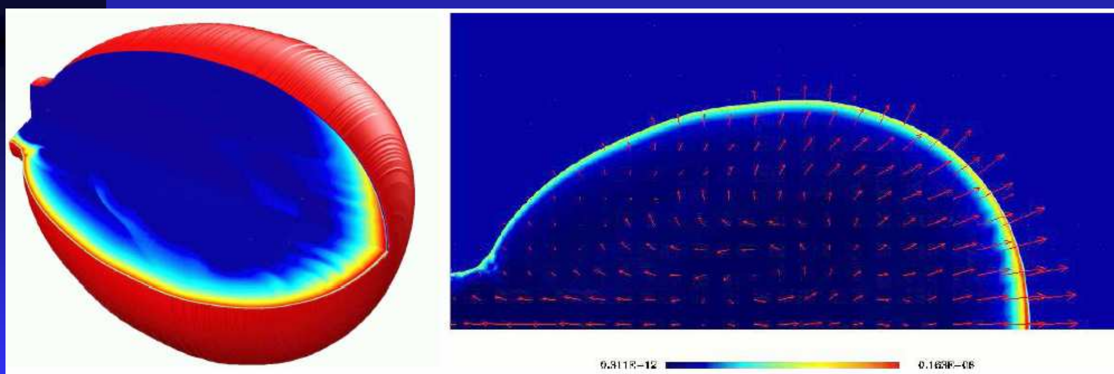
Jets in Gamma-Ray Bursts

Jonathan Granot

KIPAC @ Stanford



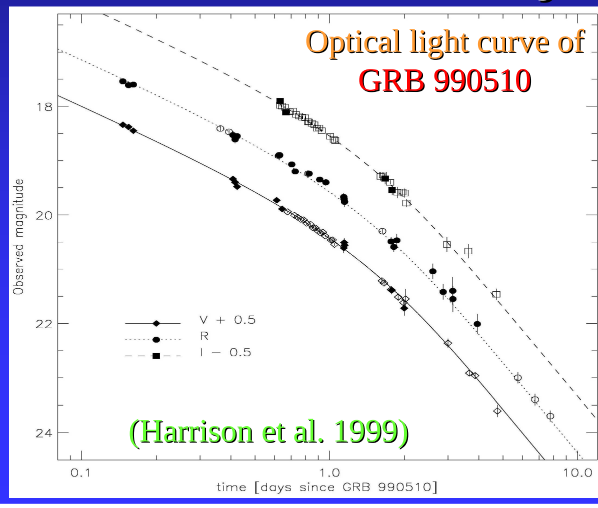
KITP, Santa Barbara, May 12, 2005

Outline of the Talk:

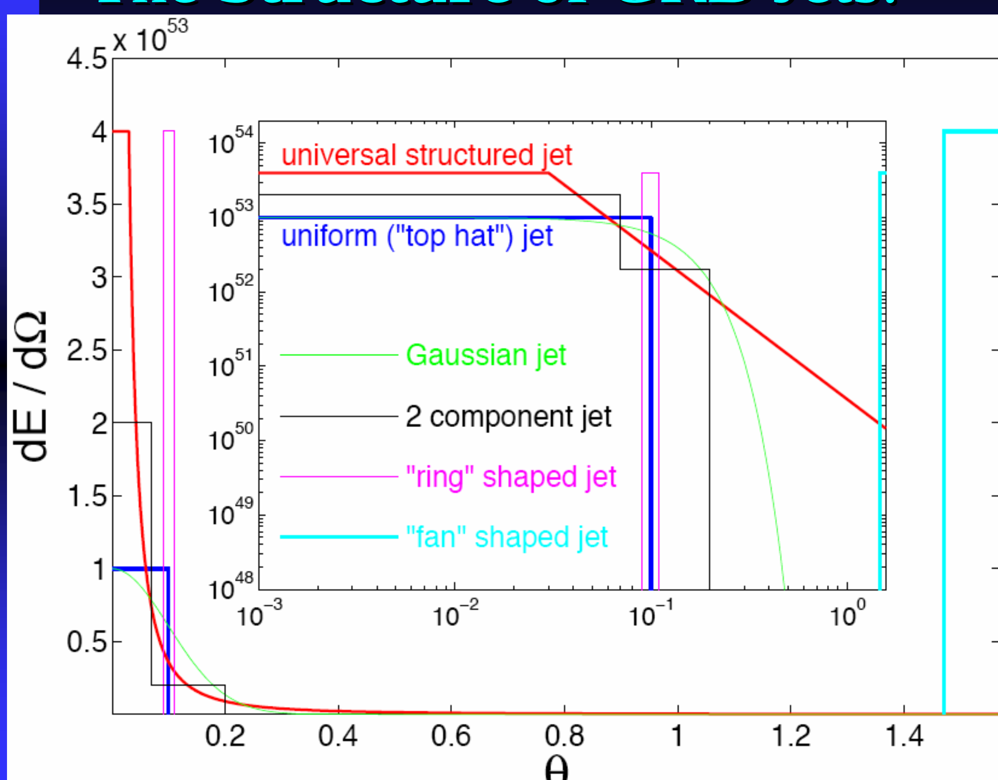
- Observational evidence for jets in GRBs
- The Jet **Structure:** how can we tell what it is
  - **Afterglow polarization**
  - **Statistics** of the prompt & afterglow emission
  - **Afterglow light curves**
- The jet **dynamics**: degree of **lateral expansion**
  - Semi-Analytic models
  - Simplifying the dynamical Eqs.: 2D $\rightarrow$ 1D
  - Full hydrodynamic simulation
- **Conclusions**

Observational Evidence for Jets in GRBs

- The energy output in γ-rays assuming isotropic emission approaches (or even exceeds) $M_\odot c^2$
  - $\Rightarrow$ difficult for a stellar mass progenitor
  - **True energy** is much smaller for a narrow **jet**
- Achromatic break or steepening of the afterglow light curves ("jet break")



The **Structure** of GRB Jets:

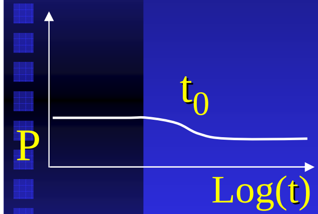


How can we determine the jet structure?

