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Open Questions in Astrophysically Triggered Gravitational Wave Searches

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Abstract. Sources of gravitational waves are often expected to also be observable through several other messengers, such as gamma rays, X-rays, optical, radio, and/or neutrino emission. Some of these channels are already being used in searches for gravitational waves with the LIGO-GEO600-Virgo interferometer network, and others are currently being incorporated into new searches. Astrophysical targets include gamma-ray bursts, soft-gamma repeaters, supernovae, and glitching pulsars. The simultaneous observation of electromagnetic or neutrino emission could be a crucial aspect for the first direct detection of gravitational waves. Information on the progenitor, such as trigger time, direction and expected frequency range, can enhance our ability to identify gravitational wave signatures with amplitudes close to the noise floor of the detector. Furthermore, combining gravitational waves with electromagnetic and neutrino observations will enable the extraction of scientific insight that was hidden from us before. The paper discusses the status of transient multimessenger detection efforts as well as intriguing questions that might be resolved in the future by advanced and third generation gravitational wave detectors.

1. Introduction

The astrophysics community expects direct detections from the advanced ground based gravitational wave detectors (aLIGO [1] and AdV [2, 3]) within the next decade [4, 5]. These detectors will achieve a tenfold increase in sensitivity around 100Hz over the initial detectors [4, 6]. Models and observations predict a detectable rate for binary neutron star coalescence between 0.4 to 400 events yearly [7].

The worldwide gravitational wave community is gearing up at the same time to evaluate the scientific reach and to produce a baseline design of the third generation of interferometric gravitational wave detectors (i.e.,Einstein Telescope (ET) [8]). These detectors will offer an order of magnitude better sensitivity around 100Hz than the advanced detectors and they could allow us to take advantage of routine detections of a wide range of gravitational wave emitters.

Gravitational wave transient events are believed to be often accompanied by other messengers [8–11], such as gamma-rays, optical photons, and/or neutrinos. It is expected that the information on the progenitor that we gain from observations through these other messengers is complementary to the information we may decipher from direct detection of gravitational waves [9]. Time, sky location, and information on the progenitor properties are often provided by multimessenger observations, that in turn could translate into more confident detection, efficient background rejection, and increased sensitivity. Some measurements are enabled only through multimessenger approaches [8, 12].

Frontier fields can be recognized easily; they often have more open questions than answers. This paper is organized as follows, to illustrate this point. In Section 2, we briefly review results of and motivation for recent multimessenger searches for transient gravitational waves. In Section 3, we provide a subset of the questions that may be answered by multimessenger searches with advanced and third generation ground based interferometric gravitational wave detector networks.

2. Brief Overview of the Status of Multimessenger Searches for Gravitational waves

The wordwide gravitatonal wave community has actively pursued multimessenger searches for more than a decade [9, 10, 13–18]. Most of observations are the results of externally triggered approaches [17, 19–26] that are summarized in this section.

Soft gamma repeaters (SGRs) [27] and anomalous X-ray pulsars (AXPs) are rare cosmic objects, less then two dozen are known in our Galaxy. Their putative engines are believed to be highly magnetized neutron stars, so called *magnetars* [28–30]. Their electromagnetic emission can correspond to single or rapidly repeated bursts of gamma-rays with isotropic energies between 10^{42} erg and 10^{46} erg. Some theories [31–36] predict that these bursts can also be accompanied by gravitational wave emission. Sporadic low energy flares are fairly common; they are observed hundreds of times per year [27].

On the other hand, so called "giant flares" with the highest energies are very rarely observed; we know only three instances [37–39]. Additionally, two of the giant flares were associated with quasiperiodic oscillations (QPOs) [40, 41], which might also be associated with gravitational wave emission. The search for gravitational waves from QPOs of the December 2004 giant flare of SGR 1806–20 [42] produced a null result but placed an observational limit on the associated gravitational wave energy. A separate search, targeting the instantaneous gravitational wave transient at the time of the giant flare [27], also returned a null result, and it also provided limits on the energetics. The analysis of a "storm" of 70 bursts of SGR 1900+14 [43] and an additional ∼200 low-energy flares of SGR 1806–20 and SGR 1900+14 also extended our observational knowledge [27]. These searches triggered by Galactic SGR activity were probing neutron star f-modes experimentally. The isotropic gravitational wave energy limits reached as low as 2.4×10^{48} erg for some of the flares and emission models assuming ∼10 kpc SGRs distance. A stacked search [44] for the gravitational wave signature of the SGR 1900+14 storm in 2006 provided an order of magnitude improvement in energy upper limits over the previous results [27].

