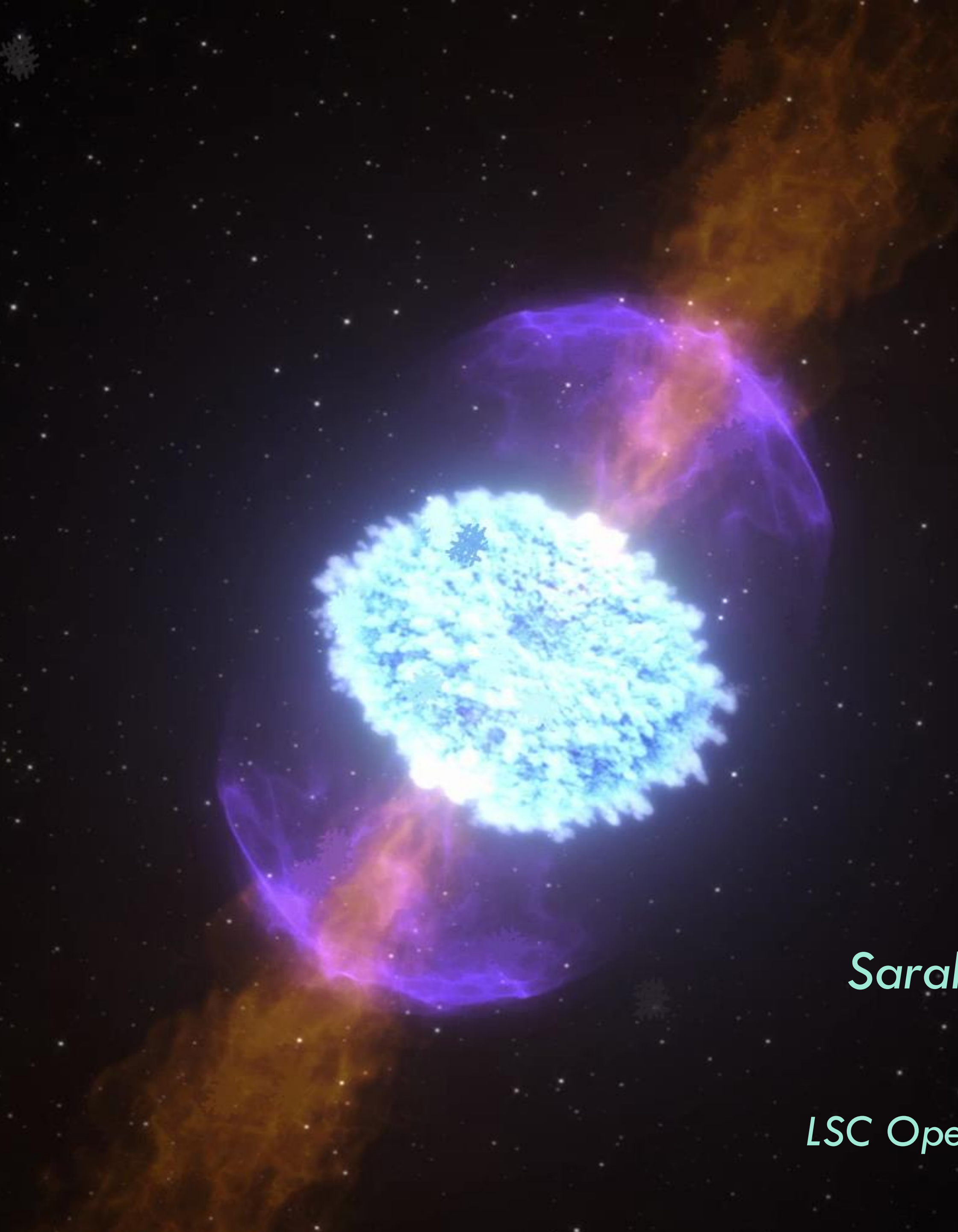


Sky localization and Gravitational waves alerts

Sarah Antier, *CNES*, *APC*, Paris

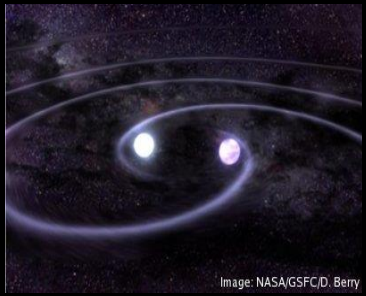
LSC Open Data Workshop – April 9, 2018

Indico.in2p3.fr/e/gw-odw2

What is multi-messenger astronomy ?

Transient phenomena: shortest times scales (milliseconds to several years)

To emit GWs, a source must be compact, relativistic and asymmetric



Merger (NS-NS; NS-BH; BH-BH)

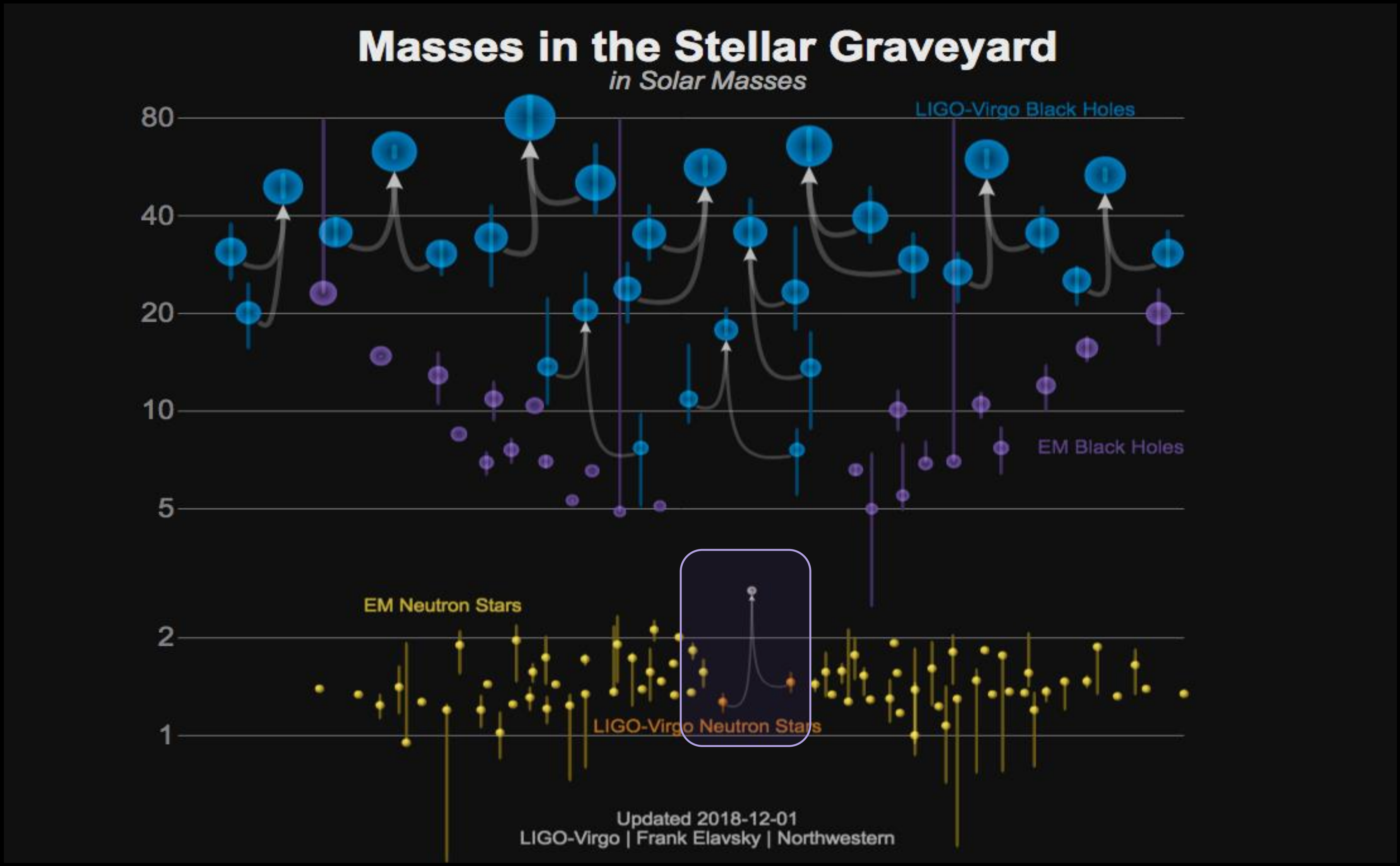
- Short GRBs, Kilonova
- Other cases ? FRB ?

