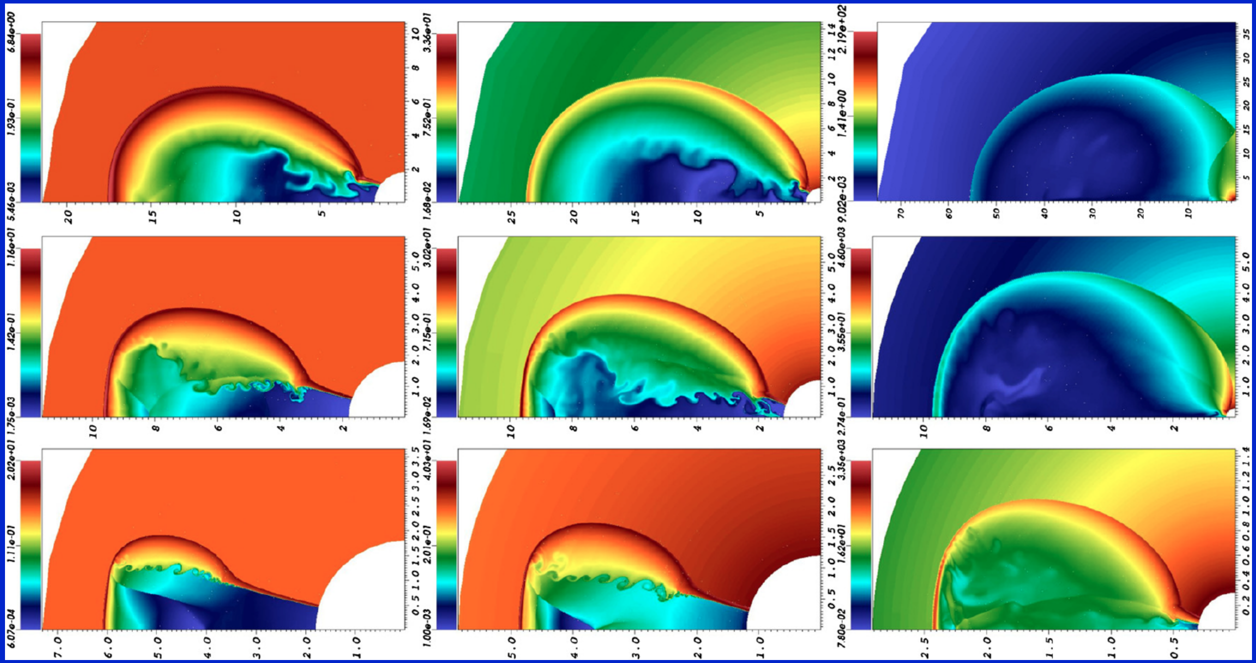
GRB Jet Dynamics
& Afterglow Lightcurves

Jonathan Granot

Open University of Israel, Hebrew University



13th Marcel Grossmann meeting, Stockholm, July 6, 2012

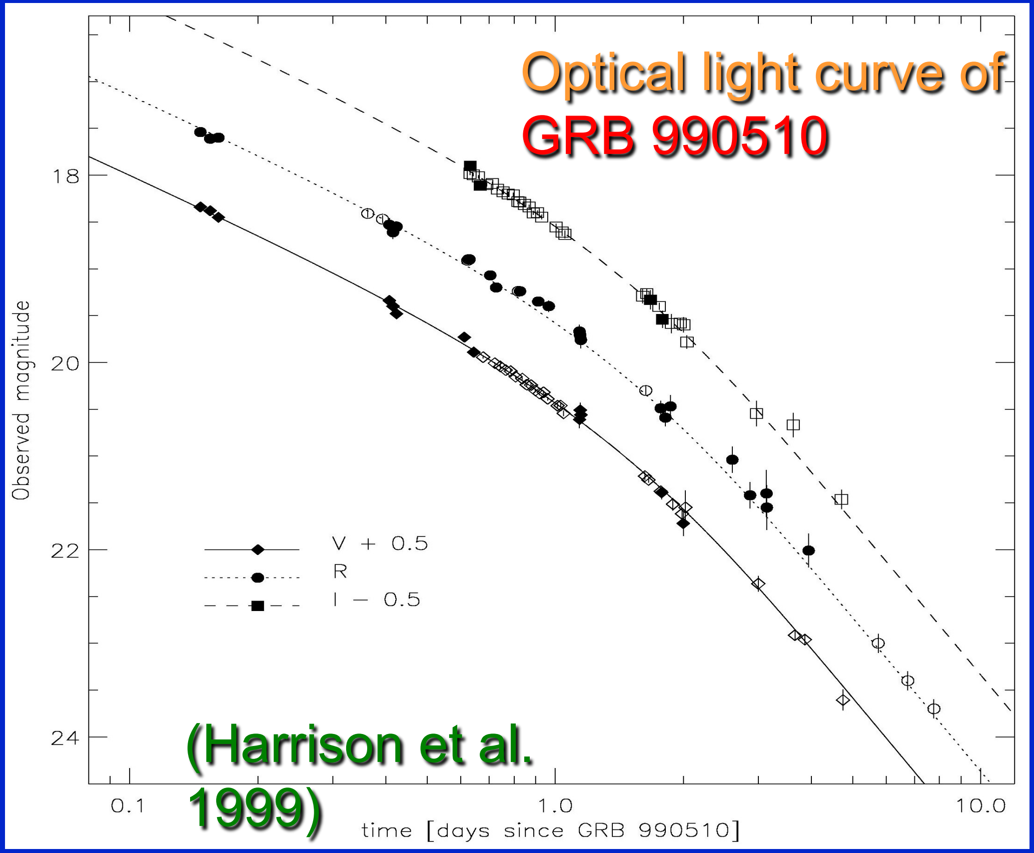
Outline of the talk:

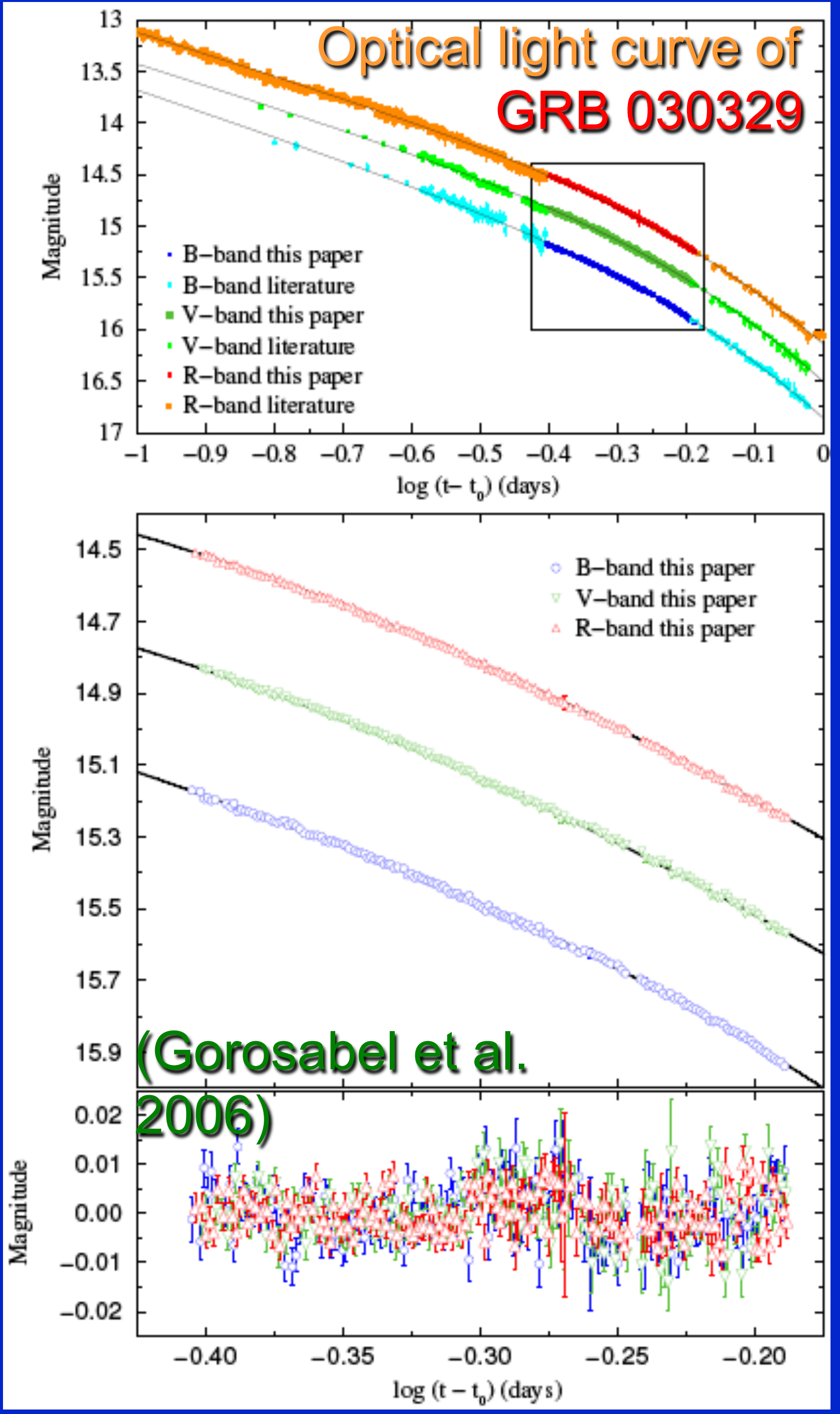
- Evidence for jets, angular structure, evolution stages
- Jet dynamics during the afterglow: an overview
- Analytic vs. numerical results: a problem?
- Recent numerical & analytic results: finally agree
- Simulations of an afterglow jet propagating into a stratified external medium: $\rho_{ext} \propto R^{-k}$ for $k = 0, 1, 2$
- Implications for GRBs: **jet breaks, radio calorimetry**

Observational evidence for jets in GRBs:

- The energy output in γ-rays assuming isotropic emission ($E_{\gamma,iso}$) approaches (and sometimes even exceeds) $M_{\odot}c^2$
  - Difficult for a stellar mass progenitor
  - **True energy** is much smaller for a narrow **jet**
- At least some long GRBs occur together with a SN Ic
  - 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**")

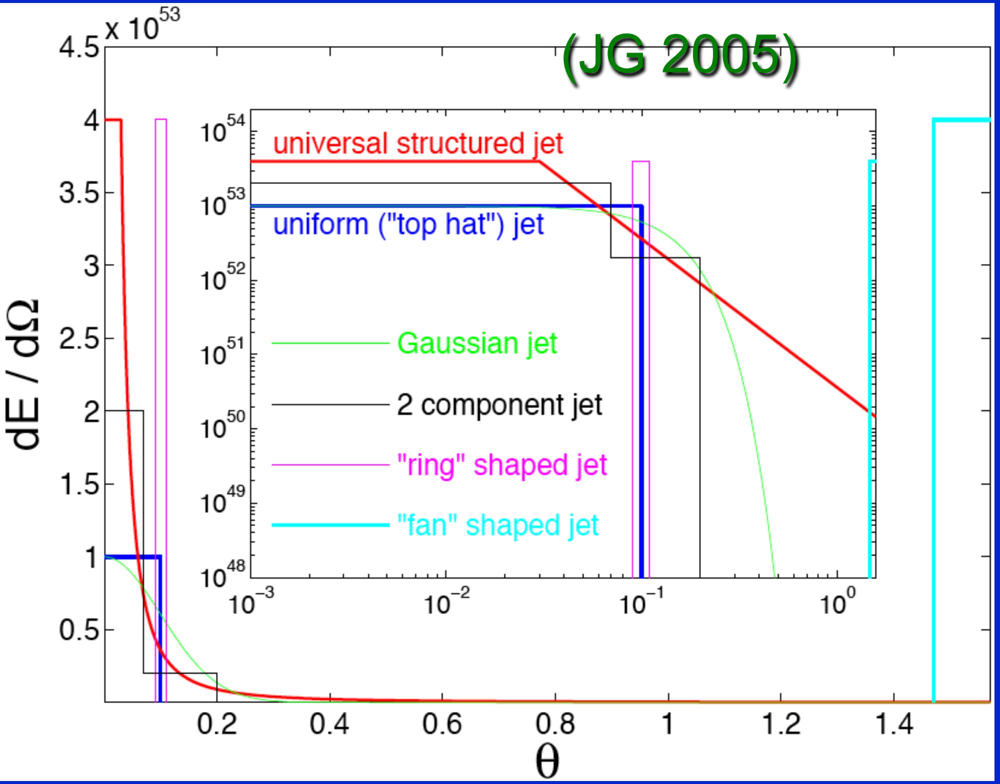
Examples of Smooth & Achromatic Jet Breaks:





