Searching for gamma-ray counterparts to Gravitational Waves from merging binary neutron stars with the Cherenkov Telescope Array

Barbara Patricelli[1,2]

[1] Università di Pisa & INFN - Sezione di Pisa

[2] INAF - Osservatorio astronomico di Roma

Multi-frequency to Multi-messenger: The new sight of the Universe

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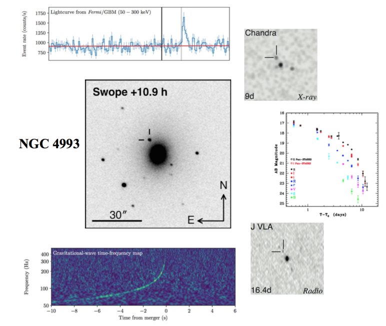
in collaboration with:
A. Stamerra, M. Razzano, E. Pian
and G. Cella

Outline

1. Introduction
2. The method: simulating BNS mergers
   - Simulation of BNSs and their GW emission and detection
   - Simulation of the VHE emission and detection
3. Results
   - GW skymap coverage
   - Joint GW and EM detection rates
4. Conclusions

The era of multi-messenger astronomy with GWs has begun!



GW170817:

- coincident short GRB detected in gamma rays
- an optical/infrared/UV counterpart (the kilonova) has been detected
- An X-ray and a radio counterparts have been identified
- HE ($E > 100$ MeV) and VHE ($E > 20$ GeV): no significant emission has been found

(Abbott et al. 2017 and refs. therein)

Next challenge:

detection of HE and VHE gamma rays associated with GW signals

Do GRBs have GeV-TeV emission?

Before *Fermi*:

limited knowledge about GRB emission above 100 MeV

- A 18 GeV photon was detected by EGRET from the long GRB 940217 (Hurley et al. 1994)
- HE emission (up to 200 MeV) was detected by EGRET from the long GRB 941017 (González et al. 2003)
- A hint of $\sim$ TeV emission was detected by Milagrito (500 GeV-20 TeV) from the long GRB 970417A (Atkins et al. 2000)

with *Fermi*:

- tens of GRBs with high energy emission ($>$ 100 MeV)
- among them, there are a few short GRBs with emission above 1 GeV

Very recently:

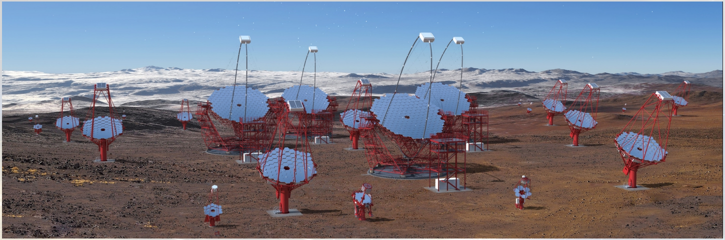
First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
on ***15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

The Cherenkov Telescope Array (CTA)

A ground-based observatory for gamma-ray astronomy at very-high energies



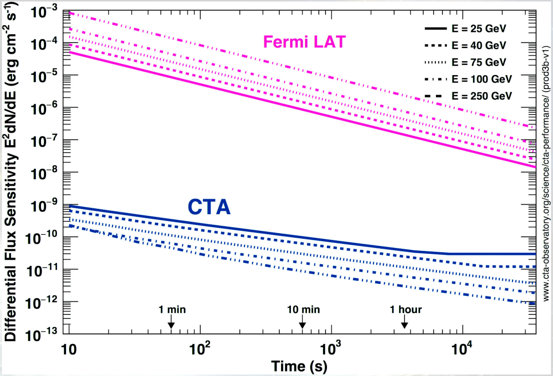
Southern Hemisphere Site Rendering; image credit: G. Perez, SMM, IAC

- two arrays: one in the Northern hemisphere, one in the Southern hemisphere
  $\Rightarrow$ **full-sky coverage**
- CTA baseline array in the North (South):
  - 4 (4) Large Size Telescopes (LSTs); $\sim$ 20 GeV - $\sim$ 200 GeV
  - 15 (25) Medium Size Telescopes (MSTs); $\sim$ 100 GeV - $\sim$ 10 TeV
  - 0 (70) Small Size Telescopes (SSTs); $\sim$ 5 TeV - $\sim$ 300 TeV

  $\Rightarrow$ **wide energy coverage**

Why CTA?