1. Afterglow polarization light curves

the polarization is usually attributed to a jet geometry

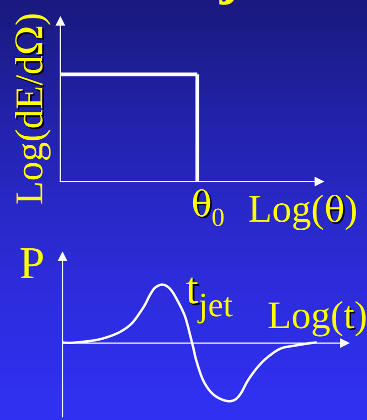
Ordered B-field*:



θ_p = const

while for jet models $P(t \square t_j)\ \square\ P(t \sim t_j)$

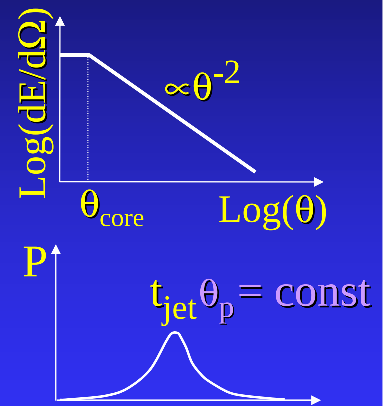
Uniform jet†:



θ_p flips by 90^o at t_{jet}

(Sari 99; Ghisellini & Lazzati 99)

Structured jet††:



$t_{jet}\theta_p$ = const

(Rossi et al. 2003)

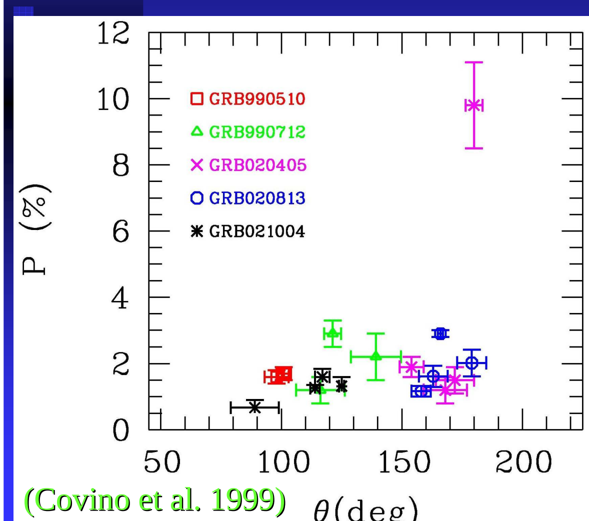
* Granot & Königl 03

† Rhoads 97,99; Sari et al. 99, …

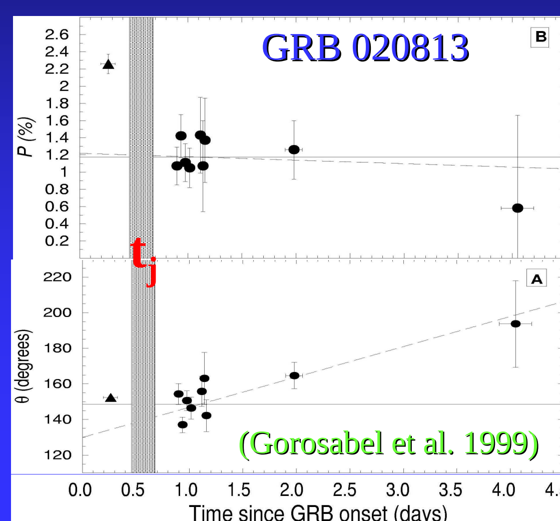
†† Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02

Afterglow Polarization: Observations

- Linear polarization at the level of P ~ 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)



(Gorosabel et al. 1999)

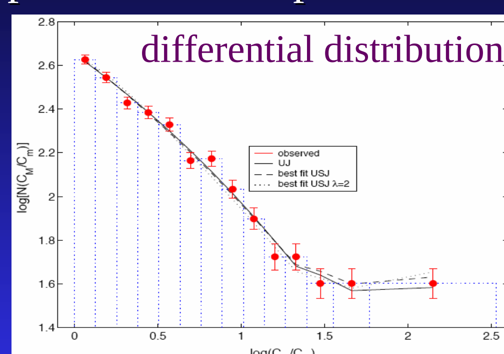
Afterglow Pol. & Jet Structure: Summary

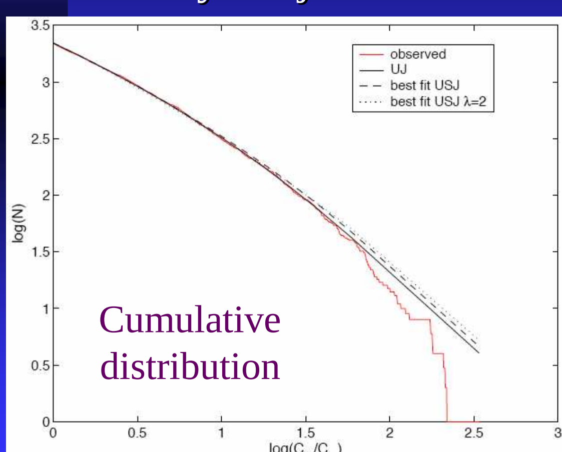
- The Afterglow polarization is affected not only by the jet structure but also by factors such as
  - the **B-field structure** in the **emitting region**
  - **Inhomogeneities** in the ambient density or in the jet (JG & Königl 2003; Nakar & Oren 2004)
  - "**refreshed shocks**" - slower ejecta catching 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

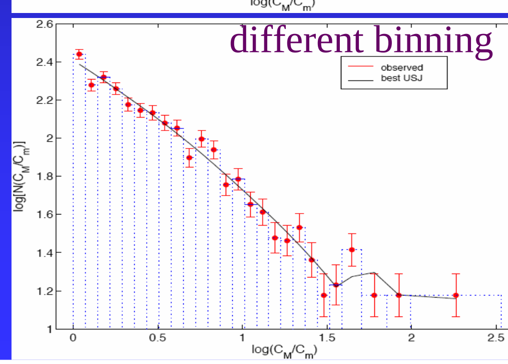
Jet Structure from log N - log S distribution

(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



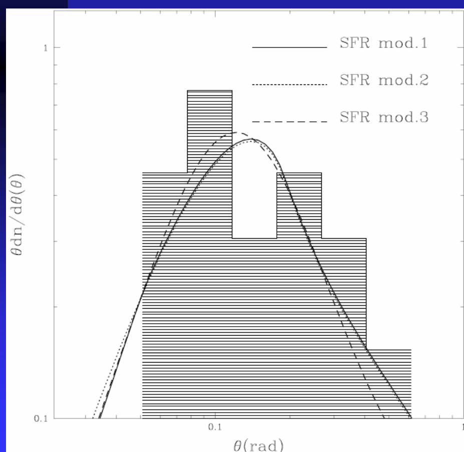




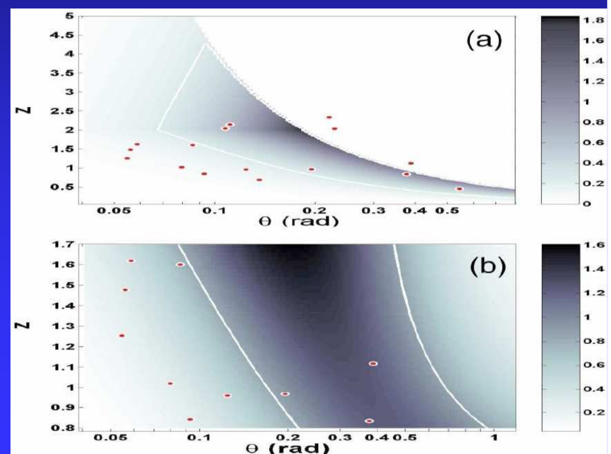
(Guetta, JG & Begelman 2005)