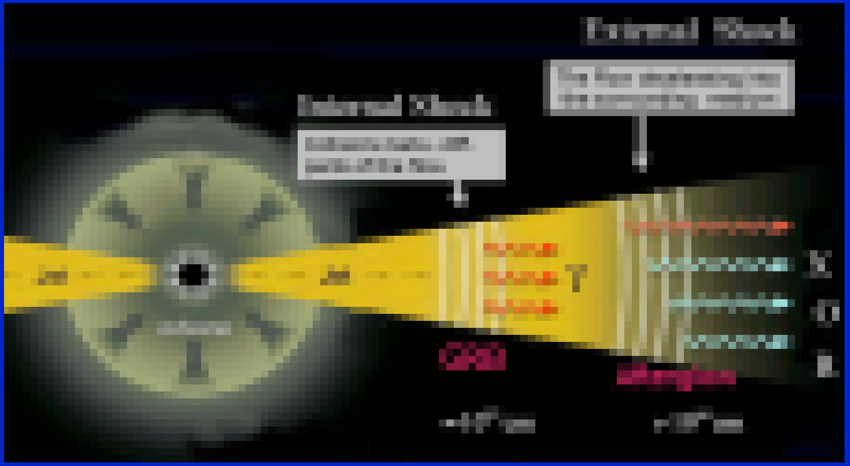
The **Angular Structure** of GRB Jets:

- **Jet structure: unclear** (uniform, structured, hollow cone,…)
  - Affects $E_{\gamma,iso} \rightarrow E_{\gamma}$ & observed GRB rate → true rate
  - Viewing-angle effects (afterglow & prompt - XRF)
  - Can also affect late time radio calorimetry
- Here I consider mainly a uniform "top hat" jet



Stages in the **Dynamics** of GRB Jets:

- **Launching** of the jet: magnetic (B-Z?) neutrino annihilation?
- Acceleration: magnetic or thermal?
- For long GRBs: propagation inside progenitor star
- Collimation: magnetic, stellar envelope, accretion disk wind
- Coasting phase that ends at the deceleration radius R_{dec}
- At $R > R_{dec}$ most of the energy is in the shocked external medium: the composition & radial profile are forgotten, but the angular profile persists (locally: BM76 solution)
- Once $\Gamma < 1/\theta_0$ at $R > R_{jet}$ jet lateral expansion is possible
- Eventually the flow becomes spherical approaches the self-similar Sedov-Taylor solution



Dynamics of GRB Jets: Lateral Expansion

- **Simple** semi-**analytic models** (Rhoads 97, 99; Sari, Piran & Halpern 99,…) make simplifying assumptions, such as:
  - 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
- $\Rightarrow$ $\Gamma \sim (c_s/c\theta_0)\exp(-R/R_{jet})$, $\theta_{jet} \sim \theta_0(R_{jet}/R)\exp(R/R_{jet})$
- **Hydro-simulations**: these simplifying assumptions fail: shock front is aspherical, velocity is not radial,…
- **Very mild** lateral expansion while jet is relativistic
- Non-uniform shocked fluid: emission mainly from $\theta<\theta_0$
- **Nevertheless**, despite the differences, there is a **sharp** achromatic **jet break** [for $\nu > \nu_m(t_{jet})$] at a similar t_{jet}

2D hydro-simulations

(JG et al. 2001)

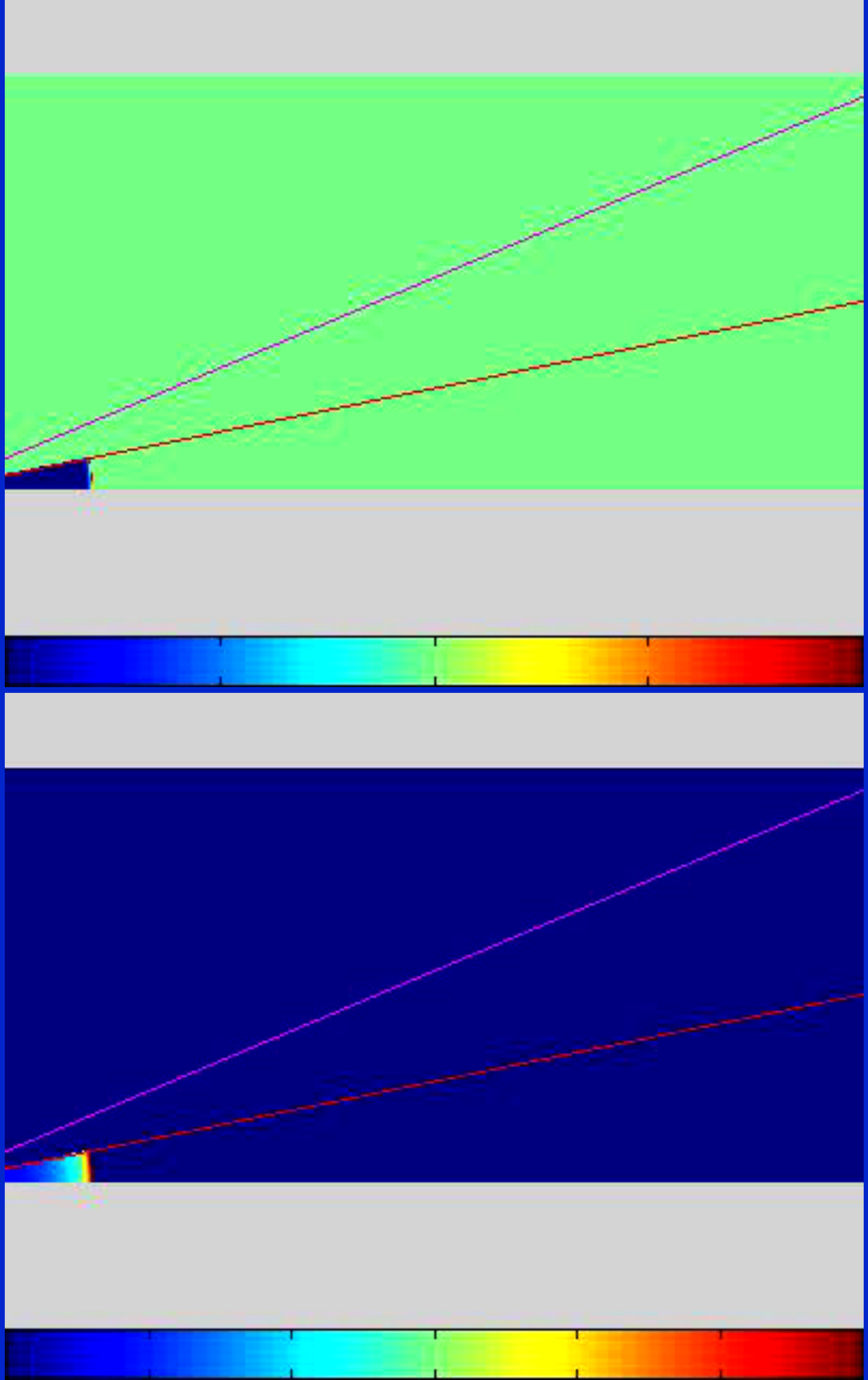
Proper Density:

(logarithmic color scale)

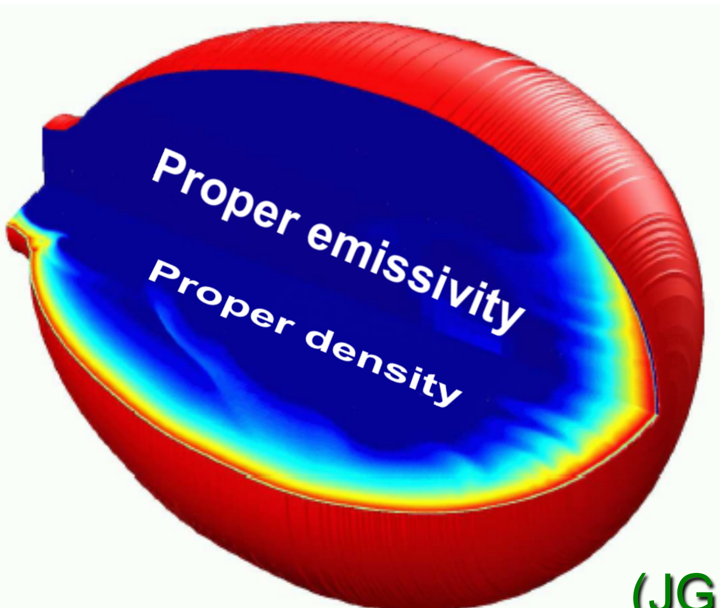
- Uniform external medium
- Initial conditions: a conical wedge from the BM solution

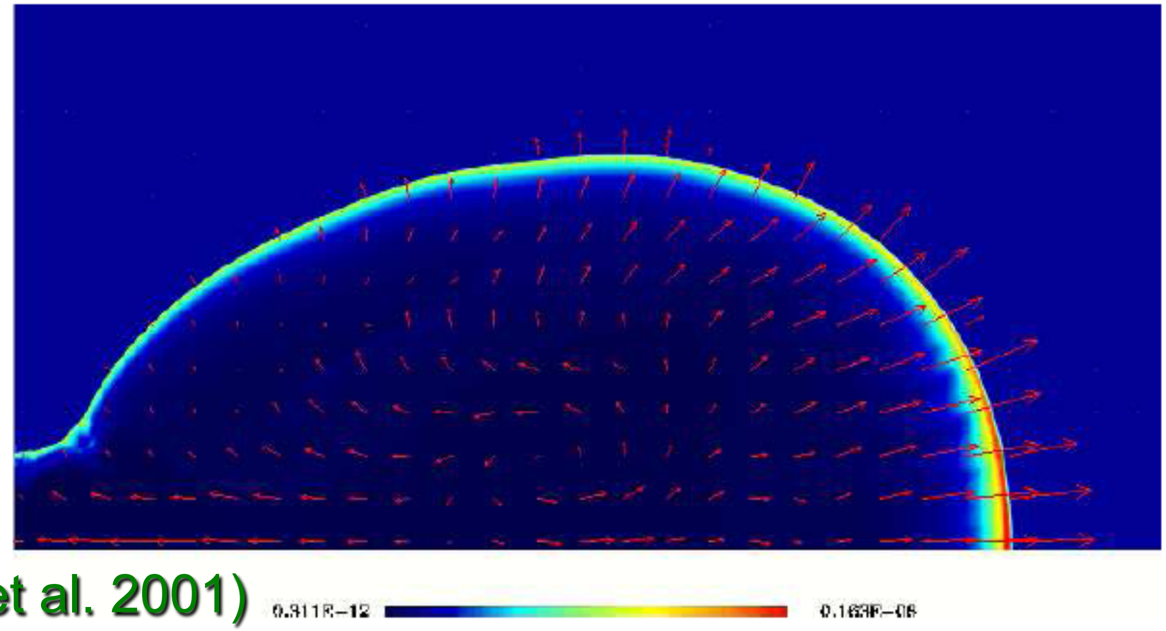
Bolometric Emissivity:

