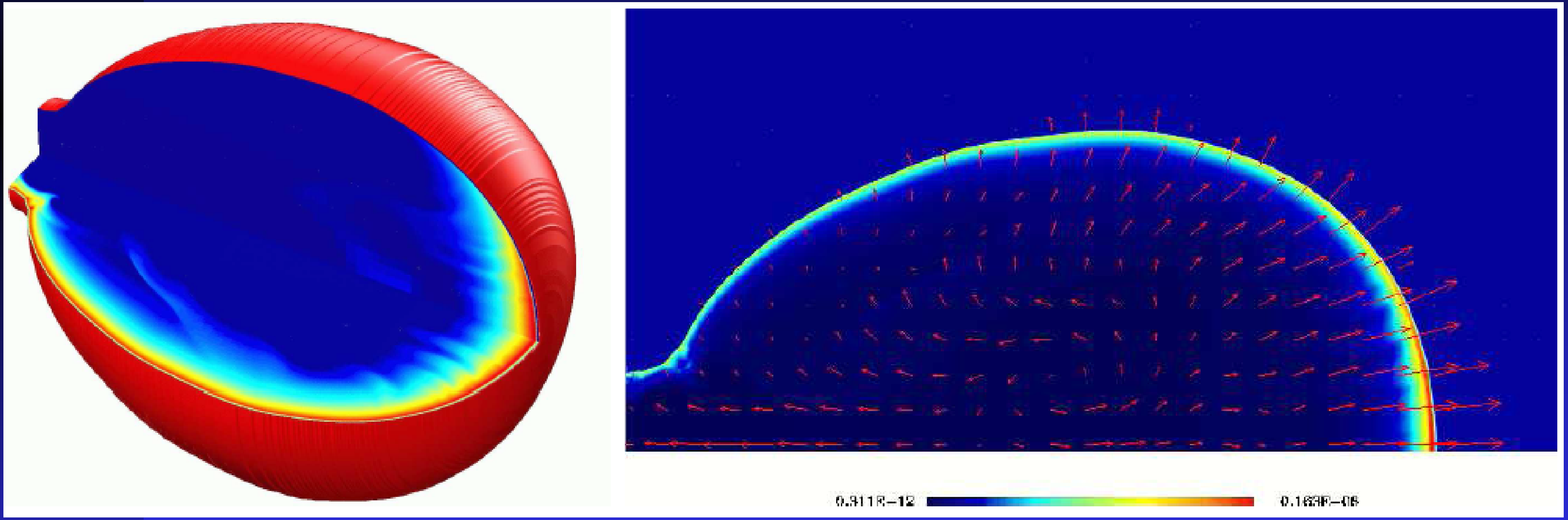
Structure & Dynamics of GRB Jets

Jonathan Granot

KIPAC @ Stanford



"Challenges in Relativistic Jets"
Cracow, Poland, June 27, 2006

Outline of the Talk:

- Differences from other relativistic jets
- Observational evidence for jets in GRBs
- The Jet **Structure:** how can we tell what it is
  - **Afterglow polarization**
  - **Statistics** of the prompt & afterglow emission
  - **Afterglow light curves**
- The jet **dynamics**: degree of **lateral expansion**
- What causes the jet break?
- The jet structure, energy, and γ-ray efficiency
- **Conclusions**

Differences between GRB jets & other Astrophysical Relativistic Jets:

- GRB jets are not directly angularly resolved
    - Typically at $z \gtrsim 1$ + early source size $\lesssim 0.1$ pc
    - Only a single radio afterglow (GRB 030329) was marginally resolved after 25 days
    - The jet **structure** is **constrained indirectly**
- GRB jets are **Impulsive:** most observations are long after the source activity
- GRBs are transient events, making the observations much more difficult

Observational Evidence for Jets in GRBs

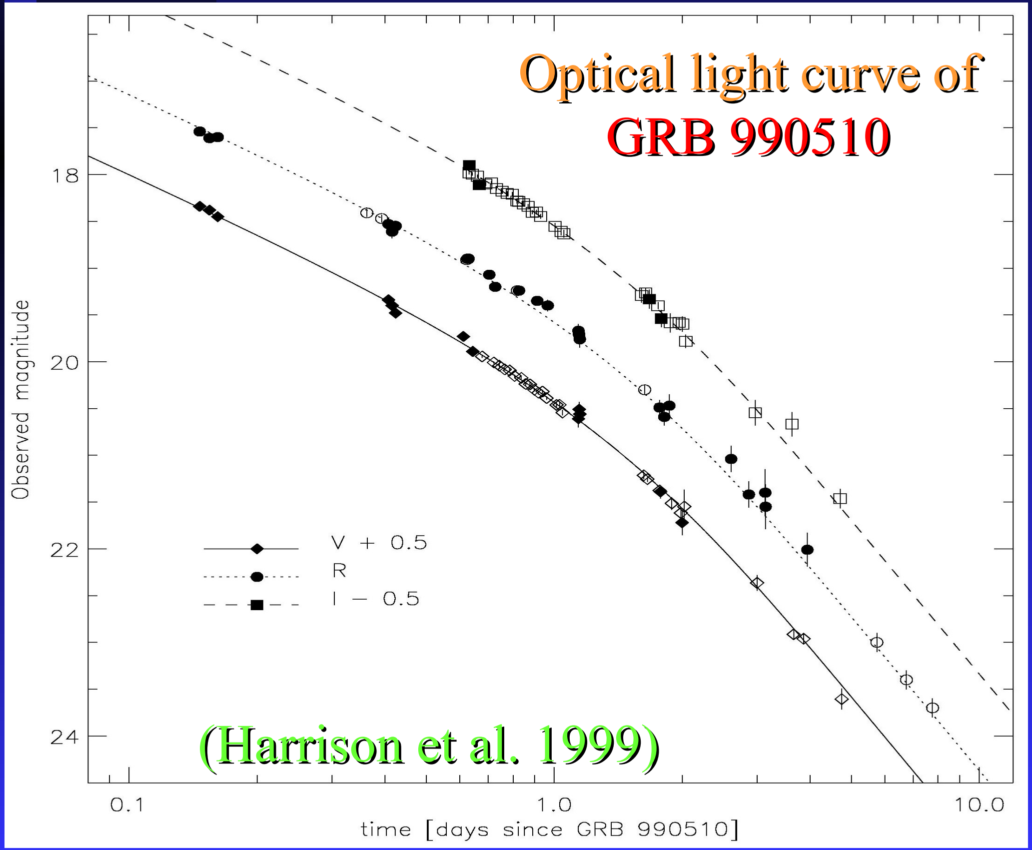
- The energy output in γ-rays assuming isotropic emission approaches (or even exceeds) $M_{\odot}c^2$
  - ⇒ difficult for a stellar mass progenitor
  - **True energy** is much smaller for a narrow **jet**
- Some long GRBs occur together with a SN

⇒ the outflow would contain $>M_{\odot}$ if spherical

⇒ only a small part of this mass can reach $\Gamma \gtrsim 100$ & it would contain a small fraction of the energy

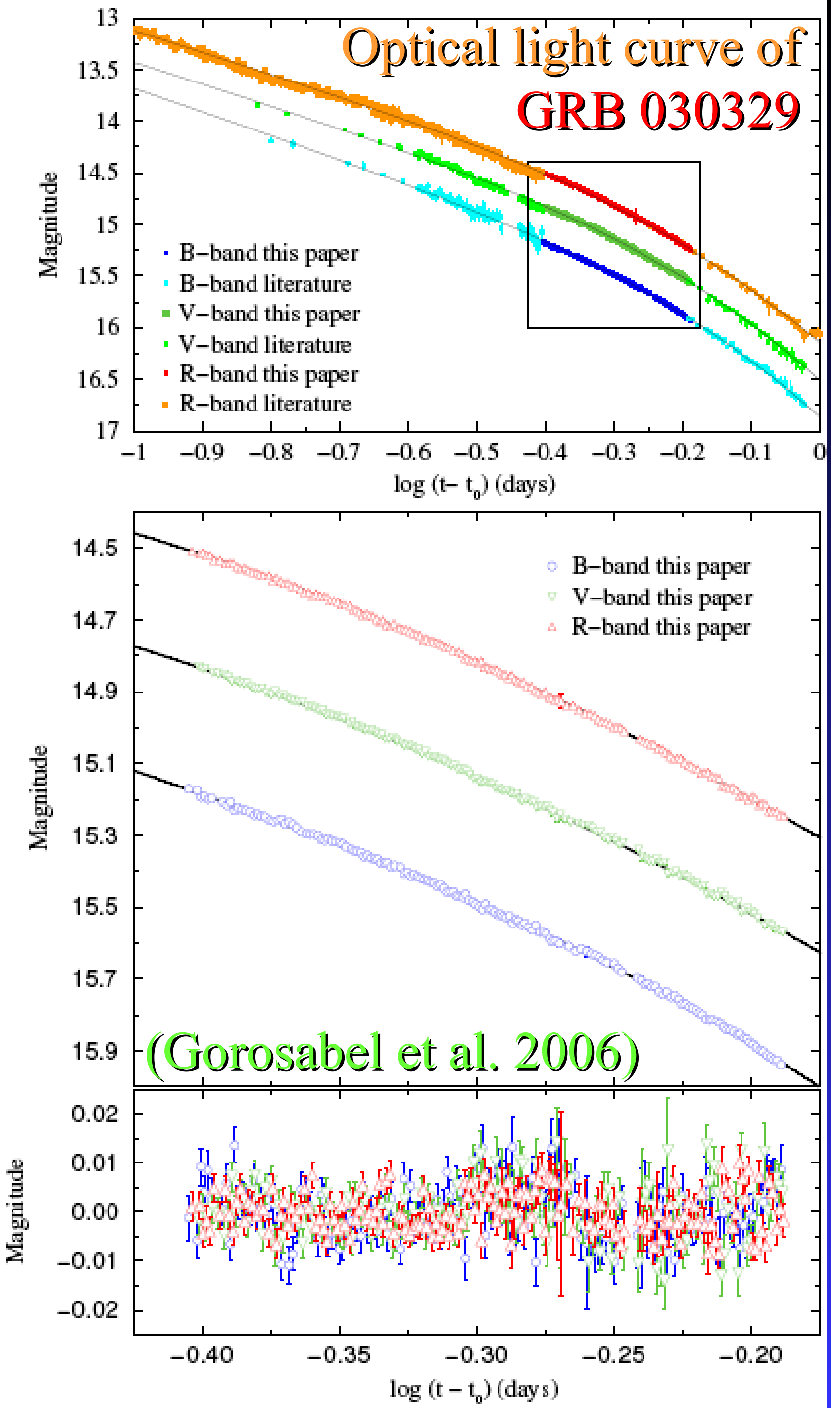
- Achromatic break or steepening of the afterglow light curves (“jet break”)

Examples of Smooth & Achromatic Jet Breaks



Optical light curve of GRB 990510

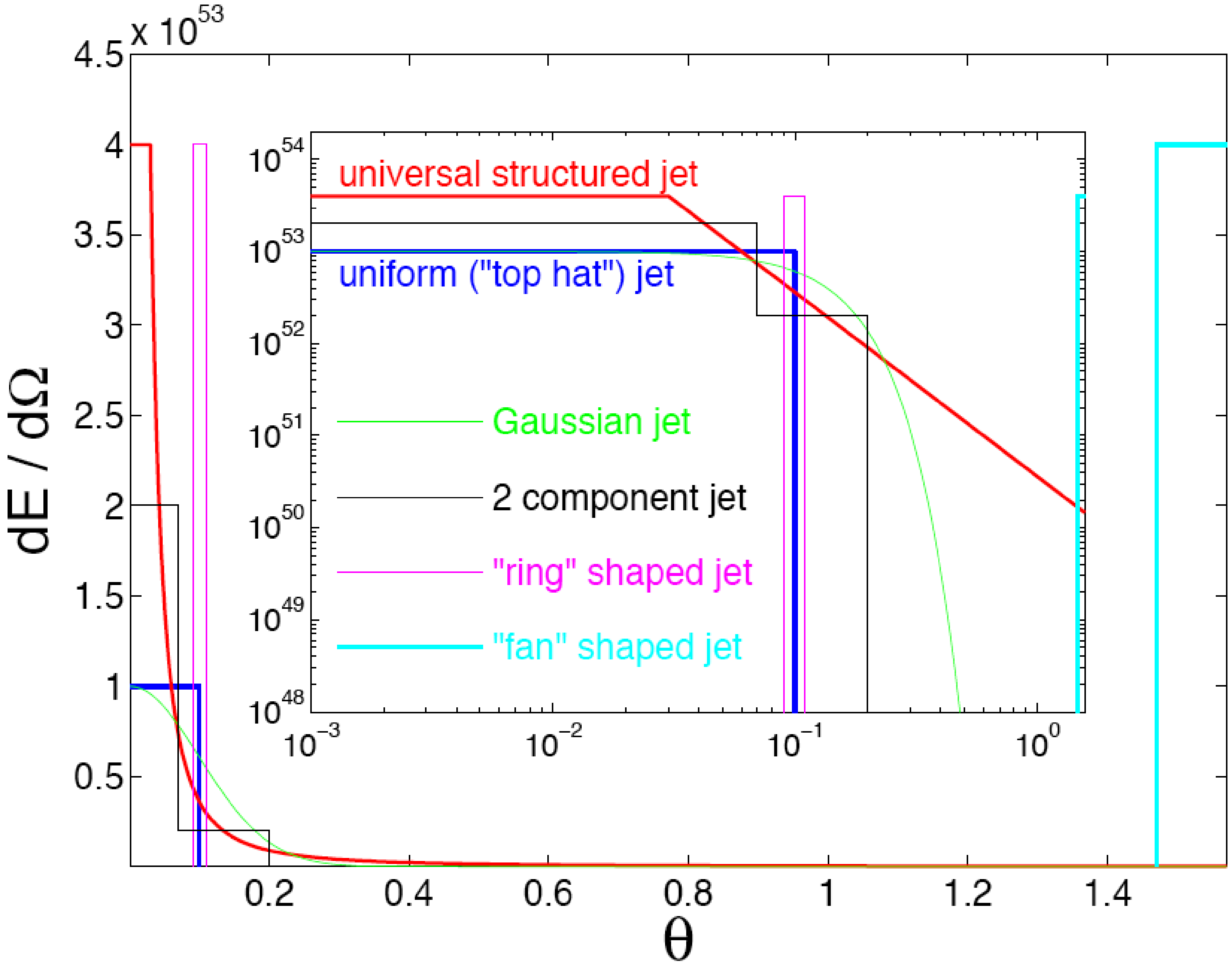
(Harrison et al. 1999)



Optical light curve of GRB 030329

(Gorosabel et al. 2006)

The **Structure** of GRB Jets:

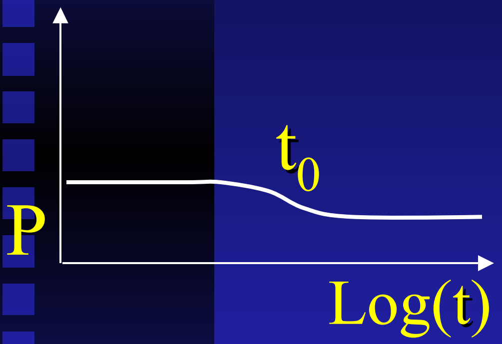


How can we determine the jet structure?

1. Afterglow polarization light curves

the polarization is usually attributed to a jet geometry

Ordered B-field[*]:

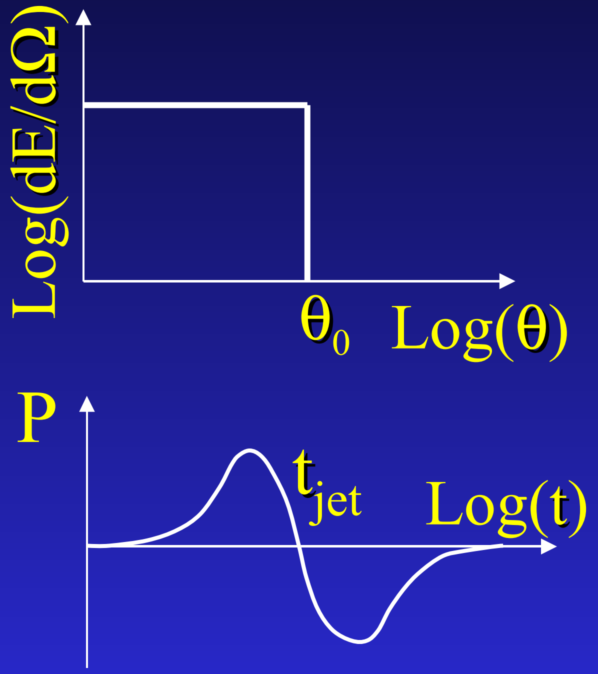


$\theta_p = \mathrm{const}$

while for jet models

$P(t\ll t_j) \ll P(t\sim t_j)$

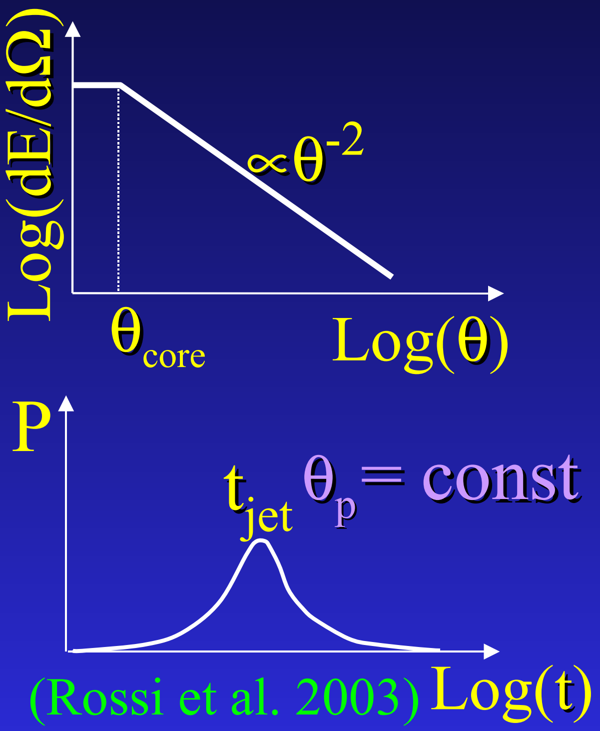
Uniform jet[†]:



θ_p flips by 90° at t_{jet}

(Sari 99; Ghisellini & Lazzati 99)

Structured jet[††]:



(Rossi et al. 2003)

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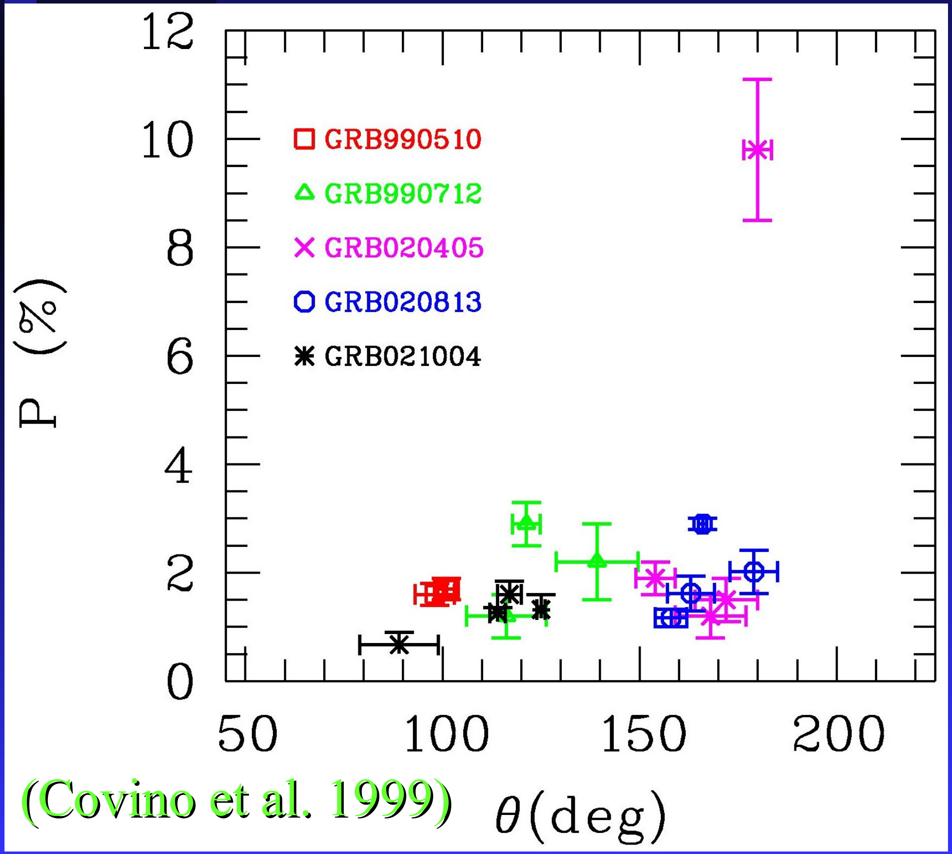
[*] JG & Königl 03

[†] Rhoads 97,99; Sari et al. 99, …

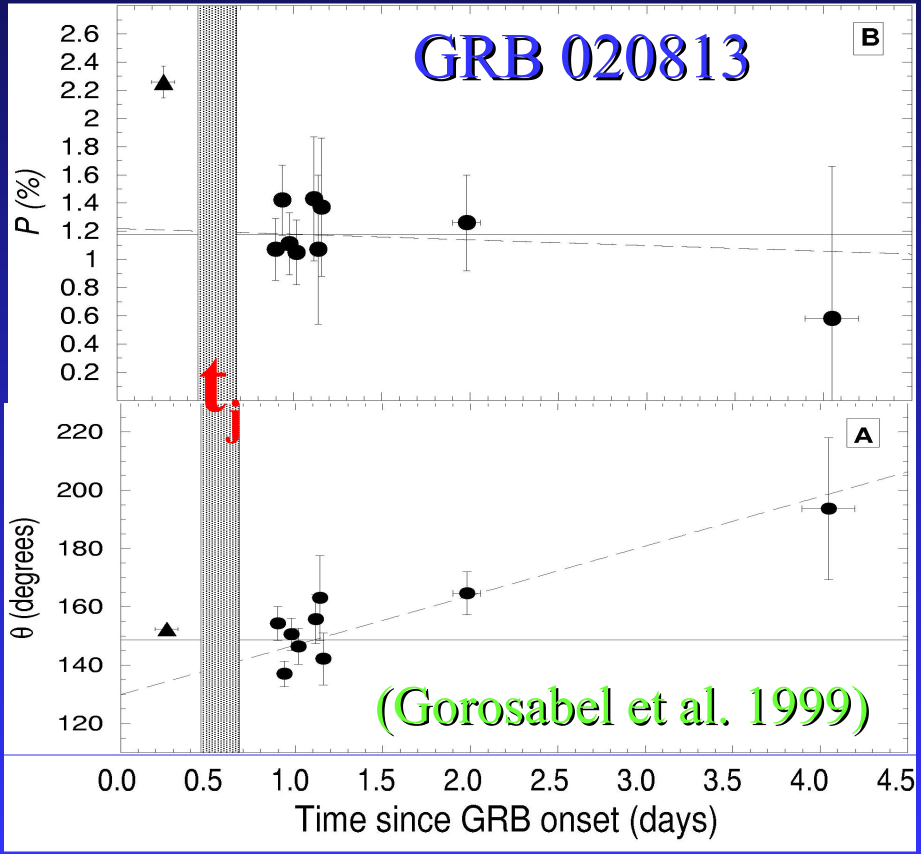
[††] Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02

Afterglow Polarization: Observations

- Linear polarization at the level of $P \sim 1\%$-3% was detected in several optical afterglows
- In some cases P varied, but usually $\theta_p \approx$ const
- Different from predictions of uniform or structured jet



(Covino et al. 1999)



GRB 020813

t_j

(Gorosabel et al. 1999)

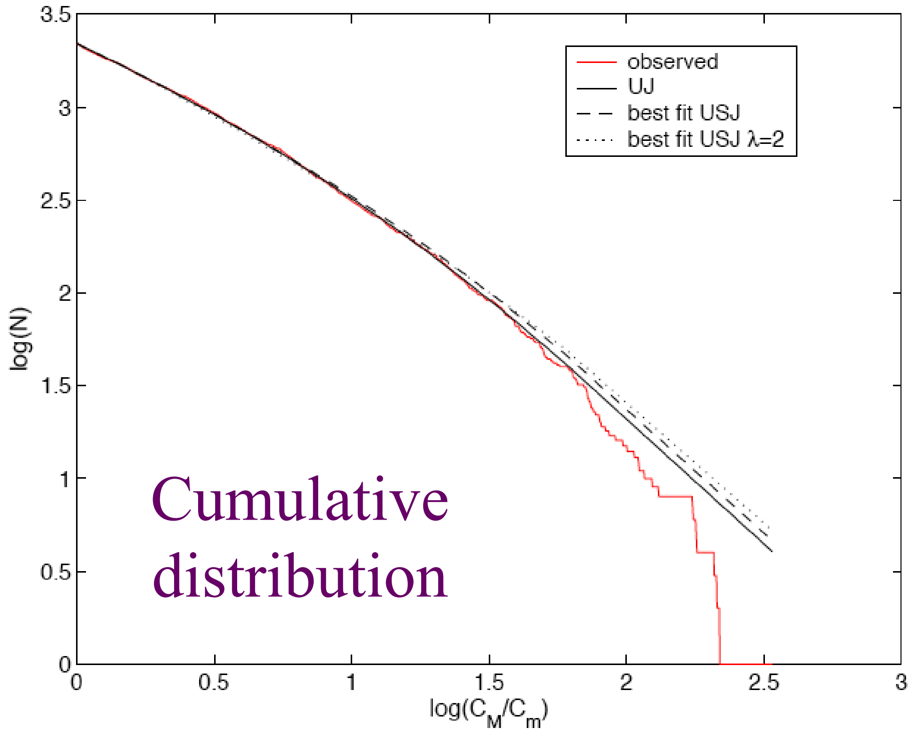
Afterglow Pol. & Jet Structure: Summary

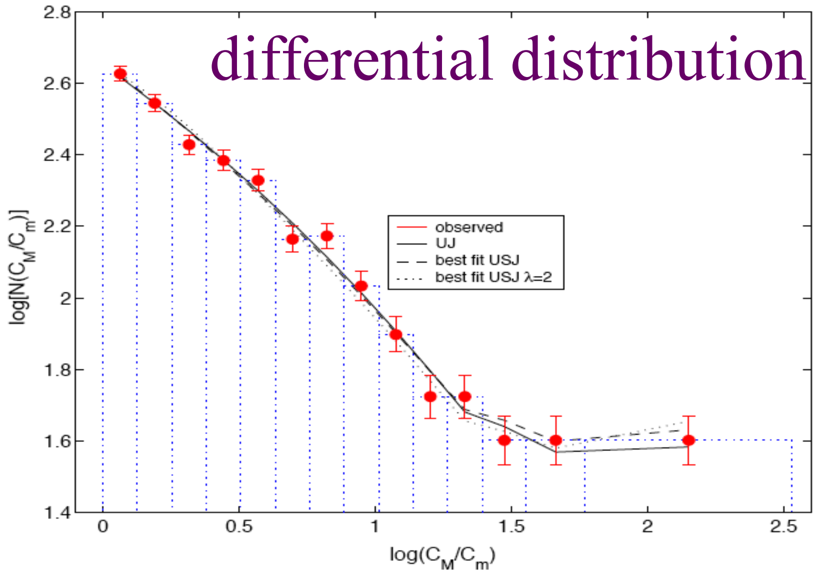
- The Afterglow polarization is affected not only by the jet structure but also by other factors, such as
  - the **B-field structure** in the **emitting region**
  - **Inhomogeneities** in the ambient density or in the jet (JG & Königl 2003; Nakar & Oren 2004)
  - “**refreshed shocks**” - slower ejecta catching up with the afterglow shock from behind (Kumar & Piran 2000; JG, Nakar & Piran 03; JG & Königl 03)
- Therefore, **afterglow polarization** is **not** a very “**clean**” method to learn about the jet structure

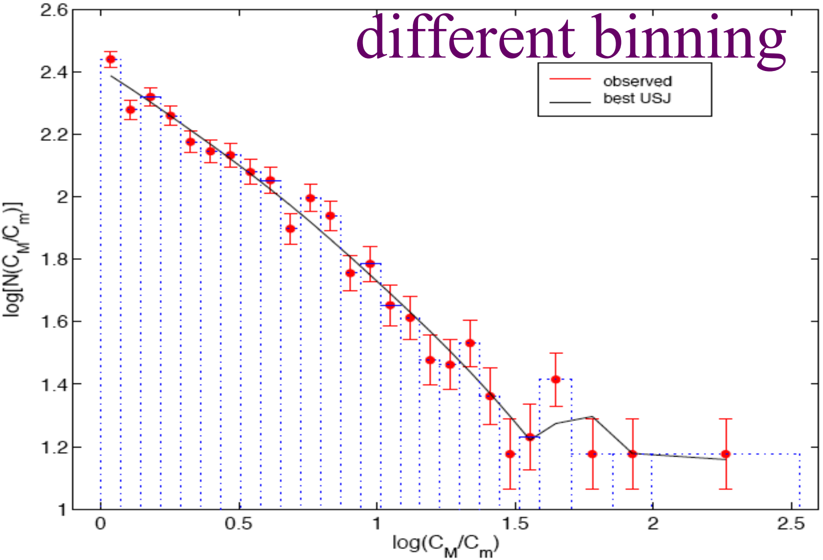
Jet Structure from log N - log S distribution

(Guetta, Piran & Waxman 04; Guetta, JG & Begelman 05; Firmiani et al. 04)

- Both the UJ & USJ models provide an acceptable fit
- Provides many constraints but not a “clean” method to study the jet structure



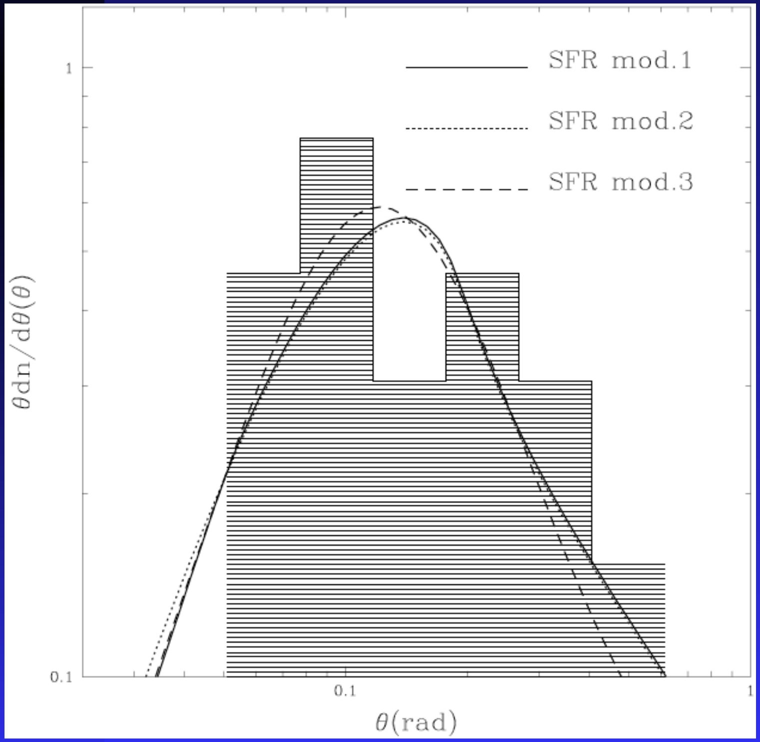




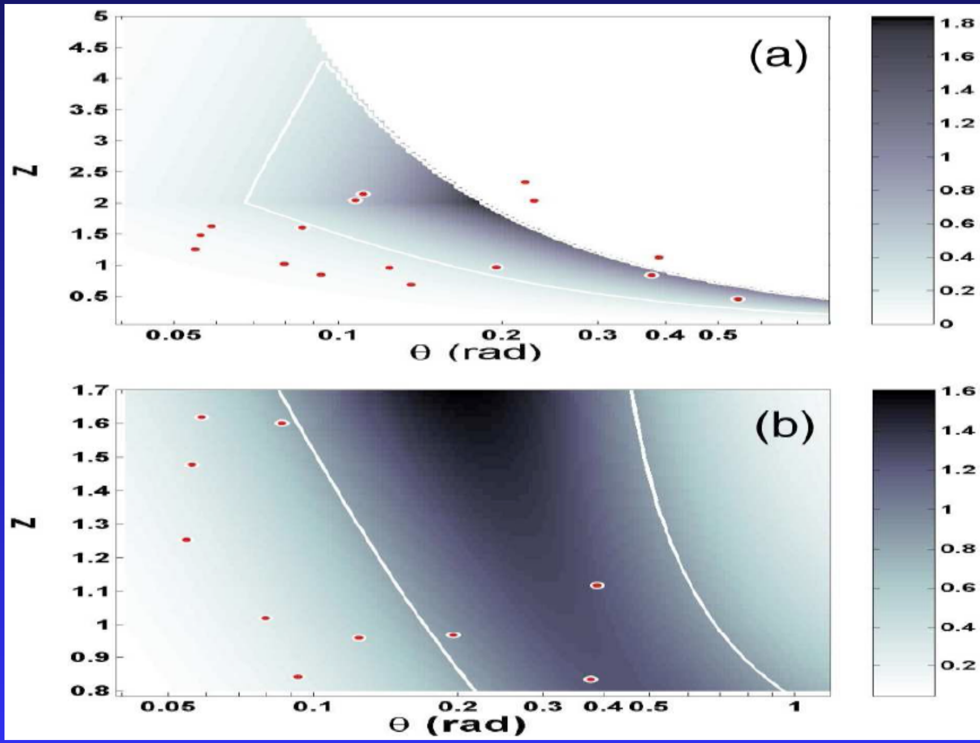
(Guetta, JG & Begelman 2005)

Jet Structure from t_{jet} (z) distribution

- dN/dθ appears to favor the USJ model
- dN/dθdz disfavors the USJ model
- It is still premature to draw strong conclusions due to the inhomogeneous sample & various selection effects
- Not yet a “clean” method for extracting the jet structure



(Perna, Sari & Frail 2003)