Core collapse supaernovae are expected to be emitters of electromagnetic, neutrino, and gravitational wave signals [45]. While our knowledge of stellar core collapses is uncertain [46, 47], it is believed that these highly energetic events in the Galaxy can be associated with gravitational wave emission observable by advanced gravitational wave detector networks. Synergistic observations [48–54] of gravitational waves and low-energy neutrinos [55, 56] (up to a few 100 MeV) from core collapse supernovae might yield new information on the supernova engine and the dynamics of matter within. While most work on the phenomenology of the topic is yet to be done, some insight can already be gained from references [57–64] on the science that can be enabled by joint observations. A comprehensive review of the gravitational-wave signature of core-collapse supernovae is provided in [61] showing that a Galactic event is an interesting target for aLIGO, AdV and ET [8]. Present day neutrino detectors have a well established Galactic reach [49] for supernovae, that is a good match to the sensitivity of the advanced gravitational wave detectors [57, 59, 65–70]. While the expected rate of Galactic supernovae is very low (<1/20 years), future megaton class water-Cherenkov neutrino detectors [71–73] might allow a few Mpc reach ‡ that is a good match to the reach of third generation gravitational wave detectors [8].

High-energy neutrinos ($\gtrsim$ 100 GeV) can conceivably be emitted from shock-accelerated ultra-relativistic particles [74] e.g. in GRB outflows. Scientific possibilities related to joint observations with high energy neutrinos and gravitational waves are discussed in detail in [75]b.

Gamma-ray bursts (GRBs) [76] are believed to be associated with compact progenitors that are also possible emitters of gravitational waves [77]. Short GRBs (duration of burst is less than 2 s long) are believed to be associated with the merger [78]

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‡ It is expected that the core-collapse supernovae rate within 5 Mpc is about 1/year.

of neutron star binaries, neutron star - black hole binaries, or rarely with giant flares [78] of extragalactic magnetars. While the gravitational wave signature of inspirals just preceding the merger is expected to be detectable to hundreds of Mpc with future detectors, the SGR reach probably remains confined to within our Galaxy. Long GRBs (>2s) are believed to be produced by energetic core-collapse supernovae [79–82]. While the model predictions for gravitational wave emission vary widely, it is likely that the advanced gravitational wave detectors can only have a reach that is well below 100 Mpc [56, 83–85]. Multiple searches for gravitational waves triggered by GRB observations were published by the LIGO and Virgo collaborations (e.g., recently [26, 86–88]). The search for the gravitational wave counterpart of GRB 070201 produced a non-detection and valuable scientific insight. The sky position error box of this short-hard GRB included the Andromeda galaxy (M31 at ∼770kpc). The result excluded binary compact coalescence in M31 at >99% confidence [86], a significant clue that the burst was due to a SGR giant flare in M31. The search for the gravitational wave counterpart of 22 short GRBs [87] produced lower limits, ∼O(several Mpc), on the binary progenitor distances. A model-independent search [88] covering 137 long and short GRBs yielded a null result, but with improved model-independent upper limits on the associated gravitational wave strain.