(logarithmic color scale)



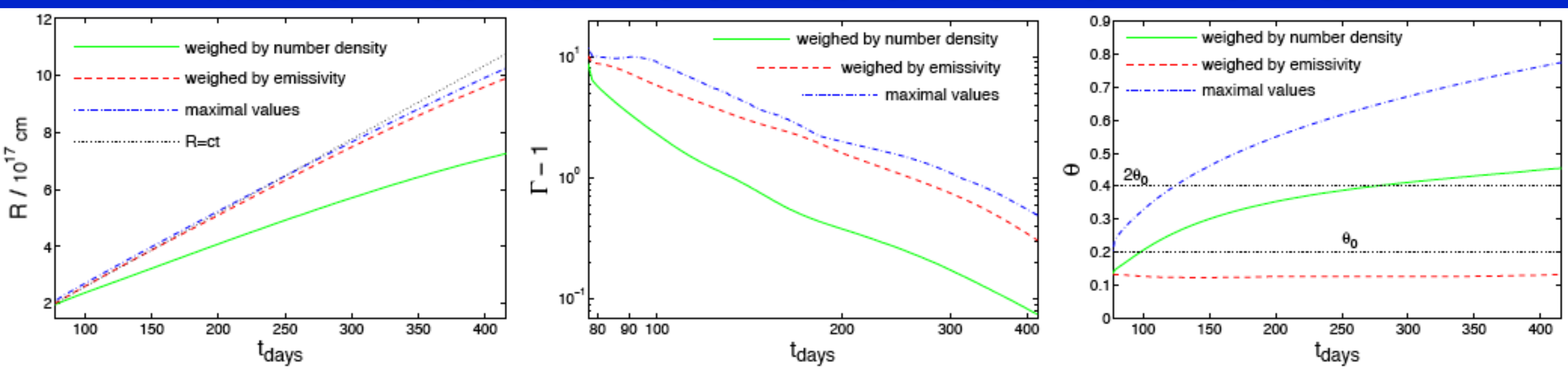
The Jet Dynamics: very modest lateral expansion





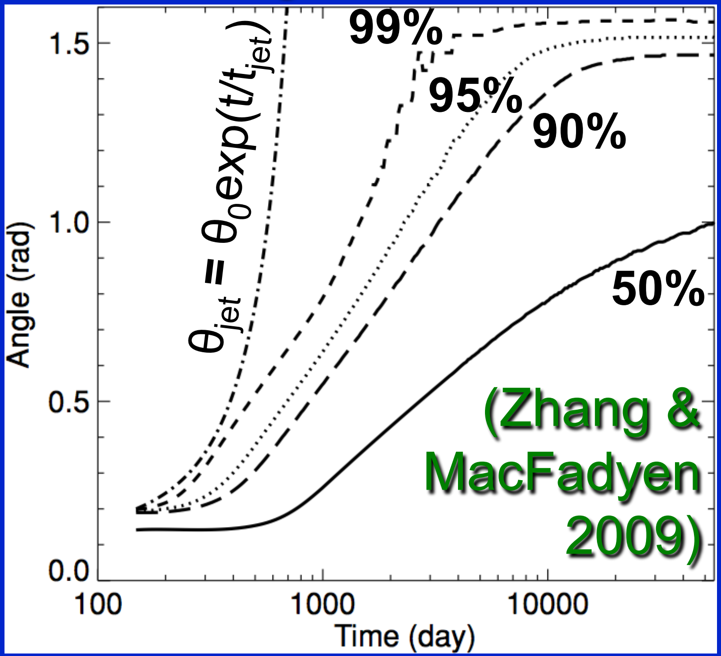
(JG et al. 2001)

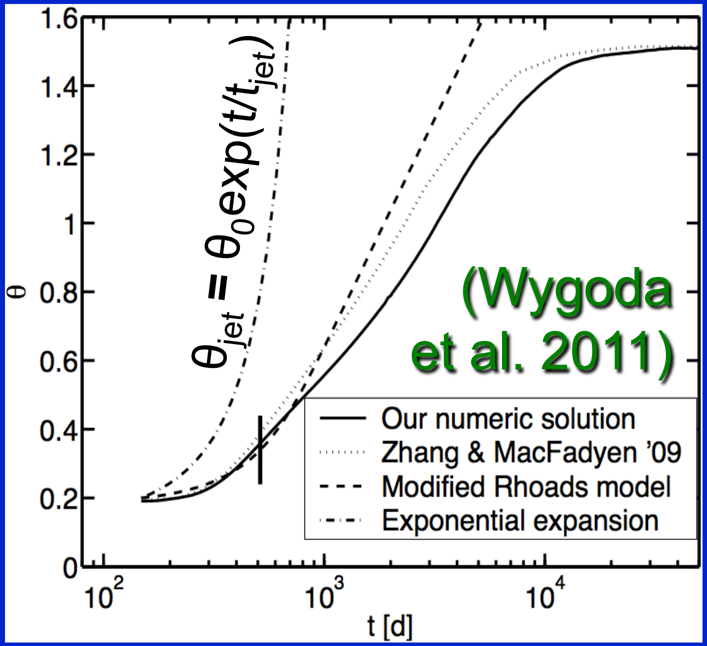
- There is slow material at the sides of the jet while most of the emission is from its front



Analytic vs. Numerical results: a problem?

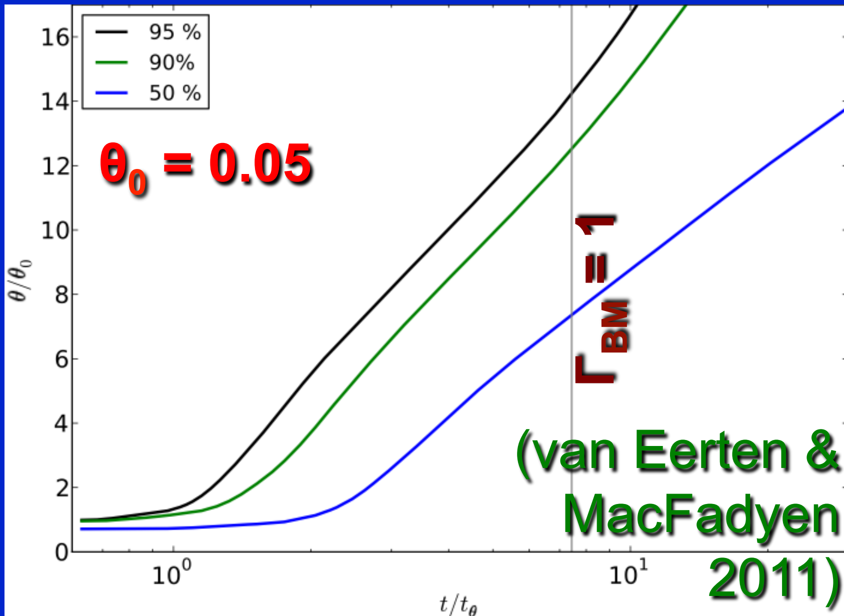
- **Analytic** results (Rhoads 1997, 99; Sari, Piran & Halpern 99): **exponential lateral expansion** at $R > R_{jet}$ e.g. $\Gamma \sim (c_s/c\theta_0)\exp(-R/R_{jet})$, $\theta_{jet} \sim \theta_0(R_{jet}/R)\exp(R/R_{jet})$
  - Supported by a self-similar solution (Gruvinov 2007)
- **Hydro-simulations**: very **mild** lateral expansion while jet is relativistic (also for simplified 2D → 1D)

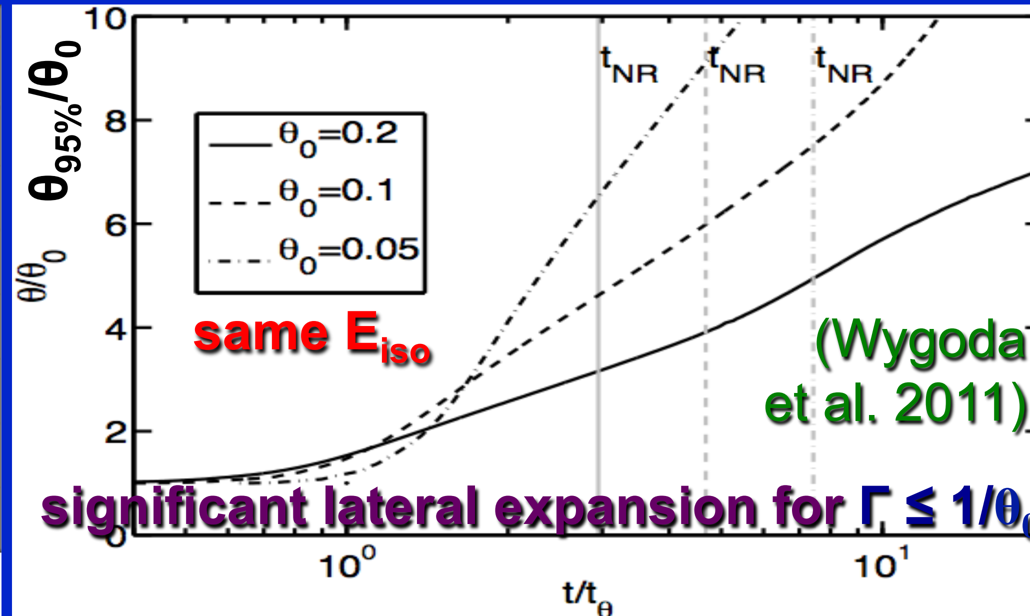


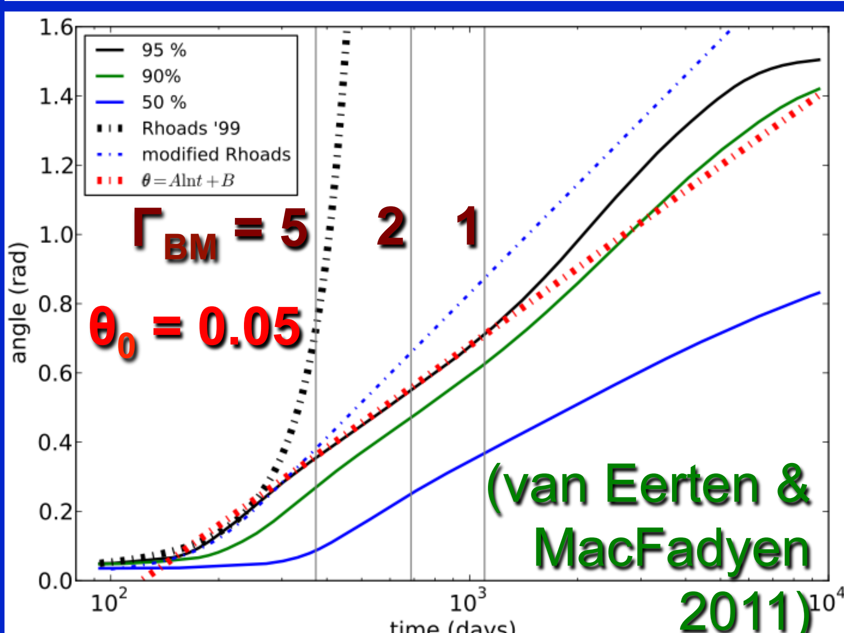


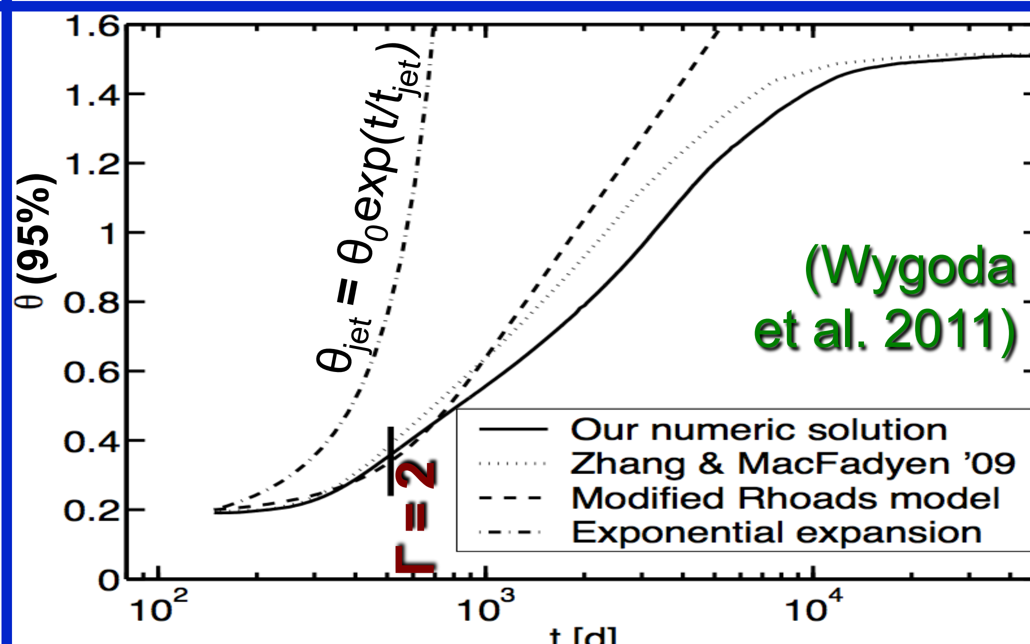
Modest θ_0 ⇒ small region of validity

Analytic vs. Numerical results: a problem?





