# The peculiar light curve of GRB100814A: an interplay of forward and reverse shocks?

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# Properties of the γ-ray prompt emission are unremarkable

Detected by Swift, Konus-Wind, Suzaku, Fermi-GBM

T90 = 174.5 ± 9.5 s in Swift

Peak count rate: 2.5±0.2 ph cm$^{-2}$ s$^{-1}$ in the 15−150 keV band.

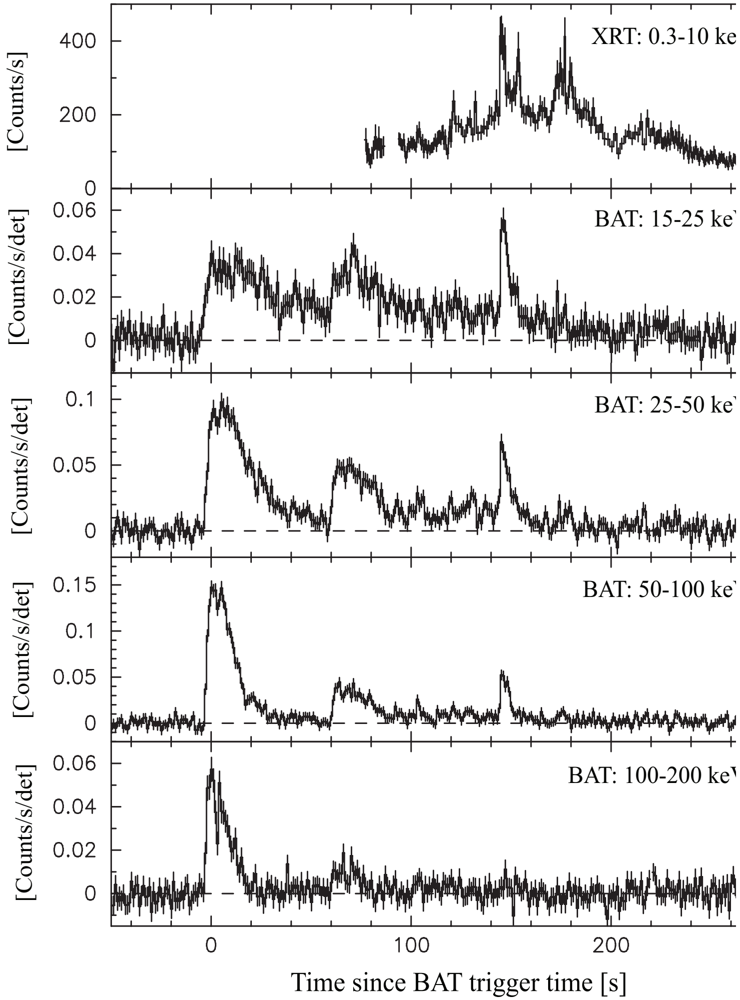
Typical powerlaw * exponetial cut-off spectrum:

Photon Index 0.4; E peak = 128 keV (Konus-Wind)

Fluence 0.02-2 MeV: 1.2 ± 0.2 10$^{-5}$ erg cm$^{-2}$

Optical source; redshift z=1.44

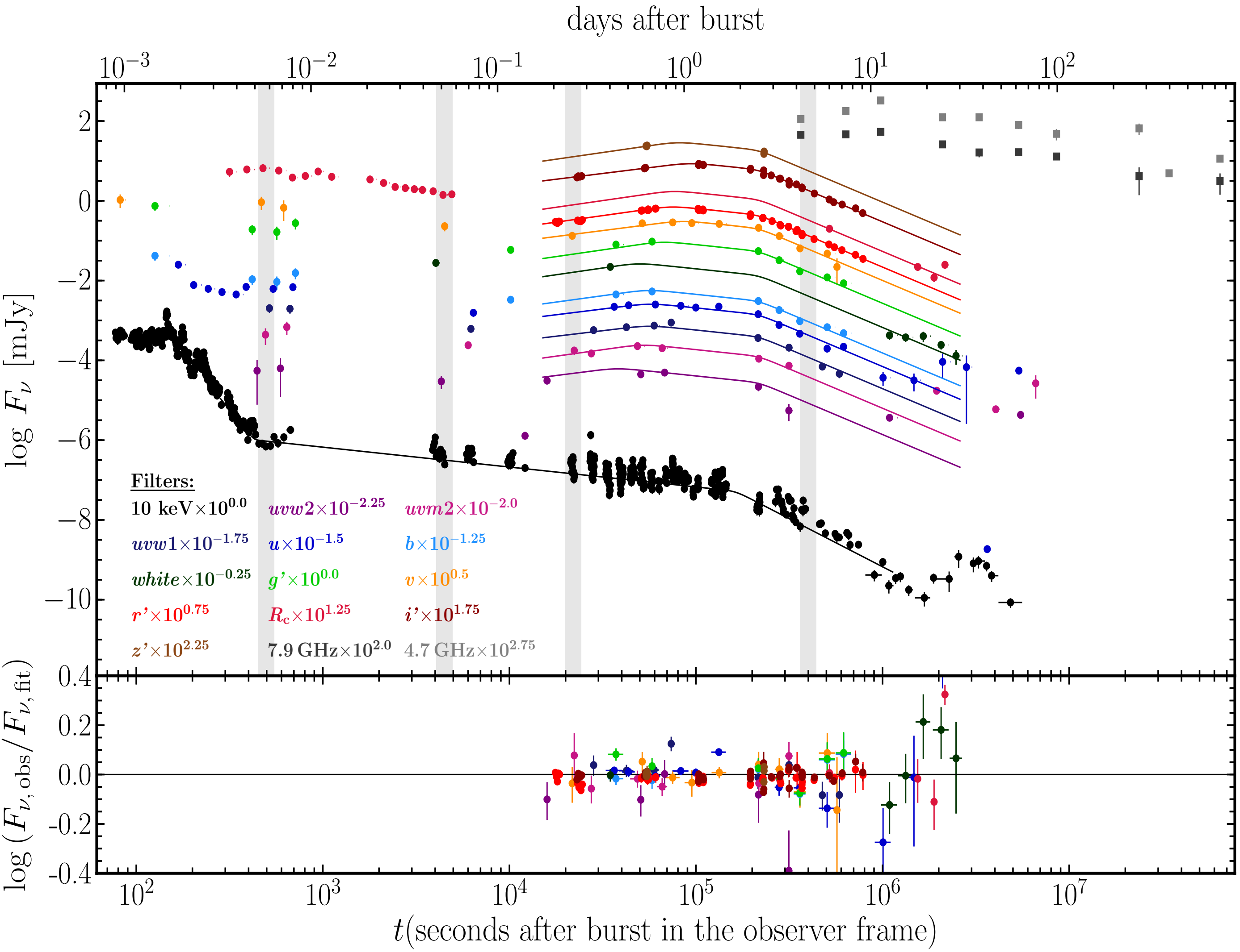
Energy emitted 1-10000 keV: 7 x 10$^{52}$ erg.



