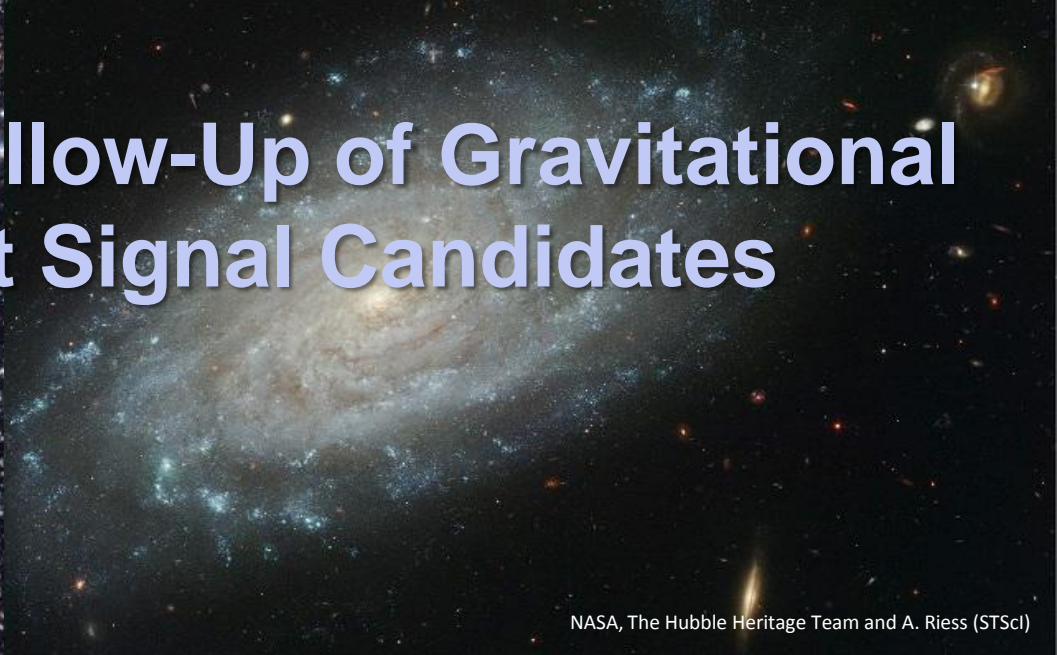
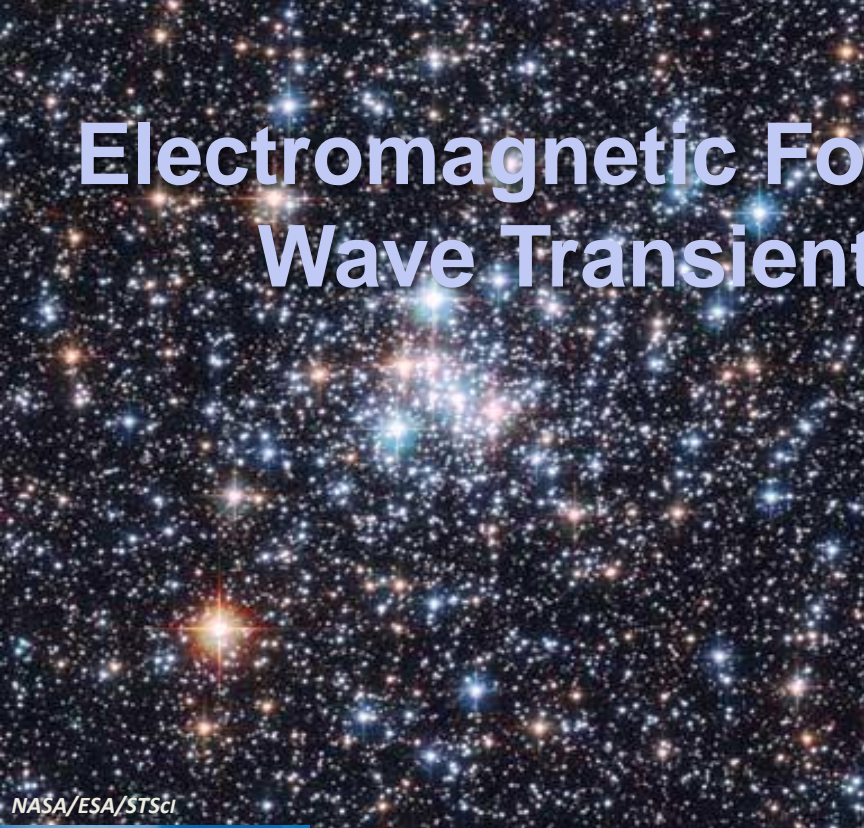
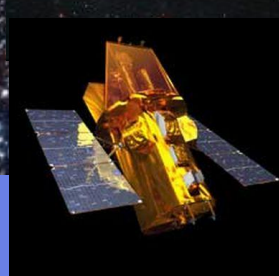


