TAUP Topics in Astroparticle and Underground Physics

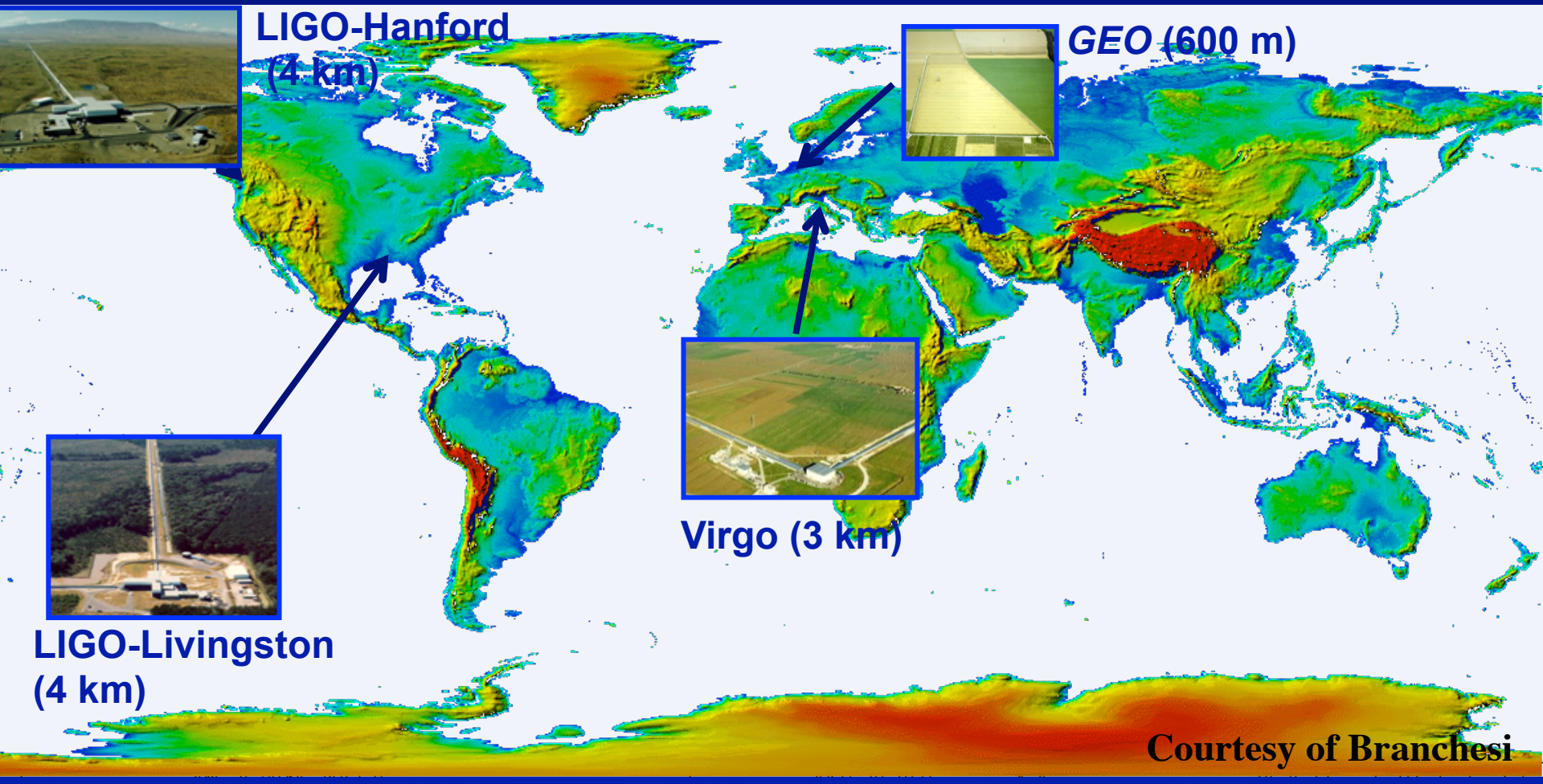
Electromagnetic follow-up of gravitational wave candidates

Silvia Piranomonte

(Istituto Nazionale di AstroFisica Osservatorio Astronomico di Roma)

on behalf of a larger collaboration ..

Ground-based Gravitational Wave Detectors



LIGO and Virgo detectors are currently being upgraded and will observe the sky (10-1000 Hz) as a single network aiming at the first direct detection of GWs

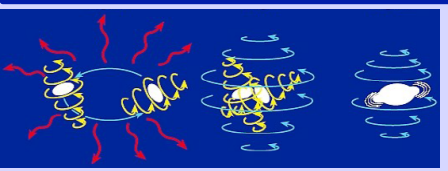
Expected "transient" GW sources detectable by LIGO/Virgo

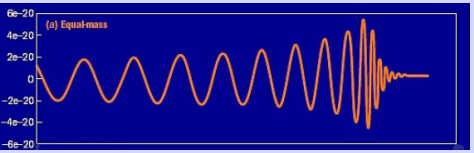
"**Transient GW signal**: signal with duration in the detector sensitive band significantly shorter than the observation time and that cannot be re-observed

Coalescence of Compact Objects

Neutron-Stars and/or Black-Holes

Inspiral | Merger | Ringdown

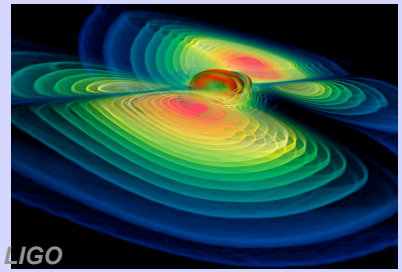




Binary containing a NS:

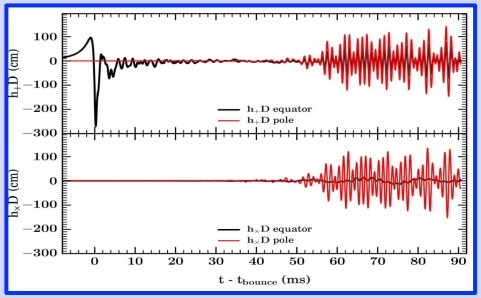
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz) **< 20 s before merger**
- **Energy emitted in GW: ~$10^{-2} M_o c^2$**

Initial LIGO/Virgo
Binary containing a NS detectable to ~50 Mpc
likely rate **0.02 yr^{-1}**



Courtesy of Branchesi

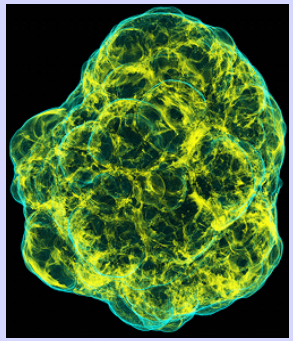
Core-collapse of Massive Stars



Ott, C. 2009, CQG, 26

Energy emitted in GW uncertain: **10^{-8} - 10^{-4} $M_o c^2$**

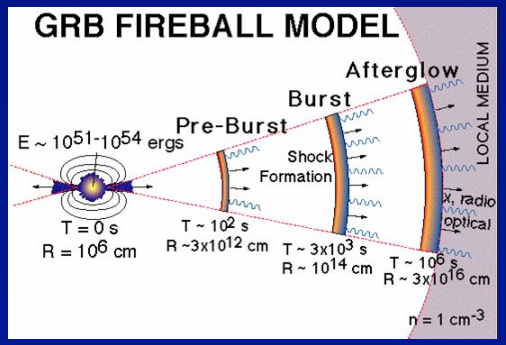
Initial LIGO/Virgo
Detectable within a fraction of the Milky Way (10 kpc)



