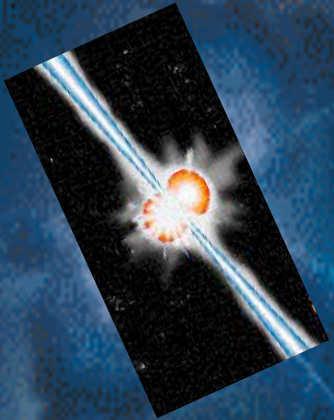
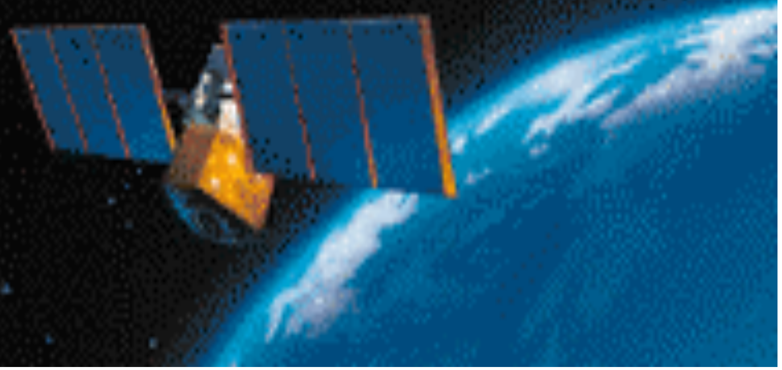


Gravitational waves from short Gamma-Ray Bursts

Dafne Guetta (Rome Obs.)