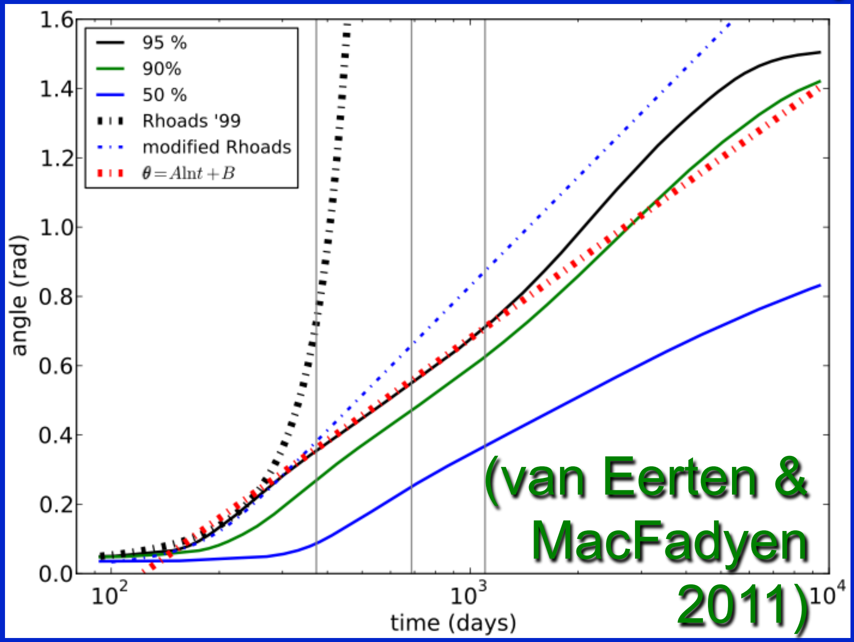




Analytic vs. Numerical results: a problem?

van Eerten & MacFadyen 11'

- No exponential lateral expansion even for $\theta_0 = 0.05$
- Lateral expansion is instead only logarithmic: $\theta_j \sim \theta_0 \ln(t/t_j)$
- Affects jet break shape + t_j & late time radio calorimetry



Lyutikov 2011

- Lateral expansion becomes significant only for $\Gamma \leq \theta_0^{-1/2}$
- Based on thin shell approx.

$$\tan\alpha = -\frac{\partial \ln R}{\partial \theta}$$ (Kumar & JG 2003)

$$\Rightarrow \beta_\theta \sim \frac{1}{\Gamma^2 \Delta\theta} \sim \frac{1}{\Gamma^2 \theta_j}$$

$r = R(\theta) \;\rightarrow$ shock radius in spherical coordinates

$\alpha =$ angle between the shock normal $\hat{\boldsymbol{n}}$ and radial direction $\hat{\boldsymbol{r}}$

Generalized Analytic model (JG & Piran 2012)

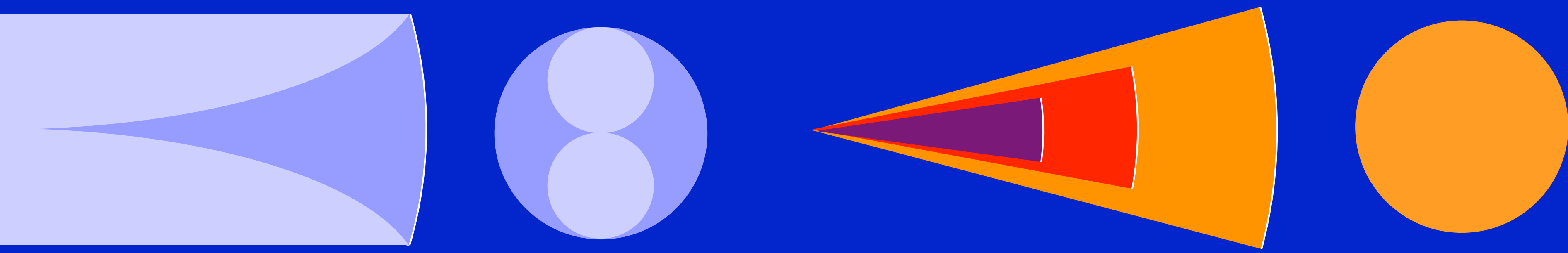
- **Lateral expansion**:

  1. new recipe: $\beta_\theta/\beta_r \sim 1/(\Gamma^2\Delta\theta) \sim 1/(\Gamma^2\theta_j)$ (based on $\hat{\beta} = \hat{n}$)
  2. old recipe: $\beta_\theta = u_\theta/\Gamma = u'_\theta/\Gamma \sim \beta_r/\Gamma$ (based on $u'_\theta \sim 1$)

Generalized recipe: $$\frac{d\theta_j}{d\ln R} = \frac{\beta_\theta}{\beta_r} \approx \frac{1}{\Gamma^{1+a}\theta_j^a}\ , \quad a = \begin{cases} 1 & (\hat{\beta} = \hat{n}) \\ 0 & (u'_\theta \sim 1) \end{cases}$$

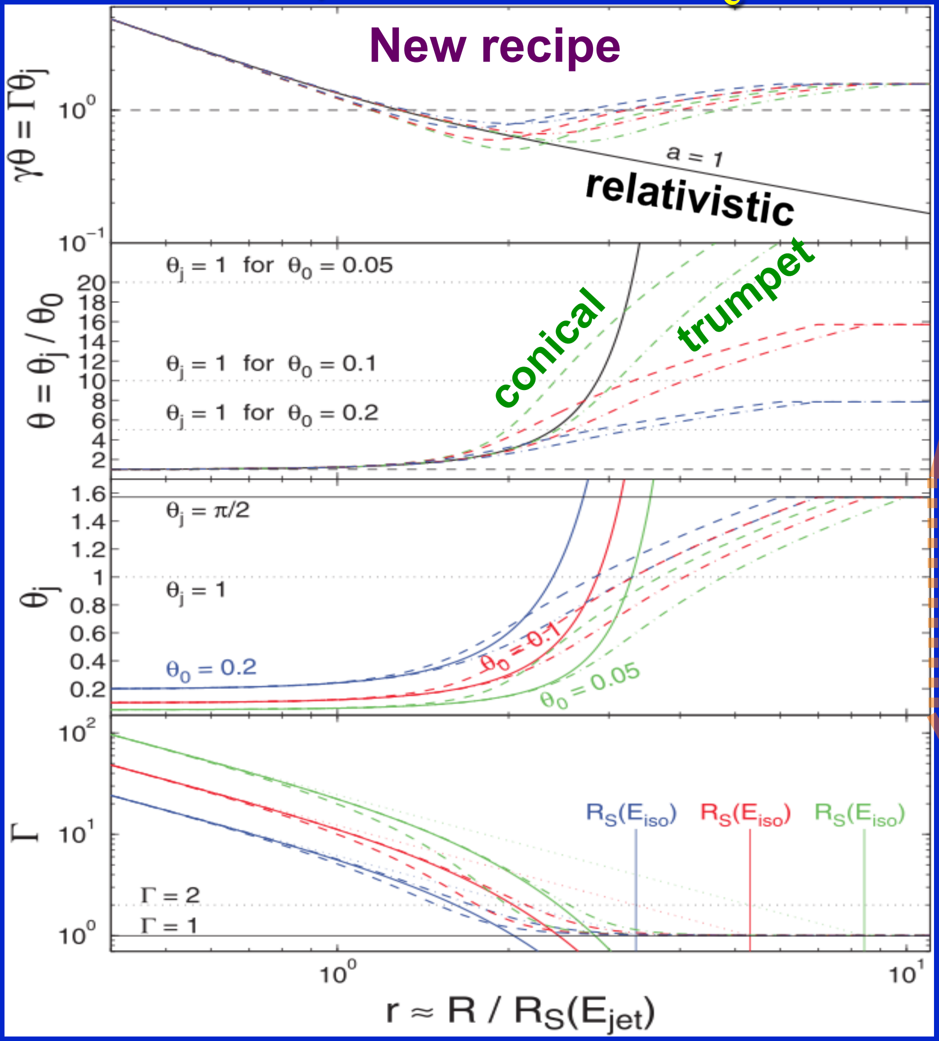
- New recipe: lower β_θ for $\Gamma > 1/\theta_0$ but higher β_θ for $\Gamma < 1/\theta_0$

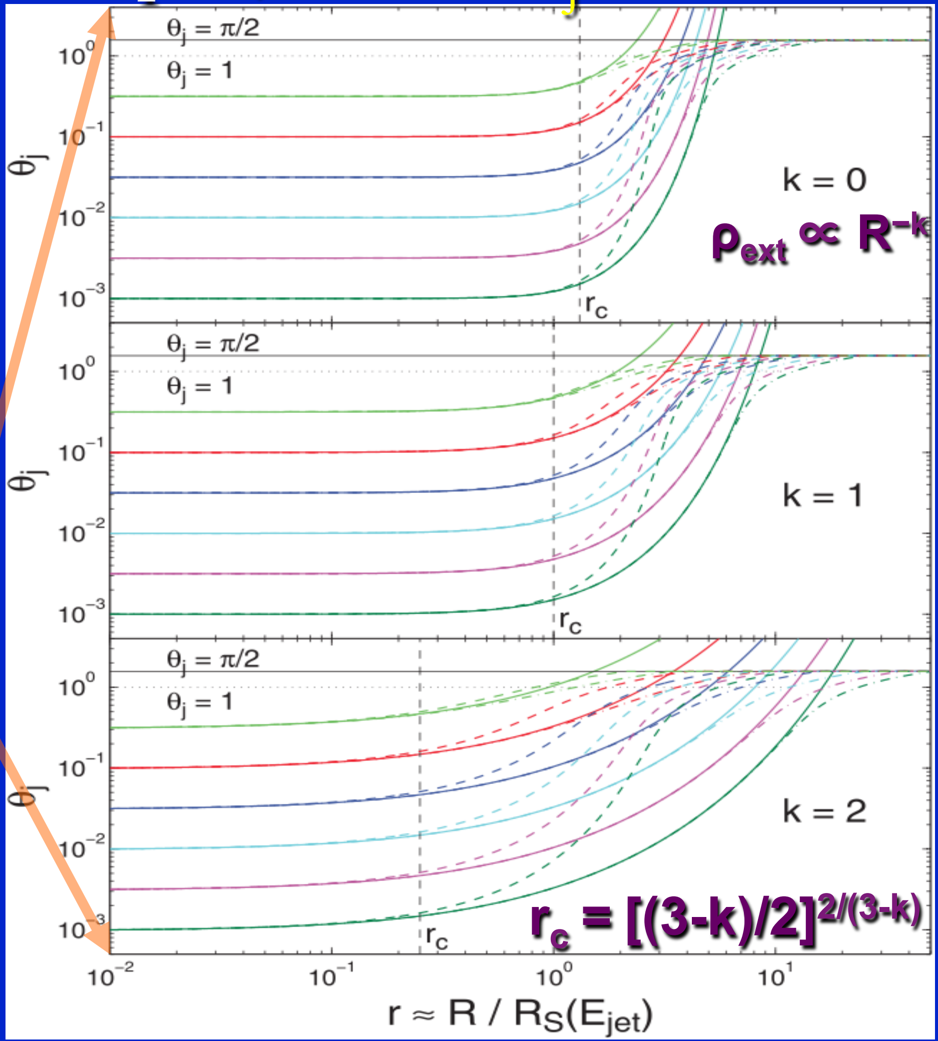
- Does not assume $\Gamma \gg 1$ or $\theta_j \ll 1$ (& variable: $\Gamma \rightarrow u = \Gamma\beta$)
- Sweeping-up external medium: trumpet vs. conical models



