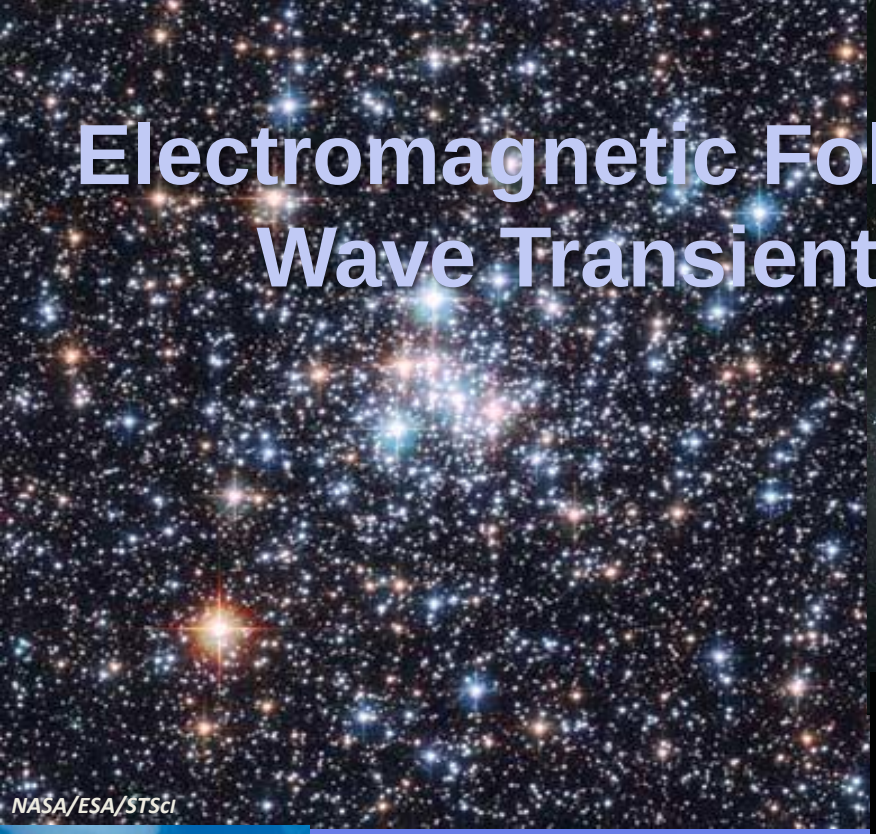
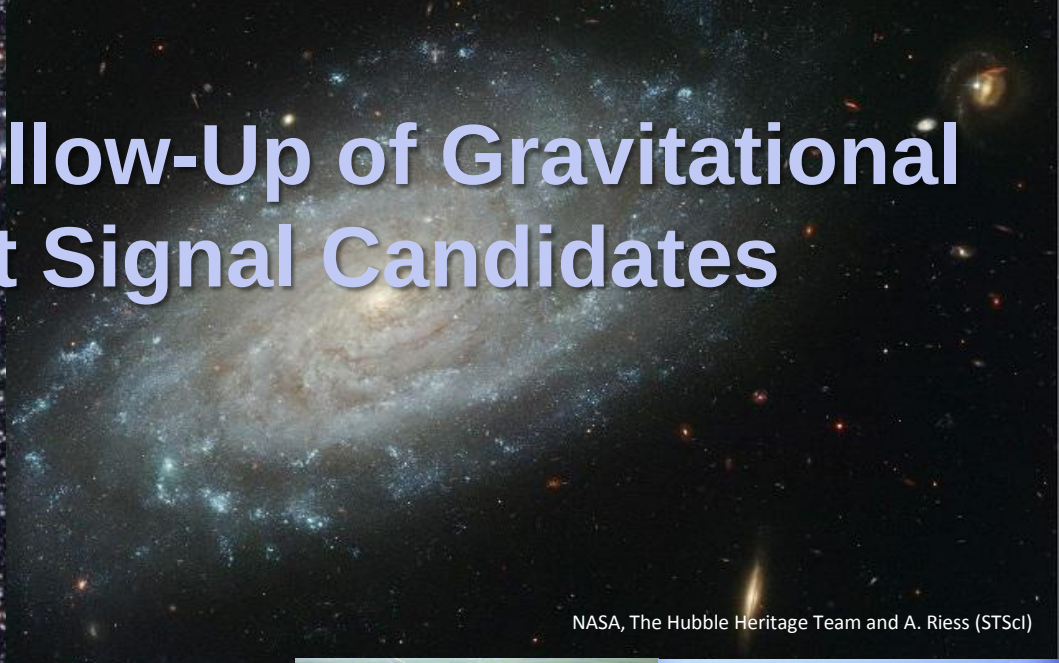
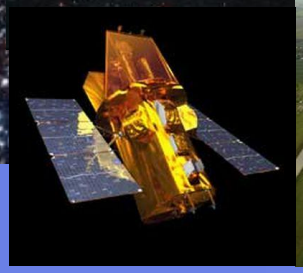
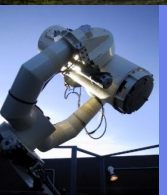
Electromagnetic Follow-Up of Gravitational Wave Transient Signal Candidates