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)



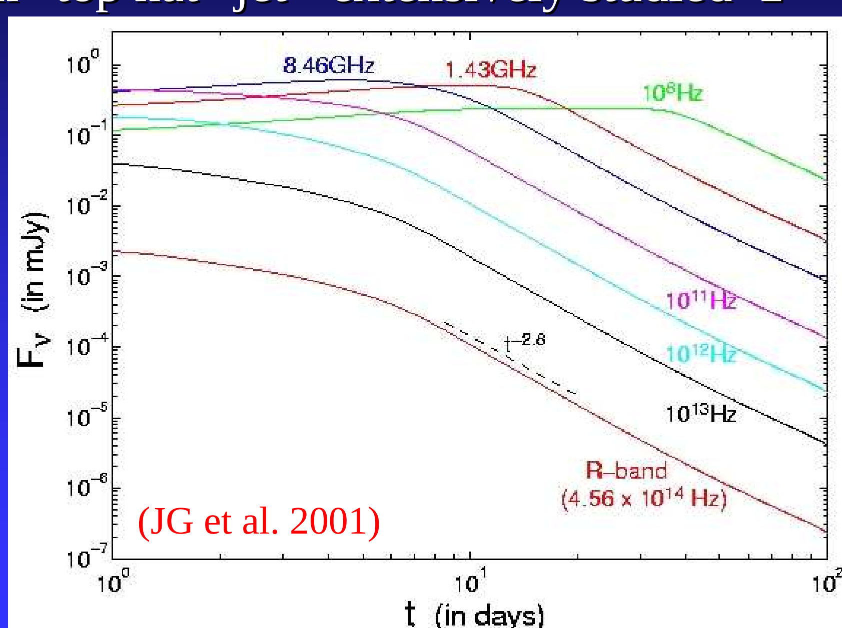
(Nakar, JG & Guetta 2004)

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

ϵ_e=0.1, ϵ_B=0.01, p=2.5, θ_0=0.2, θ_{obs}=0, z=1, E_{iso}=10^{52} ergs, n=1 cm^{-3}

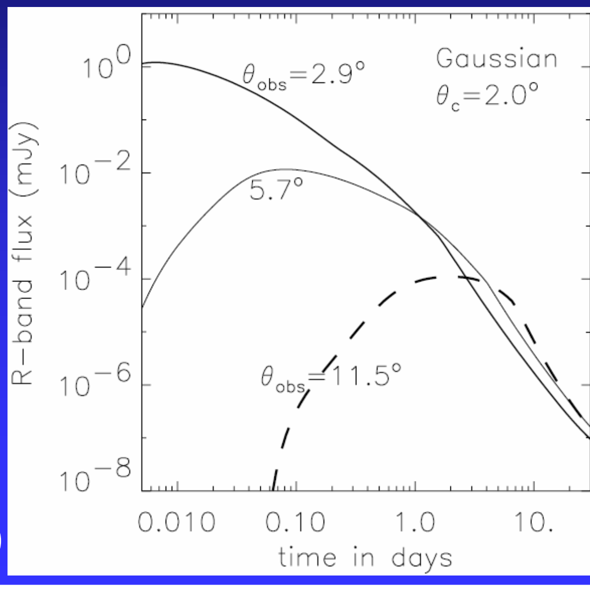


(JG et al. 2001)

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

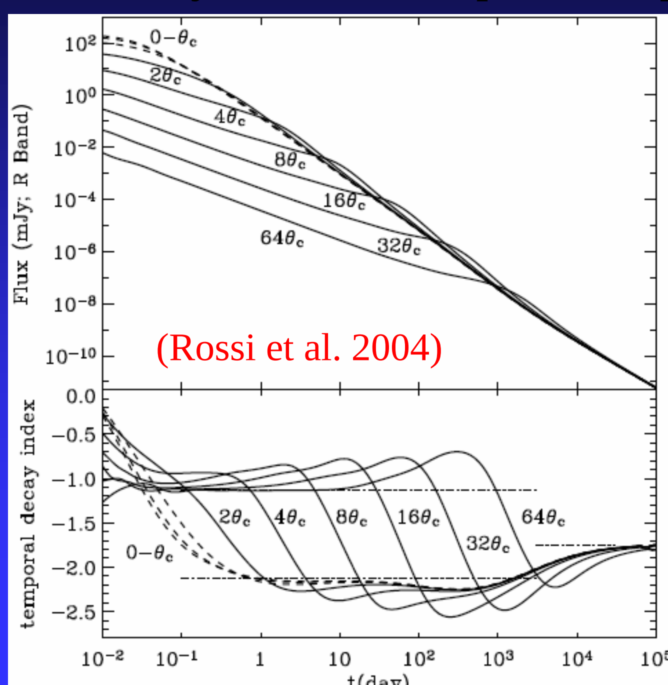


(Kumar & JG 2003)

Afterglow LCs: Universal Structured Jet

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

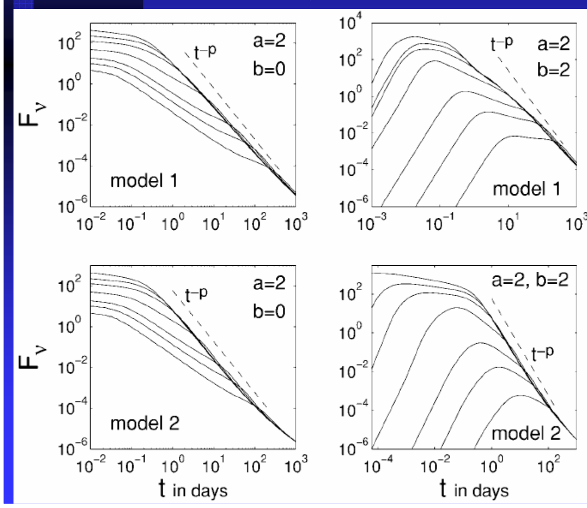
- Works reasonably well but has potential problems