Collapse of a single star

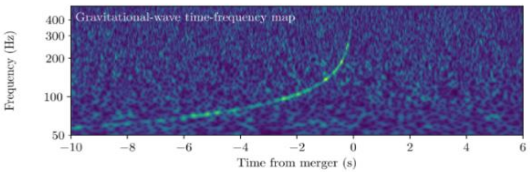
- Type Ib, Ic, II supernovae
- Long GRBs
- Intermediate cases

Neutron star instabilities

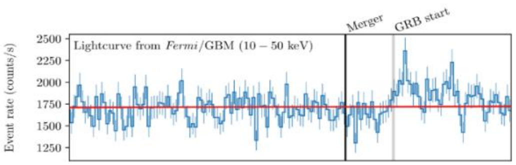
- Soft Gamma-ray repeaters
- Radio/ Gamma-ray pulsar glitches


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

GW170817- a first multi-messenger case

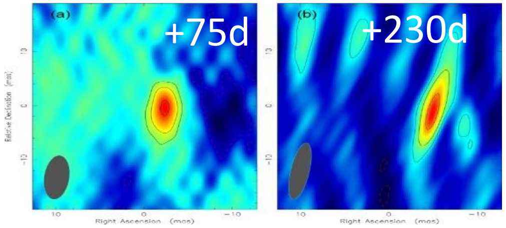


Gravitational wave
Initial system

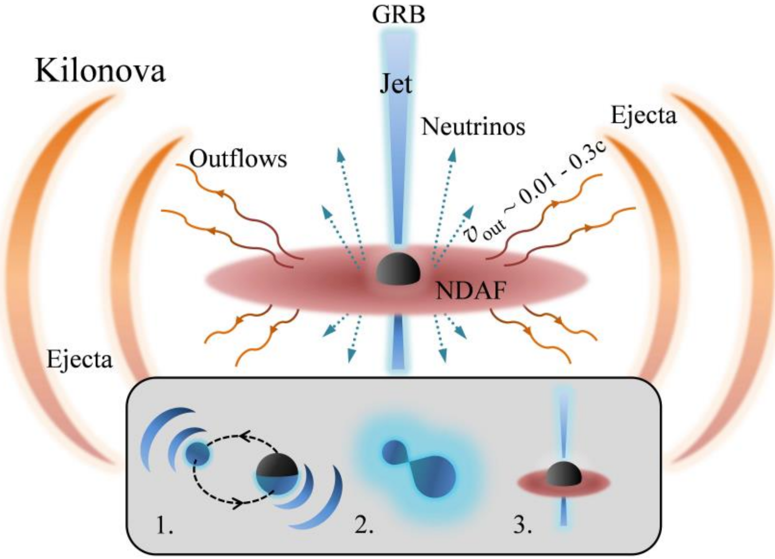


GRB
Jet
Acceleration mechanisms

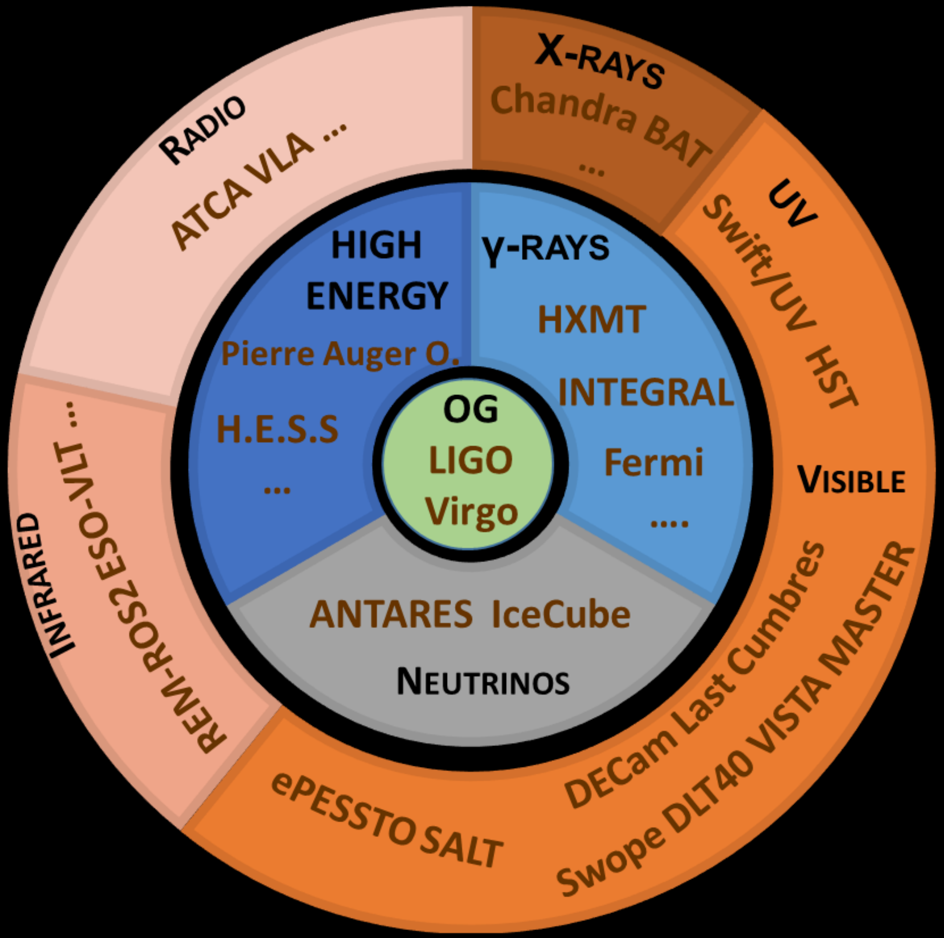
Kilonova
Localization (arcsec)
Host galaxy
Redshift

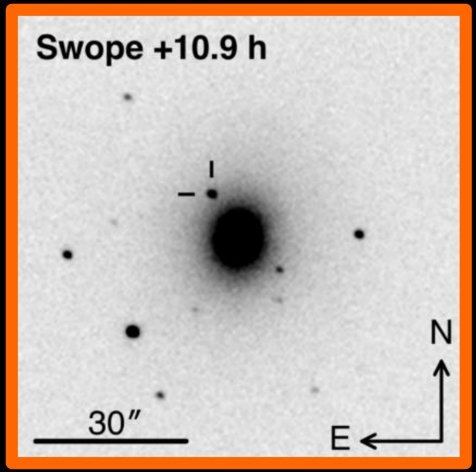


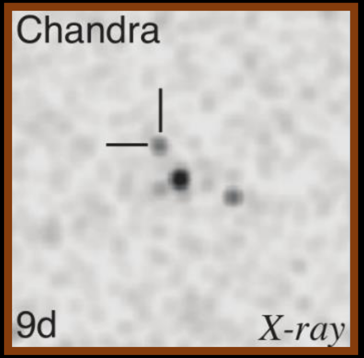
Afterglow
Geometry of the emission

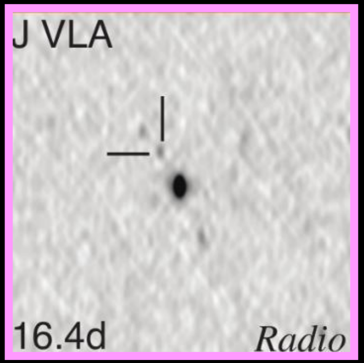


GW170817- Alert sequence









T0 GW detection → +2 s GRB170817A → +5h GW localiz. → +11h Optical counterpart → +11h Host galaxy NGC4993 → +9d X-ray counterpart → +16d Radio counterpart