3. Some Open Questions that May be Answered by Multimessenger Observations with Gravitational Wave Detectors

While multimessenger astronomy with gravitational waves has already contributed to astrophysics, most of the exciting questions still remain to be answered (see e.g., [12, 89–91]). Indeed, it is a frontier field and it will take two generations of ground based gravitational wave detectors to answer a significant fraction of current open questions in the field. To clearly illustrate this point, we will list some of the questions in multimessenger astrophysics that might be resolved by advanced or third generation ground based gravitational wave detectors:

3.1. Some generic questions accessible through multimessenger observations

- What is the speed of gravitational waves, subluminal or superluminal [92, 93]?
- Does Einstein's theory of general relativity remain valid in the strong field regime [94]?
- Does gravity violate parity [95, 96]?
- Is there a new length scale beyond which general relativity is modified [97]?
- Which alternative gravity theories can be excluded experimentally [98]?
- How often can an unidentified electromagnetic transient be explained by a gravitational wave emitter?
- Is there a high redshift population of intermediate mass black holes [8]?

- Can gravitational waves help in explaining the origin of Ultra-Luminous X-ray binaries [8]?
- Can we search for new physics in the ultra-weak field regime [99]?
- Can a massive graviton serve as a cold-dark-matter candidate [92]?
- What fraction of the cosmic source's energy is emitted in the form of gravitational waves?
- Can gravitational wave detectors provide an early warning to electromagnetic observers to allow the detection of early light curves [9–12, 14, 89, 100]?
- Do gravitational measurements of distance agree with the concordance cosmology [101, 102]?
- What is the mass spectrum and spin distribution of black holes [103, 104]?
- Are there extra gravitational wave polarizations?
- ...

3.2. Some questions related to SGRs

- Is there a significant non-axisymmetric crust or core dynamics associated with SGR flares [34]?
- What is the precise origin of SGRs [31, 36]? (e.g., What is the mechanism for GW and EM emission and how are they correlated?)
- Is there a fundamental difference between giant and common SGR flares [33]?
- Do quark stars exist [36]?
- Can we exclude or confirm some of the SGR models [8, 31]?
- What is the origin of pulsar glitches?
- What is the composition and structure of neutron stars and their cores [31]?
- What is the tallest mountain that can be supported by neutron stars [36]?
- Can we use GW-EM observations to guide or EM+null GW results to distinguish the local extragalactic SGR contributions from the short GRB population?
- ...

3.3. Some questions related to core collapse supernovae

- What is the nature of gravitational collapse [61, 105, 106]?
- What is the relationship between the supernova progenitor and remnant (e.g., final mass and spin)?
- If the supernova remnant is not a black hole, how does it behave? (e.g., a transient hypermassive remnant with unstable modes or collapse to a BH?)
- What happens in a core collapse supernova before the light and neutrinos escape?

- What is the delay in between neutrinos and gravitational waves in a core collapse supernovae [107]?
- What is the role of anisotropic neutrino emission in supernovae [108]?
- What is the mass of a neutrino [109]?
- Can we see core collapse supernovae in gravitational waves that are not visible in neutrinos [8]?
- Is there an electromagnetically hidden population of core collapse events [110–112]?
- How many dynamical scenarios are associated with core collapse supernovae? Can we distinguish between them?
- Can pulsar birth kicks result in detectable gravitational waves?
- What is the time delay between the electromagnetic brightening and the core collapse of a supernova [113]?
- What are the properties of the core collapse supernova progenitor [47, 69, 114–119]?
- What is the role of the rotation and magnetic fields in stellar core collapse [106]?
- ...

3.4. Some questions related to GRBs

- What is the origin of long and short GRBs [8]?
- What is the precise dynamics of each GRB engine?
- Is there any longer-lasting central engine left over from the GRB explosion, and what's its nature [120–123]?
- Are there electromagnetically hidden populations of GRBs [8]?
- Does the hypothesized low luminosity GRB population exist [8]?
- Can we have direct inferences on the GRB jet parameters from gravitational waves?
- Can we estimate properties of the nuclear equation state using short GRBs [124]?
- Can we relate the luminosity distribution of GRBs to beaming and the central engine mechanism?
- Is it possible to construct a competitive Hubble diagram based on gravitational wave standard sirens [8, 101]?
- What is the relationship between the parameters of a compact binary system and it's electromagnetic and neutrino emission?
- What GRB progenitor models can we confirm or reject?
- Are there other (sub)classes of GRBs?
- Do choked GRBs exist [8]?
- What is the origin of choked GRBs?
- What is the cosmic population of choked GRBs?

