Short Gamma-Ray Bursts and Compact Binary Mergers – Predictions for LIGO

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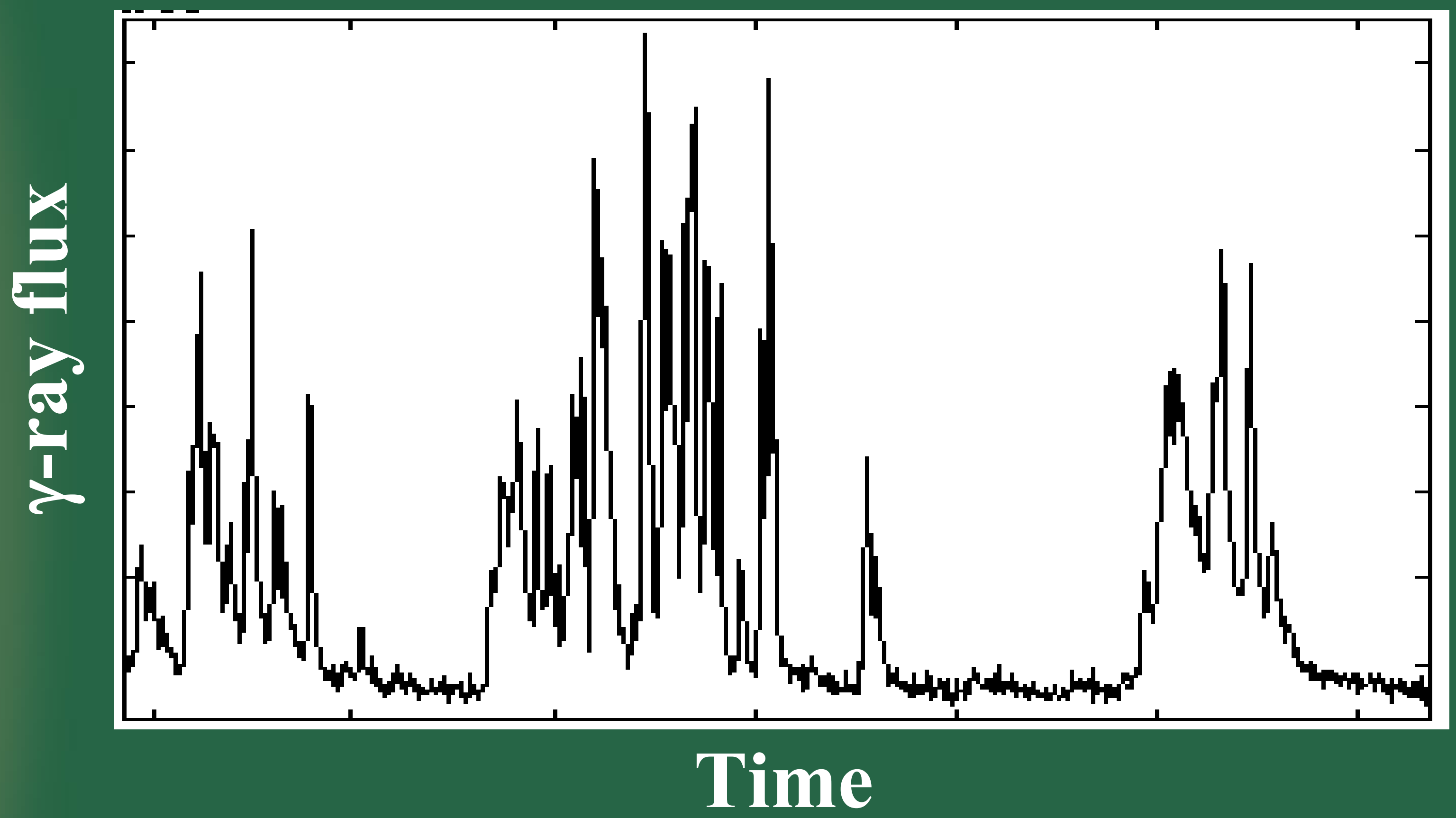
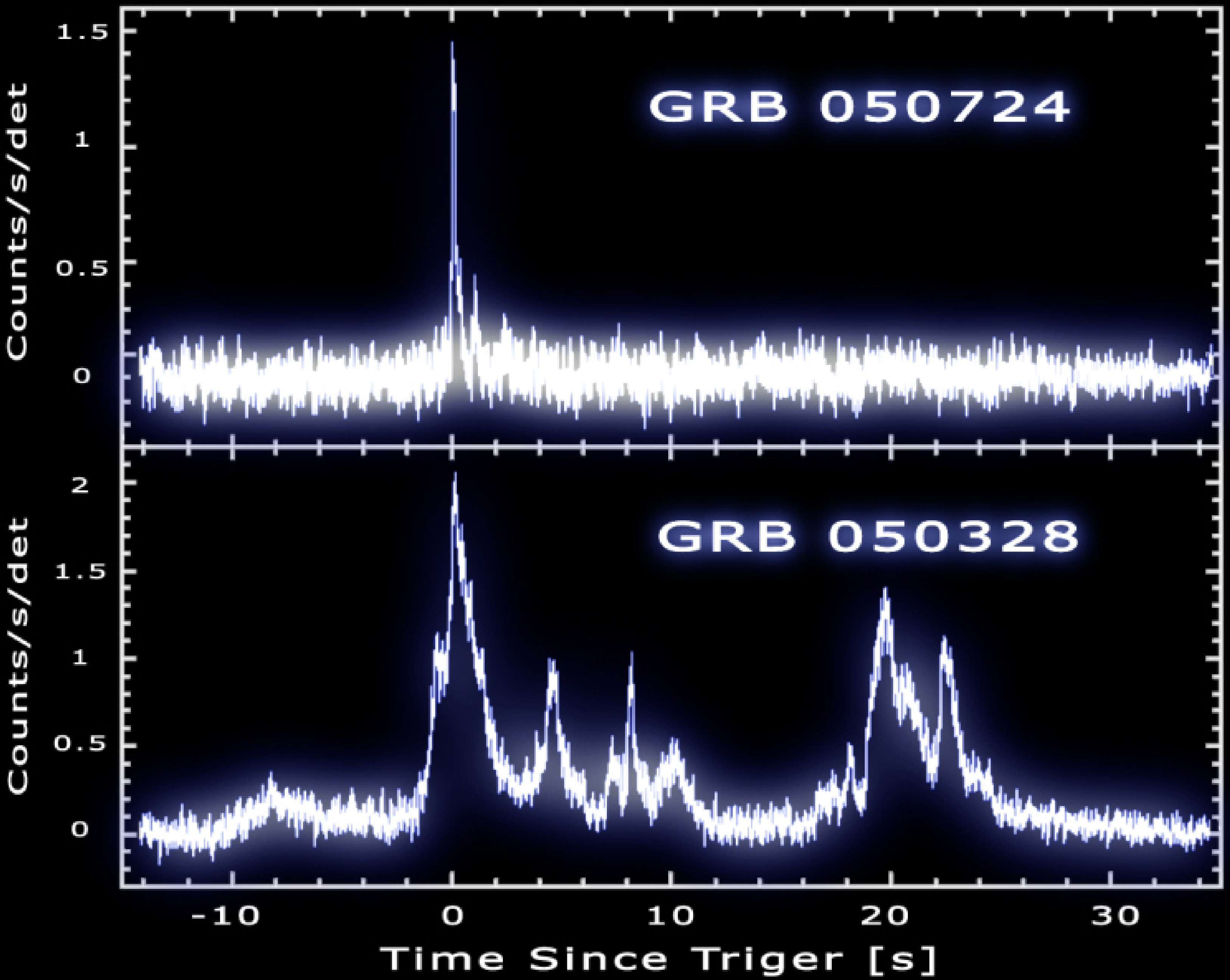
Outline

- What are long GRBs.
- The SGR episode.
- What do we know now about short GRBs That we didn’t know 6 months ago?
- Constraints on the progenitor lifetime and the local rate of short GRBs
  - Method
  - Results
- Comparison to the predictions of the merger rate and the lifetime of NS-NS and NS-BH binaries.
- Predictions for LIGO.