Generalized Analytic model (JG & Piran 2012)

- Main effect of relaxing the $\Gamma \gg 1$, $\theta_j \ll 1$ approximation: quasi-logarithmic (~~exponential~~) lateral expansion for $\theta_0 \gtrsim 0.05$
- conical ≠ rel. for $r \gtrsim r_c$ while trumpet ≠ rel. for $\theta_j \gtrsim 0.2$



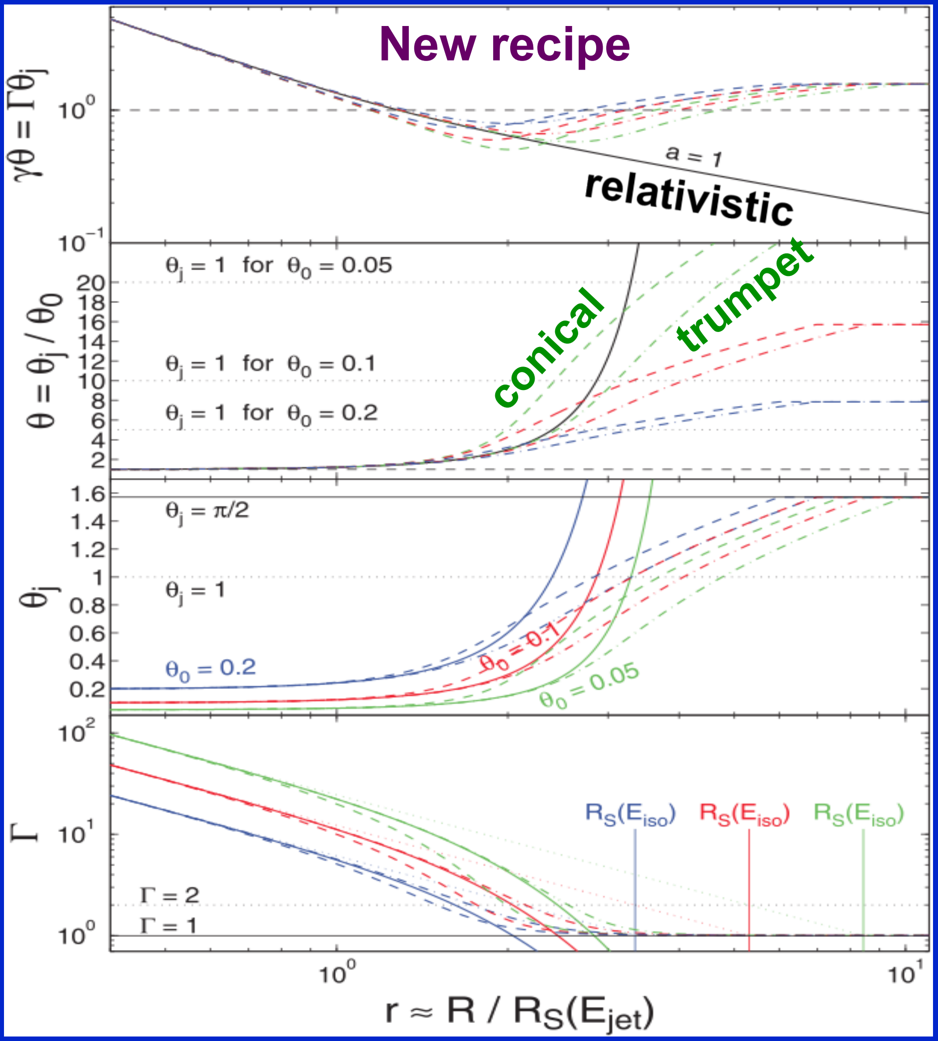


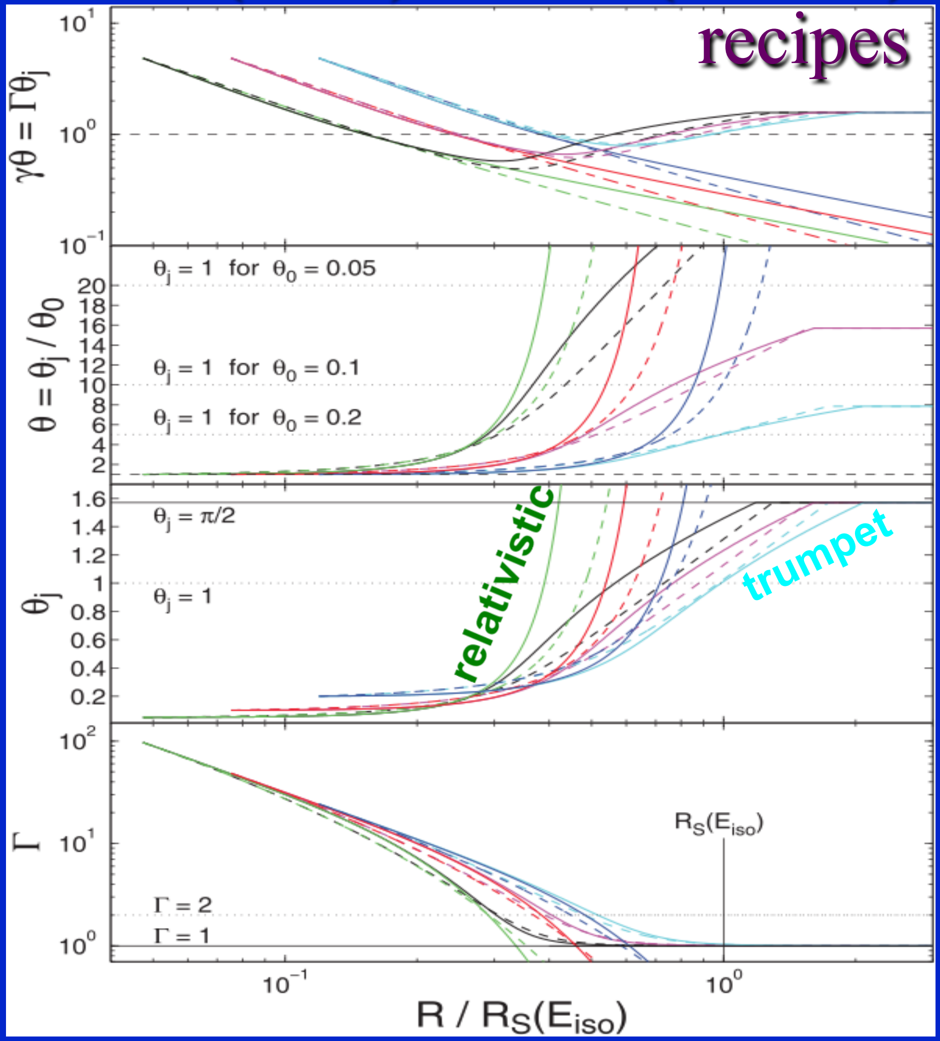
Generalized Analytic model (JG & Piran 2012)

Conical: larger M(R) than trumpet
➔ lower Γ(R) ➔ larger $\theta_j(R)$

New recipe: lower β_θ for $\Gamma > 1/\theta_0$
but higher β_θ for $\Gamma < 1/\theta_0$

New (*solid*) vs. old (*dashed*)

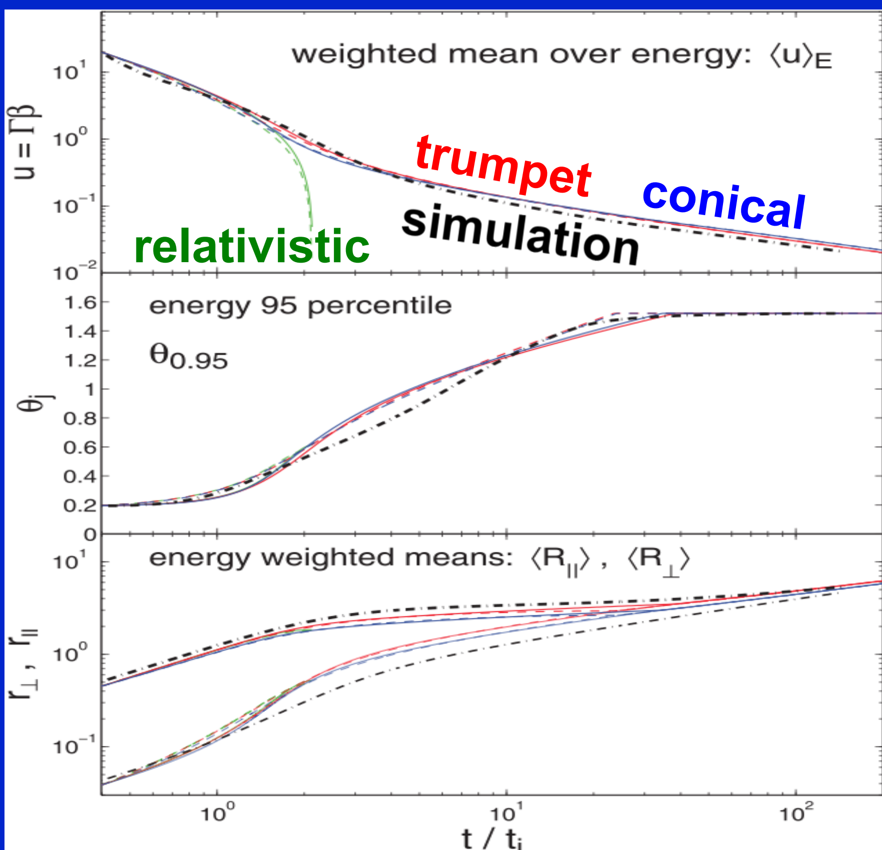


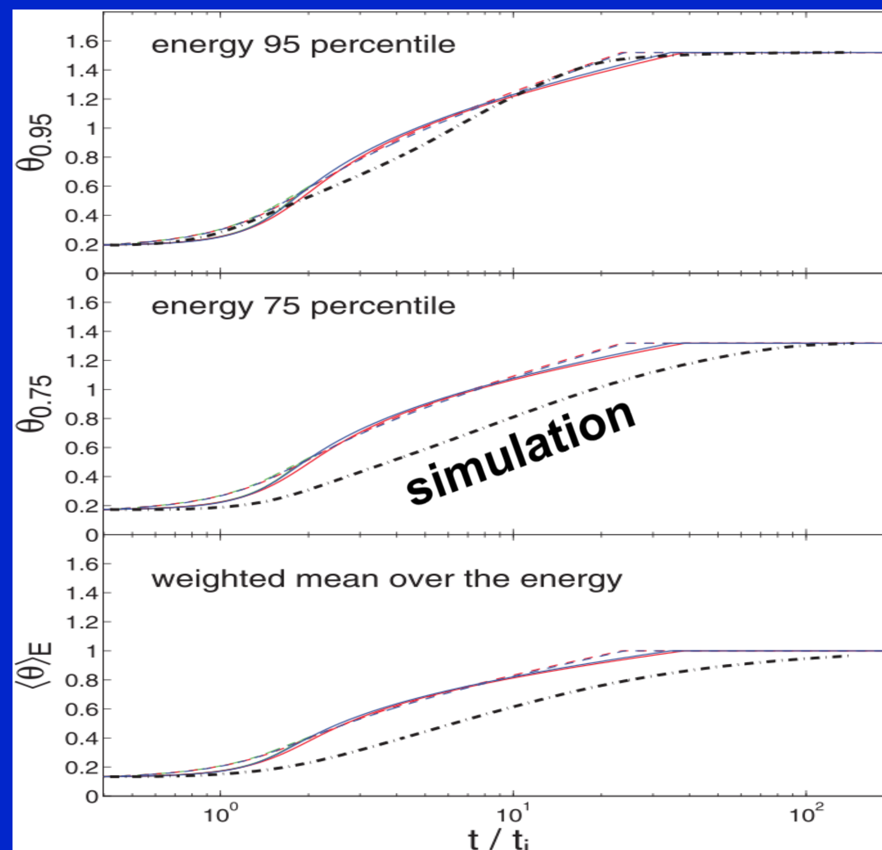


Comparison to Simulations (JG & Piran 2012)

