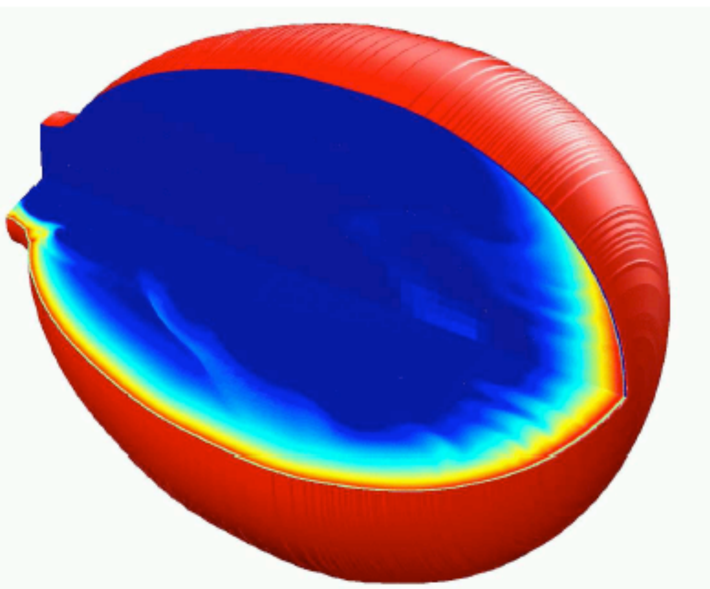
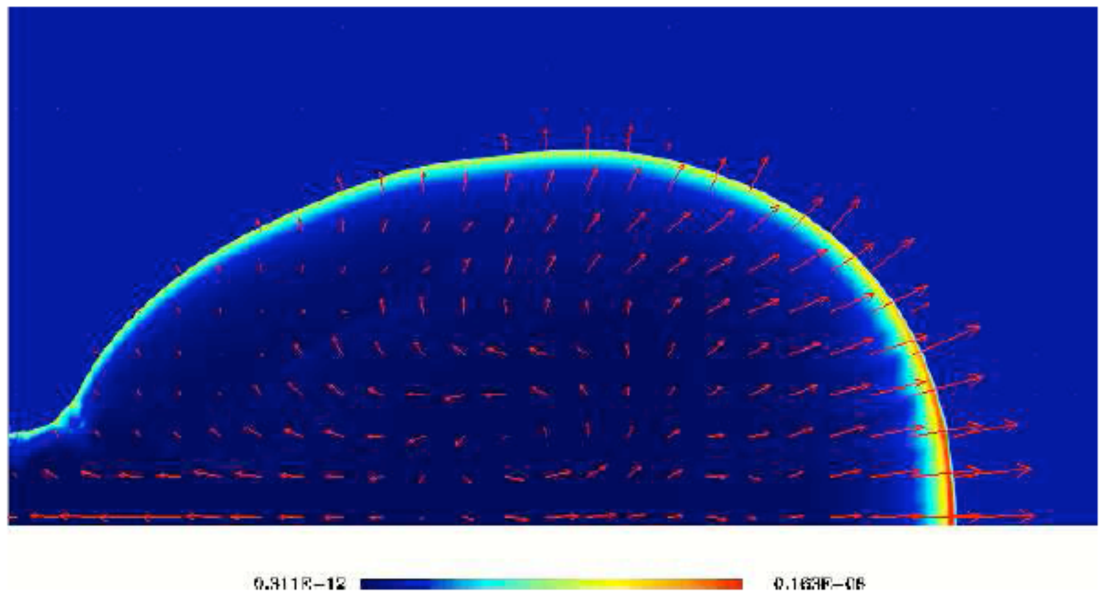
Dynamics & Structure of GRB Jets

Jonathan Granot

KIPAC @ Stanford





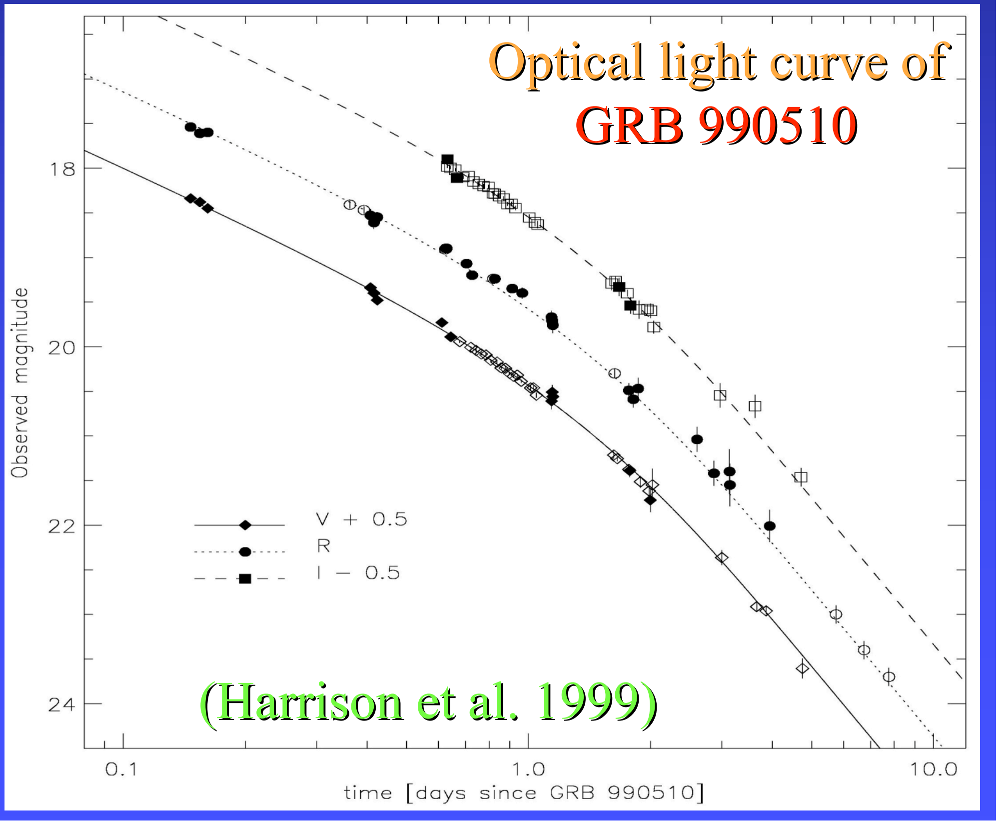
"Supernova and Gamma-Ray Burst Remnants"
KITP, Santa Barbara, February 6, 2006

Outline of the Talk:

- Observational evidence for jets in GRBs
- The jet **dynamics**: degree of **lateral expansion**
  - Semi-Analytic models
  - Simplifying the dynamical Eqs.: 2D $\rightarrow$ 1D
  - Full hydrodynamic simulations
- The Jet **Structure:** how can we tell what it is
  - Afterglow polarization, Statistical approach
  - **Afterglow light curves**
  - The jet structure, energy, and γ-ray efficiency
- **Conclusions**

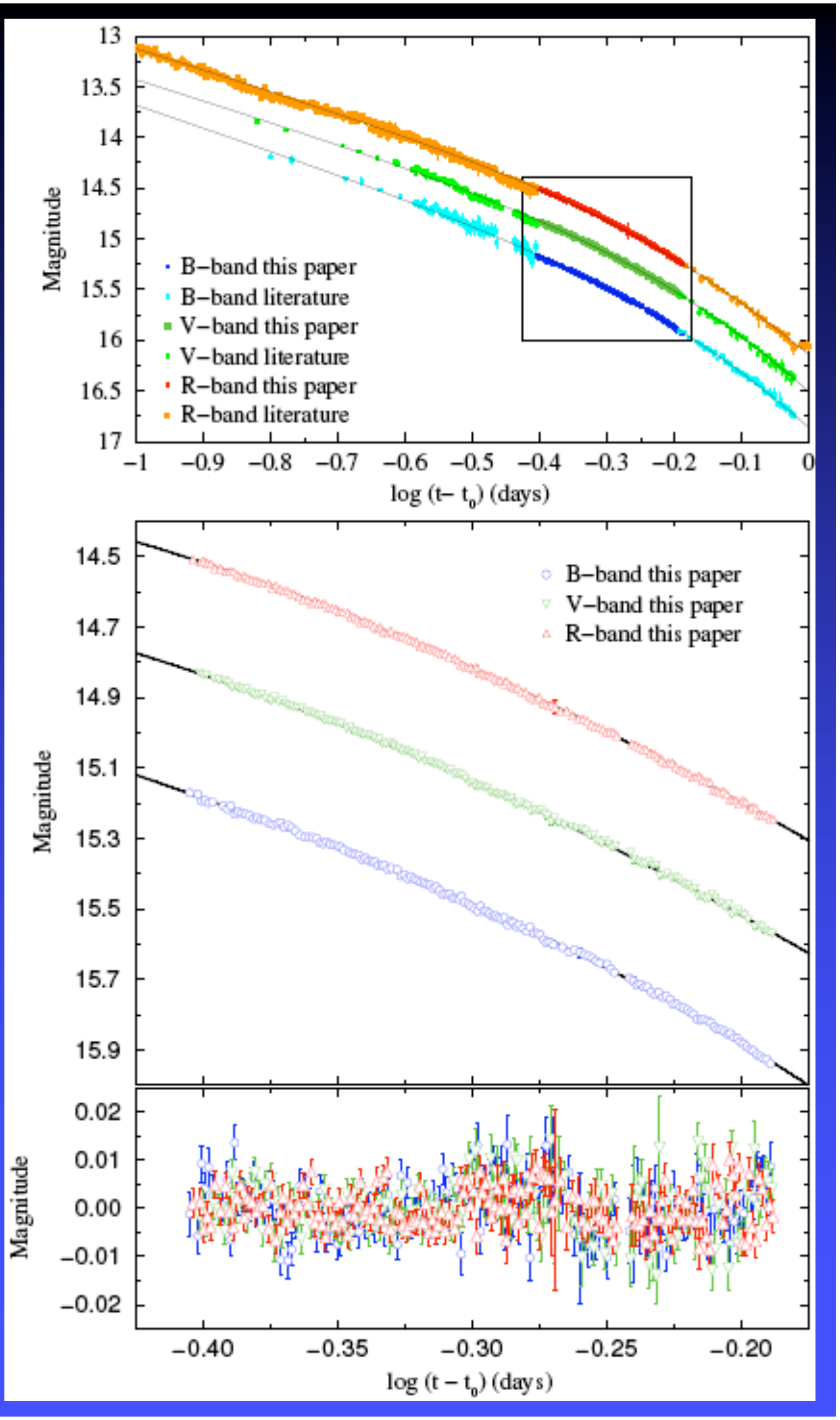
Observational Evidence for Jets in GRBs

- The energy output in γ-rays assuming isotropic emission approaches (or even exceeds) $M_{\odot}c^2$
  - $\Longrightarrow$ 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")



