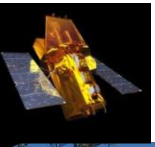
“School on Gravitational Waves, neutrinos and multiwavelength electromagnetic observations: the new frontier of Astronomy”

April 15-18 2013 , Astronomical Observatory of Rome (Monteporzio Catone)

# Electromagnetic Follow-Up of GW Candidates

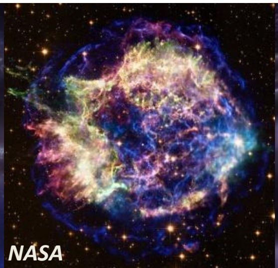
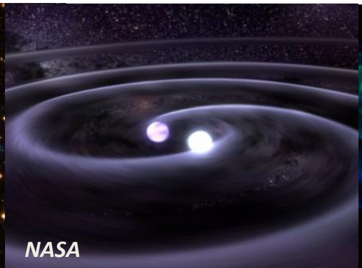

M.Branchesi

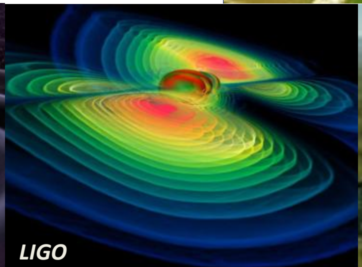
Università di Urbino/INFN Sezione di Firenze





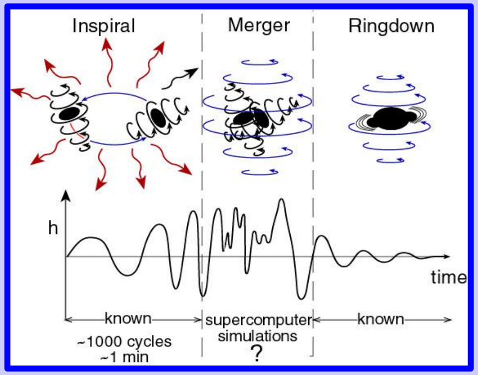



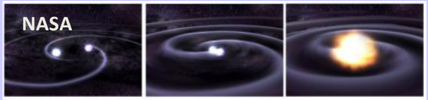


# Most promising GW sources detectable by LIGO/Virgo

## Coalescence of Compact Objects

## Neutron-Stars and/or Black-Holes

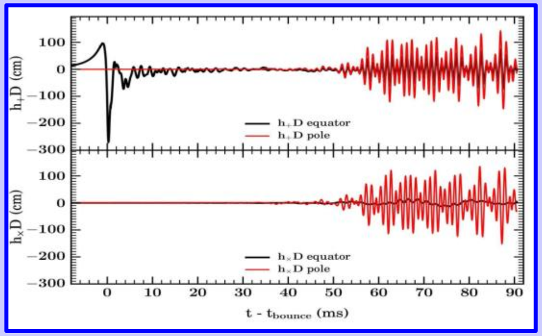



**Initial LIGO/Virgo**

Binary containing a NS detectable to ~50 Mpc likely rate 0.02 $yr^{-1}$

## Core-collapse of Massive Stars



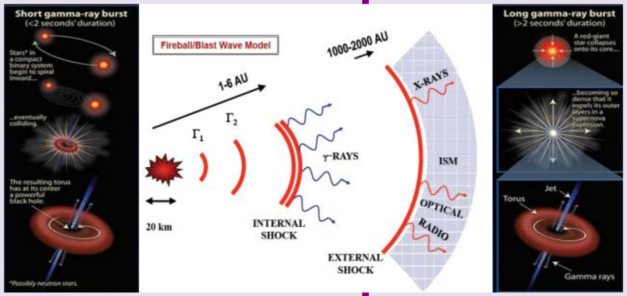

Ott, C. 2009, CQG, 26

**Initial LIGO/Virgo**

Detectable within Milky Way

## These energetic astrophysical events are expected to emit EM radiation

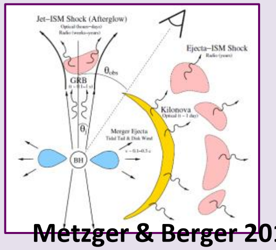
**Short Hard Gamma-Ray Bursts**




**Long Soft Gamma-Ray Burst**

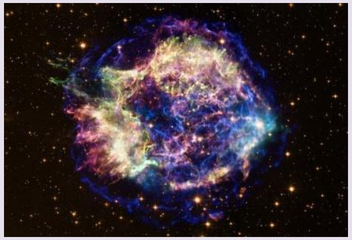
**Optical Kilonovae**

**Radio Remnant**




Metzger & Berger 2011

**Supernovae**



# Advanced Era GW-detectors (ADE)

LIGO-H

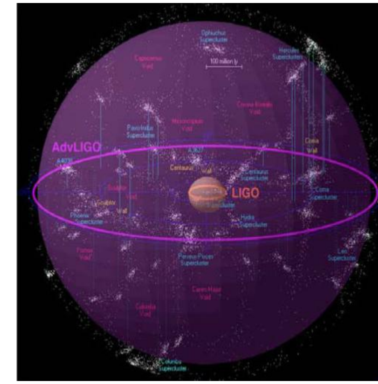
LIGO-L

Virgo

**LIGO** and **Virgo** detectors
are currently being **upgraded**

⬇

**boost of sensitivity**
by a **factor of ten**
**(of $10^3$ in number of detectable sources)**
in the 10-1000Hz range




## Advanced era
### Detection rates of compact binary coalescences

| | Source | Low $yr^{-1}$ | Real $yr^{-1}$ | High $yr^{-1}$ | Max $yr^{-1}$ |
|---|---|---|---|---|---|
| | NS-NS | 0.4 | 40 | 400 | 1000 |
| | NS-BH | 0.2 | 10 | 300 | |
| Advanced | BH-BH | 0.4 | 20 | 1000 | |