- There is a reasonable overall **agreement** between the **analytic** generalized models and the hydro-**simulations**
- Analytic models: over-simplified, but capture the essence

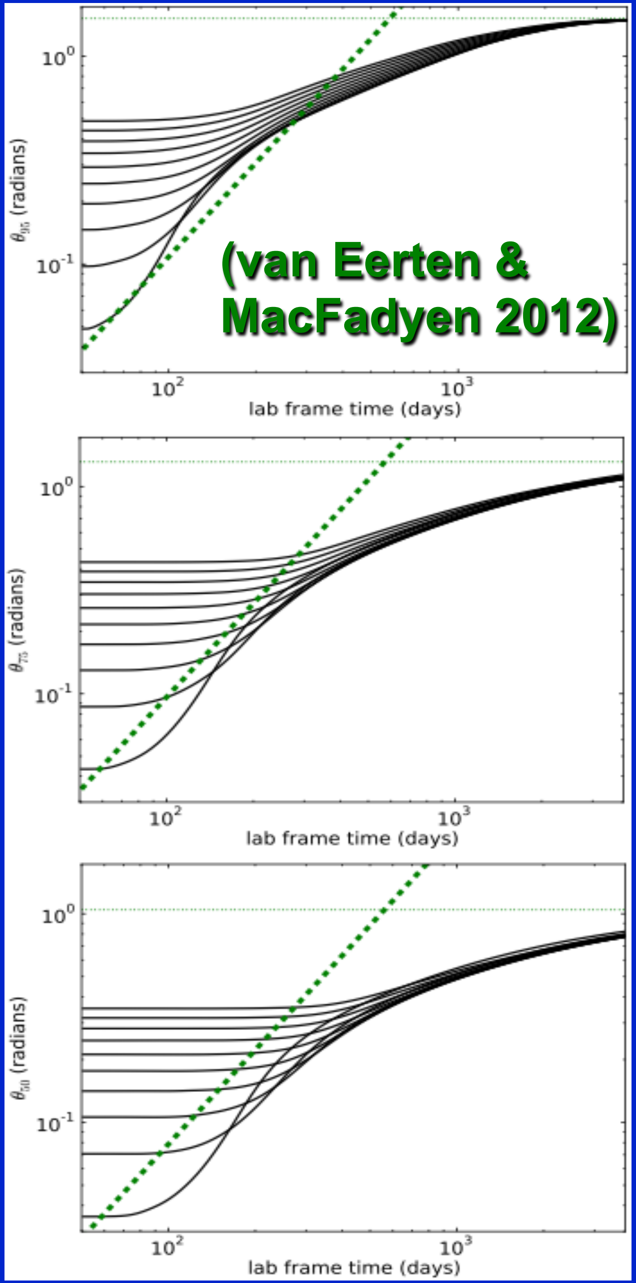
2D hydro-simulation by F. De Colle et al. 2012, with $\theta_0 = 0.2$, $k = 0$





Jet Dynamics: Intermediate Conclusions

- For $\theta_0 \gtrsim 0.05$ the lateral expansion is quasi-logarithmic (~~exponential~~), due to the small dynamical range $1/\theta_0 > \Gamma \gg 1$
- For $\theta_0 \ll 0.05$ there is an exponential lateral expansion phase (hinted also by van Eerten & MacFadyen's simulations) but such narrow GRB jets appear rare
- The jet first becomes sub-relativistic & only then gradually approaches spherical symmetry over a long time



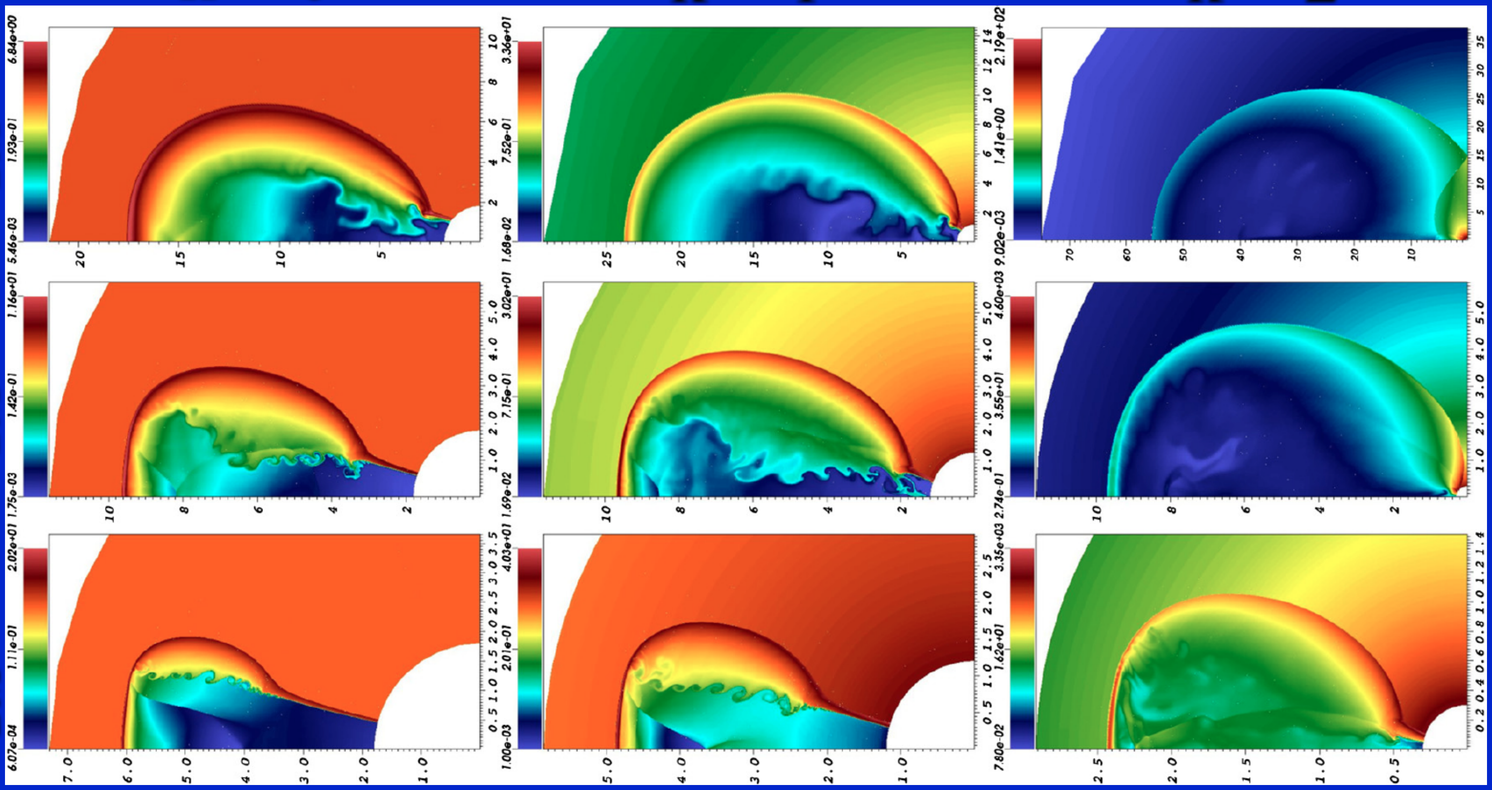
Afterglow jet in stratified external media

(De Colle, Ramirez-Ruiz, JG & Lopez-Camara 2012)

- Previous simulations were all for $k = 0$ where $\rho_{ext} \propto R^{-k}$
- Larger (e.g. $k = 1, 2$) are motivated by the stellar wind of a massive star progenitor for long GRBs

$k = 0$ $k = 1$ $k = 2$

$\Gamma_{BM} = 2$ $\Gamma_{BM} = 5$ $\Gamma_{BM} = 10$



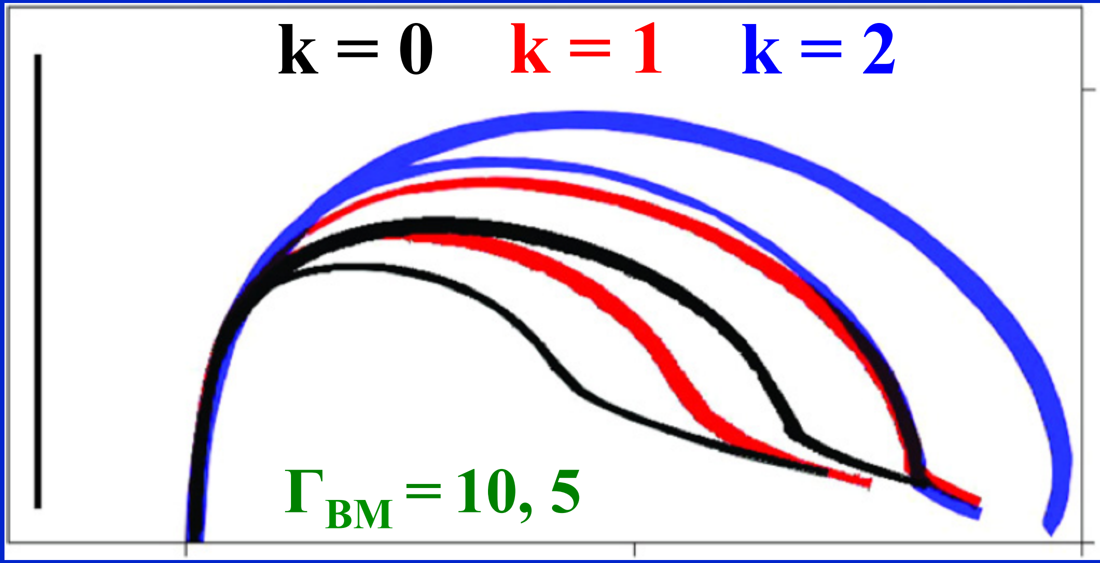
Logarithmic color map of ρ

$\theta_0 = 0.2$, $E_{iso} = 10^{53}$ erg, $n_{ext}(R_{jet}) \sim 1\ cm^{-3}$

Afterglow jet in stratified external media

(De Colle, Ramirez-Ruiz, JG & Lopez-Camara 2012)

