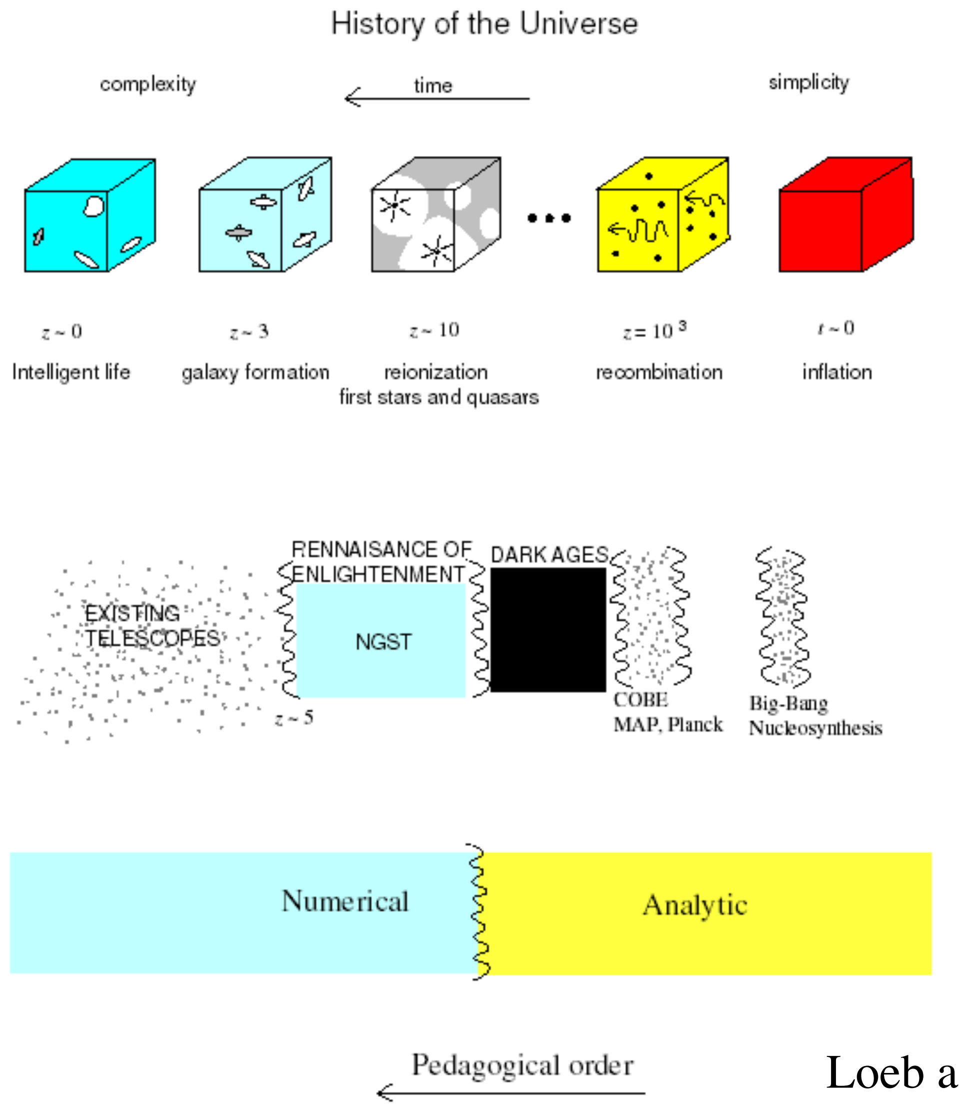
Astrofisica Nucleare e Subnucleare
“GRB” Astrophysics

Astrofisica Nucleare e Subnucleare

Gamma ray Bursts – II

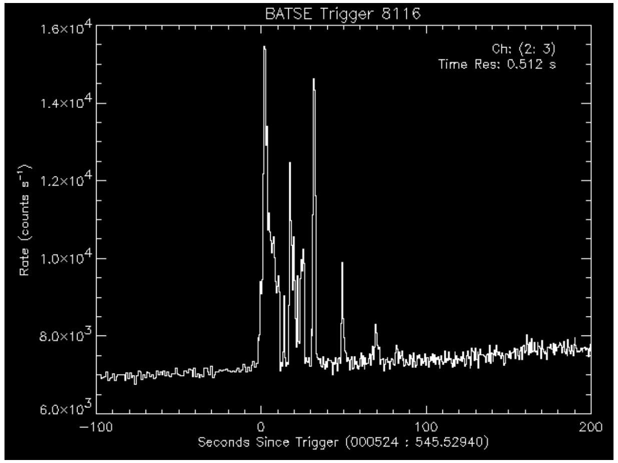
GRB Cosmology



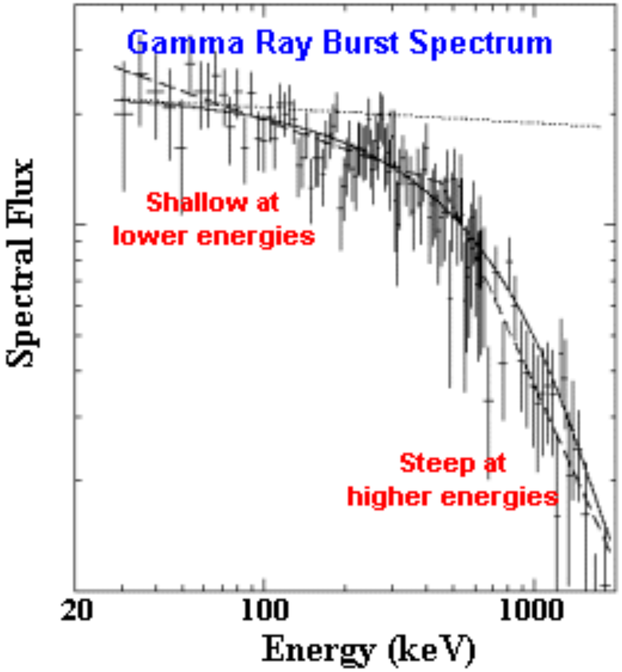
Loeb and Barkana (2000)

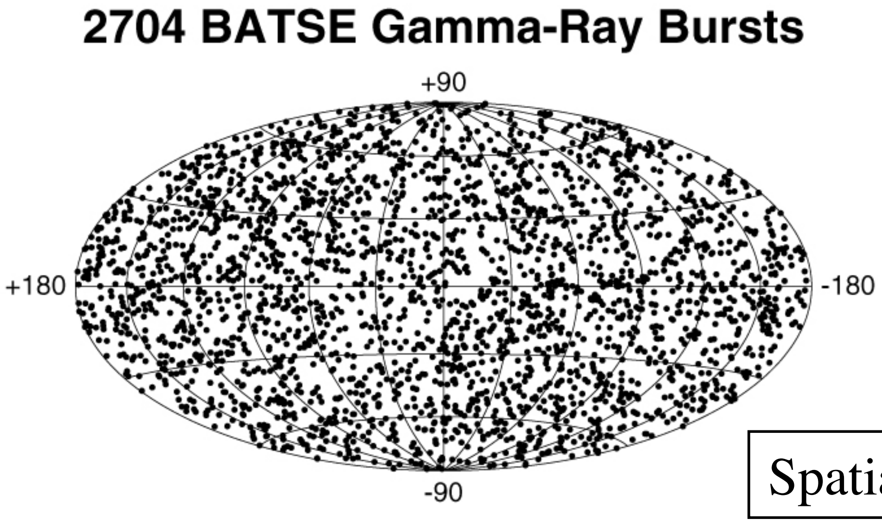
Gamma-Ray Bursts

Temporal behaviour



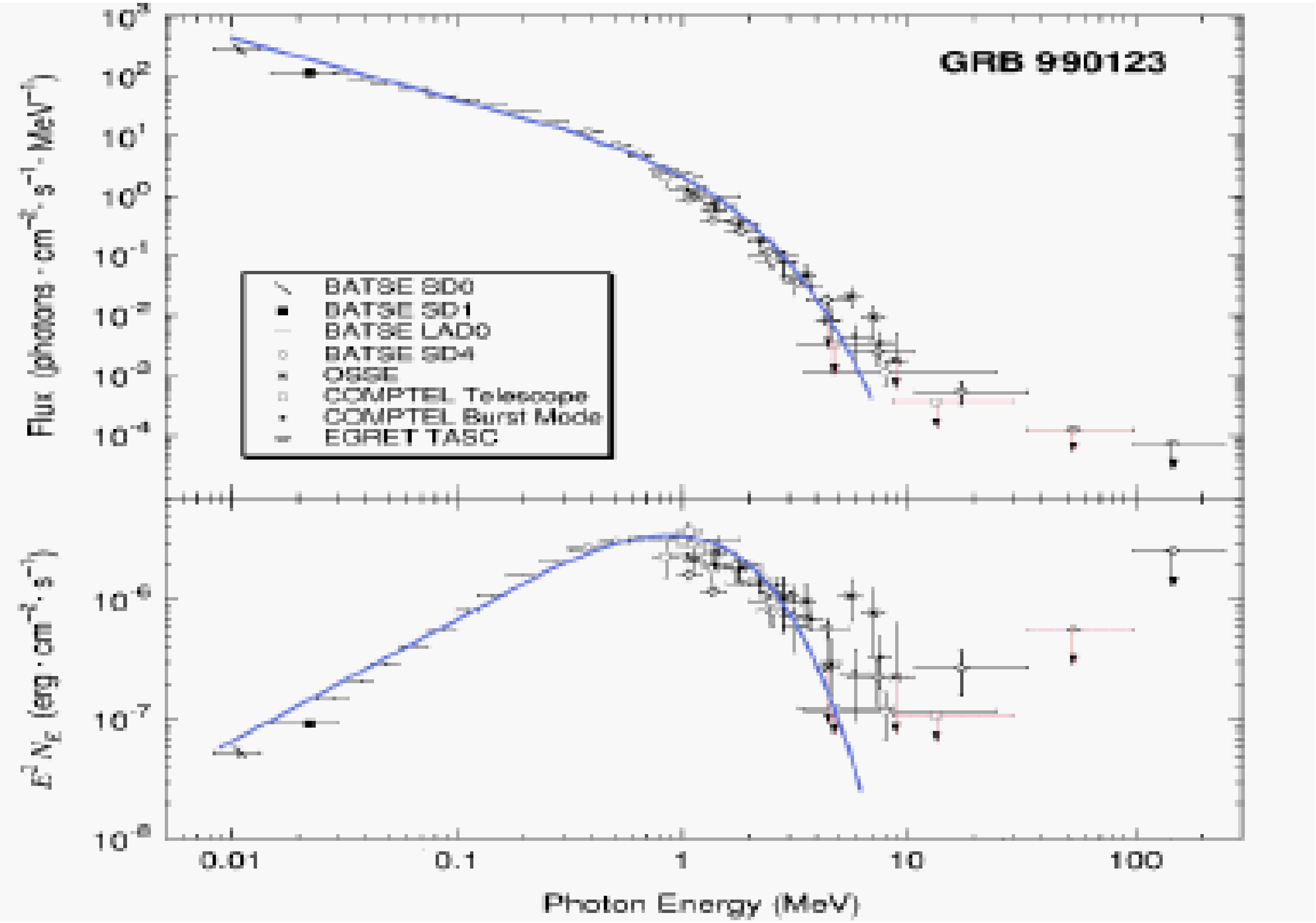
Spectral shape





Spatial distribution

BATSE (1991-2000)



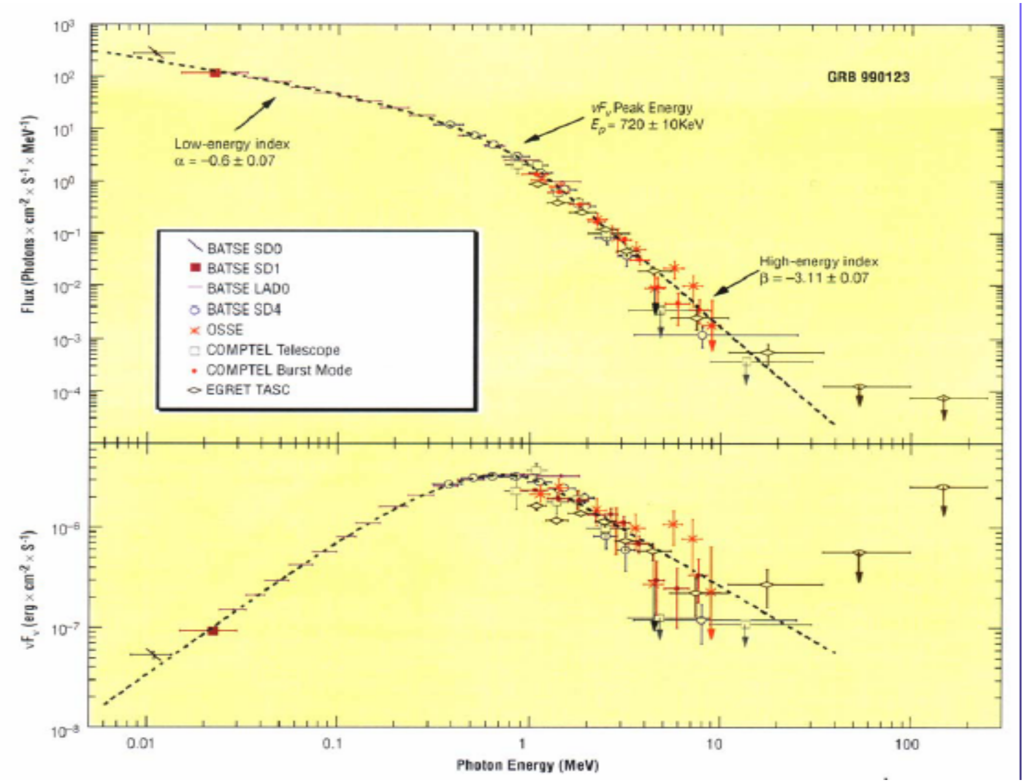
The Ep,i – Eiso correlation

- spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy

- $E_p = E_0 \times (2 + \alpha)$ = peak energy of the $\nu F\nu$ spectrum

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \qquad (\alpha-\beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \qquad (\alpha-\beta)E_0 \leq E$$

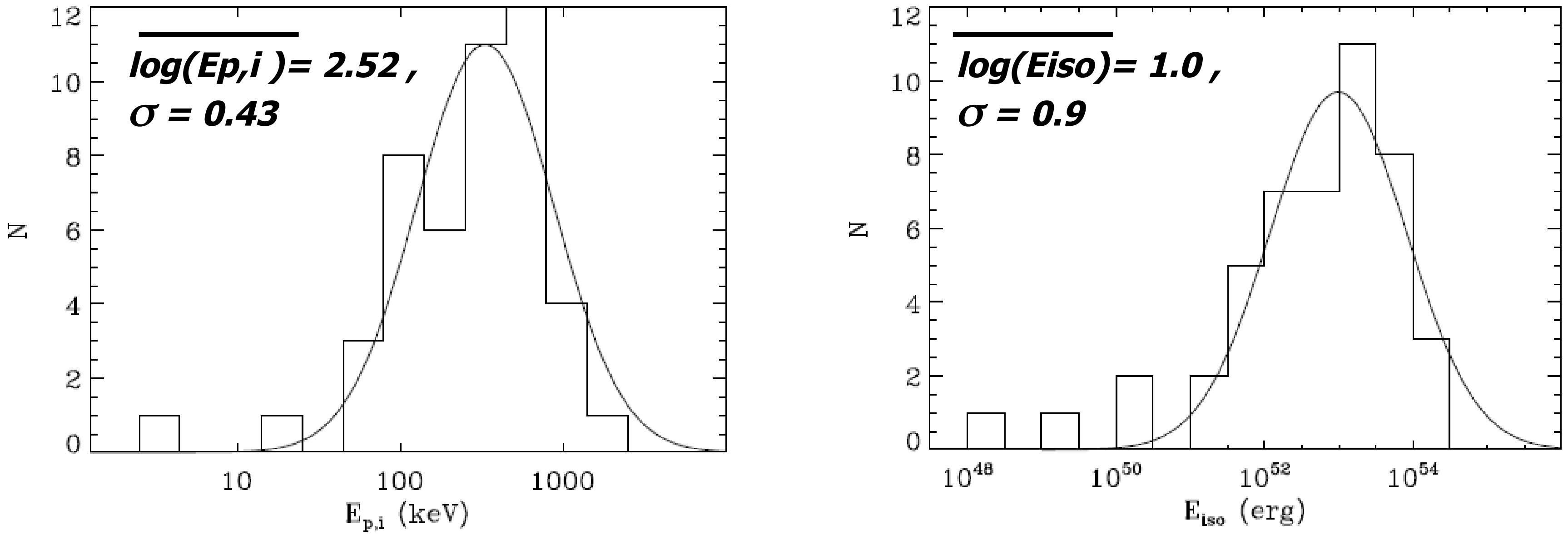


- all GRBs with measured redshift lie at cosmological distances (z = 0.033 – 6.3) (except for the peculiar GRB980425, z=0.0085)

- **from distance, fluence and spectrum, it is possible to estimate the cosmologica-rest farme peak energy Ep,i and the radiated energy assuming isotropic emission, Eiso**

$$E_{p,i} = E_p \times (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \mathrm{erg}$$

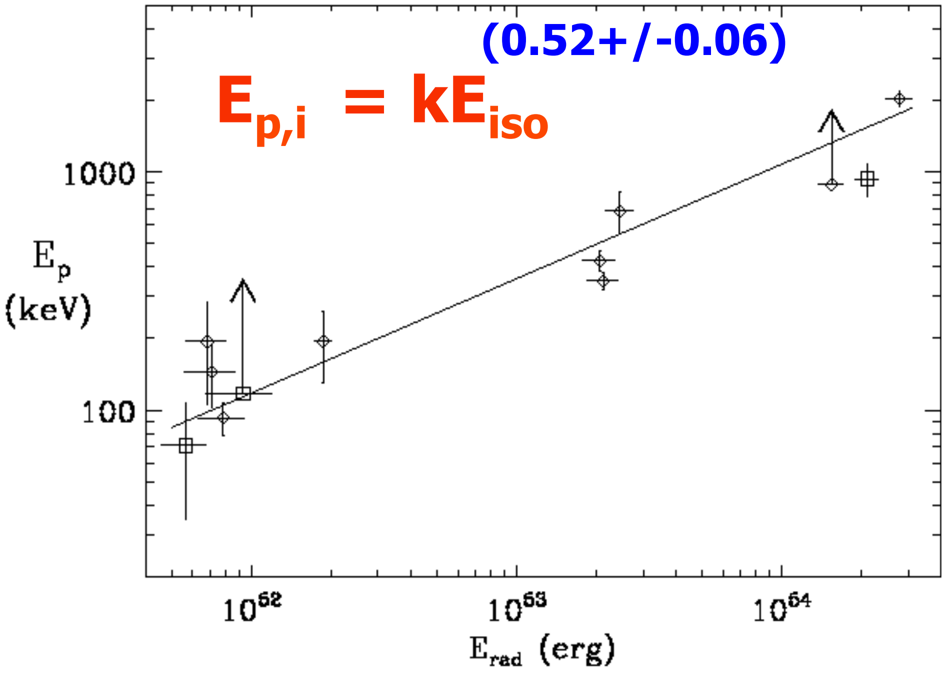


Ep,i and Eiso distributions for a sample of 41 long GRBs (Amati 2006)

The Ep,i – Eiso correlation

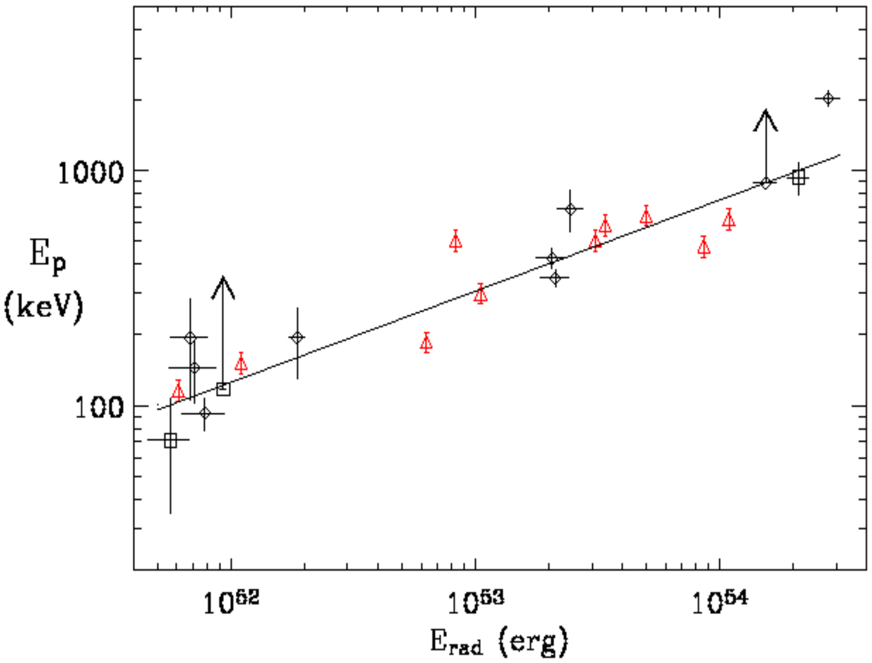
➢ Amati et al. (2002) analyzed a sample of 12 BeppoSAX events with known redshif found evidence of a strong correlation between Ep,i and Eiso , highly significant (ρ = 0.949, chance prob. 0.005%)

➢ by adding data from BATSE and HETE-2 of 10 more GRBs the correlation was confirmed and its significance increased



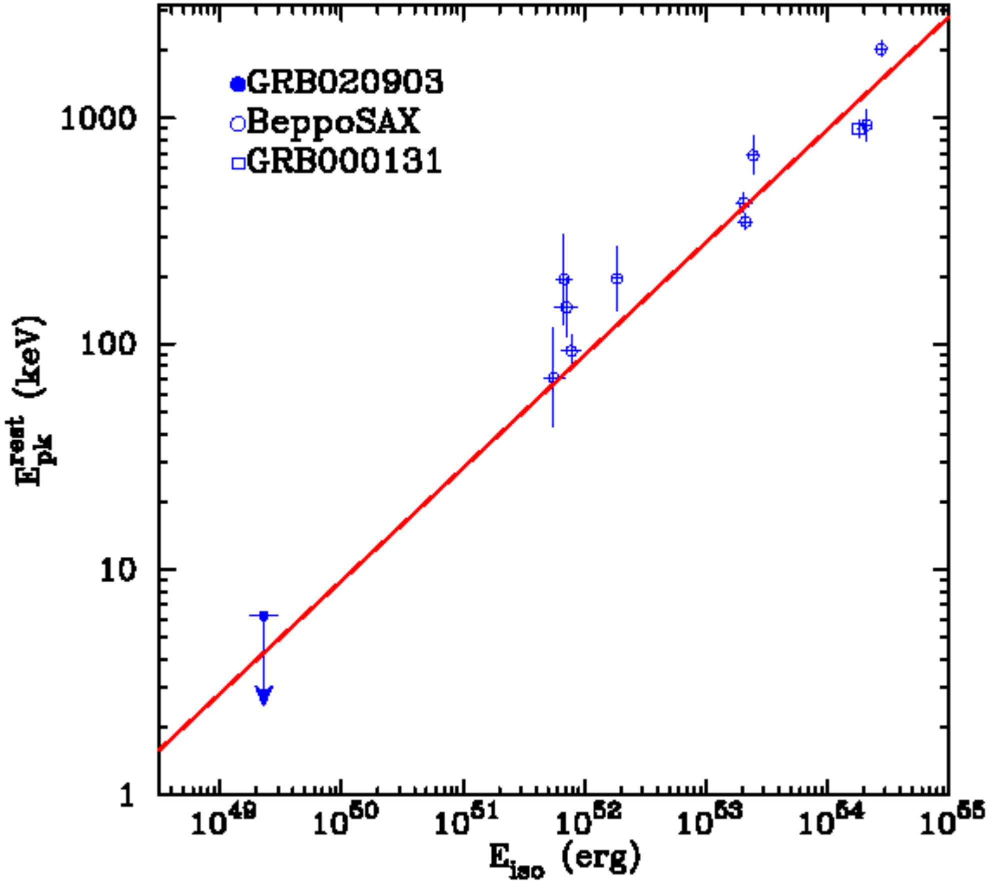
$E_{p,i} = kE_{iso}^{(0.52+/-0.06)}$

Amati et al. , A&A, 2002



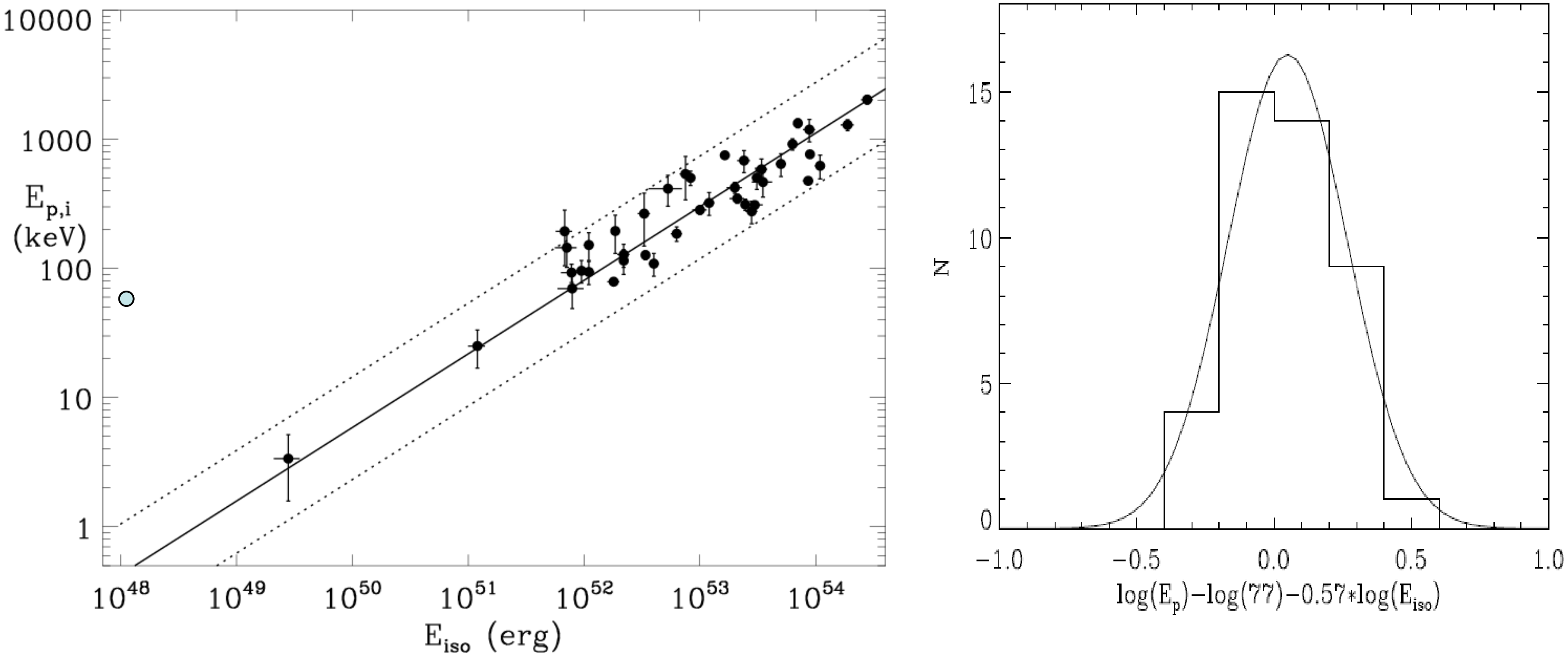
Amati, ChJAA, 2003

Peak Energy – Isotropic Energy



Sakamoto et al. (2003)

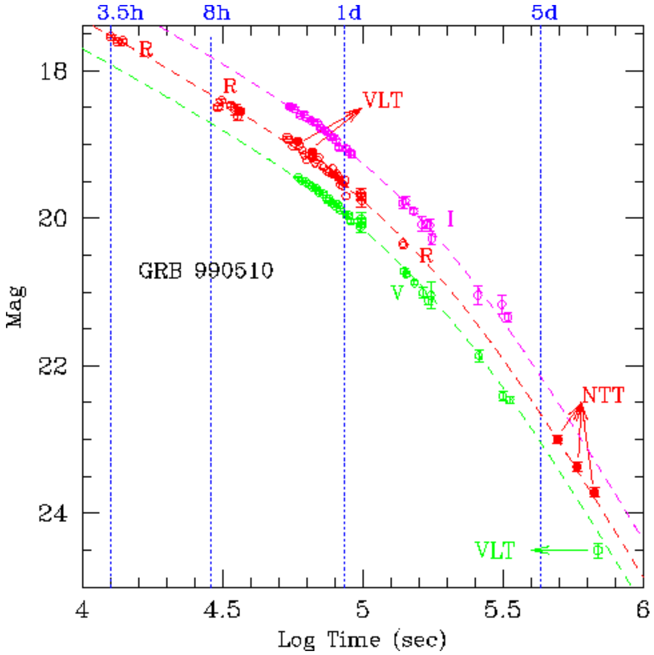
- analysis of the most updated sample of *long* GRBs/XRFs with firm estimates of z and Ep,i (41 events) gives a chance probability for the Ep,i-Eiso correlation of ~10^{-15} and a slope of 0.57+/-0.02
- the scatter of the data around the best fit power-law can be fitted with a Gaussian with σ(logEp,i) ~ 0.2 (~0.15 extra-poissonian)
- only firm outlier the local peculiar GRB 980425



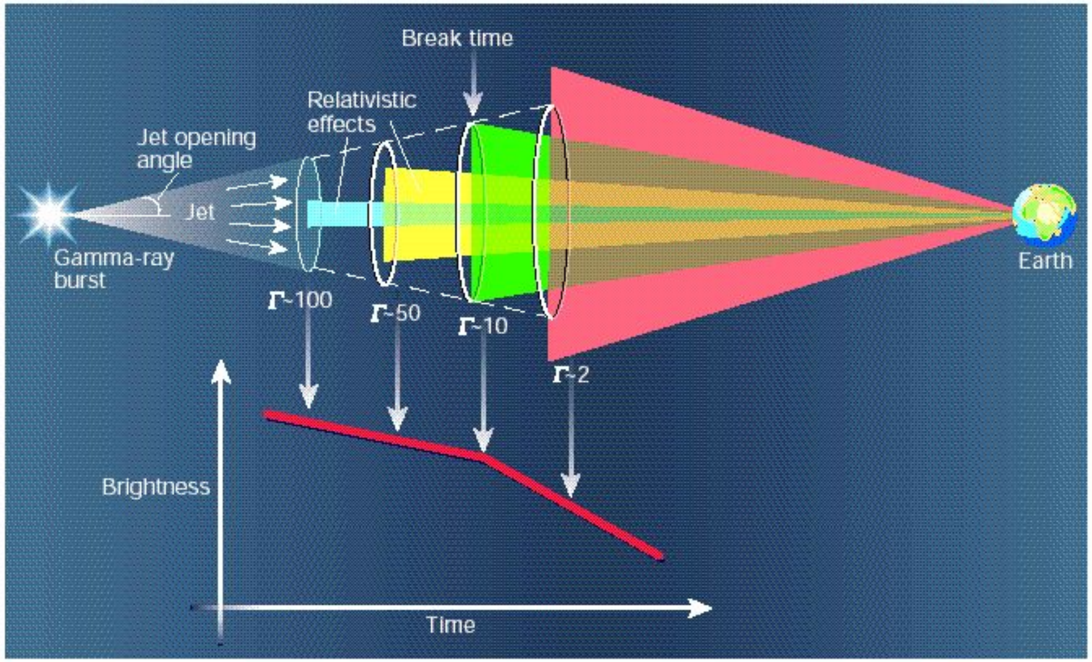
Updated from Amati, MNRAS, 2006

Afterglow Observations

Harrison et al (1999)

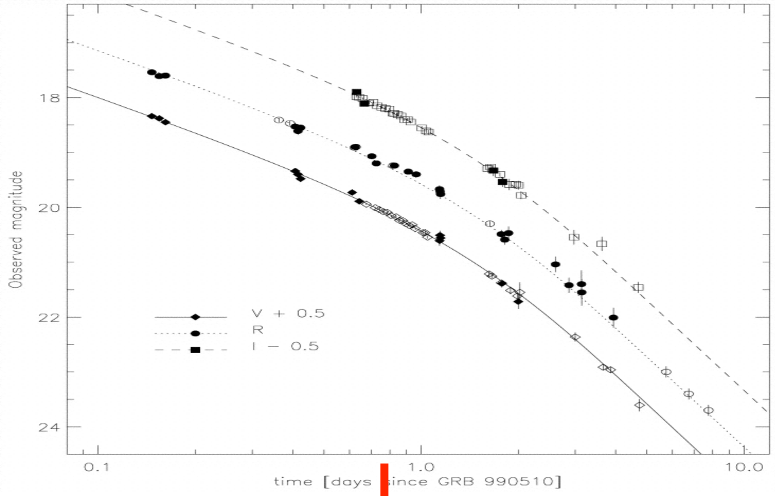


Achromatic Break



Woosley (2001)

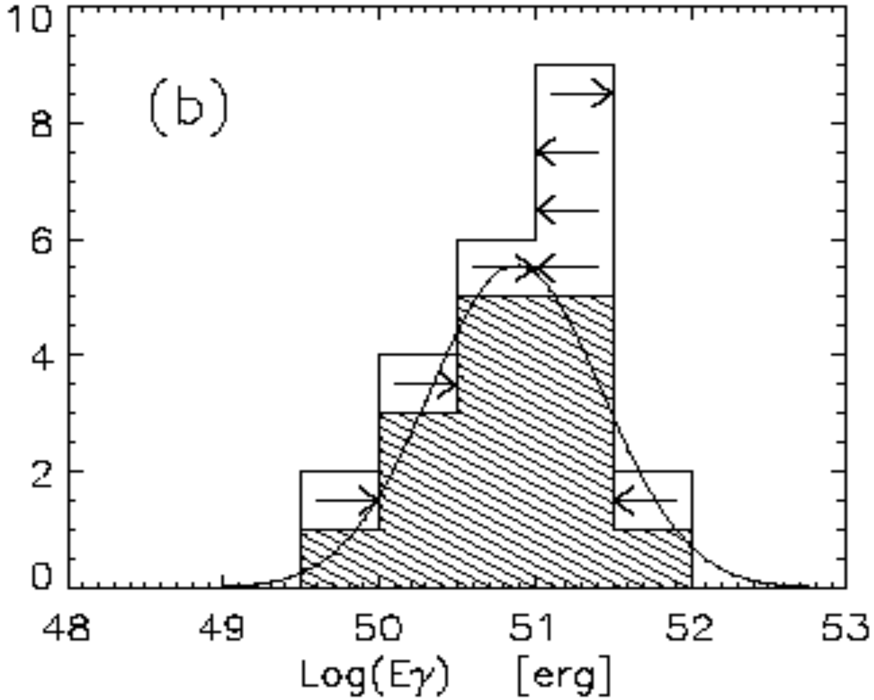
Cosmology with spectrum-energy correlation



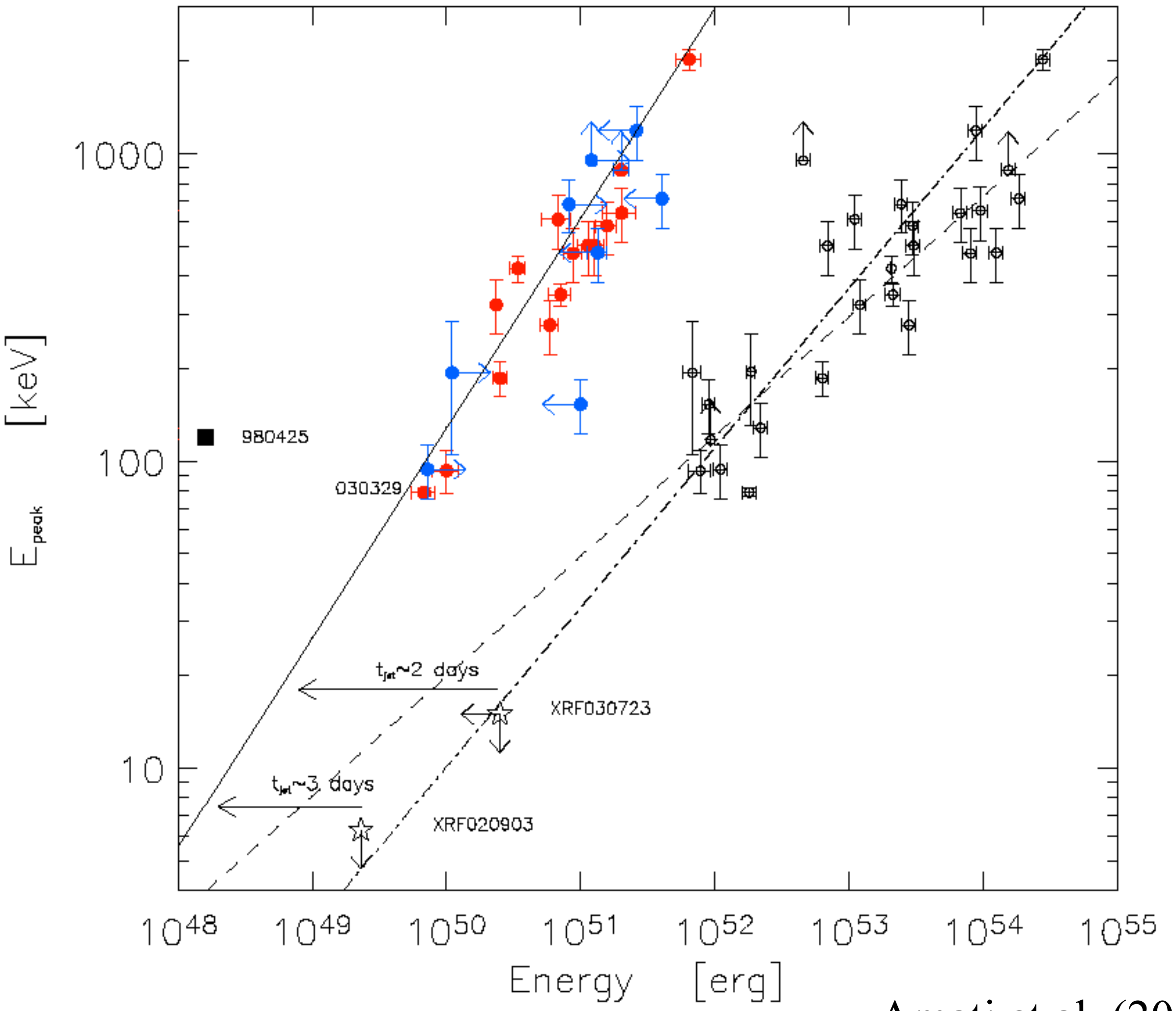
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$

- ➢ breaks in the afterglow decay light curves -> collimation ?