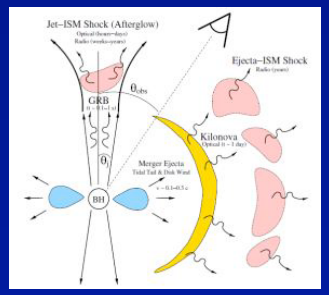
Ott et al. 2013, ApJ, 768

Energetic astrophysical events which are expected to emit EM radiation

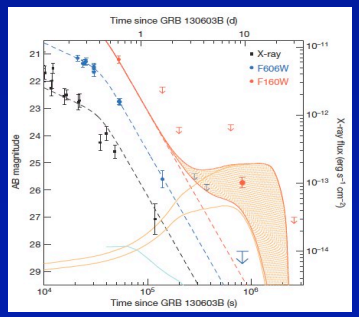
Long Soft Gamma-ray burst



Short Hard Gamma-Ray Bursts



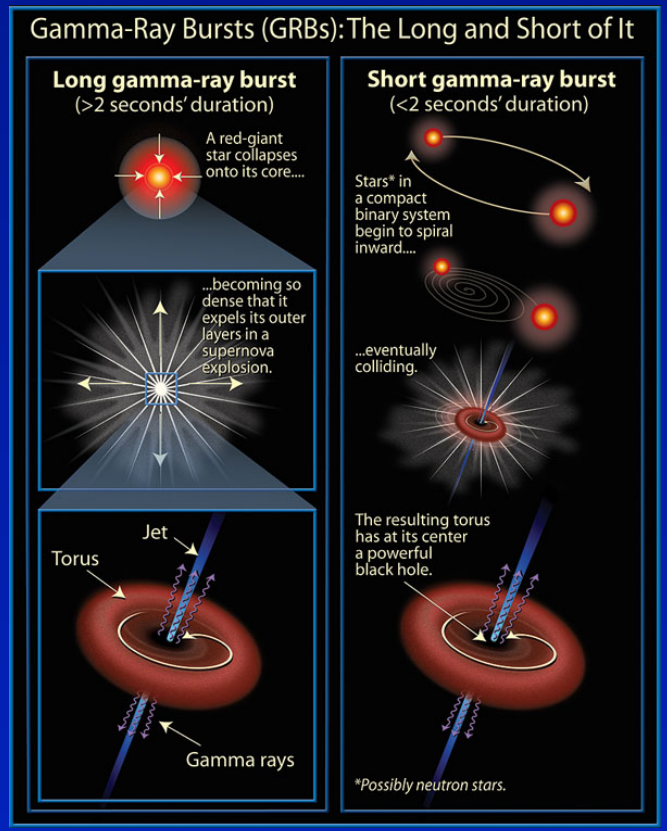
Metzger & Berger 2011



Berger et al. 2013
Tanvir et al. 2013

Ejection of r-process material from a NS merger (0.01-0.1 Mo)

Supernovae

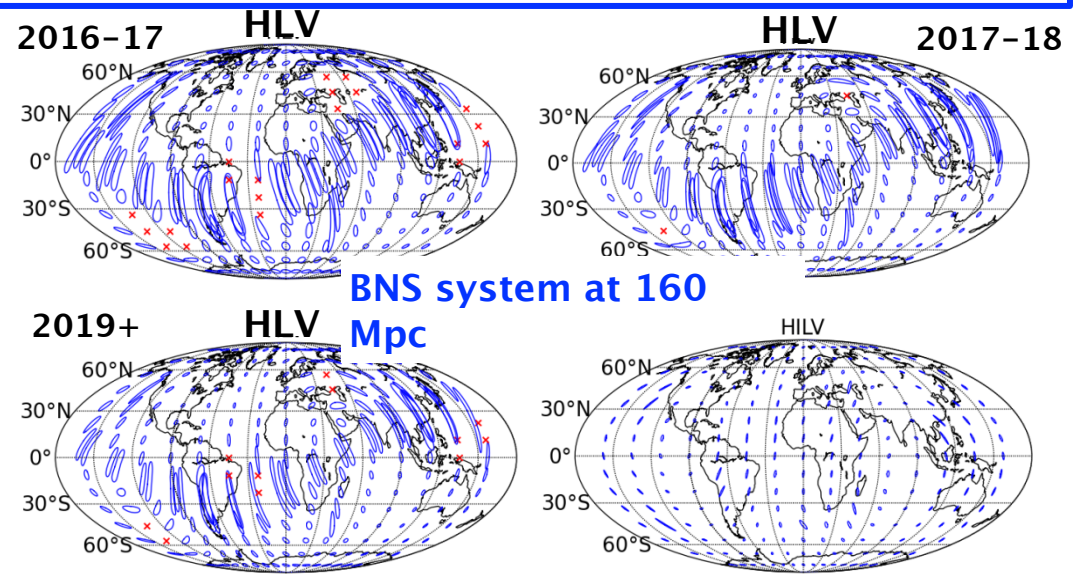


Optical Kilonovae Radio Remnant

Advanced GW detector era observing scenario

Position uncertainties with areas of **tens to hundreds of sq. degrees**

BNS system at 80 Mpc



BNS system at 160 Mpc

⬭ → 90% confidence localization areas

X → signal not confidently detected

Summary of plausible observing scenario

LSC & Virgo collaboration
arXiv:1304.0670

aLIGO/Virgo Range	Rate	Localization

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	% BNS Localized within $20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Courtesy of Branchesi

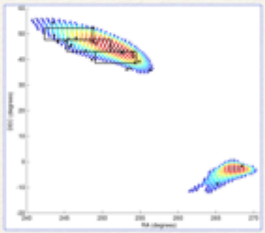
Advanced GW detector observing scenario

GW triggers

LIGO-H LIGO-L

Virgo

Sky Pointing Position



Event validation

EM facilities

EM FOLLOW-UP TEAMS

"Search Algorithms" to identify the GW-triggers

"Software" to identify GW-trigger for the EM follow-up:

- select statistically significant triggers wrt background
- determine telescope pointing

10 min. → 30 min.

ADE latency expected to be improved!

Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541
Evans et al. 2012, ApJS 203
Aasi et al. 2014, ApJS, 211

Courtesy of Branchesi

GW Electromagnetic follow-up

Electro-magnetic (EM) follow-up
PROBLEMATICS:

- several 10-100 deg^2 sky areas to cover
- large number of false positive events (background SNe, stellar flares, AGN flares, etc.)
- unknown EM counterparts in many cases (e.g. off-axis GRB, kilonova)
- unknown timing (e.g. light curve morphology of transients)
- EM follow-up will face the well known problem of conciliate large sky coverages with sufficient depth

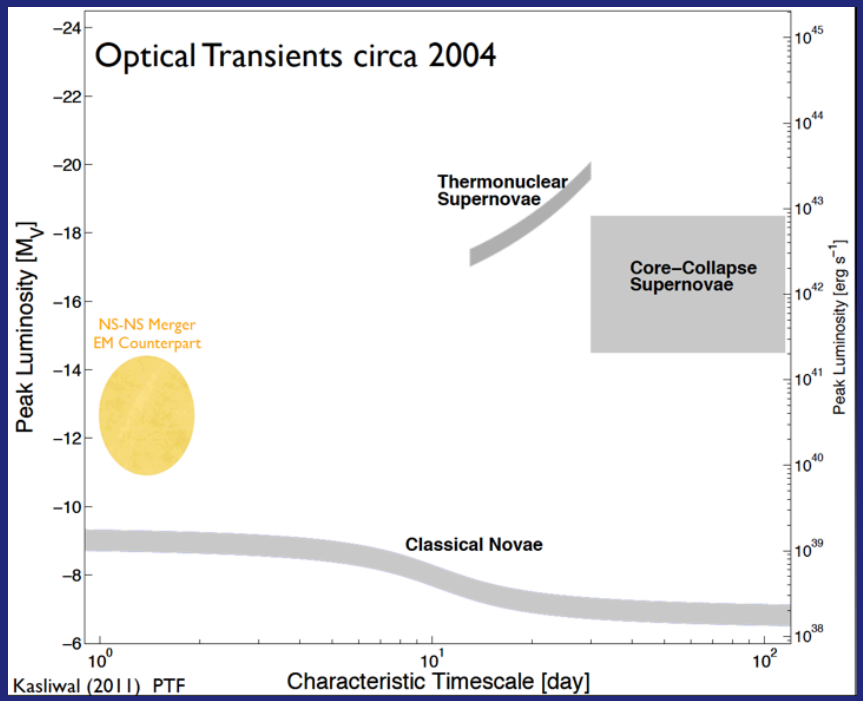
GW Electromagnetic follow-up

...but just some of the many ADVANTAGES:

- Assess the astrophysical nature of a GW event
- Localize the GW source down to arcsecond level and individuate its host galaxy from which we can measure the distance
- GW source can be identified and characterized through EM spectra and light curve
- strong feedback with GW data analysis
- first GW+EM studies of astrophysical sources (mass, spin, distance, system orientation,...)

The EM Counterpart Challenge

Time Domain Astronomy is the gateway to EM counterparts of GWs



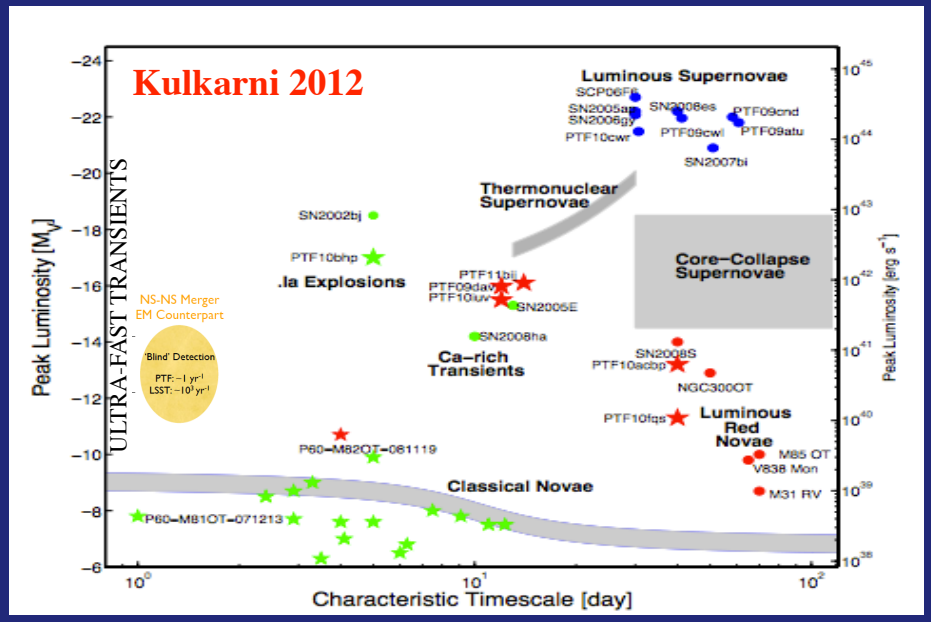
Therefore it will be important

1) to have **optical survey to study the astrophysical transients** in the space-time search region but not directly associated with a GW event

2) to have algorithms for a rapid discovery and classification of transients over a wide sky area

3) to select a small number of counterpart candidates that can be promptly followed-up spectroscopically

4) uniquely identify the optical counterpart of the GW trigger



NS-NS/BH Mergers:

- Large FOV ~several sq.deg
- rapid decay ≲ day
- sensitivity to sources ~ 30 x fainter than SNe

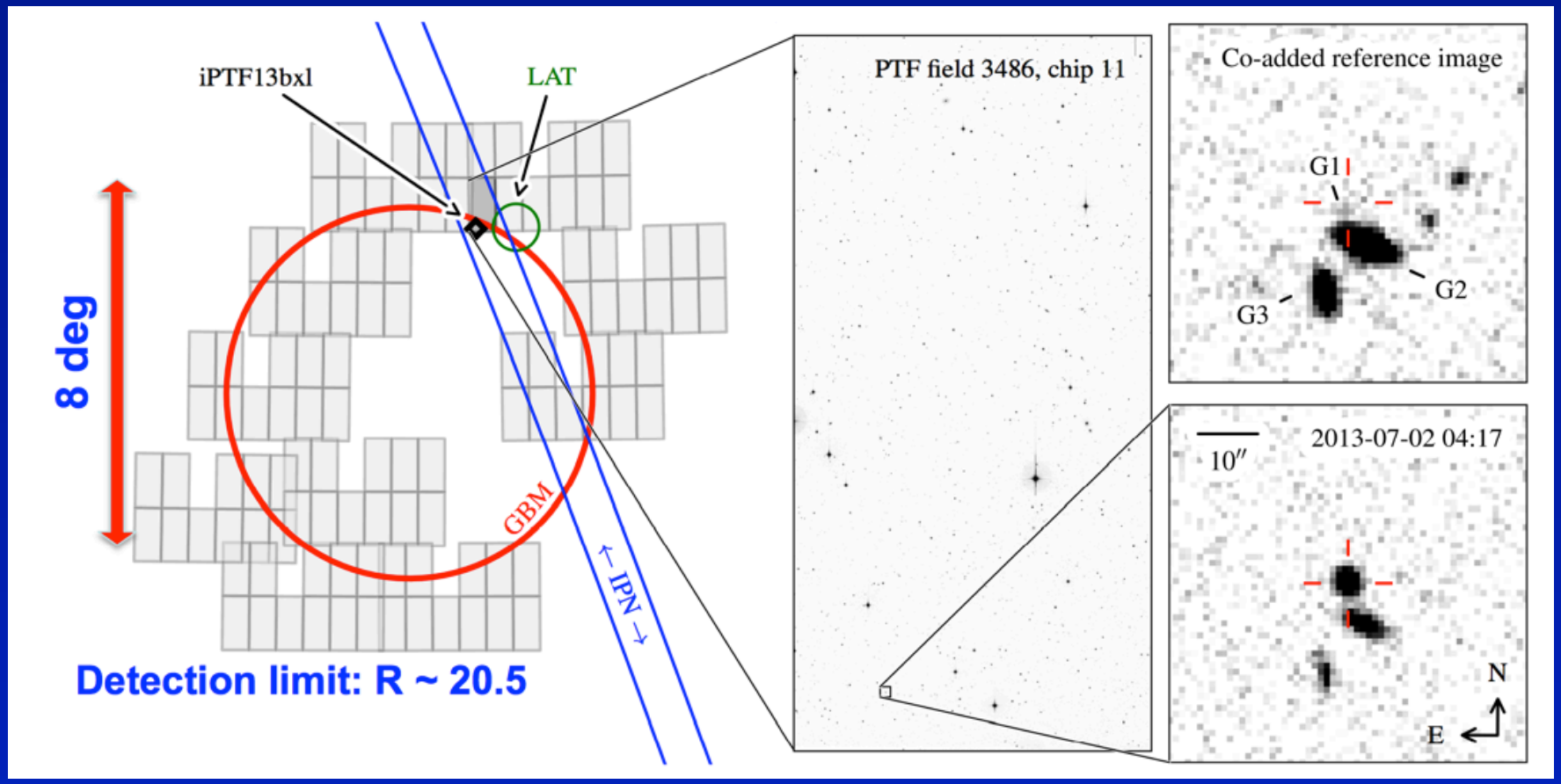
optical imaging surveys: PTF, LSST, ...

