Orphan afterglows of Gamma-Ray Bursts (GRBs)

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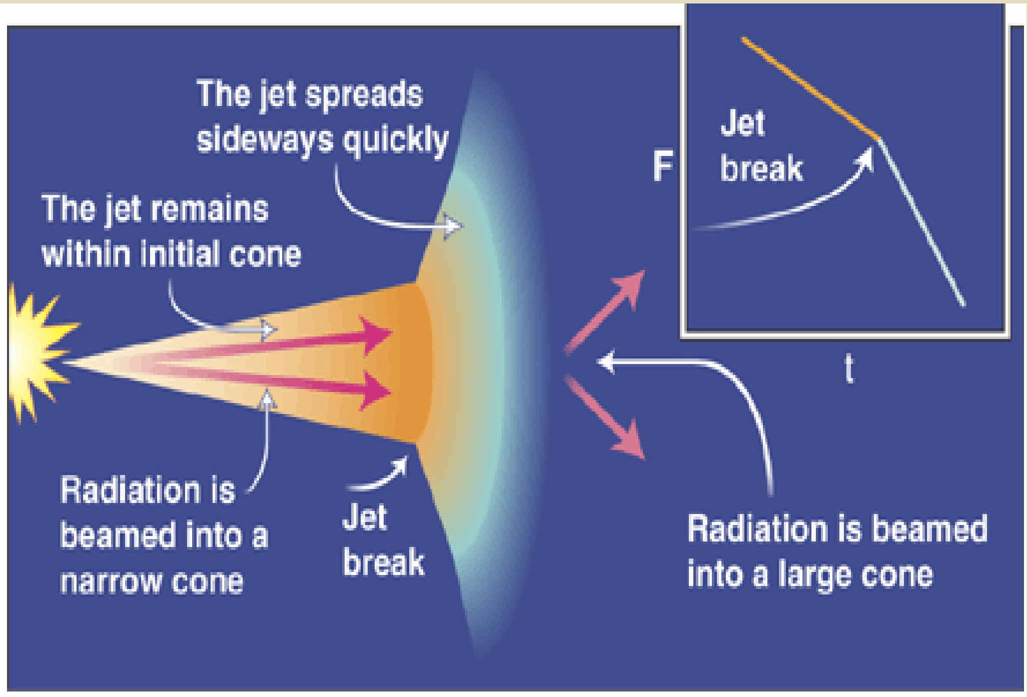


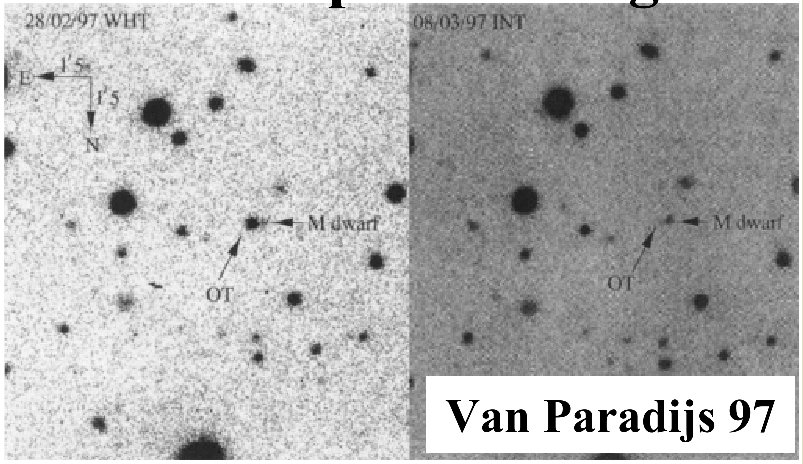
Transient Universe, March 13, 2006

GRBs Afterglow

❖GRBs: prompt flashes of soft γ-rays (seconds-minutes).

❖The afterglow - non-thermal counterpart:
- x-ray – hours-days
- optical – days-weeks
- radio – weeks-years

