GRBs and Gravitational Waves

Detectability
  > sensitivity / strength / rates

Sources of gravitational radiation
  > precursor or central engine itself
  > black hole ringdown
  > relativistic ejecta

GRB event rates
  > empirical
    from GRB detections
  > central - engine dependent
    stellar collapse, NS/NS or NS/BH coalescence

Triggered Searches
  > one-to-one or statistical
Network of GW Interferometers

- detection confidence
- source localization

LIGO: two 4km and one 2km interferometers
Detectability:

Source frequency
Detection volume
source strength
instrument sensitivity
Event Rates

- Seismic at low freq.
- Thermal at intermediate freq.
- Laser shot noise at high freq.
Central Engine and GW Production

Massive-star Collapse

Compact Object Coalescence

\[ \text{SN} \rightarrow \text{Bar-mode} \]

\[ D_{\text{max}} < ? 10 \text{Mpc} ? \]

\[ D_{\text{max}} (\text{Mpc}) \]

\[ \begin{array}{c|c|c}
\text{NS–NS} & \text{NS–BH} & \text{NS–NS} \\
\hline
20 & 40 & 15, 20–25 \\
\end{array} \]

\[ \text{advanced} \]

\[ \text{NS–NS} \text{ and } \text{NS–BH} \]

Precursor

Merger

\[ \text{inspiral chirp signal} \]

\[ \text{“cliff” and then ?} \]

Fryer et al. 2001; Shibata & Uryu 2001; Faber & Rasio 2001; Lee 2001; Finn 2001;
peak frequency: ~ 0.5–1 KHz

uncertainties:
> angular momentum content
> total mass radiating GW
> number of coherent cycles
Prototype NS–NS: **binary radio pulsar** PSR B1913+16
Four other NS–NS detected in our Galaxy

GW emission causes orbital shrinkage leading to higher GW frequency and amplitude

\[ h_c(f) \sim f^{-1/6} \]
Compact Object Mergers

NS–NS
\(\Gamma = 3, q = 1.0, \text{Irrot.}\)

Faber & Rasio 2001

NS–BH
\(q = 0.3\) Irrotational model

Lee 2001

characteristic frequency \(> 500\) Hz
fraction of total rest mass in GW: 0.5–1%
Black Hole Ringdown

Exponentially damped sinusoid with characteristic frequency:

\[ f \approx 12 \text{ KHz} \frac{M_0}{M} \frac{1 - 0.63(1 - a)^{3/10}}{0.37} \]

> decreases with increasing mass and decreasing angular momentum

> BH in mergers and core collapse events:
  – rapidly rotating
  – masses: a few to tens \( M_0 \)
    \[ f \sim 1 - 10 \text{ KHz} \text{ too high!} \]

Amplitude is quite uncertain:
  depends on how the BH grows
  and is perturbed away from the Kerr metric

Fryer et al. 2001: "extremely" optimistic estimate for collapsars \( D_{\text{max}} < 100\text{kpc} \) ...
Relativistic Ejecta

GW may be produced by relativistic collisions of particles during the acceleration phase to high $\Gamma$ values

Piran 2001: characteristic frequency: up to $\sim 100$ Hz
$D_{\text{max}} \sim 100$ Kpc (for S/N of a few ... )
GRB Rate estimates: Local

Schmidt ’01  
short GRBs: 7.5x10^{-5} Mpc^{-3}Myr^{-1}  
long GRBs: 2.5x10^{-4} Mpc^{-3}Myr^{-1}  
Frail et al. ’01  
with beaming: x100–500

How reliable are the estimates of GRB rate densities?
> e.g., may be hard to distinguish between  
  many faint GRBs at low redshifts  
or  many bright GRBs at high redshifts  
  Krumholz, Thorsett, & Harrison ’98

Population of nearby GRBs?
> Concentration of GRBs with long spectral lags  
in the supergalactic plane? Norris 2002
Radio Pulsars in NS–NS binaries \rightarrow NS–NS Merger Rate Estimates