Gamma Ray Bursts (GRBs)



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


GRB 050724
GRB 050328
Counts/s/det
Counts/s/det
1.5
1
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2
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-10
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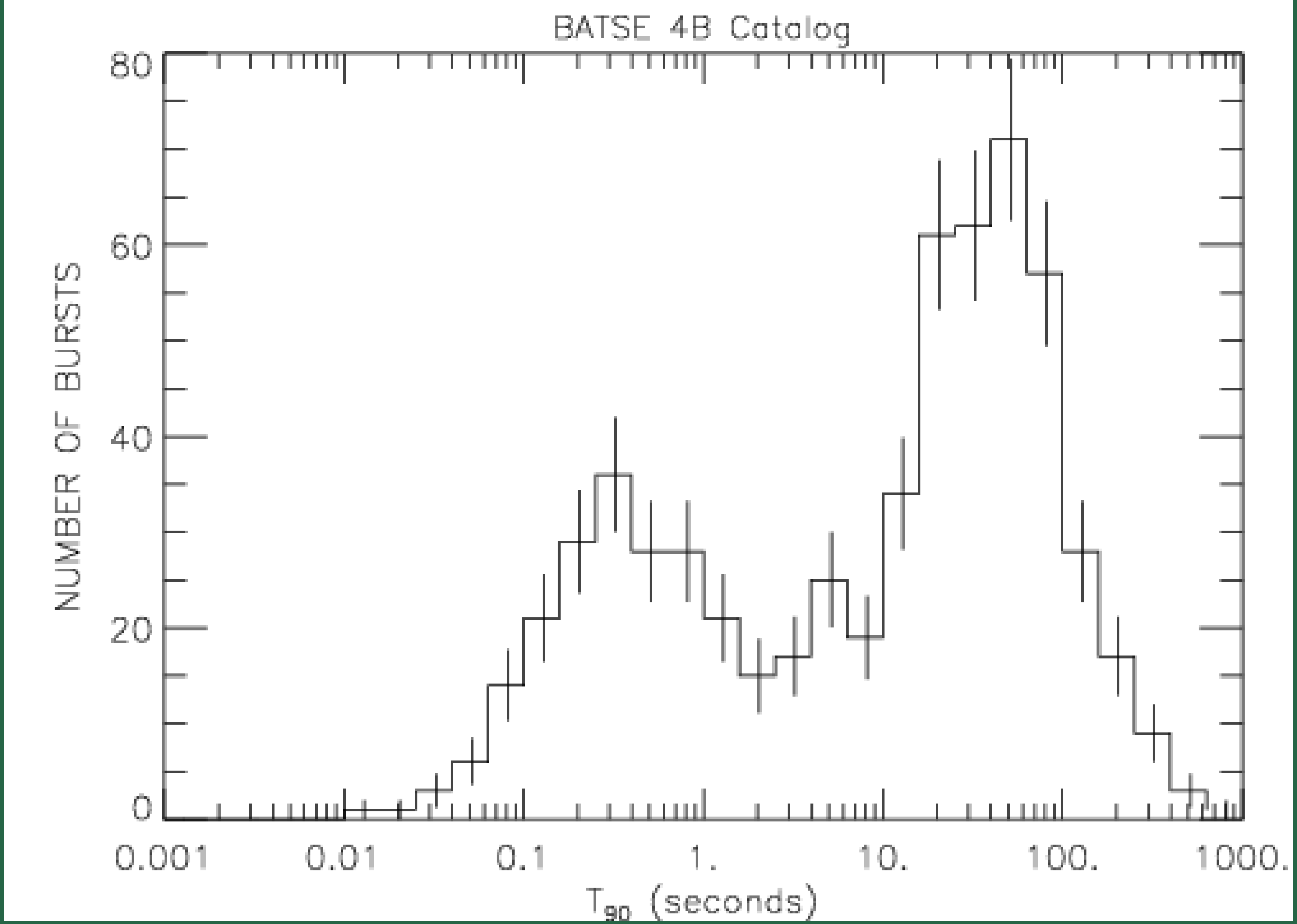
10
20
30
Time Since Triger [s]