**(Abadie et al. 2010, CQG 27)**

**Mass:** NS = 1.4 Mo
BH = 10 Mo

**Advanced era**
**Sky location and orientation averaged range**

**197 Mpc** for NS-NS
**410 Mpc** for NS-BH
**968 Mpc** for BH-BH

## Core-Collapse Supernovae

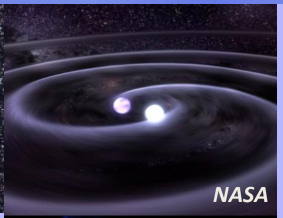
**2-4 $yr^{-1}$** EM-observed within **20 Mpc**

Rate of GW-detectable events unknown

GW-signal detectable **< Milky Way** **(Ott et al. 2012, Phy.R.D.)**
**few Mpc** **(Fryer et al. 2002, ApJ, 565)**

LONG-GRB core-collapse - **10 Mpc (?)**

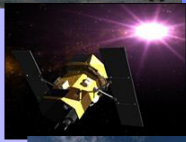
# Main motivations for joint GW/EM observations




- **Consider the GW signal in its astrophysical context**
- **Give a precise (arcsecond) localization, identify host galaxy**


- **Provide insight into the progenitor and environment physics**


- **Start the GW astronomy to answer a plethora of open questions including:**
  - **- connection between short GRBs and compact object mergers**
  - **- the birth and evolution of black holes**
  - **- ……..**


**The first program of EM follow-up of candidate GW events has been performed during the LIGO/Virgo observing periods:**

**Dec 17 2009 to Jan 8 2010 - Winter Run**

**Sep 4 to Oct 20 2010 - Autumn Run**

*Abadie et al. 2012, A&A 539; Abadie et al. 2012, A&A 541; Evans et al. 2012, ApJS 203*

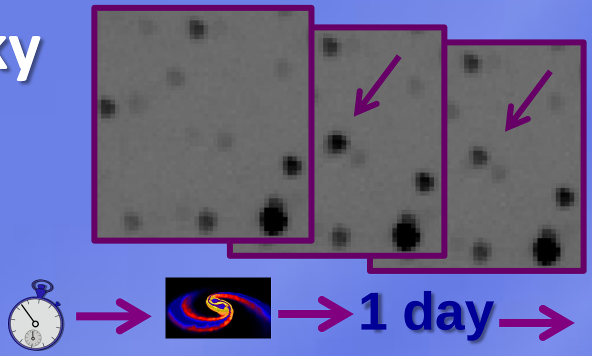


This lesson will focus on:

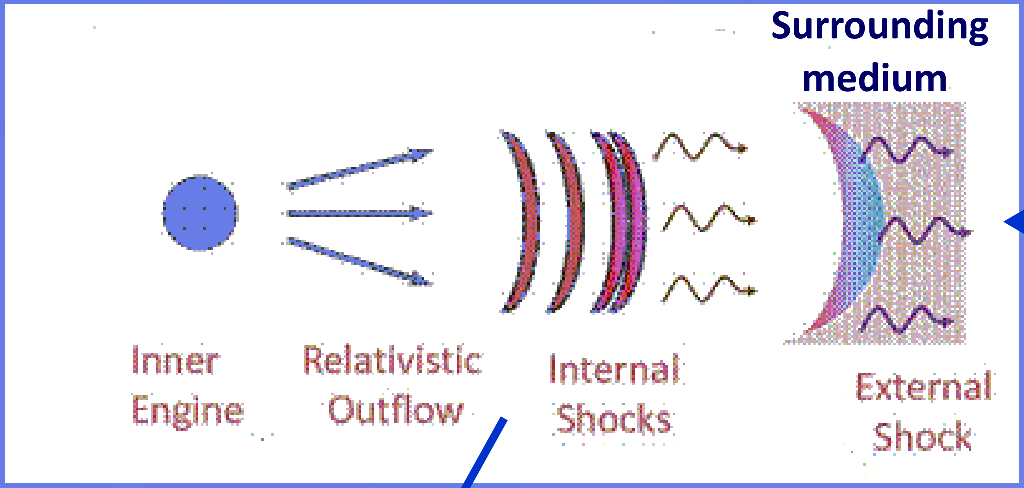
- The EM signals from transient GW sources detectable by Virgo and LIGO