- What are the engines producing high energy neutrino and gravitational wave emission together?
- What is the dynamics/energetics of joint high energy neutrino and gravitational wave emitters?
- What is the electromagnetic emission of binary neutron star coalescence [10]?
- What is the electromagnetic emission of a neutron star – black hole coalescence [10]?
- Is there any electromagnetic emission from binary black hole coalescence?
- What is the nature of XRFs and their relationship to long GRBs [8]?
- ...

It is expected that these lists of questions will evolve and grow substantially as we start answering the currently open questions. Naturally, one should not forget about the unexpected.

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References

[1] LSC http://www.ligo.caltech.edu/advLIGO/

[2] VIRGO http://wwwcascina.virgo.infn.it/advirgo/

[3] Advanced Virgo Baseline Design document https://tds.ego-gw.it/ql/?c=6589 (*Preprint* `VIR-0027A-09`)

[4] The LIGO Scientific Collaboration 2009 *Reports on Progress in Physics* **72** 076901

[5] Whitcomb S E *et al.* 2009 *Astro2010 Decadal Survey White paper* `https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=1587`

[6] VIRGO http://www.virgo.infn.it/

[7] LIGO Scientific Collaboration, Virgo Collaboration: J Abadie *et al.* 2010 *ArXiv e-prints* (*Preprint* `1003.2480`)

[8] Chassande-Mottin E, Hendry M, Sutton P J and Márka S 2010 *ArXiv e-prints* (*Preprint* `1004.1964`)

[9] Aso Y, Márka Z, Finley C, Dwyer J, Kotake K and Márka S 2008 *Class. Quantum Grav.* **25** 114039 (*Preprint* `arXiv:0711.0107`)

[10] Sylvestre J 2003 *Astrophys. Journal* **591** 1152–1156

[11] Stubbs C W 2008 *Class. Quant. Grav.* **25** 184033 arXiv:0712.2598

[12] Bloom J S *et al.* 2009 Astro2010 Decadal Survey Whitepaper: Coordinated Science in the Gravitational and Electromagnetic Skies arXiv: 0902.1527

[13] LIGO T and Collaborations V 2008 *Classical and Quantum Gravity* **25** 114051–+ (*Preprint* `0802.4320`)

[14] Kanner J *et al.* 2008 *ArXiv e-print 0803.0312* **803** (*Preprint* `0803.0312`)

[15] Clark J, Heng I S, Pitkin M and Woan G 2007 *Phys. Rev. D* **76** 043003–+ (*Preprint* `arXiv:gr-qc/0703138`)

[16] Hayama K, Mohanty S D, Rakhmanov M and Desai S 2007 *Classical and Quantum Gravity* **24** 681–+ (*Preprint* `0709.0940`)

[17] Mohanty S D, Marka S, Rahkola R, Mukherjee S, Leonor I, Frey R, Cannizzo J and Camp J 2004 *Classical and Quantum Gravity* **21** 765–+

[18] van Putten M H, Levinson A, Lee H K, Regimbau T, Punturo M and Harry G M 2004 *Phys. Rev. D* **69** 044007–+ (*Preprint* `arXiv:gr-qc/0308016`)

[19] Collaboration T V 2007 *Classical and Quantum Gravity* **24** 671–+

[20] O'Shaughnessy R and LIGO Scientific Collaboration 2008 Just Add Photons: Astrophysics From Ligo External Triggers *AAS/High Energy Astrophysics Division* (*AAS/High Energy Astrophysics Division* vol 10) pp 06.04–+

[21] Kalmus P et al 2007 *Classical and Quantum Gravity* **24** 659

[22] The LIGO Scientific Collaboration 2005 *Phys. Rev. D.* **72** 042002 (*Preprint* `gr-qc/0501068`)

[23] Finn L S, Mohanty S D and Romano J D 1999 *Phys. Rev. D.* **60** 121101 (*Preprint* `arXiv:gr-qc/9903101`)

