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OPTICAL FOLLOW-UP

The Need for Follow-up

- Existing satellite facilities have set the stage e.g.
  - Swift (gamma, X, optical/UV)
  - Fermi (gamma), MAGIC, HESS
- Ground-based facilities developed in response e.g.
  - 2-m Liverpool + Faulkes Telescopes
- New and future survey facilities all address time-domain e.g.

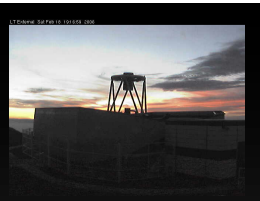
GAIA (optical)	**SVOM (Gamma, X,IR.opt)**
LSST (optical)	**A-STAR (X-ray)**
LOFAR (radio)	**NuStar (X-ray)**
SKA (radio)	**JUST (ultraviolet)**

The Need for Follow-up

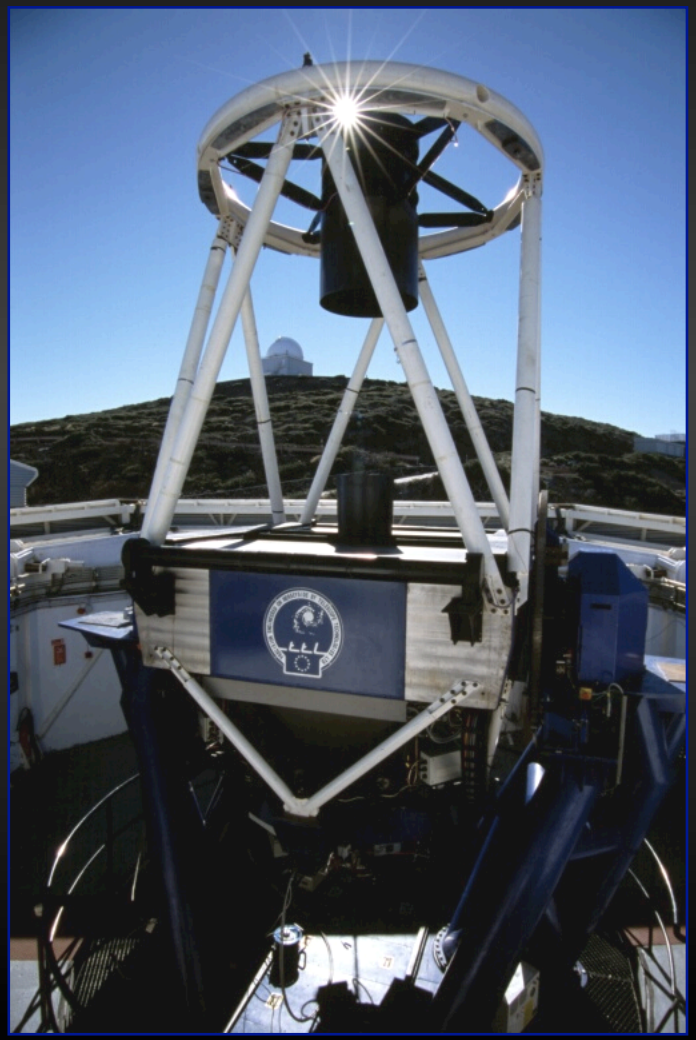
- Common need for spectroscopy capability (redshifts)
- High energy physics – additional needs
- Comprehensive instrumentation e.g. polarisation
- Rapid response (speed of acqusition; speed vs depth)
- Temporal coverage (cadence; speed vs depth)
- Sky coverage (FoV + location – area vs depth)
- Wide wavelength coverage
- Large aperture (i.e. not cm-class)
- LT example of best practice…

Large Robotic Telescopes

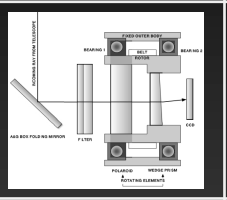
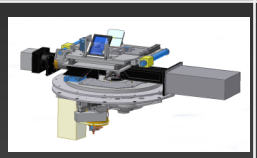
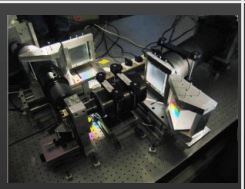
- Liverpool and Faulkes telescopes: 2-m fully autonomous robotic optical telescopes (**http://telescope.livjm.ac.uk/**)
  - Fully-open enclosure (no dome seeing and fast slew), robotic operation, large aperture, comprehensive instrumentation
- Observations coordinated with other facilities, both ground-based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