Optical Light Curve of GRB 030329 (Gorosabel et al. 2006)

smooth & achromatic break



Dynamics of GRB Jets: Lateral Expansion

Simple (Semi-) Analytic Jet Models

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

Typical Simplifying Assumptions:

- A uniform 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 uniform external medium (ISM)

Main Results: Jet Dynamics at $t > t_{jet}$:

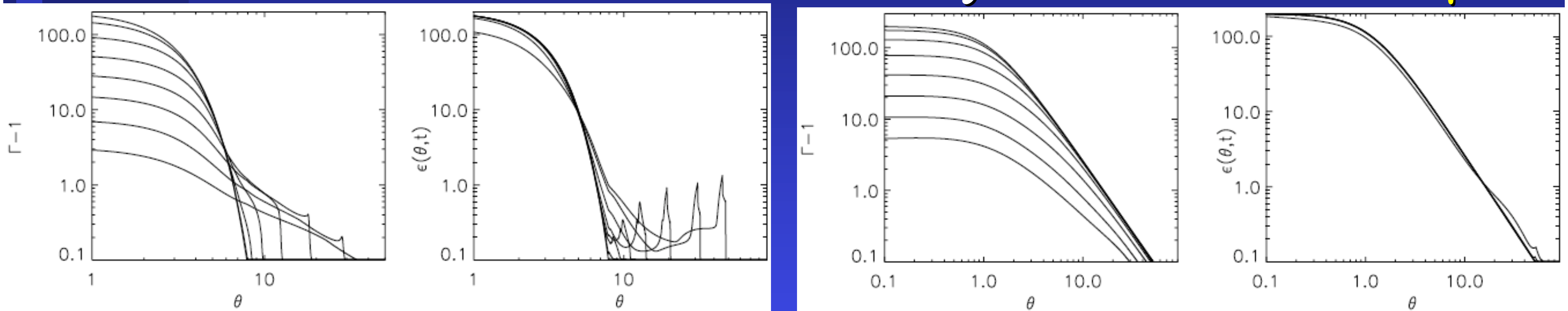
- $\gamma \sim (c_s/c\theta_0)\exp(-R/R_{jet})$, $\theta_{jet} \sim \theta_0(R_{jet}/R)\exp(R/R_{jet})$ where $R_{jet} = [E/\rho_{ext}\pi(c_s)^2]^{1/3}$ (comparable to the Sedov length for the true energy, if $c_s \sim c$)

Light Curves:

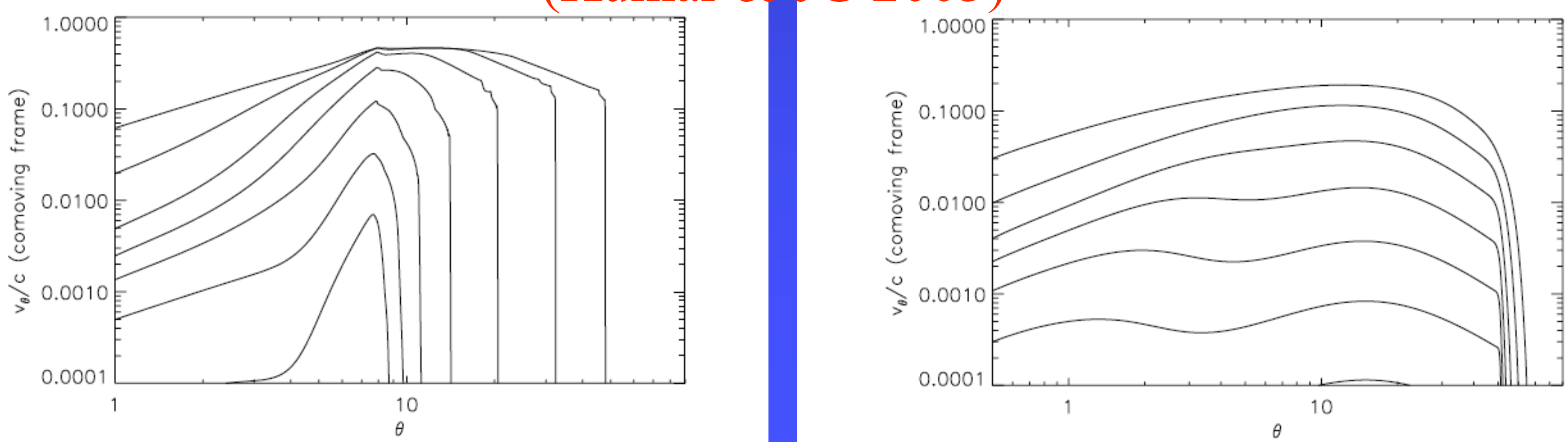
- Most models predict a jet break but differ in the details:
  - The time of the jet break t_{jet} (by up to a factor of ~20)
  - Temporal slope $F_\nu(\nu > \nu_m, t > t_{jet}) \propto t^{-\alpha}$, $\alpha \sim p\ (\pm 15\%)$
  - The sharpness of the jet break (~1-4 decades in time)
- Kumar & Panaitescu (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:

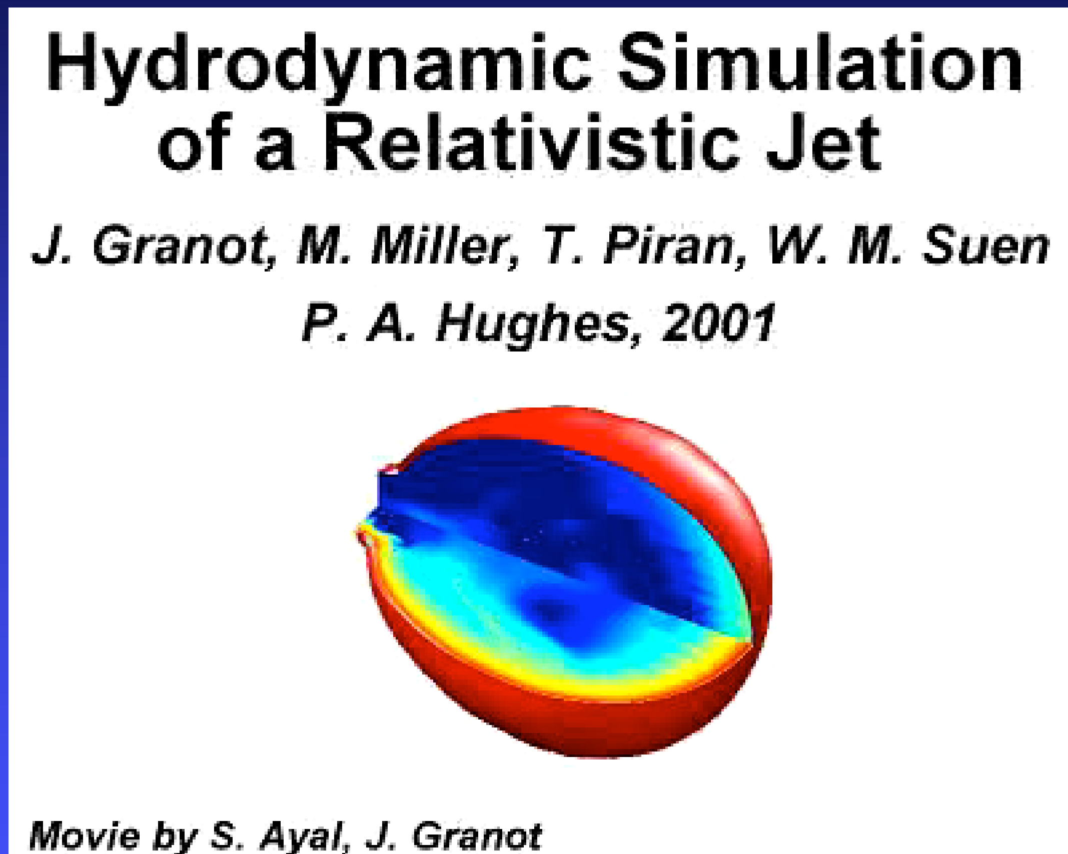
(JG et al. 2001; Cannizzo et al. 2004; Zhang & Macfayen 2006)