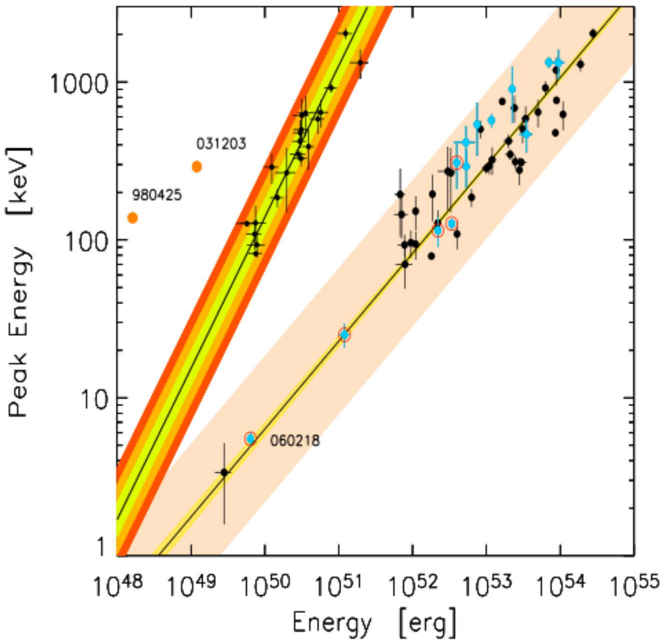


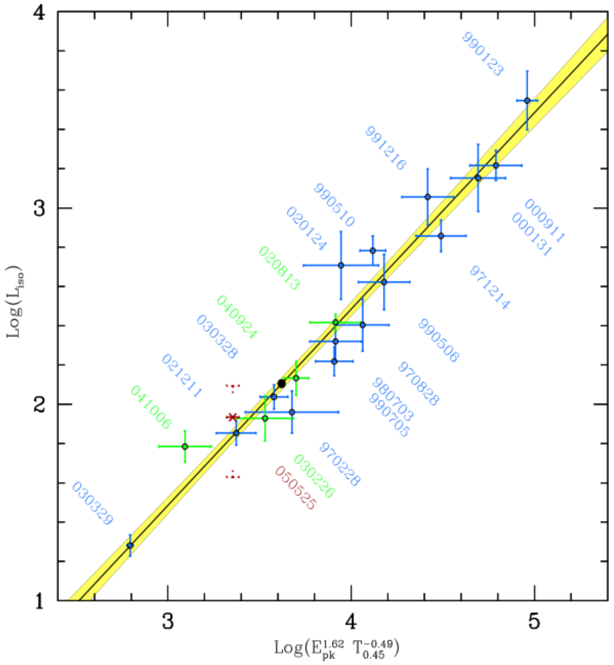
GRB for Cosmology



Amati et al. (2002)
Ghirlanda et al. (2004)

The “Relationships”

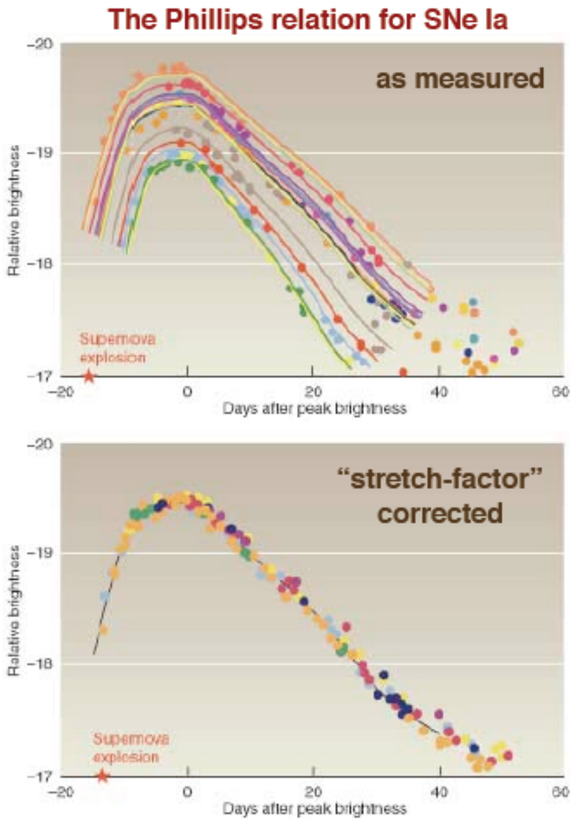


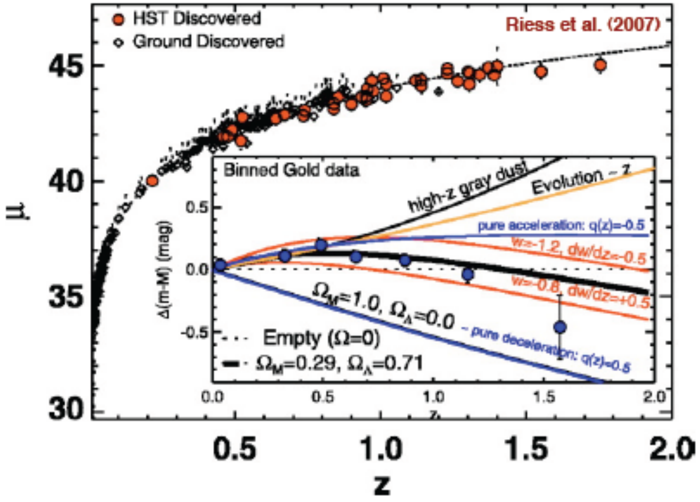


- Amati (et al. 2002): E_{peak}-E_{iso} (E_{peak}, redshift)
- Ghirlanda (et al. 2004): E_{peak}-E_{gamma} (Epeak, redshift, Tbreak)
- Firmani (et al. 2006): bring T_{45} into Epeak and Eiso.
- Fenimore & Ramirez-Ruiz (2000): E_{iso} - variability in Gamma-rays
- Norris (et al. 2000): lag-luminosity relation. Short lag = luminous.
  - (Lags measured in observer frame i.e. not z-corrected)
- Use these relationships to infer a pseudo-redshift from a measurement of spectral parameters or lags and luminosities in observer frame.... many more bursts without measured z than with.
  - =>GRB as cosmological probe

SN Ia Cosmology

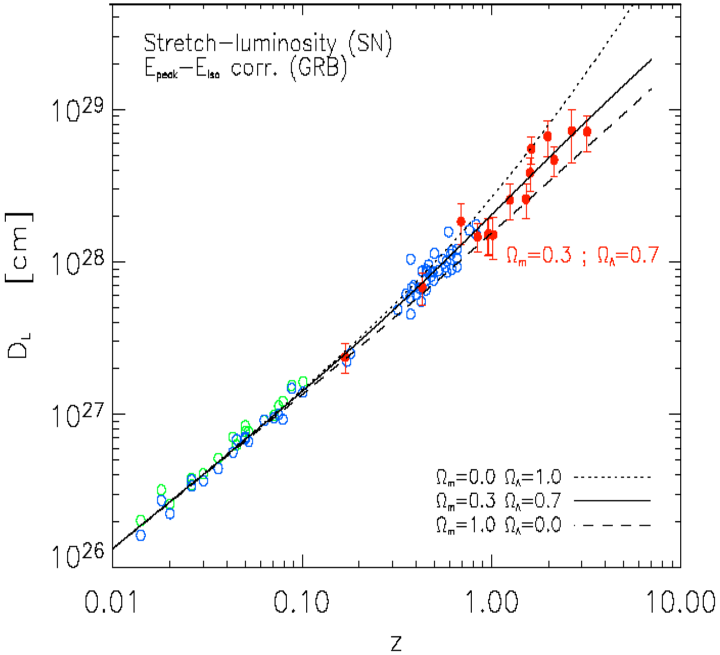
SNe Ia as a “standard candle”


The Phillips relation for SNe Ia

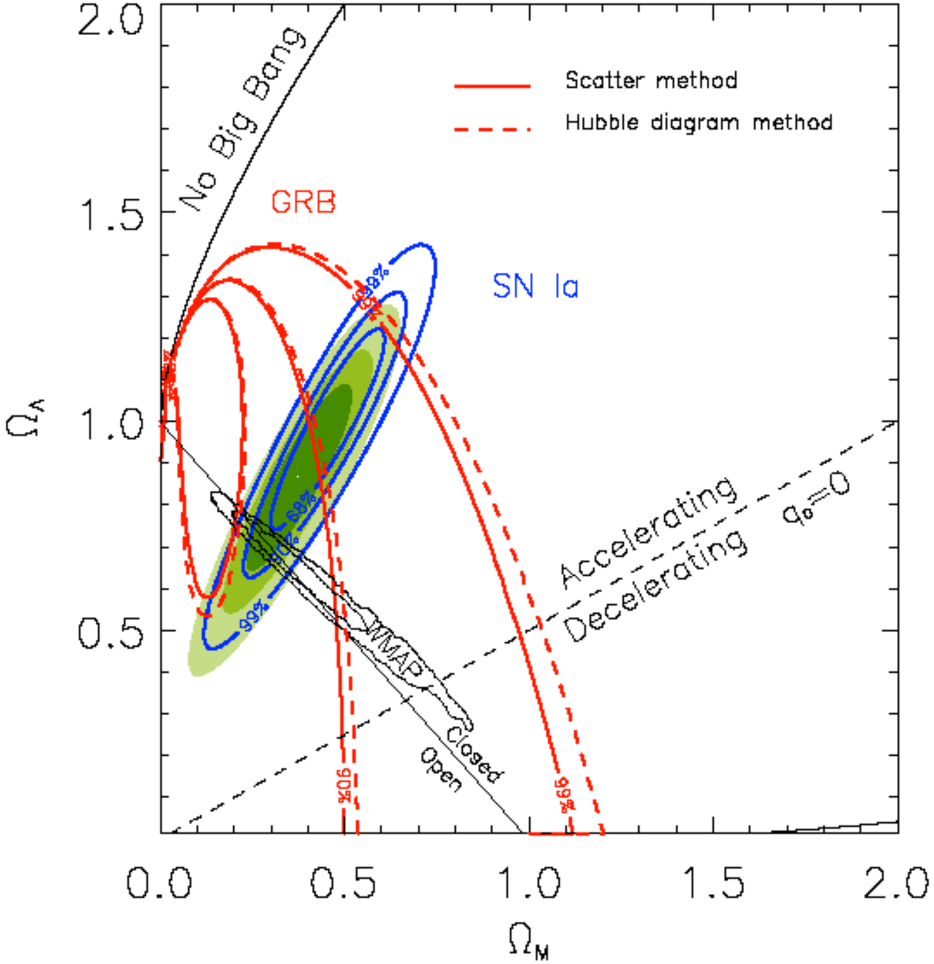

Riess et al. (2007)

Can we apply GRBs as a standardized candle?

GRB for Cosmology



Ghirlanda et al. (2004)

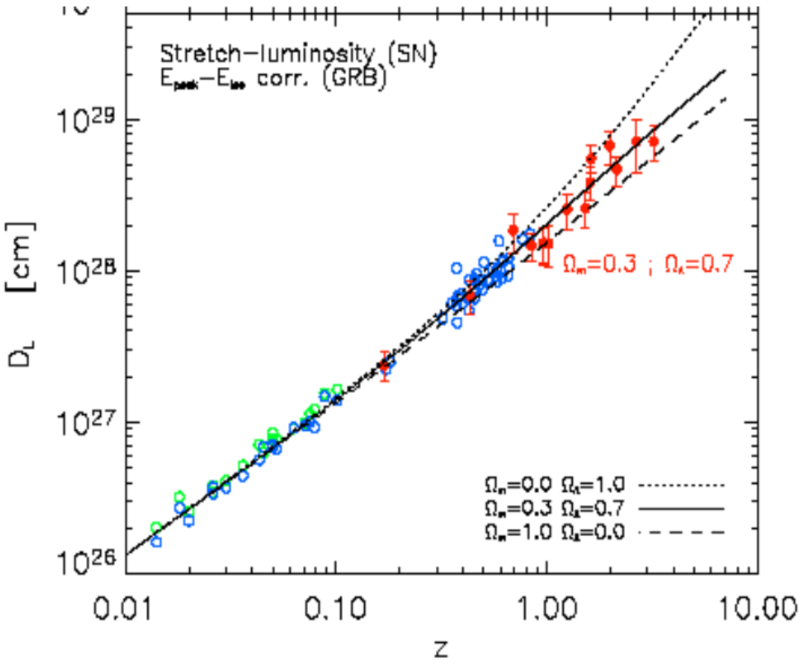


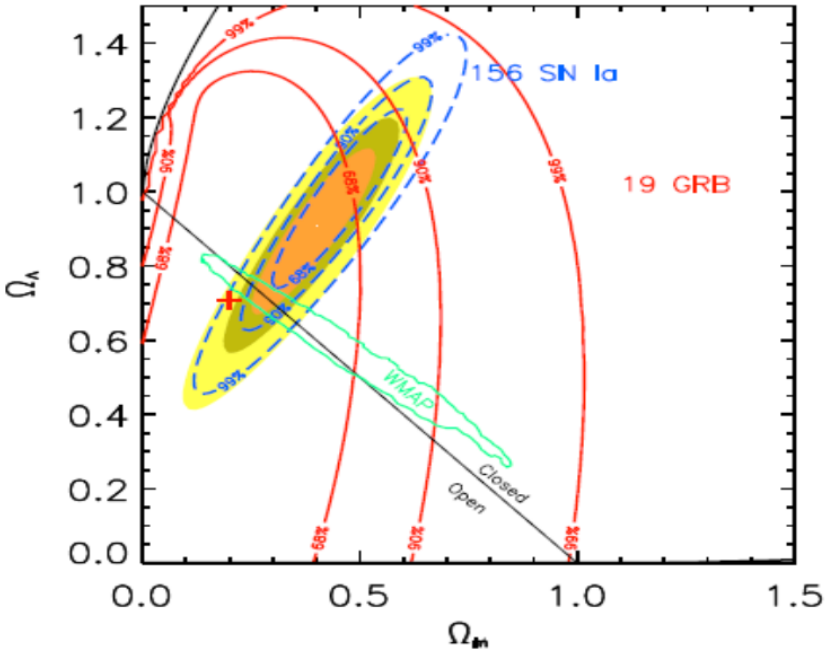
❑ **Method** (e.g., Ghirlanda et al, Firmani et al., Dai et al., Zhang et al.):

$$E_{p,i} = E_{p,obs} \times (1 + z) \ , \ t_{b,i} = t_b / (1 + z)$$

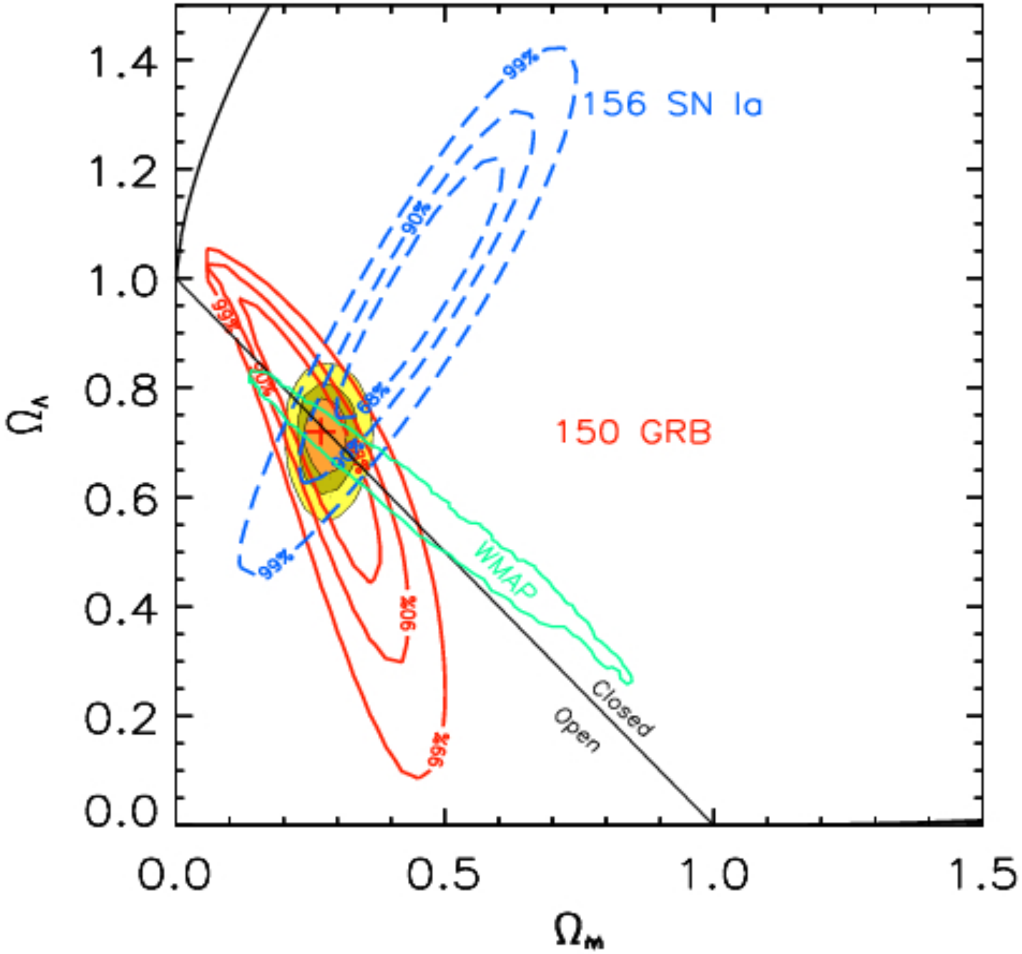
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg} \longrightarrow D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$

- ➢ fit the correlation and construct an Hubble diagram for each set of cosmological parameters -> derive c.l. contours based on chi-square





- ☐ results obtainable with 150 GRBs with estimates of z, $E_{p,i}$ and tb



Ghirlanda et al. 2006 A&A

Ghirlanda et al. 2006 JOP Review, GRB Special Issue

Caveats

GRBs as a standard candle?

Caveats:

- lack of a low-z calibration sample
- $E_{\mathrm{peak}} \in$ [10 keV, 1MeV], not always well constrained
- Θ_{jet} is model dependent

For a homogeneous circumburst medium (Sari et al. 1999)

$$\theta_{\rm jet} = 0.161 \left(\frac{t_{\rm jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\rm iso,52}}\right)^{1/8}$$

For a wind profile from massive stars (Nava et al. 2006)

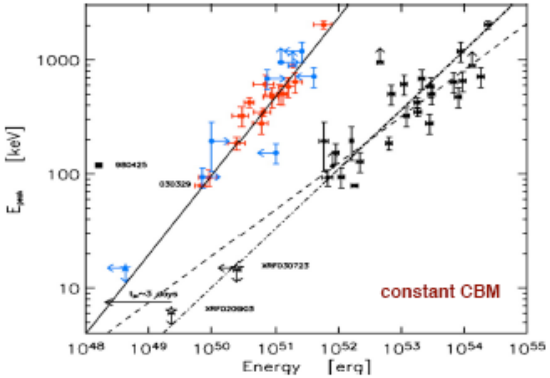
$$n(r) = A/r^2$$

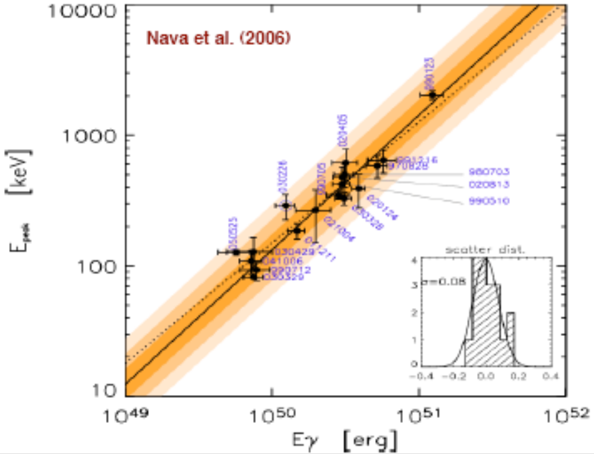
$$\theta_{\rm jet} = 0.206 \left(\frac{t_{\rm jet,d}}{1+z}\right)^{1/4} \left(\frac{A_*\,\eta_\gamma}{E_{\rm iso,52}}\right)^{1/4}$$

$$A = \dot{M}_{\rm w}/(4\pi v_{\rm w}) = 5\times10^{11}\,A_*\ {\rm g\,cm^{-1}}$$

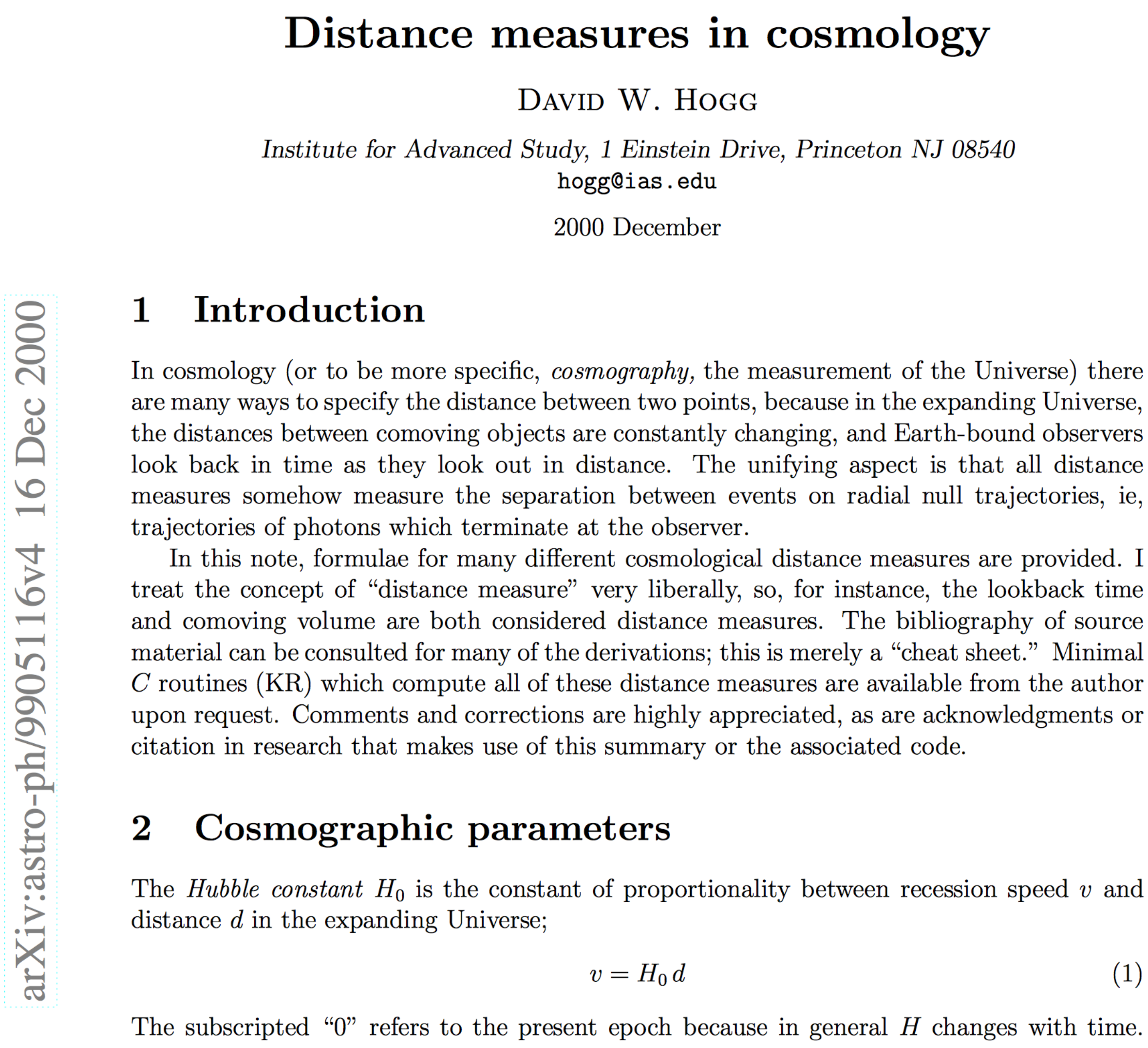
- uncertain jet break time and CBM density

The Ghirlanda E_p - E_γ relation (2004)





Luminosity distance



Distance measures in cosmology

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2000 December

1 Introduction

In cosmology (or to be more specific, *cosmography,* the measurement of the Universe) there are many ways to specify the distance between two points, because in the expanding Universe, the distances between comoving objects are constantly changing, and Earth-bound observers look back in time as they look out in distance. The unifying aspect is that all distance measures somehow measure the separation between events on radial null trajectories, ie, trajectories of photons which terminate at the observer.

In this note, formulae for many different cosmological distance measures are provided. I treat the concept of "distance measure" very liberally, so, for instance, the lookback time and comoving volume are both considered distance measures. The bibliography of source material can be consulted for many of the derivations; this is merely a "cheat sheet." Minimal *C* routines (KR) which compute all of these distance measures are available from the author upon request. Comments and corrections are highly appreciated, as are acknowledgments or citation in research that makes use of this summary or the associated code.

2 Cosmographic parameters

The *Hubble constant* H_0 is the constant of proportionality between recession speed v and distance d in the expanding Universe;

$$v = H_0\, d \qquad (1)$$

The subscripted "0" refers to the present epoch because in general H changes with time.

The Luminosity Distance

$$\Omega_{\mathrm{M}} + \Omega_{\Lambda} + \Omega_k = 1 \qquad\qquad z \equiv \frac{\nu_{\mathrm{e}}}{\nu_{\mathrm{o}}} - 1 = \frac{\lambda_{\mathrm{o}}}{\lambda_{\mathrm{e}}} - 1$$

$$E(z) \equiv \sqrt{\Omega_{\mathrm{M}}\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_{\Lambda}}$$

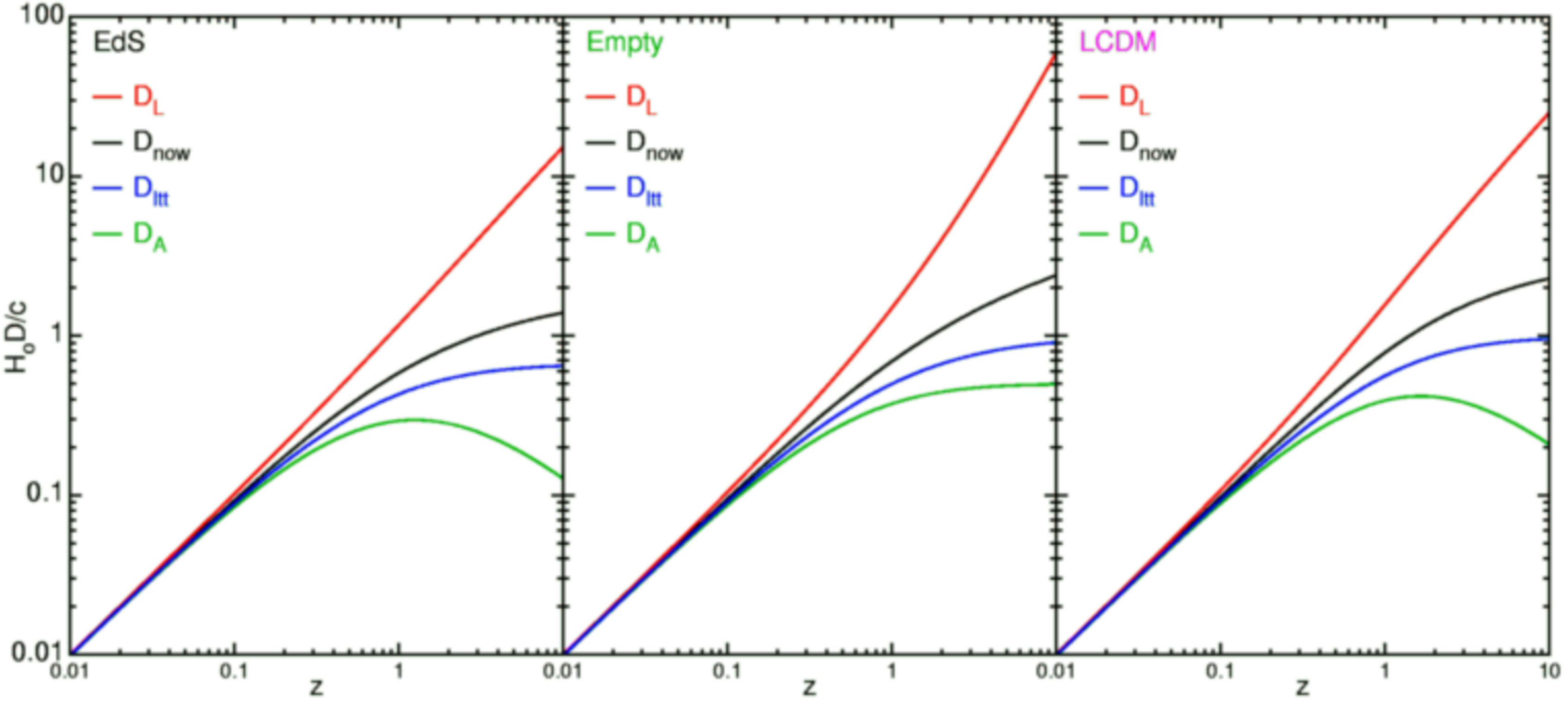
$$H_0 = 100\,h\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \qquad D_{\mathrm{H}} \equiv \frac{c}{H_0} \qquad D_{\mathrm{C}} = D_{\mathrm{H}} \int_0^z \frac{dz'}{E(z')}$$

$$D_{\mathrm{M}} = \begin{cases} D_{\mathrm{H}}\,\frac{1}{\sqrt{\Omega_k}}\,\sinh\left[\sqrt{\Omega_k}\,D_{\mathrm{C}}/D_{\mathrm{H}}\right] & \text{for } \Omega_k > 0 \\ D_{\mathrm{C}} & \text{for } \Omega_k = 0 \\ D_{\mathrm{H}}\,\frac{1}{\sqrt{|\Omega_k|}}\,\sin\left[\sqrt{|\Omega_k|}\,D_{\mathrm{C}}/D_{\mathrm{H}}\right] & \text{for } \Omega_k < 0 \end{cases}$$

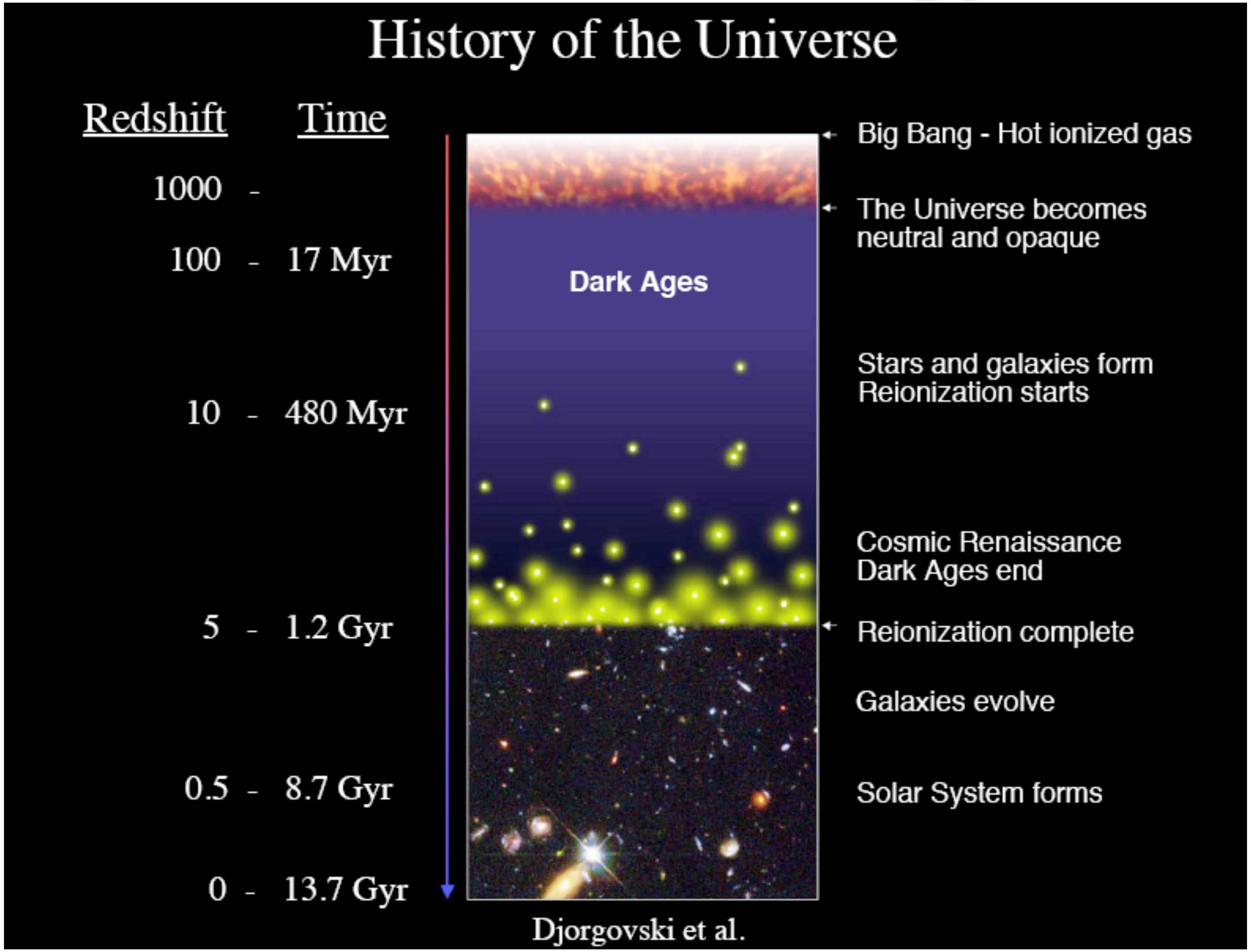
$$D_{\mathrm{L}} = (1+z)\,D_{\mathrm{M}}$$

astro-ph/9905116v4

Luminosity distance and redshift



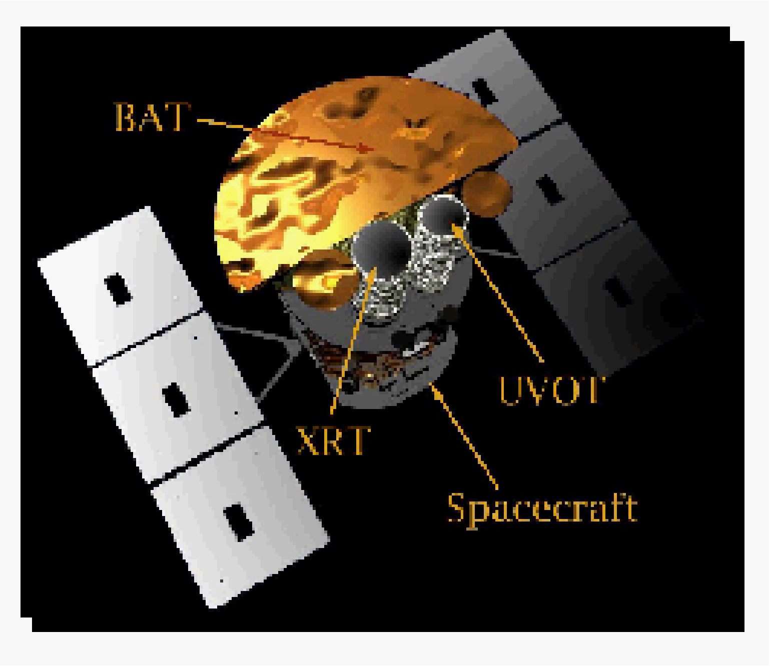
GRB & Cosmology



History of the Universe

Djorgovski et al.

SWIFT

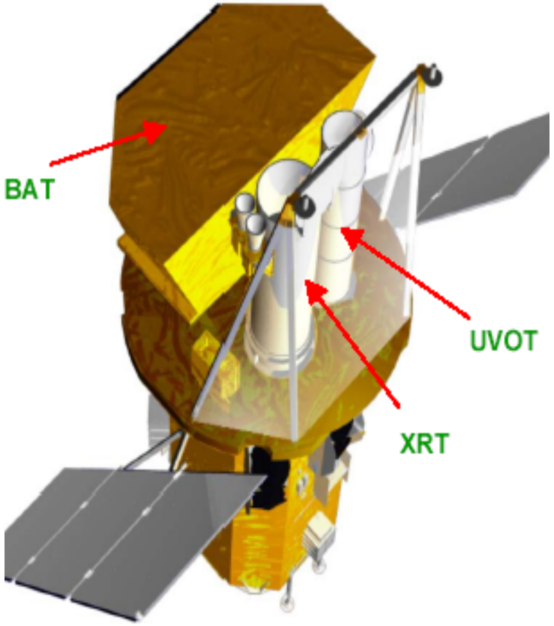


In orbita dal 2004

Adding pieces to the puzzle

- **Swift**: NASA mission dedicated to GRB studies launched 20 Nov. 2004 USA / Italy / UK consortium

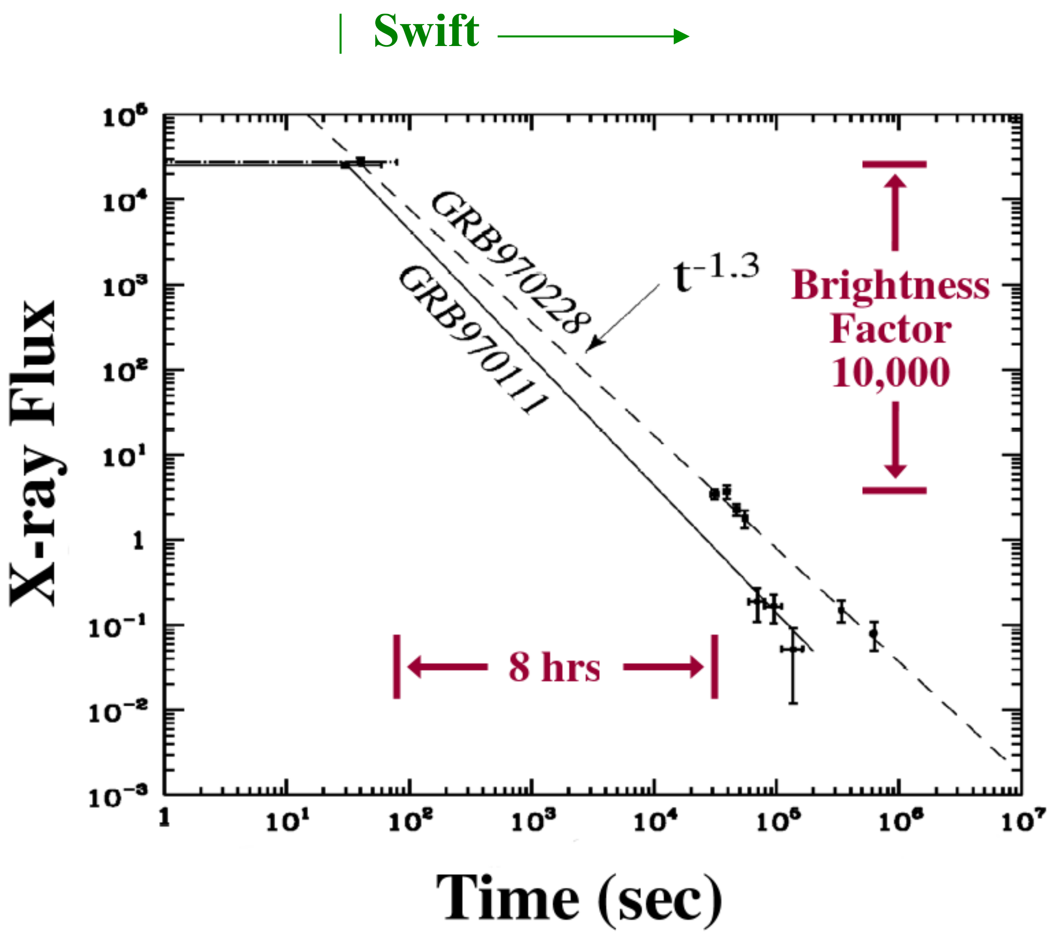
➢ main goals: afterglow onset, connection prompt-afterglow, substantially increase of counterparts detection at all wavelengths (and thus of redshift estimates)



➢ payload: BAT (CZT+coded mask, 15-350 keV, wide FOV, arcmin ang. res.), XRT (X-ray optics, 0.3-10 keV, arcsec ang.res.), UVOT (sub-arcsec ang.res. mag 24 in 1000 s)

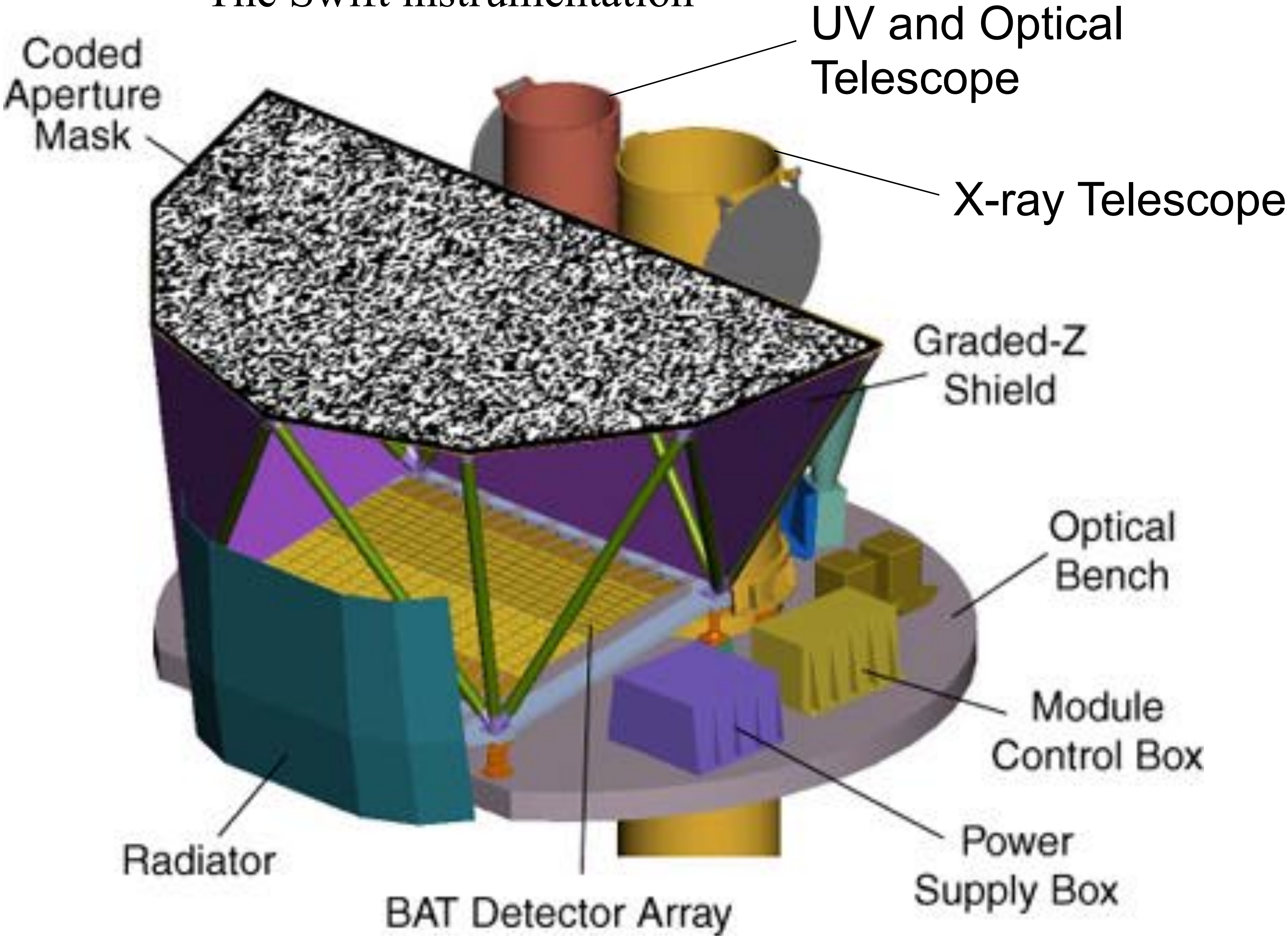
➢ spacecraft: automatic slew to target source in ~1 - 2 min.

