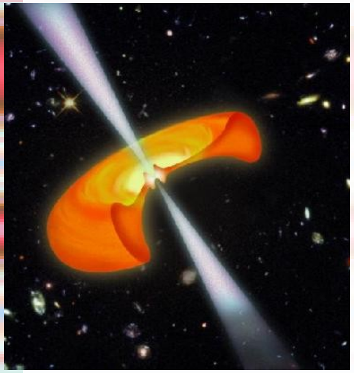
Gamma-Ray Burst: Nature's Highest Energy Process after Big Bang
&
Physics of Neutrinos

24/06/2008

Chung Yuan Christian University
Chungli, Taiwan

Sarira Sahu
ICN, UNAM
Mexico City

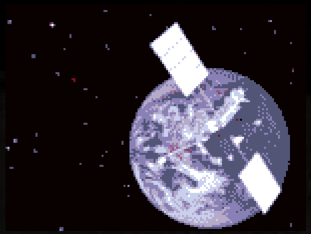


- History of GRBs
- Observations
- Modern Theory (GRB-SN connection)
- Fireball ,neutrino oscillation &
- Production of High energy neutrinos
- Summary

What are GRBs ?

Gamma Ray Bursts

Intense flashes of gamma rays lasting from fractions of a second to hours, some with fading afterglows visible for months. Apparently associated with star forming regions in galaxies, these are among the most powerful explosions in the universe. [redacted]



Example: GRB 990123
Distance – 10 billion light-years
Size – emitting region is light-seconds across
Power – at maximum up to 1,000,000,000,000,000,000 (quintillion) times the Sun's power

A Billion Trillion Suns……

Flashes have energy ~100 KeV - 1 MeV

Name: GRBYYMMDD a/b
GRB050302

Energy release: $10^{51} - 10^{53}$ **erg**

Time duration: Few seconds

Event rate: 1 event/ day

A brief moment of glory, gamma-ray bursts out shine the entire gamma- ray universe.

Energy needed (ergs)

1 → mosquito jump
10^3 → ball drop
10^10 → hit by truck
10^15 → smart bomb
10^20 → H bomb
10^26 → killer asteroid
10^40 → death star

Energy release/sec

10^33-->sun
10^39-->nova
10^41-->SN
10^52-->GRB

GRB: basic numbers

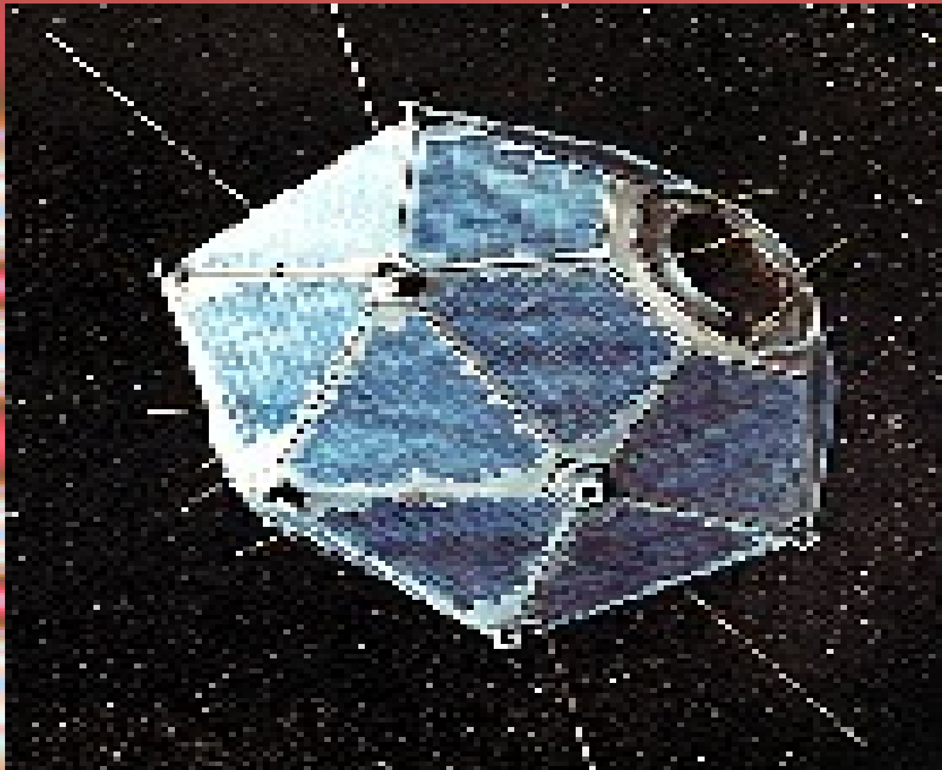
Distance: $z \leq 4.5$ ----> D $\sim 10^{28}$ cm

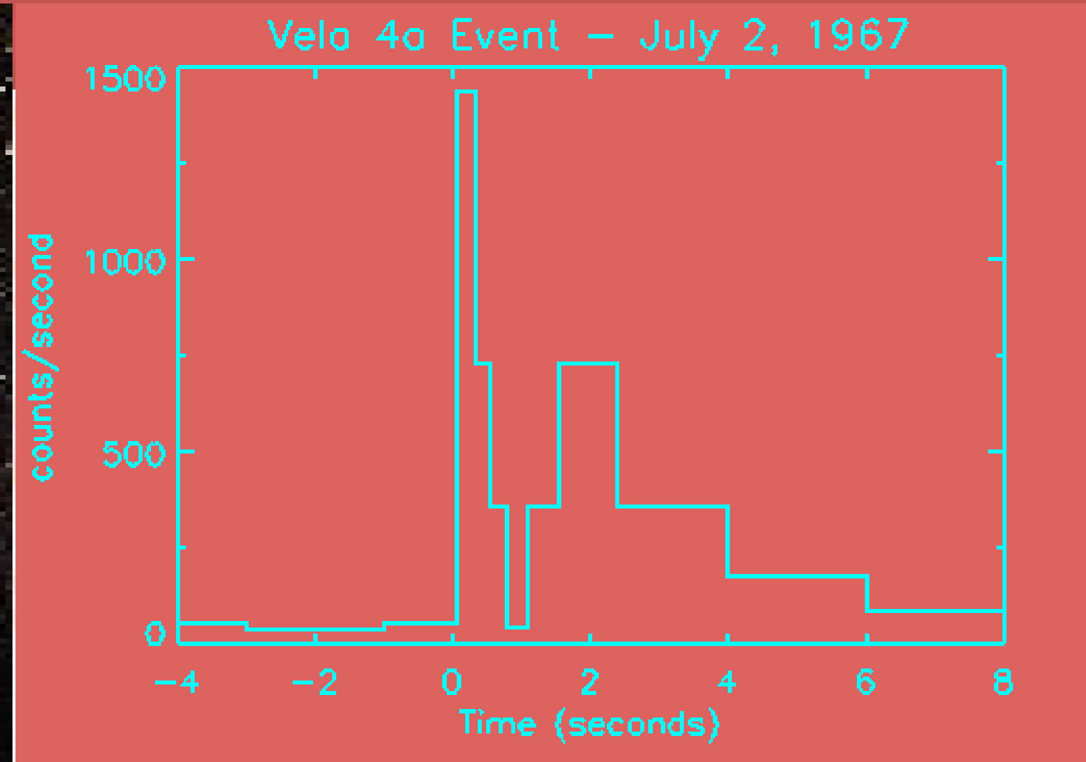
Fluence: F= $\int$ flux. dt $\sim 10^{-4}-10^{-7}\,erg/cm^2$

Energy output: $10^{53}\ (\Omega/4\pi)\ D^2_{28.5}\ F_{-5}\ erg$

Jet: $\Omega \sim 10^{-2}-10^{-1} \rightarrow E_{\gamma,tot} \sim 10^{51}\ erg$

Rate (GRB) ~ 1/day





Vela 5 b

23 May 1969-19 June 1979

Energy Range 3-750 KeV

First Event

First detection

- **Vela 4a (US DOD) monitored nuclear (& Cosmic !!) explosions**
- **First GRB det: 1967 (Klebesadel, Strong, Olsen 1973 ApJ 182, L85)**
- **Vela 5a,b/6a,b 73 GRB in 1969-79**
- **Prognoz 2 (USSR) 1972-82, Konus/Venera det. 85 GRB 1978-80**

Catching gamma-ray bursts on the fly...

- CGRO (Compton gamma-ray Observ.)
- HETE (High Energy Transient Explorer)1-500 KeV
- Swift (2004)
- GLAST , 11th June, 2008

Catching gamma-ray bursts on the fly...

CGRO (1991-2000)---4 Detectors

BATSE(burst and transient source expt.) (20 keV-1MeV)
OSS(oriented scintillation spectrometer expt.) (.05-10MeV)
COMPTEL(Compton tel.), EGRET(energetic g-ray expt. tel)
0.8-330 MeV   30 MeV-20 GeV

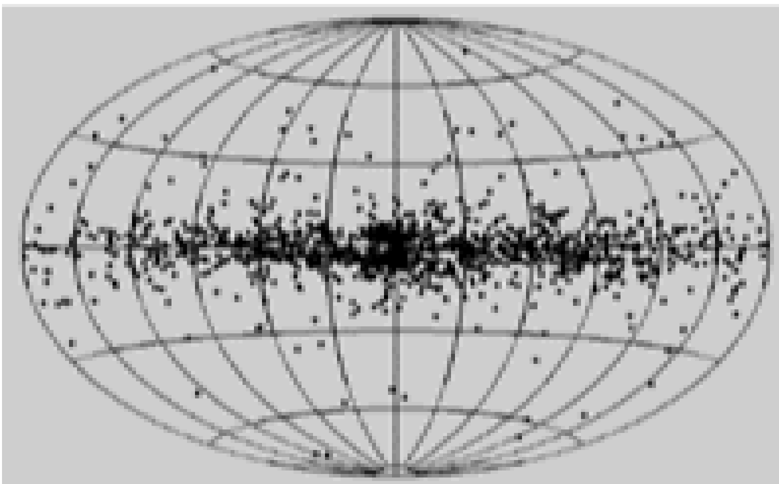
BATSE all-sky survey: **(Main Results:)**

1) GRB → isotropic distribution ⇒ Cosmol. distance

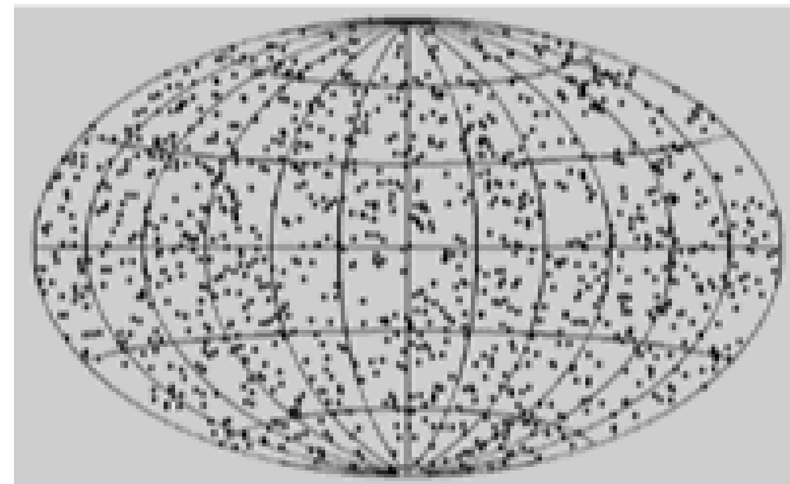
2) Long (>2 s) & Short (<2 s)

