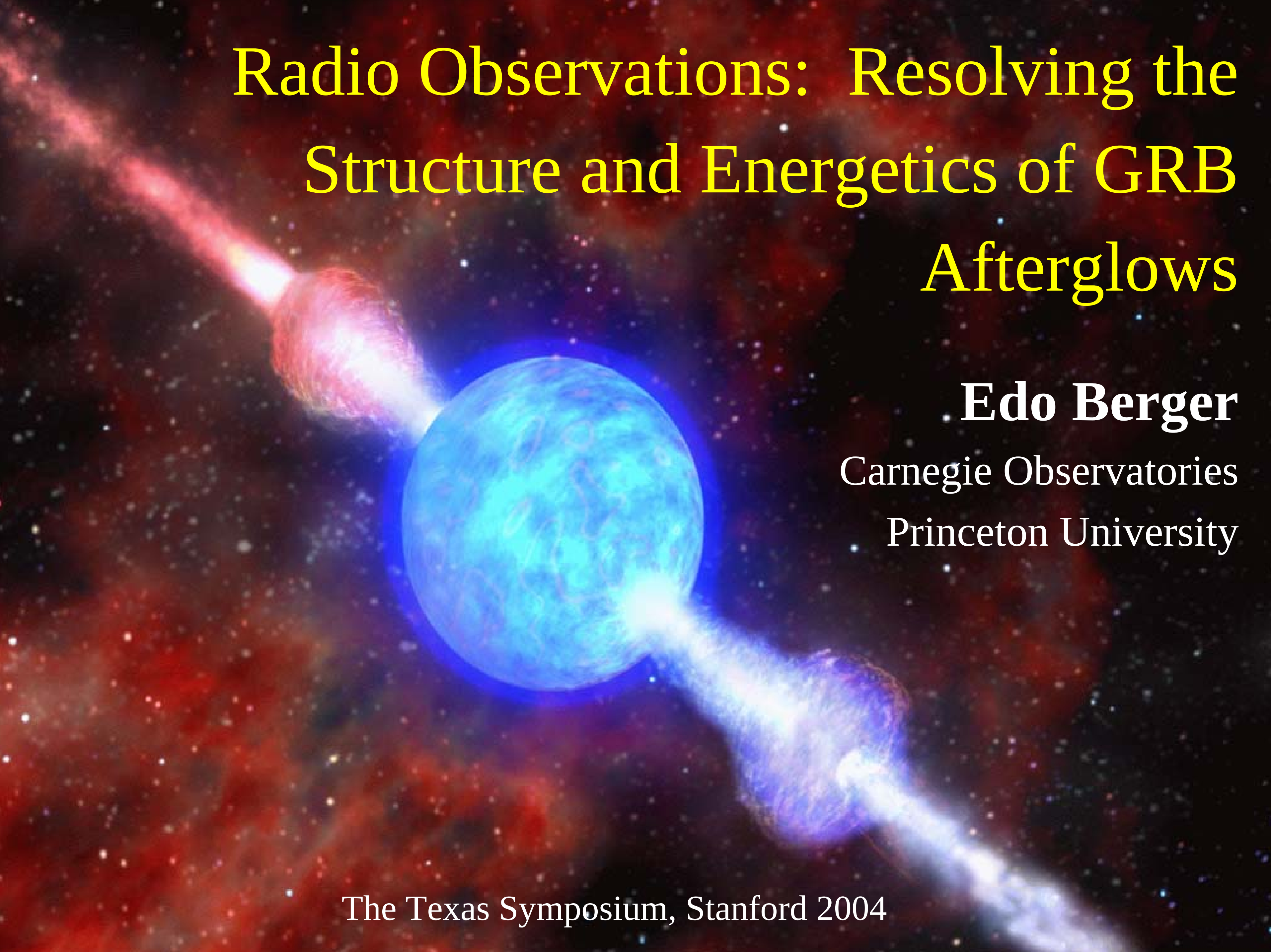

Radio Observations: Resolving the Structure and Energetics of GRB Afterglows

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The Texas Symposium, Stanford 2004

Outline

Radio Observations Primer:

Unique Information (size, energetics)

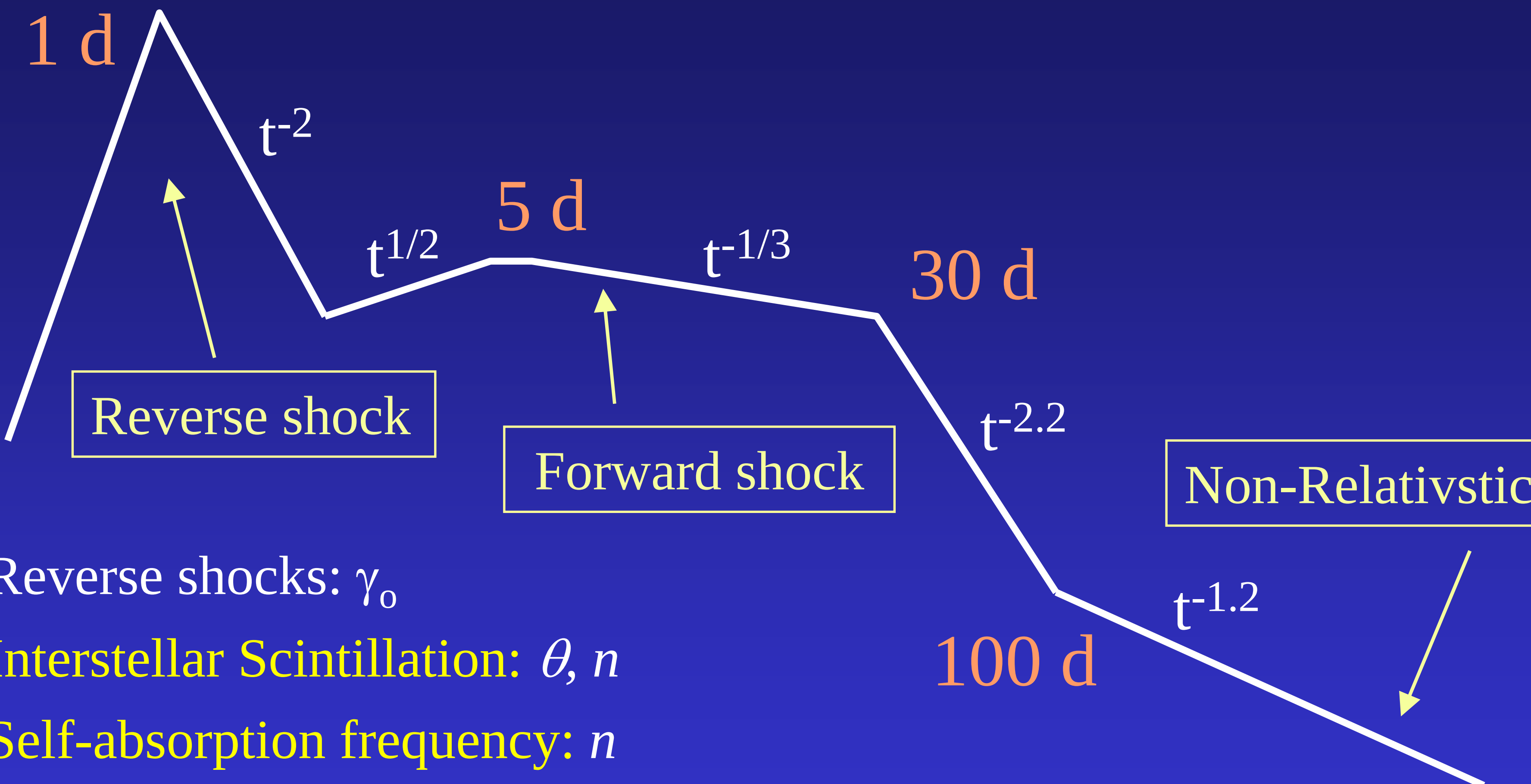
Calorimetry of the Explosion:

Tracing the total relativistic output of the engine

Resolving the Afterglow with ISS & VLBI:

A direct measurement of relativistic expansion

Unique & Complementary Diagnostics



Reverse shocks: γ_o

Interstellar Scintillation: θ, n

Self-absorption frequency: n

Wide-angle jets: $\theta_{jet} > 0.2$

Local environment: *ISM vs. Wind*, n

Non-Relativistic Evolution: E, n, B, θ

The Compactness Problems / Jets

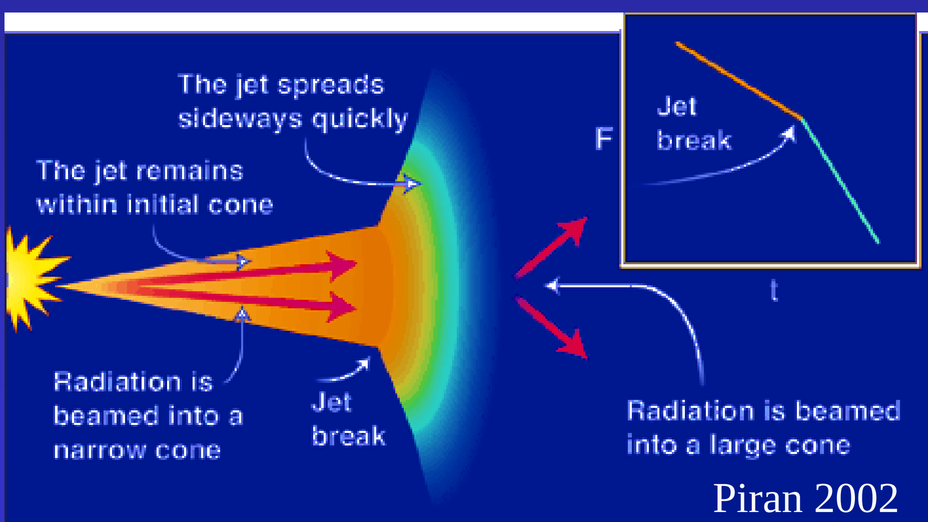
Large energy release, γ–ray emission, short duration ➔ "fireball"
(Cavallo & Rees 1978; Goodman, Pazynski 1986)

