The search for the origin of Short Gamma-Ray Bursts

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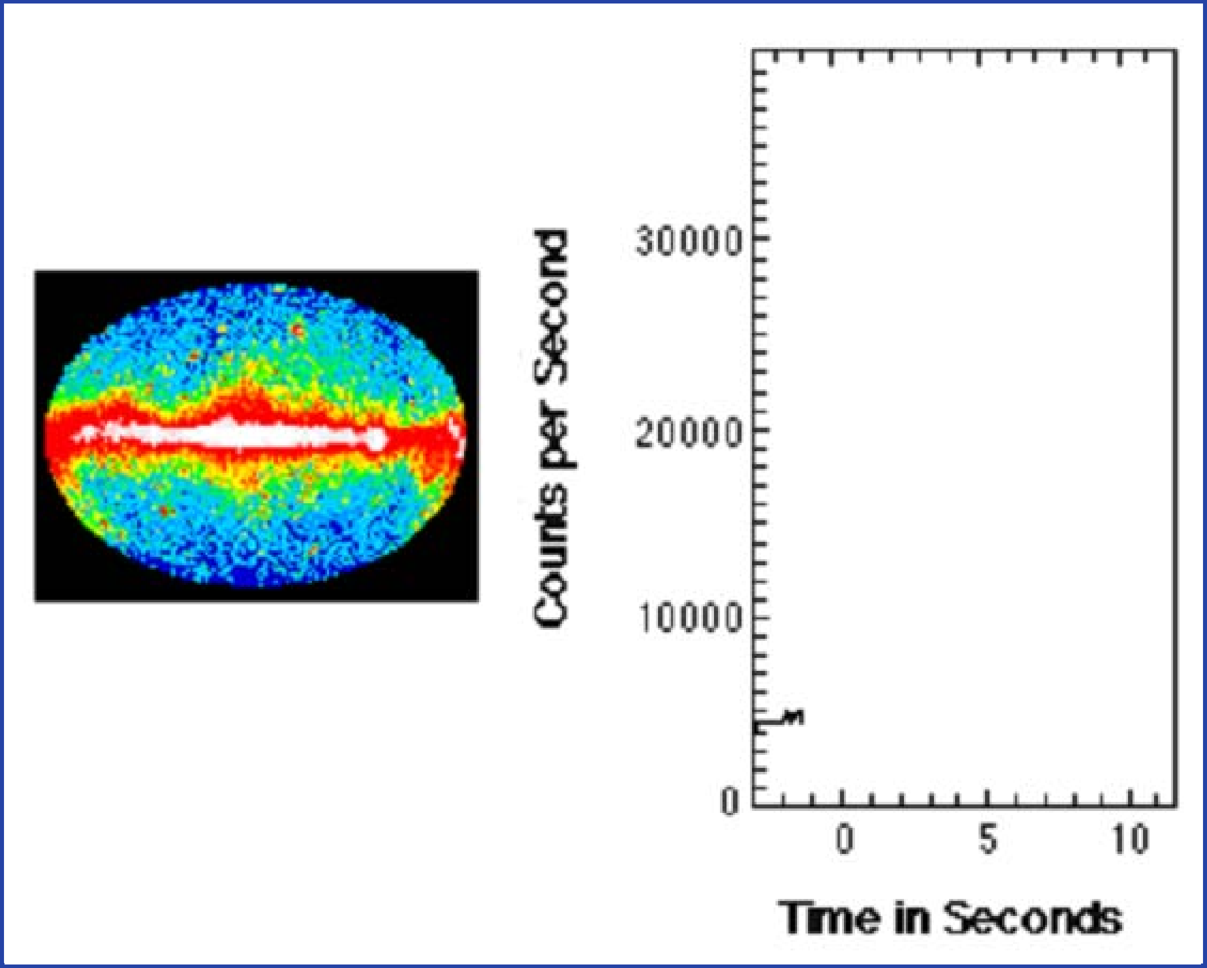
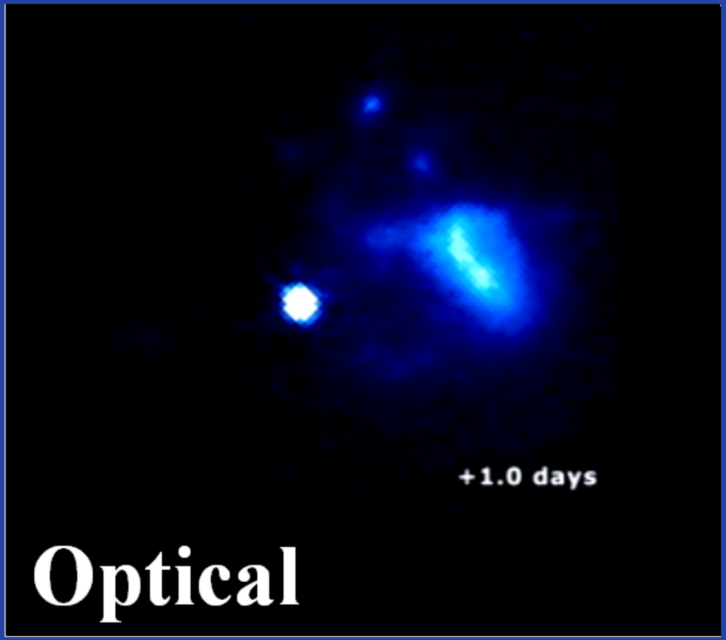
Nakar 2007, Physics Reports, 442, 166

Gamma Ray Bursts (GRBs)



Twice a day energetic flash of γ-rays hits the Earth

Afterglow
X-rays – optical – radio



Fox et. al., 05

Following soft γ-rays we observe:
X-rays (minutes-hours),
optical emission (hours-days)
radio emission (weeks-years)

Afterglow → localization → Host galaxy → distance

γ-ray Luminosity - 0.01-1% $M_{sun}c^2/s$!

Why GRBs are interesting?