The first optical afterglow



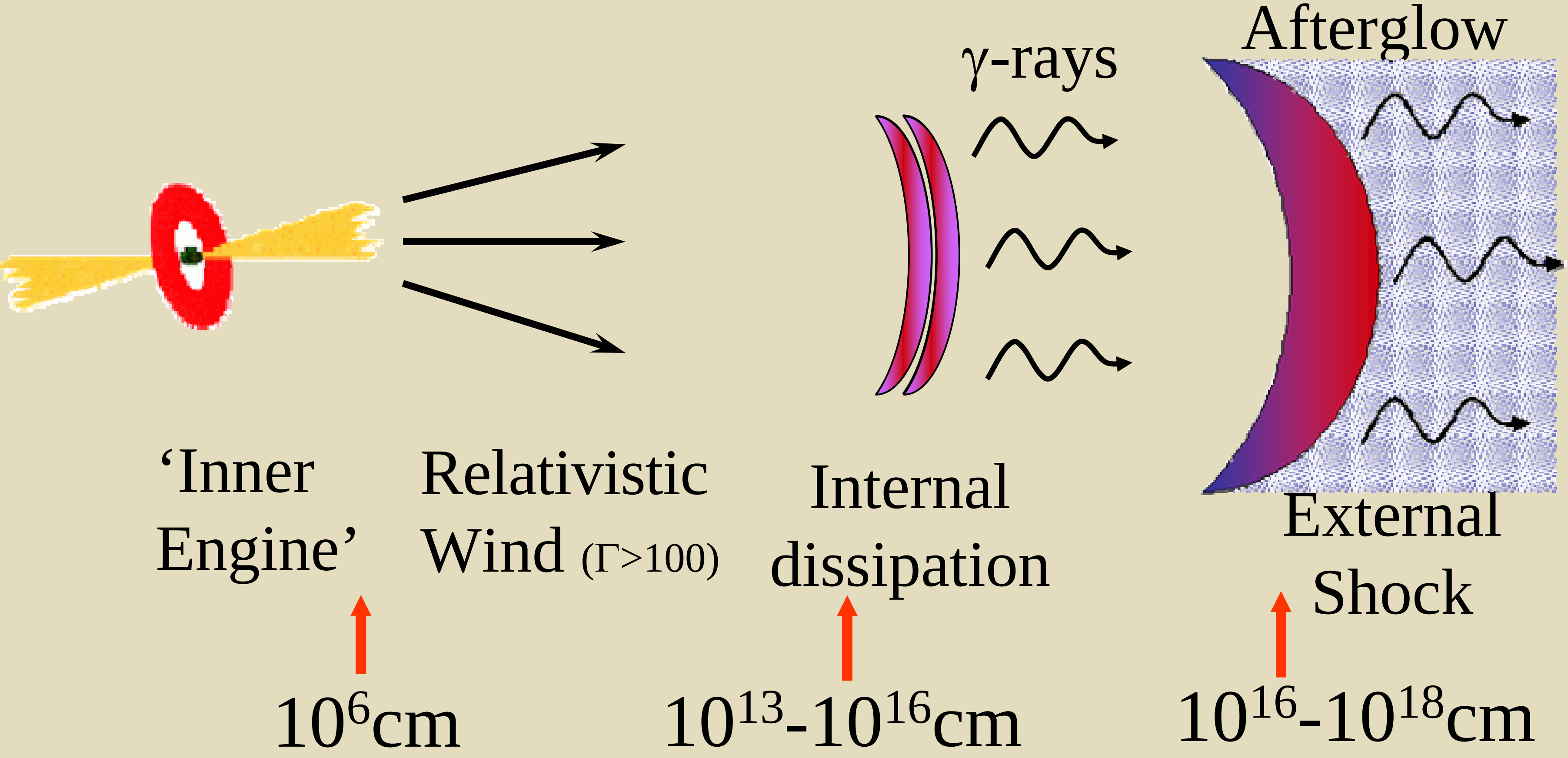
Van Paradijs 97

Orphan afterglow: an afterglow that was not preceded by prompt γ-rays

Outline

- The fireball model with a uniform (top-hat) jet structure
- Model predictions
  - Optical orphan afterglows
  - Radio orphan afterglows
- Radio search
- Summary

The Internal-External Fireball Model



‘Inner Engine’

Relativistic Wind (Γ>100)