Science impact of gravitational wave science

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes
Lorentz-invariance, equivalence principle …

Electromagnetic ejecta to GW events

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Populations studies

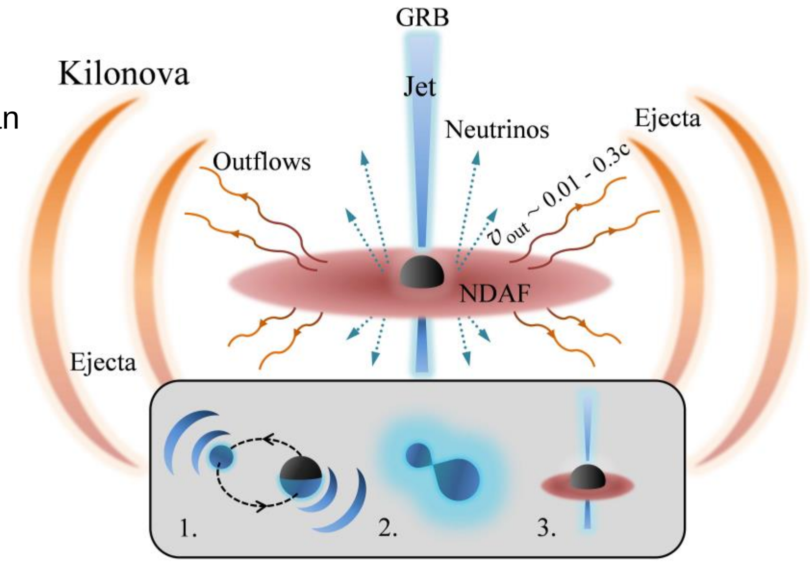
Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies
Gap between NS and BH

Cosmology

Binary neutron stars can be used as standard "sirens"
Dark Matter and Dark Energy, stochastic background

Nuclear physics

Tidal interactions between neutron



Multi-messenger astronomy with LIGO-Virgo

Coïncidence Search

Compare sets of candidates events

Triggered analysis

Search that uses EM or neutrino observations to drive the detection of GWs

GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino

Known event time and sky position

→ reduction in search parameter space for GW searchs

→ gain in search sensitivity

EM Follow-up

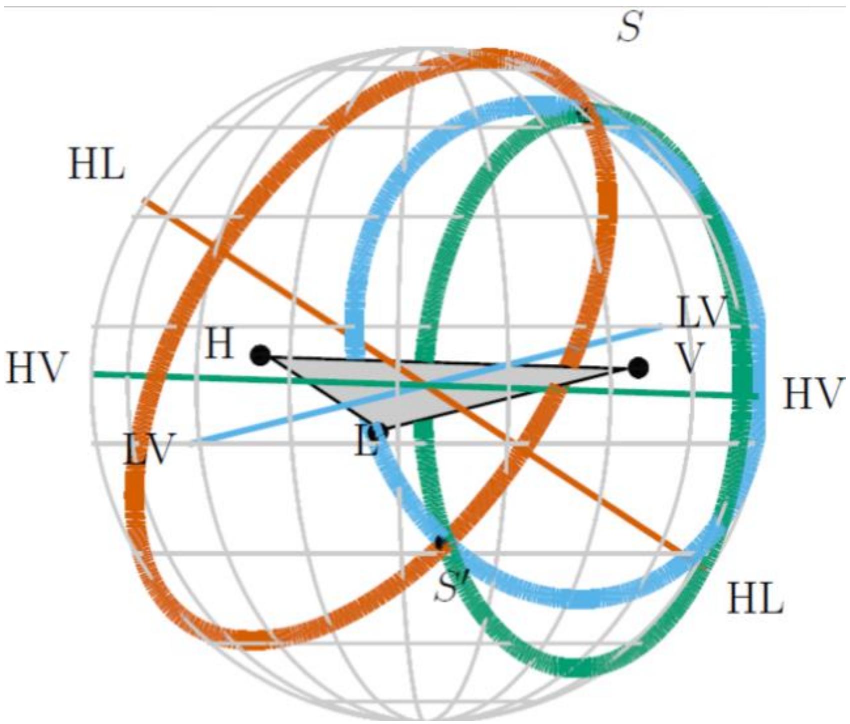
Search EM/neutrino counterpart candidates after GW identification

O2 Electromagnetic campaign

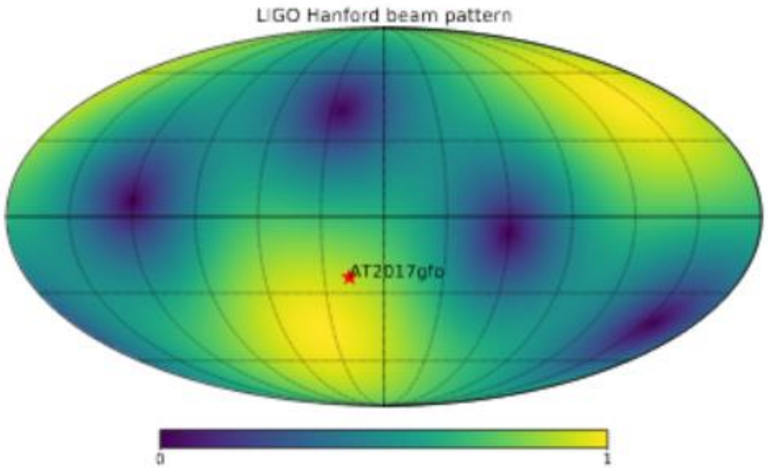
O2 MULTI-MESSENGER GROUP WITH LIGO/VIRGO > 90 MOU SIGNED

- Astronomical institutions, agencies and groups of astronomers from 20 countries
- More than 200 instruments covering the full spectrum (space and ground space telescopes)
- Telescopes in the optical band represented half of the groups

Localization of GW events



Source localization by timing triangulation for the aLIGO–AdV network

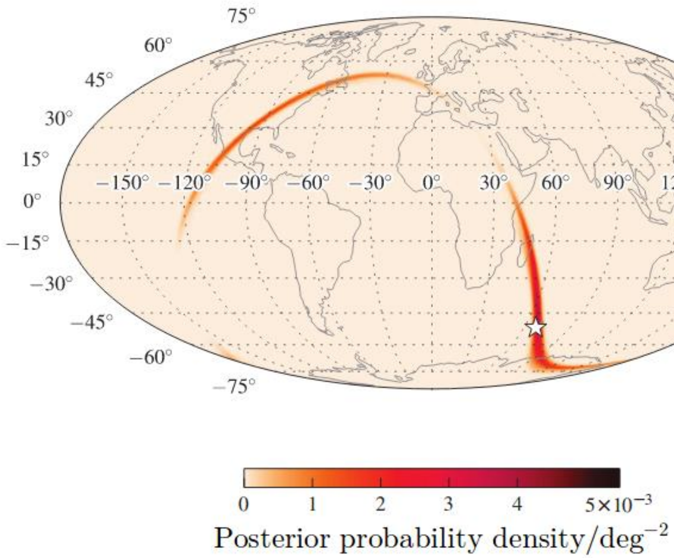


Antenna pattern of Livingston at the time of GW170817

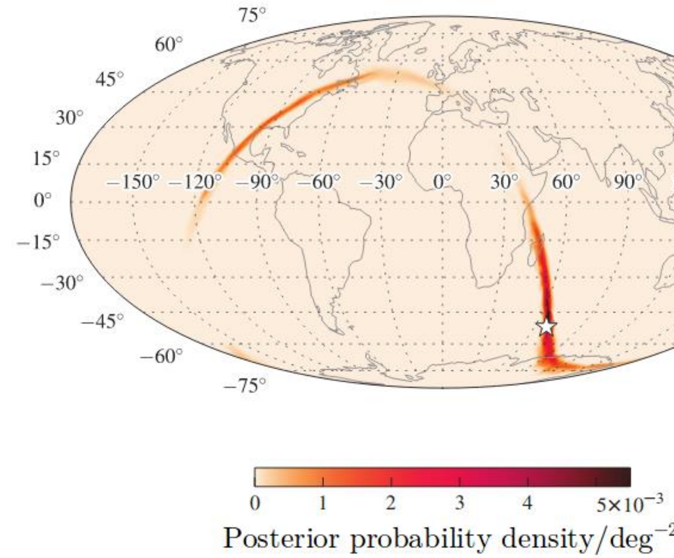
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