- The strategies to promptly observe the EM signature of a GW source

- The EM data analysis to identify the EM counterpart in the transient EM sky

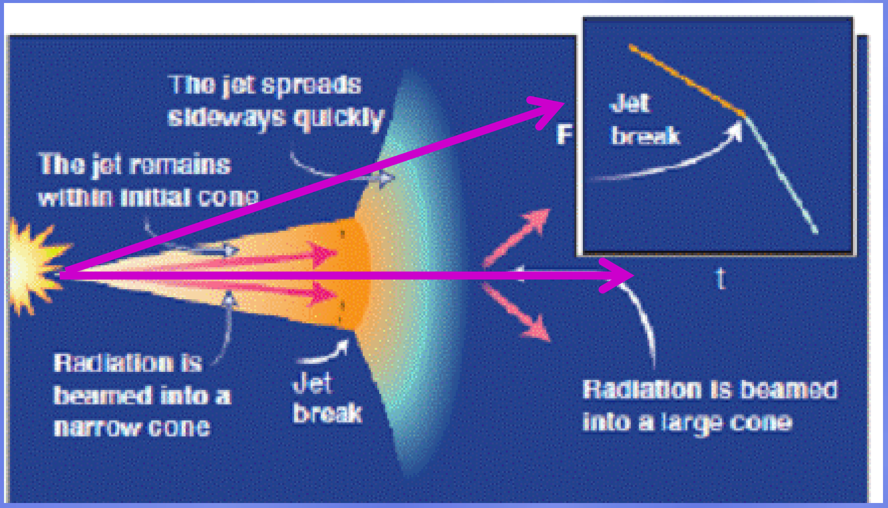


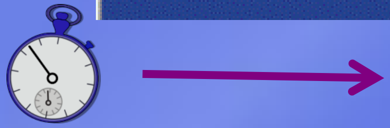
# Gamma Ray Burst Fireball Model




**Afterglow emission**
**Optical, X-ray, radio**
hours, days, months

**Prompt emission**
**Gamma-ray** - within seconds

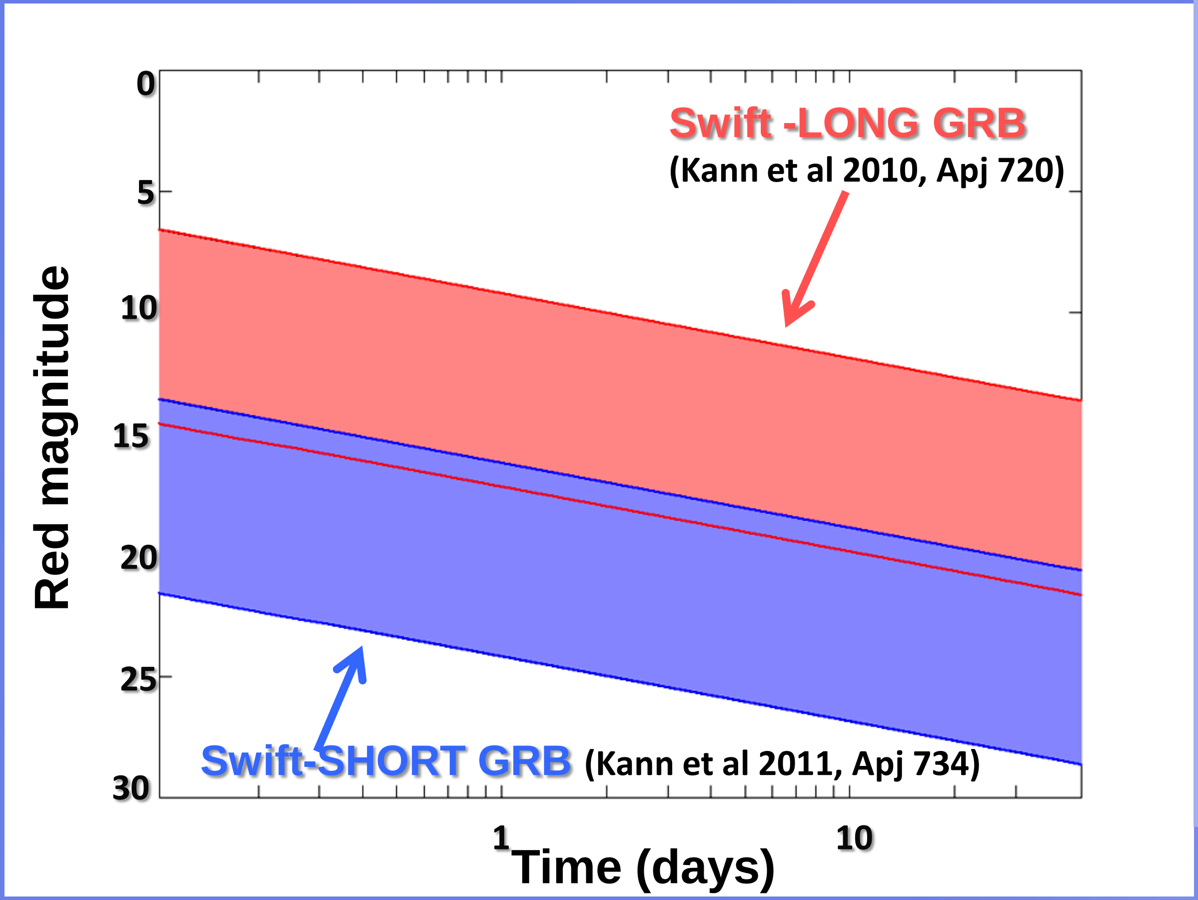