The most violent explosions in the Universe:

- Luminosity of 10^8 Galaxies
- Energy released within ~ 10 km radius

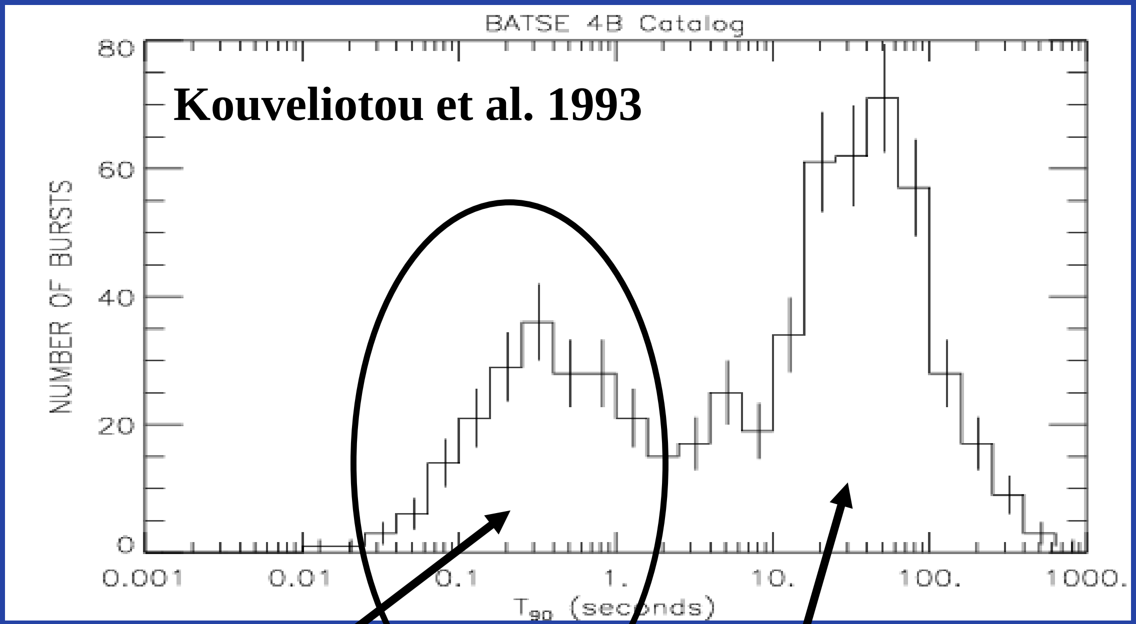
Extreme physical conditions and probable sources of:

- Ultra-high energy cosmic rays – 10^{11} GeV protons
- High-energy neutrinos
- Gravitational waves

Useful tool to probe various astrophysical aspects

- High redshift universe
- Winds from massive stars

Longs & shorts



?

Short GRBs

First afterglow detected in 2005 – Swift & HETE2

(Gehrels et. al., 05)

Long GRBs

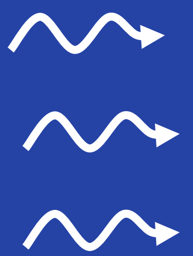
First afterglow detected in 1997 - BeppoSAX

(Costa et. al., 97)

Outline – the search for short GRB origin

Progenitor → Triggering event (‘Central Engine’) → γ-rays + Afterglow

? → ? →



- **Observations**
- **Central engine – Properties and requirements**
- **Progenitor – Age and rate**

⇓

Viable progenitor systems

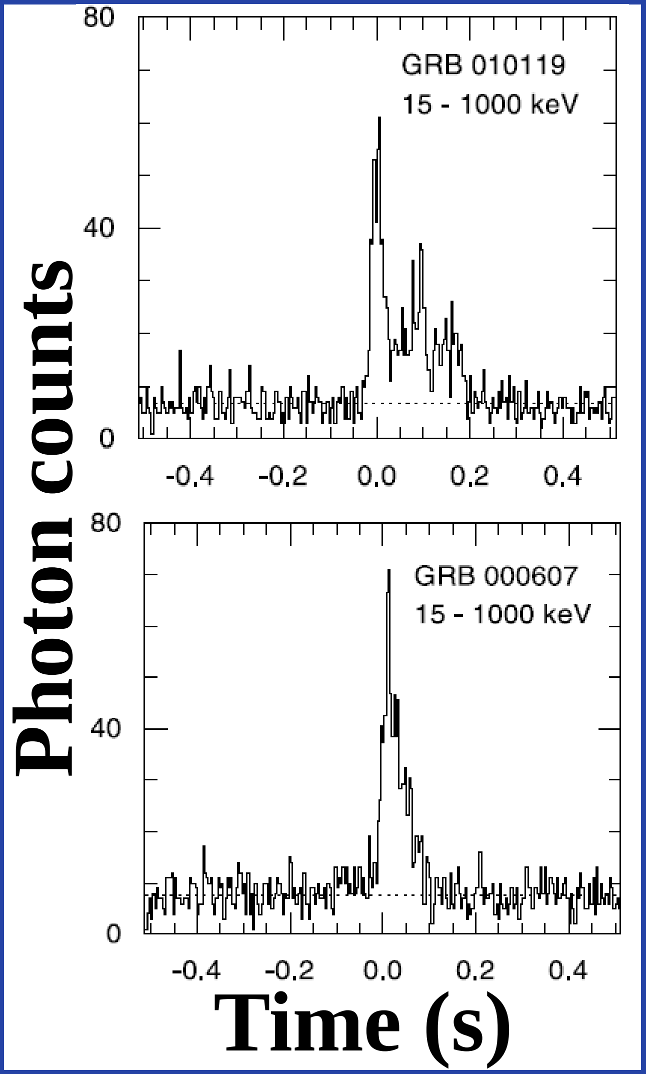
Available data to work with

Prompt γ-rays (~500 bursts)