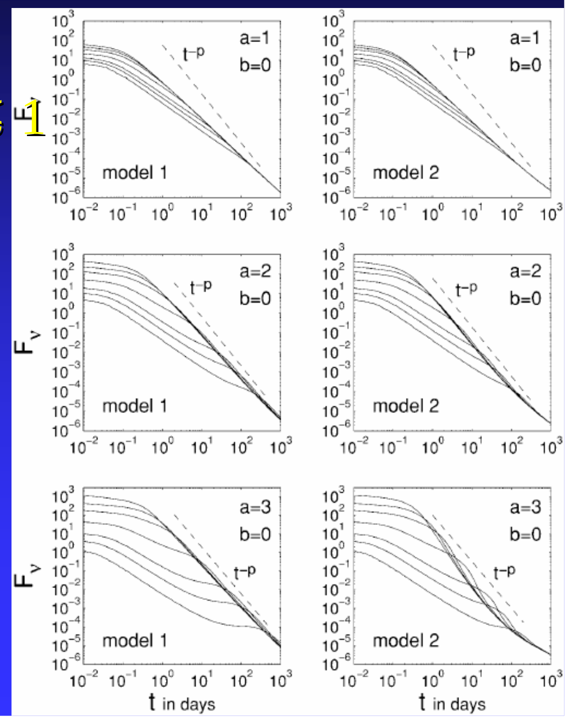


Afterglow LCs: Universal Structured Jet

- 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)



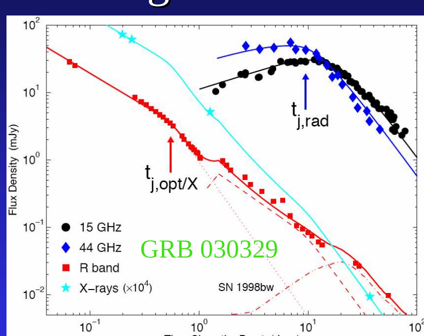


Afterglow LCs: Two Component Jet

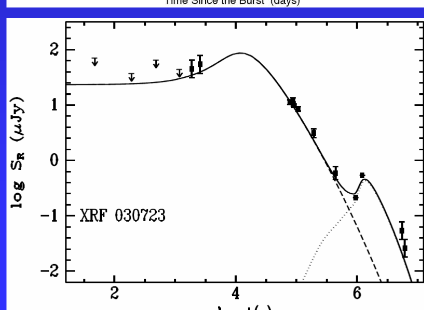
(Pedersen et al. 98; Frail et al. 00; Berger et al. 03; Huang et al. 04; Peng, Konigl & JG 05; Wu et al. 05)

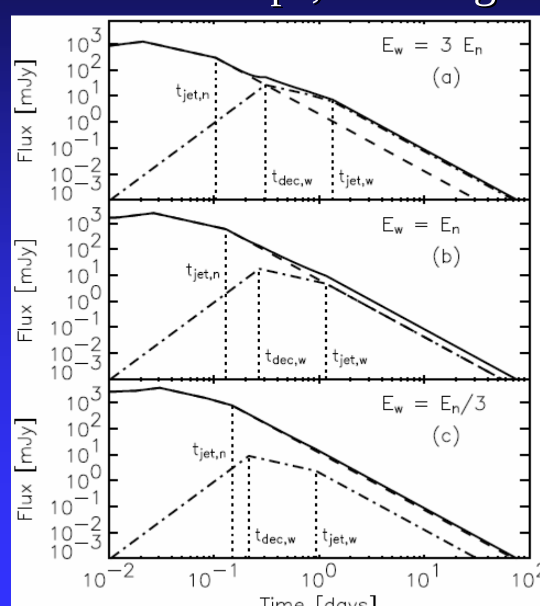
- Usual light curves + extra features: bumps, flatening

(Berger et al. 2003)



(Huang et al. 2004)

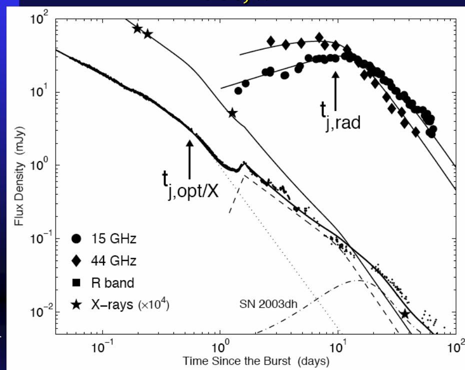


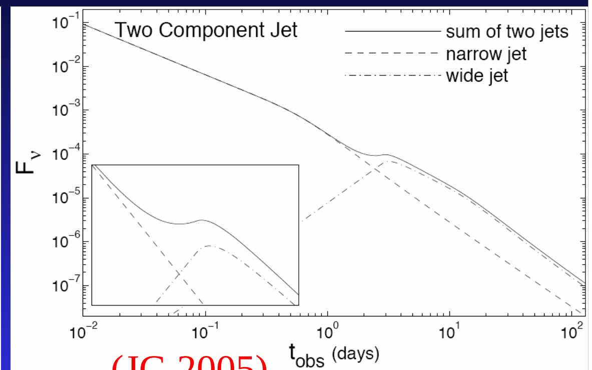


(Peng, Konigl & JG 2005)

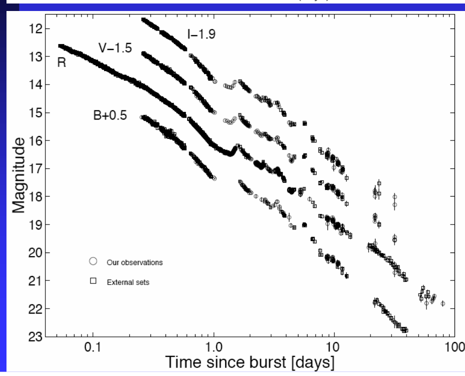
Two Component Jet: GRB 030329

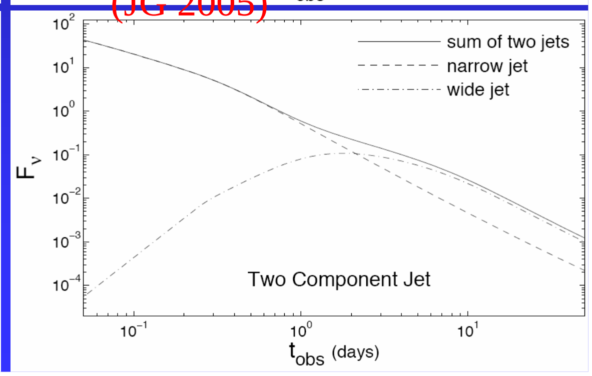
- The bump at $t_{dec,w}$ for an on-axis observer is wide & smooth





(JG 2005)