# Very rich data set for the afterglow

- Bright X-ray afterglow detected by *Swift*/XRT
- An optical source was detected by *Swift*/UVOT, ROTSE, Faulkes Telescope, Lulin Telescope, Nordic Optical Telescope, CQUEAN at McDonald Observatory, Gran Telescopio Canarias, Calar Alto and BTA 6-m
- Radio emission detected by Expanded VLA
- X-ray and optical follow up from 100 till $10^6$ second, and radio follow up till 60 $\times 10^6$ seconds

# The optical afterglow shows a rebrightening with no counterpart in the X-ray band.



Initially, both X-ray and optical LCs show similar slow decay slope

However, at ~15 ks the optical LCs show a flux rise, peaking at ~1 day followed by plateau

There is no analogous beheaviour in the X-ray: decay as before

But both the X-ray and optical break to a steep decay at ~150 ks

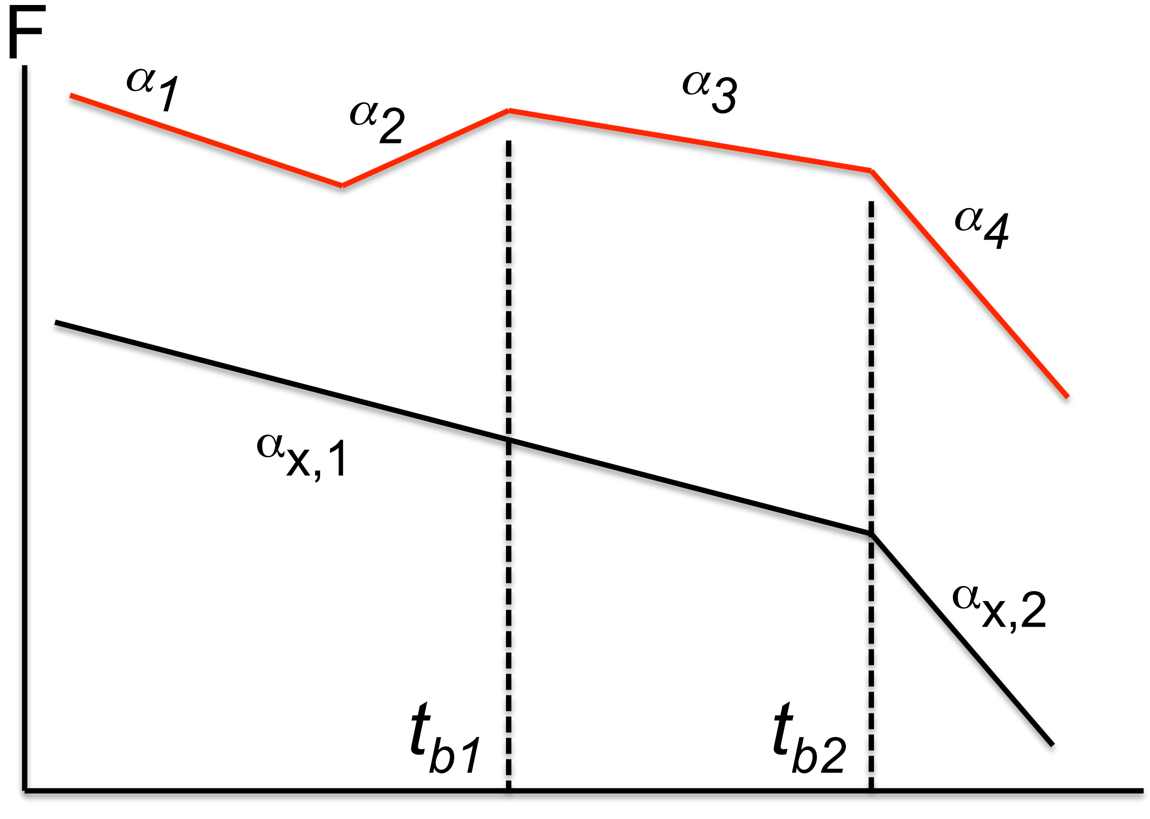
Then, while the X-ray and optical decay rapidly, we have a broad radio peak as well

# Analysis of the afterglow and rebrightening

Optical early decay slope is $\alpha_1$ = 0.55c0.03

$F \sim t^{-\alpha} \nu^{-\beta}$

X-ray LC early decay slope is $\alpha_{x,1}$ = 0.52±0.03, break time $t_{x, b2}$ = 133±2.4 ks, late decay slope is $\alpha_{X,2}$ = 2.11±0.14



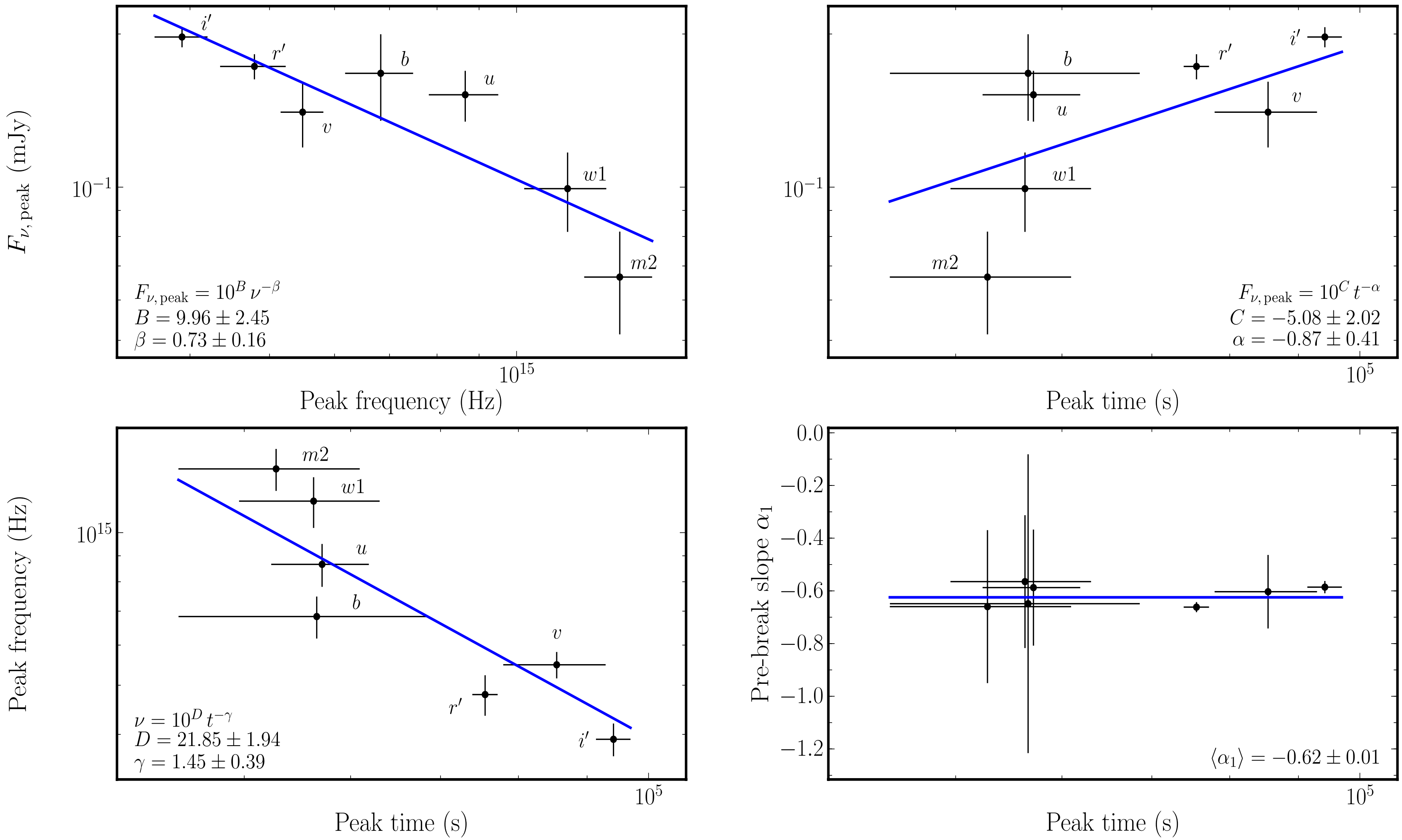
We fit of the light curves built up in several filters during the rebrightening with a double broken power law model.