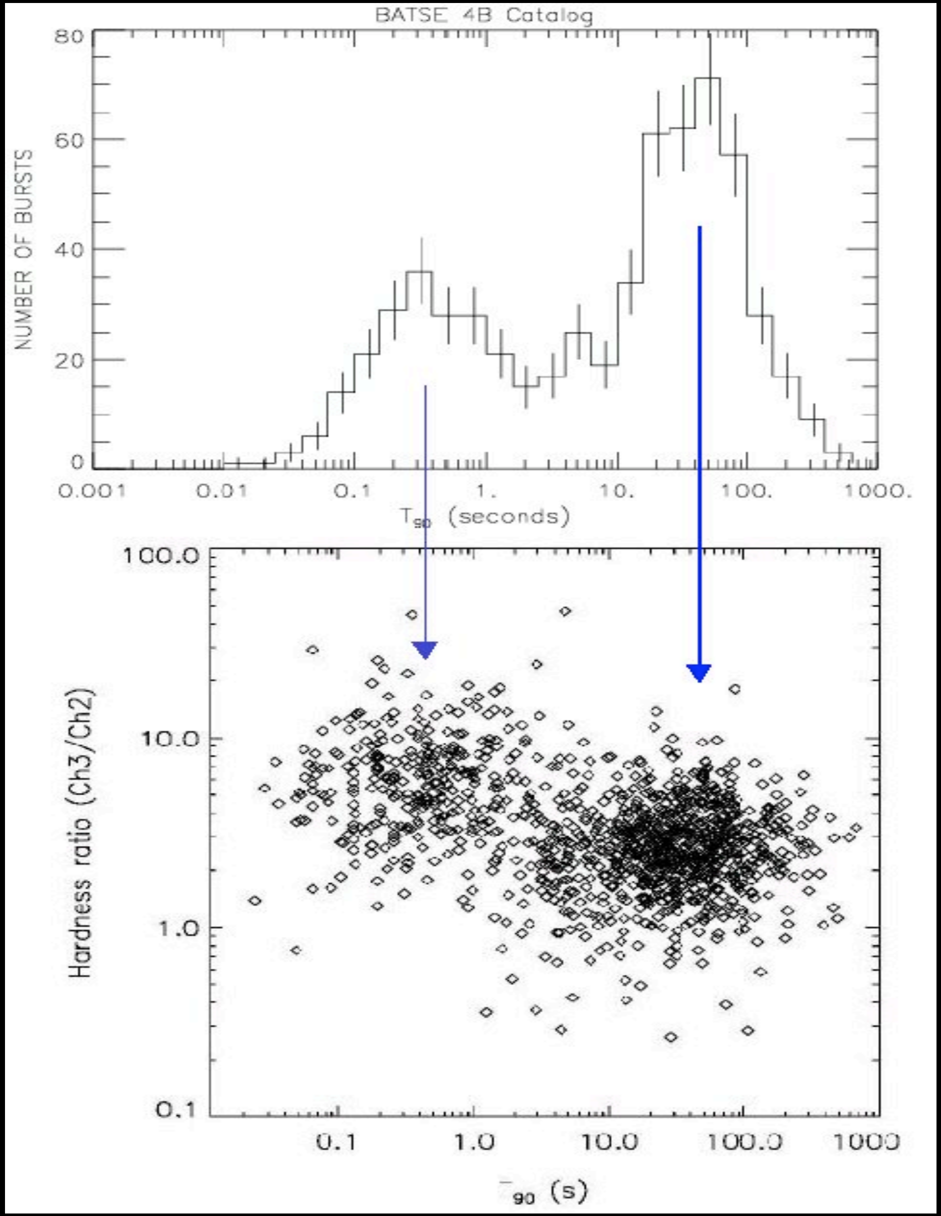
My collaborators: Luigi Stella,



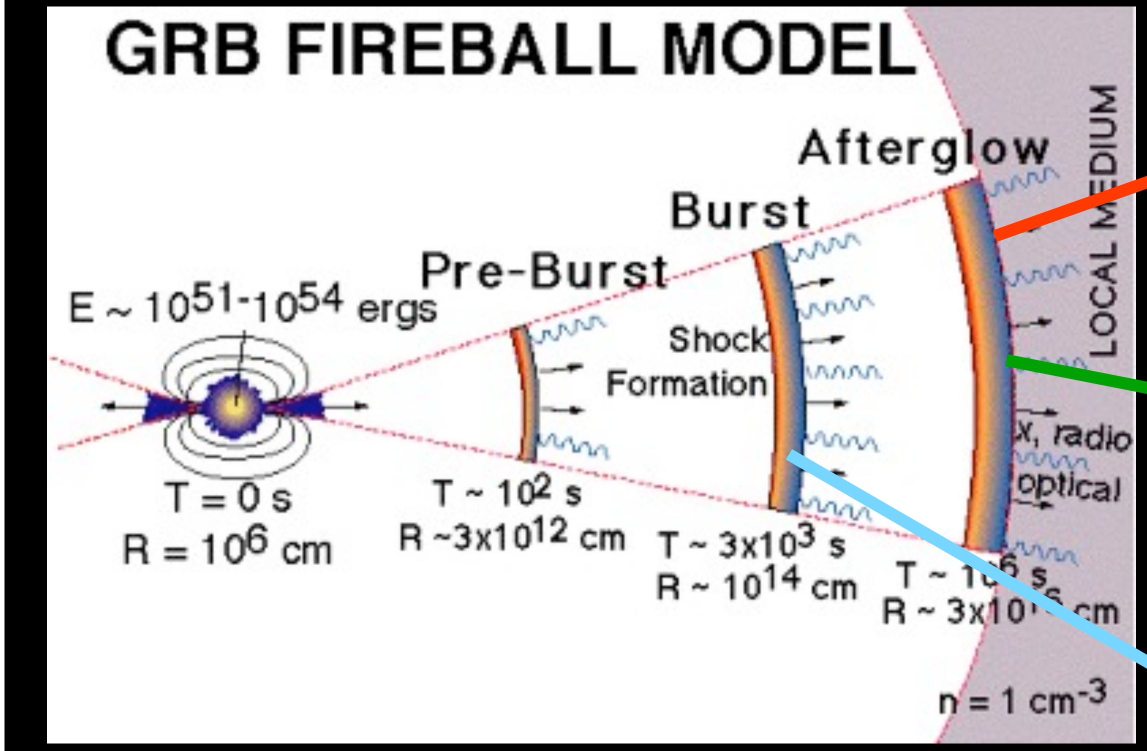
Two different classes of Gamma-Ray Bursts

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

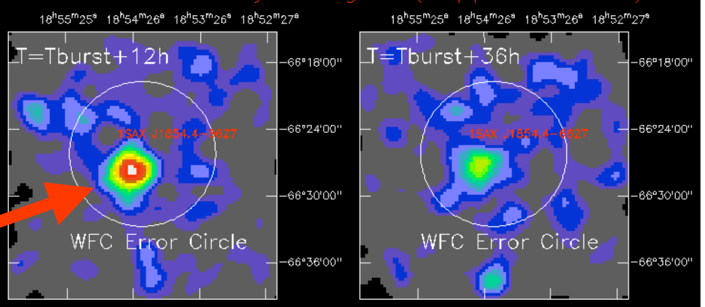
- Short GRBs are harder than long GRBs
  (e.g. Fishman & Meegan, 1995; Tavani 1996).