- Previous simulations were all for $k = 0$ where $\rho_{ext} \propto R^{-k}$
- Larger (e.g. $k = 1, 2$) are motivated by the stellar wind of a massive star progenitor for long GRBs

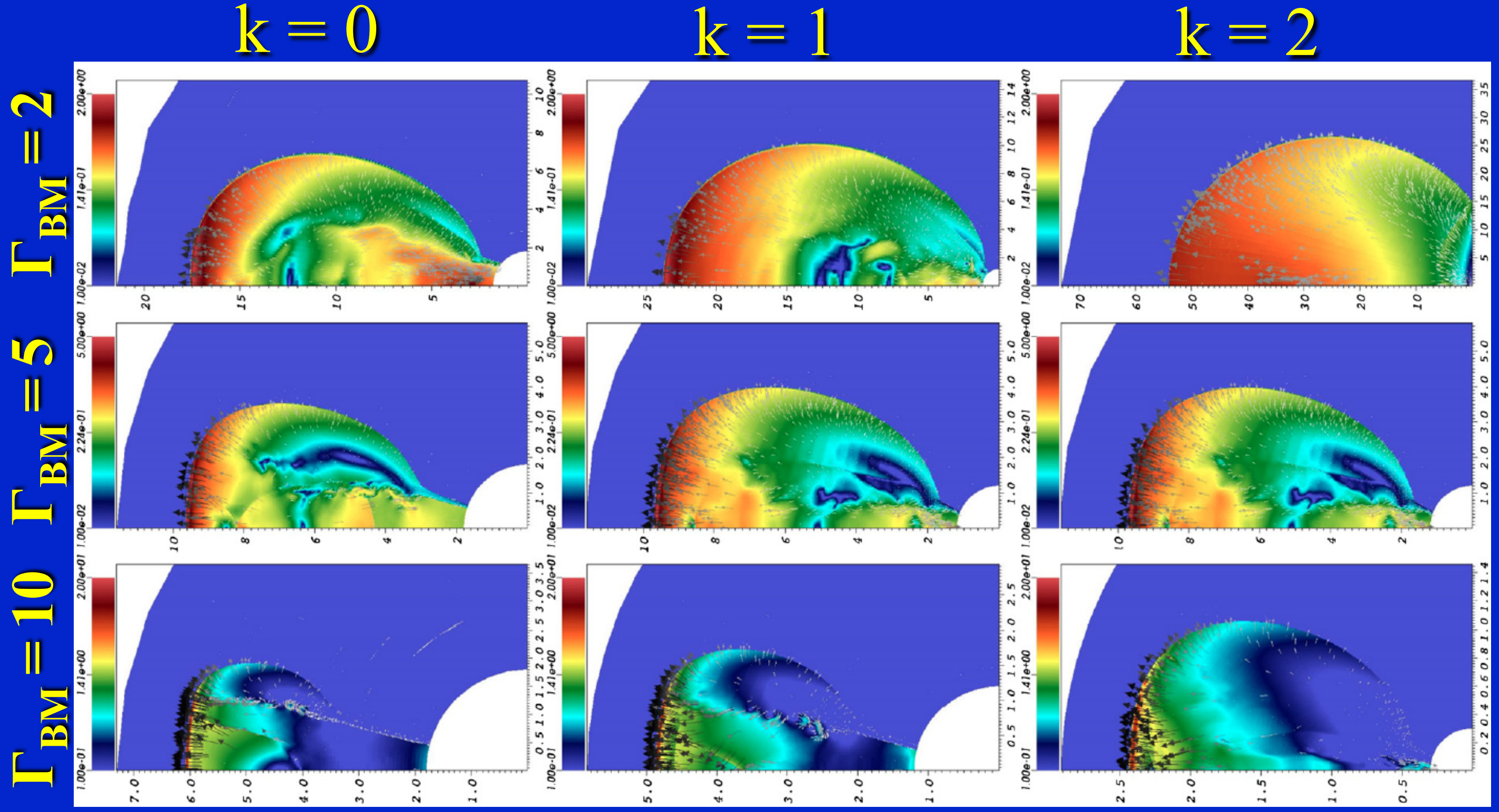


- At the same Lorentz factor larger k show larger sideways expansion since they sweep up mass and decelerate more slowly (e.g. $M \propto R^{3-k}$, $\Gamma \propto R^{(3-k)/2}$ in the spherical case) and spend more time at lower Γ (and β_θ decreases with Γ)

Afterglow jet in stratified external media

(De Colle, Ramirez-Ruiz, JG & Lopez-Camara 2012)

- The velocity just behind the shock is always normal to the shock front – radial near the head of the jet, while pointing sideways & non-relativistic at the sides of the jet

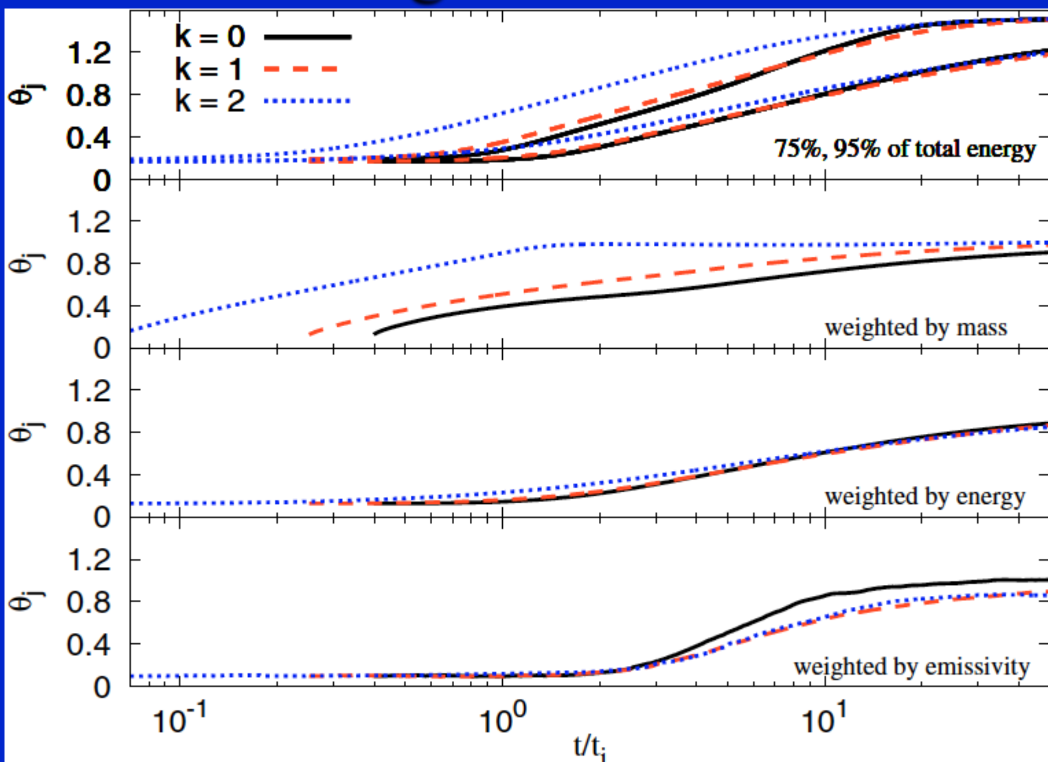


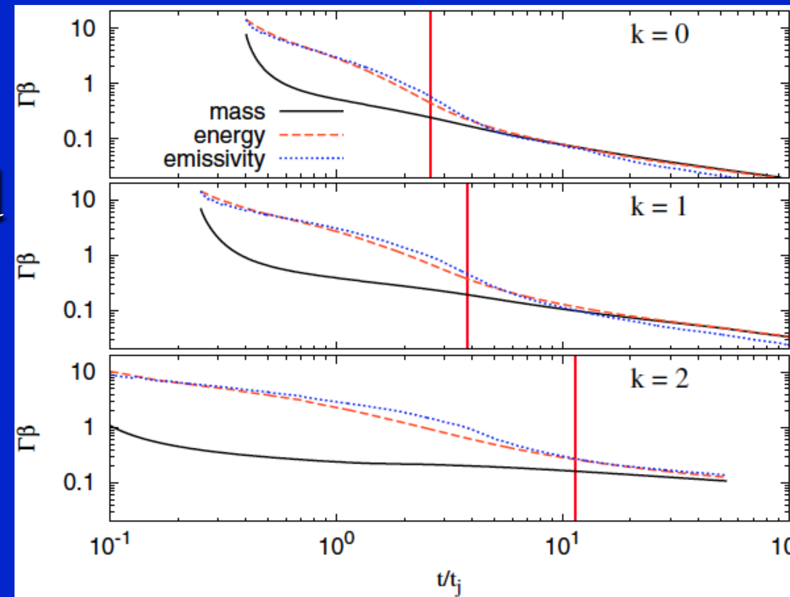
Velocity field (β) on top of logarithmic color map of ρ

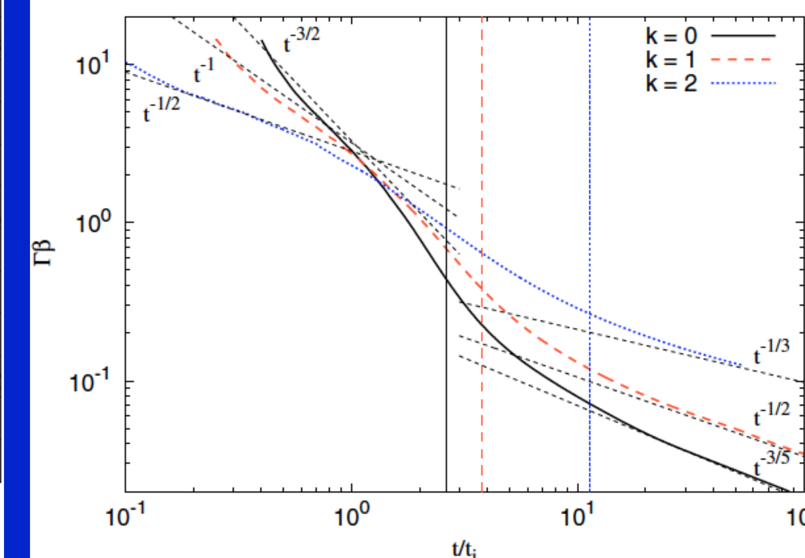
Afterglow jet in stratified external media

(De Colle, Ramirez-Ruiz, JG & Lopez-Camara 2012)

- Swept-up mass: a lot at the sides of the jet at large angles
- Energy, emissivity: near the head
- Spherical symmetry approached later for larger k