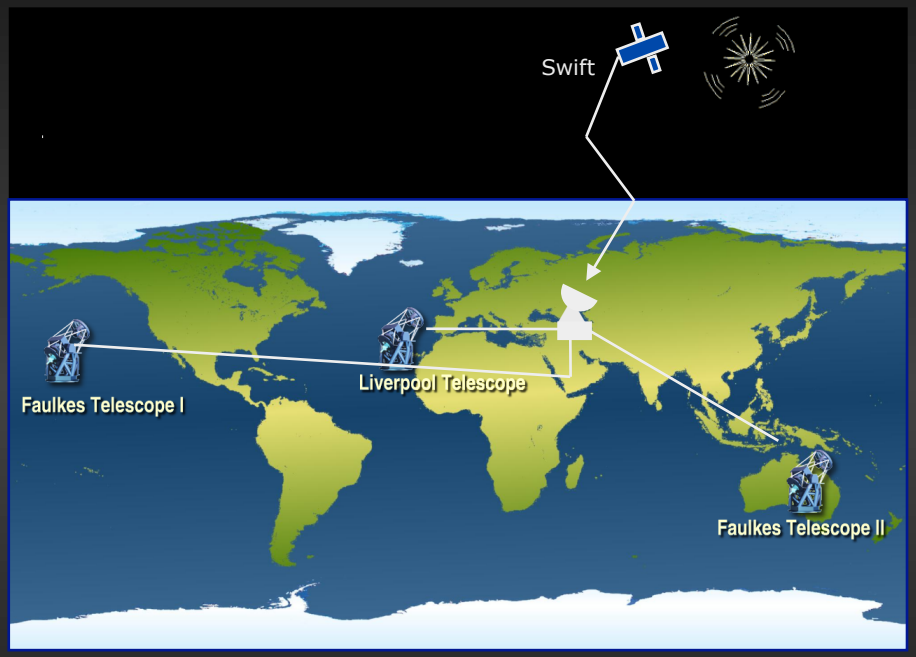
Telescope Specifications

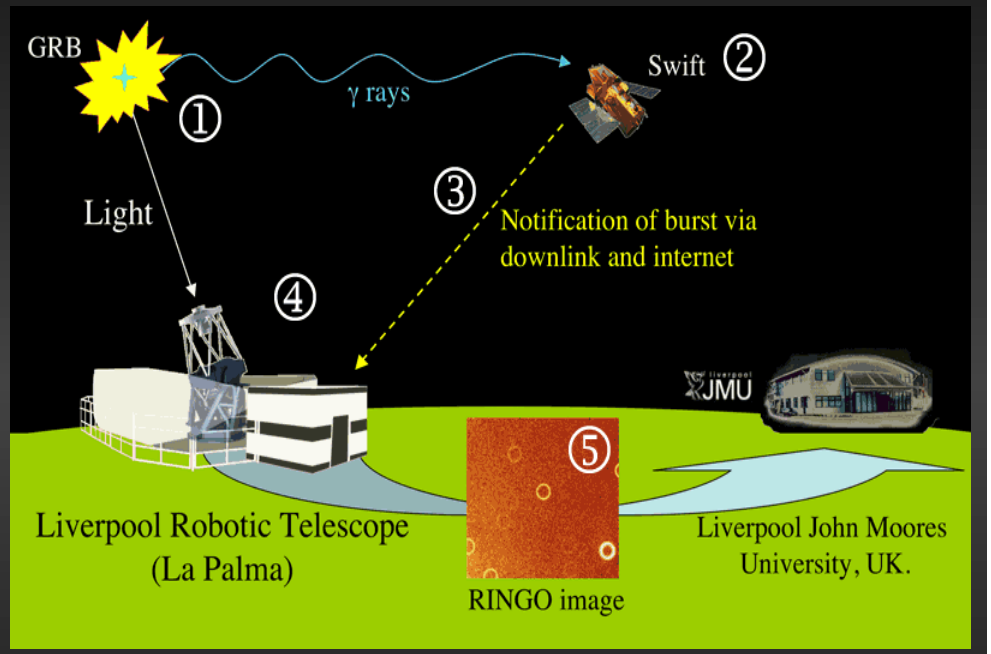


- Primary mirror diameter 2m
- Final focal ratio f/10
- Altitude-Azimuth design
- Image quality < 0.4" on axis
- Pointing < 2 arcsec rms
- Rapid slew rate > 2º/sec
- Fully open enclosure
- Five instrument ports (4 folded and one straight- through) selected by deployable, rotating mirror in the A&G Box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