NASA/ESA/STScI


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





Marica Branchesi (Università di Urbino/INFN)

on behalf of

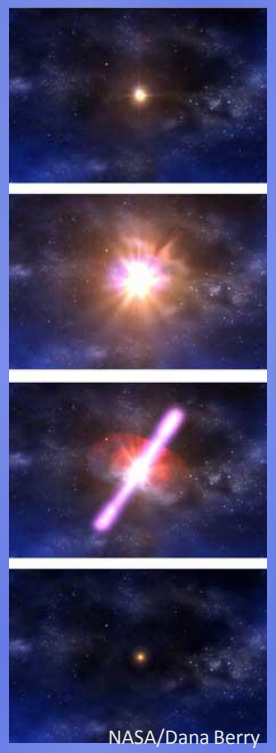
LIGO Scientific Collaboration and Virgo Collaboration

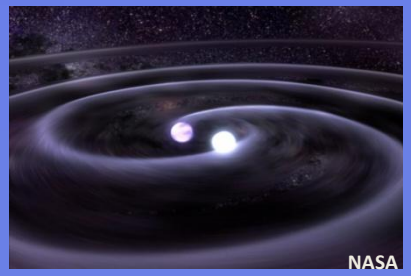
+ partner EM astronomers

LIGO-G1100580

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

- Mergers of NeutronStars and/or BlackHoles ➡ SHORT GRB
  ➡ Kilonovae
- Core Collapse of Massive Stars ➡ Supernovae
  ➡ LONG GRB
- Cosmic String Cusps ➡ EM burst

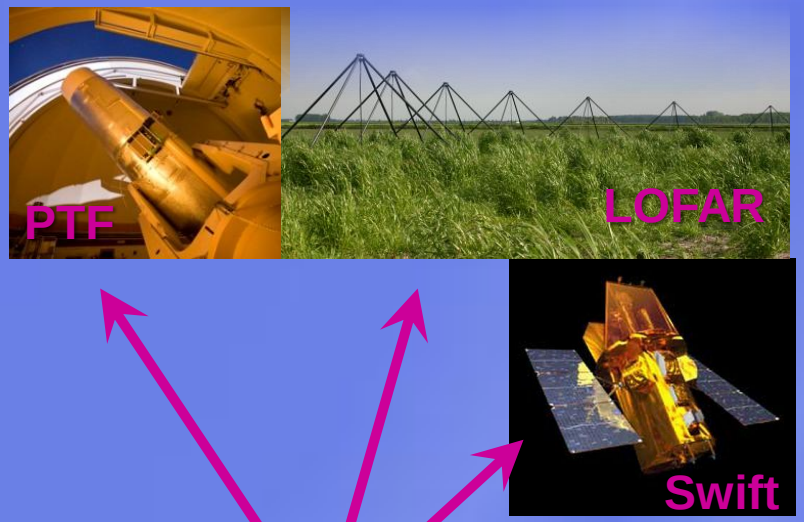




Main motivations for joint GW/EM observations:

- 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 the use **of GW triggers in real time to obtain prompt EM observations and to search for EM counterparts**



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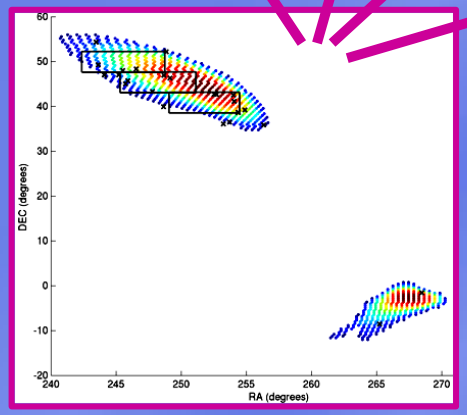
Analyze GW data, select candidates



define pointing positions

[e.g. see Kanner et al., CQG 25, 184034]

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 – Summer 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**

GW Online Analysis

H1 **L1** **V1**

- LIGO (H1 and L1) and Virgo (V1) interferometers

"LIGO/Virgo Search Algorithms"
to identify the GW-triggers

- For Unmodeled Bursts
- For signals from Compact Binary Coalescence

GW-TRIGGER ARCHIVE

"LIGO/Virgo Software" to identify the GW-trigger for the EM follow-up

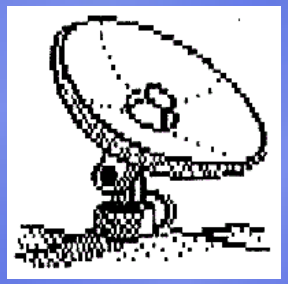
- Select Statistically Significant Triggers
- Determine Pointing Locations

10 min.

Event Validation

30 min.

Send alert to telescope



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
Summer 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 disconnetted patches

↓

Necessity of wide field of view telescopes

LIGO/Virgo horizon: a stellarmass BH/ NS binary inspiral detected out to **50 Mpc, distance** that includes thousands of galaxies