Swift's purpose



Fill the data gap!

The Swift instrumentation



NASA

The Burst Alert Telescope (BAT)

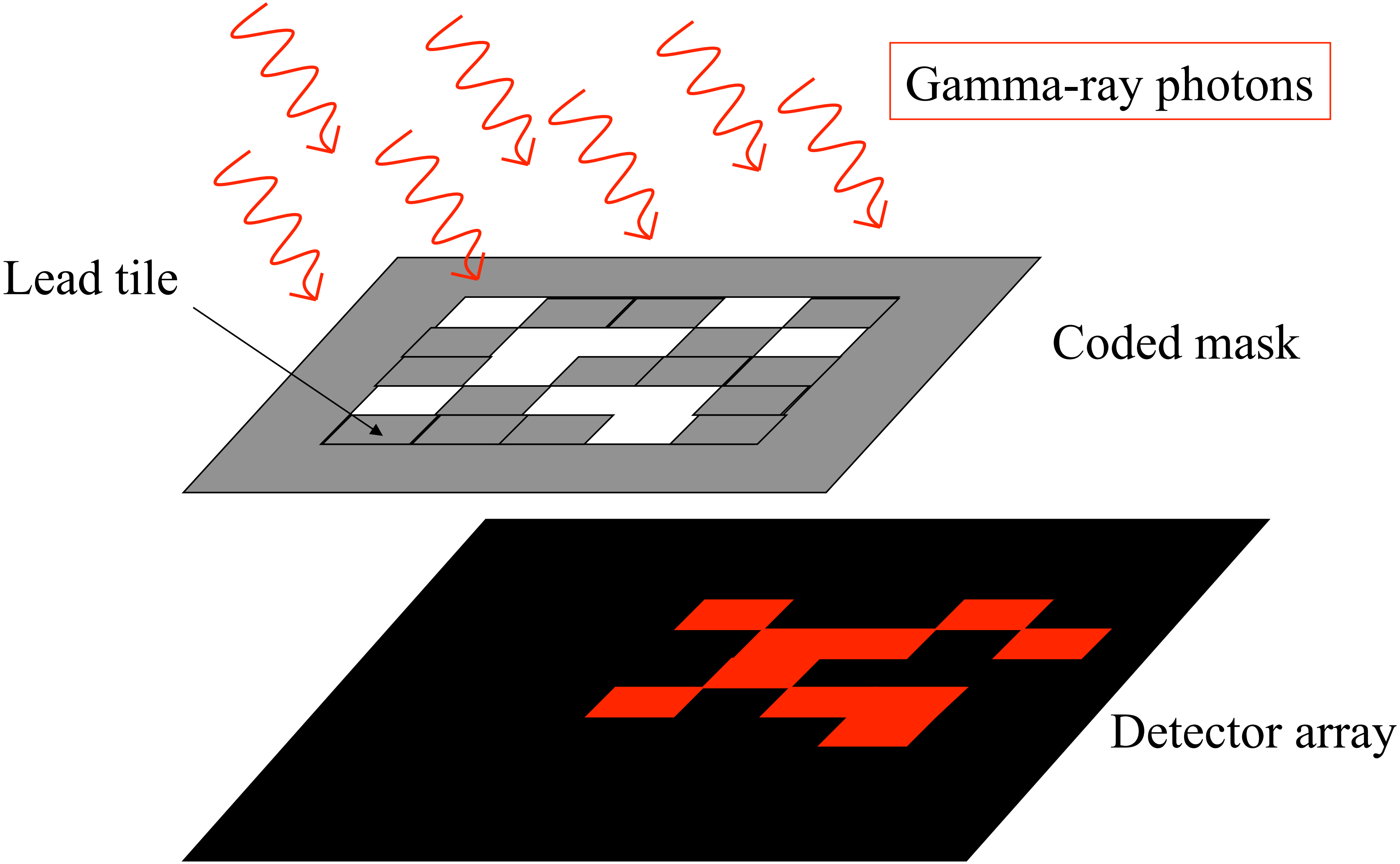
- Coded mask telescope; detector measures ‘shadow’ of random mask, which allows direction of incidence to be reconstructed.

- 1.4 Steradian field of view

- Measures GRB positions correct to 4 arcminutes

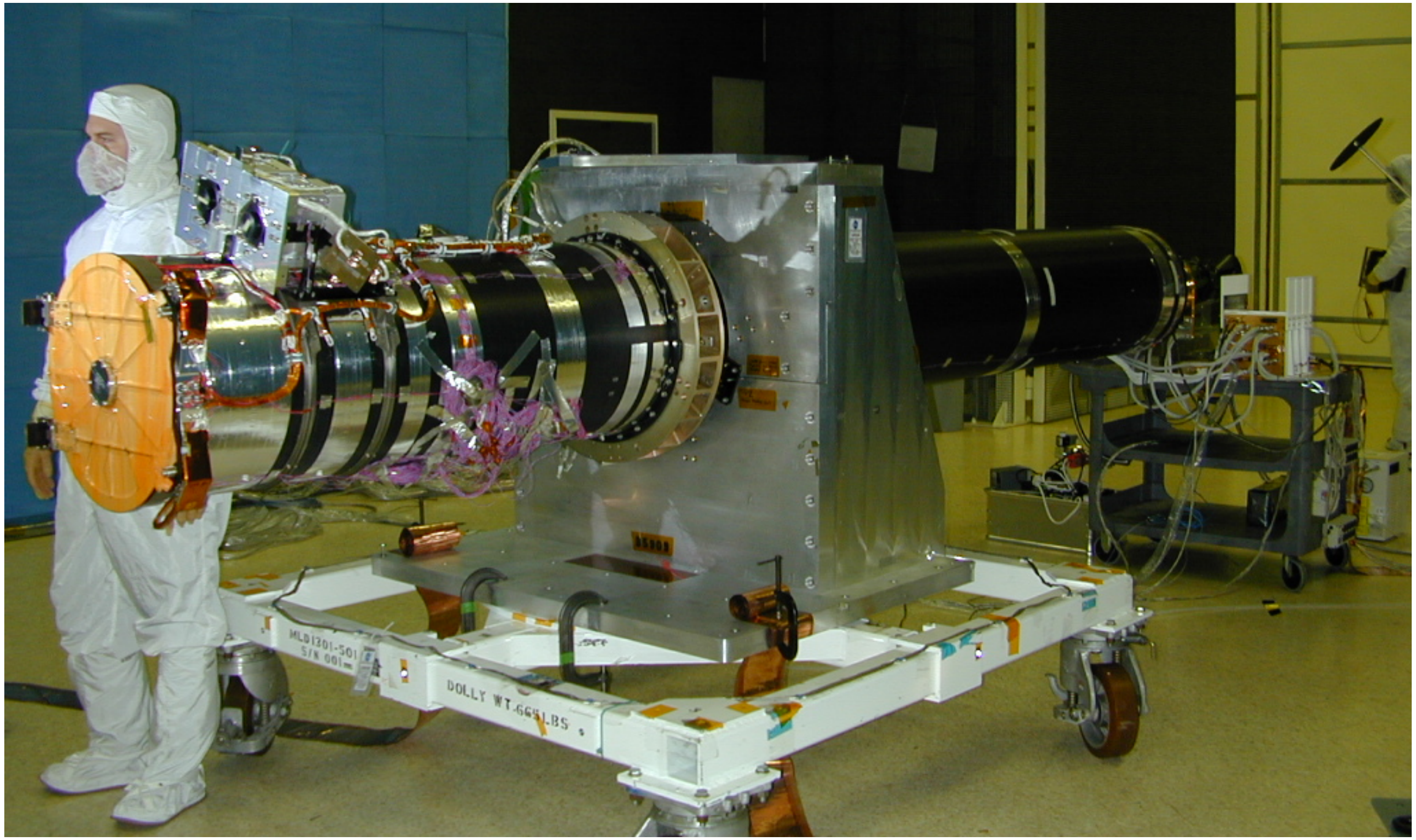
NASA

Coded mask telescopes



X-ray Telescope (XRT)

University of Leicester, Penn State University and
Osservatorio di Brera (Milan)

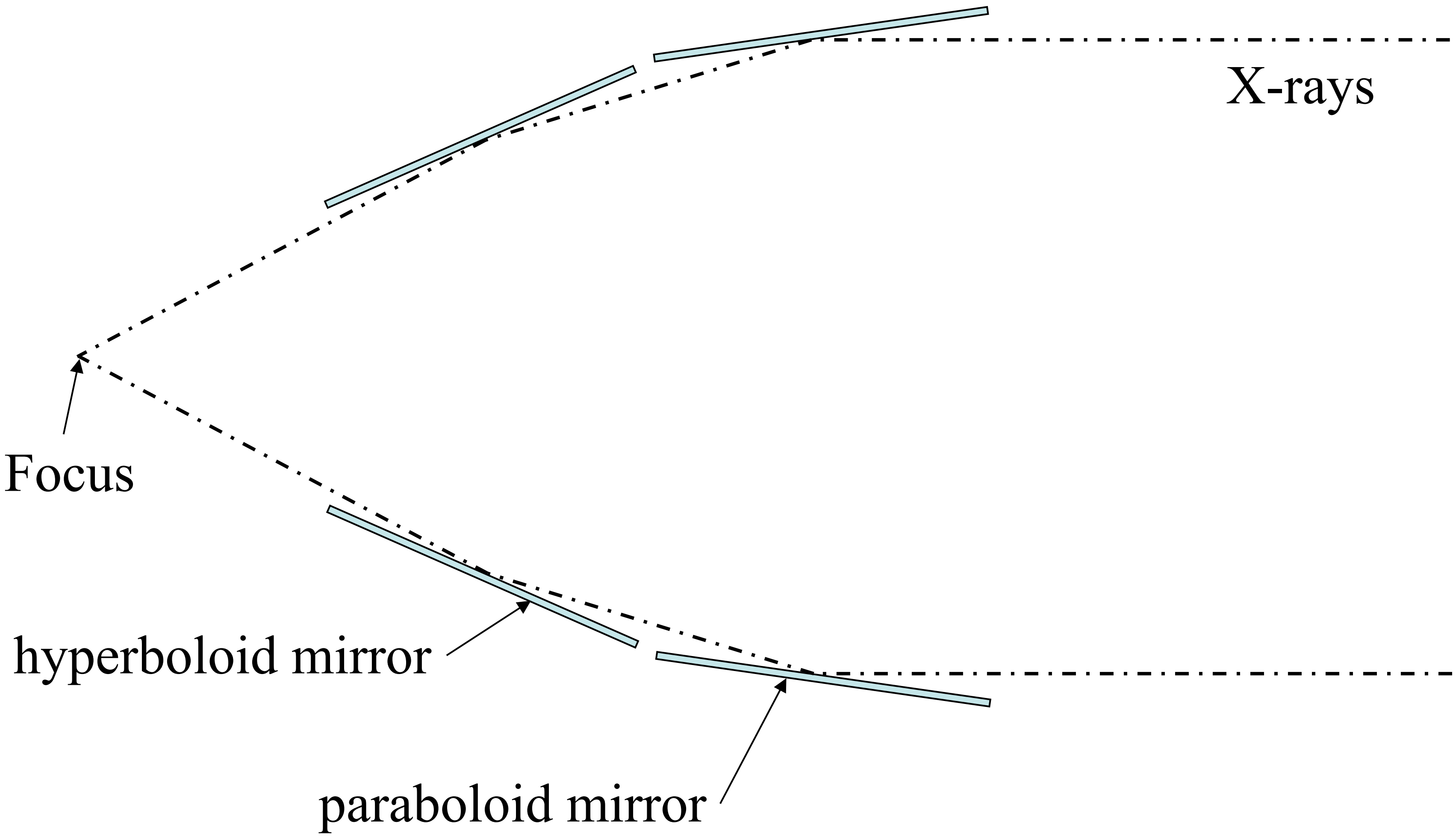


3.5 m Focal Length Telescope with cooled CCD imaging focal plane detector.

Detection of GRB X-ray afterglow, location and spectroscopy.

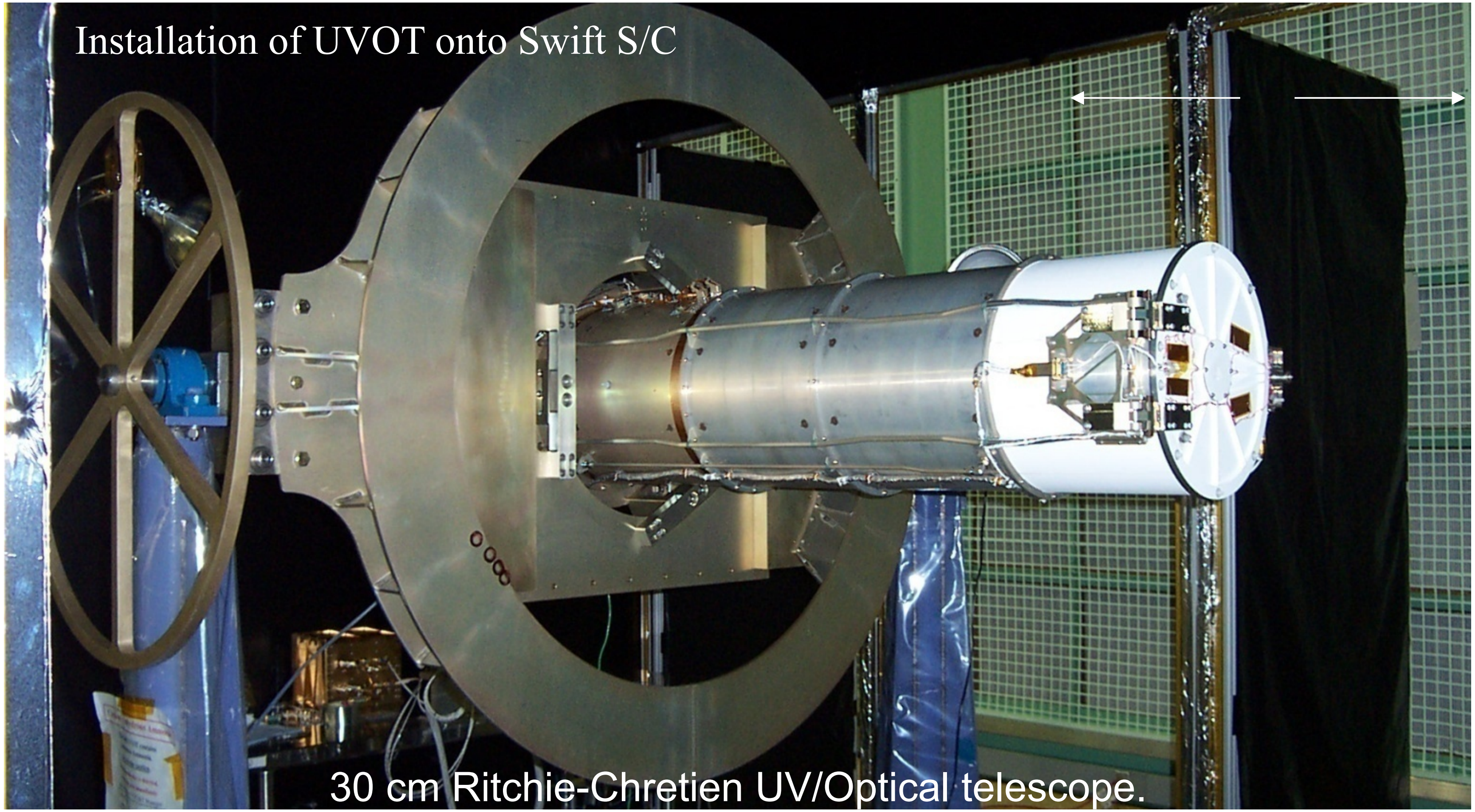
2.5 arc seconds Positional Accuracy. Energy range 0.2 – 10 keV

Cross-section of X-ray focussing optics



UV/Optical Telescope (UVOT)

Mullard Space Science Laboratory and Penn State University

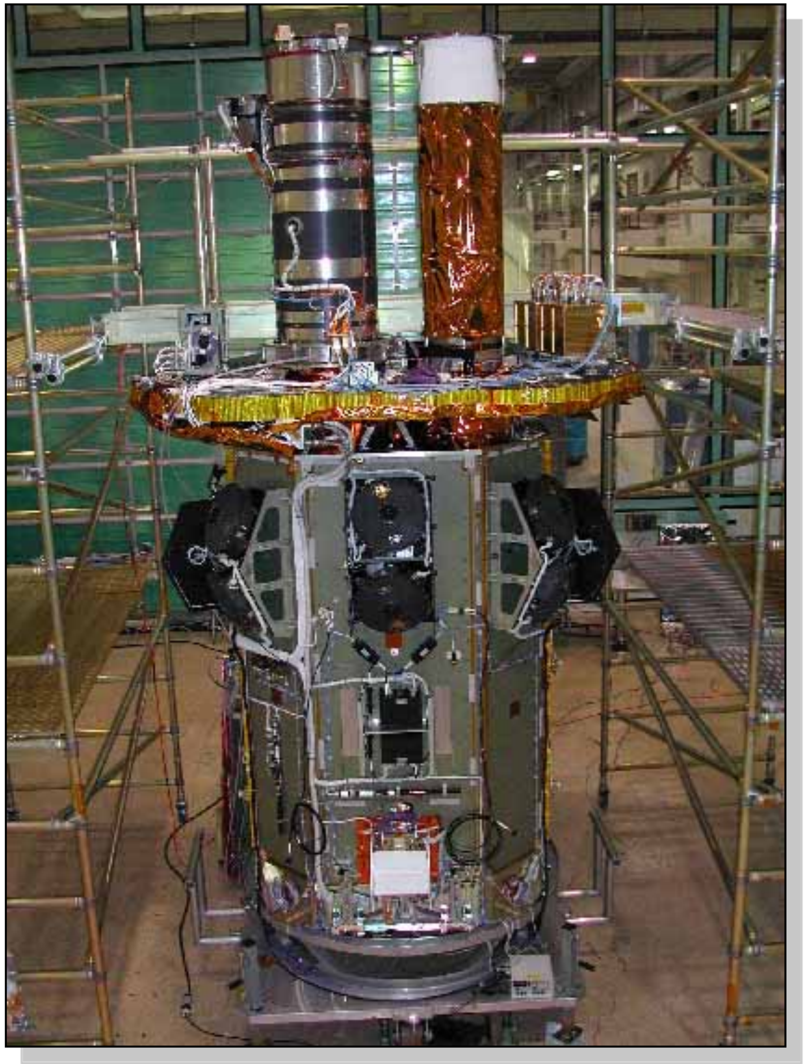


Installation of UVOT onto Swift S/C

30 cm Ritchie-Chretien UV/Optical telescope.

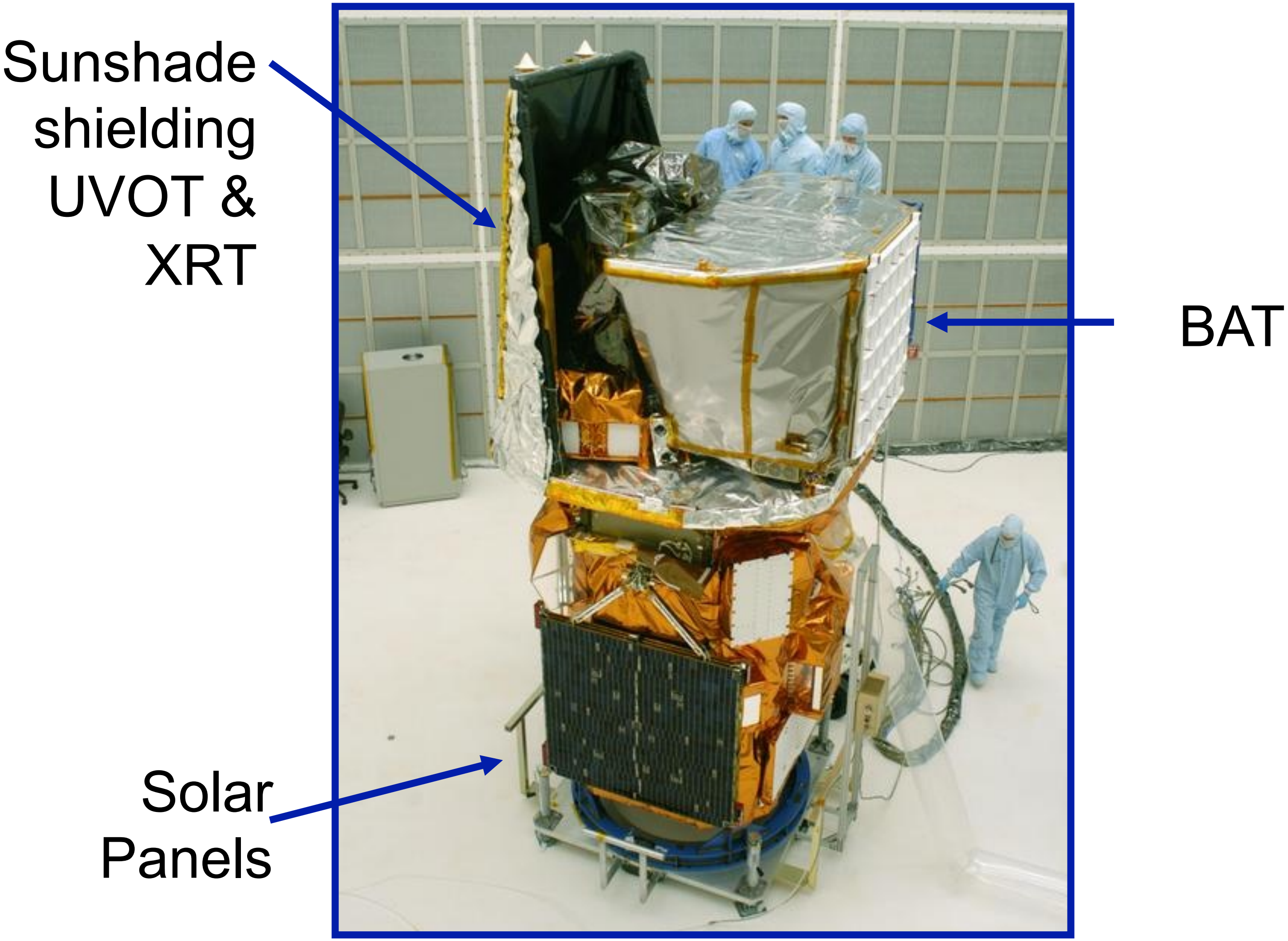
Detection of GRB optical afterglow. 0.3 arcsecond positional accuracy. Optical and UV filter photometry and grism spectroscopy.

Spacecraft with XRT & UVOT



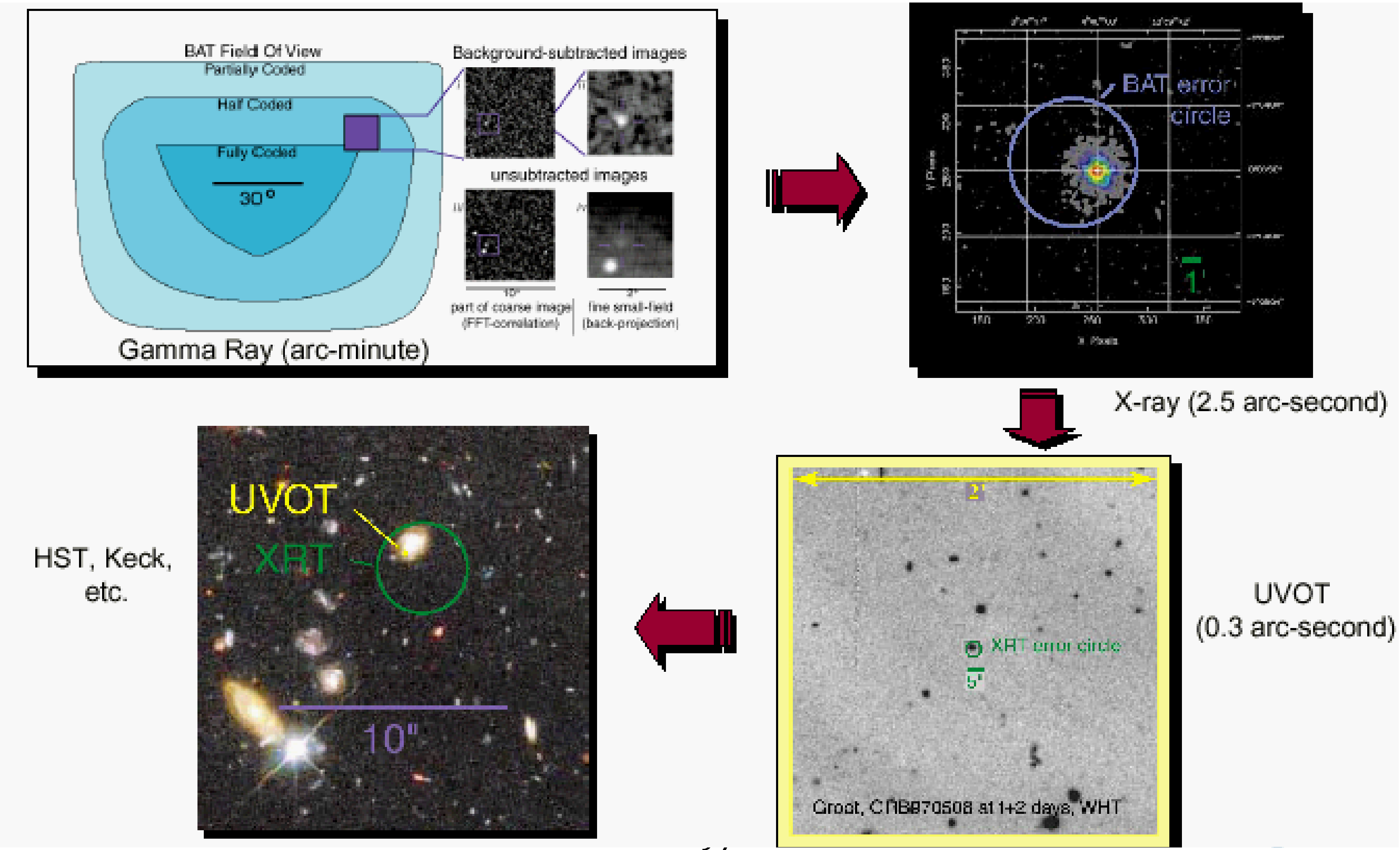
Swift Observatory in Goddard Clean Room

Swift at KSC



Swift launch 11/20/04

SWIFT



Gamma Ray (arc-minute)

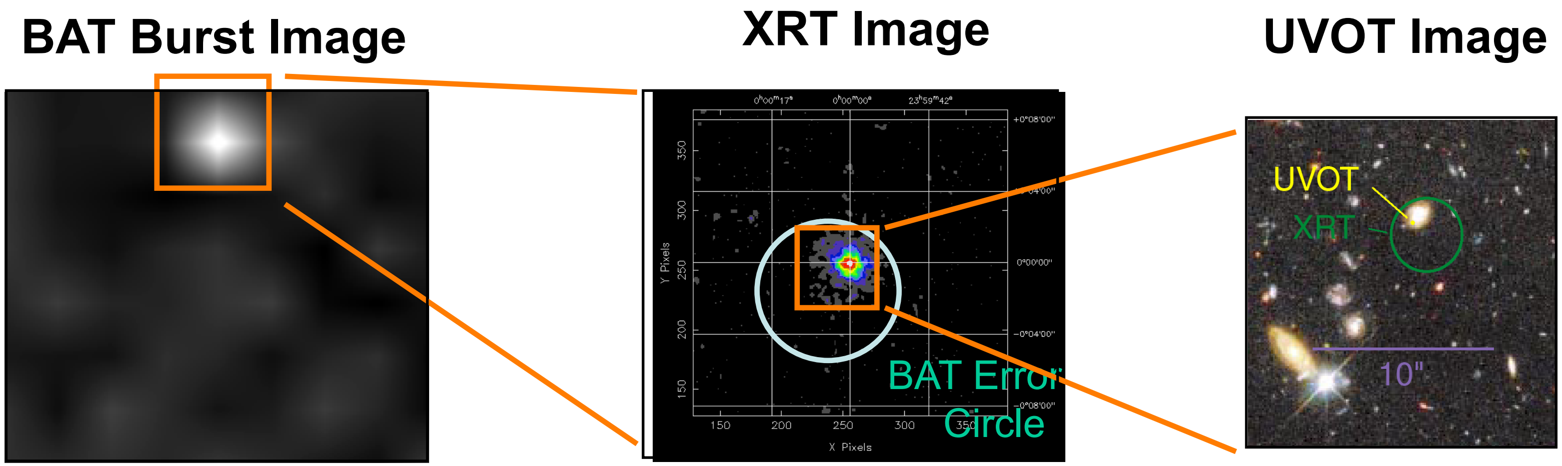
X-ray (2.5 arc-second)

UVOT
(0.3 arc-second)

HST, Keck,
etc.

Observing Strategy

- **BAT triggers on GRB, calculates position to < 4 arcmin**
- **Spacecraft autonomously slews to GRB position in 20-70 s**
- **XRT determines position to < 5 arcseconds**
- **UVOT images field, transmits finding chart to ground**



T<10 sec

$\theta < 4'$

T<100 sec

$\theta < 5''$

T<300 sec

Mission Capabilities

Multiwavelength observations on all time scales

>100 GRBs per year of all types

BAT sensitivity 2 - 5 time better than BATSE

Arcsec positions & counterparts for 100’s GRBs

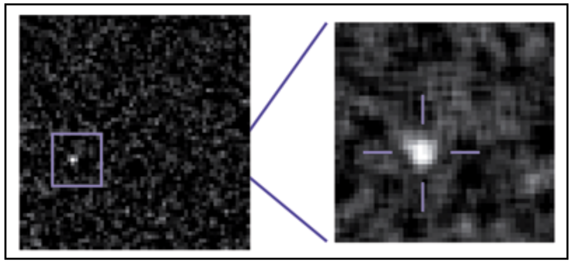
Rapid GRB notifications via GCN

Identification of host galaxies offsets

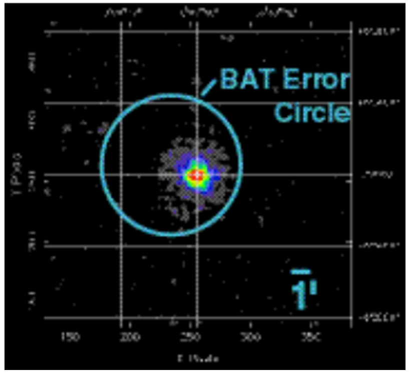
X-ray and UV/optical spectroscopy

Upload capability to slew to GRB and transients detected by other observatories

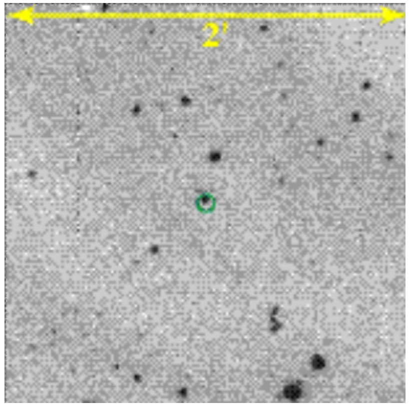
BAT



XRT



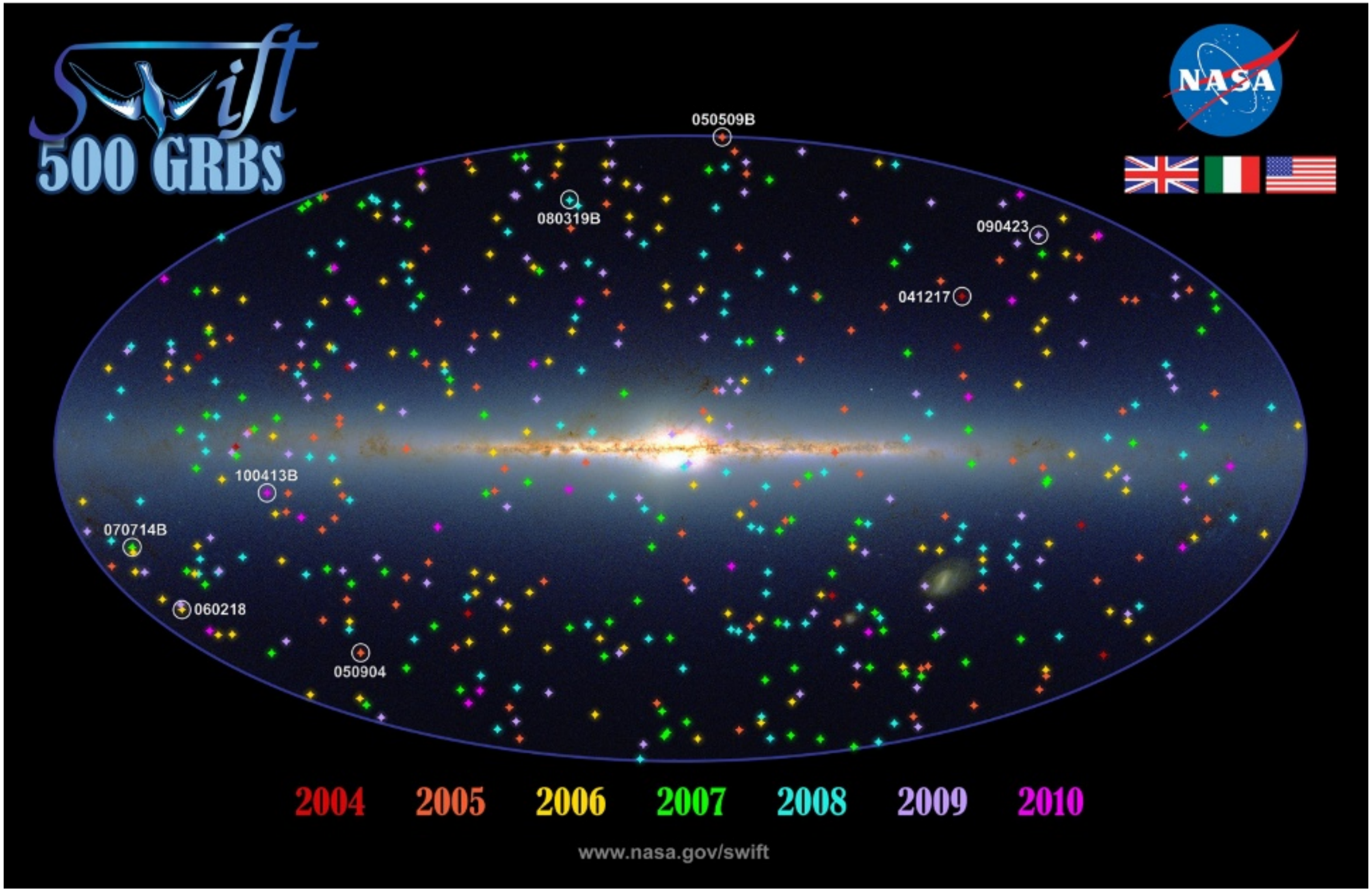
UVOT

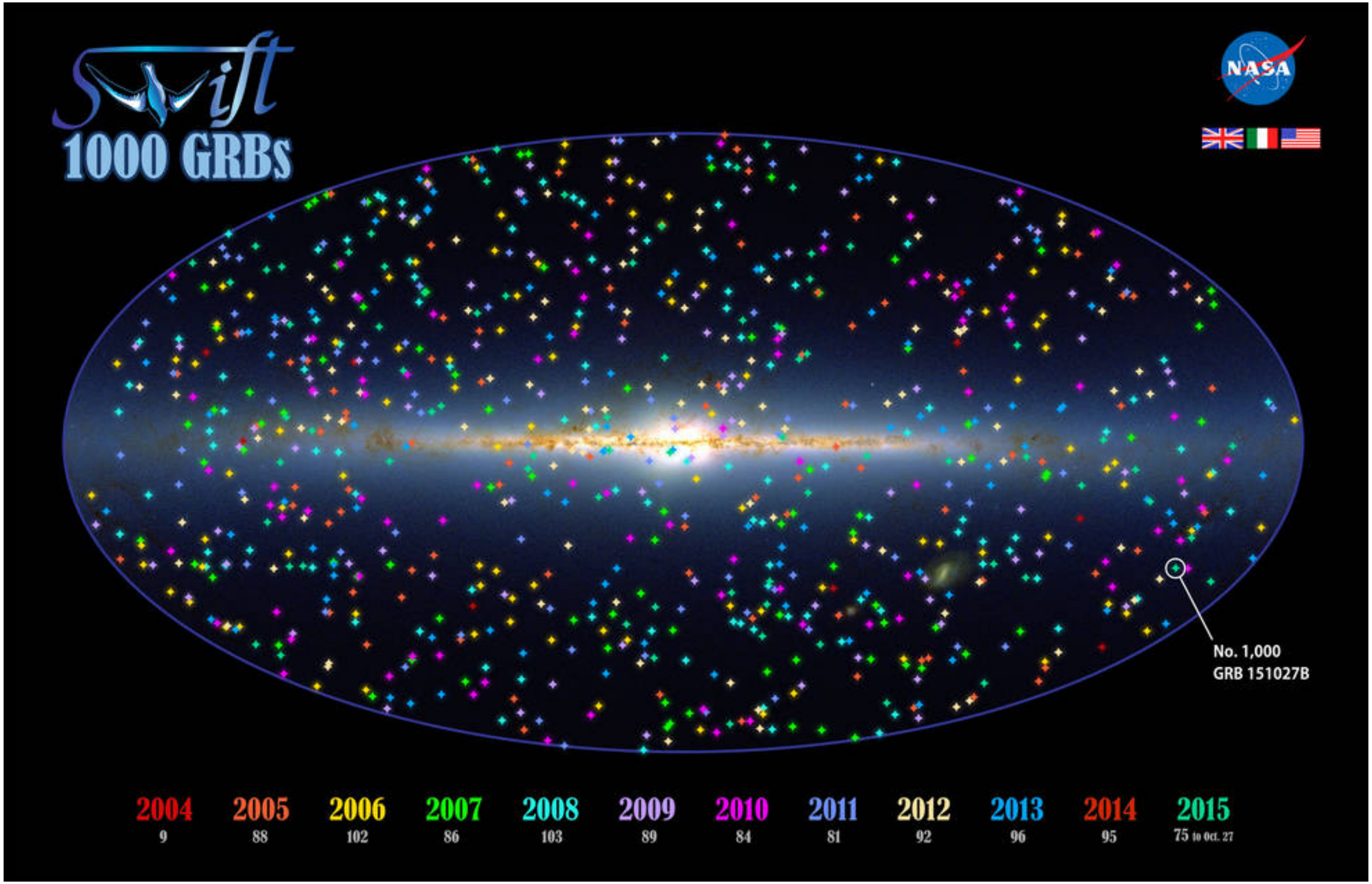


Swift

Details

- **BAT** (15-350 keV). Large (2 sr) field of view – detects bursts with arc min accuracy. And tells observers immediately.
- *Swift* automatically determines if it can view the GRB, and if so, slews to it.
- **XRT** (0.3-10 keV) and **UVOT** (~1000-6000 Å) begin observing typically within 100 s of the trigger.
- XRT can automatically detect afterglows, and downlinks limited data immediately. ~90% of BAT GRBs have promptly detected XRT afterglows.


