From the first GW detections to multi-messenger observations including CTA: insight and prospects

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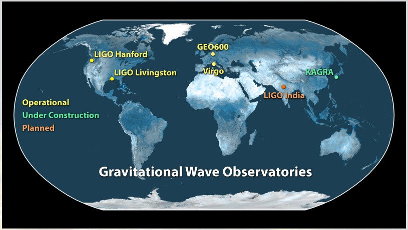
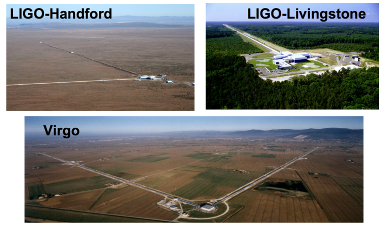
Irfu - CEA/Saclay
February 4, 2019

Outline

The first observing runs of Advanced LIGO and Advanced Virgo



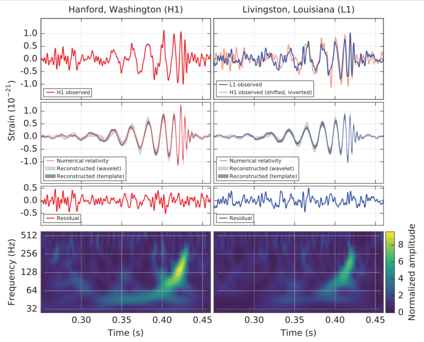


Credit: LIGO-Virgo

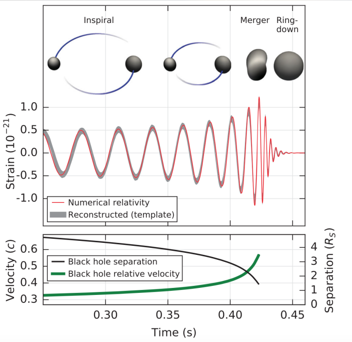
- *O1: September 2015 - January 2016*
  Only the two LIGO detectors were operating
- *O2: November 2016 - August 2017*
  Virgo joined the network on August 1

GW150914: The first observation of GWs

The observation



The model



Abbott et al. 2016, PRL, 116, 061102

The BBH detections

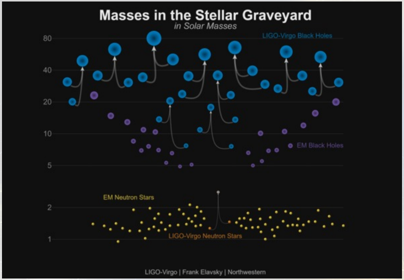
A new population of stellar mass BBH systems has been observed!

O1

GW150914, GW151012, GW151226

O2

GW170104, GW170608, GW170729, GW170809, GW170814, GW170818, GW170823



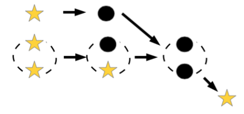
- First direct evidences for "heavy" stellar mass BHs (> 25 $M_\odot$)
- Heavy stellar mass BBHs most likely formed in low-metallicity environment (≤ 0.5 $Z_\odot$)
- BBH merger rate: 9 - 101 Gpc^{-3} yr^{-1}

Abbott et al. 2016, ApJL, 818, 22
Abbott et al. 2017, PRL 118, 221101
Abbott et al. 2018, arXiv:1811.12907

How do BHs form binary systems?

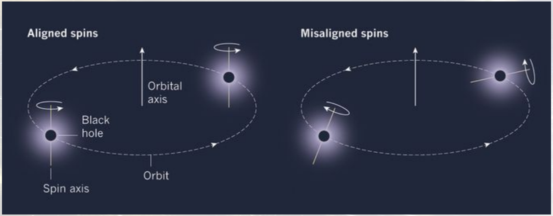
Isolated binary in galactic fields

Dynamical interactions in clusters



How can we discriminate between these two formation mechanisms?

$\rightarrow$ Spin!



