The Gamma-Ray Burst Controversy

Galactic or Cosmological

Shapley v. Curtis

Harlow Shapley

- In 1920 two of the most eminent astronomers of the time argued over "The Scale of the Universe."

Heber D. Curtis

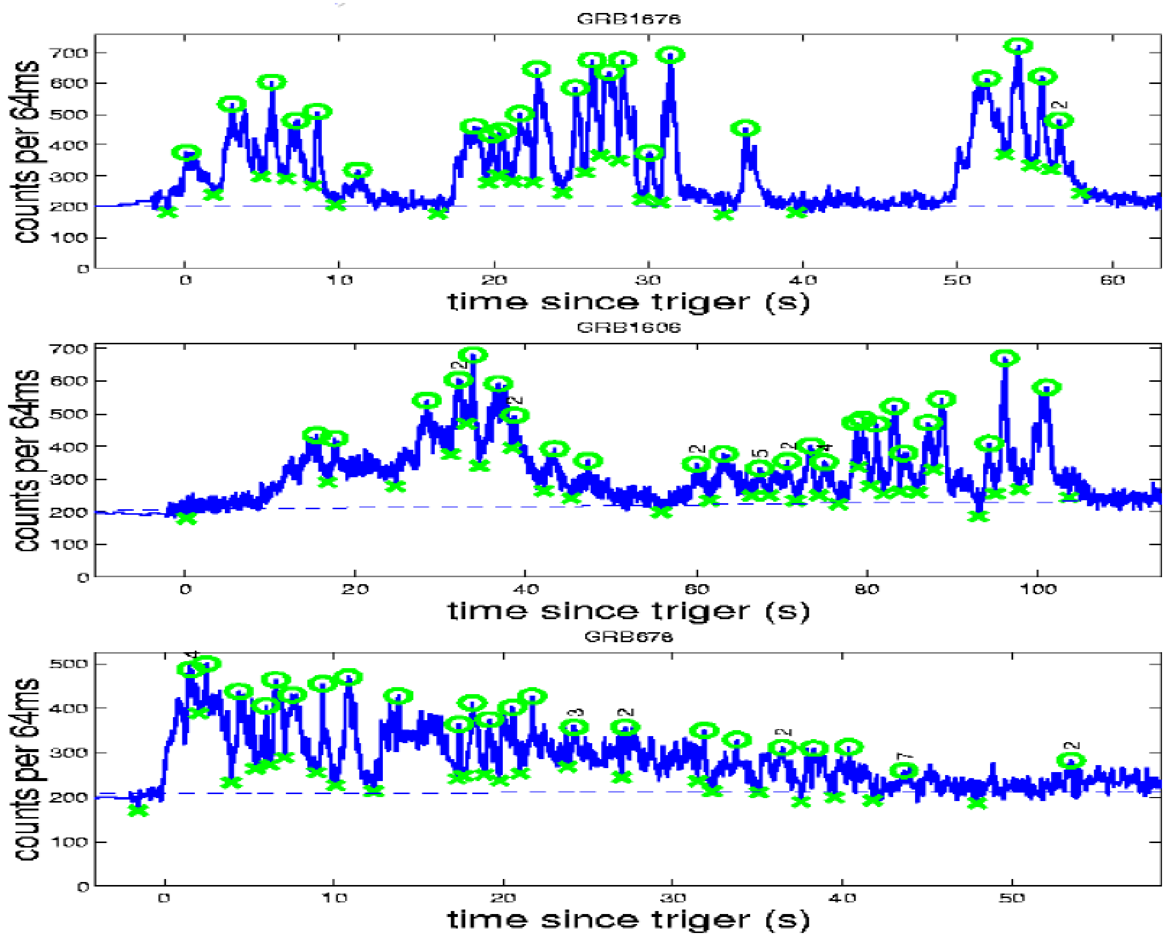
- Shapley argued that the spiral nebulae were part of our own Galaxy and the sun didn't lie near the center of the Galaxy.
- Curtis argued that the spiral nebulae were other galaxies like our own and the sun lies near the center of our Galaxy.

Who resolved the debate?

- Edwin Hubble observed Cephied variable stars in the Andromeda nebula. These Cephieds are so much fainter than those in our own galaxy that Andromeda must lie outside Shapley's idea of the Galaxy.
- Shapley was right about the side of the Galaxy and Curtis was right about the "island universes".

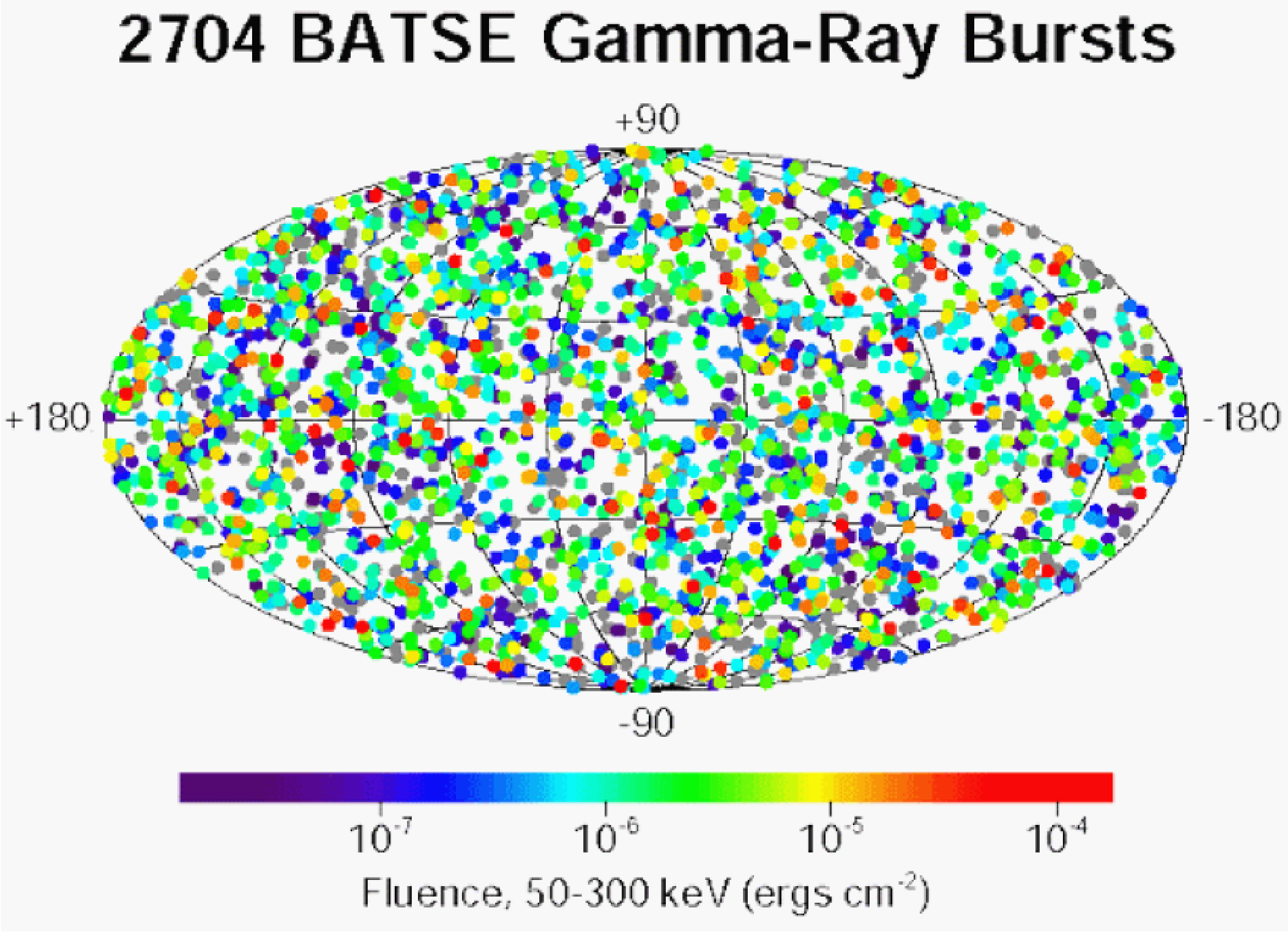
What do GRBs look like?