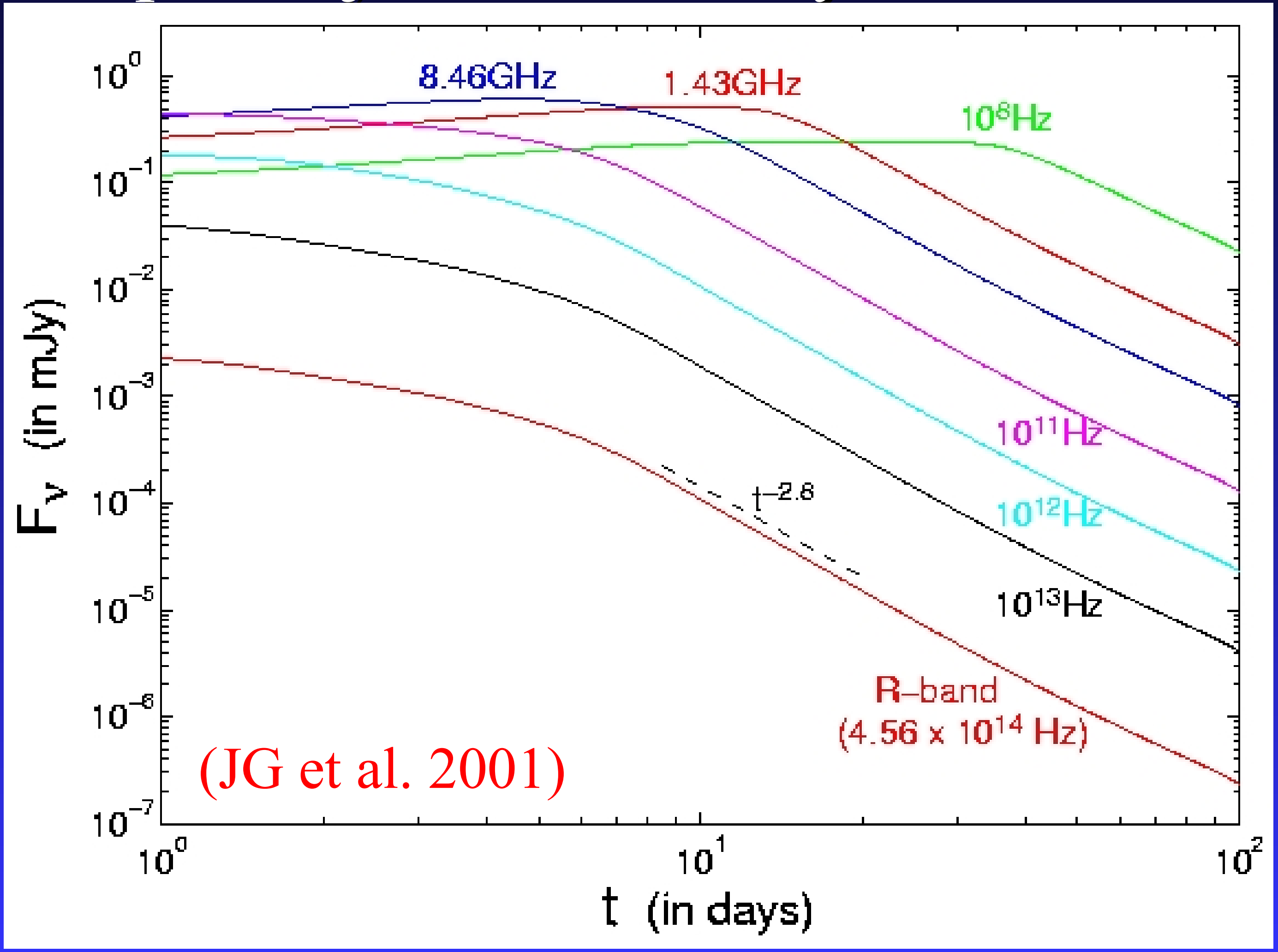
(Nakar, JG & Guetta 2004)

Afterglow Light Curves: Uniform Jet

(Rhoads 97,99; Panaitescu & Meszaros 99; Sari, Piran & Halpern 99; Moderski, Sikora & Bulik 00; JG et al. 01,02)

- Uniform "top hat" jet - extensively studied ✔

$\epsilon_e=0.1$, $\epsilon_B=0.01$,
$p=2.5$, $\theta_0=0.2$,
$\theta_{obs}=0$, $z=1$,
$E_{iso}=10^{52}$ ergs,
$n=1$ cm^{-3}

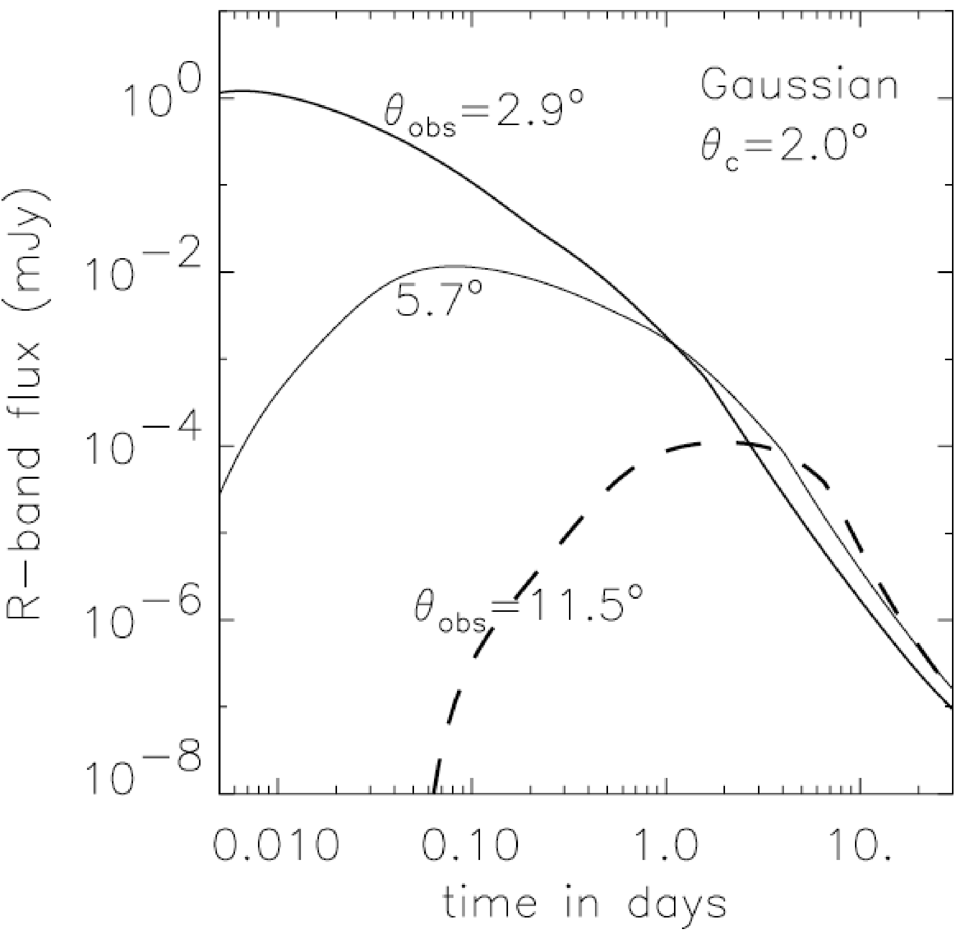


(JG et al. 2001)

Afterglow Light Curves: Gaussian Jet

(Zhang & Meszaros 02; Kumar & JG 03; Zhang et al. 04)

- It is a “smooth edged” version of a “top hat” jet
- Reproduces on-axis light curves nicely

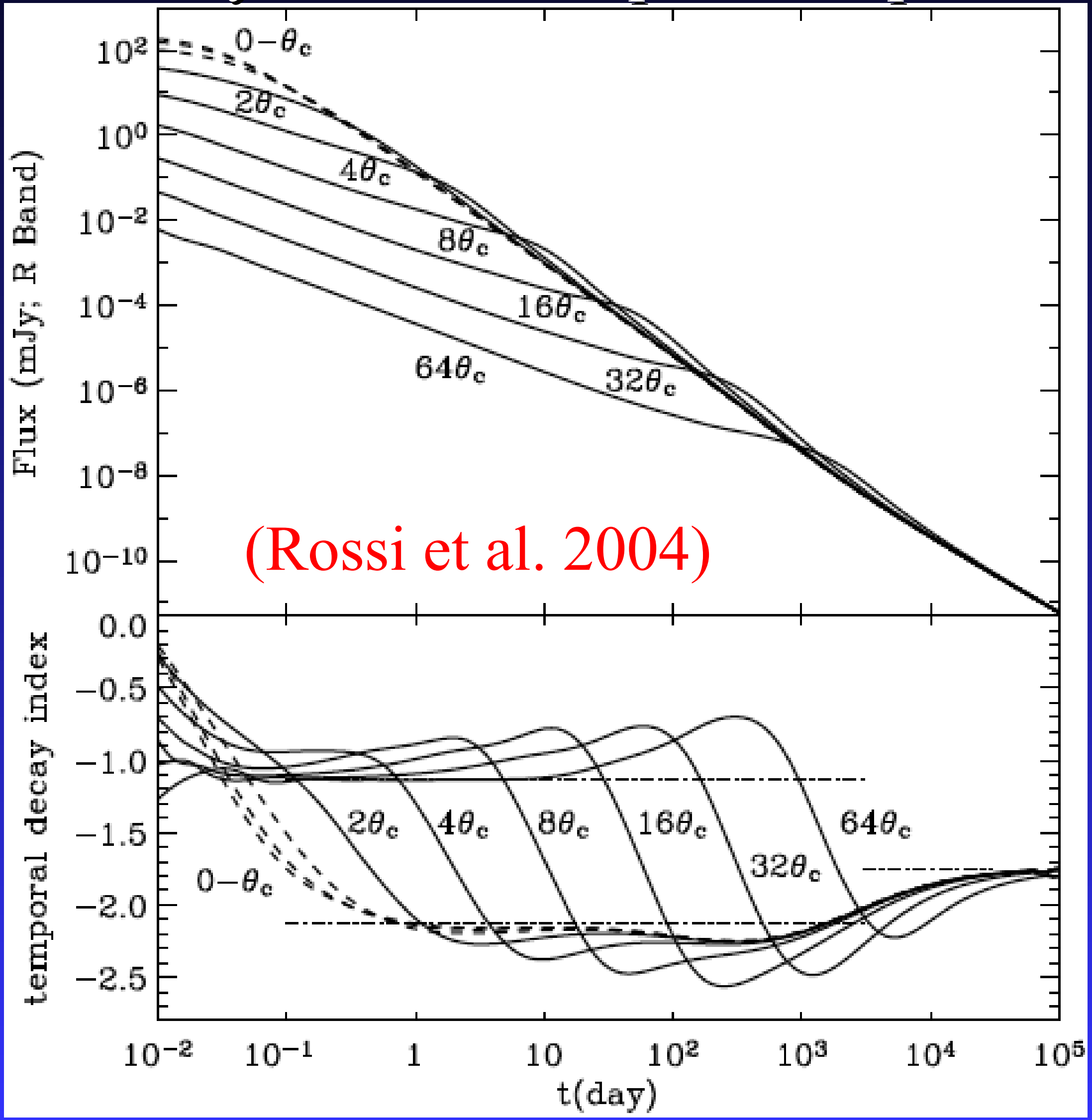


(Kumar & JG 2003)

Afterglow LCs: Universal Structured Jet

(Lipunov, Postnov & Prohkorov 01; Rossi, Lazzati & Rees 02; Zhang & Meszaros 02)

- Works reasonably well but has potential problems



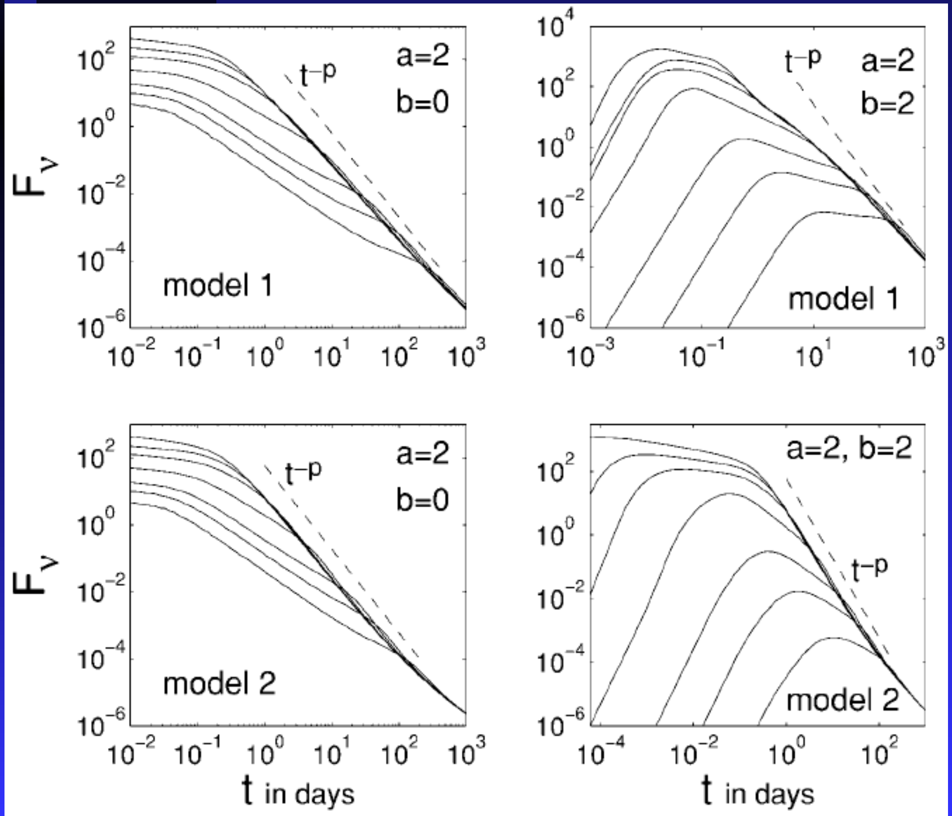
(Rossi et al. 2004)

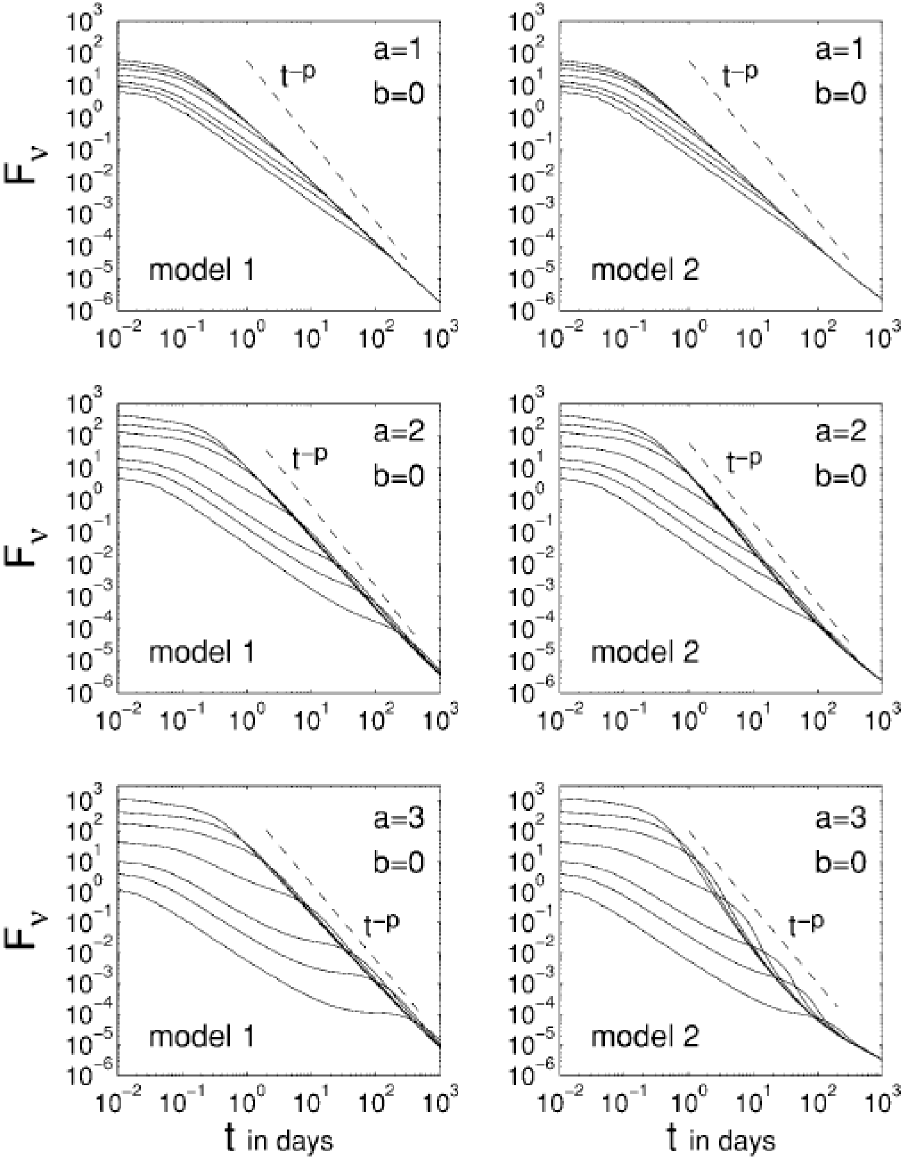
Afterglow LCs: Universal Structured Jet

- LCs Constrain the power law indexes ‘a’ & ‘b’:
  $dE/d\Omega \propto \theta^{-a}$, $\Gamma_0 \propto \theta^{-b}$

- $1.5 \lesssim a \lesssim 2.5$, $0 \lesssim b \lesssim 1$

(JG & Kumar 2003)



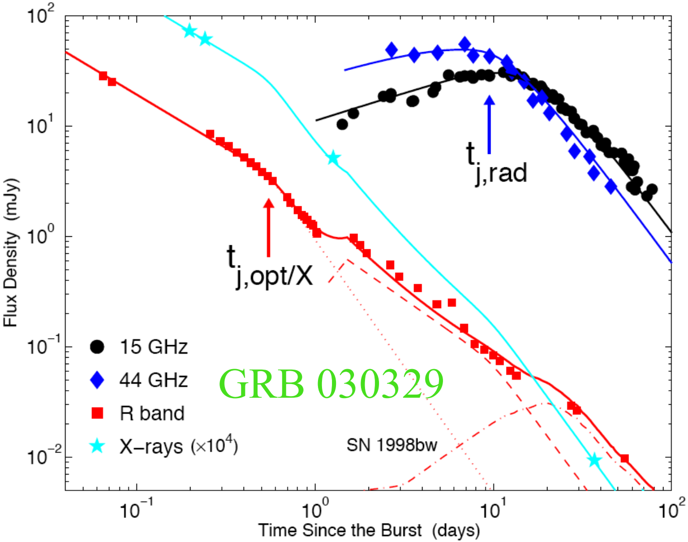


Afterglow LCs: Two Component Jet

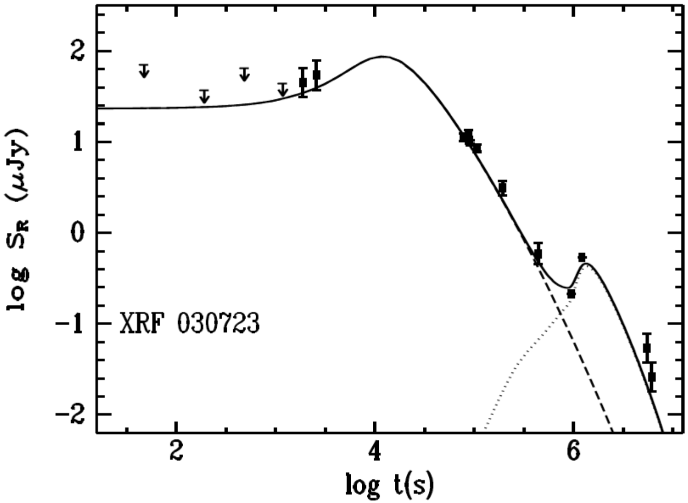
(Pedersen et al. 98; Frail et al. 00; Berger et al. 03; Huang et al. 04; Peng, Konigl & JG 05; Wu et al. 05)