Discovery of the optical GRB130702A afterglow: a successful test!

PTF - Palomar Transient Factory

"The case of GRB 130702A demonstrates for the first time that optical transients can be recovered from localization areas of ~100 deg2, reaching a crucial milestone on the road to Advanced LIGO."

Singer et al. 2013:
"We report the discovery of the optical afterglow of the γ-ray burst (GRB) 130702A, identified upon searching 71 deg2 surrounding the Fermi Gamma-ray Burst Monitor (GBM) localization."



INAF (Istituto Nazionale di Astrofisica) signed the MOU with LVC and decided to participate in the EM follow-up program <u>as an Institution</u>

To: The LIGO Scientific Collaboration and Virgo Collaboration
Professor G. Gonzales and Dr. J.-Y. Vinet

Subject: Letter of Interest in EM identification and follow up of GW candidate events by the Italian Istituto Nazionale di Astrofisica (INAF)

To whom it may concern,
as Science Director of INAF I express herewith the interest to involve selected italian observational resources in the advanced gravitational-wave detector era (ADE) EM-follow-up. In particular, to seize the opportunity of performing the follow-up of GW transients INAF intends to deploy two well suited facilities: i) VLT Survey Telescope (VST), and ii) the Campo Imperatore optical and near-IR telescopes.

The key requirements for telescopes to be suitable for the ADE follow-up are: 1) a large field of view, 2) a deep sensitivity and 3) a rapid response time with the possibility to repeat observations over longer time scale. These needs are mainly due to the expected large position uncertainties of many tens to hundreds of square degrees of GW detections (Aasi et al. 2013, arXiv:1304.1775), and to the emission properties of the expected EM counterpart (GRBs, kilonovae and Supernovae).

Project 1, VLT Survey Telescope - The 2.6m VLT survey telescope (VST), which is operating at Cerro Paranal, has remarkable strengths by design that let it be an optimal instrument to be involved in the effort to catch the elusive optical signature of GW signals:

- **Deep sensitivity and high image quality over a large sky area** The VST has a 1 deg x 1 deg corrected field of view, which the wide-field imager OmegaCAM (http://www.astro-wise.org/~omegacam/) samples with a 32-CCD, 16k x 16k detector mosaic at 0.21 arcsec per pixel. The field distortion is very low and the expected limiting magnitude in V band is 25.5 AB mag per square arcsec for 30 min exposures (Capaccioli et al. 2003, Mem. SAIt, 74, 450).
- The **excellent seeing** at Cerro Paranal and the image **pixel-scale**, which adequately samples even the best seeing conditions (0.4-0.5 arcsecond), are crucial to identify faint transient point sources, even in crowded fields and complex background conditions.
- The telescope operates from the **UV- to I-band allowing us to perform multicolor studies of the transients**, essential to select the candidate counterparts within contaminant foreground/background transients on the basis of the spectral features.
- The technical **response time** of VST for a trigger is expected to be of the order of ~ 30 min. An example of limiting magnitudes (for a point like source and in the Vega system) suitable for the detection of the EM counterpart of a GW source are summarized in table 1. Including all the camera and telescope overheads, **the time required to cover a sky area of 10 deg^2** with the Sloan bands u', g' and r' with a S/N ≥ 5 is ~ 1 hour.

Filter	Exposure time (s)	S/N	Limiting magnitude
u'	90	5	22.2
g'	45	7	23
r'	45	5	23

Table 1: VST throughput in u',g',r' SDSS filter.

- In 2016 the amount of **INAF-Guaranteed Time Observation (GTO) will increase up to** 15% **of the total observing VST time**.
- Thanks to the GTO availability, **specific VST-survey** will be planned to monitor short time-scale transients.
- The actual use of the VST as a "survey instrument" provides an archive with a large quantity of reference images of the southern sky.

Project 2, The Campo Imperatore Transient Experiment (CITE) and the near-IR telescope, AZT-24 - The CITE is a project that proposes to develop an innovative wide field imager, characterized by an 8.8 **square degrees FoV**, to be installed at the 60cm Schmidt telescope of Campo Imperatore (Aquila, Italy). The camera will be characterized using the Campo Imperatore (CI) telescope in view of its application on a new generation of robotic wide field telescopes.

LIGO-Virgo Event Follow-up Program

This form will be attached to the Memorandum of Understanding.

Full name of the partner project: **Project of Istituto Nazionale di Astrofisica**

Abbreviated name: **INAF-project**

Project web site (if available): **http://www.inaf.it/en**

Name, institution, email and title[1] of the leader(s) (who will sign the MOU):
Professor Gianpaolo Vettolani,
INAF, Via Parco Mellini, 84
I – 00136 Roma
dir.scient@inaf.it
Scientific Director of INAF

Name, institution, email, and phone numbers of the liaison with LVC:
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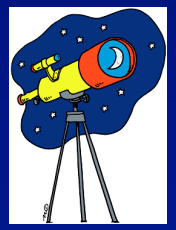
Luigi Stella, INAF-Osservatorio Astronomico di Roma,
luigi.stella@oa-roma.inaf.it, +39 06 94286436