Internal dissipation

γ-rays

Afterglow

External Shock

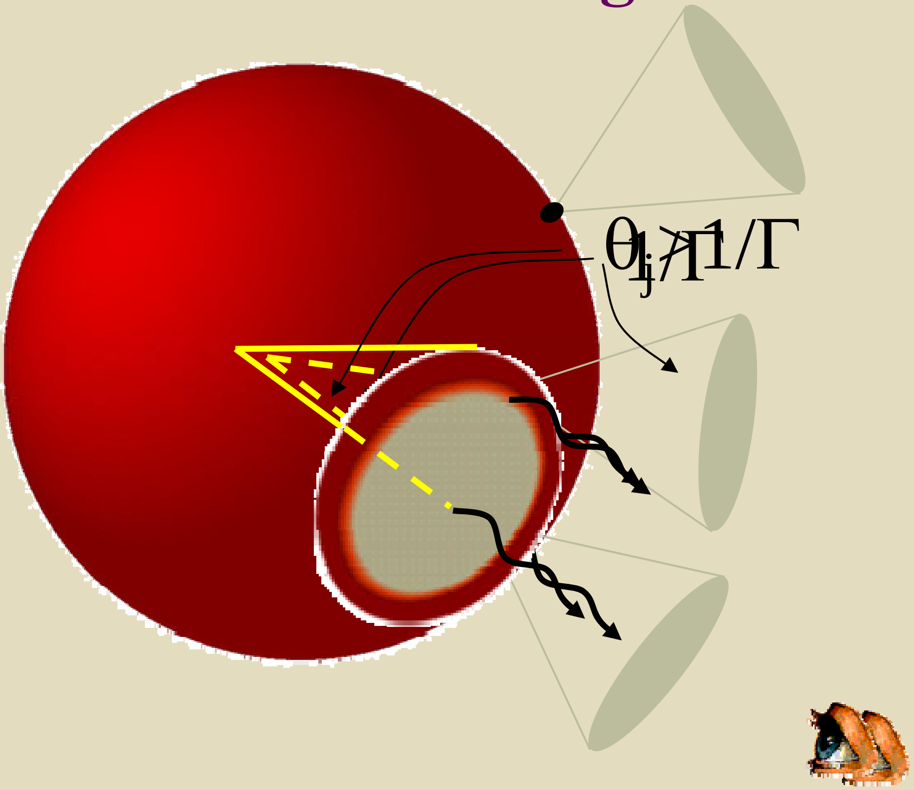
10^6cm

10^{13}-10^{16}cm

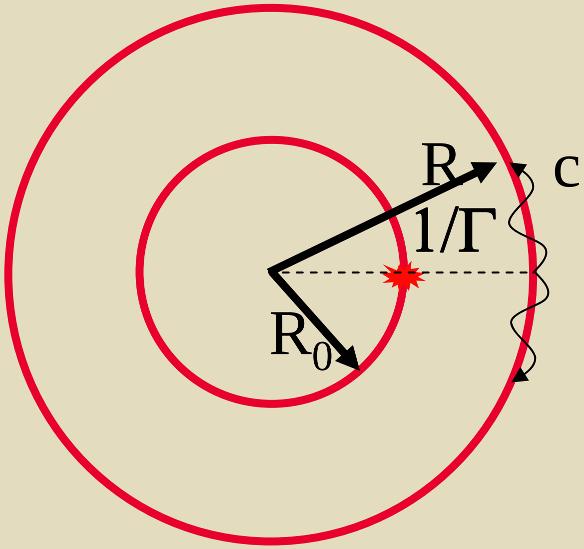
10^{16}-10^{18}cm

The afterglow is produced by the blast-wave that propagates into the circumburst medium, shovels increasing amounts of matter and decelerates in the process.

Relativistic beaming



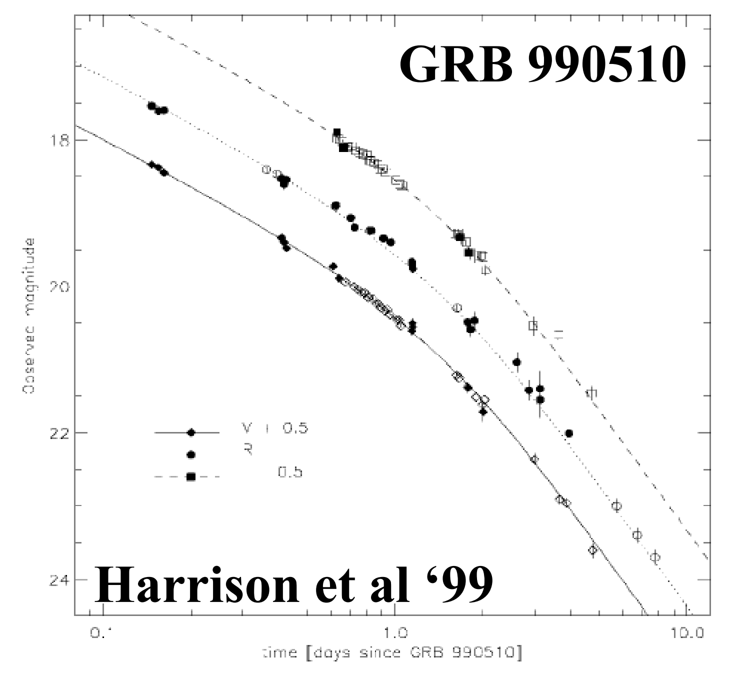
Causal connection



The observer cannot tell the difference between a jet with opening angle θ_j and a sphere as long as $\theta_j>1/\Gamma$

… But the blast-wave decelerates and if the relativistic wind is collimated (Rhoads 97, …) :

