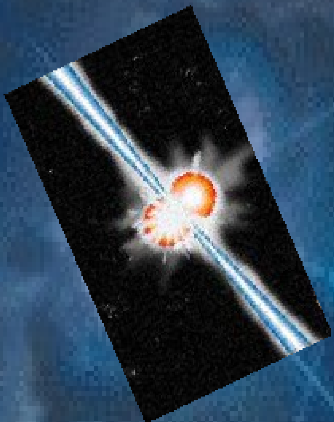


Gravitational waves from short Gamma-Ray Bursts

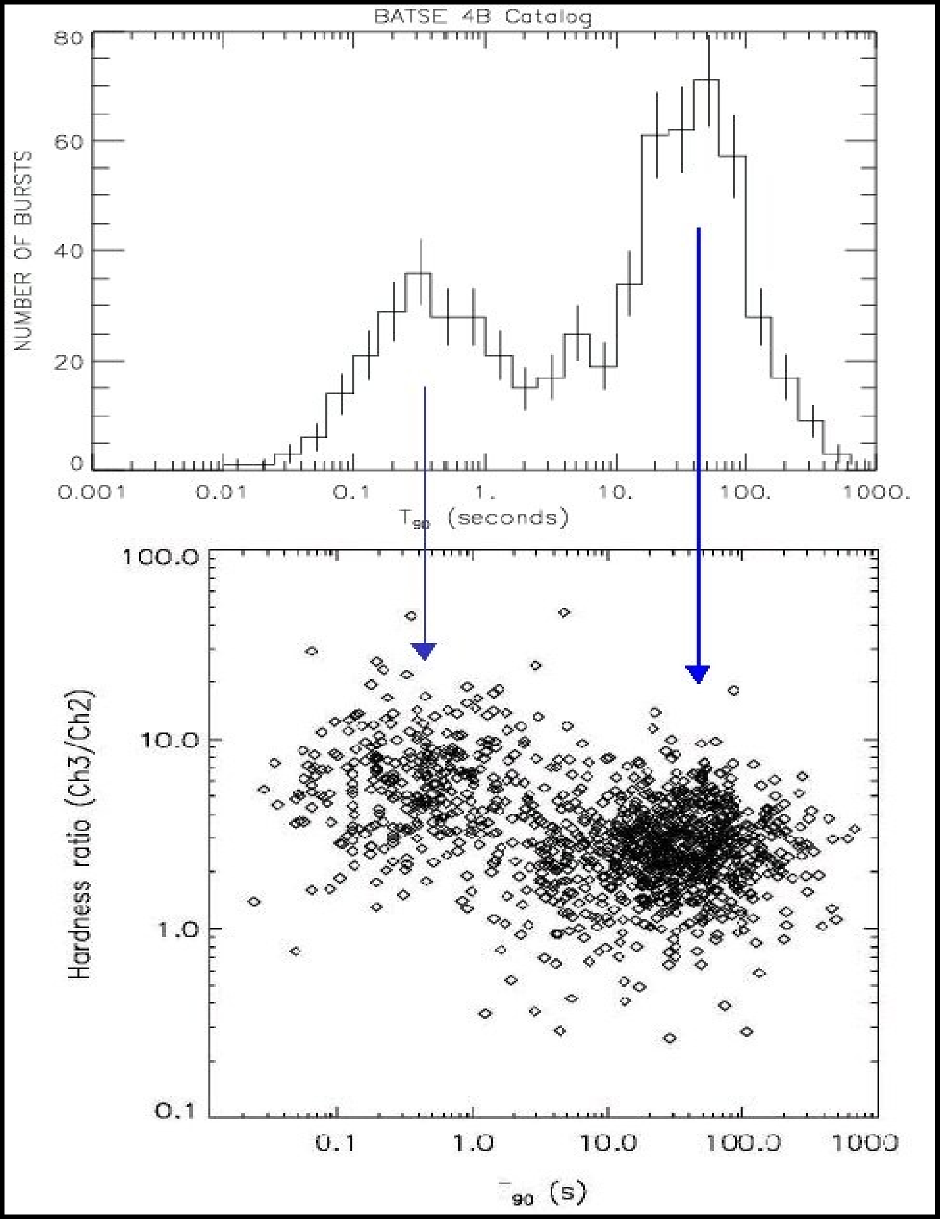
Dafne Guetta (Rome Obs.)

My collaborators: Luigi Stella, David Eichler, Eli Waxman, Tsvi Piran

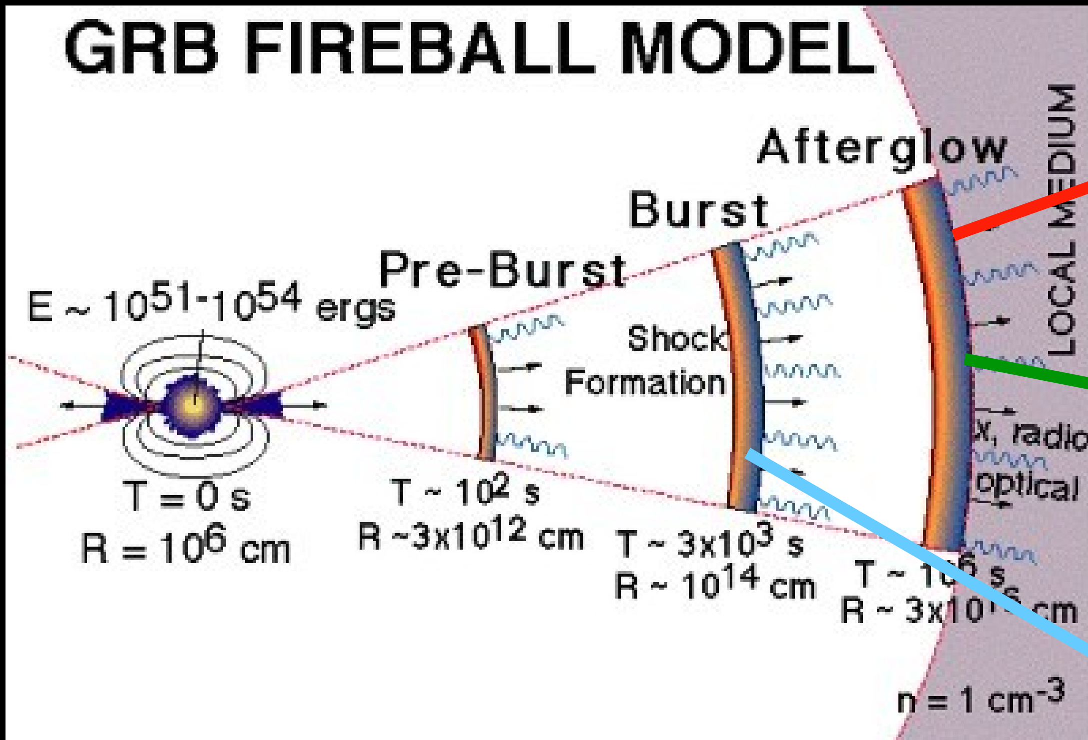
Two different classes of Gamma-Ray Bursts

