

# Bursts of Gravitational Radiation from Superconducting Cosmic Strings and the Neutrino Mass Spectrum

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Berezinsky, Hnatyk and Vilenkin showed that superconducting cosmic strings could be central engines for cosmological gamma-ray bursts and for producing the neutrino component of ultra-high energy cosmic rays. A consequence of this mechanism would be that a detectable cusp-triggered gravitational wave burst should be released simultaneously with the  $\gamma$ -ray surge. If contemporary measurements of both  $\gamma$  and  $\nu$  radiation could be made for any particular source, then the cosmological time-delay between them might be useful for putting unprecedentedly tight bounds on the neutrino mass spectrum. Such measurements could consistently verify or rule out the model, since strictly correlated behaviour is expected for the duration of the event and for the time variability of the spectra.

To appear in Physics Letters B — PACS numbers:

Cosmic strings (CSs) are topological defects formed during phase transitions in the early Universe induced by spontaneous symmetry breaking at GUT-scale energies[1]. The energy of the unbroken vacuum phase is released as GUT quanta of the gauge and scalar fields, forming the CSs[2]. It has been suggested that ordinary CSs could be the cosmological sources of the biggest explosions in the Universe[3]: the cosmological (classical) gamma-ray bursts (GRBs)[4], with energies  $E_{GRBs} \sim 10^{53-54}$  erg, timescales  $10^{-2} \leq T_{GRBs} \leq 10^3$ s, as observed by BATSE[5]. CSs may also be the origin of the ultra high energy cosmic rays (UHECRs) with energies above the Greisen-Kuzmin-Zatsepin (GZK) cut-off:  $E_{\times} \sim 10^{19}$  eV[6], as well as the very high energy neutrinos observed today[2,7,8]. Also, ordinary cosmic strings are potential sources of gravitational radiation. Emission of gravitational waves (GWs) is considered the main channel for CS loops to

decay[9,1].

Turning attention to superconducting cosmic string (SCCS) loops, Babul, Paczyński and Spergel[10], and most recently Berezinsky, Hnatyk and Vilenkin (BHV2000)[4], have proposed that such objects could be the central engines of most cosmological bursts of gamma-rays. In the first study, the currents are thought of as being induced in the strings by primordial magnetic fields, and the source distance scale is assumed to be  $(10^2 \leq z \leq 10^3)$ [10]. In the second one, on the other hand, the string currents are seeded by an intergalactic magnetic field, with the GRB sources being located at distances characteristic of superclusters of galaxies, i.e.,  $z \leq 5$ [4]. In both of the models, a surface defect referred to as a *cusp* is the trigger of the bursts, while the electric currents are induced by oscillation of string loops in an external intergalactic magnetic field.

A further by-product of these pictures is that a beamed surge develops naturally at the place

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where a superconducting string loop cusp annihilates. Because of the very large Lorentz factor achieved by the contracting cusp when it is nearly at the point where it will trigger the GRB, this beamed radiation is a very interesting feature of the model. It fits quite well with the current trend among GRB workers who claim that recent observations provide strong evidence for some degree of beaming in GRBs[11].

Based on BATSE observations, we point out that the Berezhinsky, Hnatyk and Vilenkin SCCS scenario[4] appears to be more well-motivated than the earlier one for explaining GRBs from CSs. Thus, we shall follow its main lines here in order to demonstrate that in such a view for the central engine of GRBs, an accompanying burst of gravitational radiation should also be released. As shown in Figs. 1 and 2, the characteristics of such GW bursts make them potentially observable with the forthcoming generation of Earth-based interferometric GW observatories LIGO, VIRGO, TAMA and GEO-600, and the space-borne LISA, as well as by the resonant-mass TIGAs.

A superconducting cosmic string loop, with energy per unit length  $\mu \sim \eta^2$  (where  $\eta$  is the string symmetry-breaking scale), oscillating in a magnetic field  $B$ , behaves like an *ac* generator, and an electric current  $I_0 \sim e^2 B l$  flows in it. Here  $l \sim \alpha ct$ , defines the string loop invariant wavelength ( $l \equiv E/\mu$ , where  $E$  is the energy of the loop in the center-of-mass frame), and  $\alpha \sim \kappa_g G \mu \ll 1$  is a parameter determined by the gravitational back reaction[4].