- Erratic light curves

variability time scale ~1-10ms

Duration ~10ms - 1 s



Hurley et. al., 02

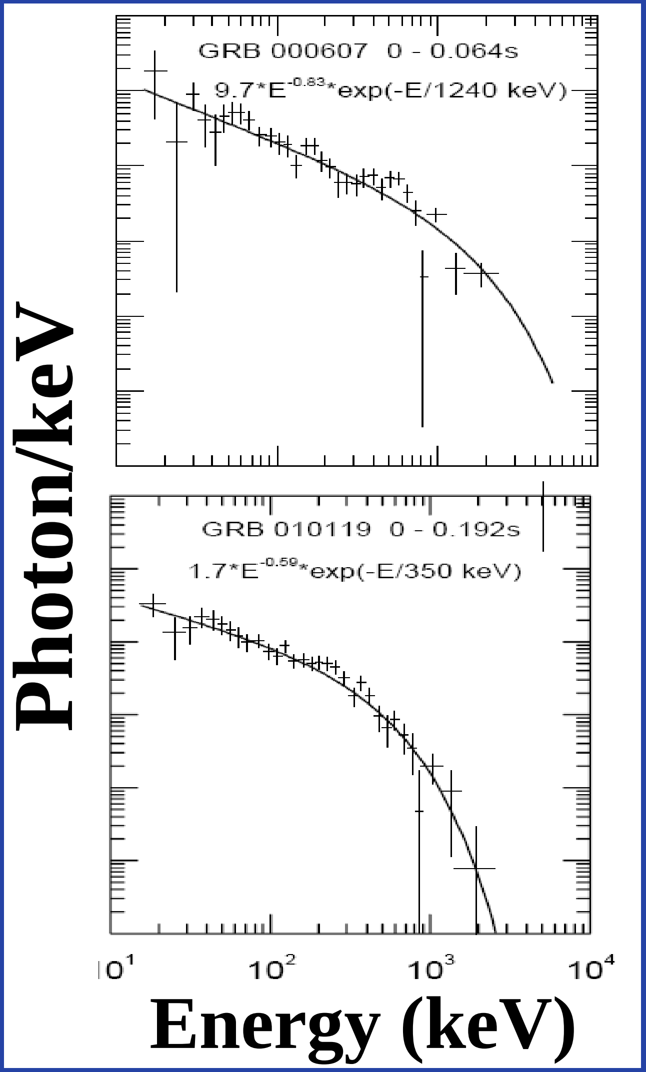
Available data to work with

Prompt γ-rays (~500 bursts)

- **Erratic light curves**
- **Non-thermal spectra**

$$\frac{dN_{ph}}{dE} \propto E^{-\alpha} \exp\left[-\frac{E}{E_0}\right]$$

~ 0.7   0.1-1 MeV



Hurley et. al., 02

Available data to work with

Prompt γ-rays (~500 bursts)

- **Erratic light curves**
- **Non-thermal spectra**

Afterglows (~20 bursts)

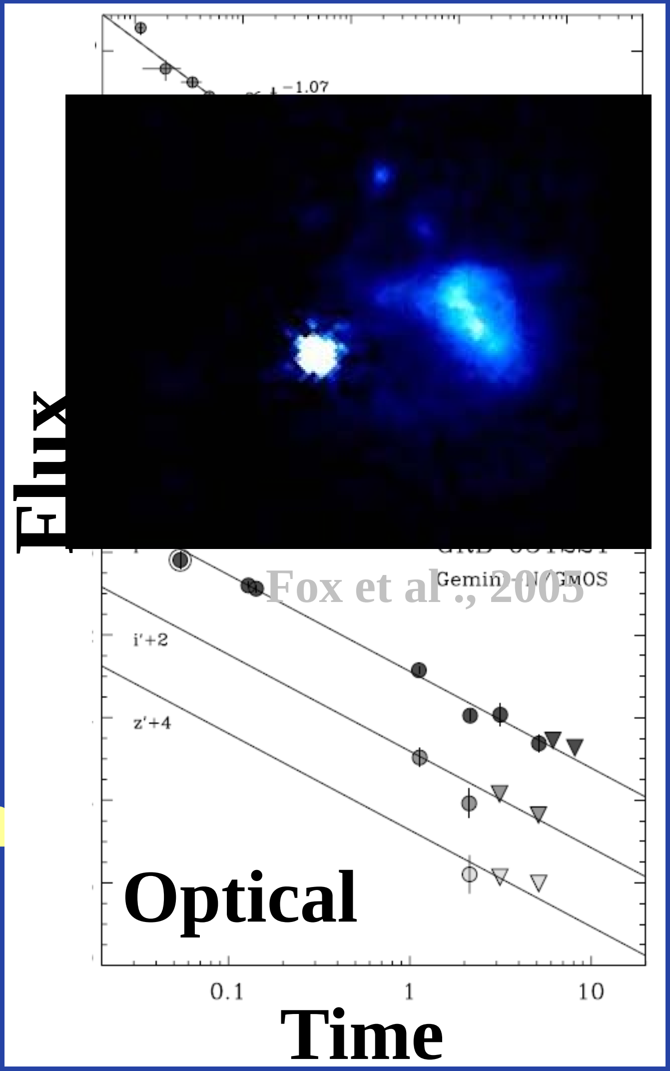
Power-law temporal decay

Power-law spectra

Faint (As predicted by Panaitescu, Kumar & Narayan 01)

Distances (6-12 bursts) redsh

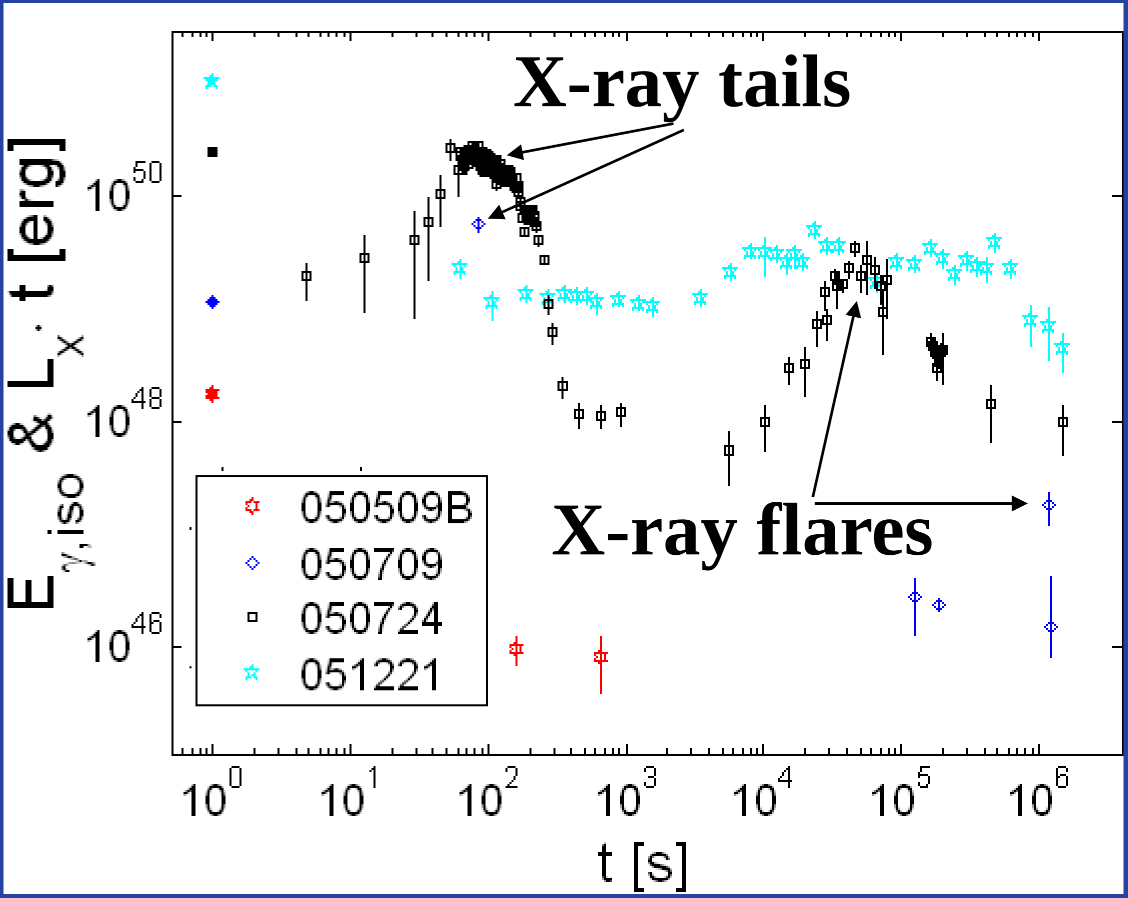
Host galaxies (6-12 bursts)