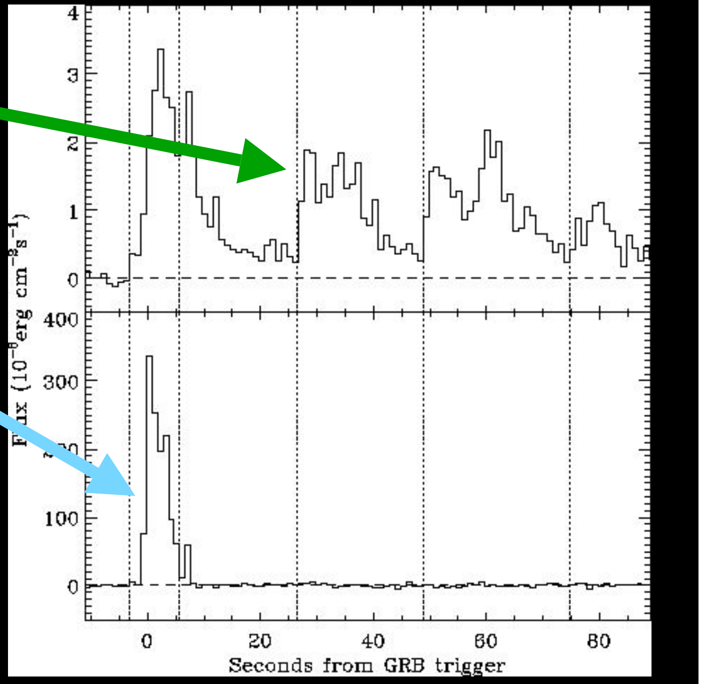
GRB Fireball, Energy and Beaming



GRB 000214 X-ray afterglow (BeppoSAX MECS)



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



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

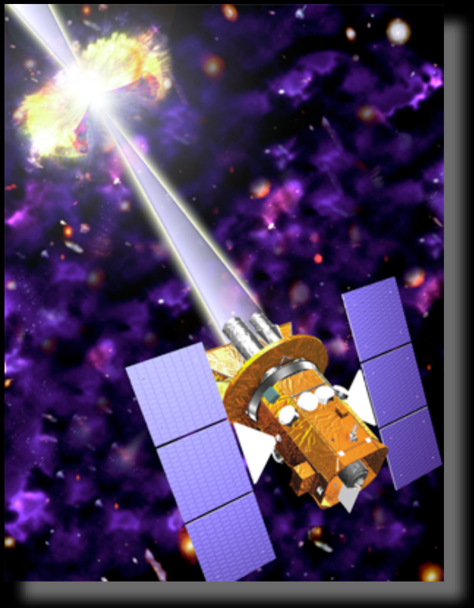
$E(iso) = 4x10^{54}$ erg

GRBs may be beamed (~few degree opening angle)

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

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

Swift



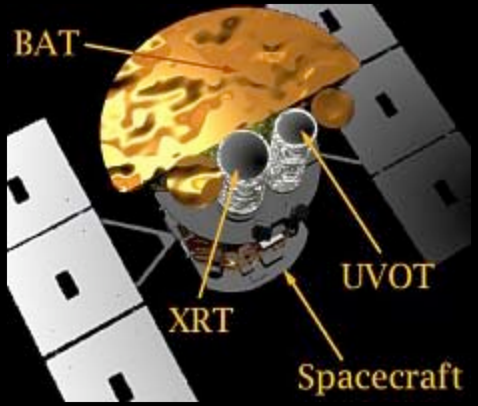
Instrumentation

Burst alert telescope (BAT) 10-150 keV

X-ray telescope (XRT) 0.3-10 keV

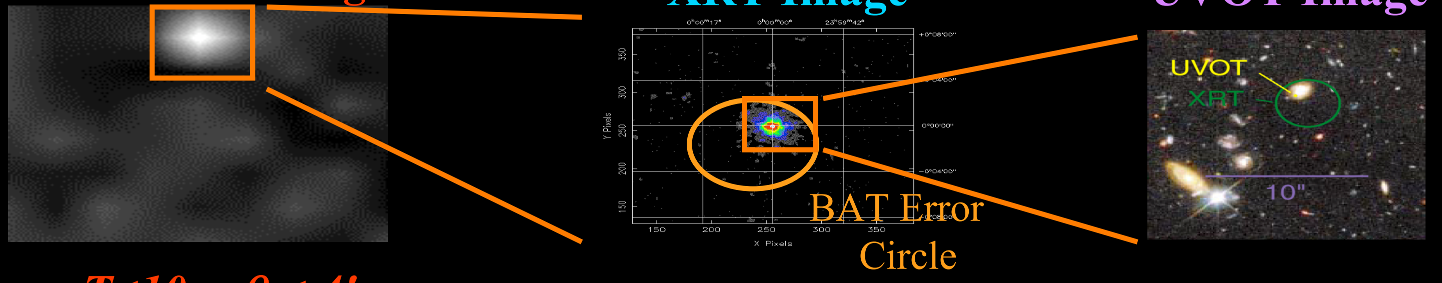
UV-optical telescope (UVOT) U-I

- 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
2. Spacecraft autonomously slews to GRB position in 20-70 s
3. X-ray Telescope determines position to < 5 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground

BAT Burst Image **XRT Image** **UVOT Image**



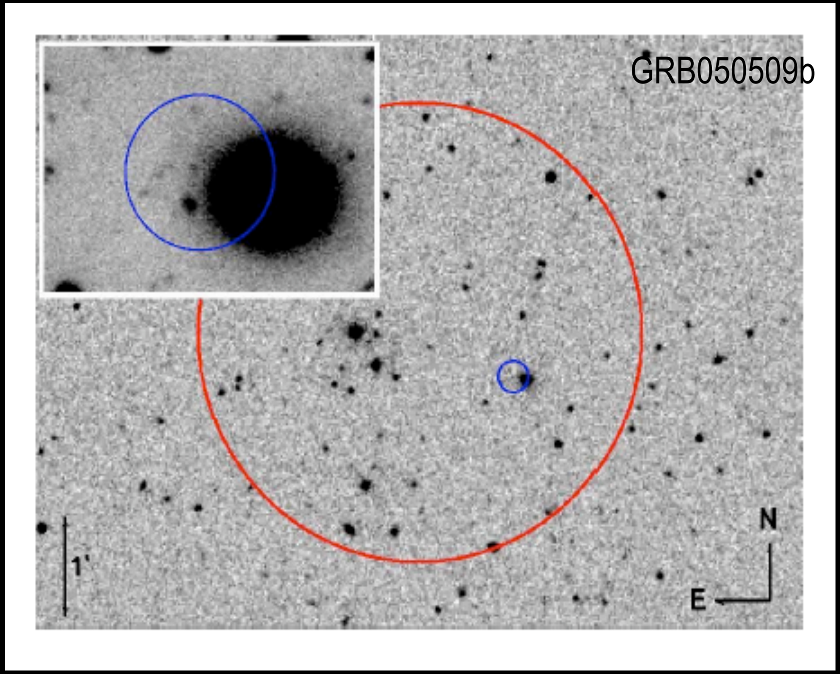
$T<10$ s, $\theta < 4'$

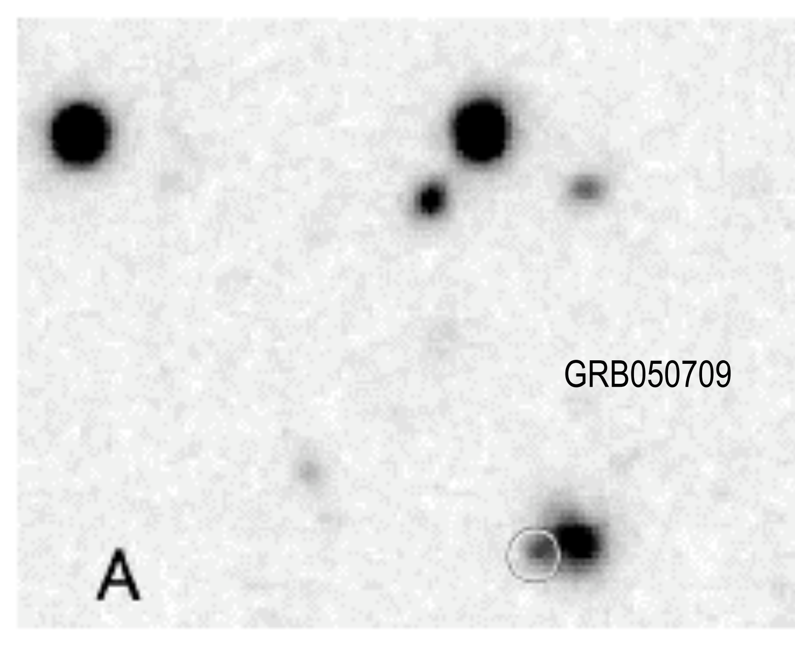
$T<100$ s, $\theta < 5''$

$T<300$ 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

Summary 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)

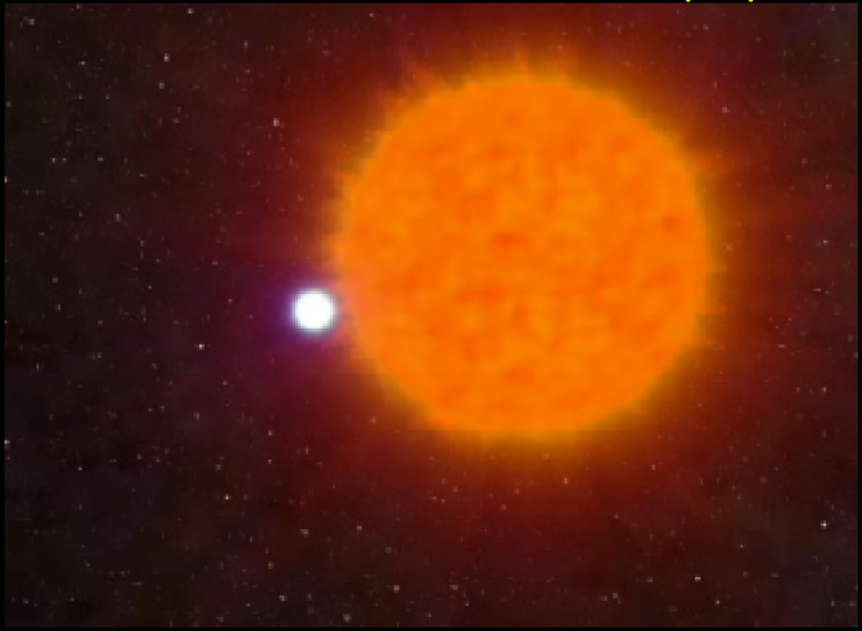
Strong Gravitational Wave Sources !