During brief time intervals, a noticeable augmentation of the local current intensity can occur in domains quite close to the cusp location, the point at which the string speed gets closest to the velocity of light. Several cusps may appear during a single loop oscillation period. Inside a cusp domain  $\delta l_c$  (at maximum contraction) the string shrinks by a large factor,  $l/\delta l$ , leading to a relativistic Lorentz factor  $\Gamma \sim l/\delta l$  (in the string rest frame)<sup>2</sup>, this condition being sustained

for a timescale  $\delta t_c \sim \delta l_c/c$ , within a physical length scale  $\delta l_c \sim \delta l/\Gamma \sim l/\Gamma^2$ . Most of the huge cusp rest energy is converted into kinetic energy. Since, in general, the string velocity is extremely high near to the cusp collapse (it spreads out inside a cone with opening angle  $\theta \sim 1/\Gamma$  oriented along the direction in which the cusp contracts), a quadrupole distribution of the local energy density is expected to develop (see Ref.[4] for further details).

This scenario implies that a short burst of GW emission should occur in the time leading up to cusp annihilation. In this brief time scale,  $\delta t_c$ , the large asymmetric cusp shrinkage and energy reconversion mean that a powerful GW burst would be emitted. As suggested above, we expect that the GW burst and the  $\gamma$ -ray burst should have exactly the same duration, and emphasize that long bursts ( $\Delta t \sim 200$ s) may also be possible[4]. This last point may be realised if a special combination of intergalactic magnetic strengths, i.e.,  $B \sim 10^{-7}$ G, and GRB fluences, e.g.,  $S \sim 10^{-8}$ erg cm<sup>-2</sup>, is invoked. This possibility is illustrated in Table I, where several  $\gamma$ -ray fluences from particular events are combined with magnetic field strengths thought to exist around the GRB sources in the context of the SCCS cusp annihilation mechanism.

The GW characteristics (amplitude and frequency) can be estimated using the typical dynamical timescale for GRBs in this model. According to BHV2000[4], the  $\gamma$ -ray timescale (GRB duration) is given by

$$\begin{aligned}
 T_{GW_s}^{GRBs} &\simeq 0.24\text{ms} \left( \frac{B}{10^{-8}\text{G}[13]} \right)^2 \left( \frac{\alpha}{10^{-8}} \right)^4 \\
 &\times \left( \frac{10^{-4}\text{ ergcm}^{-2}}{S} \right) \\
 &\times \left( \frac{(1+z)^{-1}}{[(1+z)^{-1/2} - 1]^{-2}} \right), \tag{1}
 \end{aligned}$$

where  $S$  is the GRB fluence in units of  $10^{-4}$  erg cm<sup>-2</sup>,  $B$  is the intergalactic magnetic field taken into consideration the factor reduces to  $\Gamma \leq 10^4$ [12], which is very consistent with the correspondings values inferred from BATSE observations[5,11].

<sup>2</sup>In the BHV2000 model this Lorentz factor may reach up to  $\Gamma \sim 6.7 \times 10^7$ . However, when the back-reaction effect of the electromagnetic radiation emitted in the process is

Table 1

Inferred duration of the GRB (GW) emission phase (giving a large part of the total energy  $E$ ) as a function of characteristic values for the BATSE GRB fluence  $S$ , and the assumed intergalactic magnetic field strength  $B$ , with the CS parameter  $\alpha \sim 0.4 \times 10^{-8}$ .

$T_{GWs}^{GRBs}$ [s]		$S$ [erg cm $^{-2}$ ]	$B$ [G]	$E_{\gamma}^{tot}$ [erg]	GRB
$6.7 \times 10^{-6}$		$3 \times 10^{-3}$	$10^{-8}$ [13]	$\sim 3 \times 10^{54}$	971214
$3.2 \times 10^{-4}$	@ (Fig.1)	$1 \times 10^{-4}$	$10^{-8}$	$6.7 \times 10^{53}$	991216
$2.5 \times 10^{-3}$	* (Fig.1)	$1 \times 10^{-5}$	$10^{-7}$	$6.7 \times 10^{53}$	" "
$6.7 \times 10^{-3}$	XX (Fig.1)	$3 \times 10^{-4}$	$10^{-7}$	$\geq 3 \times 10^{54}$	990123
$2.0 \times 10^{-2}$		$1 \times 10^{-5}$	$10^{-7}$		
200	LISA Target	$1.5 \times 10^{-8}$	$10^{-7}$ [4]	$\geq 5 \times 10^{51}$	

in units of  $10^{-8}$  G[13], and  $z \sim 4$  is the source redshift. This value for the redshift  $z$  at which the SCCS is located in this model has been taken in agreement with BATSE observations of the most distant and most energetic GRBs ever detected: GRB000131 at  $z = 4.5$ , Andersen et al. (VLT Team)[14]. It is also consistent with existing models for ultrahigh-energy cosmic rays and the observed shape of their spectrum.

