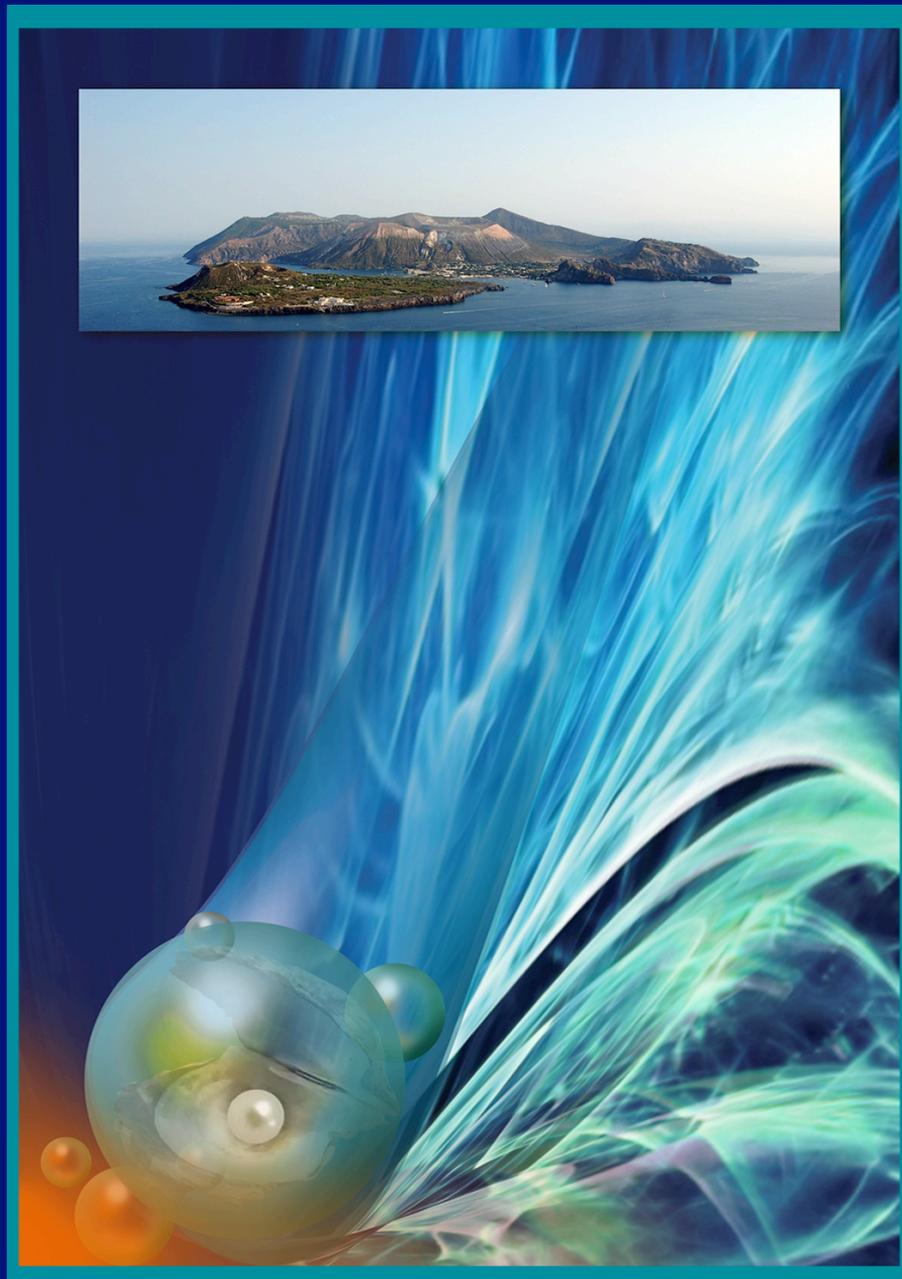




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Vulcano 2014

**Frontier Objects
in Astrophysics and Particle Physics**

Editors:

R. Fusco Femiano, G. Mannocchi, A. Morselli, G. Trincherò

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VULCANO Workshop
Frontier Objects in Astrophysics and Particle Physics
2014