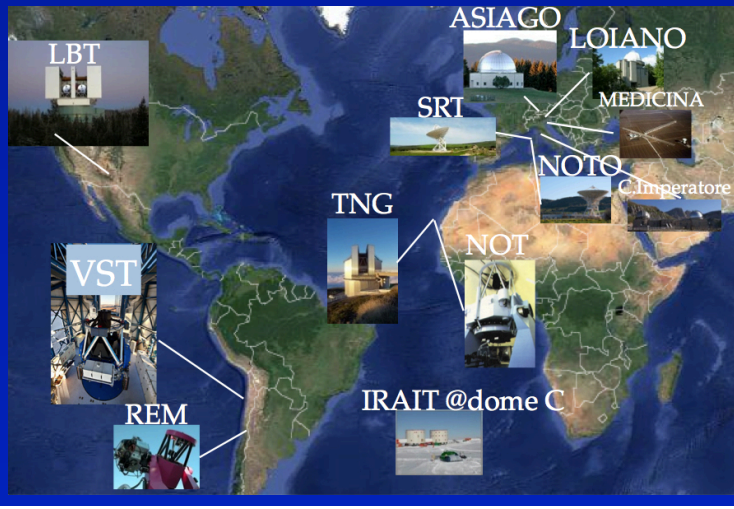
List of associated members (name, institution and email):
INAF is an institution and will sign the MoU on behalf of its members who will be involved in the EM project. The members will be required to sign a "disclaimer" to respect all the rules of the actual MoU.

INAF GW Electromagnetic follow-up collaboration

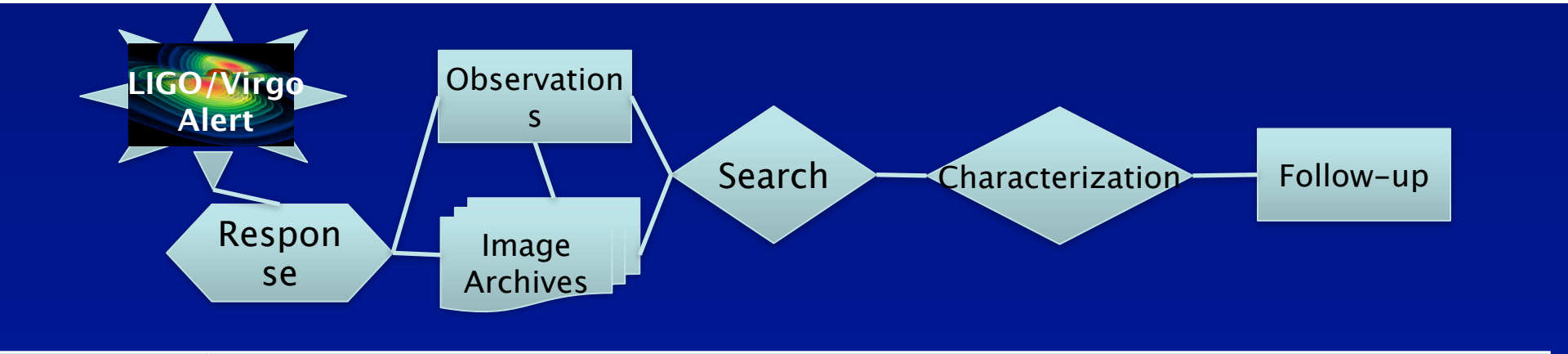


INAF OA Roma: **E.Brocato**, L. Pulone, V.Testa, M. Castellani, G. Iannicola, L.A. Antonelli, L. Stella, M. Lisi, G. Bono, G. Fiorentino, S. Piranomonte, A. Passamonti, G. Giuffrida, S. Marinoni, R. da Silva
INAF OA Napoli: **A. Grado**, F. Getman
INAF IASF Bologna: **L. Nicastro,** E. Palazzi, L. Amati, L. Masetti, D. Vergani, A. Bulgarelli, G. De Cesare, A. Rossi, P.G. Sprimont
INAF OA Milano: **S. Campana**, S. Covino, G. Tagliaferri, P. D'Avanzo, A. Melandri, M.G. Bernardini
INAF OA Padova: **E. Cappellaro**, L. Tomasella
Univ. Urbino: **M. Branchesi**, G. Stratta, G. Greco
SNS Pisa: **E. Pian**, A. Stamerra, F. Longo, M. Razzano, G. Pivato, B. Patricelli, G. Cella

Human resources: ~ 160 FTE/year
Know-how: Time Domain Astronomy, Observational Strategy, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Data Interpretation, Theoretical models
Multi-wavelength Observing Facilities:
Visible: VST, LBT, TNG, NOT + ESO +small telescopes [REM, 1.82m (Asiago, IT), 1.52m (Loiano, IT), 0.9m C. Imperatore,IT)]
Near-mid IR: 1.1m AZT-24 (C. Imperatore,IT), IRAIT (Antarctica)
Radio: 64m SRT (Cagliari, IT), 2x 32m (Medicina and Noto, IT)
High energy: space(Swift, Fermi..) + ground (ASTRI, CTA)
Near future: SOXS@NTT + NTE@NOT key tools for GWfollow-up



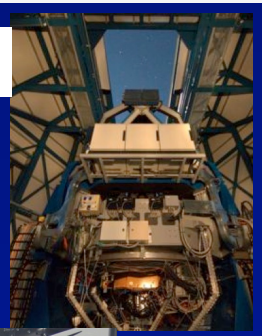
INAF GW Electromagnetic follow-up collaboration



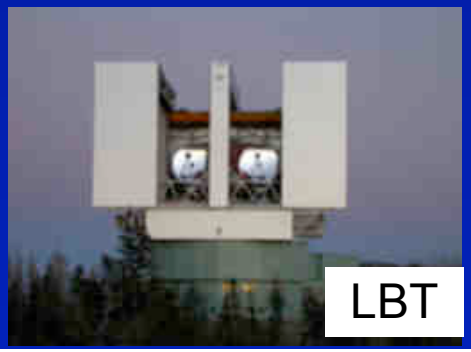
Work package	Involved Research Units	Goals
WP1	Rome, Urbino, Bologna, Milan	***Response*** of the GW alerts by LIGO/VIRGO Collaboration. Simulation and observational strategies. Contact with LVC researchers. GW Astronomy.
WP2	Naples	**Observations:** VST observational operations following GW alerts. Pre-reduction of VST images.
WP3	Rome, Bologna, Padua	**Search** of counterpart candidates in wide field images (VST and other Wide Field telescopes) and find their positions in the LVC error box. Software pipeline. Archiving activity.
WP4	Padua, Bologna, Milan, Pisa, Rome	**Characterization** of the candidate counterparts found in WP3 to identify a few possible astrophysical objects most likely emitting the GW signal. Spectroscopic and multi-wavelength observations and their data analysis.
WP5	Bologna, Milan, Padua, Pisa, Urbino, Rome	**Follow-up** of the counterpart(s) found in WP3/WP4 to study their physical properties. Spectroscopy, light curves, multi-wavelength observations at ground (ESO-VLT, LBT etc) and space facilities. Relationship with EU partners.