Swift
500 GRBs
NASA
050509B
080319B
090423
041217
100413B
070714B
060218
050904
2004
2005
2006
2007
2008
2009
2010
www.nasa.gov/swift


Swift
1000 GRBs
NASA
No. 1,000
GRB 151027B
2004
9
2005
88
2006
102
2007
86
2008
103
2009
89
2010
84
2011
81
2012
92
2013
96
2014
95
2015
75 to Oct. 27

Swift discoveries

Summary

- Currently >1500 GRBs with arc second positions from *Swift* (more from optical follow-up).
- More than 500 of *Swift* GRBs have redshifts
- Includes brightest GRB ever seen, and most distant one.

Exercise #3

- Find Jochen Greiner’s web page on GRB afterglows
- Find Swift web page.

Discoveries in the *Swift* era

① X-ray afterglow of short GRBs

② Prompt optical-IR emission and very early optical afterglows

③ X-ray flares from GRB

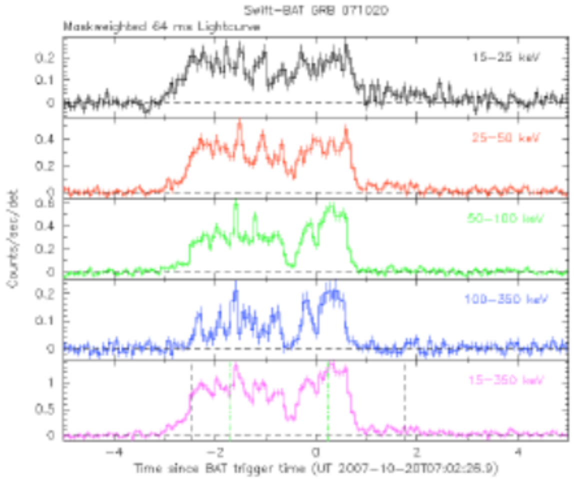
④ Early steep decay of X-ray afterglows

Swift data

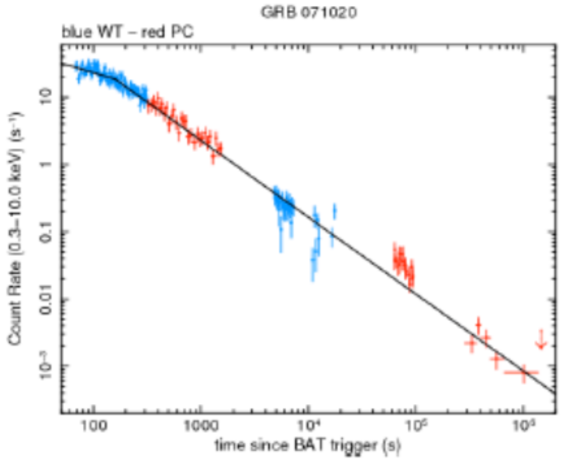
Swift GRB Data

GRB 071020

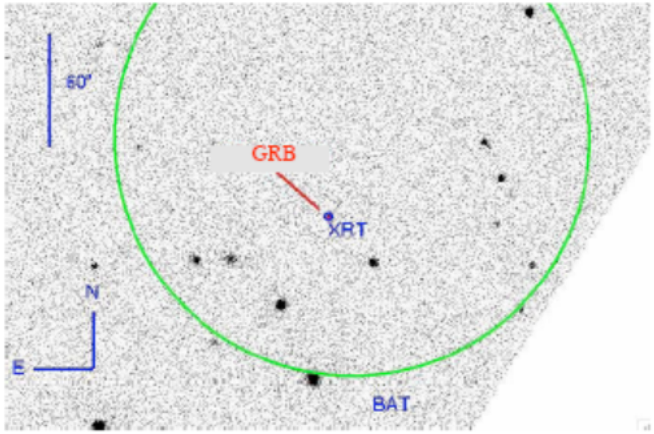
BAT lightcurve



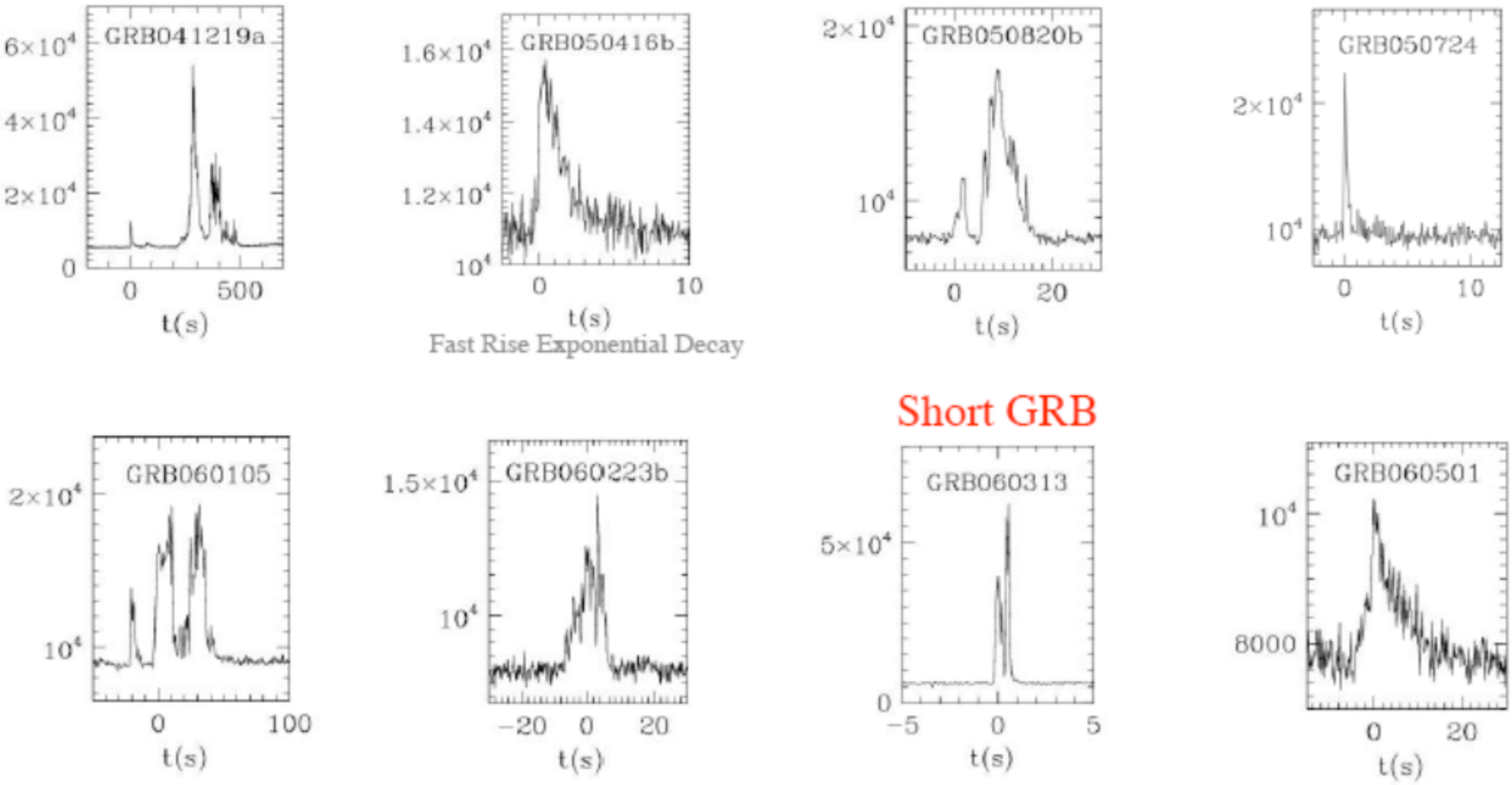
XRT lightcurve



UVOT image



Swift data



Short GRB

Fast Rise Exponential Decay

Short GRB

Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
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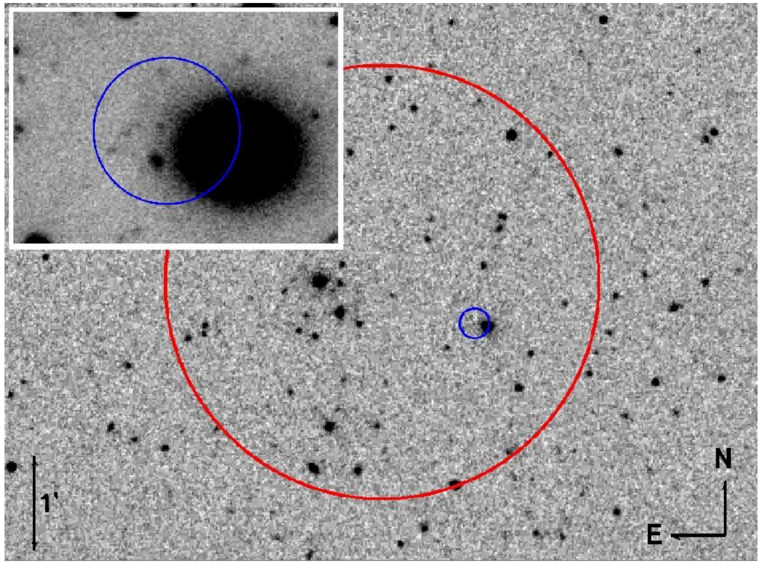
Swift discoveries

Short GRBs.

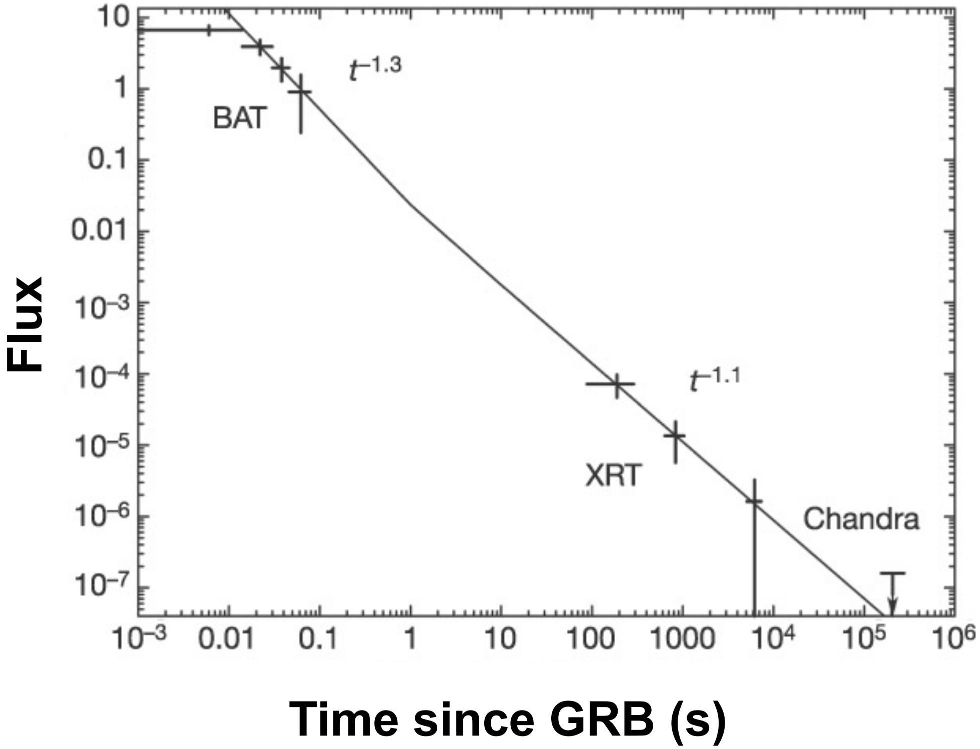
- GRB 050509B was a short GRB discovered by *Swift*, with an X-ray afterglow reported 2:29 after the trigger.

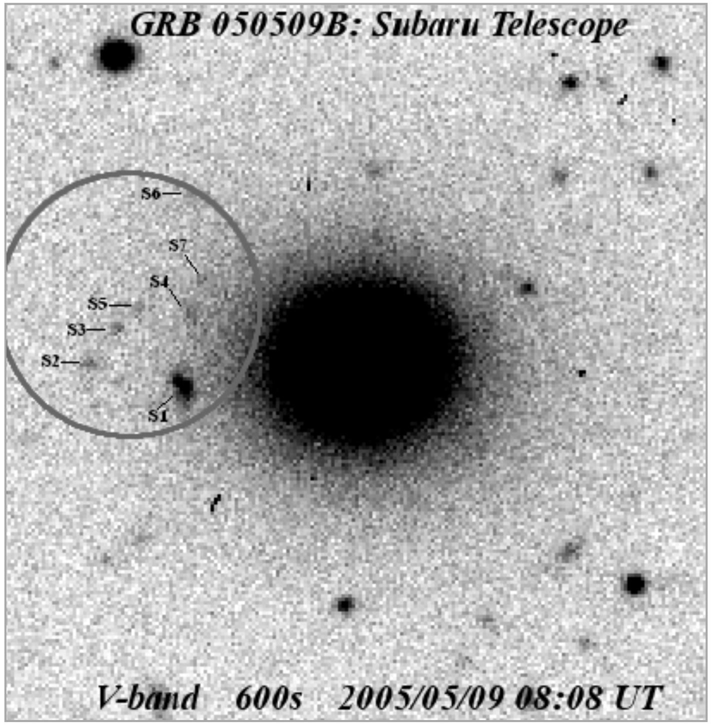
- Outskirts of an elliptical galaxy.
- Later sGRBs had optical afterglows too.
- Subsequently found in all galaxy types.

VLT image
Hjorth et al.



Afterglow of “short bursts”

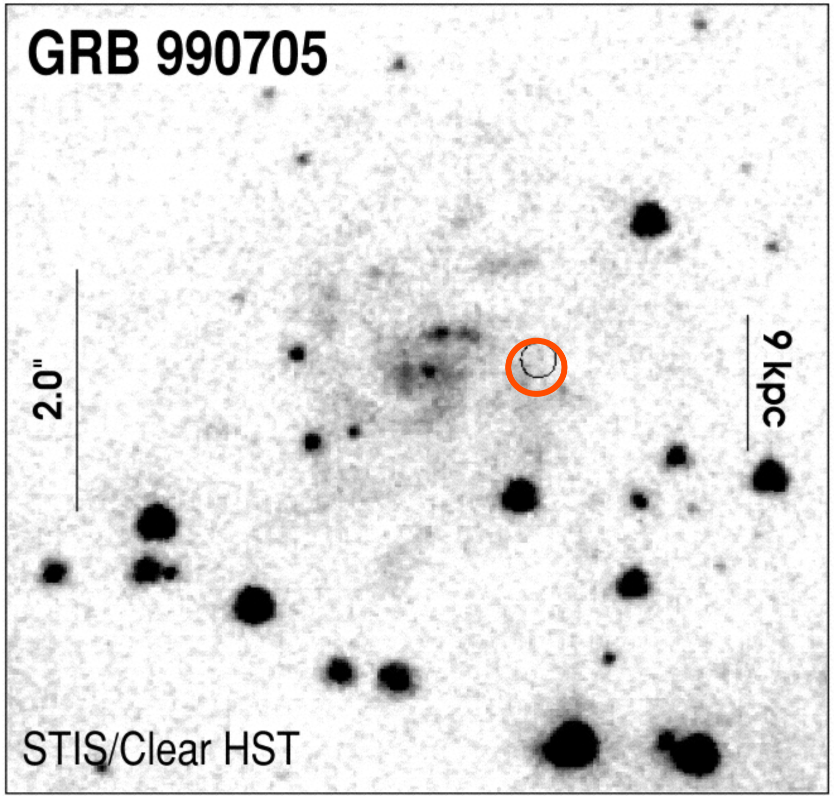




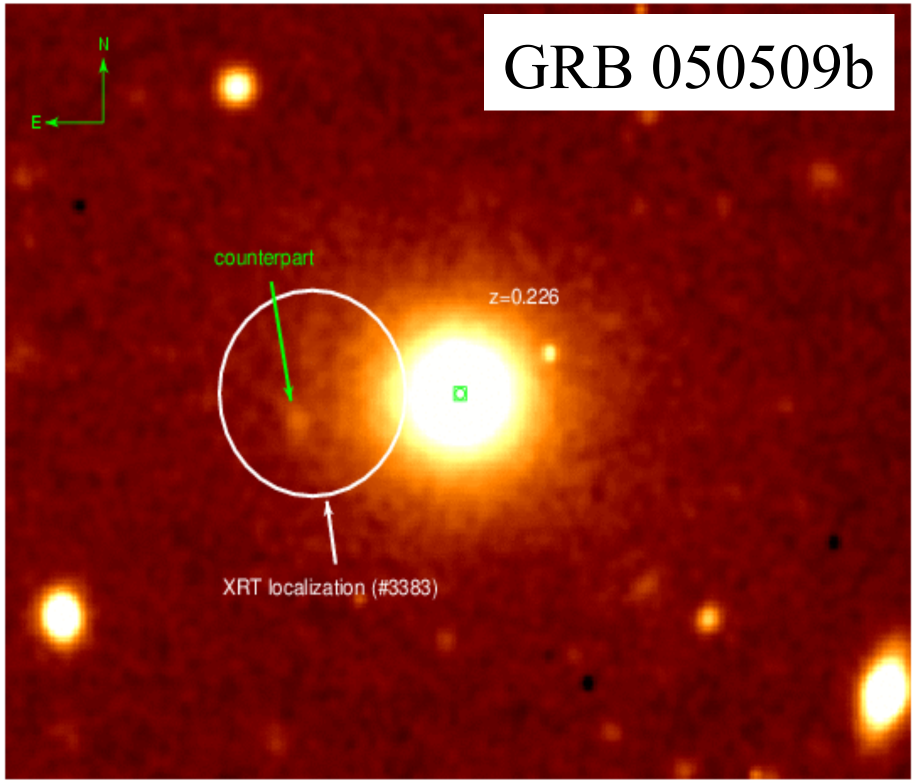
Unvealing the short GRB progenitors

- host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions
- host galaxies of short GRBs: elliptical, irregular galaxies, away from star forming region

Long



Short



Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Swift discoveries

Progenitors

- Short GRBs found in all types of galaxy – old population (compact merger/magnetar)
- Long GRBs always found in star forming galaxies and regions – deaths of massive stars.

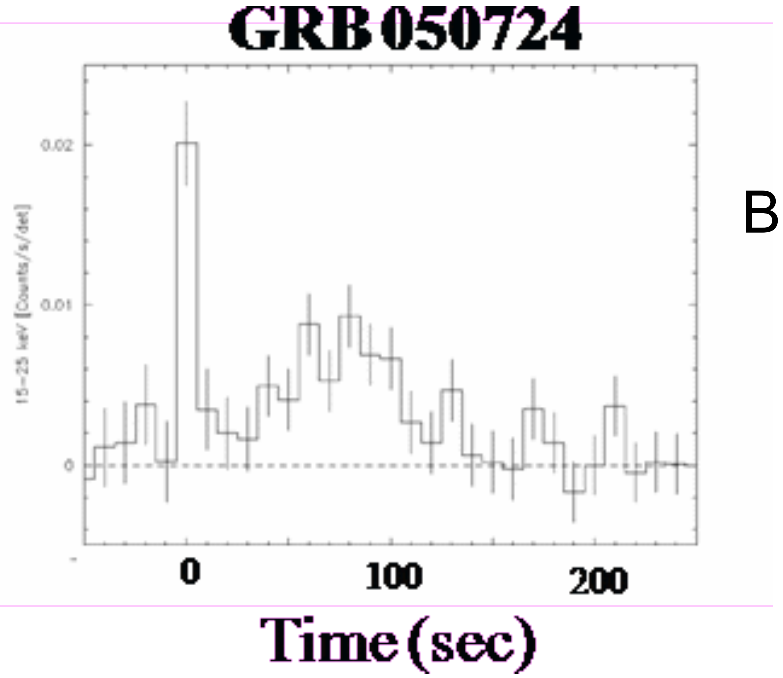
Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Swift discoveries

Short GRB with extended emission

- Blurred the distinction between “short” and “long” bursts, and made it more detector-dependent.



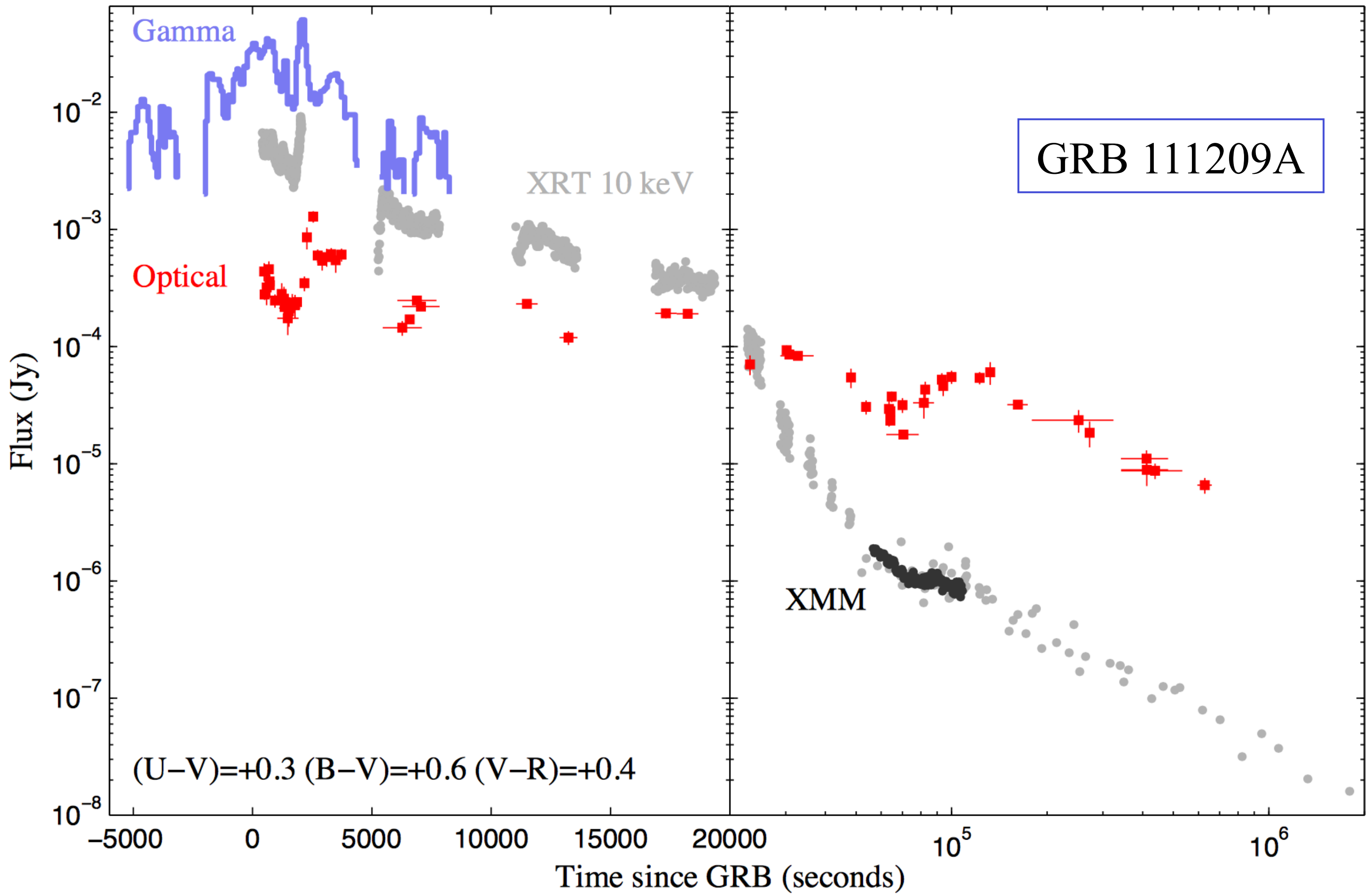
Barthelmy et al.
2005

Swift discoveries

Long GRBs with no SNe

- GRB 060614 and GRB 060505 were nearby, apparently long GRBs, with no related supernova, down to deep limits.
- The GRB taxonomy is clearly more complex than previously thought.
- Maybe a new, progenitor-based classification is needed?

Ultra Long GRBs



Questions for *Swift*

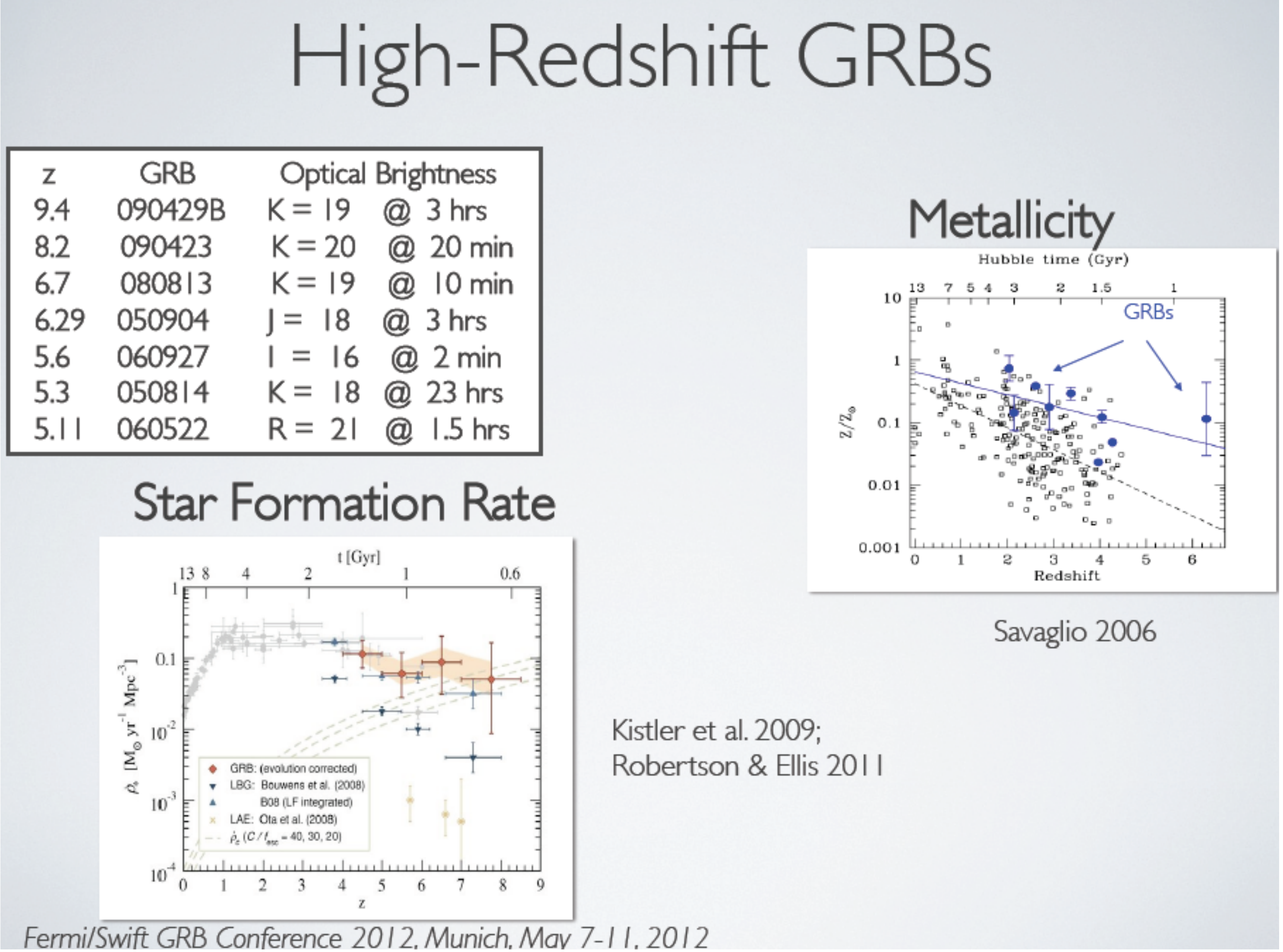
- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Swift discoveries

High redshift bursts

- 17 GRBs observed by *Swift* have $z>3.5$
- 10 have $z>4$, and 5 have $z > 5$ – a large, rapidly growing population of distant objects.
- GRB 050904 was at $z=6.29$ (Cusumano et al. 2007)
- GRB 080913 was at $z=6.7$, and was a fainter-than-normal burst! (Greiner et al. 2009)
- GRB 090423 was at $z=8.26$!!!!
- GRB 090429B was at $z=9.2$!!!!!!

High redshift GRB



High-Redshift GRBs

z	GRB	Optical Brightness
9.4	090429B	K = 19 @ 3 hrs
8.2	090423	K = 20 @ 20 min
6.7	080813	K = 19 @ 10 min
6.29	050904	J = 18 @ 3 hrs
5.6	060927	I = 16 @ 2 min
5.3	050814	K = 18 @ 23 hrs
5.11	060522	R = 21 @ 1.5 hrs

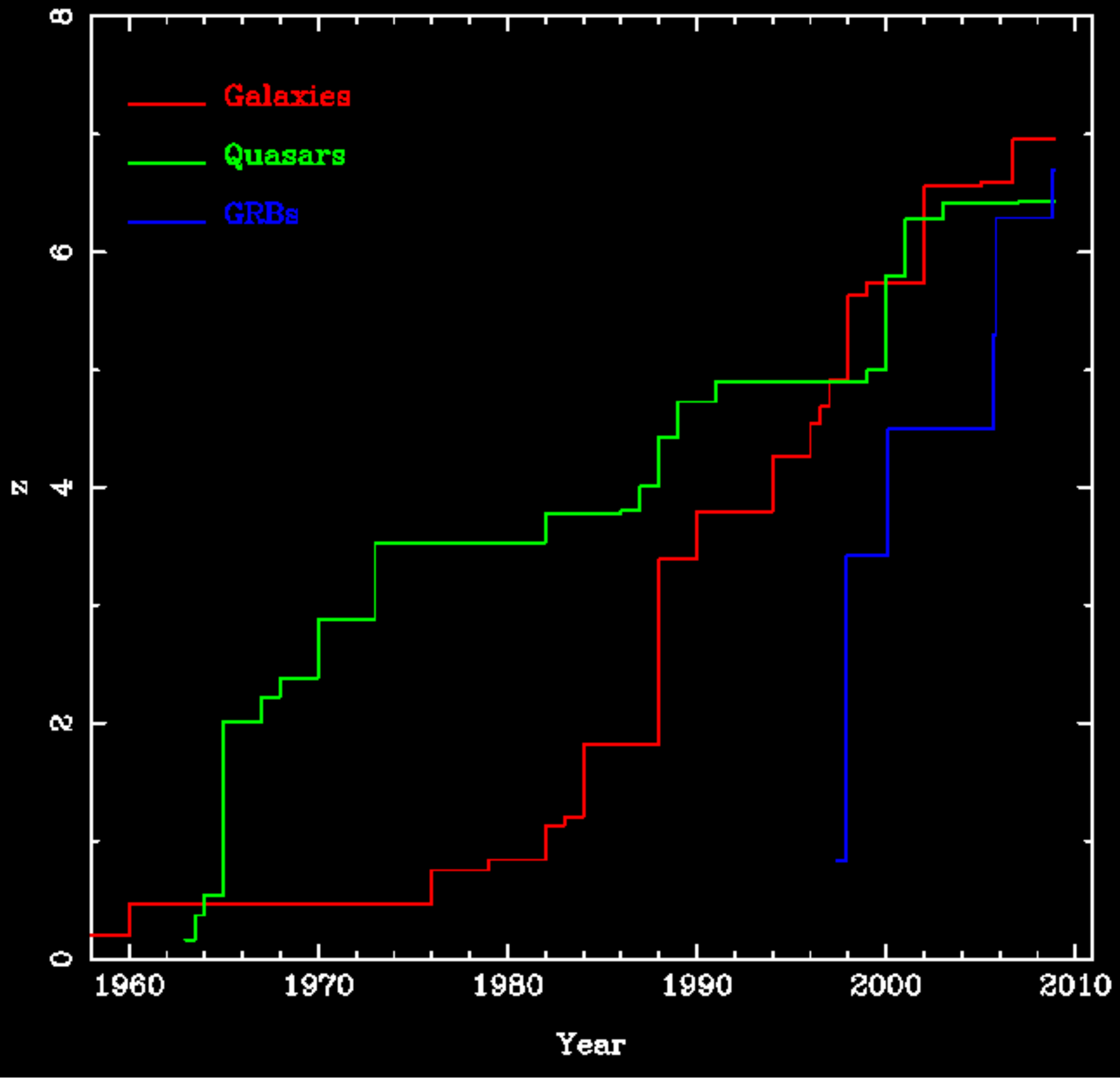
Metallicity

Savaglio 2006

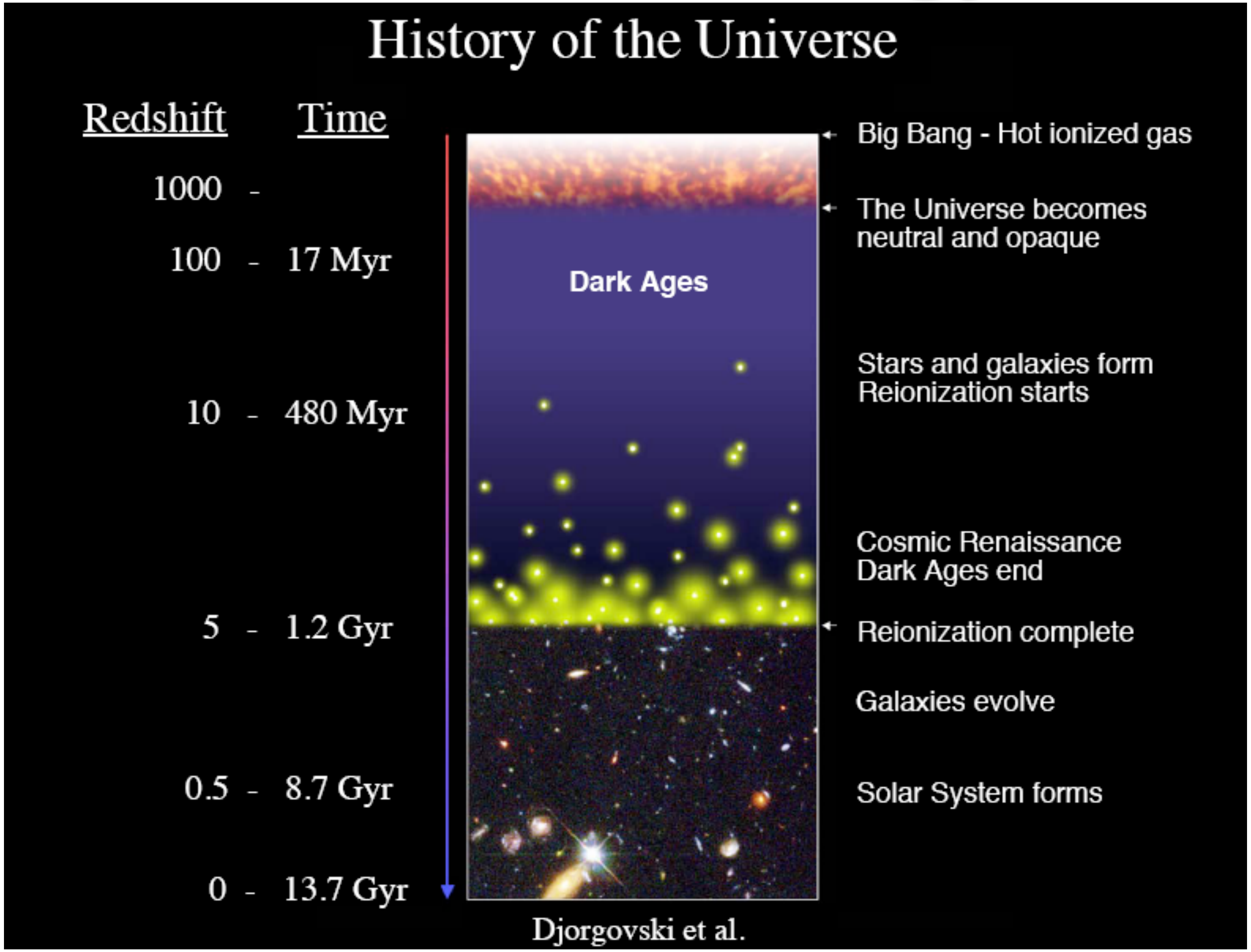
Star Formation Rate

Kistler et al. 2009;
Robertson & Ellis 2011

Fermi/Swift GRB Conference 2012, Munich, May 7-11, 2012


Galaxies
Quasars
GRBs
z
0
2
4
6
8
1960
1970
1980
1990
2000
2010
Year

GRB & Cosmology



Djorgovski et al.