3) Non-thermal gamma-spectra

Distribution of Gamma-Ray Bursts on the Sky



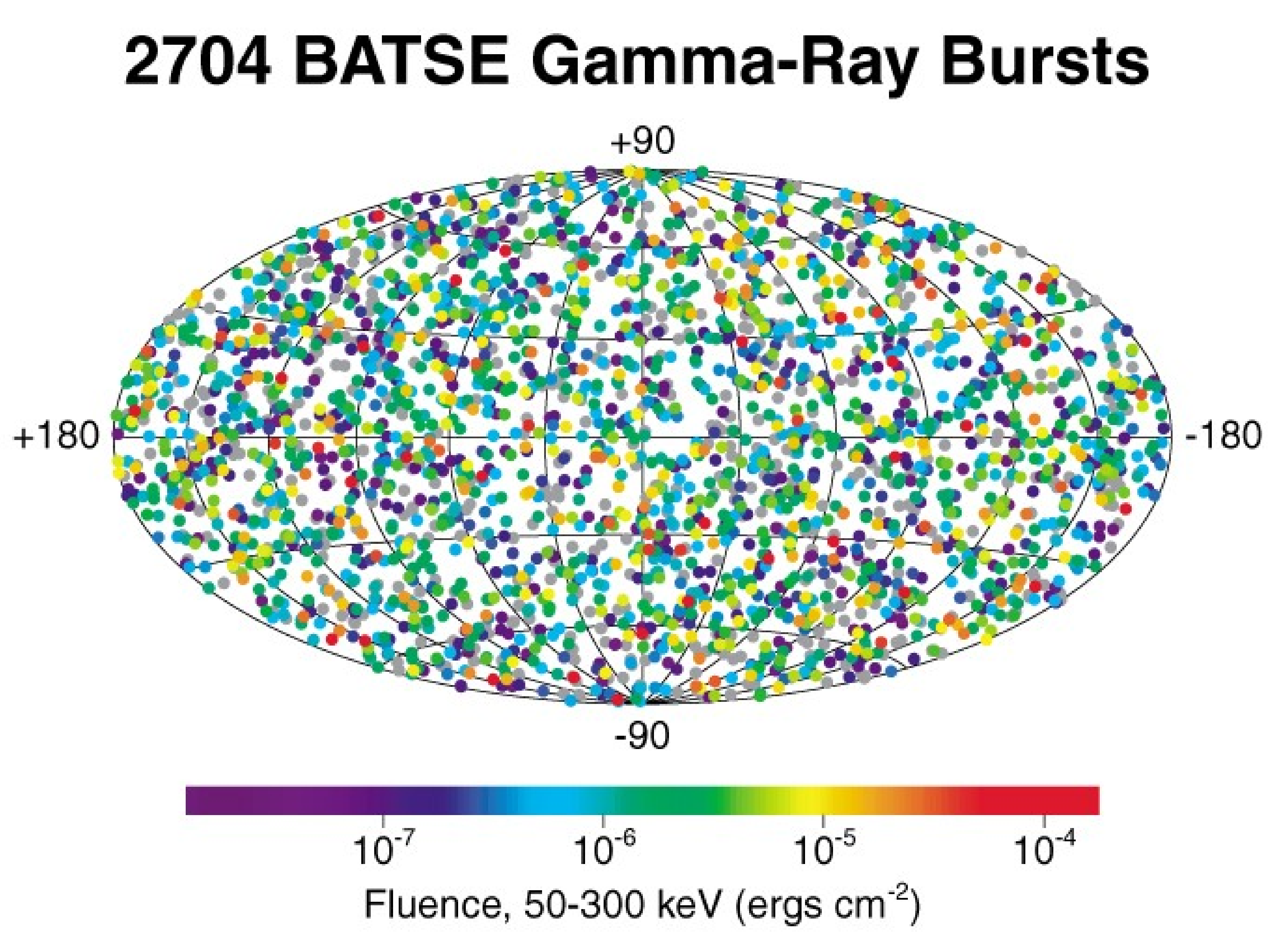
Expected



Observed

- If GRBs came from objects in our galaxy, you would expect to see more of them from the galactic equator, where we find most other galactic objects

- BATSE found that equal numbers of GRBs come from all directions



Fluence: $F = \int flux.\, dt$

Burst

The burst duration is BIOMODAL and can be divided into two subgroups

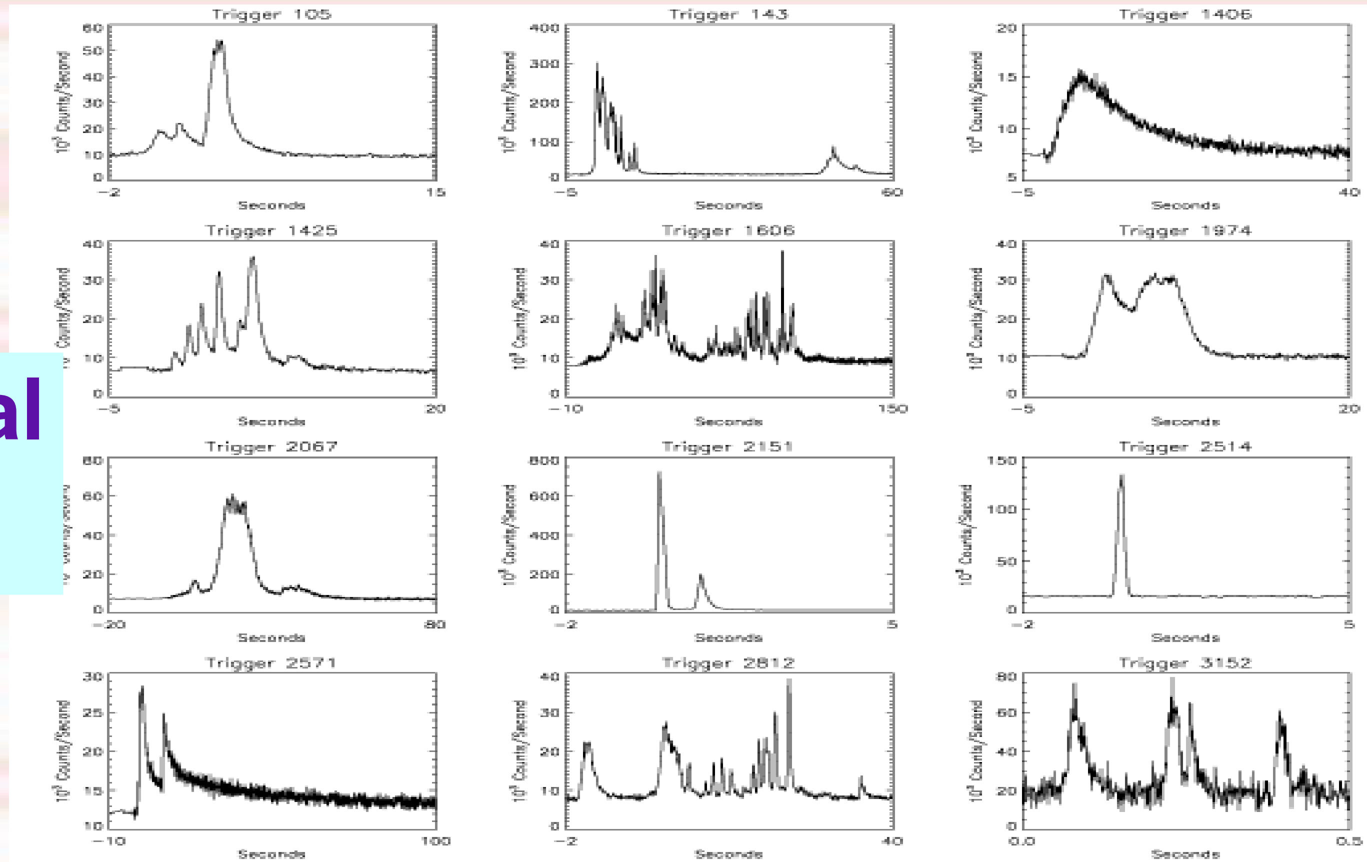
1. *Long*------ $t_{90} \geq$ 2 sec. (75%)
2. *Short*----- $t_{90} \leq$ 2 sec. (25%)

t_{90} ----The time in which 90% of the burst energy is observed

Long and Short may have completely different origin !!

All current knowledge of GRBs are mostly Long Bursts

The burst duration ranges from several micro seconds to several hundred seconds with complicated and irregular structure.