- GRBs are bursts of gamma rays lasting from less than one second to over 100 seconds.
- They exhibit structure down to timescales of one millisecond.
- Energies from 1 keV to 18 GeV.1



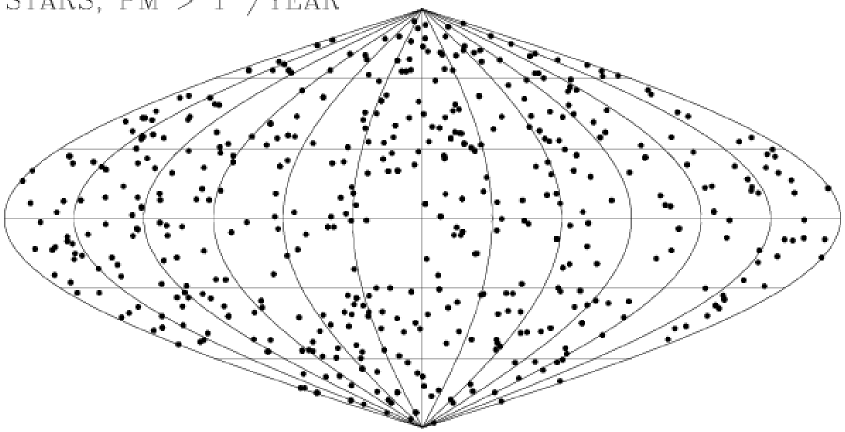
Observational Tests (1)

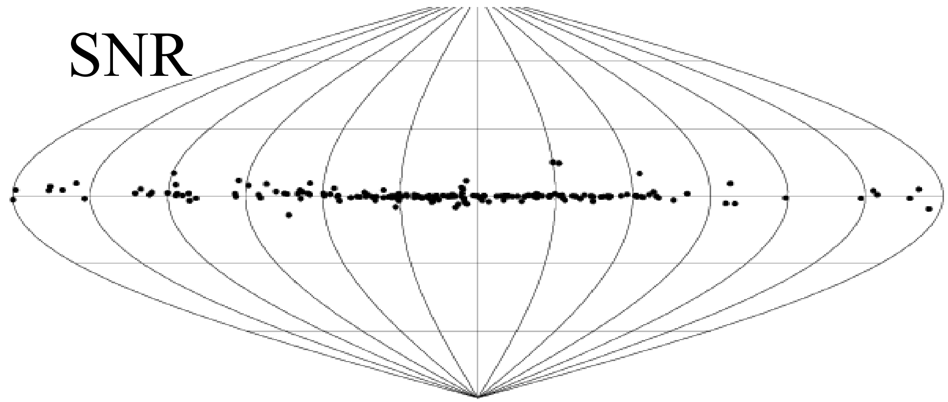
- Isotropy
- GRBs come from everywhere on the sky.
- There is no preference to the Galactic center.



Distributions (1)

STARS, PM > 1''/YEAR





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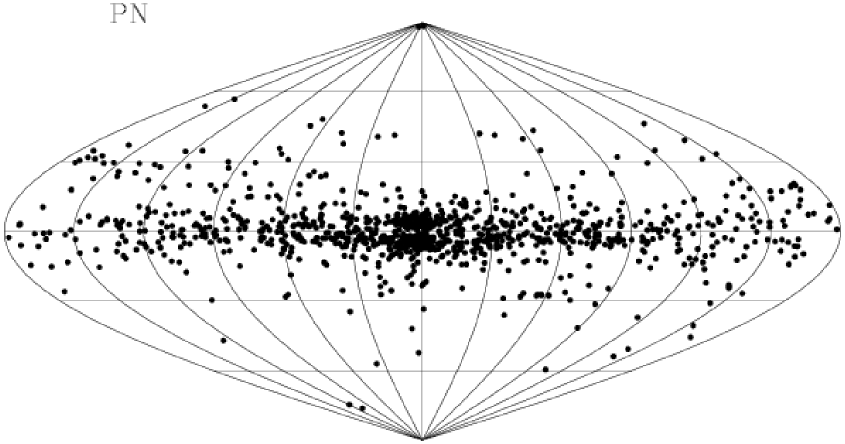

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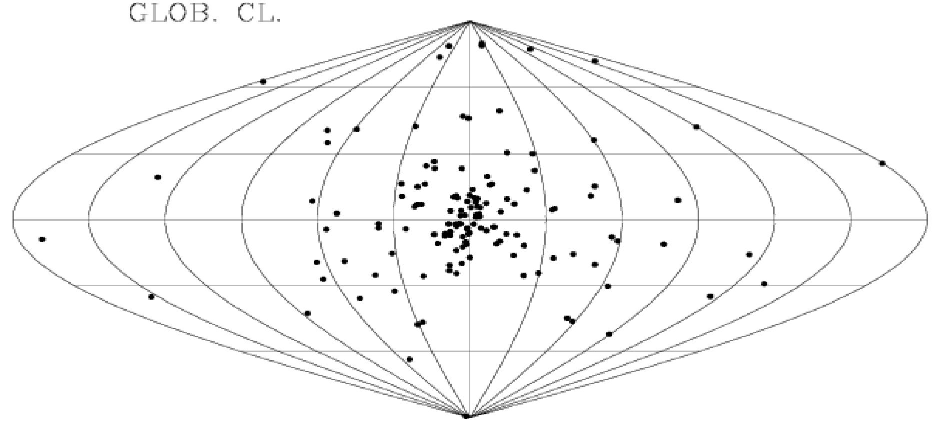
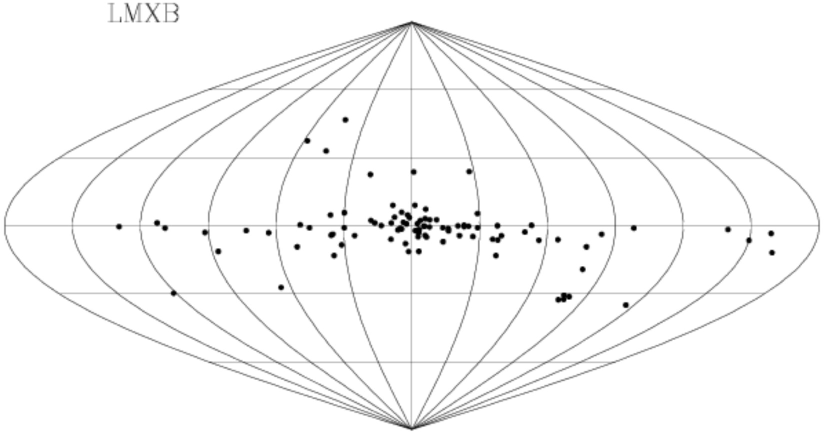
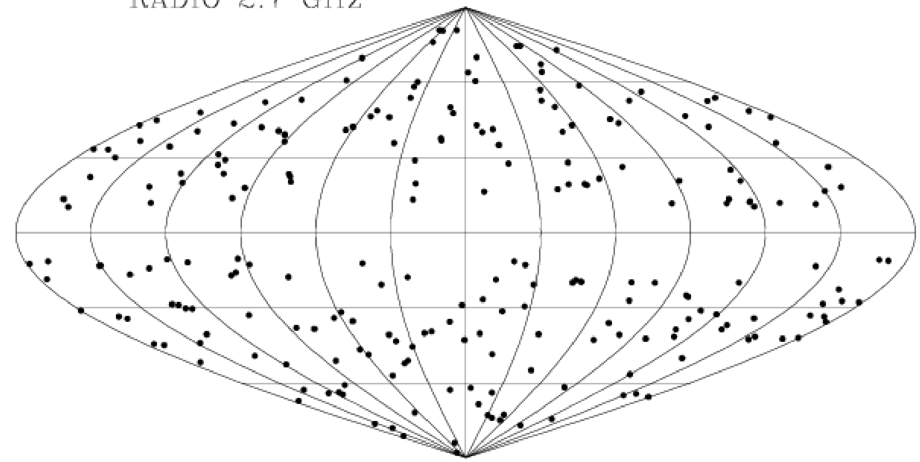


