Gamma-ray bursts: observations

Photons with E > 100 keV are typically called gamma rays (no *physical* distinction between gamma rays and hard X-rays though need different detectors for each) - absorbed by atmosphere so only detectable from space.

Gamma ray sky first studied in the 1960s, in part initially by the Vela satellites - monitoring treaty forbidding nuclear tests in space.

Several reasonably well-understood sources of γ-rays:

- Diffuse component which tracks the gas in the Milky Way
- Point sources which can be identified with known locations of pulsars (i.e. Galactic neutron stars)

Also detect extremely bright, short-lived transient sources of gamma-ray emission - **gamma-ray bursts**.

Properties of GRBs

Durations: 10^{-2} to 10^{3} s
Variability: as short as ms
Time-integrated flux: up to 10^{-4} erg cm^{-2}
Photon energies: broad range, 0.1 MeV to 1 MeV typical

Note: 1 eV = 1.6×10^{-12} erg. Using: $E = h\nu$

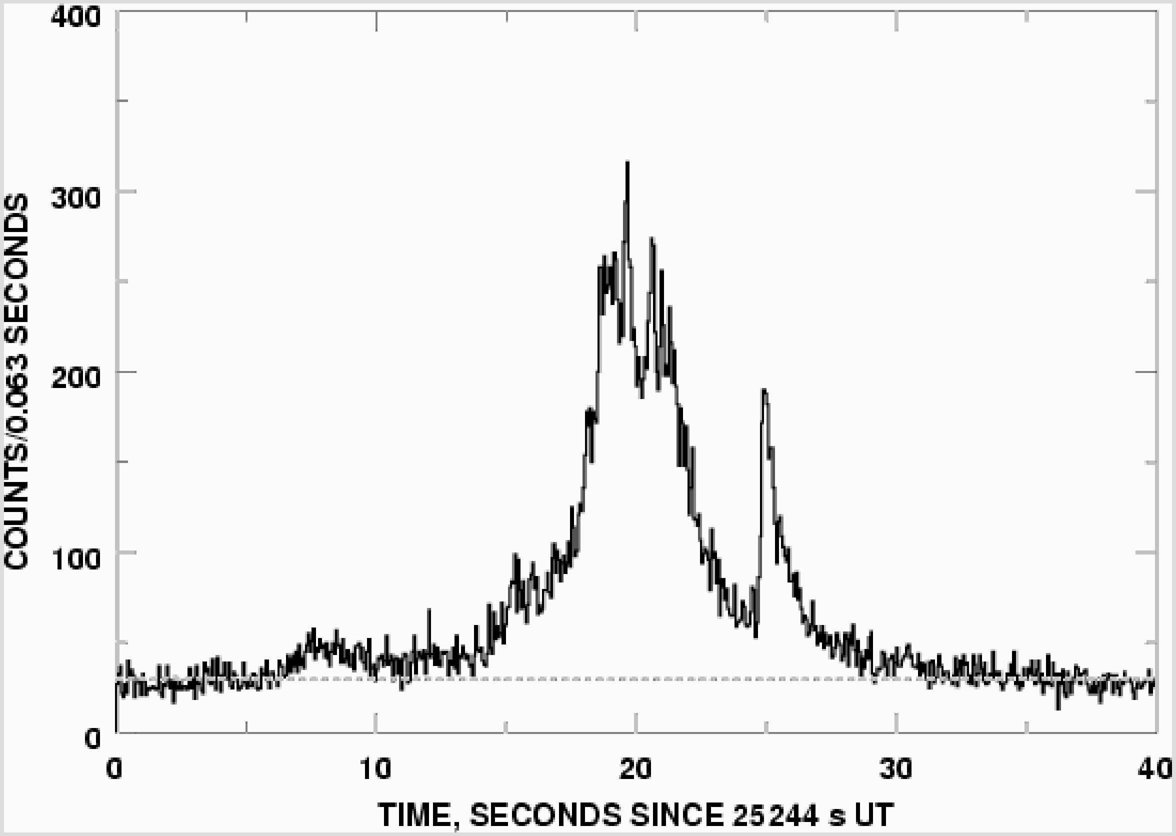
⇒ 1 MeV corresponds to a frequency 2.4×10^{20} Hz

If these photons arose from a **thermal** process, then:

$E \sim kT$, with k Boltzmann's constant ⇒ $T \sim 10^{10}$ K

Gamma-rays are produced only from very energetic, normally **non-thermal** processes.