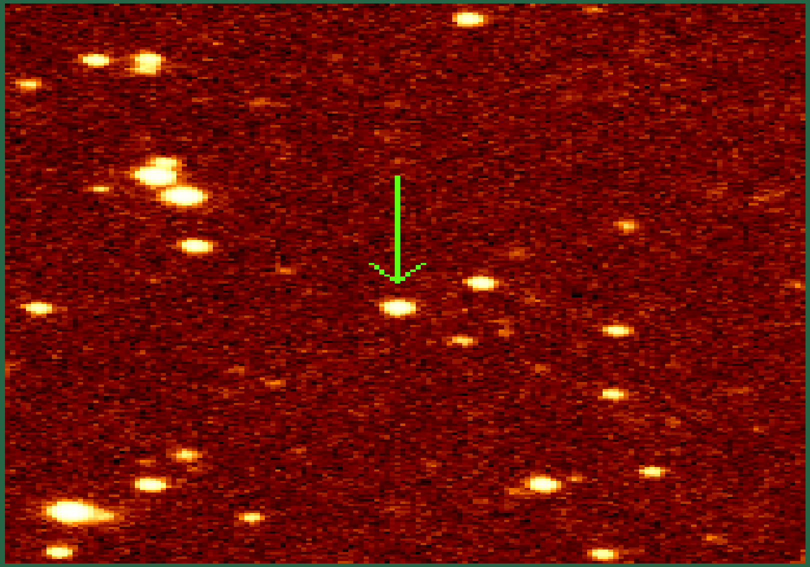
Short (SHB) and Long



Kouveliotou et al. 1993

***BATSE* (1991-2000) detected ~2700 GRBs**

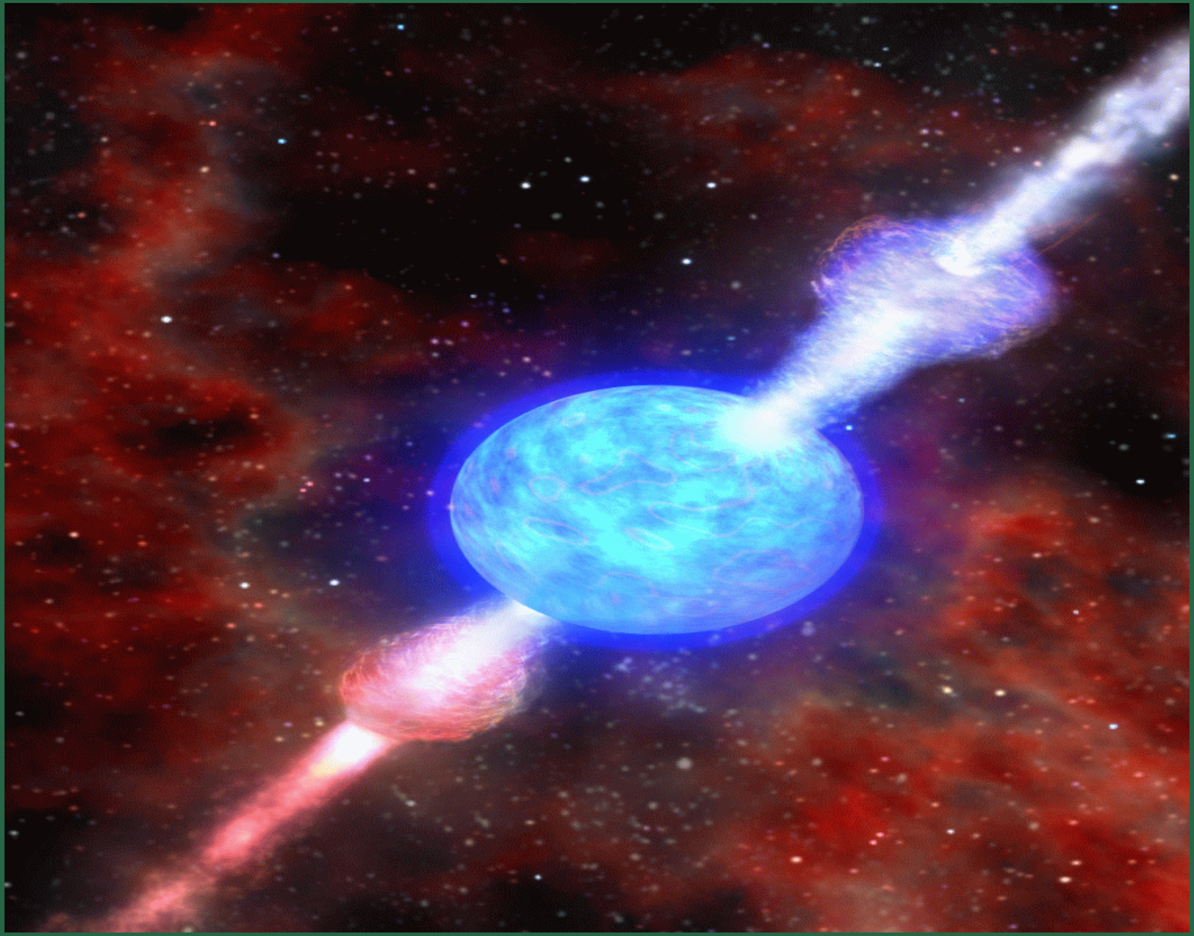
Afterglow of Long GRBs



Palazzi et al 99

Detection of X-ray, optical and radio counterpart emission (afterglow) that follows a long GRB enables sub-arcsecond localization

Long GRBs



A collapse of a massive star **(Collapsar;** Woosley et al.)

Associated with supernovae (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; …)

Short GRBs

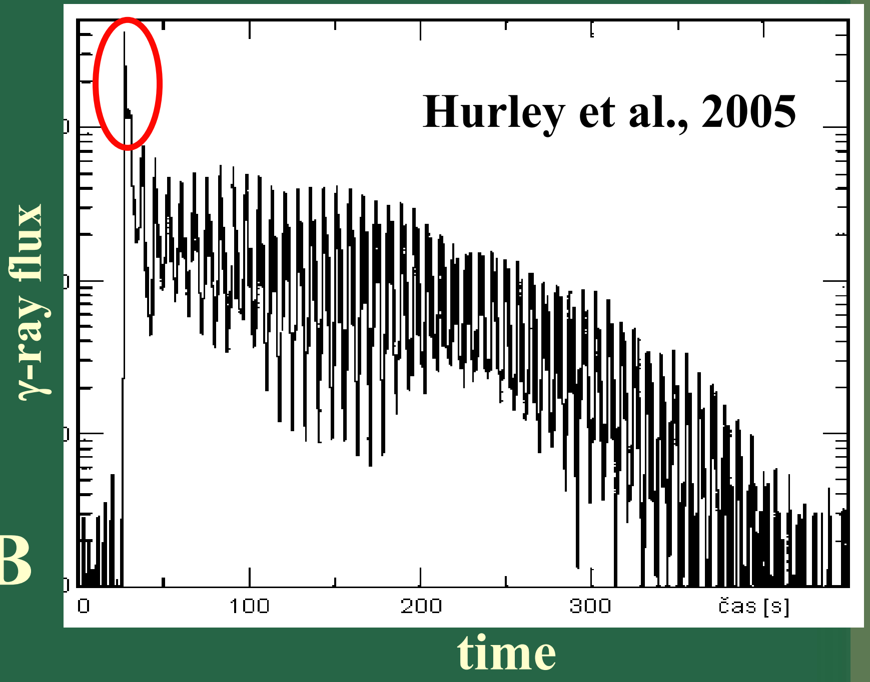
?

Distance ?
Energy ?
Progenitor ?

Short GRBs

Dec. 27, 2004: Mystery solved!

A giant γ-ray flare from the other side of the galaxy (SGR 1806-20).


Hurley et al., 2005

Such flare at a nearby galaxy would be detected as short GRB
(Duncan 2001; Boggs 2005; Dar 2005)

Short GRB = SGR!

Distance ~ 30 Mpc
Energy ~ 10^{46} erg
Progenitor - NS

Mystery solved ?

Nakar, Gal-yam, Piran & Fox (2005):

- No nearby galaxies at the locations of 6 old short GRBs
- Distance $\geq$ 100 Mpc - first direct evidence for short GRB distance!
- Energy $\geq 10^{49}$ erg

Most of the short GRBs are NOT SGRs

Popov et al. (2005), Palmer et al. (2005) and Lazzatti et al. (2005) obtained similar result using different methods.

Spring-Summer 2005 - The first detection of short GRB afterglows (by *Swift* and *Hete-2*):

Short GRB	Host galaxy	Redshift (Distance)	Energy
050509b	Very old	0.22 (~900 Mpc)	4.5×10^{48}
050709	Young	0.16 (~660 Mpc)	6.9×10^{49}
050724	Old	0.26 (~1 Gpc)	4×10^{50}
050813	Very old	0.72[?] (~2.6 Gpc)	6.5×10^{50}

Bloom et al. 2005; Kulkarni et al. 2005; Gehrels 2005; Castro-Tirado et al. 2005; Prochaska et al. 2005; Fox et al. 2005; Hjorth et al. 2005; Covino et al. 2005; Berger et al. 2005

Proposed progenitors of short GRBs

~~SGR flare~~

Hosts with no star formation; Too energetic

~~Massive star~~

Hosts with no star formation; No supernova

Compact binary merger

First discussed in detail by Eichler et al. 1989

✓

Short GRBs:

- Occur at cosmological distances
- Occur preferentially in old galaxies → do not follow star formation – different progenitor than long GRBs.
- Produce relativistic outflows with energy of 10^{-5}-$10^{-3} M_{\odot} c^2$ over 0.1-1sec → suggesting a catastrophic stellar event
- Show variability on timescales shorter than a millisecond → the engine is of the size of a neutron-star or smaller

The best progenitor candidate is a NS-NS or a NS-BH merger

Extended SHB sample

(Gal-yam et al. 2005)

SHB	Host	Redshift	Significance
050509b	E (c)	0.22	~3-4σ
050709	Sbc/Sc	0.16	Secure
050724	E	0.26	Secure
050813	E/S0 (c)	0.72	[?]
790613	E/S0 (c)	0.09	3σ
000607	Sb	0.14	2σ
001204		>0.25[0.06]	1[2]σ
021201		>0.25[0.06]	1[2]σ

A small but nearly complete sample

The rate and progenitor lifetime of SHBs

(Nakar, Gal-yam & Fox 2005)

Goals:

- Using the extended sample to constrain the local rate and the progenitors lifetime of short GRBs.
- Evaluate the compatibility of these results with the compact binary progenitor model.
- Explore the implications for gravitational wave detection of these events with LIGO.