Use of \textit{observed sample} and models for PSR survey \textit{selection effects}: estimates of \textit{total} NS–NS \textit{number} combined with \textit{lifetime} estimates

(Narayan et al. '91; Phinney '91)

\textbf{Dominant sources of estimate uncertainties identified:}

(VK, Narayan, Spergel, Taylor et al. '01)

\textbullet \ \textit{small – number} observed sample (2 NS – NS in Galactic field)

\textbullet \ PSR population dominated by \textit{faint objects}

\rightarrow \textbf{Robust lower limit for the MW: } 10^{-6} \text{ per yr}

\rightarrow \textbf{Upward correction factor for faint PSRs: } \sim 1–500
Radio Pulsars in NS–NS binaries → NS–NS Merger Rate Estimates

Recent Results: possible to assign statistical significance to NS–NS rate estimates with Monte Carlo simulations
(Kim, VK, Lorimer '02)

- Choose PSR space & luminosity distribution
- Populate Galaxy with $N_{\text{tot}}$ “1913+16–like” pulsars
- Simulate PSR survey detection and produce observed samples
- Distribution of $N_{\text{obs}}$ for a given $N_{\text{tot}}$: Poisson
- Calculate $P(1; N_{\text{tot}})$ for best–fitting Poisson distribution
- Derive $P(N_{\text{tot}})$ (Bayesian analysis) and $P(R_{1913})$
- Repeat for 1534+12 and derive $P(R_{\text{tot}})$
Radio Pulsars in NS–NS binaries

NS–NS Merger Rate Estimates

total rate for the Milky Way

"Std" model
Most likely 0.09
1 sigma 0.2 - 0.03
2 sigma 0.37 - 0.01

Systematics factor of 3

(NS-NS rate density (Mpc^{-3} Myr^{-1}))

(Kim, VK, Lorimer '02)
**MORE RATES...**

**NS – BH**
from binary evolution models and population synthesis results:
(Belczynski et al. 2002; Bloom et al. 1999; Fryer et al. 1999; ... )

\[ \sim 10^{-3} - 1 \text{ Mpc}^{-3} \text{ Myr}^{-1} \]

**Core Collapse of Massive Stars**
empirical estimates from SN and mass limits for BH formation
can give us some upper limits:
(Cappellaro et al. 1999; Fryer & VK 2001; Fryer et al. 2001; ... )

\[ <10 - 100 \text{ Mpc}^{-3} \text{ Myr}^{-1} \]
# Expected detection rates for advanced (initial) LIGO

<table>
<thead>
<tr>
<th></th>
<th>NS - inspiral</th>
<th>NS merger</th>
<th>NS - inspiral</th>
<th>BH merger</th>
<th>Bar-mode</th>
<th>BH ringing rel. ejecta</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{max}}$ (Mpc)</td>
<td>350 (20)</td>
<td>15</td>
<td>700 (40)</td>
<td>25</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>$R_{\text{det}}$ (yr$^{-1}$)</td>
<td>2 - 150 (&lt;0.03)</td>
<td>&lt;0.01</td>
<td>1.5 - 1500 (&lt;0.3)</td>
<td>&lt;0.05</td>
<td>0.05 - 0.5</td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>short 1 - 5</td>
<td>&lt;0.01</td>
<td>10 - 50</td>
<td>&lt;0.05</td>
<td></td>
<td>&lt;0.01</td>
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<tr>
<td></td>
<td>long</td>
<td></td>
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GW Triggered Searches

Current predictions for the detectability of a one-to-one association between GRB and GW are not encouraging ...

BUT! We can look for statistical correlations

(Finn et al. 1999)

Compare the distributions of correlated output from two GW IFOs evaluated at
> times just before trigger GRBs
> times non-associated with GRBs
and derive the probability they are different.

> method does not require GW waveform
> statistical significance increases with
  (i) increasing number of triggers
  (ii) decreasing time delay between GW and GRB
> GRB location is highly desirable but not necessary

Such searches are underway using LIGO data from engineering runs and IPN triggers (K. Hurley)