$\Gamma \sim 1/\theta_j \rightarrow$ achromatic light curve break



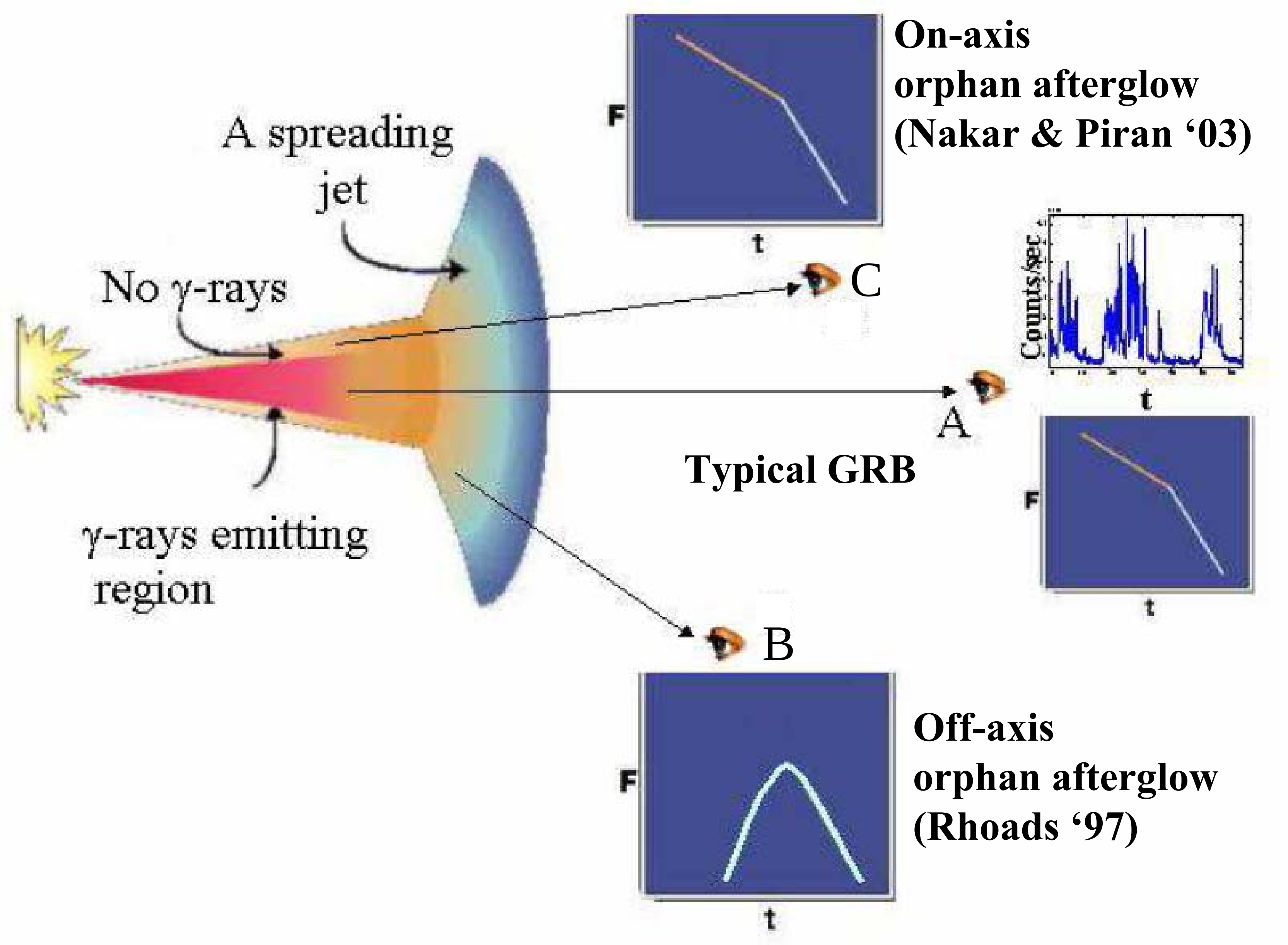
GRB 990510

Harrison et al ‘99

This break is observed in many bursts.

The typical opening angle is ~ 0.1 rad

A collimated relativistic jets predict:



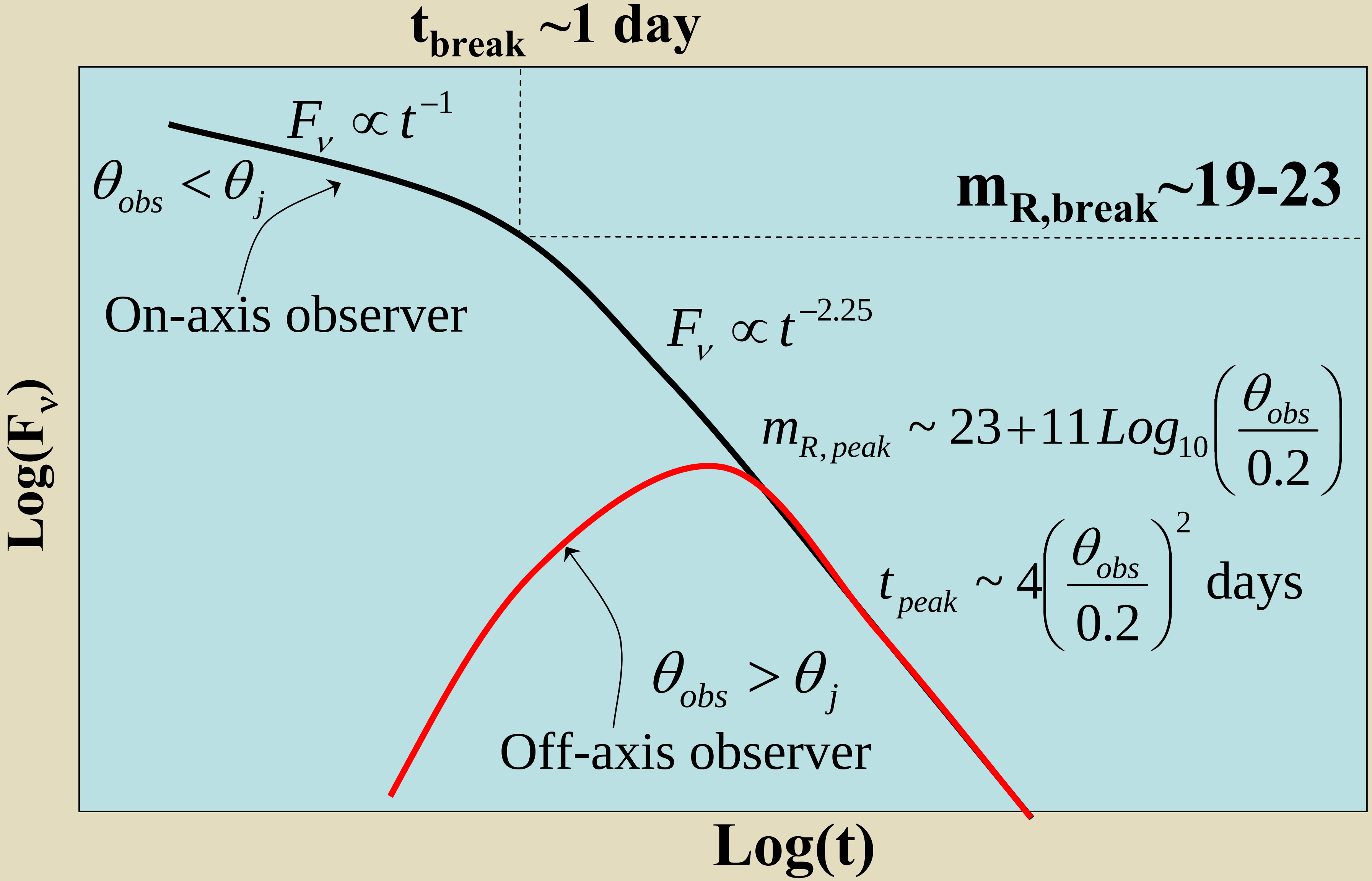
On-axis orphan afterglow (Nakar & Piran '03)