Localization of GW events

BAYESTAR



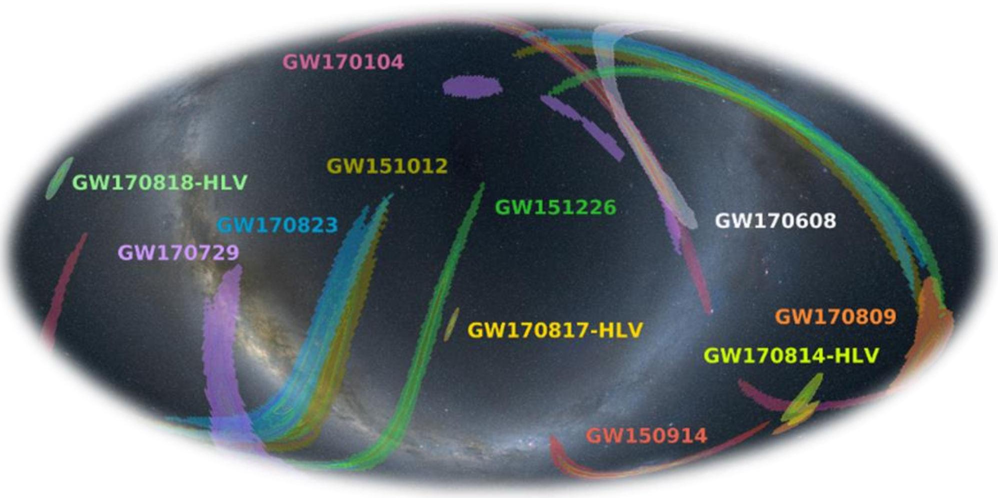
LALINFERENCE

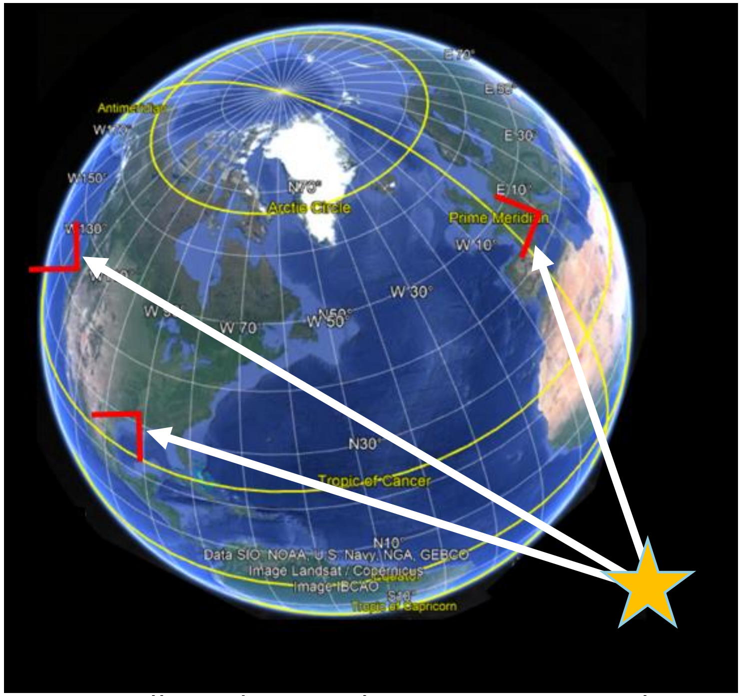


Posterior probability density for sky location with a simulated exemple. The source is at a distanceof 266 Mpc and has anetwork signal-to-noise ratio of 13.2

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

Localization of GW events



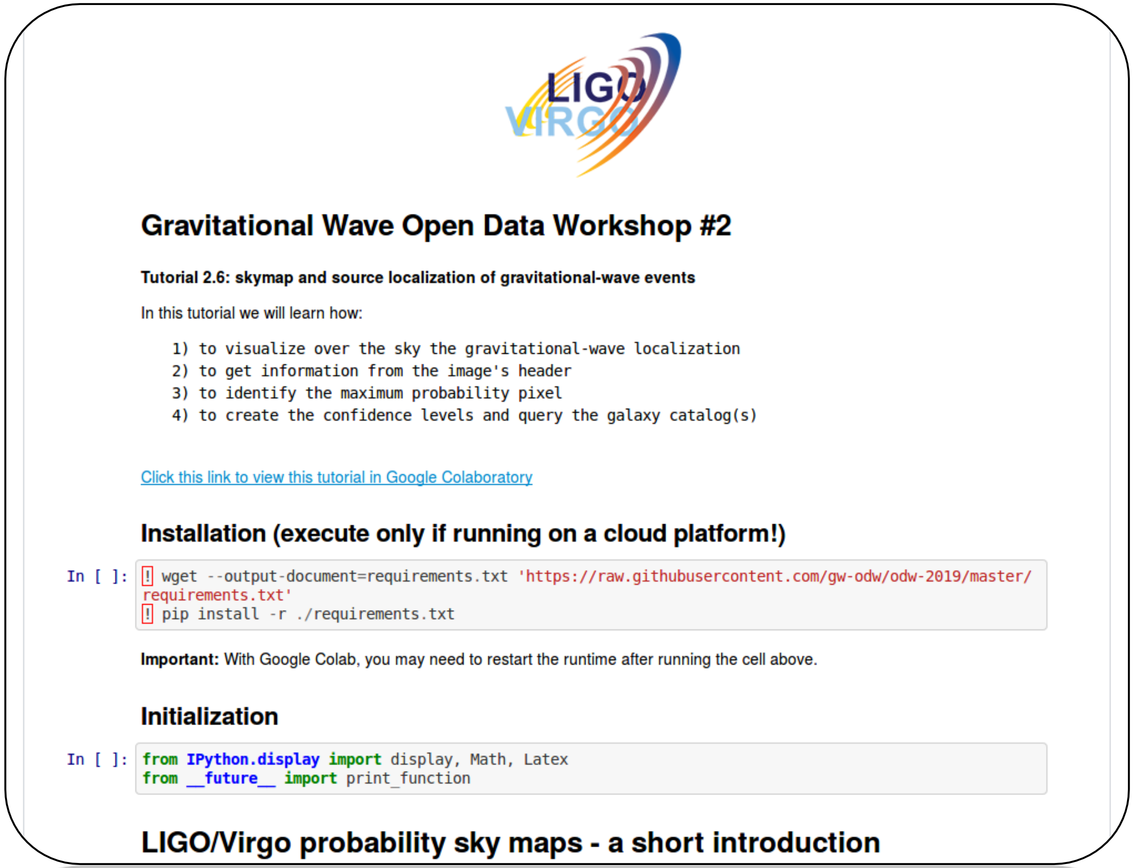


Virgo allowed source location via triangulation

14 alerts sent during O2, 6 confirmed !
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

Low latency gravitational wave alerts for multi-messenger astronomy during the second advances LIGO and Virgo observing runs APJ, 2019

Localization of GW events



Gravitational Wave Open Data Workshop #2

Tutorial 2.6: skymap and source localization of gravitational-wave events

In this tutorial we will learn how:

```
1) to visualize over the sky the gravitational-wave localization
2) to get information from the image's header
3) to identify the maximum probability pixel
4) to create the confidence levels and query the galaxy catalog(s)
```

Click this link to view this tutorial in Google Colaboratory

Installation (execute only if running on a cloud platform!)

In [ ]:
```
! wget --output-document=requirements.txt 'https://raw.githubusercontent.com/gw-odw/odw-2019/master/requirements.txt'
! pip install -r ./requirements.txt
```

Important: With Google Colab, you may need to restart the runtime after running the cell above.