Fixed $\alpha_3$ , $\alpha_4$ , $t_{b2}$ for all filters:

$\alpha_3$ = 0.48 ± 0.03 ; $\alpha_4$ = 1.97 ± 0.02 ; $t_{b2}$ = 217±2.4 ks

Peak flux, $\alpha_2$, $t_{b1}$ free to vary for each filter…

# ... and we find correlations between the fit parameters.



# The optical rebrightening itself is chromatic!

- The redder bands peak later that the bluer;

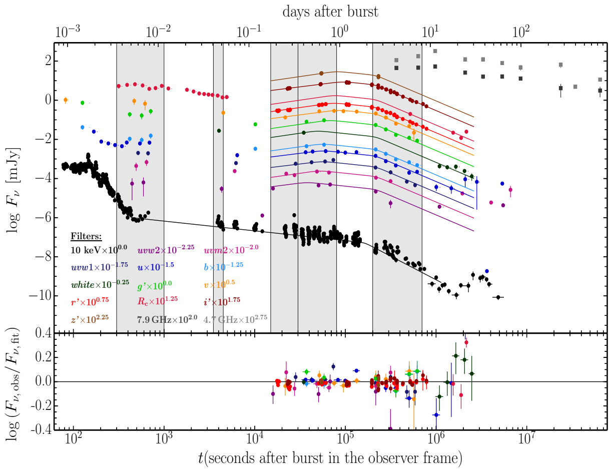
- The peak flux is higher as time goes by, that is, the redder bands have larger peak fluxes.

For example:

i’ band peaks at 90 ks, while u band peaks at 56 ks.

The peak flux in r’ band is ~180 μJy, while the peak flux in uw1 band (300 nm) is 100 μJy

# Analysis of spectral energy distributions (SEDs)



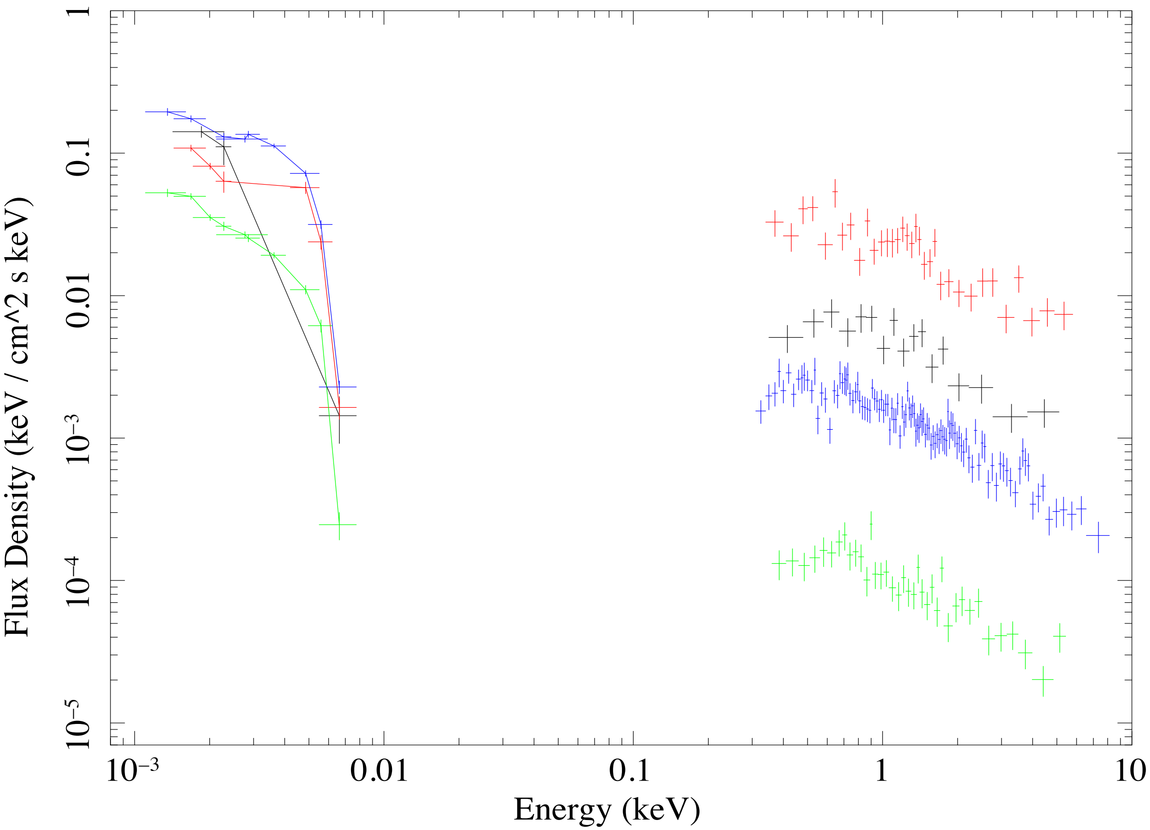


**Figure 6.** SEDs at 4500s (black), 22000s (red), 50000s (blue) and 400000s (green).

# Analysis of SEDs: spectral break in the optical

The SEDs have been fitted with:

- Simple power law;
- Broken power law;
- Broken power law with $\Delta\beta = 0.5$ (*as expected in the External Shock Afterglow model);*
- For the 50 ks SED only: Sum of two broken power law: first with low energy index $\beta_1 = -0.33$ *(this value is expected in a synchrotron spectrum below the injection frequency $\nu_M$ )*, second with $\Delta\beta = 0.5$

**Results:**

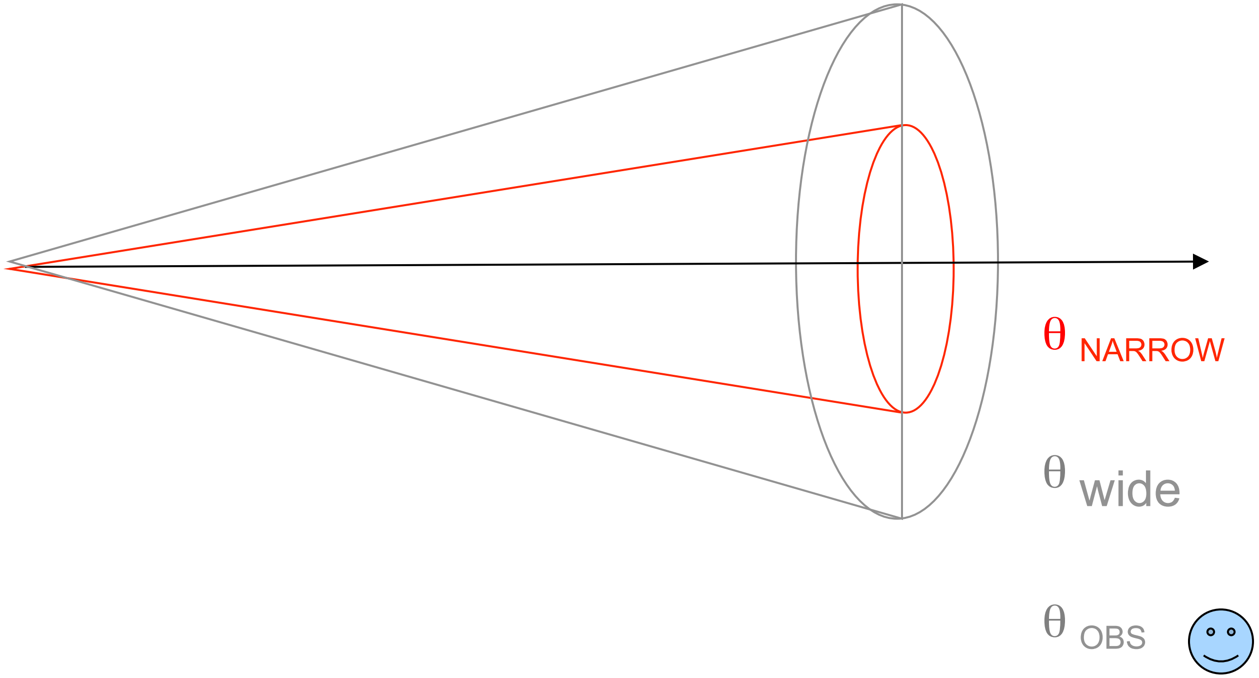
50 ks SED is best-fitted by the sum of two broken power law model;