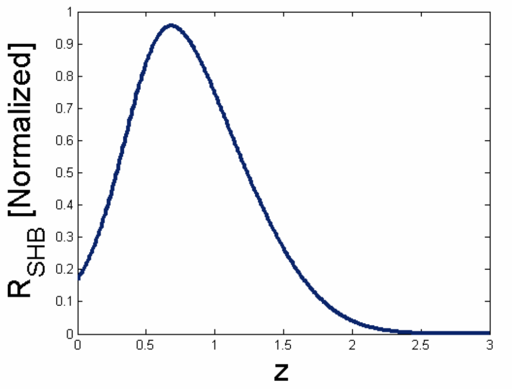
Method:

Comparing the *observed* redshift and luminosity distributions to predictions of various models of *intrinsic* redshift and luminosity distributions.

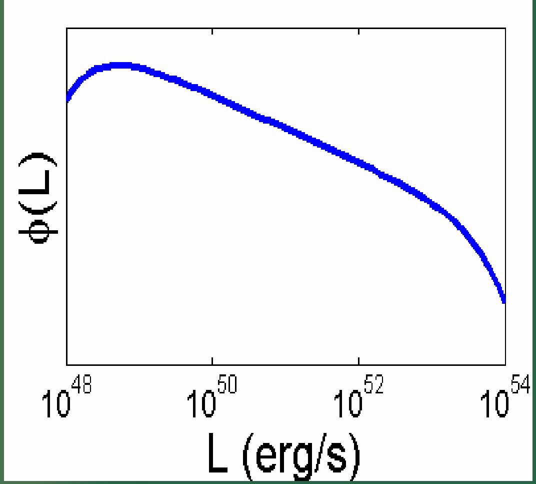
(this method is an extension of a method used by Piran 1992; Ando 2004; Guetta & Piran 2005)

Consistency test

Redshift distribution



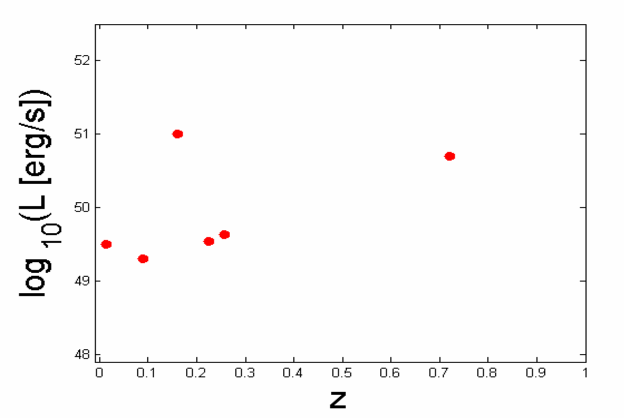
Intrinsic



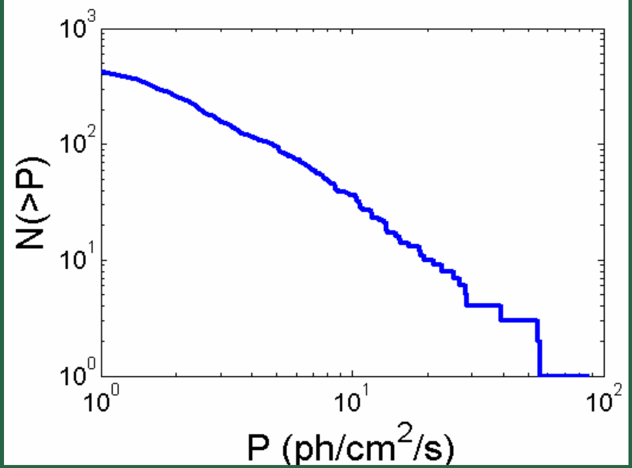
Luminosity function

Cosmology
+
Detector

Several bursts with known z

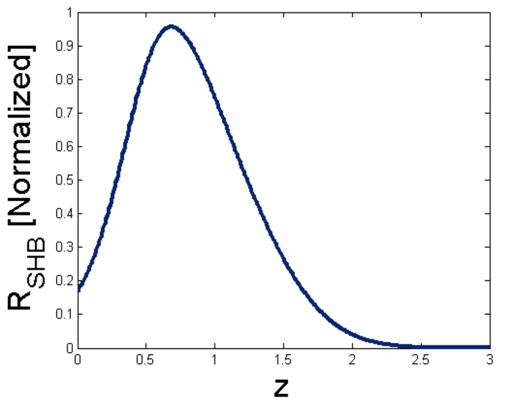


Observed

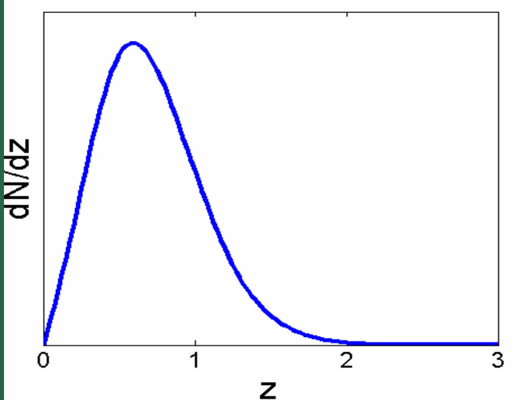


~400 BATSE bursts with unknown z

If $\phi(L)$ is a single power-law:

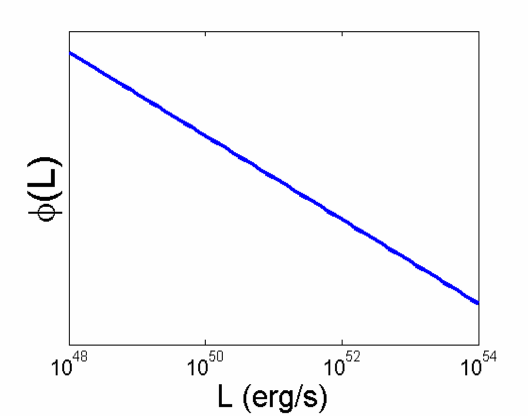


Cosmology

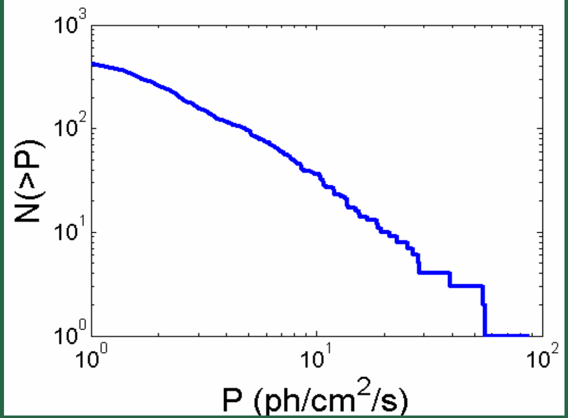


Intrinsic

Observed



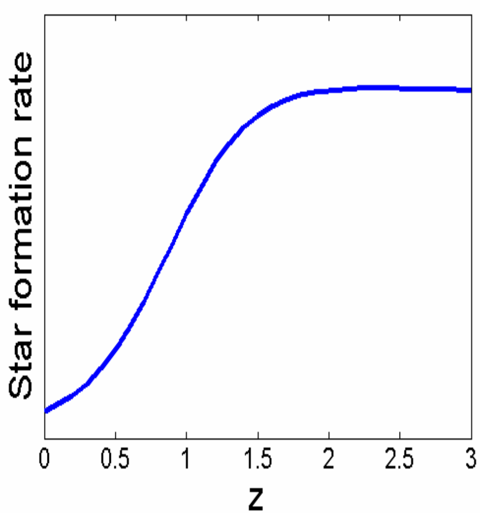
Detector



In our case a single power-law fit the data very well:

$$\phi(L) \propto L^{-2\pm0.1}$$

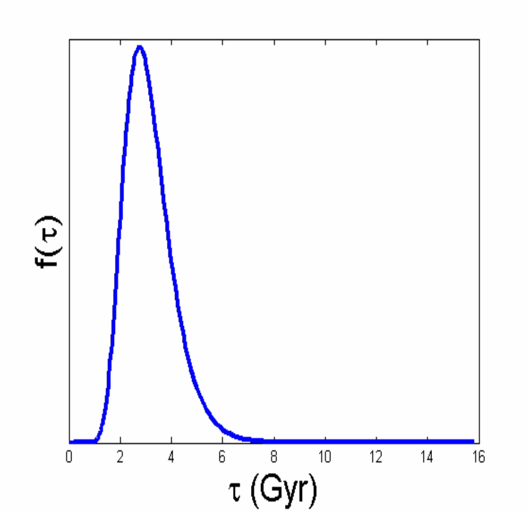
Star formation rate



Porciani & Madau 2001

+

Progenitor lifetime distribution



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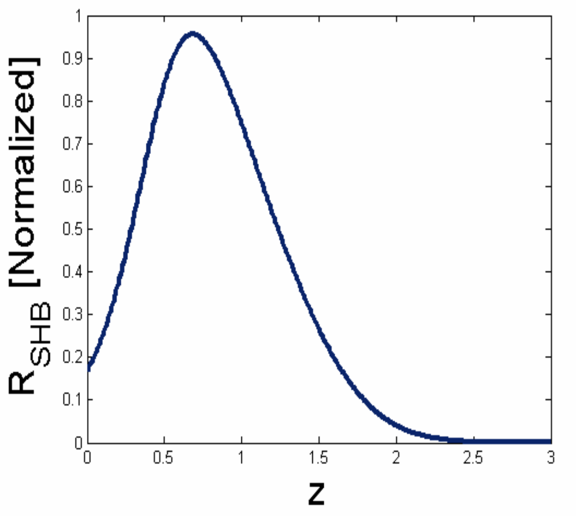
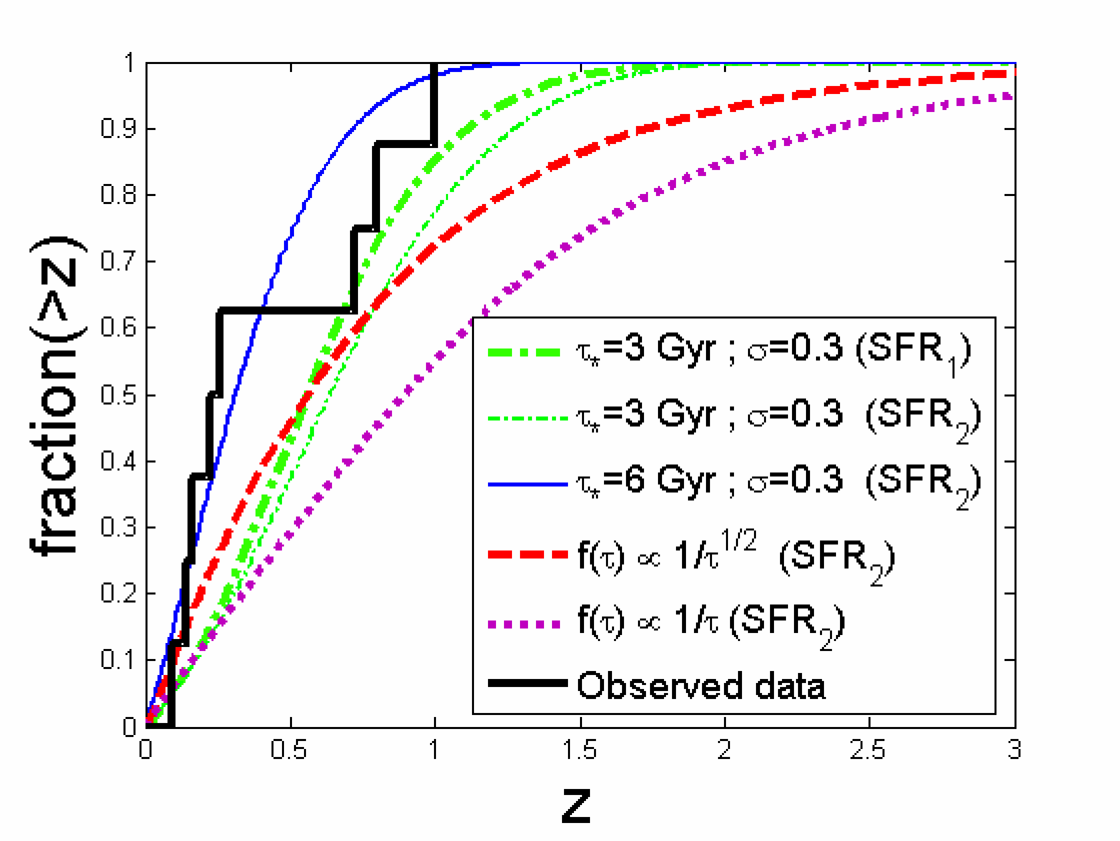
Intrinsic redshift distribution