Initialization

In [ ]:
```
from IPython.display import display, Math, Latex
from __future__ import print_function
```

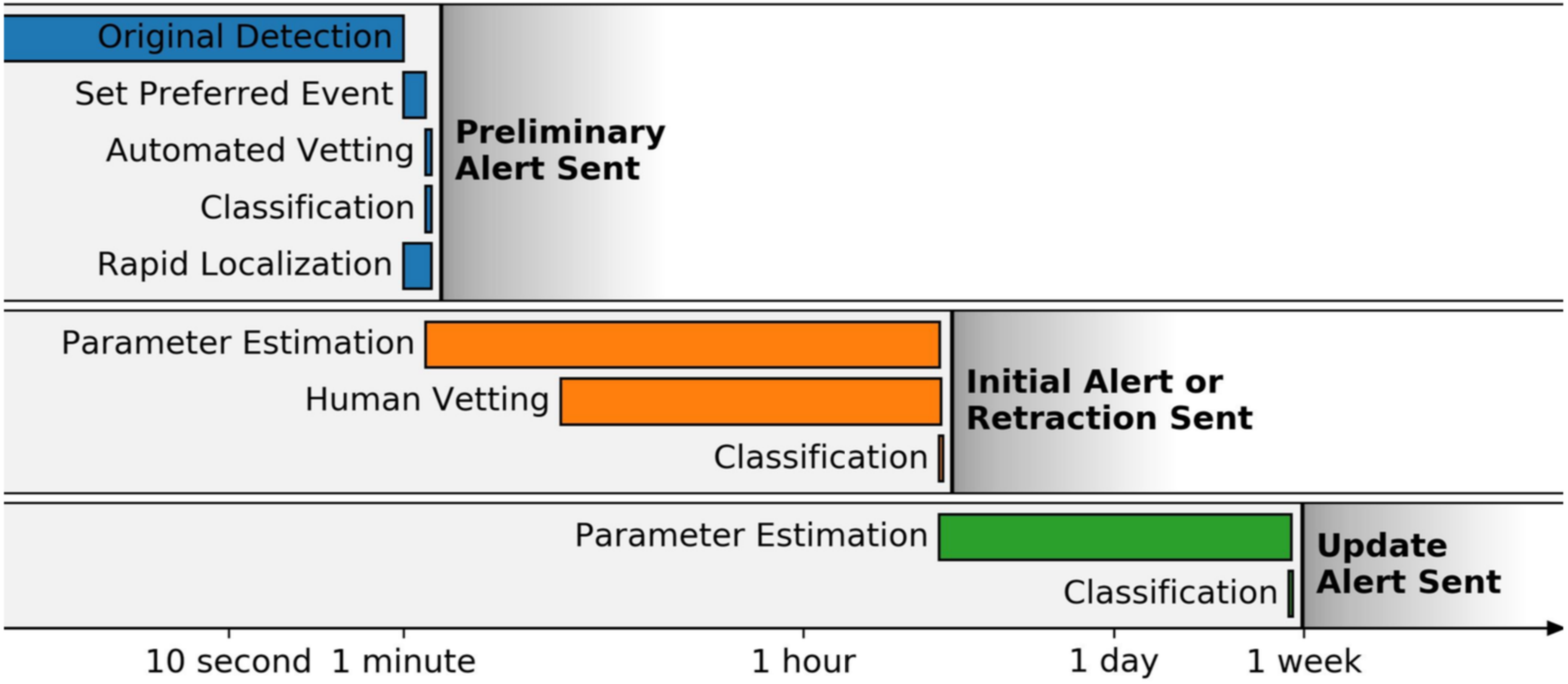
LIGO/Virgo probability sky maps - a short introduction

G. Greco Tutorial
This afternoon !

- GW170818 : BBH merger
- GW170817: BNS merger

→ Reading files
→ Parsing info (dist, …)
→ Calculate 90 c.r region
→ Collect info from host galaxy
→ And a surprise !

Timeline of the **PUBLIC** alerts



Possible triggers (from the offline analysis) **Promoted** as follow-up events

LIGO-Virgo Userguide

LIGO Scientific Collaboration

VIRGO

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories

Navigation

- Getting Started Checklist
- Observing Capabilities
- Procedures
- Alert Contents
- Sample Code

- Change Log
- Glossary

Question? Issues? Feedback?

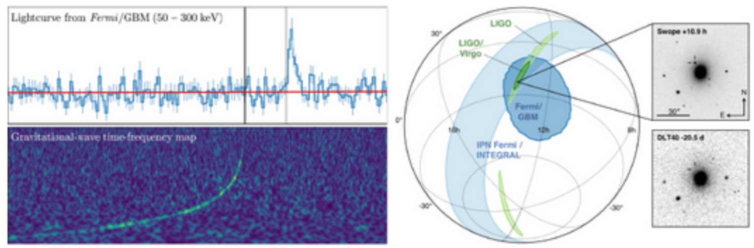
Email emfollow-userguide@support.ligo.org

Quick search

Go

Getting Started Checklist →

LIGO/Virgo Public Alerts User Guide



Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Warning:

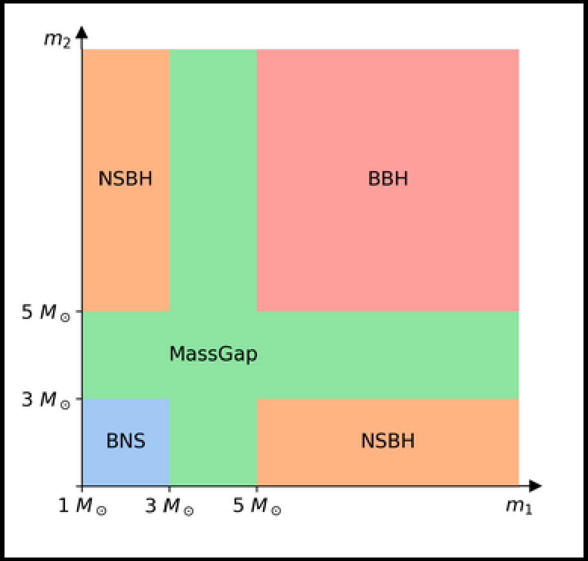
Some technical details of LIGO/Virgo public alerts may change before the start of Observing Run 3 (O3) in 2019. In particular, details of the alert format and the GraceDb public portal may evolve. Please check this document regularly for announcements and updates.

Three sites (LHO, LLO, Virgo) together form a global network of ground-based GW detectors. The LIGO Scientific Collaboration and the Virgo Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

Advanced LIGO and Advanced Virgo are preparing for their third observing run (O3) in early 2019. For the first time, **LIGO/Virgo alerts will be public**. Alerts will be distributed through NASA's Gamma-ray Coordinates Network (GCN). There are two types of alerts: human-readable GCN Circulars and machine-readable GCN Notices. This document provides a brief overview of the procedures for vetting and sending GW alerts, describes their contents and format, and includes instructions and sample code for receiving GCN Notices and decoding GW sky maps.