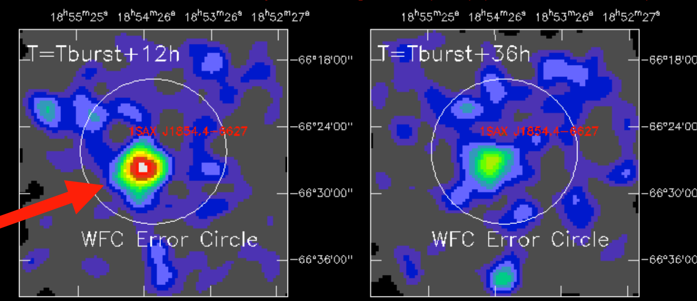
- GRBs duration distribution is bimodal (e.g. Briggs et al. 2002)
  - 0.1-1 s -> Short bursts
  - 10-100 s -> Long bursts

- Short GRBs are harder than long GRBs
  (e.g. Fishman & Meegan, 1995; Tavani 1996).

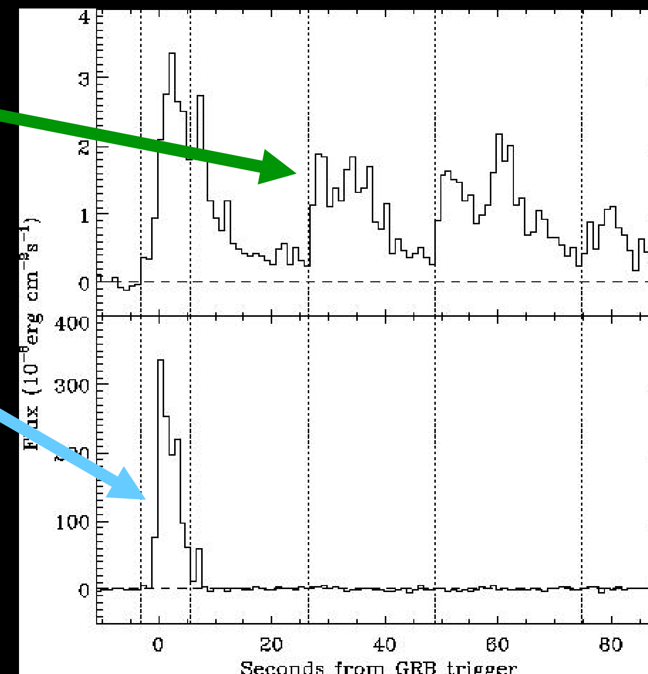


GRB Fireball, Energy and Beaming





(Antonelli et al., 2000, Ap.J.Lett., in press)



A few, very luminous GRBs (e.g. GRB990123 z=1.6) have (isotropic) energies:

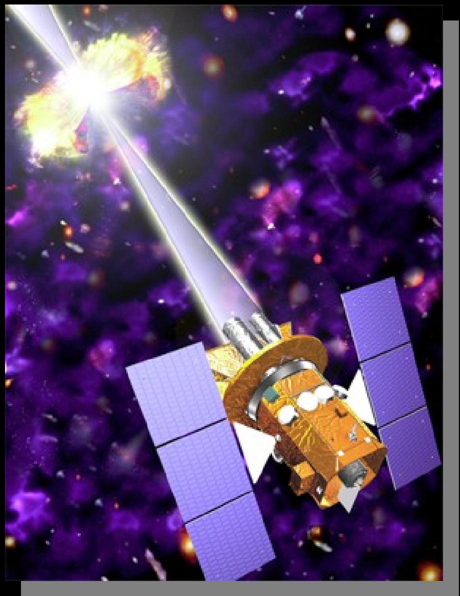
$E(iso) = 4\times10^{54}$ erg

<u>GRBs may be beamed (~few degree opening angle)</u>

$E(true) = f_b\, E(iso) = 10^{51} - 10^{52}$ erg

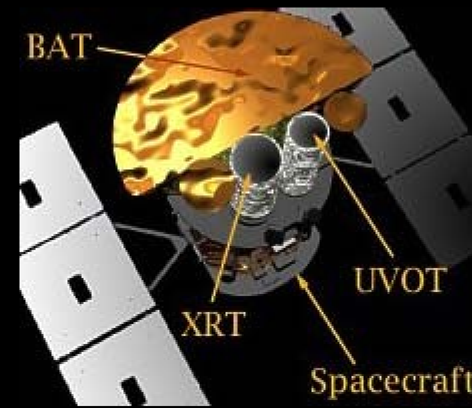
f_b is the fraction of the 4π solid angle within which the GRB is emitted

Swift



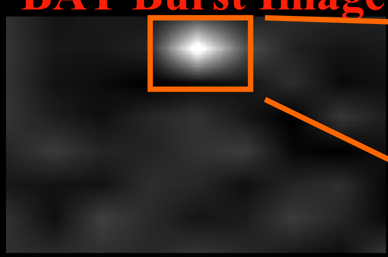
Instrumentation
Burst alert telescope (BAT) 10-150 keV
X-ray telescope (XRT) 0.3-10 keV
UV-optical telescope (UVOT) U-I