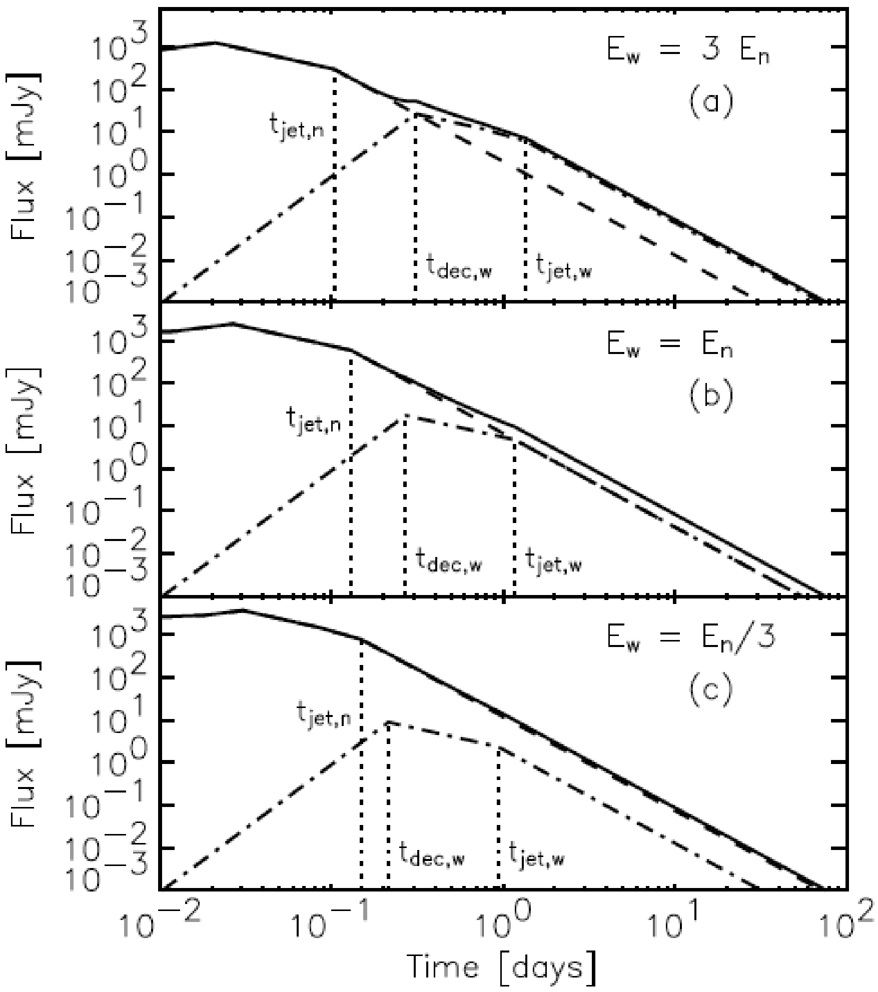
- Usual light curves + extra features: bumps, flattening

(Berger et al. 2003)



(Huang et al. 2004)

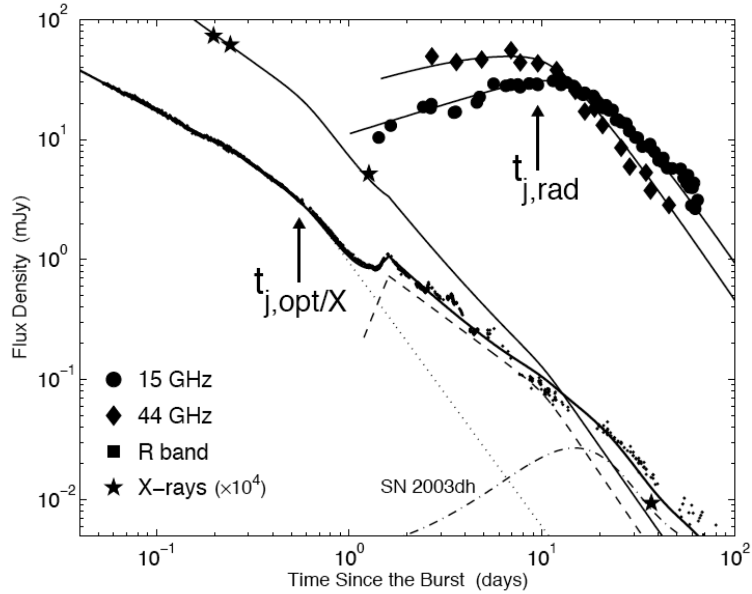


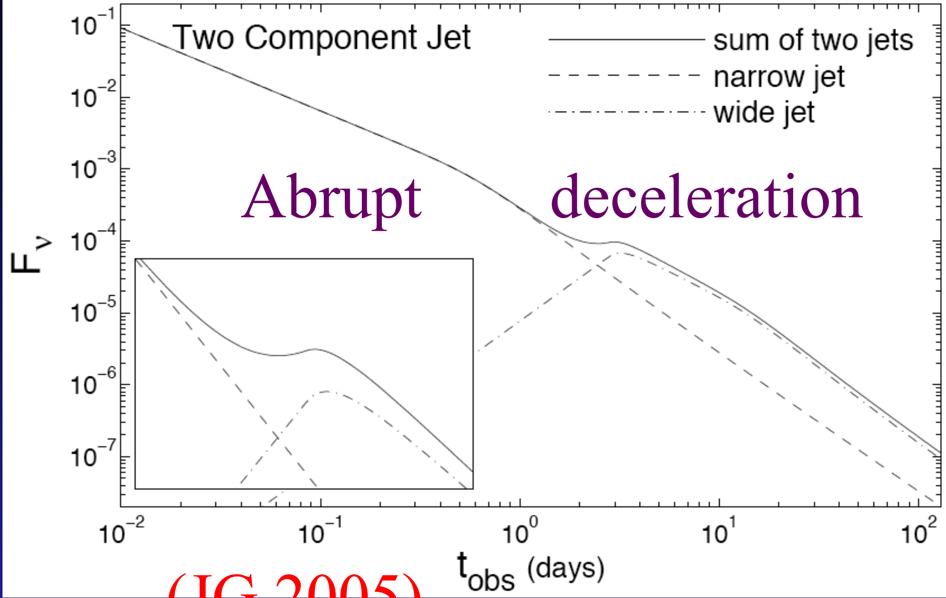


(Peng, Konigl & JG 2005)

Two Component Jet: GRB 030329

- The bump at $t_{dec,w}$ for an on-axis observer is wide & smooth

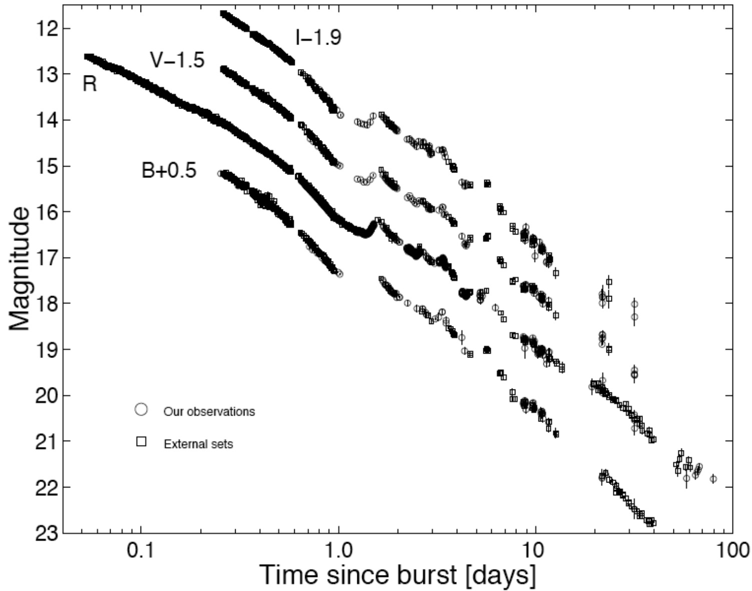


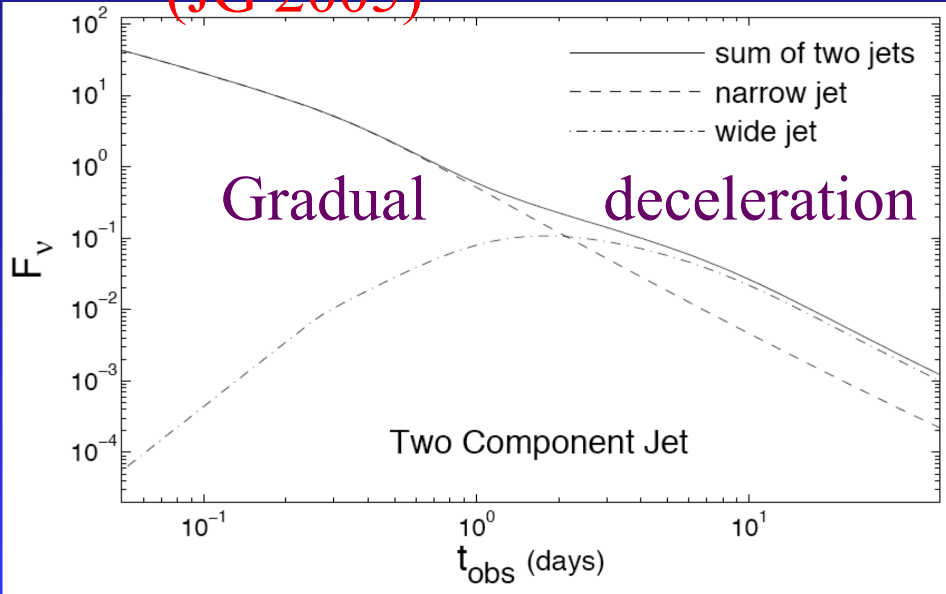


Abrupt deceleration

(Lipkin et al. 2004)

(JG 2005)

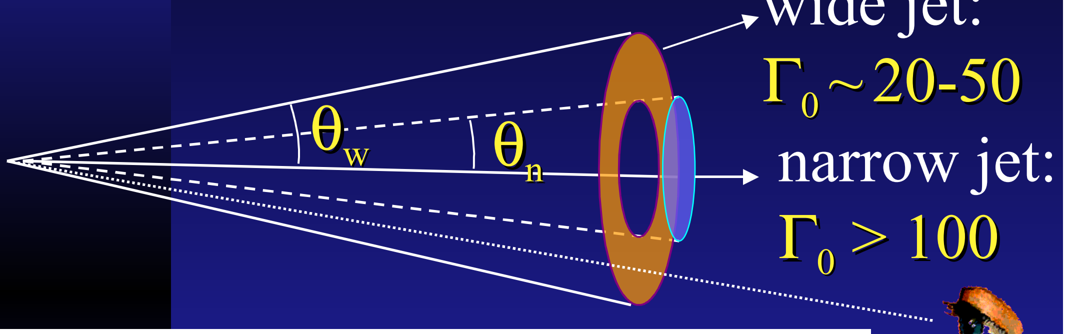




Gradual deceleration

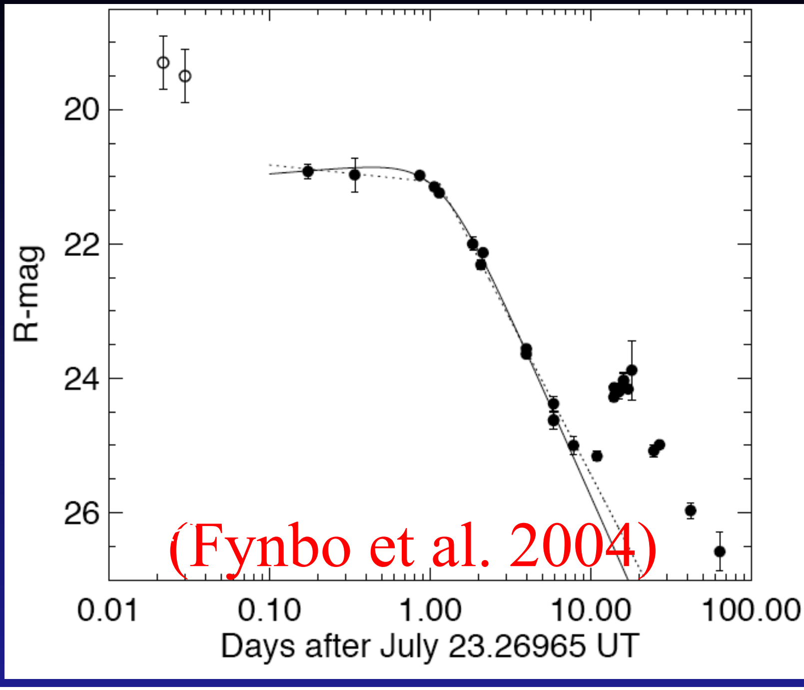
Two Component Jet: XRF 030723

- The **bump** in the light curve when the narrow jet becomes visible is **smooth & wide**

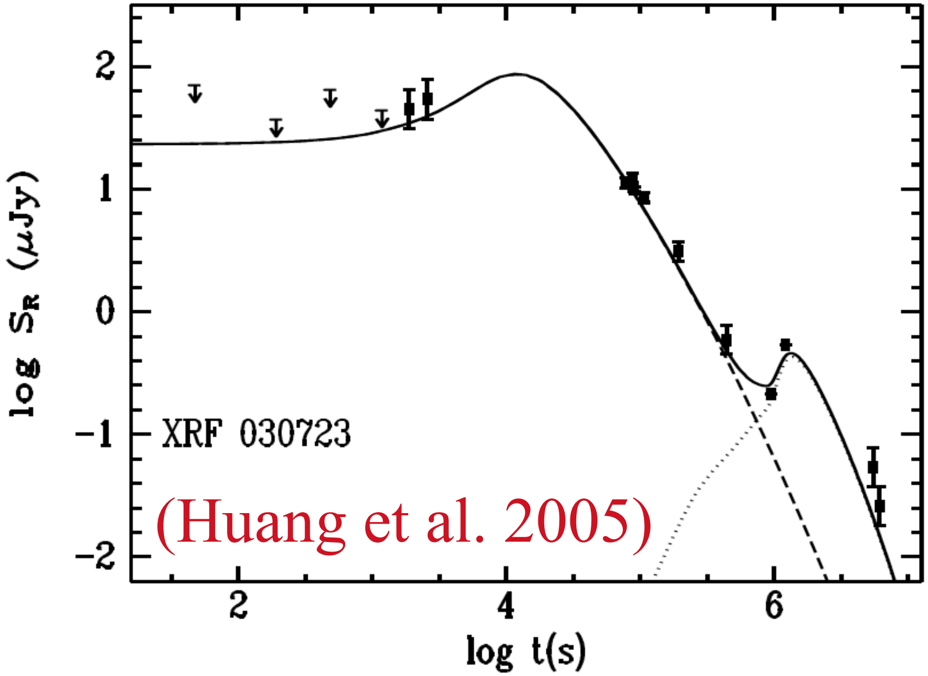


wide jet: $\Gamma_0 \sim 20\text{-}50$

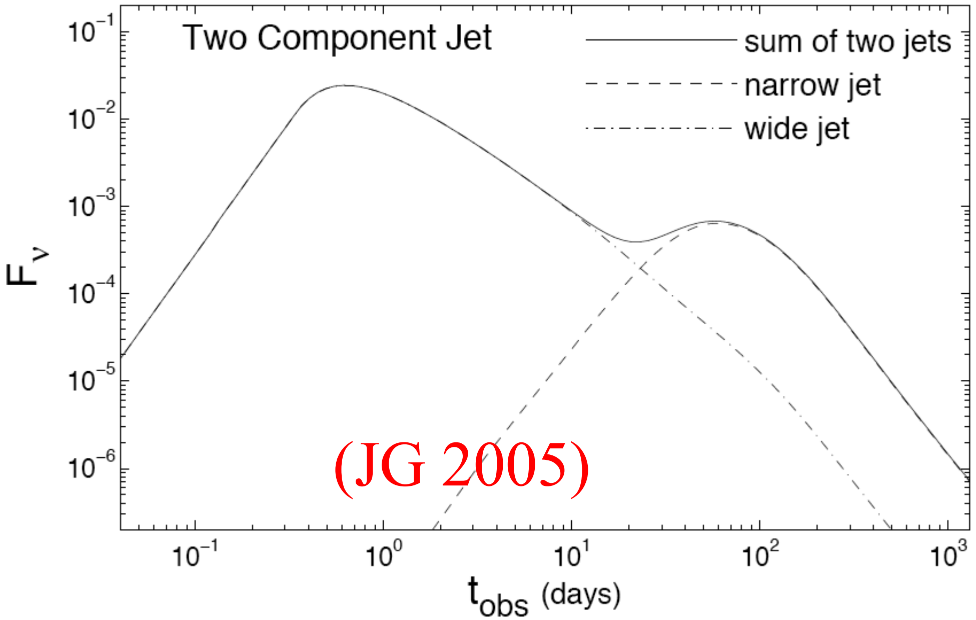
narrow jet: $\Gamma_0 > 100$



(Fynbo et al. 2004)