Isolated binary:

Spins preferentially aligned with the binary orbital angular momentum

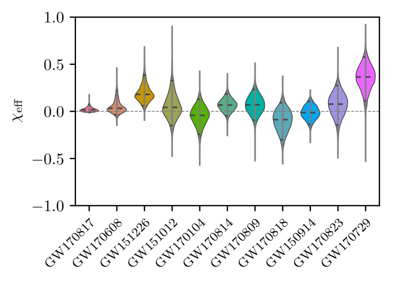
Cluster binary:

Isotropic spin orientations

Spin estimate with GWs

The effective orbital spin

$$\chi_{eff} = \frac{c}{GM}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m2}\right)\hat{\mathbf{L}}$$

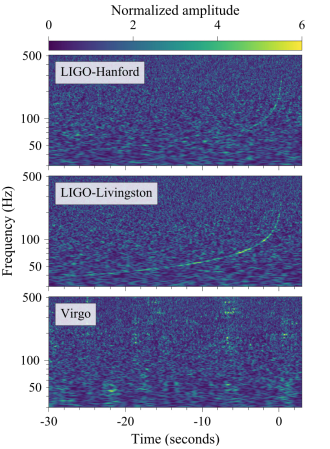


Abbott et al. 2018, arXiv:1811.12907

- Scenarios in which most BHs merge with large spins aligned with the binary's orbital angular momentum are disfavoured.
- With more detections it will be possible to determine if the BH spin is preferentially aligned or isotropically distributed.

GW170817

On August 17, 2017 at 12:41:04 UTC Advanced LIGO and Advanced Virgo made their **first observation of a binary neutron star (BNS) inspiral!**



- GW170817 swept through the detectors' sensitive band for $\sim$ 100 s ($f_{start} = 24$ Hz)
- The SNR is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal yet observed!

Abbott et al., PRL, 119, 161101 (2017)

BNS detection: component masses

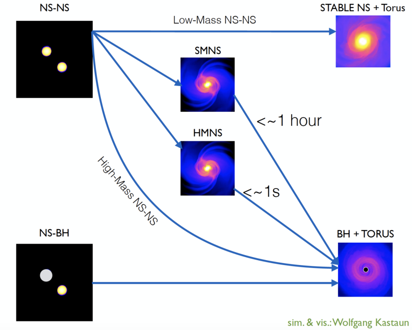
	low-spin ($|\chi| \leq 0.05$)	high-spin ($|\chi| \leq 0.89$)
m_1	1.36 - 1.60 $M_\odot$	1.36 - 1.89 $M_\odot$
m_2	1.16 - 1.36 $M_\odot$	1.00 - 1.36 $M_\odot$
M_{chirp}	$1.186^{+0.001}_{-0.001}$ $M_\odot$	$1.186^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.73^{+0.04}_{-0.01}$ $M_\odot$	$2.77^{+0.22}_{-0.05}$ $M_\odot$

Estimated masses (m_1 and m_2) within the range of known NS masses and below those of known BHs $\Rightarrow$ this suggests the source was composed of two NSs

Abbott et al., PRX, 9, 011001 (2019)

BNS detection: the compact remnant

The outcome of a BNS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state of nuclear matter.

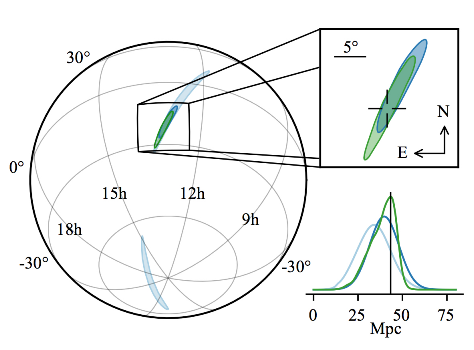


- Stable NS (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s (burst-like GW signal)
- BH prompt formation (high frequency quasi normal mode ringdown GW signal)

Searches for short (<1 s) and medium (< 500 s) duration transients have not found any post-merger signals (Abbott et al. 2017, ApJL, 851, 16).

Searches for long-duration signals have not found any significant signal candidate (Abbott et al. 2018, arXiv: 1810.02581)

Where did the BNS merger occur?