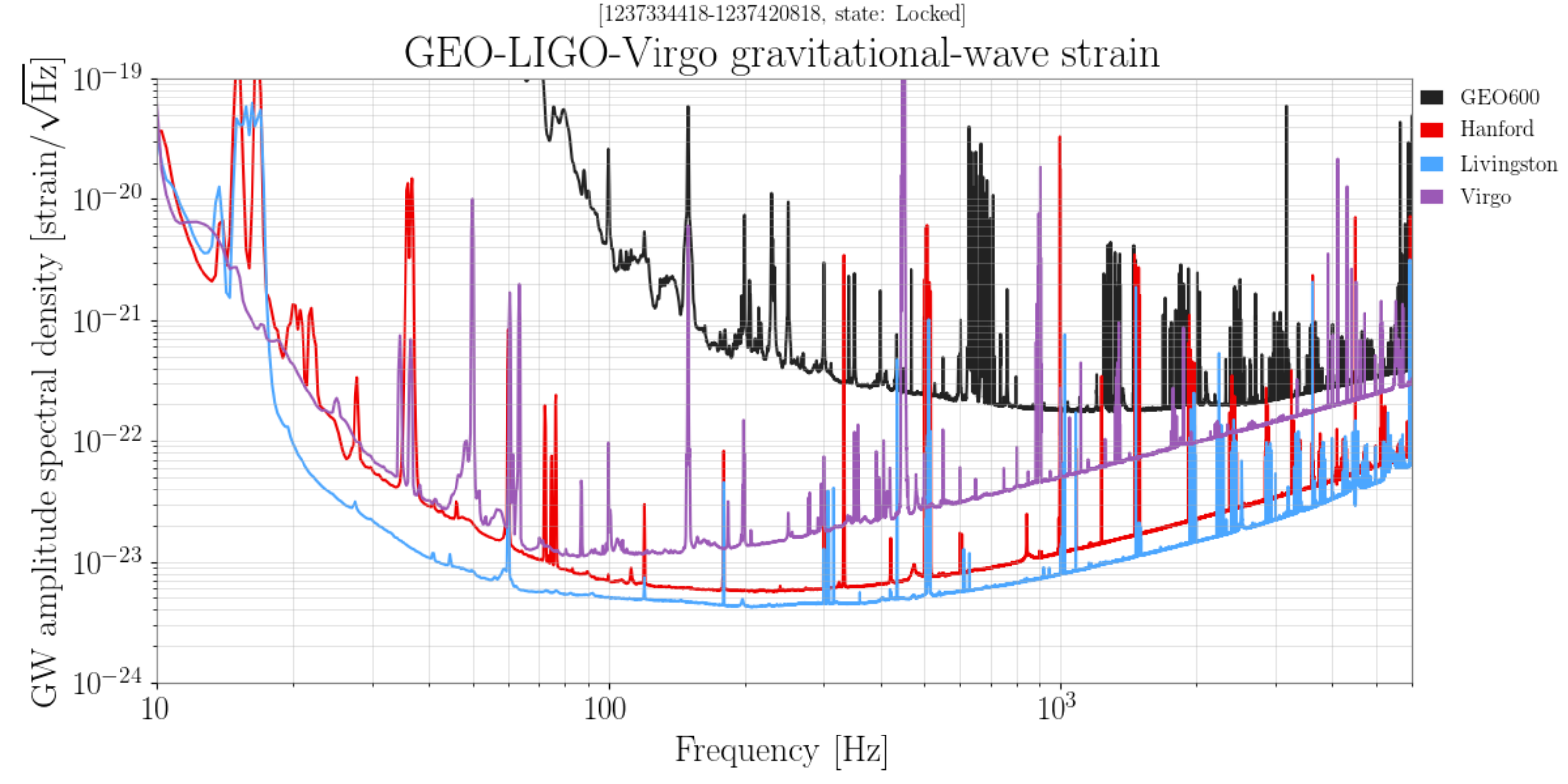
GCN Notices content

Inference: classification
Five numbers, summing to unity, giving probability that the source belongs to the following five categories:
Terrestrial, BNS, MassGap, NSBH, BBH
GW150914: 5e-40, 0.00, 0.06, 0.01, 0.93
GW170817: 1e-48, 1.00, 0.00, 0.00, 0.00



Root		
IVORN	`ivo://nasa.gsfc.gcn/LVC#[{T,M}]SYYMMDDabc-{1,2,3}-{Preliminary,Initial,Update,Preliminary-Retraction}`	
Role	`{observation,test}`	
Who		
Date	Time sent (UTC, ISO-8601), e.g. `2018-11-01T22:34:49`	
Author	`LIGO Scientific Collaboration and Virgo Collaboration`	
WhereWhen	Time of signal (UTC, ISO-8601), e.g. `2018-11-01T22:22:46.654437`	
What		
GraceID	GraceDb ID: `[{T,M}]SYYMMDDabc`. Example: `MS181101abc`	
Packet Type	GCN Notice type: `{Preliminary,Initial,Update}`	
Notice Type	Numerical equivalent of GCN Notice type: `{150,151,152}`	
FAR	Estimated false alarm rate in Hz	
Sky Map	URL of HEALPix FITS localization file	
Group	`CBC`	`Burst`
Pipeline	`{Gstlal,MBTAOnline,PyCBC,SPIIR}`	`{cWB,oLIB}`
CentralFreq	N/A	Central frequency in Hz
Duration		Duration of burst in s
Fluence		Gravitational-wave fluence in erg cm^{-2}
BNS, NSBH, BBH, Noise	Probability that the source is a BNS, NSBH, NSBH merger, or terrestrial (i.e., noise) respectively	N/A
HasNS, HasRemnant	Probability, under the assumption that the source is not noise, that at least one of the compact objects was a neutron star, and that the system ejected a nonzero amount of neutron star matter, respectively.	

O3 just starts !!!



Binary Neutron Star range Virgo : 50 Mpc Handford: 100 Mpc Livingston: 130 Mpc

A primer on gravitational wave detector with LIGO and Virgo (J.van der Brand)
Observation and calibration data quality talk (A.Weinstein)

Identification of the EM/neutrino counterpart

GW sky localisation error box (hundreds deg^2)

↓

Wide Field of view instruments

Trigger ↓ candidates

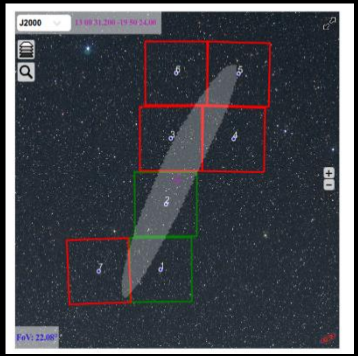
Follow-up with narrow fields instruments

↓

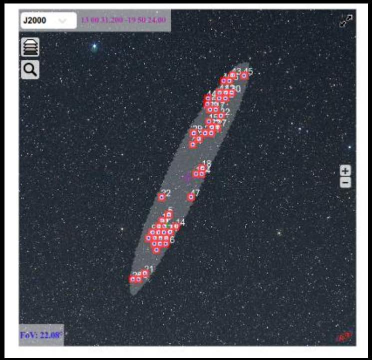
Caracterisation of the counterparts candidates

NEEDS A LARGE ASTRONOMICAL COLLABORATION

NEEDS SPECIFICS OBSERVATIONAL STRATEGIES



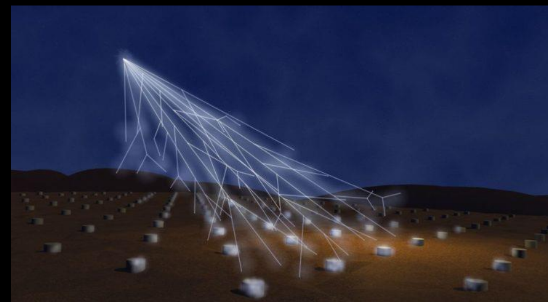
Tiling stategy



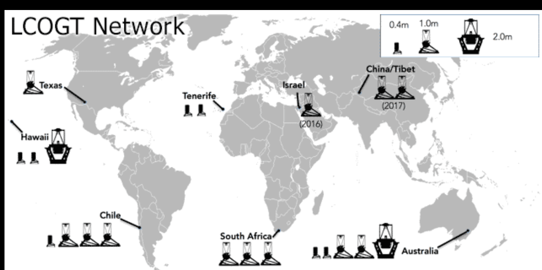
Galaxy-targeting (with distance)

Good luck to all counterpart colleagues !

IceCube



Pierre Auger



LCOGT

GRANDMA

GROWTH

SKA

VLA

ESO

The future for multi-messengers area is bright !