[24] The LIGO Scientific Collaboration 2008 *Phys. Rev. D* **77** 062004

[25] Dietz A 2008 GRB-triggered searches for gravitational waves in LIGO data *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 1000) ed M Galassi, D Palmer, & E Fenimore pp 284–288

[26] The Virgo Collaboration 2008 *Classical and Quantum Gravity* **25** 225001

[27] Abbott B *et al.* 2008 *Phys. Rev. Lett.* **101** 211102 (pages 6) URL `http://link.aps.org/abstract/PRL/v101/e211102`

[28] Duncan R C and Thompson C 1992 *ApJ Lett.* **392** L9–L13

[29] Woods P M and Thompson C 2004 Soft gamma repeaters and anomalous x-ray pulsars: Magnetar candidates *Compact Stellar X-Ray Sources* ed Lewin W G H and van der Klis M (Cambridge: Cambridge Univ. Press) (*Preprint* `astro-ph/0406133`)

[30] Mereghetti S 2008 *A&A Rev.* **15** 225–287

[31] Corsi A and Owen B J 2009 A theoretical framework for LIGO-Virgo SGR searches: exploring Ioka's 2001 model Tech. Rep. LIGO DCC Document T0900242 and VIR-0028A-09 LSC and Virgo collaboration

[32] Ioka K 2001 *MNRAS* **327** 639–662 (*Preprint* `arXiv:astro-ph/0009327`)

[33] Horvath J E 2005 *Modern Physics Letters A* **20** 2799–2804 (*Preprint* `arXiv:astro-ph/0508223`)

[34] de Freitas Pacheco J A 1998 *A&A* **336** 397–401 (*Preprint* `arXiv:astro-ph/9805321`)

[35] Xu R X 2003 *Astrophys. J. Lett.* **596** L59–L62 (*Preprint* `astro-ph/0302165`)

[36] Owen B J 2005 *Phys. Rev. Lett.* **95** 211101 (*Preprint* `astro-ph/0503399`)

[37] Mazets E P *et al.* 1979 *Nature* **282** 587–589

[38] Hurley K *et al.* 1999 *Nature* **397** 41–43 (*Preprint* `astro-ph/9811443`)

[39] Hurley K, Boggs S E, Smith D M, Duncan R C, Lin R, Zoglauer A, Krucker S, Hurford G, Hudson H, Wigger C, Hajdas W, Thompson C, Mitrofanov I, Sanin A, Boynton W, Fellows C, von Kienlin A, Lichti G, Rau A and Cline T 2005 *Nature* **434** 1098–1103 (*Preprint* `arXiv:astro-ph/0502329`)

[40] Watts A L and Strohmayer T E 2006 *ApJ Lett.* **637** L117–L120 (*Preprint* `astro-ph/0512630`)

[41] Israel G L, Belloni T, Stella L, Rephaeli Y, Gruber D E, Casella P, Dall'Osso S, Rea N, Persic M and Rothschild R E 2005 *ApJ Lett.* **628** L53–L56 (*Preprint* `arXiv:astro-ph/0505255`)

[42] Abbott B *et al.* (LIGO Scientific Collaboration) 2007 *Phys. Rev. D* **76** 062003 (*Preprint* `astro-ph/0703419`)

[43] Israel G L, Romano P, Mangano V, Dall'Osso S, Chincarini G, Stella L, Campana S, Belloni T, Tagliaferri G, Blustin A J, Sakamoto T, Hurley K, Zane S, Moretti A, Palmer D, Guidorzi C, Burrows D N, Gehrels N and Krimm H A 2008 *ApJ* **685** 1114–1128 (*Preprint* `0805.3919`)

[44] The LIGO Scientific Collaboration 2009 *Astrophys. J.* **701** L68–L74 arXiv: 0905.0005

[45] Arnaud N, Barsuglia M, Bizouard M, Brisson V, Cavalier F, Davier M, Hello P, Kreckelbergh S and Porter E K 2004 *Astroparticle Physics* **21** 201–221 (*Preprint* `arXiv:gr-qc/0307101`)

[46] Janka H T, Langanke K, Marek A, Martínez-Pinedo G and Müller B 2007 *Phys. Rep.* **442** 38

