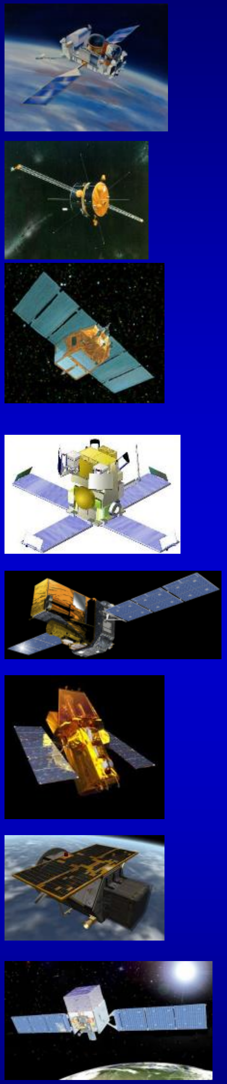
Ioffe Workshop on GRBs and other transient sources:
20 Years of the Konus-Wind Experiment
St. Petersburg September 22nd – 26th 2014

Gamma Ray Bursts in the Swift Era

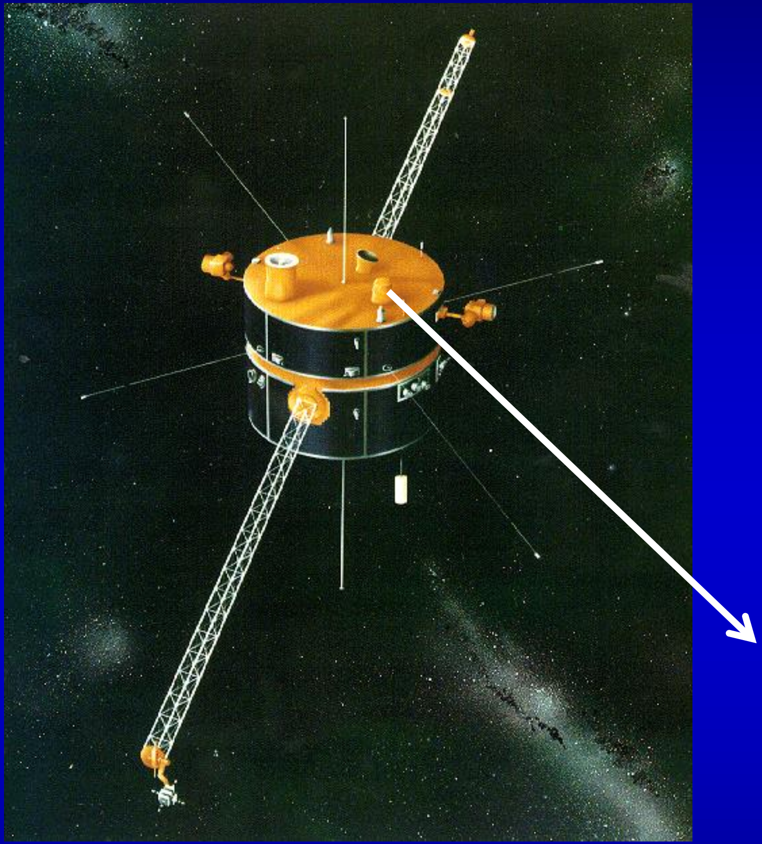
Dick Willingale
University of Leicester

The Swift Era – Chasing GRBs

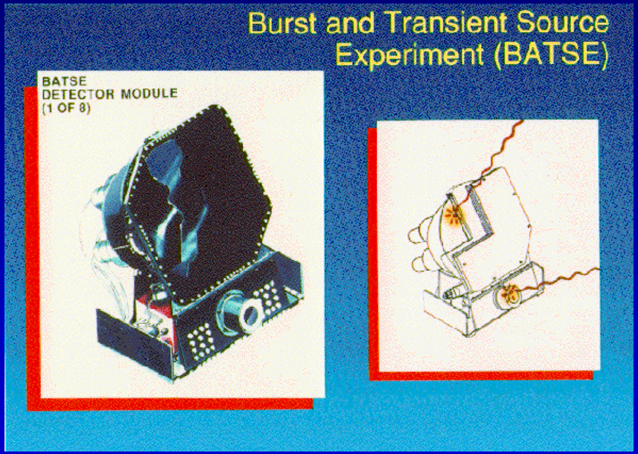
• CGRO	5th April 1991
– BATSE (to 4th June 2000)	
• WIND	1st November 1994
– Konus-Wind Experiment	
• BeppoSAX	30th April 1996
– LECS, WFC (to 29th April 2003)	
• HETE-2	9th October 2000
– FREGATE, SXC, WXM (to March 2006)	
• INTEGRAL	17th October 2002
– SPI-ACS, IBIS	
• Swift	November 20th 2004
– BAT, XRT, UVOT	
• AGILE	23rd April 2007
– GRID, SA	
• Fermi	11th June 2008
– LAT, GBM	



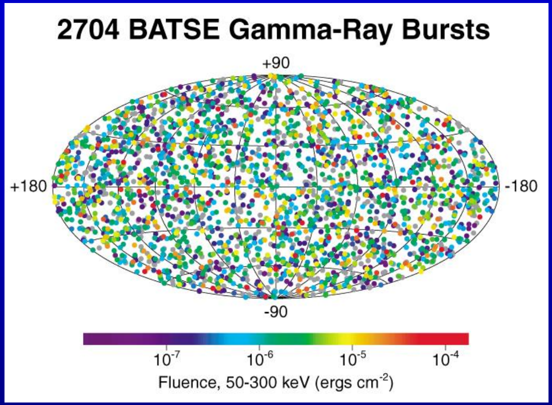
Pre-Swift Era



Konus-Wind
~200 cm^2
20keV-15MeV



BATSE LAD 2025 cm^2 x8 20 keV-1.9 MeV
SD 127 cm^2 x8 10 keV-100 MeV



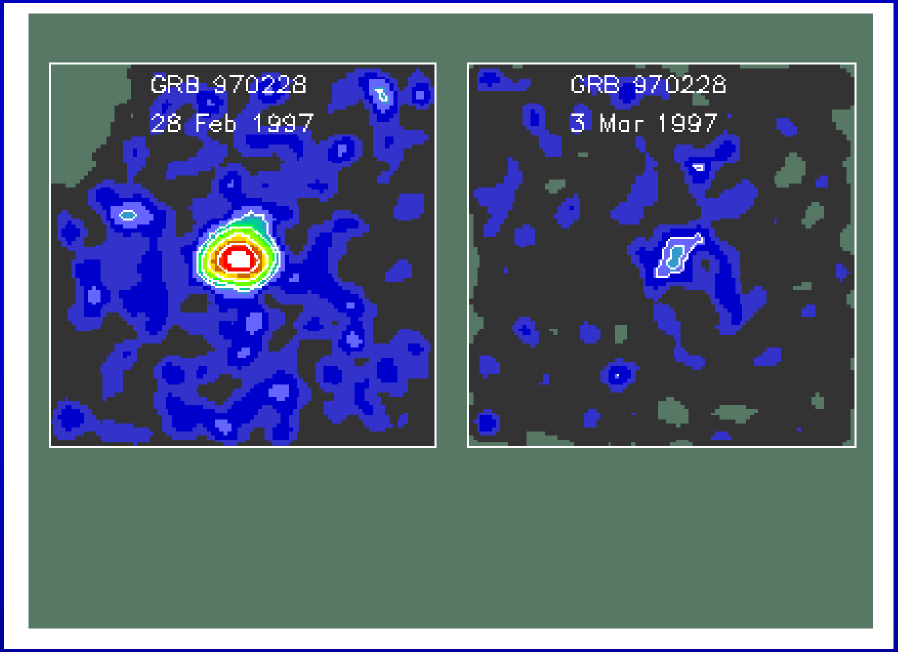
Position accuracy 10s degrees

All-sky - gamma rays (i.e.>100 keV)

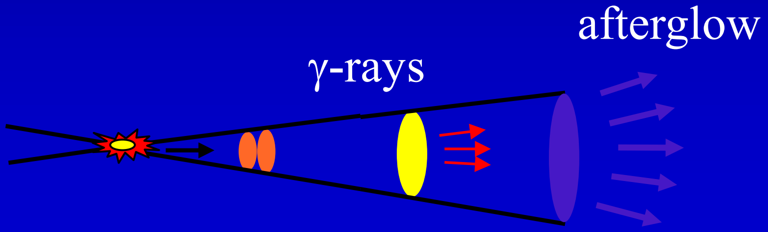
The dawn of the Swift Era – GRB 970228

BeppoSAX (1996-2003)

GRB 970228: First X-ray afterglow detected ~8 hours after the burst, z = 0.695



Costa et al. 1997



Fireball Model
(Meszaros & Rees 1997)

All bursts with known redshifts are cosmological

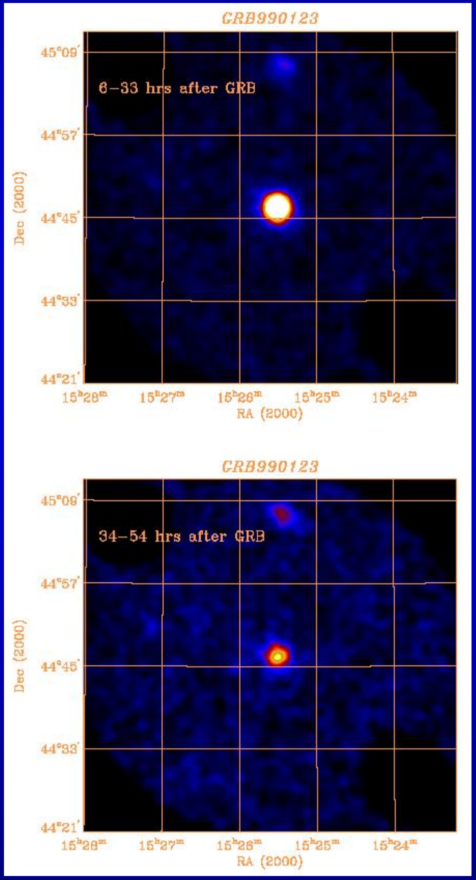
Mean redshift pre-Swift ~1.2

Mean redshift Swift ~2.5

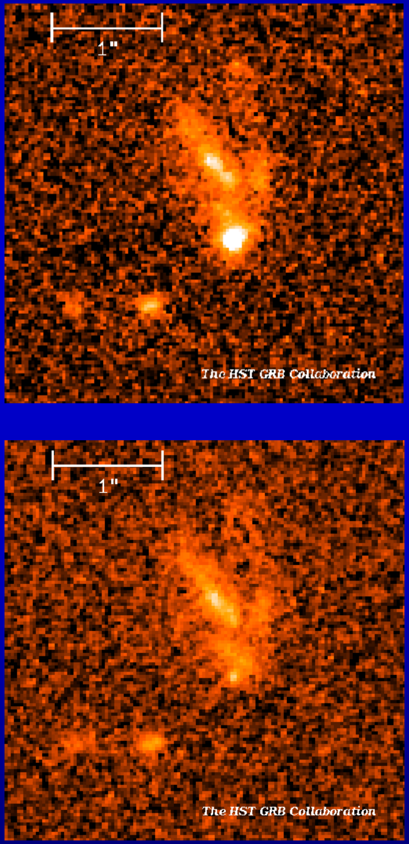
Pre-Swift Problem

Follow-up only possible hours or days later

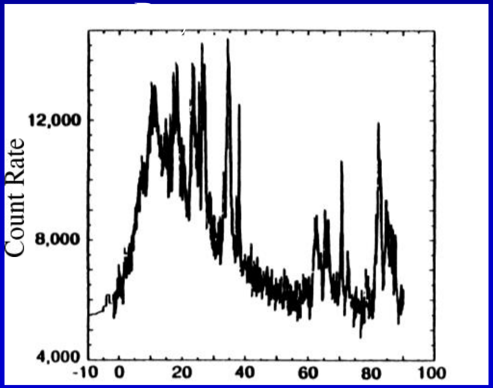
BeppoSAX & HETE-2 X-ray

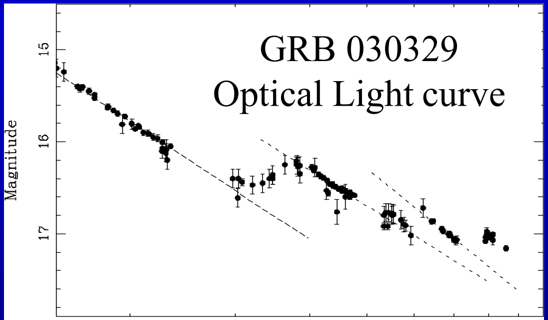


HST & Ground Optical



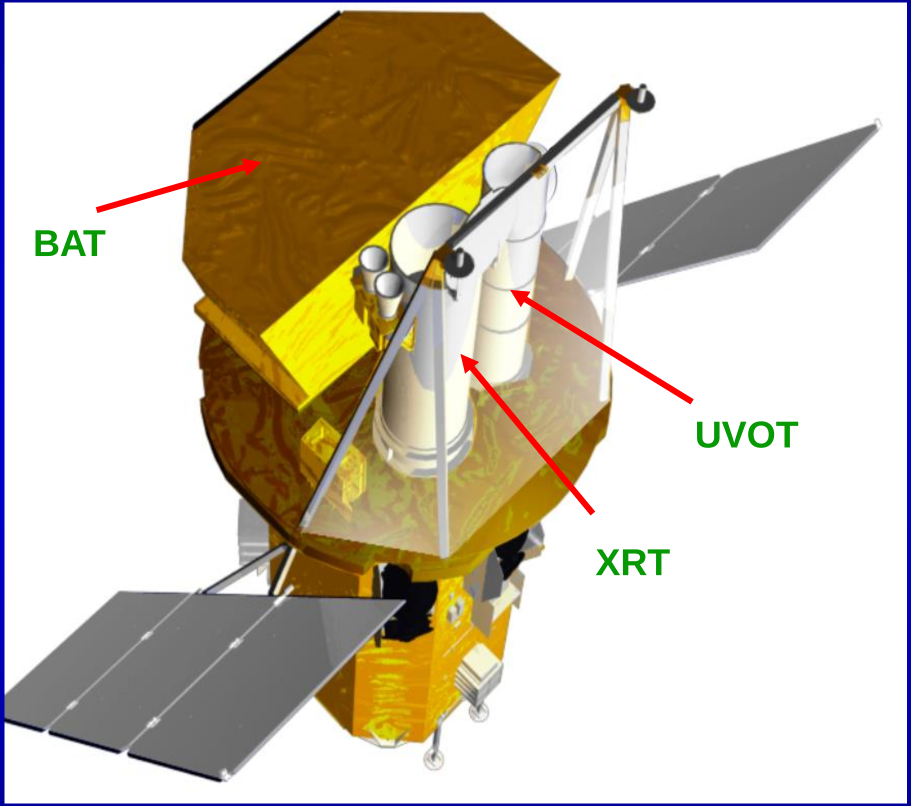
BATSE Gamma



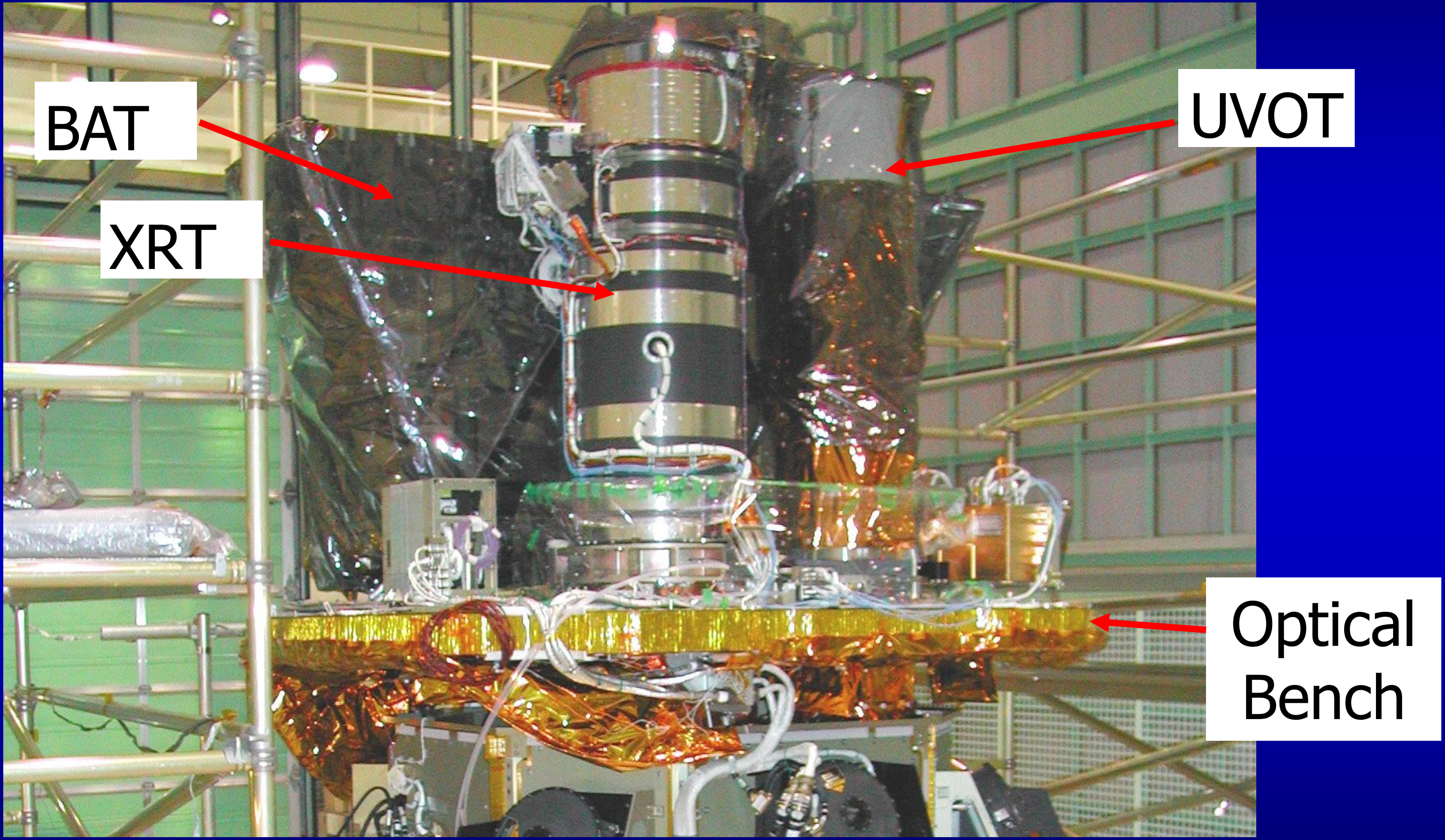


The Swift Solution

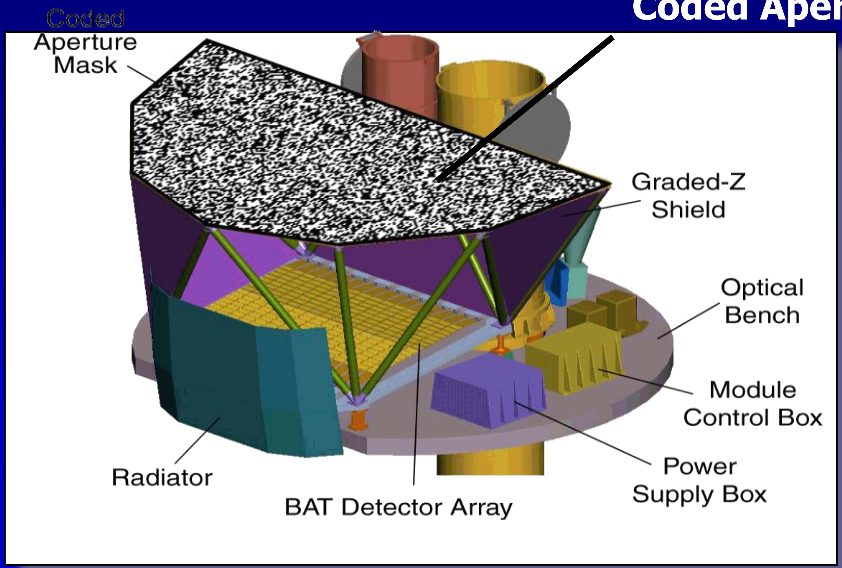
- Wide field gamma-ray imager detects and finds position of GRB - BAT
- On-board decision making
  - Spacecraft slews autonomously
- Rapid slewing capability
  - Get to GRB quickly, sometimes while the prompt emission is still occurring
- Complement of sensitive narrow field X-ray and UV-Optical instruments to follow the afterglow
- Rapid ground notification of GRB
- Extensive follow-up network on the ground
- Automated science data processing within 2 hours