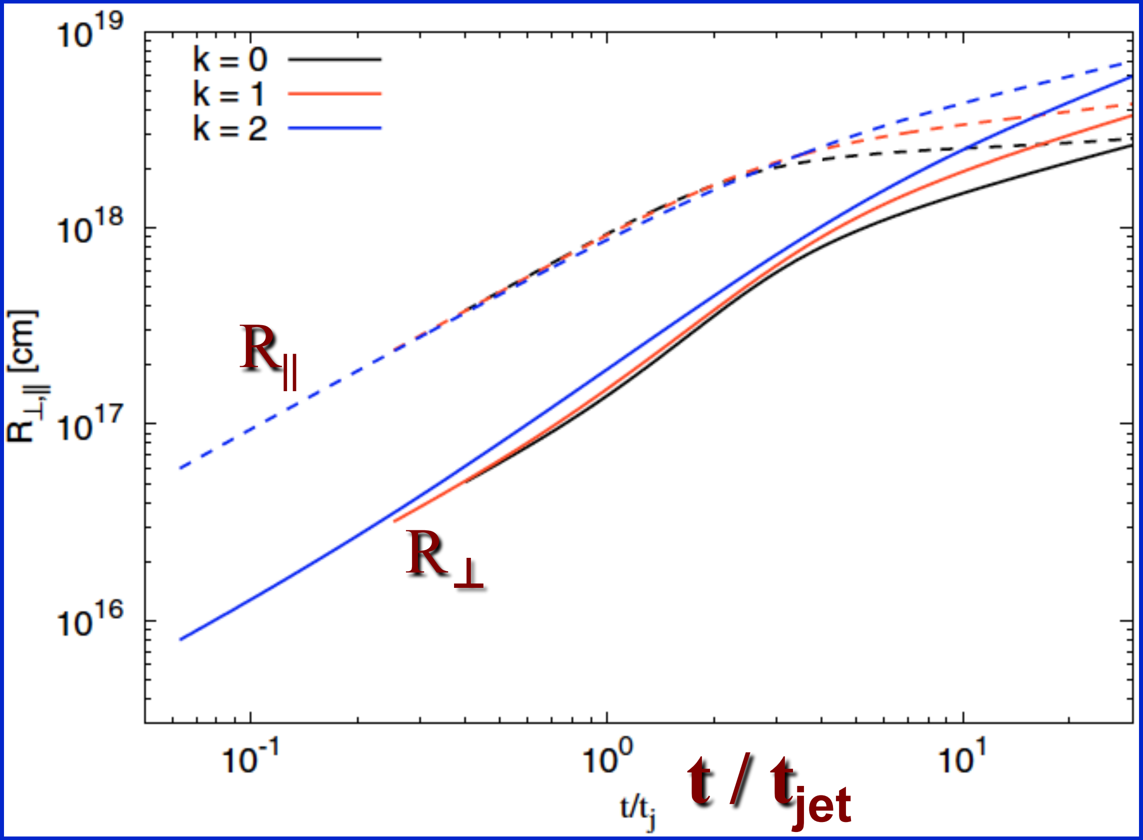




Afterglow jet in stratified external media

(De Colle, Ramirez-Ruiz, JG & Lopez-Camara 2012)

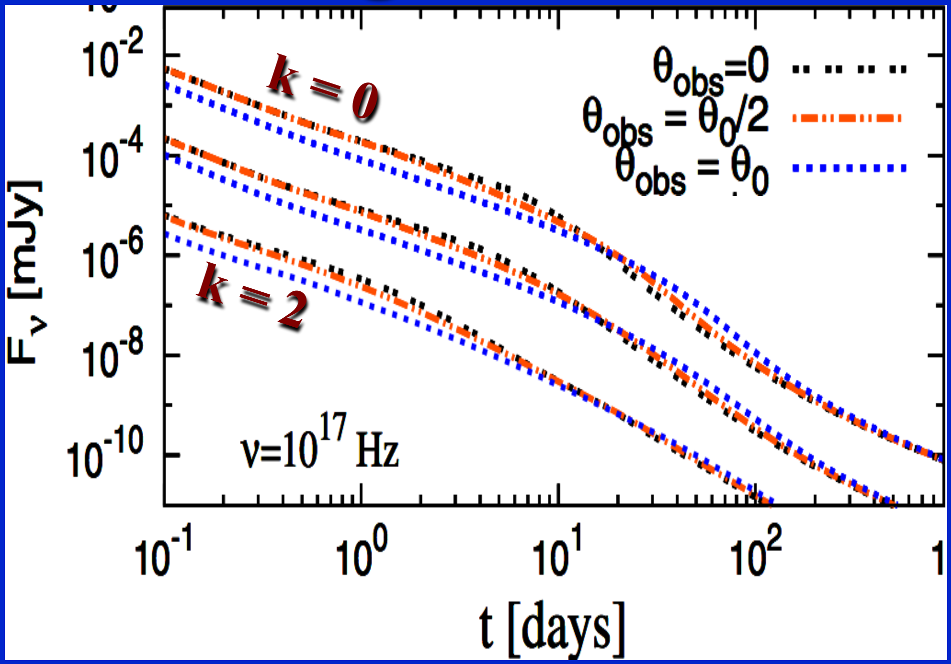
- For $k = 0$ the growth of $R_{||}$ is stalled at $t_{NR}(E_{iso})$ while $R_{\perp}$ continues to grow → helps approach spherical symmetry
- Less pronounced for larger k as the slower accumulation of mass enables $R_{||}$ to grow more → become spherical more slowly



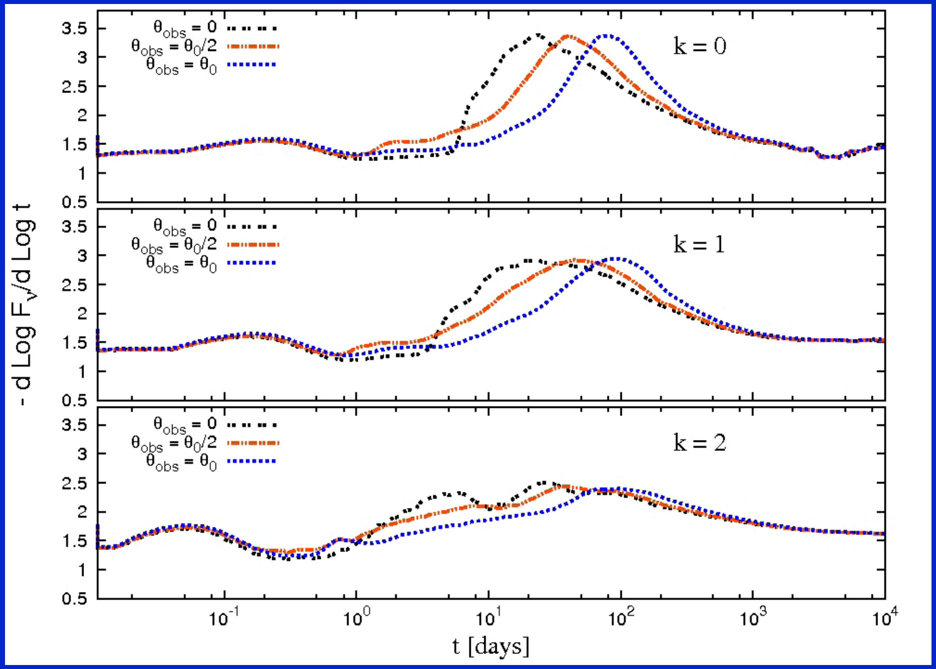
The shape of the jet break

- Jet break becomes smoother with increasing k (as expected analytically; Kumar & Panaitescu 2000 – KP00)
- However, the jet break is significantly sharper than found by KP00 ➔ better prospects for detection
- Varying $\theta_{obs} < \theta_0$ dominates over varying $k \lesssim 2$

Lightcurves



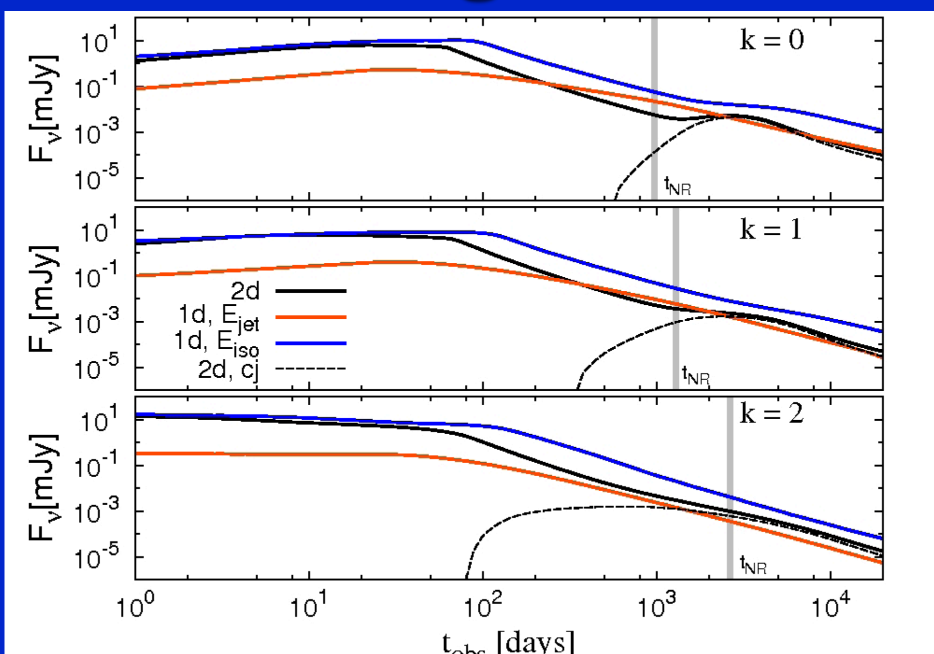
Temporal index



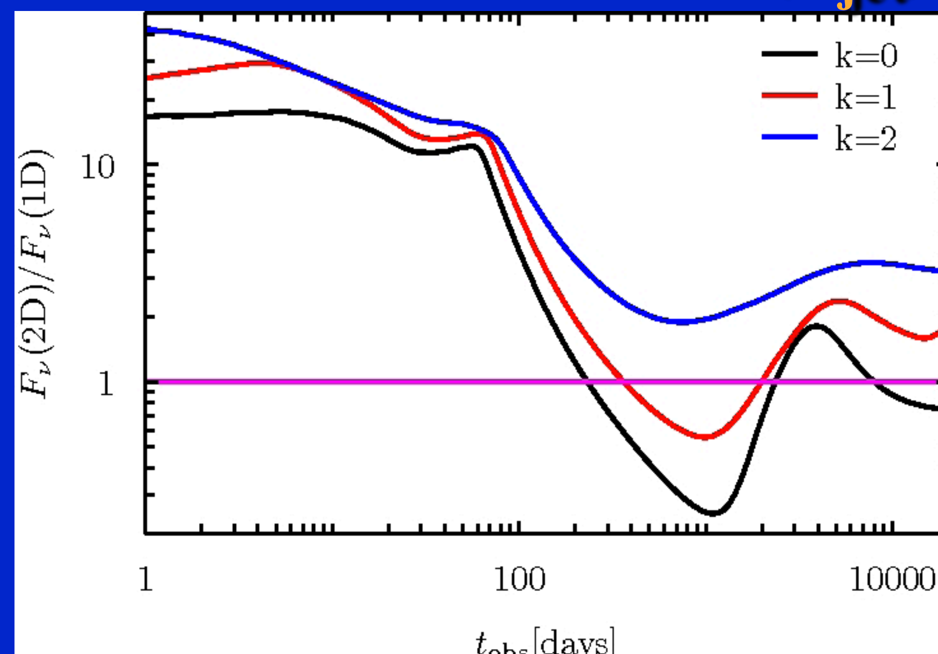
Late time Radio emission & Calorimetry

- The bump in the lightcurve from the counter jet is much less pronounced for larger k (as the counter jet decelerates & becomes visible more slowly) ➔ hard to detect
- The error in the estimated energy assuming a spherical flow depends on the observation time t_{obs} & on k

Radio Lightcurves



Flux Ratio: 2D/1D(E_{jet})



Conclusions:

- Jet lateral expansion: analytic models & simulations agree
  - For $\theta_0 \gtrsim 0.05$ the lateral expansion is quasi-logarithmic (~~exponential~~), due to small dynamic range $1/\theta_0 > \Gamma \gg 1$
  - For $\theta_0 \ll 0.05$ there is an exponential lateral expansion phase early on (but such narrow GRB jets appear rare
  - The jet first becomes sub-relativistic & only then slowly approaches spherical symmetry over a long time
- Jet in a stratified external medium: $\rho_{ext} \propto R^{-k}$ for $k = 0, 1, 2$
  - larger k jets sweep-up mass & slow down more slowly
    ➔ sideways expansion is faster at $t < t_j$ & slower at $t > t_j$
    ➔ become spherical slower; harder to see counter jet
  - Jet break is smoother for larger k but possibly detectable
  - Jet break sharpness affected more by $\theta_{obs} < \theta_0$ than $k \lesssim 2$
  - Radio calorimetry accuracy affected both by t_{obs} & k