Swift discoveries

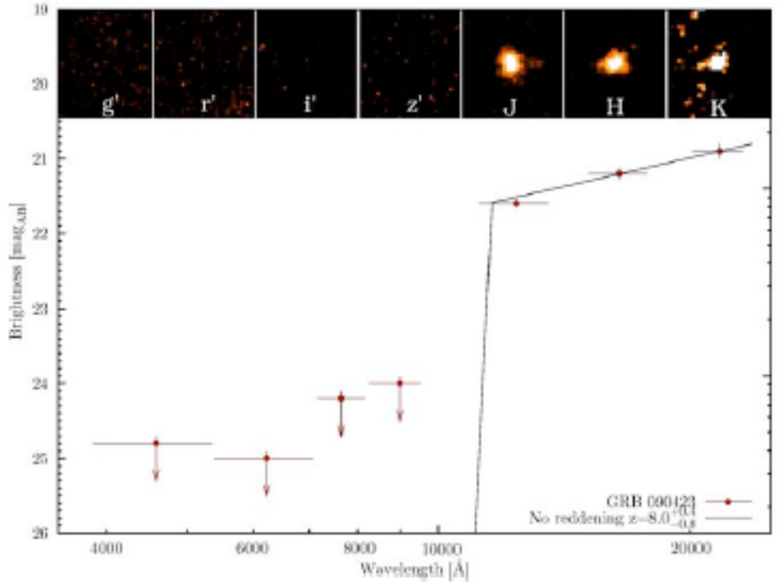
High redshift bursts

- 2-m class telescopes should give reliable photo-*z* for many *z*>6 bursts.
- With GROND online, X-shooter, and increasing numbers of small (ish) telescopes observing every GRB, the next high-*z* burst could be just round the corner....

090423

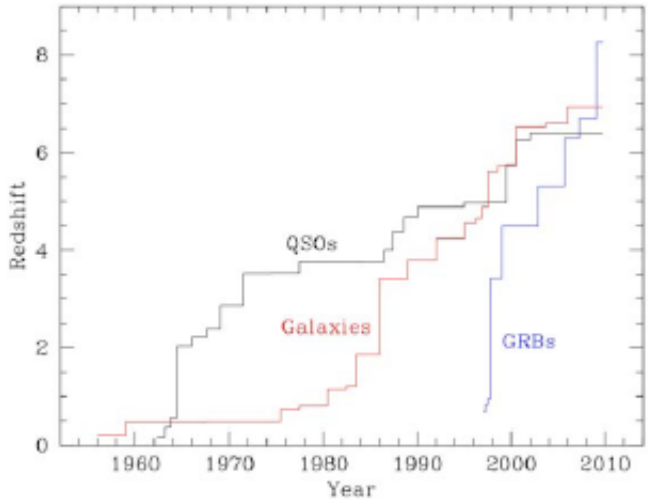
z = 8.2 look back time = 13.0 billion light years

Lyman break redshifted from UV to IR



GROND Grenier et al

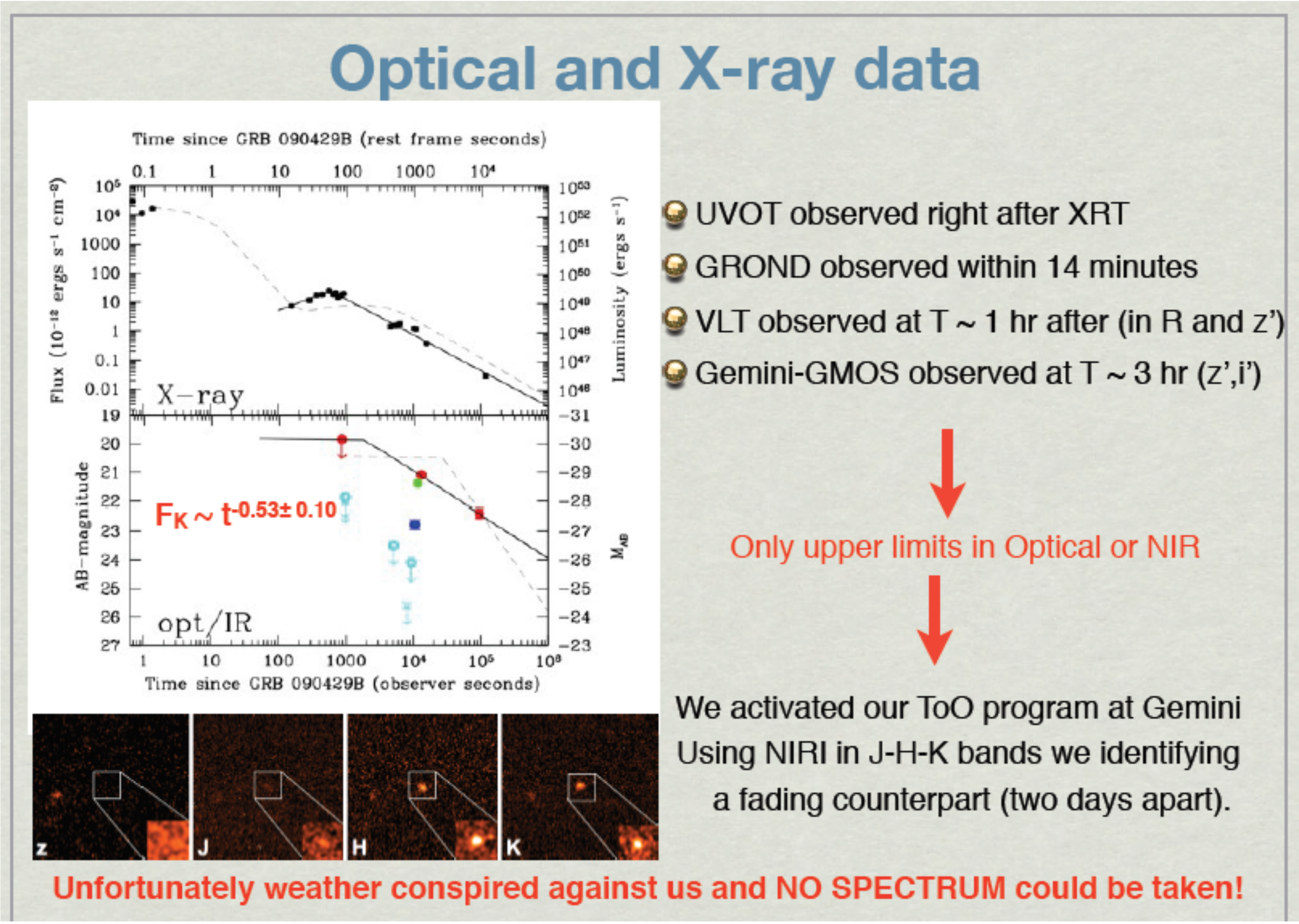
Redshift records



Tanvir & McMahon

Tanvir et al. 2009; Salvaterra et al.

090429B



Optical and X-ray data

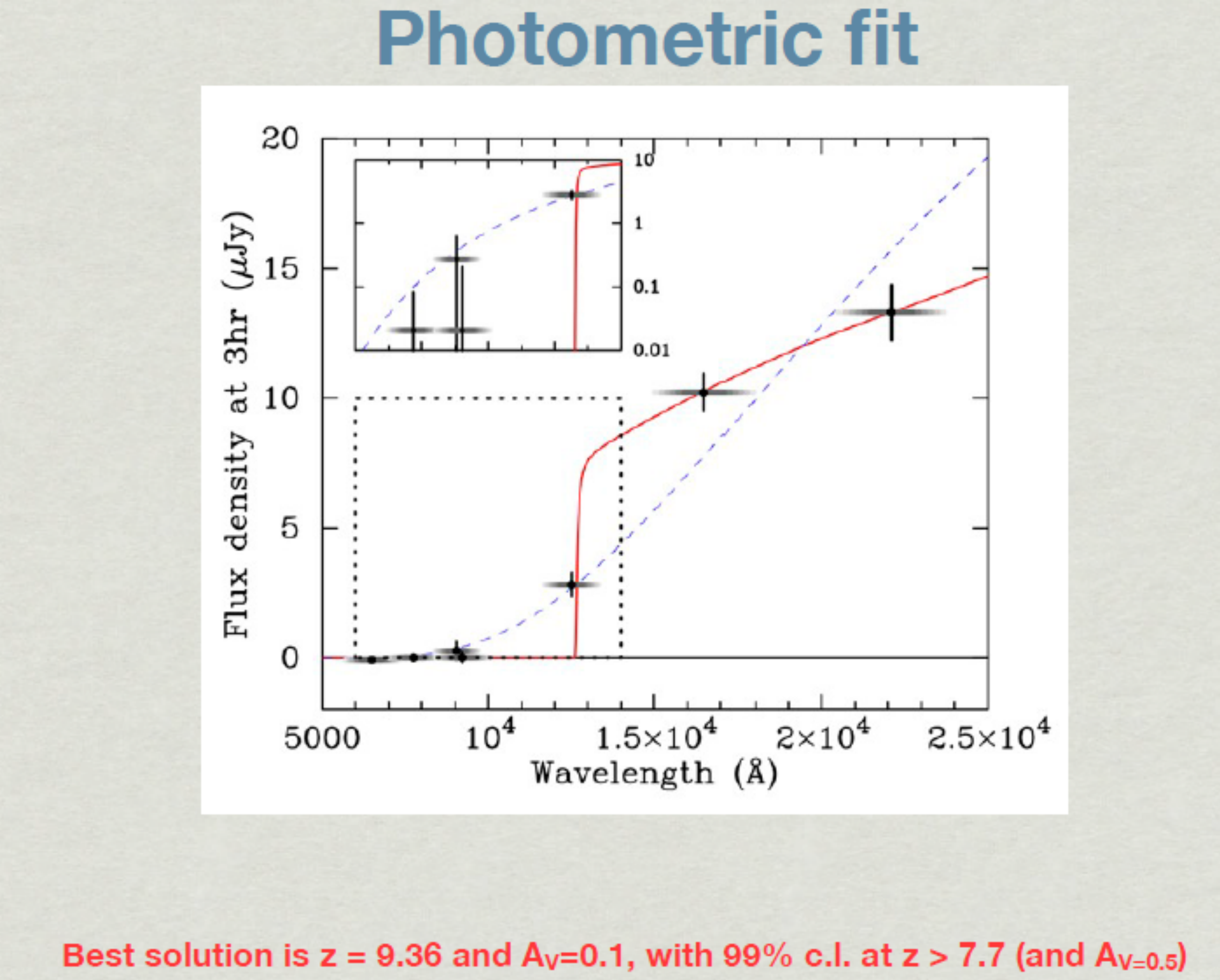
- UVOT observed right after XRT
- GROND observed within 14 minutes
- VLT observed at T ~ 1 hr after (in R and z')
- Gemini-GMOS observed at T ~ 3 hr (z',i')

Only upper limits in Optical or NIR

We activated our ToO program at Gemini
Using NIRI in J-H-K bands we identifying
a fading counterpart (two days apart).

Unfortunately weather conspired against us and NO SPECTRUM could be taken!

090429B



Photometric fit

Best solution is z = 9.36 and A_V=0.1, with 99% c.l. at z > 7.7 (and $A_{V=0.5}$)

High z - searches

High-z Universe: searching for the best probe

Galaxies

Pros

- ★ Multiband data are available (some)
- ★ Refurbished HST
- ★ Different technique (LBG/Lyα emission)
- ★ Do not “disappear”

Cons

- ★ Small region of the sky (11 arcmin^2)
- ★ Required several hours of observations
- ★ Very faint objects
- ★ Galaxy templates are complex
- ★ Difficult determination of Age/dust/SFR

Gamma-ray Bursts

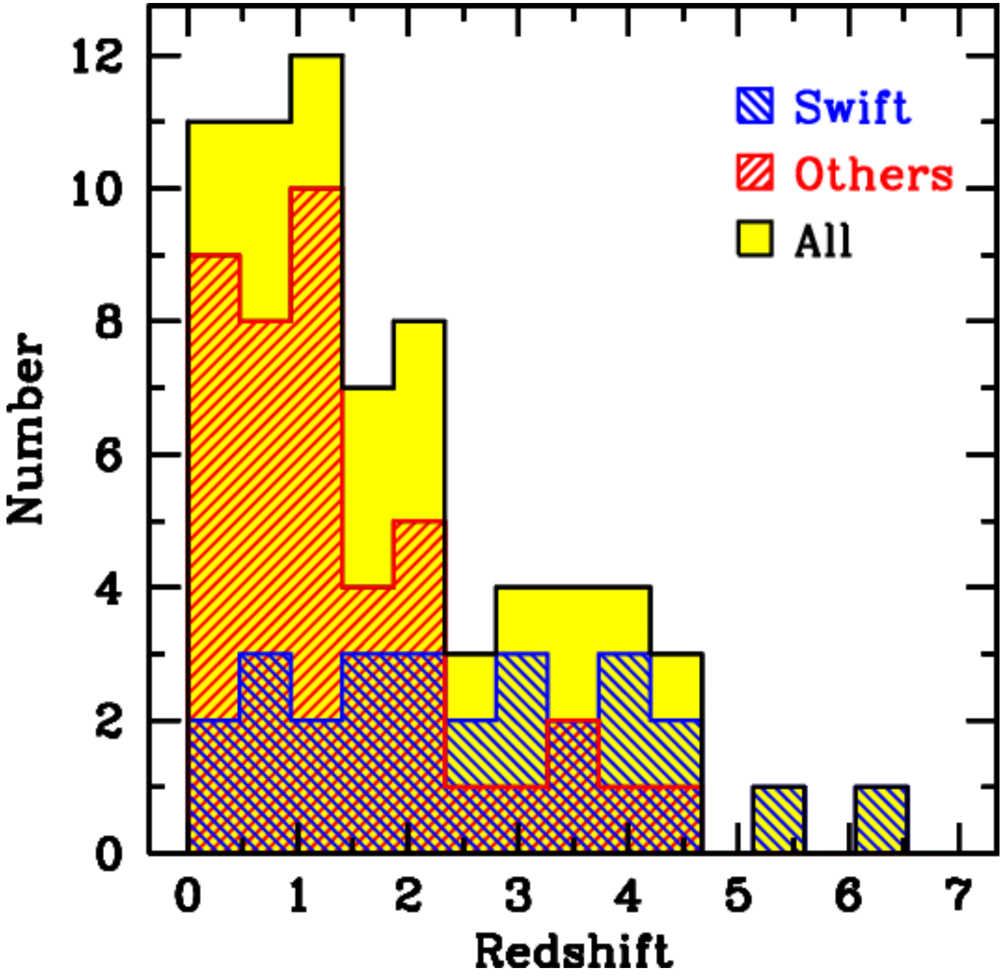
Pros

- ★ Very bright
- ★ Happens everywhere
- ★ Can be followed quickly from space and ground (now at least)
- ★ **Have a very simple spectrum** (synchrotron, simple power-law)
- ★ Allow better investigation of τ_{HI}

Cons

- ★ Rare (few “good ones”)
- ★ Fade fast, ~minute position identification (space mission)
- ★ Require multiband observations

New redshift distribution



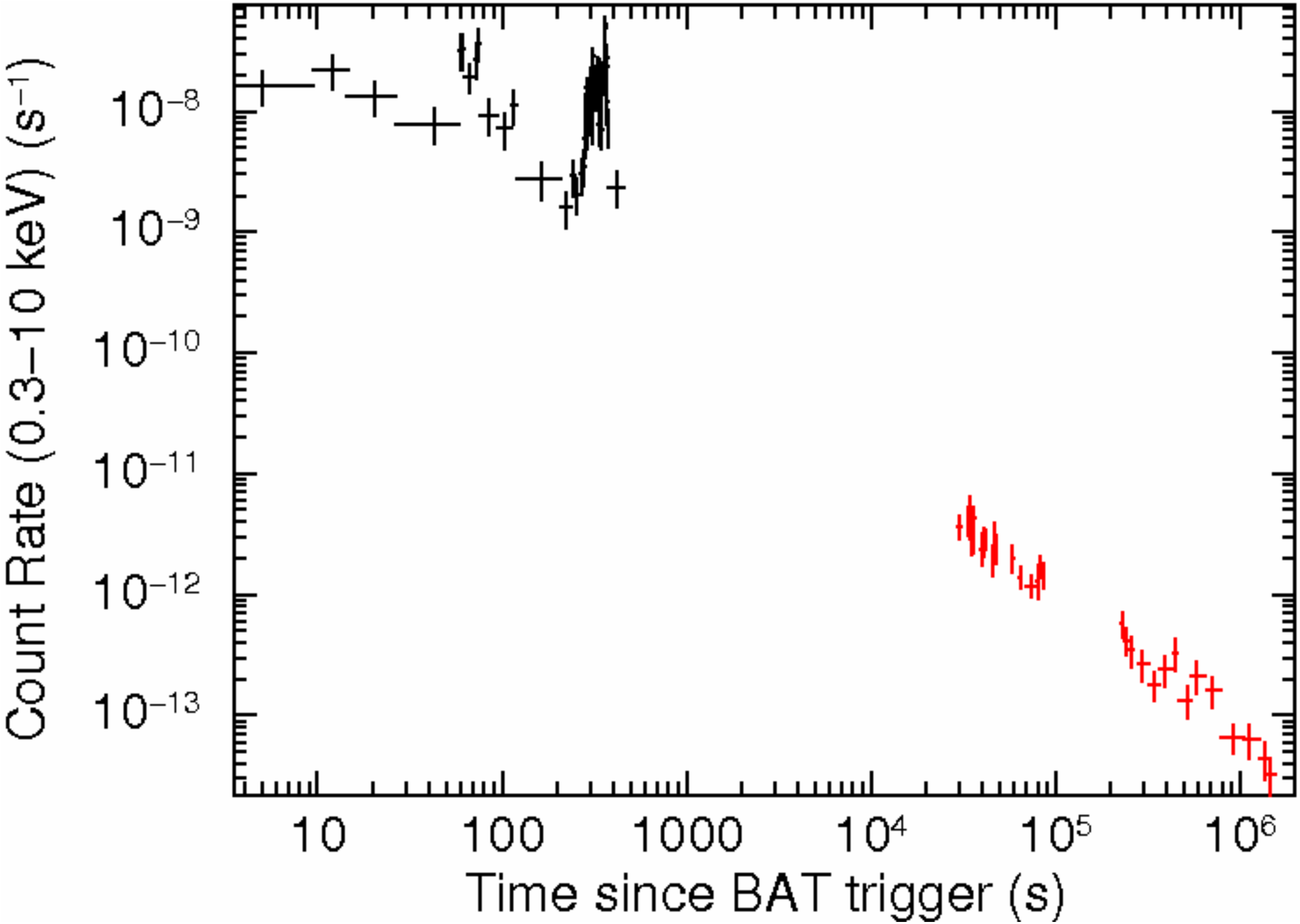
Towards the High z Universe
with Swift!

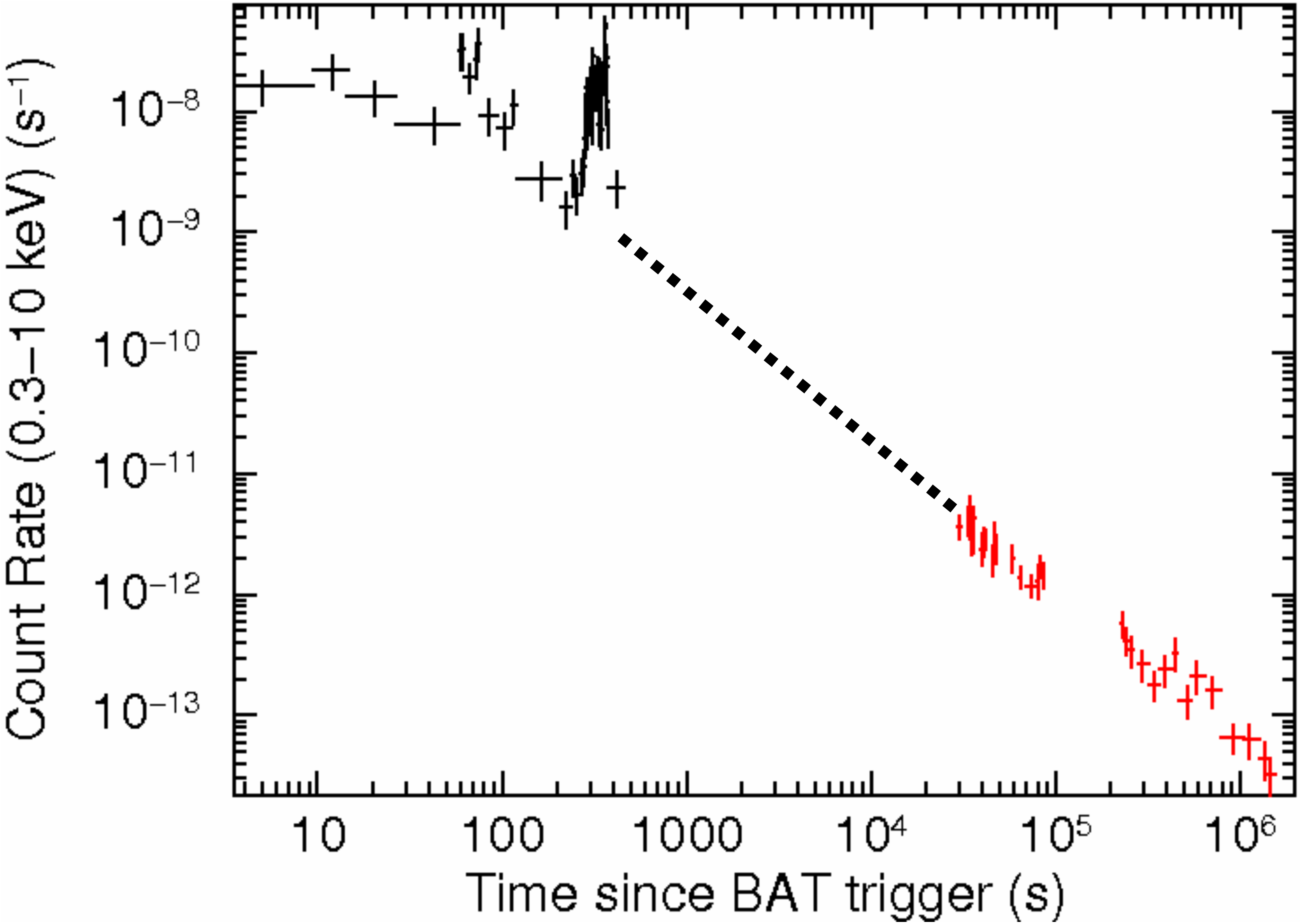
Record:
Z = 9.4 !!

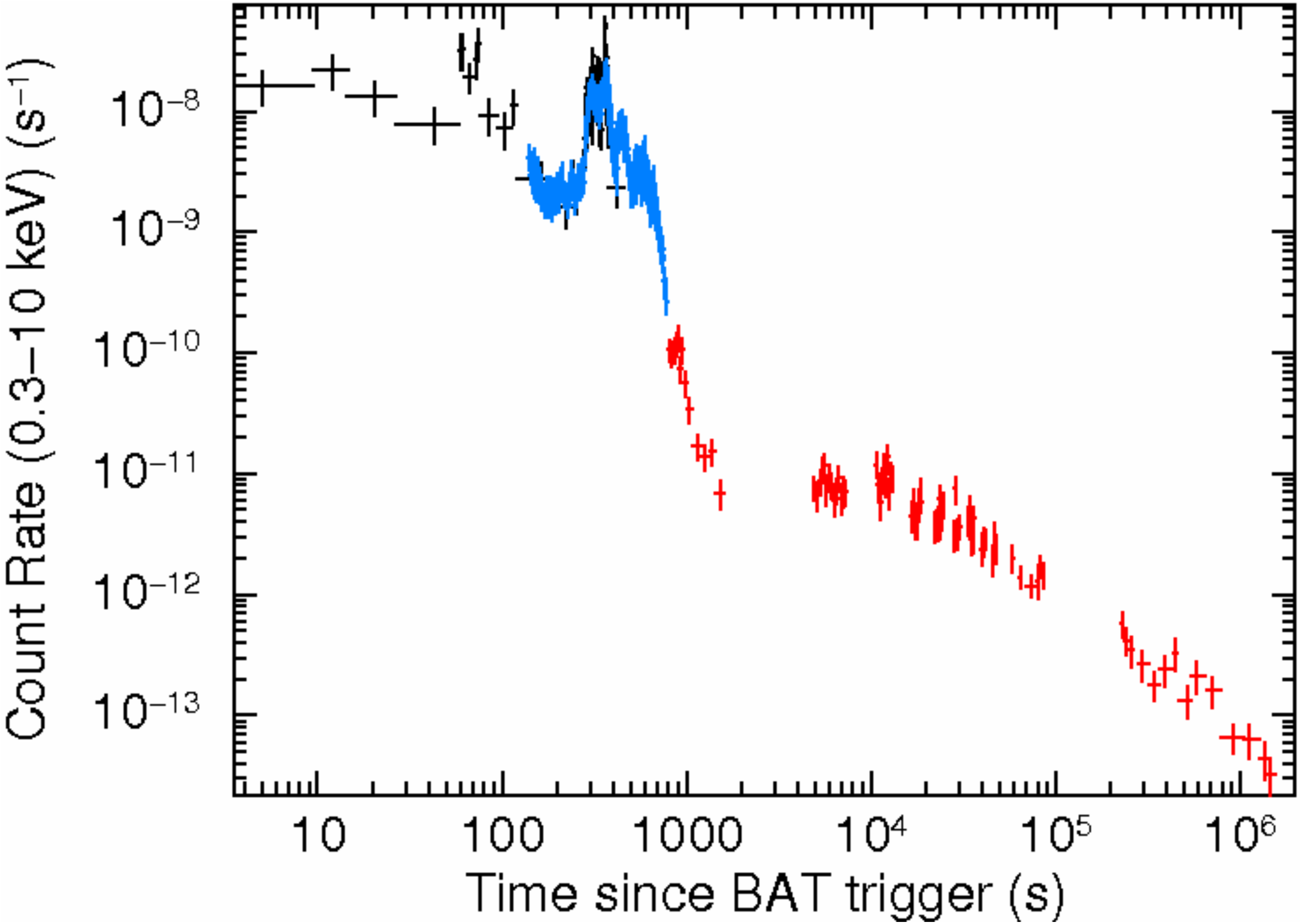
Questions from *Swift*

New mysteries

- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different types of GRB have such similar afterglows?
- Why is the ambient medium (apparently) constant-density, not WR-wind type environment?
- What are the microphysics parameters?


Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^4
10^5
10^6
Time since BAT trigger (s)

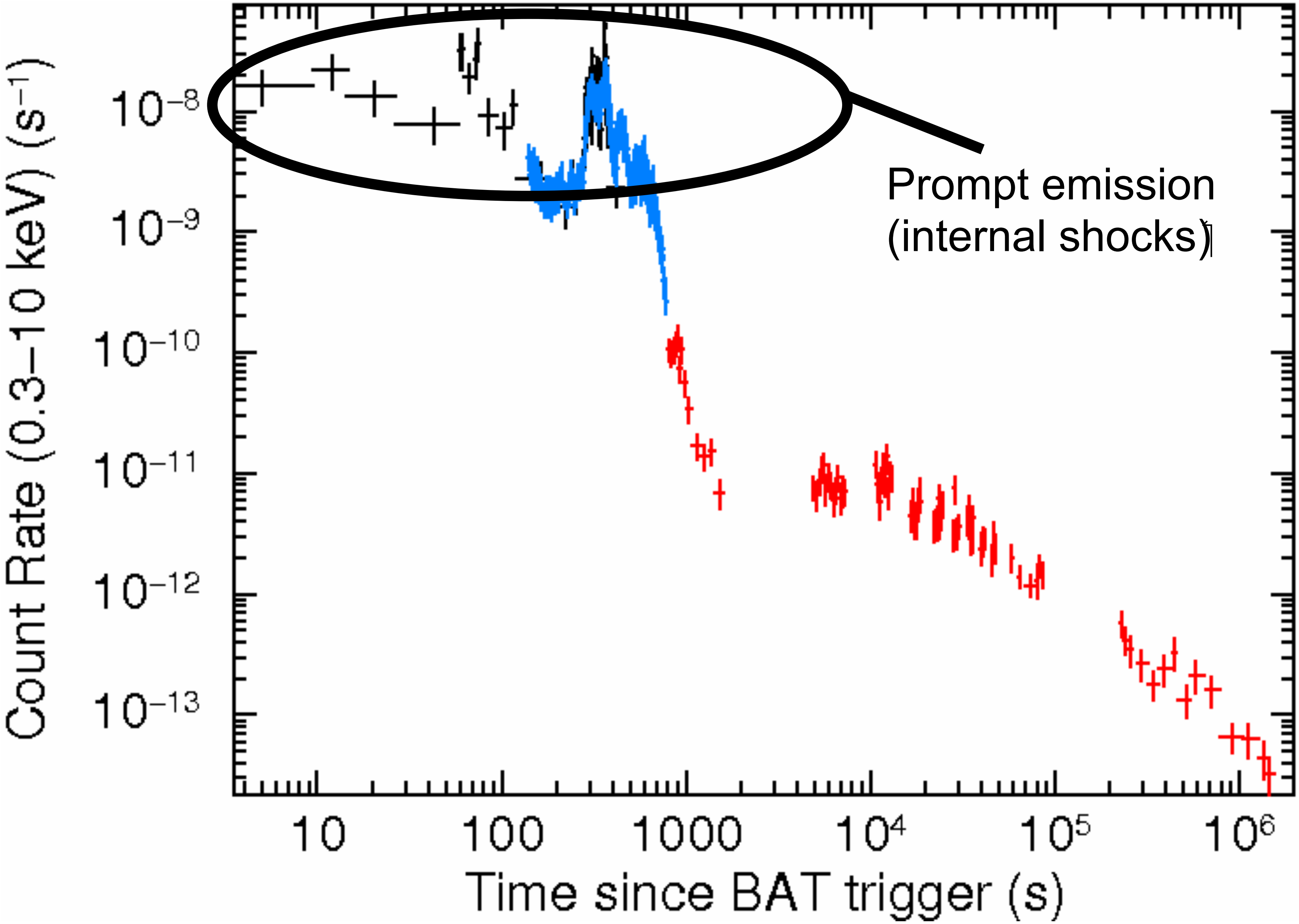

Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^4
10^5
10^6
Time since BAT trigger (s)


Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^4
10^5
10^6
Time since BAT trigger (s)

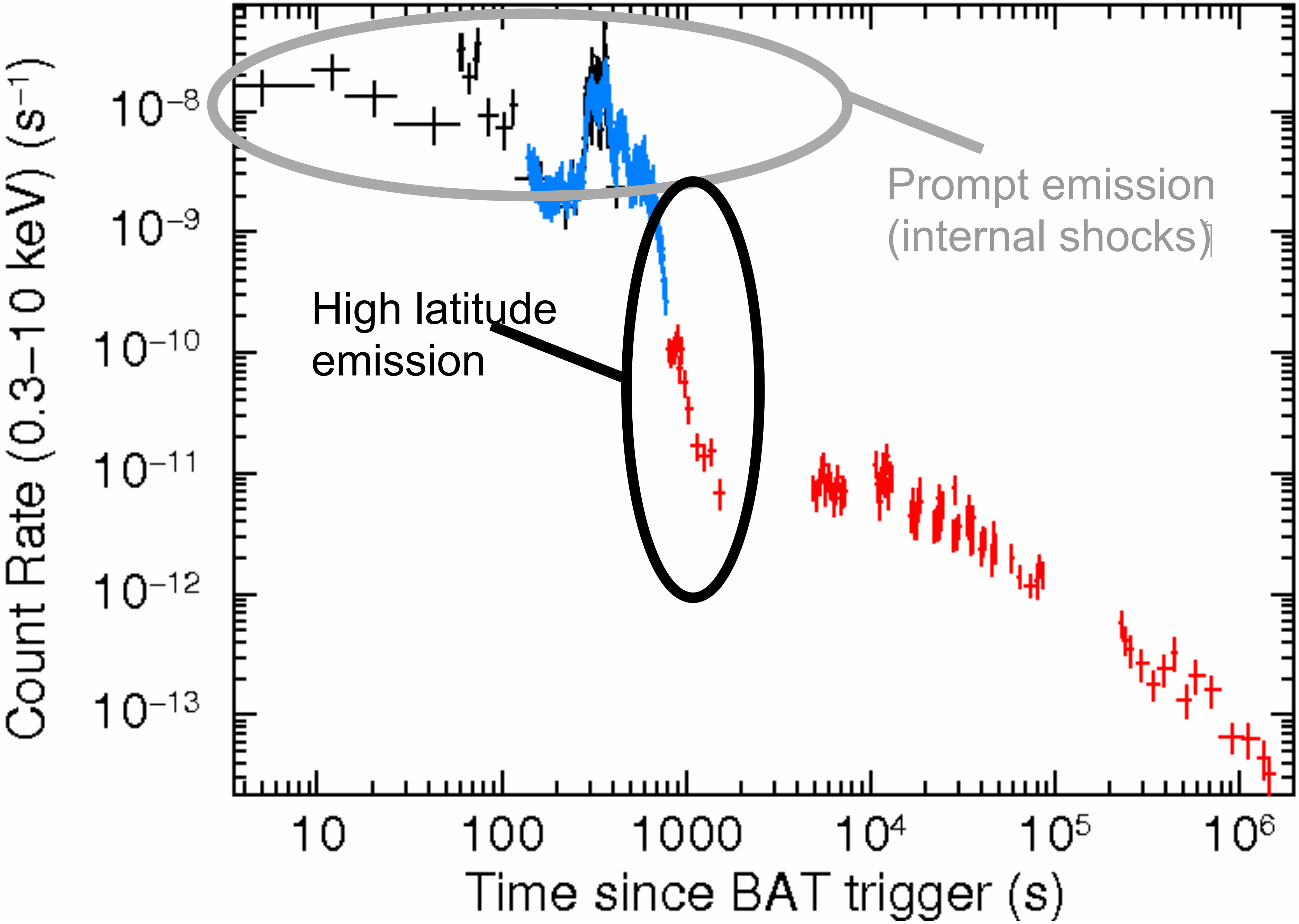
Swift discoveries

Complex X-ray light curves

- Most X-ray afterglows don't show the simple power-law decay seen at late times.
- The “canonical” light curves has 3 phases:

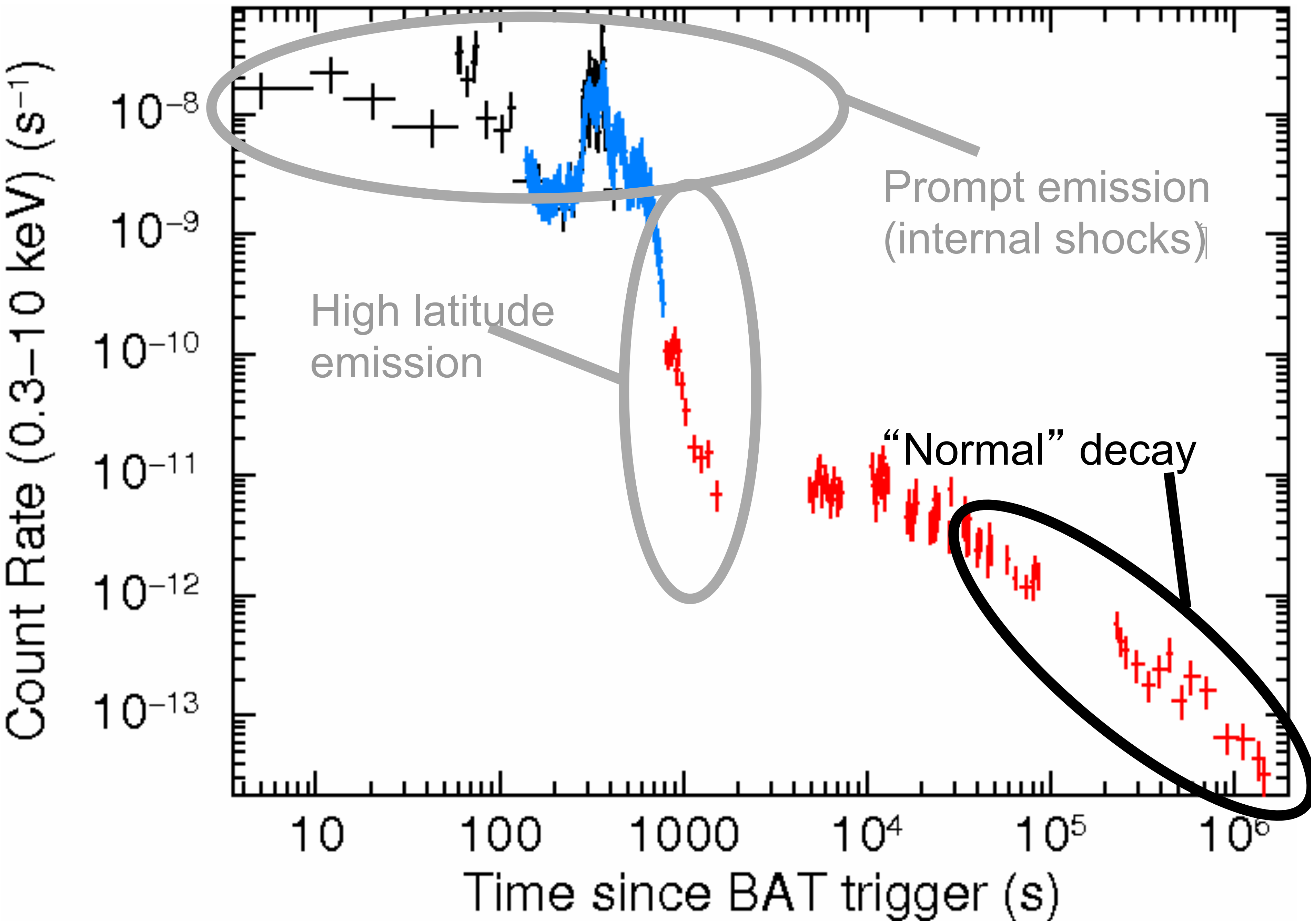


Prompt emission
(internal shocks)



Prompt emission
(internal shocks)

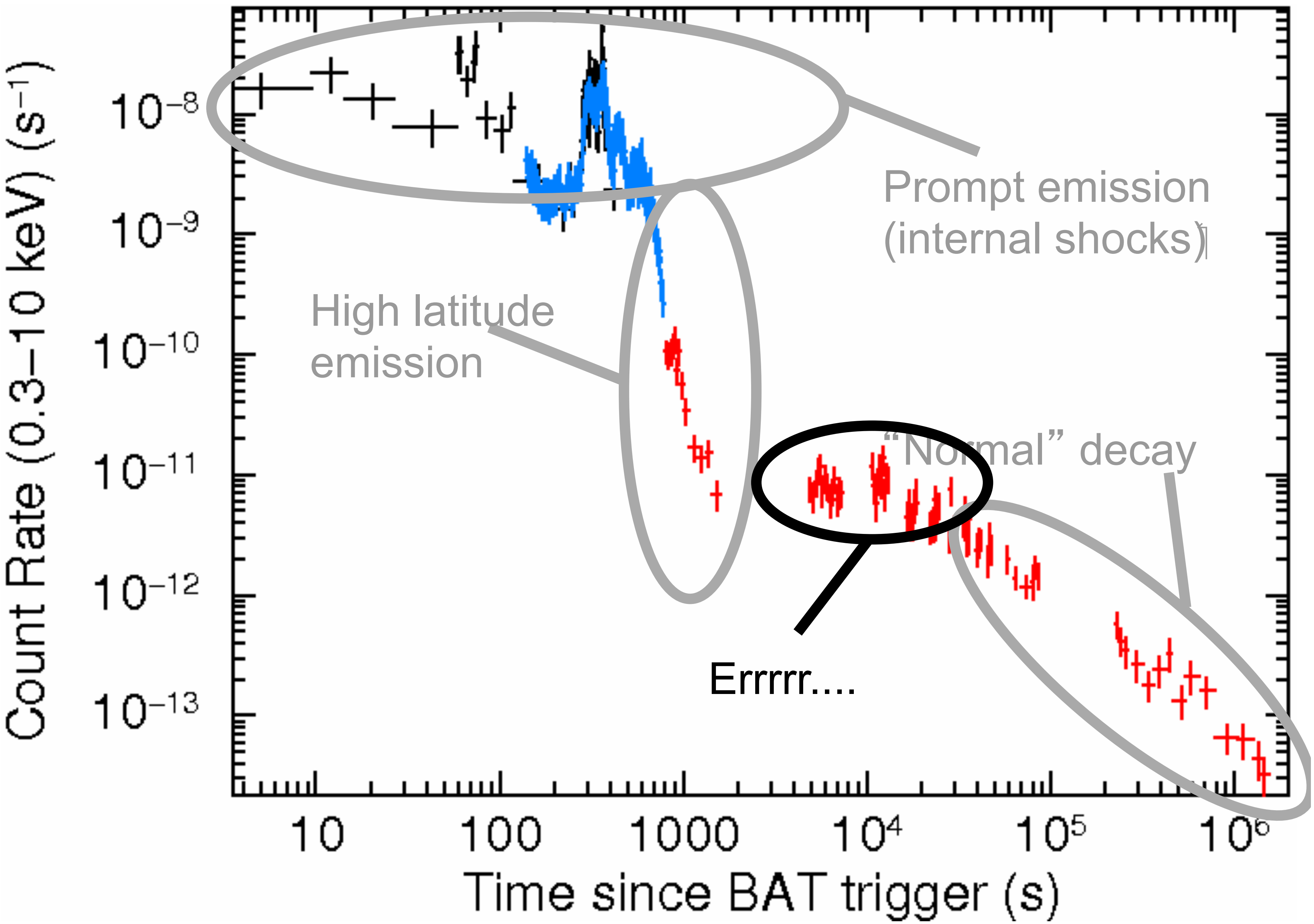
High latitude
emission



Prompt emission (internal shocks)

High latitude emission

“Normal” decay



Prompt emission (internal shocks)

High latitude emission

"Normal" decay

Errrrr....