# Electromagnetic Follow-Up of Gravitational Wave Transient Signal Candidates



NASA, The Hubble Heritage Team and A. Riess (STScI)

NASA/ESA/STScI



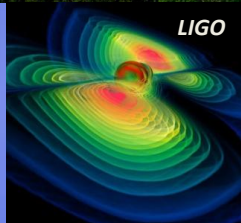
**Marica Branchesi (Università di Urbino/INFN)**

on behalf of

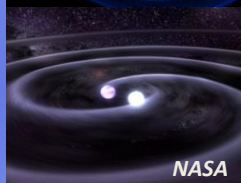
**LIGO Scientific Collaboration and Virgo Collaboration**



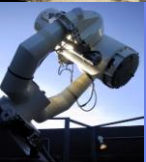
**+ partner EM astronomers**



LIGO



NASA



The goal of LIGO and Virgo interferometers is the first direct detection of gravitational waves from **ENERGETIC ASTROPHYSICAL** events such as:

➤ Mergers of Neutron Stars and/or Black Holes

➔ **SHORT GRB**

➔ **Kilonovae**

➤ Core Collapse of Massive Stars

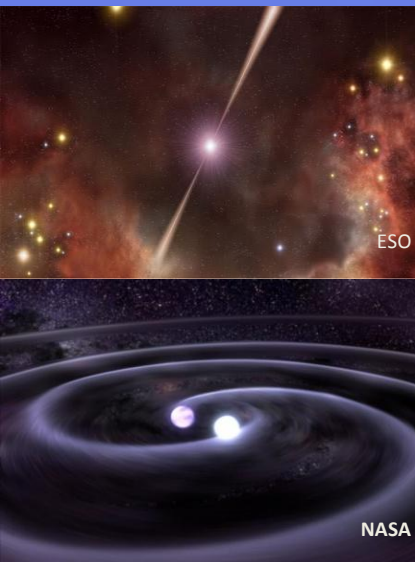
➔ **Supernovae**

➔ **LONG GRB**



**Main motivations for joint GW/EM observations:**

- Increase the GW detection confidence;
- Get a precise (arcsecond) localization, identify host galaxy;
- Provide insight into the progenitor physics;
- In the long term start a joint GW/EM cosmology.

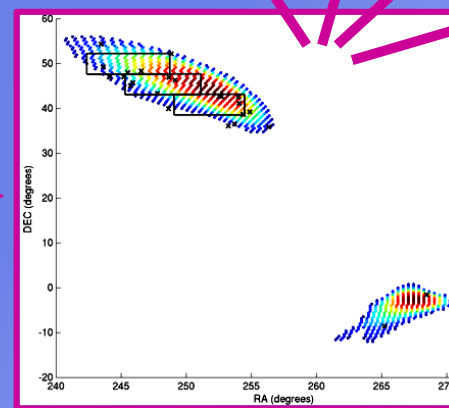


# Low-latency GW data analysis pipelines allow us to use GW triggers in “real time” to obtain prompt EM observations and to search for EM counterparts



Analyze GW data,  
select candidates

(Kanner et al. 2008, CQG 25, 184034)  
(Abadie et al. 2011, arXiv1109.3498)