Example of burst `light curve' in gamma-rays



Large range of durations, evidence for bimodal distribution of bursts - `short' bursts lasting ~ 0.1 s and `long' bursts lasting ~ 10 s.

Initial models

Until late 1990's, distance scale to GRBs was unknown. If we assume **isotropic emission**, then a source emitting energy E in gamma-rays at distance d would give a time integrated flux S:

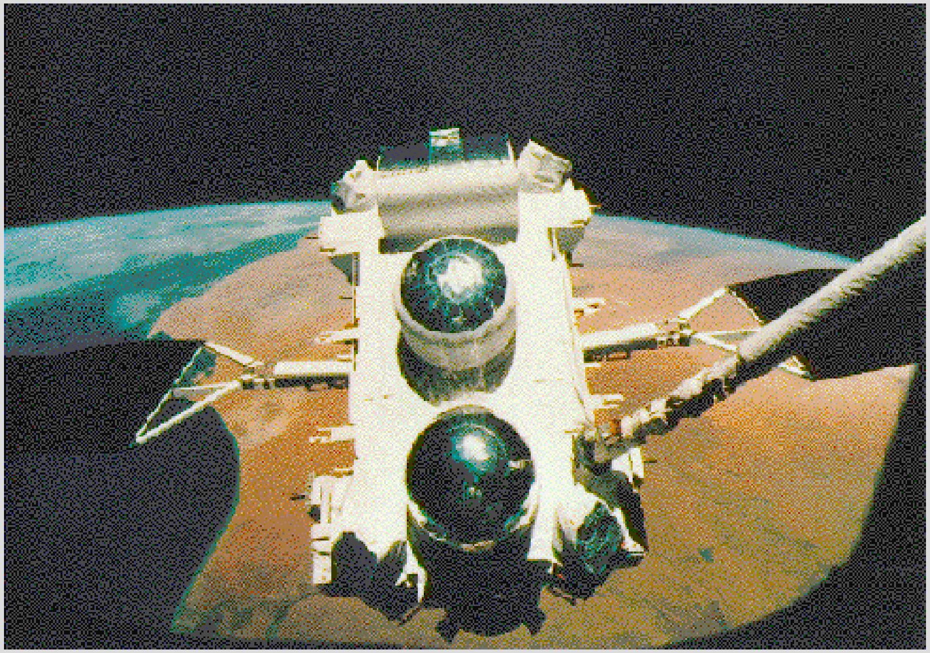
$$S = \frac{E}{4\pi d^2}$$

Suggested models:

- Comets: d ~ 100 au: E ~ 10^{27} erg
- Events on surface of Galactic neutron stars
  d ~ 1 kpc: E ~ 10^{40} erg
- Cataclysmic events in distant external galaxies
  d ~ 1 Gpc: E as large as 10^{52} erg

Most popular models in the early 1990s involved explosive events on the surfaces of Galactic neutron stars:

- analogy with X-ray bursts
- modest energetics
- apparent observation of cyclotron lines in one source
- similarity to soft gamma-ray repeaters

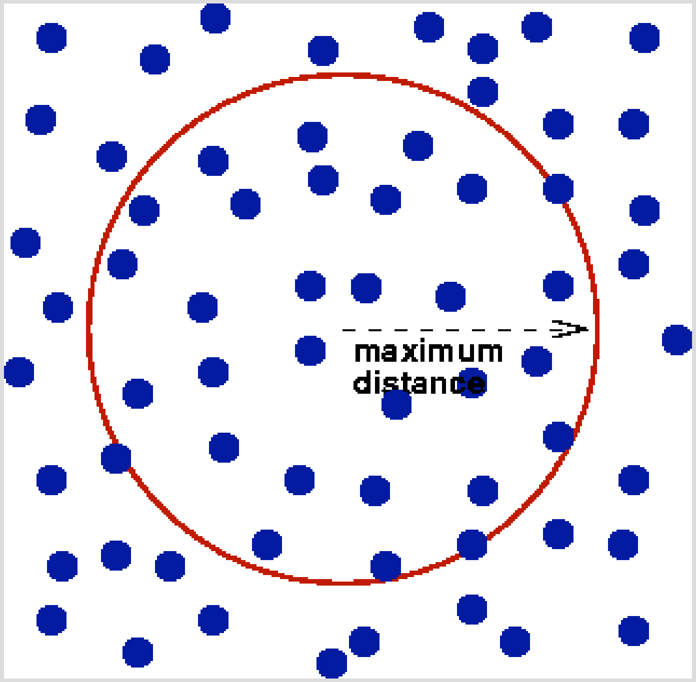


Observations with the Compton Gamma Ray Observatory provided the first hint this consensus was wrong.

