A broadband detection algorithm for LIGO-Virgo and KAGRA searches of long gravitational wave bursts in energetic core-collapse supernovae

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Gravitational waves

Lessons from Swift, BeppoSAX, BATSE:

GRB-SNe from spin down of near-extremal black holes

Search algorithm for broadband long-duration GWBs from nearby CC-SNe
Dynamical curvature

Rotating tidal field

\[ \omega = 2\Omega_{\text{orbit}} \]

\[ \Omega_{\text{orbit}} \equiv \sqrt{\frac{M}{a^3}} \]

Dimensionless strain

\[ h = h_0 + h_1(t) = \frac{M}{D} + h_1(t) \]
Gravitational waves

GR: a coupled elliptic-hyperbolic system of equations
(in SO(3,1) four-covariant form, van Putten & Eardley 1996)

Newton’s law embodied by elliptic part
GW waves embodied by hyperbolic part

\[ G_{ab}(GW) = \text{rotating tidal fields} \]

http://carina.astro.cf.ac.uk/groups/relativity/research/part4.html
PSR 1913+16

\[ P = 7.75 \text{ hr} \]
\[ e = 0.617 \]
\[ F(e) = 11.8 \]
\[ L_{GW} = 0.2\% \ L_{\text{Solar}} \]

Hulse-Taylor 1974
Nobel Prize 1993
Extreme transient events: CC-SNe and LGRBs

GRB 980425/SN1998bw

SN1987A Type II

Radio-loud, aspherical

\[ E_k \approx 2 \times 10^{51} \, \text{erg} \left( \frac{M_{ej}}{2M_\odot} \right) \]

\[ v_{ej} \approx 0.2 \, c \]

Hoeflich et al. 1999
Wieringa et al. 1999

Radio-loud, aspherical, relativistic radio jets, BH remnant?

\[ E_k \approx 1 \times 10^{51} \, \text{erg} \]

\[ E_\nu \approx 10^{53} \, \text{erg} \]

Turtle et al. 1987
Nisenson & Papaliolios 1999

Probably powered by magnetic winds from an angular momentum-rich inner engine

Swift phenomenology

LGRBs, SGRBs, SGRBEEs, LGRBNs: soft EE satisfy same Amati relation

BHs as a common inner engine

BeppoSAX sample of LGRBs at 2 kHz

*Red*: 1.26 photons/0.5 ms bin: non-trivial autocorrelation fn

*White*: 0.59 photons/0.5 ms bin: trivial autocorrelation fn

Matched filtering analysis of 2 kHz light curves (1.26 photons/0.5ms bin)

BeppoSAX phenomenology


no evidence for proto-PSR
Spin-down in BATSE light curves of LGRBS

Matched filtering analysis against model of BH spin down against torus at ISCO

van Putten, 1999, Science, 284, 115

LGRBs from near-extremal BHs
Enhanced luminosity from intermittency

Intermittent black hole-torus magnetosphere

Intermittent luminosity $\gg$ continuous luminosity:

$$\langle L^i_w \rangle = \frac{4}{3} L^c_w \left( \frac{T}{\tau} \right)$$

e.g. with random reversals of the orientation of magnetic fields in the inner engine

Intermittent inner engines


LGRB from intermittent outflows
Magnetically striped long-lived relativistic MHD ejecta

“Double shot” experiment:

- velocity
- density
- hydrostatic pressure
- azimuthal magnetic field

Formation of rapidly rotating BHs

Bardeen accretion: \[
\begin{align*}
\dot{M} &= e\dot{m} \\
\dot{J} &= j\dot{m}
\end{align*}
\]


Surge in mass and angular momentum
End point will be near-extremal close to the Thorne limit
Modified Bardeen accretion

Hyper-accretion with outflows

\[
\begin{aligned}
\dot{M} &= e\dot{m} - L_j \\
\dot{J} &= j\dot{m} - 2\frac{L_j}{\Omega_H}
\end{aligned}
\]

Surge continues unless efficiency is anomalously high
End point is still a rapidly rotating black hole

Near-extremal black holes as initial conditions to LGRBs

Non-relativistic frame dragging

Gravity Probe B: Everitt et al., 2011, PRL. 106, 221101

Relativistic frame dragging

\[ E_r \equiv 6 \times 10^{54} \left( \frac{M}{10 M_\odot} \right) \text{ erg} \]

van Putten, 2015, MG13, 1799
Calorimetric ratios from BH spin down

\[ R_* \equiv \frac{E_*}{E_{\text{rot}}} \cong \frac{E_*}{(1-2)M_\odot} : \]

\[ R_j + R_k + R_D + R_S \cong 1 \]

Jets          kinetic energy accompanying supernova
dissipation inner disk or torus
entropy creation event horizon

(more detailed balance would include finite efficiencies for \( j, k \))

Near-extremal black holes as initial conditions to LGRBs

From forced turbulence, Non-axisymmetric instabilities excited by heating, magnetic pressure

Magnetic moment in lowest energy state

Black hole in its lowest energy state supports open flux tubes from H to infinity
**Effective calorimetric ratios**

**Table 1.** Sample of GRB-SNe. References refer to SNe except for GRB 070125. $E_*$ is expressed in units of $10^{51}$ erg.

