Gamma Ray Bursts (GRBs)

Reviews: A. Gomboc 2012 Contemp. Physics (General)

T. Piran 1999 Physics Reports (Fireball Model)

Non-repetitive flashes of $\gamma$-rays lasting $\sim 10^{-2} - 10^{3}$ s

Discovered first in late 1960's, publisched first 1973

For a long time only $\gamma$-rays observed

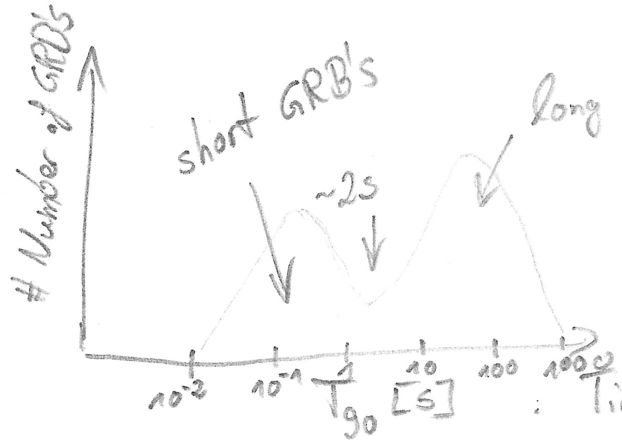
→ no precise localization on the sky

$\gamma$'s neutral + Universe transparent

~~but~~ • distribution isotropic → probably very distant sources (or very close, far away MW halo)

BATSE (1991 - 2000) observed 2700 GRB's (spatial resolution few degrees)

• Bimodal distribution in durations:

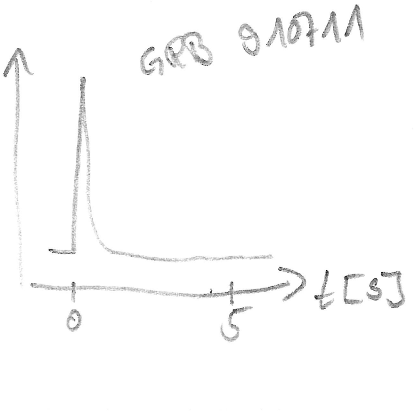


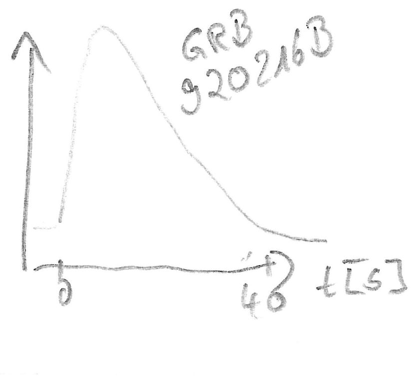

: Time until 90% of flux emitted

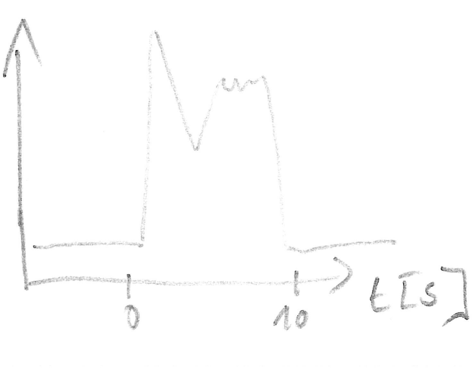
Also difference in hardness of spectra:

short GRB's have higher fraction of high to low energy photons than long GRB's

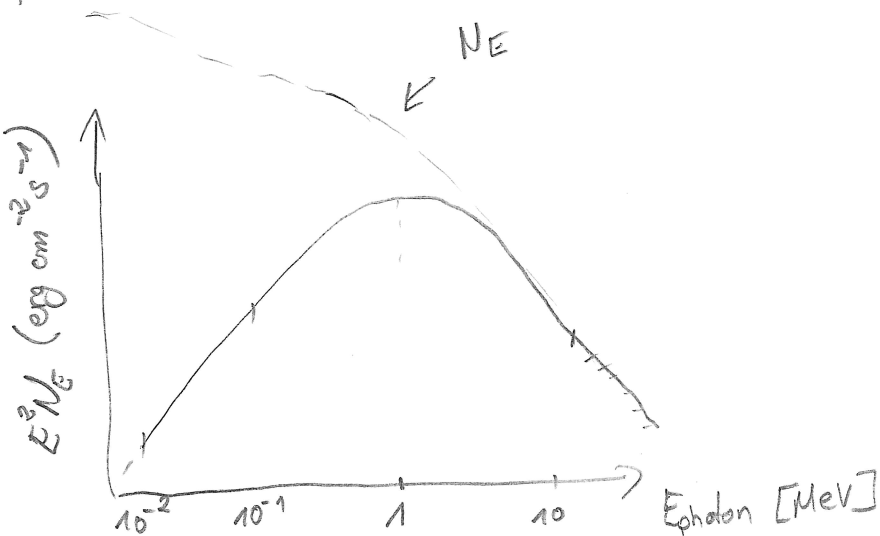
$\gamma$-LC's are very diverse, individual for every event:



$\gamma$ - Spectrum:




Continuum spectra without any features

→ No distance determination possible (redshifted lines)

Well fitted with broken power-law

Typical photon energies are 30 keV – 1 MeV, most energy emitted around 200 keV

First source identification when BeppoSAX - sattellite came online with 5 arcmin resolution:

Detection of optical and X-ray afterglow of GRB 970228 ~8 hrs after GRB → Identification of host galaxy at $z \sim 0.7 \sim$ 4 Gpc $D_L$
$t \sim 6$ Gyrs

→ GRBs are at cosmological distances

→ very energetic events GRB 970228 : $E_\gamma = 1.6 \cdot 10^{52}$ erg (isotropic)

Even more extreme: GRB 990123 : $E_\gamma > 10^{54}$ erg (isotropic)

→ Problem... ($> M_\odot c^2$)

Questions:

- Progenitors?
- Explosion? (Energetics, ...)
- How are the $\gamma$'s created?

Energetics requires outflow to be ~~radiation~~ relativistic because of compactness problem:

$\gamma$-rays escape → outflow has to be optically thin

$$\underbrace{\tau}_{\text{optical depth}} \sim n_e \underbrace{\sigma_T}_{\text{Thomson cross section}} \cdot \underbrace{D}_{\text{size of emission region}}$$

$\gamma$-ray emission shows variability on $\Delta t \leq 10^{-2}\,s$

$$\rightarrow D \leq c \cdot \Delta t \leq 10^{-2} s \cdot c$$

$$n_e = \underbrace{f_e}_{\text{fraction of photons that produce } e^+e^- \text{ pairs}} \cdot \underbrace{n_\gamma}_{\text{photon number density}}$$

$$n_\gamma \sim \frac{\overbrace{E_{iso}}^{\text{Involved energy assuming isotropic emission}}}{\underbrace{\bar{E}_\gamma}_{\text{typical photon energy} \sim 1\,MeV} \cdot D^3}$$

$$\Rightarrow \tau \sim 10^{13} f_e \left(\frac{E_{iso}}{10^{49} J}\right)\left(\frac{1\,MeV}{\bar{E}_\gamma}\right)\left(\frac{0.01 s}{\Delta t}\right)^2 \gg 1$$

But: In relativistic outflow:

$$\Delta t_{obs} = \frac{\Delta t_{emission}}{2\Gamma^2}$$

$\Rightarrow$ Source can be larger by $\sim \Gamma^2$

Also: $\bar{E}_{\gamma,obs} = \Gamma \, E_{\gamma,emitted} \rightarrow f_e$ low

Detailed calculations: $\Gamma > 100$ needed to get $\tau \sim 1$

→ Outflow is highly relativistic

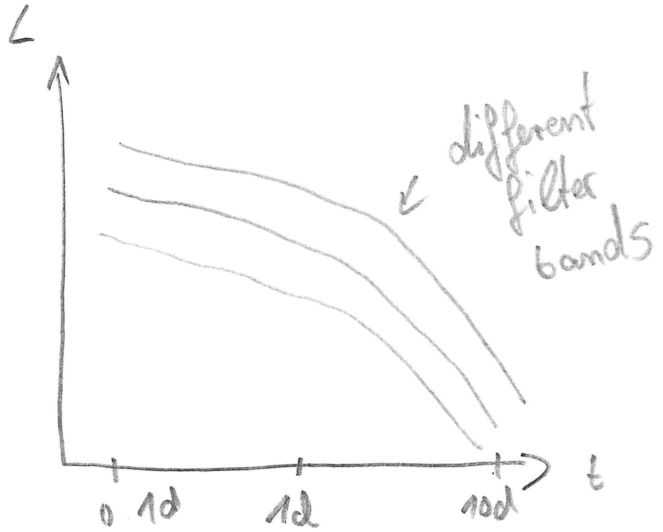
Solution to energetics problem:

$\gamma$-emission is ~~beamed~~ collimated in two opposite jets

$\rightarrow$ opening angle $\theta_j \ll 1$ $\Rightarrow$ lower energy by $\theta_j^2/2$

But: total number of events increases by the same factor

Observational evidence from Jet break in afterglow:




Before break: $\Theta_{beam} \sim \frac{1}{\Gamma} \ll \theta_j$, particles confined to jet

Expansion $\rightarrow$ $\Gamma$ drops

at break: $\Gamma^{-1} \sim \Theta_j$

$\Rightarrow$ Estimate for $\Theta_j$ from $t_{break}$:

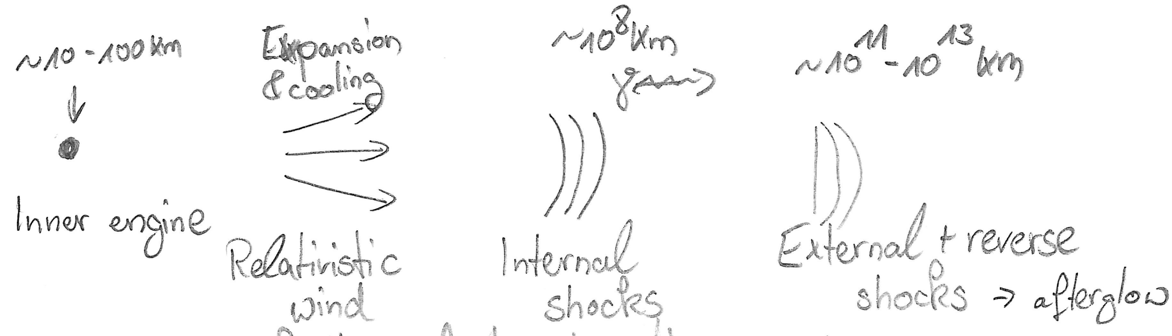
$$\Theta_j \sim t_{break}^{3/8} \left(\frac{E}{\rho}\right)^{-1/8}$$

Energy and density of shock

Typical values for $\Theta_j \sim 4°$, rarely $> 10°$

Afterwards: emission not collimated any more, drops faster in direction ~~of~~ to observer

More general: fireball model:




Wind: conversion of thermal to kinetic energy

Relativistic internal shocks lead to synchroton and inverse Compton emission, as soon as ejecta become optically thin → γ-ray burst

The afterglow is caused by interaction of the outflow with the surrounding medium

The fireball model assumes, that magnetic fields in the jet are energetically irrelevant

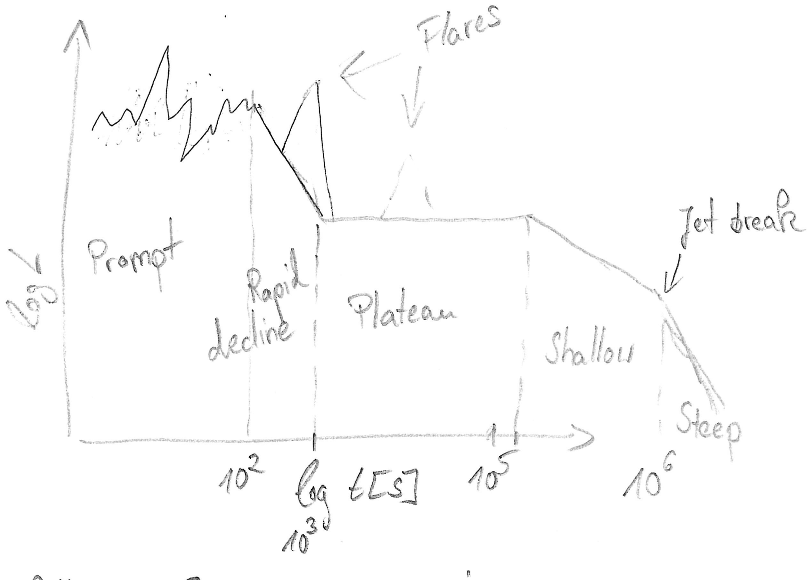
Alternative electromagnetic models exist with $\sigma = \frac{B^2}{4\pi\Gamma\rho c^2} > 1$

Main difference: acceleration of particles directly by B-fields, not necessarily internal shocks needed

Summary so far: Diversity in LC's, 2 types (short/long), at cosmological distances → huge energy output → collimated outflows/jets, detection of X-ray, optical afterglow, confirmation of jets, fireball model, only 1/500 visible/pointed at us

Swift satellite: ~~98%~~ Detection of X-ray afterglow for > 95% of detected GRBs with precise location,
optical afterglow < 50%
radio afterglow ~20%

Canonical x-ray light curve




Prompt: follows @ $\gamma$-ray emission

Rapid decline: central engine shuts down? (curvature effects?)