Distributions (2)

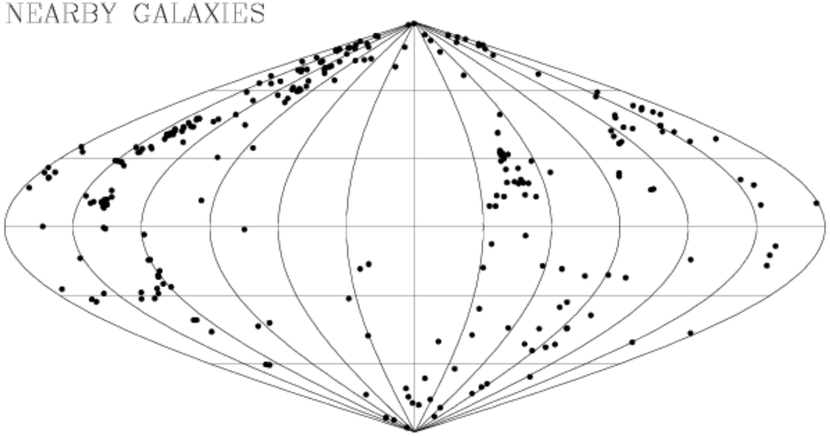
LMXB

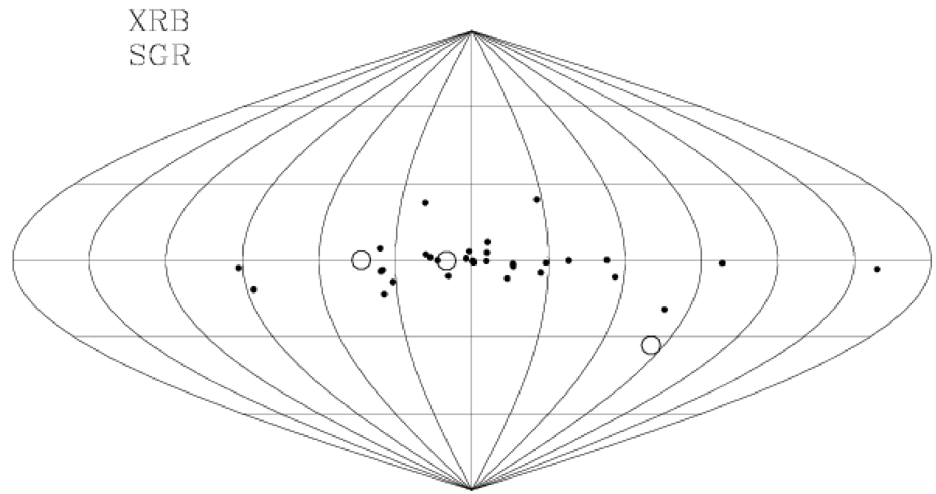


RADIO 2.7 GHz



NEARBY GALAXIES





Observational Tests (2)

- Let us imagine that each GRB has the same luminosity and they fill space uniformly. What would the flux distribution look like? Specifically, how many are brighter than a particular threshold?

$$f_{\min} = \frac{L}{4\pi d_{max}^2}, N = \frac{4}{3}\pi d_{max}^3 n \rightarrow N \propto f^{-3/2}$$

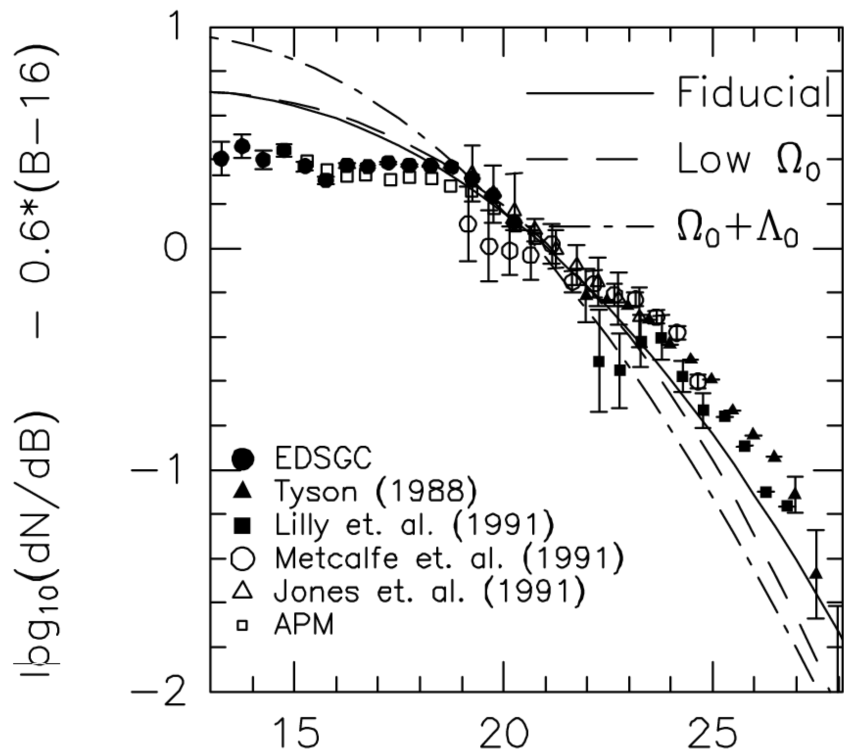
- Also what would you expect the median value of $(f/f_{\min})^{-3/2} = V/V_{max}$ to be?
- The observations give $\langle V/V_{max} \rangle \approx 0.3$ or equivalently the number counts increase more slowly than $f_{min}^{-3/2}$.
- $N \sim f^{-1.4}$ for bright bursts and $N \sim f^{-0.8}$ for weaker ones.