Optical Camera (LT/FTN/FTS) ~5' FOV	• Early multicolour light curves • Shock physics/ISM • Later-time light curves/Jet breaks • GRB-Supernova connection
RINGO/2/3 *Polarimeter* (LT only) ~5' FOV 	• Early-time polarisation studies • 1% polarisation at r' > 17 mag • Fundamental tests of jet models
IO *optical-NIR imager* Filters: Hα B V u' g' r' i' z' J H O=10' FoV I=6' FoV 	• High z 'naked' bursts vs • Low-z 'obscured' bursts • Fast timing/lucky imaging
FRODOSpec : dual-beam *IFU* R~2600/5500 λ=3900 – 9400 A V <15 mag FoV: 11" 	• Early time evolution of circumburst medium • SNe redshift/typing
SkyCamA : All sky < 6 mag SkyCamT : 21° < 12 mag SkyCamZ : 1° V< 18 mag 	•Bright bursts/neutrino counterparts •Gravitational wave counterpart •LOFAR/CTA counterparts
RISE – fast readout camera V+R; FoV 9.2'; min exp time ~1s	•Fast timing- transiting exoplanets •Not currently used for GRBs/AGN

GRB Robotic Followup

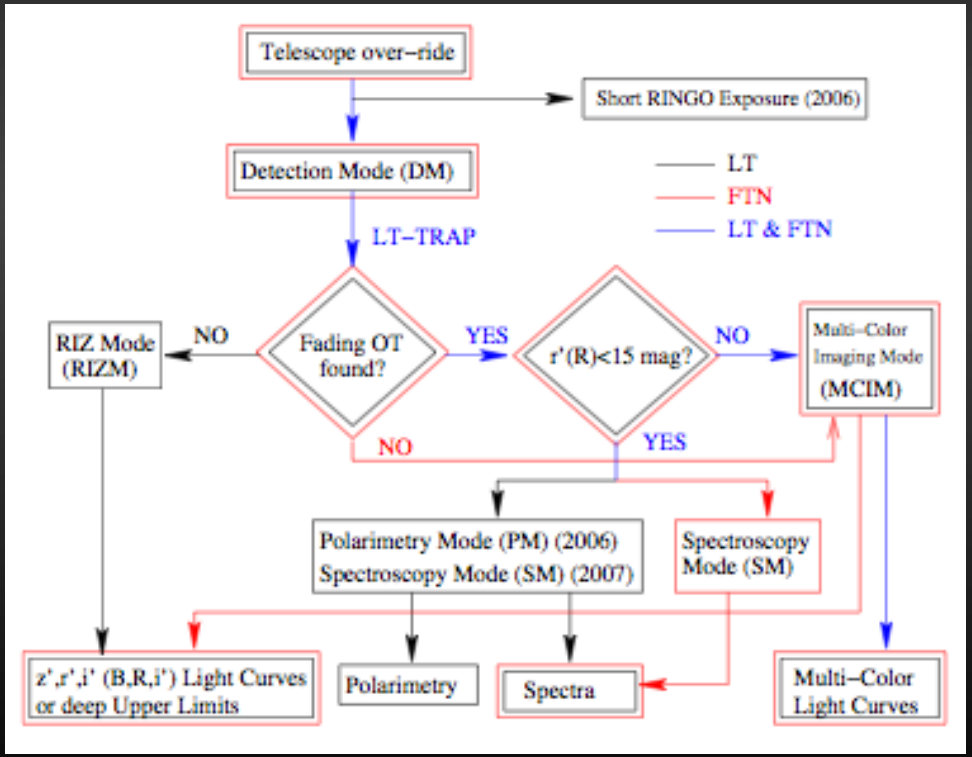




- Optimisation for GRB science goals:
  - Immediate automatic response (over-ride), data analysis & interpretation strategy
  - No human intervention from receipt of alert ➜ observations ➜ automatic object ID ➜ choice and execution of subsequent observations