Sky localization:

- rapid loc., HL: 190 deg^2
- rapid loc., HLV: 31 deg^2
- final loc.*, HLV: 28 deg^2

Luminosity distance:

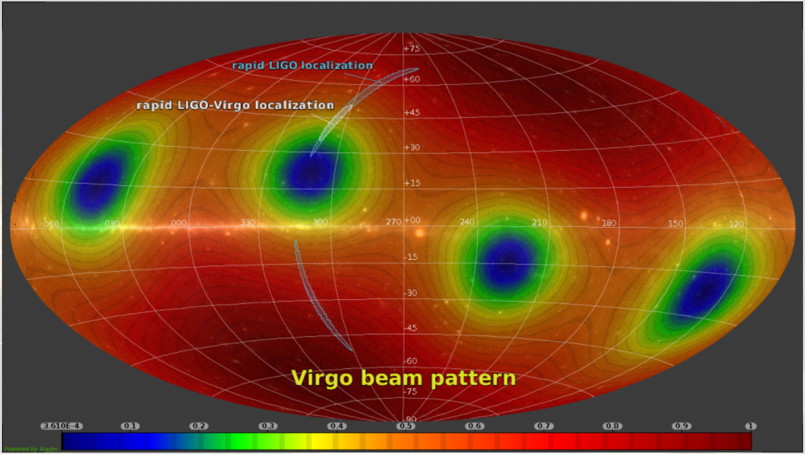
40^{+8}_{-14} Mpc

This is the closest and most precisely localized gravitational-wave signal!

Abbott et al., PRL, 119, 161101 (2017)

* More refined analysis allowed to reduce the sky localization to 16 deg^2
Abbott et al., PRX, 9, 011001 (2019)

The role of Virgo in the sky localization



Credits: G. Greco, N. Arnaud, M. Branchesi, A. Vicere

The role of Virgo in the sky localization

Credit: L. Singer

Which were the expected EM counterparts?

- Short GRBs:
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

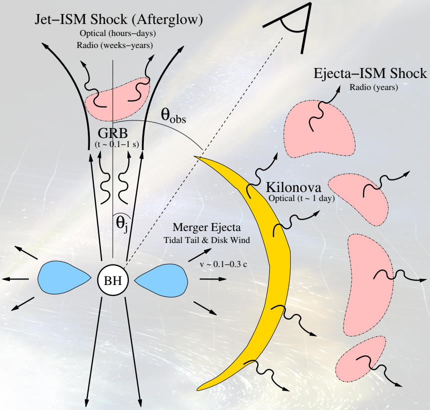
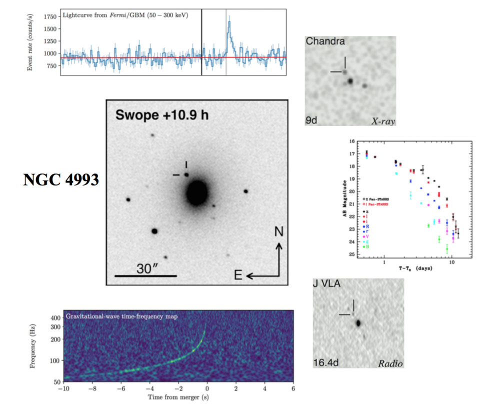


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

What did we observe?



- coincident short GRBs detected in gamma rays

  ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**

- the **host galaxy** has been identified: NGC 4993

- an optical/infrared/UV counterpart has been detected

  ⇒ first spectroscopic **identification of a kilonova**

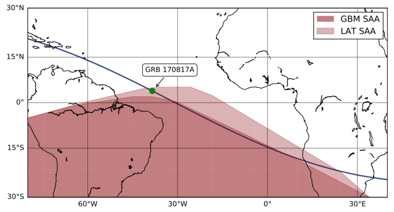
- An X-ray and a radio counterparts have been identified

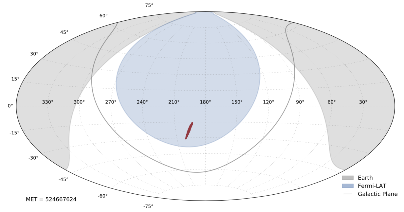
  ⇒ possibly off-axis afterglow from a structured jet

Abbott et al., ApJ Letters, 848, 2 (2017)
Pian et al., Nature, 551, 67 (2017)

What's missing?