This is a timescale that could be observed by BATSE (time resolution  $\Delta t \sim 100\mu s$ ) in very short GRBs from this sort of cosmological source (see Table I), were it not for its low efficiency for such bursts (see for example Trigger Number 01453,  $\Delta t = 0.006 \pm 0.0002$  in Table 1 in Cline, Matthey and Otwinowski[15]). In what follows we concentrate on this kind of GRB.

One can use the general relativity (GR) quadrupole formula to make an estimate of the characteristic GW amplitude: the dimensionless space-time strain ( $h$ ), generated by the non-spherical dynamics of the *cusp* kinetic energy, is related to the distance of the CS ( $D$ ) by  $h_{ij} = \frac{2G}{c^4 D} \frac{d^2 Q_{ij}}{dt^2}$ , where  $Q_{ij}$  is the second moment of the mass distribution (quadrupole mass-tensor) in the transverse traceless (TT) gauge and is given by  $Q_{ij} \equiv \int \rho(x_i x_j - 1/3 x^2) d^3 x$ , with  $\rho$  being the mass-energy density of the source. This expression can be rewritten as [16]

$$h = \frac{2G}{c^4} \frac{E_{Non-Sym}}{D_L}, \quad (2)$$

where  $D_L$  is the luminosity distance defined by  $D_L = r_z(1+z)$ , with  $z$  being the source red-

shift (inferred from the spectrum of the GRB host), and  $r_z$  is the comoving distance given by  $r_z = 2 \frac{c}{H_0} (1 - [1+z]^{-1/2})$ . Here  $H_0$  is the present-day value of the Hubble constant. For the case which we are studying, we can approximate the non-symmetric part of the kinetic energy of the annihilating cusp as  $E_{Non-Sym} \sim M_c \left(\frac{dl}{dt}\right)^2$ , where  $M_c \sim \mu \delta l_c \sim \mu c \delta t_c$  is the total mass of the cusp. At the time when the gamma-ray outburst occurs, we can express the time derivative of the cusp characteristic linear dimension as  $\left(\frac{\delta l}{\delta t}\right)^2 \sim \left(\frac{\Gamma \delta l_c}{\delta t_c}\right)^2 \sim \Gamma^2 c^2$ , with  $\delta t \sim \delta t_c$ , as discussed by BHV2000. We also identify the GW pulse duration as  $\delta t_c \sim T_{GWs}^{GRBs}$ , given by Eq.(1). Using these expressions, we can write  $E_{Non-Sym} \sim \mu c^3 \Gamma^2 \delta t_c$ , and Eq.(2) becomes

$$h \sim \left[ \frac{G}{c D_L} \right] \mu \Gamma^2 T_{GWs}^{GRBs} \sim 1.9 \times 10^{-22} \Gamma^2 \times (T_{GWs}^{GRBs}) \left( \frac{10^{28} \text{ cm}}{D_L} \right) \left( \frac{\mu}{(10^{16} \text{ GeV})^2} \right), \quad (3)$$

where we have used as the GUT symmetry breaking scale for the SCCS:  $\eta \sim 10^{16}$  GeV, and have assumed that the source is at a distance equal to the Hubble radius. Consistently with current observations, and following BHV2000, we will consider sources at low  $z \sim 5$ [14] for which  $\Gamma = 300$  and  $\Gamma = 10^3$  are plausible Lorentz factors according to BATSE observations and the fireball model[5]. Recall that high  $\Gamma$  values are needed in order for the fireball to avoid overproduction of

electron-positron pairs[17]. From Eq.(3) we then have  $h_{6.7\text{ms}}^{\Gamma=300} \sim 9.4 \times 10^{-21} \text{Hz}^{-1/2}$ ,  $h_{2.4\text{ms}}^{\Gamma=300} \sim 2.1 \times 10^{-21} \text{Hz}^{-1/2}$  and  $h_{0.32\text{ms}}^{\Gamma=10^3} \sim 1.5 \times 10^{-21} \text{Hz}^{-1/2}$ , for the burst duration and Lorentz factor, as indicated.