- USA, I, UK mission dedicated to GRB Science
- Italian contribution:
  - XRT
  - Malindi Ground Station
  - MISTICI follow up



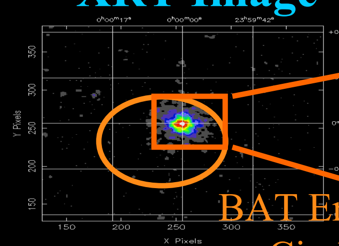
1. Burst Alert Telescope triggers on GRB, calculates position to < 4 arcmin
1. Spacecraft autonomously slews to GRB position in 20-70 s
1. X-ray Telescope determines position to < 5 arcseconds
1. UV/Optical Telescope images field, transmits finding chart to ground

BAT Burst Image



T<10 s, $\theta < 4'$

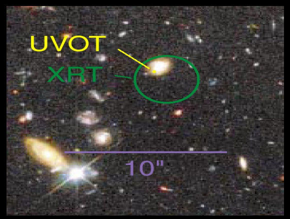
XRT Image



BAT Error Circle

T<100 s, $\theta < 5''$

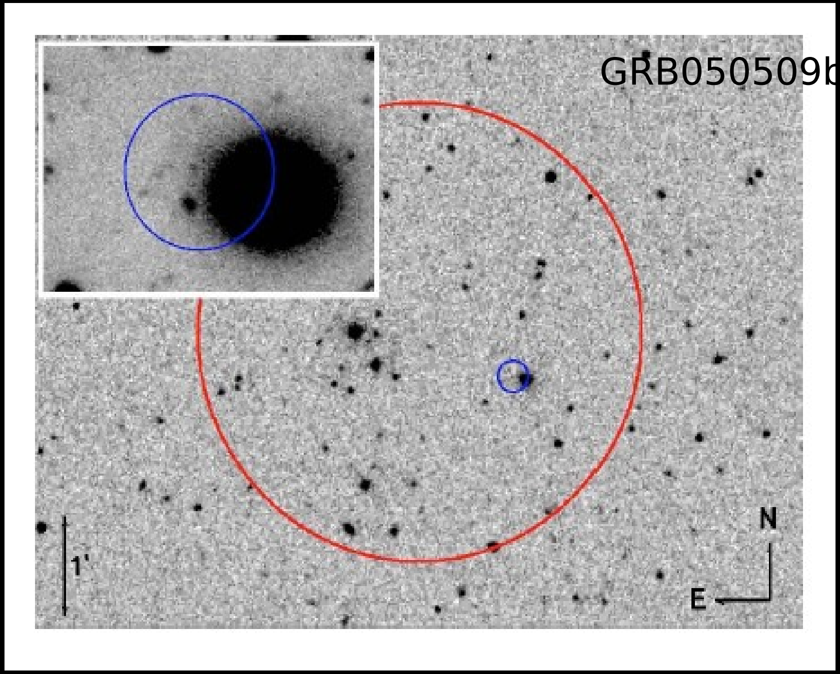
UVOT Image

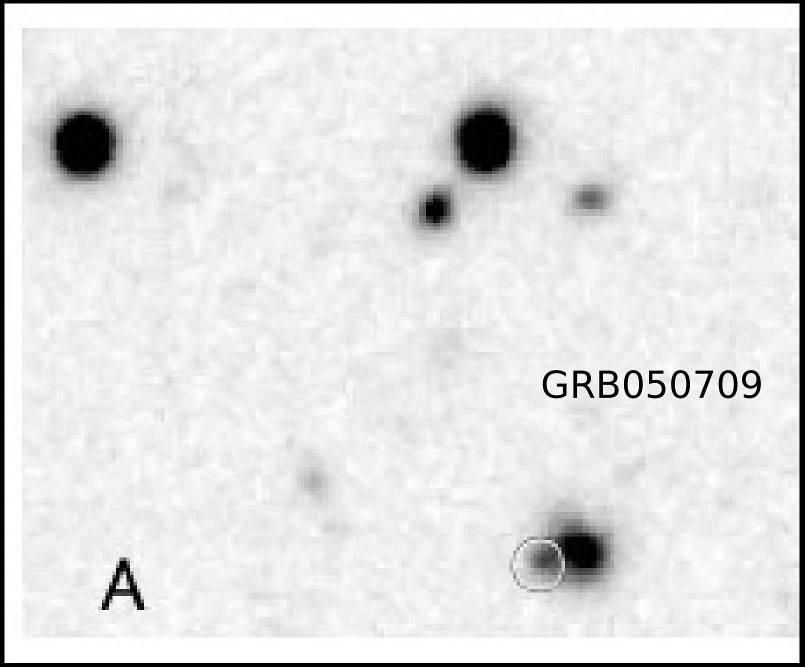


T<300 s

Host Galaxies of Short GRBs

- Short GRBs are located inside or close to early type galaxies with low star formation activity, BUT some are found in galaxies with star formation activity.





- Short GRBs are NOT associated to Supernovae
- Short GRB are at cosmological distances but at smaller redshifts than Long GRBs Average <z> ~ 0.2 for short and <z> ~ 2 for long
- Short GRB are ~100 times less energetic than Long GRBs

ummary on short GRBs (SHB)

- Bursts that last less than 2 sec
- SHBs are harder than long bursts and comprise 1/4 and 1/10 of the BATSE and Swift samples
- Swift first determination of SHBs afterglows and host galaxies
- First detemination of the redshift ~ 11 bursts over 30 detected
- First indication of beaming.

Coalescing binary models

Association of Short GRBs to low SFR galaxies + absence of SN :

favors models in which there is a long delay (Gyrs) between the formation of the neutron star (or black hole) and the Short GRB explosion.

Merging (or Coalescing) binary models for Short GRBs

Neutron Star + Neutron star (NS-NS) or Neutron Star + Black hole (NS-BH)

Strong Gravitational Wave Sources !