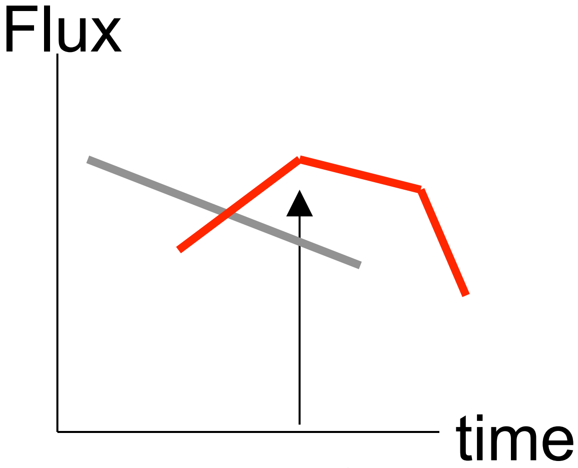
The break of the first component is at ~4.1 eV, in the near UV;

Consistent with the peak of the rebrightening reached at ~50 ks in the UV.

| | 500 s | 4.5 ks | 22 ks | 50 ks | 400 ks |
|---|---|---|---|---|---|
| Simple power law | | | | | |
| $\beta$ | | | | | $0.96 \pm 0.01$ |
| $\chi^2$ | | | | | $53.1/44$ |
| Broken power law | | | | | |
| $\beta_1$ | $0.07^{+0.31}_{-0.26}$ | $0.52^{+0.07}_{-2.30}$ | $0.16^{+0.05}_{-0.13}$ | $0.10 \pm 0.22$ | |
| $E_{break}$eV | $90.4^{+910}_{-47.4}$ | $641^{+313}_{-640}$ | $482^{+600}_{-282}$ | $9.9^{+1.5}_{-3.8}$ | |
| $\beta_2$ | $0.89^{+0.04}_{-0.06}$ | $1.02_{-0.08}$ | $0.84^{+0.09}$ | $1.02_{-0.05}$ | |
| $\chi^2/dof$ | $5.8/4$ | $11.8/14$ | $58.3/34$ | $119.3/113$ | |
| Broken power law with $\Delta\beta = 1/2$ | | | | | |
| $\beta_1$ | $0.34^{+0.06}$ | $0.52_{-0.06}$ | | $0.50^{+0.02}_{-0.04}$ | |
| $E_{break}$eV | $540^{+580}_{-138}$ | $655^{+305}_{-390}$ | | $46.36^{+41.22}_{-21.55}$ | |
| $\beta_2$ | $0.84^{+0.06}$ | $1.02_{-0.06}$ | | $1.00^{+0.02}_{-0.04}$ | |
| $\chi^2/dof$ | $5.95/5$ | $11.8/15$ | | $123.4/114$ | |
| Sum of two power laws | | | | | |
| $\beta_{1,I}$ | | | | $-0.33$ | |
| $E_{break,I}$eV | | | | $4.10^{+0.5}_{-0.3}$ | |
| $\beta_{2,I}$ | | | | $8.5^{+unconstrained}_{-6.3}$ | |
| $\beta_{1,II}$ | | | | $0.52_{-0.04}$ | |
| $E_{break,II}$eV | | | | $92.5^{+43.5}_{-20.1}$ | |
| $\beta_{2,II}$ | | | | $1.02_{-0.04}$ | |
| $\chi^2/dof$ | | | | $111.6/111$ | |

# Off-Axis double jet model





$\Gamma_{Narrow}^{-1} \sim \theta_{OBS} - \theta_{NAR}$

For an observer angle $\theta_{obs} \approx 1.5\ \theta_{wide}$ and $\theta_{narrow} = 0.5\ \theta_{wide}$, the temporal slopes of the observed light curves can be explained (Granot, Panaitescu et al. 2005).

# Parameters in the double jet model

We use

$$\nu(\theta_{obs}) = a\nu(\theta = 0) \qquad F(\nu, \theta_{obs}, t) = a^3 F(\nu/a, 0, at)$$ where $$a \equiv (1 + \Gamma^2\theta^2)^{-1}$$

The synchrotron peak frequency $\nu_M$ and peak flux $F(\nu_M)$ are given by

$$\nu_M = 3.3 \times 10^{14} (z+1)^{1/2} \epsilon_{B,-2}^{1/2} \left(\frac{p-2}{p-1}\right)^2 \epsilon_e^2 E_{52}^{1/2} t_d^{-3/2} \mathrm{Hz}$$

$$F(\nu_M) = 1600(z+1) D_{28}^{-2} \epsilon_{B,-2}^{1/2} E_{52} n^{1/2} (t/t_j)^{-3/4} \ \mu\mathrm{Jy}$$

Conditions:

- Peak flux of rebrightening (narrow jet) is ~ 200 μJy at 90 ks after trigger.

- Flux at the slow decline (wide jet) is ~100 μJy at 4.5 ks after trigger

Solutions:

For n=10, $\epsilon_e = \epsilon_B$ =1/3, p=2.02, the observed fluxes can be explained if:
$E_{Narrow}$ = 2 x $10^{54}$ erg, $E_{Wide}$ = 5.6 x $10^{54}$ erg; $\theta_{Narrow}$ = 0.023 rad; $\theta_{wide}$= 0.046 rad.

# Chromatic behaviour: problem the double jet model

If $\nu_M$ does cross the optical band at ~90 ks, we must have

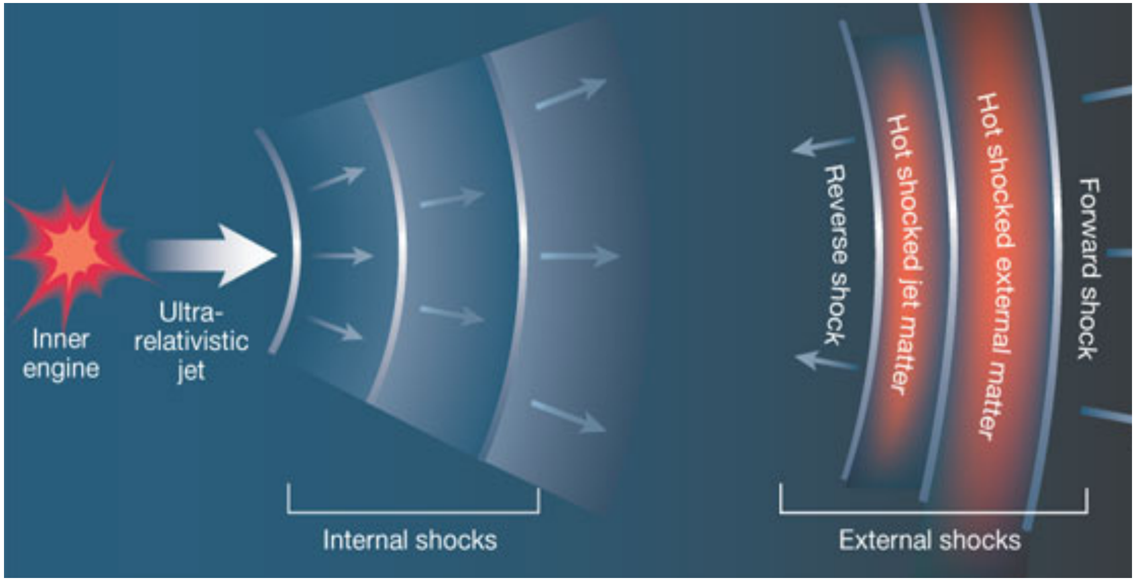
$$E_{52}^{1/2}\epsilon_{B,-2}^{1/2}\epsilon_e^2 \simeq 4.2 \times 10^3$$

This high value is needed to keep $\nu_M$ inthe optical range ~ 90 ks after the trigger, also from a largely off-axis observer.