Vulcano Workshop 2014

Frontier Objects in AstroPhysics and Particle Physics

R. Fusco Femiano, G.Mannocchi Foreword

Astrophysics and Cosmology

M. Boer	The eve of multimessenger astronomy	*
S. Etori	Cosmology and astrophysics with the thermal component of the Clusters of Galaxies	1
G. Brunetti	Diffuse radio emission in galaxy clusters: crossroad between astrophysics and cosmology	*
F. Nicastro	Missing Baryons at all Astronomical Scales: current evidence and future prospects	*
M. Lattanzi	Cosmic Microwave Background from ground based and space experiments	*
C. Gustavino	BBN, neutrinos and nuclear astrophysics	9
R. Battiston, F. Pilo	AMS Experiment	*
S. Capozziello	Open Problems in Gravitational Physics	17
L. Cacciapuoti	Fundamental physics in the ESA Program	*

Gravitational Waves and Gravity

M. Branchesi	on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration Observational Prospects in the Electromagnetic Domain of Gravitational Wave Sources	25
D. Currie	Precision tests of General Relativity and Gravitation by Lunar Laser Ranging	*
J. Páramos	Cosmological Dynamics of Nonminimal Coupled Theories	33
F. Sorrentino	Fundamental physics with space and ground atomic quantum sensors	*
A. Orlando	Detection of B-mode Polarization using BICEP2	*

Future Prospects

S. N. Zhang	China's Programs of Astroparticle Physics in Space	*
-------------	----------------------------------------------------	---

Dark Matter

P. Ullio	An update on dark matter searches	*
M. Pietroni	Digging out Dark Energy properties from the Large Scale Structure of the Universe	*
D. G. Cerdeño	SuperCDMS: Recent results on low mass WIMPs	
R. Bernabei	New Results from DAMA/LIBRA: Final Model-Independent Results ff Dama/Libra-Phase1 and Perspectives of Phase2	41
V. Gehman on behalf of the LUX collaboration	Direct Search for Dark Matter with Two-Phase XENON Detectors: Current Status of Lux and Plans for LZ	51
M. Messina on behalf of the XENON collaboration	Recent results from the XENON100 experiment and future goals of the XENON project	59
A. Albert on Behalf of the Fermi-LAT Collaboration	Search for Gamma-Ray Spectral Lines with the Fermi Large Area Telescope and Status of the 135 GeV Feature	67
R. Scaramella	Euclid space mission: a challenge devoted to the study of Cosmological Dark Energy & Dark Matter	*
German A. Gomez-Vargas	Are we Really Seeing Dark Matter Signals from the Milk Way Center?	76
N. Menci	Warm Dark Matter vs. Cold Dark Matter Scenarios for the Formation of Cosmic Structures	*
J. Siegal-Gaskins	Dark matter signals from the Inner Galaxy?	*
C. Farnier for the CTA Consortium	Searches for dark matter with the Cherenkov Telescope Array	87
A. Pullia	Dark Matter: A new Detector, the Geysler	95

Cosmology and Astroparticle

A. Masiero	LHC: link with cosmology and astroparticle	*
------------	--------------------------------------------	---

Astrophysics and Cosmology

K. Dolag	Formation and Evolution of LSS	*
----------	--------------------------------	---

Particle Physics and Interactions

S. Bertolucci	Higgs bosons in the Standard Model and beyond	*
G. Altarelli	The Higgs and the Excessive Success of the Standard Model	102
Y. Mambrini	Dark Z' : from direct detection to LHC	*
R. Engel	LHC results and the interpretation of cosmic ray data	*
R. Ulrich	Hadronic Cross Sections in UHECR Air Showers and Accelerator Measurements	122
C. Brogini	LUNA: From Sun to Novae and Beyond	128
J. P. Harding	The TeV Cosmic-Ray Anisotropy from Local Dark Matter Annihilation	*
S. Ragazzi	Astroparticle Physics at LNGS	*
A. Tricomi	Astroparticle Physics with the LHCf Detector at LHC	136