define pointing positions

**The first program of EM follow-up to GW candidates has been performed during two LIGO/Virgo observing periods:**

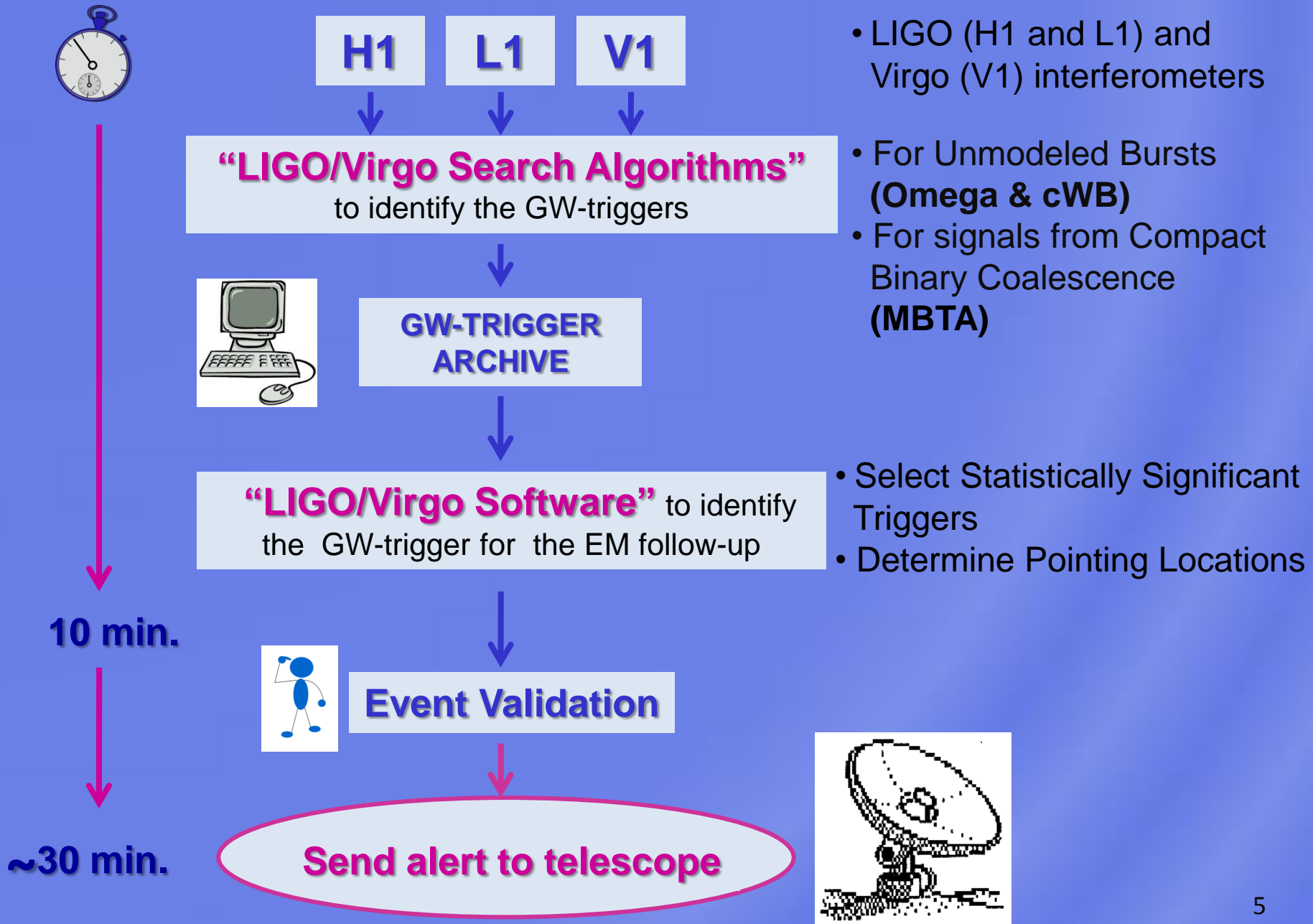
**Dec 17 2009 to Jan 8 2010 – Winter Run  
Sep 4 to Oct 20 2010 – Autumn Run**

**The EM-follow-up program in S6-VSR2/3 is a milestone towards the advanced detectors era where the chances of GW detections are strongly enhanced**

**Presentation Highlights:**

- GW-data analysis for a prompt EM follow-up**
- EM-observation strategy**
- Image analysis procedures to identify the EM-counterpart**
- Advanced era GW/EM astronomy**

# GW Online Analysis



## Requirements to select a trigger as a candidate for the EM follow-up:

- Event occurring in simultaneous observations of all three detectors
- Power above a threshold estimated from the distribution of background events

### False Alarm Rate

Winter Run

< 1.00 event per day

Autumn Run

< 0.25 event per day for most of optical facilities

< 0.10 event per day for PTF and Swift

## GW Source Sky Localization

low SNR signals are localized into regions of  
**tens of square degrees** possibly in  
several disconnected patches