Where could they be?

- What other objects are isotropic on the sky and have $<(f/f_{min})^{-3/2}> < 1/2$?

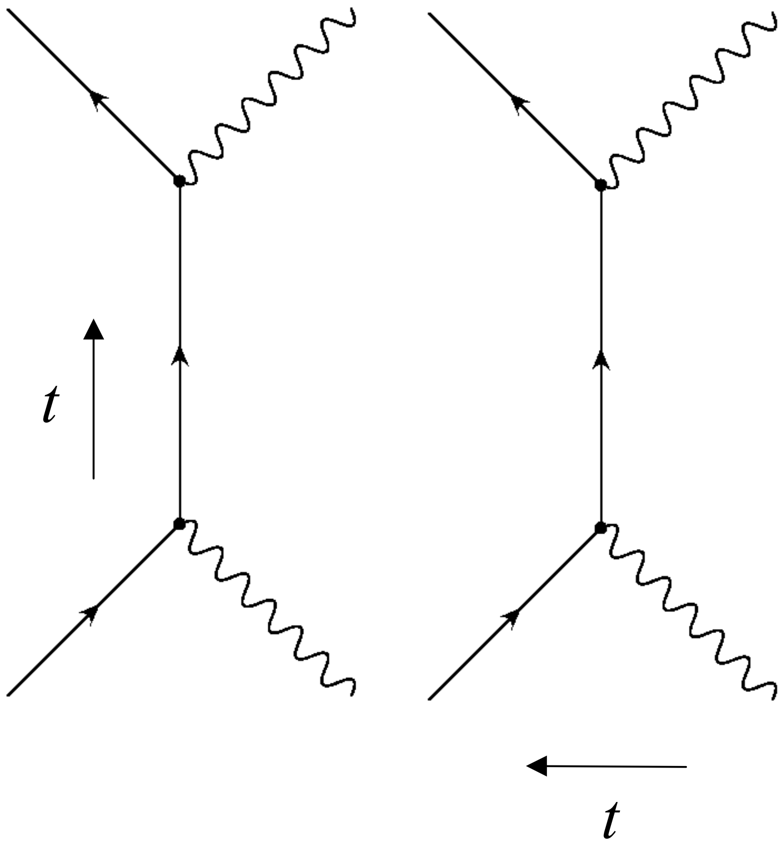
Galaxy Number Counts

- The number of galaxies brighter than a particular threshold falls short of what you would expect f they were standard candles filling Euclidean space.
  - Galaxies evolve.
  - Galaxies don't fill Euclidean space - they lie at cosmological distances.
- GRBs are cosmological or the distribution ends.



Theoretical Issues (1)

- Compactness problem
  - The minimum timescale in GRBs is around 1ms. This gives a size less than 3 x 10^7 cm.
  - If GRBs are cosmological, they emit 10^{51} ergs of 1 MeV photons (10^{57} photons).



Theoretical Issues (2)

- Two photons above an energy of 511MeV can produce an electron-positron pair. What is the optical depth?

  $$\tau = \sigma_T R n = \sigma_T R \frac{3L}{4\pi R^3 E} \sim 10^{18} L_{51} R_7^{-2}$$

- If GRBs are indeed cosmological, the photons that they produce should be thermal.
- The photon spectrum is ***non-thermal***.

Theoretical Issues (3)

- Energy Problem:
  - The energy of cosmological GRBs has to be around 10^{51} erg (one foe) in gamma rays.
  - A supernova produces:
    - 10^{51} erg of neutrinos
    - 10^{49} erg of kinetic energy
    - 10^{47} erg of light
  - How can GRBs produce such a large fraction of their energy as photons?

What to conclude? (1)

- The observations indicate the the bursts have a cosmological origin.
- Theoretically it is difficult to account for the energy and thermal spectrum of cosmological bursts.

"One does not have to know much about the subject to realize that if there is one correct theory of the bursts then all but one are wrong. One may continue this reasoning to note that if 99 out of 100 hundred published theories are wrong then most likely all 100 are wrong." -- Bohdan Paczynsky

Galactic Evidence (1)

- The key pieces of evidence are
  - Highly magnetized neutron stars (I.e. the soft-gamma repeaters) sometimes produce gamma-ray bursts (e.g. the March 5 event).
  - Some neutron stars are born with high velocities and might form a galactic corona at a distance of about 100 kpc.

Galactic Evidence (2)

- Additional supporting evidence includes:
  - Observation of cyclotron lines in GRBs
  - GRBs that apparently repeat on week-to-month timescales.
  - A lack of bright galaxies in the error box of bursts.
  - To see bursts from Andromeda you would need a much more sensitive instrument.

Galactic Evidence (3)

Comparison of evidence for ($\surd$) and against ( ) the cosmological and Galactic hypotheses.

EVIDENCE	COSMOLOGICAL	GALACTIC
Isotropy and Brightness Distribution	$\surd$	$\surd$
Similarities of SGRs & GRBs		$\surd$
Famous 1979 March 5 Event		$\surd$
Cyclotron Lines		$\surd$
Repeating		$\surd$
Time Stretching	—	—
No Bright Optical Counterparts		$\surd$

Who resolved the debate?