Plateau: Parts of central engine (reduced activity?) still up? (Flares)

Flares: random events on top of LC, not related to structure of prompt emission

Some x-ray afterglows show (Fe) absorption lines → direct redshift measurement

If jets: orphan afterglows should exist, but no evidence yet (angle increases with time as $\Gamma$ decreases)

GRB- SN connection: (similar energies, same events?)

GRB 980425 associated with SN 1998bw, a very bright SN Ic with broad spectral features (large velocities, high $E_{kin}$)

closest GRB so far ($z = 0.0085$, 37 Mpc), but quite faint (~$10^{-3}$ of typical GRB energy ~ $10^{48}$ erg isotropic)

Today: ✱ 14 (2014) solid detections of SN associated with GRBs, all very similar broad line Ic's ($z_{max} \approx 0.6$)

+ „SN bumps" in late-time LC's

But: most bl Ic's have no observed GRB (75%)

→ orientation effect of GRB?

most Ic's have no GRB, bl Ic's are special subclass, prob. different progenitors

There are also long GRBs without SN! (GRB 060505, $z = 0.089$)

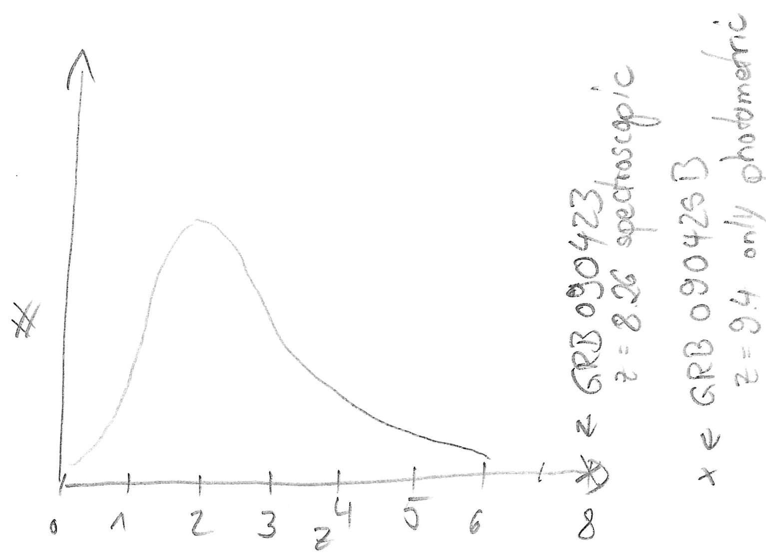
Number estimates today: 0.1% - 10% of all SN Ibc have GRB's

Fraction of no-SN long GRB may be substantial (not many good limits)

Short GRB: first afterglow detection for GRB 050509b

no ~~dete~~ connection to SN

Redshift distribution of GRB's:




→ Most GRB's are far far away

~2 GRB's seen per day ⇒ ~$10^3$ per day in obs. Universe

GRB environment:

very different for short/long GRB's!

long GRBs:

only found in starforming regions, very blue parts of galaxies → connected to young massive stars!

Prefer low-metallicity environment

Galaxies usually smaller than MW, often irregular galaxies, sizes similar to GMC, SMC, dwarfs

short GRBs:

follow general stellar distribution in galaxies

~ 10 - 20 % of short GRBs in old galaxies without recent star formation ($\tau$ > 1 Gyr)

but many in „normal" galaxies

no known metallicity preference

Progenitor requirements:

~ $10^{50}$ - $10^{51}$ erg liberated in ~ seconds

~ $10^{-5}$ $M_\odot$ accelerated to relativistic outflows

variability: energy injection into few 100 km

variability on 10 ms, duration 10 s:

if GRB caused by internal shocks: continuous energy injection required

No direct detection of progenitor or engine so far!

General picture:

GRB is powered by rapid accretion of a massive ($\sim 0.1 M_\odot$) disk onto a compact object, most likely a newly born BH

Energy release from binding energy of accreted material + spin energy of BH

→ BH launches jet that eventually leads to GRB

Models / Scenarios:

1) The collapsar model → main model for long GRBs

→ Core collapse of rotating massive stars

Requirements:

- massive core → collapse
- hydrogen envelope removed → path for jet
- high angular momentum in the core → formation of accretion disk

Two incarnations:

Type I collapsars: $M_{progenitor} \gtrsim 35 M_\odot$

Massive iron core directly collapses to BH

Infalling matter with ang. mom. forms disk

Hyperaccretion may lead to energetic stellar explosion (up to $10^{52}$ erg)

In next few seconds polar jet is launched, punches hole through envelope → GRB precursor

Second jet leads to GRB $\sim 10$ s after BH formed, $\gamma$-rays produced $10^{14}$ - $10^{15}$ cm away from BH