↓

GW observable sources are likely to be extragalactic

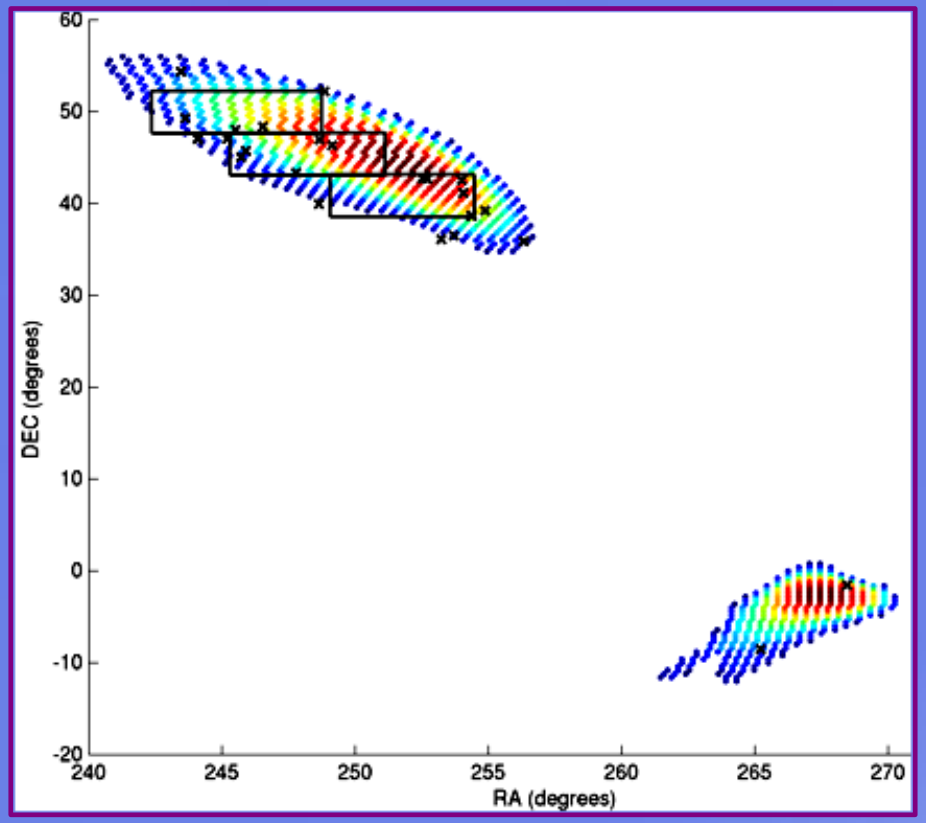
EM-observation is restricted to the regions occupied by Globular Clusters and Galaxies within 50 Mpc
(GWGC catalog White et al. 2011, CQG 28, 085016)

Nearby galaxies and globular clusters (< 50 Mpc) are weighted to select the most probable host of a GW trigger:

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

- **Likelihood** based on GW data
- **Mass** and **Distance** of the galaxy or the globular cluster

Probability Skymap for a simulated GW event

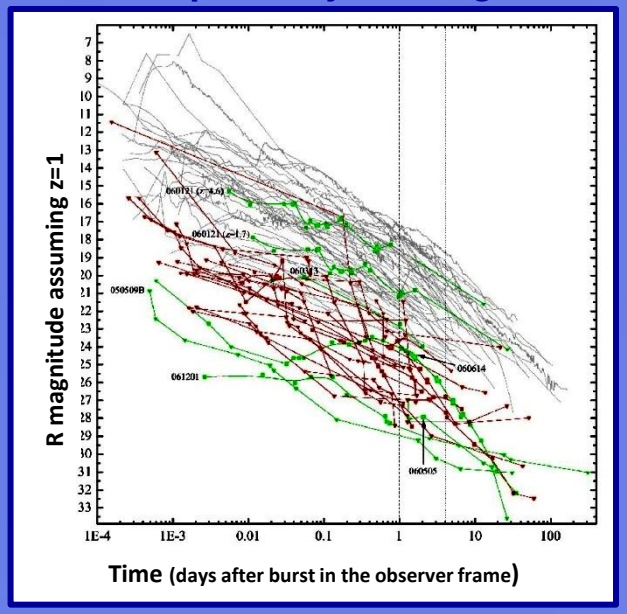


- Black crosses ➡ **nearby galaxies locations**
- Rectangles ➡ **pointing telescope fields chosen to maximize the chance to detect the EM counterpart**

The expected EM counterpart afterglows guide observation schedule time

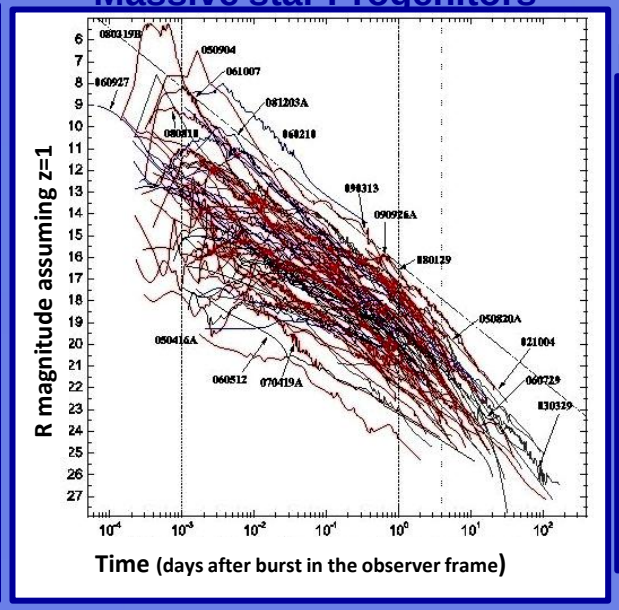
Optical Afterglows:

SHORT/HARD GRB
Compact Object mergers



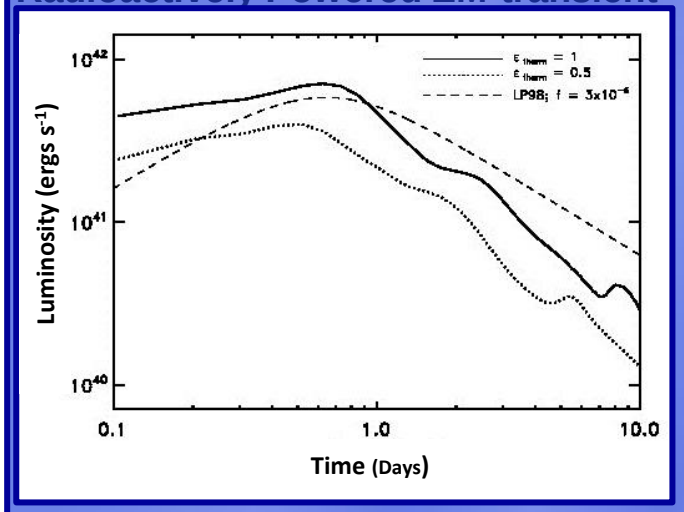
Kann et al. 2011, ApJ, 734.96

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

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

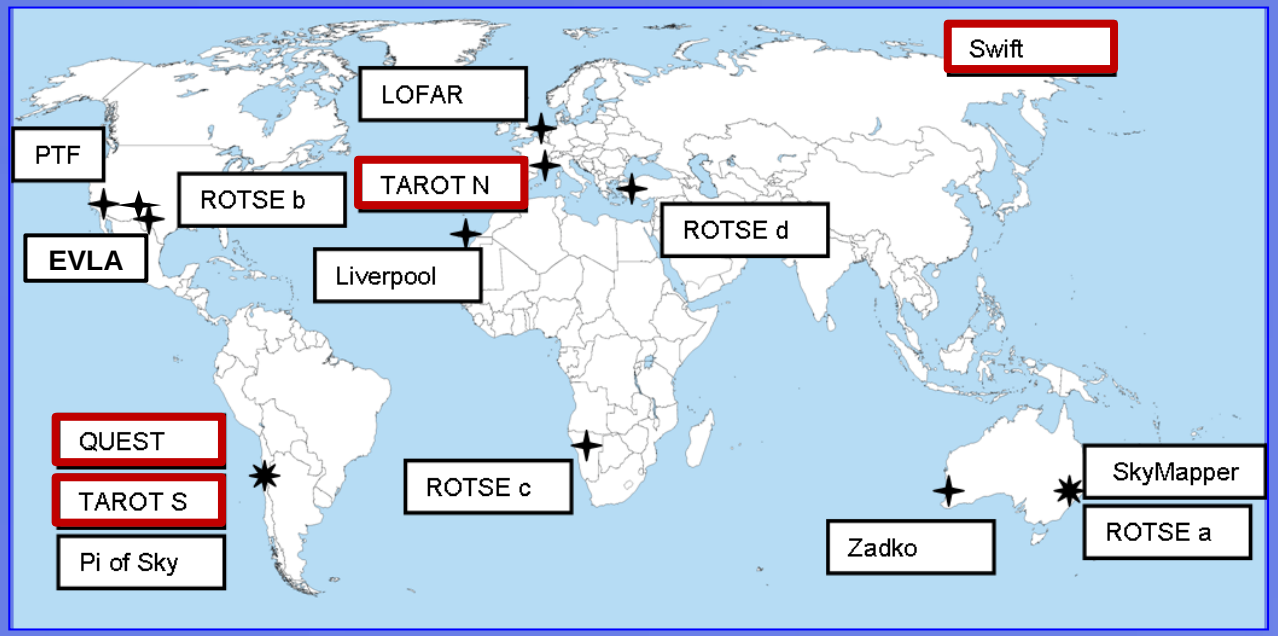
Kilonova model afterglow peaks about **a day** after the GW event

→ **EM observations a day after** the GW trigger validation

To discriminate the possible EM counterpart from contaminating transients

→ **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/Summer Run

Only Summer 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

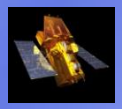
Pi of the Sky
400 sq. degree FOV

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 - **25** sq. arcminute FOV

Optical Telescopes

Winter run ➡ **8** candidate GW triggers, **4** observed by at least one telescope

Summer run ➡ **6** candidate GW triggers, **5** observed by at least one telescope

Analysis Procedure for Wide Field Optical Images

Limited Sky localization of GW interferometers

⬇

Wide field of view optical images

⬇

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

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

1) **Detection** of all **"Transient Objects"** visible in the target images
2) **Discriminate** the **EM-counterpart** from "Contaminating Transients"

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**

The **removing of contaminating transients** is one the **main challenges** due to the **"large sky area"** to analyze

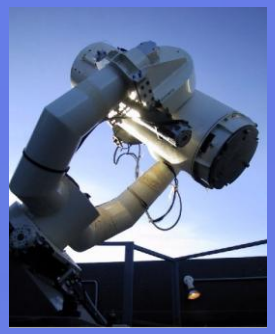
image areas occupied by globular cluster and galaxies (< 50 Mpc)
that take into account the possible offset between the host center and the transient

The next 5 slides focuses on a

Fully automated "Catalog-based Detection Pipeline"

developed for images taken with **TAROT** and **Zadko telescopes:**

methodology and preliminary results obtained using images where simulated transient are injected