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

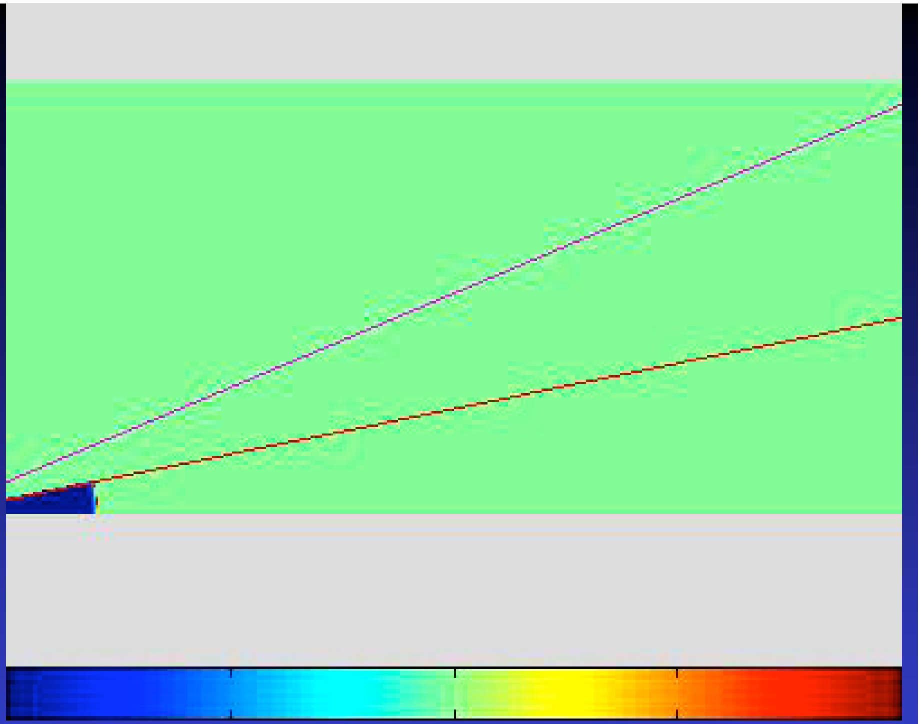
Very few attempts so far

Movie of Simulation



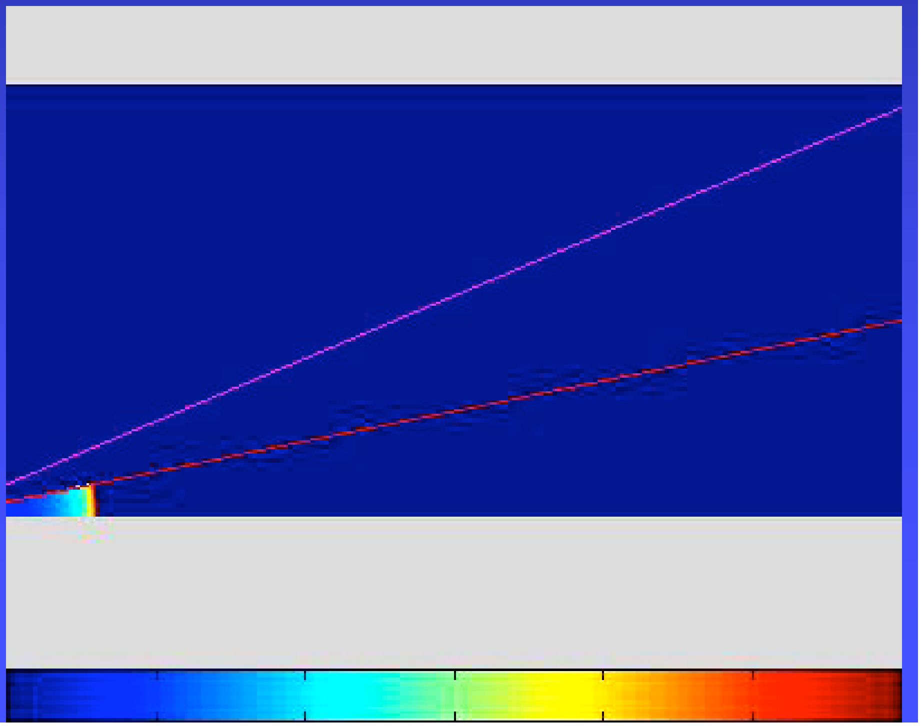
Proper Density:

(logarithmic color scale)

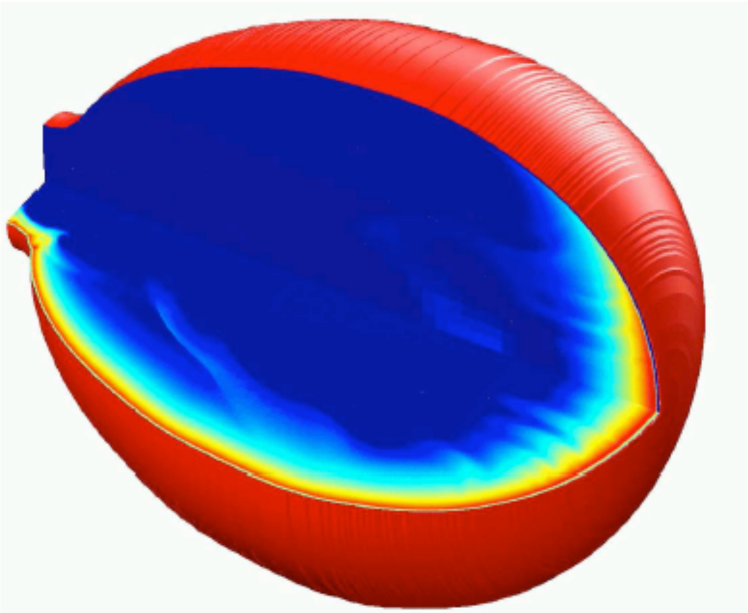


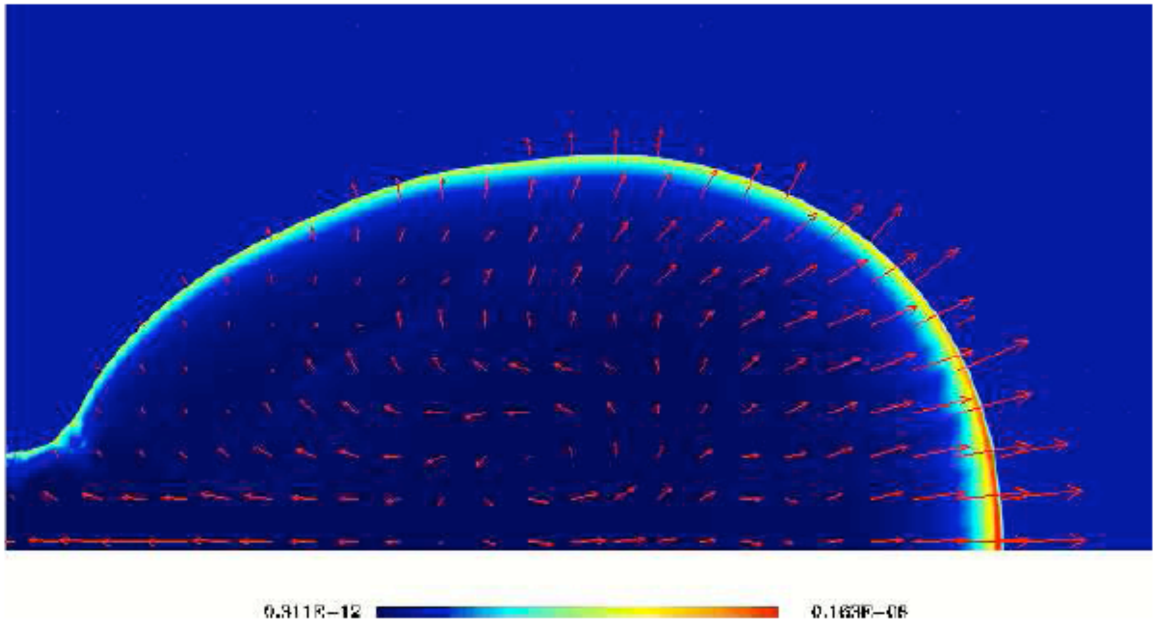
Bolometric Emissivity:

(logarithmic color scale)

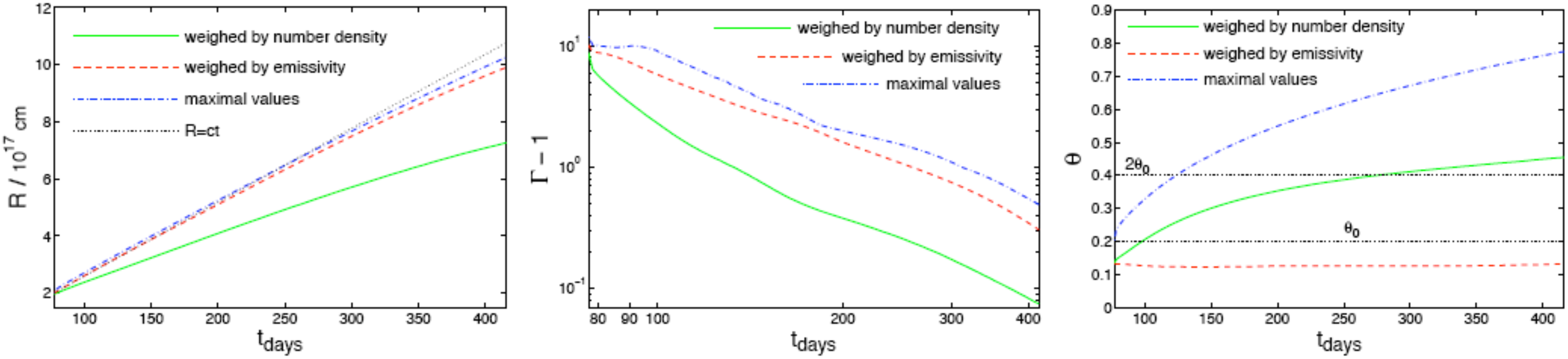


The Jet Dynamics: very modest lateral expansion





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



Main Results of Hydro-Simulations:

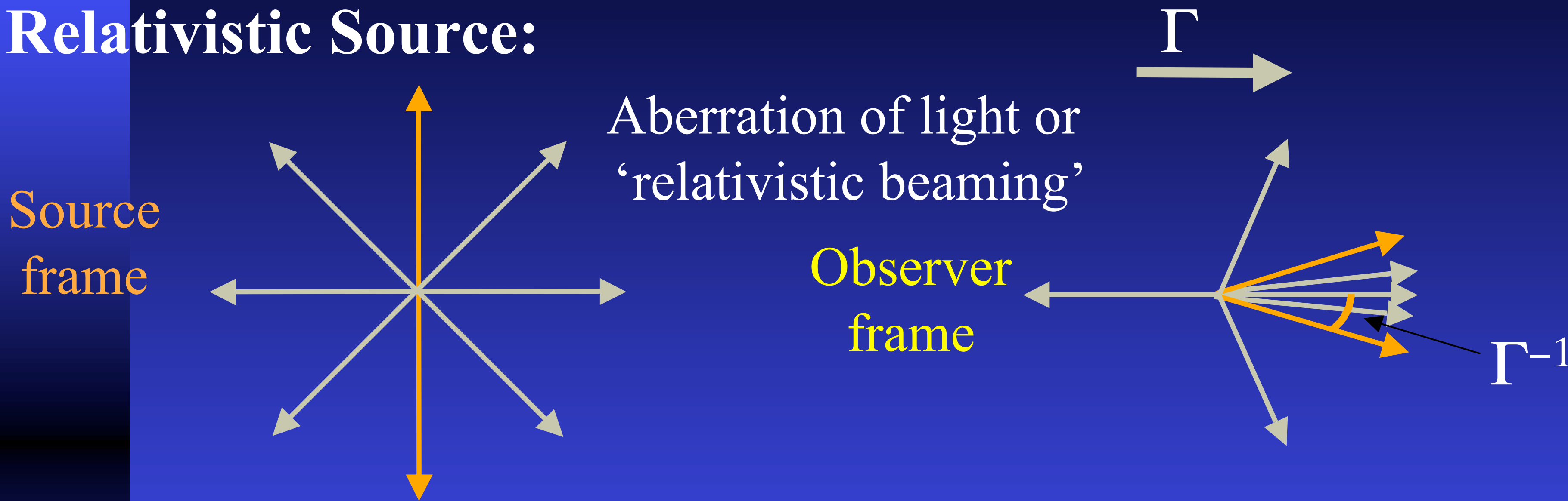
- The assumptions of simple models fail:
  - The shock front is not spherical
  - The velocity is not radial
  - The shocked fluid is not homogeneous
- There is only very mild lateral expansion as long as the jet is relativistic
- Most of the emission occurs within $\theta < \theta_0$
- **Nevertheless**,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

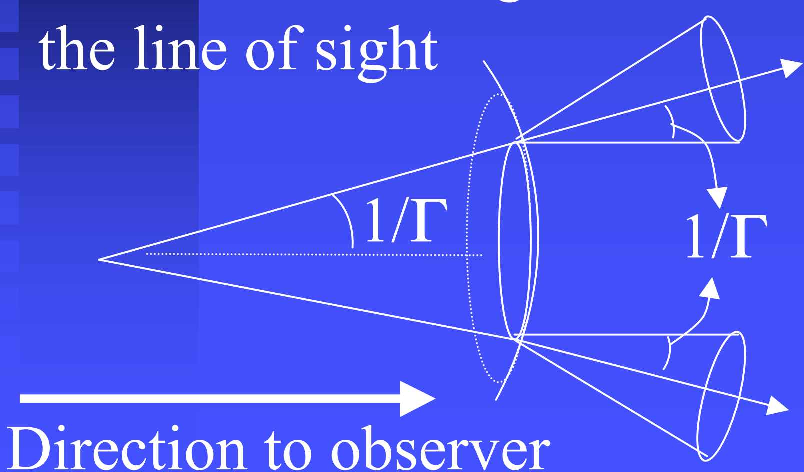
- Similarities:
  - An achromatic **jet break** at t_{jet} for $\nu > \nu_m(t_{jet})$
  - The value of t_{jet} is similar
  - Temporal slope, $F_\nu (\nu > \nu_m, t > t_{jet}) \propto t^{-\alpha}$, is close to the analytic value $\alpha \approx p$ ($\alpha = 1.12p$ for $p = 2.5$ and is even closer to 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 $\theta_{obs} \approx \theta_0$

Why do we see a Jet Break:

Relativistic Source:



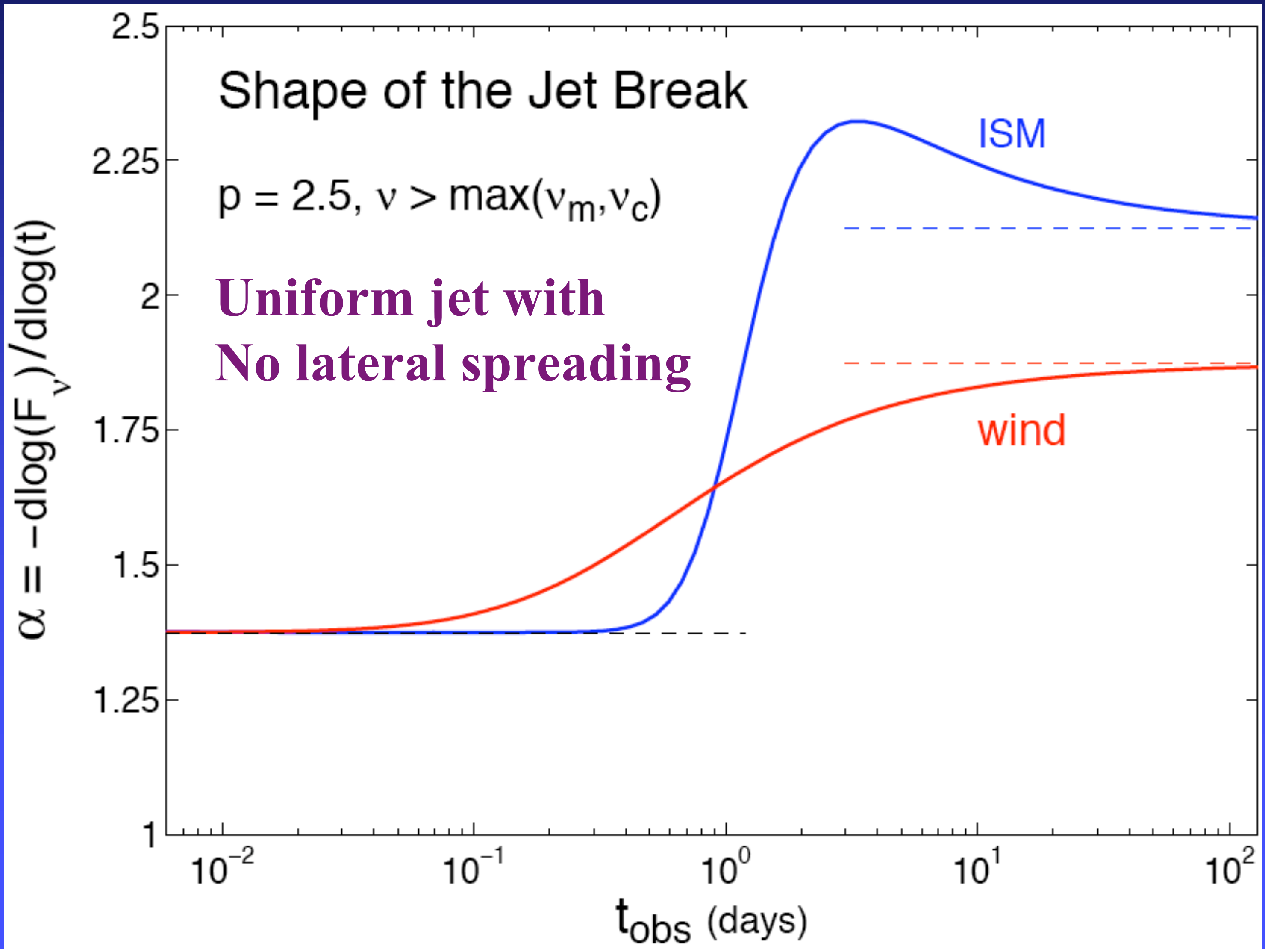
The observer sees mostly emission from within an angle of $1/\Gamma$ around the line of sight