Typical GRB

Off-axis orphan afterglow (Rhoads '97)

Optical off-axis orphan afterglows

(Dalal et al ‘02; Granot et al ‘02; Nakar et al ‘02; Totani & Panaitescu ’02; Zou et al ’06)



$$m_{R,peak} \sim 23 + 11\,Log_{10}\left(\frac{\theta_{obs}}{0.2}\right)$$

$$t_{peak} \sim 4\left(\frac{\theta_{obs}}{0.2}\right)^2 \text{ days}$$

Rate and Properties

(Nakar et al ‘02)

- **$N_{\text{all sky}} \sim 3[100]$ @ $m_{R,\text{Lim}}=23[27]$ at a <u>single snapshot</u>** (Zou et al ‘06 obtained similar results based on updated data)
- **Uncertainty ~ an order of magnitude. Main sources:**
  - **Distribution of opening angles** (e.g., Guetta et al ‘05)
  - **Hydrodynamics when $\Gamma<1/\theta_j$** (e.g., Kumar & Granot ‘03)
  - **Properties of the on-axis afterglows**
- **Typical $\theta_{obs}\sim 0.15$-0.25 rad**
- **$N_{orph} \propto F_{lim}$ → A ground-based shallow and wide (but m_R >23mag) search is better than a deep and narrow search**

Radio off-axis orphan afterglows

(Perna & Loeb ‘98; Paczynski ‘01; Levinson et al ‘02)

Isotropic emission after ~0.5-1yr (Frail et al ‘00)

Detectable to ~200Mpc @ 5 mJy (Levinson et al ’02)**:**

$$N_{Radio} \sim 20 \underbrace{\left(\frac{\Re_{GRB,obs}}{0.5 Gpc^{-3} y^{-1}}\right)\left(\frac{\theta_j}{0.1}\right)^{-2}}_{\propto \Re_{GRB}} \left(\frac{E}{2\cdot 10^{51}\ \mathrm{erg}}\right)^{11/6} \left(\frac{f_{\nu,\lim}}{6\ \mathrm{mJy}}\right)^{-3/2}$$

$$E = E_{iso}\frac{\theta_j^2}{2} \longrightarrow \sim 20 \left(\frac{\tilde{\theta}_j}{0.1}\right)^{5/3} \left(\frac{E_{iso}}{5\cdot 10^{53}\ \mathrm{erg}}\right)^{11/6} \left(\frac{f_{\nu,\lim}}{6\ \mathrm{mJy}}\right)^{-3/2}$$

Assuming typical parameters (e.g., Panaitescu & Kumar 2002; Yost et al. 2003)

The rate is dominated by events with large θ_{obs}

↓

N_{radio} counts all explosions with $\Gamma>2$

$$N_{Radio} \sim 0.01\mathfrak{R}_{\Gamma>2}\left(\frac{E}{10^{51}\ \mathrm{erg}}\right)^{11/6}\left(\frac{f_{\nu,\mathrm{lim}}}{6\ \mathrm{mJy}}\right)^{-3/2}$$

The real trick is to identify a transient as an orphan afterglow:

- Smooth power law spectrum $F_\nu \propto \nu^{-0.6}$-$\nu^{-1.1}$
- Temporal decay $F_{\nu,rad} \propto t^{-1.2}$; $F_{\nu,otp} \propto t^{-2}$ (t_0 is unknown!)
- Archival search + continuous monitoring (e.g., excluding AGN; Gal-yam et al ‘02)
- Detection of a host galaxy + properties + offset
- Luminosity
- Optical - Detection of radio afterglow
- Radio - Consistent remnant size (i.e., VLBI)

The main polluting sources are AGNs and radio SNe remnant.