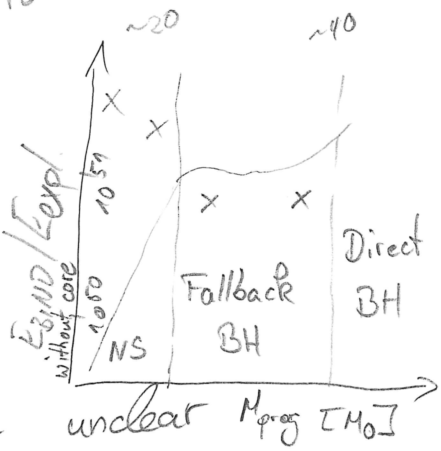
Jet launched by combination of $\nu$'s, magnetic fields, angular momentum of BH

Explains a lot of features of many long GRB's
(energetic SN, GRB duration, beam collimation, ...)
$\rightarrow$ accretion timescale of disk on BH; $\rightarrow$ ~~size~~ properties of disk, mag. fields
can not explain short GRB's

Type II collapsars:

$35 M_\odot \gtrsim M \gtrsim 25 M_\odot$ $\rightarrow$ core collapses first to NS
$\rightarrow$ weak explosion $\rightarrow$ accretion on NS leads to second collapse to BH

Must be more frequent than Type I collapsars
(more progenitor stars!)




Issues:

- Mass threshold for BH formation is quite unclear and depends on rotation, metallicity
  Low metallicity $\rightarrow$ less mass loss by winds
  $\rightarrow$ more massive cores and less angular momentum lost
  $\rightarrow$ faster rotation
- However: ~~the~~ progenitor needs to be compact
  $\rightarrow$ H-envelope either lost or completely burned to He to C/O (SN Ic ..)
- Binary systems help with removing envelope and increasing rotation (accretion $\rightarrow$ spin up)
  or even mergers of two He-stars
- Almost all very massive stars are in binaries!

Models: No SN Ic at solar metallicity for single stars, needs $Z < 0.02 Z_\odot$

Collapsars can explain long GRB's without SN, long GRB's with SN, and SN without GRB's

2) Mergers of compact objects (NS, BH (,WD))

- poss. Progenitors known (i.e. Hulse-Taylor pulsar 2NS $1.44\,M_\odot + 1.39\,M_\odot$ will merge in $3 \cdot 10^8$ years)
  Merger will create BH!

- Estimated merger rates (NS + NS, NS + BH) [BH + WD, BH + He star] seem to match observed GRB rate

- Variability timescales (ms) match light travel dist. between the two objects at time of merger

- Total grav. energy available easily enough for observed GRB + afterglow

- But no SN, long delay times → excluded for long GRBs
  However: best candidate for short GRBs (follow general stellar population, partly long delay times ∃, locations in outer parts due to NS kicks)
  + Lots of angular momentum
  + Clean environment

NS + NS mergers: detailed evolution only from numerical simulations (GR + MHD + ν's + nuclear EoS)
state of the art:

$M_{tot} \lesssim 2.8 \div 2.9\,M_\odot$:

Merger forms diff. rotating hyper-massive NS, initially stable (> 10 ms)
Viscosity → transport of angular momentum from inner region to outer envelope
→ Envelope forms torus, HMNS collapses to BH
$M_{torus} \sim 0.01 - 0.03\,M_\odot$ no B-fields, but $\gtrsim 0.05\,M_\odot$ with B-fields
B-fields spun up to typically $10^{15} - 10^{16}$ G, collimated along polar axis

Accretion of torus on BH, $\dot{M} \sim 10\, M_\odot/s \to \tau \sim 10\,ms$

Torus very hot ($\sim 10^{12}$ K) $\to$ ample production of $\nu$'s, annihilation produces $\sim 10^{14}$ erg in $\gamma$-rays

$M_{tot} \gtrsim 2.9\, M_\odot$:

Direct formation of BH

$q = \frac{M_<}{M_>} \gtrsim 0.7$

$\downarrow$

Most material in BH, small disk

$\downarrow$

no GRB, because energy available is insufficient

$q \lesssim 0.7$

$\downarrow$

thick torus around BH

$M_{torus} \sim 0.01 - 0.1\, M_\odot$

$\tau \sim 10 - 1000$ ms, $\dot{M} \sim 0.1 - 1\, M_\odot/s$

$E_{thermal} = 10^{51} - 10^{52}$ erg

$\downarrow$

good candidate for short GRB's

So far no direct evidence, potentially by grav. wave detectors: GRB should be preceded by signature of NS+NS merger and BH formation