Spectrum

Non-thermal Power-Law

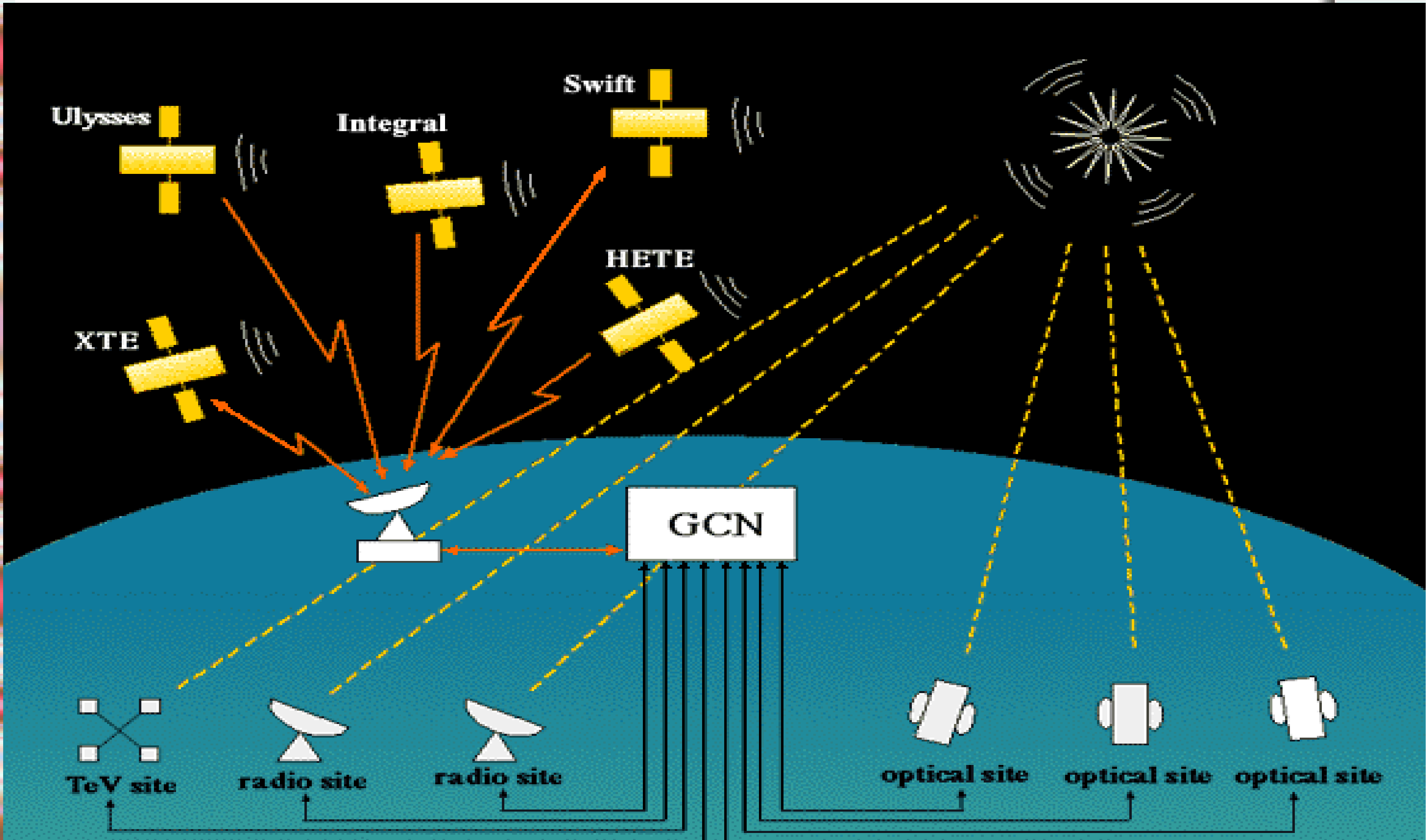
$N(E)\,dE \propto E^{-\alpha}$

$\alpha \simeq 2$

No two grbs are the same. Some are short, some are long, some are weak, some are strong, some have many spikes, some have none, each unlike the other one.

Let's all be informed.......

GRB Coordinates Network (GCN)

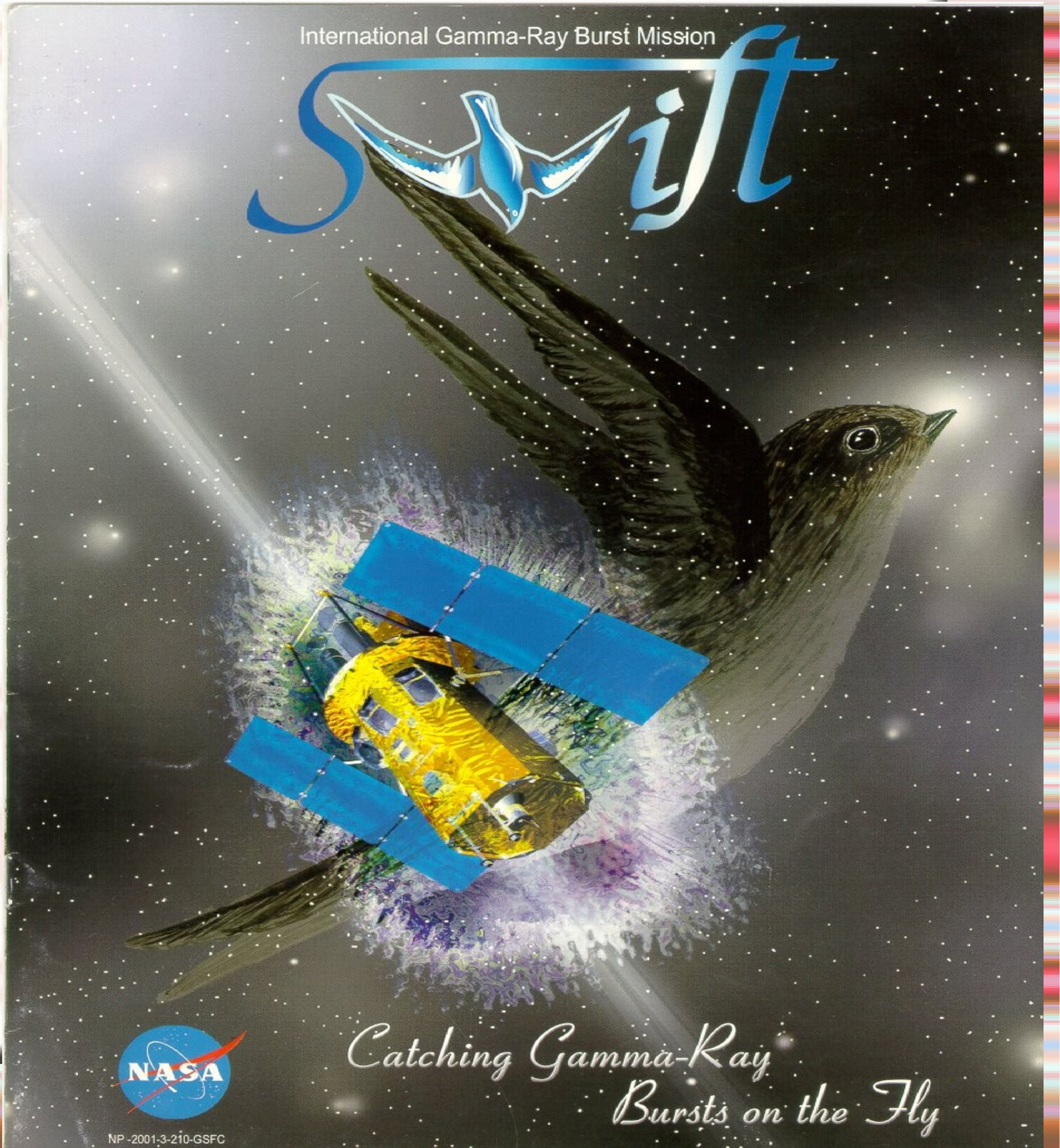


Swift Mission

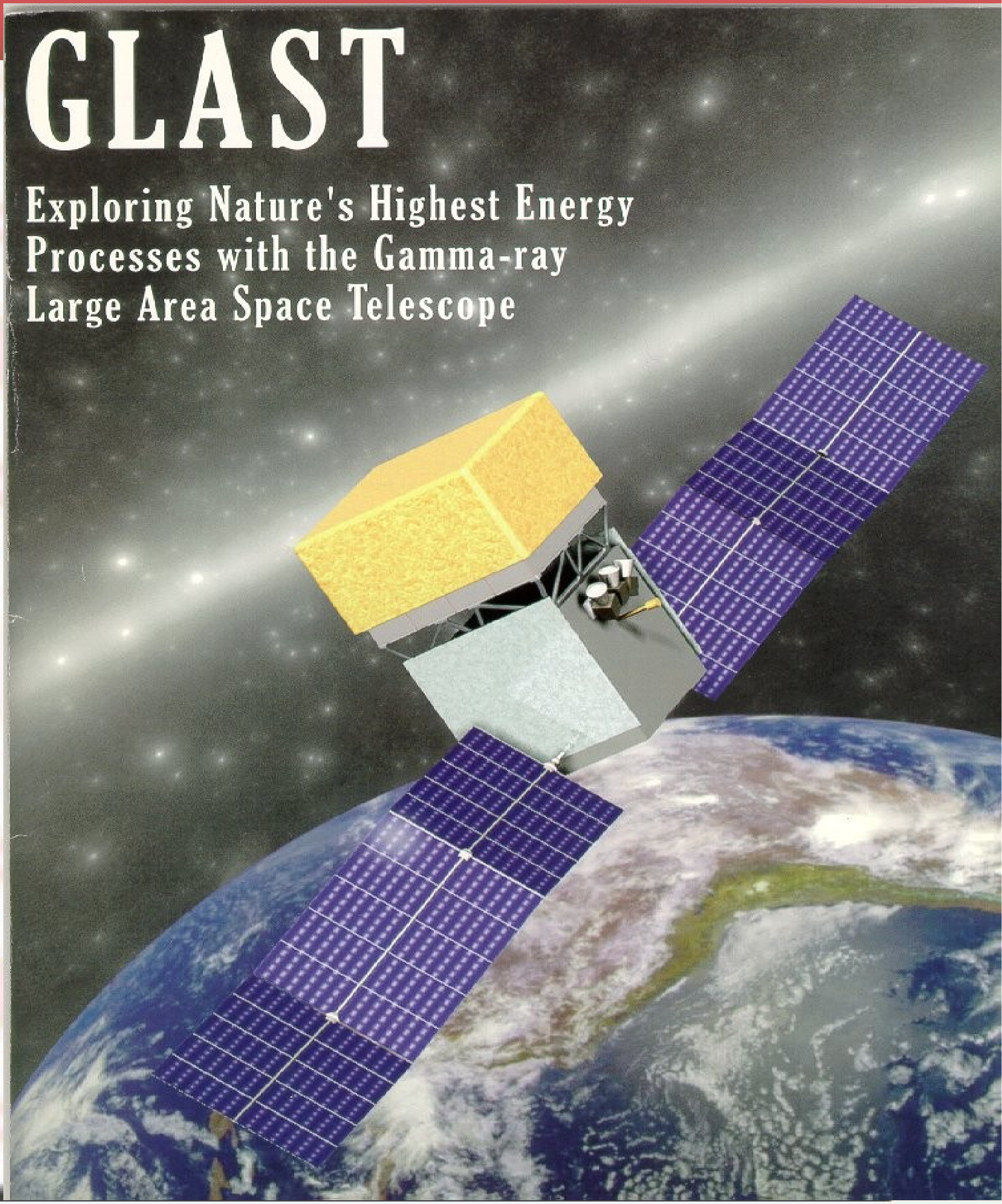
Launched: 20 Nov. 2004

Life Time: 3 Years
Det. Rate: > 100 Year
Reporting Time: 75 sec.
Detectors:
BAT (Burst Alert Telescope)
15-150 keV
XRT (X-ray Telescope)
.2-10 keV
UVOT (UV/Optical Tel.)
Wavelength Range
170 nm-600 nm