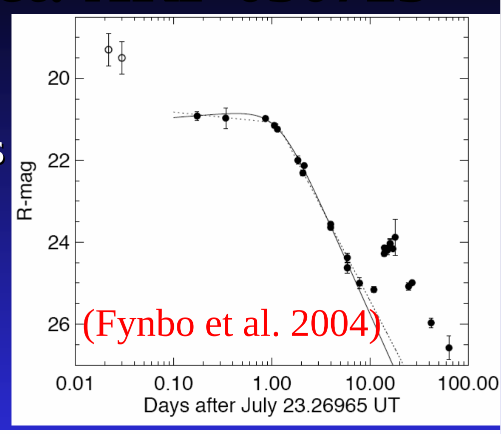




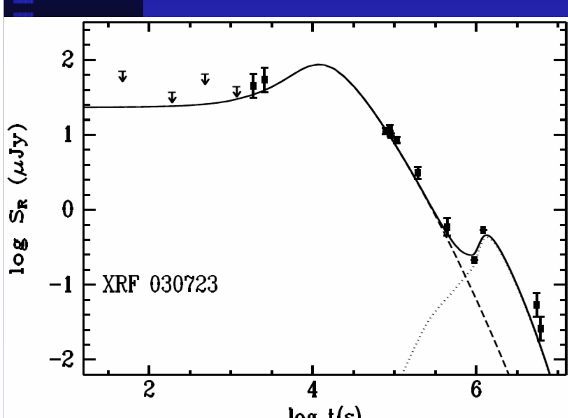
(Lipkin et al. 2004)

Two Component Jet: XRF 030723

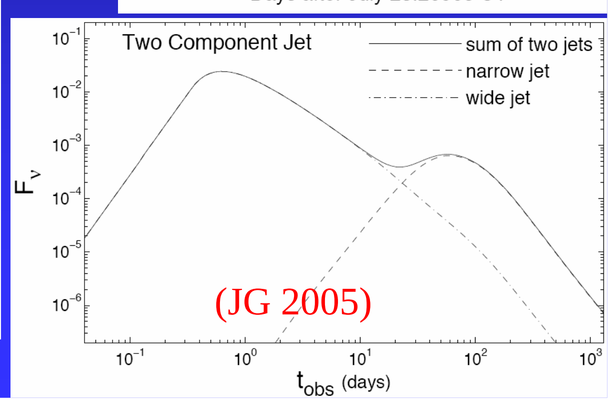
- The **bump** in the light curve when the narrow jet becomes visible is **smooth & wide**



(Fynbo et al. 2004)



(Huang et al. 2005)

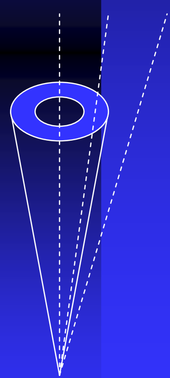


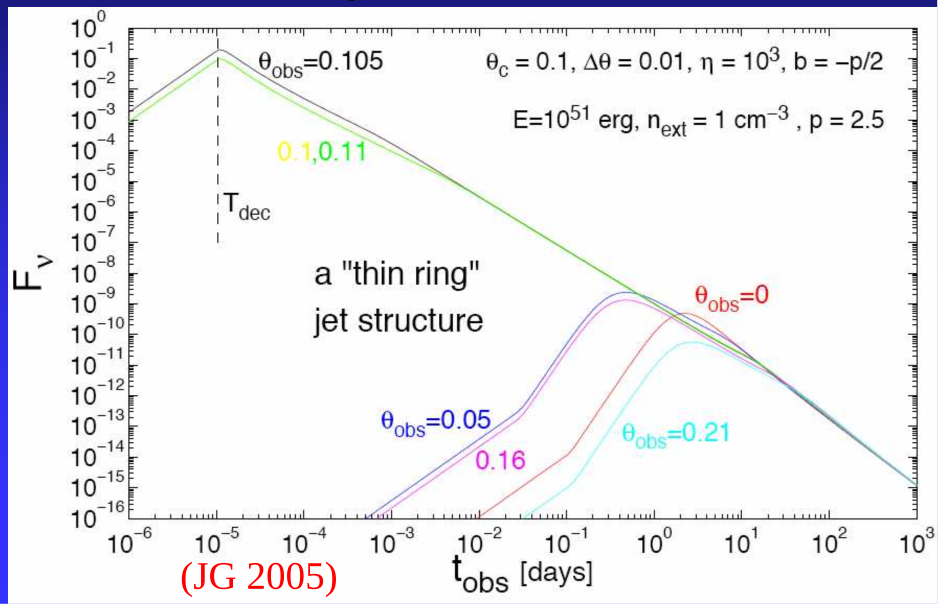
(JG 2005)

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 $\gamma\theta_c \sim 1/2$



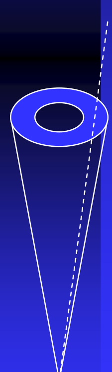


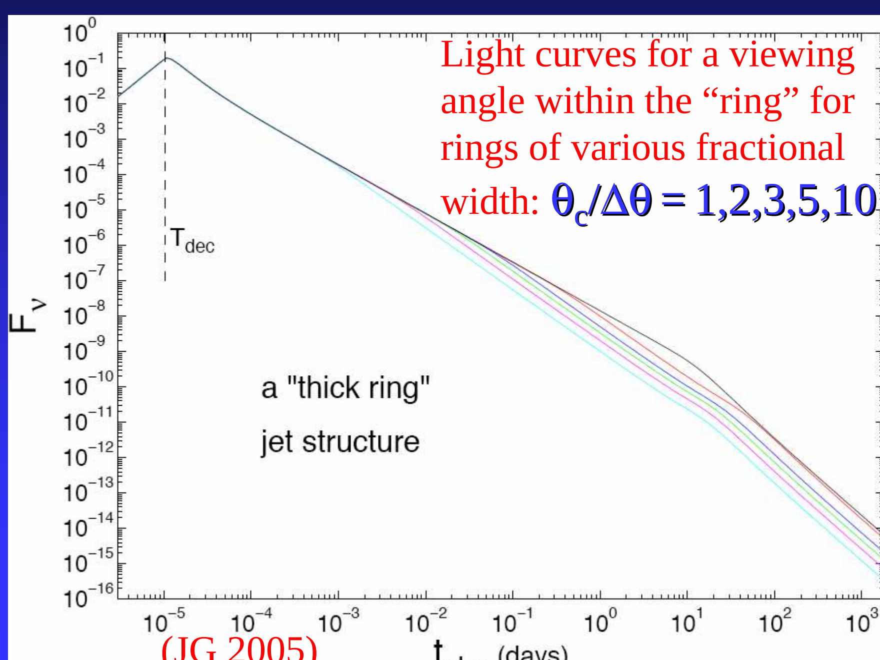
(JG 2005)