Results

Progenitor lifetime

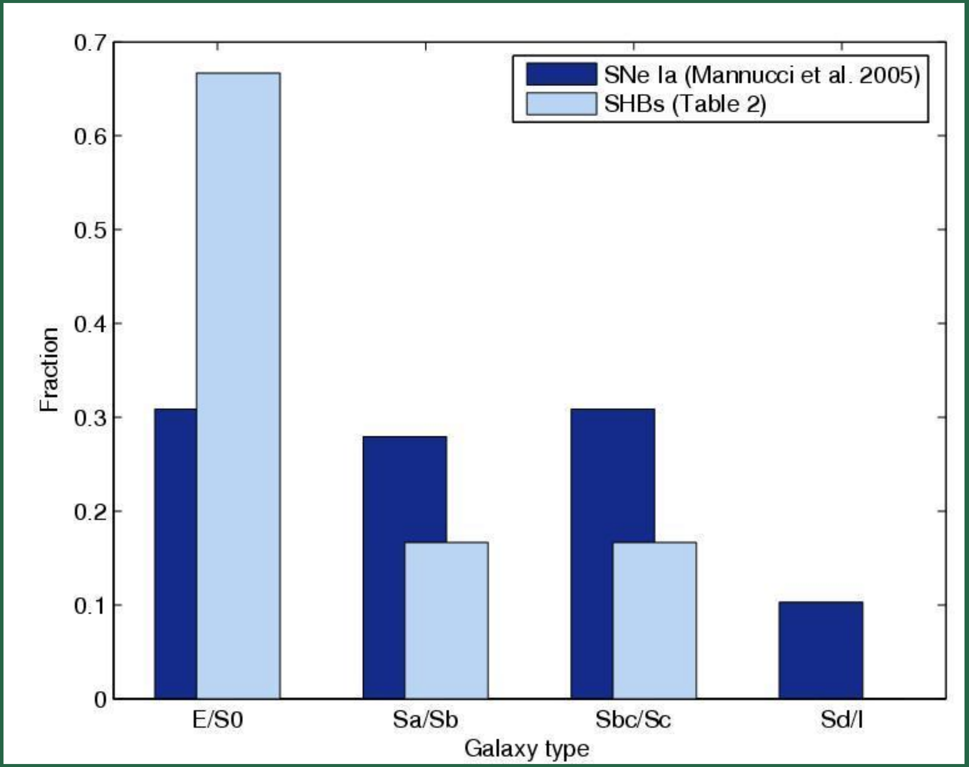


$\tau_{\mathrm{typical}} > 3\mathrm{Gyr}$ (2σ)

or if $f(\tau) \propto \tau^{-\eta}$ then $\eta > -0.5$ (2σ)

Comparison with SNe Ia

(Gal-yam et al., 2005)



SHBs are older than type Ia SNe (2σ confidence level)

$$\tau_{typical} > 1\text{Gyr}$$

Observed SHBs are old

τ is several Gyr

Observed SHBs are (relatively) nearby

$z \sim 0.2$-0.3 ($D \sim 1$Gpc)

Observed Local Rate

-BATSE observed rate was ≅ 170 yr^{-1}
-At least ¼ of these bursts are at D < 1Gpc

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

(Similar result is obtained by Guetta & Piran 2005)

Total Local Rate

Bursts avoid detection if they are:
- too dim to be detected
- beamed away from the observer

(Fox et al. 2005: hints for a beaming factor of 30-50)

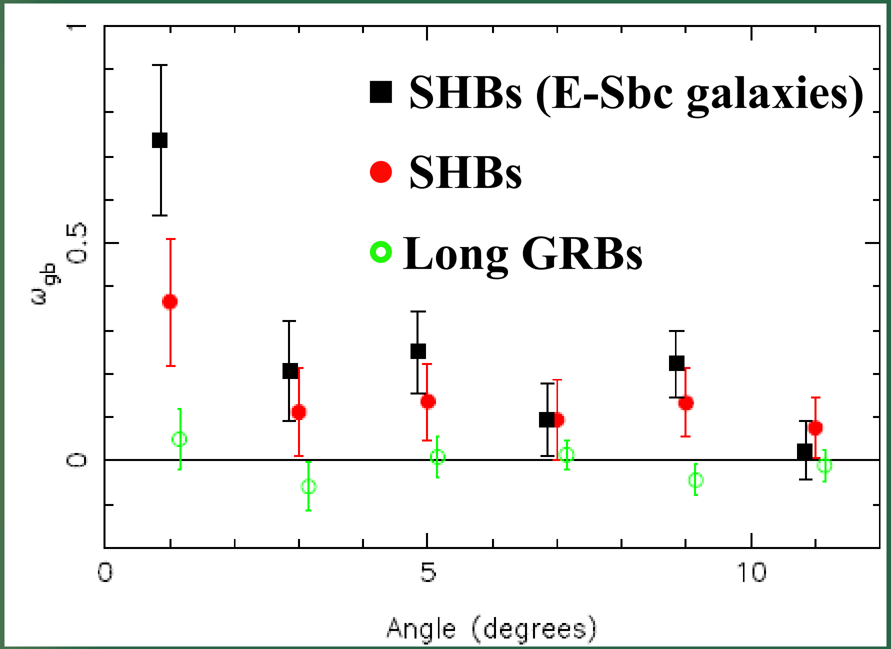
Dim Bursts

The rate of dim bursts depends strongly on the low end of the luminosity function

Current observations dictate:

$L_{min} < 10^{49}$ erg/s

SHBs 🔗 Galaxies at D<100Mpc



Tanvir et al. 2005

At least 5% of BATSE SHBs are at D<100Mpc

Our model predicts that 3% of the SHBs are at D<100Mpc if $L_{min} \cong 10^{47}$ erg/s

Total Local rate

Robust lower limit:

$$\Re_{SHB} \approx 20\, f_b \left(\frac{L_{\min}}{10^{49}\ \mathrm{erg/sec}} \right)^{-1} \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Beaming correction (30-50) [Fox et al. 2005] + evidence for population of SHBs within ~100Mpc [Tanvir et al. 2005] ($L_{\min} < 10^{47}$ erg/sec) :

$$\Re_{SHB} \approx 100{,}000 \left(\frac{f_b}{50} \right) \left(\frac{L_{\min}}{10^{47}\ \mathrm{erg/sec}} \right)^{-1} \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Local rate – upper limit

SHB progenitors are (almost certainly) the end products of core-collapse supernovae (SNe).

The rate of core-collapse SNe at z~0.7 is 5×10^{5} Gpc^{-3} yr^{-1} (Dahlen et al. 2004), therefore:

$$\Re_{SHB} \leq 5\times10^{5}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Comparison to mergers of NS-NS and NS-BH binaries

Rate of NS-NS mergers

Evaluated in two ways:

-Based on observed systems in our galaxy

(e.g., Phinney 1991; Narayan, Piran & Shemi 1991; Curran & Lorimer 1995; van den Heuvel & Lorimer 1996; Arzoumanian, Cordes &Wasserman 1999; Kalogera et al. 2001, 2004; de Freitas Pacheco et al. 2005)

-Using theoretical population synthesis

(e.g. Lipunov et al. 1995; Portegies Zwart & Yungelson 1998; Bethe & Brown 1998; Bloom, Sigurdsson & Pols 1999; Fryer,Woosley & Hartmann 1999; Belczy´nski & Kalogera 2001; Belczynski, Kalogera & Bulik 2002; Belczynski, Bulik & Kalogera 2002; Perna & Belczynski 2002)

Observed NS-NS systems in our galaxy

Based on three systems, Kalogera et al. (2004) find:

$1.7\times10^{-5} \leq \Re_{NS-NS} \leq 2.9\times10^{-4}\ \mathrm{yr}^{-1}\ (95\%)$ **in our galaxy**

And when extrapolating to the local universe:

$$200 \leq \Re_{NS-NS} \leq 3000\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

This rate is dominated by the NS-NS system with the shortest lifetime – τ~100 Myr (the double pulsar PSR J0737-3039). Excluding this system the rate is lower by a factor 6-7 (Kalogera et al. 2004).