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:

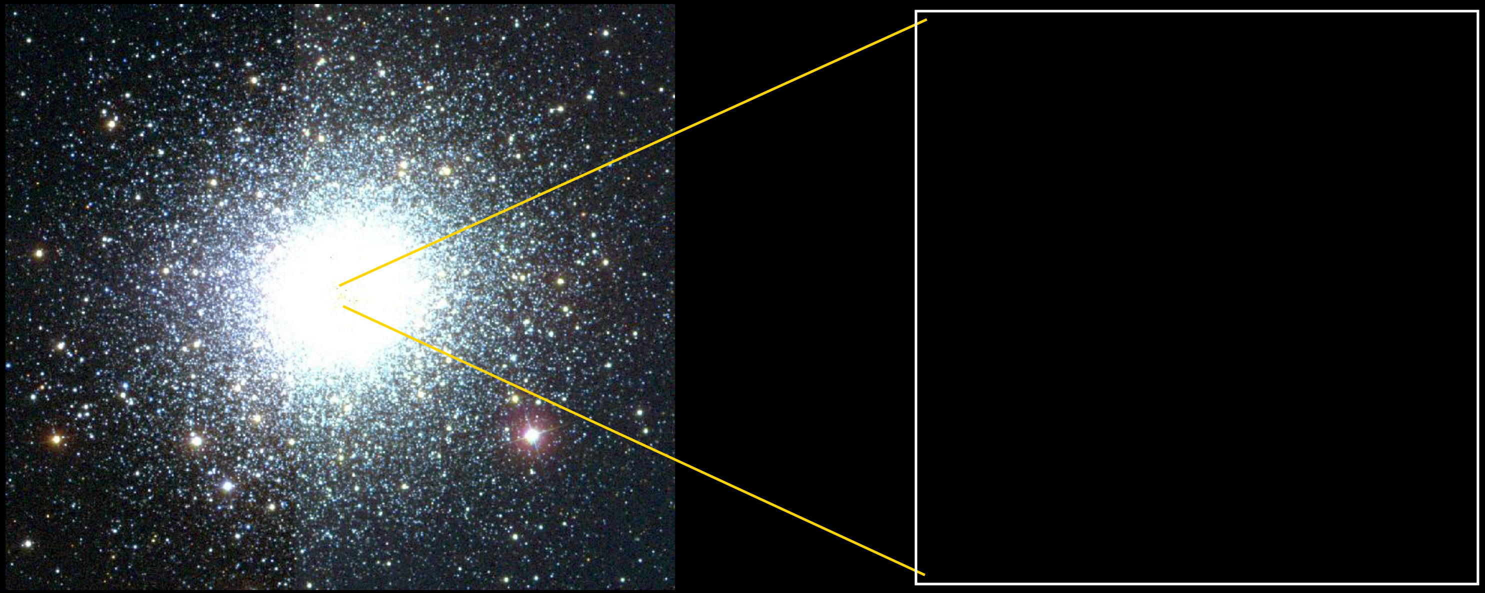
this suggests an undetected population of merging binary systems !

(Nakar et al 2005; Piran & Guetta 2005)

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

(Grindlay et al 2006; Hopman et al 2006)

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)

10-30% of DNS mergers may stem from dynamically formed systems *(Grindlay et al. 2006)*