Cosmic Ray origin, Gamma and Neutrino Astronomy

G. Sinnis	Ground-Based Gamma-Ray Astronomy	*
M. Miceli	SNRs as Cosmic Accelerators	144
J. Knödlseeder	Cherenkov Telescope Array: Science prospects and project status	*
C. Pittori	Crab observations with AGILE	*
F. Longo on behalf of the Fermi /LAT Collaboration	Observations of Gamma-ray Bursts with the Fermi Large Area Telescope	152
E. Troja	GRBs in the multimessenger era	*
J. Cortina for the MAGIC collaboration	The Magic Legacy to Next Generation of Iacts: Results, Recent Highlights and Prospects	159
S. Buson	Flaring Gamma-Ray AGNs	167
S.N. Zhang	Correlation analysis between sky maps of Tibet cosmic rays and microwave observed with WMAP and Planck	*

Neutrinos

F. Gatti	Detection technique for neutrinos and high energy astrophysics	*
G. Golup	Latest Results from the IceCube Neutrino Telescope	173

A. Capone	High-Energy Neutrino Astronomy with the ANTARES Deep-Sea Cherenkov detector and with the future KM3NeT Telescope	*
L.F.F. Stokes	Double Chooz: Towards the near detector phase	*
C. Sirignano	The OPERA experiment: new results	*
C. Giunti	Status of Neutrino Oscillations and Sterile Neutrinos	181
A.A Petruhin	Are the IceCube Neutrino Events Extraterrestrial or can be of Atmospheric Origin?	189

Cosmic Rays

R. Sparvoli	Direct measurements of cosmic rays in space	*
E. Mocchiutti	Results from the PAMELA Space Experiment	197
R. Aloisio	Spectra of Astrophysical Particles at Ultra High Energy and the Auger Data	205
G. Di Sciascio	Measurement of the Cosmic Ray Energy Spectrum with ARGO-YBJ	215
Z. Cao	The knee of the proton spectrum at 630 TeV	227
P. Desiati	High energy cosmic ray anisotropy	*
A. Haungs on behalf of the KASCADE-Grande Collaboration	The heavy knee and the light ankle observed with KASCADE-Grande	238
P. Sokolsky	Recent Results from the Telescope Array Experiment	*
A. Castellina for the Pierre Auger Collaboration	The Pierre Auger Observatory: Results, Open Questions and Future Prospects	247
R. Bonino	Large Scale Distribution of Arrival Directions of Cosmic Rays Detected at the Pierre Auger Observatory Above 10 PeV	255
D. Fargion	UHECR and GRB Neutrinos: an Incomplete Revolution?	263
A. Grillo	Are Cosmic Rays Still a Valuable Probe of Lorentz Invariance Violations in the Auger Era?	274
F. Pilo for the AMS-02 ECAL Group	High-Energy Gamma Rays detection with the AMS-02 electromagnetic calorimeter	284
M. Marisaldi	High-Energy Atmospheric Physics and Terrestrial Gamma-Ray Flashes	292

V. Bonvicini on behalf of the GAMMA-400 collaboration		
	The GAMMA-400 Mission	300
P. Maestro for the CALET collaboration		
	The CALET mission on the International Space Station	307
R. Krause	AERA - The Auger Engineering Radio Array	315
Future Projects		
G. Matt	The Hot and Energetic Universe with Athena	323
C. Zhen	LHAASO: Science and Status	331
C. Zhen	Future reactor neutrino experiments in China	*
F. Ferroni	Future in Astroparticle at INFN	*
S. Katsanevas	Astroparticle in Europe	*
A. Santangelo	JEM-EUSO	*
E. Coccia	The quest of gravitational waves: a global strategy	*

* Slides are available at <https://agenda.infn.it/conferenceOtherViews.py?view=nicecompact&confId=7266>

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OBSERVATIONAL PROSPECTS IN THE ELECTROMAGNETIC DOMAIN OF GRAVITATIONAL WAVE SOURCES

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Abstract

A new exciting frontier of observational astronomy will soon start to be explored: the current upgrade of gravitational wave ground-based detectors, LIGO and Virgo, should make possible to observe gravitational wave signals for the first time. Expected sources of gravitational waves include the most energetic astrophysical events such as the merger of neutron stars and/or black holes and the core collapse of massive stars. These events are believed to produce electromagnetic transients, like gamma-ray bursts and supernovae. The simultaneous use of electromagnetic facilities and gravitational-wave detectors will give the unique opportunity to catch the electromagnetic signatures of gravitational wave sources and to observe the same source with different messengers (GW and photons). The paper outlines the challenges, opportunities and strategies to develop and carry on multi-messenger searches.