- coincident observational schedule with GW detectors at design sensitivity (CTA completion expected by 2025)
- large field of view (LST: 4.5 deg)
- scan mode
- **Rapid response ($\leq$ 30 s) of LST**
- **Very high sensitivity**



Simulation of BNSs and their GW emission and detection

BNS mergers

- $\rho_{galaxies}$=0.0116 Mpc^{-3} (Kopparapu et al. 2008)
- Maximum distance: 500 Mpc
- Merging systems: Synthetic Universe[1] (Dominik et al. 2012)
- Bimodal distribution in metallicity: half at $Z=Z_\odot$ and half at $Z=0.1 \cdot Z_\odot$ (Panter et al. 2008)
- Merger rate: 830 Gpc^{-3} yr^{-1} (within the range in Abbott et al. 2017)

GW emission and detection

- Non spinning systems; TaylorT4 waveforms (Buonanno et al. 2009)
- Matched filtering technique (Wainstein 1962)
- aLIGO (Aasi et al. 2015) and AdV (Acernese et al. 2015) at design sensitivity
- 80 % independent duty cycle for each interferometer (Abbott et al. 2016)
- Trigger: at least 2 detectors; combined SNR threshold: 12
- GW localization with BAYESTAR (Singer et al. 2014)

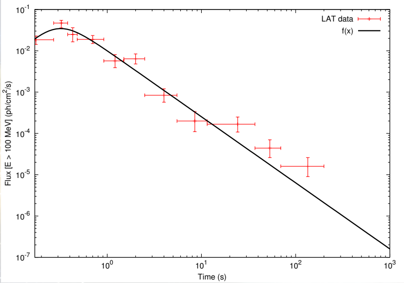
Simulations are available in the public database GW COSMoS

Patricelli et al. 2016,2018

[1] www.syntheticuniverse.org

GRB simulations

- Each BNS merger is associated to a short GRB;
- Only on-axis GRBs are considered; θ_j=10° (Fong et al. 2014);
- **GRB 090510** as a prototype:



Light curve:

$$F(\mathrm{t}) = \mathrm{A}\frac{(\mathrm{t}/\mathrm{t_{peak}})^{\alpha}}{1+(\mathrm{t}/\mathrm{t_{peak}})^{\alpha+\omega}}$$

Spectrum:

$$N(E) \propto E^{\beta}, \qquad \beta = -2.1$$

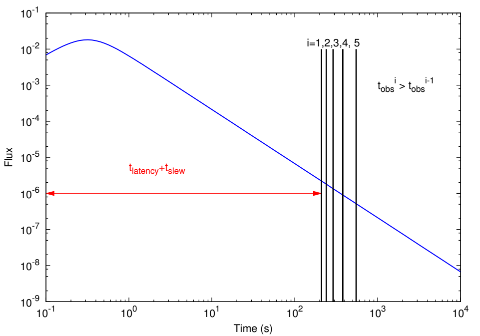
(De Pasquale et al. 2010)

- We corrected $F(\mathrm{t})$ to take into account the different distance of the sources;
- We re-scaled $F(\mathrm{t})$ considering the following range of isotropic energy: 10^{49} ergs $\leq E_\gamma \leq 3.5\times10^{52}$ ergs (Ghirlanda et al. 2010, Fong et al. 2015)
- We extrapolate the flux to higher energies assuming a power-law with exponential cut-off spectrum: E_c=30 GeV, 100 GeV

Proposed strategy

Step 1:

We estimate the observing time t^i_{obs} needed for the simulated GRBs to have a fluence equal to the CTA sensitivity, considering a set of consecutive pointings



$$t^i_{start} = (t_{slew} + t_{latency}) + t^{i-1}_{obs}$$
$$t^i_{stop} = t^i_{start} + t^i_{obs}$$
$$i = 1, \ldots, n_p$$

⇒ This will tell us the maximum number of observations n_p that we can do and the observing time of each observation

Proposed strategy

Step 2

We construct a 2D grid of CTA pointings:

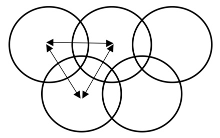
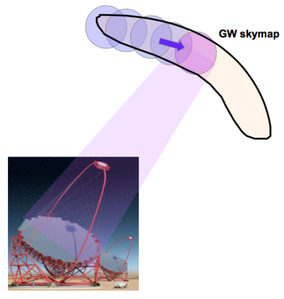