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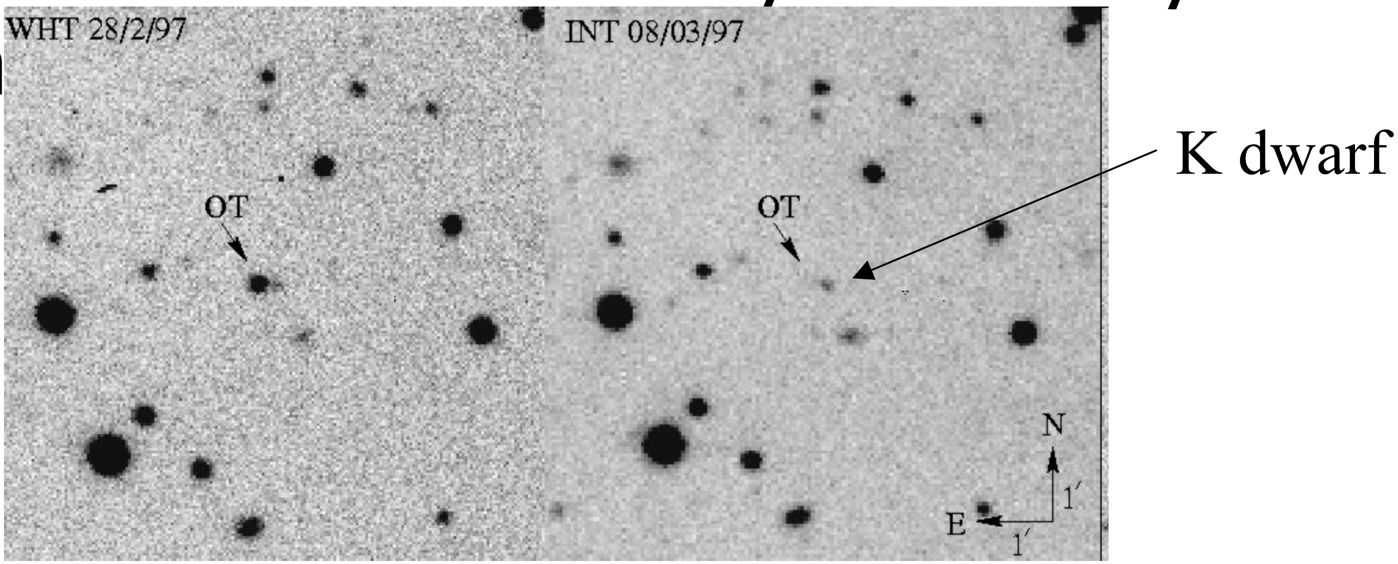
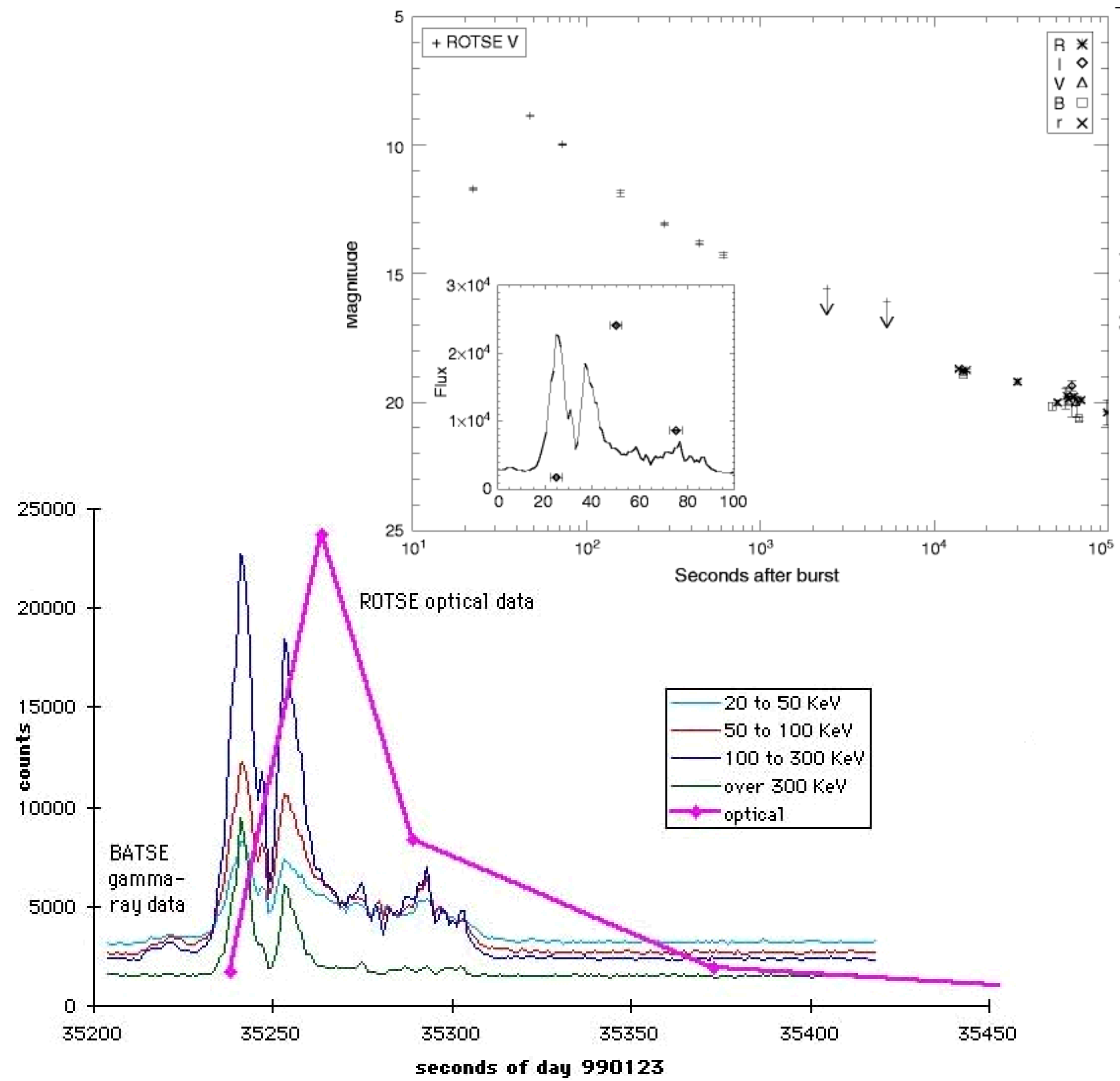
- Edwin Hubble again.
- On February 28, 1997 the satellite BeppoSAX pinpointed the location of a GRB with sufficient accuracy to identify a host ga



Famous Bursts

- 970228 - first afterglow
- 970508 - first redshift (0.835)
- 971214 - z=3.24, E=0.16 $M_X c^2$
- 990123 - 9th magnitude optical transient (z=1.6)



Boom, Boom!

- Let's look at a big explosion. Neglect
  - the mass of the initial ejecta
  - the internal energy of the surrounding matter
  - asphericities
  - radiation
- What is left?
  - Energy of explosion, E
  - Density of matter, ρ
  - Radius, r, and time, t

Similarity Solutions (1)