Afterglow Light Curves: Wide Ring

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

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

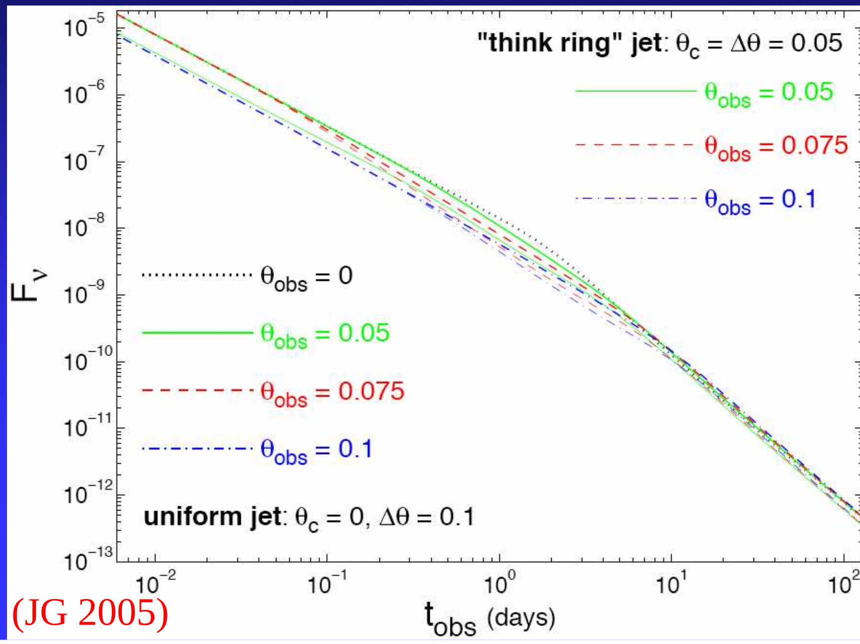




(JG 2005)

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

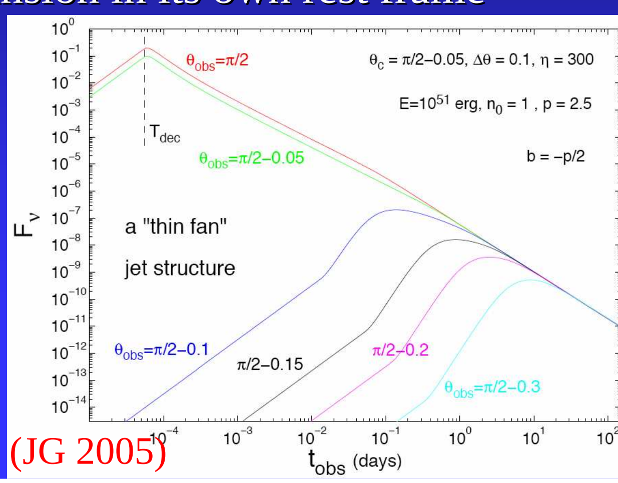


(JG 2005)

Afterglow Light Curves: Fan Shaped Jet

(Thompson 2004)

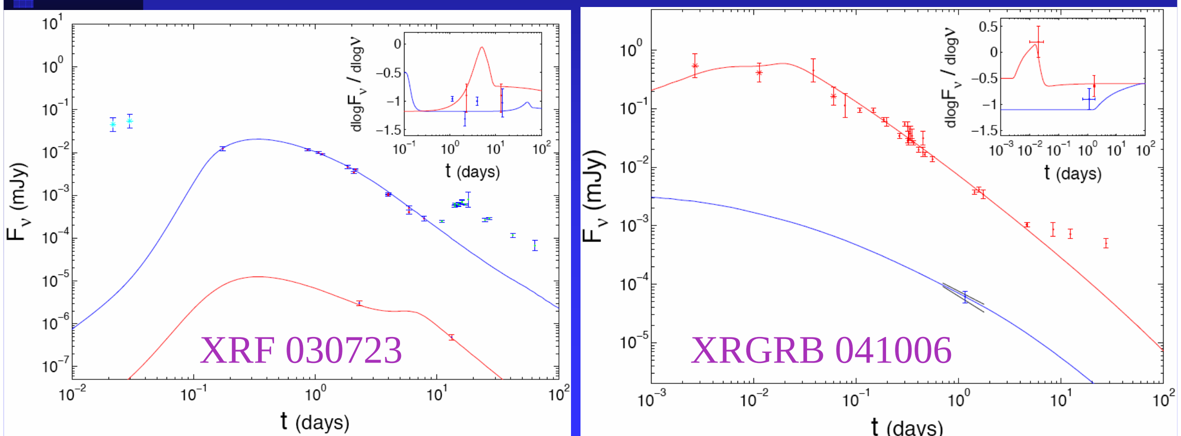
- There are two distinct jet breaks as long as $\Delta\theta \lesssim \theta_c$
- The jet break is a factor of 2 shallower than for a uniform conical jet for no lateral spreading, and even shallower [a factor of (7-2k)/(3-k) > 2 instead of 2] for relativistic lateral expansion in its own rest frame



(JG 2005)

Light Curves of X-ray Flashes & XRGRBs

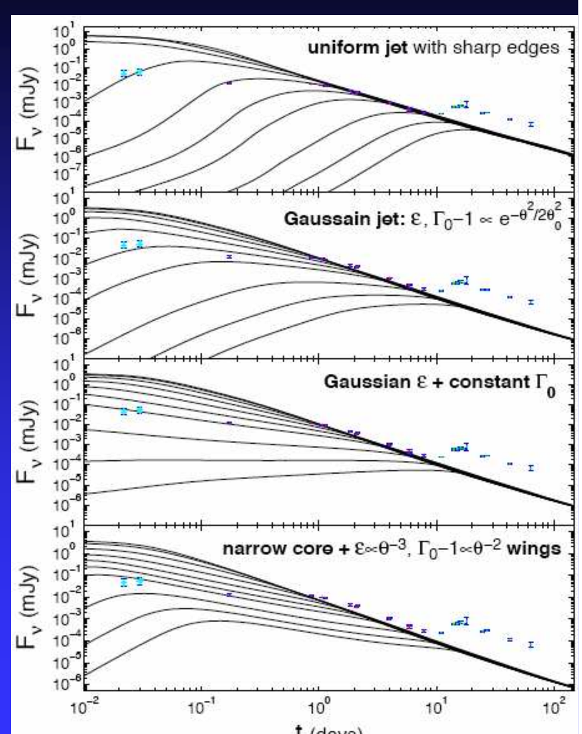
- Suggest a roughly uniform jet with reasonably sharp edges, where GRBs, XRGRBs & XRFs are similar jets viewed from increasing viewing angles (Yamazaki, Ioka & Nakamura 02,03,04)



(JG, Ramirez-Ruiz & Perna 2005)