- *Fermi*-LAT was entering the SAA at the time of the GW trigger
- Later, no significant EM counterpart at HE (E > 100 MeV) was detected by the LAT on timescales of minutes, hours, or days after the GW detection.

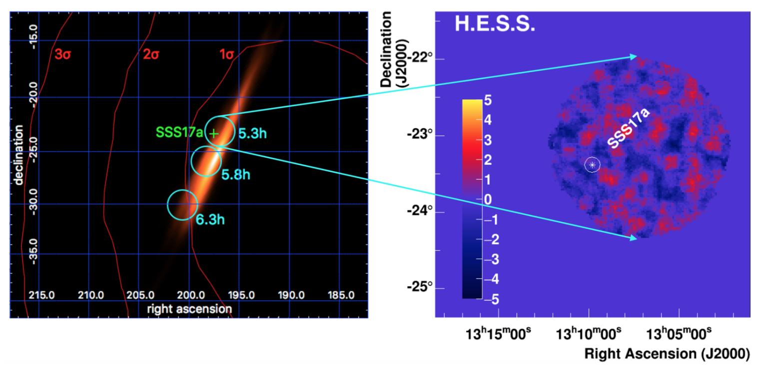




Fermi-LAT collaboration, ApJ, 861, 85 (2018)

What's missing?

- H.E.S.S. started the observations 5.3h after the GW trigger
  ⇒ it was the first ground-based instrument to observe the sky region containing the source)
- No significant VHE (E > 100 GeV) gamma-ray emission has been found



Abdalla et al. 2017, ApJ, 850, 22

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. 94)
- 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 are short GRBs with emission above 1 GeV

Most 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

What did we learn from HE and VHE observations?

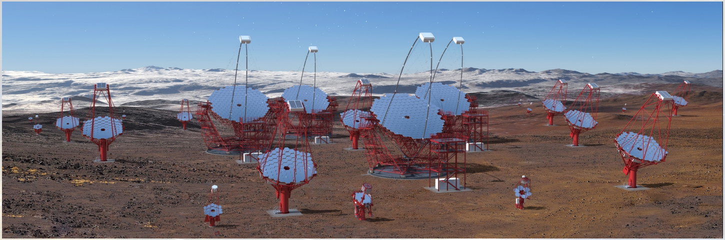
- Both prompt and afterglow emission can have photons with E > 100 MeV
- HE emission can last up to 10^4 s
- HE emission is sometimes consistent with being just the continuation of the spectral component dominating at lower energies...
- But sometimes an additional spectral component is needed

- Emission process: synchrotron? SSC? hadronic processes?
- More observational data will help us to constrain the acceleration and radiation mechanisms.

How can we do better? ⇒ **Higher sensitivity detector is needed!**

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

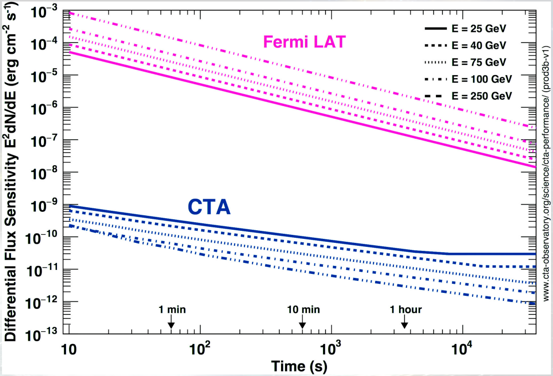
  ⇒ **full-sky coverage**

- 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

  ⇒ **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)
- survey 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