[47] Ott C D 2009 *Class. Quant. Grav.* **26** 204015

[48] Scholberg K 2001 *Nuclear Physics B Proceedings Supplements* **91** 331–337 (*Preprint* `arXiv:hep-ex/0008044`)

[49] Fulgione W 2010 *J. Phys. Conf. Ser.* **203** 012077

[50] Fukuda S *et al.* 2003 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **501** 418 – 462 ISSN 0168-9002 URL `http://www.sciencedirect.com/science/article/B6TJM-4811KNK-B/2/efe9c5f7c6e3ae12e4764369e71910bf`

[51] KamLAND URL `http://www.awa.tohoku.ac.jp/KamLAND/`

[52] for the LVD Collaboration F W 2006 *Memorie della Societa Astronomica Italiana Supplement* **9** ”388–+”

[53] Alimonti et al G 2009 *Nuc. Inst. Meth. Phys. Res. A* **600** 568

[54] Ahrens J *et al.* 2004 *Astroparticle Physics* **20** 507 – 532 ISSN 0927-6505 URL `http://www.sciencedirect.com/science/article/B6TJ1-49W31VF-1/2/7d423e933a84316c3be00b1c193cbd77`

[55] Arnett W D, Bahcall J N, Kirshner R P and Woosley S E 1989 *Annu. Rev. of Astron. and Astrophys.* **27** 629–700

[56] Bethe H A 1990 *Rev. Mod. Phys.* **62** 801

[57] Marek A, Janka H T and Müller E 2009 *A&A* **496** 475

[58] Ott C D, Burrows A, Dessart L and Livne E 2008 *ApJ* **685** 1069

[59] Dimmelmeier H, Ott C D, Marek A and Janka H T 2008 *Phys. Rev. D* **78** 064056

[60] Röver C, Bizouard M, Christensen N, Dimmelmeier H, Heng I S and Meyer R 2009 *Phys. Rev. D* **80** 102004

[61] Ott C D 2009 *Class. Quantum Grav.* **26** 063001 arXiv:0809.0695

[62] Summerscales T Z, Burrows A, Finn L S and Ott C D 2008 *ApJ* **678** 1142

[63] Sagert I, Fischer T, Hempel M, Pagliara G, Schaffner-Bielich J, Mezzacappa A, Thielemann F and Liebendörfer M 2009 *Phys. Rev. Lett.* **102** 081101

[64] Abdikamalov E B, Dimmelmeier H, Rezzolla L and Miller J C 2009 *MNRAS* **392** 52

[65] Leonor I, Cadonati L, Coccia E, D'Antonio S, Di Credico A, Fafone V, Frey R, Fulgione W, Katsavounidis E, Ott C D, Pagliaroli G, Scholberg K, Thrane E and Vissani F 2010 *Class. Quant. Grav.* **27** 084019

[66] Kotake K, Iwakami W, Ohnishi N and Yamada S 2009 *ApJ Lett.* **697** L133

[67] Ott C D, Dimmelmeier H, Marek A, Janka H T, Hawke I, Zink B and Schnetter E 2007 *Phys. Rev. Lett.* **98** 261101

[68] Murphy J W, Ott C D and Burrows A 2009 *ApJ* **707** 1173

[69] Takiwaki T and Kotake K 2010 *Submitted to ApJ. ArXiv:1004.2896*

[70] Ott C D, Burrows A, Dessart L and Livne E 2006 *Phys. Rev. Lett.* **96** 201102

[71] Maricic J and the Lbne Dusel collaboration 2010 *Journal of Physics Conference Series* **203** 012109–+

[72] Nakamura K 2003 Hyper-kamiokande âĂŤ a next generation water cherenkov detector *Neutrinos and implications for Physics beyond the Standard Model* ed Shrock R (World Scientific)

[73] Spiering C 2008 Status and Perspectives of Astroparticle Physics in Europe arXiv: 0804.1500

[74] Waxman E and Bahcall J 1997 *Physical Review Letters* **78** 2292 URL `http://www.citebase.org/abstract?id=oai:arXiv.org:astro-ph/9701231`