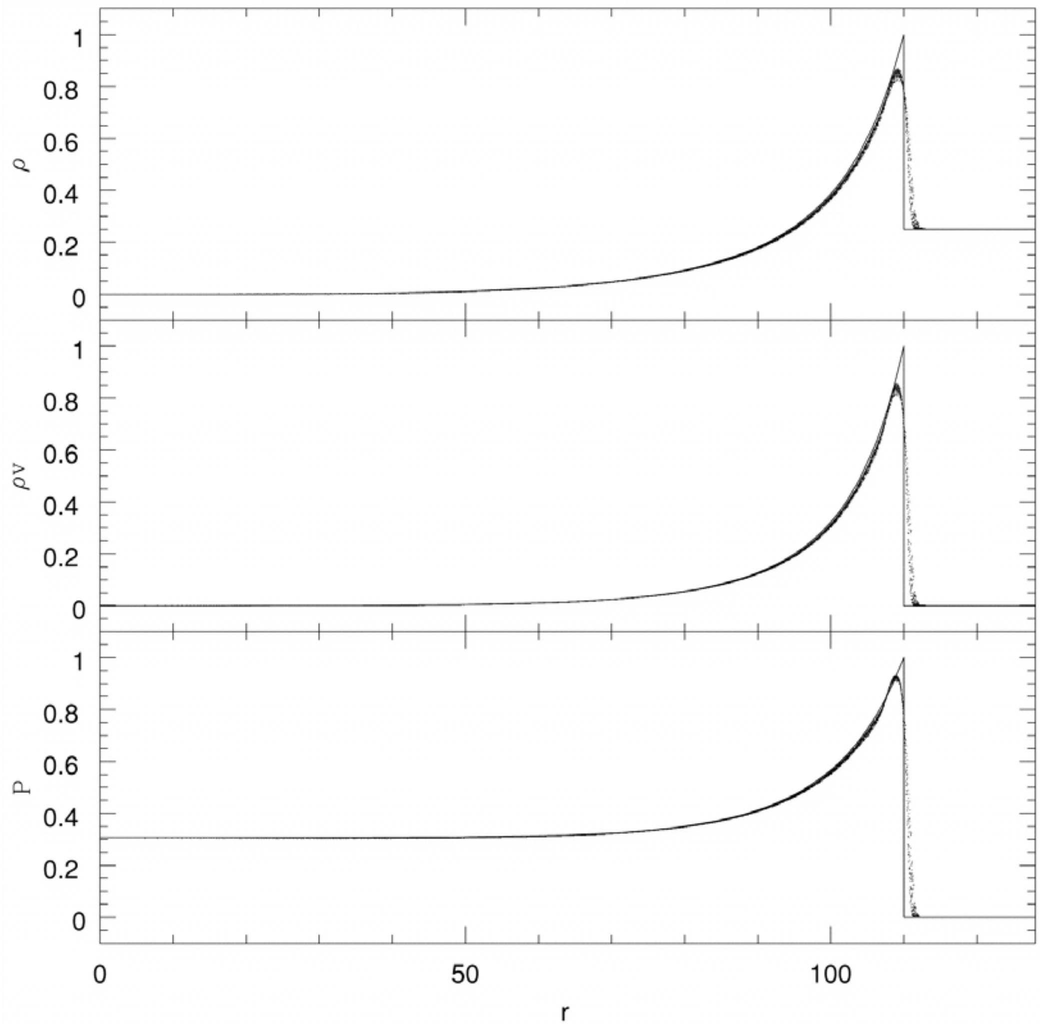
- There is only one dimensionless number that combines these variables: $\frac{E}{\rho}\frac{t^2}{r^5}$.
- We actually don't have to solve anything to get the evolution.
- If we had made different assumptions, we would have a different similarity variable.
  - If we neglect the mass of surroundings compared to the ejecta, $\frac{E}{m}\frac{t^2}{r^2}$. This is a free expansion stage with constant velocity.

Similarity Solutions (2)

- Let's make a variable that is proportional to distance. $\xi = \beta r \left(\frac{\rho_0}{E}\right)^{1/5} t^{-2/5}$
- Let's take the fluid variables to be functions of ξ. The radius of the blast wave is proportional to $t^{2/5}$.
- What this does is convert the fluid equations from partial differential equations to ordinary differential equations.

Similarity Solutions (3)

- Because the solution that we seek is a function of ξ, the evolution is self-similar, the fluid looks the same at all times, just the scale changes.



Relativistic Blast Wave (1)

- In the relativistic problem there is another quantity, the speed of light so it is not straightforward to make a similarity variable.
- Let’s make the same assumptions and think about the energetics.

Relativistic Blast Wave (2)

- The total energy of the blast is *E* and it is shared with all the material behind the shock.
- The total energy of the material behind the shock may be approximated by $E = w\Gamma^2\beta^2 V$ where *w* is the relativistic enthalpy. In the non-relativistic limit it is the density of the material and we recover the Sedov-Taylor solution.

Relativistic Blast Wave (3)

- Blandford and McKee found a similarity solution that is valid in the limit of high Γ.

$$E = \sigma w \Gamma^2 \beta^2 V = 8\pi w t^3 \Gamma^2 / 17$$

- The radius of the blast wave increases as t while the value of Γ decreases as $t^{-3/2}$.
- How far does the blast wave lag behind the photons emitted at the start?

Relativistic Blast Wave (4)

- The photons go a distance *ct* after a time *t*. The velocity of the blast wave varies so it goes a distance $d = \int_0^t \beta c dt'$.
- Let's take the difference of these distances.

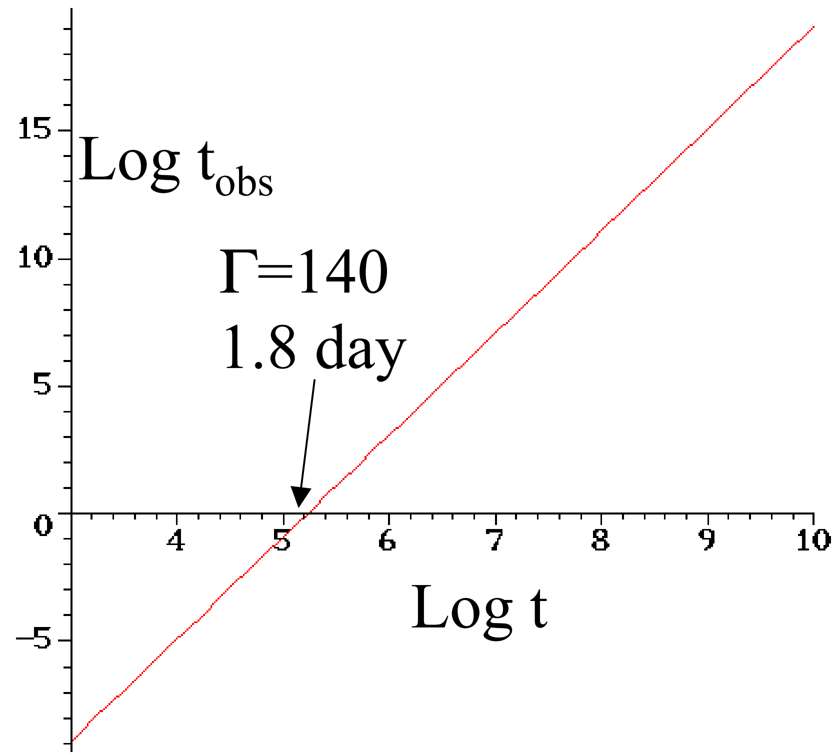
$$\Delta d = \int_0^t (1-\beta) c dt',$$

$$\Gamma^2 = A t^{-3} = \frac{1}{1-\beta^2} = \frac{1}{(1-\beta)(1+\beta)}$$

$$\Delta d \approx \int_0^t \frac{1}{2\Gamma^2} c dt = \int_0^t \frac{1}{2A} (t')^3 c dt' = c \frac{t^4}{8A}$$

Relativistic Blast Wave (5)

- Let's say we receive the first photon from the gamma-ray burst at time t_0. We will receive photons emitted at time t in the blast at $t_0 + \Delta d/c$.
- Let's say that we observe the blast wave to be at Γ=2 around one month after the burst, then $A=(4 \times 10^6\ \mathrm{s})^3$.