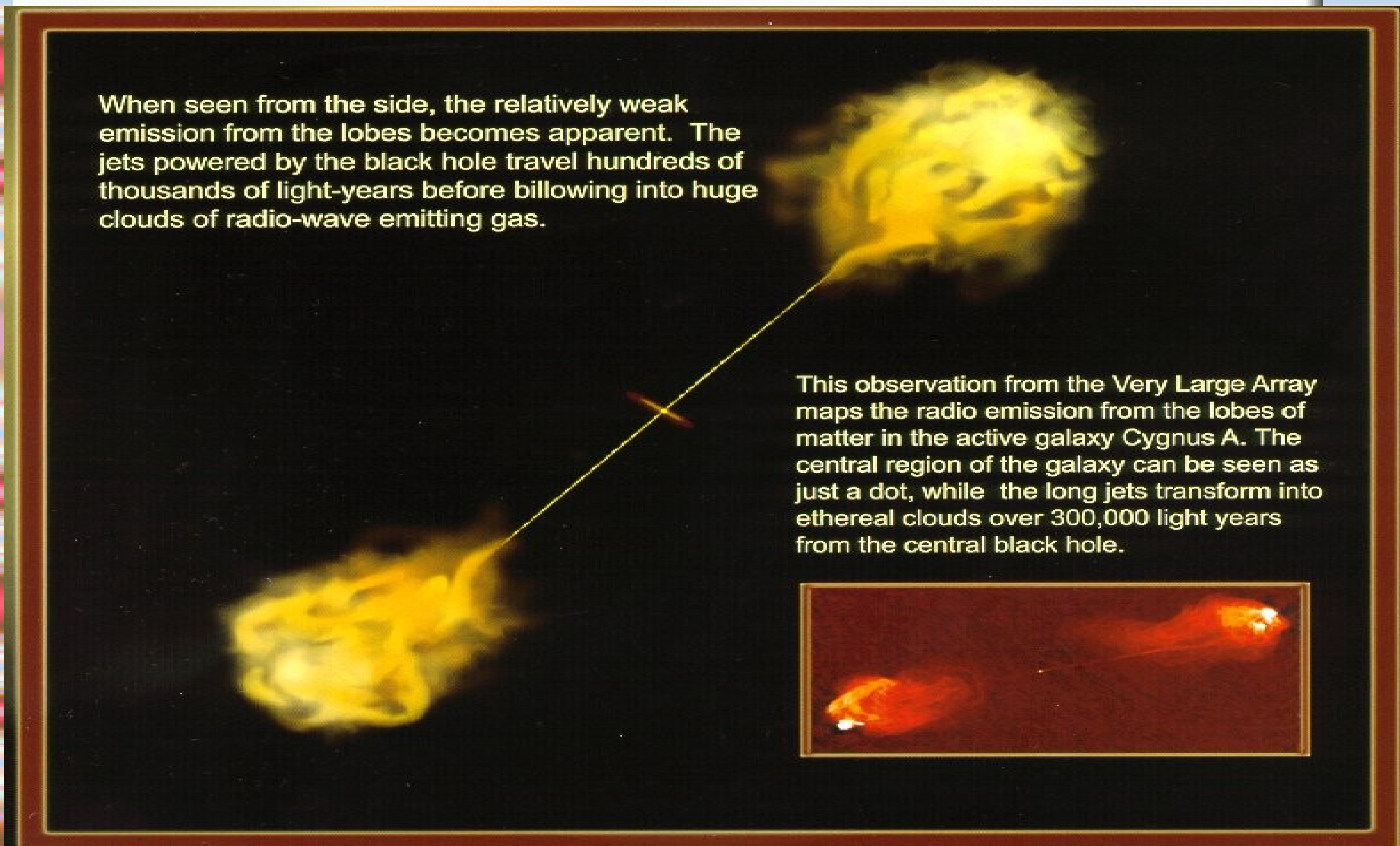
~171detected so far
First: GRB041217
Latest : GRB061121



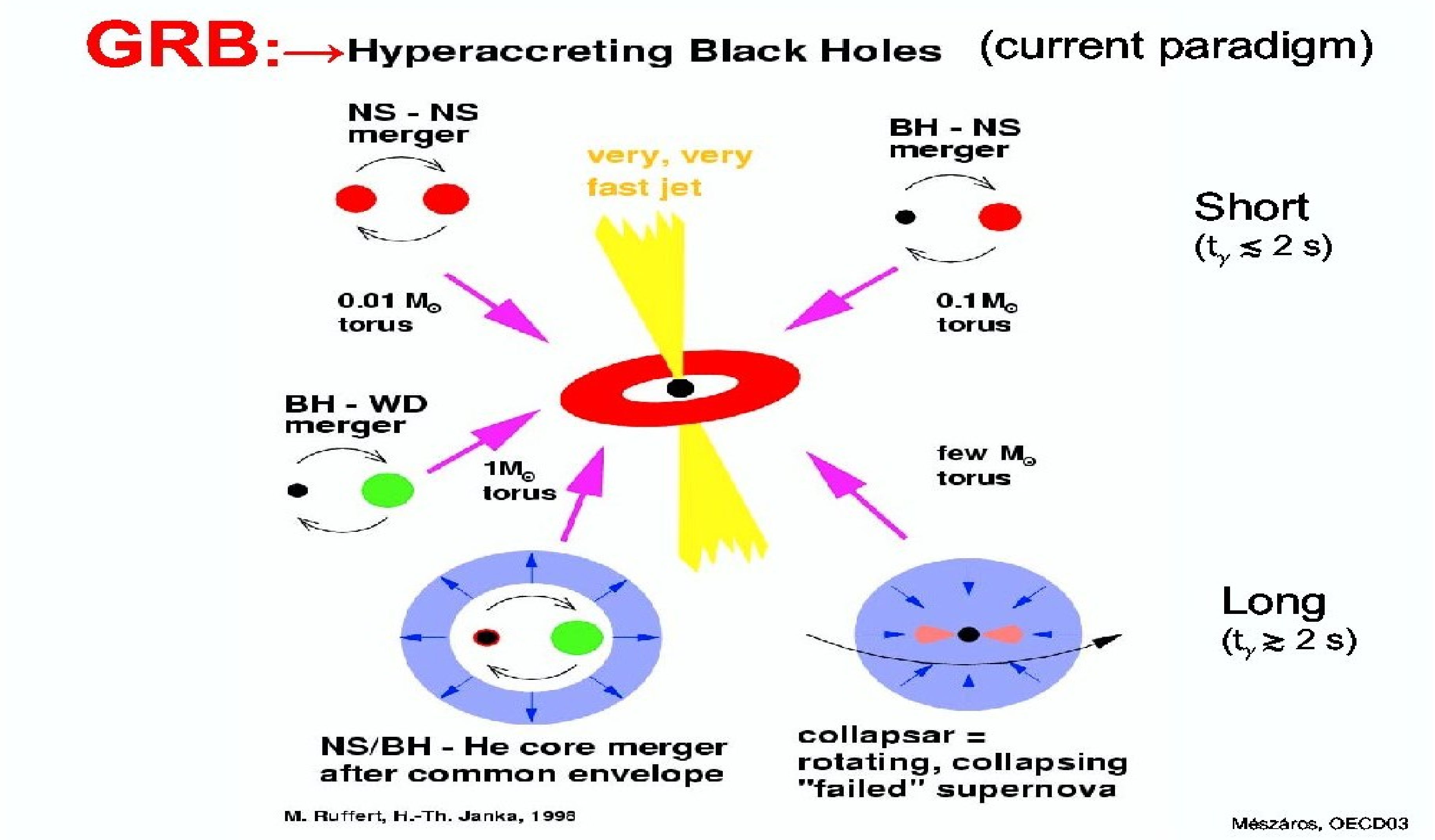
Detectors
•LAT(large area tel.)
20 MeV-300 GeV
•GBM (grb burst monitor)
<10 keV- > 25 MeV
GRB, DARK MATTER.......



So Energetic, Yet So Mysterious……



The models of GRBs.....



The supernova connection

Peter Mészáros

They are the most energetic events in the Universe, but the origin of γ-ray bursts has been hard to establish. Observations of a burst close to our Galaxy now show that supernovae are, as suspected, likely culprits.

The fog surrounding the identity of the progenitors of γ-ray bursts (GRBs) is beginning to lift, at least for the class of GRBs known as 'long' bursts. This is thanks to a series of observations of a burst that began on 29 March 2003, very close to our Galaxy. On pages 843, 844 and 847 of this issue, Uemura *et al.*[1], Price *et al.*[2] and Hjorth *et al.*[3] reveal the evolution of this burst in unprecedented detail — and show that behind the GRB is the unmistakable signature of a supernova.

The GRB population divides neatly into long ones and short ones, depending on whether the burst of γ-rays lasts more or less than a few seconds[4]. About two-thirds of all observed bursts are long, and these are the only ones for which longer-lasting 'afterglows' at X-ray, optical and radio wavelengths have also been found. These afterglows may last up to several months, and from them the distance to the GRB and the identity of its host galaxy can be determined. There is good evidence that long bursts are largely associated with active, star-forming regions in small, blue galaxies. And, in at least three cases, there has been tantalizing evidence that GRBs are associated with a particular type of supernova[4] — although that interpretation has so far been fraught with uncertainty.

A 'usual' supernova arises when the core of a massive star collapses, ejecting the stellar outer envelope. The majority of such supernovae result from parent stars that are less than about 30 times heavier than the Sun, and the core collapse produces a neutron star. These supernovae are normally detected weeks after the collapse, because the ejected envelope only brightens sufficiently to be detected at optical wavelengths some weeks later. The only signals of the collapse that are expected to reach the Earth promptly are a flux of tiny particles called neutrinos (which was picked up for the supernova SN1987a by the Japanese neutrino detector Kamiokande) and gravitational waves (which have yet to be detected).

For heavier stars, however, the core is thought to collapse into a black hole, and the resulting brief episode of mass accretion has been proposed as the central engine driving GRBs[5]. This kind of collapse was initially referred to as a 'failed' supernova, as it was thought that the stellar envelope would not be ejected. A GRB would instead result from a relativistic jet of gas fed by the black hole; it would break through the stellar envelope, leading to radiative shocks in the rarefied environment outside the star.

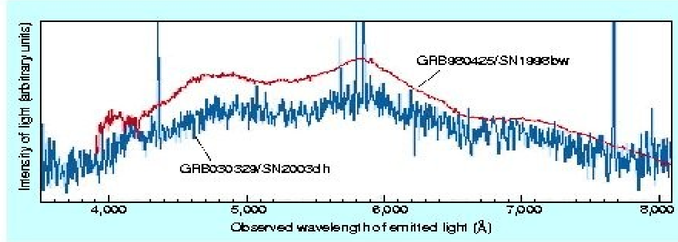


Figure 1 A good match. The spectra of the wavelengths of radiation from the γ-ray burst GRB030329, believed to be associated with the supernova SN2003dh, and from GRB980425/SN1998bw are remarkably similar in shape[1,5], suggesting that in general the GRB and supernova phenomena are related. Detailed observations[1–3] of GRB030329 offer the strongest proof yet that γ-ray bursts are indeed produced by supernovae that result when the core of a massive star collapses.