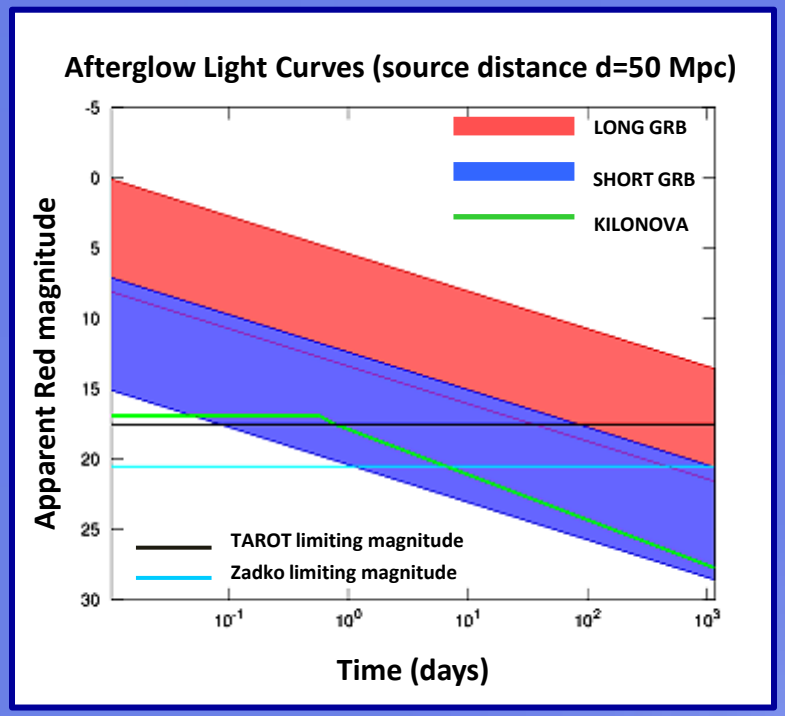


TAROT South/North

- **0.25 meter** telescope
- FOV **3.4** sq. degrees
- **Single Field** Observation of **180 s** exposure
- Red **limiting magnitude** of **17.5**

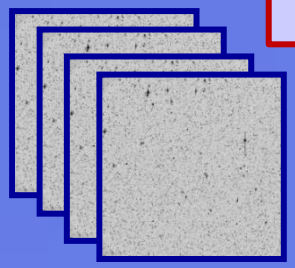
Zadko

- **1 meter** telescope
- FOV **0.17** sq. degrees
- **Five Fields** Observation of **120 s** exposure
- Red **limiting magnitude** of **20.5**



"Afterglow light curves" for LONG/SHORT and Kilonova transients at a distance of 50 Mpc

Catalog-based Detection Pipeline – Octave Code



detect sources in each image

SExtractor ➡ build catalog of all the objects visible in each image

select "unknown objects"

Match (Valdes et al 1995; Droege et al 2006) ➡ to identify "known stars" in **USNO catalog** (catalog of stars)

Magnitude consistency

Recover possible transients that overlap with "known obkects":
|USNO_mag – TAROT_mag| > 4σ

reject cosmic rays, noise, asteroids

search for objects in common to several images

Spatial cross-positional check

reject background events

"ON-SOURCE" ANALYSIS
regions occupied by galaxies with a distance within 50 Mpc

ALL-FOV ANALYSIS
select objects with magnitude brighter than a threshold

"Light curve" analysis: slope index

reject "contaminating objects" (galaxy, variable stars, false transients..)

"Light curve" analysis - cut based on the expected luminosity dimming of the EM counterparts

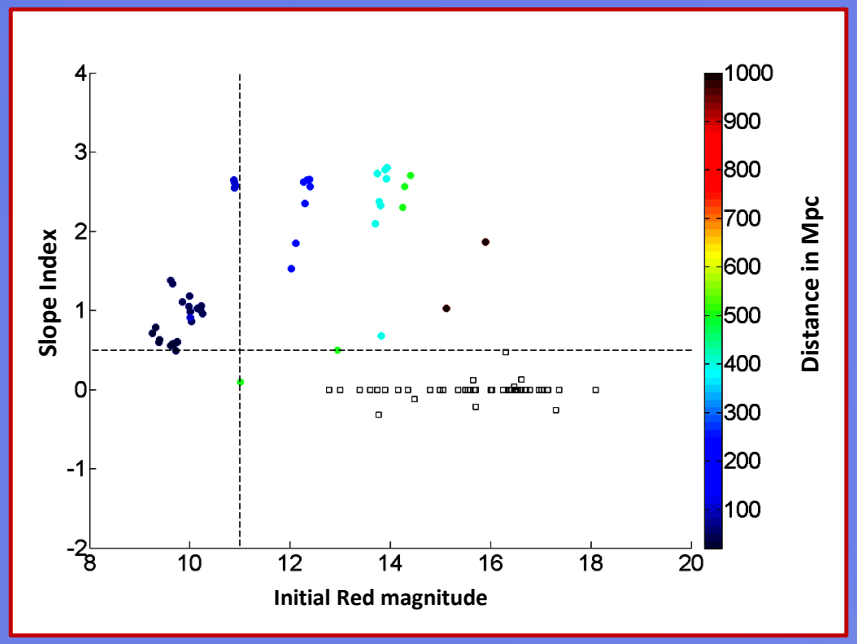
recall magnitude α [$-2.5 \log_{10}$ (Luminosity)]

expect Luminosity α [time$^{-\beta}$] $\longrightarrow$ magnitude = [2.5 $\beta \log_{10}$(time)]+k

slope index = measurement of **(2.5 β)**

to discriminate expected light curve from "contaminating events"

The expected slope index for SHORT/LONG GRB is around 2.7 and kilonova is around 3