**Necessity of wide field of view telescopes**

**Additional priors to improve the location accuracy and  
increase the chance to observe the EM counterpart**

## **LIGO/Virgo horizon:**

a stellar mass BH/ NS binary inspiral detected out to **50 Mpc**  
distance that includes **thousands of galaxies**



**GW observable sources are likely to be extragalactic**

**EM-observation is restricted to the regions occupied by  
Globular Clusters and Galaxies within 50 Mpc**

(GWGC catalog White et al. 2011, CQG 28, 085016)

**To determine the telescope pointing position:**



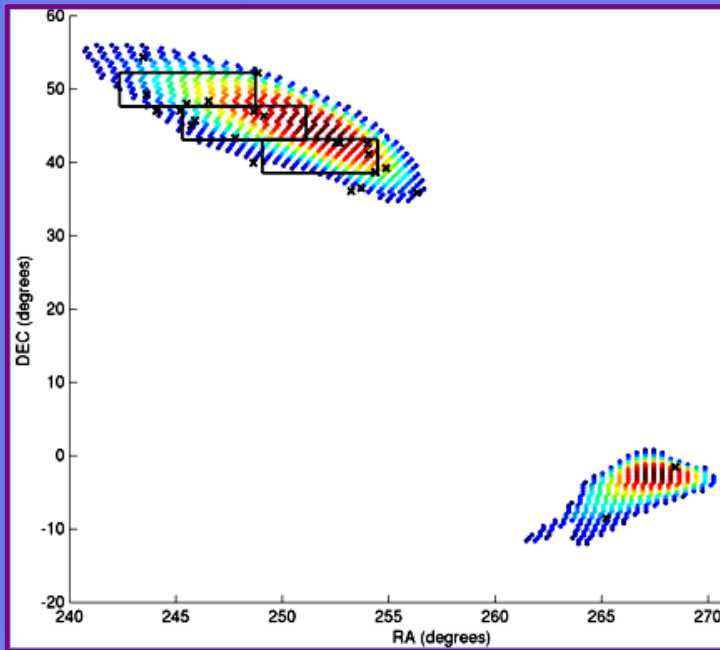
**Probability GW sky map weighted  
taken into account**

**distance** and **luminosity** of nearby galaxies and globular clusters

**Burst Search** - probability for nearby (<50 Mpc) galaxies and globular clusters to be the host of the GW source is assumed:

$$P = \frac{M * \text{Likelihood}}{\text{Distance}}$$

- **Likelihood** based on GW data
- **M** is **blue luminosity**, that is a proxy of **star formation**



### Probability Skymap

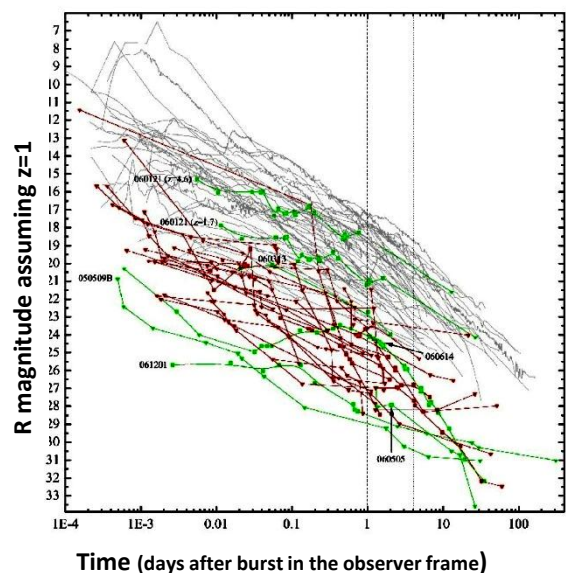
- **Black crosses** → nearby galaxies locations
- **Rectangles** → pointing telescope fields chosen to maximize the chance to detect the EM counterpart

**MBTA** - “Effective distance” (if < 50 Mpc) used to select the possible host from GWGC catalog

Probability to be the host of the GW source is assumed:  $P = M * \text{Likelihood}$