1 Introduction

In the next decade the new generation of ground-based gravitational wave detectors, the advanced LIGO ¹⁾ and advanced Virgo interferometers ^{2, 3)}, will come on-line and will observe the sky as a network with the aim to directly detect for the first time gravitational wave (GW) signals. Detectable astrophysical sources can be divided into two classes on the basis of their emitted signals: transient and continuous sources. The former emit signals with a duration in the detection band significantly shorter than the observation time and which cannot be re-observed, the latter emit quasi-periodic waves whose frequency changes slowly. Transient GW signals are expected to be emitted from the coalescence of binary systems of compact objects (COs), neutron stars (NS) and/or stellar mass BHs ^{4, 5)} and core-collapse of massive stars ⁶⁾. Continuous GW signals are expected from spinning NSs if they are not perfectly symmetric around their rotation axis.

The initial LIGO and Virgo observations have not detected gravitational-wave signals, but they have estimated upper limits on the source rate and on GW emission amplitude. The search for GWs from compact binary coalescence with total mass between 2 and 25 solar masses, for example, have given cumulative rate upper limits of the binary coalescence of binary neutron star, neutron star- black hole and binary black hole systems of 1.3×10^{-4} , 3.1×10^{-5} and $6.4 \times 10^{-6} \text{Mpc}^{-3} \text{yr}^{-1}$, respectively ⁷⁾. These rates are two to three orders of magnitude above the astrophysically predicted ones. The detection probability will dramatically improve with the advanced detectors which will provide a factor of ten increase in sensitivity over the initial detectors, corresponding to a factor of thousand increase in the number of detectable sources. Tens of binary coalescence per year are expected to be observable ⁸⁾.

GW searches for 195 known targeted pulsars ⁹⁾ with initial LIGO and Virgo made it possible to place upper limits on the rotational energy loss due to the emission of GWs, and thus on the NS ellipticity. For the Crab and Vela pulsars, the results constrain the fraction of rotational energy loss to less than about 1% and 10%, respectively, of their spin-down luminosities.

The advanced GW detectors are expected to come on-line in 2015 ¹⁰⁾. Their sensitivity should make it possible to observe GW signals by opening a new window in the (astro)physical study of gravitational collapse, explosion mechanisms, and ultra-dense matter stellar structure. The simultaneous availability of sensitive GW detectors and ground-based and space electromagnetic

(EM) observatories will allow scientists to use powerful multi-messengers, GWs and photons, to probe the most energetic events in the Universe.

2 Electromagnetic Emission from Gravitational Wave Sources

The discovery of the EM counterpart of a GW signal will be a key ingredient to characterize the astrophysical source and maximize the science return of GW observations. It would increase the confidence in the astrophysical origin of the GW signal. It would give a precise localization and potentially lead to the identification of the host galaxy. GW and EM radiations will provide complementary insight into the progenitor (mass, spin, distance, etc.) and the environment physics (temperature, density, redshift), giving a complete picture to understand the engines that power the double-messenger emission, e.g. ^{12, 11}). The GW/EM observations compared with theoretical models will shed light on a plethora of open questions including the birth and evolution of CO and the Equation of State of matter at extreme densities in the stellar crust and interiors of NS.

The merger of NS-NS or NS-BH, and the core collapse of massive stars are expected to produce the gamma ray bursts (GRBs) and supernovae (SN). GRBs release a huge amount of energy (up to 10^{53} erg isotropic-equivalent energy ¹³) within a few seconds that results in a hot, highly relativistic fireball, which undergoes internal dissipation and leads to gamma-ray prompt beamed emission. The fireball evolves later into a blast wave as it decelerates against the external medium, producing an afterglow emission ¹⁴) visible in X-rays, optical, radio, and in some cases gamma rays. The afterglow emission can last minutes, hours, months after the prompt emission and it can be observed over a wider viewing angle. According to the traditional classification schemes GRBs are divided into long GRBs and short GRBs on the basis of the prompt emission duration. While for the long GRBs, SN emission in the same location of the GRB strongly support the core-collapse of massive star as progenitor ¹⁵), for the short GRBs there are some observational evidences that indicate the NS-NS and NS-BH merger as possible progenitor. Their association with older stellar populations and the larger distance to the host galaxy centers compared to long-GRBs are in good agreement with predictions for the binary NS system distribution, see ¹⁶).