Population synthesis (NS-NS & BH-NS mergers)

- Roughly consistent with the observational method
- Highly uncertain
- Can provide upper limit:

At most ~1% of the core-collapse SNe produce DNS systems that merge during a Hubble time **(e.g., Lipunov et al. 1997; Portegies Zwart & Yungelson 1998; Pfahl *et al.* 2002)**

Short lived binaries (<1Gyr): $\Re_{NS-NS} \leq 10^{3}\ \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Long lived binaries (~ 6Gyr): $\Re_{NS-NS} \leq 10^{4}\ \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

SHBs and NS-NS mergers

NS-NS (Kalogera et al. 2004):
$200 < R_{NS\text{-}NS} < 3000$ Gpc^{-3} yr^{-1}
Dominated by binaries that merge within ~100 Myr

SHBs (Nakar et al. 2005):
$10 < R_{NS\text{-}NS} < 5 \cdot 10^5$ Gpc^{-3} yr^{-1}
Dominant by old progenitors >3 Gyr

For the two to be compatible there should be a hidden population of old long-lived NS-NS systems.

Can it be a result of selection effects?

Maybe, but we cannot think of an obvious one.

Caveat: small number statistics

If SHBs are NS-NS mergers:

- An assumed large population of undetected short-lived NS binaries needs to be suppressed
- A large population of old, long lived binaries must be invoked (undetectable)

- $10^3 \leq \Re_{SHB} = \Re_{NS-NS} \leq 10^4 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

SHBs and BH-NS mergers

This progenitor model cannot be constrained:

- No observational data
- Theoretical models are highly uncertain

If SHBs are BH-NS mergers

$$10 \le \Re_{SHB} = \Re_{BH-NS} \le 10^{4}\ \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

Implications for LIGO

Assuming that SHBs are mergers of NS-NS or BH-NS binaries

Detection range in a blind search

Initial LIGO (LIGO-I) :

NS-NS merger – **20 Mpc**

BH-NS merger (10 $M_\odot$ BH) – **40 Mpc**

Advanced LIGO (LIGO-II) :

NS-NS merger – **300 Mpc**

BH-NS merger (10 $M_\odot$ BH) – **650 Mpc**

(Cutler & Thorne 2002)

Probability for blind search detection

LIGO-I: Taking a speculative but reasonable SHB rate of 10^4 Gpc^{-3} yr^{-1} predicts a detection rate of:

$$R(\text{NS-NS}) \sim 0.3\ \text{yr}^{-1}$$

$$R(\text{BH}^{*}\text{-NS}) \sim 3\ \text{yr}^{-1}$$

LIGO-II: The SHB rate lower limit of 10 Gpc^{-3} yr^{-1} implies:

$$R(\text{NS-NS}) \geq 1\ \text{yr}^{-1}$$

$$R(\text{BH}^{*}\text{-NS}) \geq 10\ \text{yr}^{-1}$$

$^{*}M_{BH} \sim 10M_{\odot}$

Detection of SHB increases LIGO range by a factor of 1.5-2.5 (Kochanek & Piran 1993):

- Timing information (~1.5)
- Beaming perpendicular to the orbital plane (~1.5)
- Localization information

GRB missions

Mission	Operational	SHB rate (yr^{-1})	
		localized	non-localized
Swift	2005-2007+	~10	?
HETE-2	2001-2005+	~1	-
IPN	yes	~1	Much more
GLAST	2007-	~30*	-

***my rough estimate**

LIGO-I: Probability for simultaneous detection

Swift detects and localizes ~10 SHBs yr^{-1}. If L_{min}~10^{47} erg/s and $\phi(L) \propto L^{-2}$ then ~3% of these SHBs are at D<100 Mpc and ~1% at D<50 Mpc

$$R(\text{merger+SHB}) \sim 0.1\ \text{yr}^{-1}$$

Notes:

- This result depends weakly on beaming
- In this scenario $R_{SHB} \sim 1000\ f_b\ \text{Gpc}^{-3}\text{yr}^{-1}$
- Comparison with *Swift* and IPN non-localized bursts may significantly increase this rate

LIGO-II: Probability for simultaneous detection

- This year 3 bursts detected at D < 1Gpc
- GLAST is expected to detect several SHBs at D<500Mpc every year
- LIGO-II range for simultaneous detection is ~700 Mpc (NS-NS) and ~1.3 Gpc (BH-NS)

Simultaneous operation of LIGO-II and an efficient SHB detector could yield at least several simultaneous detections each year.

Non-detection will exclude the compact merger progenitor model

Conclusions (I)

- SHBs are old (several Gyr)
- SHBs are frequent:
  - Observed local rate $R_{SHB,obs} \sim 10\ Gpc^{-3}\ yr^{-1}$
  - Total local rate $10 < R_{SHB} < 5 \cdot 10^{5}\ Gpc^{-3}\ yr^{-1}$
- The old age of the SHBs is hard to reconcile with the NS-NS merger progenitor model, given the dominance of observed short-lived binaries.

Conclusions (II)

If SHBs are mergers of NS-NS [BH-NS] binaries

LIGO-I detection rate can be as high as:

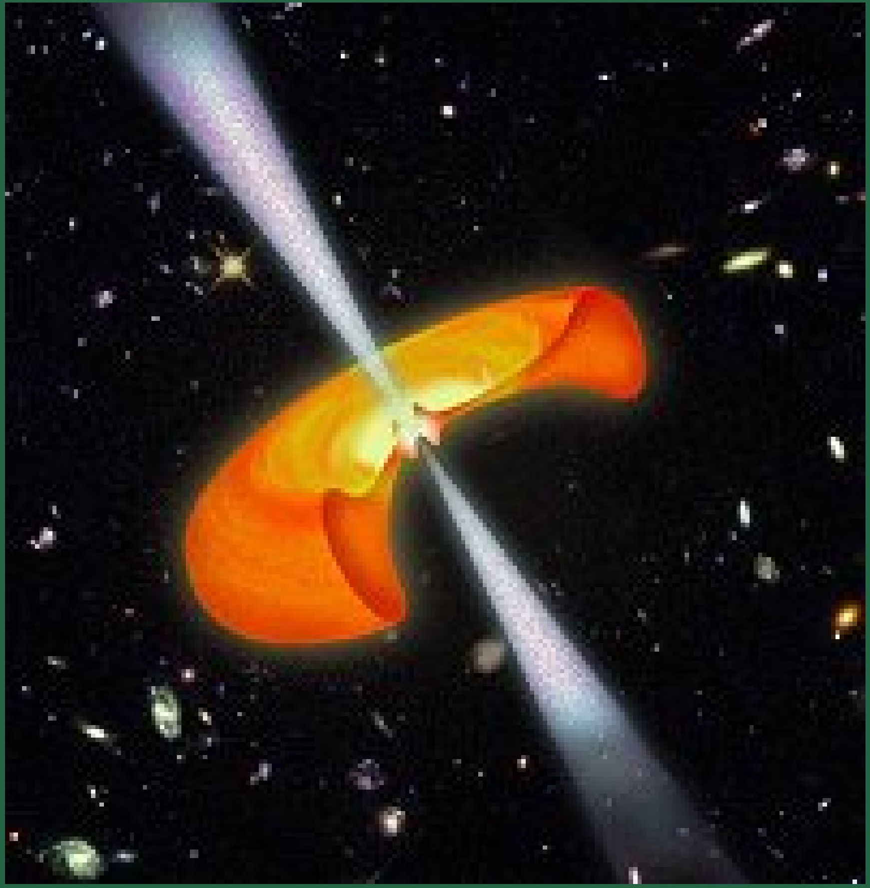
simultaneous – 0.1 yr^{-1}
blind search - 0.3 [3] yr^{-1}