Pair opacity ➔ thermal GRB

$$\frac{f_{pp}\ \ {}_{T} F d^2}{m_e c^2 R^2} \sim 10^{13}$$

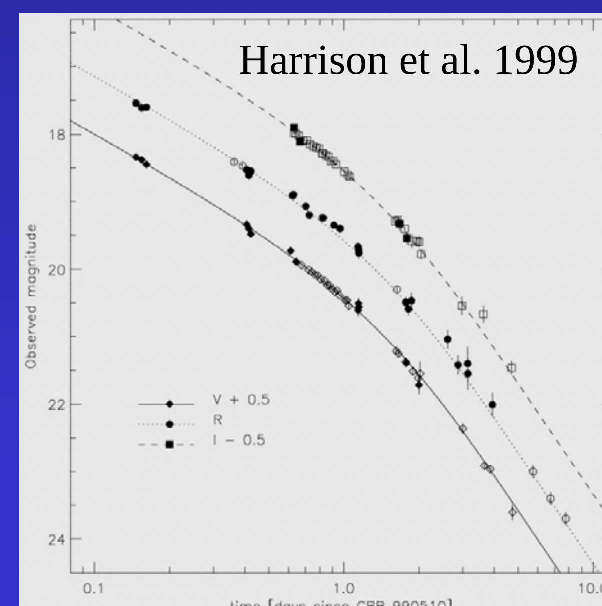
Relativistic motion

$$\sim 10^{13} \frac{\ ^2\ ^2}{\ ^4} \qquad 100$$



Piran 2002

$$E \quad E_{iso}[1 \quad \cos(\ _j)]$$



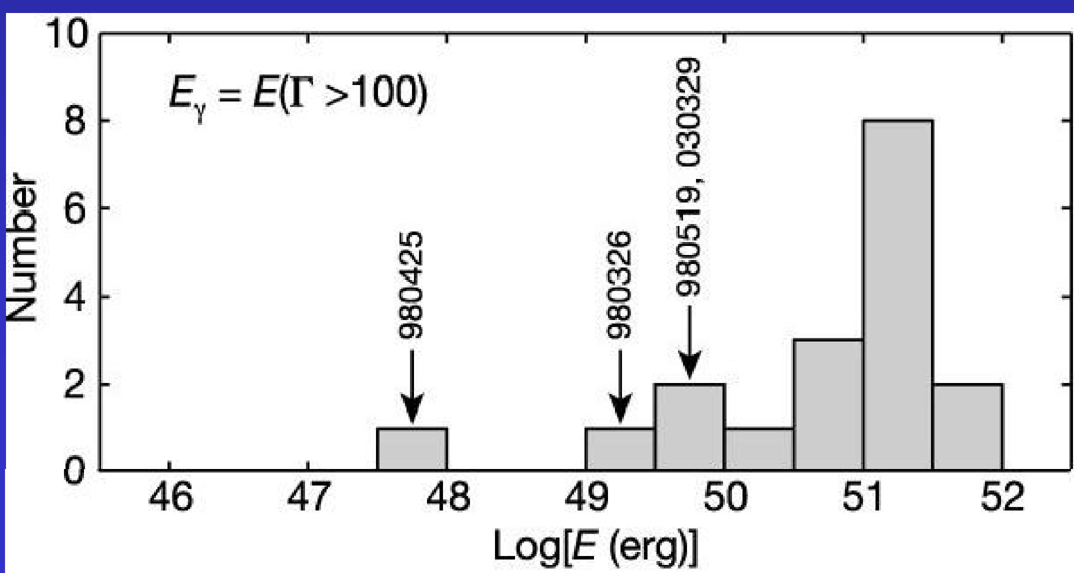
Harrison et al. 1999

The Energetics of Gamma-Ray Bursts

$$E_{rel} \quad E \quad E_{K,ad} \quad E_{rad}$$

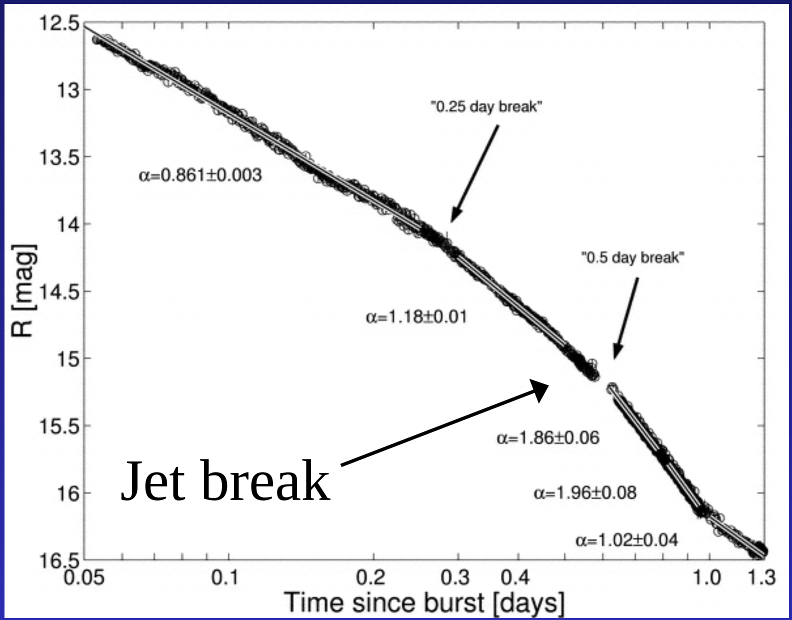
E_{rel}	energy in the relativistic ejecta (2)
E	energy emitted in the GRB phase $\boxed{(\quad 100)}$
E_{rad}	energy radiated away in the early afterglow
$E_{K,ad}$	kinetic energy in the afterglow phase $\boxed{(\quad \sim \; few)}$

Frail et al. 2001; Berger et al. 2003; Bloom et al. 2003



- Standard γ–ray energy reservoir for most GRBs
- GRB rate $\langle f_b^{-1} \rangle \sim 100$ times the observed rate
- Sub-energetic tail