NS-NS/BH merging progenitors of SHBs

- Merging binary systems containing two collapsed objects: DNS, BH-NS and BH-BH, emit most of their binding energy in gravitational waves (GW), they are prime targets for **LIGO and VIRGO and their advanced versions.**
- Horizons LIGO: 20 Mpc, 40 Mpc and 100 Mpc advanced LIGO: 300 Mpc, 650 Mpc, 1.6 Gpc
- Fundamental: the number of events, we should know the **merger rate**
- DNSs BH-NS are thought to be the sources of Short GRBs (SHBs)

How are Merging Binaries Formed ?

Through the (complex) evolution of massive binary systems:

"PRIMORDIAL
BINARIES"

Average delay time between neutron star formation and merging: 1-2 Gyr

(from population synthesis models)

BUT:

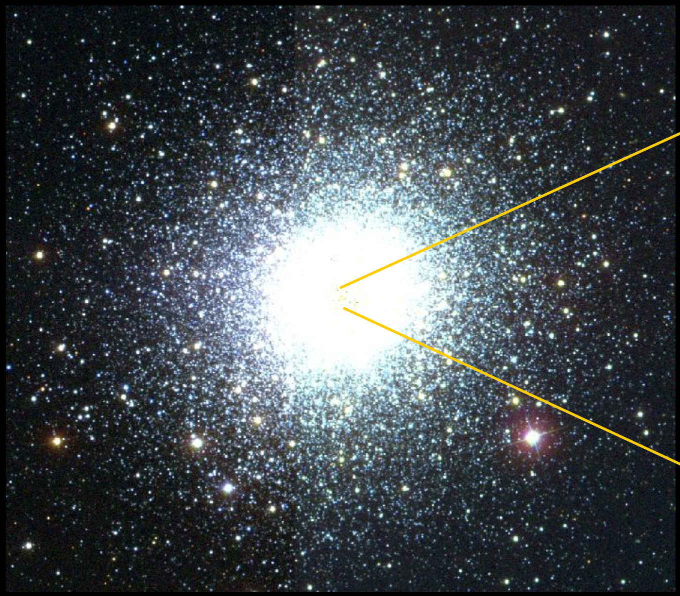
redshift distribution of short GRBs imply a longer delay of 1.5-6 Gyr:

this suggests an undetected population of merging binary systems !

(Nakar et al 2005; Piran & Guetta 2005)

Could these merging binaries form via 3-body interactions in globular clusters?

Merging Binaries can also form in Globular clusters



"Dynamically Formed Binaries"

- NS (BH) captures a normal star forming a binary system.
- The binary "exchanges" the normal star with a single NS in a 3-body
  interaction and forms a NS-NS or a BH-NS binary

(Grindlay et al 2006; Hopman et al 2006)

- Higher probability in post core collapse cores: <Delay time > ~ 6 Gy ~ CC time

→**more low-z SHBs**

(Guetta and Piran 05, 06, Hopman et al. 06, Salvaterra et al. 07)

Primordial Binaries' Merging Rates

Estimates are based on known NS-NS systems containing at least a radio pulsar, these were reevaluated after the discovery of double radio pulsar PSR J037-3039 selection effects *(Kalogera 2004)*

Estimates based on population synthesis studies *(Belczynski et al. 2001)* give a similar rate.

$R \sim 80^{+200}_{-60}$/Myr or

$R \sim 800^{+200}_{-600}$/Gpc3/yr for a galaxy density of 10^{-2}/Mpc^3

⇒ one event every 10 years for LIGO/Virgo

⇒ one event every 2 days for Adavnced LIGO/ Virgo

BH-NS and BH-BH are expected to be 1% and 0.1 % of NS-NS binaries

⇒ BH-NS and BH-BH mergers contribute marginally to the GW event rate despite the larger distance up to which they can be detected.

(Belczynski et al. 2007)

Merging Binary Rates as derived from Short GRB observations

If NS-NS and NS-BH mergers give rise to Short GRBs, we can infer :

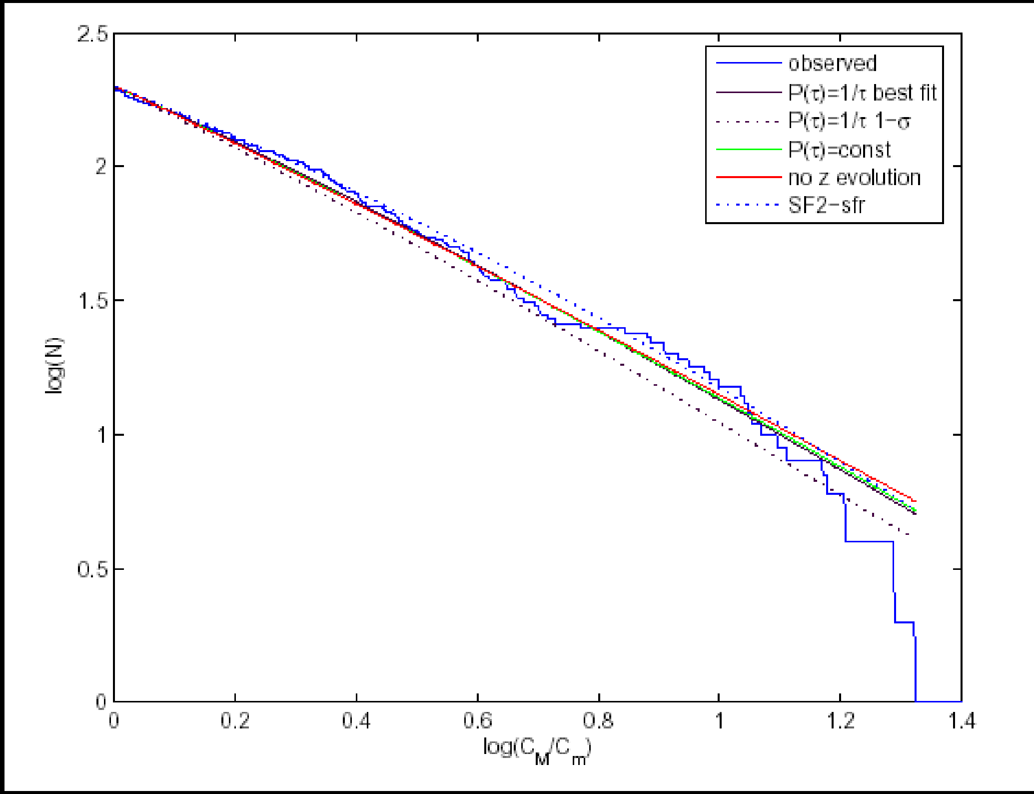
- Merging rate (and detectable GW event rate) from observations of Short GRBs
- Contribution of dynamically formed binaries to the Short GRB and GW rates