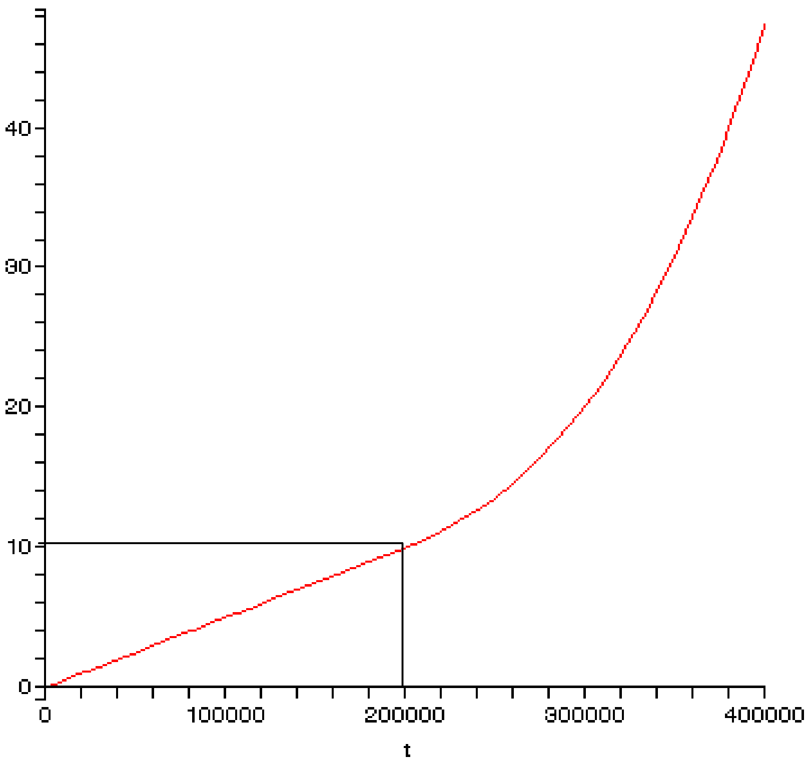
Relativistic Blast Wave (6)

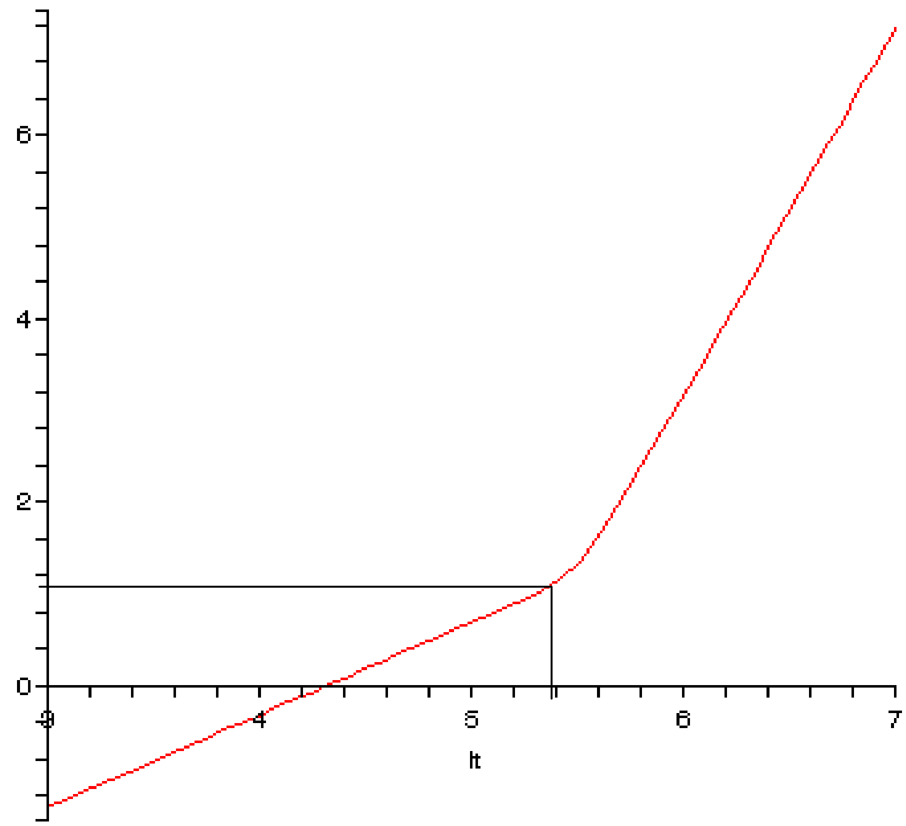
- This was of course a bit unrealistic because at such early times the mass of the ejecta are important, so you're in the coasting phase with constant Γ.
- The more realistic result is

$$t_{\mathrm{obs}} = \begin{cases} \frac{t}{2\Gamma_0^2} & t < t_c \qquad \mathrm{GRB} \\ \frac{t_c}{2\Gamma_0^2} + \frac{t^4 - t_c^4}{8\Gamma_0^2 t_c^3} & t > t_c \qquad \mathrm{Afterglow} \end{cases}$$

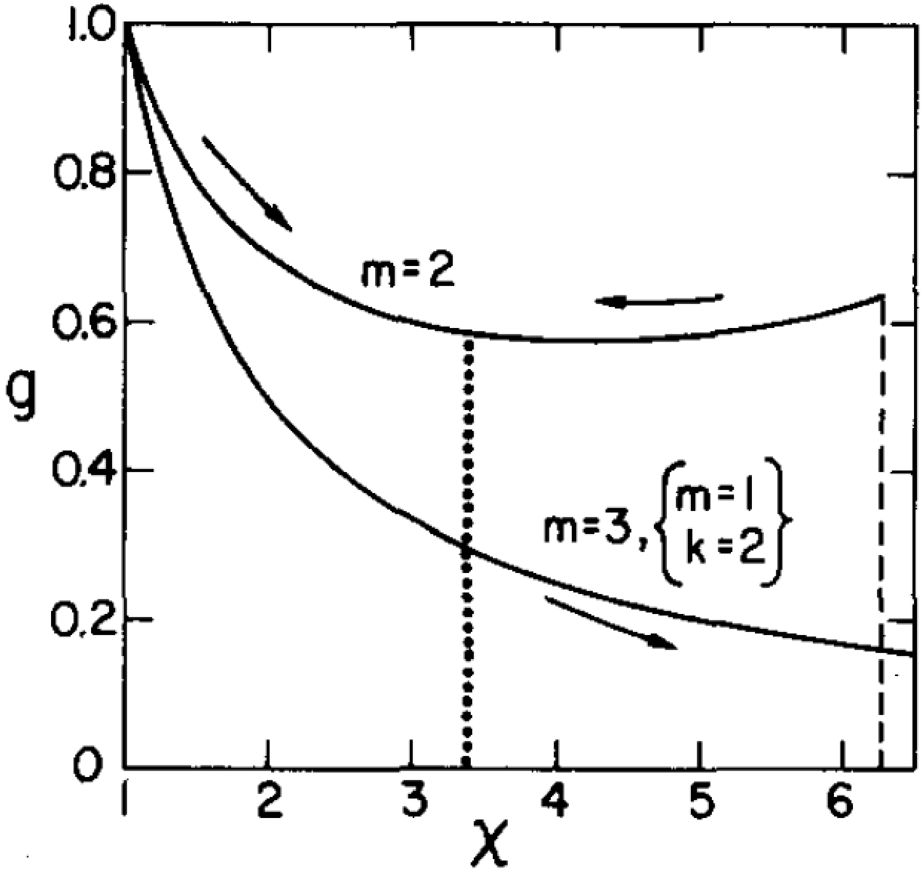
Relativistic Blast Wave (7)