GRB 030329 and "Sub-energetic" bursts



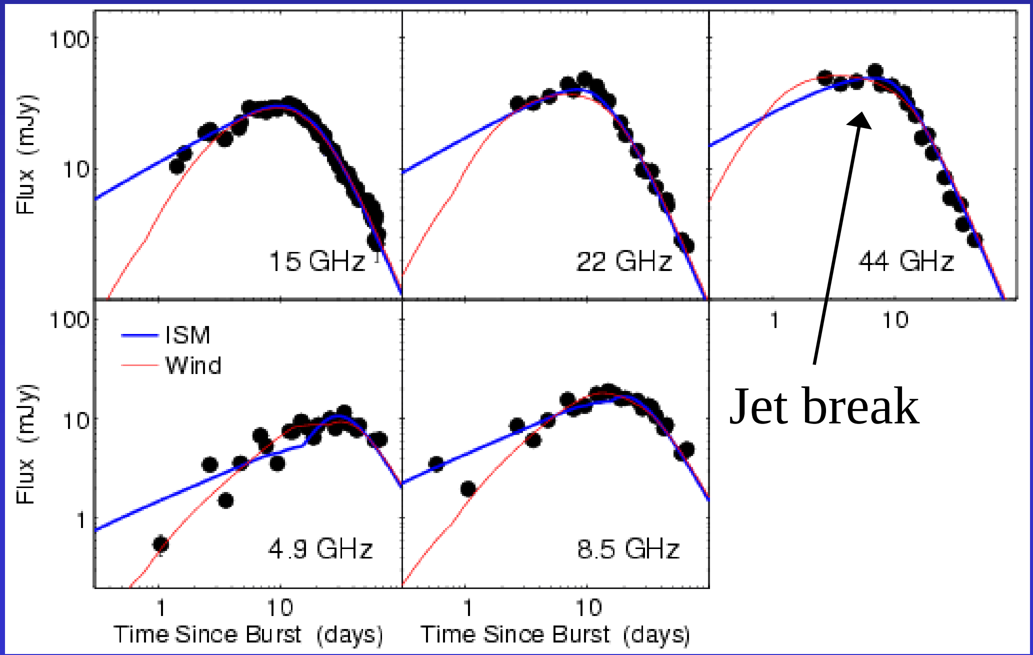
Lipkin et al. 2004

The optical afterglow indicates a jet break at 0.5 d

$\Rightarrow \theta_j = 5^{\mathrm{o}}$

$E_\gamma \sim 5\times10^{49}$ erg

Berger et al. 2003

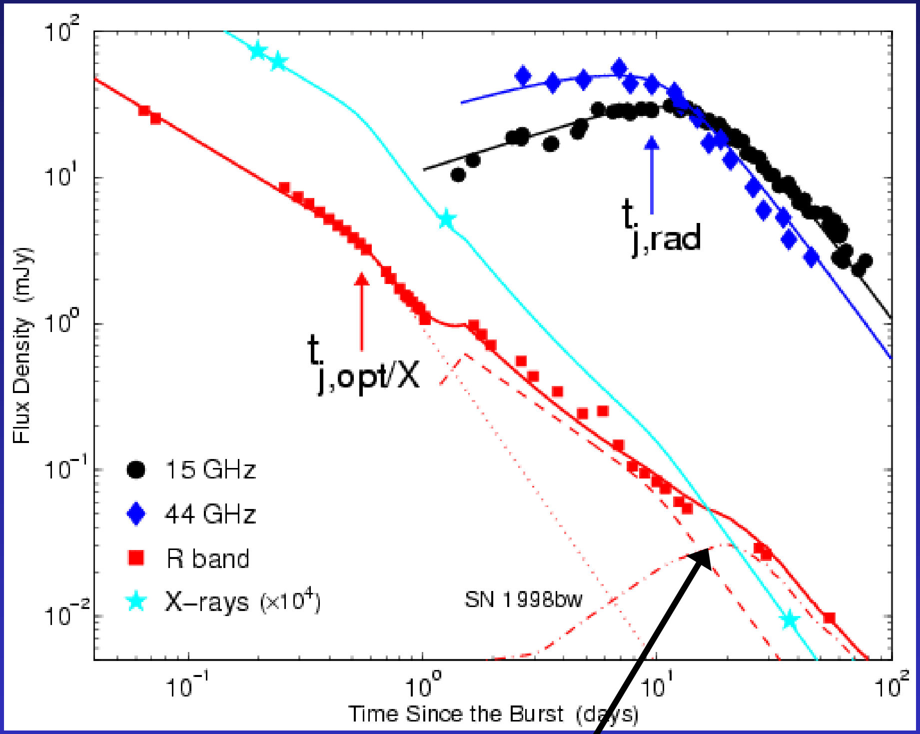


The radio afterglow requires a jet break at 10 days $\Rightarrow$

$\theta_j = 17^{\mathrm{o}}$

$E_K \approx 8\times10^{50}$ erg

GRB 030329: A Two-Component Jet



Berger et al. 2003

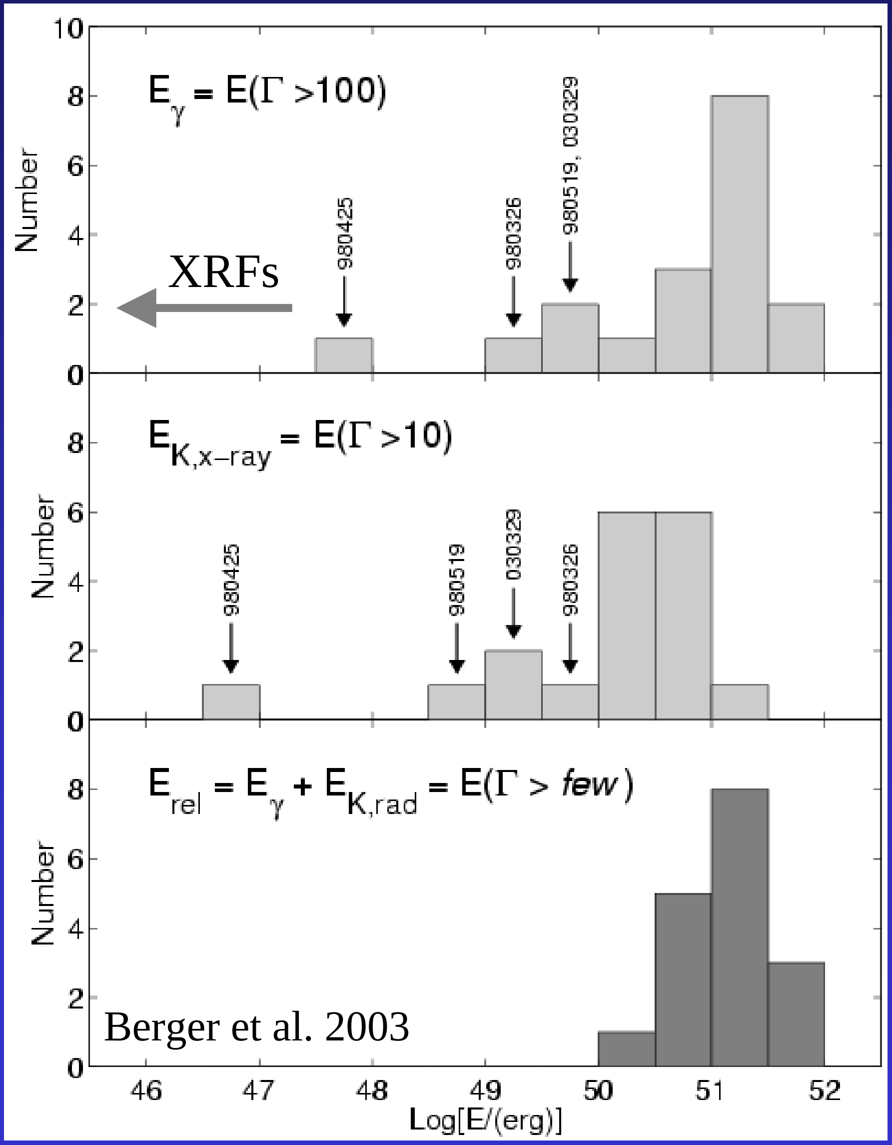
The expected second jet break in the optical is observed (Matheson et al. 2003)

Energy injection: factor of 10 increase between 0.5 to 10 days (Granot et al. 2003)

Two-component jet: (Berger et al. 2003)

- A narrow, ultra-rel. jet w/ low energy (optical/X-ray)
- A wide, mildly-rel. jet carrying the bulk of the energy (>90%)