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:

- A homogeneous jet with sharp edges (even at $t > t_{jet}$)
- 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 in a velocity of $c_s \approx c/\sqrt{3}$ or $\approx c$ in the local rest frame
- The jet dynamics are obtained by solving simple 1D equations for conservation of energy and momentum
- Most works assume a homogeneous ambient medium (ISM)

Main Results:

Jet Dynamics:

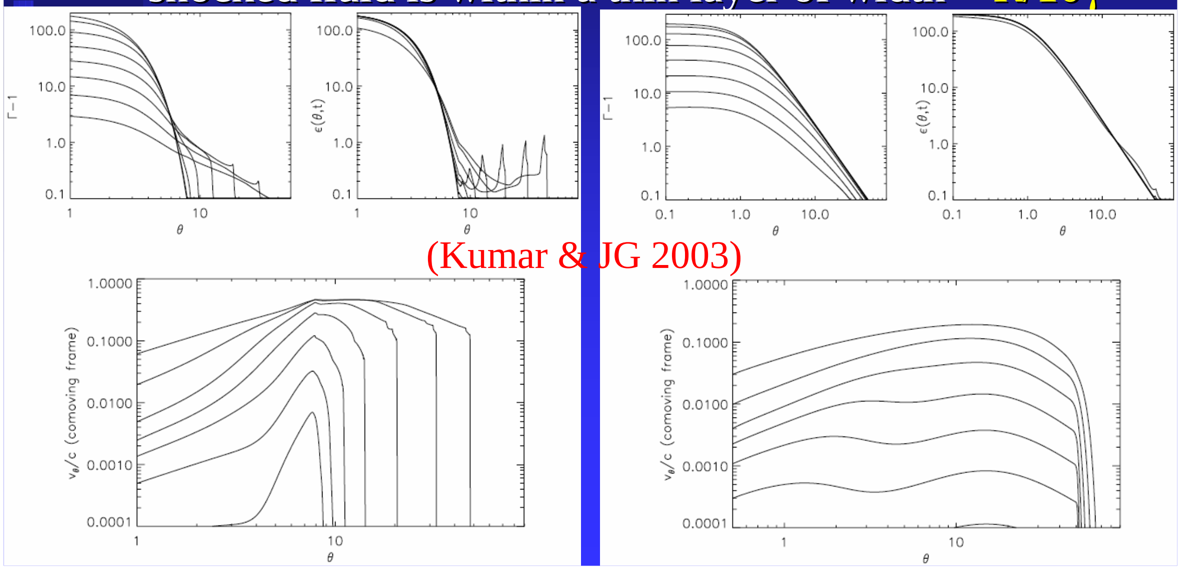
- At $t > t_{jet}$: $1/\theta_{jet} \sim \gamma \propto \exp(-R/R_{jet}) \Rightarrow t \sim R/c\gamma^2 \propto 1/\gamma^2$

Light Curves:

- Most models predict a jet break but differ in the details:
  - The time of the jet break t_{jet} (by a factor of ~20)
  - Temporal slope $F_\nu(\nu > \nu_m, t > t_{jet}) \propto t^{-\alpha}$, $\alpha \sim p$ (±15%)
  - The sharpness of the jet break (~1-4 decades in time)
- Kumar & Panaitescu (2000) predicted a significantly smoother jet break for a stellar wind environment (this was reproduced in other works but was never observed)

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 ~ $R/10\gamma^2$



(Kumar & JG 2003)

Numerical Simulations:

(JG et al. 2001; Cannizzo, Gehrels & Vishniac 2004)

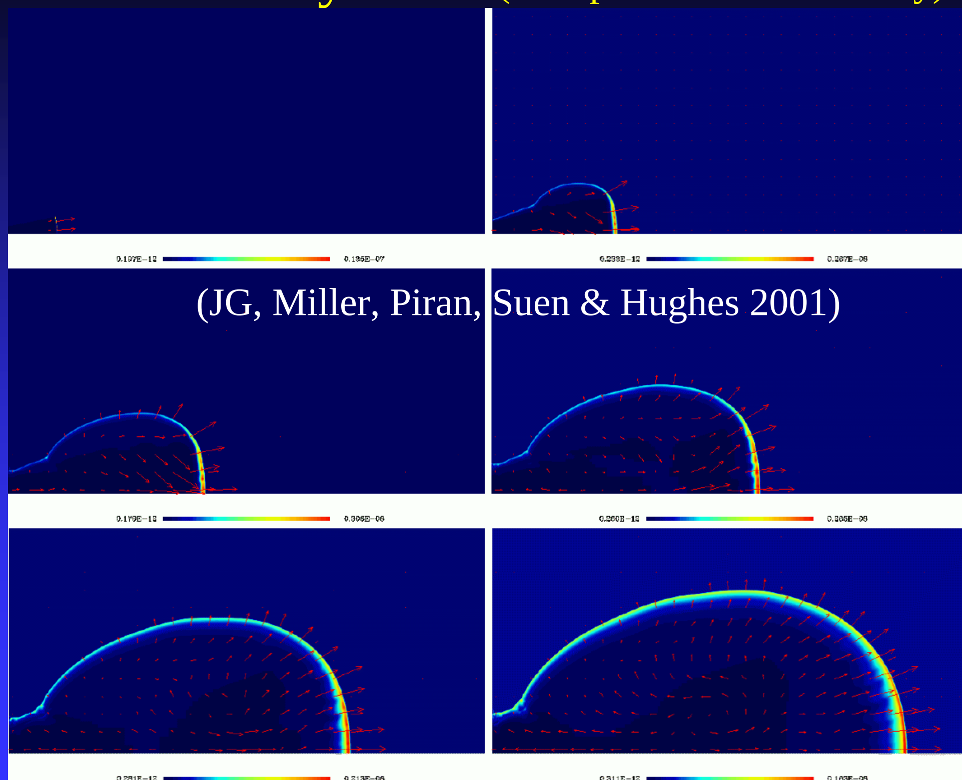
The difficulties involved:

- The hydro-code should allow for both γ □ 1 and $\gamma \approx 1$
- Most of the shocked fluid lies within in a very thin shell behind the shock ($\Delta \sim R/10\gamma^2$) ⇒ hard to resolve
- A relativistic code in more than 1D is required
- A complementary code for the radiation calculations