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

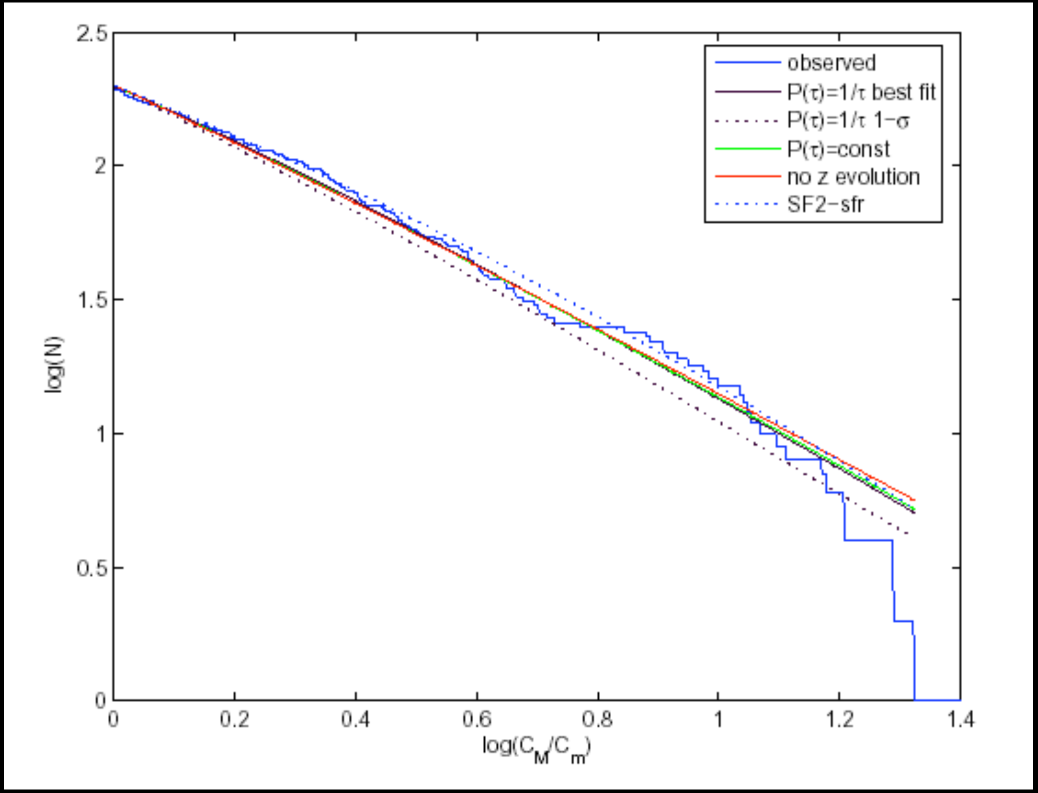
If NS-NS and NS-BH mergers give rise to Short GRBs, we can infer :

- 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

$$\Rightarrow \left\{ \begin{array}{l} n(z) \text{ Rate as a function of } z \\ \phi(L) \text{ Luminosity function} \end{array} \right.$$

Rates from Flux

$$N(>F) = \int_0^{Z_{\max}(L,F,p)} dz\, n(z) \int_0^{\infty} dL\, \phi(L)$$

- 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

$$n(z) = \int_0^{t(z)} R_{SFR}[t(z) - \tau]\, p(\tau)\, d\tau$$

Convolution of SFR with the merging time distribution

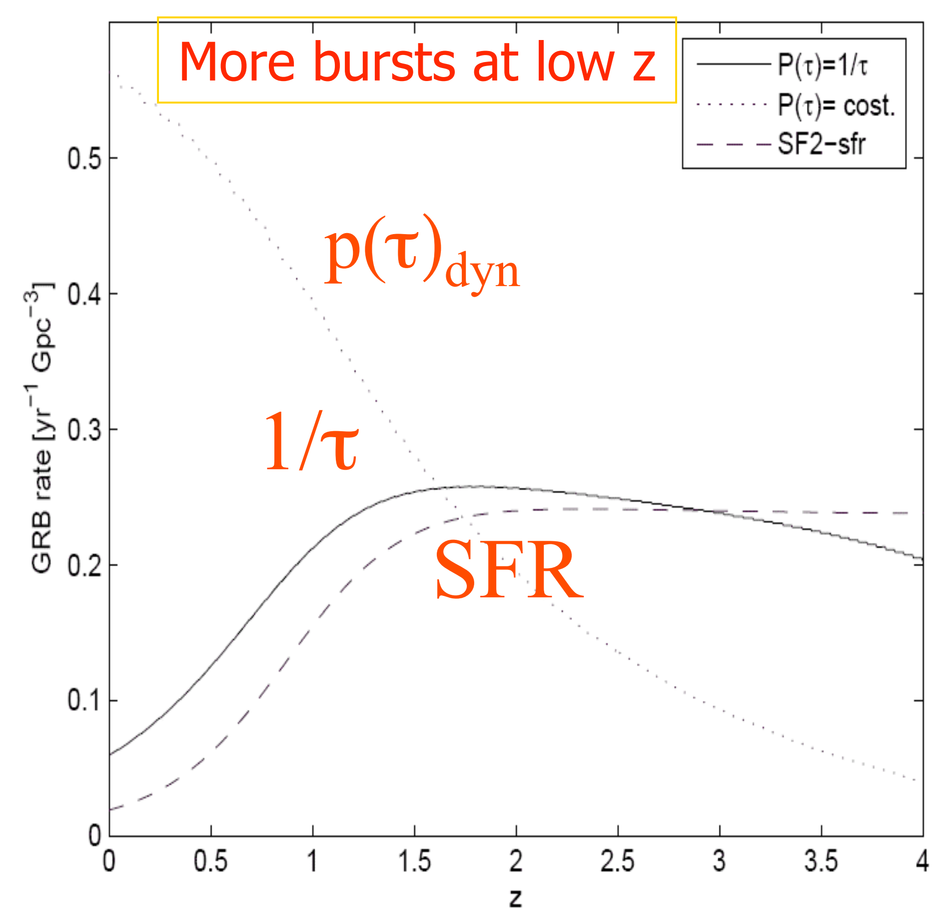
- $p(\tau) \sim 1/\tau$ – probability for a time lag $\tau \sim \tau_{GW}$ (time over which GW losses bring a binary to its pre-merging stage).-for primordial *(Belcynski et al 2007)*