Swift Optical Bench

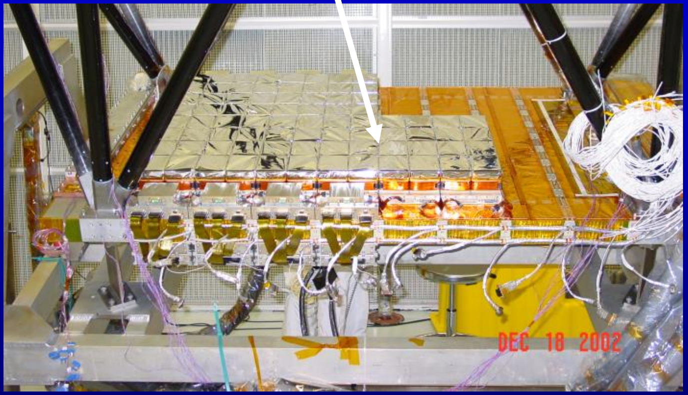


Swift Burst Alert Telescope (BAT)



Coded Aperture Mask

BAT Detector Array



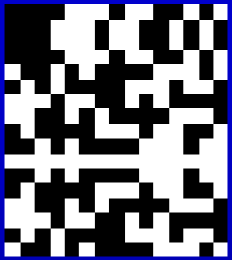
BAT Characteristics

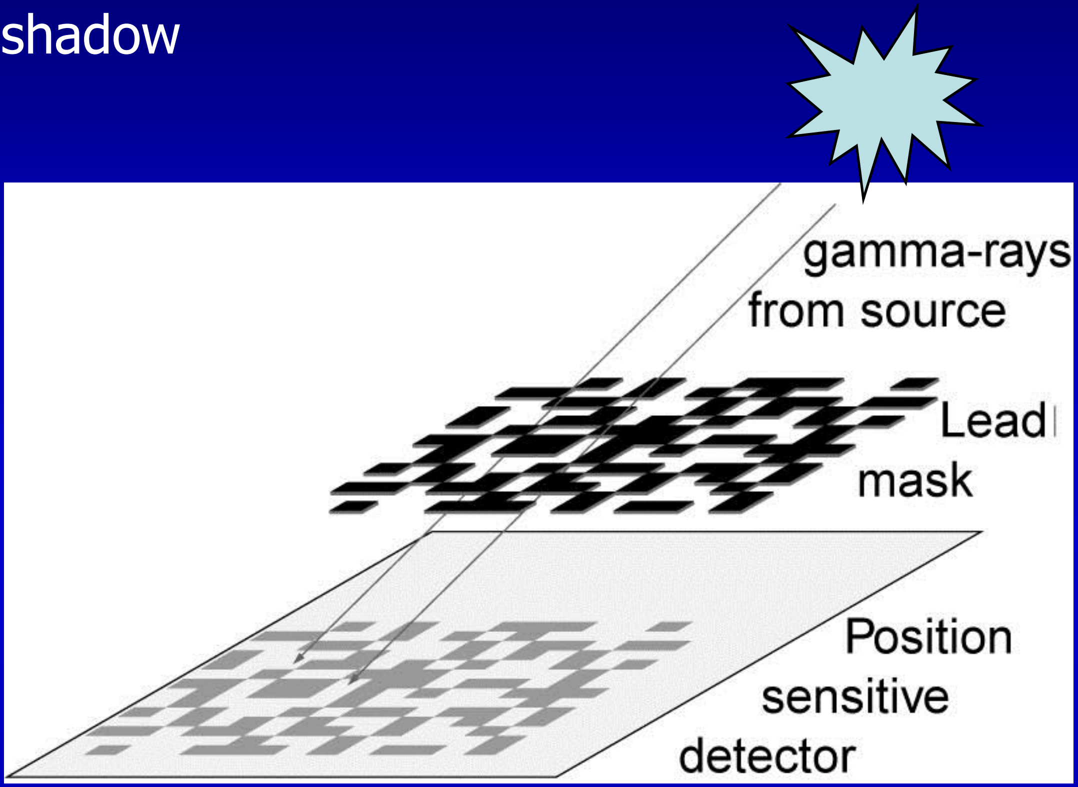
Telescope	Coded Aperture
Telescope PSF	17 arcmin FWHM
Position Accuracy	1-4 arcminutes
Detector	CZT
Detector Format	32768 pixels
Energy Resolution	7 keV FWHM (ave.)
Timing Resolution	100 microseconds
Field of View	2 Steradians, partially-coded
Energy Range	15 – 150 keV
Detector Area	5200 cm^2
Sensitivity	0.2 $\text{photons/cm}^2\text{/s}$
Max Flux	195,000 cps (entire array)
Operation	Autonomous

Swift Era - Coded Aperture Imaging

- Source casts gamma-ray shadow on detector
- Location of shadow yields location of source
- Coded aperture mask pattern

5mm square Pb tiles

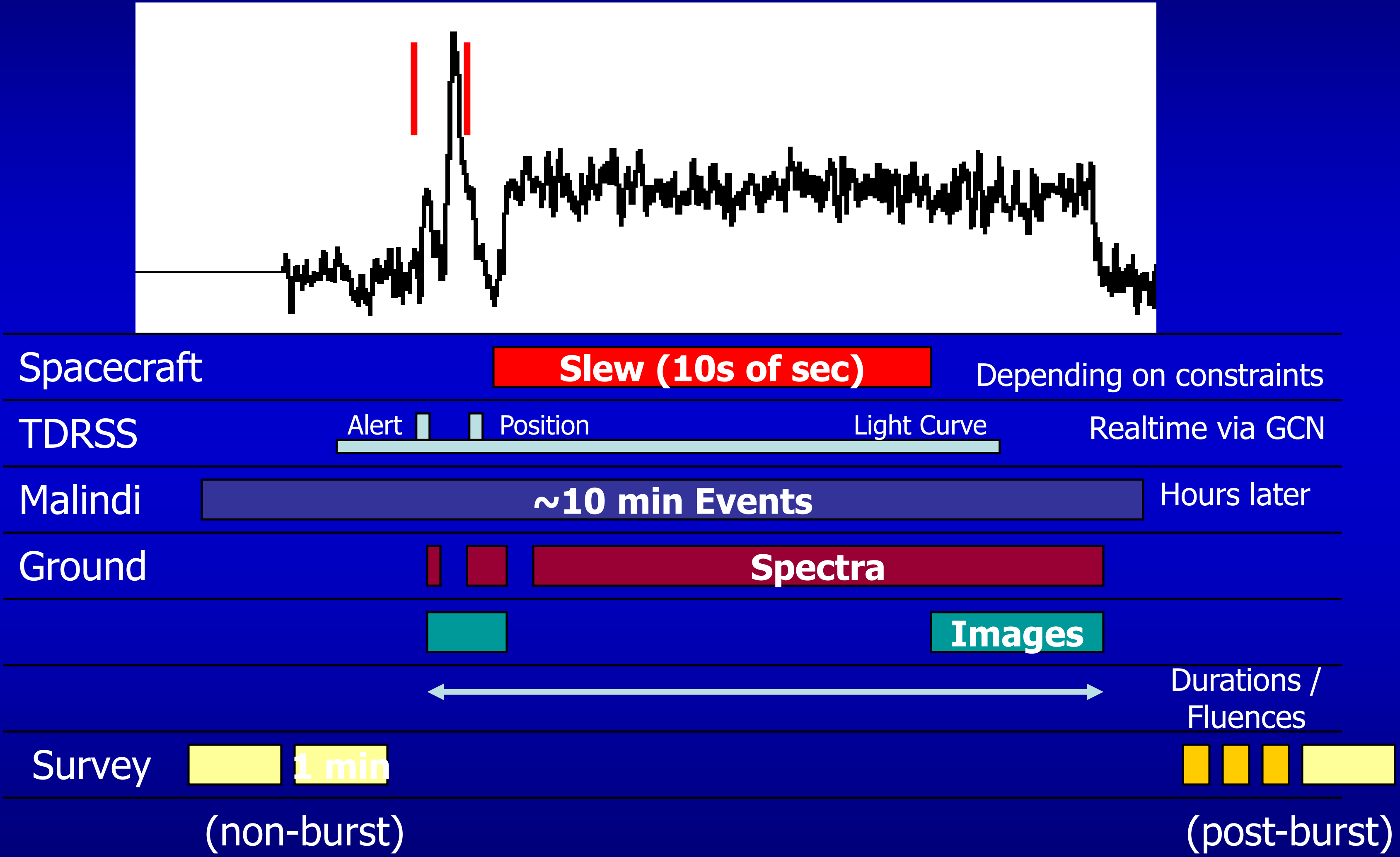




Dicke (1968)

High sensitivity – collecting area ~50% detector area (~2600 cm^2)
Every detector pixel sees every mask pixel – many sky pixels

BAT Burst Products



Spacecraft — Slew (10s of sec) — Depending on constraints

TDRSS — Alert — Position — Light Curve — Realtime via GCN

Malindi — ~10 min Events — Hours later

Ground — Spectra

Images

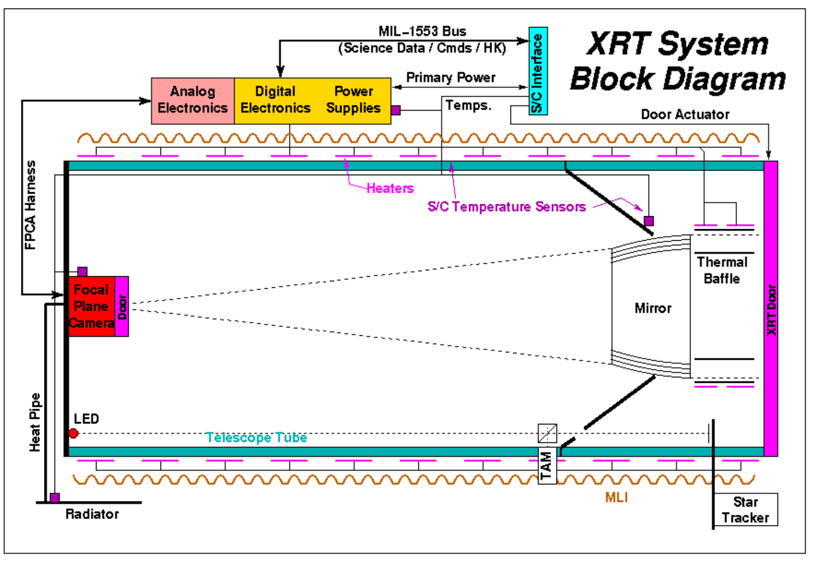
Durations / Fluences

Survey — 1 min

(non-burst)

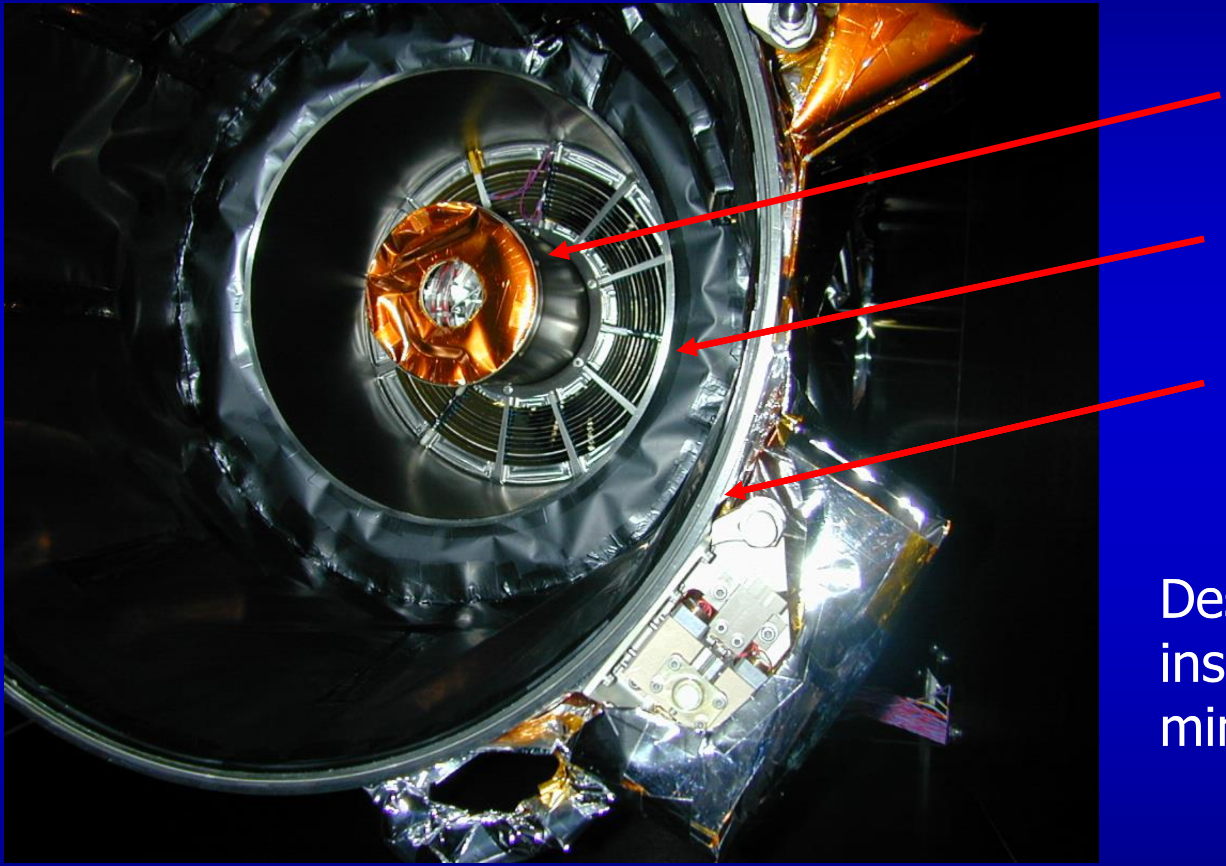
(post-burst)

Swift X-ray Telescope (XRT)



F=3.5 m
Collecting Area ~120 cm^2
0.3-10 keV
PSF diameter ~0.5 mm

XRT Forward elements

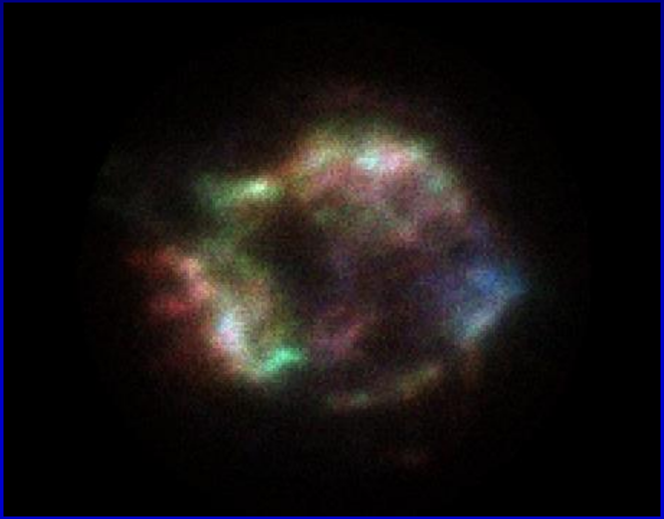


Design of baffle and insulation crucial to minimise stray light.

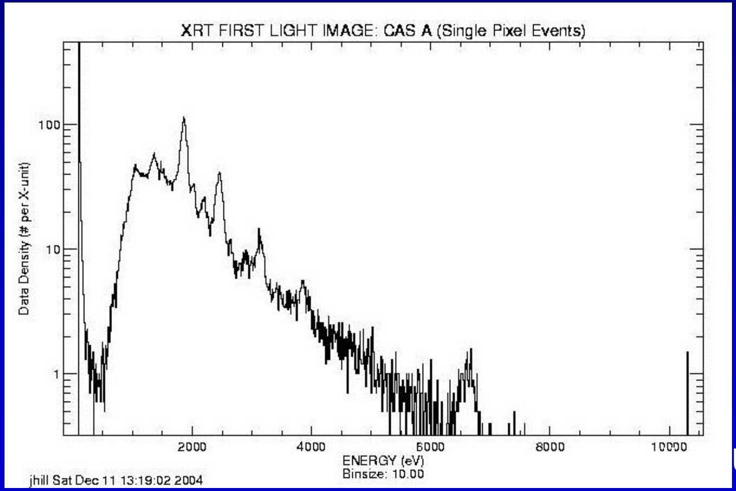
Swift Era – soft X-ray imaging XRT

Cas A:

(13 ks)



M. Goad, UL



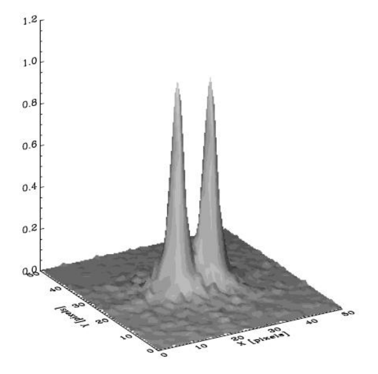
U

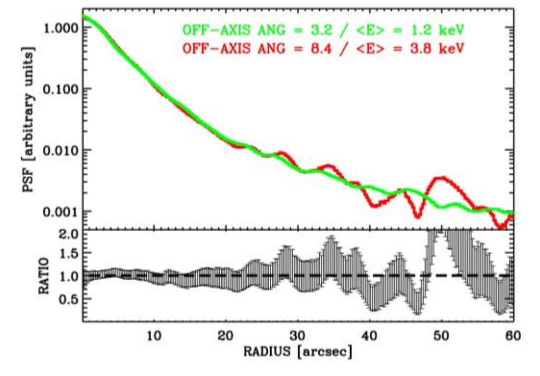
Soft X-ray spectra

Focusing gain ~48000

High sensitivity 0.3-10 keV

Position accuracy ~few arc secs

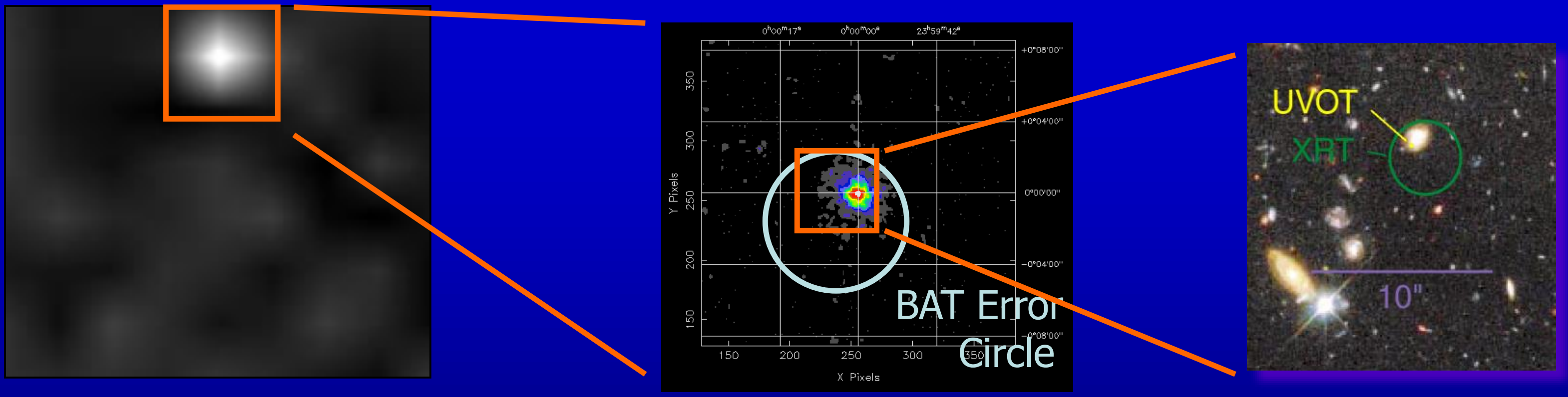




PSF A. Moretti, OAB

Swift Observing Scenario

1. Burst Alert Telescope triggers on GRB, (rate trigger+image or just an image) calculates position to ~ 1 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 s
3. X-ray Telescope determines position to ~ 2 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground



BAT Burst Image

XRT Image

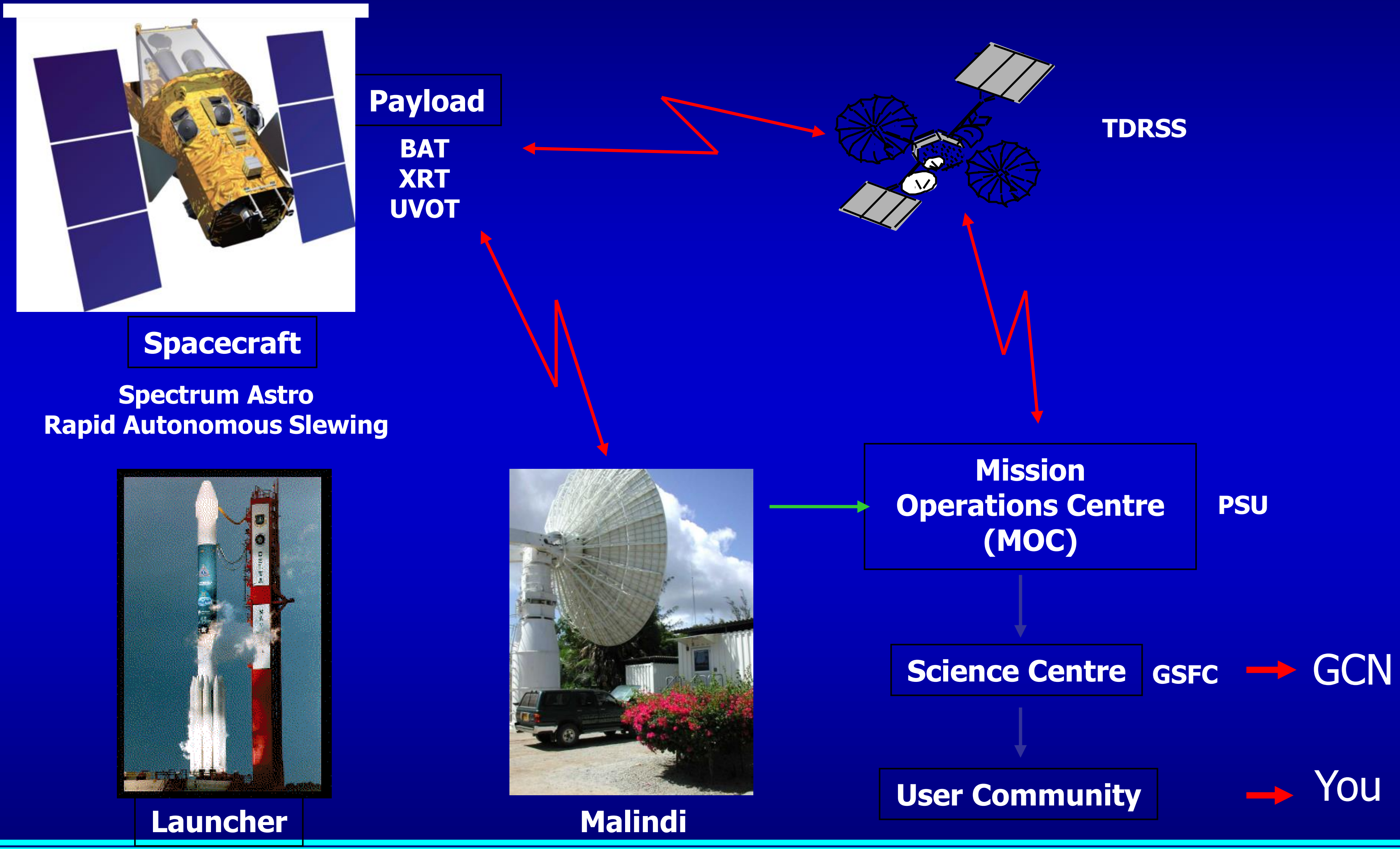
UVOT Image

T~10 sec

T~100 sec

T~300 sec

Swift Mission Operations



Payload

BAT
XRT
UVOT

TDRSS

Spacecraft

Spectrum Astro
Rapid Autonomous Slewing

Mission Operations Centre (MOC)

PSU

Science Centre

GSFC → GCN

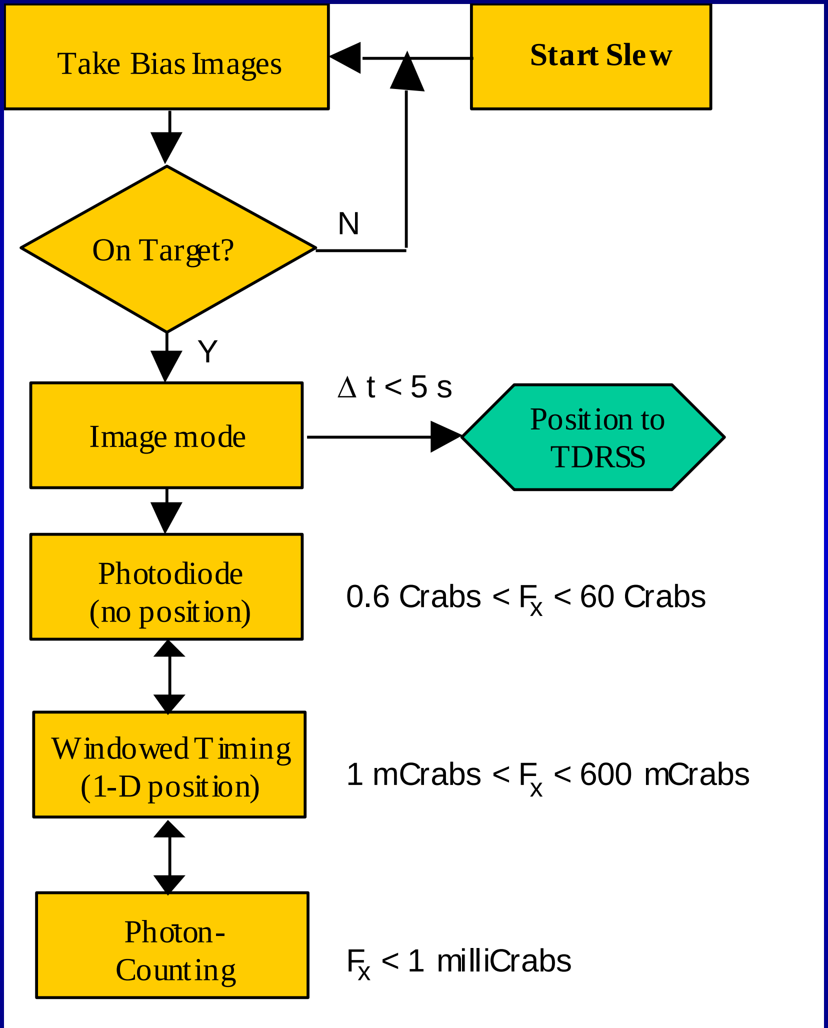
User Community

→ You

Launcher

Malindi

XRT Autonomous Observation



Take Bias Images

Start Slew

On Target?

N

Y

Image mode

$\Delta t < 5$ s

Position to TDRSS

Photodiode (no position)

0.6 Crabs < F_X < 60 Crabs

Windowed Timing (1-D position)

1 mCrabs < F_X < 600 mCrabs

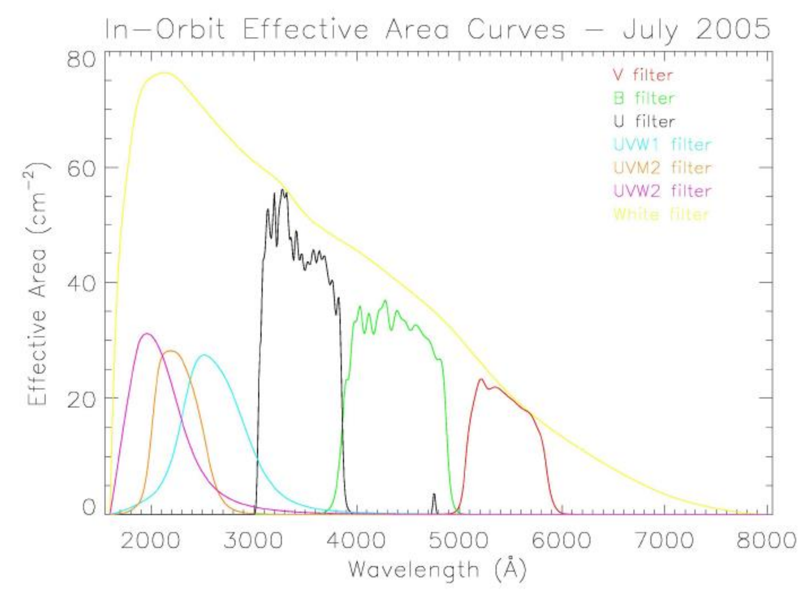
Photon-Counting

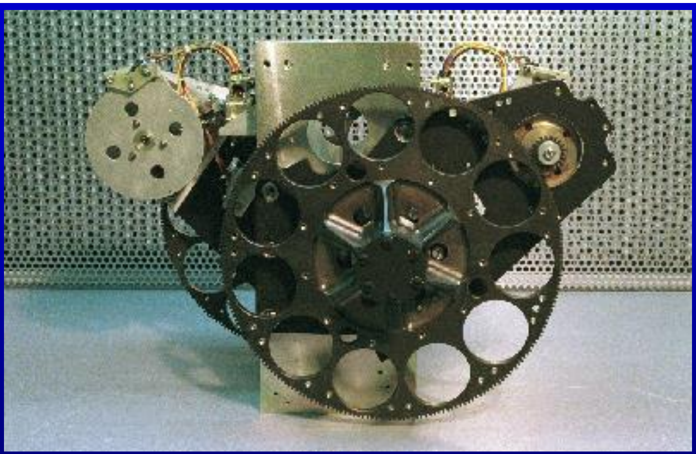
F_X < 1 milliCrabs

SPER data ←

GRB fading ↓

Swift UVOT

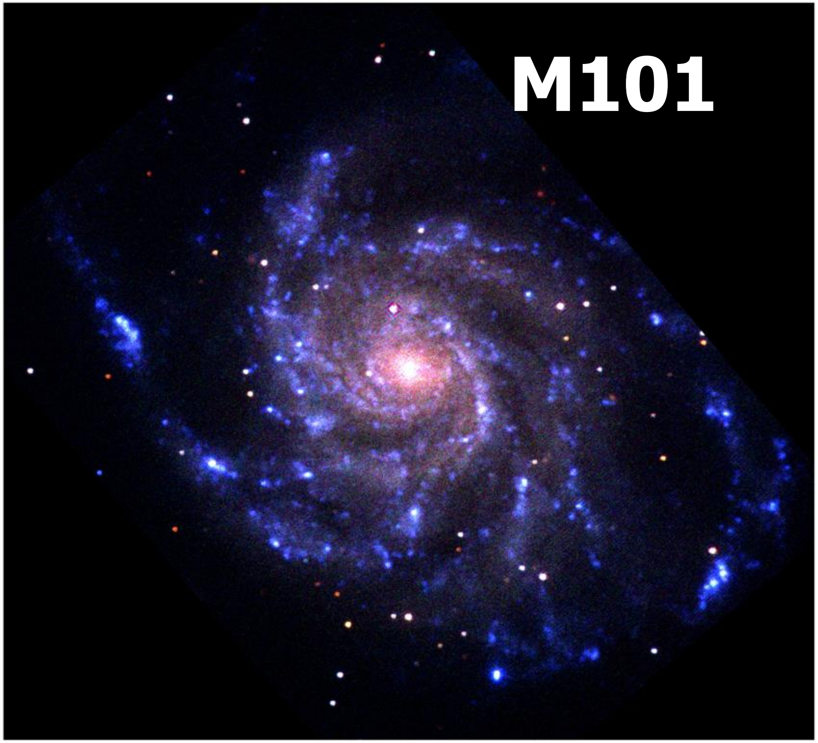


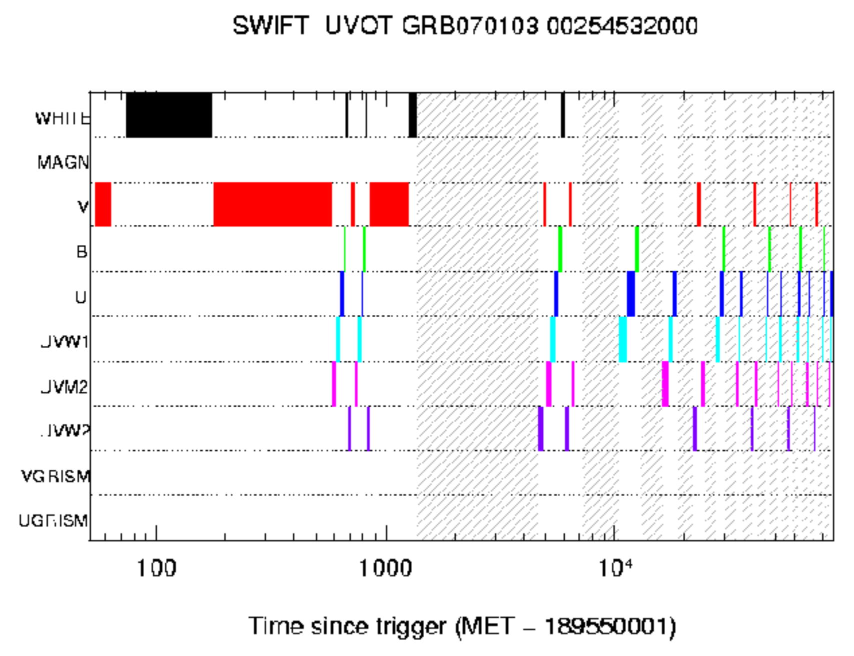


UVOT Characteristics

- 170 - 650 nm wavelength band
- 0.5 arcsec pixels
- ~0.3 arcsec astrometry
- 17' x 17' field of view
- 7 UV/Optical filters
- 2 grisms (~15Å resolution)

UVOT data

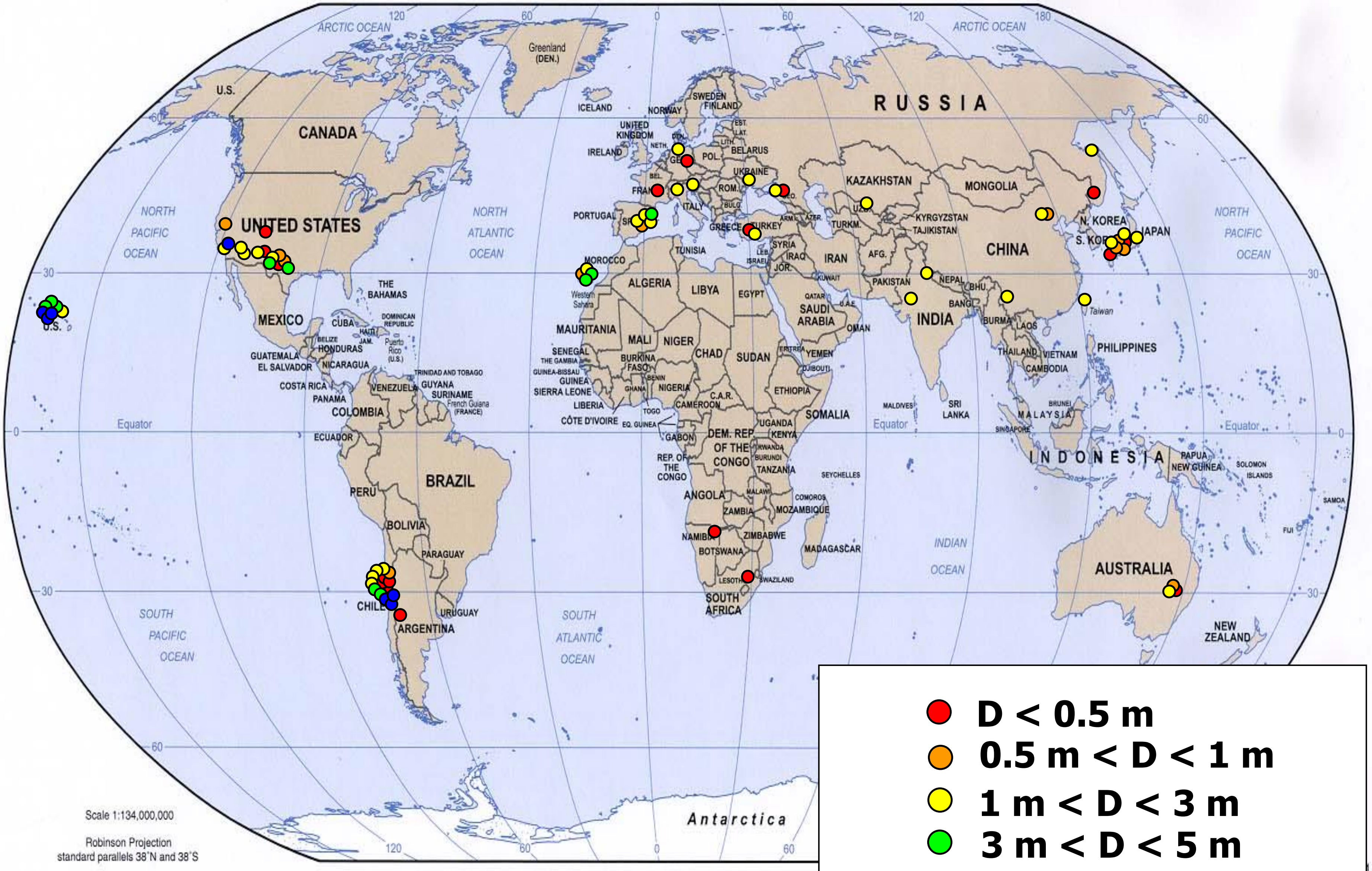




Multi-colour image: Blue=UV, Red=optical

Filter selected in sequence. Small fraction of UVOT data collected in “event” mode. Mostly imaging mode.