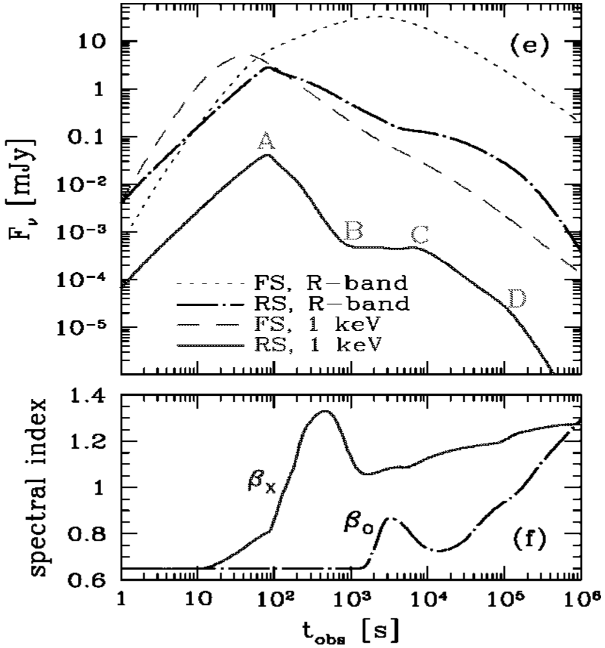
Even assuming the largest possible values for $\varepsilon_e = \varepsilon_B$ , E ~ $10^{61}$ erg !!

**Therefore, the model cannot be considered viable if, during the rebrightening, there is chromatic evolution due to the transit of $\nu_M$**

# Reverse Shock and Forward Shock interplay



Piran et al. 2003



Uhm & Beloberodov 2007

If the central engine produces a long-lived relativistic outflow, emission from Reverse Shock may be significant and extend for long time.

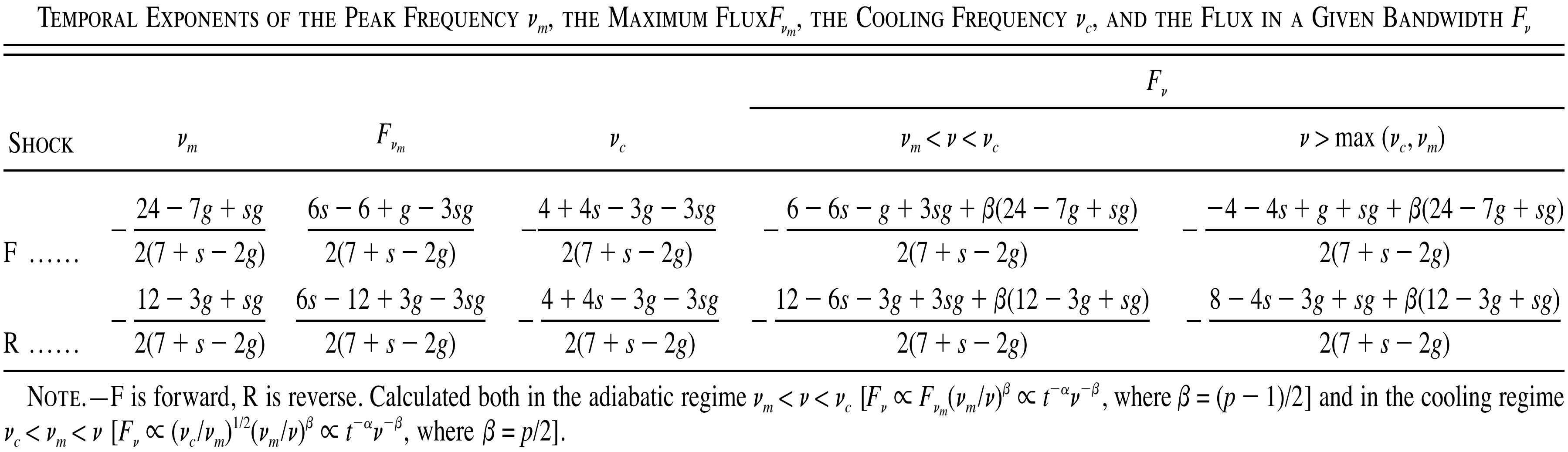
Depending on physical parameters, the RS can give different contributions in Opt and X-ray

Can a superposition of Reverse Shock and Forward Shock emissions reproduce the complex behaviour of GRB 100814A ?

# Modeling of RS and FS emission

- **Light curve slopes**

We use the predictions of Sari & Meszaros 2000 (SM00):



Temporal Exponents of the Peak Frequency $\nu_m$, the Maximum Flux$F_{\nu_m}$, the Cooling Frequency $\nu_c$, and the Flux in a Given Bandwidth $F_\nu$

| | | | | $F_\nu$ | |
|---|---|---|---|---|---|
| Shock | $\nu_m$ | $F_{\nu_m}$ | $\nu_c$ | $\nu_m < \nu < \nu_c$ | $\nu > \max(\nu_c, \nu_m)$ |
| F ...... | $-\frac{24-7g+sg}{2(7+s-2g)}$ | $\frac{6s-6+g-3sg}{2(7+s-2g)}$ | $-\frac{4+4s-3g-3sg}{2(7+s-2g)}$ | $-\frac{6-6s-g+3sg+\beta(24-7g+sg)}{2(7+s-2g)}$ | $-\frac{-4-4s+g+sg+\beta(24-7g+sg)}{2(7+s-2g)}$ |
| R ...... | $-\frac{12-3g+sg}{2(7+s-2g)}$ | $\frac{6s-12+3g-3sg}{2(7+s-2g)}$ | $-\frac{4+4s-3g-3sg}{2(7+s-2g)}$ | $-\frac{12-6s-3g+3sg+\beta(12-3g+sg)}{2(7+s-2g)}$ | $-\frac{8-4s-3g+sg+\beta(12-3g+sg)}{2(7+s-2g)}$ |

Note.—F is forward, R is reverse. Calculated both in the adiabatic regime $\nu_m < \nu < \nu_c$ $[F_\nu \propto F_{\nu_m}(\nu_m/\nu)^\beta \propto t^{-\alpha}\nu^{-\beta}$, where $\beta = (p-1)/2]$ and in the cooling regime $\nu_c < \nu_m < \nu$ $[F_\nu \propto (\nu_c/\nu_m)^{1/2}(\nu_m/\nu)^\beta \propto t^{-\alpha}\nu^{-\beta}$, where $\beta = p/2]$.

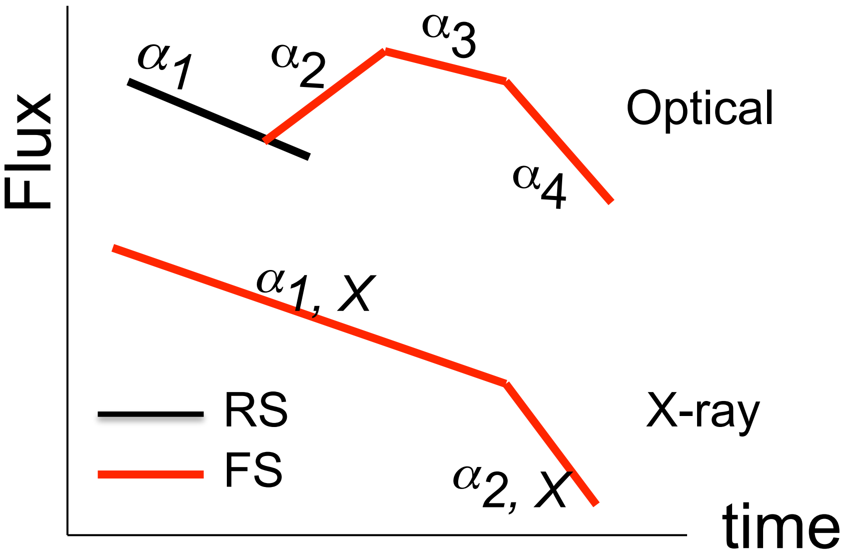
Parameter s describes the energy associated with the shells: $E(>\Gamma) \sim E_0\ (\Gamma/\Gamma_0)^{-s+1}$
It is also tells us the rate of energy injection into the front shell.

Parameter g describes the density profile of the external medium: $\rho \sim r^{-g}$

# RS + FS interplay: Scenario I

The early optical is RS emission; the X-ray emission and optical rebrightening is from FS

Late steep decay is jet break.



No solutions for g=0, (interstellar medium, ISM), nor for g=2, the density profile of stellar wind expected around a massive star progenitor.

Instead, g=1.15, s =2.75, p=2.02, can reproduce the decay slopes within 3 sigma: $\alpha_1 = \alpha_{1,X} = 0.58$; $\alpha_3 = 0.51$. Note g=1.15 is intermediate between ISM and wind.