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 $\Gamma(t)$

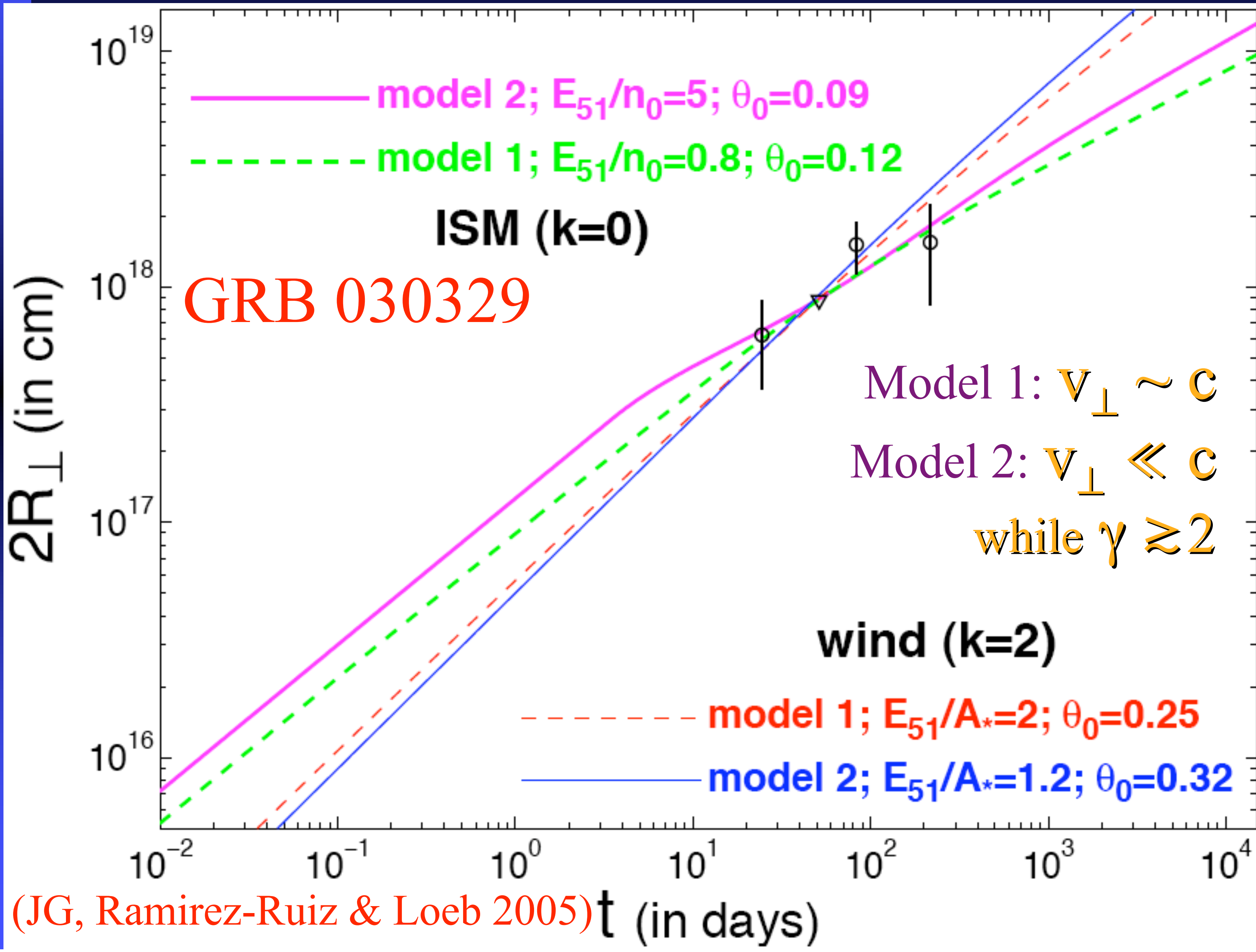
Limb Brightening of the Image + a rapid transition ⇒ an "overshoot"



Lateral Expansion: Evolution of Image Size

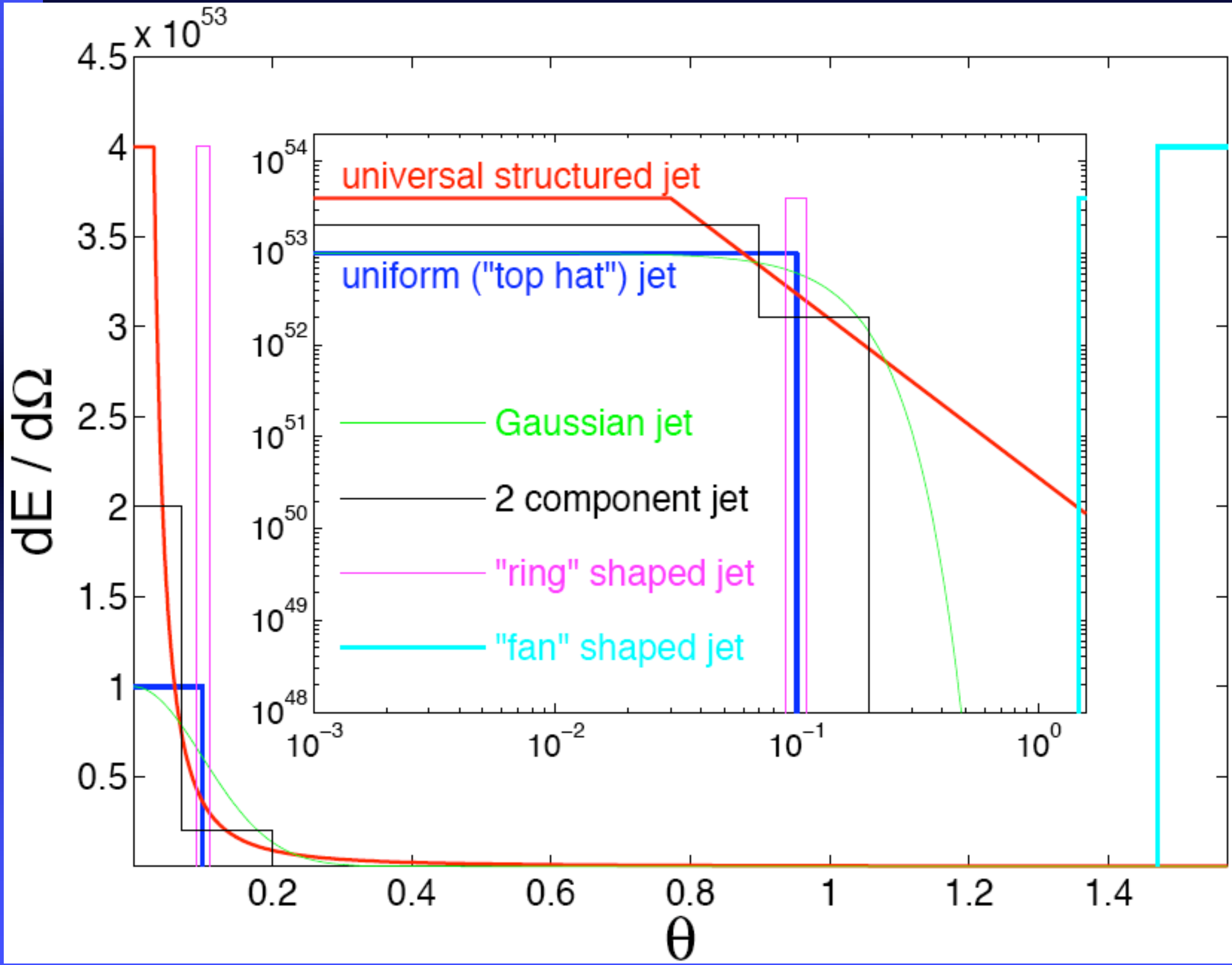
(Taylor et al. 04,05; Oren, Nakar & Piran 04; JG, Ramirez-Ruiz & Loeb 05)

Image diameter



(JG, Ramirez-Ruiz & Loeb 2005)

The **Structure** of GRB Jets:



How can we determine the jet structure?

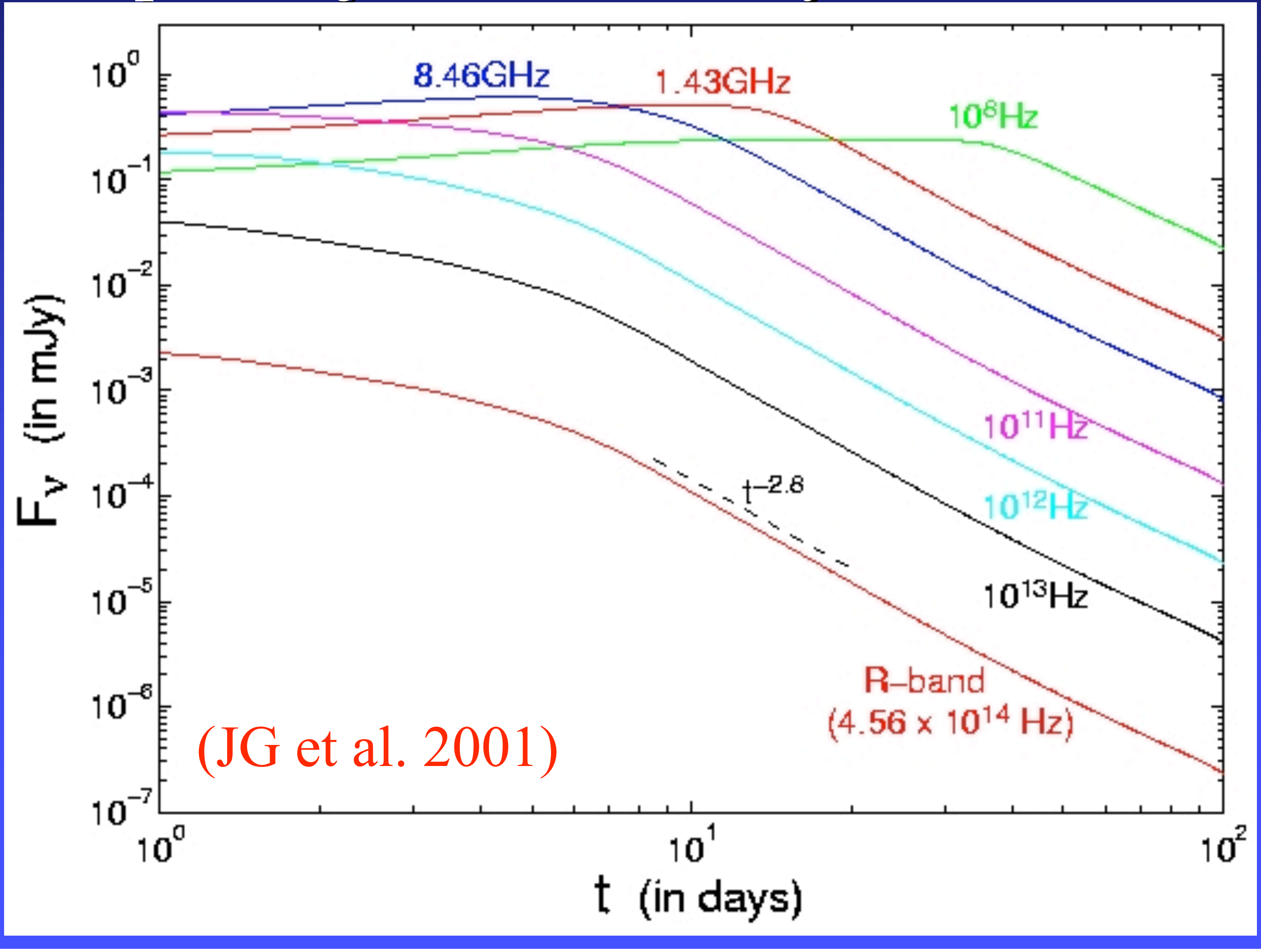
- Afterglow (linear) polarization light curves
  - The pol. is usually attributed to jet geometry
  - Also depends on the magnetic field structure
  - Effected by density bumps, refreshed shocks
  - $\Rightarrow$ not a very "clean" probe of jet geometry
- Statistical studies of prompt GRB & afterglow
  - $\log N - \log S$, $dN/d\theta$, $dN/d\theta dz$, orphan AGs,…
  - Difficult: not always "clean" or conclusive
- Afterglow light curves: fewer assumptions are required & good obs. are frequently available