GRB follow-up telescopes



(T. Sakamoto, From GCNs: Sept. 2006 – March 2007)

- 🔴 **D < 0.5 m**
- 🟠 **0.5 m < D < 1 m**
- 🟡 **1 m < D < 3 m**
- 🟢 **3 m < D < 5 m**
- 🔵 **D > 5 m**

Swift Era – rapid follow-up observation

Swift has a follow-up network of dozens of telescopes:

- Fully robotic response (e.g. ROTSE III, MASTER II, FT, P60, REM…)
- Rapid trigger but with human in the loop (e.g. VLT, Gemini, GROND, XMM-Newton…)
- Later trigger (e.g. HST, Chandra…)

These facilities provide vital data: redshifts, light curves (from radio to X-ray) and some non-electromagnetic data (neutrinos, gravity waves?)

ATTENTION!

Rapid Response Request Received.

THE TELESCOPE WILL PRESET!

Please follow the instructions below without delay.

Telescope Operator:

The telescope will preset when the countdown reaches zero.

To preset now: press PRESET. If is is unsafe to preset: press STOP.

RA 200645.000

Dec -240000.000

26

Instrument Operator:

Any previous observation is being ended now (shutter closed, reading out).

The Rapid Response Mode OB has been started on a new BOB: the Acquisition is running.

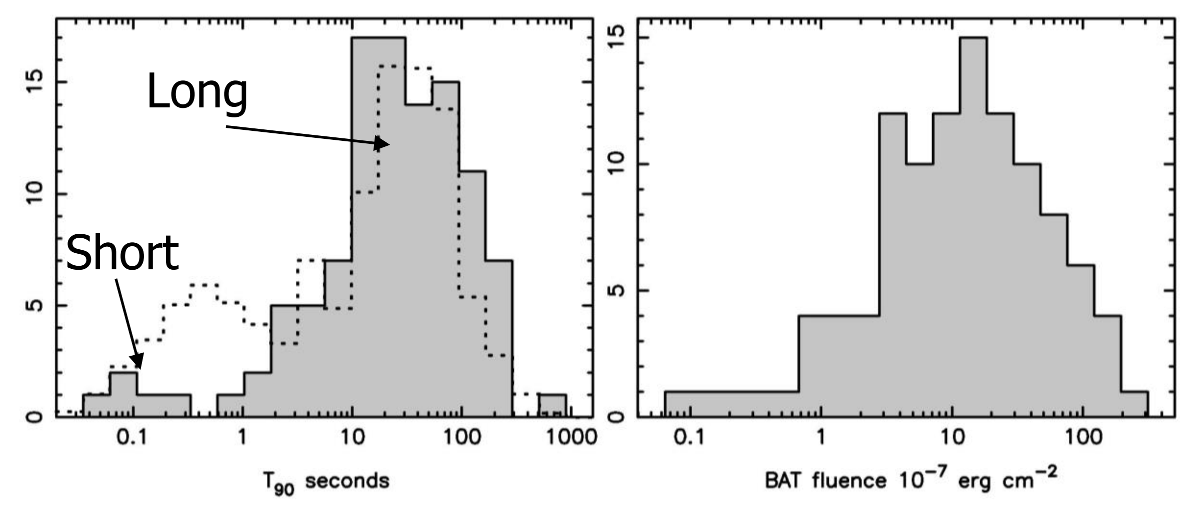
Please execute the rest of the RRM OB WITHOUT DELAY.

Check the e-mail account for the finding chart, and the RRM PSO procedure web page for more information.

VLT RRM alert

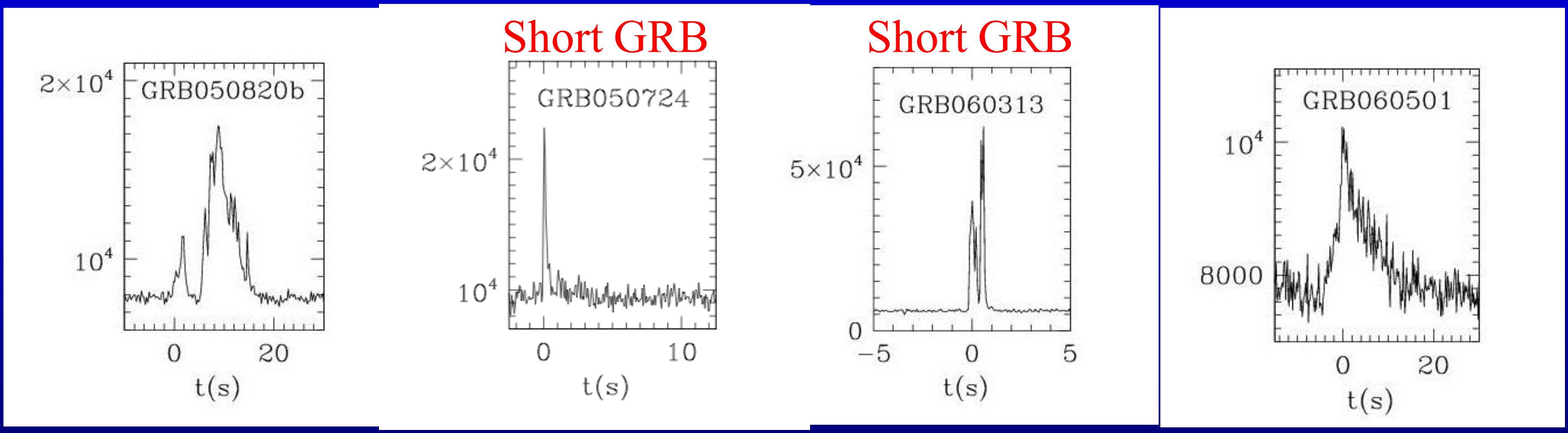
Swift Performance

- Fully operational & all data public since 2005 April 5
- GRBs detected at a rate of ~100 per year
- XRT detects >95% of bursts, UVOT detects ~1/3
- BAT sensitivity is <1 mCrab as predicted
- Ground follow-up detects ~60% of Swift GRBs
- Now have >150 redshifts for GRBs
- Detected >900 bursts to date

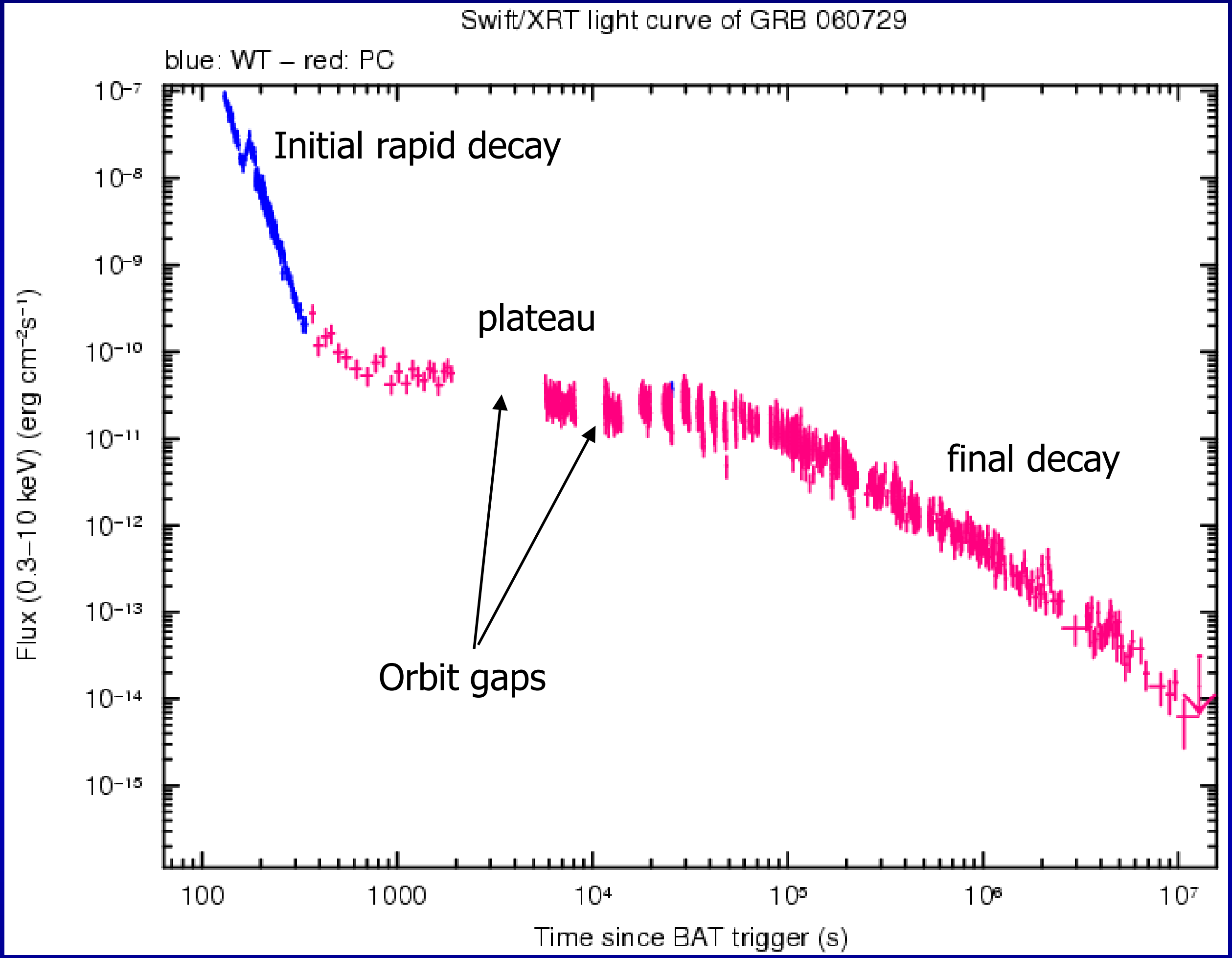


Swift Highlights

- First accurate localizations and redshifts for short GRBs
- Highest redshift GRBs
- Lowest luminosity GRB
- Brightest optical GRB
- Prompt to afterglow multi-wavelength light curves + spectra



Canonical X-ray Afterglow

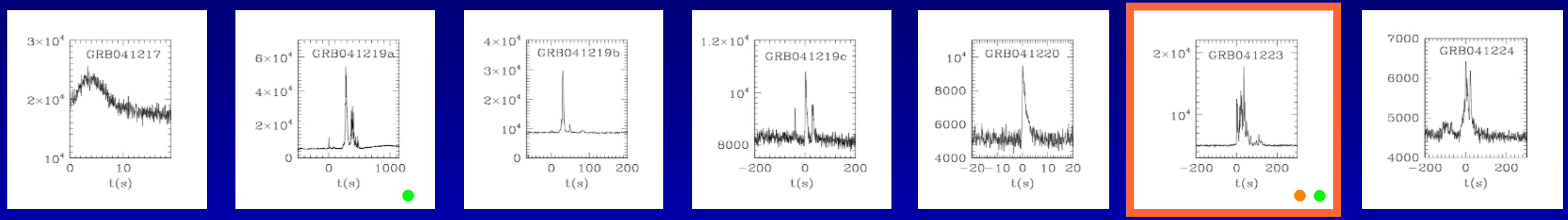


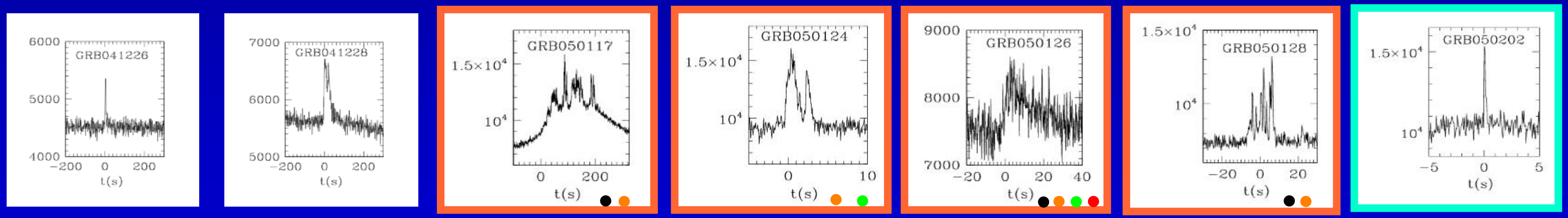
not expected to have this form pre-Swift

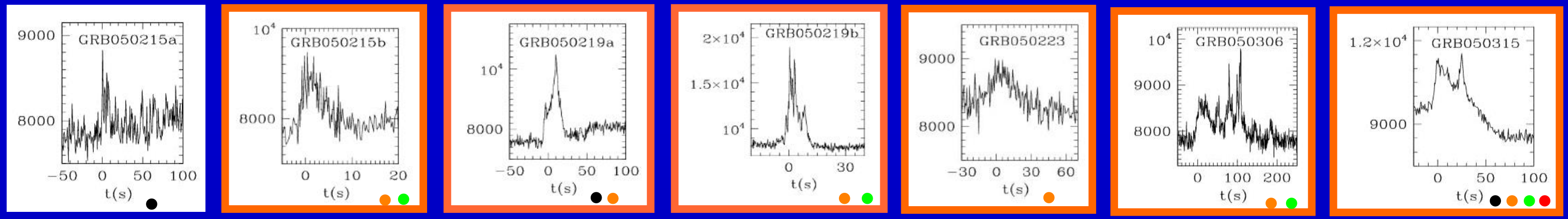
We can track the X-ray afterglow to very low flux levels

(Nousek et al. 2006, Evans et al. 2007)

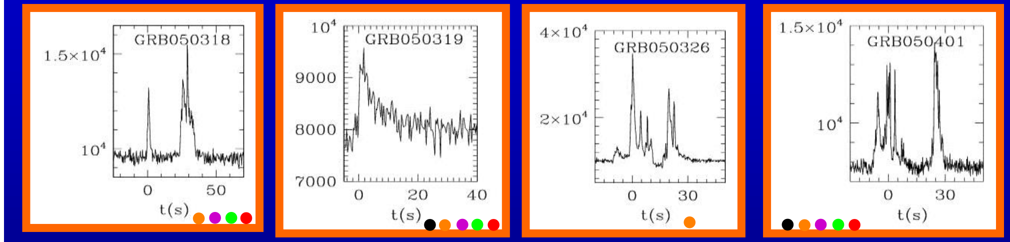
BAT light curves





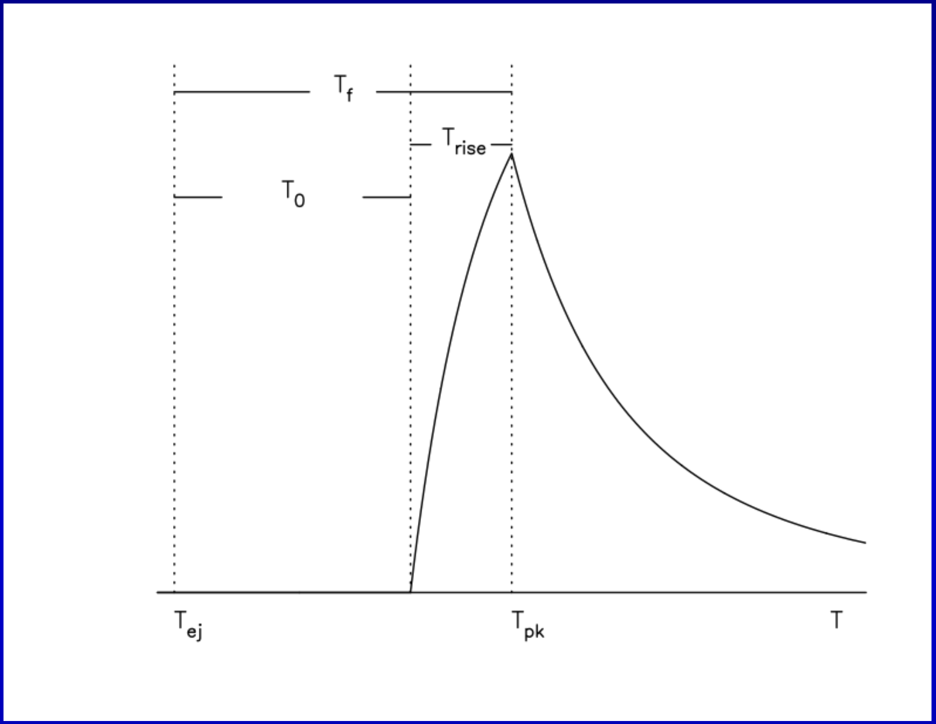


- = prompt slew
- = detected by XRT
- = detected by UVOT
- = detected by ground-based optical/IR
- = redshift measurement



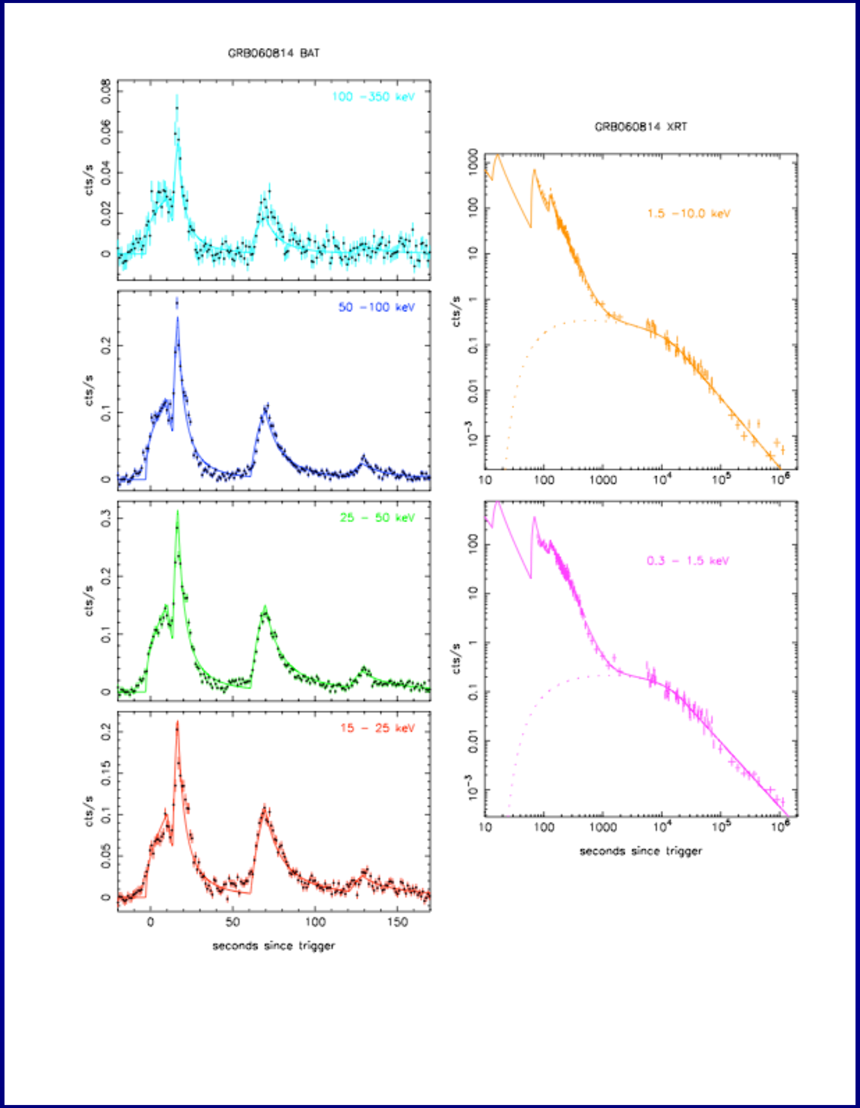
Temporal-spectral pulse profile

- In the observer frame the shell is ejected at T_{ej} (unseen)
- In the observer frame the shell emission starts at T_0 and stops at T_f
- For $T>T_f$ see delayed High Latitude Emission
- The power law rise and fall is moderated by the continuous evolution of the emission spectrum, E_p α R^d
- In the decaying tail have closure between the temporal and spectral indices $α=2+β$
- Because a Band spectrum β depends on observed energy band b_1 low spectral index, b_2 high
- F_f is flux at $T=T_f$
- E_f is characteristic Band energy at $T=T_f$