Rate of SHB from dynamically formed DNS

- We have long $\tau=\tau_{cc}+\tau_{GW}$ 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 z

$p(\tau)_{dyn}$

$1/\tau$

SFR

More bursts at low redshift from dynamically formed systems !

Constraints on $\phi(L)$

Sample of 194 bursts detected by BATSE

The method *(Schmidt 1999)*

$$\Phi(L) = \begin{cases} (L/L^*)^{\alpha} & L^*/\Delta_1 < L < L^* \\ (L/L^*)^{\beta} & L^* < L < \Delta_2 L^* \end{cases}$$

- 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 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
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}~50)

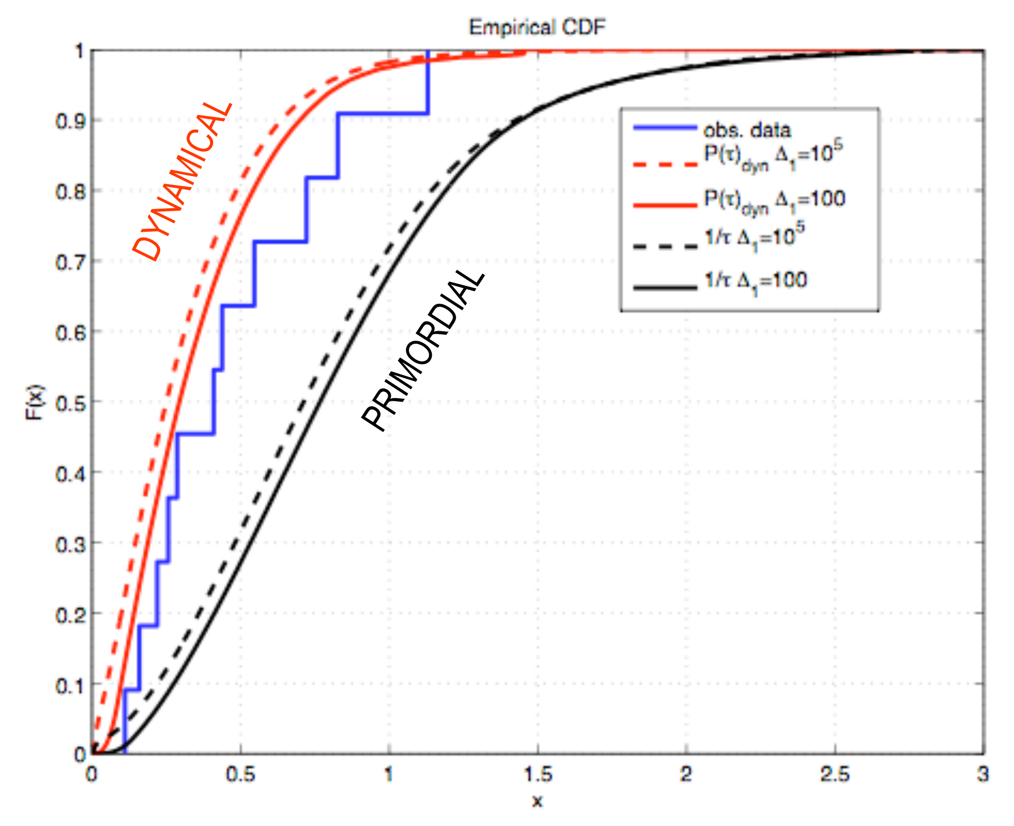
(Fox et al. 2005)