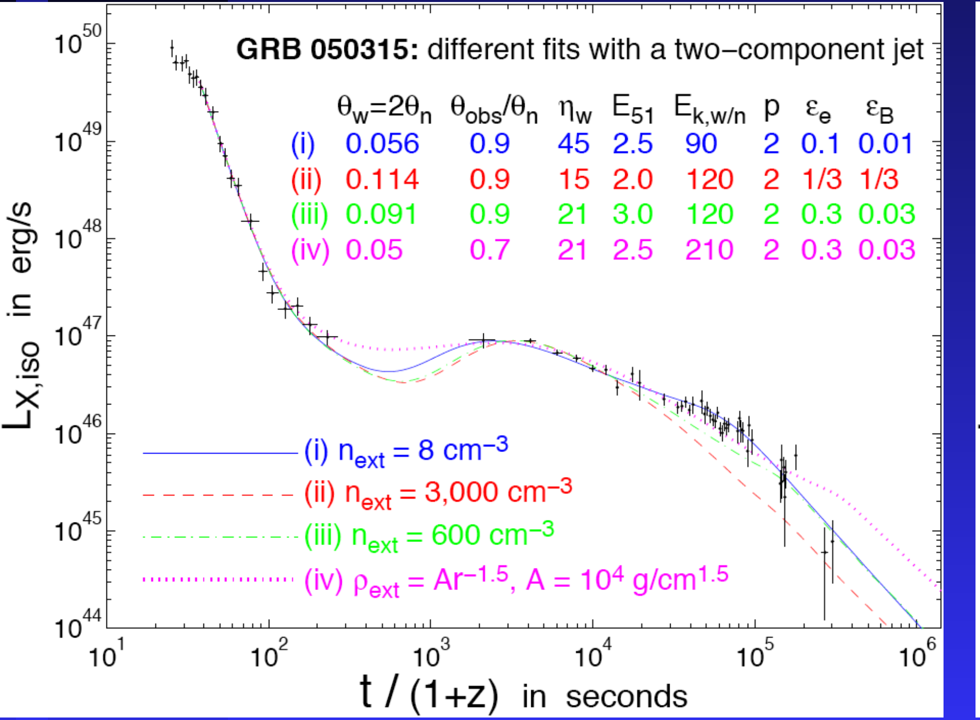
(Huang et al. 2005)



(JG 2005)

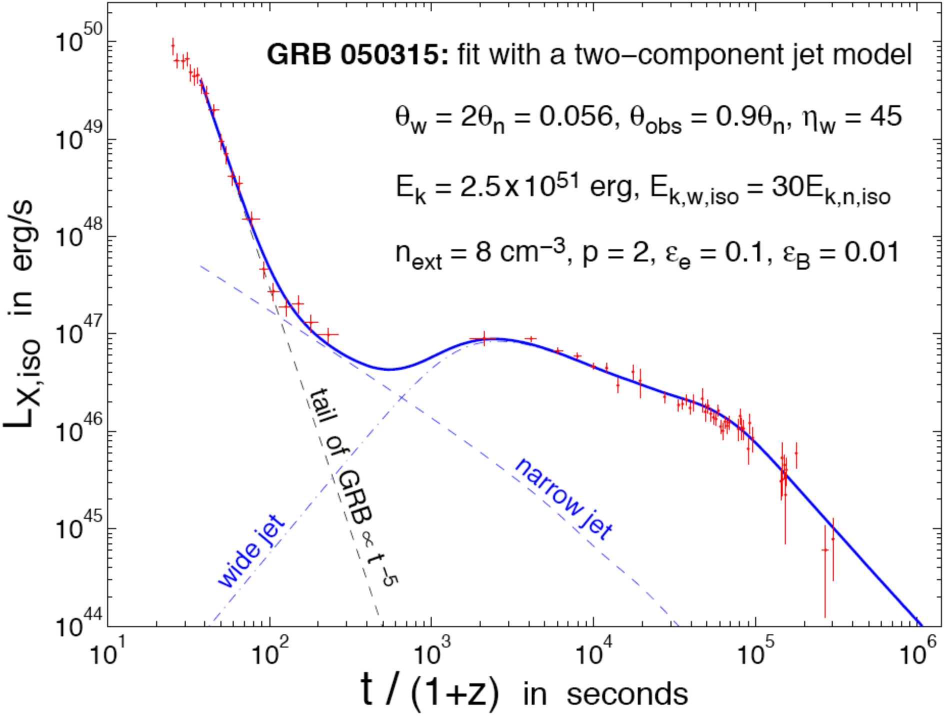
Explaining flat decay phase observed by Swift

- The X-ray afterglow of GRB 050315 requires that $f = E_{iso,w}/E_{iso,n} \gtrsim 30$ and more generally $f > 1$ so that the required gamma-ray efficiency is not lowered
- $E_w/E_n \gtrsim 100$ is challenging for theoretical models



GRB 050315: different fits with a two–component jet

	$\theta_w=2\theta_n$	θ_{obs}/θ_n	η_w	E_{51}	$E_{k,w/n}$	p	ε_e	ε_B
(i)	0.056	0.9	45	2.5	90	2	0.1	0.01
(ii)	0.114	0.9	15	2.0	120	2	1/3	1/3
(iii)	0.091	0.9	21	3.0	120	2	0.3	0.03
(iv)	0.05	0.7	21	2.5	210	2	0.3	0.03



GRB 050315: fit with a two–component jet model

$\theta_w = 2\theta_n = 0.056$, $\theta_{obs} = 0.9\theta_n$, $\eta_w = 45$

$E_k = 2.5 \times 10^{51}$ erg, $E_{k,w,iso} = 30E_{k,n,iso}$

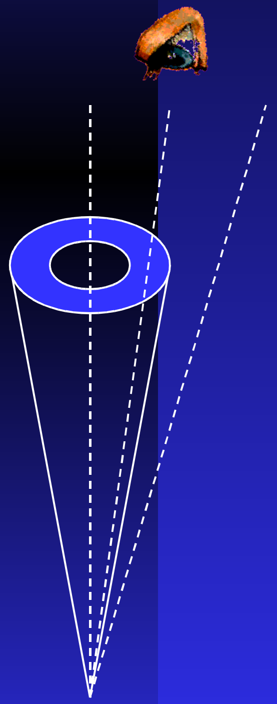
$n_{ext} = 8\ \mathrm{cm}^{-3}$, $p = 2$, $\varepsilon_e = 0.1$, $\varepsilon_B = 0.01$

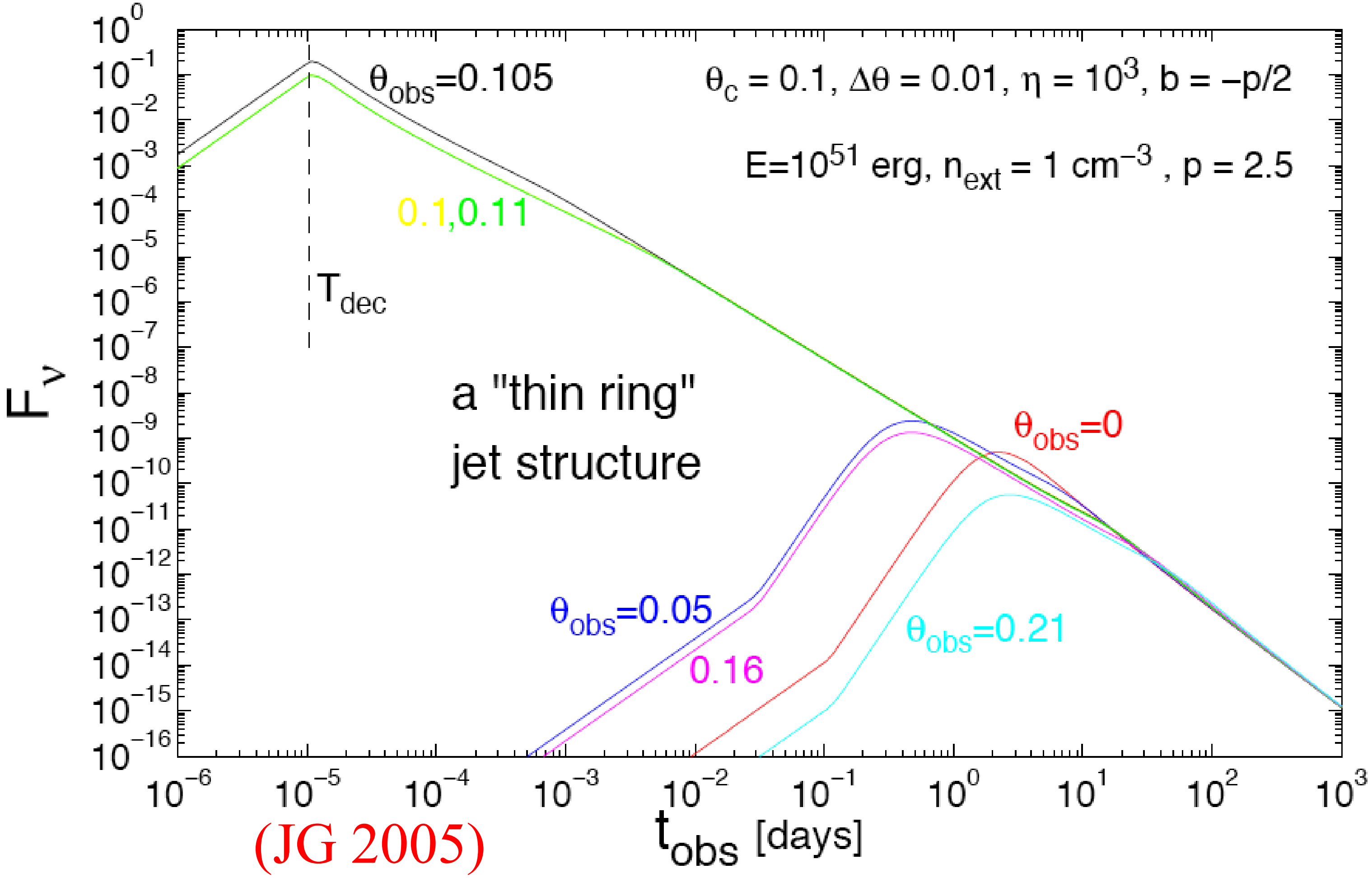
(JG, Königl & Piran 2006)

Afterglow LCs: Ring Shaped Jet

(Eichler & Levinson 03,04; Levinson & Eichler 04; Lazzati & Begelman 05)

- The jet break splits into two, the first when $\gamma\Delta\theta \sim 1\text{-}2$ and the second when $\gamma\theta_c \sim 1/2$



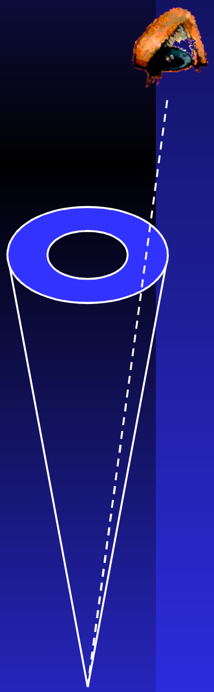


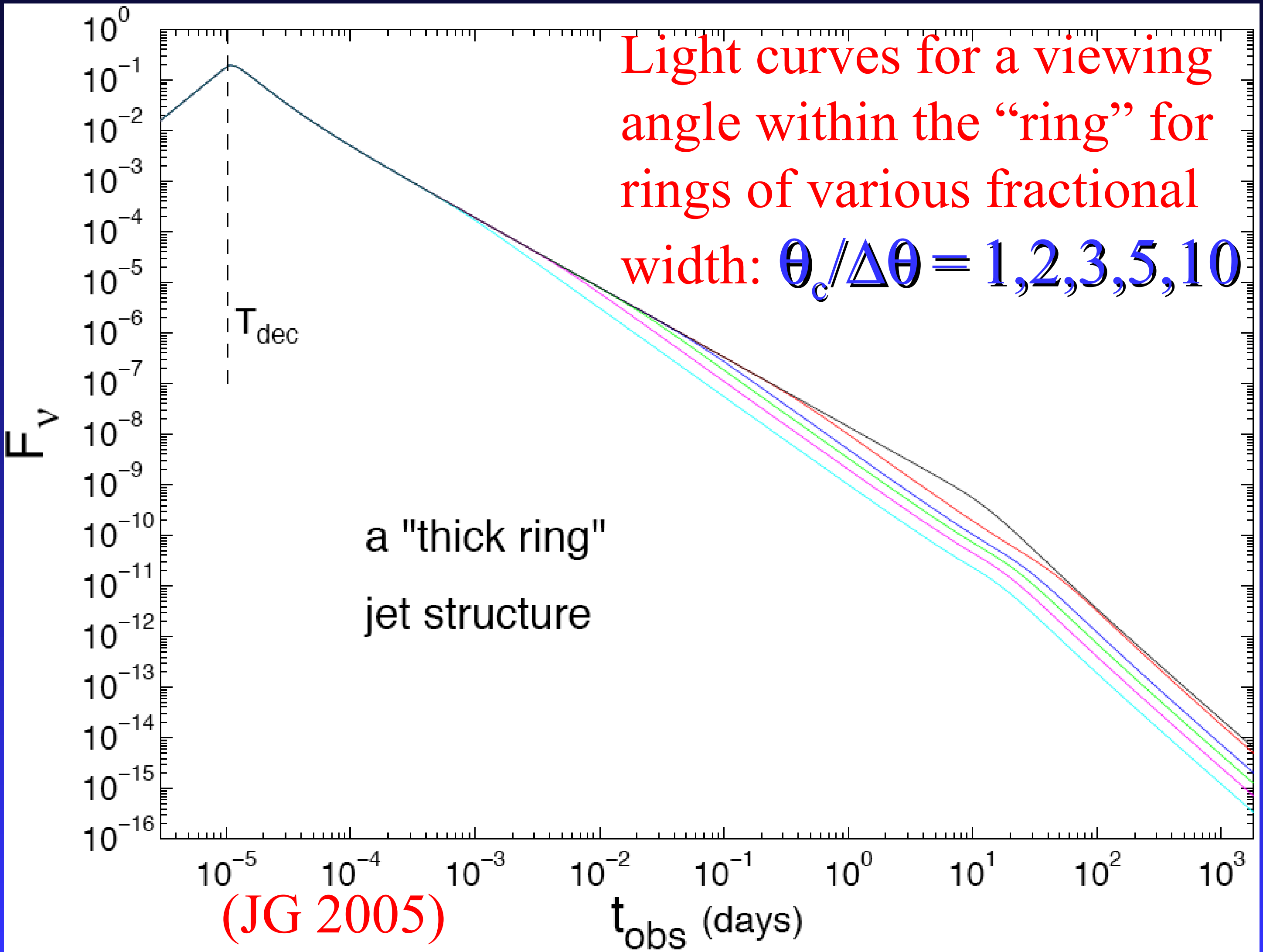
(JG 2005)

Afterglow Light Curves: Wide Ring

(Eichler & Levinson 03,04; Levinson & Eichler 04)

- There are two distinct jet break unless ring is very thick



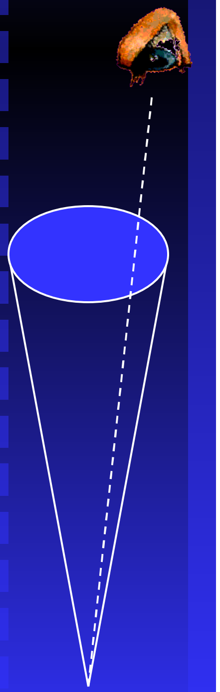


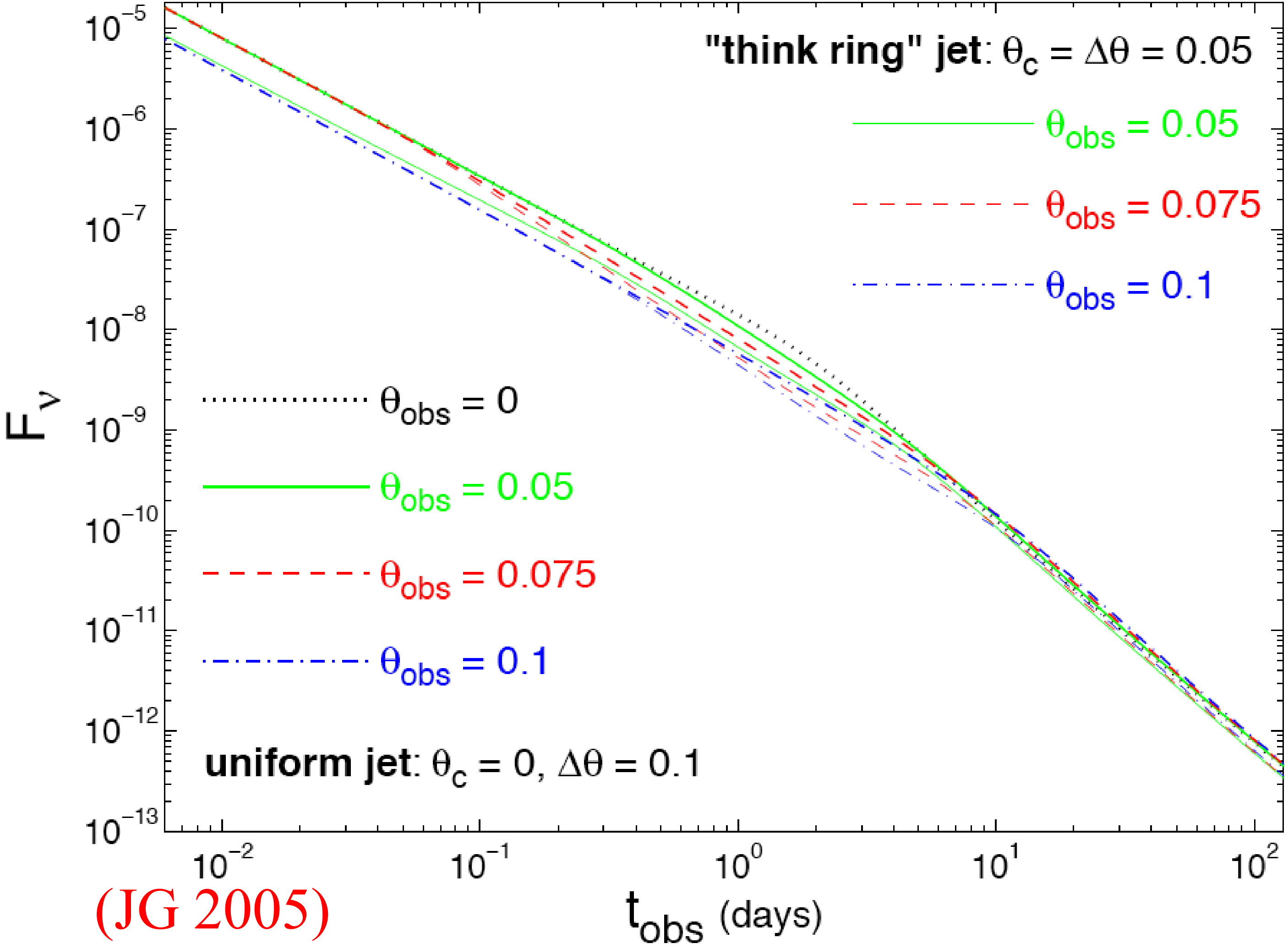
Light curves for a viewing angle within the "ring" for rings of various fractional width: $\theta_c/\Delta\theta = 1,2,3,5,10$