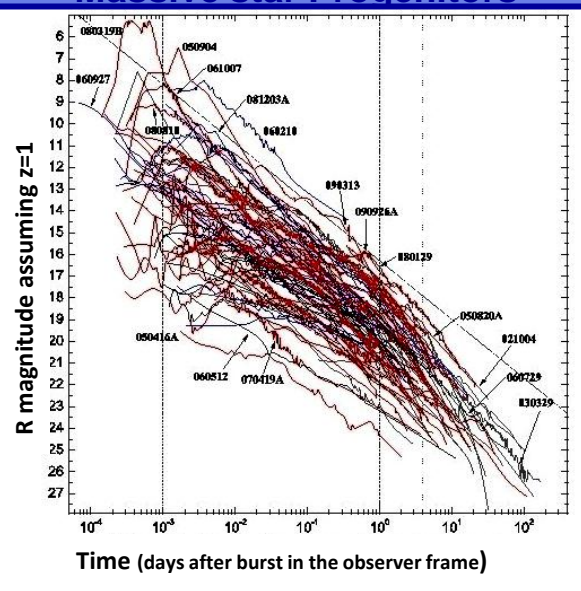
# The expected EM counterpart afterglows guide observation schedule time

## SHORT/HARD GRB Compact Object mergers



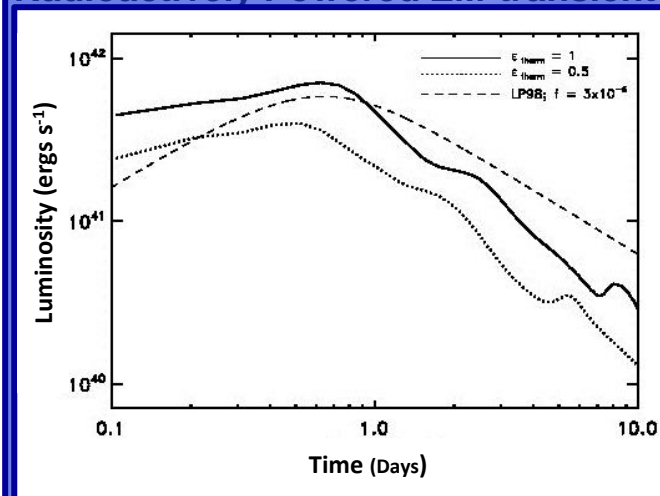
Kann et al. 2011, ApJ, 734.96

## Optical Afterglows: LONG/SOFT GRB Massive star Progenitors



Kann et al. 2010, ApJ, 720.1513

## KILONOVAS Radioactively Powered EM-transient



Metzger et al. 2010, MNRAS, 406.265

Observed **on-axis LONG and SHORT GRB** afterglows peak **few minutes** after the EM/GW prompt emission

**Kilonova model** afterglow peaks about **a day** after the GW event

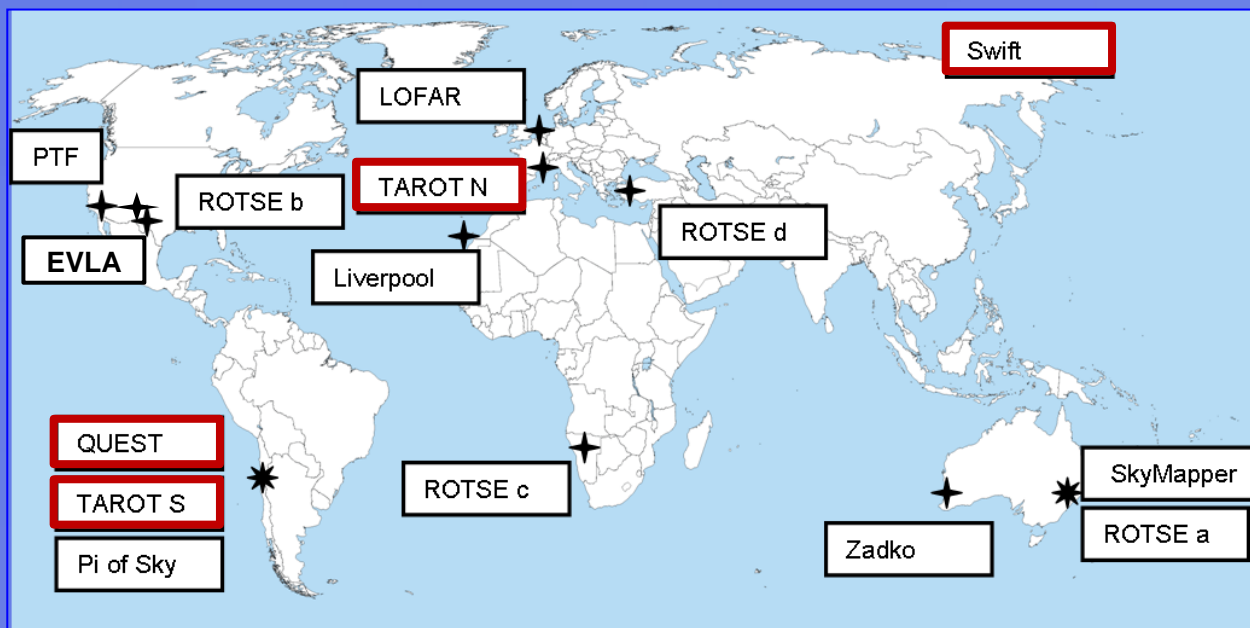
To discriminate the possible EM counterpart from contaminating transients