Willingale, Genet, Granot, O'Brien (2010)

Prompt through afterglow

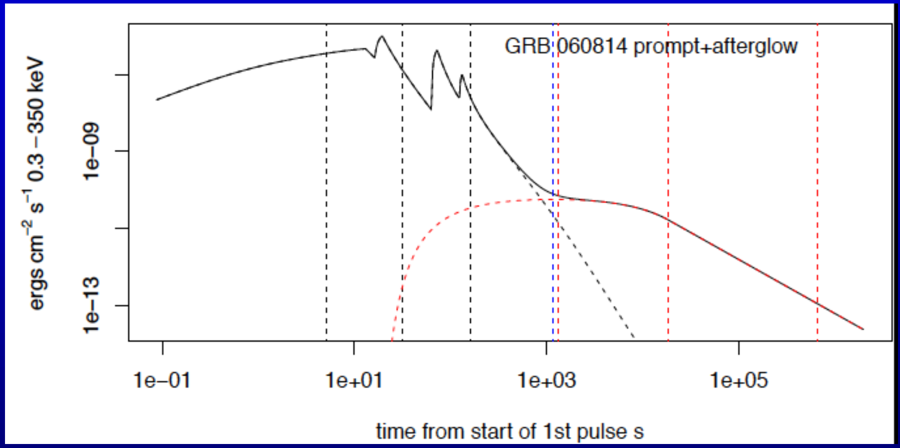


To date fitted 128 GRBs with prompt + afterglow model

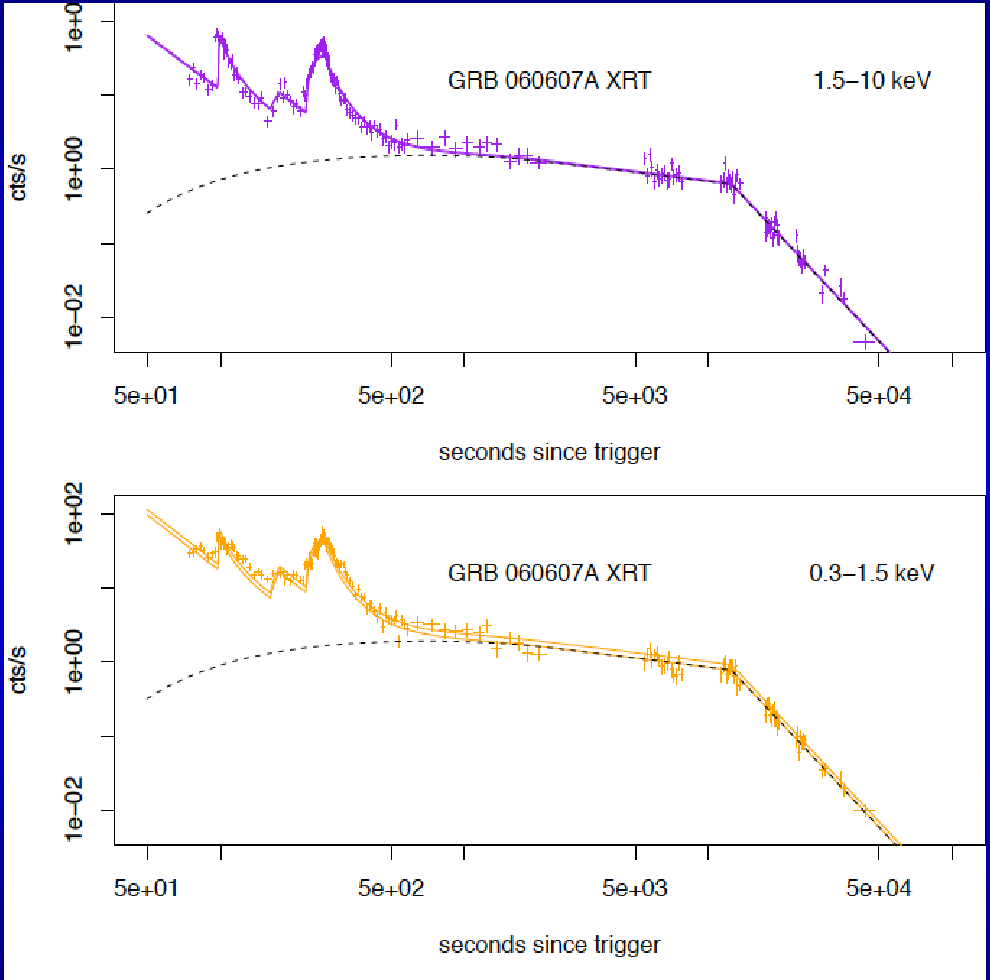
Initial afterglow decay always fit by high latitude emission from pulses

Plateau and final decay a separate component – external shock

Energy injection continues until end of plateau



X-ray flares

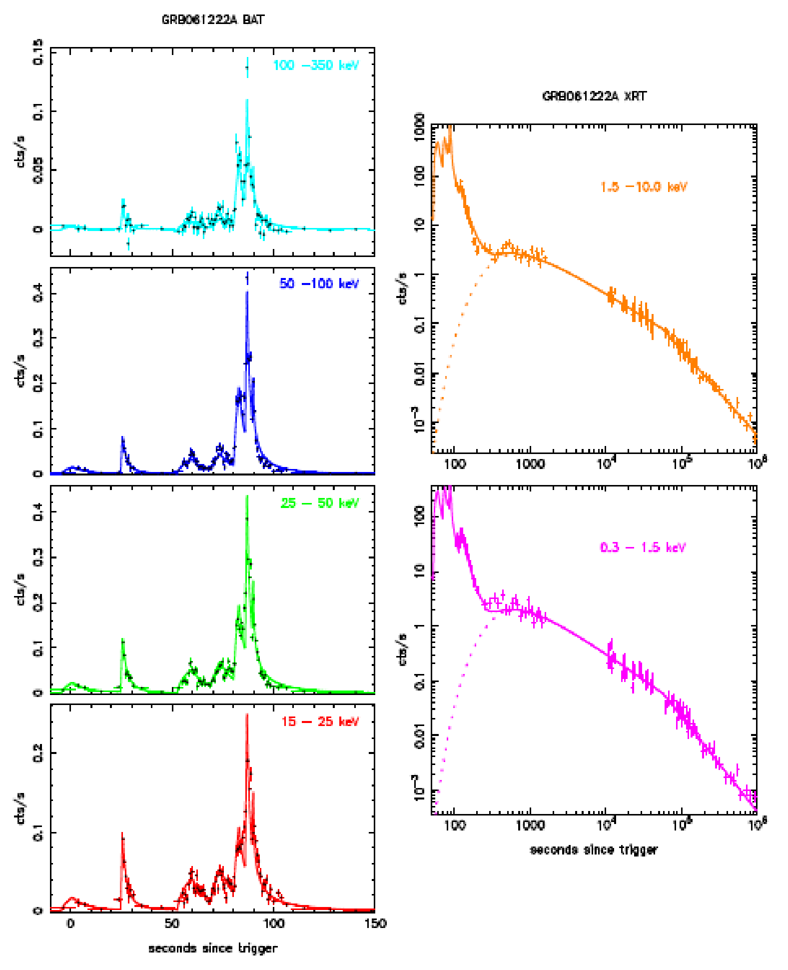


Continued prompt activity not seen by BAT

Chincarini et al. (2007)

Empirical afterglow model
Willingale et al. (2007)

Late breaks

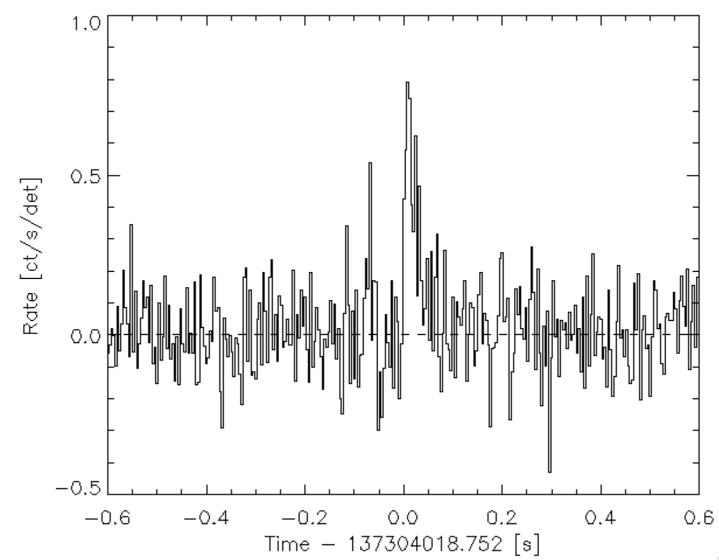


Sometimes a late break is seen

achromatic

Jet breaks?

1st Swift Short – 050909B



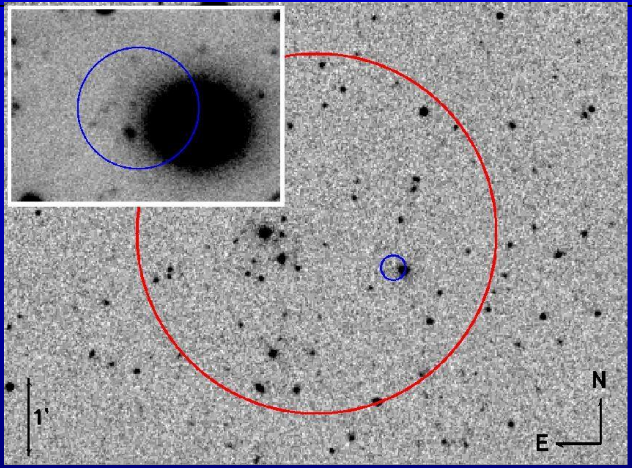
BAT (Gehrels et al. 2005)
- 30 ms duration
- spectrum is medium hard
- very weak, 2×10^{-8} erg/cm^2

Spacecraft slew in 52 sec

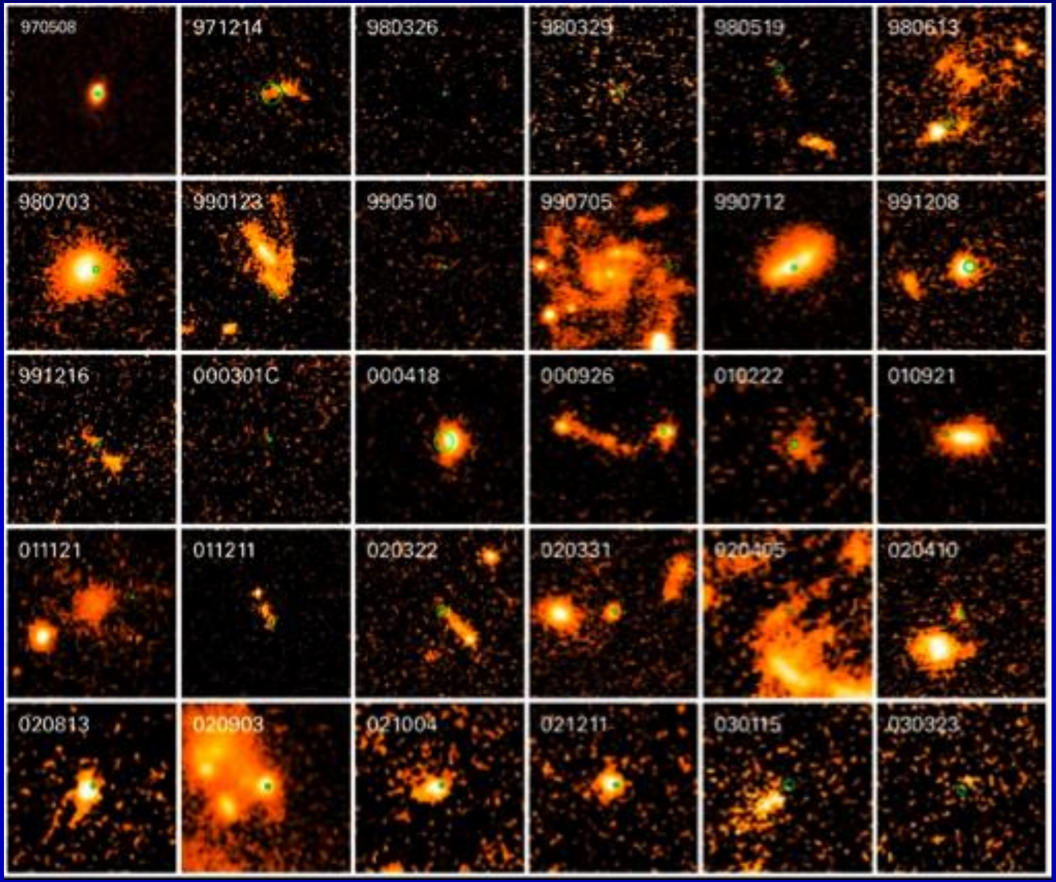
XRT
- faint source, fading
- 11 cts = 1×10^{-12} erg/cm^2/s

Host:
- cD Elliptical
- $K = 14.1$
- $L = 3\ L_x^*$
- $z = 0.225$
- SFR < $0.2\ M_O\ yr^{-1}$

VLT image
Hjorth et al.

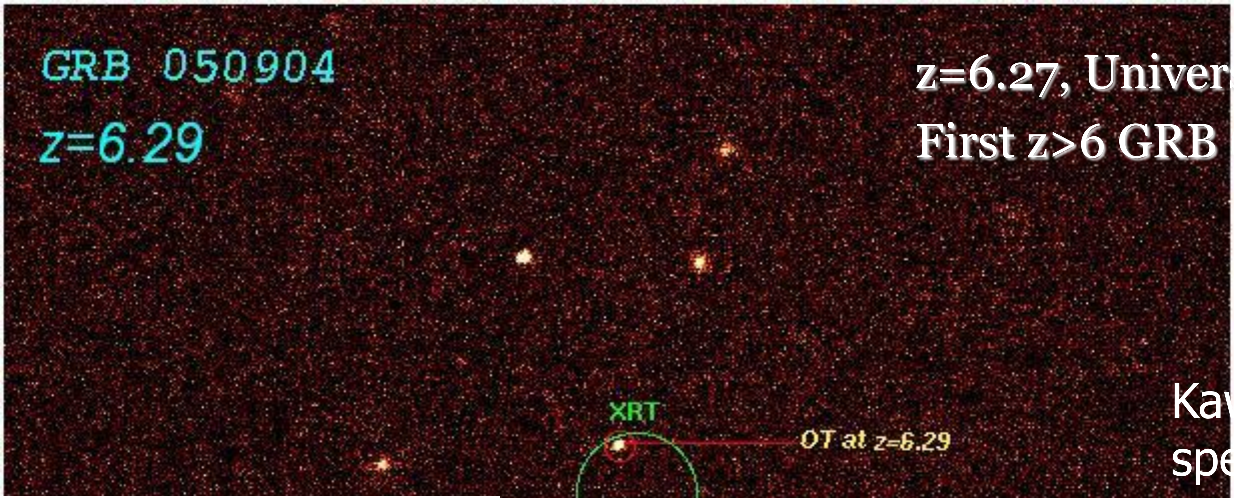


GRB Host Galaxies



HST imaging: GRBs occur on UV bright (star-forming) region in distant galaxies

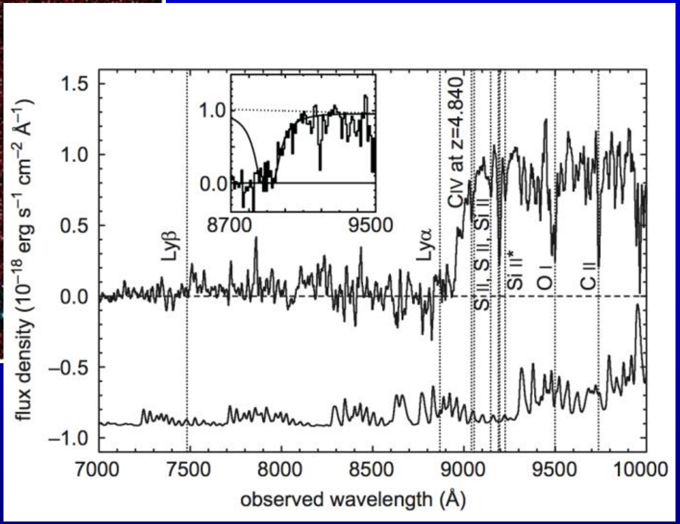
1st GRB Z>6 – 050904

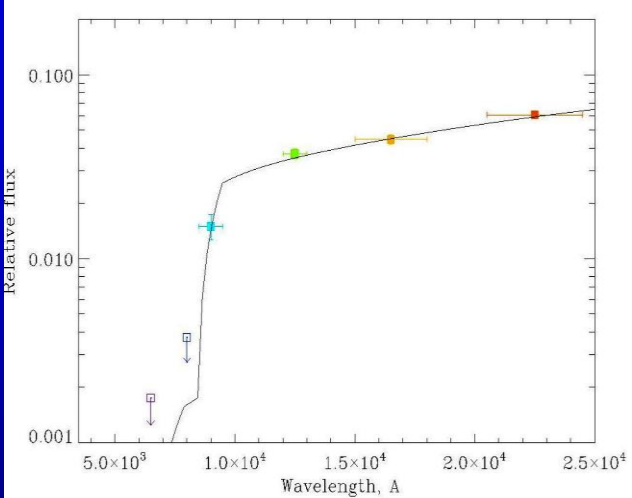


z=6.27, Universe only ~900 Myr old

First z>6 GRB (Haislip et al. 2006)

Kawai et al. 2006 Subaru spectrum

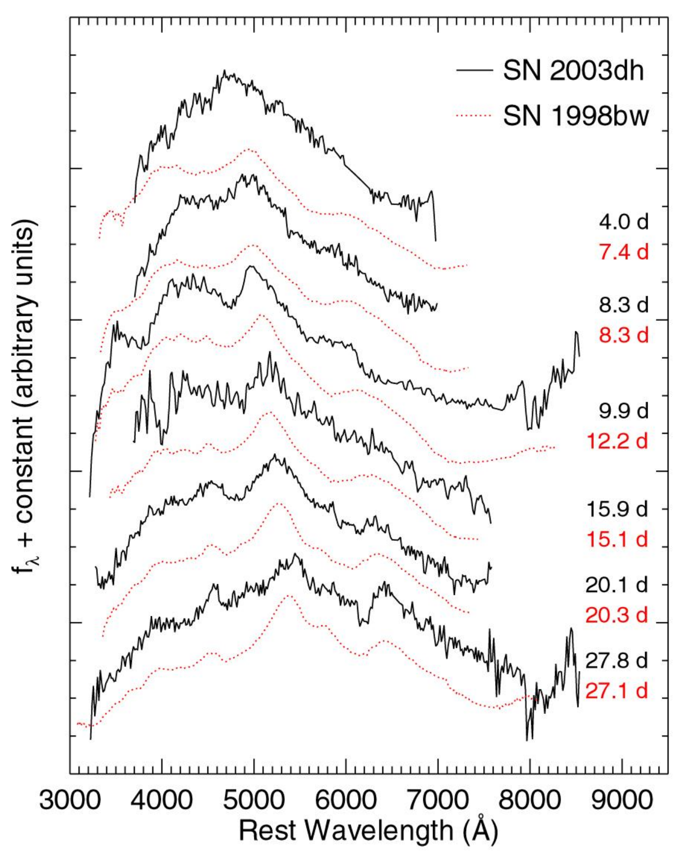




Photometry from SOAR, UKIRT and Gemini-S

The GRB-SuperNova connection

GRB030329/SN 2003dh



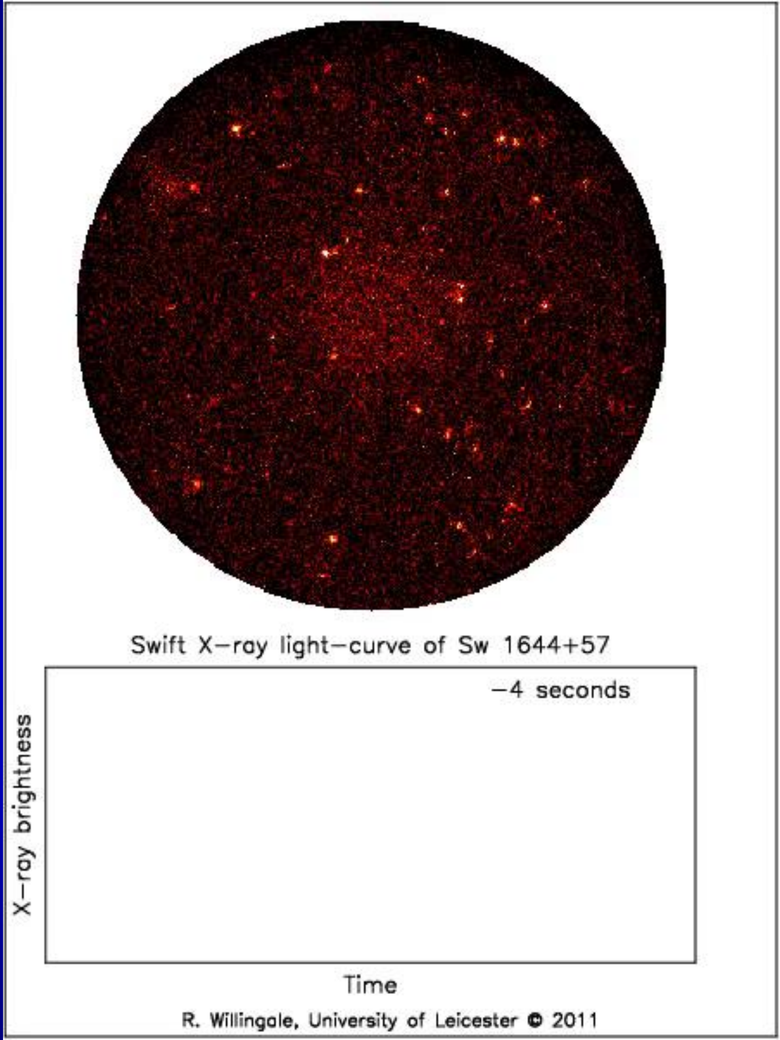
Broad line type Ic SNe.

