## Observing the formation of stellar mass black holes

**Supernovae** are examples of cataclysmic stellar events. Properties:

- Two main types: white dwarf / core collapse
- Prominent in the optical, durations ~months
- Rate is around $10^{-2}$ per galaxy per year

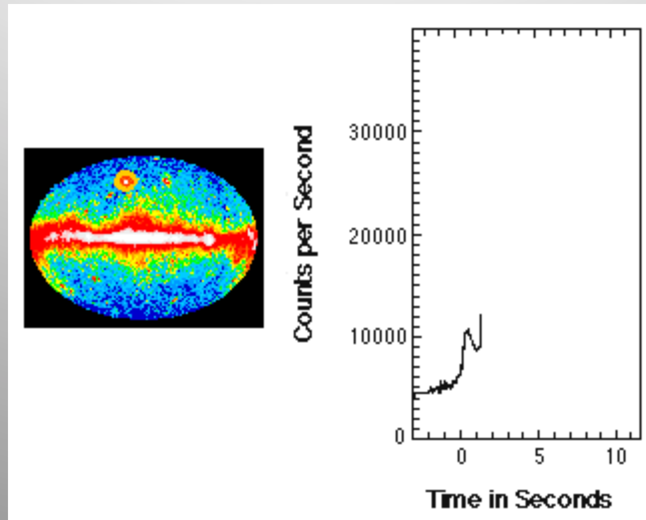
Rarer: Gamma-ray bursts

## Gamma-ray bursts: observations

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

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

Found bright, short-lived transient sources of gamma-ray emission - **gamma-ray bursts**.

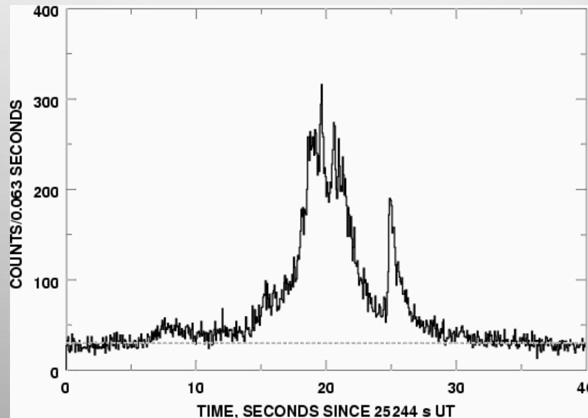



# Properties of GRBs

**Durations:** $10^{-2}$ to $10^{3}$ s
**Variability:** as short as ms

Light travel time argument suggests a compact source as the origin of GRBs

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.

# A mystery

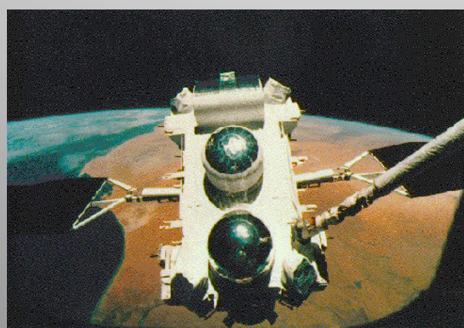
Until late 1990's, distance scale to GRBs was unknown. Could be nearby (not very luminous) or extremely distant (tremendously luminous)

Suggested models:

- Comets: d ~ 100 au
- Events on surface of Galactic neutron stars
  d ~ 1 kpc
- Cataclysmic events in distant external galaxies
  d ~ 1 Gpc: E larger than supernovae

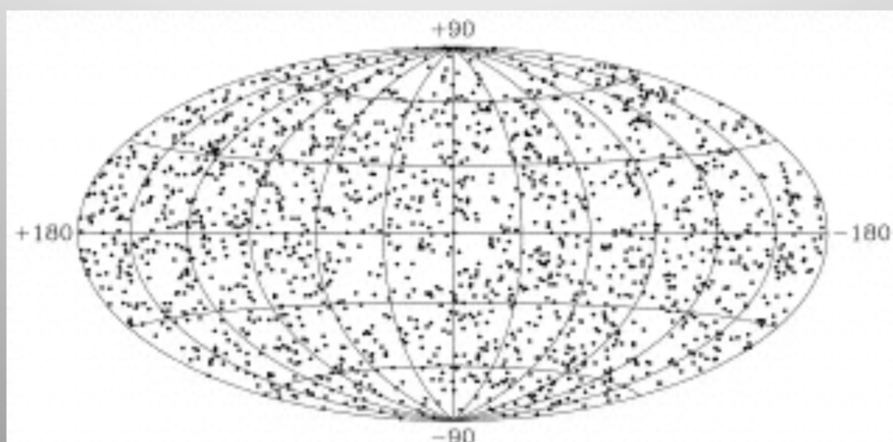
Most popular models in the early 1990s involved explosive events on the surfaces of Galactic neutron stars:

- analogy with X-ray bursts
- modest energetics



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

Distribution on sky in Galactic co-ordinates



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).

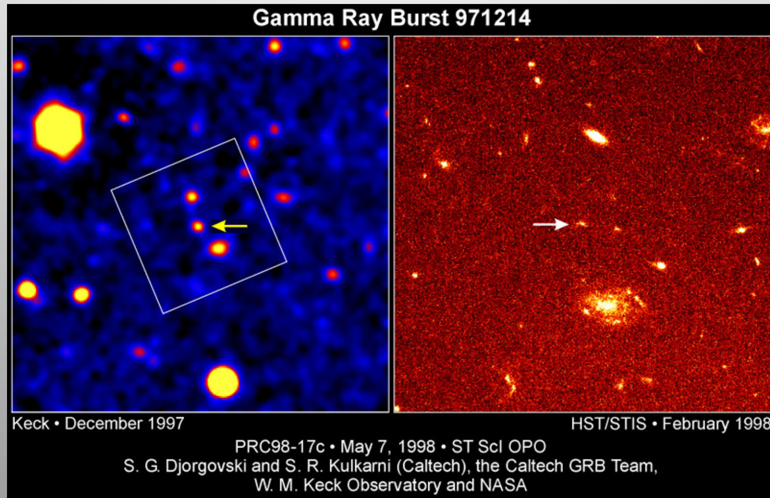
Actual spatial distribution is perfectly isotropic!

## Afterglows

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

- X-ray imager detected X-ray emission from location where GRB had been seen
- **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




Knowing the distance, can convert the measured energy release (at Earth) to the amount of energy emitted by GRB, assuming spherical (isotropic) emission

Typical result: 3 x $10^{47}$ Joules

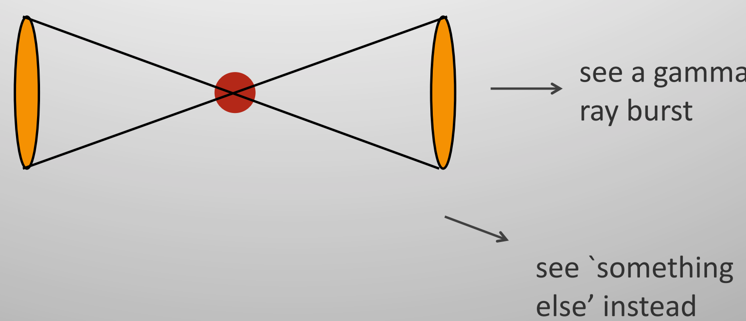
Can use $E = mc^2$ to determine the rest mass equivalent of this much energy:

$$m = \frac{E}{c^2} = \frac{3 \times 10^{47} \text{ Joule}}{\left(3 \times 10^{8} \text{ ms}^{-1}\right)^2} \approx 3 \times 10^{30} \text{ kg} \approx 1.5\, M_{sun}$$

Almost impossible to envisage a stellar process that could convert the energy equivalent of a Solar mass of matter into just gamma rays.

Implies that the assumption of isotropic emission is too simple.

Emission is *beamed* along a *jet*



Two classes of model:

- Neutron star mergers: A GRB arises when two neutron stars in a close binary coalesce due to the emission of gravitational radiation.

- Collapsar: A GRB arises from the collapse of the cores of (some) massive stars. Different from core collapse supernovae in that much of the energy goes into a jet rather than a spherically symmetric explosion.

Either case: GRBs are observational sign posts of the formation of a black hole

Many questions:

- what determines if a collapsing star produces a supernova or a gamma-ray burst?
- why do some GRBs have much brighter afterglows than others?
- …

In one case, optical flash reached magnitude 9 – almost bright enough to be seen with the naked eye