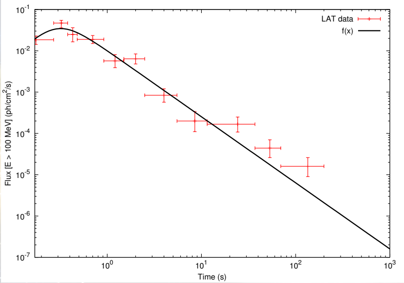
- Non spinning systems; TaylorT4 waveforms (Buonanno et al. 2009)
- Matched filtering technique (Wainstein 1962)
- aLIGO and AdV at design sensitivity, with 80 % independent duty cycle (Abbott et al. 2016)
- Trigger: at least 2 detectors; combined SNR threshold: 12
- GW localization with BAYESTAR (Singer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

Patricelli et al., JCAP 11, 056 (2016)

[1] www.syntheticuniverse.org

GRB simulations

- All BNS mergers are 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:

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

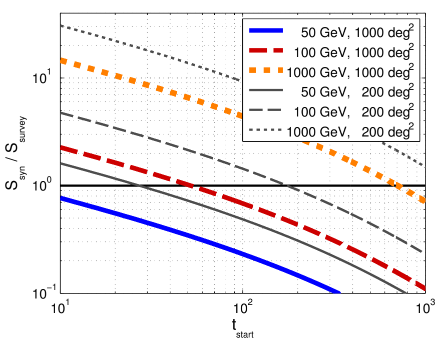
(De Pasquale et al. 2010)

- 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

Several CTA pointings will be needed to cover the GW skymap...

which is the best observational strategy?

Previous investigations



- GRB 090510 as a prototype
- $E_{ISO} = 10^{51}$ erg, D_L = 300 Mpc
- Constant observing time for each pointing
- Total observing time: 1000 s

Joint GW and EM detection rate:

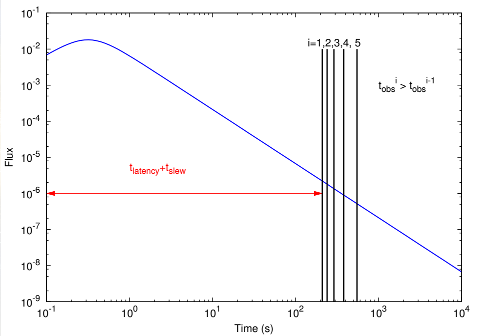
0.03 yr^{-1}

Bartos et al. 2014, MNRAS, 443, 738

A novel approach

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 constructed a 2D grid of CTA pointings:

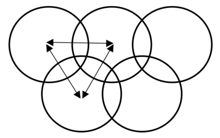


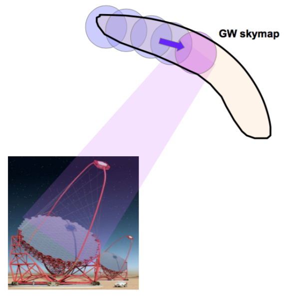
Image credit: Dubus et al. 2013

- multiple evenly-spaced row of pointings
- FoV: 4.5° (LSTs)
- Angular step: 2°

  (maximum step that provides nearly uniform sensitivity coverage, see Dubus et al. 2013)

Step 3

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:

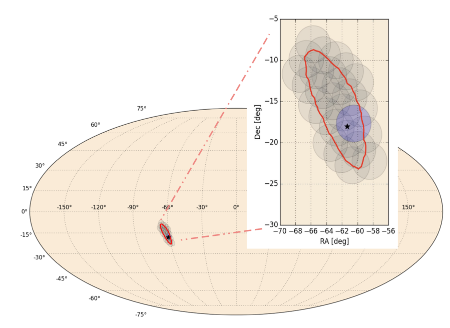
- We assumed a conservative duty cycle of $\sim$ 10 %