Alert from LVC: starting a EM-follow up

VST



VLT



LBT

STEP 1
Search & Detect
Transients in the error box provided by LVC have to be discovered and measured
as soon as possible

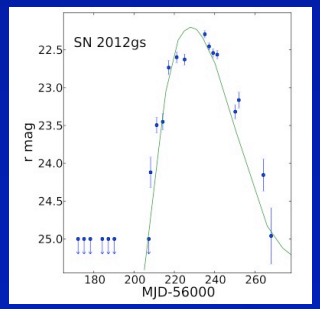
STEP2
Observe & Characterize
The detected transients have to be observed to infer their nature

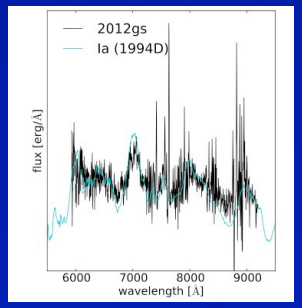
STEP 3
Follow & Study
Follow-up at all observable λ for an adequate time to study the physical properties of
the EM counterparts of GW

Telescopes to find transients in the LVC error box
Distributed at different latitudes/longitudes

Computing Facilities "Fast" and "Smart" software to select a handful of transients

Telescopes to obtain spectral features of transients





time

λ

INAF Observation Procedure: from GW alert to ToO

To determine the telescope pointing position: The probability skymap of each GW trigger was 'weighted' taken into account **luminosity** and **distance** of nearby galaxies and globular clusters

GCN/LVC_TEST_INITIAL_SKYMAP - TITLE: GCN/LVC NOTICE NOTICE_DATE: Mon 07 Sep 15 00:36:19

Function to call every time a GCN is received

-

automatic download from GraceDB

-

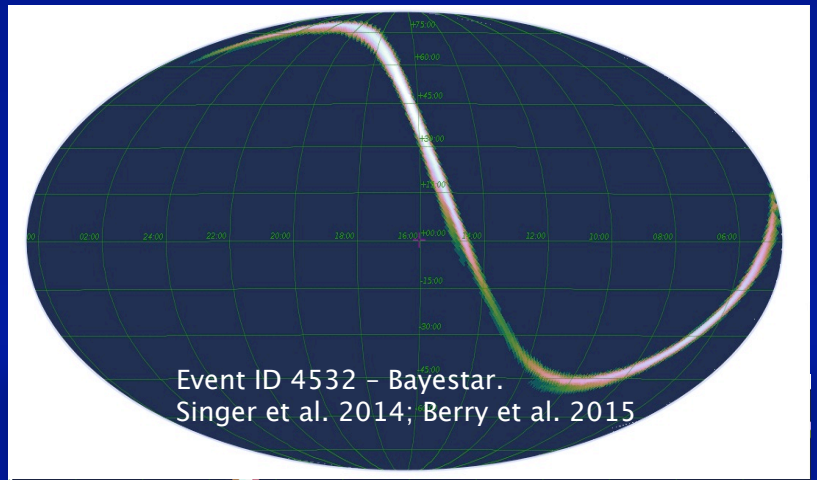
healpix sky map reprojected (3° x 3°)

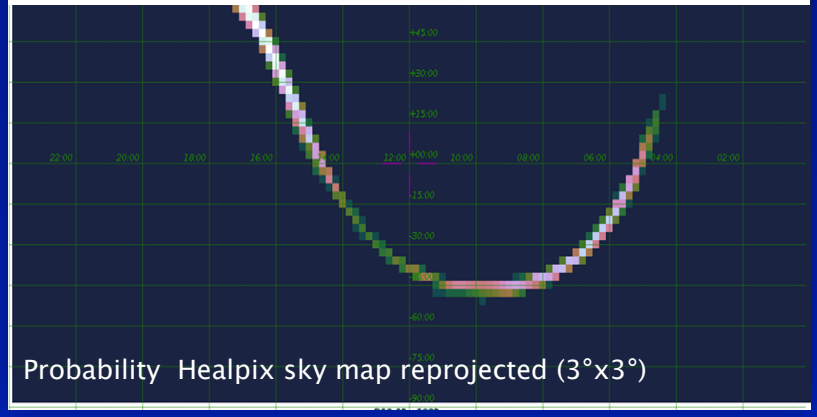
-

observability calculation at VST site

-

Target of Opportunity request form





*The pipeline is based on the python codes provided by the TechInfo page
https://gw-astronomy.org/wiki/LV_EM/TechInfo

WIDE-FOV telescopes to cover the GW error box

VST - 2.6m VLT Survey ESO telescope

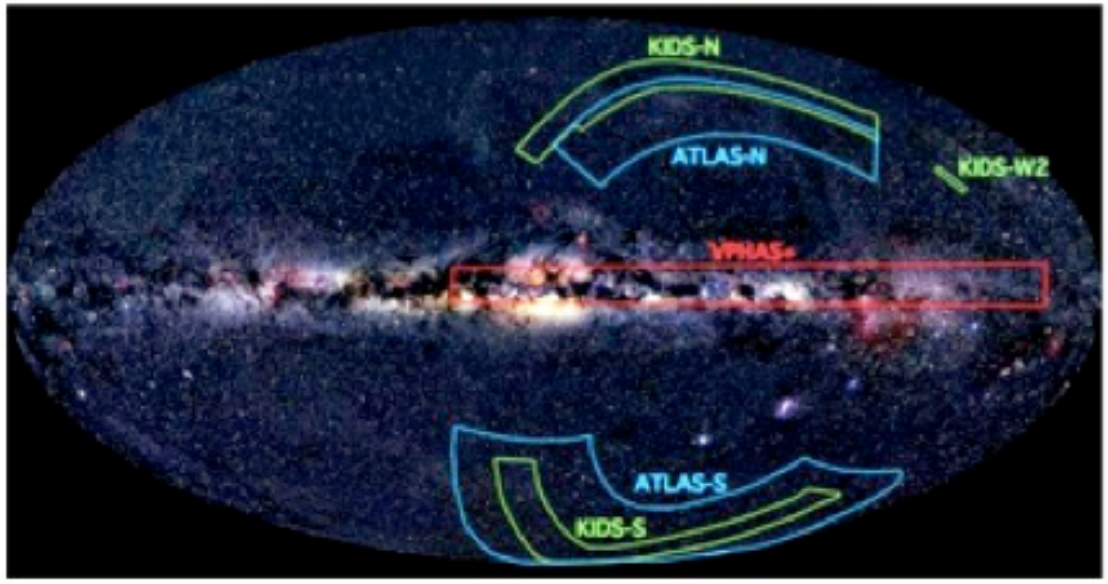
→ **corrected FOV 1 deg x 1 deg, pixel scale of 0.21”/pixel**

1 hour to cover a sky area of 40 sq. deg.
reaching **r ~ 23 mag**

→ **ToO available after agreement with ESO**

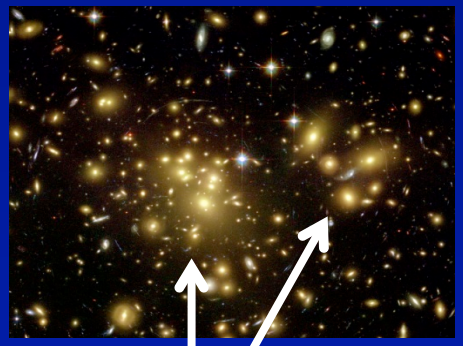
→ in 2016 the **INAF-Guaranteed Time Observation**
20% of the total observing VST time
→ **Public Surveys: a sample of Reference Images available**