$\alpha_2 = -0.57$ is **not** consistent with observation, and $\alpha_{2,X} = 1.3$ **is way off**. However, the model is approximate and numerical simulations indicate that jet break decay slope might be steeper (Granot et al. 2006, Van Eerten et al. 2010, etc.)

# But Model I cannot explain chromatic behaviour due to transit of $\nu_M$ at rebrightening.

For wind-like media, the synchrotron peak frequency $\nu_M$ is given by

$$\nu_M = 4\times10^{14}(z+1)^{1/2}(p-0.69)\epsilon_{B,-2}^{1/2}\left(\frac{p-2}{p-1}\right)^2 \epsilon_e^2 E_{52}^{1/2} t_d^{-3/2}\mathrm{Hz}$$

(Yost et al. 2003). At rebrightening, all emission is from Forward Shock.

The 50 ks SED indicate FS electrons have p=2.02.

To have $\boldsymbol{\nu}_M$ at optical band at rebrightening, the equation above* requires

$$\epsilon_{B,-2}^{1/2}\epsilon_e^2 E_{52}^{1/2} \approx 760$$

Even assuming $\varepsilon_e = \varepsilon_B = 1/3$, E ~ $10^{58}$ erg. **Too much for any GRB model.**

* GRB100814A medium has profile intermediate between ISM and Wind. We therefore calculate $\nu_M$ at deceleration time ~860 s as in wind medium and then we follow its evolution with s=2.75, g=1.15, as in SM00.

# Numerical simulations for Scenario I

Detailed simulations, which takes into account:

Stratification in the Lorentz factors of ejecta;

Mechanical work (*pdV*) done by the gas.

Parameters of the simulation:

Kinetic Energy E = $10^{54}$ erg;

$\varepsilon_{e,FS} = 0.1$, $\varepsilon_{B,FS} = 0.01$;

$\varepsilon_{e,RS} = 0.1$, $\varepsilon_{B,FS} = 0.05$;

$p = 2.1$ ; $\theta_{jet} = 0.07$ rad

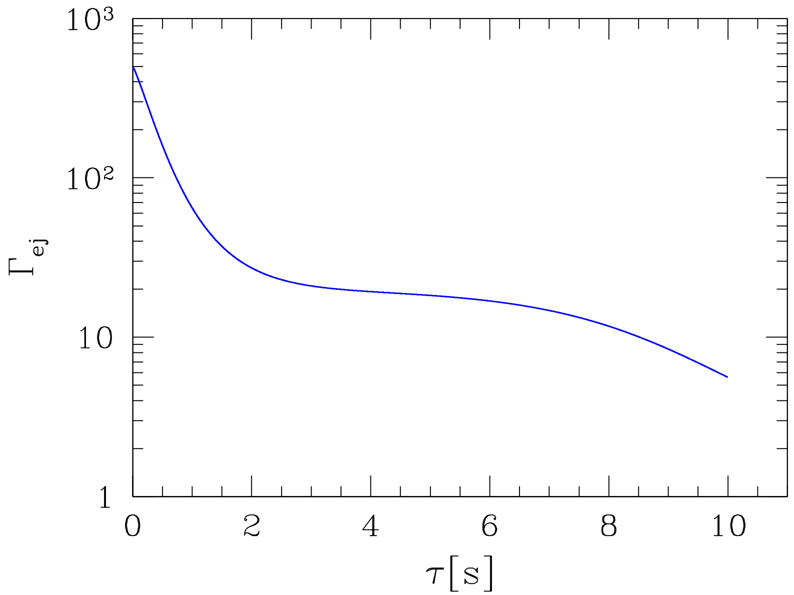
RS energizes 100% of electrons of ejecta; **but FS energizes only 1.5% of medium.**

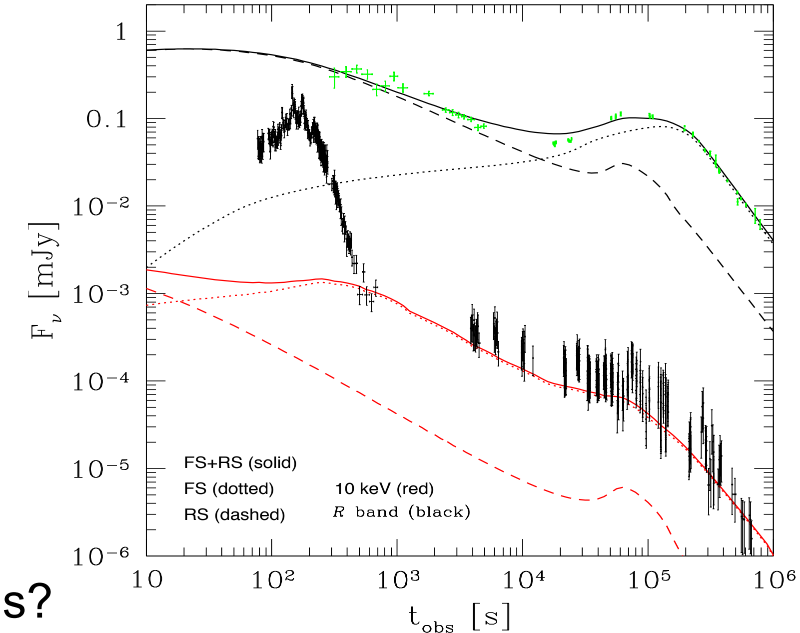
Agreement of light curves with observations;

Harder spectrum around peak time predicted;

It can produce many curves changing $\Gamma(t)$.

Problem: how FS energizes only ~1.5% of electrons?



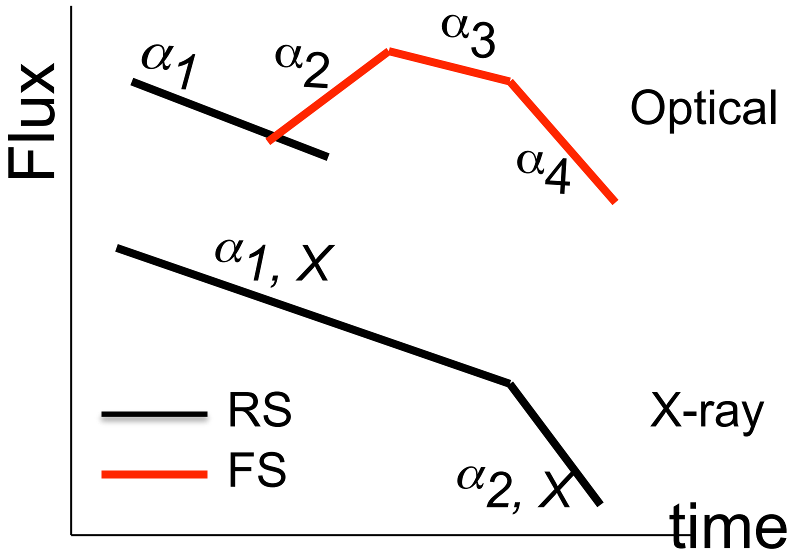


# RS + FS interplay: Scenario II

The early optical **and X-ray** are RS emission;

The optical rebrightening is FS emission;

Late steep decay is jet break.



We can now model the FS assuming a very steep spectrum. **This eases the energy requirements.** We take $p_{FS}$=2.85. We take $p_{RS}$ = 2.02 to explain the hard X-ray spectrum.