(JG 2005)

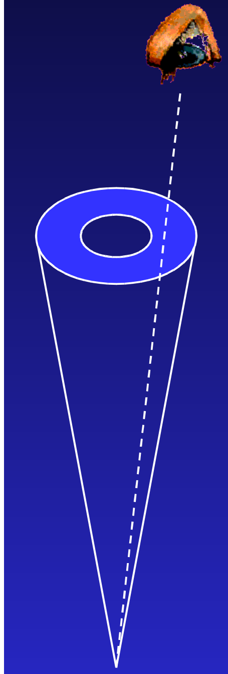
Wide Ring vs. Uniform Conical Jet

- For $\Delta\theta \gtrsim \theta_c$ the jet break becomes rather similar to that for a conical uniform jet and gets closer to observations





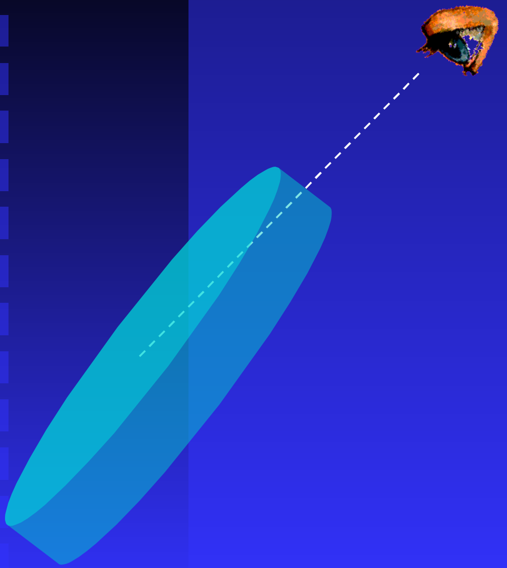
(JG 2005)

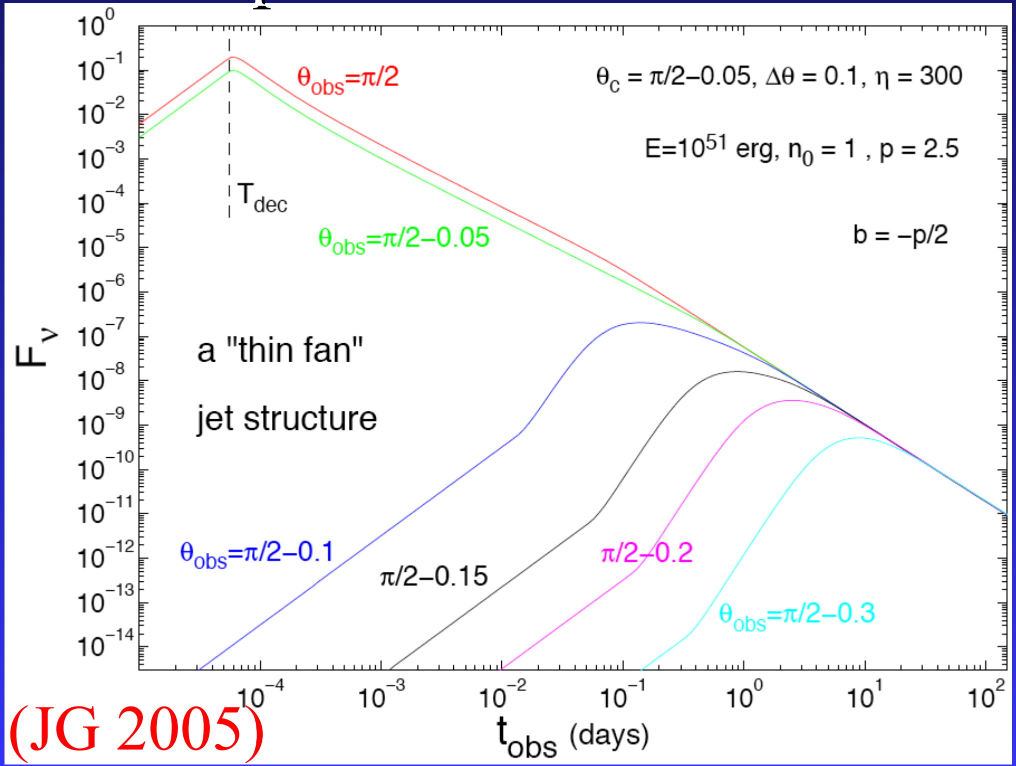


Afterglow Light Curves: Fan Shaped Jet

(Thompson 2004)

- The jet break is a factor of 2 shallower than for a uniform conical jet for no lateral spreading, and even shallower [a factor of $(7-2k)/(3-k) > 2$ instead of 2, where $\rho_{ext} \propto R^{-k}$] for relativistic lateral expansion in its own rest frame

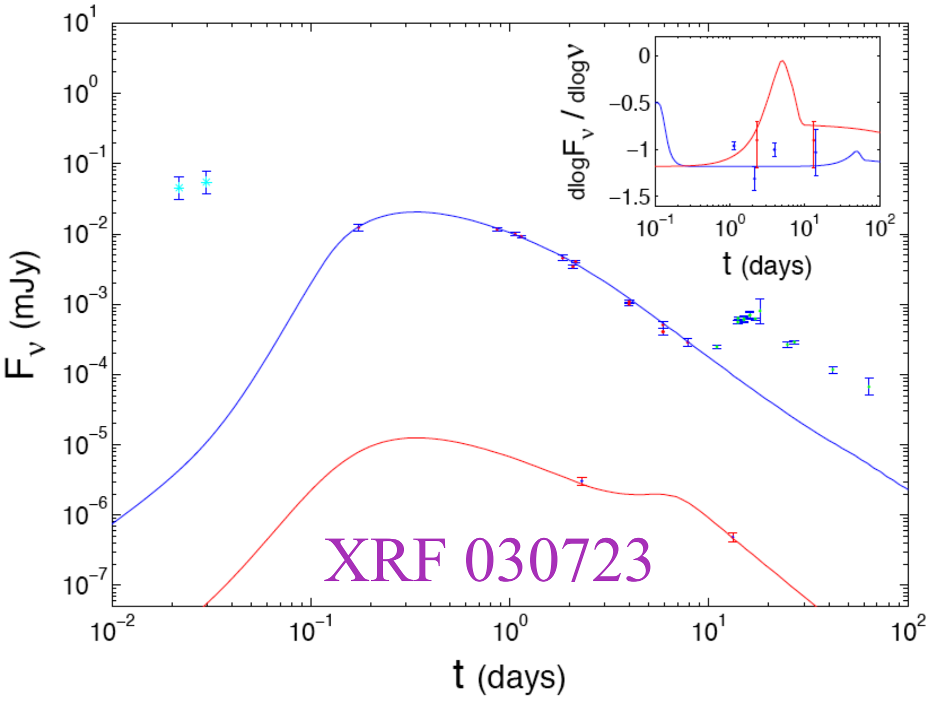


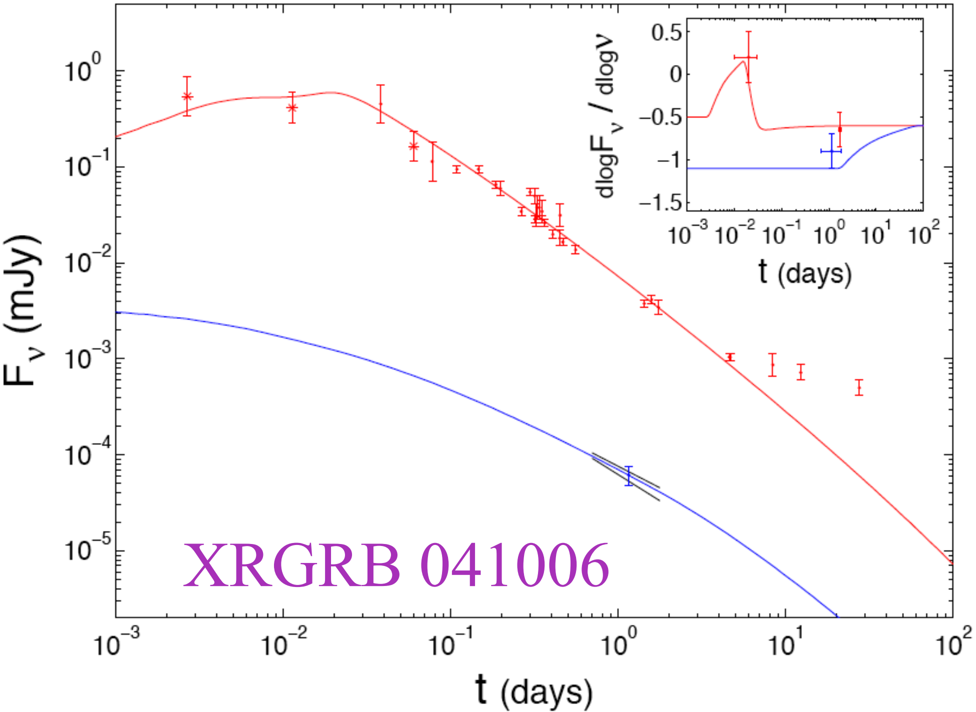


(JG 2005)

Light Curves of X-ray Flashes & XRGRBs

- Suggest a roughly uniform jet with reasonably sharp edges, where GRBs, XRGRBs & XRFs are similar jets viewed from increasing viewing angles (Yamazaki, Ioka & Nakamura 02,03,04)

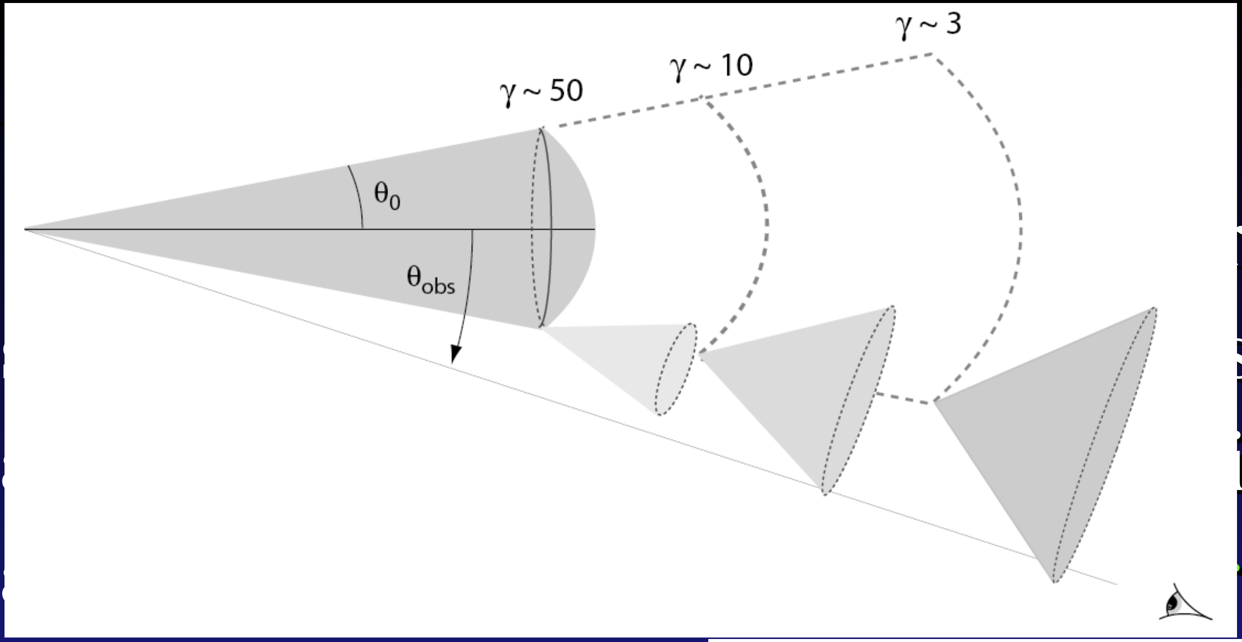


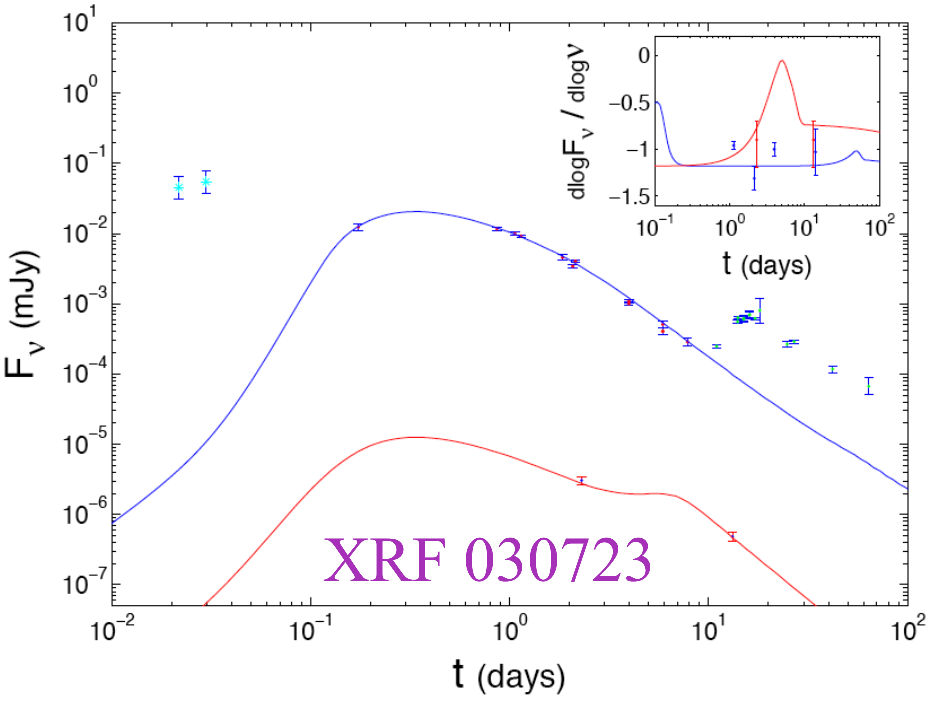


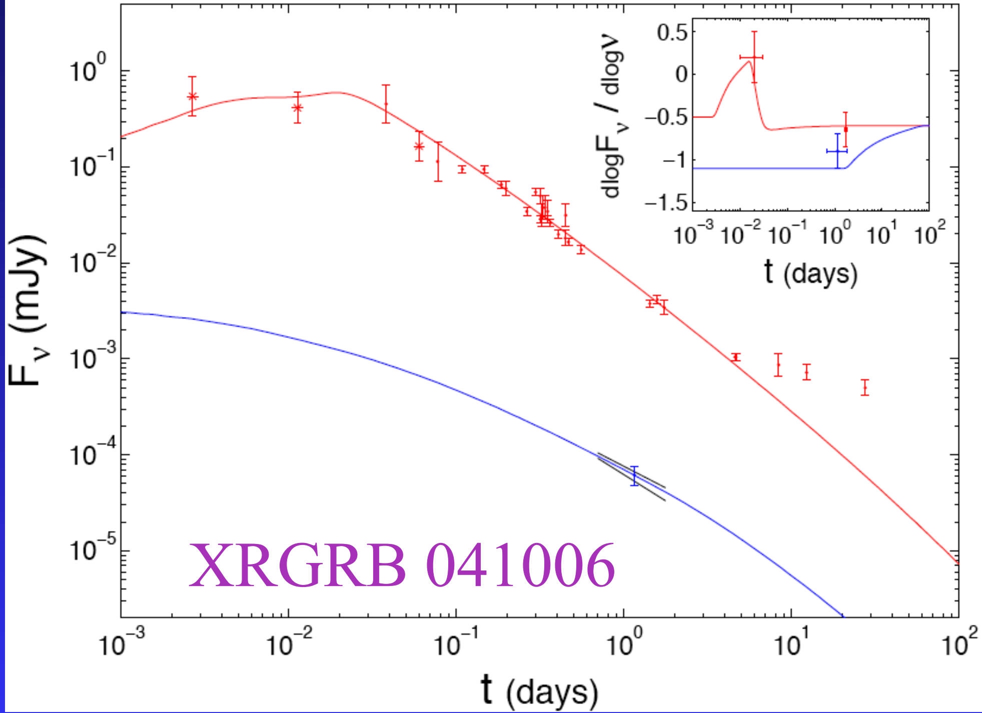
(JG, Ramirez-Ruiz & Perna 2005)

Ligh XRGRBs

- reasonably
  s & XRFs
  ing viewing
  a 02,03,04)