[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/`

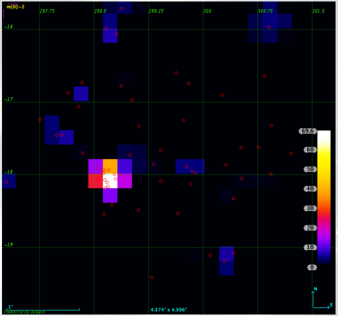
Test case

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

GW skymap and CTA tilings

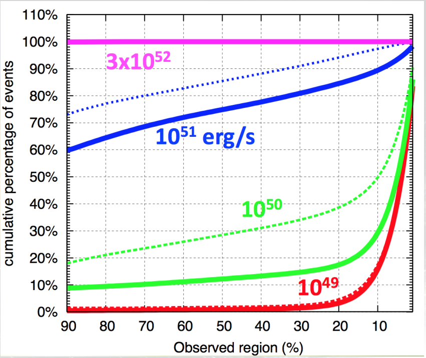


Event and Significance (TS) Map



Patricelli et al. 2018, JCAP, 5, 56

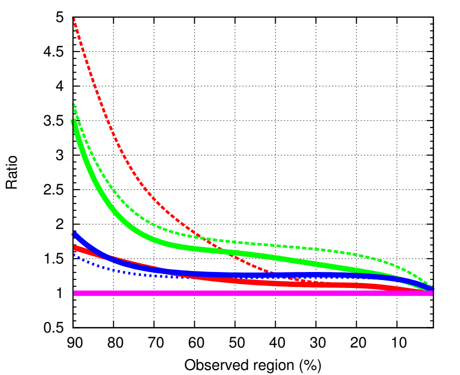
Results: GW skymap coverage with CTA pointings



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

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 ~ 2

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

Future extension of the work

The work in Patricelli et al. 2018 is the starting point for a more extended work within the CTA consortium:

- BNS mergers and associated GW signals:

  Simulations in Patricelli et al. 2016, 2018 ⇒ Now available in the public database GW COSMoS

- VHE emission:

  Extension of the phenomenological model used in Patricelli et al. 2018 (off-axis emission, spectrum with no cut-off, EBL absorption...)

- CTA response

  Sensitivity estimated for different configurations of the arrays and for different zenith angles

- CTA observing strategies:

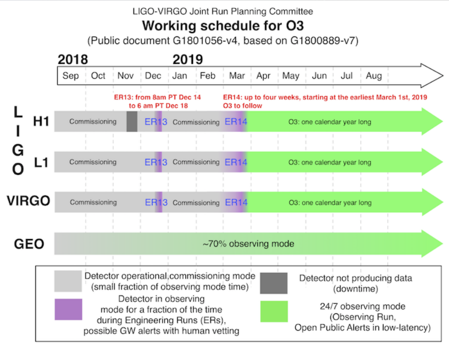
  - galaxy targeted searches
  - Different pointing modes: divergent pointing, single shot ...

Conclusions

- We observed for the first time GWs from merging binary BH and NS systems
- We had the first multi-messenger (GWs+photons) observation of a binary system
- Other sources still to be detected (supernovae, pulsars...)
- CTA will have a key role in the EM follow-up of GWs at VHE

Prospects: towards O3

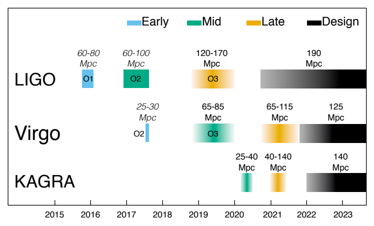
Plans are under way to improve LIGO and Virgo sensitivity for O3 and beyond



LIGO/Virgo will immediately release alerts for transient event candidates

- These alerts will be publicly available through the Gamma-ray Coordinates Network (GCN)
- Event candidates will be publicly available in `https://gracedb.ligo.org`
- There will be no human vetting for the preliminary alert
- The preliminary alert will be followed by an initial alert or a retraction alert

Prospects: towards O3



Abbott et al. 2018, LRR, 21, 3

Expected detection rates during O3:

- *BBHs: few/week to few/month*
- *BNSs: 1/month to 1/year*
- *NS-BHs: uncertain*

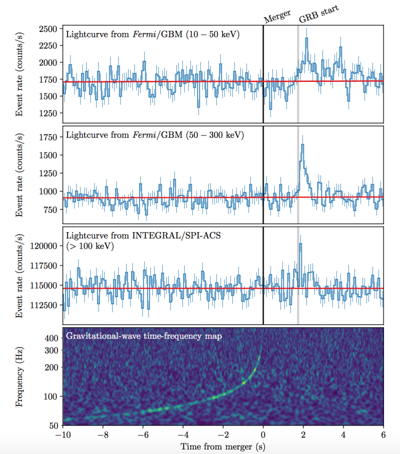
Many other discoveries are expected in the near future...stay tuned!