In the PAST

O1/O2 campaign

BH-BH mergers
NS-NS merger

In the future: O3 and beyond

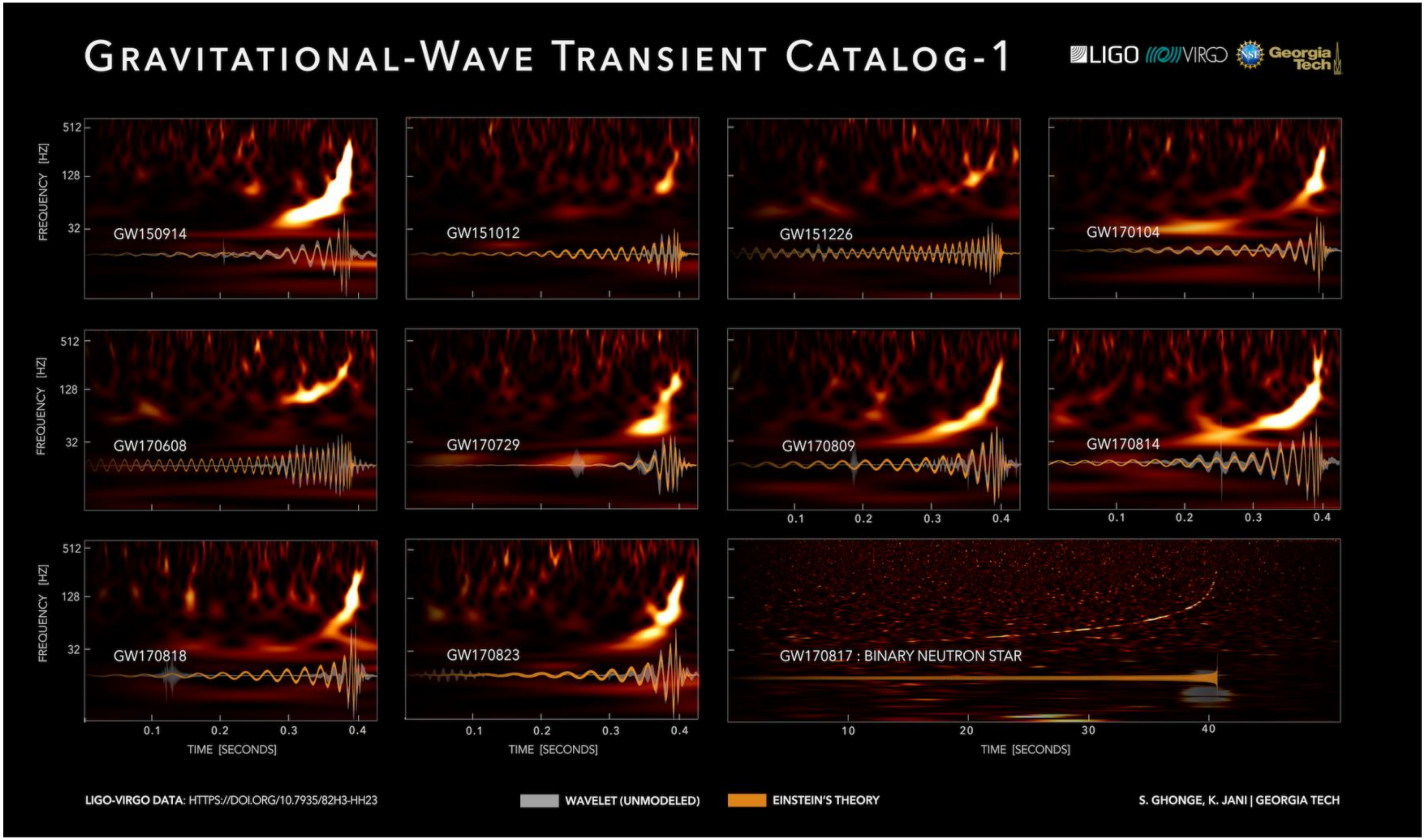
Mergers
Collapse of massive star
Isolated neutrons star instabilities

Populations studies
Remanent studies

Electromagnetic emissions
On different angles

→ Global picture of the Violent Universe

Thanks !



[GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs](arxiv.org/abs/1811.12907) arxiv.org/abs/1811.12907

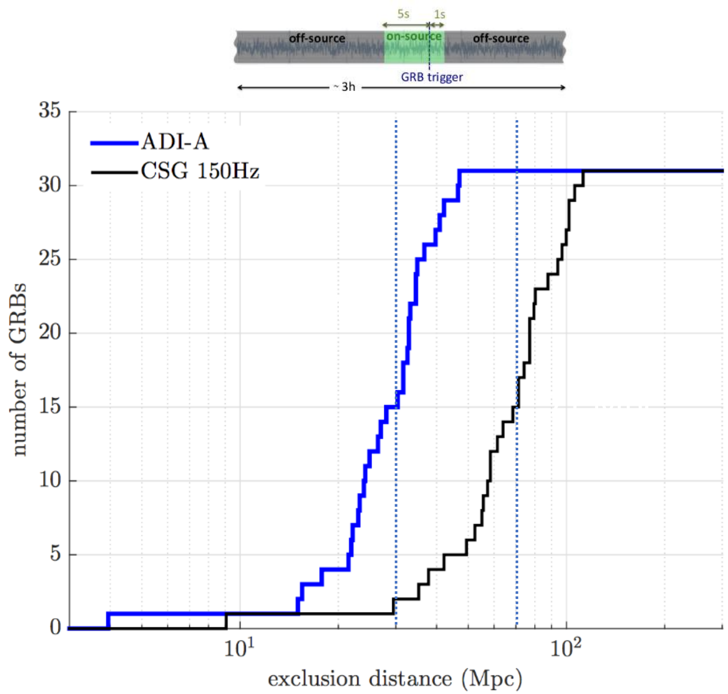
Confident events: FAR < 1 per 30 years,
Probability of physical origin greater than 50%

10 BBH + 1 BNS + 14 other marginal events

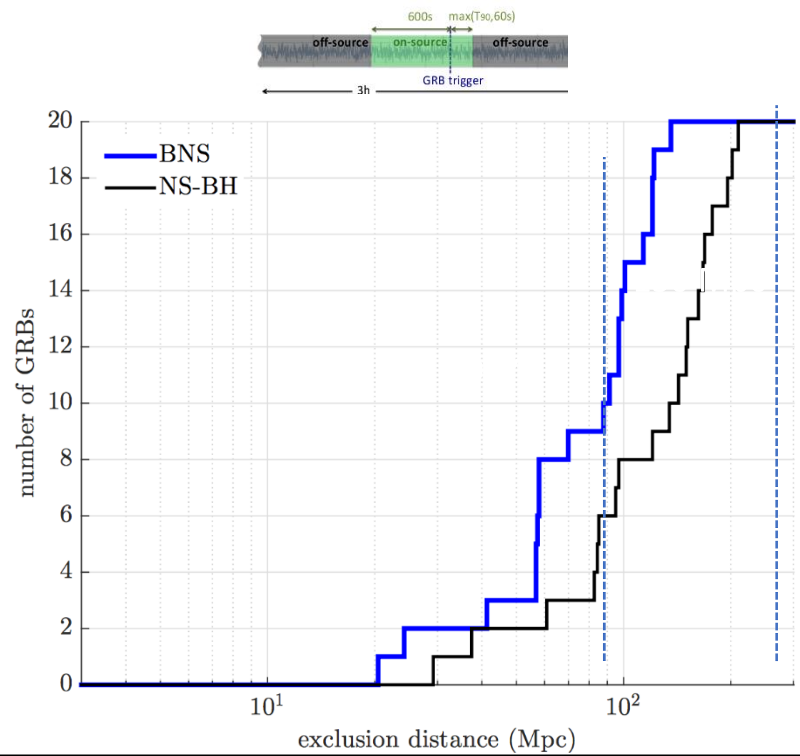
External triggers and GWs: triggered analysis

GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino

Unmodeled GW search (31 GRBs)
with 10^{-2} $M_o c^2$ energy in GW (optimistic)