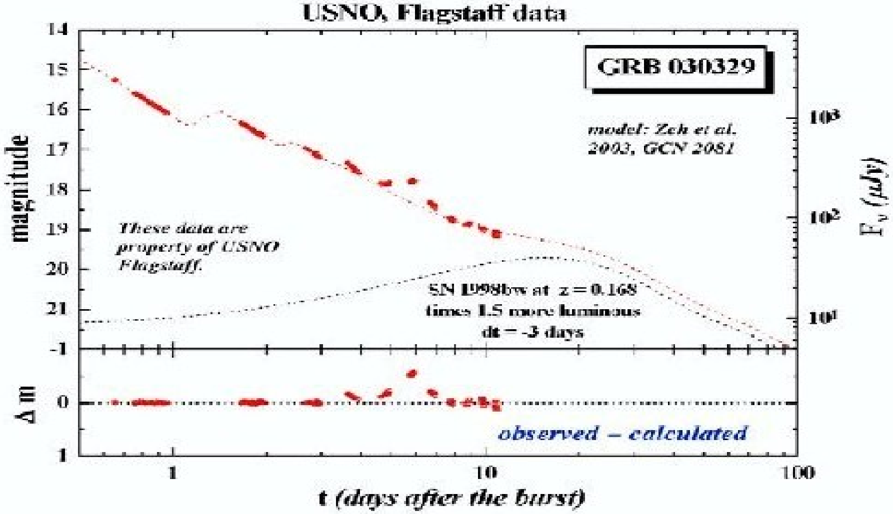
In 1998, observations of GRB980425 showed an anomalous brightening of its optical afterglow a few weeks after the burst, possibly linking it to a roughly contemporaneous supernova, known as SN1998bw, whose ejected envelope would have brightened at about that time. Suspicions grew that long GRBs might, after all, be associated with 'successful' supernovae. In fact, the few supernovae tentatively linked to GRBs appeared even more energetic than usual, and were dubbed 'hypernovae'[6], or 'collapsars'[7]. There is also a more elaborate offshoot of the supernova idea — the 'supranova'[8]. Here, the core collapse is assumed to be a two-step affair: the first step produces a temporary neutron star and a supernova; in the second step, a few weeks or months later, the neutron star collapses into a black hole, producing a GRB.

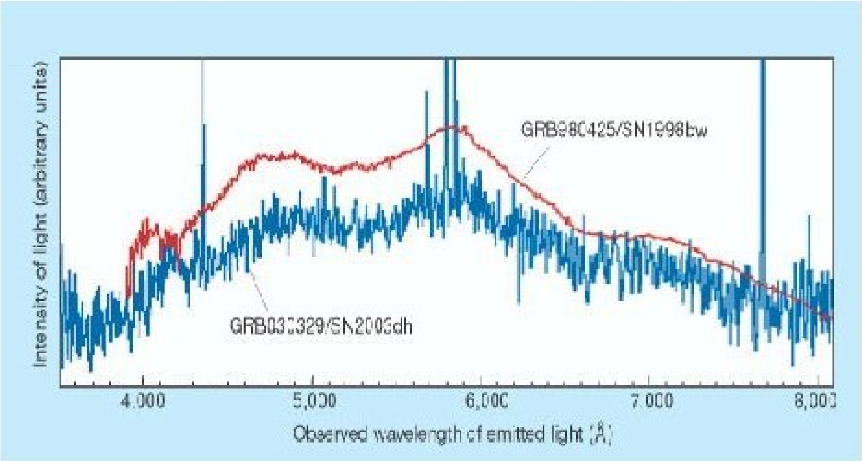
The association of long GRBs with supernovae (or even supranovae) is based on the approximate coincidence in time of the GRB and the inferred instant of the supernova core-collapse. The latter is deduced from an extrapolation back from the peak brightness of emitted light — an extrapolation that is model-dependent and uncertain, not least because these objects are so far away and very faint. This situation changed dramatically with the observation of GRB030329 in March of this year. Its coordinates were disseminated by the HETE-2 spacecraft within 90 minutes of its detection, enabling ground-based telescopes to make follow-up observations almost immediately. Although more than two billion light years away, GRB030329 may be the nearest cosmological GRB yet seen[1,9]. (In terms of the conventional astronomical distance measure, its 'redshift', z, is 0.169; previous GRBs have usually only been seen in the range 0.4–4.5; the exception is GRB980425, if its association with SN1998bw at $z = 0.008$ is real.)

After a week, the pattern of light emitted by GRB030329 — its 'light curve' — started to show the beginnings of a slight bump. Ten days later, this bump was identified as being caused by an energetic supernova, labelled SN2003dh[3,10]. Because this GRB is relatively close to us, the identification of the light-curve peak, and its wavelength spectrum, is significantly stronger than in previous cases. The extrapolation from the peak brightness indicates that the time off-set between the GRB and the collapse of the supernova is unlikely to be greater than about two days, and is compatible with the two events being simultaneous. Hjorth *et al.*[3] interpret this as ruling out the supranova model: if the two-step collapse of a supranova were to happen within two days, it is unlikely that its γ-ray emission and afterglow would match the observations.

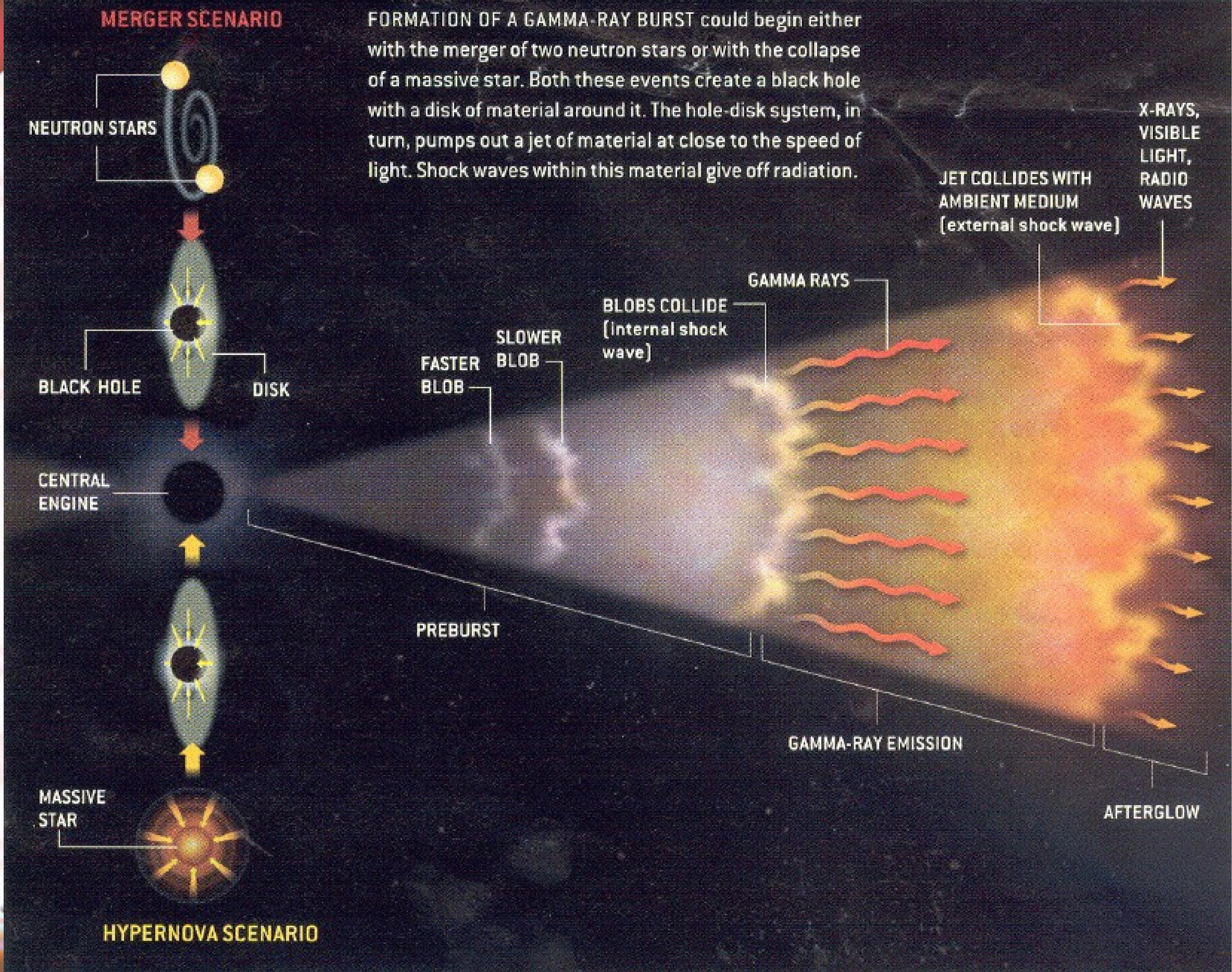
Another remarkable feature of GRB030329 is the spectrum of wavelengths it has emitted. There is a tantalizing match between the shape of the distribution for GRB030329/SN2003dh and that of

GRB 030329 ⇔ SN 2003dh : Yes !