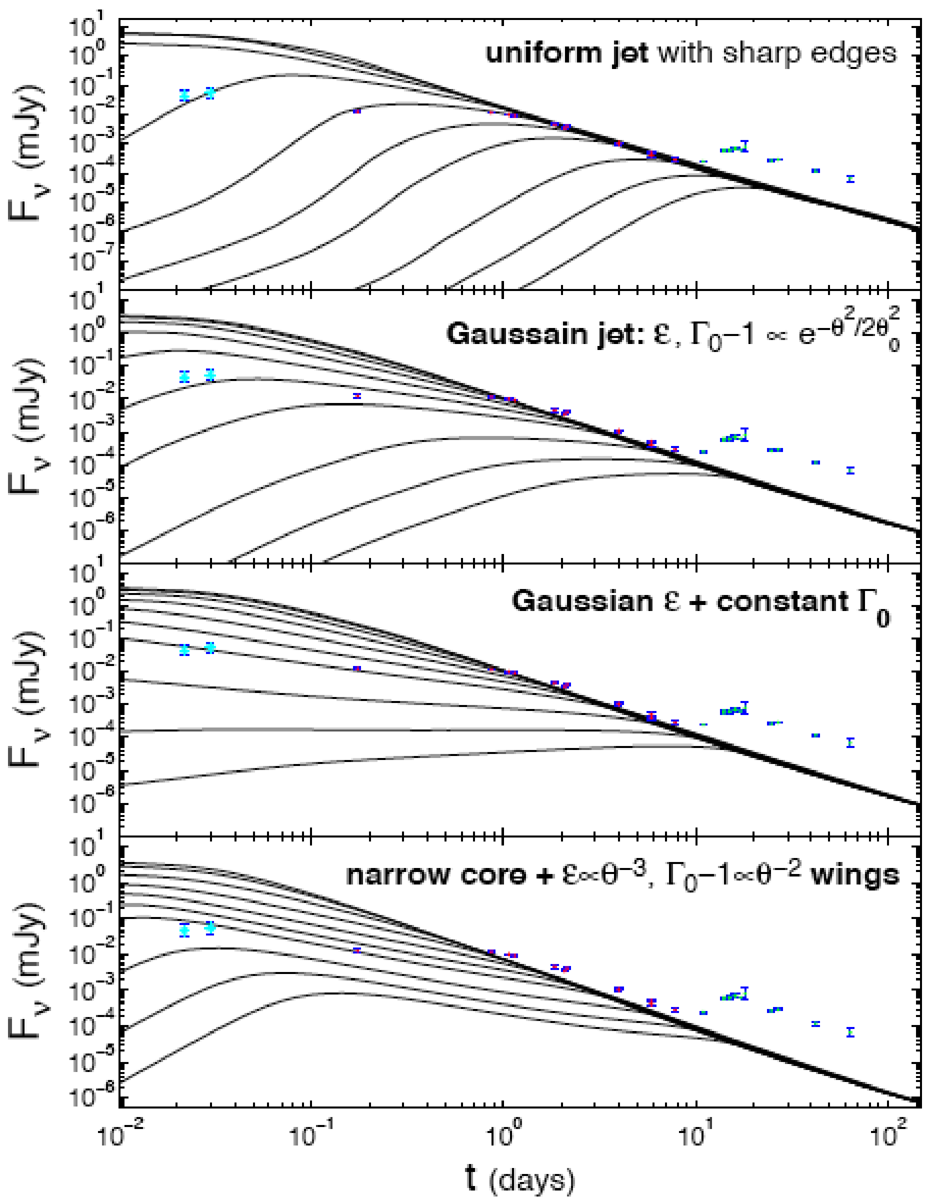




(JG, Ramirez-Ruiz & Perna 2005)

Afterglow L.C. for Different Jet Structures:

- Uniform conical jet with sharp ejdges: ✔
- Gaussian jet in both Γ_0 & $dE/d\Omega$: might still work
- Constant Γ_0 + Gaussian $dE/d\Omega$: not flat enough
- Core + $dE/d\Omega \propto \theta^{-3}$ wings: not flat enough



$\theta_{obs}/\theta_{0/c} = 0, 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6$

(JG, Ramirez-Ruiz & Perna 2005)

Dynamics of GRB Jets: Lateral Expansion

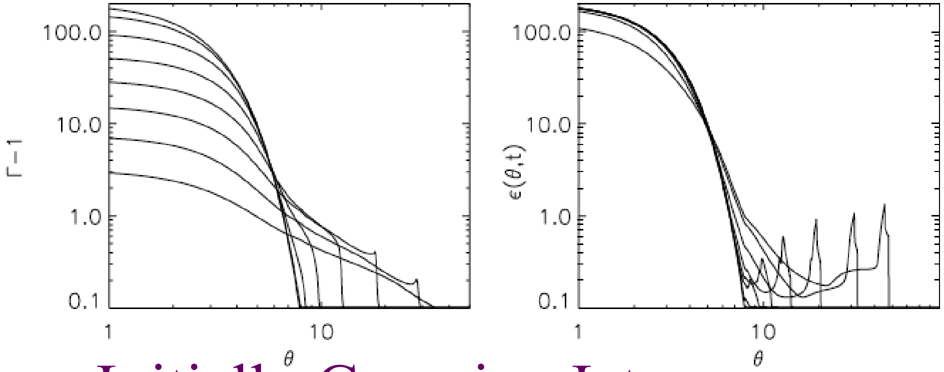
Simple (Semi-) Analytic Jet Models

(Rhoads 97, 99; Sari, Piran & Halpern 99,…)

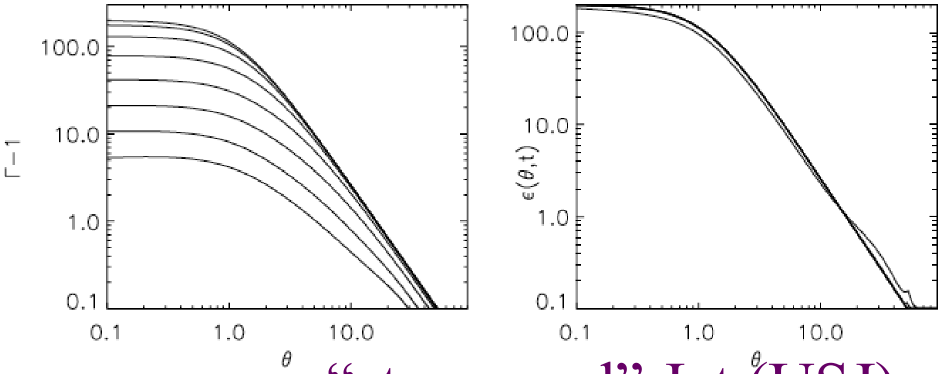
- Typical simplifying assumptions:
  - The shock front is a part of a sphere within $\theta < \theta_{jet}$
  - The velocity is in the radial direction (even at $t > t_{jet}$)
  - Lateral expansion at $c_s \approx c/\sqrt{3}$ in the comoving frame
  - The jet dynamics are obtained by solving simple 1D equations for conservation of energy and momentum
- $\gamma \sim (c_s/c\theta_0)\exp(-R/R_{jet})$, $\theta_{jet} \sim \theta_0(R_{jet}/R)\exp(R/R_{jet})$
  - Most models predict a jet break but differ in the details:
    - The jet break time t_{jet} (by up to a factor of ~20)
    - Temporal slope $F_\nu(\nu > \nu_m, t > t_{jet}) \propto t^{-\alpha}$, $\alpha \sim p$ (±15%)
    - The jet break **sharpness** (~1- 4 decades in time)

Simplifying the Dynamics: 2D → 1D

- Integrating the hydrodynamic equations over the radial direction significantly reduces the numerical difficulty
- This is a reasonable approximation as most of the shocked fluid is within a thin layer of width ~ $R/10\gamma^2$

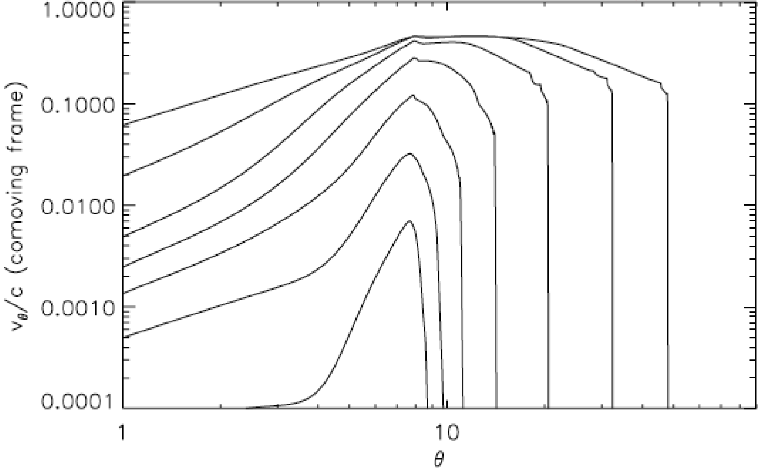


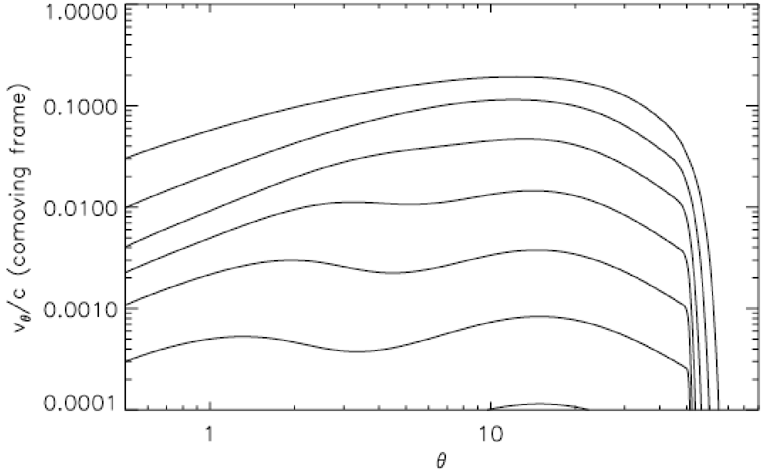
Initially Gaussian Jet



“strucrured” Jet (USJ)

(Kumar & JG 2003)





Numerical Simulations:

(JG et al. 2001; Cannizzo et al. 2004; Zhang & Macfayen 2006)

The difficulties involved:

- The hydro-code should allow for both $\gamma \gg 1$ and $\gamma \approx 1$
- Most of the shocked fluid lies within in a very thin shell behind the shock ($\Delta \sim R/10\gamma^2$) $\Rightarrow$ hard to resolve
- A relativistic code in **at least 2D** is required
- A complementary code for calculating the radiation

⇓

Very few attempts so far

Movie of Simulation

QuickTimeŞ and a
YUV420 codec decompressor
are needed to see this picture.

Upper face: Lorentz factor
Lower face: proper density

(Logarithmic
Color scale)

Proper Density:

(logarithmic color scale)

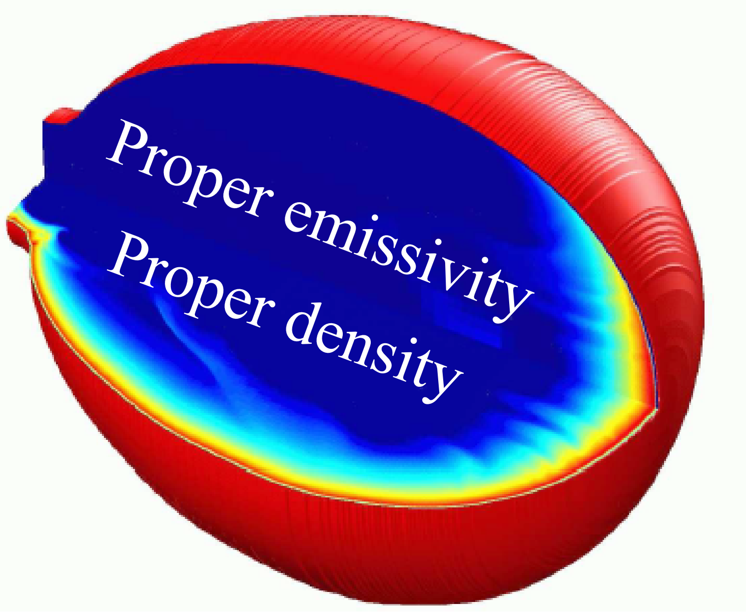
QuickTimeȘ and a
YUV420 codec decompressor
are needed to see this picture.

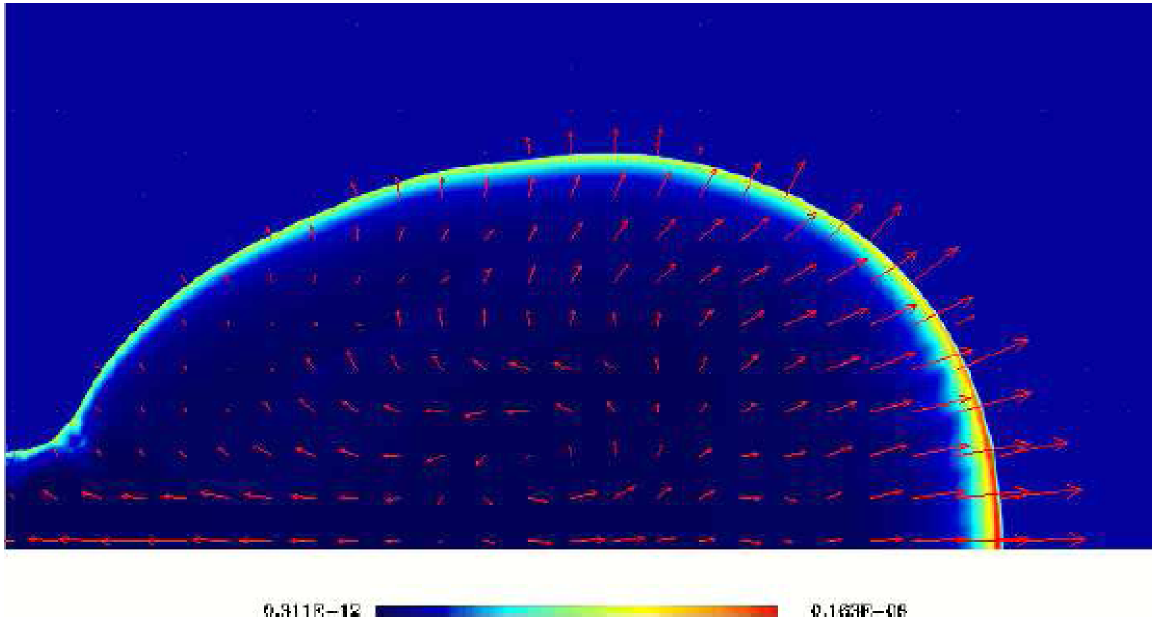
Bolometric Emissivity:

(logarithmic color scale)

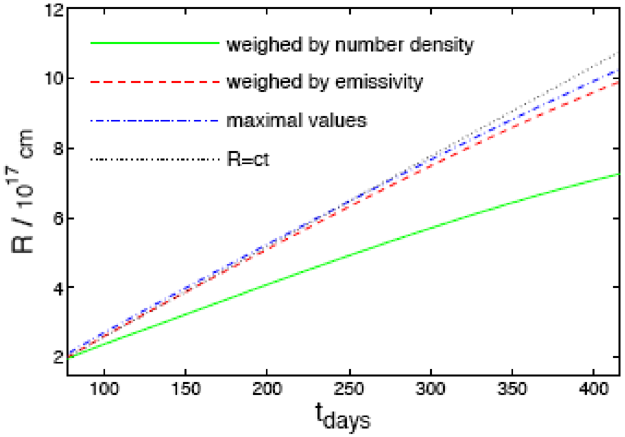
QuickTimeȘ and a
YUV420 codec decompressor
are needed to see this picture.