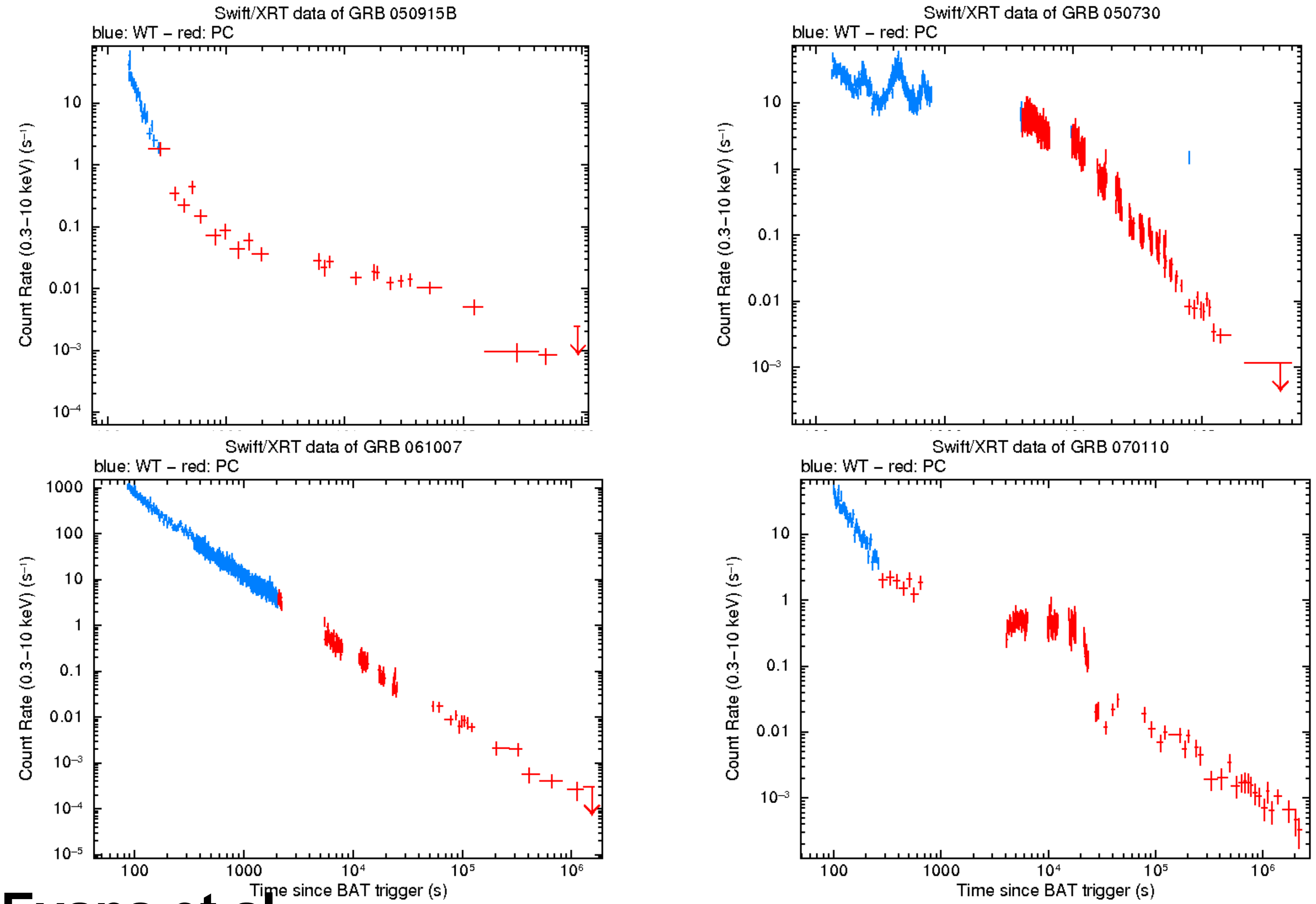
Swift discoveries

Shallow decay phase

- Energy injection? (Zhang et al 2006). *But it has to go on for ~1 day.*
- Dust? [models light curves really well – Shao & Dai (2007). *But not the spectra (Shen et al. 2009)*.
- Upscattered forward shock emission?
- Long-lived central engine (i.e. internal shock emission).
- And more....

Swift discoveries

Complex X-ray afterglows



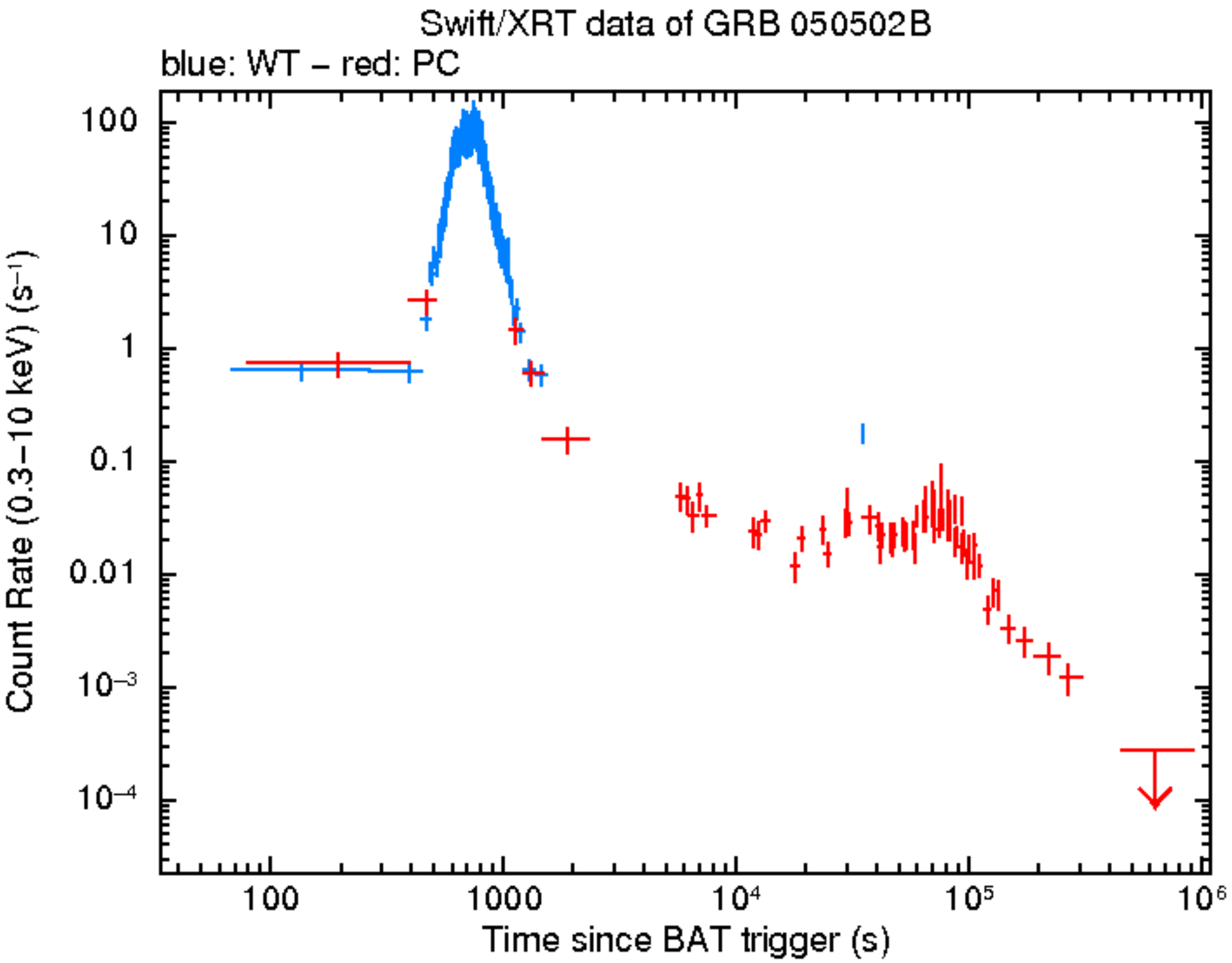
Evans et al. 2009

Questions from *Swift*

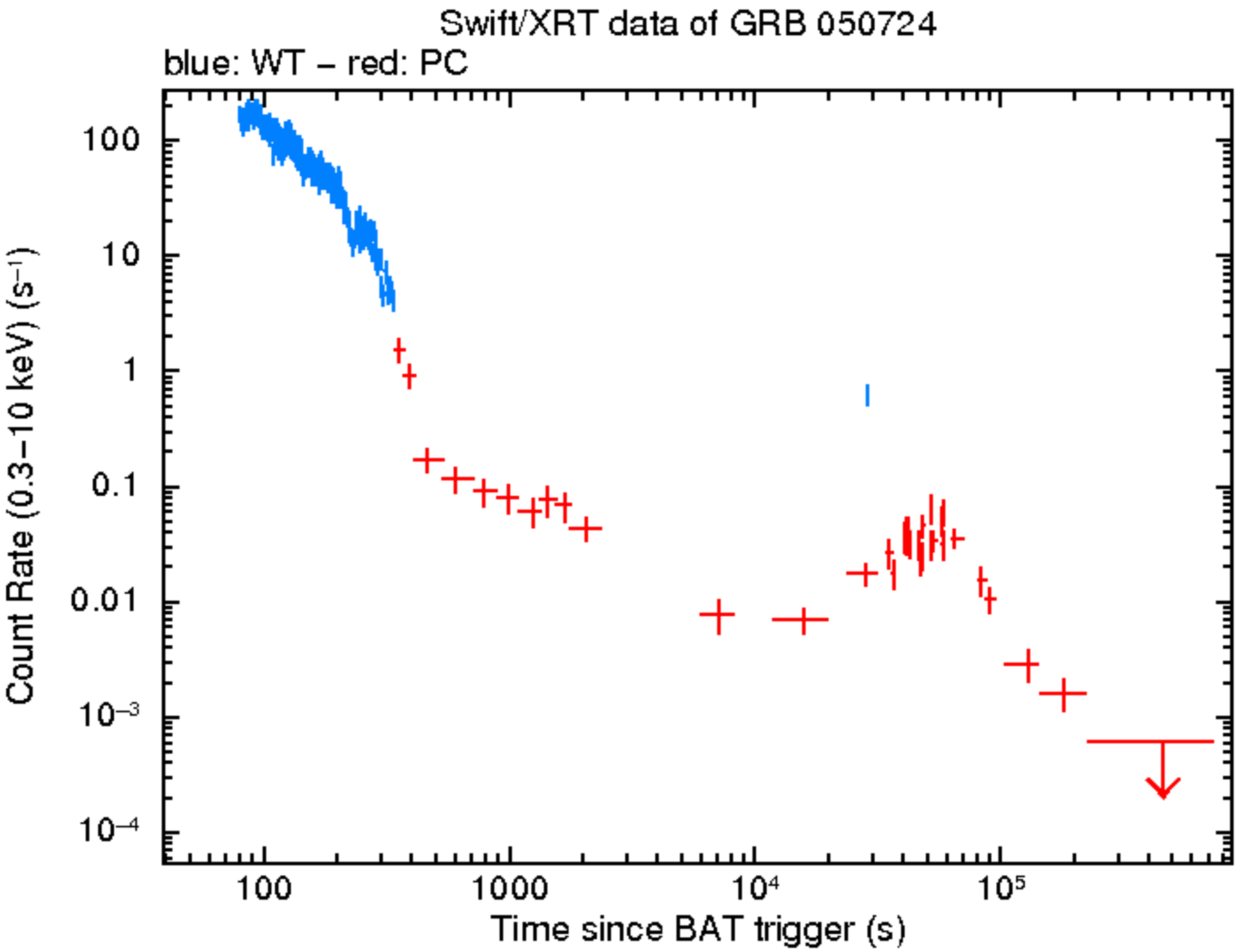
New mysteries

- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different GRBs have such similar afterglows?
- Why is the ambient medium (apparently) constant-density?
- What are the microphysics parameters?

Swift discoveries

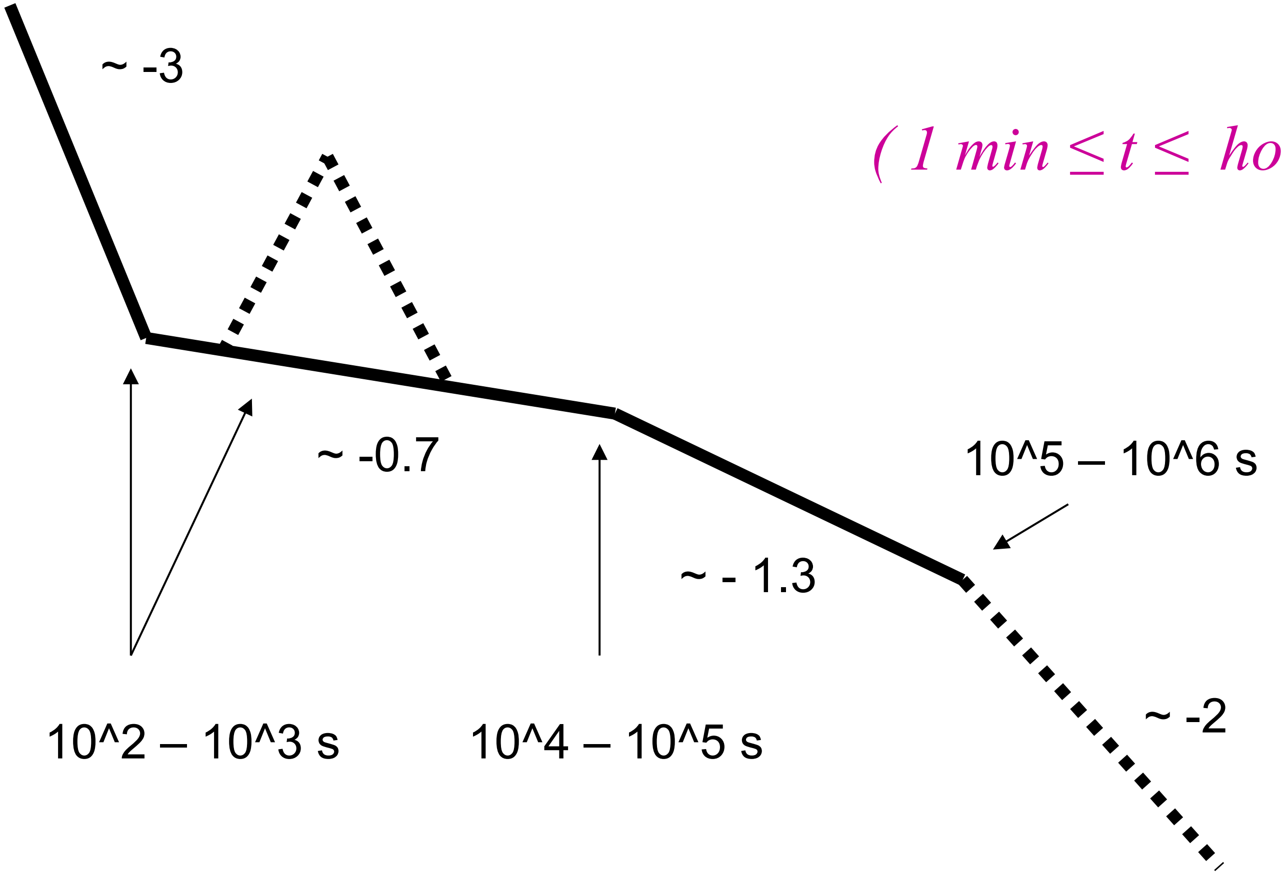


Swift discoveries



Adding pieces to the puzzle

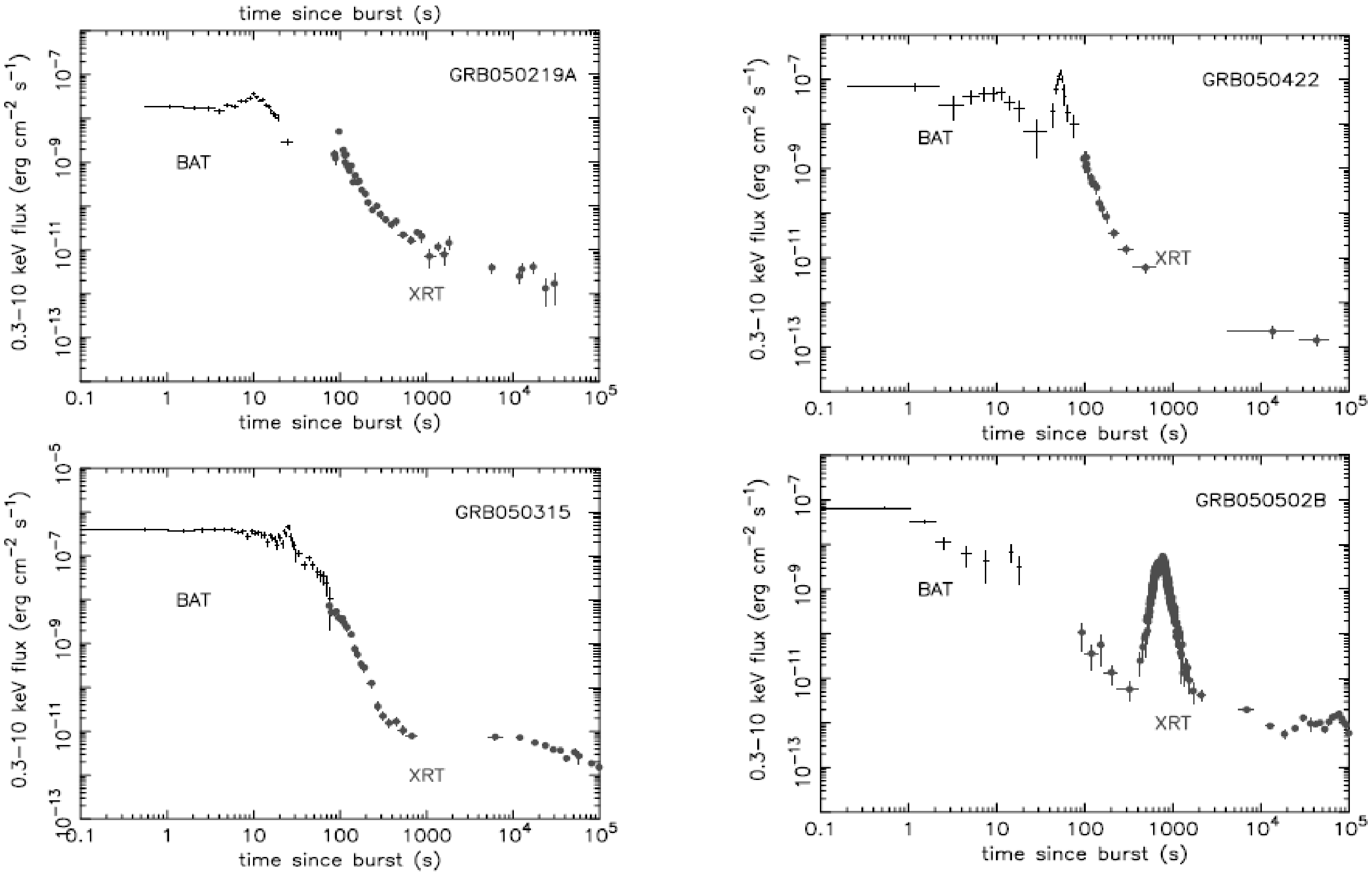
- **“canonical” early afterglow light curve**



(1 min $\leq t \leq$ hours)

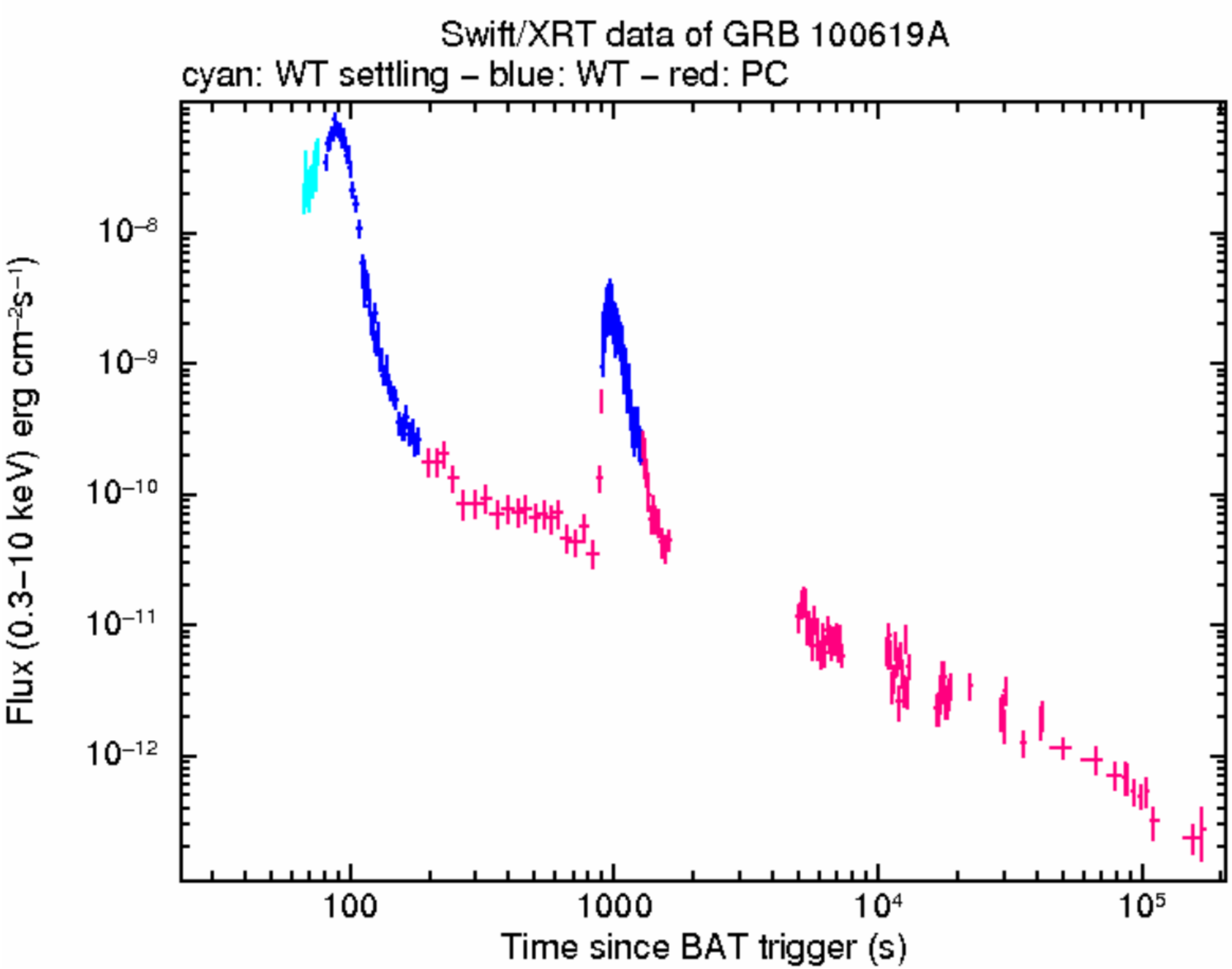
Adding pieces to the puzzle

- **new features seen by Swift in X-ray afterglow light curves: initial very steep decay, early breaks, flares; may occurr all together or only some of them**



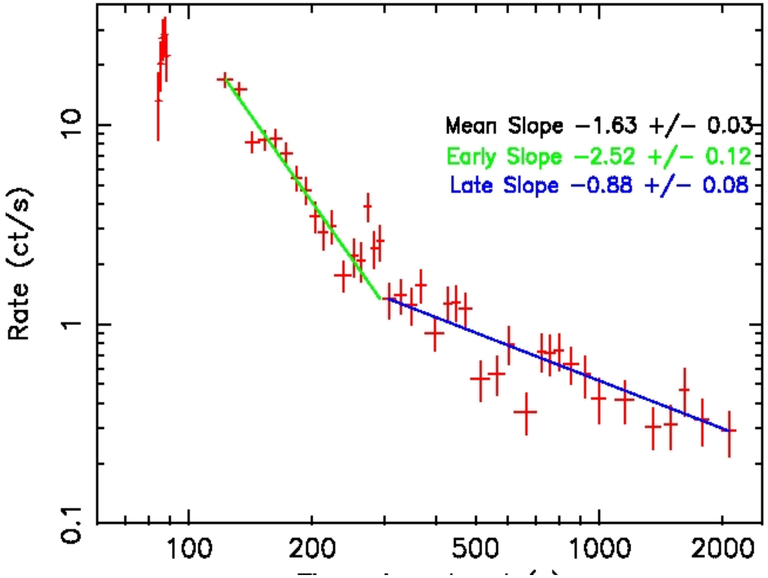
O’Brien et al. ApJ, 2006

XRT light curves

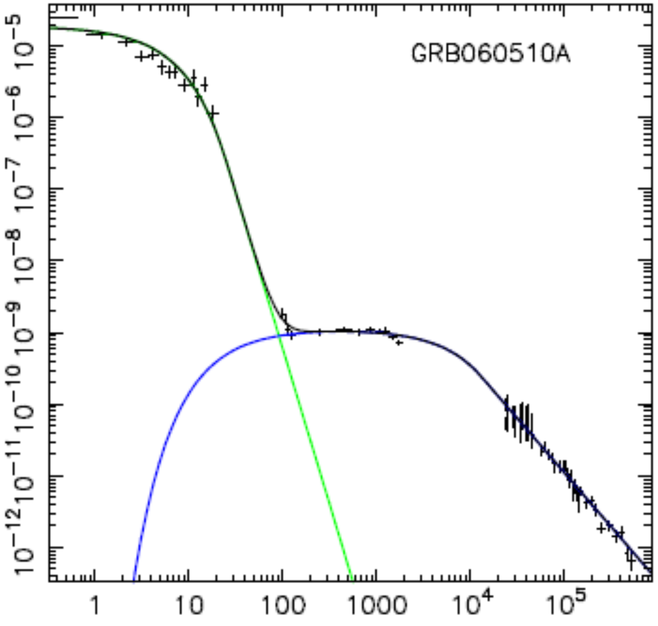


Adding pieces to the puzzle

- flat decay: probably “refreshed shocks”, due either to:
  - *Long* **duration ejection ($t \sim t_{flat}$)**
  - *Short* **ejection ($t \sim t_{\gamma}$), but with range of Γ**



- flat decay: superposition of end of prompt emission with start of afterglow emission



Questions from *Swift*

New mysteries

- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different GRBs have such similar afterglows?
- Why is the ambient medium (apparently) constant-density?
- What are the microphysics parameters?

Swift discoveries

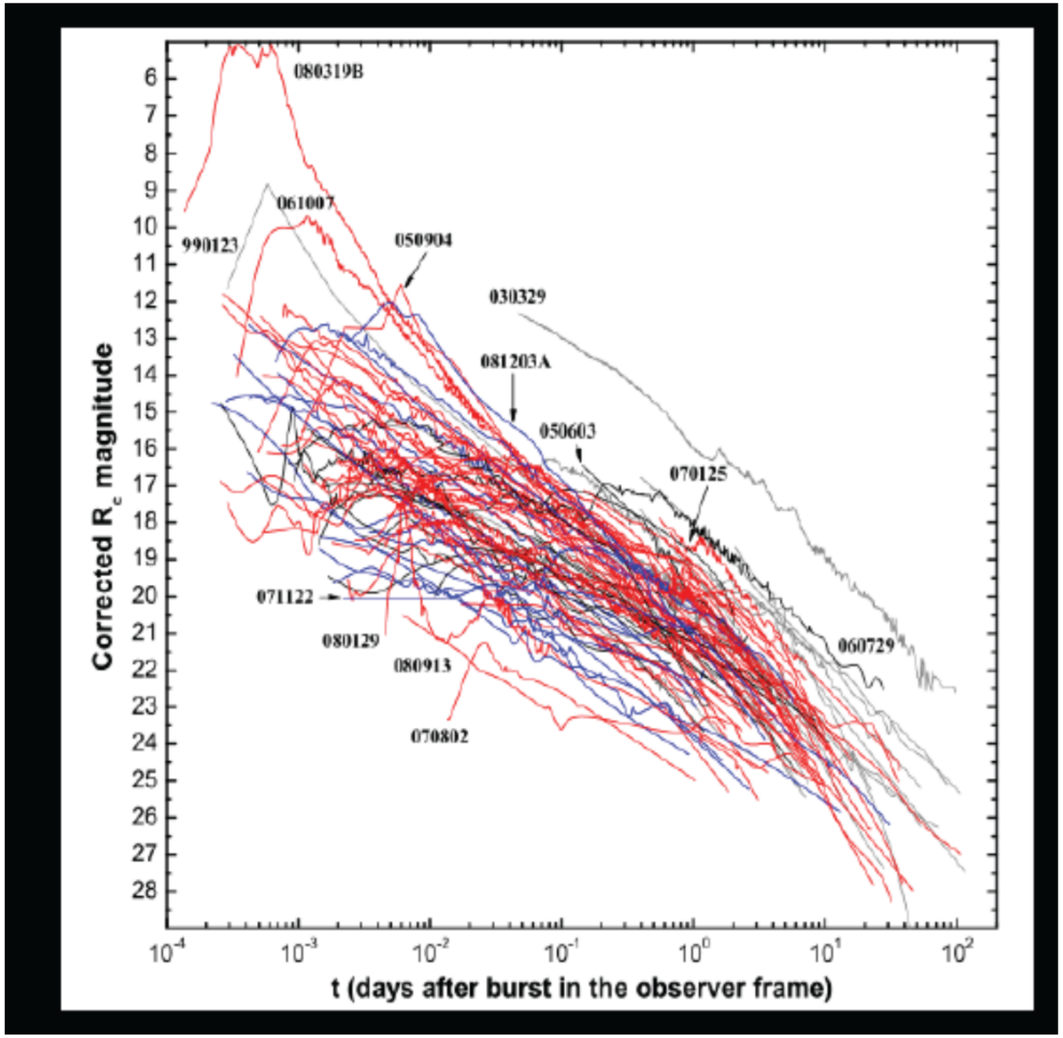
Where are the jet breaks?

- Strong, achromatic light curve steepening was expected in most/all GRBs – it's now exciting if we think we've got one!

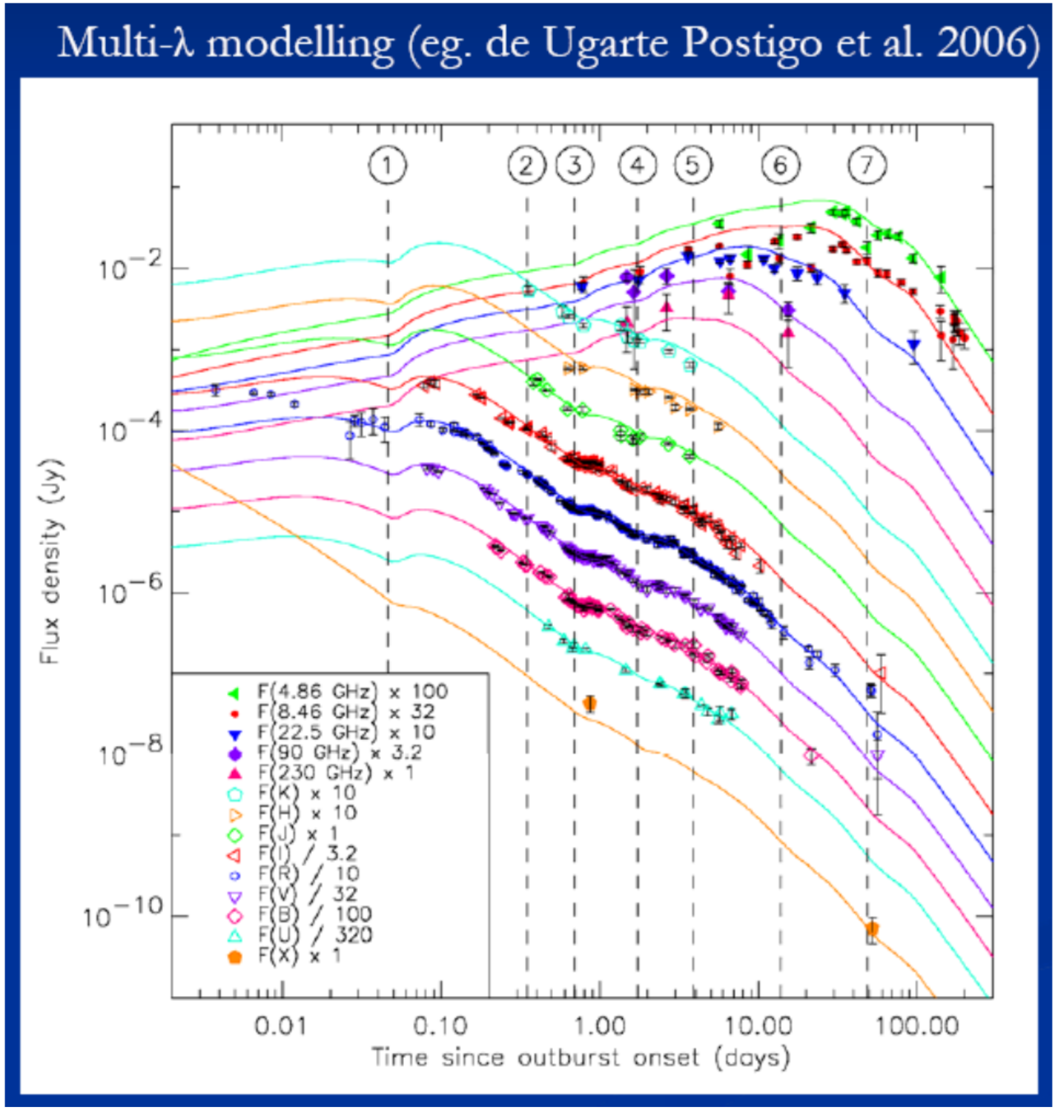
- They could be hidden (Curran et al. 2008), or we're not considering enough possibilities (Racusin et al. 2009)

- Perhaps the jets are structured/complex, so breaks are not achromatic? (e.g. Oates et al. 2007, de Pasquale et al. 2008).

Afterglows in the Swift era …



Afterglows in the Swift era



Multi-λ modelling (eg. de Ugarte Postigo et al. 2006)

Swift discoveries

GRB 080319B

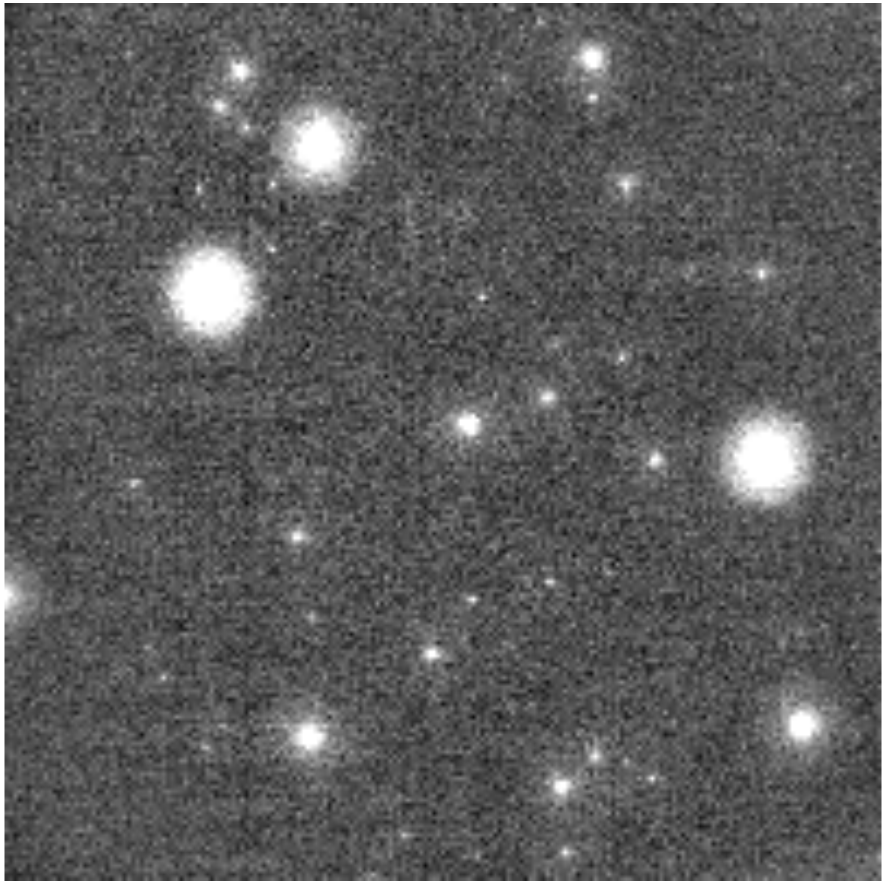
- Very bright – reached m_v=5.3.

Swift discoveries

GRB 080319B

- Very bright – reached m_v=5.3

Observations from Pi of the sky.