→ EM observations as soon as possible after the GW trigger validation

→ EM observations a day after the GW trigger validation

→ repeated observations over several nights to study the light curve

# Ground-based and space EM facilities observing the sky at Optical, X-ray and Radio wavelengths involved in the follow-up program



Winter/Autumn Run  
 Only Autumn Run

## Optical Telescopes

### TAROT SOUTH/NORTH

3.4 sq. degree FOV

### Zadko

0.17 sq. degree FOV

### ROTSE

3.4 sq. degree FOV

### QUEST

9.4 sq. degree FOV



### SkyMapper

5.7 sq. degree FOV

### Pi of the Sky

400 sq. degree FOV

### Palomar Transient Factory

7.8 sq. degree FOV

### Liverpool telescope

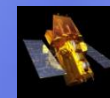
21 sq. arcminute FOV



## X-ray and UV/Optical Telescope

### Swift Satellite

0.15 sq. degree FOV



## Radio Interferometer

### LOFAR

30 - 80 MHz

110 - 240 MHz

Maximum **25** sq. degree FOV



### EVLA

5 GHz - **7** arcminute FOV



# Optical Telescopes

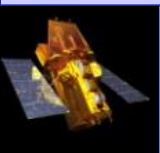
**Winter run:** 8 GW alerts → 4 observed by at least one telescope

**Autumn run:** 6 GW alerts → 5 observed by at least one telescope



## Swift Satellite: X-ray and UV/Optical telescope

2 GW alerts sent and observed by **SWIFT** → **XRT**  
→ **UVOT**



# Radio Interferometers

## LOFAR

5 GW alerts sent and observed

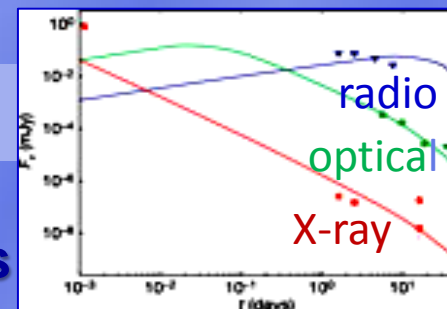


## Expanded-VLA

**Low-Latency Follow-up** (October 14 to 20) → **No GW alerts**

**High-Latency Follow-up** → **2 GW alerts observed**

3 weeks, 5 weeks + 8 months later



Fox et al. 2005, Nature 437,835

# EM Image Analysis Procedure

**Goal:** detect the transient object counterpart of the GW signal by analyzing a series of images taken in consecutive epochs

Limited Sky localization of GW interferometers



Wide field of view EM images



Require to develop specific methods to detect the EM Transient Counterpart of the GW trigger

Main steps for a **EM-counterpart Detection Pipeline:**

- 1) **Identification** of all “Transient Objects” visible in the images
- 2) **Removal** of “Contaminating Transient events”

**Main challenges** due to the “large sky area” to analyze

image areas occupied by globular cluster and galaxies (< 50 Mpc) taking into account the possible offset between the host center and the transient

# Optical Telescopes: Image Analysis

LIGO/Virgo collaborations with partner astronomers are actually **testing and developing several Image Analysis Techniques** to **1)** indentify the “**Transient Objects**” based on:

## **Image Subtraction Methods**

(for Palomar Transient Factory, ROTSE and SkyMapper)