Nakar & Piran 2003

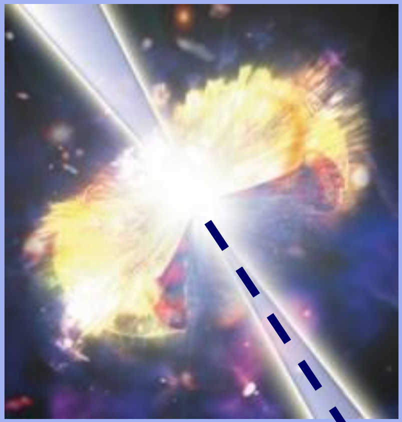
# Optical afterglow ON-AXIS GRB

Source at distance of 200 Mpc




Observer along the jet axis

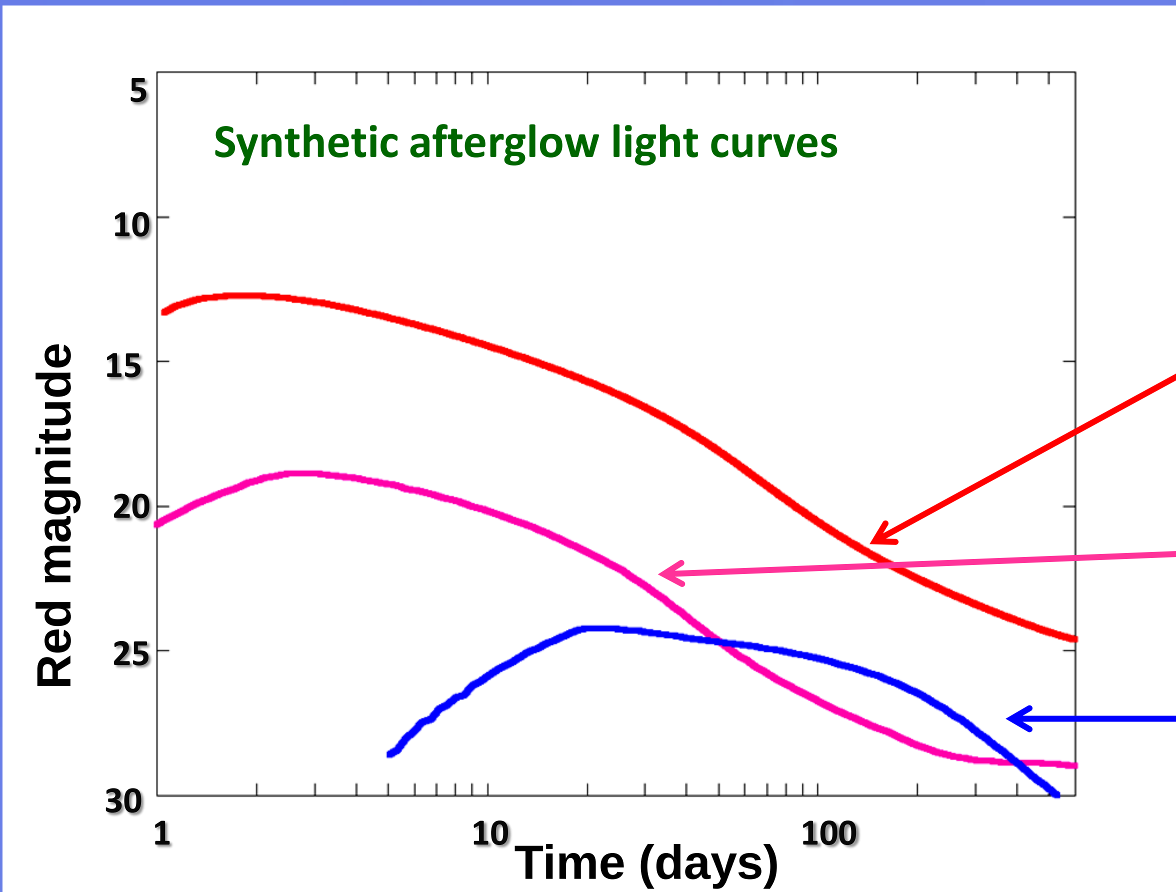
$\theta_{obs} < \theta_{Jet}$



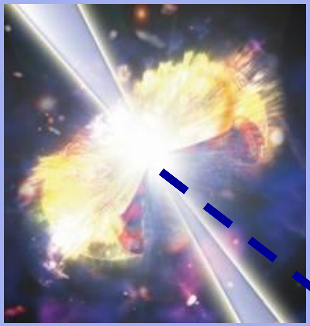
**Power-law luminosity decay with time $t^{-\beta} \rightarrow \beta = 1 \div 1.5$**