[75] for the LIGO Scientific Collaboration and the Virgo Collaboration E C M 2010 *Journal of Physics Conference Series, Same Volume, submitted*

[76] Meszaros P 2006 *Reports of Progress in Physics* **69** 2259–2322 (*Preprint* `arXiv:astro-ph/0605208`)

[77] Kobayashi S and Mészáros P 2003 *Astrophys. Journal* **589** 861–870 (*Preprint* `arXiv:astro-ph/0210211`)

[78] Nakar E 2007 *Physics Reports* **442** 166–236 (*Preprint* `arXiv:astro-ph/0701748`)

[79] Galama T J *et al.* 1998 *Nature* **395** 670 arXiv:astro-ph/9806175

[80] Kulkarni S R *et al.* 1998 *Nature* **395** 663–669

[81] Campana S *et al.* 2006 *Nature* **442** 1008–1010 arXiv:astro-ph/0603279

[82] Cobb B E, Bailyn C D, van Dokkum P G and Natarajan P 2006 *Astrophys. Journal* **645** L113–L116 (*Preprint* `arXiv:astro-ph/0603832`)

[83] Woosley S E and Bloom J S 2006 *Ann. Rev. Astron. Astrophys.* **44** 507

[84] Davies M B, King A, Rosswog S and Wynn G 2002 *Astrophysical Journal* **579** L63–L66 (*Preprint* `arXiv:astro-ph/0204358`)

[85] Piro A L and Pfahl E 2007 *Astrophysical Journal* **658** 1173–1176

[86] The LIGO Scientific Collaboration 2008 *Astrophysical Journal* **681** 1419–1430

[87] and The Virgo Collaboration T L S C 2010 *The Astrophysical Journal* **715** 1453 URL `http://stacks.iop.org/0004-637X/715/i=2/a=1453`

[88] and The Virgo Collaboration T L S C 2010 *The Astrophysical Journal* **715** 1438 URL `http://stacks.iop.org/0004-637X/715/i=2/a=1438`

[89] Phinney E S 2009 Finding and Using Electromagnetic Counterparts of Gravitational Wave Sources arXiv:0903.0098

[90] Kulkarni S R and Kasliwal M M 2009 Astro2010 Decadal Survey Whitepaper: Transients in the local Universe arXiv:0903.0218

[91] Kocsis B, Frei Z, Haiman Z and Menou K 2006 *Astrophys. Journal* **637** 27–37 (*Preprint* `arXiv:astro-ph/0505394`)

[92] Dubovsky S L, Tinyakov P G and Tkachev I I 2005 *Phys. Rev. Lett.* **94** 181102

[93] Jacobson T and Mattingly D 2004 *Phys. Rev. D* **70** 024003

[94] Kocsis B, Haiman Z and Menou K 2008 *ApJ* **684** 870–887 (*Preprint* `0712.1144`)

[95] Yunes N, O'Shaughnessy R, Owen B J and Alexander S 2010 *ArXiv e-prints* (*Preprint* `1005.3310`)

[96] Alexander S and Yunes N 2009 *Phys. Rep.* **480** 1–55 (*Preprint* `0907.2562`)

[97] Deffayet C and Menou K 2007 *The Astrophysical Journal Letters* **668** L143–L146 (*Preprint* `0709.0003`)

[98] Desai S, Kahya E O and Woodard R P 2008 *Phys. Rev. D* **77** 124041–+ (*Preprint* `0804.3804`)

[99] Kahya E O 2010 *ArXiv e-prints* (*Preprint* `1001.0725`)

[100] Kulkarni S R and Kasliwal M M 2009 *Astro2010 Decadal Survey White paper* ArXiv:0903.0218

[101] Sathyaprakash B S, Schutz B and Van Den Broeck C 2009 Cosmography with the Einstein Telescope arXiv: 0906.4151

[102] Nissanke S, Hughes S A, Holz D E, Dalal N and Sievers J L 2009 *ArXiv e-prints* (*Preprint* `0904.1017`)