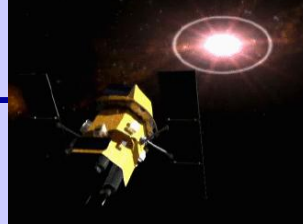
## **Catalog Cross-Check Methods**

(for TAROT, Zadko, QUEST and Pi of the Sky)

Followed by the **2) “EM counterpart identification”** from the **background/contaminating events** based on:

**{ analysis of transient light curves**

# Swift Satellite: Image Analysis



## X-ray image analysis :

- 1) detection of the X-ray sources visible in the FOV,
- 2) comparison with the number of serendipitous sources expected in the FOV
- 3) X-ray variability analysis

## Optical and UV analysis:

- 1) search of the UVOT counterparts of the X-ray sources detected with XRT
- 2) cross-check with DSS to identify “unknown objects” or objects with flux variations
- 3) Optical/UV variability analysis

# Radio interferometers: Image Analysis

## Image Analysis:

- 1) transient detection
- 2) light curve analysis
- 3) identification of contaminating radio sources

### LOFAR

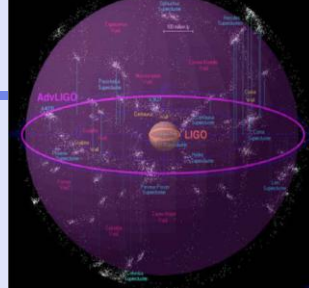
#### low-frequency sky:

- noise transients from the atmosphere (like meteor trail)
- time/space varying ionosphere

### EVLA

- variability of Radio AGN emission caused by scintillation of our Galaxy ISM

# Advanced detector LIGO/Virgo era



## Detection Rates of compact binary coalescences

IFO	Source <sup>a</sup>	$N_{low}$ yr <sup>-1</sup>	$N_{re}$ yr <sup>-1</sup>	$N_{high}$ yr <sup>-1</sup>	$N_{max}$ yr <sup>-1</sup>
<b>Initial</b>	NS-NS	$2 \times 10^{-4}$	0.02	0.2	0.6
	NS-BH	$7 \times 10^{-5}$	0.004	0.1	
	BH-BH	$2 \times 10^{-4}$	0.007	0.5	
<b>Advanced</b>	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	

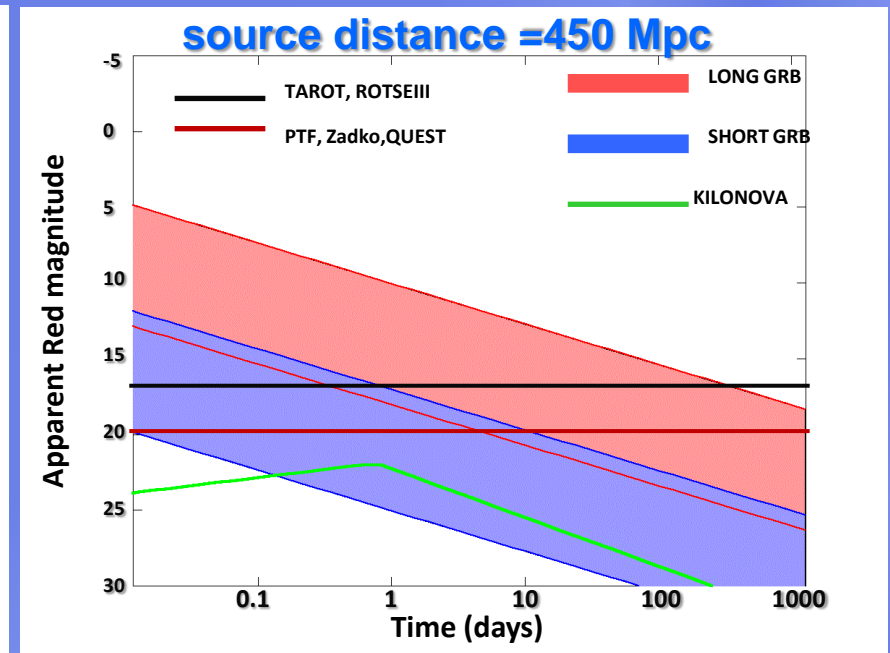
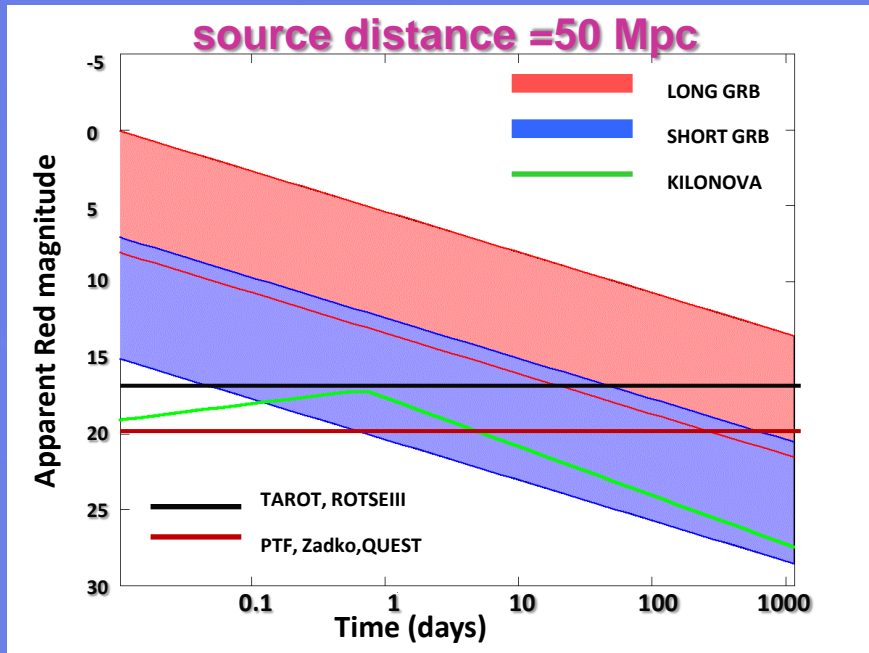
Mass: NS = 1.4 Mo  
BH = 10 Mo