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

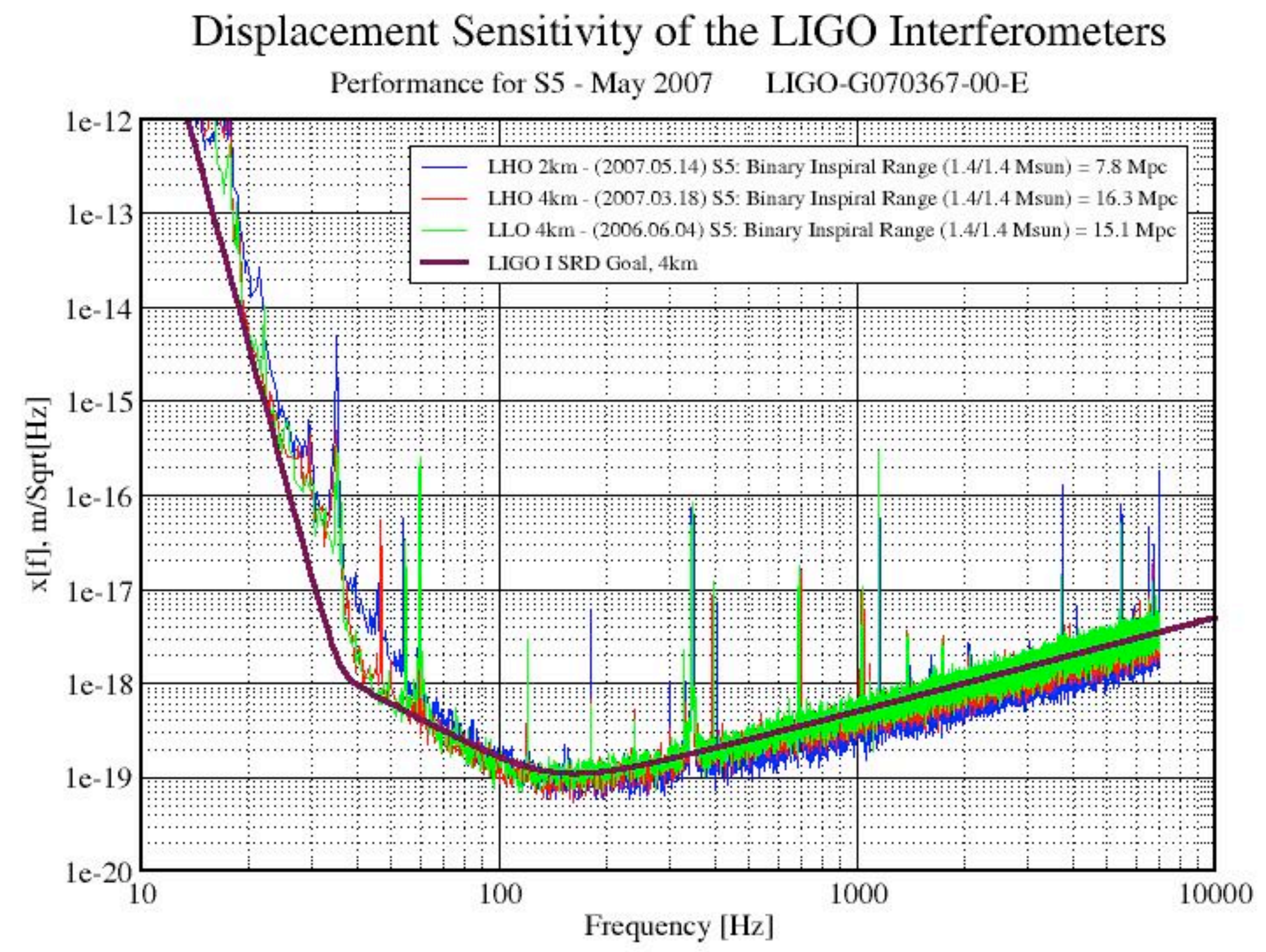


$$N(z) = \frac{R_{GRB}(z)}{(1+z)}\frac{dV}{dz}\int_{L_{\min}(P_l,z)}^{L_{\max}} \Phi(L)\,d\log L$$

- 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

$$N_{GW} \sim 40\eta\left(\frac{f^{-1}b}{100}\right)\left(\frac{\rho_0}{4Gpc^{-3}yr^{-1}}\right)\left(\frac{\Delta_1}{100}\right)^{\alpha}[(1-g_B)+g_B\frac{V_{BHNS}}{V_{DNSs}}]yr^{-1}$$

- η ~1 for Advanced LIGO/Virgo and 3x10^{-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)

Conclusions

- Short Gamma Ray Burst, if (for the most part) due to coalescing binaries, provide an independent way of estimating the NS-NS and NS-BH merging and GW detection rates (selection effects Coward et al 2012)

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

We expect that further SHBs observations in Swift era will lead to a more accurate determination of f_b and R_0, while more advanced dynamical cluster simulations will allow a better determination for g_B

The γ-ray emission seems to be beamed in a small solid angle and therefore only a fraction of detectable GW events is expected to be coincident with SHBs.