Optical imaging: u g r i



Observational strategy

OB definition



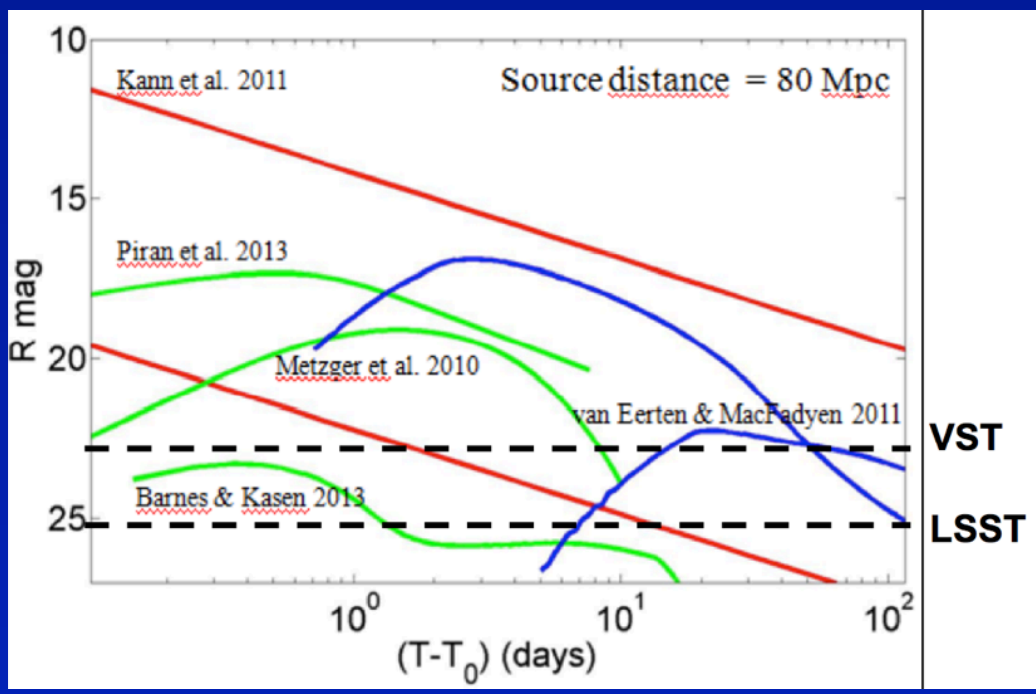
Galaxy targeting?

Aasi et al. 2014, ApJS, 211

EM emission for a source at 80 Mpc

The most promising astrophysical sources of kHz gravitational waves are the inspiral and merger of binary NS/BH systems

The plot shows the EM emission in the R band expected from a NS-NS and NS-BH merger at the distance of 80 Mpc



- Kilonova models predictions (varying ejecta mass, ejecta velocity, opacity)
- On-axis sGRB observed afterglows (brightest and faintest)
- Off axis low energy GRB (ISM)

Courtesy of Branchesi

INAF GW Electromagnetic follow-up collaboration

Experience with VST: **SN2012fa**

Alert Sept 14.24

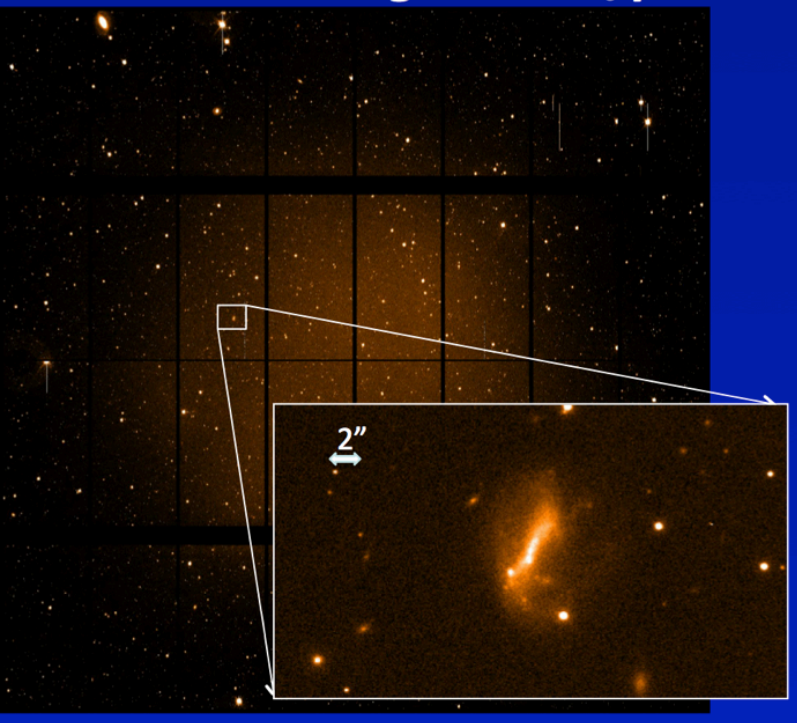
Data acquisition	service observing @ VST (Chile)
Data delivery	via ESO archive (<1–2 h)
Calibration	VSTtube (Naples)
Search	SUDARE pipeline (Padua)
Validation	visual inspection
Classification	**Spectroscopic Classification**

Sept 15.27

Telescope	Proposal approved	Proposal Submitted PI
VST	ToO 30h	Cappellaro Grado
LBT	ToO 7h	Palazzi
TNG	ToO 12h	Palazzi
NOT	ToO 8h	Pian
VLT	-	Pian
It Antartic Tel	-	Col Brocato

HST, VISTA, Swift - proposals submitted with INAF CoIs

VST 2.6m 1 deg² 0.21 "/pix



INAF: VST ToO mini-survey for GW triggers

- 100 deg² to be repeated at three epochs:
  t_0, t_0+(5-10d), t_0+(20-40d)
- 2 filters (g, r)
- 2 dithered exposures per pointing, 40" each (limiting mag *22.5 - 23*)

Fine tuning of the observing strategy according to trigger characteristics, observing constraint, synergy with others groups

STEP 1+2: VST transient search SUDARE (Supernovae)

Processing steps (~ 24 hours)

- **Observations (VST)**
  - **Data delivery (>2h)**
  - **Calibration**
  - **Search of transient**
  - **Validation**
- **Characterization (VLT)**

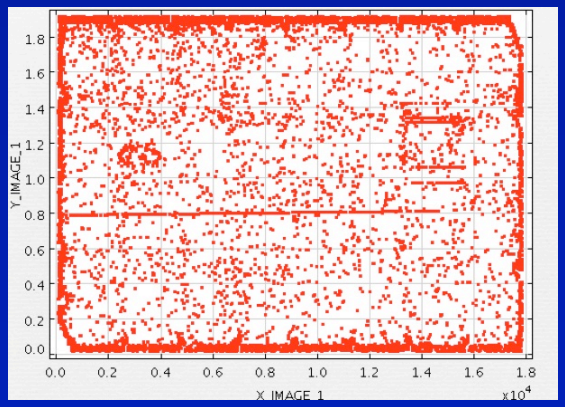
  How to identify uniquely the EM counterpart ?
  - **Comparison with template spectra**
  - **Light curves**