## Optimal Horizon Distances

Initial	Advanced	
<b>33 Mpc</b>	<b>445 Mpc</b>	for NS-NS
<b>70 Mpc</b>	<b>927 Mpc</b>	for NS-BH
<b>161 Mpc</b>	<b>2187 Mpc</b>	for BH-BH

[Abadie et al. 2010, CQG 27 173001]

## Optical Afterglows Light Curves for GRBs and Kilonovae



# Towards advanced detector LIGO/Virgo era

In order to improve EM counterpart search strategy

## GW Triggers:

- ❖ improvement and development of more efficient low-latency pipelines
- ❖ reduce target alert latency (no human validation)

## EM-telescope Pointing position:

- ❖ use of estimated GW parameters?
- ❖ galaxy catalog weighting?
  - 1) new catalog up to advanced detector horizon
  - 2) evaluation of appropriate galaxy parameter priors to detect binary compact object systems

## EM-Observation Strategy :

- ❖ coordinated observations by different telescopes?
- ❖ need for high etendue telescopes
- ❖ usefulness of optical spectrums in identifying transients

## EM Image analysis:

- ❖ Low-latency image analysis
- ❖ EM False Alarm Rate studies

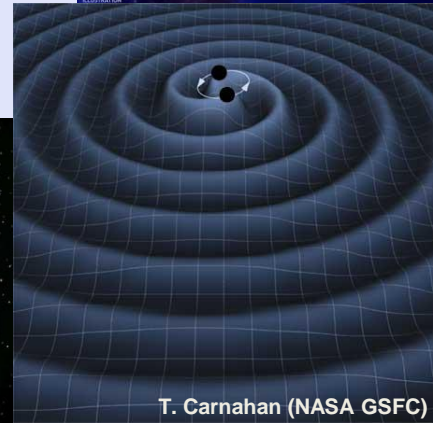
**Very important  
joint collaboration between EM/GW communities!!!**

# Conclusions:

- ❑ The **first EM follow-ups to GW candidates** have been performed by the LIGO/Virgo community and several Partner EM-Observatories
- ❑ **Different procedures to detect the “EM-counterpart” of a GW-candidate event are followed to analyze** images taken in the different **EM-bands** (evaluation of the **rate of astrophysical and technical contaminants** is under study)
- ❑ The **analysis of the images** taken during the EM-follow up program is in progress
- ❑ Towards the **advanced GW-detector era**: need to develop **joint GW/EM search strategies** to start **multimessenger GW astronomy!**



NASA/Zhang & Woosley



T. Carnahan (NASA GSFC)