The maximum frequency of the GW burst in the reference frame of the loop can be approximated as  $f_{GW} \sim t_{dyn}^{-1}$ , with  $t_{dyn} \sim T_{GWs}^{GRBs}$  being the dynamical timescale for annihilation of the cusp. This then implies  $h \sim f_{GW}^{-3/2}$  and so we can write

$$f_{GW} \equiv (T_{GWs}^{GRBs})^{-1} \sim \left(\frac{\delta l_c}{c}\right)^{-1} \sim 150, 420, 3200 \text{ Hz}, \quad (4)$$

for GRBs with the durations given in Table I. Such frequencies fall just within the range of highest sensitivity for the LIGO (I,II), VIRGO and GEO-600 interferometers, and for the Brazilian Mário Schönberg and Dutch Mini-GRail TIGAs, as shown in Figure 1. Thus, in the high frequency regime, the bursts may be detectable for higher  $\Gamma$  and much lower  $\eta$ , for a given  $\Delta t$ , than is the case at lower frequencies.

For the very low GW frequency band  $10^{-4} - 10^0$  Hz, the LISA antenna could observe these signals even for extremely low GUT energy scales but large  $\Gamma$  factors, as shown in Figure 2 (of course, it could also observe the GW pulses for higher  $\eta$  and lower  $\Gamma$ ).

In the context of the BHV2000 SCCS model for GRBs it is also possible for an outburst of ultra high energy cosmic rays to be released simultaneously with the GRB surge. Assuming that a packet of such particles comes in the form of a neutrino burst, we can estimate the neutrino time-of-flight delay with respect to both the GRB and GW signals. This measurement can provide an indication of the neutrino mass eigenstates. Next we make a rough estimate of the overall characteristics of such a  $\nu$ -spectrum, and use it to constrain the predicted time lag. (A more consistent calculation of the actual UHECR spectrum in this picture, in the light of their detectability by the AUGER experiment, is now under way[18].)

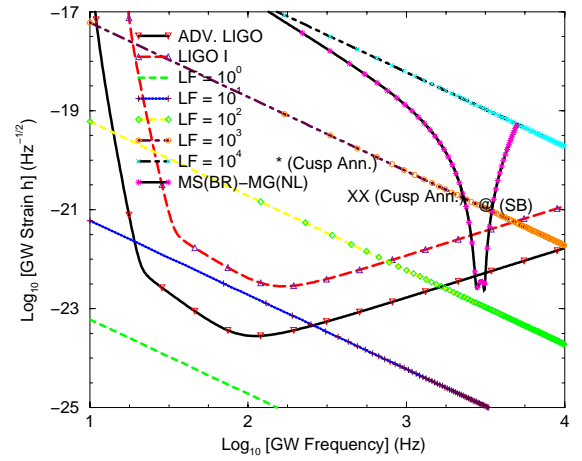


Figure 1. Locus of the GW characteristics ( $-3/2$  slope equally spaced lines) of the burst produced by the SCCS cusp annihilation (computed for  $\eta = 10^{16} \text{GeV}$  and  $\Delta t = 2.4 \text{ms}$ ) plotted against strain (burst) spectral densities and frequency bandwidth of the interferometers LIGO(I,II) and the future *twin* TIGAs: the *Mário Schönberg* (MS, Brazil) and the *Mini-GRail* (MG, Netherlands). Symbols \*, XX and @ denote GW bursts with frequencies 150 Hz ( $\Gamma = 300$ ), 420 Hz ( $\Gamma = 300$ ) and 3200 Hz ( $\Gamma = 10^3$ , very short bursts (SB)), respectively. These GW signals may be triggered simultaneously with GRBs having the characteristics shown in Table I and Lorentz factors (LF)  $\Gamma$  as indicated here.

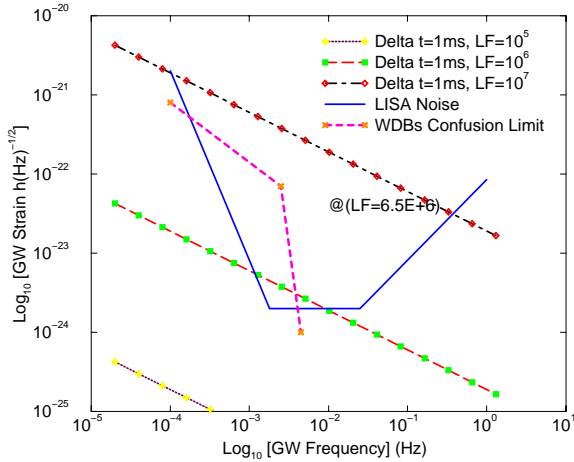


Figure 2. Locus of the GW characteristics (computed for  $\eta = 10^{10}$  GeV and  $\Delta t = 1$ ms) compared with the strain (burst) spectral density and the frequency bandwidth of LISA. The confusion limit produced by the background of white dwarf binaries is also plotted. The symbol @ indicates a GW burst with frequency  $10^{-2}$  Hz and  $h = 4 \times 10^{-23}$ , in units of  $(\text{Hz})^{-1/2}$ , for a GRB with  $\Gamma = 6.5 \times 10^6$ .