A Common Total Energy Scale

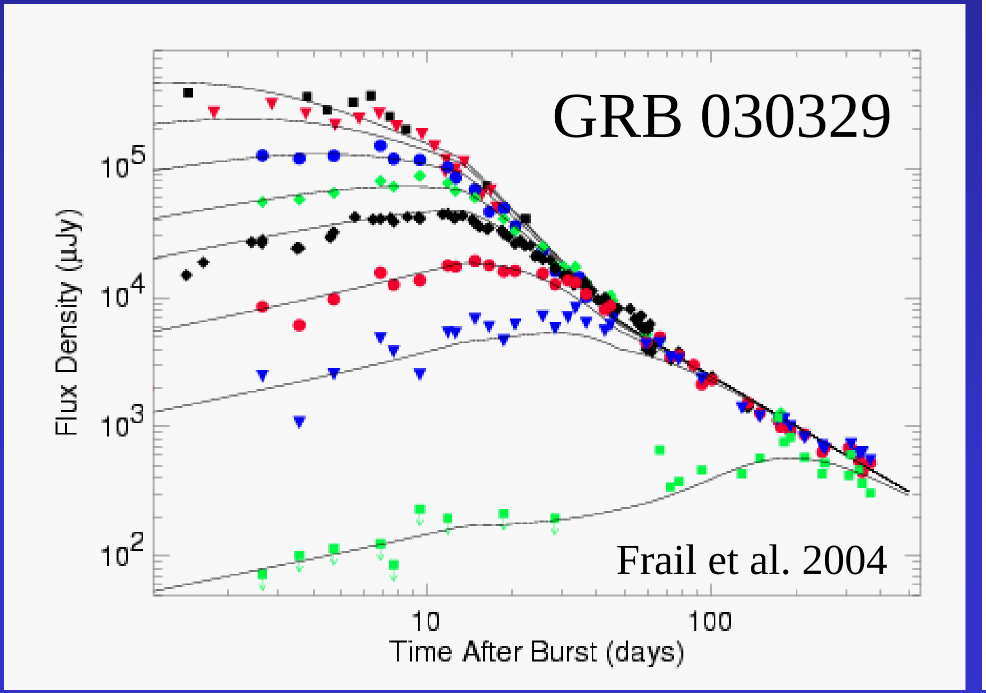


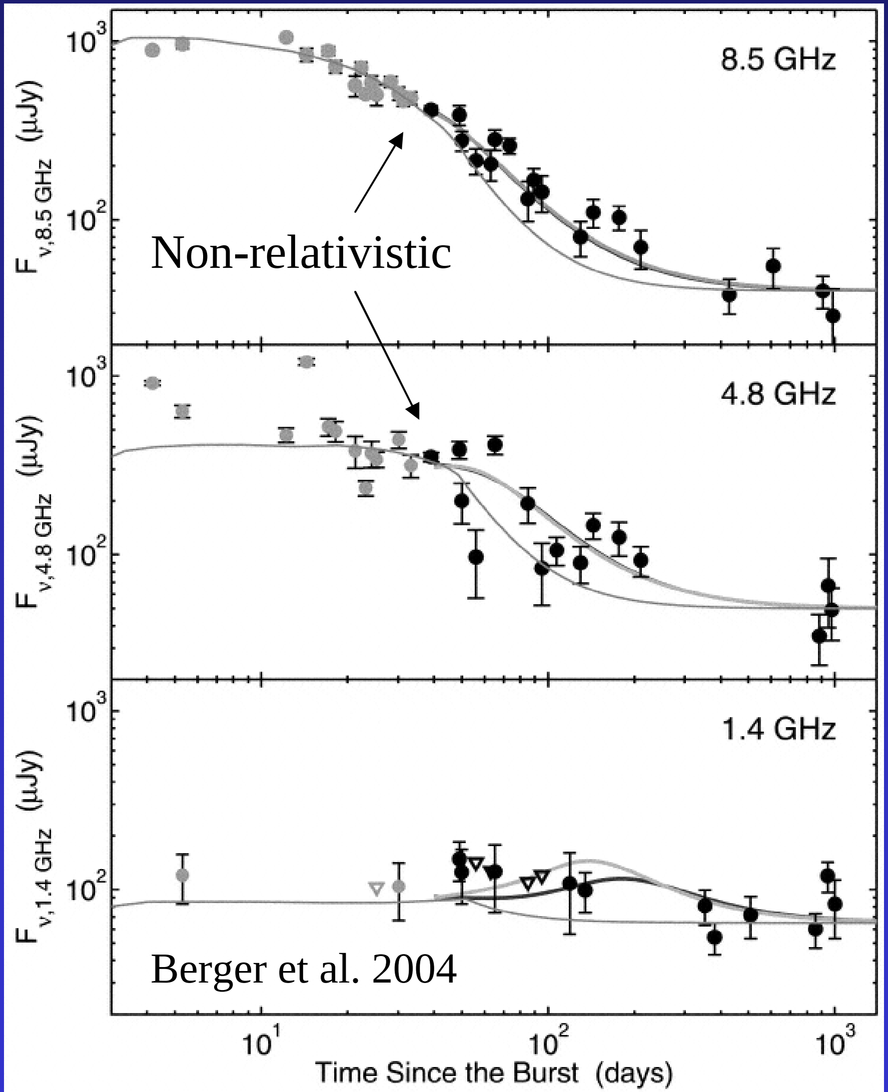
GRBs and XRFs have a standard total energy yield of a few 10^{51} erg ($\Gamma>2$), but the fraction coupled to $\Gamma>100$ varies widely.

GRB Calorimetry

When $M_{sw} \approx E_0/c^2$ the blast-wave becomes non-relativistic and nearly spherical:

- Flattening
- $t_{NR} \sim 65\ (E_{iso,52}\ /\ n_0)^{1/3}$ days





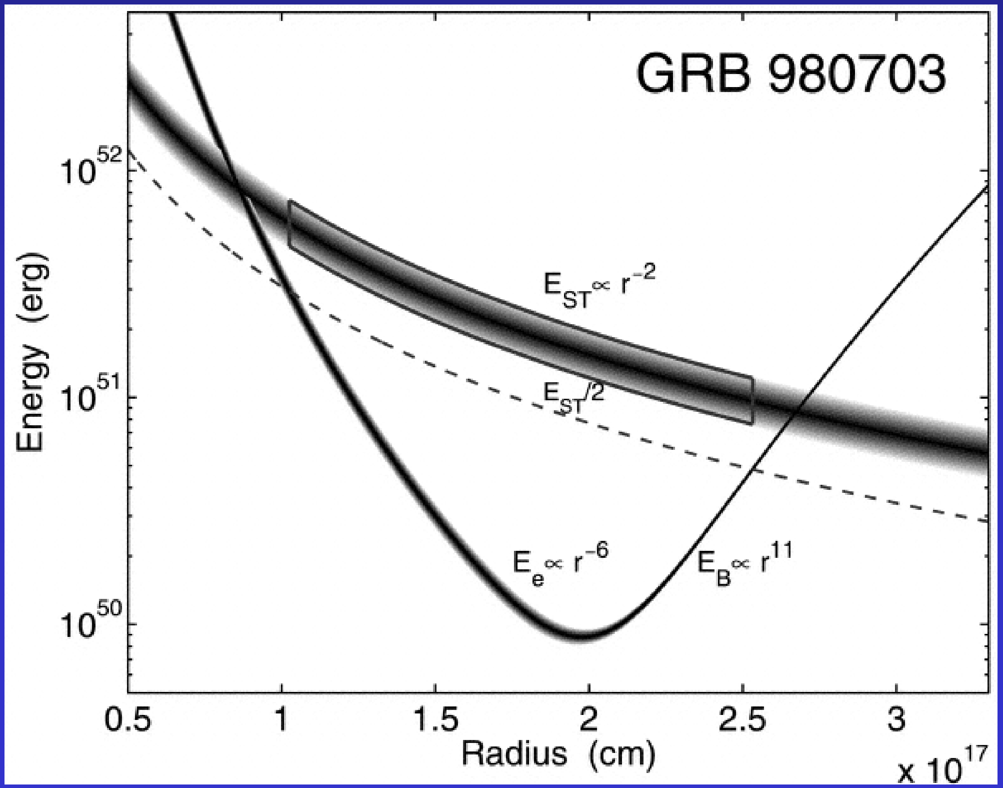
GRB Calorimetry

In the absence of optical/X-ray data the radius is unconstrained.