Image credit: Dubus et al. 2013

- multiple evenly-spaced row of pointings
- Angular step: 2°
  (maximum step that provides nearly uniform sensitivity coverage, see Dubus et al. 2013)

Step 3

We do the intersection between the GW skymap and the 2D grid of pointings, taking into account n_p



⇒ percentage of the GW skymap that can be covered with n_p observations

GRB simulations at VHE

Observation time:

- We considered a latency to send the GW alert t_l=3 minutes
- We considered a slewing time t_{slew}=30 s (LSTs)

Sensitivity:

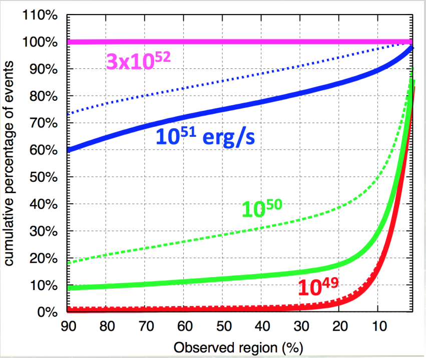
- We estimated the sensitivity with the function *cssens* of `ctools`[2] (Knödlseder et al. 2016)
- We used the instrument response functions (IRFs)[3] "North_0.5h" and "South_0.5h" (zenith angle=20 deg)
- We considered a 5 σ (post-trials) detection threshold

CTA Duty cycle:

- We assumed a conservative duty cycle of $\sim$ 10 %

[2] http://cta.irap.omp.eu/ctools/; in this work we used the `ctools` version 1.4.0
[3] `https://www.cta-observatory.org/science/cta-performance/`

Results: GW skymap coverage with CTA pointings



E_{iso} (ergs)		cut-off (GeV)	% of events Obs. region =90 %	% of events Obs. region ≥ 50 %
10^{49}	—	30	< 1	< 1
	- -	100	1.5	1.9
10^{50}	—	30	8.8	12.2
	- -	100	18.0	28.8
10^{51}	—	30	59.7	74.5
	- -	100	73.0	85.1
3.5×10^{52}	—	30	99.9	100
	- -	100	99.9	100

Patricelli et al. 2018, JCAP, 5, 56

Results: joint GW and EM detection rates

E_{iso} (ergs)	cut-off (GeV)	EM and GW (yr^{-1})
10^{49}	30	$< 10^{-3}$
	100	< 0.001
10^{50}	30	0.01
	100	0.03
10^{51}	30	0.06
	100	0.07
3.5×10^{52}	30	0.08
	100	0.08

Rates are expected to increase if:

- Higher CTA duty cycle is considered (e.g., observations during moonlight): **factor $\sim$ 2**
- Higher BNS merger rates are considered (see Abbott et al. 2017): **factor $\sim$ 6**

$\Downarrow$

For most energetic events up to **1 event per year!**

- Higher θ_j is assumed
- Off-axis GRBs are included

Patricelli et al. 2018, JCAP, 5, 56

Conclusions

Summary:

- We presented a comprehensive study on the prospects for joint GW and VHE EM observations of BNSs with CTA
- We proposed an observational strategy that combines the maximum coverage of the GW skymaps and the maximum probability of EM detection
- We estimated the expected joint GW and VHE EM detection rates, that go from 0.08 up to 1 event per year for the most energetic GRBs
- The observational strategy proposed can be generalized to other telescopes and/or other EM emission models

Backup slides

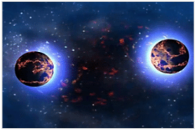
Backup slides

GW CoSMOS

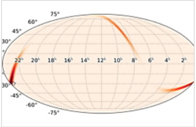
GW COSMoS: Gravitational Wave COmpact binary SysteM Simulations

+ Follow   Published on 05 Oct 2018 - 17:01 by Barbara Patricelli

GW COSMoS is a public database of simulated merging compact binary systems, together with the associated Gravitational Wave (GW) detection and sky localization with Advanced LIGO and Advanced Virgo at design sensitivity.