Parameters s=2.65, g=1.25 can reproduce the decay slopes within 3 sigma:

$\alpha_1 = 0.57$; $\alpha_{1,\,X} = 0.58$; $\alpha_4 = 2.07$; $\alpha_{2,X} \sim \alpha_4$

$\alpha_2 = -0.52$ is **not** consistent with observation, and $\alpha_3 = 1.1$ **is way off**. However, the model is approximate; and observed $\alpha_3 < 1.1$ can be explained because $\nu_M \sim \nu_{opt}$

# Modeling of FS and RS in Scenario II

**FS modeling**

The condition $\nu_M \sim \nu_{opt}$ at the rebrigtening time becomes

$$\epsilon_{B,-2}^{1/2}\epsilon_e^2 E_{52}^{1/2} \simeq 0.58$$

The condition $F(\nu_M) \sim 200$ μJy at the rebrigtening time is

$$\epsilon_{B,-2}^{1/2} E_{52}^{1/2} A_* \simeq 1.6 \times 10^{-3}$$

These equations must be solved together. Assuming $\varepsilon_e = \varepsilon_B = 1/3$, we obtain

$$A_* \simeq 3 \times 10^{-4}. \qquad E_{52} \simeq 0.86$$

# Modeling of FS and RS in Scenario II - 2

**Modeling of RS**

At 50 ks, the X-ray is RS. The 50 ks SED tells us there is a cooling break at ~0.1 keV (not well constrained). We calculate $\nu_C$ at deceleration time, ~860 s:

$$\nu_{C,RS} = 2.12 \times 10^{11} \left(\frac{1+z}{2}\right)^{-3/2} \epsilon_{B,RS,-2}^{-3/2} E_{52}^{1/2} A_*^{-2} t_{\rm dec}$$

(Kobayashi & Zhang 2003). From SM00, we calculate how much it becomes at 50 ks. We find

$$\nu_{C,RS} = 4.7 \times 10^{19} \epsilon_{B,RS,-2}^{-3/2}$$

$\varepsilon_{B,RS}$ must be very large; but it can't be too large, otherwise the RS would not produce emission. Since the cooling break has a large error, we take $\varepsilon_{B,RS}$ **= 0.60**.

# Modeling of RS and FS in Scenario II - 3

At deceleration time ~860 s, the flux is ~ 300 $\mu$Jy. It is given by

$$F(\nu_{\rm Opt}) = F\,(\nu_{peak,RS})\,(\frac{\nu_{\rm Opt}}{\nu_{peak,RS}})^{-\beta}$$

For the values of parameters at hand, self-absorption frequency $\nu_{\rm SA,RS} > \nu_{\rm M,RS}$ ; thus $\nu_{\rm peak,RS} = \nu_{\rm SA,RS}$

We know that

$$F(\nu_{{\rm peak},RS}) = \Gamma F(\nu_{M,{\rm FS}}) \left(\frac{\epsilon_{B,RS}}{\epsilon_{B,{\rm FS}}}\right)^{1/2}$$

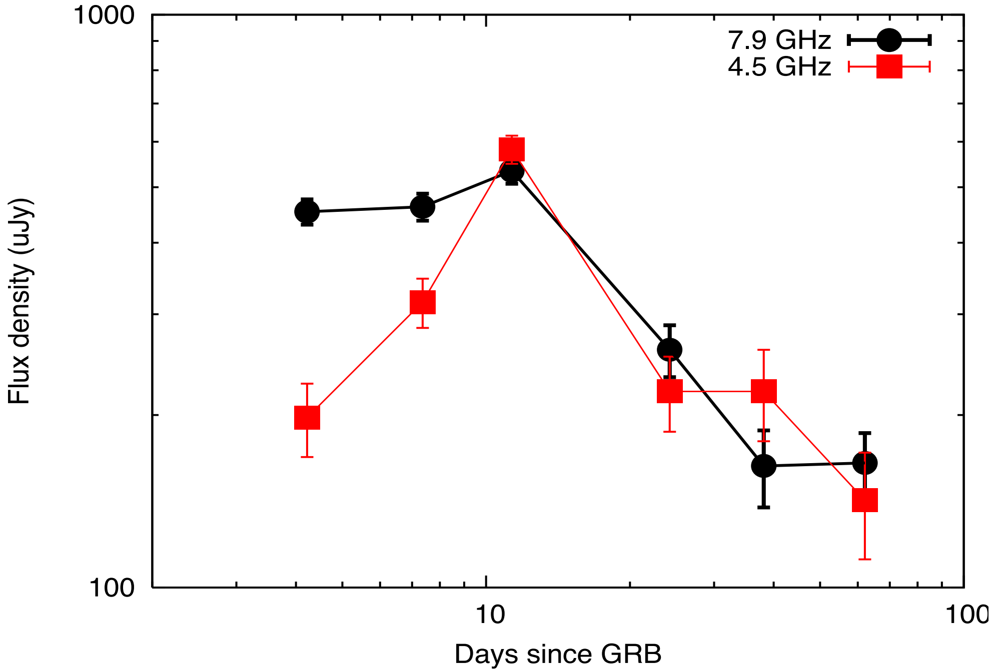
From deceleration time 860 s and $A_* = 3 \times 10^{-4}$, we find $\Gamma = 125$. Since $\varepsilon_{\rm B,RS} = 0.60$, we find $F(\nu_{\rm peak,RS}) = 2.2 \times 10^4$ $\mu$Jy.

From first equation above, we thus find $\nu_{\rm peak,RS} = \nu_{\rm SA,RS} = 9.8 \times 10^{10}$ Hz.

Since $\nu_{\rm SA,RS}$ depends on known parameters and $\varepsilon_{\rm e,RS}$, we can determine it.

**We find $\varepsilon_{\rm e,RS} \sim 0.21$**

# Modeling of the radio afterglow - 1



**What causes the late radio peak?**

**$\nu_{M,FS}$** (optical rebrightening). It must evolve fro $10^{14}$ Hz at ~$10^5$ s to $10^9$ Hz at t ~$10^6$ s. **Can't be**.

**$\nu_{M, RS}$** ~ 9 x$10^9$ Hz at deceleration time. According to SM00, evolves as t $^{-0.8}$. It will be $\nu_{M, RS}$ ~ 1.5 x$10^8$ Hz at 1 day after trigger, then decays faster (jet break). **Can't be.**

**$\nu_{SA, FS}$** . We have $\nu_a = 3.3\times10^9\,(z+1)^{-0.4}\,f_W(p)\,\bar{\epsilon}_e^{-1}\,\epsilon_{B,-2}^{0.2}\,E_{52}^{-0.4}\,A_*^{1.2}\,t_d^{-0.6}\quad \mathrm{Hz}$ (Yost et al. 2003). $\nu_{SA, FS}$ will be below $10^6$ Hz at deceleration time. **Can't be.**

**$\nu_{SA,RS}$** ~ 9.8 $10^{10}$ Hz at deceleration time. Following SM00, it evolves as t $^{-0.65}$. Thus $\nu_{SA,RS}$ ~ 3.5 $10^9$ Hz at jet break time. Then, $\nu_{SA,RS} \sim \Gamma^{8/5}\,\nu_{SA,FS}$ ; $\Gamma \sim t^{-1/2}$ , $\nu_{SA,FS} \sim t^{-1/5}$ ; thus $\nu_{SA,RS} \sim t^{-1}$ after jet break. At 10 days, $\nu_{SA,RS}$ ~ 0.5 GHz. However, energy injection will likely push $\nu_{SA,RS}$ into ~ GHz range. **Could be.**

# Modeling the radio afterglow - 2

- **$\nu_{SA,RS}$ can be the peak frequency crossing the observing radio band. Is the observed flux right?**

We found that $F(\nu_{SA,RS}) \sim 2.2 \times 10^4$ μJy at deceleration time 860 s.

For the chosen values of s and g, the flux at peak frequency evolves as $t^{-0.16}$ up to $t_{jet} = 1.3 \times 10^5$ s.

F (peak,RS) ~ $\Gamma$ F (peak,FS). In jet break regime, $\Gamma \sim t^{-1/2}$ while F (peak,FS) ~ $t^{-1}$. But the late shells produce energy injection and $E \sim t^{0.4}$ and F (peak,FS) ~ $E^{1/2}$. All together, we expect F (peak,RS) ~ $t^{-1.3}$. We have F (peak,RS) ~ 700 μJy at 10, **as observed.**

# Some comments on Scenario II

- Physical parameters are not uniquely determined: other values of *s* and g can reproduce similar light curves.