(Guetta & Piran 2005, 2006; Nakar et al. 2006, Guetta & Stella 2008)

Use:

- peak flux distribution
- redshift
- estimates of the beaming factor

Rates from Flux



N(>F) Number of bursts with flux >F $\Rightarrow$

- n(z) Rate as a function of z
- ϕ(L) Luminosity function

Rates from Flux

- Number of bursts with flux >F
- Rate as a function of z
- Luminosity function
- Maximal redshift for detection of a burst with a luminosity L given the detector's sensitivity P.

Rate of SHB from primordial DNS

Convolution of SFR with the merging time distribution

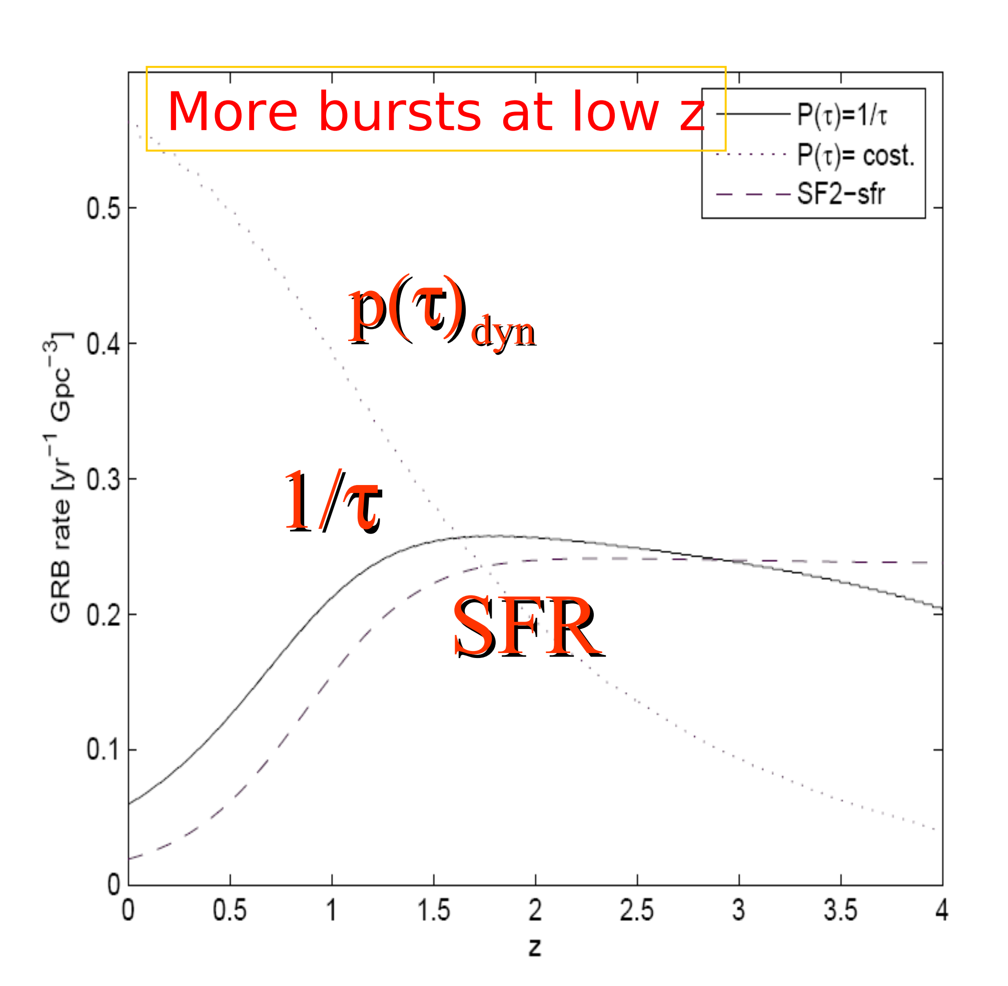
- $p(\tau) \sim 1/\tau$ – probability for a time lag $\tau \sim \tau_{GW}$ time over which GW losses bring a binary to its pre-merging stage)̃.for primordial *(Belcynski et al 2007)*

Rate of SHB from dynamically formed DNS

- We have long $=\tau_{cc}+\tau_{GW}$ where $\tau_{cc} >> \tau_{GW}$ rapresents the elapsed time between the birth of NSs and BHs in GCs and the dynamical formation of NS-NS/BH systems following core collapse.

$$\left(\frac{dp}{d\tau}\right)_{\rm dyn} = \frac{d}{d\tau}\int_0^{\tau} dt_{\rm cc}\,\frac{dp_{\rm cc}}{dt_{\rm cc}}\int_0^{\tau - t_{\rm cc}} dt_{\rm GW}\,\frac{dp_{\rm GW}}{dt_{\rm GW}}.$$

P(τ) increases with τ *(Hopman et al. 2006)*



More bursts at low redshift from dynamically formed systems !