Soderberg et. al., 06

Available data to work with

X-ray tails and late time afterglow variability



Nakar 07

Central engine properties

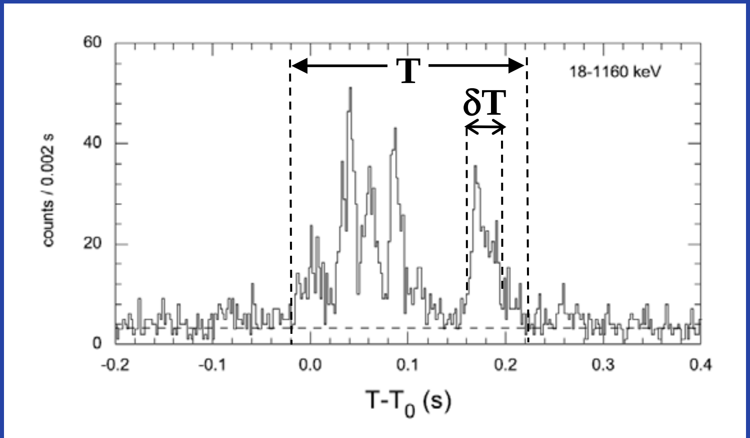
Central engine properties

Isotropic equivalent γ-ray luminosity: $10^{50\text{-}52}$erg/s
Isotropic equivalent total emitted energy: $10^{49\text{-}51}$erg

Size

Variability time scales (δt) < 1ms

engine < 10^7 cm



Two time scales

δt ~ engine variability
T ~ engine activity duration

Central engine properties
Relativistic outflow

Observations: non-thermal spectra → optically thin source

Photon optical depth $\tau(\nu) \sim \sigma_T\, n\, R < 1$

Thomson
cross-section

source width

$n_{e-,e+} \sim n_{ph}(\varepsilon'_{ph} > m_e c^2)$
or
$n_{ph}(\varepsilon'_{ph} > m_e^2\, c^4/h\nu')$

Central engine properties

Relativistic outflow

Observations: non-thermal spectra → optically thin source

$\sim 10^{54}$ $\quad$ ~ 1 (Typical $\varepsilon_{ph} \sim m_e c^2$)

$$\tau \sim \frac{\sigma_T N_{ph} f_{\varepsilon'_{ph} > m_e c^2}}{R^2} \sim 10^{14}$$

$(c\delta t)^2 \sim 10^{15}$

A conflict! (Schmidt 1978)

Central engine properties

Relativistic outflow

(Guilbert et. al, 83, Piran & Shemi 93)

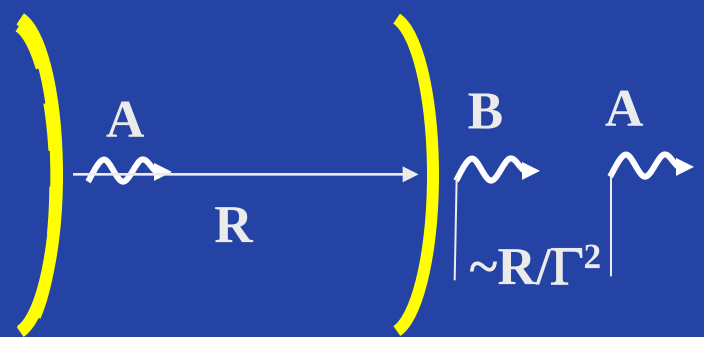
Source with a Lorentz factor Γ

$$\tau \sim \frac{\sigma_T N_{ph} f_{\varepsilon'_{ph} > m_e c^2}}{R^2}$$

$$\varepsilon'_{ph} \rightarrow \varepsilon_{ph} / \Gamma \rightarrow f\,(\varepsilon'_{ph} > m_e c^2) \downarrow$$

Rest frame photon energy

Observed photon energy



Central engine properties

Relativistic outflow

(Guilbert et. al, '83, Piran & Shemi '93)

Source with a Lorentz factor Γ

$$\tau \sim \frac{\sigma_T N_{ph} f_{\varepsilon'_{ph} > m_e c^2}}{R^2}$$

$\varepsilon'_{ph} \rightarrow \varepsilon_{ph} / \Gamma \rightarrow f(\varepsilon'_{ph} > m_e c^2) \downarrow$

$R \rightarrow c\delta t\Gamma^2 \uparrow$

Relativistic source

$$\tau_T \approx \frac{\sigma_T N_{ph} f_{\varepsilon_{ph}>\varepsilon_{an}}}{4\pi\left(\Gamma^2 c\delta T\right)^2} \approx 10^{13} E_{\gamma,49}\delta T_{-2}^{-2}\cdot\Gamma^{-4} f_{\varepsilon_{ph}>\varepsilon_{an}} \quad ; \quad \left(\varepsilon_{an} = m_e c^2\Gamma(1+z)^{-1}\right)$$

$f_{\varepsilon_{ph}>\varepsilon_{an}}$

Long GRBs

$$\propto \Gamma^{1-\beta} \; ; \; \beta \approx 2.2 \;\Rightarrow\; \Gamma > 10^{13/5.25} \approx 300$$

(e.g., Lithwick & Sari 01)

Short GRBs

$$\propto \Gamma^{-\alpha} \exp\left[-\frac{\Gamma m_e c^2}{\varepsilon_0 (1+z)}\right] \;\Rightarrow\; \Gamma > 10-30$$