<table>
<thead>
<tr>
<th>GRB</th>
<th>Supernova</th>
<th>$z$</th>
<th>$E_{\gamma}$</th>
<th>$E_{SN}$</th>
<th>$\eta$</th>
<th>$E_{r}/E_{c}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>980425</td>
<td>Sn1998bw</td>
<td>0.008</td>
<td>$&lt; 0.001$</td>
<td>50</td>
<td>1</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>031203</td>
<td>SN2003lw</td>
<td>0.1055</td>
<td>$&lt; 0.17$</td>
<td>60</td>
<td>0.25</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>060218</td>
<td>SN2006aj</td>
<td>0.033</td>
<td>$&lt; 0.04$</td>
<td>2</td>
<td>0.25</td>
<td>0.25</td>
<td>3</td>
</tr>
<tr>
<td>100316D</td>
<td>SN2006aj</td>
<td>0.0591</td>
<td>0.037-0.06</td>
<td>10</td>
<td>0.25</td>
<td>1.3</td>
<td>4</td>
</tr>
<tr>
<td>030329</td>
<td>SN2003dh</td>
<td>0.1685</td>
<td>0.07-0.46</td>
<td>40</td>
<td>0.25</td>
<td>5.3</td>
<td>5</td>
</tr>
</tbody>
</table>

Jet-to-rotational energy:

$$R_j \equiv \frac{E_j}{E_{rot}} \approx 0.2\% \left(\frac{\varepsilon}{0.16}\right)^{-1}$$

Kinetic energy-to-rotational energy:

$$R_k \equiv \frac{E_{SN}}{E_{rot}} \approx 0.5\%$$

Spin down against HD matter:

$$R_D = O(1), \quad R_{jD} = \frac{R_j}{R_D} << 1$$

Probing inner engines by matched filtering

Side step Fourier by TSMF using a bank of chirp templates

Did SN1987A produce a GWB?

All ingredients are there!
Aspherical explosion and massive MeV burst with no PSR remnant:
angular momentum-rich high density matter around newly formed BH

\[ L_{GW} = 2 \times 10^{51} \left( \frac{\xi}{0.1} \right)^2 \left( \frac{\sigma}{0.01} \right)^2 \left( \frac{4M}{a} \right)^5 \text{ erg s}^{-1} \]

\[ h = 3.4 \times 10^{-23} M_1 \frac{\xi}{0.1} \frac{\sigma}{0.01} \left( \frac{D}{20 \text{ Mpc}} \right)^{-1} \left( \frac{f}{600 \text{ Hz}} \right)^{\frac{2}{3}} \]

\[ L_{GW} \sim 10^{51} \text{ erg s}^{-1} \]
Gravitational-wave Detectors in US, EU and Japan

Probing CC-SNe by TSMF

\[ h_{\text{eff}} \sim \left( \frac{M}{D} \right) \left( \frac{E_{\text{GW}}}{M} \right)^{\frac{1}{2}} \sim 10^{-21} \]

\[ h_{\text{eff}}^{(r)} = h_{\text{eff}} \left( \frac{\tau}{T} \right)^{\frac{1}{2}} \sim 10^{-22} \]

Chirp detection by TSMF (\(\tau=1\ s\))

van Putten, Tagoshi, Tatsumi, Masa-Katsu & Della Valla, 2011, PRD, 83, 044046

Expected sensitivity distance \(\sim 100\ \text{Mpc}\) for Adv LIGO-Virgo (at high laser power)
Maximal sensitivity source detection by TSMF

Broadband GW emission from CC-SNe

van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle
(under review)
Conclusions and outlook

*Swift, BeppoSAX, BATSE:*

LGRBs from spin down of near-extremal black holes

GWBs expected from energetic CC-SNe forming near-extremal BHs

- High density matter in aspherical SN1987A
- SNIc association with normal long GRBs
- SNIc event rate of \(~100/yr\) within 100 Mpc

*GWBs from SNIc are competitive with mergers if just 1\% is successful*

We propose

(a) Search for the most nearby CC-SNe by dedicated optical surveys
e.g., one every decade in M51, M82 (J.-E. Heo et al., NewA, to appear)

(b) Probe nearby CC-SNe with TSMF using \(~10\) million chirp templates

*Sensitivity range \(~100\) Mpc for Advanced LIGO-Virgo, KAGRA*
Fig. 1. Histograms of the ejection velocities in core-collapse events compiled by Maurer et al. (2010), in 44 normal and 12 broad-line (BL) events. The mean velocity 5680 km s$^{-1}$ of the latter is 3.9 standard deviations away from the mean velocity 4720 km s$^{-1}$ of the first, which is indicative of a separate group of relatively hyper-energetic events.