BNS simulations - ascii table
Barbara Patricelli 05/10/2018



Skymaps - TAR archives of fits and png files
Barbara Patricelli 05/10/2018

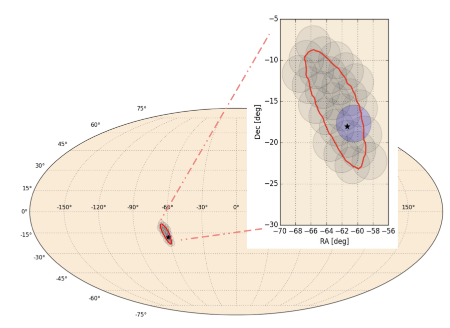
Python scripts
Barbara Patricelli 05/10/2018

https://doi.org/10.6084/m9.figshare.c.4243595

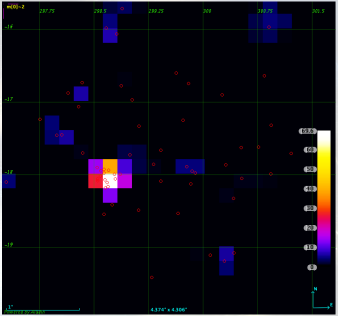
Test case

- SNR=18; 90 % credible region $\sim$ 56 deg^2
- $E_{ISO} = 10^{51}$ ergs; $E_{cut-off}$=100 GeV

GW skymap and CTA tilings



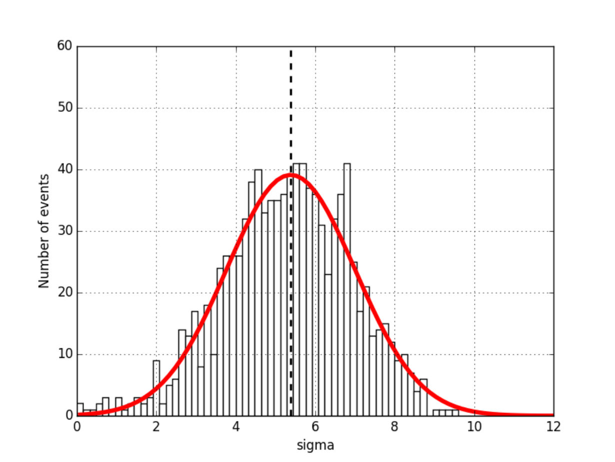
Event and Significance (TS) Map



Patricelli et al. 2018, JCAP, 5, 56

Post-trial significance distribution

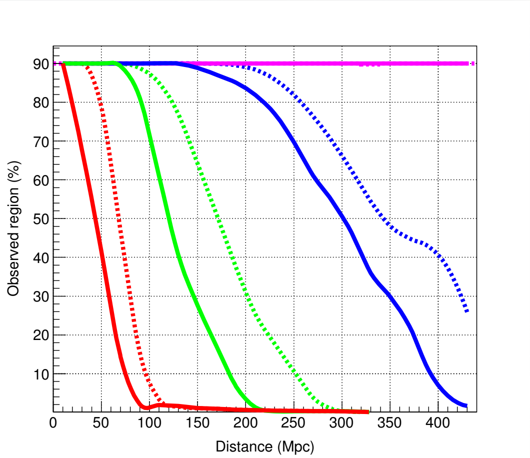
To estimate the statistical uncertainties, we simulated 1000 times the same event with `ctools`



Patricelli et al. 2018, JCAP, 5, 56

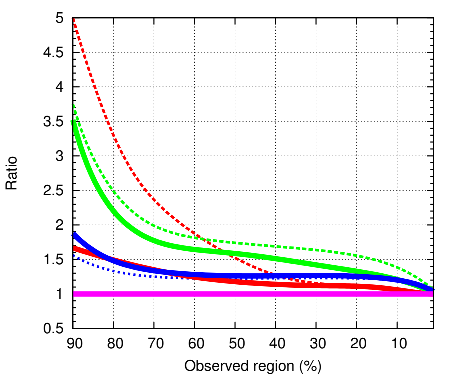
CTA coverage vs Distance

The distance of the source possibly provided in the GW alert can be used to further optimize the observational strategy



Patricelli et al. 2018, JCAP, 5, 56

Improvement with respect to “standard” strategies (constant obs time)



Improvement in the GW sky coverage

⇓

increase in the joint GW and EM detection rates!

example:

- - $E_{iso}=10^{50}$ ergs, cut-off=100 GeV

the rate increase by a factor $\sim$ 2

Patricelli et al. 2018, JCAP, 5, 56