Backup slides

Backup slides

Constraints on fundamental physics

The observed time delay between GRB170817A and GW170817 (∼1.7 s) can be used to put constraints on fundamental physics:



- **Speed of gravity vs speed of light**

$$-3 \times 10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7 \times 10^{-16}$$

- **Test of Equivalence Principle**
  - Shapiro delay δt_S: time difference travelling in a curved spacetime relative to a flat one
  - Effects of curvature quantified with the parameter $\gamma \rightarrow \delta t_S \propto (1+\gamma)$
  - Weak equivalence principle:

    Shapiro delay affects both GW and EM waves in the same manner ($\gamma_{\rm GW}$=$\gamma_{\rm EM}$)

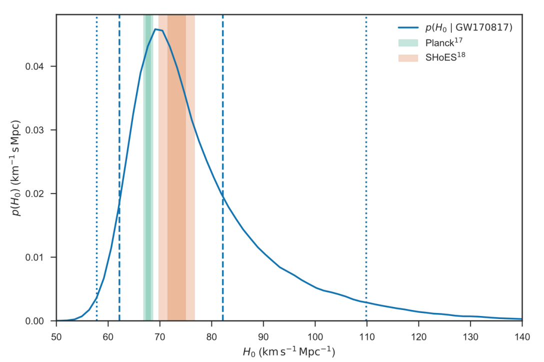
$$-2.6 \times 10^{-7} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 1.2 \times 10^{-6}$$

Abbott et al. 2017, ApJL, 848, 13

Implications for Cosmology

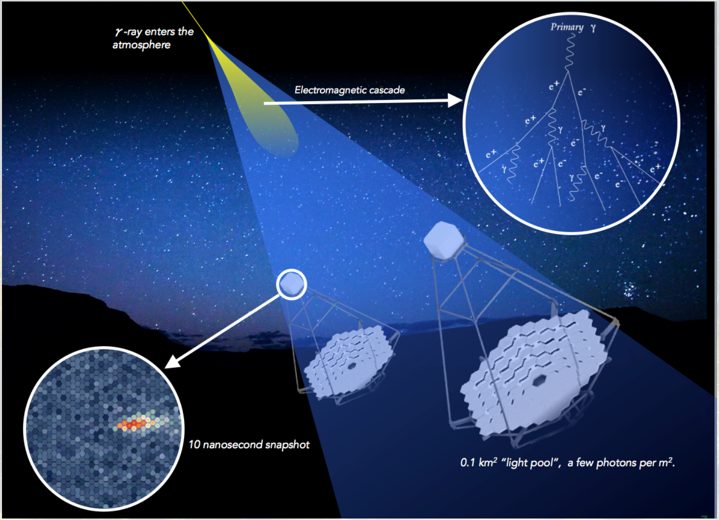
GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**

$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$



Abbott et al., Nature, 551, 85 (2017)

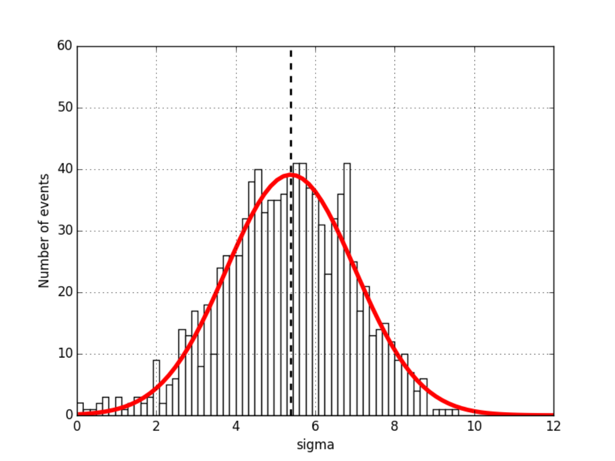
How do Imaging Atmospheric Cherenkov Telescopes work?



https://www.cta-observatory.org

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