⇩

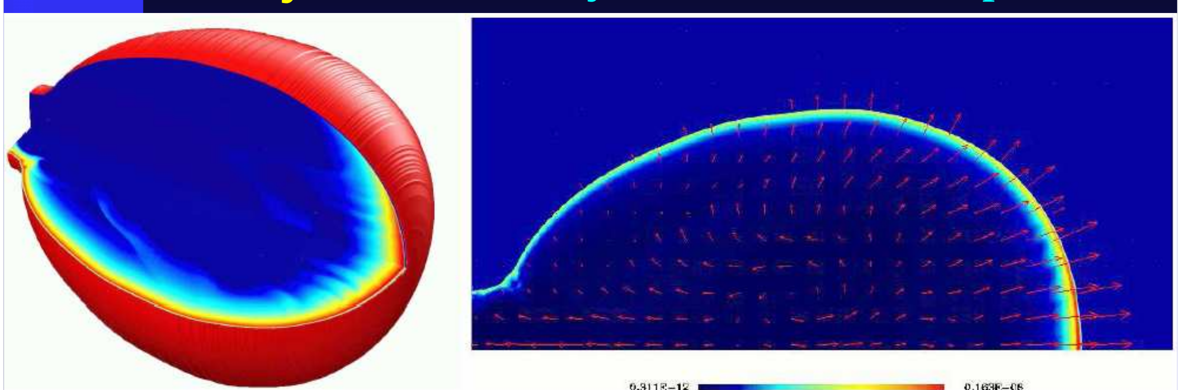
Very few attempts so far

The Velocity Field (on top of lab frame density)

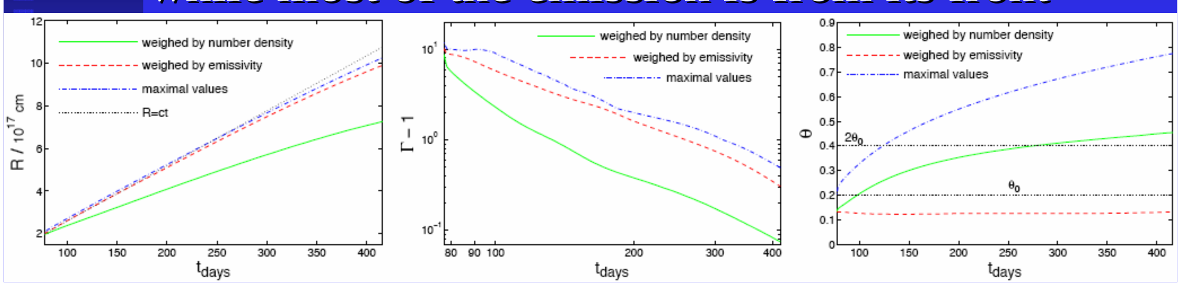


(JG, Miller, Piran, Suen & Hughes 2001)

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:

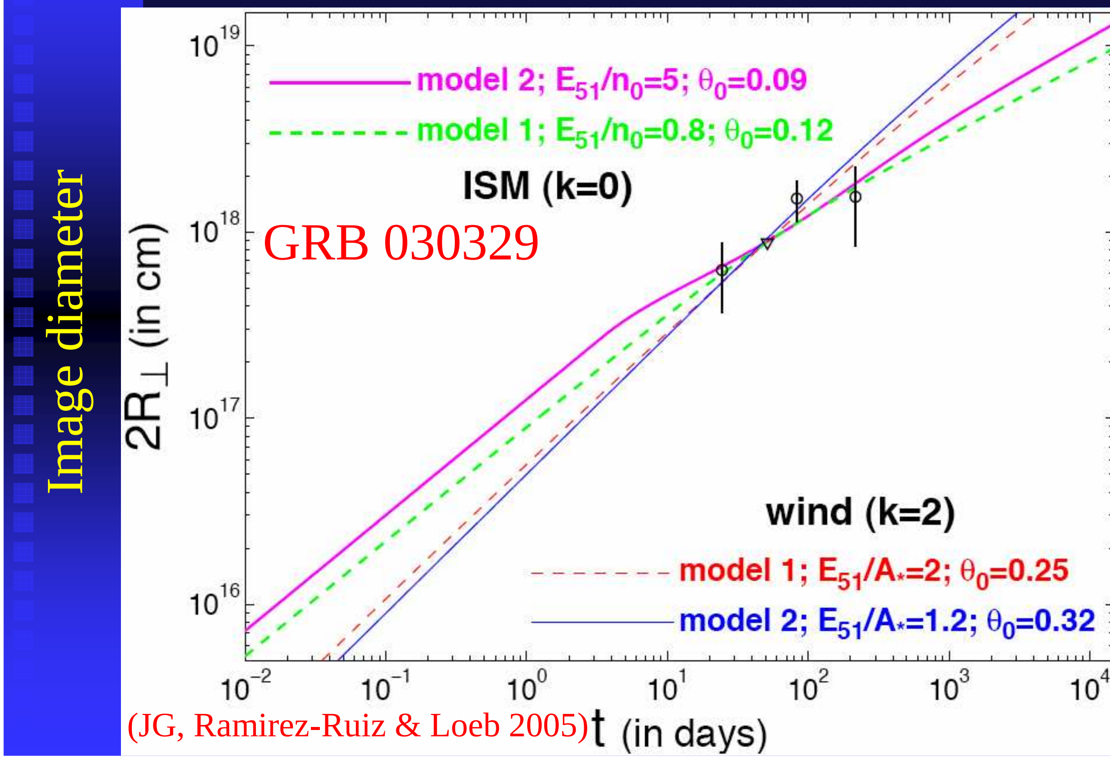
- The assumptions of simple models fail:
  - The shock front is not spherical
  - The velocity is not radial
  - The shocked fluid is not homogeneous
- There is only very mild lateral expansion as long as the jet is relativistic
- Most of the emission occurs within $\theta < \theta_0$
- **Nevertheless**, 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

Comparison to (Semi-) Analytic Models:

- Similarities:
  - An achromatic **jet break** at t_{jet} for $\nu > \nu_m(t_{jet})$
  - The value of t_{jet} is similar
  - Temporal slope, $F_\nu(\nu > \nu_m, t > t_{jet}) \propto t^{-\alpha}$, is close to the analytic value $\alpha \approx p$ ($\alpha = 1.12p$ for $p = 2.5$ and is even closer to p for $p < 2.5$)
- Differences:
  - The jet dynamics are very different
  - For $\nu < \nu_m(t_{jet})$ (radio) α changes more gradually and moderately at t_{jet} and changes more sharply only at a later time when ν_m decreases below ν_{obs}
  - Jet break is sharper than in most analytic models, and is somewhat sharper for $\theta_{obs} = 0$ than for $\theta_{obs} \approx \theta_0$

Lateral Expansion: Evolution of Image Size

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



Conclusions:

- The most promising way to constrain the jet structure is through the afterglow light curves
- Numerical studies show very little lateral expansion but still give a sharp jet break
- Some jet structures can be ruled out by the afterglow light curves (“hollow cone” or “narrow ring”, “fan”)
- XRF & XRGRB afterglow light curves favor a roughly uniform jet with rather sharp edges