# Optical afterglow "Orphan GRB"

## Source at distance of 200 Mpc




OFF-AXIS GRB



$\theta_{obs} > \theta_{Jet}$

$\theta_{Jet} = 0.2$ rad

**LONG bright GRB**
$\theta_{obs} = 0.3$ rad

**LONG low-luminosity GRB**
$\theta_{obs} = 0.4$ rad

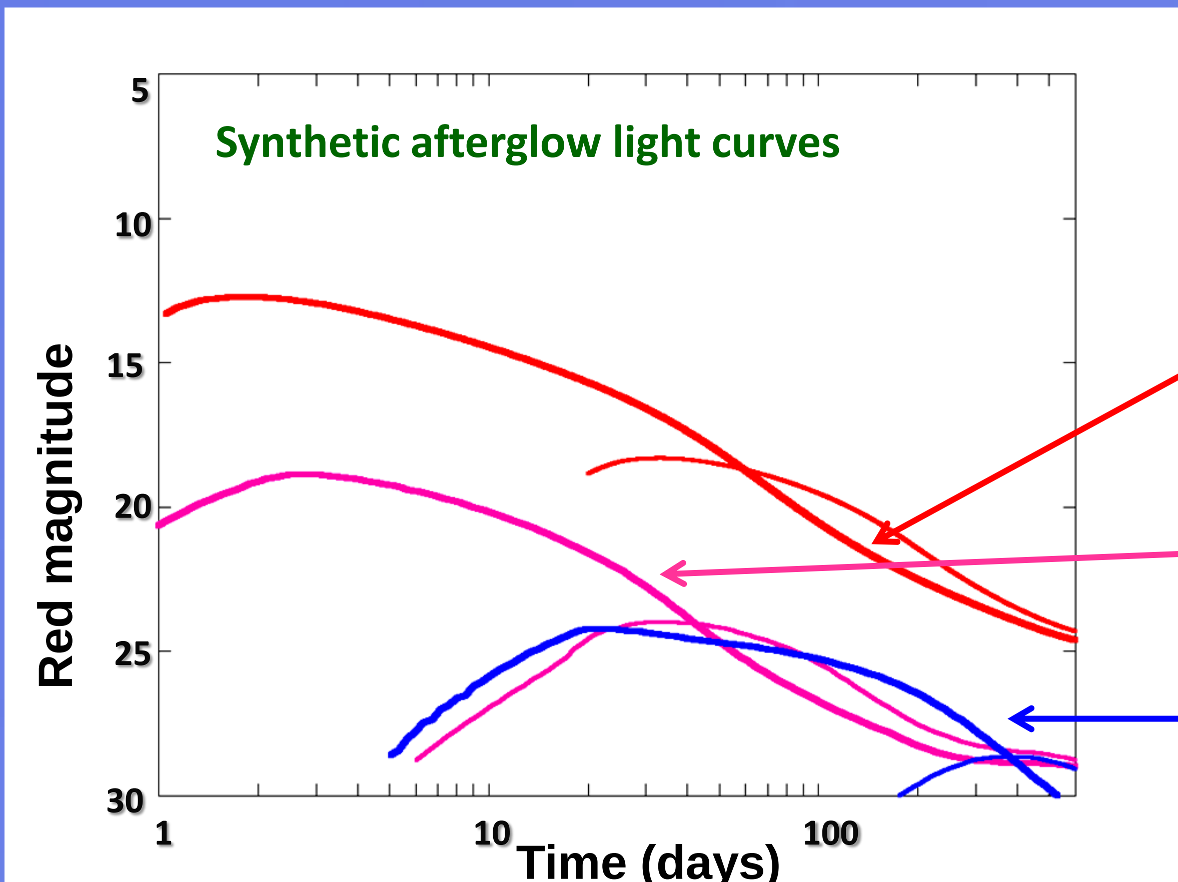
**SHORT GRB**
$\theta_{obs} = 0.4$ rad

http://cosmo.nyu.edu/afterglowlibrary/index.html

By van Eerten & MacFadyen

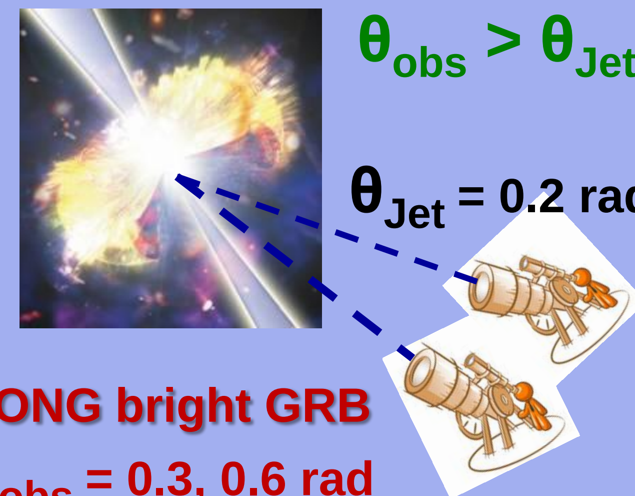
# Optical afterglow "Orphan GRB"

Source at distance of 200 Mpc




OFF-AXIS GRB

$\theta_{obs} > \theta_{Jet}$




**LONG bright GRB**
$\theta_{obs}$ = 0.3, 0.6 rad

**LONG low-luminosity GRB**
$\theta_{obs}$ = 0.4, 0.8 rad

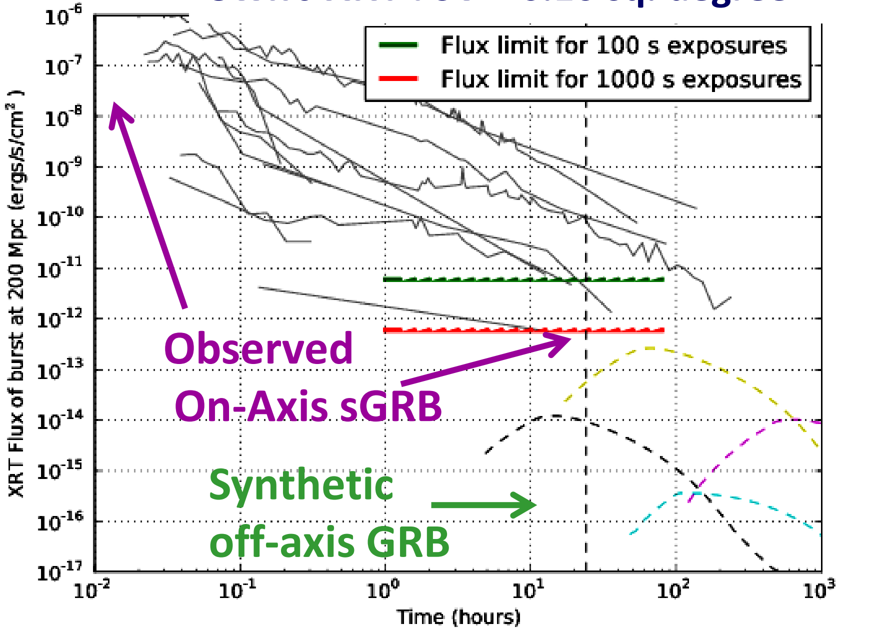
**SHORT GRB**
$\theta_{obs}$ = 0.4, 0.8 rad

http://cosmo.nyu.edu/afterglowlibrary/index.html
By van Eerten & MacFadyen

# X-RAY and Radio GRB afterglow

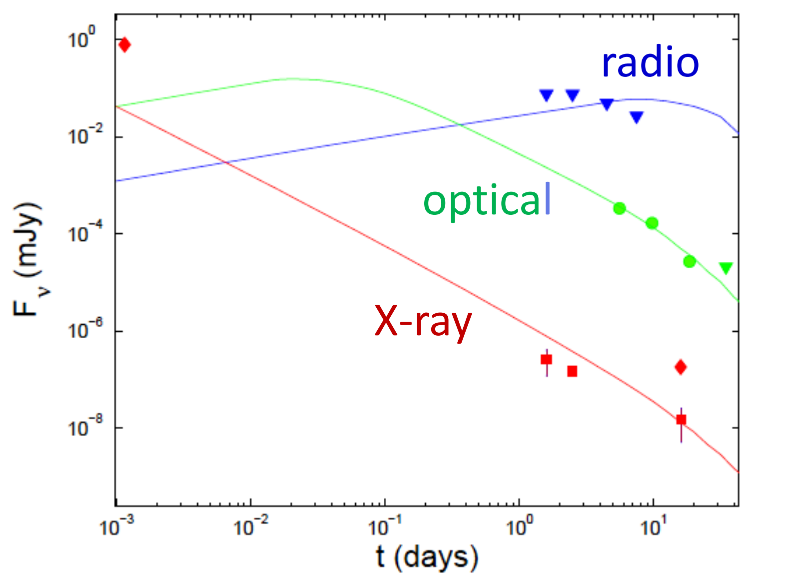
## X-RAY: GRB at distance of 200 Mpc

Swift-XRT FoV = 0.16 sq. degree




Kanner et al. 2013, ApJ, 759

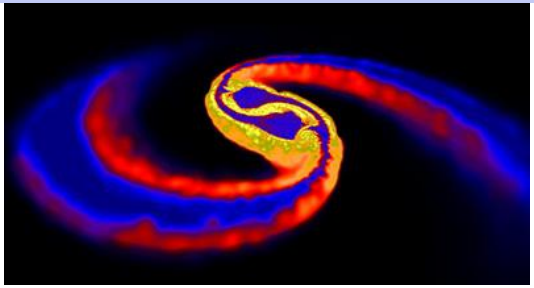
## Short GRB 050709:



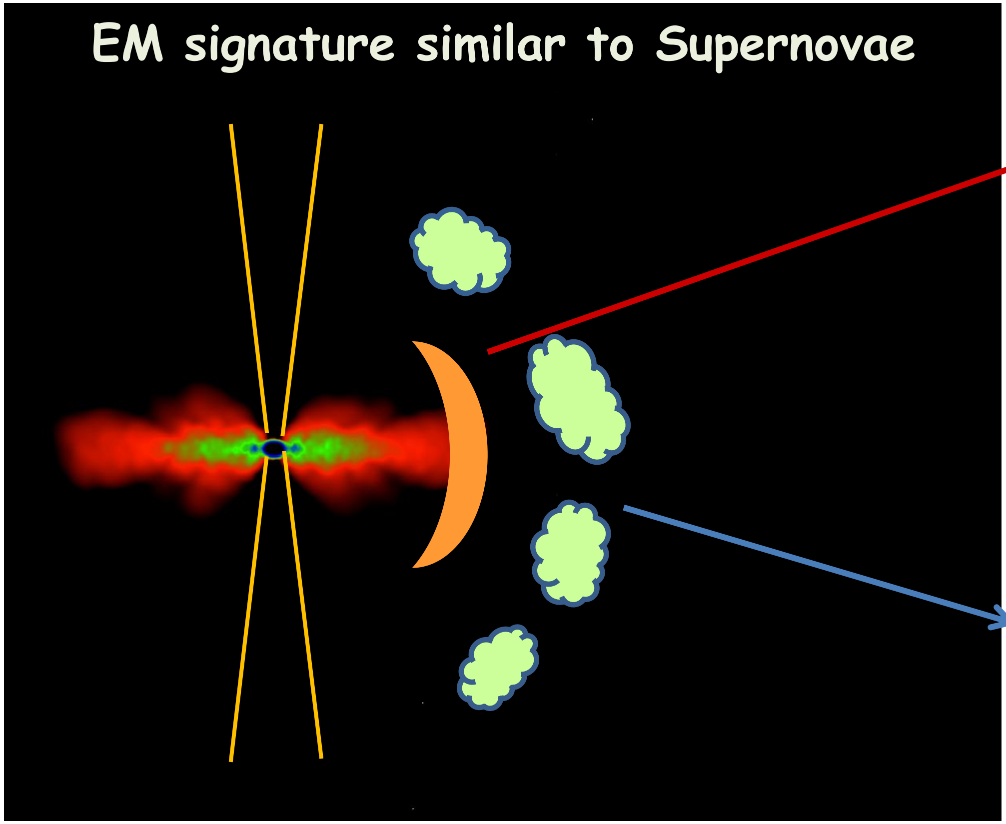

Fox et al. 2005, Nature 437

# Kilonovae and Radio Flares

Significant **Mass (0.01-0.1 $m_o$)** is **dynamically ejected** during a **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.2 c)**



**(Piran et al. 2013, MNRAS, 430; Rosswong et al. 2013 , MNRAS, 430)**




## Macronova – Kilonova

**short lived IR-UV signal (days)** powered by the radiocative decay of heavy elements synthesized in the ejected outflow

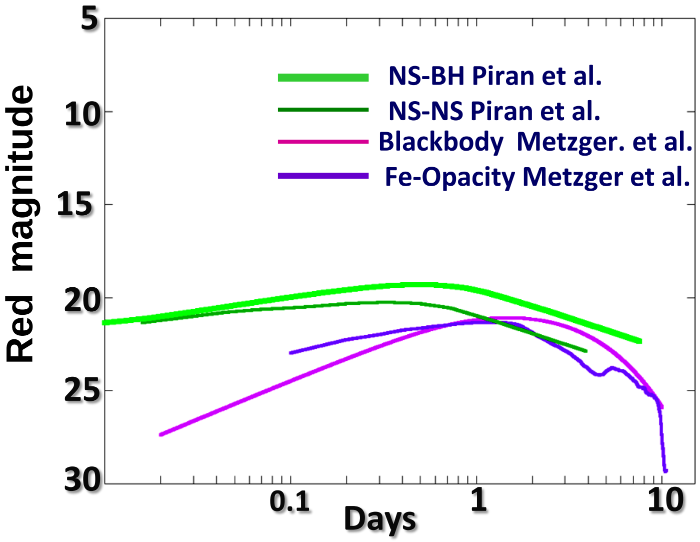
**Kulkarni 2005, astro-ph0510256;**
**Li & Paczynski 1998,ApJL, 507**
**Metzger et al. 2010, MNRAS, 406;**
**Piran et al. 2013, MNRAS, 430**

## RADIO REMNANT

**long lasting radio signals (years)** produced by interaction of ejected sub-relativistic outflow with surrounding matter **Piran et al. 2013, MNRAS, 430**