Distribution of integrated flux from the bursts

Even if we have no idea of the distance to any burst, can learn something by comparing the number of faint bursts to the number of bright ones.

Consider a population of sources uniformly distributed in space. Each source emits energy (in some waveband) E isotropically in a burst:



Integrated flux detected at distance d:

$$S = \frac{E}{4\pi d^2}$$

All sources with $S > S_{min}$ will be detected out to a maximum distance:

$$d_{\max} = \sqrt{\frac{E}{4\pi S_{\min}}}$$

Volume in which sources with S > $S_{\rm min}$ are detectable is thus:

$$V = \frac{4}{3}\pi d_{\rm max}^{3}$$

If number density of sources is n, number in that volume is:

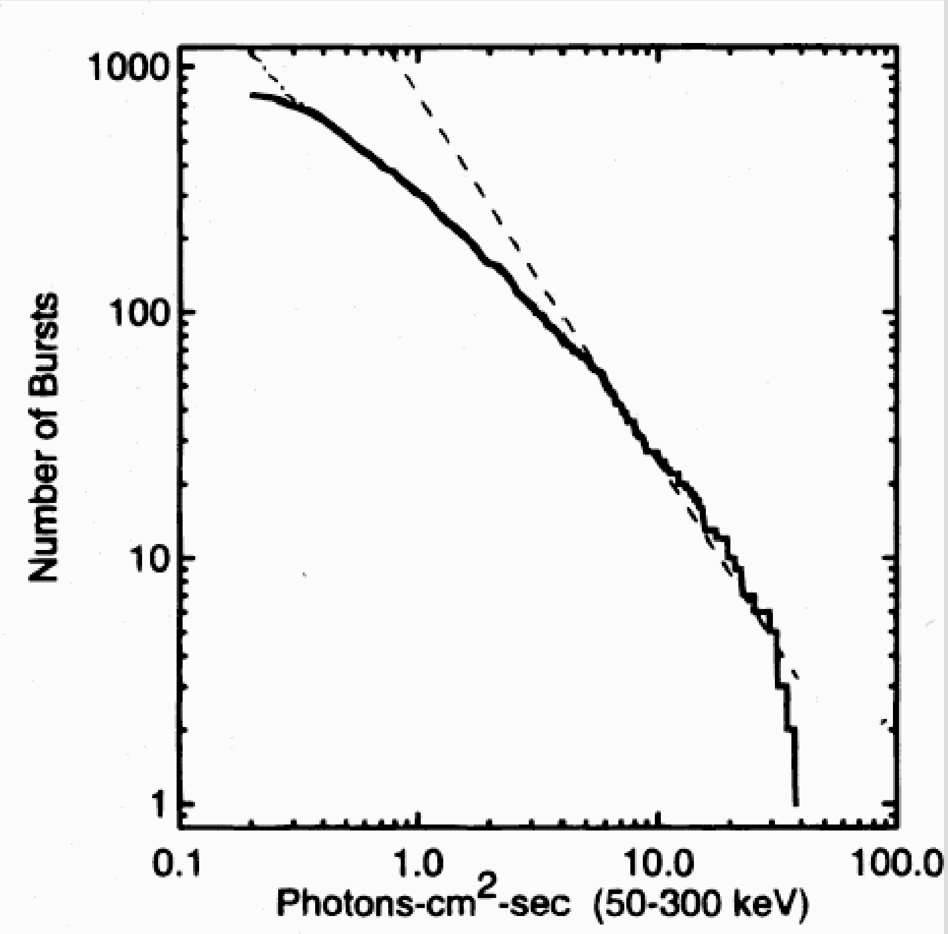
$$N = nV = n\frac{4}{3}\pi\left(\frac{E}{4\pi S_{\rm min}}\right)^{3/2}$$

$$N \propto S_{\rm min}^{-3/2}$$

If we plot the number of bursts N with integrated flux above some threshold $S_{\rm min}$ on a log-log plot, expect a straight line with a slope of -1.5.

