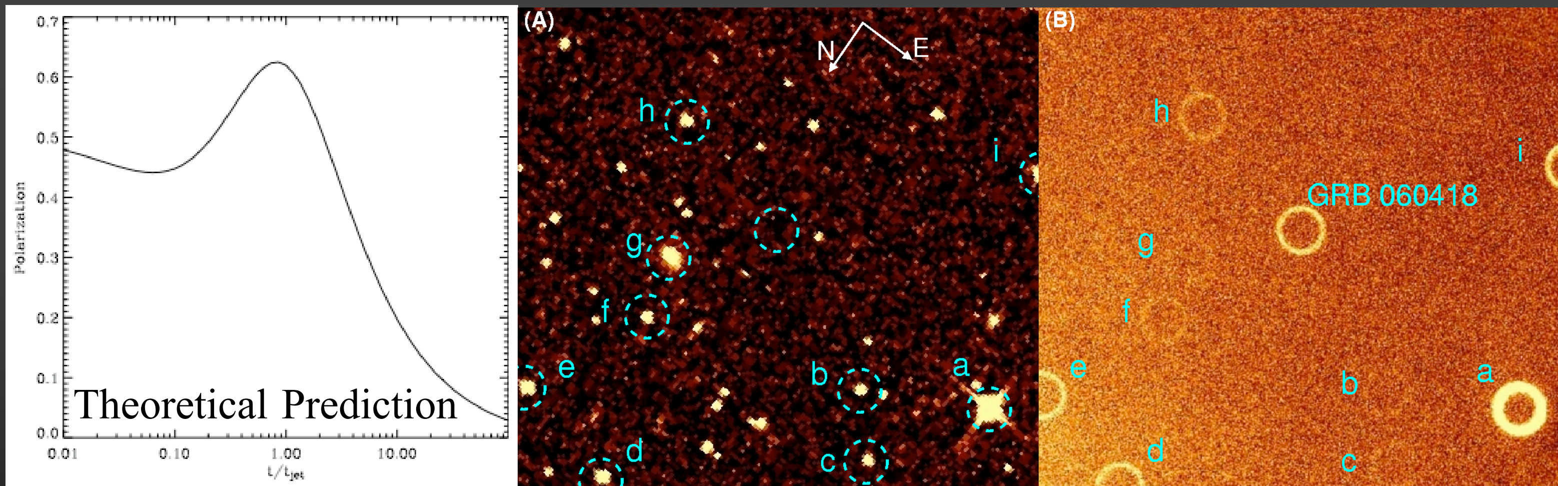


$\Gamma_0 \sim 400$
$R_{dec} \sim 10^{17}$ cm

Molinari et al. 2007, A&A, 469, L13

Earliest Polarimetry

- RINGO polarimetry of GRB 060418 at 203*s*
  - Nearly 100× earlier than anything measured previously
  - Rigorous checking of technique and calibration
  - Strongly-constrained upper-limit: P<0.08 (<8%)



  - Strongly-magnetised jet precluded
  - Current models pushed to the limit

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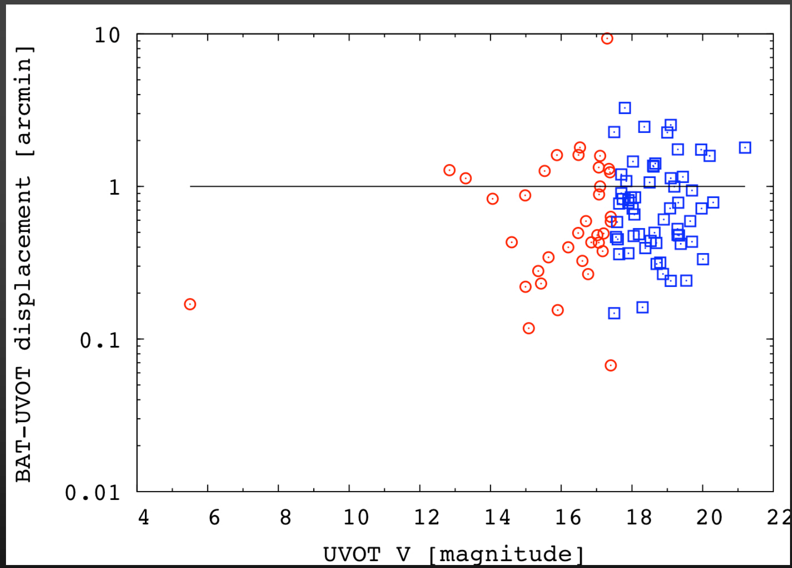
Steele et al. 2006, SPIE, 6269 ,179; Mundell et al. 2007, Science, 315, 1822

Future Prospects

- GRB 090102 - bright afterglow
- LT-RINGO measurement at ~150s
- Polarization detected
- Bright OTs rare
  - RINGO2 - new design to detect R>17 mag
- Population statistics
  - Time evolution of % and PA
  - Redshift evolution
- Quantum physics tests



Capabilities & Open Issues

- Can probe extreme physics at early times
  - Automatic, well-sampled light curves from *seconds* to *weeks*
  - Lack of human intervention requires robustness at *all* stages
- New observations provide tight constraints on models
  - Jets widely accepted but complex and simple afterglow evolution challenging
  - Long-lived central engines required but not understood
  - Energy re-injection can explain anomalous light curves *and* dark bursts
- GRB standard internal shock model broadly works
- Detailed predictions from simulations now needed

Capabilities & Open Issues

- Magnetization remains fundamental open issue
  - Significant magnetization suggested by
    - Lack of bright optical flashes from reverse shocks
    - Lack of GeV detections
  - But alternatives remain valid
    - Low magnetization predicts flashes at lower energies (e.g. GRB061007)
  - Early-time polarimetry
    - Low optical polarisation precludes *strongly*-magnetised jet in GRB060418
    - Optical + γ-ray polarisation can revolutionise GRB studies
    - Population statistics and time evolution critical
- Detection of neutrinos/gravitational waves
  - Identification of electromagnetic counterparts feasible and important (e.g. IceCube + LT)
- Major breakthroughs ongoing - watch this space.