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)
```

```
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.
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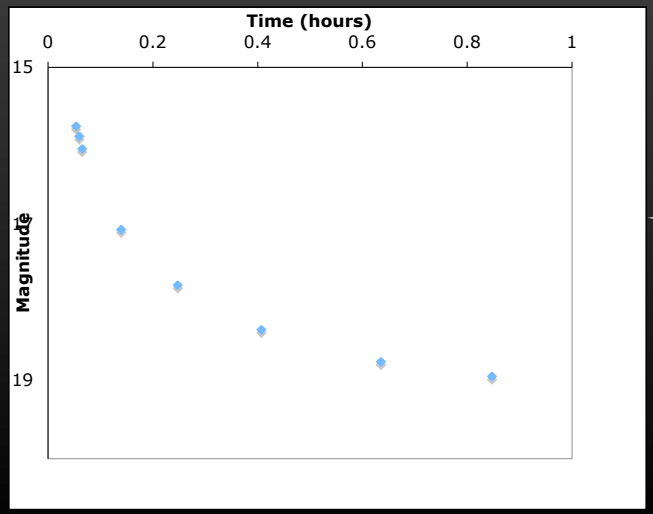
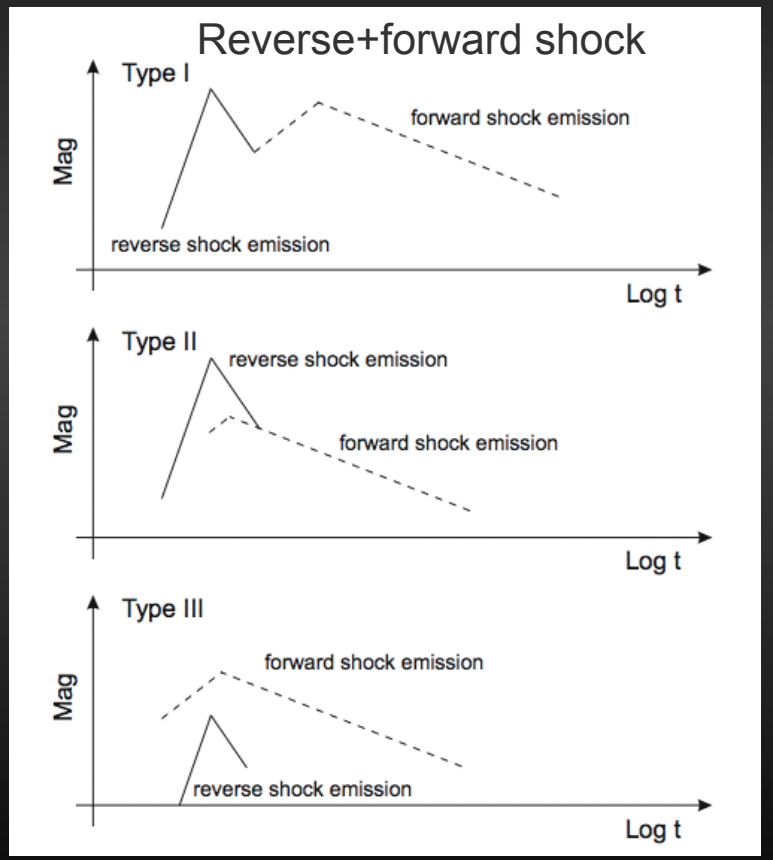


Guidorzi et al. 2006

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

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)