→ log N - log S test of whether distribution of unknown sources is homogenous

log N - log S test for GRBs

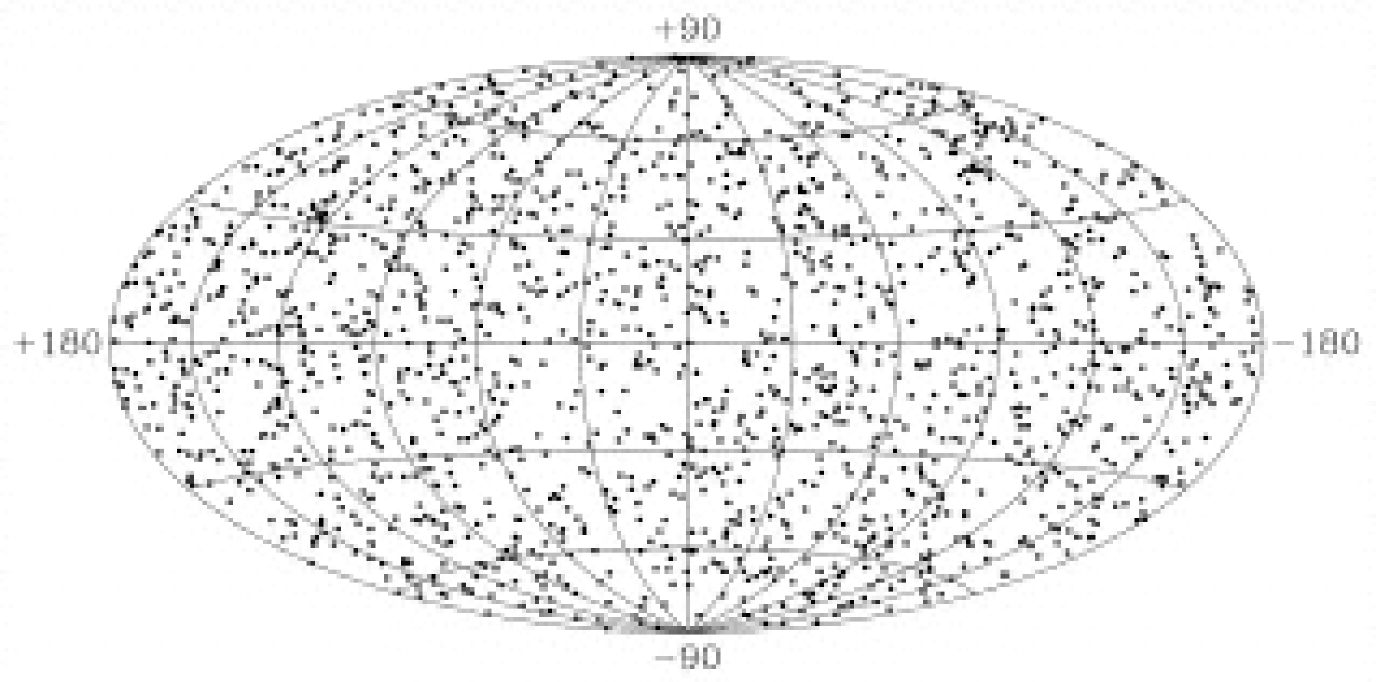


BATSE results showed that a slope of -1.5 fit the distribution of the brightest bursts, but that there were **fewer** faint bursts.

We can see the `edge' of the distribution.

If GRBs originated on Galactic neutron stars, the `edge' of the population would be defined by the size of the Galaxy. Since the Sun is not in the Galactic center, expect an anisotropic distribution of bursts on the sky (more towards the Galactic center).

Actual spatial distribution is perfectly isotropic:



With log N - log S results, inconsistent with Galactic origin.

Conclusion:

- Distribution on the sky is isotropic because bursts arise in distant galaxies, far enough away that the Universe is almost homogenous.
- See an edge to the distribution because the Universe is:
  - (a) finite - at large enough distances reach very early time before galaxies had formed - no bursts
  - (b) evolving - rate of GRBs was probably different in the past as compared to today
  - (c) can have a non-Euclidean geometry