However: $E_e(r) + E_B(r) \le E_{ST}(r)/2$ since $E_{thermal} \sim E_{ST}/2$

Berger et al. 2004

	970508	980703	030329
t_{NR} (days)	90	40	50
R (10^{17} cm)	3.7-6	1-2.5	2-4
E_{ST} (10^{51} erg)	**1.5 - 4**	**1 - 6**	**0.7 - 2.2**



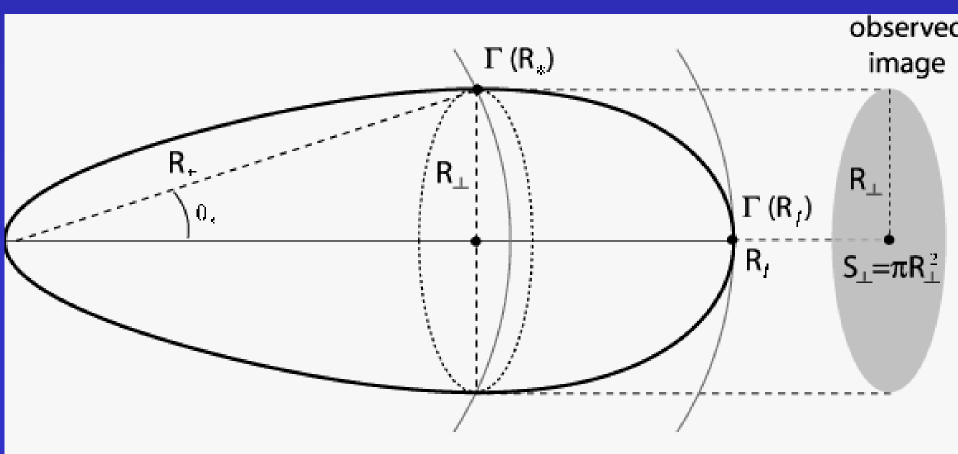
$$\boxed{E_{rel} \approx (1\text{-}5) \times 10^{51}\ \text{erg}}$$

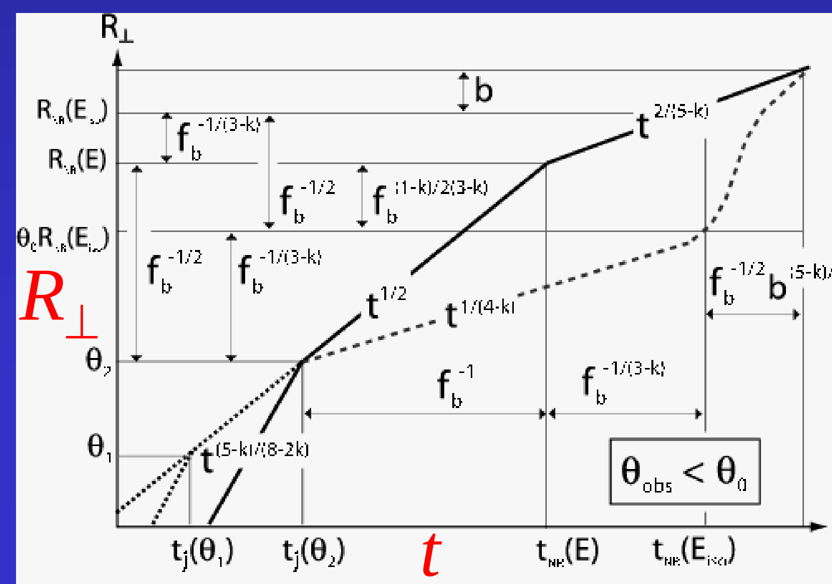
Resolving the Afterglow

$$R_{\ ,BM} \quad R\sin \quad \sim R/$$
$$1.6 \quad 10^{17} \quad E_{iso,52}/n_0 \ ^{1/8} \quad t_{d,1}/(1 \quad z)^{5/8} \quad \mathrm{cm}$$
$$18 \quad E_{iso,52}/n_0 \ ^{1/8} \quad t_{d,2}^{5/8} \quad \text{as} \quad (030329)$$
$$6 \quad E_{iso,52}/n_0 \ ^{1/8} \quad t_{d,2}^{5/8} \quad \text{as} \quad (z \sim 1)$$
$$R_{\ ,ST} \quad t^{2/5}$$

The main uncertainty is in the phase $t_j \rightarrow t_{NR}$: models range from relativistic lateral expansion to no lateral expansion