Constraints on $\phi(L)$

Sample of 194 bursts detected by BATSE

The method *(Schmidt 1999)*

- SHB follow NS-NS formation rate $p(\tau) \propto 1/\tau$
- $p(\tau) = p(\tau)_{dyn}$

$$\Delta_1 \sim \Delta_2 \sim 100$$

Fitting the logN-logS the best fit values for α, β, L^* and the local rate ρ_0 can be found

Best Fit Values (using the two models separately)

Model	L^* [10^{51} erg/sec]	α	β	ρ_0 $Gpc^{-3}yr^{-1}$
Primordial Binaries SF2-1/τ	2	0.6	2	1.3
Dynamically Formed Binaries SF2-p(τ)	0.8	0.8	2	4.0

In the dynamical model, the rate is higher!!
More promising for GW detection

Beaming in Short GRBs and Merger Rate

In a few short GRB there is evidence of beaming
(from jet break in 050709 and 050724 $f_b^{-1} \sim 50$)

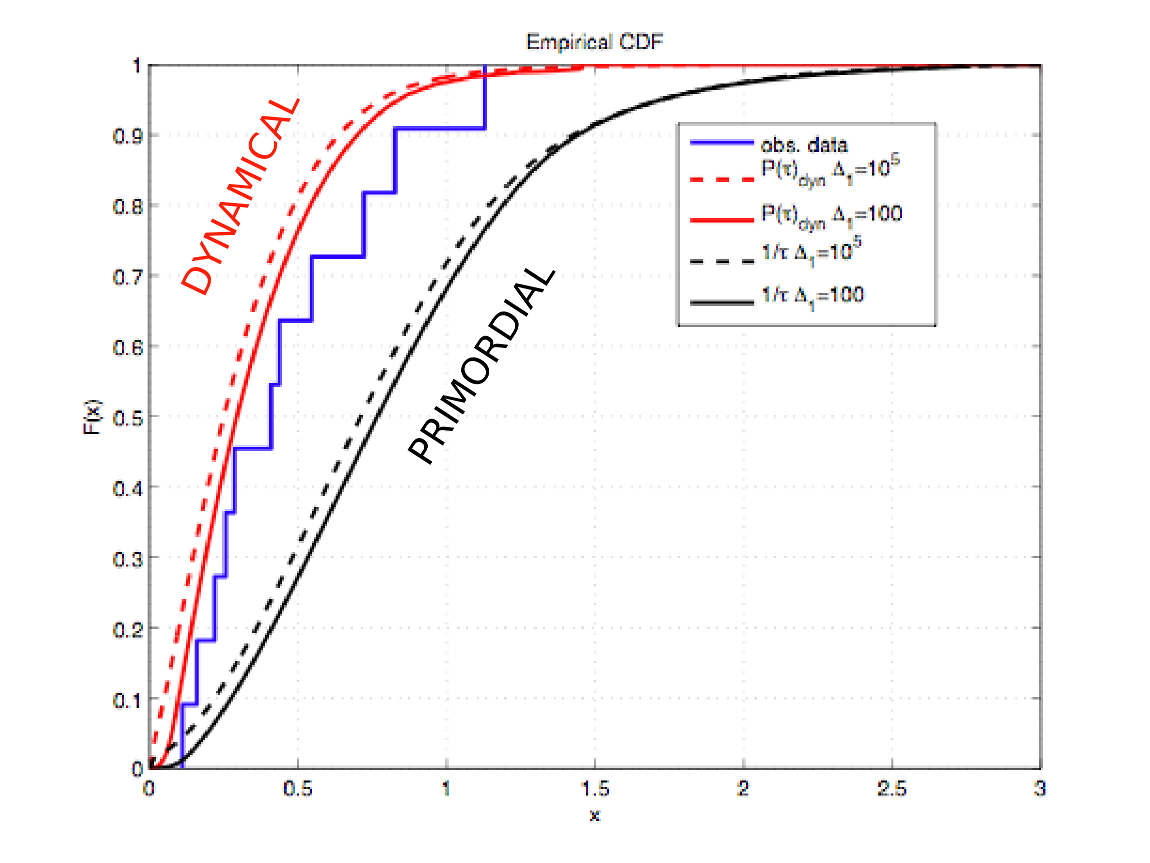
(Fox et al. 2005)

We take a beaming factor of $f_b^{-1} \sim 100$

$R \sim \rho_0 f_b^{-1} \sim 130\ (400)/\mathrm{Gpc}^3/\mathrm{yr}$
For primordial (dynamical) models.

This rate compares well with the lower end of the range
for primordial NS-NS mergers 200-2800/Gpc^3/yr

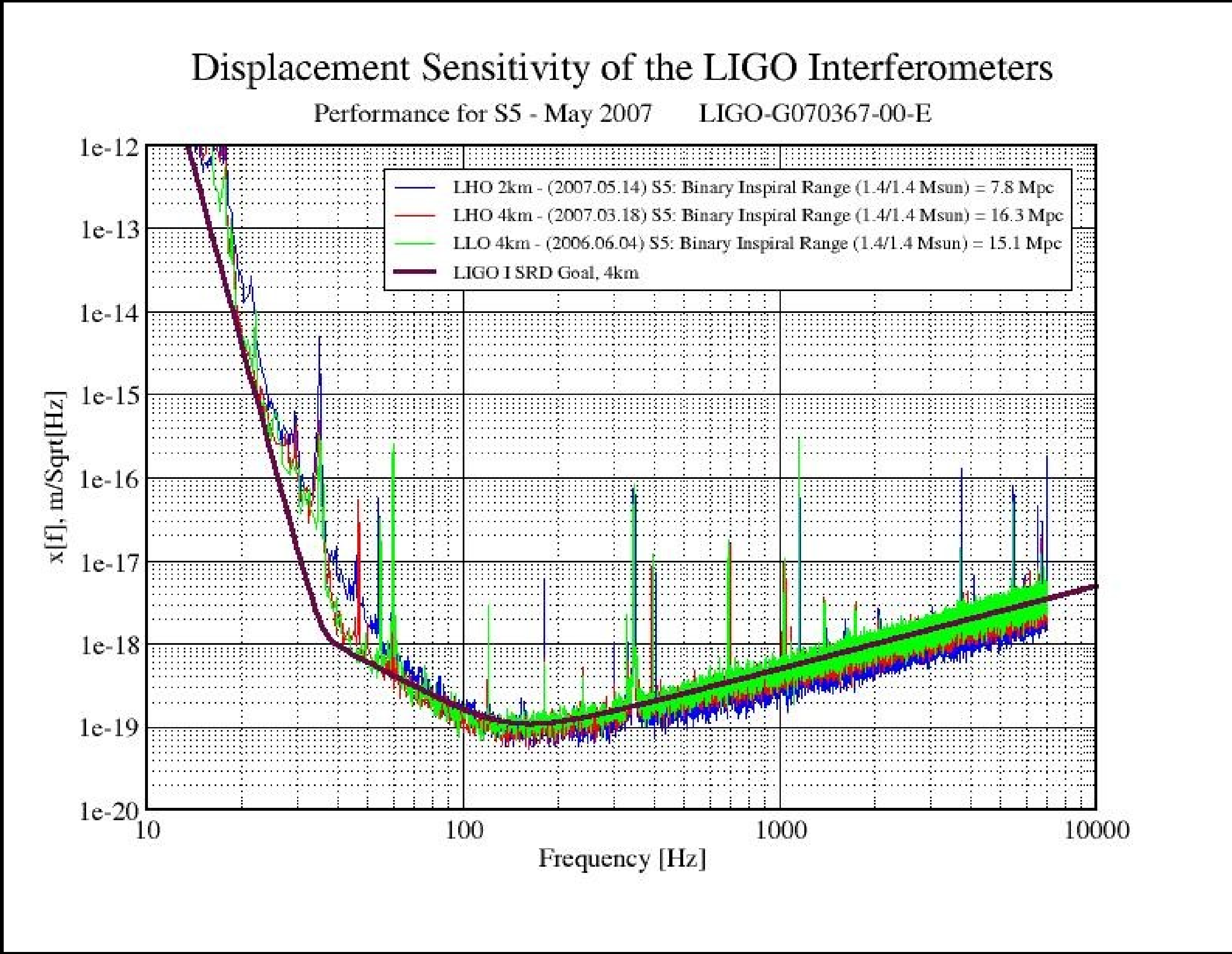
Observed Redshift Distribution vs Models