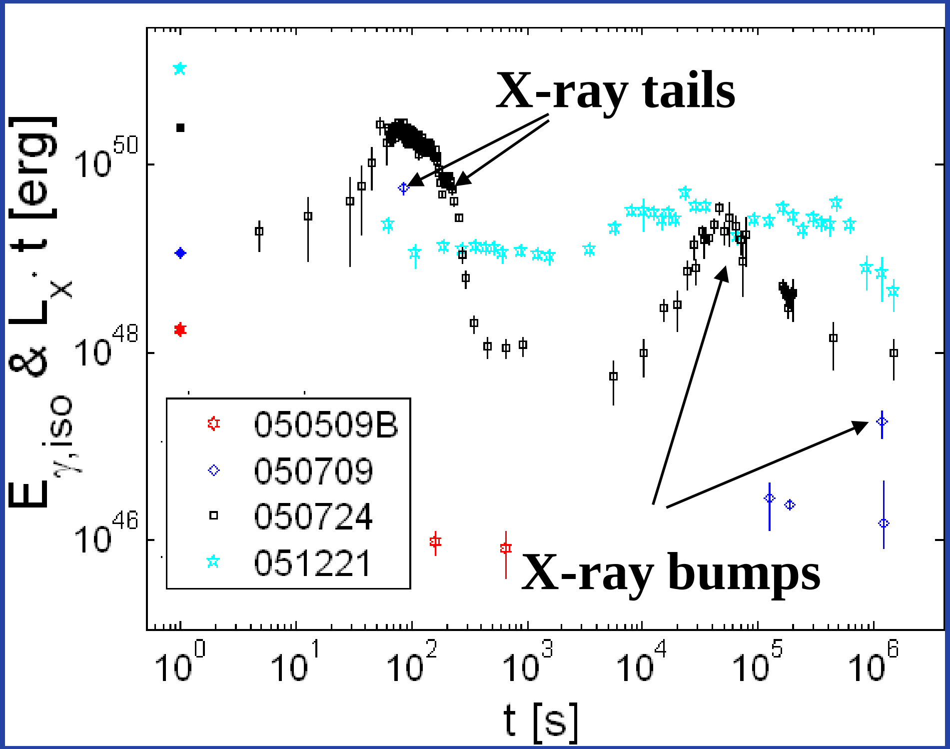
(Ghirlanda et. al., 04)

(Nakar 07)

Recently Fermi detected a 3GeV short GRB photon ➔ $\Gamma > 300$

X-ray tails and late time afterglow variability

Angular smoothing



Possibly result from late engine activity

High Luminosity + **non-thermal MeV photons** + **Short time scale** + **Variability**

Progenitor

?

Central Engine

- Compact ($<10^7$ cm)
- Active ~ 0.1-1 s (many dynamical times) minutes-hours ???
- $L_{iso} > 10^{-3}\, M_{sun}c^2/s$
- $E_{iso} > 10^{-4}\, M_{sun}c^2$

Relativistic outflow

$\Gamma > 20$

Energy Dissipation

γ-rays

Afterglow

γ-ray efficiency

A short detour – external shock afterglow theory

Compact engine | Relativistic wind | Internal Dissipation $E_\gamma < E$ | External Dissipation $E_{aft} = \kappa E_\gamma$

γ-rays | Afterglow

The afterglow – a blast wave in the ambient medium

Afterglow theory

(Meszaros & Rees; Kumar & Panaitescu; Sari, Piran & Narayan; Waxman …)

Shocked plasma

Collisionless Shock

Ambient medium

Relativistic electrons + magnetic field = synchrotron radiation

ε_e – fraction of internal energy in relativistic electrons

ε_B – fraction of internal energy in magnetic field

$$E_{x-ray} = f(E_{aft}, n, d, \mathrm{microphysics})$$

external density **distance to Earth**

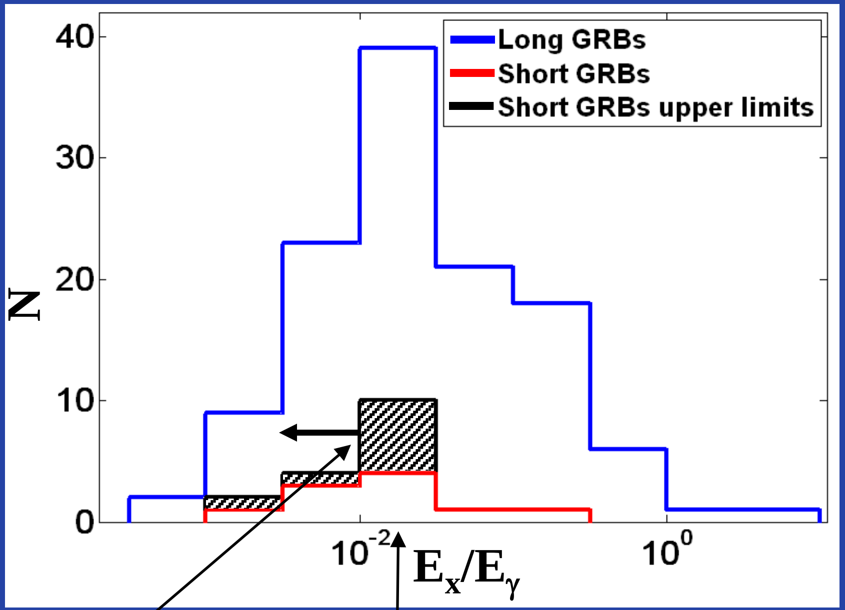
~1 in *long* GRB

$$\frac{E_{x-ray}}{E_\gamma} \sim \begin{cases} 0.01\kappa^{-1}\ g(microphysics) & \text{if X-ray electrons cool down} \\ 0.01\kappa^{-1}\left(\dfrac{n}{0.1\mathrm{cm}^{-3}}\right)^{1/2} h(microphysics) & \text{if X-ray electrons \textit{not} cool down} \end{cases}$$

$$\kappa \equiv \frac{E_\gamma}{E_{aft}}$$

$E_{x\text{-ray}}$ - X-ray afterglow energy

E_γ- prompt γ-ray energy



κ ~ 1

Possibly n << 0.1cm^{-3}

Progenitor properties

Host Galaxies and supernova limits

Long GRBs

- Only highly star forming ($\sim 10\ M_O$/yr/L^*) hosts
- GRBs strongly follow the blue light in the host (Fruchter et al. 06)
- SN (Ibc) is typically detected following nearby long GRBs