Granot et al. 2004

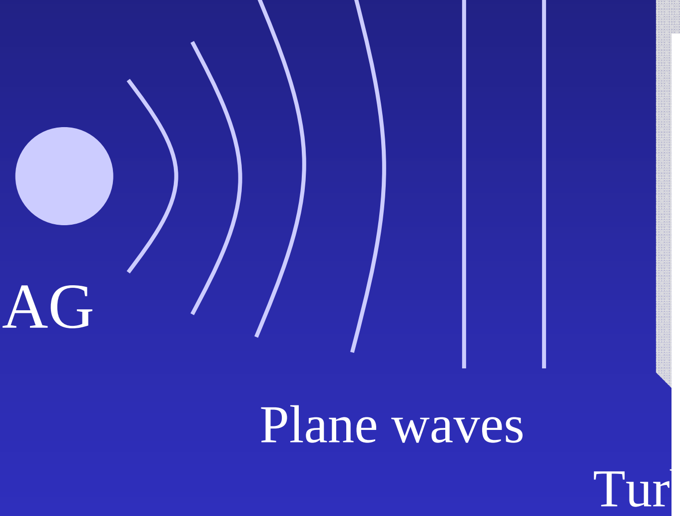


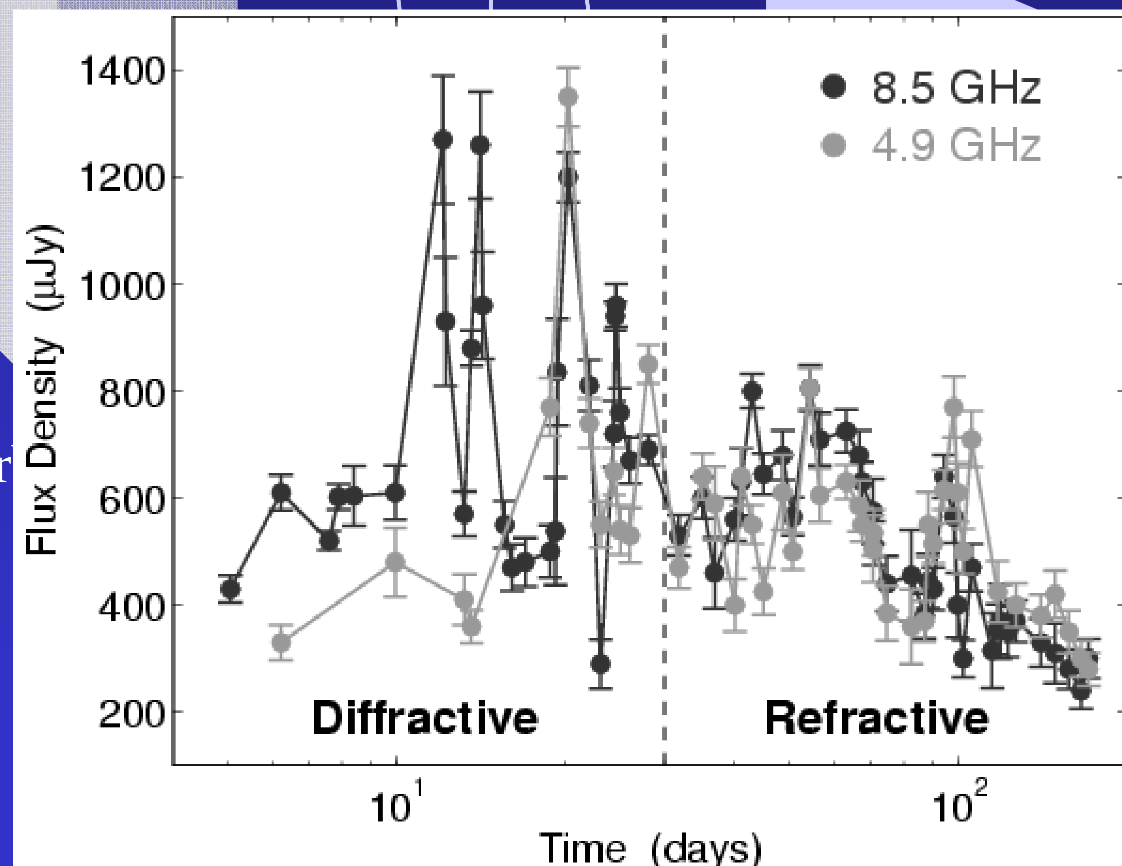


Resolving the Afterglow: Scintillation

The scintillation quenches as the source size increases

diffractive → refractive ⇒ ~ 5 μas (~ 2×10^{17} cm)