- Dynamical formed mergers fit the data better
  (but primordial mergers cannot be excluded)

- Bimodal origin of Short GRBs:
  low-z (mainly) from dynamically formed coalescing binaries
  high-z from primordial coalescing binaries

LIGO Livingston Observatory
Laser Interferometer GW-Observatory


Displacement Sensitivity of the LIGO Interferometers
Performance for S5 - May 2007 LIGO-G070367-00-E
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LIGO I SRD Goal, 4km
x[f], m/Sqrt[Hz]
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
1e-19
1e-20
10
100
1000
10000
Frequency [Hz]

Perspectives for GW detections

Local rate of SHBs has implications for the number of GW events that can be detected. NS-NS and NS-BH systems formed in GCs may well improve the chances of detecting GW signals because:

1. Local SHB rate has a substantial contribution from dynamically formed mergers (best fit to current data gives 60 %; unlikely to be < 10%)
2. The incidence of BH-NS binaries formed dynamically is still unknown (but is likely higher than that formed in the field) and the horizon of GW interferometers to BH-NS binaries is larger than that of NS-NS systems

Number of detectable GW events

Ratio of GW accessible volumes ~ 8

- η~1 for Advanced LIGO/Virgo and 3×10^{-4} for LIGO/Virgo
- g_b incidence of BH-NS systems among merging events giving rise to short GRBs: ~0.01 for primordial; ~1 dynamical (??)
- f_b^{-1} beaming factor ~100

N_{GW} ~ 1/238 /yr (LIGO/Virgo) and
14 /yr (Advanced LIGO/Virgo) for Primordial Mergers

1/9 yr (LIGO/Virgo),
360/yr (Advanced LIGO) for Dynamically Formed Mergers.

GW – Short GRB coincidence events will afford a factor of 2.4 larger horizon in GWs: for a f_b^{-1} beaming factor ~100 the incidence of these events will be ~$(2.4)^3$/100~15 %

(Guetta& Stella 2008)

versal central engine hypothesis for GRI

(Eichler, Guetta & Manis 2008) See Eichler's talk

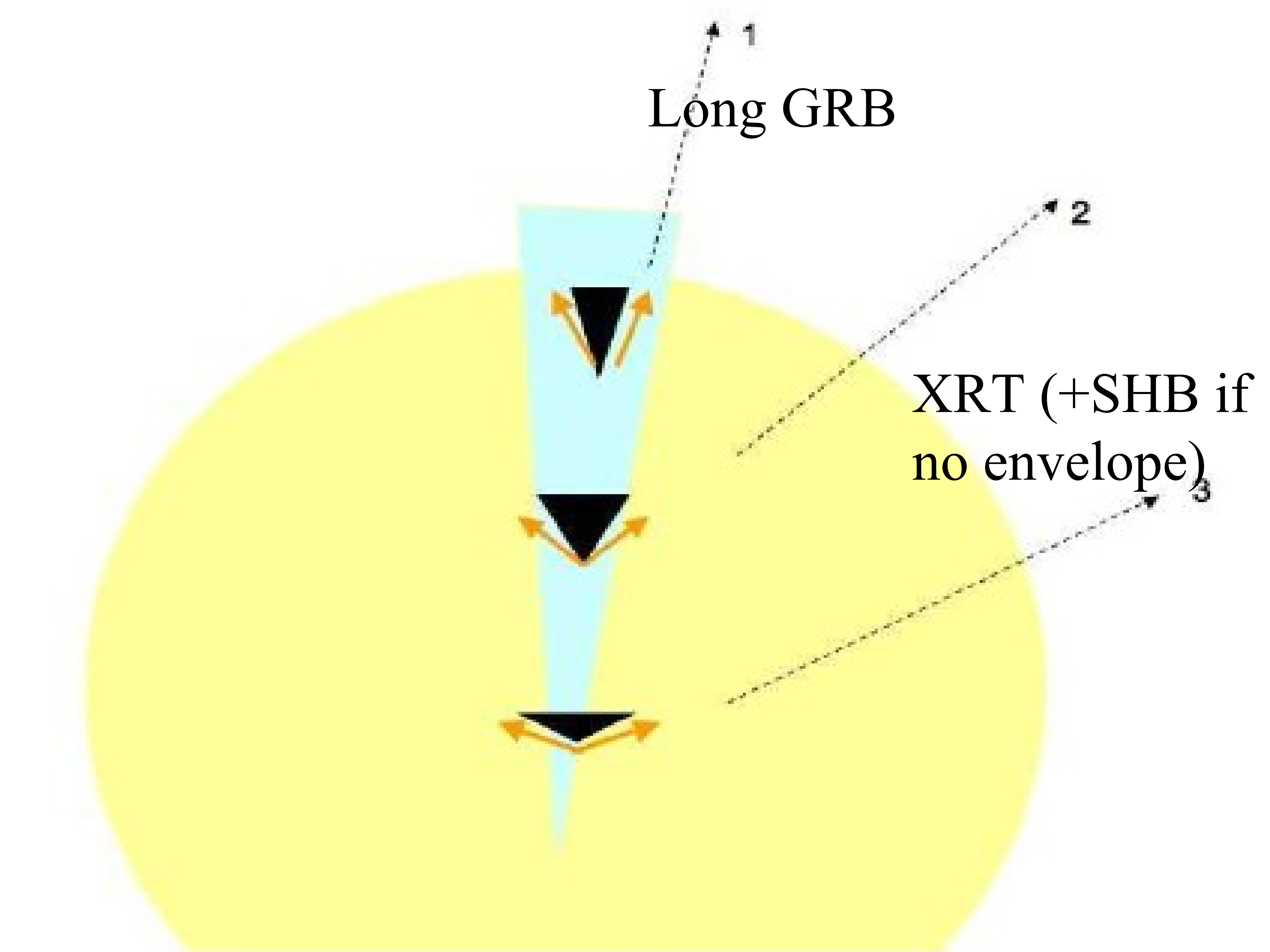
model can account for several SHB propertie