# Kilonovae Light Curves

## Source at distance of 200 Mpc

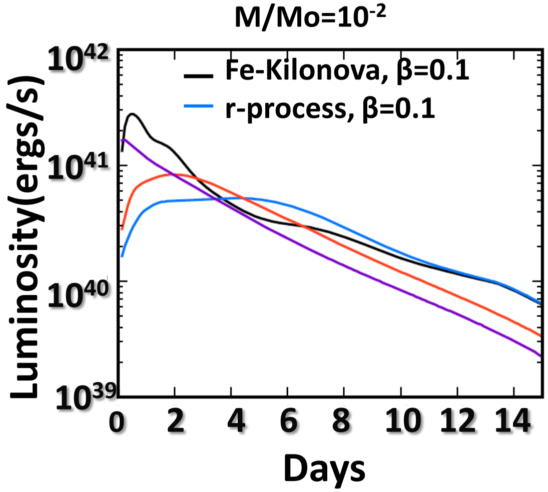


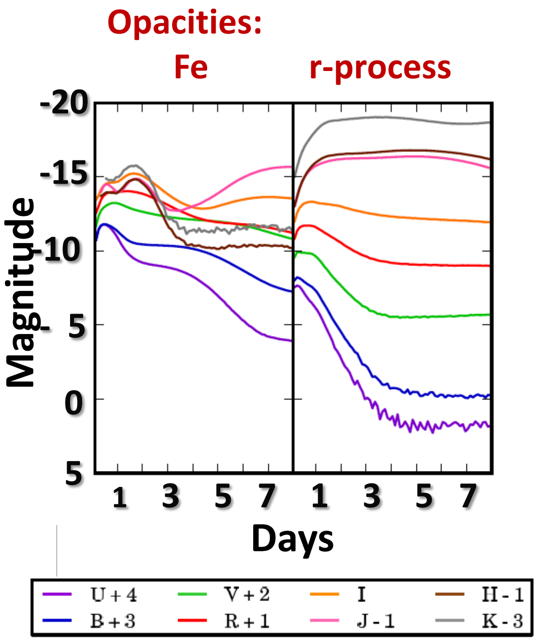

***Kilonova* model afterglow** peaks about **a *day* after** the merger/GW event

**Major uncertainty OPACITY** of "heavy r-process elements"

New simulations including **lanthanides opacities** show:

- **broader light curve**
- **suppression of UV/O** emission and **shift to infrared bands**