Radio search

(see abstract by E. Ofek)

A comparison of the FIRST and the NVSS (1.4 Ghz) surveys (Levinson et al '02; Gal-yam et al '06) **:**

- **A one snapshot variability survey**
- **f_{lim}=6 mJy**
- **1/17 of the sky**
- **4 transients are found:**
    - **1 PSR (variable source)**
    - **1 low-z AGN (variable source)**
    - **1 radio SN (identified by light curve and size)**
    - **1 high-z transient (not orphan; AGN? Galactic?)**
- **No radio orphan → $N_{radio} < 62$ @ 95% C.L.**

Implications

- $N \sim 20\left(\frac{\tilde{\theta}_j}{0.1}\right)^{5/3} < 62$ ➔ $\tilde{\theta}_j \leq 0.2\ \mathrm{rad}$

- $\Re_{\Gamma\geq 2} < 1000\ \mathrm{Gpc^{-3}\ yr^{-1}} \quad (\sim 0.01\Re_{\mathrm{SNe}})$

Consistent with limits on SNe-GRBs (Berger et al ’03; Soderberg et al ‘06)

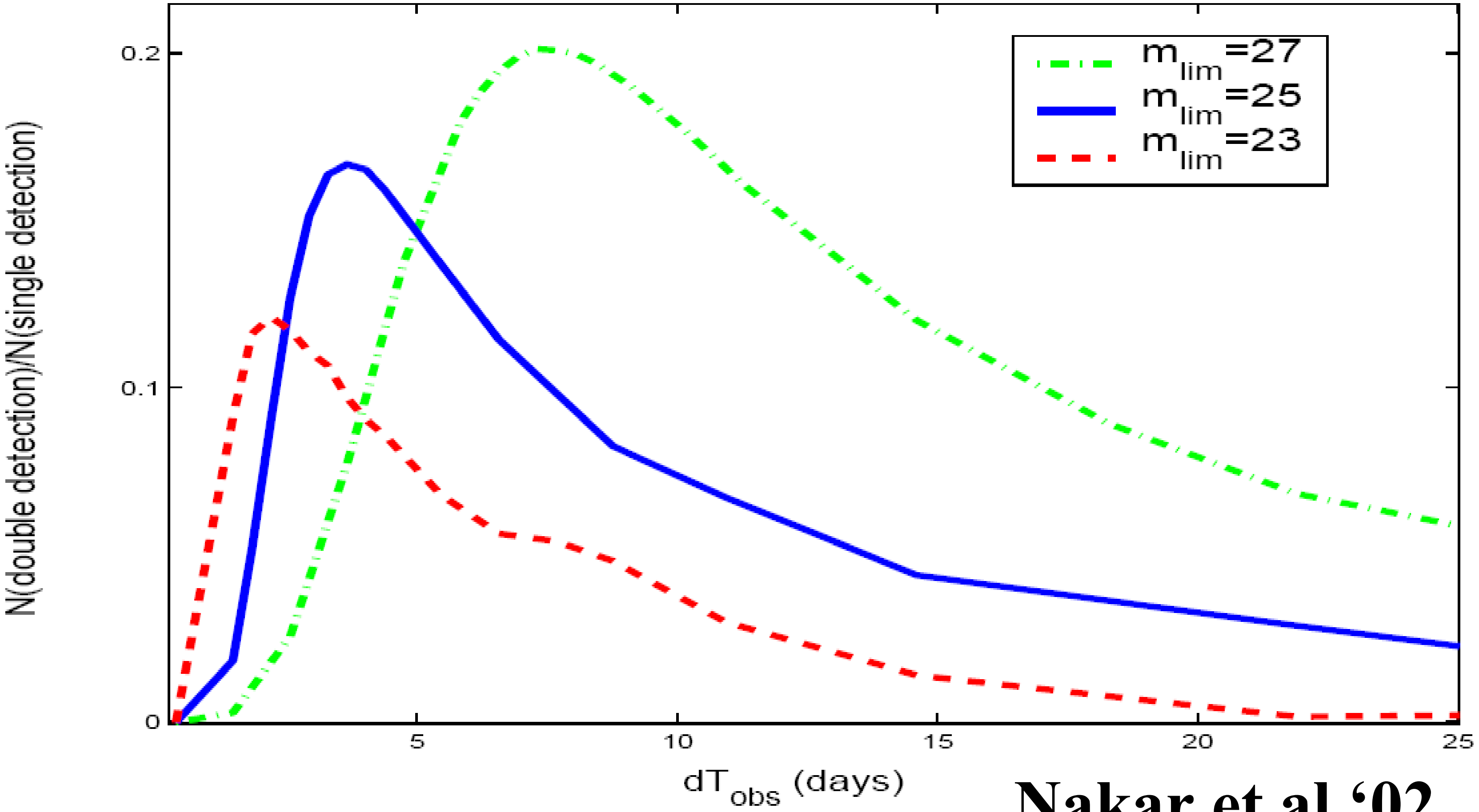
- >1000 sources in an all-sky 1mJy (e.g, ATA) snapshot