Γ_0=100, t_c=2 x 10^5 s=2.3 days

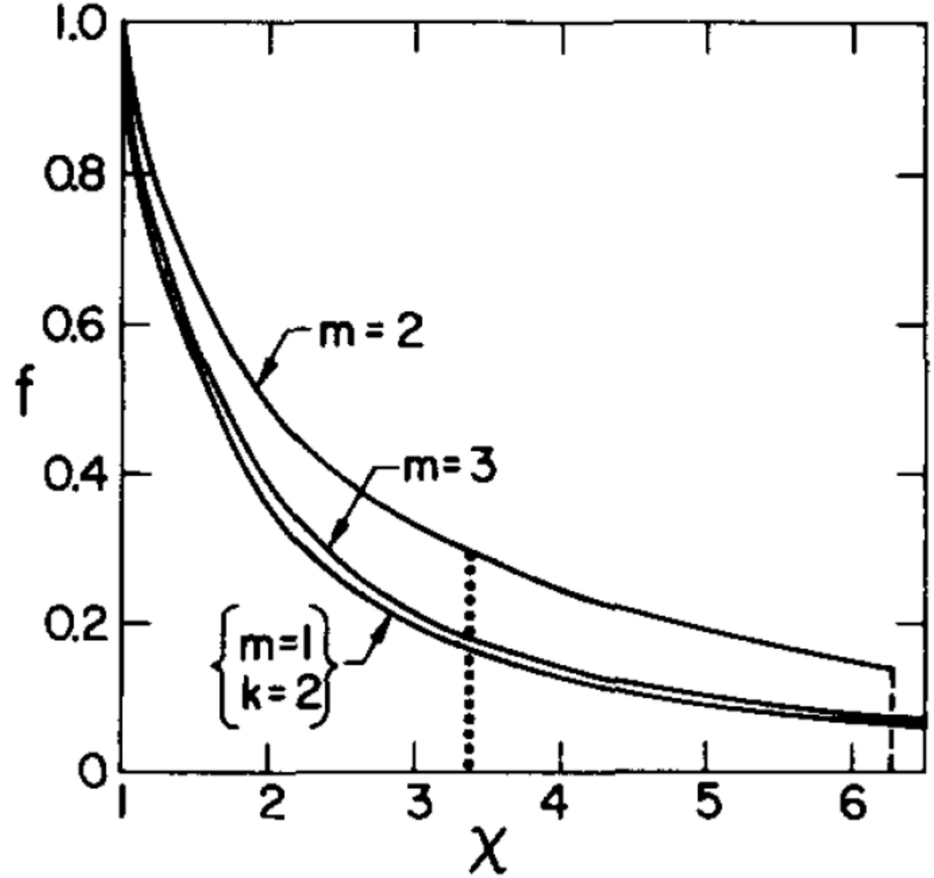




Shock Structure



Velocity

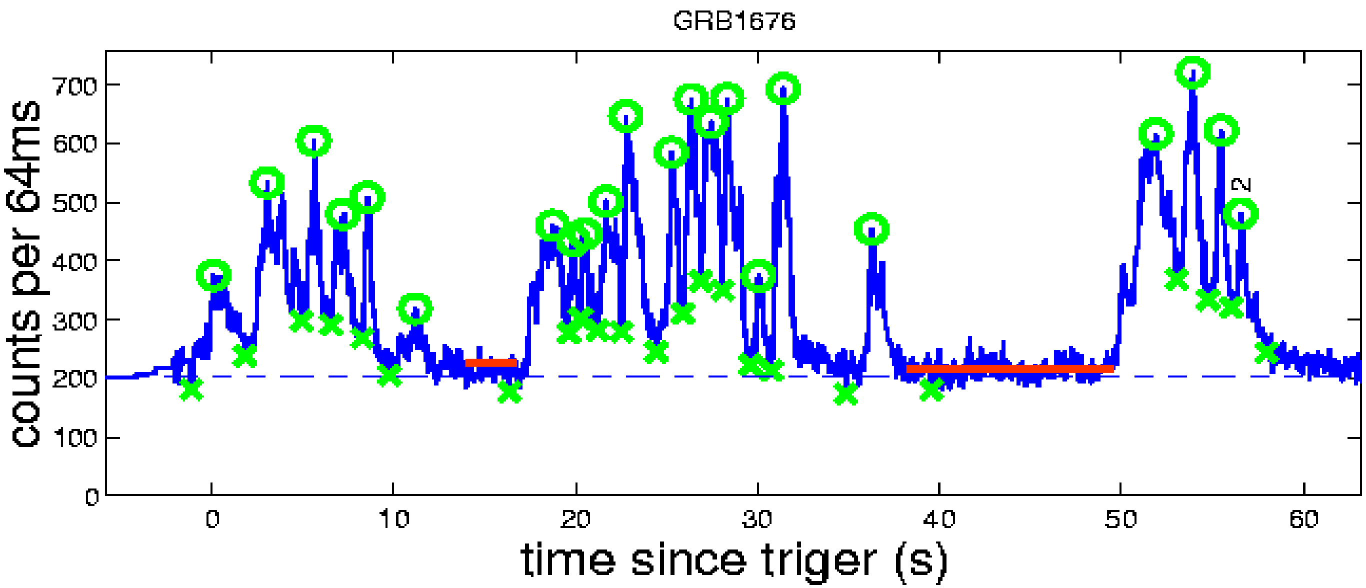


Pressure

Does this work?

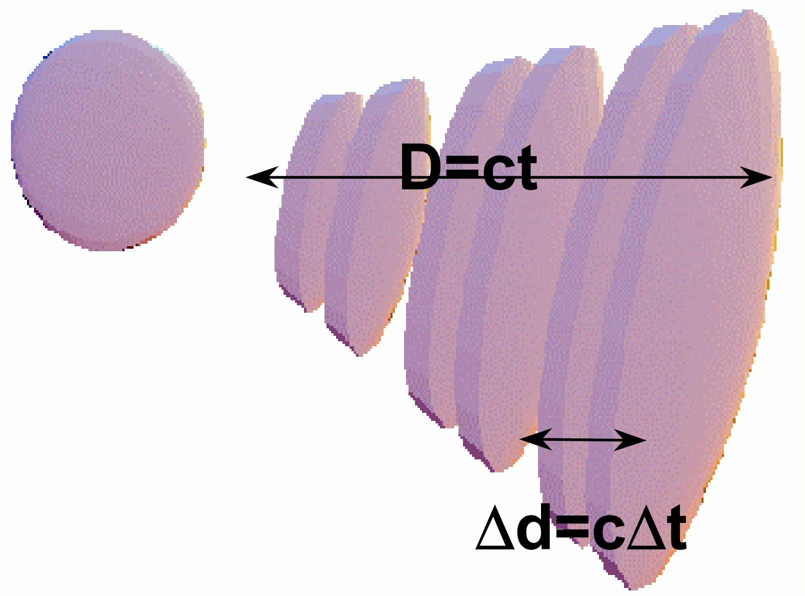
Does this work?

- Yes and no. All of these similarity solutions give a smooth lightcurve like a supernova but…



External v. Internal Shocks

- The observed light curve reflects the activity of the "inner engine". <u>Need TWO time scales.</u>
- To produce internal shocks the source must be active and highly variable over a "long" period.



The Whole Picture