The merger of COs is also expected to emit ¹⁷), an isotropic optical/infrared thermal short-lived emission, called “kilonova”, powered by the

radioactive decay of heavy elements synthesized through rapid neutron capture in the sub-relativistic merger ejecta (18, 19, 20). The Hubble Space Telescope follow-up of the short GRB130603B showed the first observational tentative evidence of kilonova emission (21) by observing, 9 days after the prompt emission, an excess in the near-infrared consistent with kilonova predictions.

The NS-NS (NS-BH) mergers are expected to be detectable by the advanced detector network up to the range (location- and system orientation-averaged distance) of 200 Mpc (400 Mpc) with corresponding likely rate of 40yr^{-1} (10 yr^{-1}) (8). The core-collapse of massive stars, due to the small energy emitted in GWs, are expected to be detectable within our Galaxy (6), and out to larger distances of 1 Mpc to tens of Mpc in more optimistic scenarios e.g. (22, 23).

The most promising EM counterpart emission is expected to be associated with NS-NS and NS-BH merger. Figure 1 shows the optical emissions expected for a source at a distance of 200 Mpc. The solid lines represent the brightest and faintest on-axis (whose narrow relativistic jet points towards the observer) short GRB observed afterglows (24). The afterglow brightness decays rapidly as a power law $t^{-\alpha}$ with α in the range 1 to 1.5 (13). The small-dashed lines represent the synthetic off-axis afterglows of GRBs (25) with energy jet of 10^{50}erg , jet angle of 0.2, observer angle of 0.4, and a uniform interstellar medium density of 10^{-3}cm^{-3} (bottom line) and 1cm^{-3} (top line). The dashed lines represent three different models of kilonova emission. The Piran et al. (2013) kilonova is a bolometric light curve obtained for a BH-NS merger with NS mass of $1.4M_{\odot}$, BH mass of $10M_{\odot}$, and iron opacity. The curve represents an upper-limit to the true R-band luminosity since it assumes that all of the bolometric luminosity is emitted in the R-band. The Metzger et al. (2010) kilonova is a blackbody emission for an ejecta mass of 10^{-2} solar mass, and iron opacity. The Barnes & Kasen (2013) assumes an ejecta with low velocity (0.1 c) and mass (10^{-3} solar mass), and lanthanides opacities.

The above emissions can be detectable with sensitive instruments. Each of them require an adequate plan of observational epochs to detect and follow the light curves (flux vs time). A GW event, which is observable independently of the system orientation, is more likely to be associated with an isotropic kilonova and off-axis GRB signals than an on-axis GRB afterglow. The rate of on-axis GRBs with respect to off-axis depend on the jet beaming angle, whose value is poorly constrained so far (18, 26).