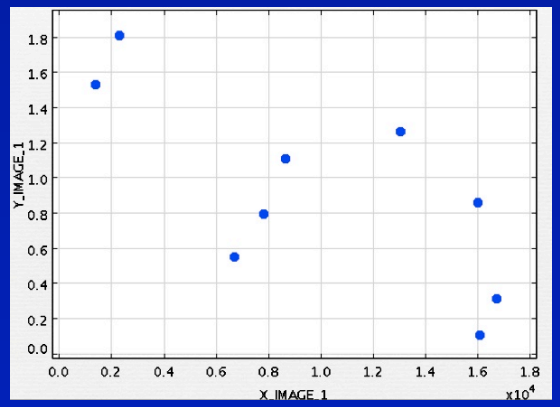
- **Image Analysis is performed by running specific pipelines.**
- **The human intervention is not yet negligible.**
- **Efforts are needed to improve and automatize these procedures and speed up the process**

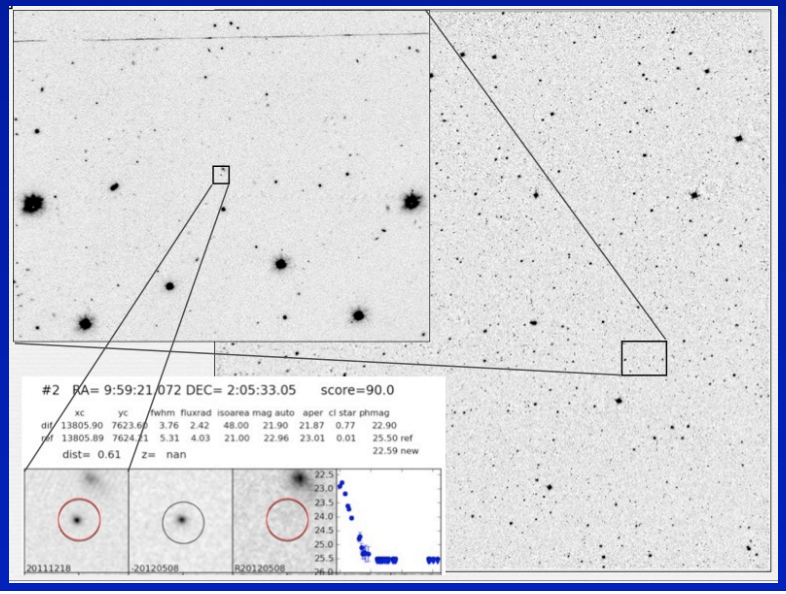
Botticella et al 2013

11050 transients
in 1 sq degree

9 SN detections



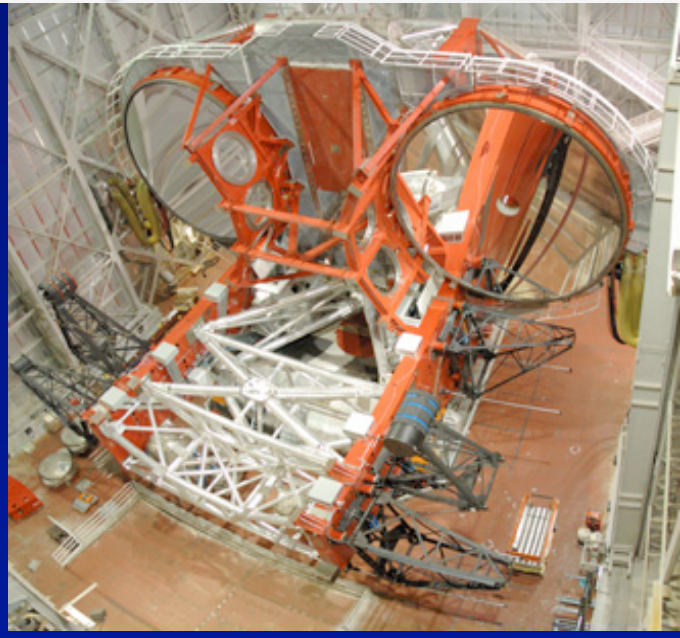




SUDARE@VST Cappellaro et al 2013

INAF: Characterization of the EM counterparts candidates

North America



➡ **Large Binocular Telescope (Arizona) excellent for characterization, INAF GTO+ToO** (25 % INAF)

→ two **8.4 meter primary mirrors**

→collecting area equivalent to an ***11.8*-meter circular aperture**

→Optical/IR spectrographs

→ Large Binocular Camera, FOV 23'x23' , sampling of 0.23”/pixel

South America

➡ **Very Large Telescope (VLT, ESO)**

→ **four unit telescopes** with main mirrors of **8.2m diameter**

→ very useful **X-shooter spectrograph** covering a very wide range of wavelengths [**UV to near infrared**] simultaneously

➡ INAF intends **to coordinate collaborative ToO proposal** involving other European groups working in the field

INAF: Characterization of the EM counterparts candidates

Canarie

TNG (Telescopio Nazionale Galileo)

→ **3.58m optical/infrared telescope**
→ currently optimally equipped for "exoplanet search"
→ its position could be crucial for the EM-follow up, (few) possibility to set up instruments for this program

NOT (Nordic Optical Telescope 2.5 m)

→good candidate for GW follow-up, thanks to its good optics and versatile instruments: e.g. ALFOSC (Andalucia Faint Object Spectrograph and Camera)
→ GTO (fraction) + proposal for ToO

INAF: Radio facilities

➡ **INAF radio antennas:**

→ **Medicina** (30 m parabolic antenna)

→ **Noto** (32 m parabolic antenna)

→ **Sardinia Radio Telescope** (64 m)

SMALL FOV → characterization

INAF: Space high-energy facilities

➡ **From space**

→ INAF can guarantee access – through submission of regular or DDT proposal starting from coordinated initiatives of the INAF scientists to Swift, XMM, Chandra, Fermi, INTEGRAL.

INAF: Archival search

➡ **LBT + VST image archives**
ASDC Archive of space missions + ESO data archive

INAF- project: Gravitational Astrophysics

- **Large FoV** (1x1 d)**+ mag limits** (< 23 m) **+ High resol.** (0.2 p/”)
- **Characterization:** up to 8m class telescopes
- **Site**: southern and northern hemisphere
- **Wide wavelength coverage:** ground based facilities from optical to radio + high-energy space facilities

- **Know-how**: Time Domain Astronomy, Observational Strategy, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Data Interpretation, Theoretical models

◆ ***Collaboration with LIGO-Virgo teams is crucial***

Why searching for the EM counterpart signal of a GW event?

Some, not exhaustive, hints:

- **To maximizing the science return of GW observations**
- **To unveil the nature and structure of compact objects**
- **To investigate the most energetic emission mechanisms**
- **To give a precise (arcsecond) localization, identify host galaxy, determination of the distance and energy scales**
- **A coincident detection of a short GRB and a GW signal would provide the final proof of models which predict the merging of two compact objects as origin of short GRBs.**
- **To start the multi-messenger (GW and photon) astronomy**
- **GW + γ + ν → Messengers to open a new window in astrophysics**
- **To reveal the unknown…exotic sources, new physics**

……Thank you and good luck to all of us!!! :)

BACKUP SLIDES