Summary

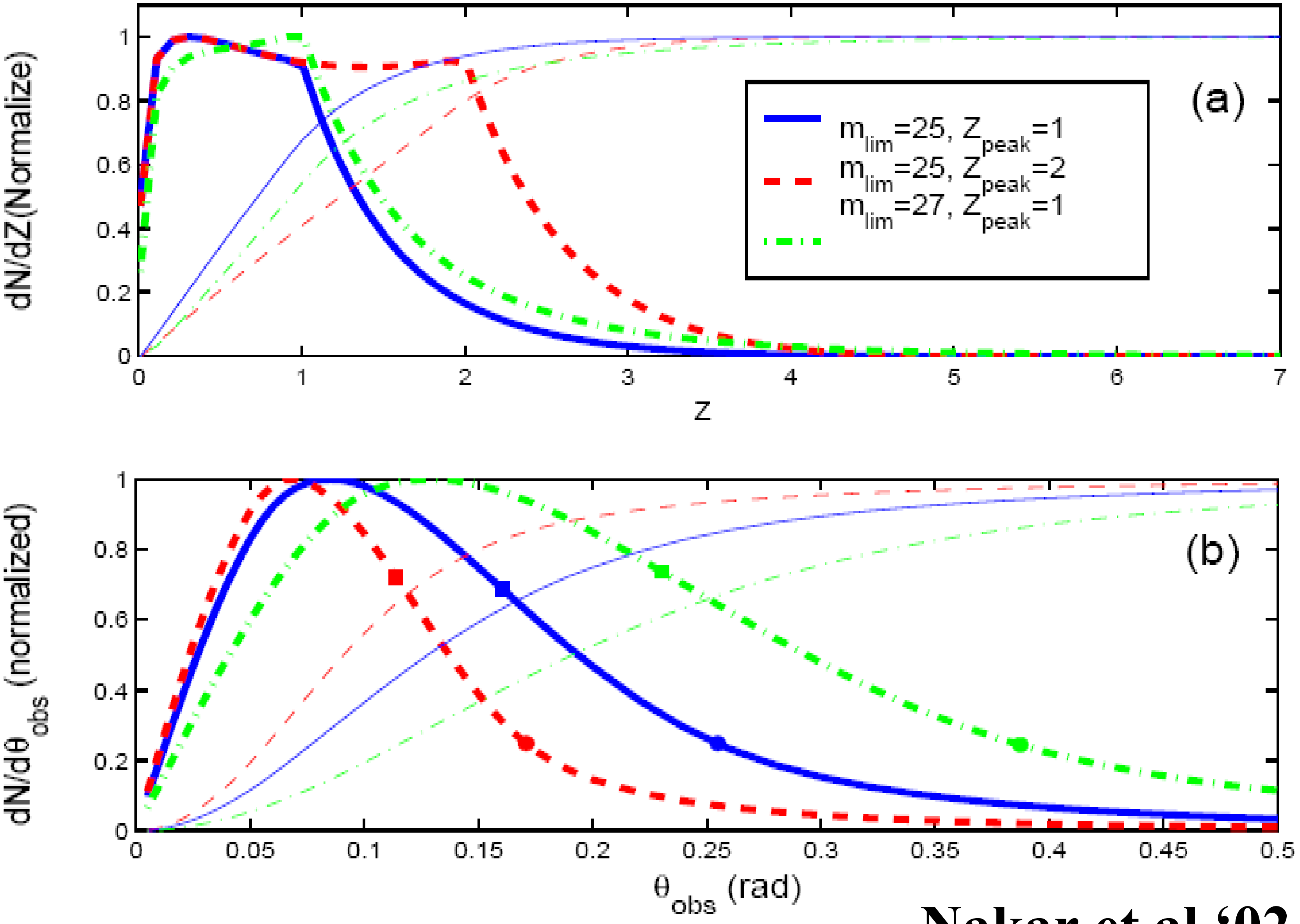
- Optical and radio orphan afterglows are predicted by GRB models and are a result of the relativistic wind and its geometry.
- $N_{opt} \sim 3[100]$ @ $R_{Lim}=23[27]$ in a single all-sky snapshot.
- $N_{radio} \sim 20$ @ $f_{\nu,lim}=6$ mJy in a single all-sky snapshot.
- One of the main challenges is identifying a transient as an orphan afterglow.
- An alternative viable jet model ($E \propto \theta^{-2}$) predicts less off-axis orphan afterglows

Thank you

The ratio of double detections (in which the afterglow faded by more than 1mag but is still detectable) to single detections as function of the time delay between the two observations