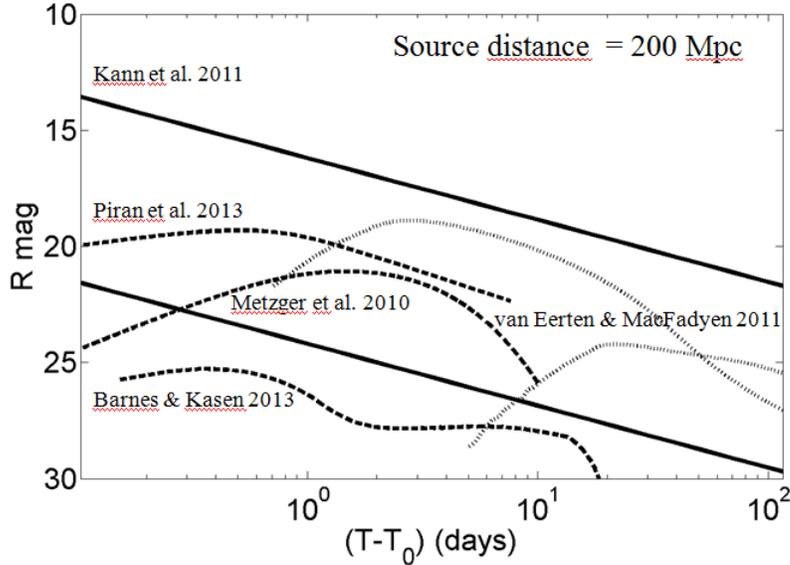


Figure 1: *Optical R-band emission expected from a NS-NS and NS-BH merger at a distance of 200 Mpc. The coalescence of NS-NS and NS-BH is the most promising source of GW transient signals*

3 Multi-messenger searches

On the basis of the emission timescales, two types of searches have been developed to detect the GW and EM signals associated with the same astrophysical source: the “*electromagnetically triggered search*” and the “*electromagnetic follow-up of GW events*”. The former search uses the EM detections to perform the GW analysis, the latter uses the GW candidate events to trigger EM observations.

The most promising analysis able to associate the GW event with the prompt emission of a GRB is the “*electromagnetically triggered search*”, which searches for GW signals in temporal and spatial coincidence with the observed GRBs (27, 28). This search can be used to investigate the nature of a single gamma-ray event, e.g. (29), and also for statistical studies over the GRB population (27, 28).

Vice versa, a prompt identification of GW candidates will allow astronomers

to organize EM-follow up observations able to detect GRB afterglow, kilonova and supernova emissions. The Virgo and LIGO collaborations (LVC) have developed low-latency GW pipelines to detect compact binary coalescence³⁰⁾ and unmodeled GW bursts. The pipelines generate alerts for significant GW-candidate events and send alerts in low latency. The first EM follow-up program (Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010) was performed during the last LIGO/Virgo science run³¹⁾. The off-line analysis^{32, 33)} of the GW data alone showed no evidence of an astrophysical origin for the GW candidates identified by the low-latency pipelines. All the detected EM transients were consistent with the EM background^{34, 35)}. The 2009-2010 EM follow-up program was a great exercise to point out all the challenges to search for an EM counterpart.

The main challenge is the sky location uncertainty associated with a GW signals. The sky position is mainly evaluated by “triangulation” using the arrival time delay between detector sites and it is of order of several tens to hundreds of square degrees. These sky areas are larger than the field of view of the majority of the EM telescopes. Thus, adequate observational strategies, which use tiling of many telescopes and/or galaxy targeting, need to be developed. Furthermore, in large sky area there are many contaminating transients not associated with the GW event, which need to be removed to detect the EM counterpart.

4 Electromagnetic Follow-up of Gravitational Wave Candidate Events in The Advanced Detector Era

Since the advanced LIGO and Virgo network will continue to consist of three sites (until additional detectors come on-line in Japan and possibly in India, 2022+) the GW events will continue to be typically localized into regions of tens to hundreds of square degrees¹⁰⁾. The detection of relatively faint rapid transients in large sky areas and the identification of a unique counterpart will require hierarchical searches: 1) sensitive wide-FOV (about 10 sq. degrees) telescopes able to cover the entire GW sky localization area, 2) “Fast and smart” software to rapidly detect and classify transient events, and select a sample of candidate counterparts, 3) larger telescopes and spectroscopic follow-up to characterize the candidates, see e.g.^{34, 36)}.

In 2012 LVC agreed on the policy to share significant GW candidates. “Until the first four GW events have been published, triggers will be shared

promptly only with groups of astronomers who have signed a Memorandum of Understanding (MoU) with LVC”. At the end of 2013 a call for proposals to sign MoUs was opened and it received high participation. Currently about sixty astronomer groups, agencies and astrophysical institutions are involved in the LVC EM follow-up program with about 150 instruments, which will cover the entire accessible EM spectrum and which are distributed worldwide. The call for MoU will be renewed every year. The field of multi-messenger astronomy is ready to enter a new and exciting era.

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