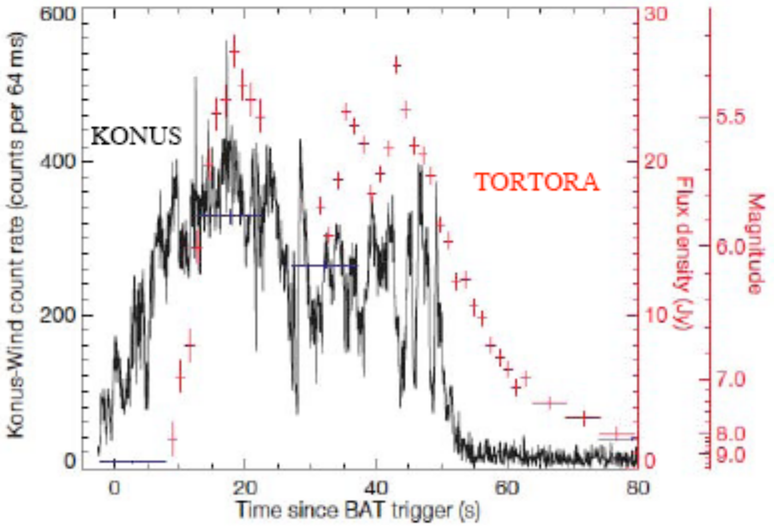
Swift discoveries

GRB 080319B

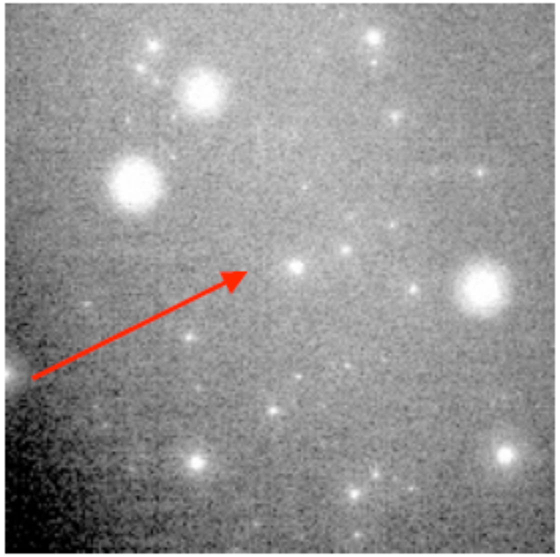
- Very bright – reached m_v=5.3
- z=0.9
- If it were at the Galactic centre, it would appear as bright as the Sun!
- Bright in X-rays and Gamma-rays, but nothing like as extraordinary as in the optical.
- Implies a complex jet structure (Racusin et al. 2008, Nature).

080319B

First "naked-eye" Burst GRB 080319B



Racusin et al.
2008



Pi-of-the-Sky

T90 = 50s   z = 0.94

Prompt optical observations:
Pi-of-the-Sky (Chile) pre-burst
RAPTOR (New Mexico)
REM/TORTORA (Chile)

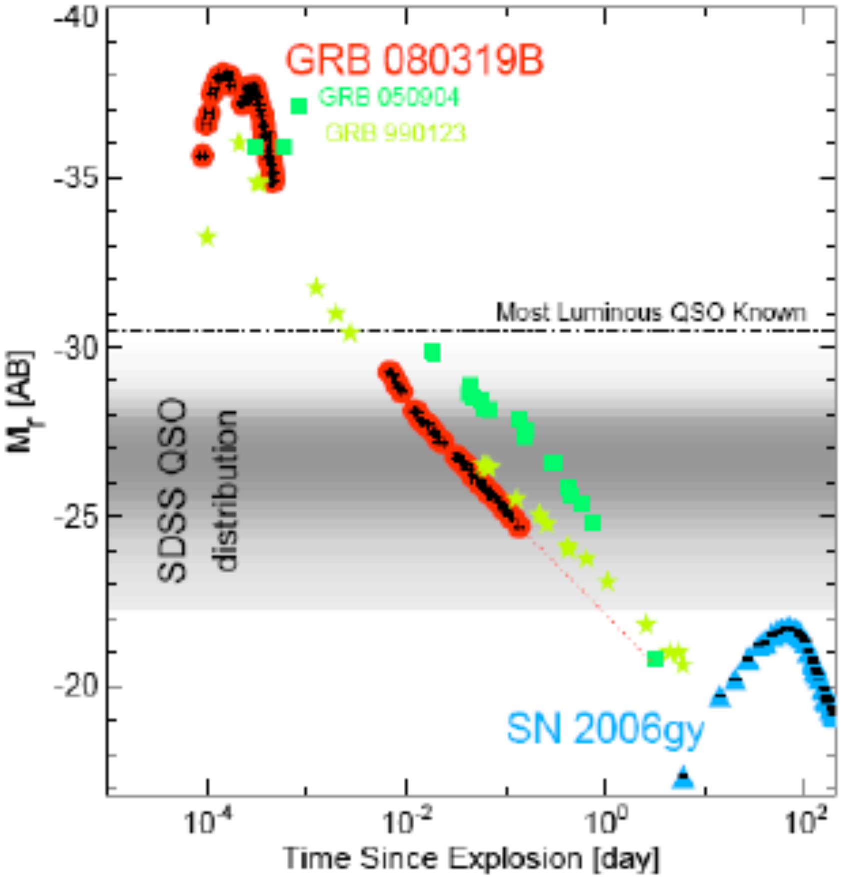
Peak brightness of 5.6 magnitudes!!

080319B

Even corrected for distance, brightest optical burst

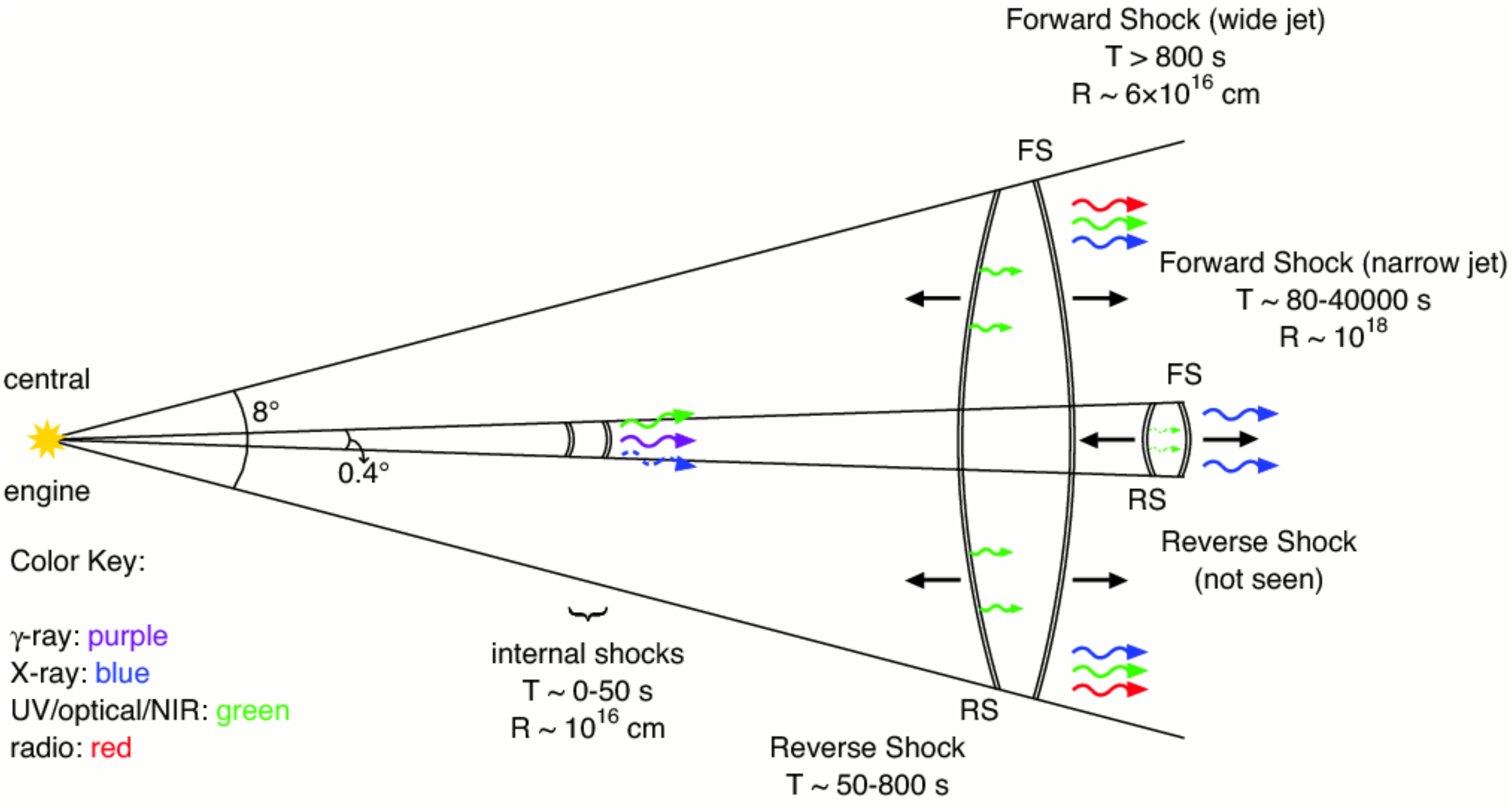
In our Galaxy, such a burst would be brighter than the sun!

GRBs much more luminous than most energetic quasars & SNe



Bloom et al. 2008

Swift discoveries



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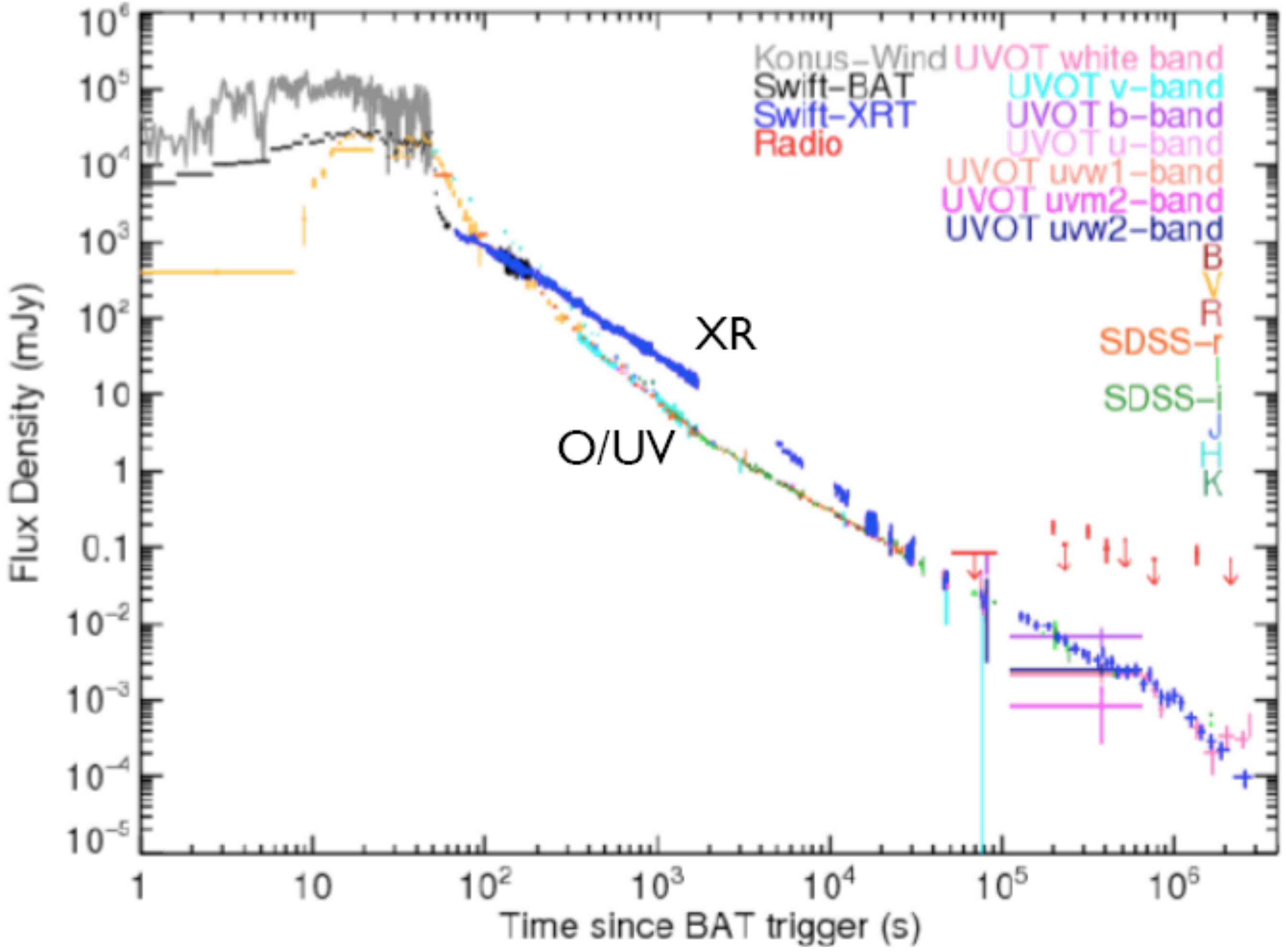
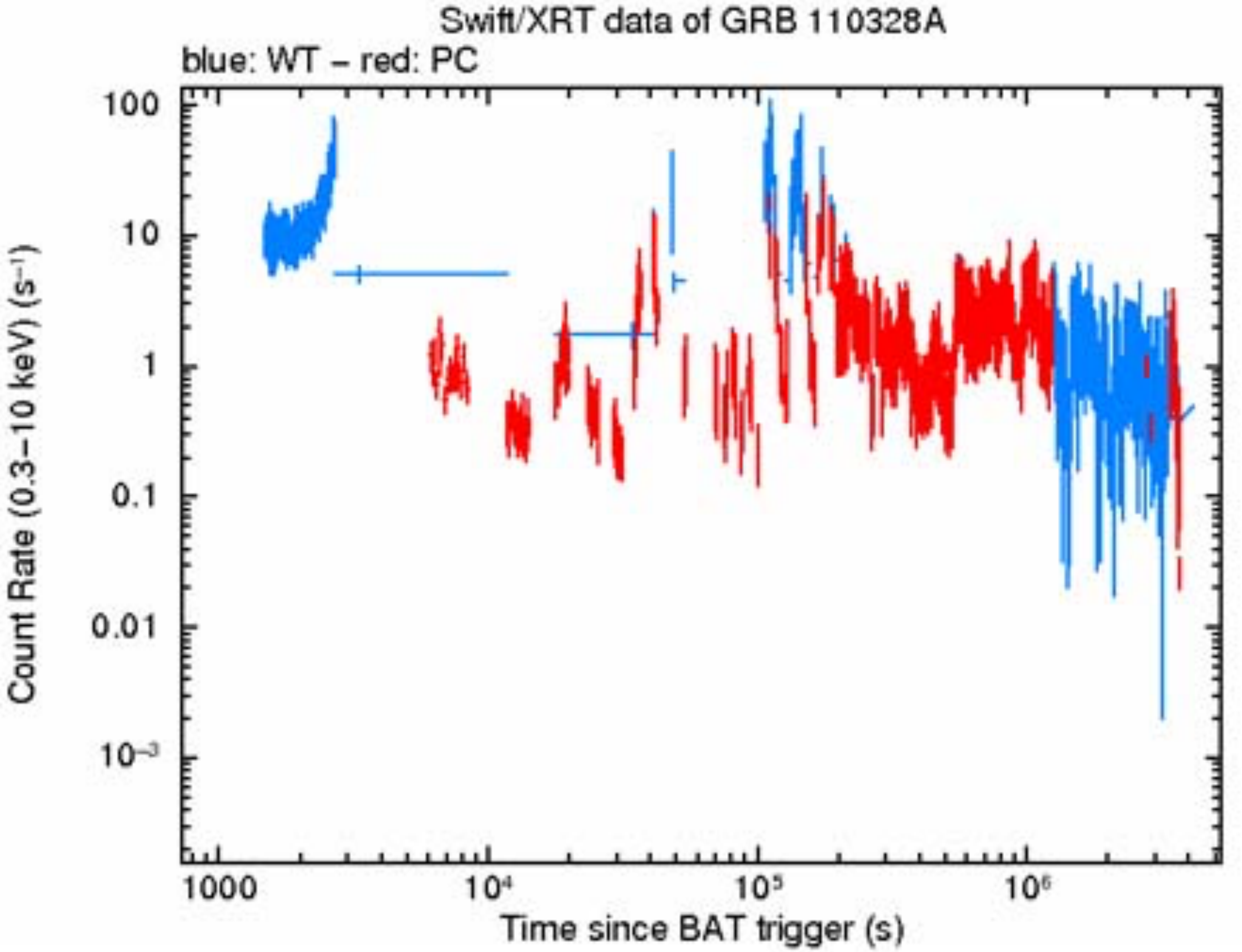

Konus–Wind
Swift–BAT
Swift–XRT
Radio
UVOT white band
UVOT v–band
UVOT b–band
UVOT u–band
UVOT uvw1–band
UVOT uvm2–band
UVOT uvw2–band
B
V
R
SDSS–r
I
SDSS–i
J
H
K
XR
O/UV
Flux Density (mJy)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
10^2
10^3
10^4
10^5
10^6
Time since BAT trigger (s)

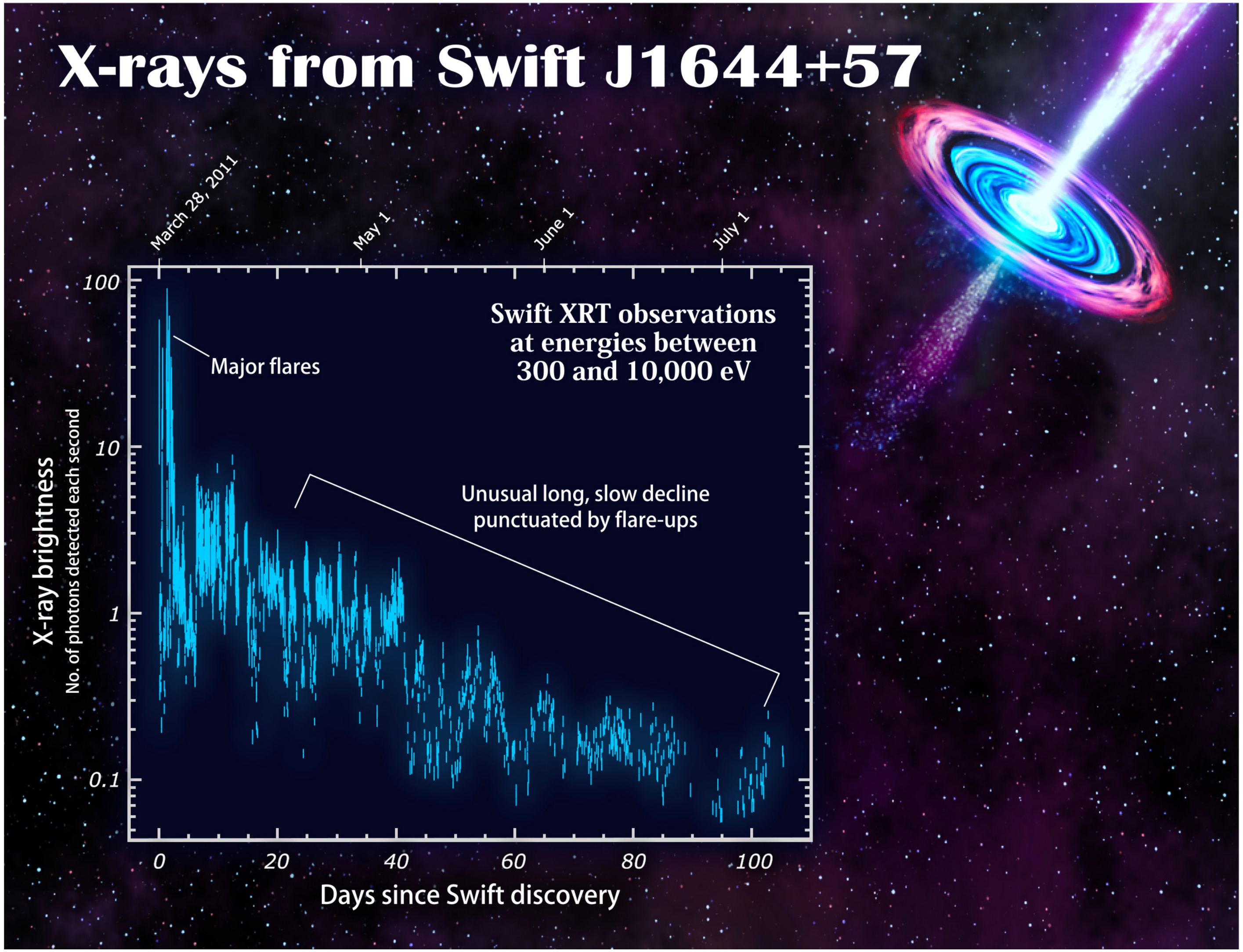
Summary

- *Swift* has helped to answer some questions:
  - Localised short GRBs
  - Supported collapsar and compact merger progenitor models.
- Asked a load of new questions!
  - What are the subtypes?
  - How do we get X-ray afterglows? And flares?
  - What is the jet structure?

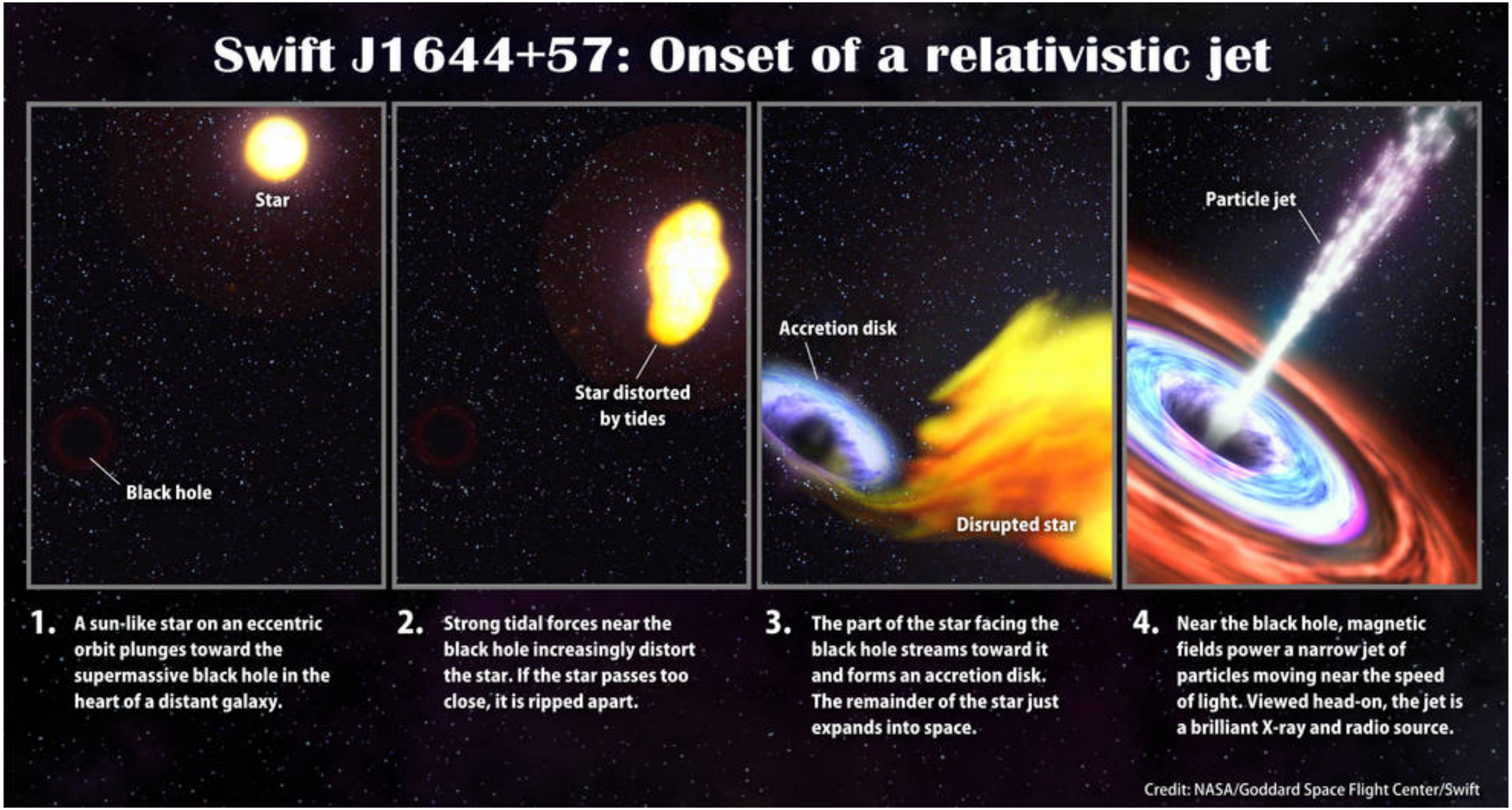
A peculiar GRB?



A peculiar GRB?



A peculiar GRB?

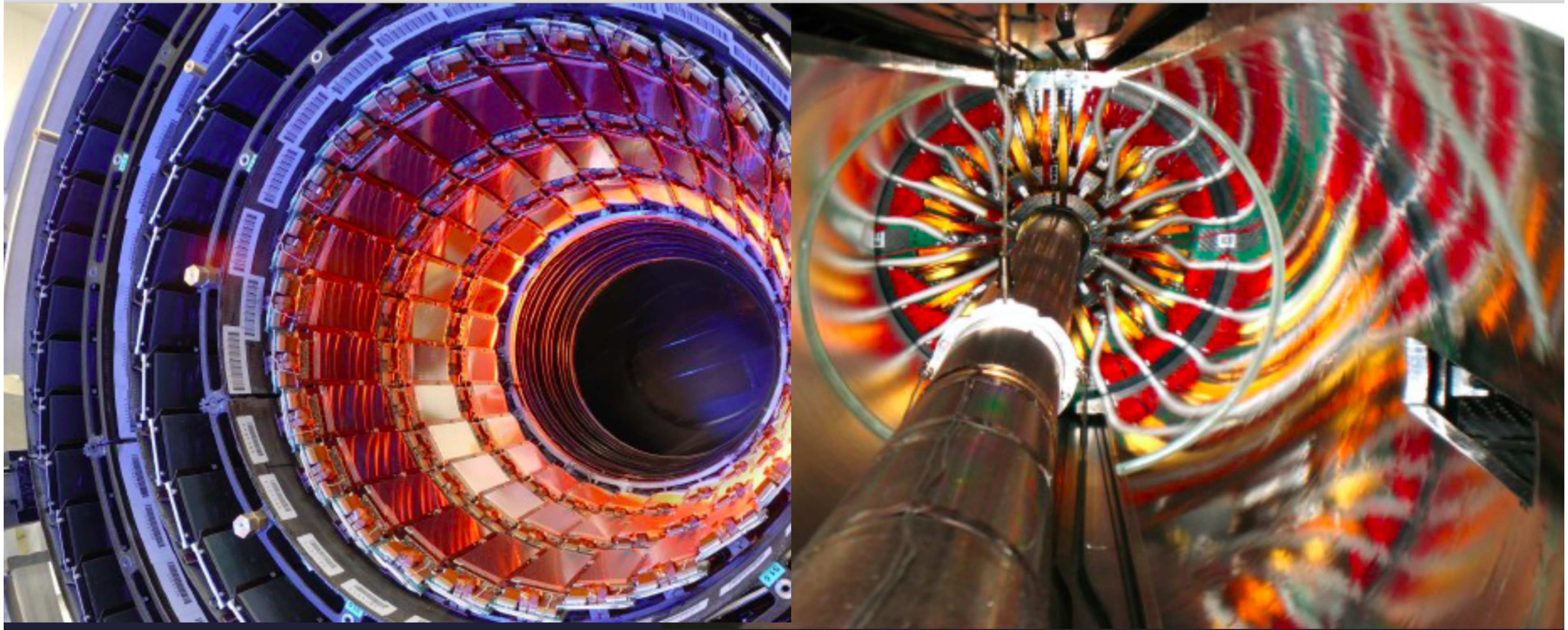


Swift J1644+57: Onset of a relativistic jet

1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.
2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.
3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.
4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

Credit: NASA/Goddard Space Flight Center/Swift

Astrofisica Nucleare e Subnucleare
Solid State Detectors



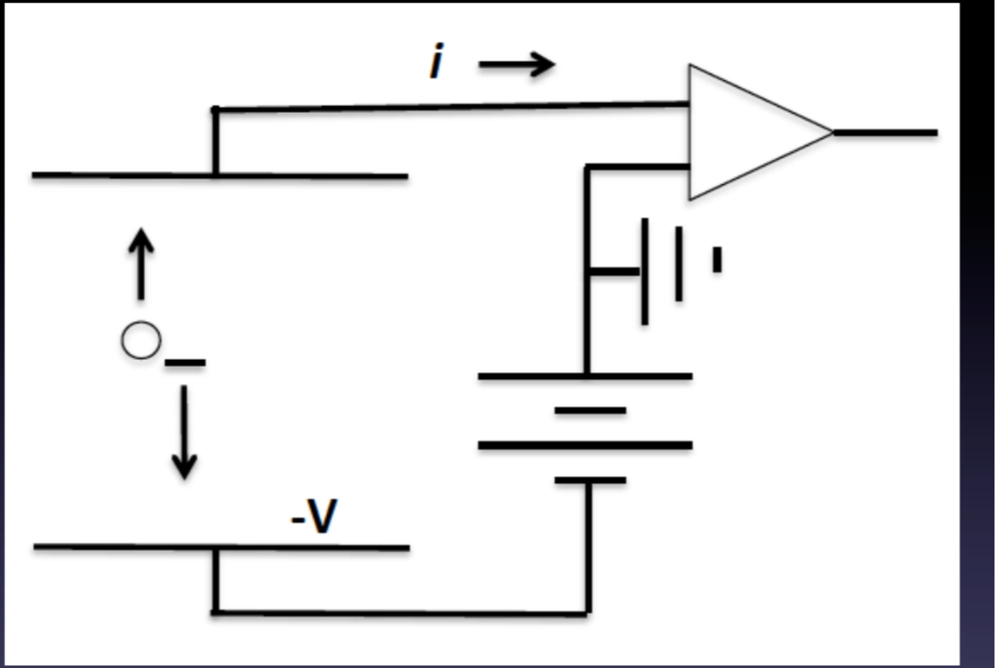
Detectors for Particle Physics

Semiconductor Detectors

D. Bortoletto

Solid State Detector

- A solid state detector is an ionization chamber
  - Ionizing radiation creates electron/hole pairs
  - Charge carriers move in applied E field
  - Motion induces a current in an external circuit, which can be amplified and sensed.



	Gas	Solid
Density	**Low**	**High**
Atomic number (Z)	**Low**	**Moderate (Z=14)**
Ionization Energy (ε_I)	**Moderate (≈ 30 eV)**	**Low (≈3.6 eV)**
Signal Speed	**Moderate (10ns-10μs)**	**Fast (<20 ns)**

Comparison solid state versus gas

Ionization chamber medium could be gas, liquid, or solid

- **Gas ⇒ electron and ion pairs; Semiconductor ⇒electron and hole pairs**

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Density	**Low**	**High**
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Solid State Detectors

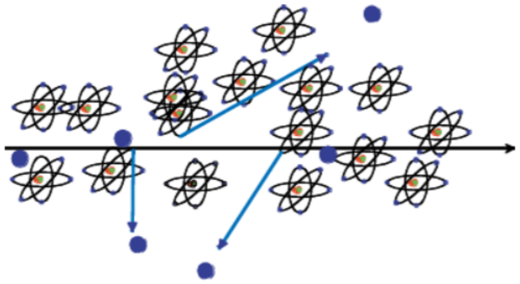
- Energy (E) to create e-h pairs 10 times smaller than gas ionization ⇒ increase charge⇒ good E resolution

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_I}} \propto \sqrt{\varepsilon_I}$$

- Greater density:
  - Reduced range of secondary electrons ⇒ excellent spatial resolution
  - Average E_{loss} ≈390eV/ µm ≈108 e-h/ µm (charge collected is a function of thickness d. Up-to-now no multiplication)
- To minimize multiple scattering d is small
  - 300 µm ≈32,000 e-h pairs ➔ good S/N

Solid State Detectors

Gas Detectors

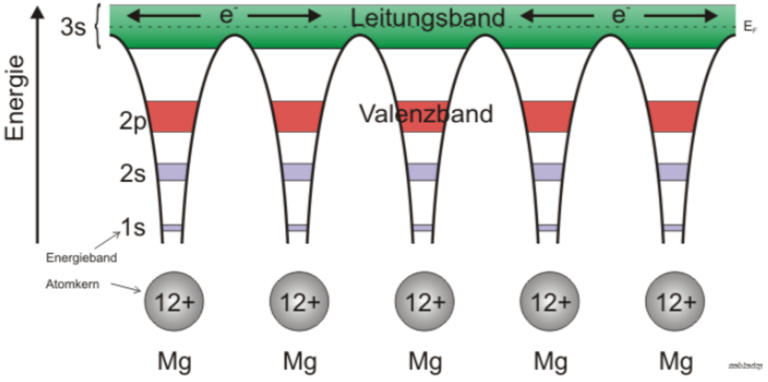


In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.

An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

For individual gas atoms, the electron energy levels are discrete.

Solid State Detectors

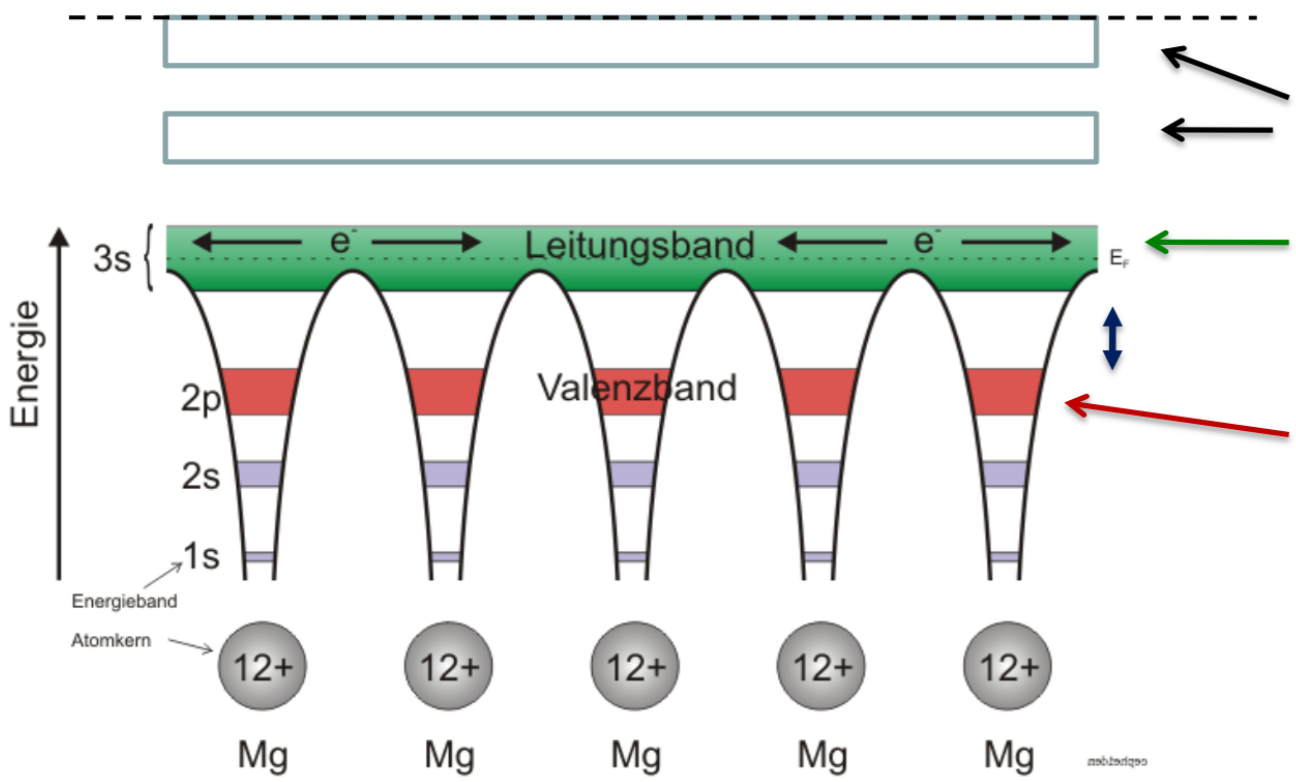


In solids (crystals), the electron energy levels are in 'bands'.

Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with 'their' atoms.

In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in these bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.

Solid State Detectors



Free Electron Energy

Unfilled Bands

Conduction Band

Band Gap

Valance Band

Conductor, Insulator, Semiconductor

In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and 'far away' from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.

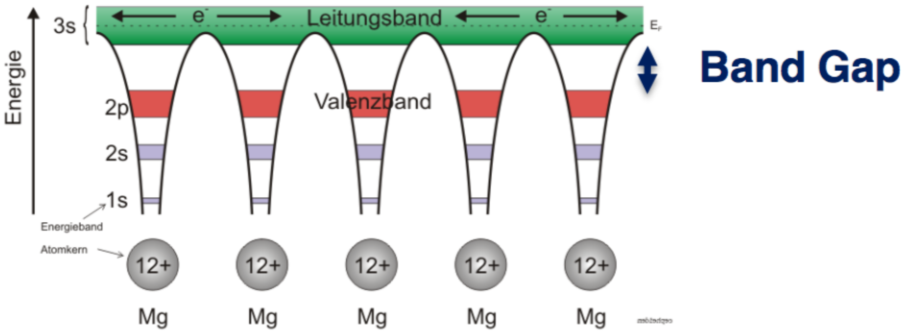
Solid State Detectors

Band Gap, e-h pair Energy

The energy gap between the last filled band – the valence band – and the conduction band is called band gap E_g.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.



Temperature, Charged Particle Detection

In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation → probability is proportional $\mathrm{Exp}(-E_g/kT)$.

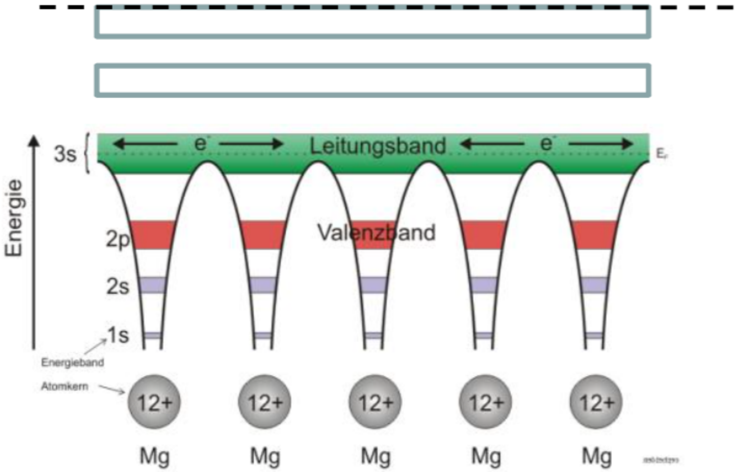
The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.

Solid State Detectors

Electron, Hole Movement:

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal (solid state physics).



Cooling:

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond (E_g=5.5eV) can be used for particle detection at room temperature,
Silicon (E_g=1.12 eV) and Germanium (E_g=0.66eV) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.