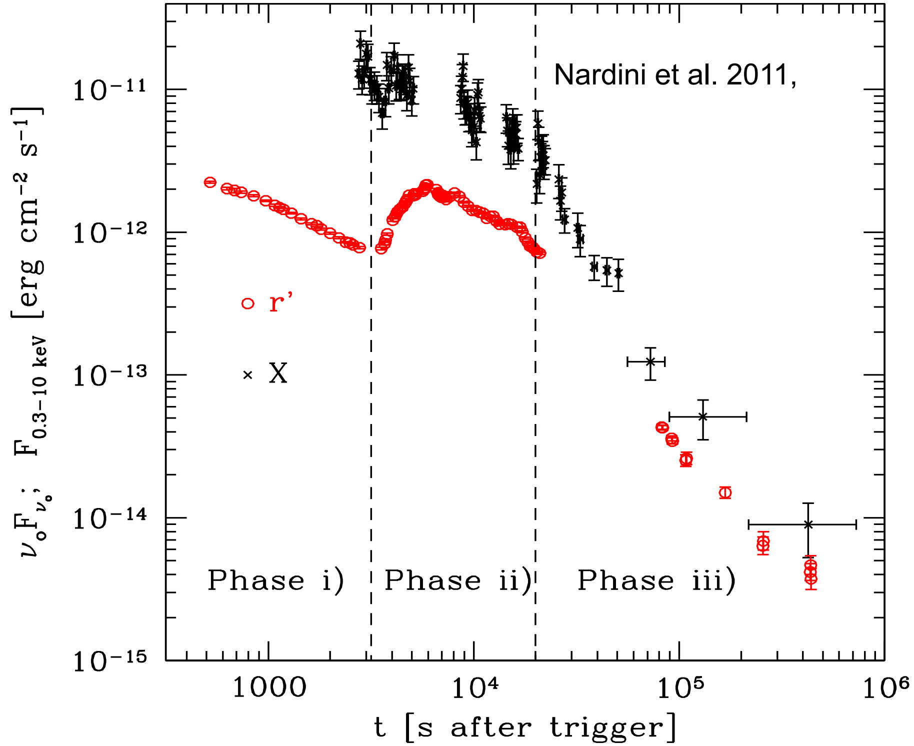
- A kinetic energy $E_{52}$ ~ 0.86 implies an efficiency $\eta = E\gamma / (E\gamma + E_{kin}) \sim 0.9$, **rather high for any model to produce the gamma-ray emission.**

- However, $E_{52}$ is only the energy at deceleration time, when energy injection begins. It is possible that the energy injection is due to trailing shells that have produced Eγ as well. **If we use E at the end of observation, we have $\eta = E\gamma / (E\gamma + E_{kin}) \sim 0.2$, more reasonable.**

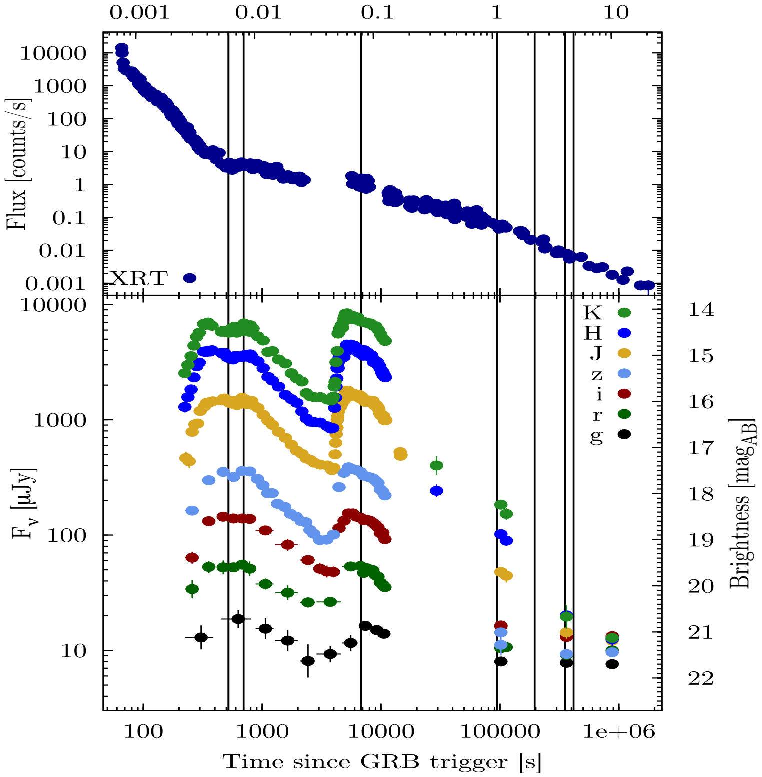
- The beaming-corrected energetics is much smaller. A jet break occurs when $\Gamma \sim \theta^{-1}$ . Γ=125 at deceleration time, then evolves as $t^{-0.21}$ . Then, at 133 ks $\Gamma \sim 44$ and θ = 0.023 rad. Correcting for beaming, $E\gamma = 1.9 \times 10^{49}$ erg.

  The circumburst medium is very thin, with $A_* = 3\ 10^{-4}$, which implies $n \sim 3 \times 10^{-4}$ at ~ 1 light year from the burst. This is not unusual (observed for other bursts, e.g. 130427A, Perley et al. 2013). **Some GRB progenitor emit a very thin wind at the end of their lives.**

# Is GRB100814A unique? No.



GRB081029A (Nardini et al. 2011, Holland, DP et al. 2012)



GRB100621A (Greiner et al 2013)

Can a complex ejecta structure explain this fast variability?

# Other scenarios

- **Internal dissipation**: the optical emission occurs when shells interact with each others and $\Gamma$ is very high. Some GRBs shows optical flares and fast and variable rebrightening. Internal dissipation can explain these features, **but the emission mechanism itself is not clear and we lack predictions;**

- **Change of microphysical parameters.** If $\varepsilon_e$ and $\varepsilon_B$ of the shocks evolve in certain ways, one could have an optical rebrightening without X-ray counterpart. But the required evolution is un-explained and contrived;

- **End of energy injection.** When the energy emission process ceases, bright FS and RS reverberates throughout the ejecta, causing the rebrightening. Before and after the rebrightening, the emission is from FS only. The rebrightening is prominent only if the ejecta are narrowly collimated. **However, this model predicts a radio flare at the time of the rebrightening, while in GRB100814A the radio peak is ~10 times later than the optical peak.** Some peculiar values of parameters might allow for an extended radio rebrightening.

# Conclusions

- We have gathered a rich set of X-ray, UV/Opt/IR and radio data of the *Swift* GRB100814A. The afterglow shows a prominent optical rebrightening peaking at ~1 day, which has no counterpart in the X-ray. The rebrightening is chromatic. Shortly after the optical rebrightening, *both* X-ray and optical fluxes start to decay fast. A radio transient peaks ~ 10 days after the trigger.

- A double component jet observed off-axis can explain the observed light curves. However, it cannot explain the rebrightening chromatic behaviour if this is due to transit of synchrotron peak frequency $\nu_M$;

- In a second scenario, the early optical afterglow is due to Reverse Shock emission, caused by energy injection in form of late shells, while the X-ray and the optical rebrightening and Forward Shock emission. This model can reproduce the observed light curves. However, the transit of $\nu_M$ in the optical as late as 1 day requires implausibly high Energy. Numerical modeling constrains how the Lorentz factor of ejecta evolves in time to produce the light curves. But it still requires that the FS imparts all its energy only to 1% of electrons.

- A third scenario assumes that early optical and all X-ray emission is from RS, while FS with a steep spectrum produces the rebrightening. The required E is ~ $10^{52}$ erg. The light curves features can be recovered, and the late radio peak can be qualitatively explained.

There are other GRBs like 100814A!

# What are Gamma-Ray Bursts?

- Cosmological sources of gamma-ray occurring randomly in the sky, associated with an explosion of a massive star (long GRBs) or the merge of two compact objects such two Neutron Stars or Neutron-Star and Black Hole
- Last from ~10e-3 to 1000 s
- Followed by a long-lived