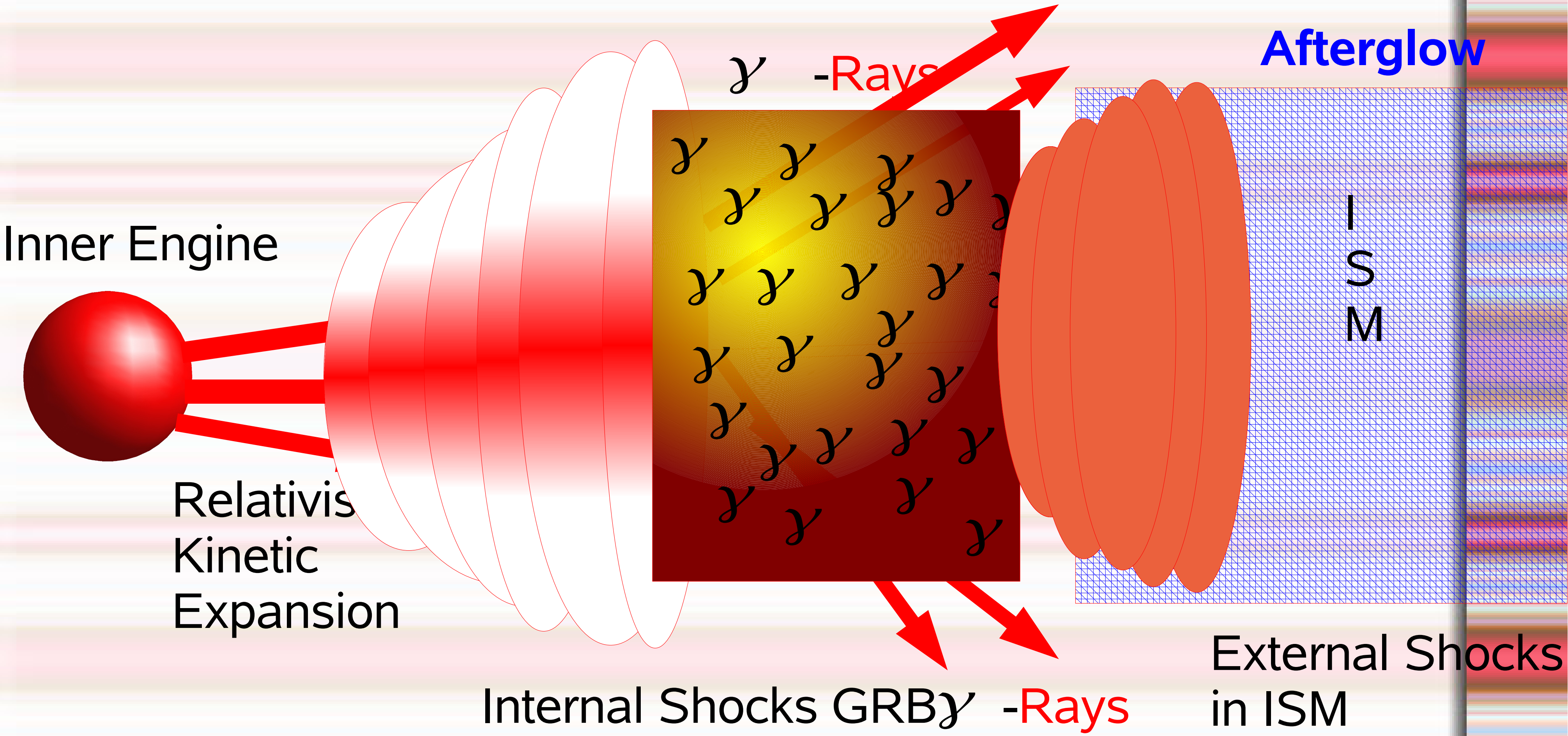


- Nearest "unequivocal" cosmological GRB: z=0.17
- GRB-SN associaton: **"strong"**
- Fluence: 10^{-4} erg cm^{-2} ,
  among highest in BATSE,
  but $\Delta t_\gamma \sim 30s$, nearby;
  $E_{\gamma,iso} \sim 10^{50.5}$erg: ~typical,
- $E_{SN2003dh,iso} \sim 10^{52.3}$ erg
  $\sim E_{SN1998bw,iso}$ (↔grb980425)
  $v_{sn,ej} \sim 0.1c$ (→ "hypernova")
- GRB-SN time off-set ? at most:
  ≲ 2 days (from opt. lightcurve)
  (⟹ i.e. not a "supra-nova")
- But: could be 2-stage (<2 day delay) ⋆- NS-BH collapse ?
  →ν predictions may test this !

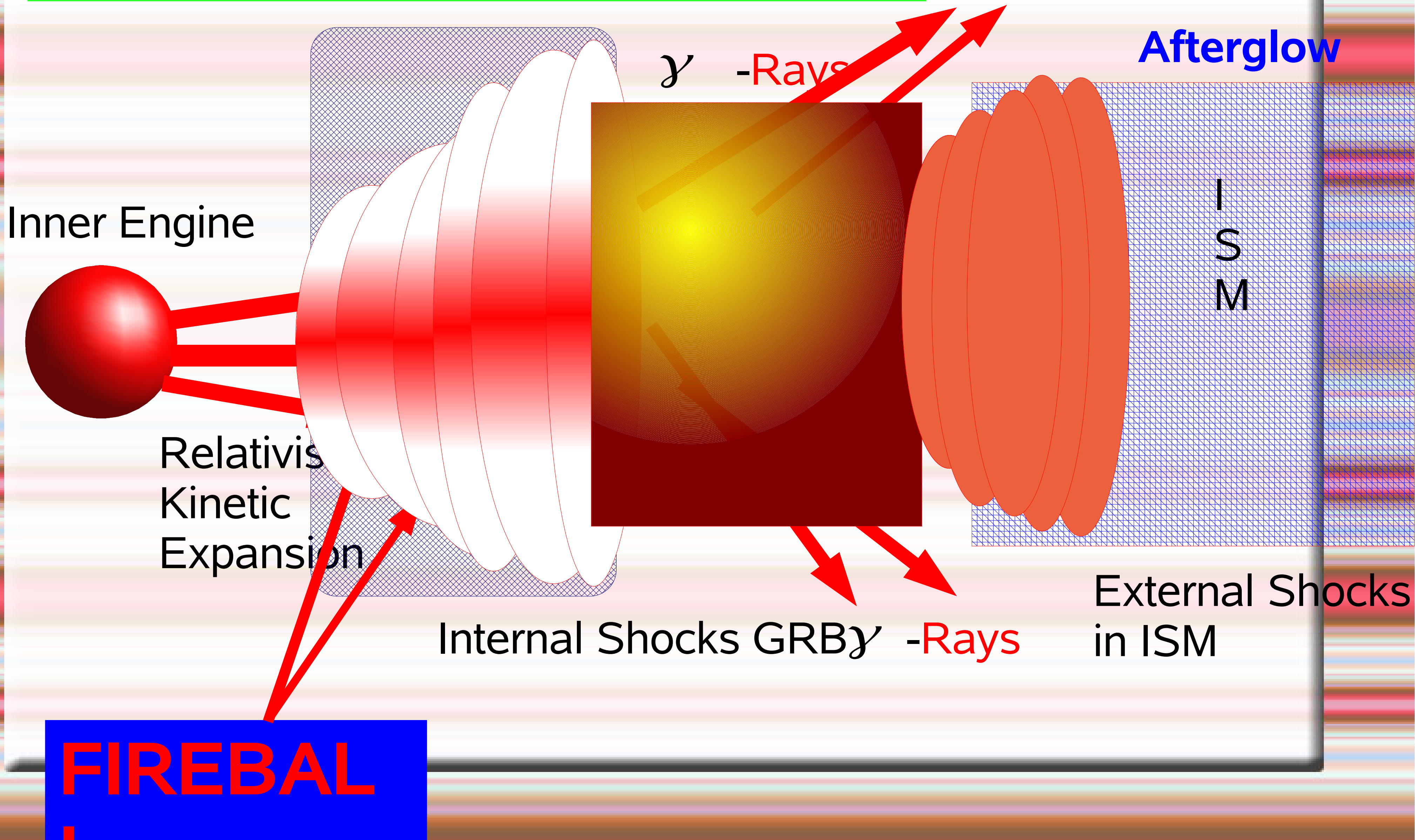


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

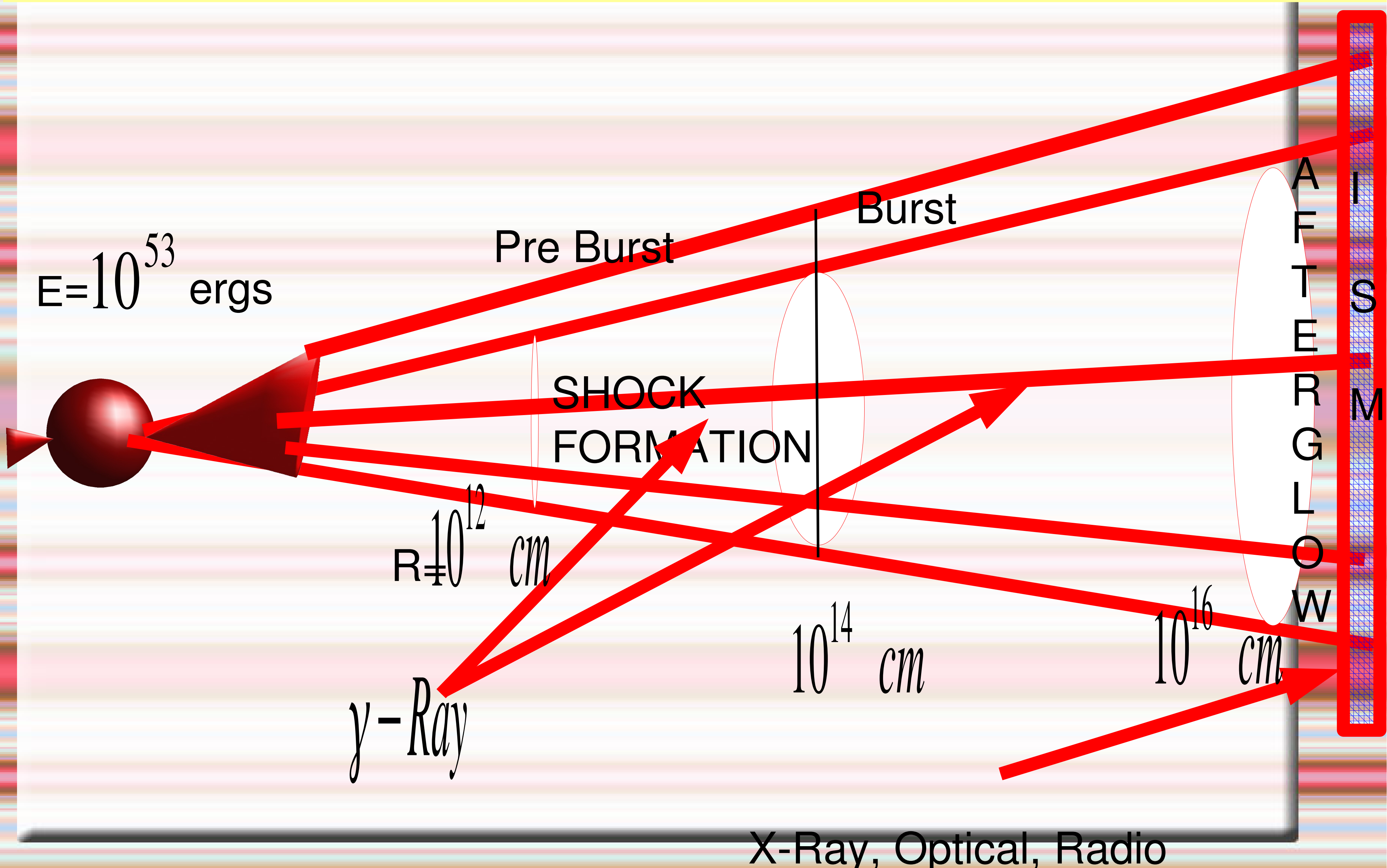
Internal External Fireball Model



Internal External Fireball Model



How far from the Hidden Central Engine......



Fireball : Internal, External Shocks

Internal Shocks:

- Central engine injects energy intermittently in the form of SHELLS, with non-uniform Lorentz factor

- First moving shell will collide with slower one

- Collisions produces a pair of shocks going into both shells

- Heating them and accelerating *e* and *p*.