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 ✓

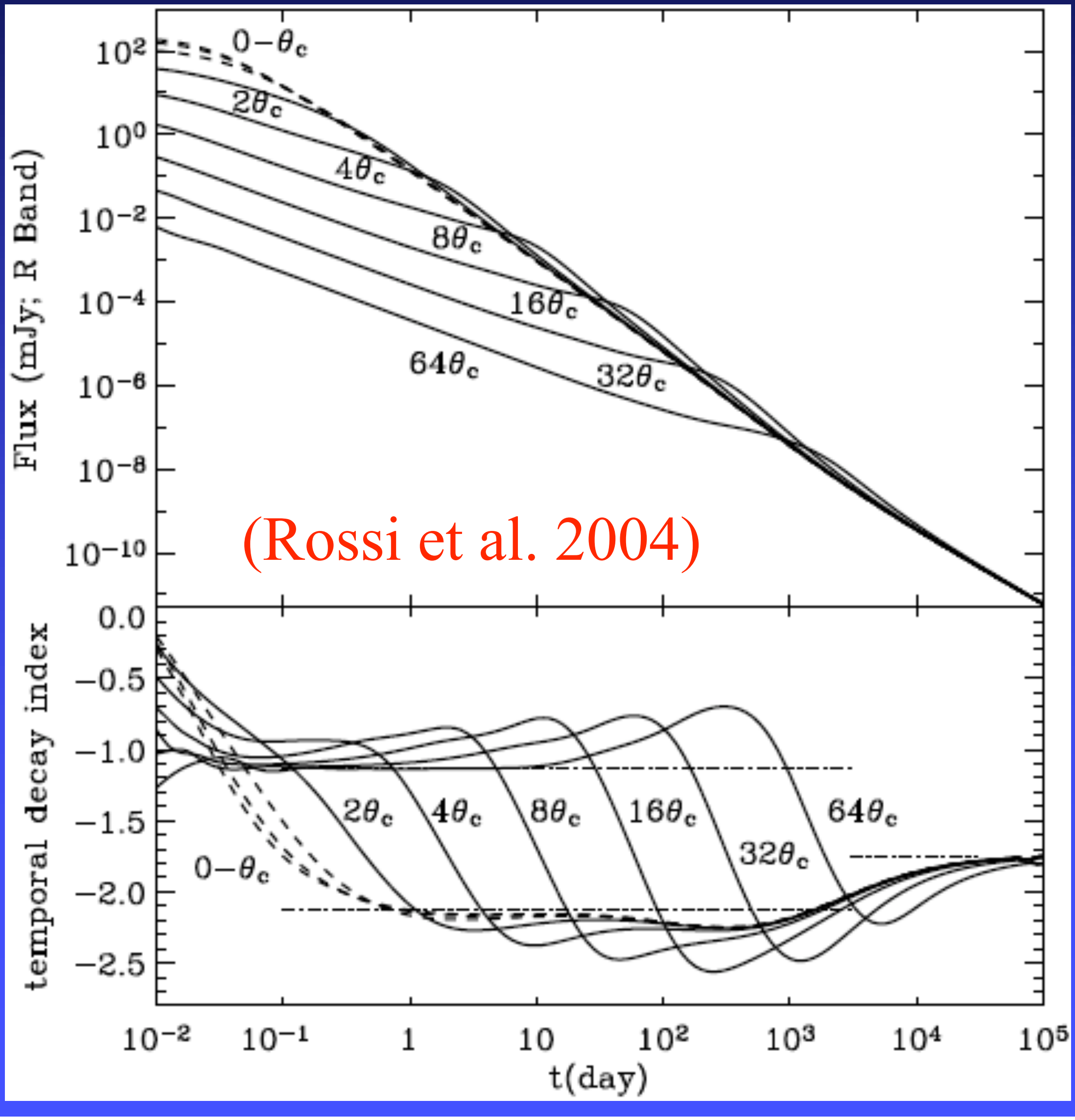
ϵ_e=0.1, ϵ_B=0.01, p=2.5, θ_0=0.2, θ_{obs}=0, z=1, $E_{iso}=10^{52}$ ergs, n=1 cm^{-3}



Afterglow LCs: Universal Structured Jet

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

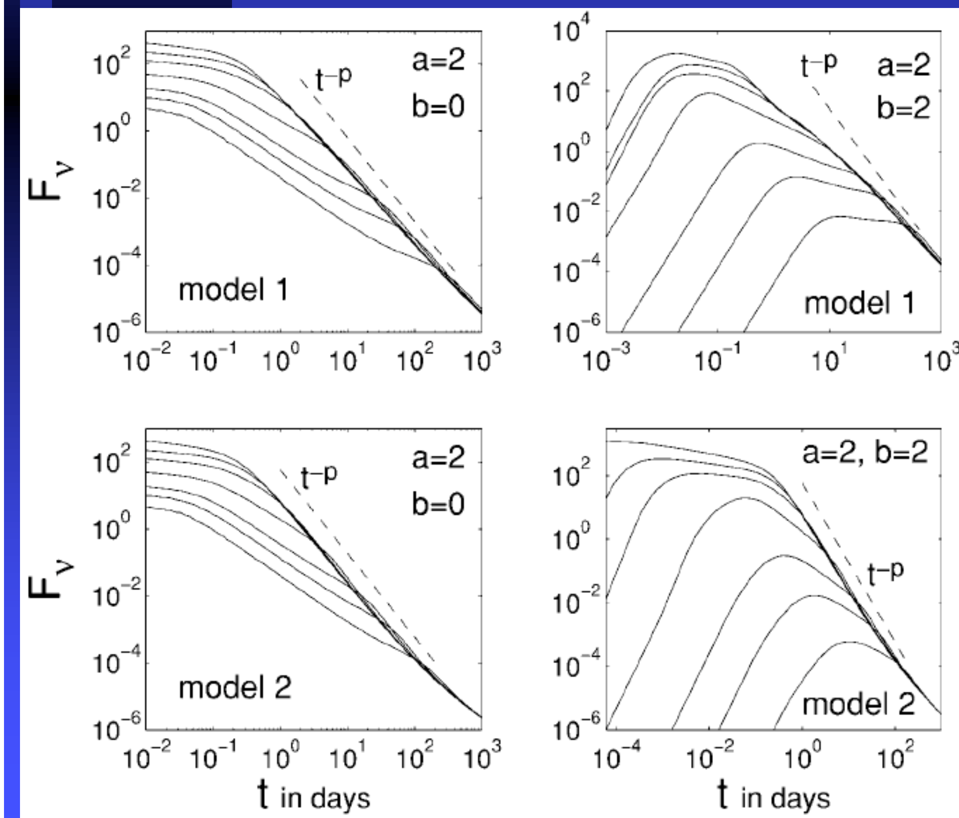
- Works reasonably well but has potential problems