Nakar et al ‘02



Nakar et al '02

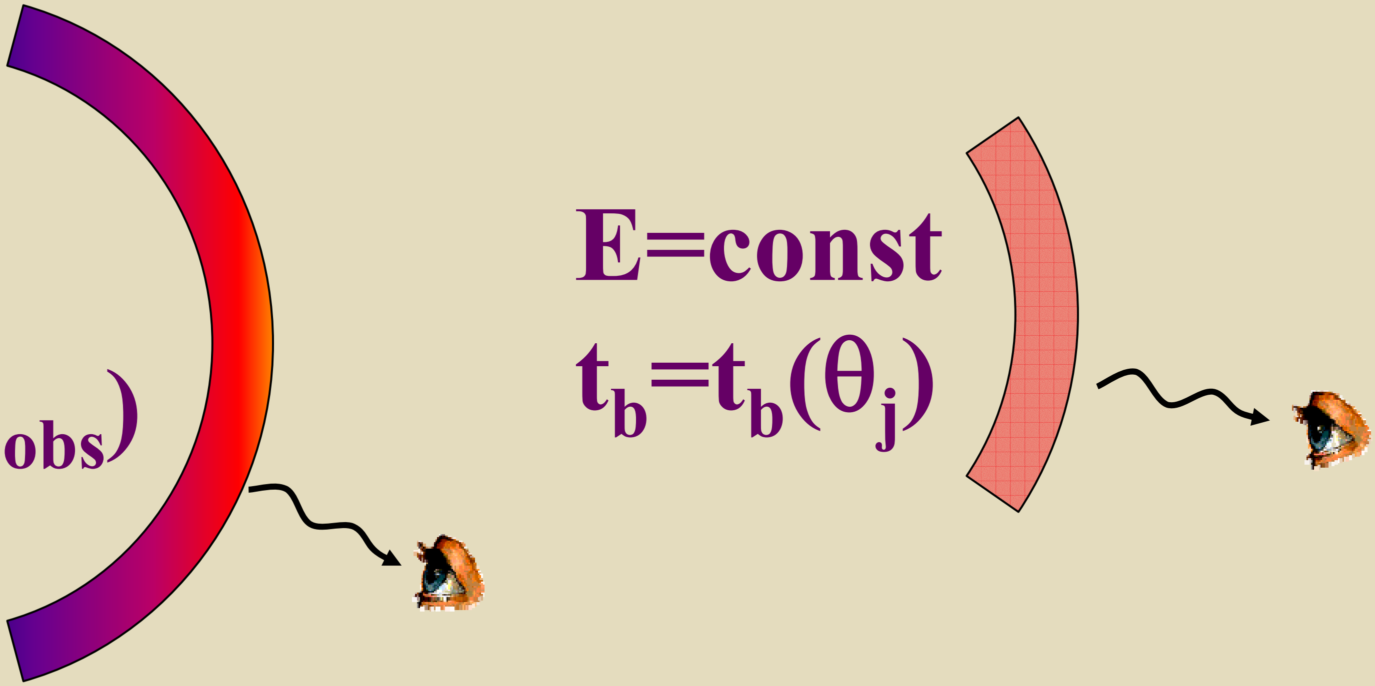
A single one-band snapshot is not enough

An identification requires:

- **Smooth power law spectrum $F_\nu \propto \nu^{-1}$**
- **Fast decay: $F_\nu \propto t^{-2}$ (t_0 is unknown!)**
- **Archival search + continuous multi-wavelength monitoring (e.g., excluding AGN;** Gal-yam et al '02**)**
- **Detection of radio afterglow**
- **Detection of host galaxy + properties + offset**

An alternative model – The structured jet

(Postnov et al '01; Rossi et al '02; Zhang & Meszaros '02)



$E \propto \theta^{-2}$

$t_b = t_b(\theta_{obs})$

$E = const$

$t_b = t_b(\theta_j)$

Structured jet

Uniform jet

A structured jet model predicts less off-axis orphan afterglows

X-rays:

Only on-axis afterglows

Rate in a single snapshot: ~1 @ $5 \cdot 10^{-13}$ erg/s/cm^2 (non-orphan)

Optical:

- On-axis (non-orphan) afterglows will be significant fraction of the afterglows at R<21mag.
- single snapshot all-sky rate of on-axis (non-orphan) afterglows ~0.25 @ R=19mag and ~1 @ R=21mag
- A significant access will be due to on-axis orphan afterglow

Radio:

Afterglow rate dominated by off-axis orphans (the radio is typically still rising at the time of the jet-brake).

Searches for orphan afterglows
X-rays

- **Rosat All Sky Survay (RASS)** [Greiner '99]:

$F_{x,lim}=10^{-12}$ erg/s/cm^2

- Coverage: 76435 deg^2×days
- Results: 23 afterglows candidates, 6 randomly chosen are turned out to be flaring stars.

Conclusions [Nakar & Piran '02]:

- Expected on-axis non-orphan transients: 3

The beaming of wind with $\Gamma \approx 20$ is at most comparable to the beaming of high Lorentz factor wind.