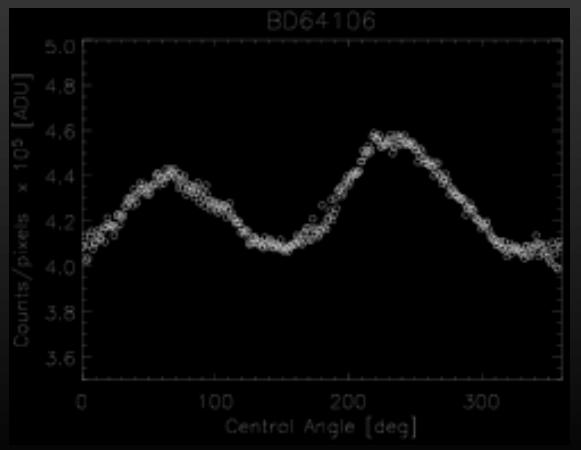
Fireball Magnetization

- Direct diagnostics
  - Synchrotron 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) (also GAP - Yonetoku et al.)
  - Fast-fading signal and spatially unresolved
  - Model light curves ambiguous
  - *Early-time* optical polarisation powerful

RINGO Polarimeter

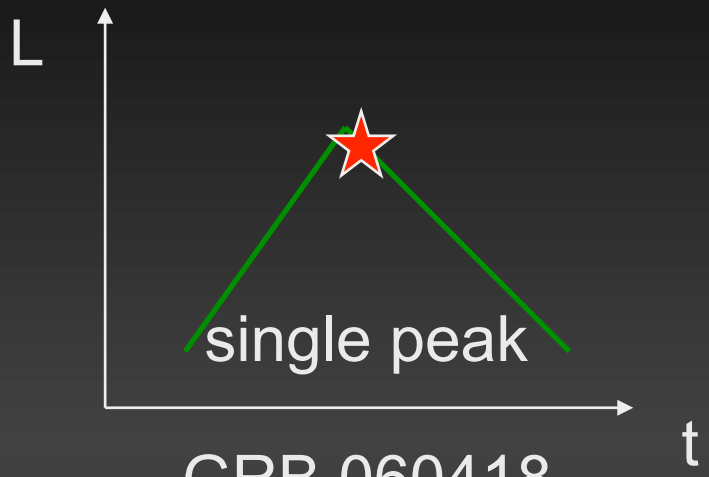
- Novel design (D. Clarke): rotating polaroid (500rpm) in telescope beam
- CCD field of view ~5 arcmin
- Variable signal for polarised sources
- Time variable signal ➜ spatial signal by small angle wedge prism rotating with polaroid
- Signal recorded on CCD
- Each point source is a ring
- Polarisation 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



Interpretation and Unification

Mundell et al. Science 2007



GRB 060418

P < 8%

Steele et al. Nature 2009

GRB 090102

Detection P = 10.2%

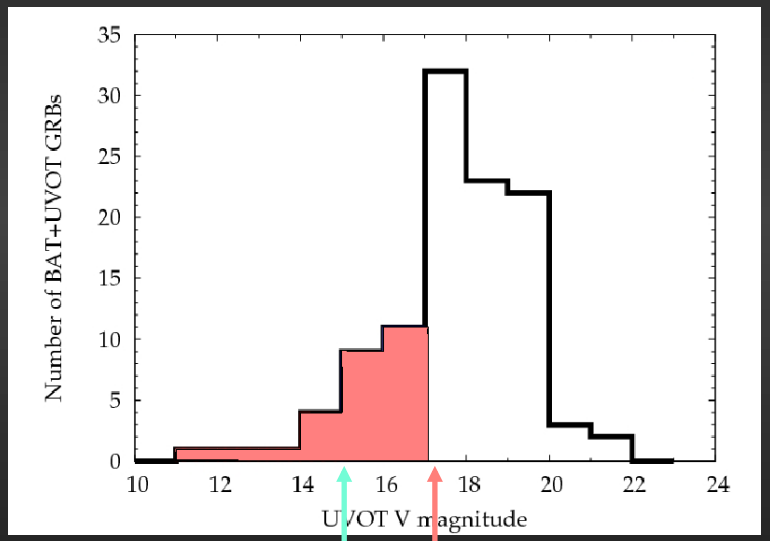
Ordered magnetic fields plus ratio of magnetic to kinetic energy flux, $\sigma \sim 1$

GRB 060418: σ slightly higher to suppress RS

GRB 090102: σ slightly lower for bright RS

Or, each has completely different magnetization (sample of 2!)