Coloured points = Optical LGRB Transients
Black squares = contaminating objects

Optical counterparts the ones with slope index > 0.5

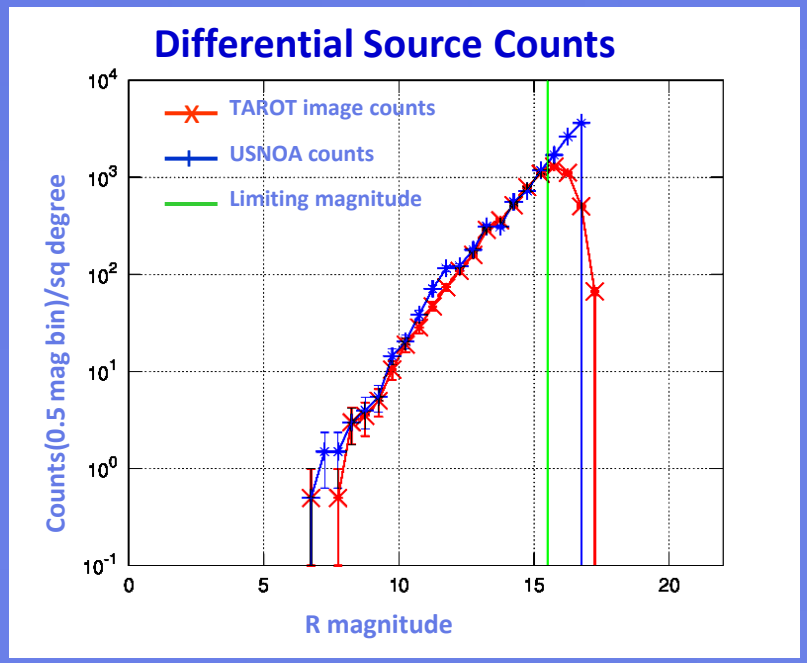
Contaminating objects that could pass the cut are only variable AGN or Cepheid stars

Image Sensitivity – Limiting Magnitude

used a set of 10 test TAROT images (**180 sec** exposure)

⬇

limiting magnitude of 15.5 for all images



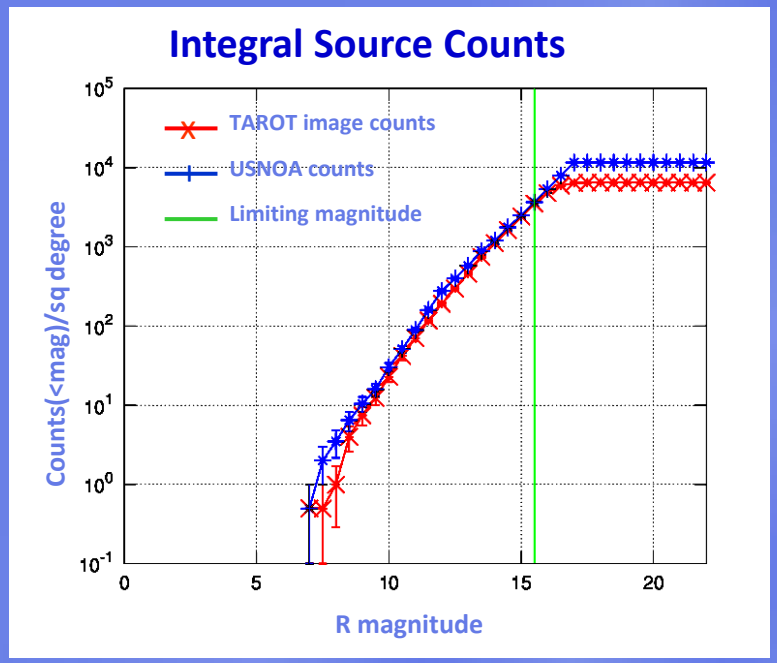


Image Limiting Magnitude:

point where **Differential/Integral Source Counts distribution** (vs magnitude) bends and moves away from the power law of the reference USNOA

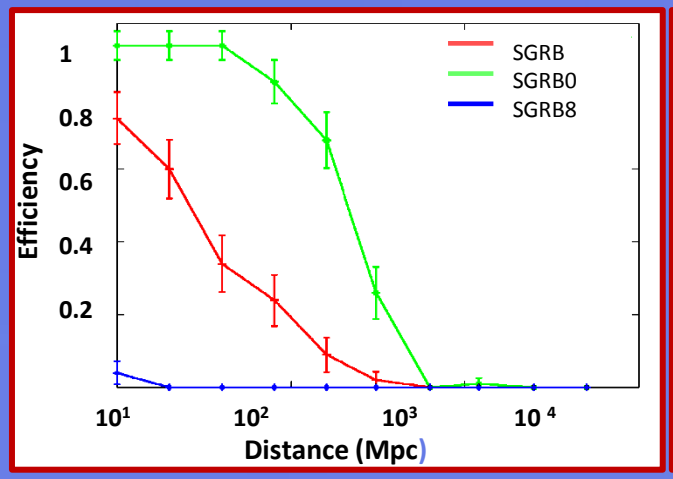
Preliminary results on Sensitivity: obtained by running the ***Detection Pipeline*** over images with **injections of Fake Transients**

Monte Carlo simulations at the Computing Center in Lyon:

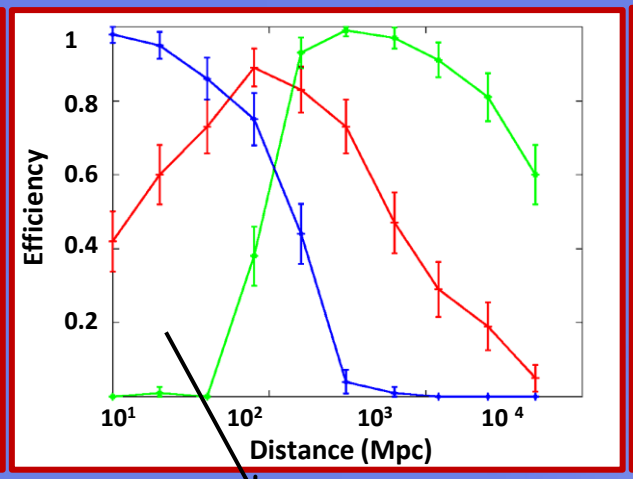
Time origin (time of GW trigger) set 1 day before the first image

Time latency for the images 1, 2, 3 days after the GW trigger

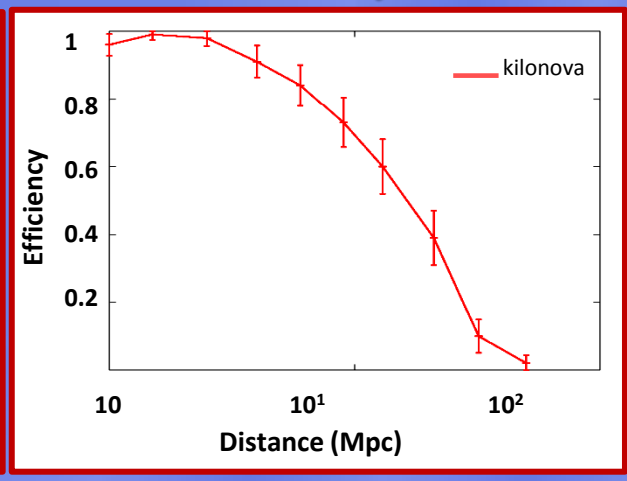
SHORT/HARD GRB



LONG/SOFT GRB



Kilonova Objects



SGRB, LGRB→ intrinsic luminosity range parametrized by a magnitude offset 0 ÷ 8

SGRB, LGRB: random offset 0 ÷ 8

SGRB0, LGRB0: offset set to 0

SGRB8,LGRB8: offset set to 8

Efficiency loss at low distances is an **artifact of the "injection code"** not able to reproduce saturated objects

Distance_50% horizon (Mpc):

SGRB	SGRB0	SGRB8	LGRB	LGRB0	LGRB8	Kilonova
30	230	------	600	5000	160	15

Swift Satellite: X-ray and UV/Optical telescope

(LIGO/Virgo + Swift team members)

2 candidate GW-trigger alerts sent to **SWIFT**

- **XRT** — **0.3 – 10 keV**, **0.15 sq. degree FOV**
- **UVOT** — **170 to 600 nm band**, **0.08 sq. degree FOV**

Observation Strategy:

- possibility to observe **five 0.15 sq. degree XRT-FOV** for each GW-trigger
- **two-time** observations : time latency few months
- **exposure time: 10 ks** to split within fields necessary to cover the target

X-ray image analysis :

- **detection of the X-ray sources** visible in the FOV
- **comparison with the number of seredipitous sources** expected in the FOV that is estimated using the 2XMMi-DR3 catalog source counts
- **light curve** of each source to investigate the variability

Optical and UV analysis:

- search of the **UVOT counterparts** of the X-ray sources detected with XRT
- **cross-check with DSS** catalog to identify “unknown objects” or objects that show flux variations
- **light curve** to investigate source variability in the images

Radio Interferometers

Radio-band Advantages:

- **observations in daylight** and **no obscuration by dust**
- **radio arrays** (nowadays **LOFAR**) **cover multiple sky patches of few tens of sq. degrees in a single observation**

Possibility to observe EM-counterpart not detected in other EM-bands

LOw Frequency ARray

- currently **36 antennas:** Core in the Netherlands + stations across Europe
- Frequency range: **30-80/110-240 MHz**

5 candidate GW-trigger alerts sent and observed by **LOFAR**

Observation Strategy:

- **Four-hour observation** in LOFAR high frequency band ➡ **25 sq. degree** FOV

Analysis Strategy (LIGO/Virgo + LOFAR Transients Key Project members):

- **transient detection** and **estimation of astrophysical/technical radio background**

"Technical Challenges" :

- **automated analysis procedure** to detect transients still **under development**
- **low-frequency sky:** noise transients from the atmosphere (like meteor trail) and time/space varying ionosphere

The analysis of radio data for the 5 target fields is on-going

Expanded Very Large Array

- Array of **27 antennas**, each of which **25 meters** in diameter
- Point-source sensitivity after one hour observation between **2** and **6μJy** (1 and 50 GHz)
- FOV of **25 sq. arcminutes** at 5 GHz

Observation Strategy:

- **Low-Latency Follow-up** (October 14 to 20) → **No Science GW-trigger**
- **High-Latency Follow-up** → **2 GW-triggers** (fisrt days of October)

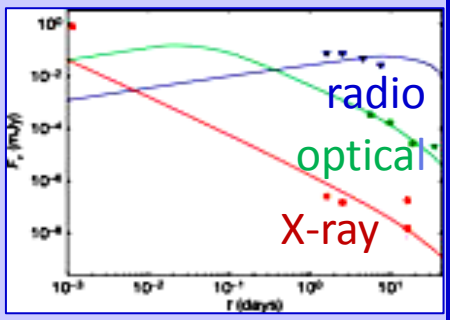
Observation Latency: 3 weeks, 5 weeks + 8 months later