[103] Fregeau J M, Larson S L, Miller M C, O'Shaughnessy R and Rasio F A 2006 *ApJ Lett.* **646** L135–L138 (*Preprint* `arXiv:astro-ph/0605732`)

[104] Brown D A, Brink J, Fang H, Gair J R, Li C, Lovelace G, Mandel I and Thorne K S 2007 *Physical Review Letters* **99** 201102–+ (*Preprint* `arXiv:gr-qc/0612060`)

[105] Kotake K, Sato K and Takahashi K 2006 *Reports on Progress in Physics* **69** 971–1143 (*Preprint* `arXiv:astro-ph/0509456`)

[106] Ott C D, Dimmelmeier H, Marek A, Janka H T, Zink B, Hawke I and Schnetter E 2006 *ArXiv Astrophysics e-prints*

[107] Pagliaroli G, Vissani F, Coccia E and Fulgione W 2009 *Physical Review Letters* **103** 031102–+ (*Preprint* `0903.1191`)

[108] Buonanno A, Sigl G, Raffelt G G, Janka H and Müller E 2005 *Phys. Rev. D* **72** 084001–+ (*Preprint* `arXiv:astro-ph/0412277`)

[109] Arnaud N, Barsuglia M, Bizouard M A, Cavalier F, Davier M, Hello P and Pradier T 2002 *Phys. Rev. D* **65** 033010–+ (*Preprint* `arXiv:hep-ph/0109027`)

[110] Fischer T, Whitehouse S C, Mezzacappa A, Thielemann F K and Liebendörfer M 2009 *Astron. Astrophys.* **499** 1–15

[111] Sumiyoshi K, Ishizuka C, Ohnishi A, Yamada S and Suzuki H 2009 *ApJ Lett.* **690** L43–L46 (*Preprint* `0811.4237`)

[112] O'Connor E and Ott C D 2010 *Class. Quant. Grav. in press, arXiv:0912.2393 [astro-ph]*

[113] Matzner C D and McKee C F 1999 *ApJ* **510** 379 (*Preprint* `arXiv:astro-ph/9807046`)

[114] Gezari S, Dessart L, Basa S, Martin D C, Neill J D, Woosley S E, Hillier D J, Bazin G, Forster K, Friedman P G, Le Du J, Mazure A, Morrissey P, Neff S G, Schiminovich D and Wyder T K 2008 *ApJ Lett.* **683** L131

[115] Hamuy M 2003 *ApJ* **582** 905

[116] Smartt S J 2009 *ARA&A* **47** 63 (*Preprint* `0908.0700`)

[117] Soderberg A M, Chakraborti S, Pignata G, Chevalier R A, Chandra P, Ray A, Wieringa M H, Copete A, Chaplin V, Connaughton V, Barthelmy S D, Bietenholz M F, Chugai N, Stritzinger M D, Hamuy M, Fransson C, Fox O, Levesque E M, Grindlay J E, Challis P, Foley R J, Kirshner R P, Milne P A and Torres M A P 2010 *Nature* **463** 513 (*Preprint* `0908.2817`)

[118] Kasen D and Bildsten L 2009 *ArXiv:0911.0680*

[119] Fryer C L, Holz D E and Hughes S A 2004 *ApJ* **609** 288

[120] King A, O'Brien P T, Goad M R, Osborne J, Olsson E and Page K 2005 *The Astrophysical Journal Letters* **630** L113 URL `http://stacks.iop.org/1538-4357/630/i=2/a=L113`

[121] Perna R, Armitage P J and Zhang B 2006 *The Astrophysical Journal Letters* **636** L29 URL `http://stacks.iop.org/1538-4357/636/i=1/a=L29`

[122] Rosswog S 2007 *MNRAS* **376** L48–L51 (*Preprint* `arXiv:astro-ph/0611440`)

[123] Corsi A and Meszaros P 2009 *The Astrophysical Journal* **702** 1171 URL `http://stacks.iop.org/0004-637X/702/i=2/a=1171`

[124] Ferrari V, Gualtieri L and Pannarale F 2009 *ArXiv* (*Preprint* `arXiv/0912.3692`)