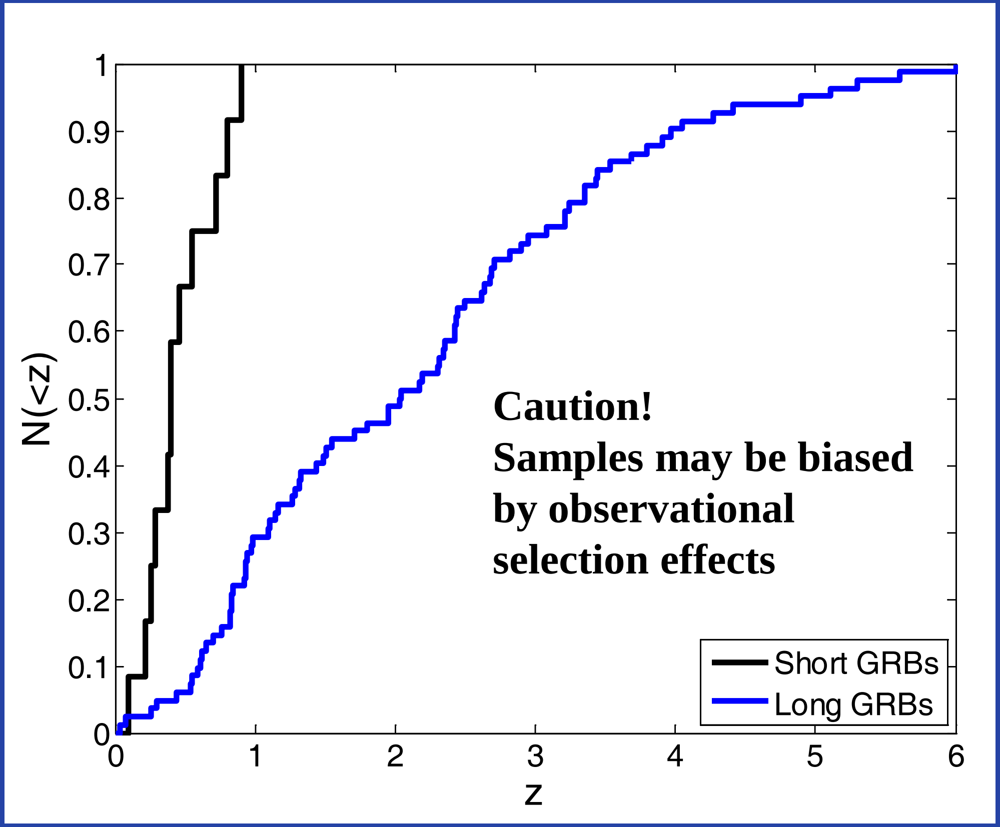
Associated with the death of massive stars

Short GRBs

- Many early type hosts (~50%)
- Moderate Star forming ($\sim 1\ M_O$/yr/L^*) late type hosts
- No Supernova detection to strict limits ($M_R > -12$)

Old progenitors (not massive stars)

Redshift distribution



Progenitors of Short GRBs are older

Progenitor lifetime

Most host galaxies are of early type

⬇

The typical progenitor lifetime is several Gyr

(Gal-Yam et. al., 06; Zheng & Ramirez-Ruiz 06; Shin & Berger 06)

Short GRBs are at low-redshift

⬇

The typical progenitor lifetime is several Gyr
or if $f(\tau)\propto\tau^{\eta}$ then $\eta>-1$

(Nakar, Gal-Yam & Fox 06; Guetta & Piran 06)

Evidence suggesting that more than ¼ of the SHBs are at $z>0.7$

⬇

lifetime distribution is wide, e.g., if $f(\tau)\propto\tau^{\eta}$ then $\eta<0$

(Berger et al., 07)

Observed Local Rate
(and robust lower limit on the true rate)

-BATSE observed rate was ≅ 170 yr^{-1}
-At least 15% of these bursts are at D < 1Gpc

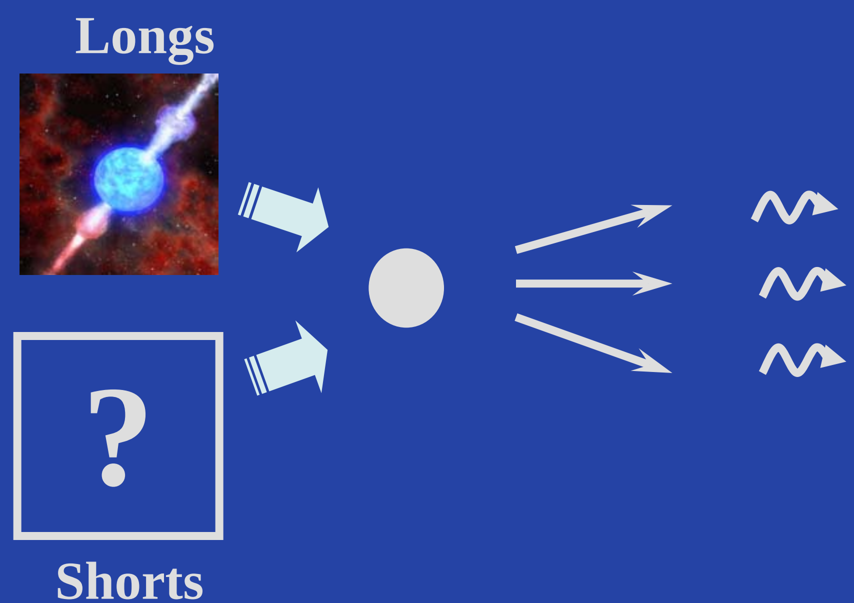
$$\Re_{SHB,obs} \approx 10\,\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Additional clue

Long and short GRBs have similar temporal and spectral properties of the prompt and afterglow emission

(Nakar & Piran 02; Mcbreen et al., 02; Ghirlanda et al., 04; Kaneko et al., 06)

suggesting similar engines



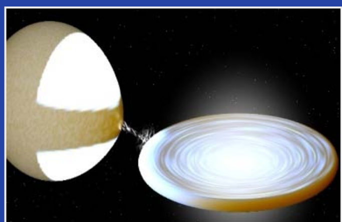
Viable progenitor systems and compact binary mergers