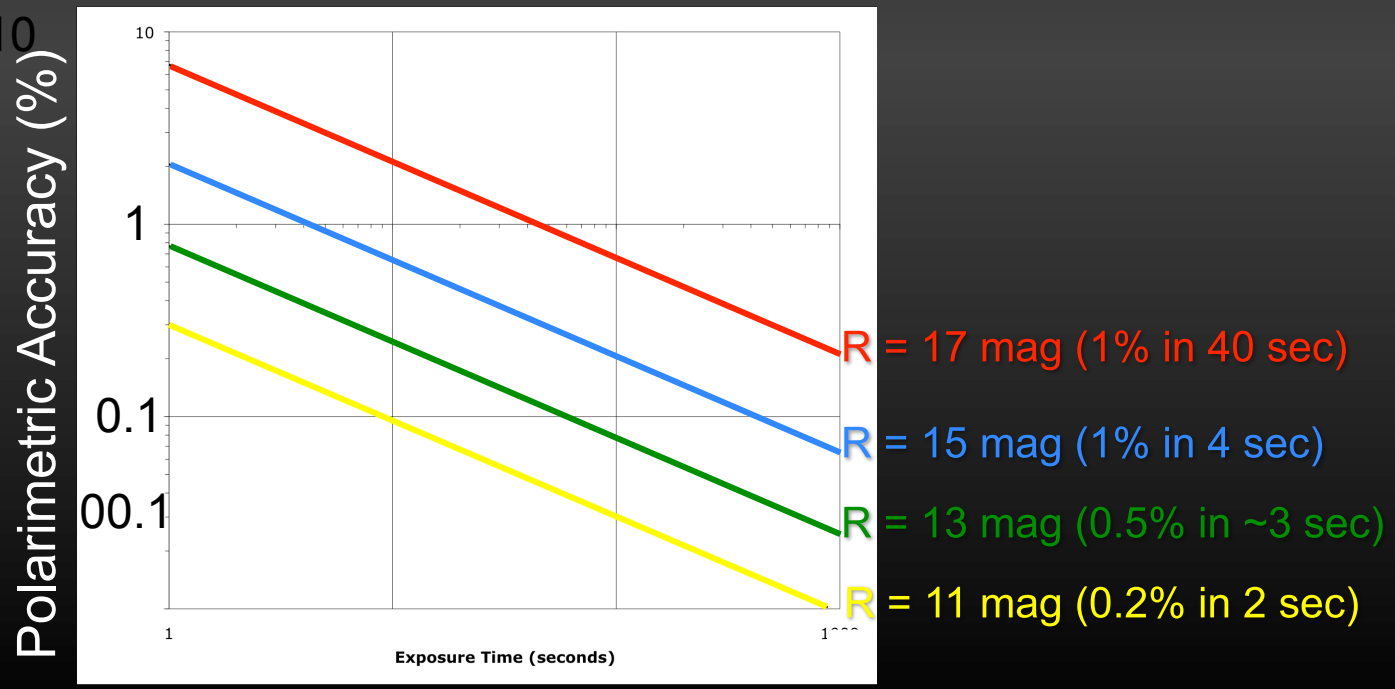
Early Time Polarization: Evolution + Color



- RINGO2 detect fainter objects
- *Time evolution* of polarisation
- Population statistics
- Redshift evolution
- Comparison with γ-ray polarisation (e.g. Japanese GAP/IKAROS)
- Foundation for X-ray polarisation
- Programme now running for AGN (Mundell, Steele, Barres de Almeida, Nilsson, Lindfors, Takalo)

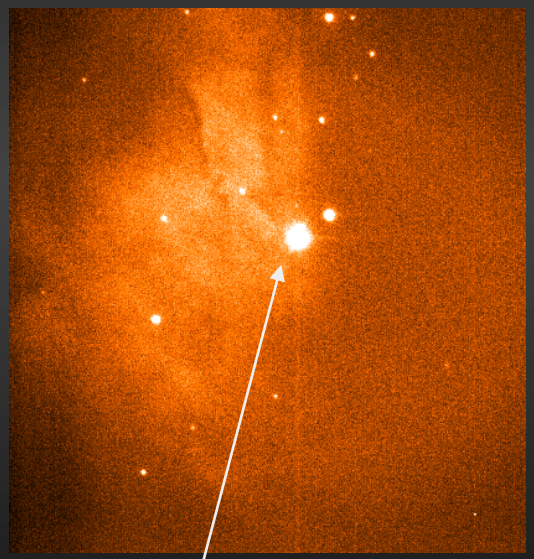
RINGO2

- Fast-readout imaging polarimeter (EMCCD)
- 5 arcmin FoV; V+R filter
- 125-ms exposures; 8 polaroid positions per sec