1) hard spectra

2) low E

3) short duration

1) long soft X-ray tails (Chincarini talk).



1
Long GRB
2
XRT (+SHB if no envelope)
3

GRB	z	S_γ 10^{-7} erg/cm^2	$E_{\gamma,iso}$ 10^{49} erg	F_x 10^{-11} erg/cm^2/s	$E_{x,iso}$ 10^{49} erg	F_x (@ 300 Mpc) 10^{-11} erg/cm^2/s
050709*+	0.16	3 ± 0.38	1.4	800	3.4	3.3×10^3
050724+	0.258	6.3 ± 1	7.2	1200	10.1	9.9×10^3
051210+		1.9 ± 0.3		90		
051221+	0.546	22.2 ± 0.8	84	20	0.6	590
060313 +		32.1 ± 1.4		30		
071227+	0.383	2.2 ± 0.3	4.0	46	0.87	854
050509B	0.225	0.23 ± 0.09	0.2	0.06	4.5×10^{-4}	0. 44
050813	0.7	1.24 ± 0.46	5.2	0.6	0.025	25
050906		0.84 ± 0.46		< 0.007		
050925		0.92 ± 0.18		< 0.003		
060502B	0.287	1 ± 0.13	1.15	0.1	0.001	0.98
060801		0.8 ± 0.1		0.1		
061201	0.11	3.3 ± 0.3	0.7	10	0.02	24
061217	0.827	0.46 ± 0.08	2.4	0.1	0.005	4.9
070429B	0.904	0.63 ± 0.1	3.5	0.11	0.006	5.9
070724	0.45	0.3 ± 0.2	0.6	0.05	0.0012	1.2
070729	0.904	1.0 ± 0.2	5.6	0.024	0.001	0.98
070809		1.0		0.179		
071112B		0.48		< 0.02		

WFC? YES

etected in coincidence with XRT emission from

(Guetta & Eichler 2009)

Some SHB show X-ray tails (XRT): emission in X lasting ~ 100 sec similar to X-ray flashes

e XRF, XRT may have angle > SHB ones
erefore MAY improve GW detection

rtant parameter is the rate of XRT, R_{XRT} to dete
W number of events use XRF from WXM, WFC
z>$_{XRF}$~1 close sources (Piro et al. 2007).

...tes: X-ray Wide Field detectors characte...

Detector	Sky coverage sr	Sensitivity erg cm^{-2} s^{-1}	Effective Operation T years
WXM on HETE-2	0.806	~ $9X10^{-9}$	~ 4
WFC on Sax	0.123	~ $4X10^{-9}$	~2

WXM+WFC have detected 26 XRF

The Rates

GRB	ρ_0 $Gpc^{-3}yr^{-1}$	Reference
Long GRBs	0.1-1.1	*Guetta, Piran & Waxman 2005*
SHBs	1.3-4.0	*Guetta & Piran 2005, 2006* *Guetta & Stella 2009*
XRF (WXM & WFC)	~15	*Pelangeon et al. 2008,* *Guetta & Eichler 2009*
XRT	>1.3 & <10	*Guetta & Eichler 2009*

te XRF rate >> long GRBs, SHB ?

→ the beaming is wider

$$R_{XRT}=\rho_{0,XRT}\, f_{b,XRT}^{-1}$$

Conclusions

t Gamma Ray Burst, if (for the most part) due to coalescing
inaries, provide an independent way of estimating the NS-N
IS-BH merging and GW detection rates

Evidence that the local Short GRB rate is dominated by
and NS-BH binaries formed in globular clusters through
dynamical interactions: this increases the local rate an
chances of detecting GWs from these events

pect that further SHBs observations in Swift era will lead to
ate determination of f_b and R_0, while more advanced dynami
r simulations will allow a better determination for g_B

ay emission seems to be beamed in a small solid angle and
re only a fraction of detectable GW events is expected

Conclusions....

Alternative ways to confirm LIGO signals from coalescing neutron stars are therefore all the more desirable like X-ray tails (XRT).

We cannot prove that XRT are more common than SHB in gamma.
However the fact that a fair fraction could be seen by a WFC in X ray
AND the fact that the event rate for XRF is much higher than for long bursts per unit volume time, suggests that it might very well be. WFC NEEDED !!!