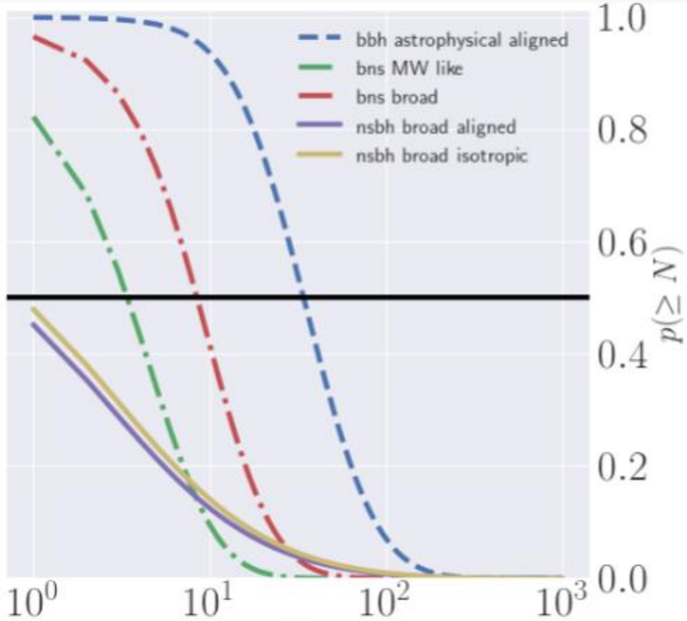
Binary system coalescence (19 short GRBs)



Non GW-detection result: lower bounds on the progenitor distance

Abbott et al. 2016,ApJ,

The O3 multi-messenger campaign



source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

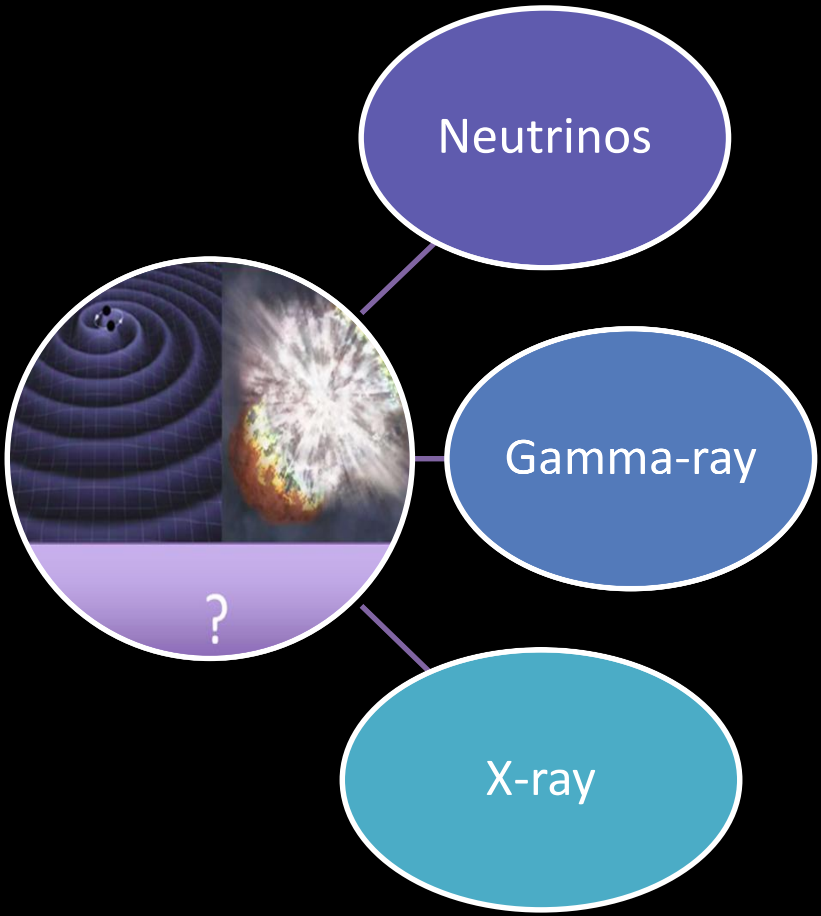
Pankow et al. on behalf on LIGO/Virgo colla.

BBH rate will dominate, at least ~few/month up to few/week

1-10 BNS

NS-BH=0 not ruled out in any scenario, most give ~50% N>0

COINCIDENCE SEARCH – EARLY SEARCH



Ice-cube + Antares
Monitor the all sky
Model dependant

less contaminants
all-sky survey
Beamed emission

less contaminants
No wide-field telescope

TRACK the em/neutrino counterpart of GW ALERTS

EARLY SEARCH

Optical

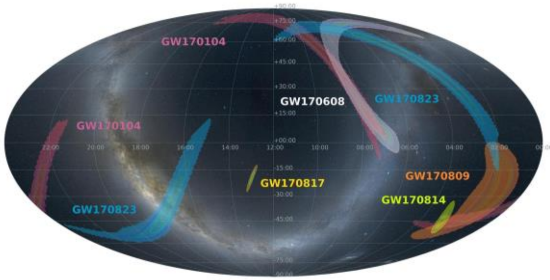
Lot of contaminants
10^4-10^5 variable objects
over 100 sq. degrees
Difficult to monitor the whole sky

Radio

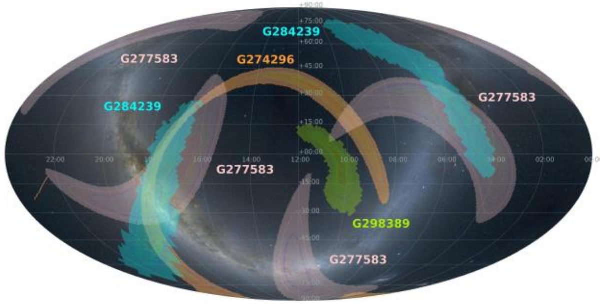
Less contaminants
Wide-field array at low frequencies (MHz)
Faint sources
Long delay between GW and radio emission

O2 Electromagnetic campaign

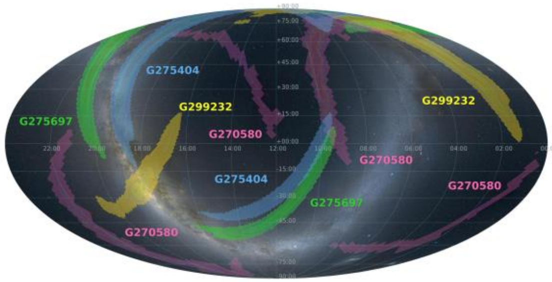
14 ONLINE ALERTS



Confident

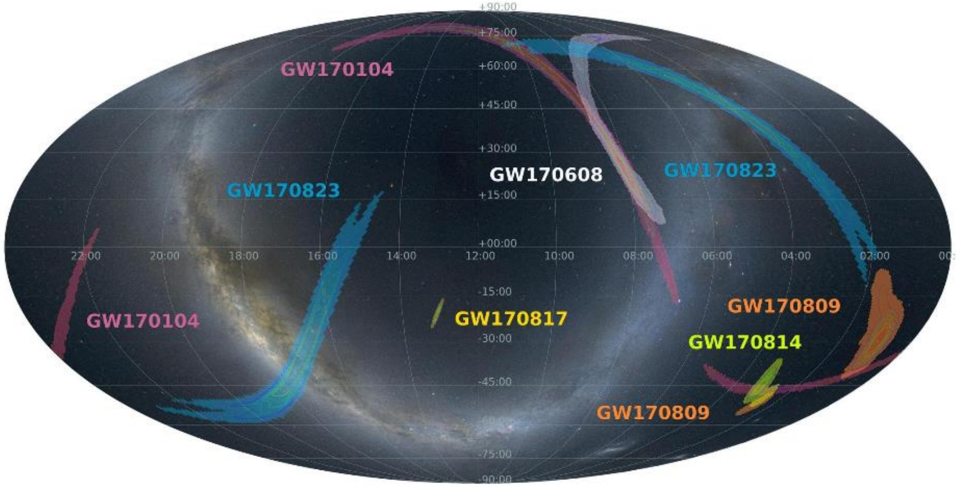


Consistent with noise



Rejected

6 ALERTS confirmed as BBH + BNS
Offline sky localization area



Low latency gravitational wave alerts for multi-messenger astronomy during the second advances LIGO and Virgo observing runs APJ, 2019