GRB and SN simultaneous to <1day.

High expansion velocity (30,000 km/s); 3 times larger than typical Ic SN - hypernovae

All long GRBs which should show an SN signature do.

Tidal Disruption Events

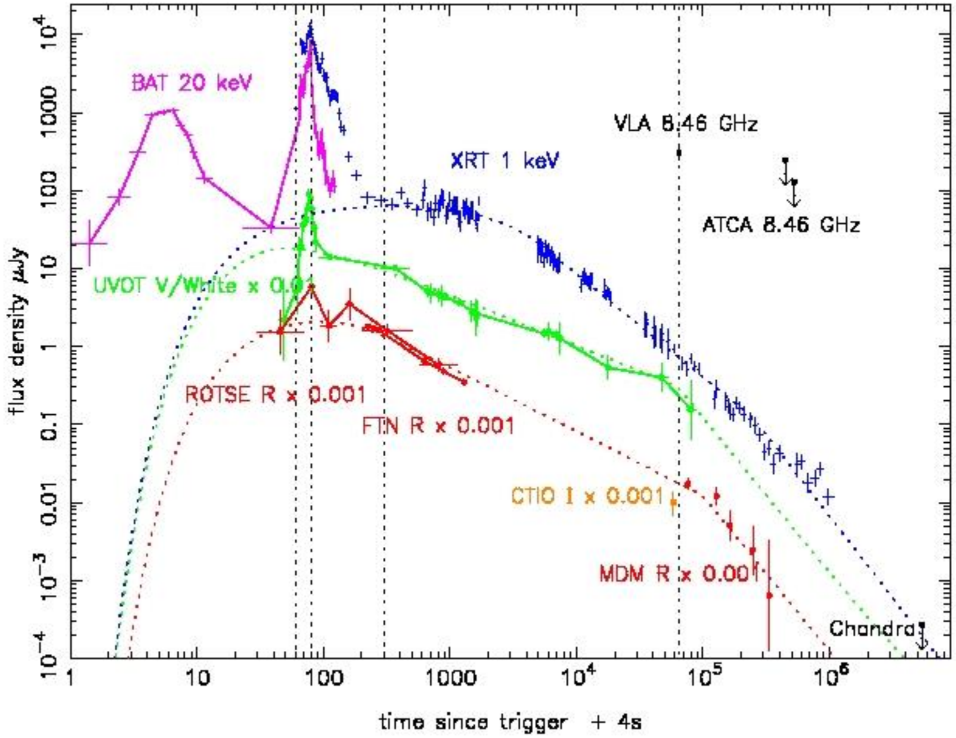


Sw 1644+57

Originally designated GRB110328A
More than 1 BAT trigger
Repeated outbursts over many days
(unlike any GRB)
Host galaxy at z=0.351

Multi-energy band light curves

GRB 061124 Page et al. 2007



Optical-X-ray spectra require break

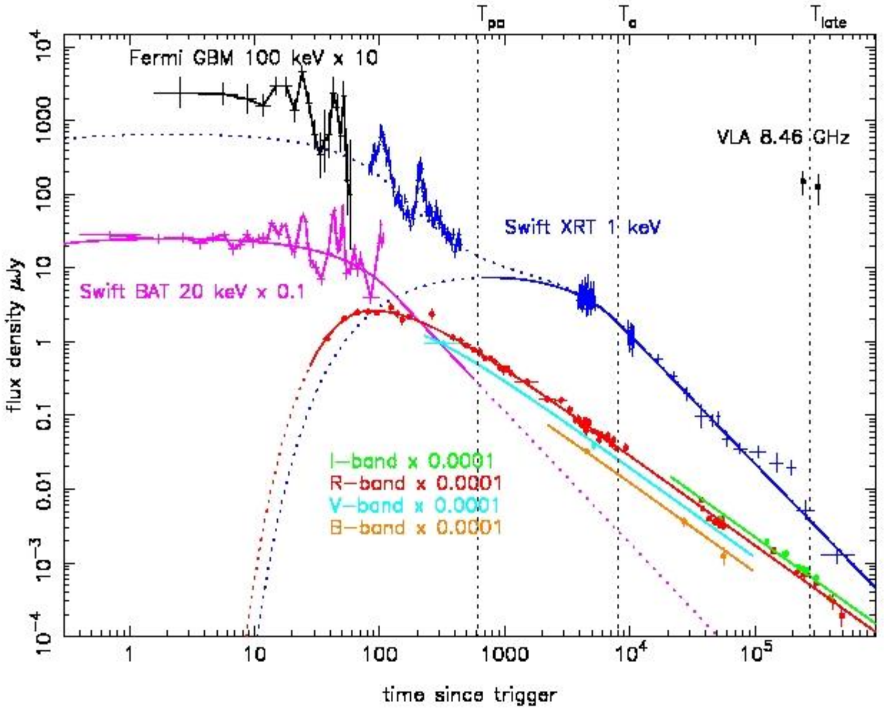
Optical prompt and afterglow emission seen

Afterglow shows spectral
evolution but decays too slowly compared with standard models

Possible late/jet break

+ Fermi

- 080810 Page et al. 2009 – includes GLAST data
- Fermi launched 11th June 2008 **Telescope**



Epeak of prompt spectrum evolves with time

The X-ray/optical afterglow intially hardens and subsequently softens

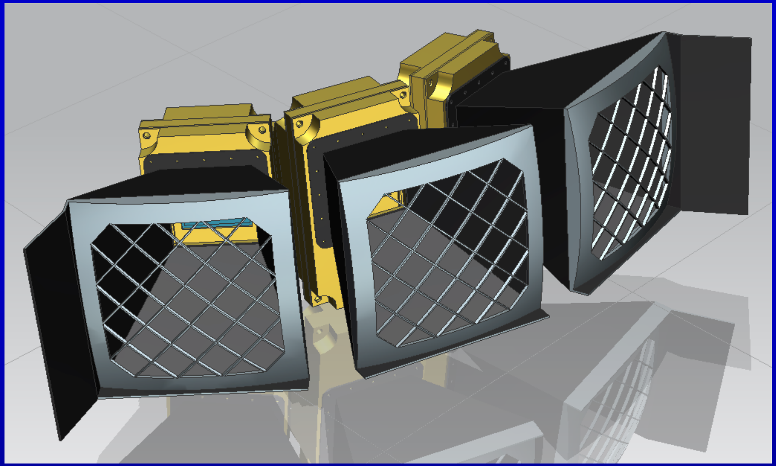
Swift Era Success

- Prompt to afterglow light curves – high latitude prompt emission
- The afterglow plateau phase – what drives it?
- Localisation of short GRBs
- Host galaxies for many long GRBs
- High red shift burst population z>6 (mean z ~2.5 for whole population)
- Late/very late prompt emission – X-ray flares
- Spectral evolution of afterglows optical to X-ray
- Simultaneous gamma ray to optical coverage of prompt emission (just)
- Other transients e.g. Tidal Disruption Events

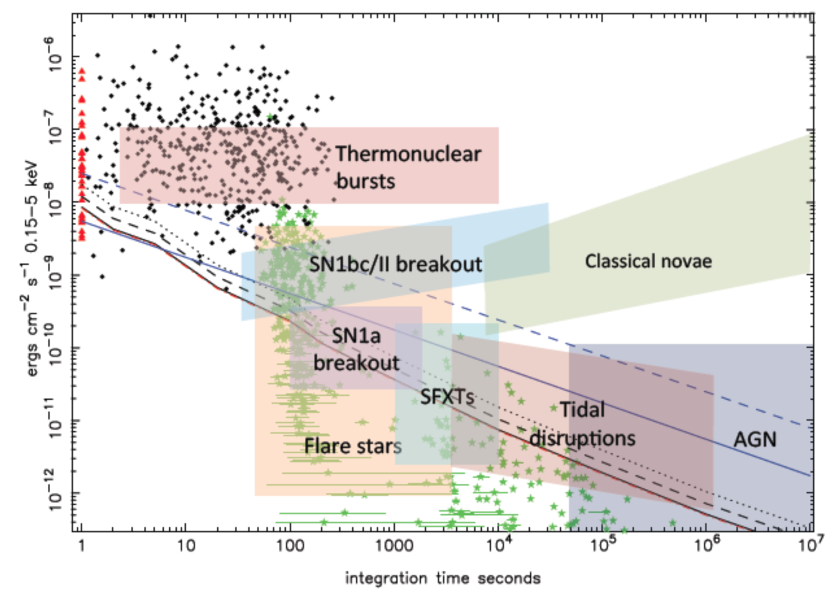
Post-Swift Era

- Can we improve on the BAT-XRT combination to trigger on fainter sources over a larger area of sky to find the high-z GRBs?
- Can we get gamma ray and optical coverage of the prompt emission simultaneously with hard/soft X-ray detection? Broadband prompt spectrum.
- Can we get rapid follow-up (<100 s) in the IR? Identify high-z GRBs

Key component – lobster eye soft X-ray transient monitor



A-STAR Osborne et al. 2012, 0.15-5 keV
FOV 17x52 deg^2, positions<30 arc secs

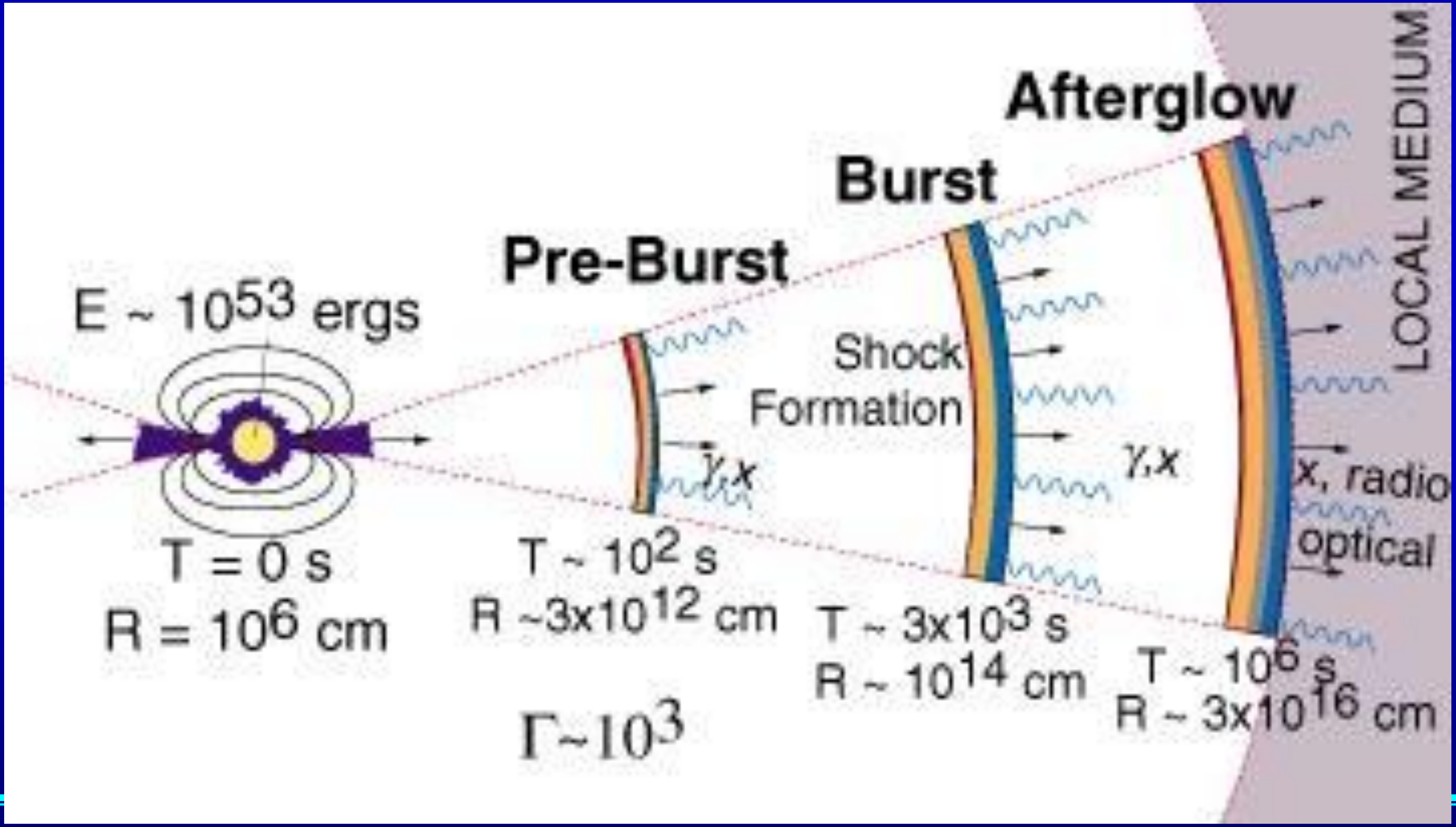


The Swift Era Continues

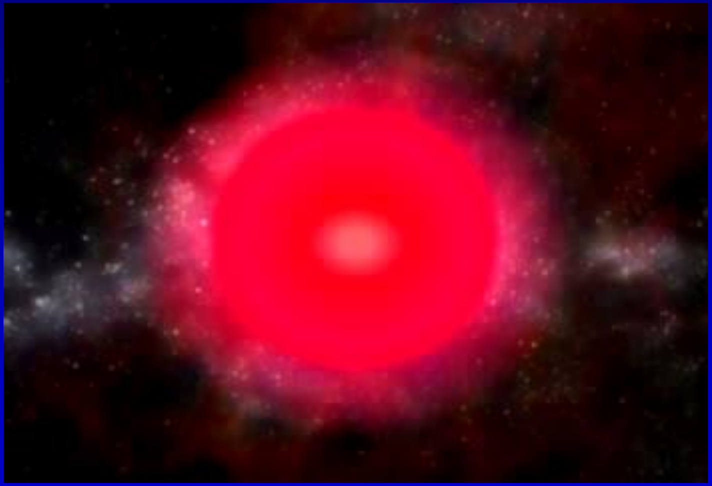
- But this talk ends

1997 Theoretical Breakthrough

2/10/97: Meszaros and Rees GRB relativistic fireball model published in ApJ; predicted broadband afterglows

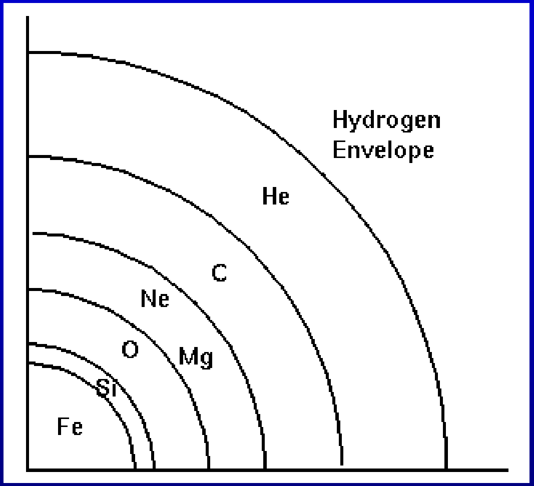


Disaster: creating a supernova



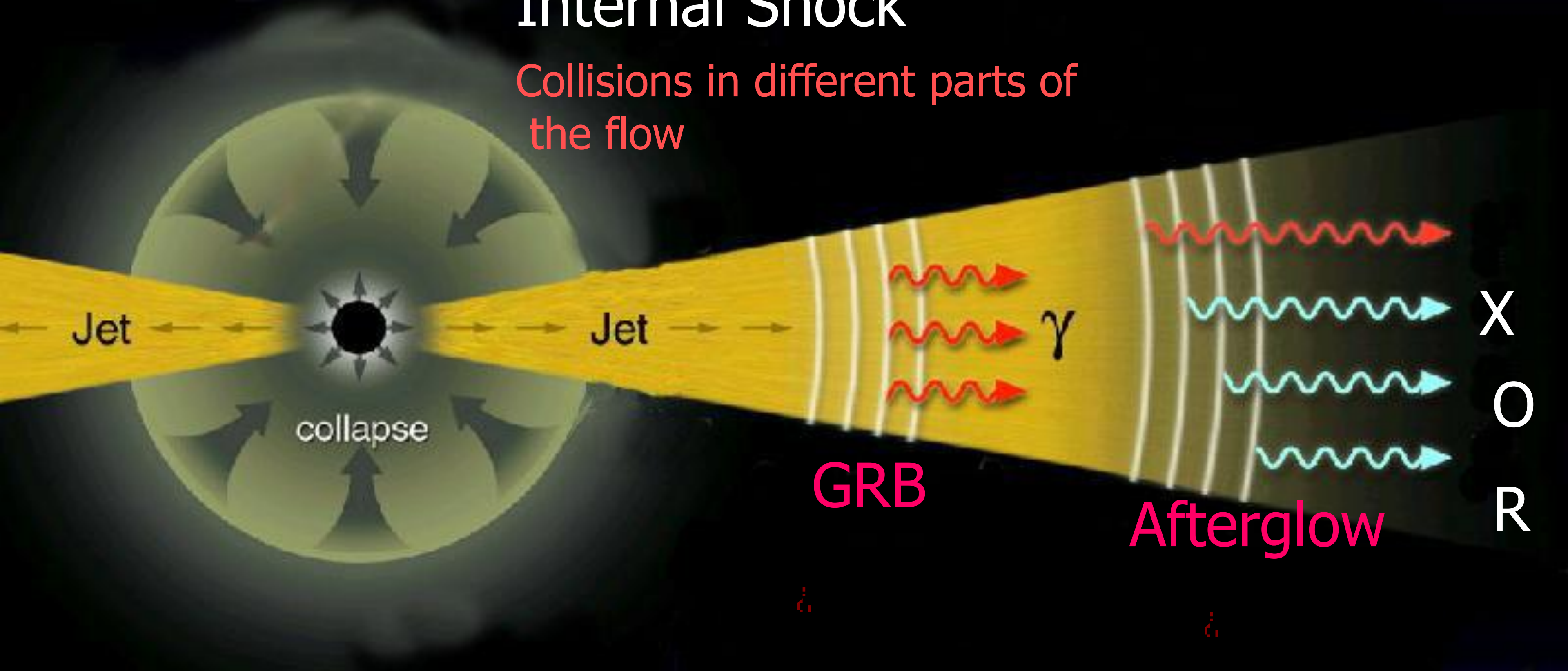
- Massive star (>8 solar masses)
- Fusion generates heat
- Gravity inward balances pressure
- Core fusion builds up “onion layer