- With some magnetic field in the shell, these *e* & *p* emit Synchrotron radiation (non-thermal) in the gamma-ray (blue shift)

Merit of the Collapsar Model:

- Involve a GRB-SN association
- GRBs are associated with star forming regions
- Existence of stellar envelope helps to collimate a jet and can help to regulate the jet flow intermittently.
- The duration of a burst is the fall-back time scale (between two successive shells)

All these are consistent with the observations:

GRB980425-SN1998bw (z=0.008)

GRB030329-SN2003dh (z=0.169)

Fireball

Rapid rise time of the gamma-ray spectra implies sources are compact size ~ 100 – 1000 Km

Temperature ~ 3 - 10 MeV

Sudden release of copious amount of gamma-ray photons in to a compact region creates an opaque photon-lepton fireball due to the formation of electron-positron pair.

Radiation can not escape, optical depth is very high.

Dirty Fireball

- Baryon contamination in addition to $e^+ e^-$

- Electron associated with the baryons increase the opacity of radiation

- Are dragged by accelerated electrons and part of the radiation is converted to kinetic energy of the baryons

- If baryon load is high ($\geq 10^{-8} M_{sun}$), no relativistic expansion

Baryon Load in the fireball:

Computer simulation suggests baryon load has to be very small (outstanding problem)

$$\sim 10^{-8} M_\odot \ - \ 10^{-5} M_\odot$$

Otherwise the expansion is Newtonian & NO GRB

Fireball has to expand relativistically !!!
Consistent with the OBSERVATION.

T.Piran Phys. Rep. 314, 575 (1999)
E. Waxman, Lect. Notes Phys. 598, 393 (2003)

Neutrino oscillation in the fireball

Sources for the neutrinos:

- Neutrinos of about 5-20 MeV are generated due to the stellar collapse or merger event that trigger the burst.
- Nucleon bremsstrahlung, N+N------->N+N+ $\nu + \bar{\nu}$

$$e^+ + e^- = e^+ + e^- + \nu + \bar{\nu}$$

And

- In the Fireball

$$p + e^- \longrightarrow n + \nu_e$$

All have energy in the MeV range.

All these neutrinos will propagate through the fireball.

Neutrino oscillations:

In a relativistic and non degenerate e^+e^- plasma, the effective potential experience by a electron neutrino is

$$V_{\nu_e} \simeq \sqrt{2} G_F N_\gamma \left(L_e - 7 \frac{\xi(4)}{\xi(3)} \frac{T^2}{M_W^2} \right).$$

By a muon neutrino

$$V_{\nu_\mu} \simeq \sqrt{2} G_F N_\gamma L_{\mu,\tau}$$

We study the oscillation processes

$$\nu_e \leftarrow\rightarrow \nu_{\mu,\tau}, \quad \nu_e \leftarrow\rightarrow \nu_s, \quad \bar{\nu}_e \leftarrow\rightarrow \bar{\nu}_{\mu,\tau}$$

Neutrino potential:

$$V \simeq 4.02 \times 10^{-12}\, T_{MeV}^{3} \left[\pm L_e - 6.14 \times 10^{-9}\, T_{MeV}^{2} \right] MeV. \qquad \pm \to \nu, \bar{\nu}$$

Probability of conversion after a time t

$$P(t) = \frac{\Delta^2 \sin^2 2\theta}{\omega^2} \sin^2\left(\omega \frac{t}{2}\right) . \quad \Delta = \frac{\Delta m^2}{2E_\nu}$$

$$\omega = \sqrt{\left(V - \Delta \cos 2\theta\right)^2 + \Delta^2 \sin^2 2\theta}$$

E_ν is the neutrino energy (5-20 MeV), θ is the mixing angle

Resonance condition

$$V = \Delta \cos 2\theta$$

We assume:

$$L_e > 6.14\times10^{-9}\ T_{MeV}^2$$

At resonance:

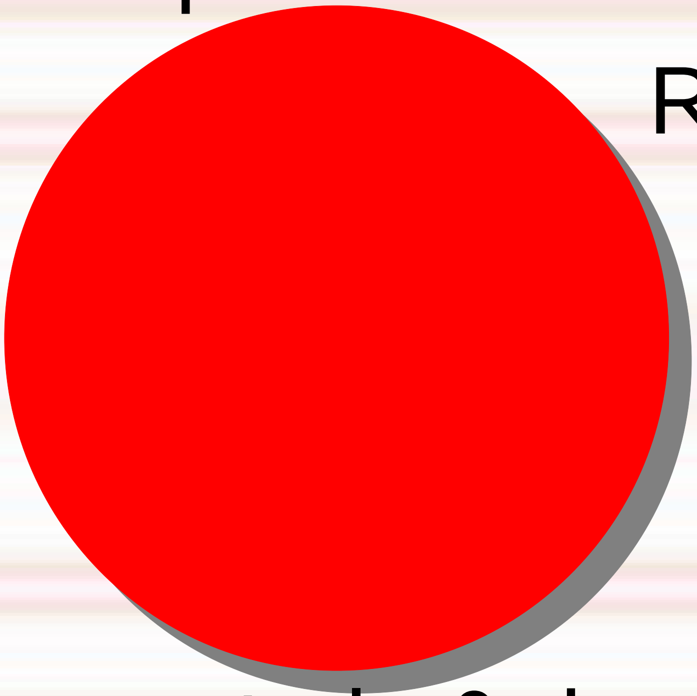
$$L_{res} \simeq 248 \frac{E_{MeV}}{\Delta \tilde{m}^2 \sin 2\theta}\ cm$$

$$M_{baryon} \sim 2.23\times10^{-4}\ R_7^3\ T_{MeV}^3\ L_e\ M_\odot$$

$$T_{MeV}^5 < 0.2\times10^8 \frac{\Delta \tilde{m}^2 \cos 2\theta}{E_{MeV}}$$

Assumptions

The fireball is spherical with radius



R~100-1000 KM

T.Piran, Phys. Rep. 314,575 (1999)

It is charge neutral & having equal number of protons and neutrons.

Derishev et al., A&A 345, L51 (1999); APJ 521, 640 (1999)

Solar neutrinos:

SNO + KamLAND (reactor)

SNO Collaboration, PRL 92, 181301 (2004)

KamLAND Collaboration, hep-ex/0406035

Best fit is at

$$6\times10^{-5}\ eV^2 < \Delta m^2 < 10^{-4}\ eV^2 , \quad 0.8 < \sin 2\theta < 0.98$$

$$\Delta m^2 \sim 7.1 \times 10^{-5}\ eV^2, \quad \sin 2\theta \sim 0.83$$

$$L_e \cong 0.5 \times 10^{-5}\, T_{MeV}^{-3}\, E_{MeV}^{-1},$$

$$T_{MeV} < 2.8$$

$E_{MeV} = 5$:

$$M_{baryon} \sim 0.23\times10^{-9} R_7^3\, M_\odot$$

$$L_{res} \sim 211\,Km$$

$E_{MeV} = 20$:

$$M_{baryon} \sim 0.58\times10^{-10} R_7^3\, M_\odot$$

$$L_{res} \sim 845\,Km$$

Probably very few or NO resonant oscillations take place within the fireball and most of the neutrinos will come out.

Atmospheric Neutrinos:

Super-Kamiokande:
SK Collaboration, PRL 93, 101801 (2004)

We take Average Value

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$, $0.9 \leqslant \sin^2 2\theta \leqslant 1.0$

$\Delta m^2 \sim 2.5 \times 10^{-3}\ eV^2 , \quad \sin^2 2\theta \sim 0.9$

gives $L_e \simeq 0.98 \times 10^{-4}\ T_{MeV}^{-3}\ E_{MeV}^{-1}$

$T_{MeV} < 5$

$E_{MeV} = 5$

$E_{MeV} = 20$

$M_{baryon} \sim 0.44 \times 10^{-8} R_7^3\ M\odot$

$L_{res} \sim 5\ Km$

$M_{baryon} \sim 0.11 \times 10^{-8} R_7^3\ M\odot$

$L_{res} \sim 21\ Km$

Neutrinos can have many resonant oscillations within the fireball.

Reactor Neutrinos:

Liquid Scintillator Neutrino Detector (LSND) & KARMEN 2, combined Analysis:

Phys. Rev D66, 013001 (2002)

We consider

$$0.45\ eV^2 < \Delta m^2 < 1\ eV^2, \quad 2\times10^{-3} < \sin^2 2\theta < 7\times10^{-3}$$

$$\Delta m^2 \sim 0.5\ eV^2, \quad \sin 2\theta \sim 0.07$$

Gives

$$T_{MeV} < 18$$

$$E_{MeV} = 5$$

$$E_{MeV} = 20$$

$$M_{baryon} \sim 0.3\times10^{-5} R_7^3\ M_\odot$$

$$L_{res} < 1\ Km$$

$$M_{baryon} \sim 0.7\times10^{-6} R_7^3\ M_\odot$$

$$L_{res} < 1.4\ Km$$

Neutrinos will oscillate several times before coming out of the fireball.

Summary:

From the Collapsar/Hypernova model of GRBs lots of neutrinos will be produced and fractions of these neutrinos will propagate through the fireball.

We studied the resonant oscillation of these neutrinos in the fireball.

Conclusions: (cont.)

We assume

1.) Spherical Fireball R~100-1000 Km.
2.) Charge neutral
3.) No. of Protons = No. of Neutrons
4.) $L_e > 6.14 \times 10^{(-9)} T^2_{MeV}$

Conclusions: (cont.)

Neutrino oscillation is possible

If.....

Neutrino mass square difference & mixing angle are in the

Atmospheric and/or Reactor expt. ranges

for SOLAR *May be just............*

Is it possible to detect these neutrinos....

Unfortunately not with the present generation detectors.........
Similar to SN1987A burst but very very far, flux is very small

The road leading to an understanding the nature of these objects is bumpy......

A List of outstanding problems:

1.) Hidden Central Engine....

2.) Means of transport of energy ....

3.) Why almost baryon free fireball....

4.) Polarization of GRBs....

5.) UHE neutrinos......

Many more...................

Generation of magnetic field in the GRB by electron-neutrino interaction.

J. F. Nieves, S. Sahu, PRD 71, 073006 (2005)

Effect of temperature on the electron mass and subsequently on electron+hadron (proton, neutron) scattering within the fireball.

This will affect the production of UHE neutrinos due to the change in the ratio

Role of Neutron in GRBs

- Changes the dynamics of the fireball (Derishev et. al.)
- Dynamical decoupling of the neutron from the rest of the shell will give rise to inelastic n-p scattering and lead to the emission of observable multi-GeV (5-10 GeV) neutrinos (Bahcall, Mészáros, PRL 2000; Mészáros, Rees, APJ 2000).

Is baryon number a good symmetry of Nature ?

- It is believed that Baryon number is not a good symmetry of Nature (Universe in matter dominated) and it require baryon number violating interactions: proton decay, $n\bar{n}$ oscillation (no success so far)
- $n\bar{n}$ oscillation occurs due to ΔB=2 transition
- Present experimental limit for unbound neutron oscillation is $\tau_{n\bar{n}} \simeq 10^9$ sec.