LIGO-II detection rate should be higher than:

simultaneous – several yr^{-1}
blind search - 1 [10] yr^{-1}

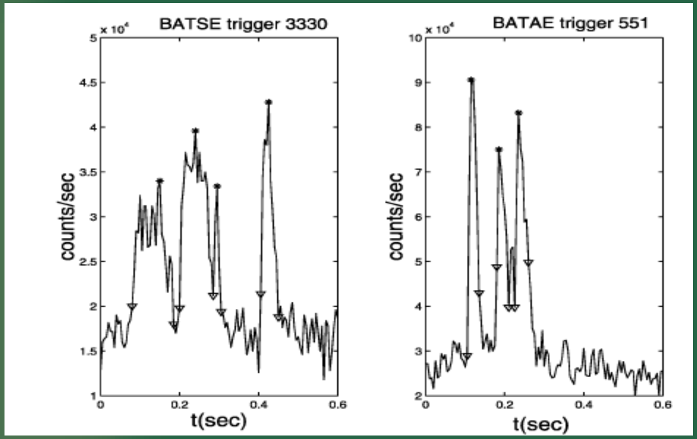
Thanks!

Long GRBs

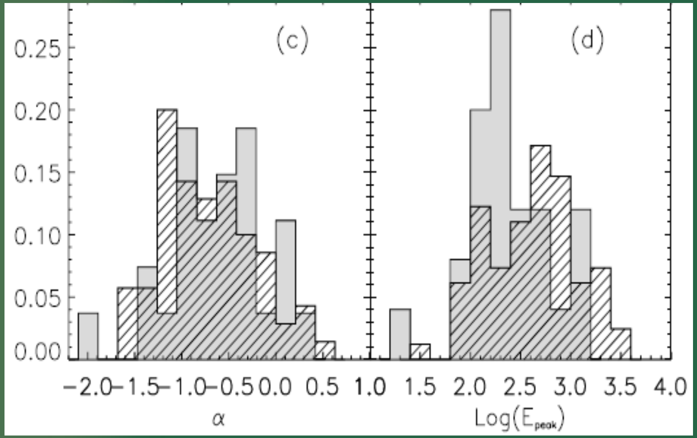


Central engine: accretion on a newborn black-hole

Relativistic jets: 0.1-1% of a solar rest-mass energy is ejected in narrow relativistic jets



Long and short GRBs have similar temporal properties on short time scales (Nakar & Piran 2002)

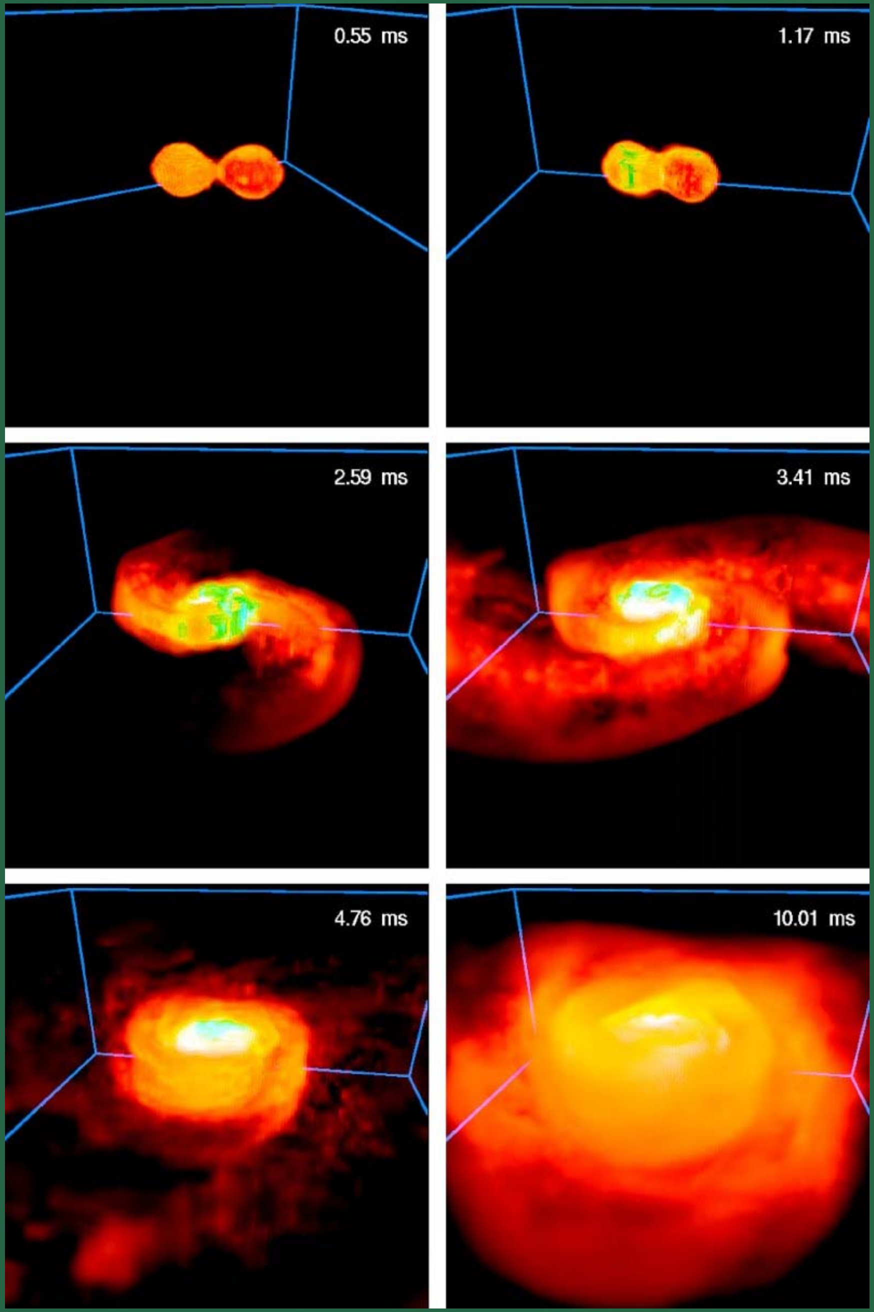


The spectral properties of the first 2sec of Long GRBs are similar to these of short GRBs (Ghirlanda et al., 2003)

Suggesting that similar engines produce both classes of GRBs. Most likely an accretion on black-hole

Numerical simulations (e.g., Ruffert & Janka 1999; Janka et al. 1999; Rosswog et al. 2003; Lee et al. 2005; Oechslin & Janka 2005):

Compact binary mergers produce a disk accreting on a black-hole. The accretion time is comparable to the duration of short GRBs.



Ruffert & Janka 2001

Several numerical simulations of BH-NS mergers show a production of an accretion disk around the black-hole, even for $M_{BH} \sim 10M_{\odot}$ (e.g., Janka et al. 1999; Lee 2000; Rosswog et al. 2004), these simulations use Newtonian potentials.

Miller (2005) points out that in reality, only rapidly rotating BH with mass comparable to the NS can produce a stable accretion.

BACK