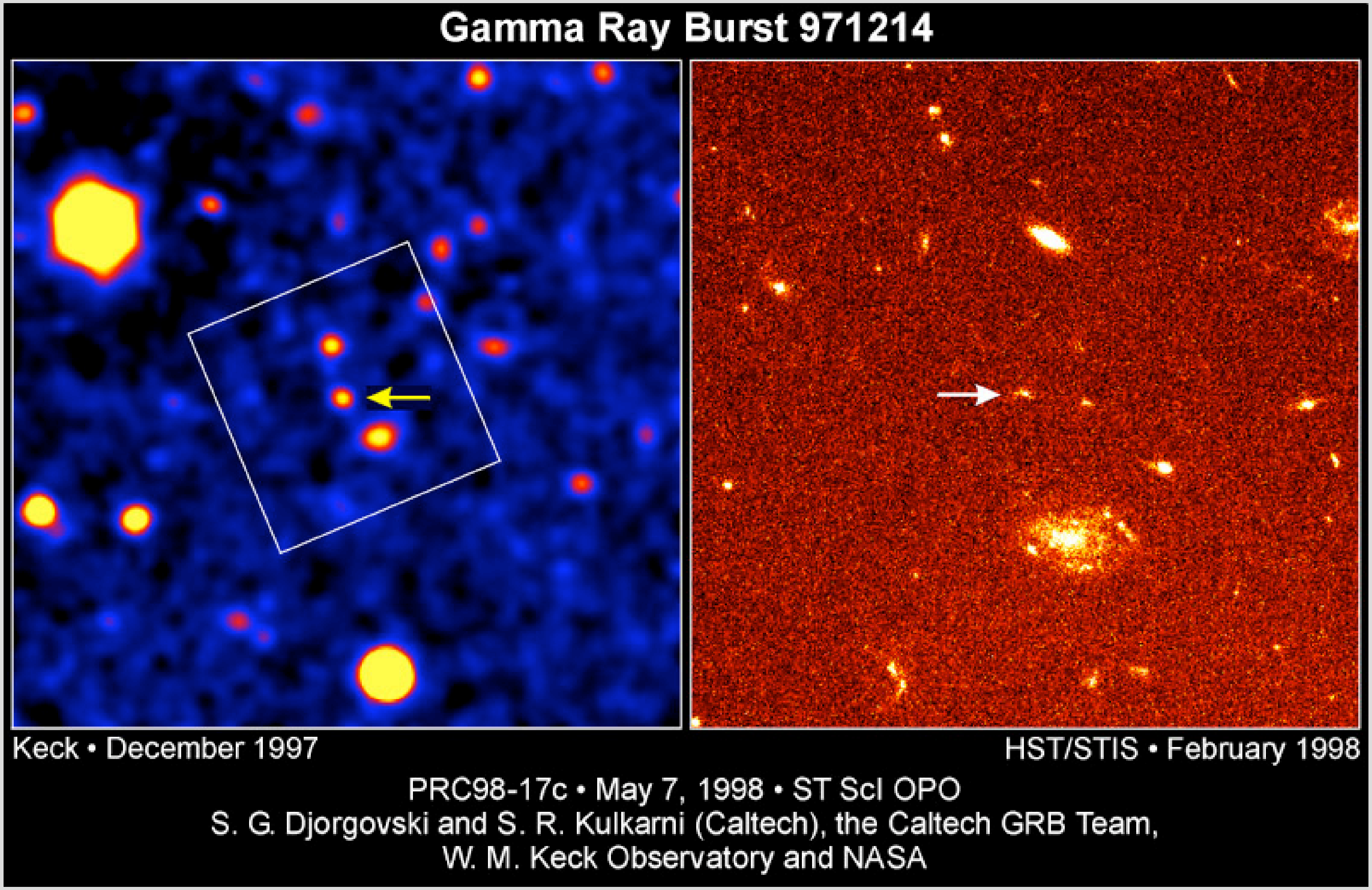
Cosmological distance scale implies very large energies, comparable or larger than supernovae but with much of the energy in gamma-rays.

Gamma-ray bursts: afterglows

Cosmological origin of gamma-ray bursts was definitively established in 1997, following launch of Italian X-ray satellite *BeppoSAX*:

- Wide field X-ray imager detected X-ray emission from location where GRB had been seen in gamma-rays
- **Much** more precise positions
- Made possible follow-up observations in other wavebands
- Detection of fading **afterglows** in the optical and radio for some (not all) GRBs

Once the afterglow has faded, host galaxies are typically found to be faint, distant galaxies



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Afterglows are **not** found only in galactic nuclei, but may be preferentially associated with regions of star formation.