$n\bar{n}$ oscillation mechanism

- In the presence of a magnetic field, neutrons energy levels are splitted by an amount
- ΔE=gμB and this is responsible for the oscillation.
- Due to oscillation, the number of anti-neutron is

$$N_{\bar{n}} = \frac{1}{2} N_n \left(\frac{\delta m}{\Delta E} \right)^2 = 0.6 \times 10^{-25} N_n \left(\frac{B}{G} \right)^{-2}$$ with

$$\delta m = \tau_{n\bar{n}}^{-2} \qquad \tau_{n\bar{n}} \simeq 10^9 \quad sec.$$

Magnetic Field in the Jet Outflow

- It is believed that non-thermal emission is due to synchrotron emission/inverse Compton scattering. For synchrotron emission strong magnetic field is required. There is no way to estimate the magnetic field from the first principle.
- Large magnetic field is expected if the progenitor is highly magnetized. Also amplification of small field due to turbulent dynamo mechanism, compression or shearing.
- Decrease of Magnetic field due to expansion at larger radii.

Magnetic Field in ....

- Recently it has been suggested that, emission in GRBs cab be explained through Compton-drag process and no magnetic field is needed (APJ 529, 2000; APJ 511, 1999, APJ 491, L15, 1997)
- Despite all these, there is no satisfactory explanation for the existence of strong field.
- We use Magnetic field as a parameter here.

- Number of anti-neutron at a distance r from the source is

$$N_{\bar{n}} \simeq \frac{1}{2}\left(\frac{\xi}{1+\xi}\right)\frac{E}{\eta m_p} e^{-r/r_\beta}\left(\frac{\delta m}{\Delta E}\right)^2 = 2\times 10^{27}\left(\frac{B}{G}\right)^{-2}\left(\frac{2\xi}{1+\xi}\right)\frac{E_{53}}{\eta_{100}} e^{-r/r_\beta}$$

- $\xi \simeq 1$ neutron to proton ration and e^{-r/r_β} due to neutron decay.
- protons, neutrons and electrons are coupled with the radiation in the expanding jet outflow until the Compton scattering time scale $t'_{Th} \simeq \left(n'_p \sigma_{Th}\right)^{-1}$ and the elastic n-p scattering time scale $t'_{np} \simeq \left(n'_p \sigma_{np}\right)^{-1}$ are shorter than the co-moving plasma expansion time scale $t'_{\exp} \simeq r/\Gamma$

$$\sigma_{np} \sim 3\times 10^{-26} \quad cm^2$$

- The neutrons and protons are coupled until the opacity $\tau_{np} > 1$, which corresponds to neutron, proton decoupling radius

$$r_{np} < \frac{L\sigma_{np}}{(1+\xi)4\pi m_p \Gamma^2 \eta} \sim 6\times 10^{10} \frac{L_{52}}{(1+\xi)\Gamma_{100}^2 \eta_{100}} \quad cm$$

- The np coupling radius r lies

$$r < r_{np} < r_\beta \quad = \quad r < 6\times 10^{10} \quad cm \quad < 10^{16} \quad cm$$

- So we can neglect the effect of neutron beta decay.
- Decay of

$$\bar{n} \rightarrow \bar{p} + e^+ + \nu_e$$

◆Produced anti-protons will annihilate with the protons in the background through

$$\bar{n}+n\to\pi^{+}\ \pi^{-}\ +\pi^{0}$$

$$\bar{n}+n\to\pi^{+}\ +\pi^{-}$$

$$\bar{n}+n\to\pi^{0}\ \ +\pi^{0}$$

◆ Pion decay

$$\pi^{\pm}\ \to\mu^{\pm}\ \ +\ \nu_{\mu}\ (\bar{\nu}_{\mu})$$

$$\mu^{\pm}\ \to e^{\pm}\ \ +\ \nu_{e}(\bar{\nu}_{e})\ +\ \bar{\nu}_{\mu}(\nu_{\mu})$$

$$\pi^{0}\to\gamma+\gamma$$

- Proton anti-proton annihilation, each pion carry energy $1.88\ GeV/k_\pi$
- Average energy carried by muons is 80% and rest is by neutrinos. in the pion decay.
- In muon decay ~1/3 energy is carried by each particle. Average energy of neutrino in muon decay $\epsilon'_{\nu,\bar{\nu}} \simeq 0.5\ GeV/k_\pi$ the co-moving frame. In observer frame normalizing at z=1

$$\epsilon_{\nu,\bar{\nu}} \simeq \frac{75\ GeV}{k_\pi} \Gamma_{300} \frac{2}{1+z}, \quad k_\pi = 3, 2$$

- Energy of muon neutrinos due to pion decay

$$\epsilon_{\nu_\mu,\bar{\nu}_\mu} \simeq \frac{56\ GeV}{k_\pi} \Gamma_{300} \frac{2}{1+z}$$

- The neutral pion decay will give photons of energies 45 and 71 GeVs.
- The optical depth $\tau_{\gamma\gamma} \gg 1$, so GeVs photons will degrade by pair production and can not escape.
- The total amount of energy released in $p\bar{p}$ annihilation is

$$\epsilon_{p\bar{p}} = 2 m_p N_{\bar{n}} \simeq 6 \times 10^{24} \frac{E_{53}}{\eta_{100}} \left(\frac{B}{G} \right)^{-2} \left(\frac{2\xi}{1+\xi} \right) \quad erg$$

- A major fraction of it will be in the form of neutrinos.

Neutrino Event Rate

- Short and Long GRBs rate within a Hubble radius of $R_b \sim 10^5 \; R_{b5}$ per year, number of events per year in a detector with N_t protons is

$$R_{\nu\bar{\nu}} \sim \left(\frac{N_t}{4\pi D^2} \right) R_b N_{\bar{n}} \bar{\sigma}_{\nu\bar{\nu}}$$

By considering Earth as the detector with 10^{51} protons and a magnetic field of $10^{-6} G$ in the jet outflow the event rate is

$$R_{\nu\bar{\nu}} \sim 3.6\, h_{65}^2 R_{b5} \frac{E_{53}}{\eta_{100}} \Gamma_{300} \left(\frac{B}{10^{-6} G} \right)^{-2} \left(\frac{2\xi}{1+\xi} \right) \left(\frac{3-2\sqrt{2}}{2+z-2\sqrt{1+z}} \right) \; year^{-1}$$

-

- Production of neutrinos and anti-neutrinos due to nnbar annihilation is inversely proportional to the square of the mag. filed. So if nnbar oscillation exist in the GRBs outflow, mag. field can't be arbitrarily strong or weak.
- Very Weak filed enhance neutrino production and take away huge energy.

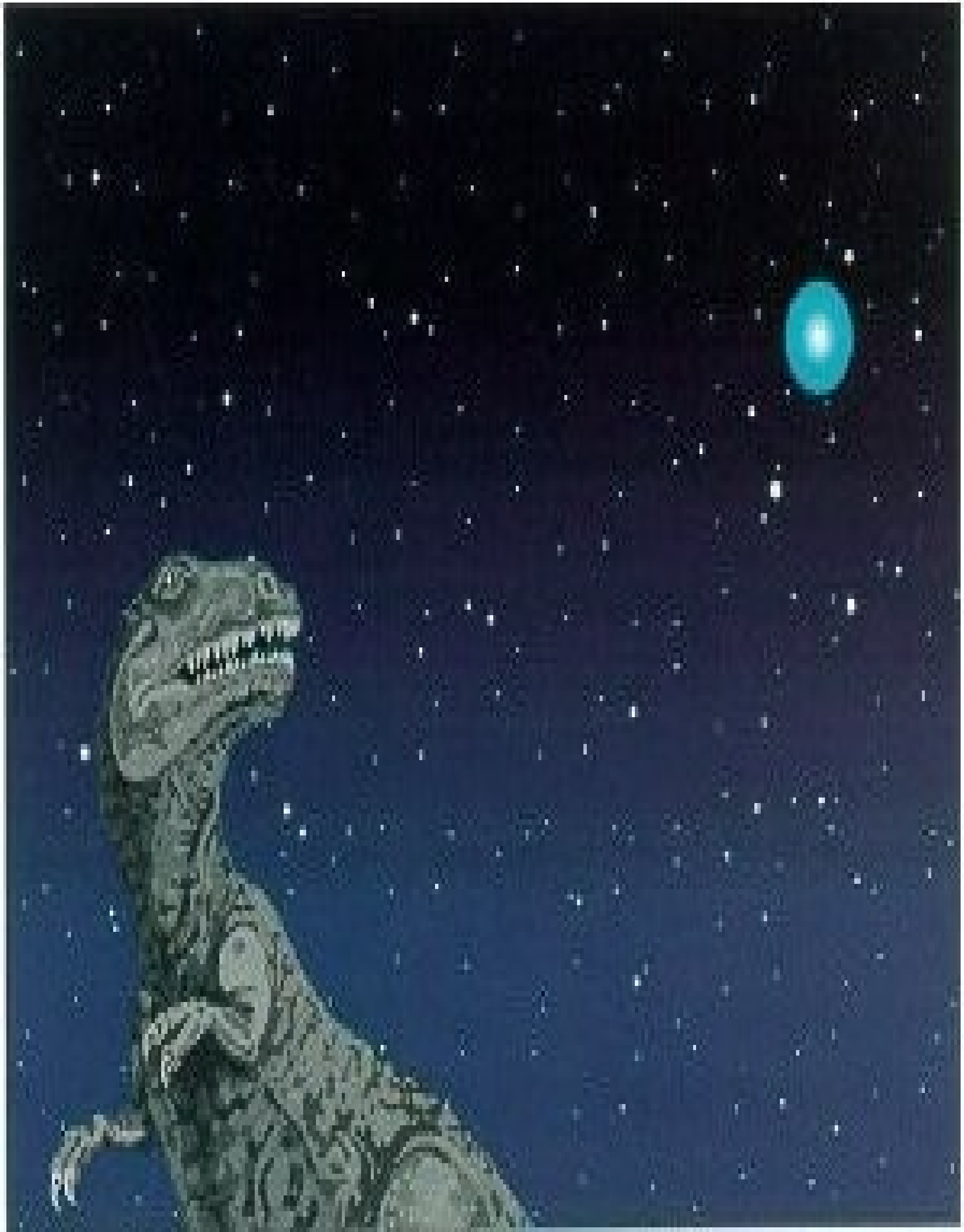
Is it possible to observe these neutrinos?

May be in future, the Extreme Universe Space Observatory (EUSO) will be able to see it !

Summary

- No other process can give rise to neutrinos inbetween source and the n-p decoupling radius.
- 19-38 GeV neutrinos will be produced much before the 5-10 GeV neutrinos due to dynamical decoupling of neutrons.
- It will tell about the nature of the progenitor of GRBs.
- Observation of these multi-GeV neutrinos will be unique signature of Physics Beyond the Standard Model.

...a Gamma-Ray burst could blow away the Earth's atmosphere and cause mass extinction.



Explore More

Sherlock Holmes