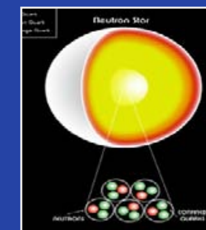
Observational constraints

- Engine size < 10^7 cm
- Total energy output $>10^{49}$ erg
- Isotropic luminosity > 10^{51} erg/s
- Launching relativistic outflow with $\Gamma>20$
- Characteristic engine activity time ~0.1s
- Long lived progenitor (Gyrs)
- Rate > 10 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- No accompanied supernova
- (?) Similar central engine to long GRBs
- (?) Prolonged engine activity for ~100-1000 s and possibly weeks
- (?) Wide range of collimation angles.
- (?) Wide range of circum burst densities

Some viable progenitor and central engine systems

(See review by Lee & Ramirez-Ruiz 07)



X-ray Binary

NS-NS
NS-BH

WD - WD

NS
Quark star

AIC

Merger

Merger
(AIC)

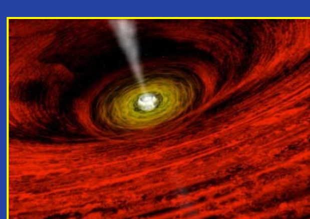
Phase
transition

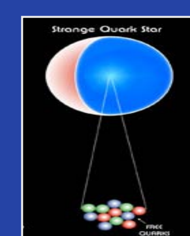
Accretion disk +
Black whole

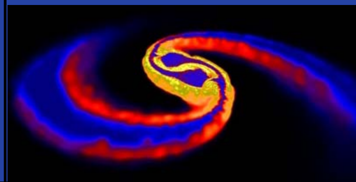
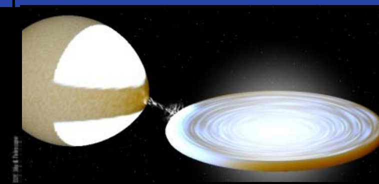
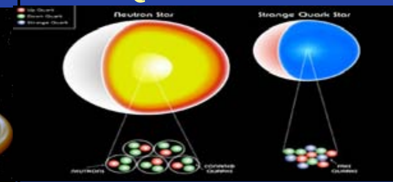
msec
magnetar

$>10^{16}$ G
magnetar

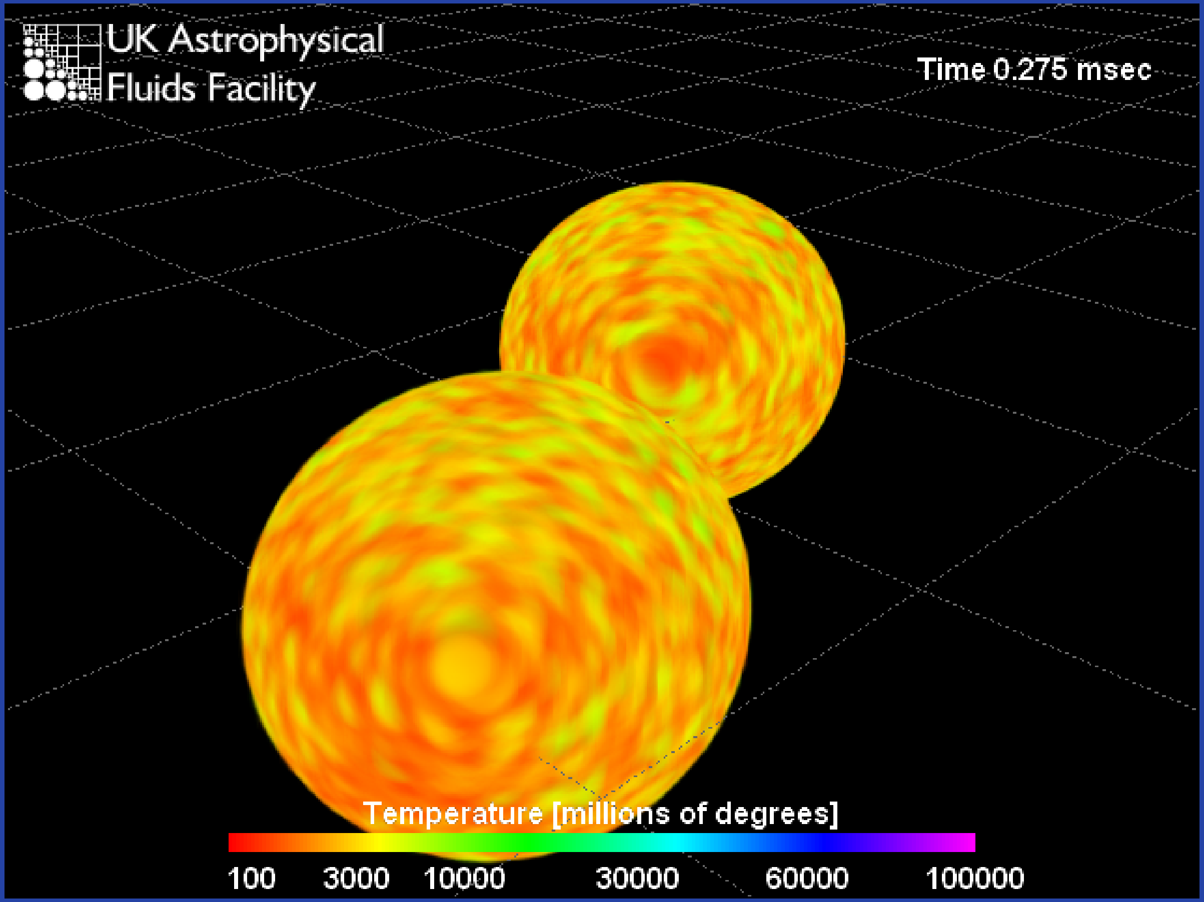
Quark star





	NS-NS/BH	WD-WD	NS AIC	Quark Star
				
Progenitor Exist	✓	✓	✓	?
Central engine	✓	?	✗	?
$<10^{7}$ cm	✓	✓	✓	✓
Active ~ 0.1s	✓	✓	?	✓
Late activity(?)	?	✓	?	?
$E_{tot} > 10^{49}$ erg	✓	✓	✗	✓
$L_{\gamma,iso} > 10^{51}$ erg	✓	✓	✗	✓
$\Gamma>20$	✓	?	?	✓
Long lived	✓	✓	✓	?
Rate	✓	?	?	?
Low density (?)	✓	?	?	?
Similar to long(?)	✓	✓	✓	?
Refs.	Eichler et al 89; Narayan, Piran &Kumar 01; …	Vietri & Stella 98 McFadyen et al. 05 Dermer & Atoyn 06	Usov 92; Thompson et. al., 04 Levan et al 06	Schramm & Olinto 92 Ma & Xie 96; Dar 99; …