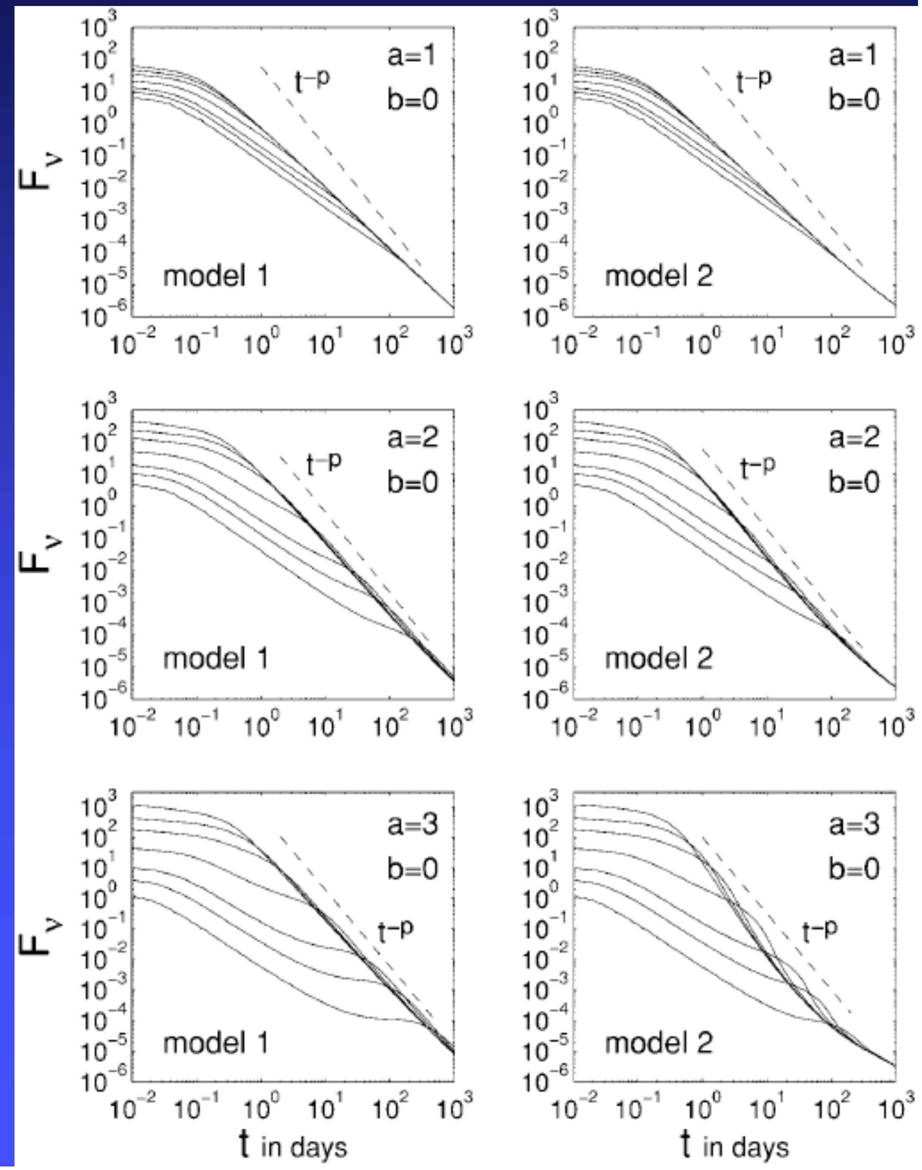


Afterglow LCs: Universal Structured Jet

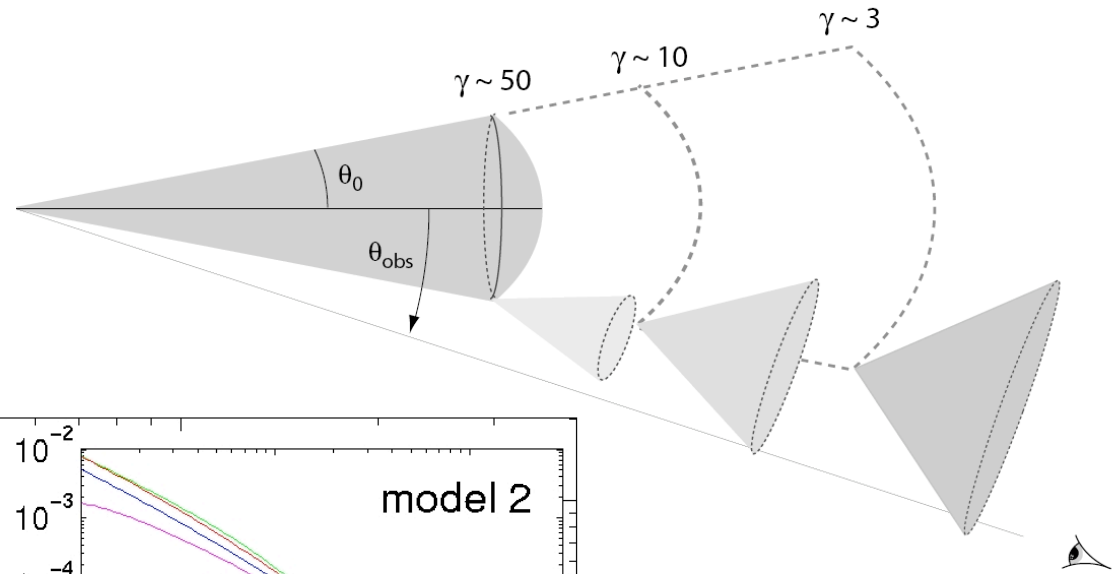
- LCs Constrain the power law indexes ‘a’ & ‘b’: $dE/d\Omega \propto \theta^{-a}$, $\Gamma_0 \propto \theta^{-b}$
- $1.5 \lesssim a \lesssim 2.5$, $0 \lesssim b \lesssim 1$

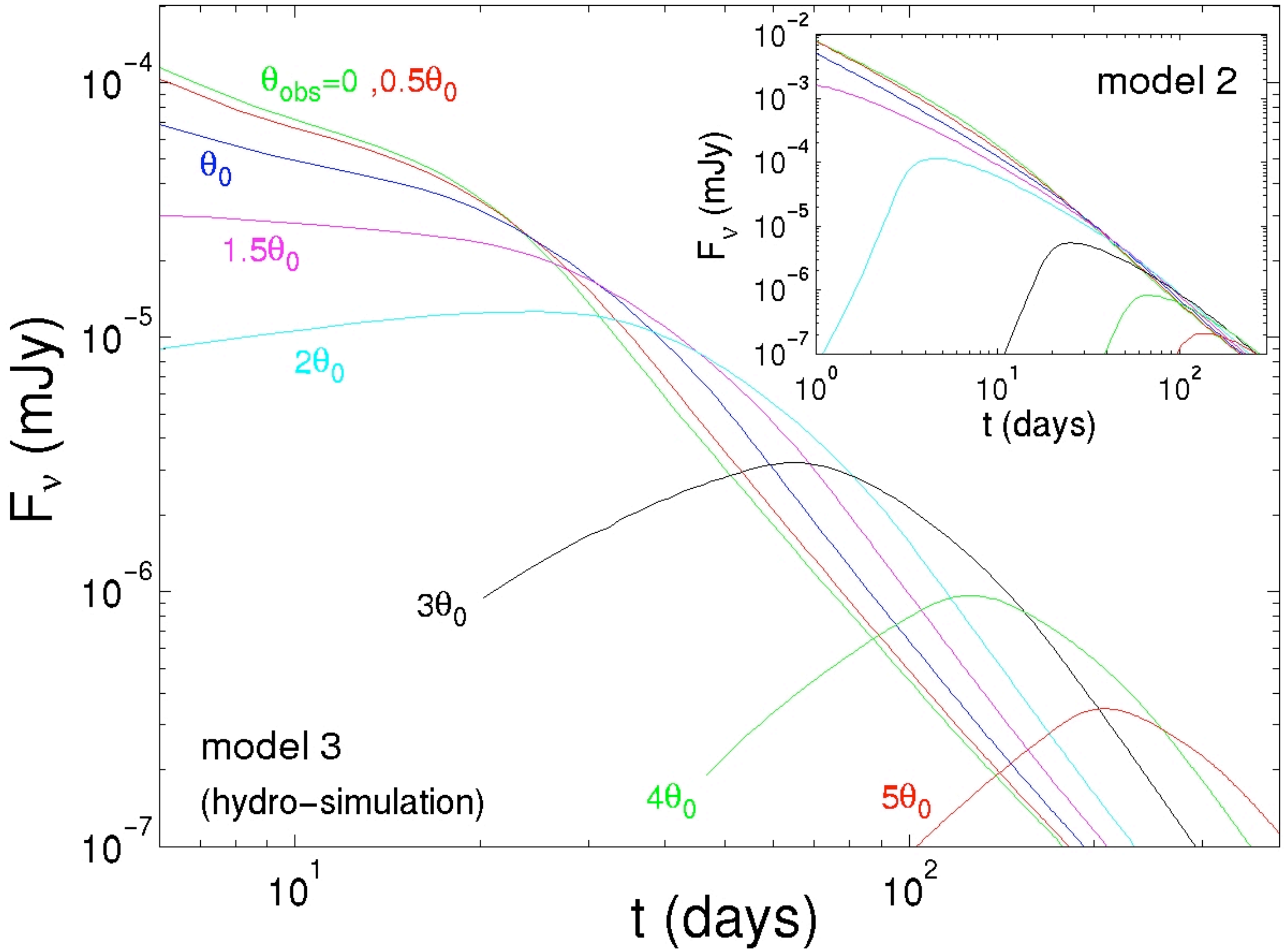
(JG & Kumar 2003)





Afterglow Light Curves: **Off-Axis** Viewing Angles





Model 2: uniform jet + sharp edges &

$v_\perp = c_s$

θ_0=0.2, $E_{jet}=3 \cdot 10^{51}$ erg, n=1 cm^{-3}, z=1, p=2.5, ε_e=0.1, ε_B=0.01