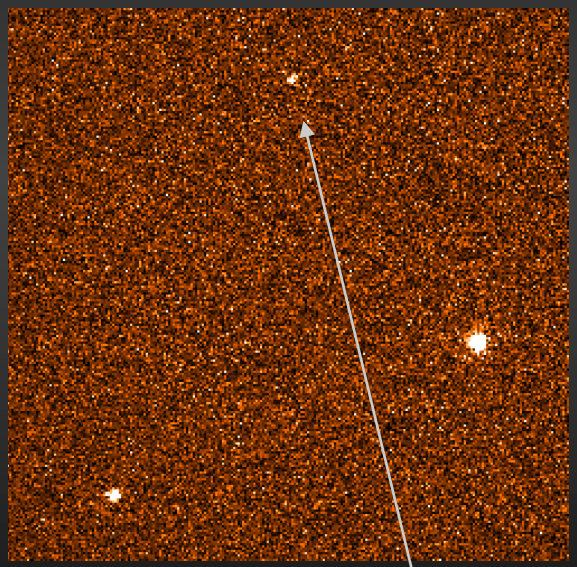
RINGO2 First-Light Images (15 Oct 2009)

Polarized Standard Star



NGC 2024 (12.2. mag)
embedded in nebula
10-s exposure

Photometric Standard Field



Detect 16th mag object in
single 0.1-sec exposure

RINGO2 125 msec co-added images

Important for host subtraction e.g. M87

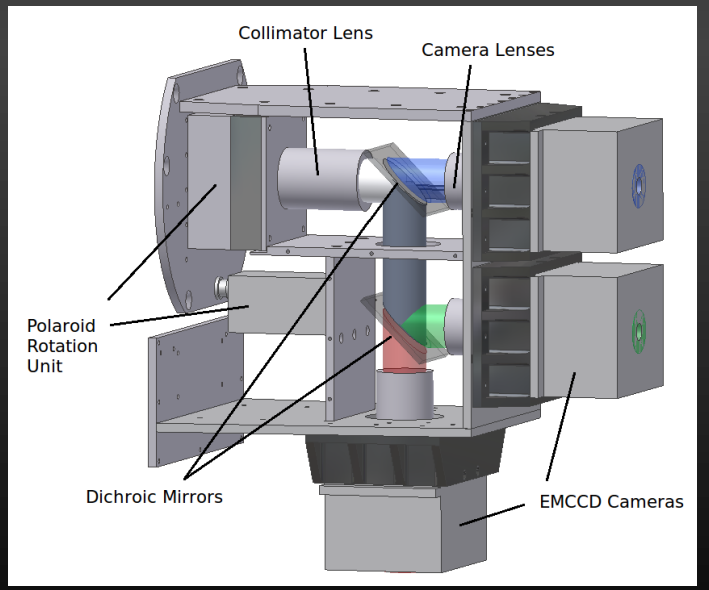
The Future

- Many old, small traditional telescopes being recycled for followup (e.g. PTF)
- Funding agencies closing some existing facilities
- New facilities need to include/own everything to do their science??

The Future from Liverpool …

- IO – O (2012), I (2013)
- RINGO3 – 3-band fast-readout imaging polarimeter

  - Oct 2012
  - Simultaneous 3-band polarimeter
  - 4000-9000 A (BV,R,I)
  - 1 sec time resolution
  - Polarisation purity 1% at 17 mag in 20s
  - All GRBs from ~t_0+100s



Arnold et al. 2012, SPIE, in press

The Future from Liverpool …

- IO – O (2012), I (2013)
- RINGO3 – 3-band fast-readout imaging polarimeter
- Design study for next generation Liverpool Telescope (LT2)
  - **2012 - 2014**
  - exploit new technologies, materials etc..
  - all aspects open for discussion incl. site
  - community input solicited – have your say!!