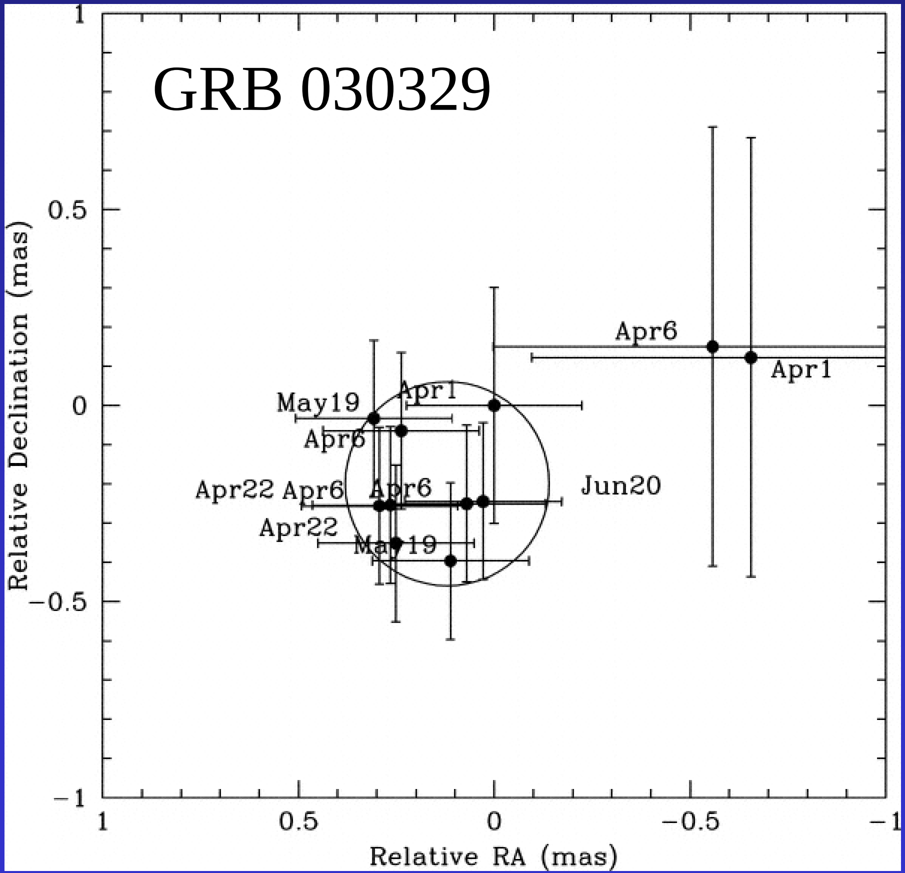




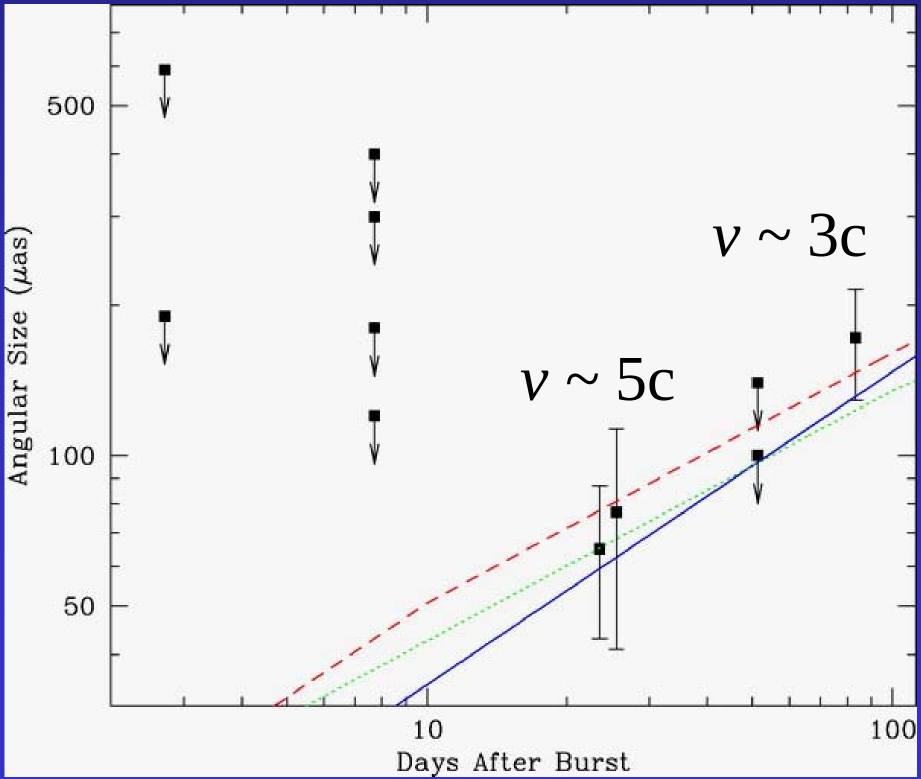
Resolving the Afterglow: VLBI

Proper motion: 0.10±0.14 mas in 80 days

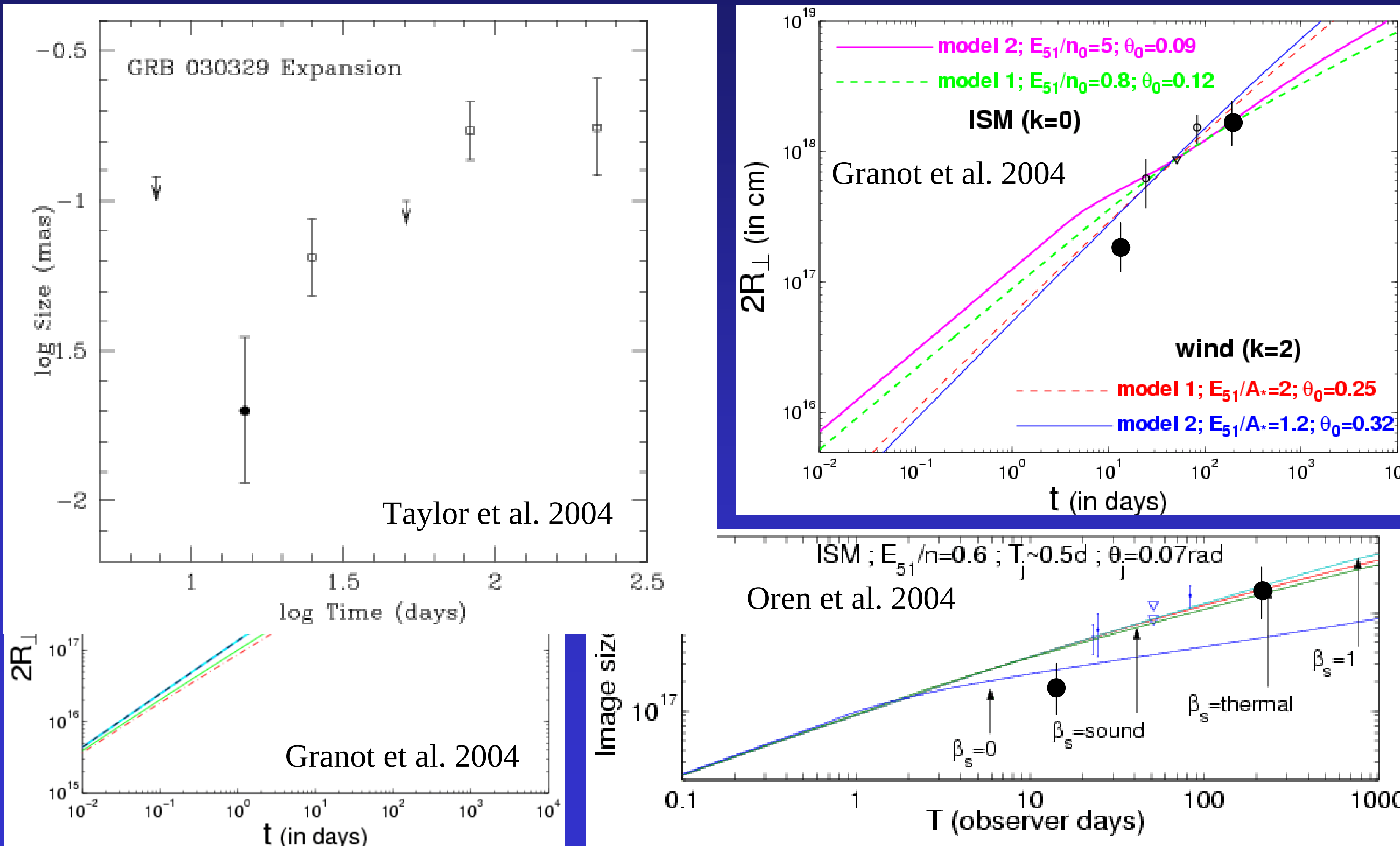
Angular size: 65±22 μas (5.7×10^{17} cm) @ 25 days



Taylor, Frail, Berger, & Kulkarni 2004



Resolving the Afterglow: VLBI



Conclusions

- Radio observations allow us to meaure the size of the afterglow and to trace the total relativistic output

- GRB 030329 was dominated by mildly relativistic ejecta; in some bursts the ultra-relativistic output is negligible; total energy nearly standard

- Radio calorimetry in the NR phase confirms that $E_{\rm rel} \approx 5\times10^{51}$ erg independent of beaming

- Radio scintillation confirms that GRBs have a size of about 5 μas at ~10 days, corresponding to $R \approx 1.5\times10^{17}$ cm & $v \sim 6c$

- VLBI observations of GRB 030329 provide the first direct measurement of the afterglow; probably requires significant side-ways expansion of the jet