- Iron builds up in core
- Iron fusion robs core of electrons, heat
- Collapse: Kaboom!
- Result: neutron star or black hole and an expanding shell of radioactive matter which fades



Fireball-shock model
Meszaros and Rees
1997

Ultra-relativistic expanding fireball-shock model ➔ evolving synchrotron spectrum



External Shock

Collision with surroundings

Internal Shock

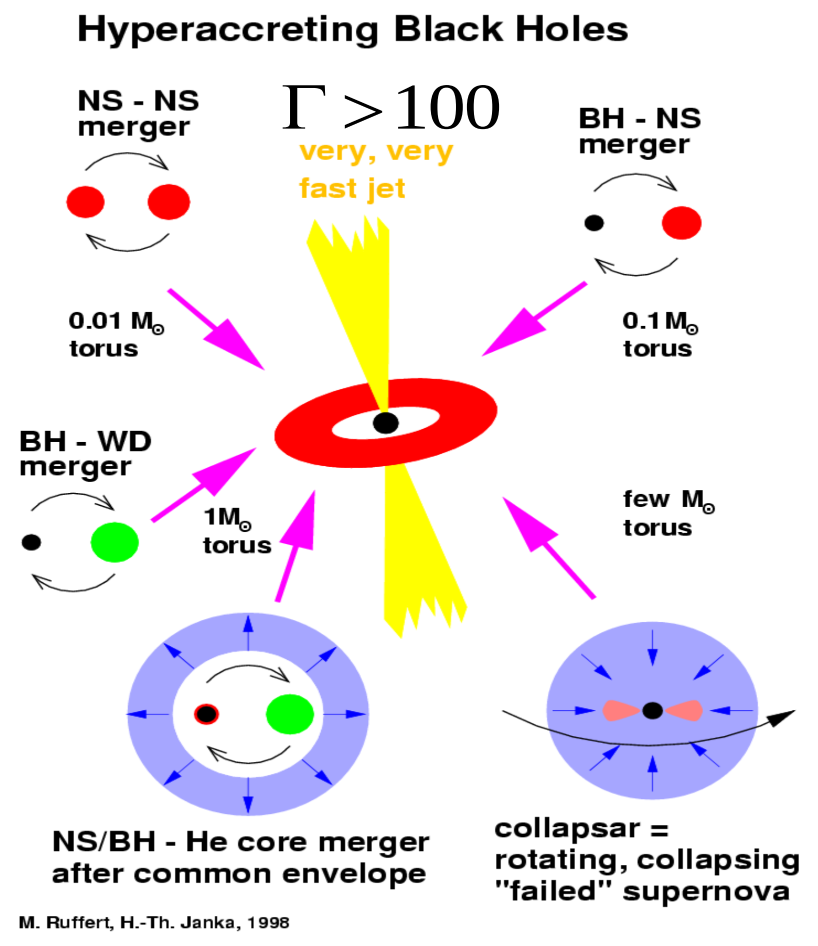
Collisions in different parts of the flow

GRB

Afterglow

X
O
R

How to make a GRB


Hyperaccreting Black Holes

M. Ruffert, H.-Th. Janka, 1998

Short

Long

Swift designed in part specifically to find faint afterglows (i.e. short and high-redshift objects)

Theory, what theory?

- Some of the models published 1973-1975

•supernovae
•neutron sta
•starquakes
“glitches”
•neutron sta
binaries
•black holes
•novae
•white holes
•flares on “normal”
stars

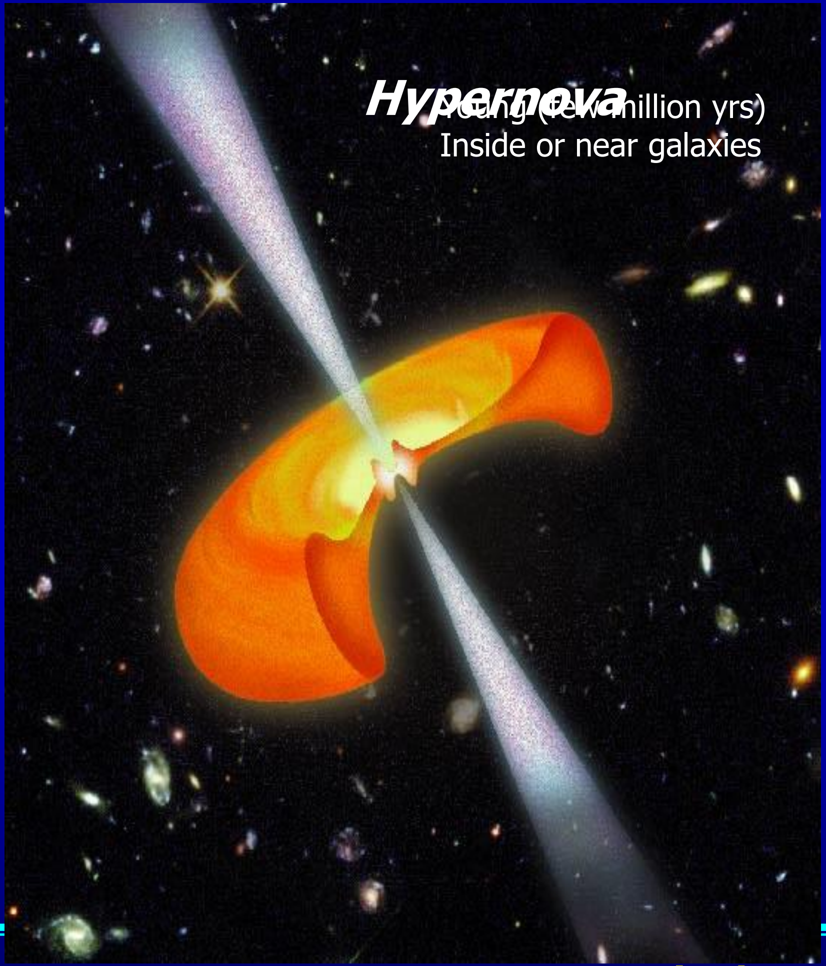
•instabilities near rotating
charged black holes
•instabilities in pulsar
magnetospheres

“Scientists detect
Alien spacecraft
making jump to
hyper-space”

GRB Models

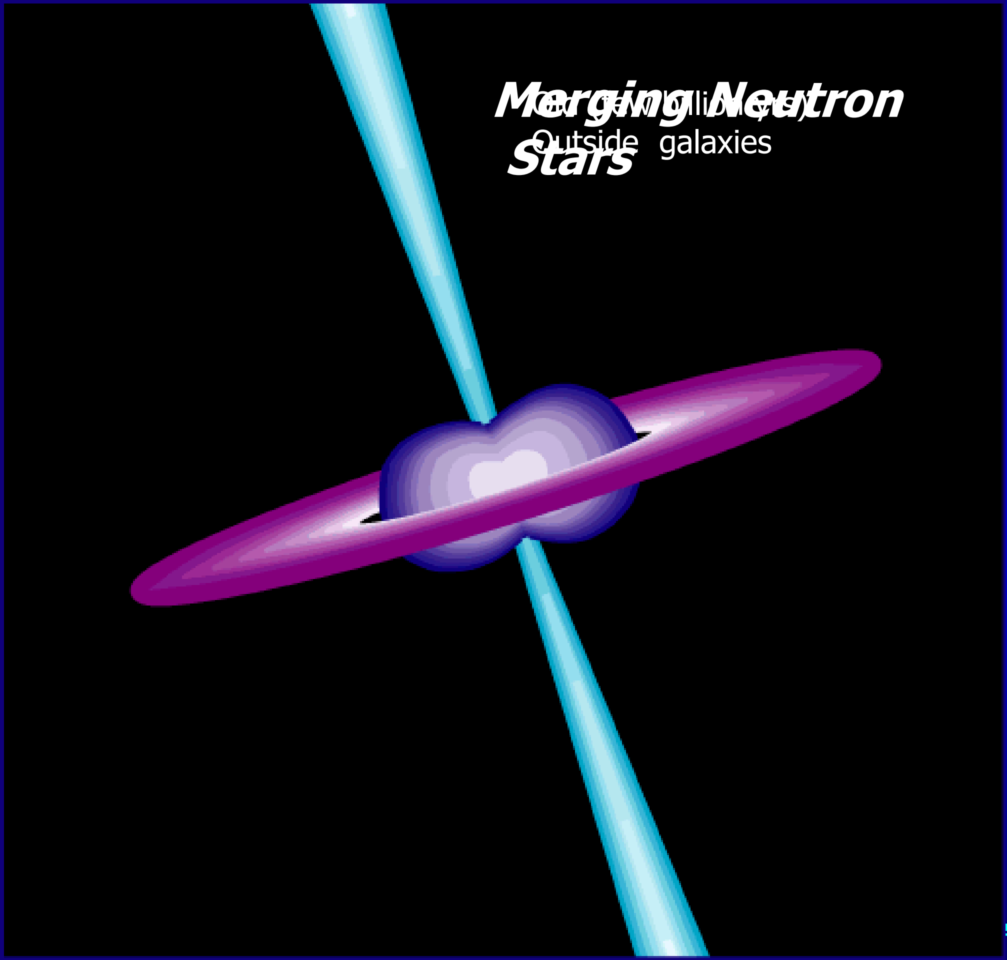
Hypernova – Long GRB

Merging Neutron Stars – Short GRB



Hypernova

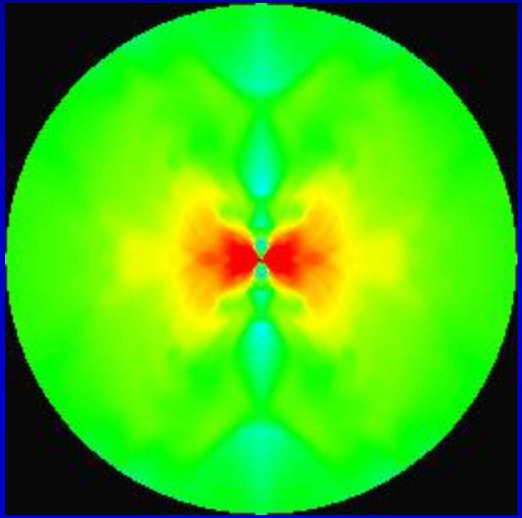
Young (few million yrs)
Inside or near galaxies



Merging Neutron Stars

Old (few billion yrs)
Outside galaxies

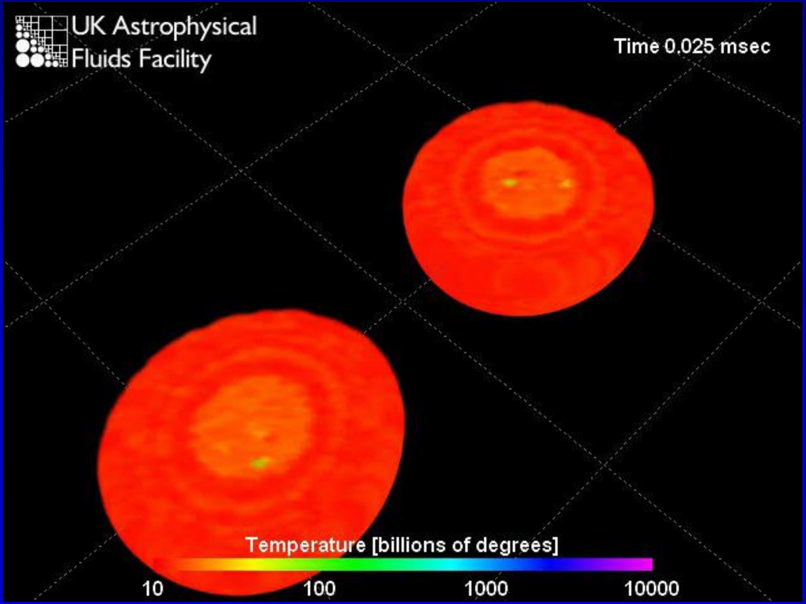
Supernova/GRB model

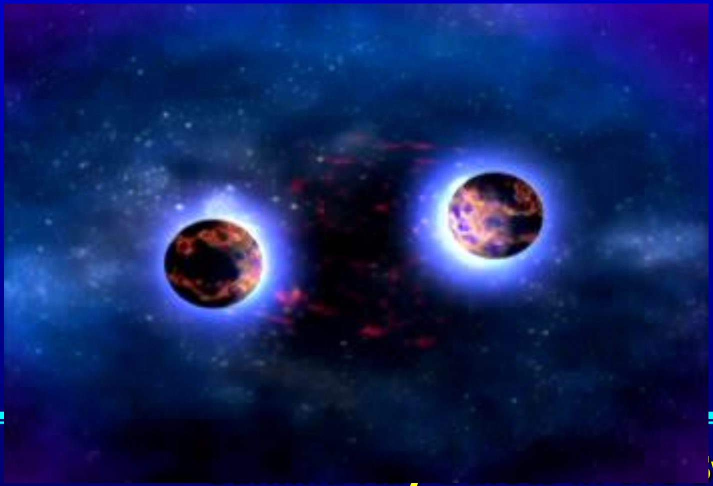


- Massive star (>30 M) dies – center collapse to BH
- Get Supernova + "feeding Black Hole"
- In some cases get very fast jets (>0.9999c) emitted ⇒ GRB

(need fast jet to explain spectrum, variability, reasonable energy)

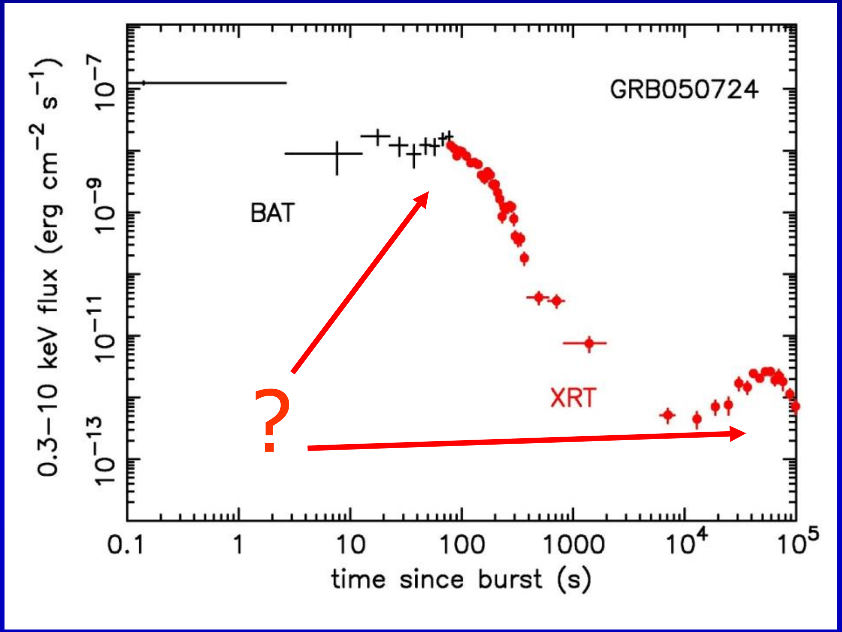
Short GRB model – NS-NS merger





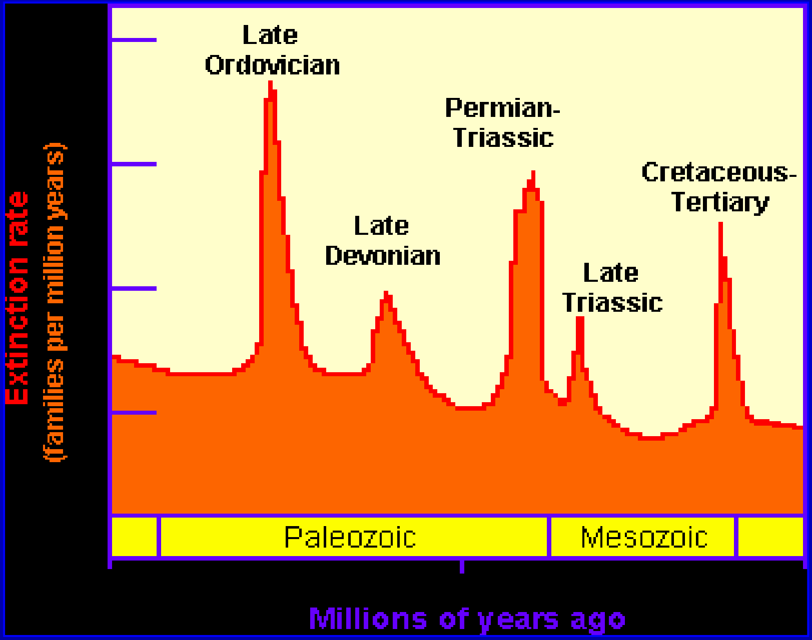
- Merger is fast (msec) ⇒ BH
- Can occur in any type of galaxy.
- Dynamical "kick" can move NS from original location so final merger can be in low density environment ⇒ weak X-rays
- Expect ~4000 NS-NS mergers yr^{-1} at <1 Gpc. See far fewer – beaming?
- Could this produce short-lived millisecond pulsars (Dai et al. 2006)?

Or NS + black hole?



Some “shorts” bursts show later “flares” – a long-short burst. Perhaps later accretion by shredding a NS in a black hole-NS binary.

Should we be worried…?