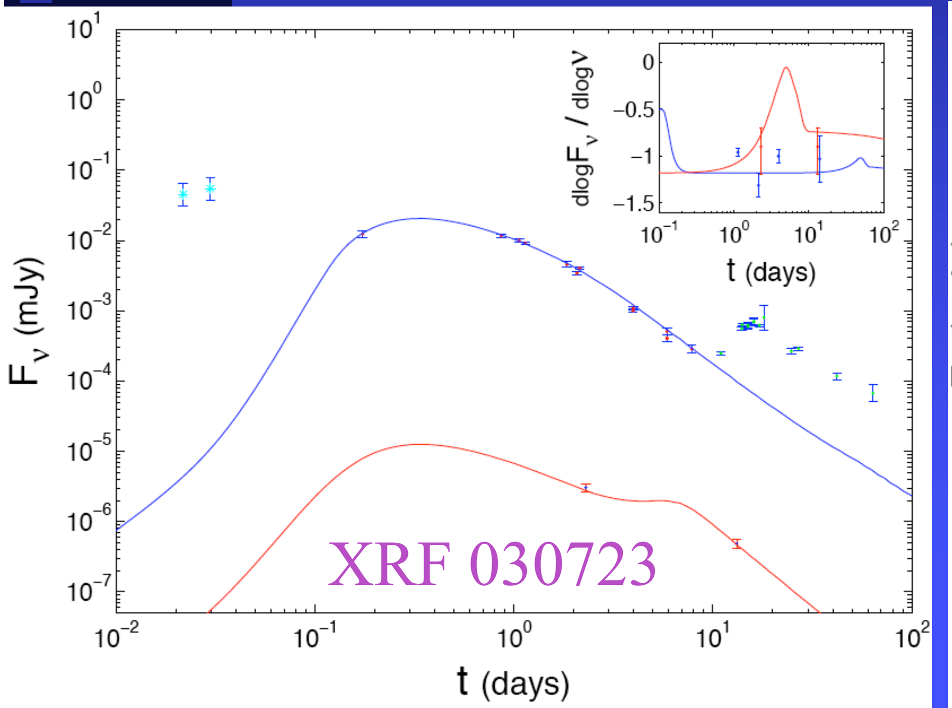
Granot et al. (2002)

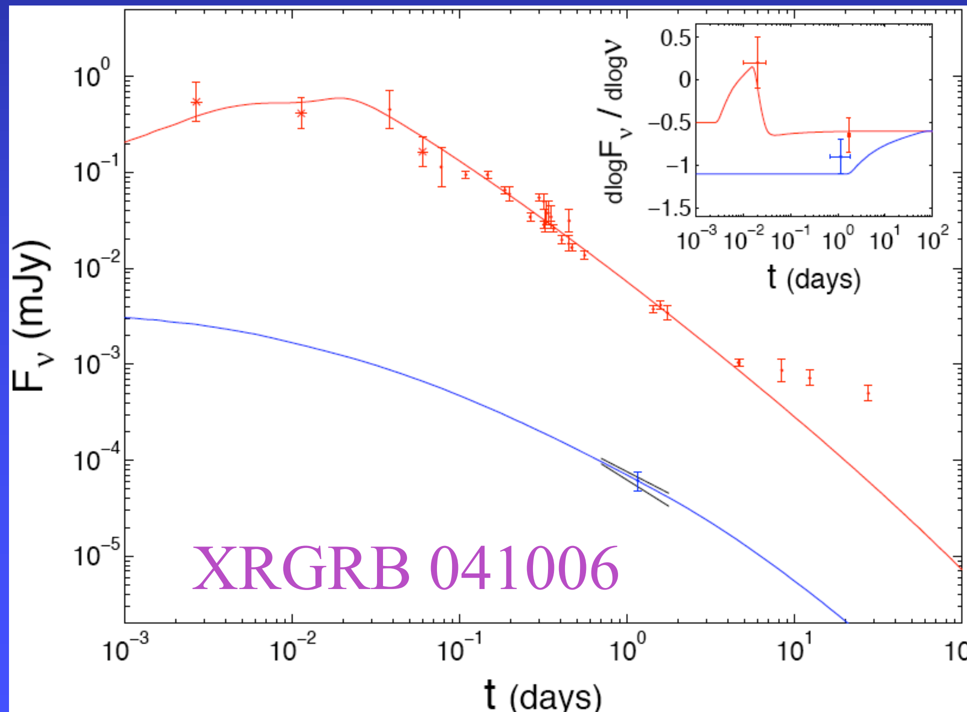
Prompt Emission: **Off-Axis** Viewing Angles

- $E_{peak} \propto \delta^{-1}$, $f \propto \delta^{-a}$ where $\delta \approx 1+[\Gamma(\theta_{obs} - \theta_0)]^2$ & $a \approx 2$ for $\theta_0 < \theta_{obs} \lesssim 2\theta_0$; $a \approx 3$ for $\theta_{obs} \gtrsim 2\theta_0$
- The prompt emission from **large** off-axis viewing angles, $\delta \gg 1$ or $\theta_{obs} \gtrsim 2\theta_0$, will not be detected ("orphan afterglows")
- The prompt emission from slightly off-axis viewing angles might still be detected, but peaks at lower E_{peak} & has a much smaller fluence f (X-ray flashes or X-ray rich GRBs)

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)

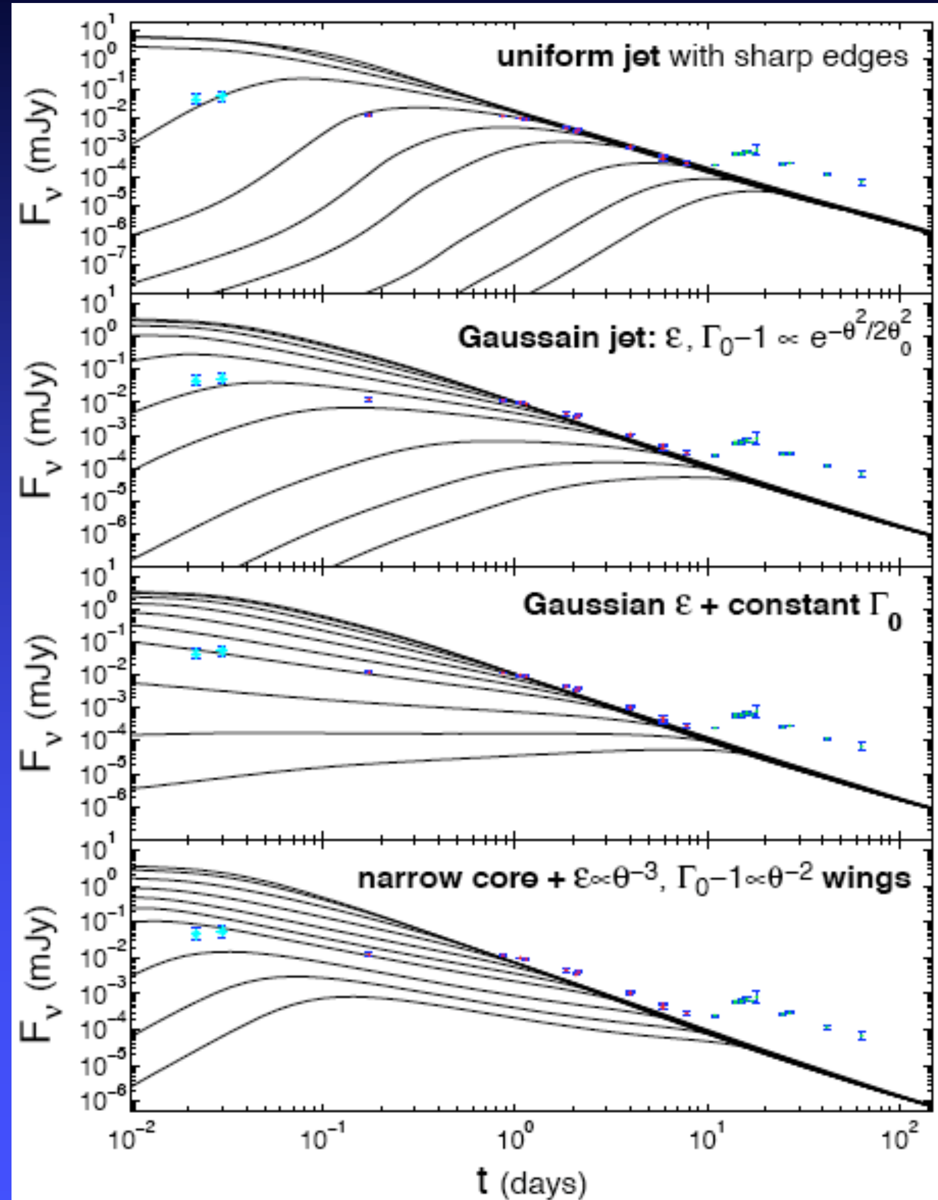




(JG, Ramirez-Ruiz & Perna 2005)

Afterglow L.C. for Different Jet Structures:

- Uniform conical jet with sharp edges: ✓
- 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)

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, $\epsilon_\gamma \sim 90\%$, if it is due to energy injection + standard AG theory
- The flat decay is due to an increase in time of AG efficiency $\Rightarrow \epsilon_\gamma$ does not change ($\sim 50\%$)
- Pre-*Swift* estimates of $E_{kin,AG} \sim 10^{51}$ erg for a uniform jet relied on standard afterglow theory
- Different assumptions: $E_{kin,AG} \sim 10^{52}$ erg, $\epsilon_\gamma \sim 0.1$
- $\epsilon_\gamma \lesssim 0.1 \Rightarrow E_{kin,AG} \gtrsim 10^{53}$ erg for a structured jet

Conclusions:

- 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)
- The most promising way to **constrain the jet structure** is through the **afterglow light curves**
- A low γ-ray efficiency requires a high afterglow kinetic energy: $\epsilon_\gamma \lesssim 0.1 \Rightarrow E_{kin,AG} \gtrsim 10^{53}$ erg for a structured jet & E [illegible] $\gtrsim 10^{52}$ erg for a uniform jet