Topological defects or unstable relic particles produce ultra high energy photons at a rate  $\dot{n}_p = \dot{n}_{p,0}(t/t_0)^{-m}$ , where  $m = 0, 3, 4$  for decaying particles, ordinary CSs and necklaces, and SCCS, respectively[1,2]. In the GRB fireball picture[17], the detected  $\gamma$ -rays are produced via synchrotron radiation coming from ultrarelativistic electrons boosted by internal shocks in an expanding relativistic blast wave (wind) consisting of electron-positron pairs, some baryons and a huge number of photons. The typical synchrotron frequency is constrained by the characteristic energy of the accelerated electrons and also by the intensity of the magnetic field in the emitting region. Since the electron synchrotron cooling time is short compared with the wind expansion time, electrons lose their energy radiatively. The standard energy of the observed synchrotron photons (see Refs.[19,20] for a more complete review of this mechanism) is  $E_\gamma^b = \frac{\Gamma \hbar \gamma_e^2 e B}{m_e c}$  which is then given by

$$E_\gamma^b \simeq 45 \text{MeV} \xi_B^{1/2} \xi_e^{3/2} \left( \frac{L_\gamma}{10^{54} \text{ergs}^{-1}} \right)^{1/2} \times \left( \frac{10^3}{\Gamma} \right)^2 \left( \frac{0.25 \text{ms}}{\Delta t} \right), \quad (5)$$

where  $L_\gamma = 10^{54}$  ergs $^{-1}$  is the power released in the most energetic GRBs observed by BATSE. This  $L_\gamma$  may imply Lorentz expansion factors  $\Gamma \sim 10^3$ , and we assume this in the following.  $\Delta t = 0.25$ ms is the *inferred* timescale for the shorter  $\gamma$ -ray bursts from the BHV2000 SCCSs,  $\xi_B$  is the fraction of the energy carried by the magnetic field:  $4\pi r_d^2 c \Gamma^2 B^2 = 8\pi \xi_B L$ , where  $L$  is the total wind luminosity, and  $\xi_e$  is the luminosity fraction carried away by electrons. No theory is available to provide specific values for  $\xi_B$  and  $\xi_e$ . However, for values near to equipartition, the break energy  $E_\nu^b$  for photons in this model is in agreement with the observed one for  $\Gamma \sim 10^3$  and  $\Delta t = 0.25$  ms, as discussed below. More precisely, the hardness of the GRB spectra, which extend up to 18 GeV, constrains the wind to have Lorentz factor  $\Gamma \sim 10^3$ , while the observed variability of the GRB flux on a timescale  $\Delta t \leq 1$ ms implies that the internal collisions oc-

cur at a distance from the center of  $r_d \sim \Gamma^2 \Delta t$ , due to variability of the central engine on the same timescale. Since most of the BATSE observed GRBs show variability with  $\Delta t \leq 10$  ms and there is rapid variability with  $\Delta t \leq 1$  ms, the implied characteristic size of the emitting region is  $r_{em} \sim 10^7$  cm which means that it must be a compact domain. The SCCS loop cusp clearly satisfies this constraint.

In the acceleration region, protons (the fireball baryon load) are also expected to be shocked. Their *photo-meson* interaction with observed  $\gamma$ -burst photons should produce a surge of neutrinos almost simultaneously with the GRB via the decay  $p + \gamma^0 \rightarrow \pi^+ \leftrightarrow \mu^+ + \nu_\mu \leftrightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ . The neutrino spectrum for a fireball driven explosion is expected to follow the observed  $\gamma$ -ray spectrum, which is approximately a broken power-law  $\frac{dN_\gamma}{dE_\gamma} \propto E_\gamma^{-\beta}$ , with  $\beta \sim 1$  for low energies and  $\beta \sim 2$  for high energies as compared with the observed *break energy*  $E_\gamma^\beta \sim 45$  MeV, where  $\beta$  changes. The interaction of protons from the surrounding medium, accelerated to a power-law distribution  $\frac{dN_p}{dE_p} \propto E_p^{-2}$ , with the fireball photons, leads to a broken power-law neutrino spectrum  $\frac{dN_\nu}{dE_\nu} \propto E_\nu^{-\beta}$ , with  $\beta = 1$  for  $E_\nu < E_\nu^b$ , and  $\beta = 2$  for  $E_\nu > E_\nu^b$ . Thus the neutrino break energy  $E_\nu^b$  is fixed by the threshold energy of photons from *photo-production* interacting with the dominant  $\sim 45$  MeV fireball photons (in our case), and is