Solid State Detectors

Primary 'ionization':

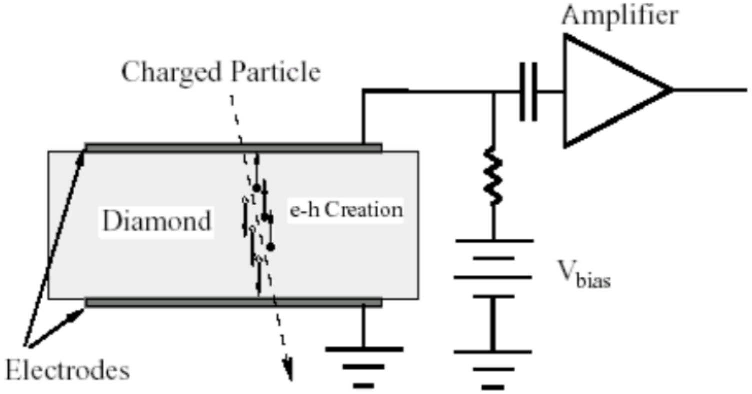
The average energy to produce an electron/hole pair is:
Diamond (13eV), Silicon (3.6eV), Germanium (2.9eV)

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

Solid State vs. Gas Detector:

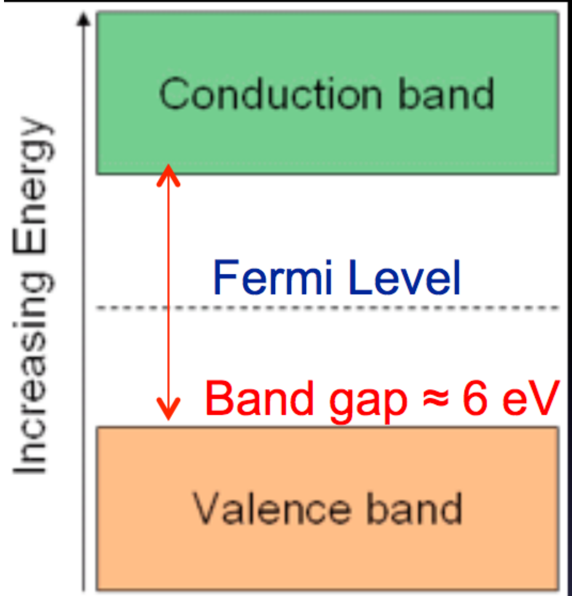
The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don't need internal amplification.

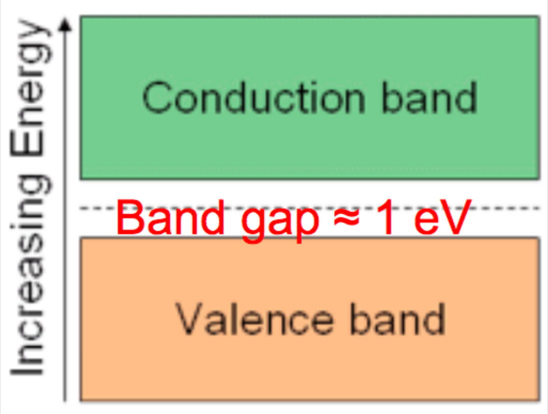
While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar → very short signals.

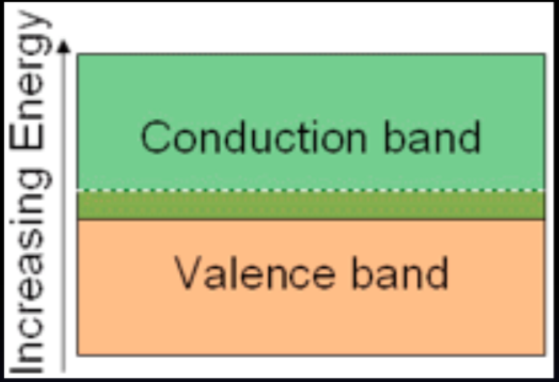


Diamond → A solid state ionization chamber

Semiconductor

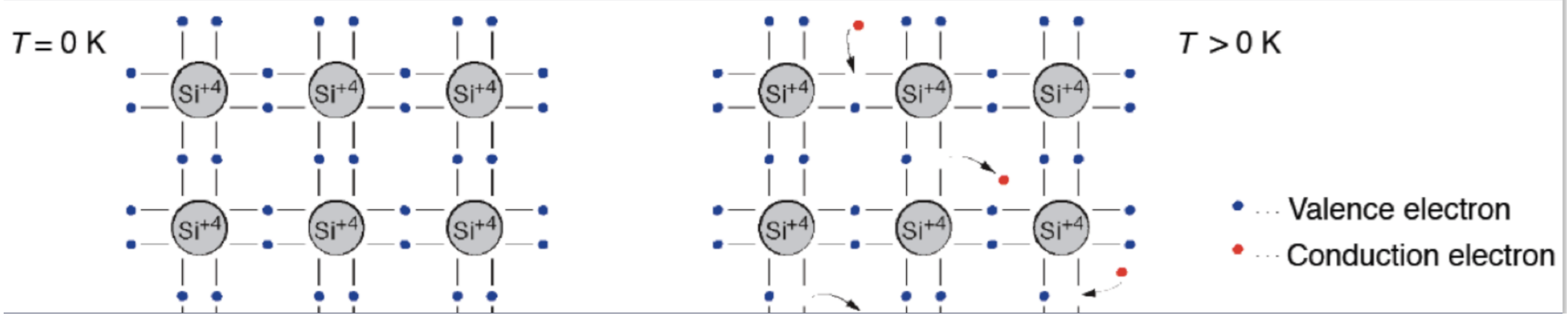






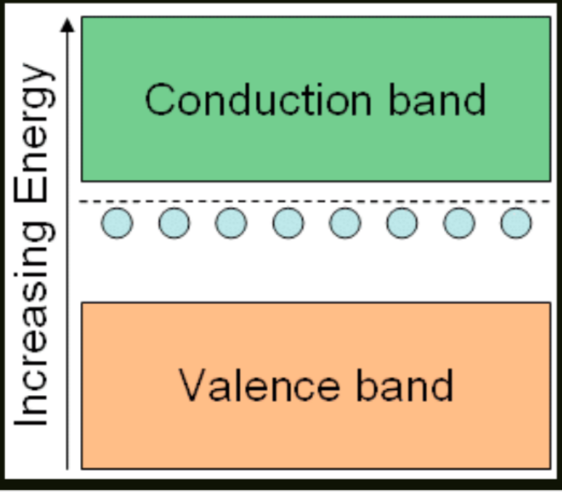
- Fermi level
  - Maximum electron energy at T = 0 K

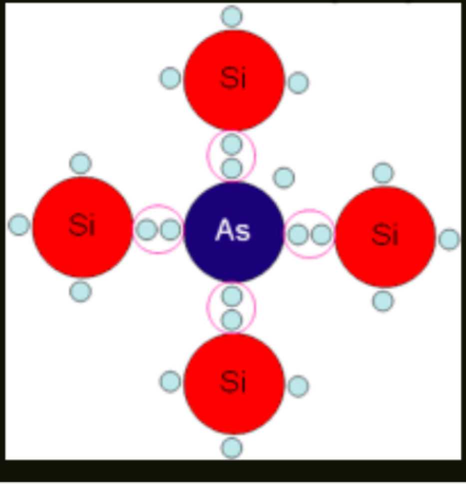
- Semiconductor: at room temperature electrons can already occupy the conduction band and may recombine with holes.
- Thermal equilibrium is reached between excitation and recombination when the charge carrier concentration $n_e = n_h = n_i$= intrinsic carrier concentration≈1.5×10^{10} cm^{-3}

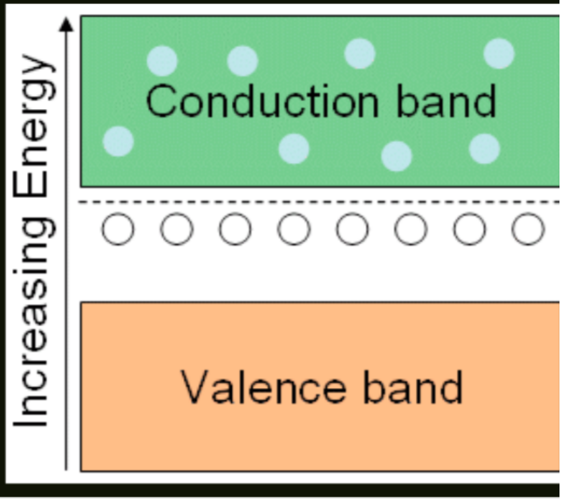


Doped semiconductors

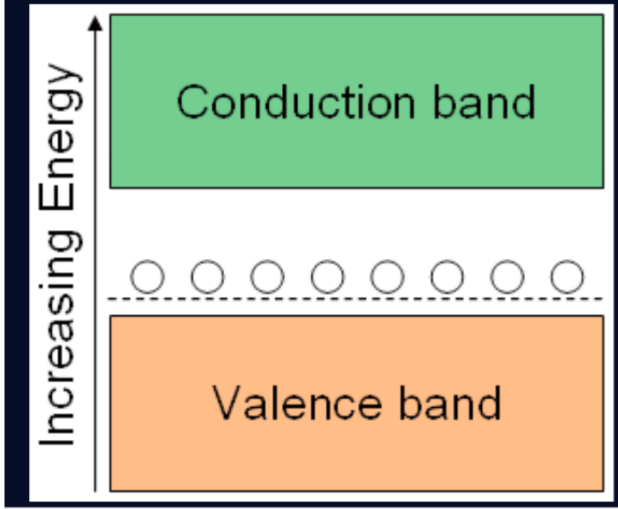
DONOR (N)

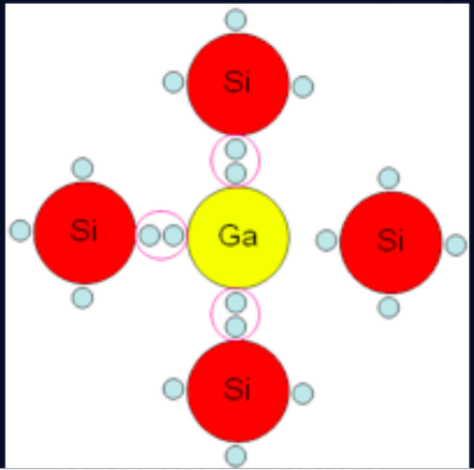


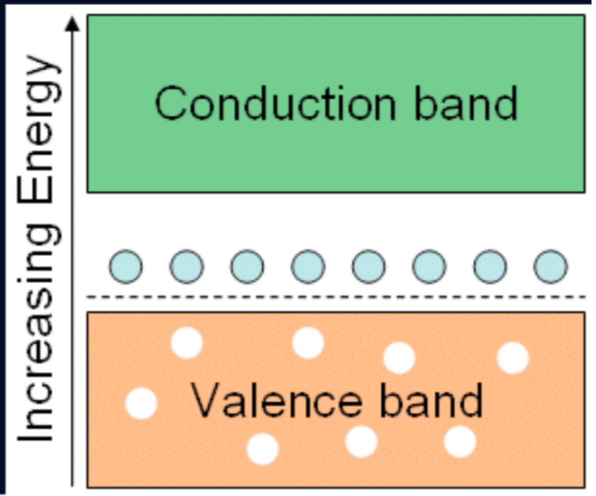




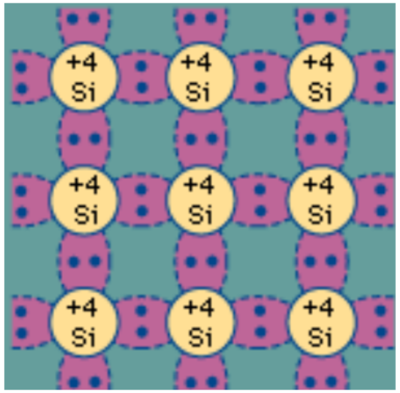
ACCEPTOR (P)



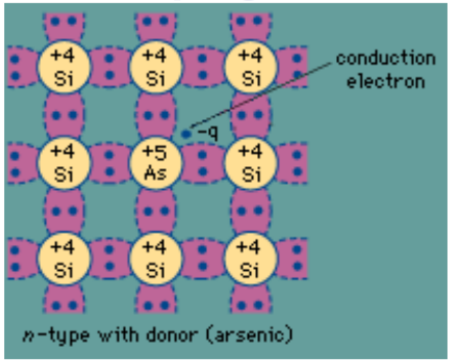


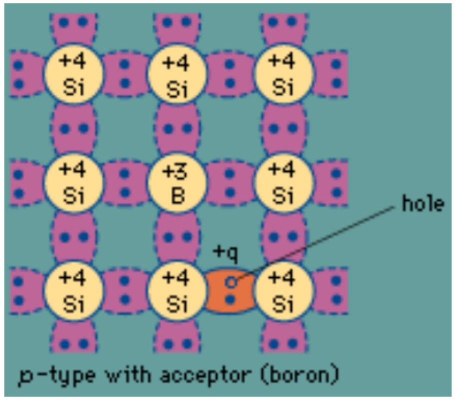


Doping of Silicon



doping



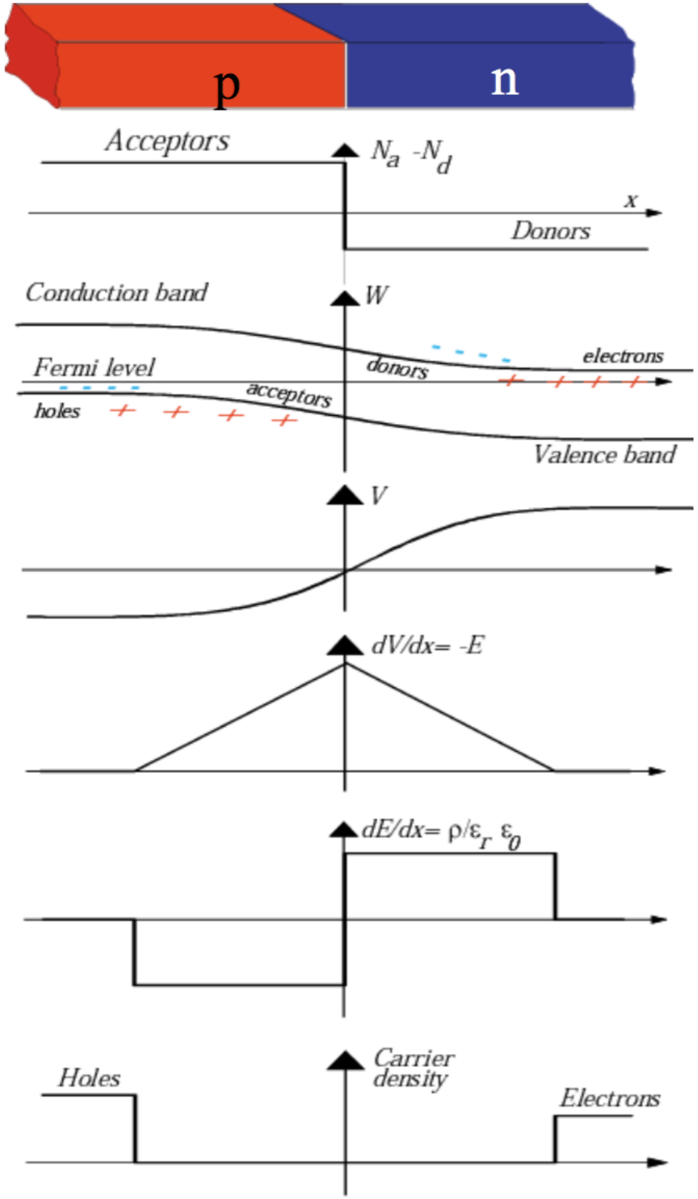


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

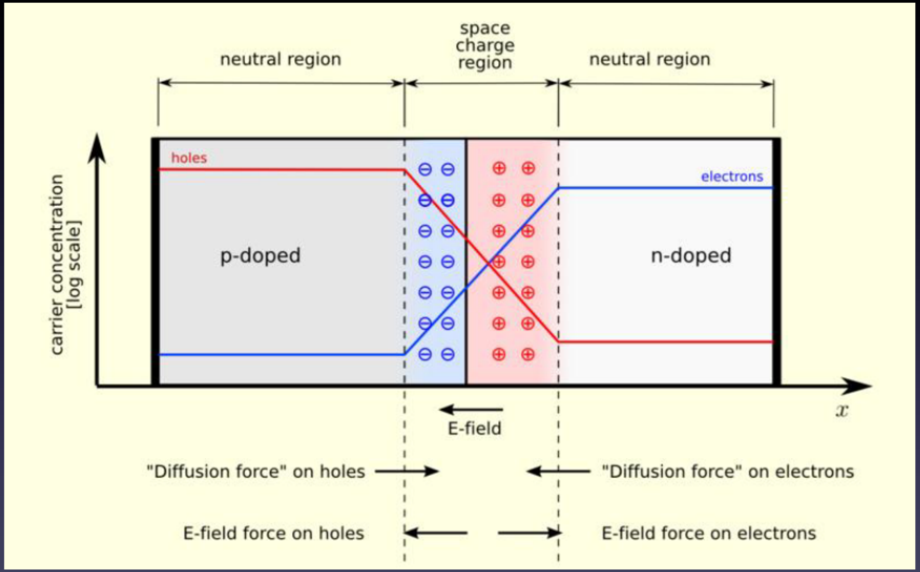
Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

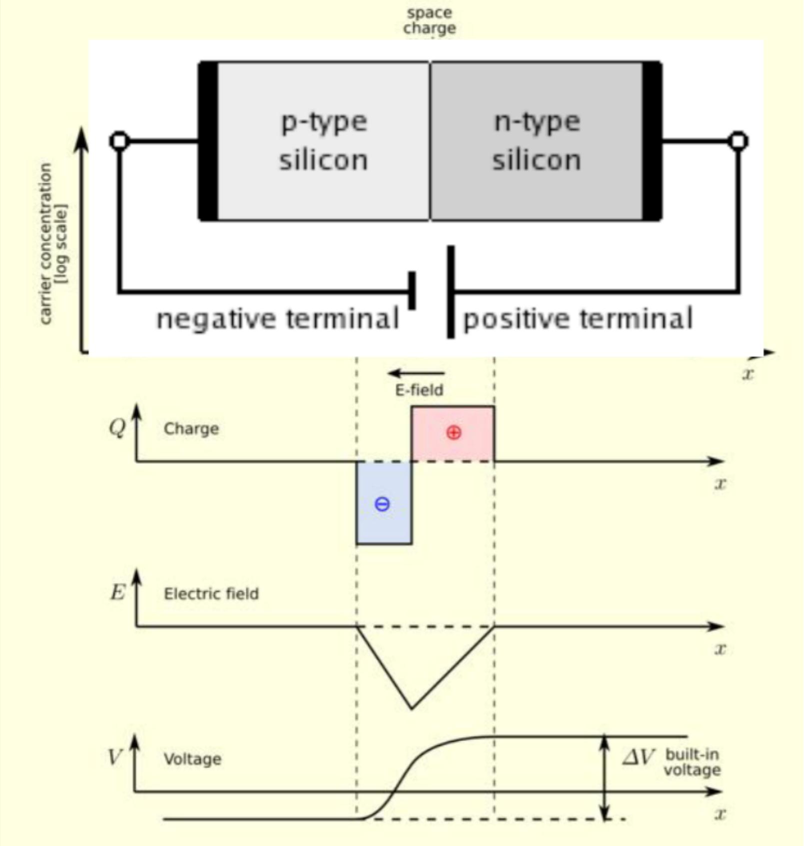
Bringing p and n in contact makes a diode.



PN Junction

- PN junction without external voltage
  - Free charges move until the chemical potential is balanced by an electrical potential called the built-in potential





- The space charge (depletion) region can be made bigger by applying a reverse bias voltage

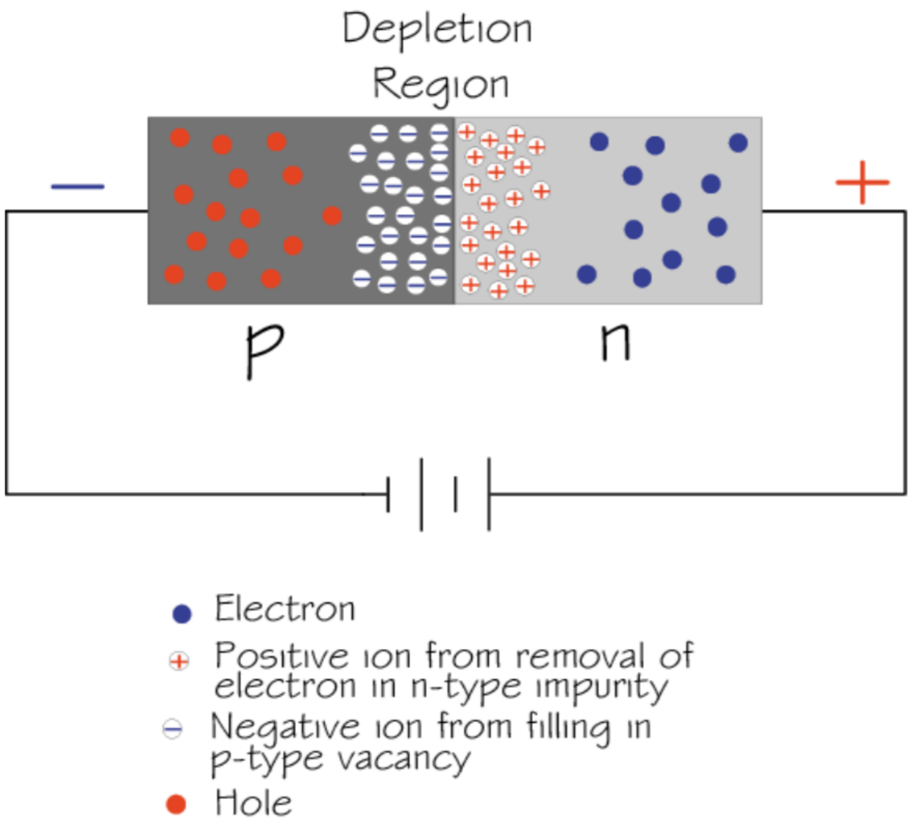
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

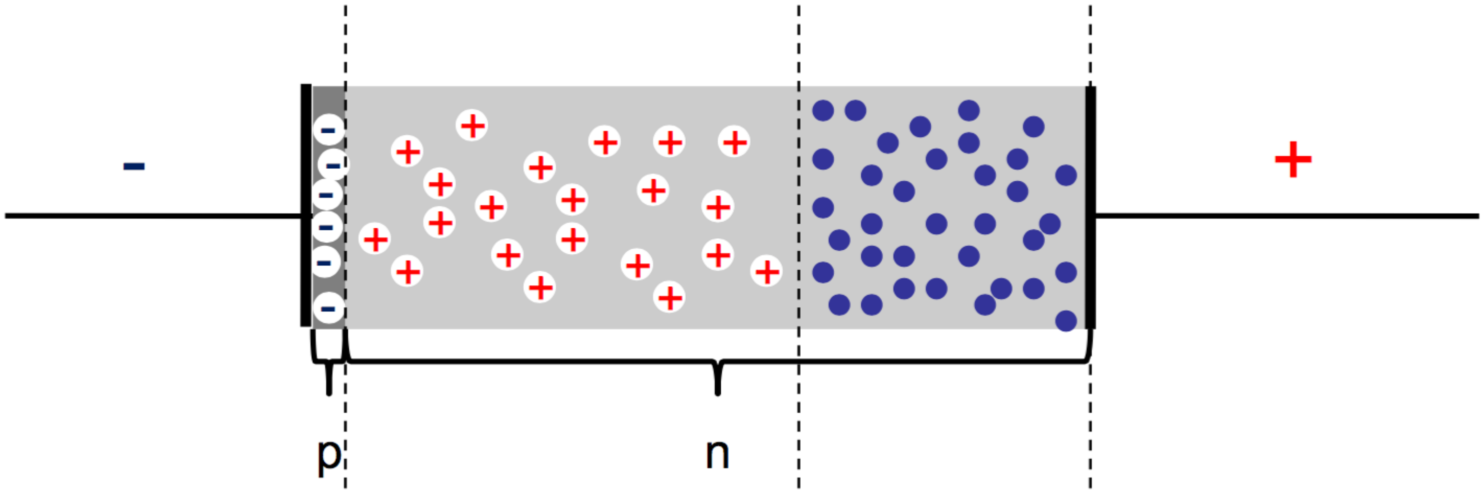
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.



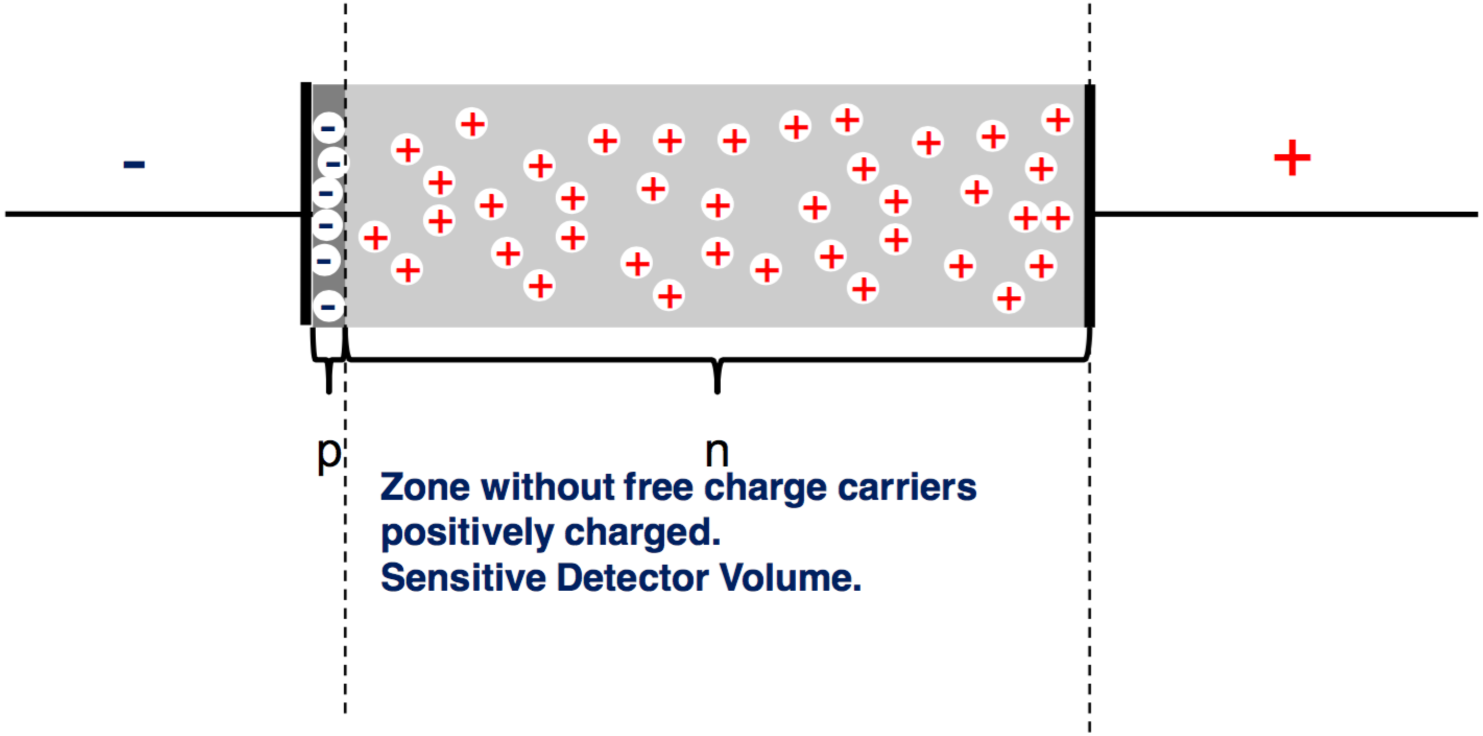
Under-Depleted Silicon Detector



Zone without free charge carriers positively charged. Sensitive Detector Volume.

Zone with free electrons. Conductive. Insensitive to particles.

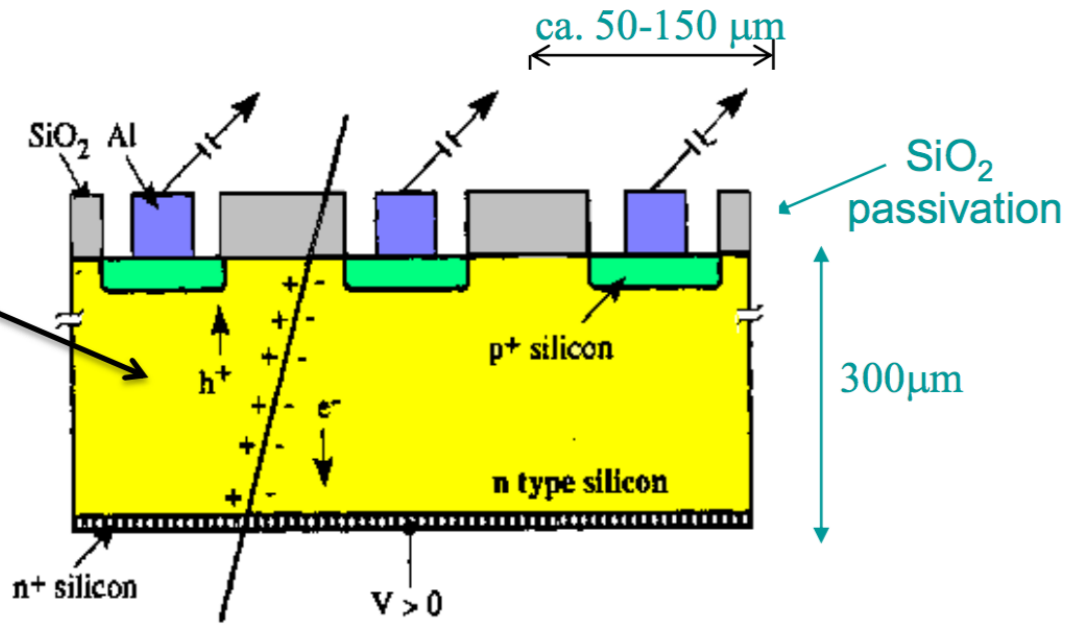
Fully-Depleted Silicon Detector



Zone without free charge carriers positively charged.
Sensitive Detector Volume.

Silicon Detector

Fully depleted zone

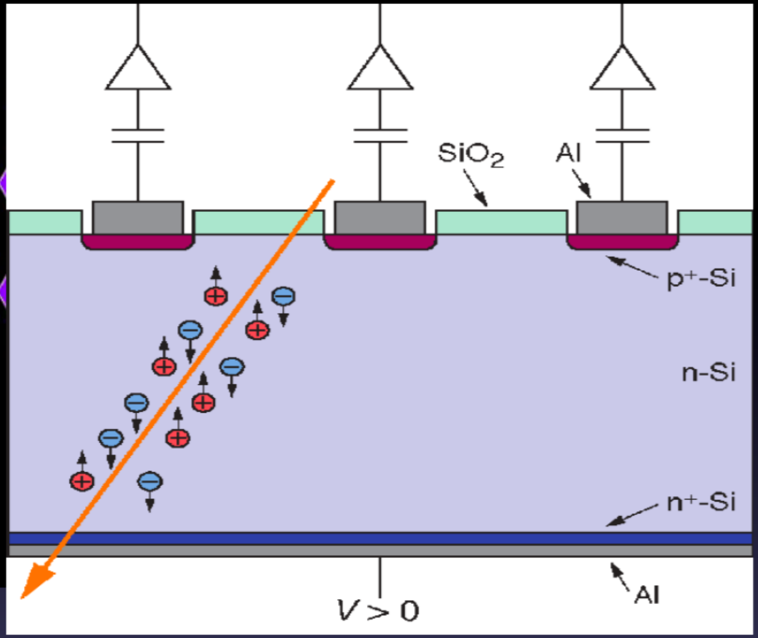


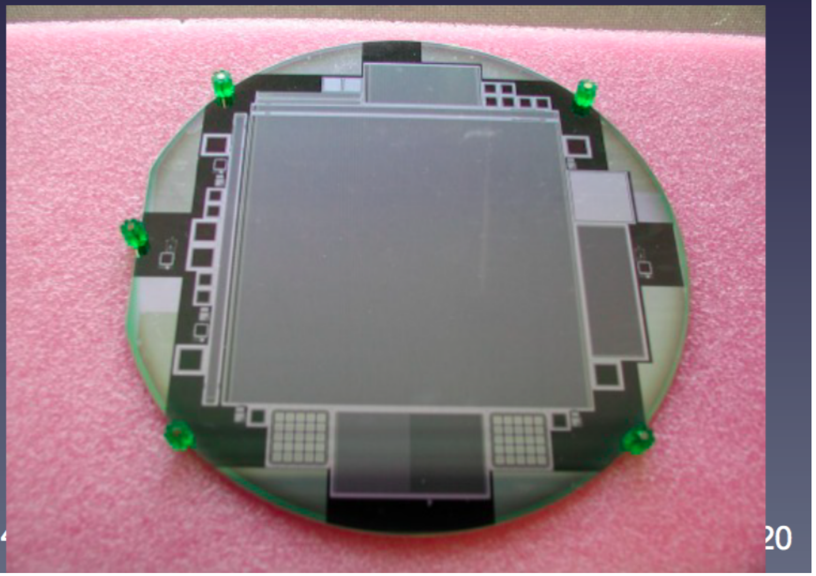
N (e-h) = 11 000/100µm

Position Resolution down to ~ 5µm !

Silicon Strip Detectors (SSD)

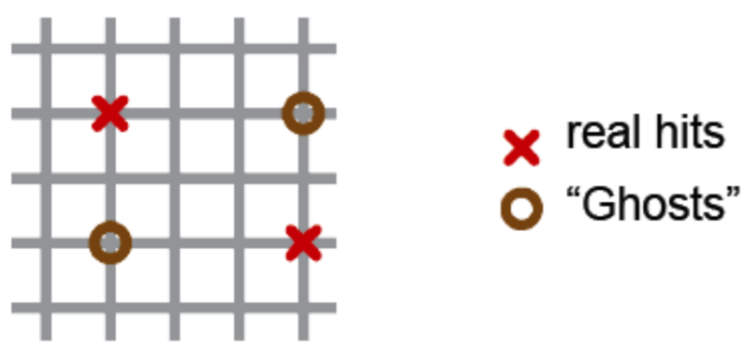
- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension
- DC-coupled strip detector – simplest position sensitive Silicon detector
- Standard configuration:
  - Strips p implants
  - Substrate n doped (~2-10 kΩcm) and ~300μm thick
  - $V_{dep} < 200$ V
  - Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown
- Highest field close to the collecting electrodes (junction side) where most of the signal is induced

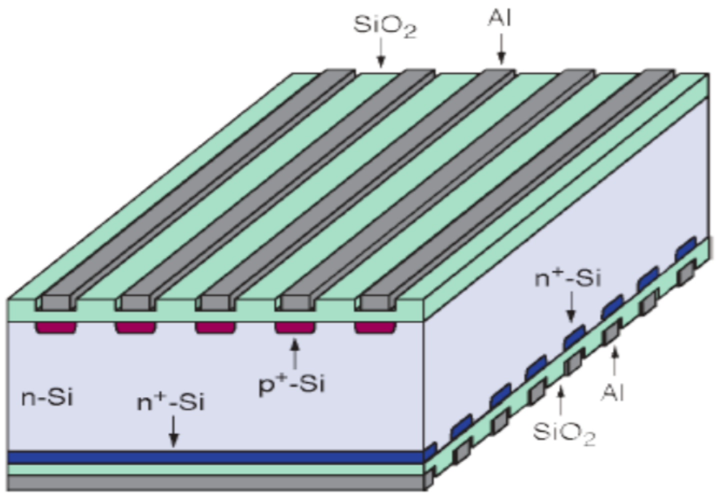




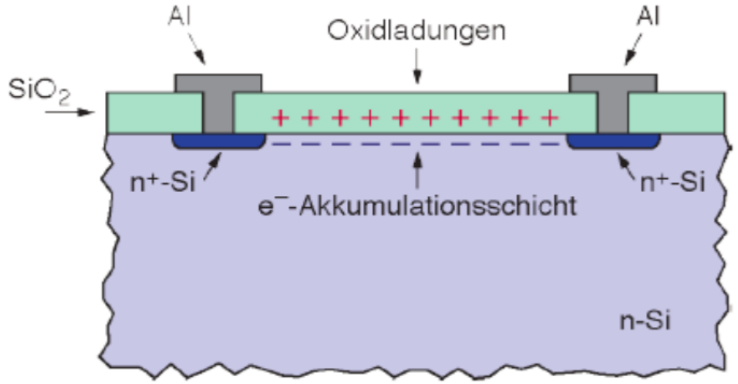
Double Sided Silicon Detectors

- **Advantages:**
  - More elegant for measuring 2 coordinates than using stereo modules
  - Saves material
- **Disadvantages:**
  - Needs special strip insulation of n-side (p-stop, p-spray techniques)
  - Complicated manufacturing and handling procedures
- Expensive
- Ghost hits possible





Scheme of a double sided strip detector (biasing structures not shown)

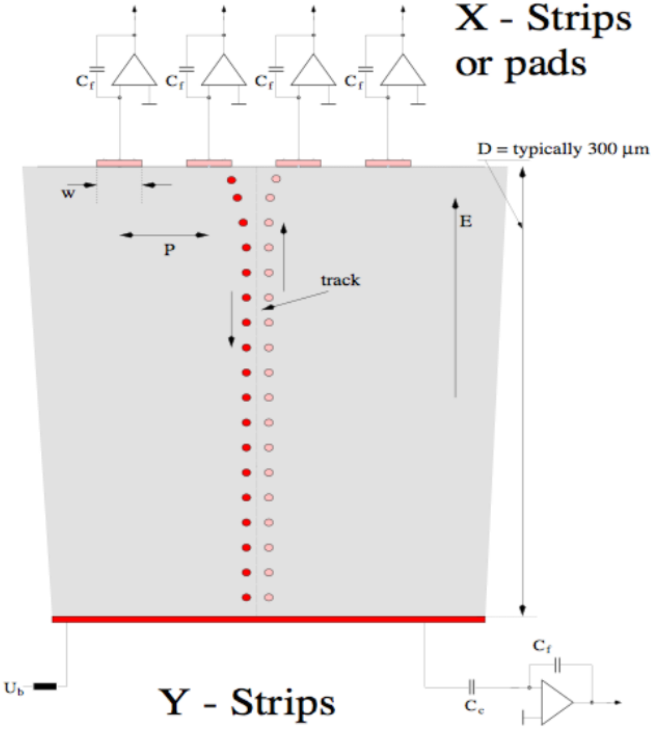


Positive oxide charges cause electron accumulation layer.

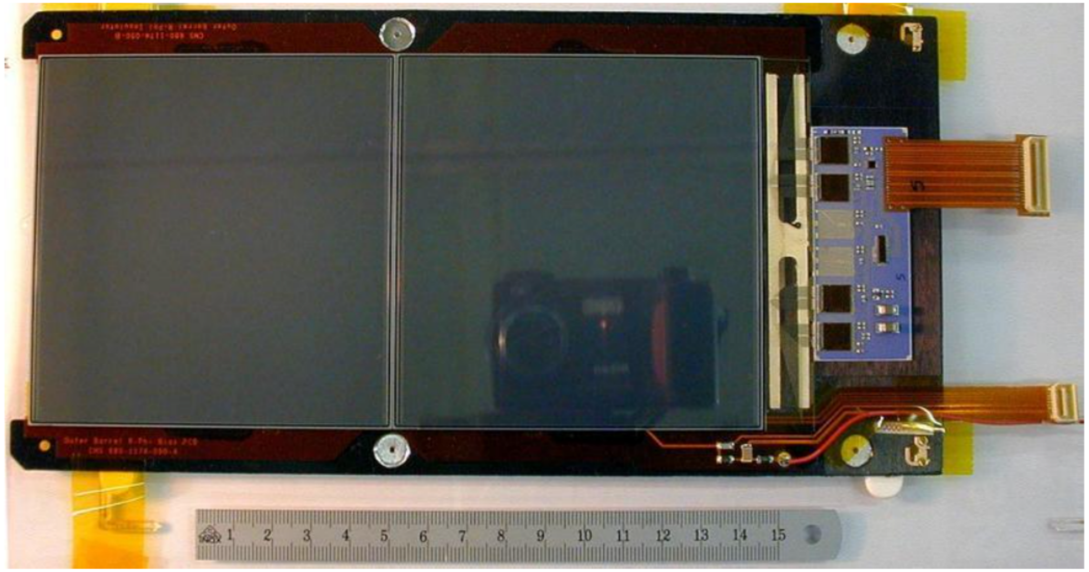
Silicon Detector

Every electrode is connected to an amplifier →
Highly integrated readout electronics.

Two dimensional readout is possible.



CMS Outer Barrel Module



Silicon Drift Detector (like gas TPC !)