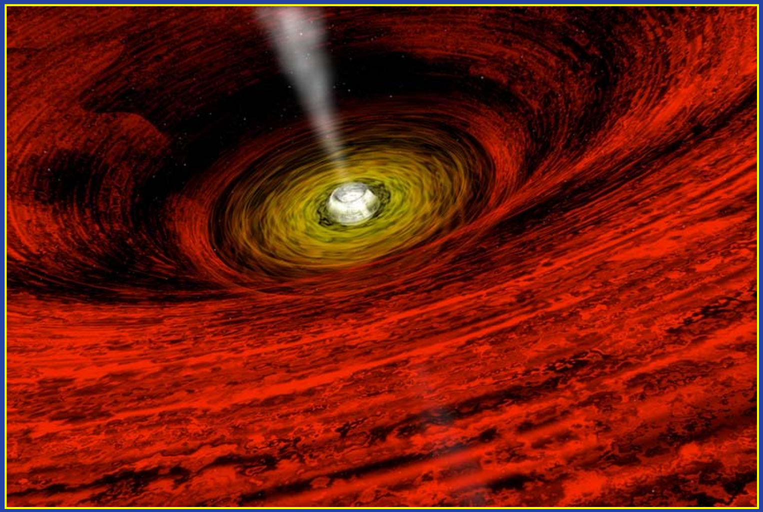
Merger of double neutron stars



Rosswog et. al.

Simulations: **Rosswog et al; Ruffert, Janka et al; Lee et al ; Shibata et al; Freyer et al; Faber et al; …**

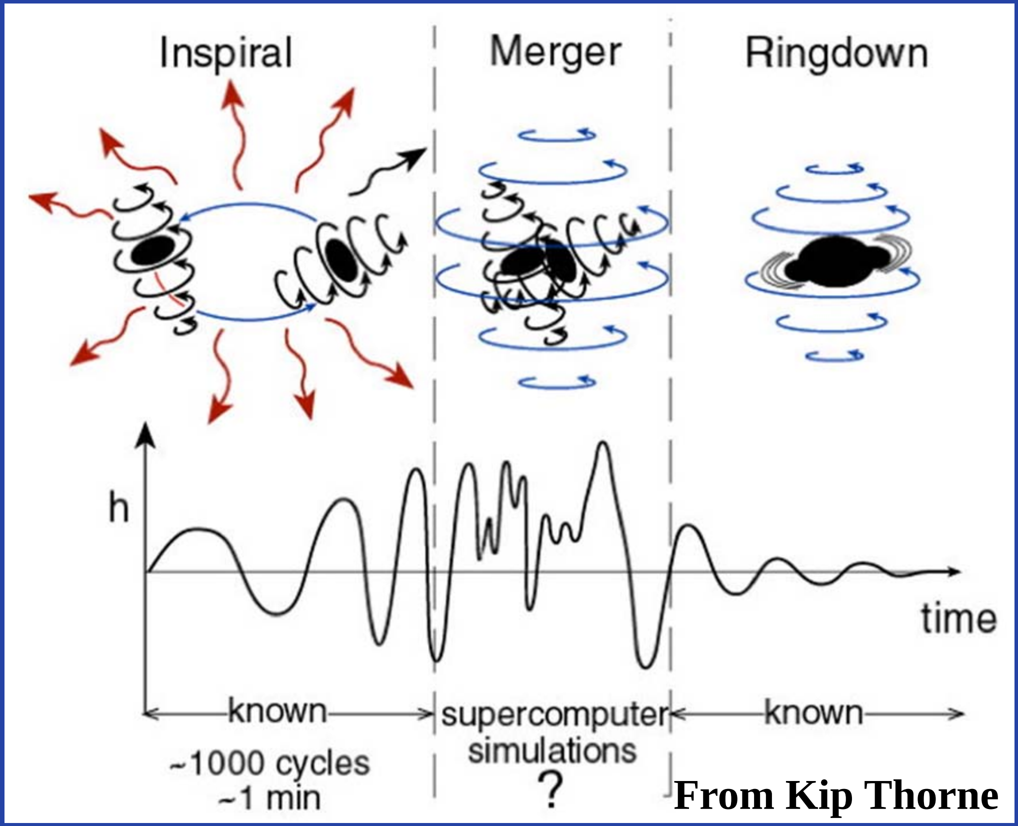
Central engine
accretion disk – black hole system



- Powered by gravity
- Activity time = Accretion time ~ 0.1s (e.g, Narayan et. al., 01)
- Outflow is launched by neutrino annihilation (e.g., Goodman, et. al., 87; …) or by electromagnetic processes (e.g., Blandford & Znajek 77; Narayan et. al., 92; Levinson & Eichler, 93; …)
- Similar to long GRBs where the time scale (~ 100 s) is set by the collapsing star infalling time.

Gravitational-wave detection

The Laser Interferometer Gravitational-Wave Observatory (LIGO)



From Kip Thorne

Inspiraling NS binary detection ranges:

Initial LIGO (operational): 15Mpc

Intermediate LIGO (2010): ~ 30-40Mpc

Advanced LIGO (2013+): ~ 300Mpc

If short GRBs are NS-NS mergers:

Short GRB rate → LIGO detection rate: detection is "guarantied" for advanced LIGO (Nakar et. al., 06)

Coincident EM+GW detection increases LIGO range by a factor of ~2 (Kochanek & Piran 93)

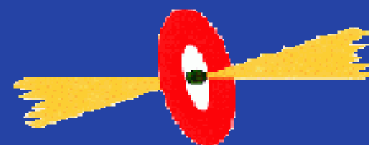
A valuable source of information on the binary evolution and short GRB physics

A strong cosmological probe – Within 1 yr next generation GW observatories may improve the constraints on the Hubble constant to ~2% (Dalal et al., 06)

Conclusions

Progenitor

Central Engine



$\Gamma > 20$

- Old (typically > Gyr)
- Rate > 10 $Gpc^{-3}\ yr^{-1}$
- leading Candidate:

Compact binary merger

- Compact ($< 10^{7}$ cm)
- Active ~ 0.1-1 s
- Late activity ?
- $L_{iso} > 10^{-3}\ M_{sun} c^2/s$
- $E_{iso} > 10^{-4}\ M_{sun} c^2$

Leading Candidate:

0.1 M_{sun} disk - black hole

γ-rays

Afterglow

Promising gravitational wave sources

Thanks!