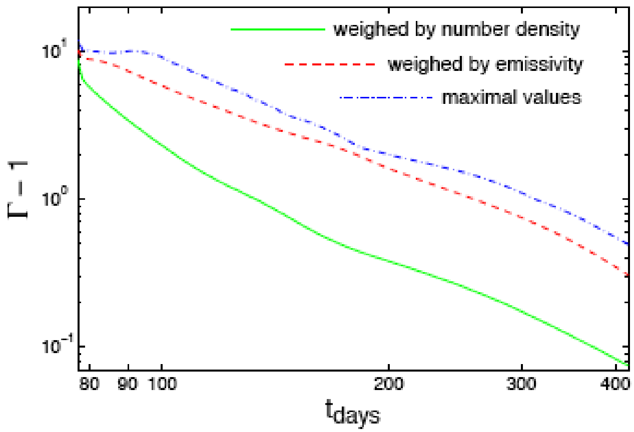
The Jet Dynamics: very modest lateral expansion

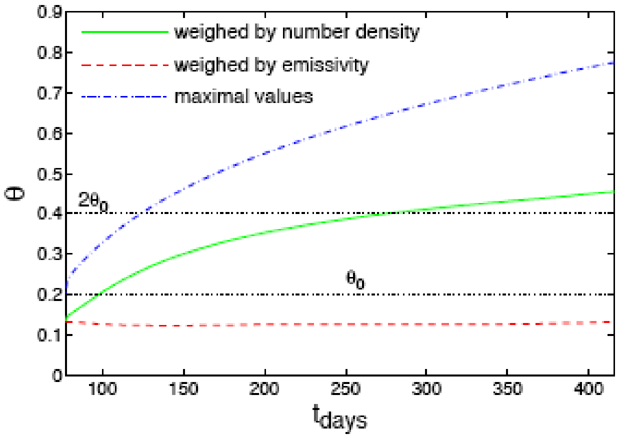




- There is slow material at the sides of the jet while most of the emission is from its front







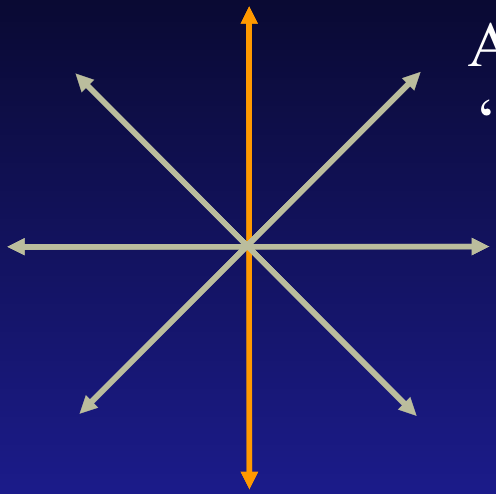
Main Results of Hydro-Simulations:

- The assumptions of simple models fail:
  - The shock front is not spherical
  - The velocity is not radial
  - The shocked fluid is not homogeneous
- There is only very mild lateral expansion as long as the jet is relativistic
- Most of the emission occurs within $\theta < \theta_0$
- **Nevertheless**, despite the differences, there is a **sharp** achromatic **jet break** [for $\nu > \nu_m(t_{jet})$] at t_{jet} close to the value predicted by simple models

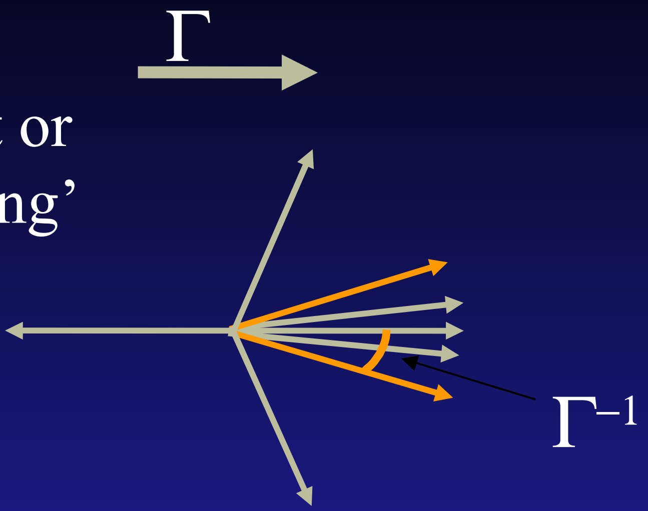
Why do we see a Jet Break:

Relativistic Source:

Source frame



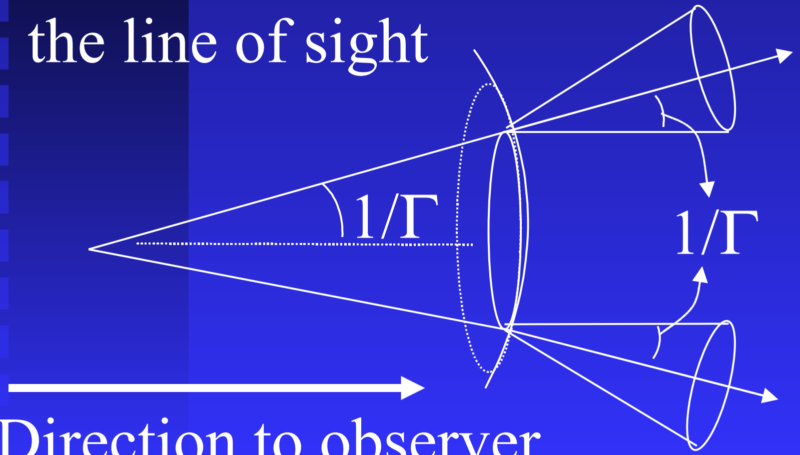
Aberration of light or ‘relativistic beaming’



Observer frame

The observer sees mostly emission from within an angle of $1/\Gamma$ around the line of sight

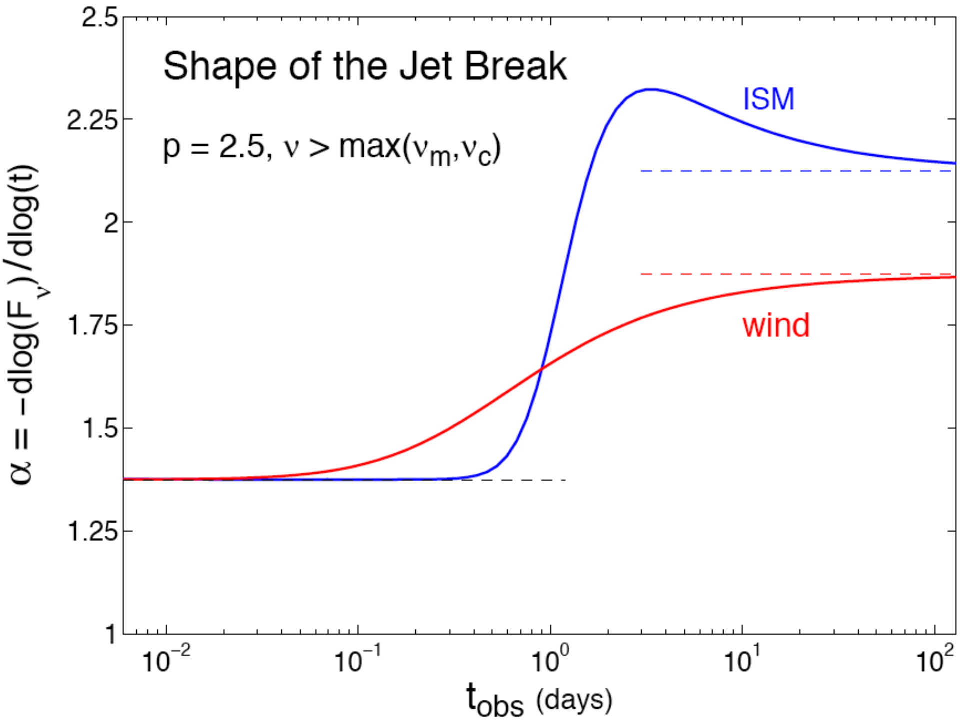
The edges of the jet become visible when Γ drops below $1/\theta_{jet}$, causing a jet break

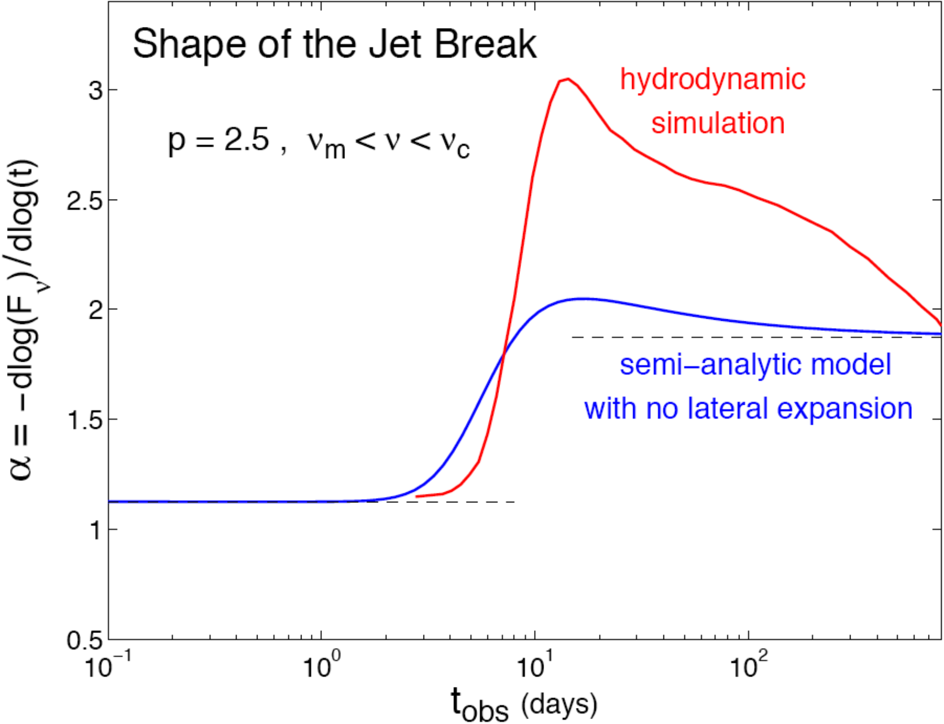


For $v_\perp \sim c$, $\theta_{jet} \sim 1/\Gamma$ so there is not much “missing” emission from $\theta > \theta_{jet}$ & the jet break is due to the decreasing $dE/d\Omega$ + faster fall in $\Gamma(t)$

Direction to observer

Limb Brightening of the Image + a rapid transition ⇒ an "overshoot"





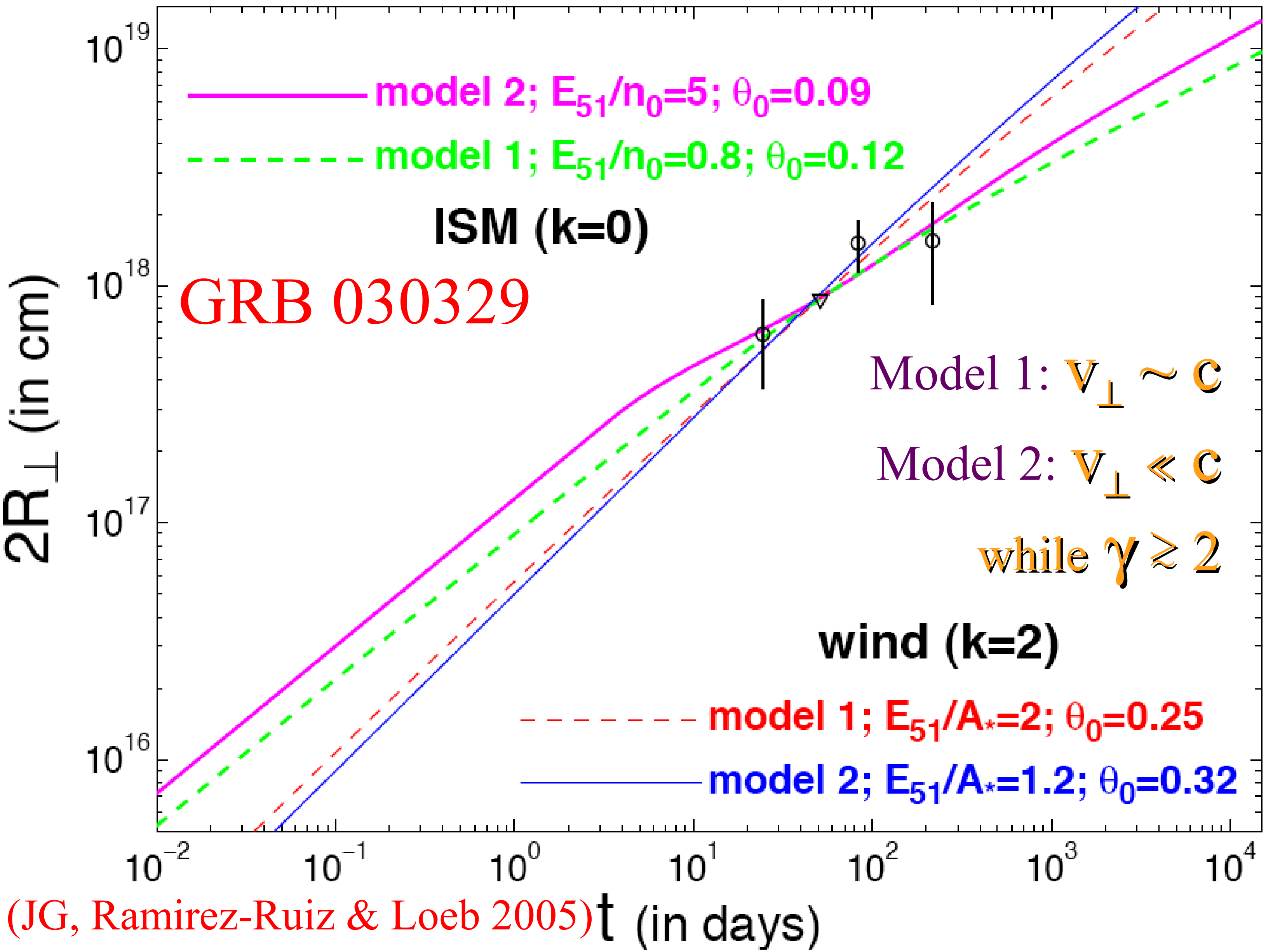
<u>Semi-analytic model</u>: stellar wind density ⇒ slower transition + less limb brightening ⇒ no overshoot

<u>Hydro-simulation</u>: more limb brightening + slightly faster transition ⇒ larger overshoot

Lateral Expansion: Evolution of Image Size

(Taylor et al. 04,05; Oren, Nakar & Piran 04; JG, Ramirez-Ruiz & Loeb 05)

Image diameter



GRB 030329

Model 1: $v_\perp \sim c$

Model 2: $v_\perp \ll c$

while $\gamma \gtrsim 2$

(JG, Ramirez-Ruiz & Loeb 2005)

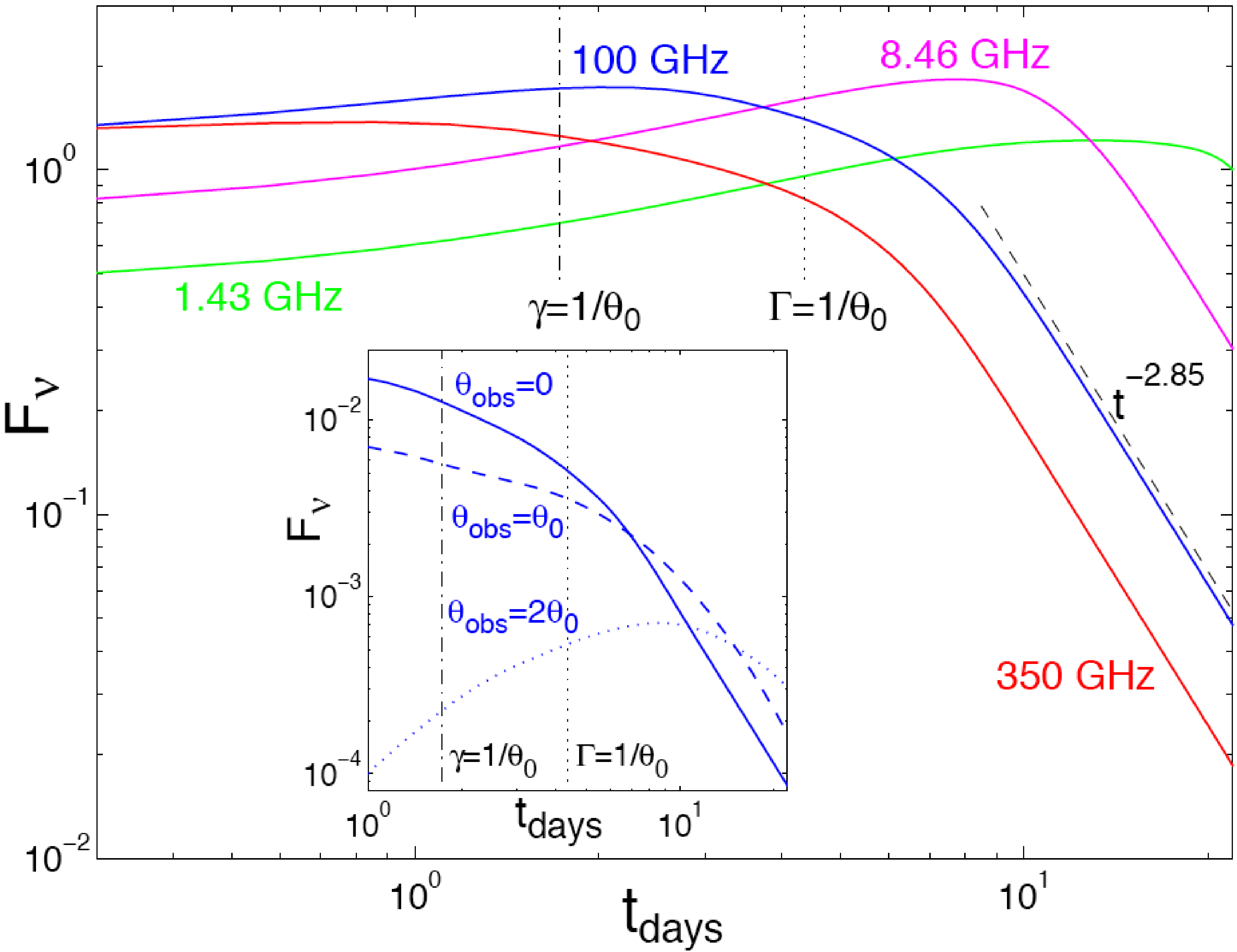
The Jet **Structure** and its **Energy**

- The same observations imply ~10 times more energy for a structured jet than for a uniform jet: $\sim 10^{52}$ erg instead of the "standard" $\sim 10^{51}$ erg
- Flat decay phase in *Swift* early X-ray afterglows imply very high γ-ray efficiencies, $\varepsilon_\gamma \sim 90\%$, if it is due to energy injection + standard AG theory
- The flat decay is due to an increase in time of AG efficiency ⇒ ε_γ does not change ($\sim 50\%$)
- Pre-*Swift* estimates of $E_{\mathrm{kin,AG}} \sim 10^{51}$ erg for a uniform jet relied on standard afterglow theory
- Different assumptions: $E_{\mathrm{kin,AG}} \sim 10^{52}$ erg, $\varepsilon_\gamma \sim 0.1$
- $\varepsilon_\gamma \lesssim 0.1 \Rightarrow E_{\mathrm{kin,AG}} \gtrsim 10^{53}$ erg for a structured jet

Conclusions:

- The most promising way to **constrain** the **jet structure** is through the **afterglow light curves**
- Numerical studies show **very little lateral expansion** while the jet is relativistic & produce a **sharp jet break** (as seen in afterglow obs.)
- The jet break occurs predominantly since its edges become visible (not lateral expansion)
- A low γ-ray efficiency requires a high afterglow kinetic energy: $\varepsilon_\gamma \lesssim 0.1 \Rightarrow E_{\rm kin,AG} \gtrsim 10^{53}$ erg for a structured jet & $E_{\rm kin,AG} \gtrsim 10^{52}$ erg for a uniform jet

Afterglow Light Curves from Simulations



Afterglow Image

$F_\nu \propto \nu^\beta$, $\rho_{ext} \propto R^{-k}$

$r = R_\perp / R_{\perp,max}$