Observation Frequency: 5GHz, bandwidth 128MHz

TARGET: 3 most likely host galaxies (< 50 Mpc) for each GW-trigger

Mosaic of pointings if galaxy size exceeds 5 arcmin

Integration Time: 30 minutes for each galaxy



Fox et al. 2005, Nature 437,835

Analysis Strategy (LIGO/Virgo + radio-astronomers):

- **detection** of the **radio sources** in the FOV
- **light curves** for variability study
- **identification of contaminating radio sources,** like Radio Active Galactic Nucleii

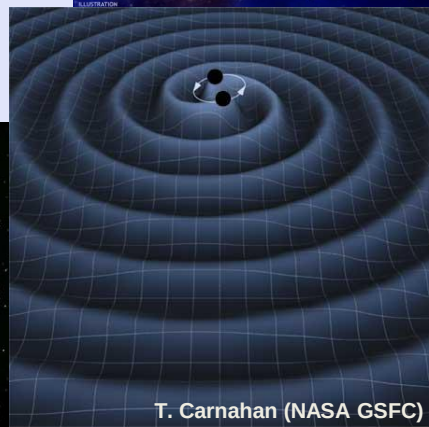
Conclusions:

- 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 **under test** and **development** for the different EM-bands

- Evaluation of the **rate of EM-false detections** (unrelated to the GW event and observed by chance in the field) **due to astrophysical or technical contaminants** is **under study** for each analysis procedure and EM-band

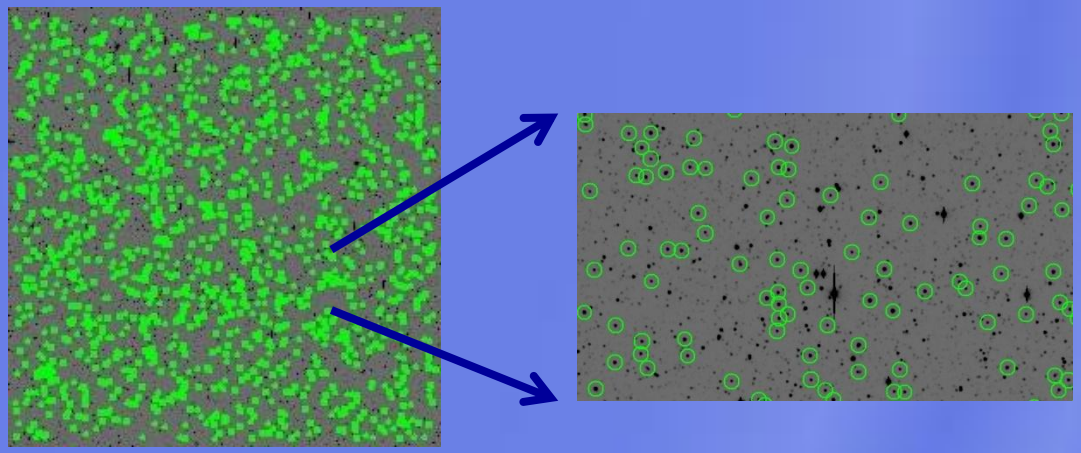
- **The analysis of the images observed during the Winter/Summer LIGO/Virgo run is on-going**



Extra Slide

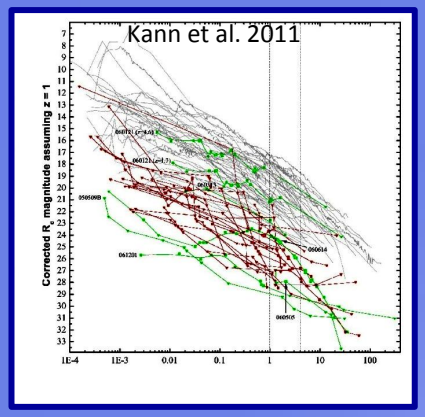
Injection Pipeline

Selection of model stars nearby to the injection position in order to take into account the PSF variations

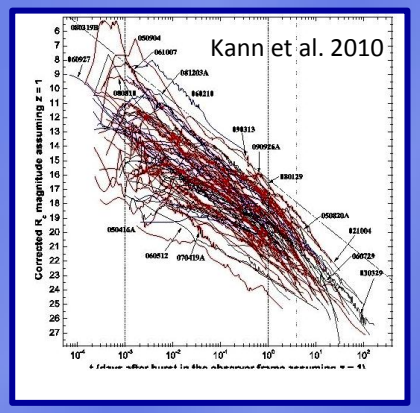


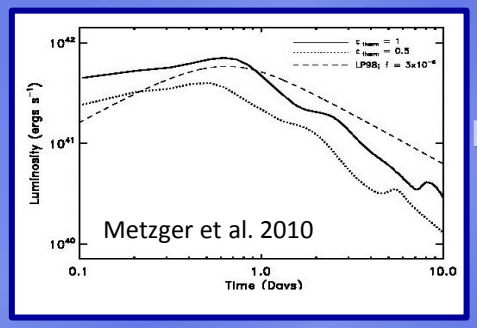
Injection by normalizing the star magnitude to the magnitude expected for on-axisSHORT/LONG GRB or Kilonova object at different times after the GW/EM prompt event

SHORT/HARD GRB



LONG/SOFT GRB





KILONOVAS