$$E_\nu^b \simeq 1.3 \times 10^{15} \left( \frac{\Gamma}{10^3} \right)^2 \left( \frac{45 \text{ MeV}}{E_\gamma^b} \right) \text{ eV}. \quad (6)$$

Thus, for  $\nu$ s produced with the above energy a further Fermi cycle in the ultrarelativistic blast wave may amplify the UHECR energy by a factor of  $\Gamma^2$  which, for the case of protons, may push them over the GZK limit[6] ( $\nu$ s do not have a GZK cut-off). The part of the total fireball luminosity that escapes as the  $\nu$ -flux is determined by the efficiency of pion production. The energy fraction lost via pion production by protons *producing  $\nu$ s above the break energy* is essentially independent of the energy and can be expressed as

$$f_\pi = 0.23 \left( \frac{L_\gamma}{10^{54} \text{ ergs}^{-1}} \right) \left( \frac{45 \text{ MeV}}{E_\gamma^b} \right) \left( \frac{10^3}{\Gamma} \right)^4 \times \left( \frac{0.25 \text{ ms}}{\Delta t} \right). \quad (7)$$

Thus, an important part of the total wind energy is given to these very high energy  $\nu$ s.

The time-of-flight delay of the  $\nu$ s with respect to the GWs (and the GRB) may be computed by using the spectrum (Eq.6) and Table II, above. This gives[21]

$$\Delta T_\nu^{GWs-GRBs} \sim 1.545 \text{ s} \left( \frac{D}{3 \text{ Gpc}} \right) \times \left( \frac{m_\nu^2}{100 \text{ eV}^2} \right) \left( \frac{100 \text{ GeV}^2}{E_\nu^2} \right). \quad (8)$$

This equation was originally derived as a way of estimating the *time-of-flight lag* between massive neutrinos and massless ones, which should travel at the speed of light[21]. However, it can also be applied to the problem which we are studying here, since we assume that the GWs propagate at the velocity of light, as in GR. It turns out that the detection of such a neutrino pulse with a delay of approximately 1.5 seconds (for  $E_\nu \sim 10^{10}$  eV) after the GRB and GW outbursts from the same source on the sky would make it possible to impose tighter bounds on the neutrino mass spectrum, since the source distance may be estimated from its redshift and the GWs detected. Of course, there are some uncertainties involved in the derivation of Eq.(8). However, it is foreseeable that if atomic clocks were installed in both the GW and  $\nu$  observatories, a very precise measurement of the arrival times might be obtained, making this determination a plausible one in the near future.

To summarize, since the  $\nu$ -spectrum ranges over fourteen orders of magnitude (MeV  $\nu$ s from SN1987A, above GZK  $\nu$ s detected by AGASA, Fly's Eye, etc., see Table II), and the  $\nu$ -energy can be measured directly at the detector, the detection of any species of neutrino in near spatial and temporal coincidence with observed GW + GRB

Table 2

Time delay between GWs (GRBs) and  $\nu$ -bursts as a function of the  $\nu$ -energy in the BHV2000 SCCS model.

$\Delta T_{\nu_s}^{GRBs-GW_s}$ [s]	$\nu$ Energy [eV]
1.545	$10^{10}$
$1.545 \times 10^{-8}$	$10^{14}$
$1.545 \times 10^{-20}$	$10^{20}$

signals might yield a very accurate estimate of the time-delay between them. Through the analysis of such a time lag, one may verify or rule out the BHV2000 SCCS model, and also clarify the value of the GW propagation velocity which is a quantity of great interest for discriminating between different relativistic theories of gravity[22,23].

#### Acknowledgements

We are indebted to Prof. John C. Miller (SISSA and OXFORD) for his patience in reviewing our paper and for his important suggestions for making this manuscript comprehensible. HJMC thanks the Centro Latino-Americano de Física (Rio de Janeiro) and Conselho Nacional de Desenvolvimento e Pesquisa (CNPq, Brazil) for financial support. DMG also thanks CNPq for a Graduate Scholarship.

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