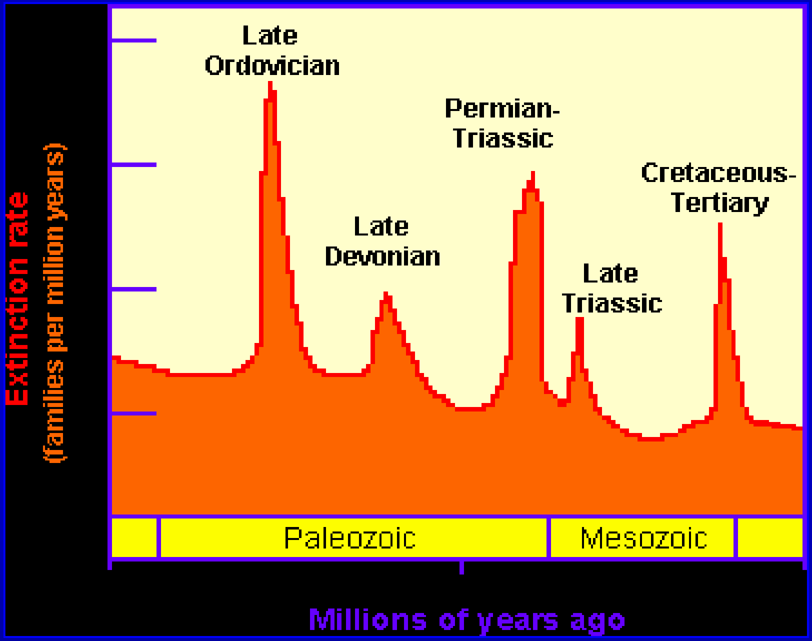
Gamma-Ray Burst

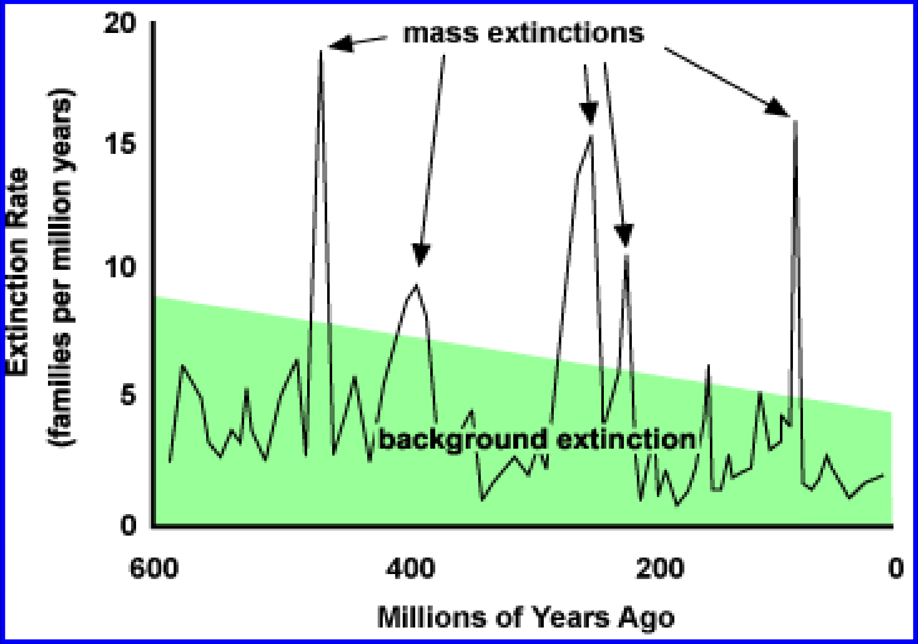
Estimate >2-3 GRBs per Gyr within a distance of 10000 lt. yr. Probably less likely in our Galaxy now as metallicity high

- GRB dumps energy into atmosphere much faster than a supernova does. Initial UV level could be >x10 Solar.
- Ozone depletion, acid rain and global cooling which spreads around the planet. If close also get an EM pulse.
- Higher but uncertain risk due to cosmic rays (the GRB acts like a particle accelerator) which cause direct DNA damage

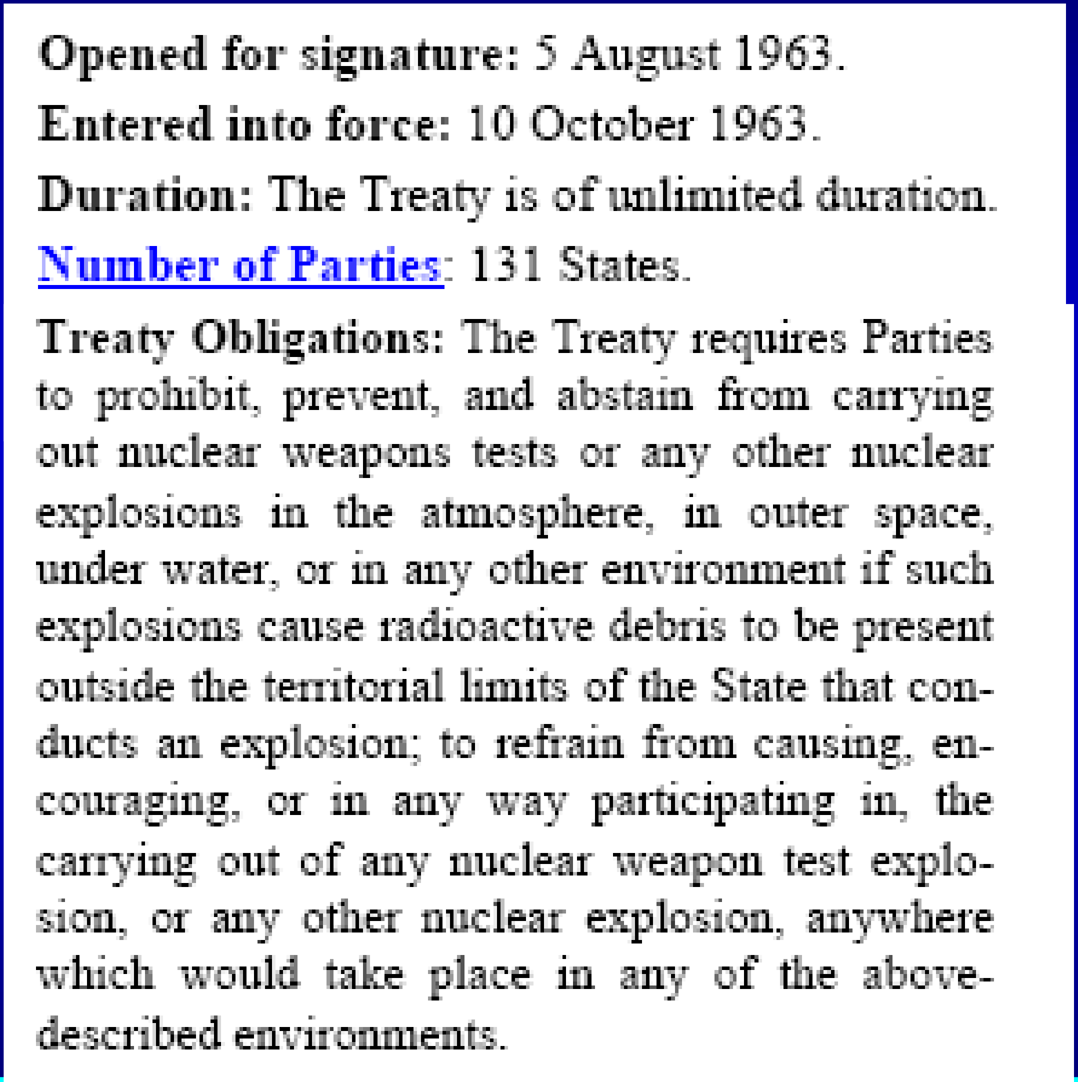
Predicted as GRB Effects	Observed in late Ordovician
Extinction of shallow (not deep) water organisms	Yes
Extinction of free-swimming organisms	Yes
Extinction of surface floaters (plankton) and organisms with planktonic larval forms	Yes
Nitric acid rain	Productivity oscillation in biosphere possibly related to nitrate boost
Reduction of solar radiation – cooling	Possibly – glaciation probably needed a “kick-start”

There have been ~5 massive species extinction events in last 500 Myr: Why?





1963 – partial test ban treaty



Opened for signature: 5 August 1963.

Entered into force: 10 October 1963.

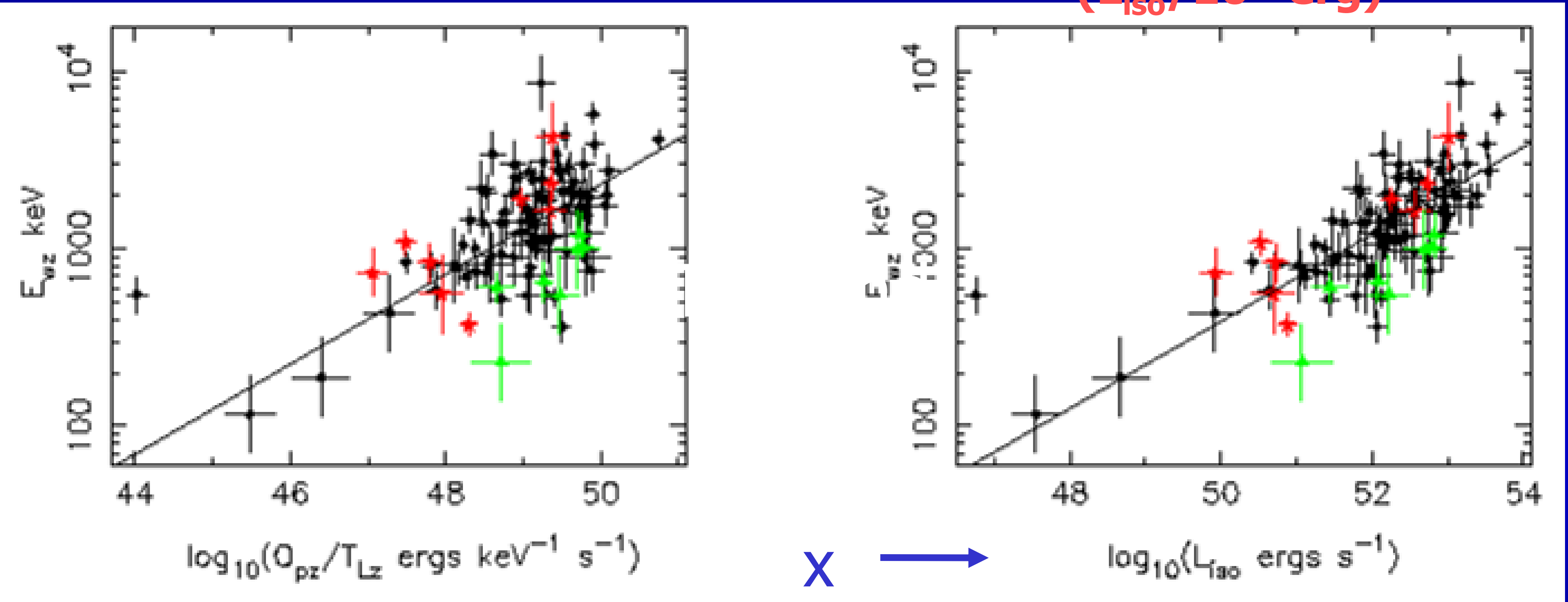
Duration: The Treaty is of unlimited duration.

Number of Parties: 131 States.

Treaty Obligations: The Treaty requires Parties to prohibit, prevent, and abstain from carrying out nuclear weapons tests or any other nuclear explosions in the atmosphere, in outer space, under water, or in any other environment if such explosions cause radioactive debris to be present outside the territorial limits of the State that conducts an explosion; to refrain from causing, encouraging, or in any way participating in, the carrying out of any nuclear weapon test explosion, or any other nuclear explosion, anywhere which would take place in any of the above-described environments.

$E_{wz} \sim L_{iso}^{0.25}$

$E_{wz}/381\text{keV} = (L_{iso}/10^{50}\text{erg})^{0.25}$



peak luminosity density

x E_{wz} →

peak luminosity

Colour-luminosity diagram

for *all* bursts except GRB980425/SN1998bw

Emission mechanism

- Can we explain the correlation between E_{wz} and L_{iso}?
- It is tempting to think that E_{iso} could be something to do with the progenitor or the size of the initial reservoir of energy – Frail and subsequent authors.
- E_{iso} has a very large dynamic range and is different for long and short bursts
- On the other hand the instantaneous peak luminosity may have nothing to do with the total energy available/released
- L_{iso} may be more closely related to the emission mechanism
- The E_{wz} – L_{iso} relationship is the same for the short and long bursts possibly independent of the progenitor

$E_{wz} \sim L_{iso}^{0.25}$

$$K_z=(E_{wz}/1320\ \mathrm{keV})^{0.97}(L_{iso}/1.45\times10^{52}\ \mathrm{ergs\ s^{-1}})^{-0.24}$$

Internal Shocks:

The new relationship is consistent with the synchrotron internal shock model (which has $E_{pz} \sim \Gamma^{-2}\ t_{var}^{-1} L^{0.5}$, Zhang & Mészáros 2002) if $\Gamma \sim L^{1/8}$ and t_{var} is the same for all bursts.

Thermal origin:

We have a form of the Stephan-Boltzmann law for Black Body radiation modified to take account of the relativistic expansion Thompson (2006).

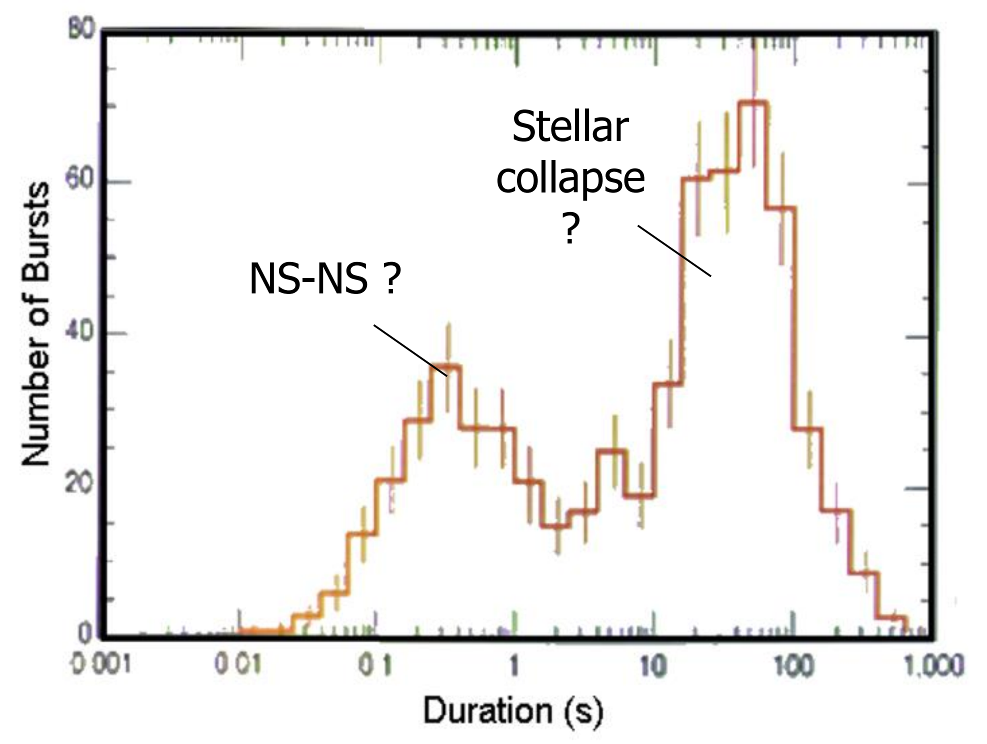
Multi-temperature blackbody photosphere gives rise to an effective temperature E_{wz} and $10^7\Gamma_0/R_0 \sim K_z^2 \sim 1$, and so $R_0 \sim 3\mathrm{x}10^9$ cm for $\Gamma_0 \sim 300$, ie this is thermalisation radius estimated by Thompson, Mészáros & Rees (2007)

$E_{wz} \sim L_{iso}^{0.25}$

Summary:

- $E_{iso}=Q_{pz}E_{wz}$
- $L_{iso}=Q_{pz}E_{wz}/T_{Lz}$
- $E_{wz}\sim L_{iso}^{0.25}$ for 100 out of 101 bursts, short and long
- Relates source frame characteristic photon energy to peak luminosity
- Holds for short, long, pre-Swift and Swift
- There is real scatter about the correlation, may be related to dimensions of fire ball, $10^7\Gamma_0/R_0 \sim K_z^2$
- This new relationship is suggestive of a thermal origin of the prompt emission
- But…

The long and the short



See double-peaked distribution of burst durations:

- Short, faint, hard bursts
- Long, bright, soft bursts

(N.B. shape of duration distribution is instrument & bandpass dependent)

Vital statistics

Using the redshift we find:

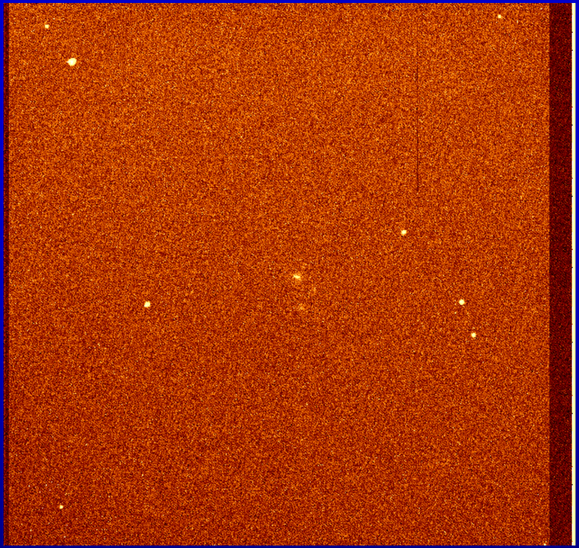
- The equivalent isotropic energy released in Gamma-rays is enormous , up to $E_{iso} \sim 10^{47}$ J
- Even if beamed the collimated energy is huge $E_{\gamma} \sim 10^{44}$ J
- The energy is released in a few second $L_{iso} \sim 10^{45}$ J s^{-1}
- They emit more energy in 10 seconds than our Sun will emit in its entire 10 billion year lifetime
- Short burst $T_{90}<2$ seconds, long burst $T_{90}>2$ seconds

  - 10^{47} J = rest-mass energy of Sun
  - T_{90} contains 90% of detected fluence

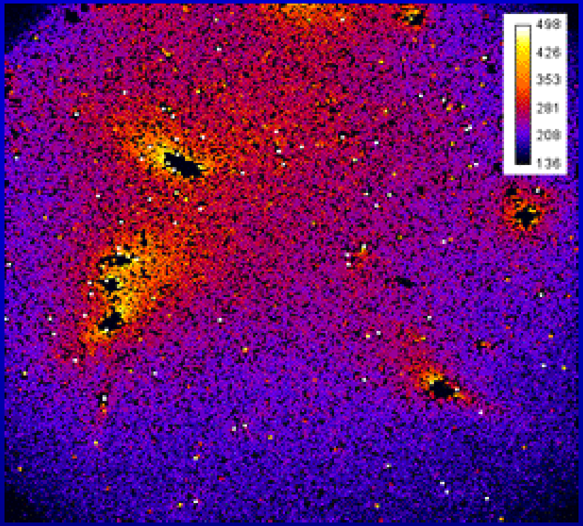
XRT micrometeoroid impact

At 5:22UT on 2005 May 28, the XRT CCD was struck by something.
Bright event created several “very hot” pixels that saturate columns on the detector causing very high count rates. Masked out during data processing.
Effect is very temperature dependant.

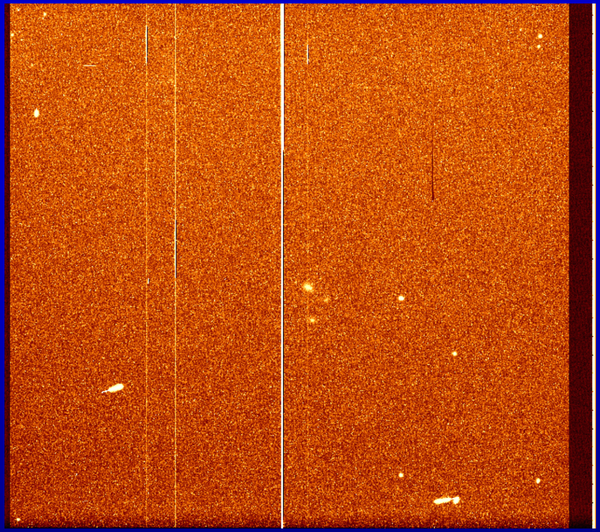
Before



During



After



Implication: space is a dangerous place!