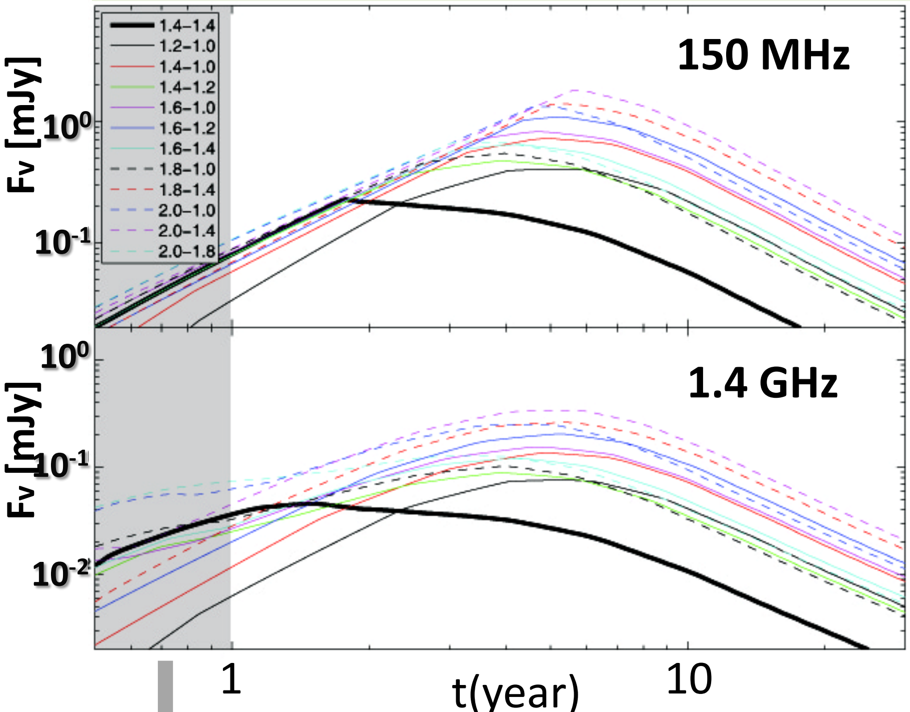




Barnes & Kasen 2013, arXiv:1303.5787

# Radio Flare Light Curves

**Source at distance of 300**

**External ambient density $n = 1\,cm^{-3}$**




**150 MHz**

**$F_{peak}$ ~ 0.2- 1 mJy**

**$t_{peak}$ ~ 2-5 years**

**1.4 GHz**

**$F_{peak}$ ~ 0.04-0.3mJy**

**$t_{peak}$ ~ 1.5-5 years**

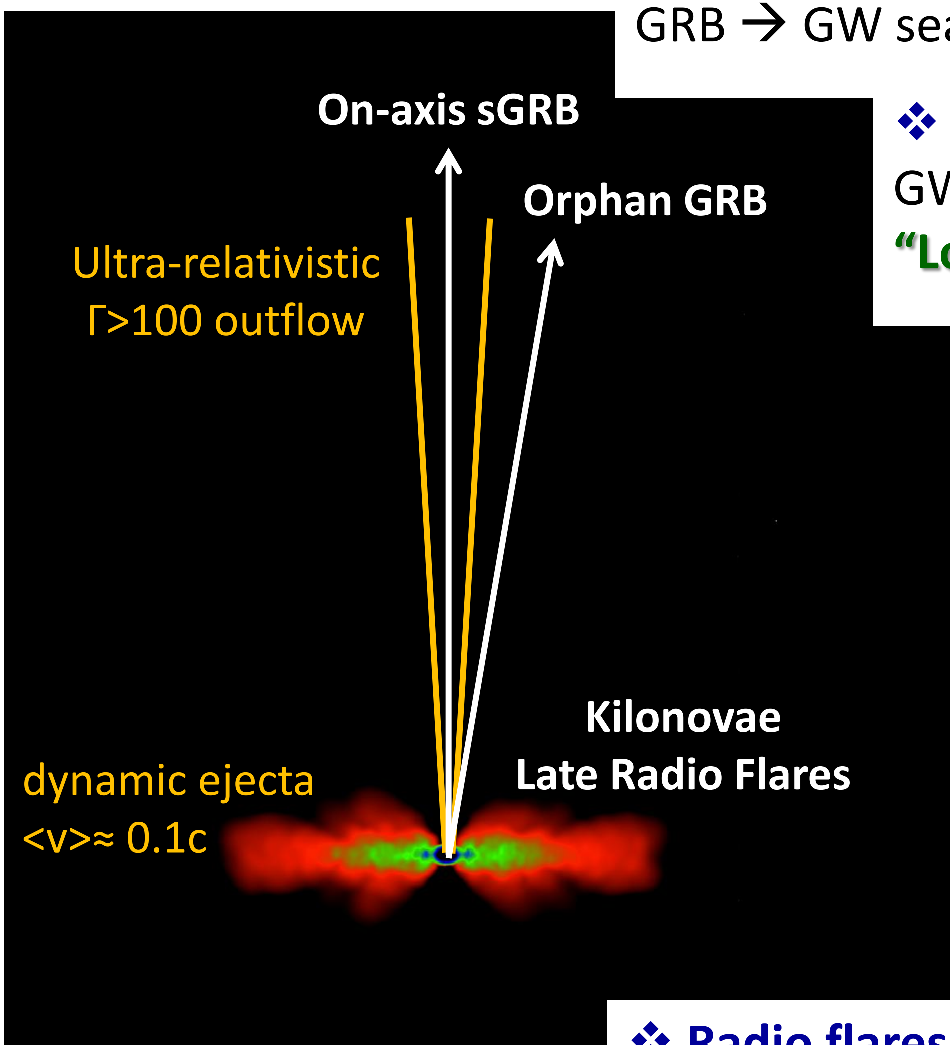
Piran et al. 2013, MNRAS, 430

Dominated by **mildly relativistic outflow v>0.3c** not included in the simulation **expected brighter emission**

**External ambient density critical parameter**

**$n = 0.1\ cm^{-3}$ ⟶ an order of magnitude fainter signals**

# EM signals from NS-NS/NS-BH merger



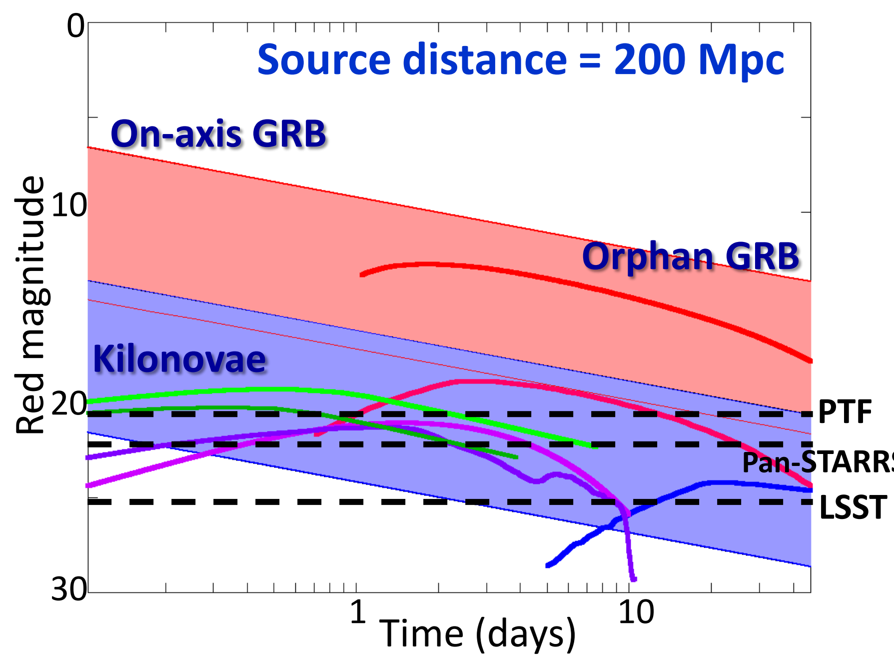

❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"Off-line analysis"**

❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

**"Low-latency EM follow-up"**




❖ **Radio flares:**

GW trigger → radio search **"High-latency follow-up"**

Blind radio search → GW search **"Off-line analysis"**

# 2009-2010 first EM follow-up

**Low-latency GW data analysis pipelines enabled us to: 1) identify GW candidate signals in "real time" and 2) obtain prompt EM observations to detect the EM signature of the possible GW source**

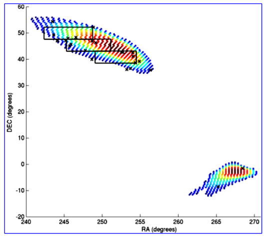
GW triggers

Sky Pointing Position

EM facilities

LIGO-H LIGO-L

Virgo



Event validation

**"Search Algorithms"** to identify the GW-triggers:

- **Unmodeled Burst Search**
- **Matched Filter Search** for Compact Binary Coalescence

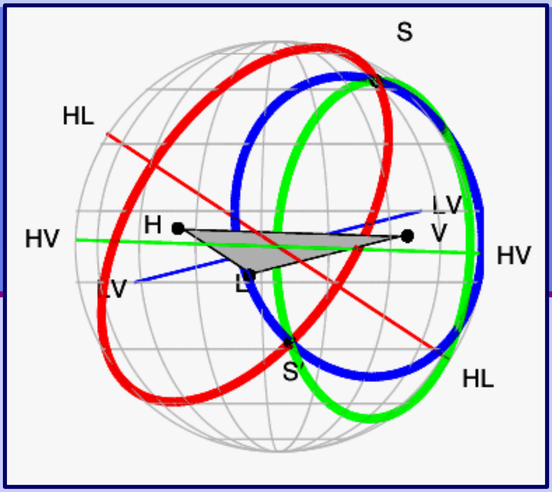
**"Software"** to identify GW-trigger for the EM follow-up:

- select statistically significant GW triggers
- determine telescope pointing

→ **~ 10 min.** → **~ 30 min.**

**ADE Latency expect to be improved!**

# Sky Localization of GW transients



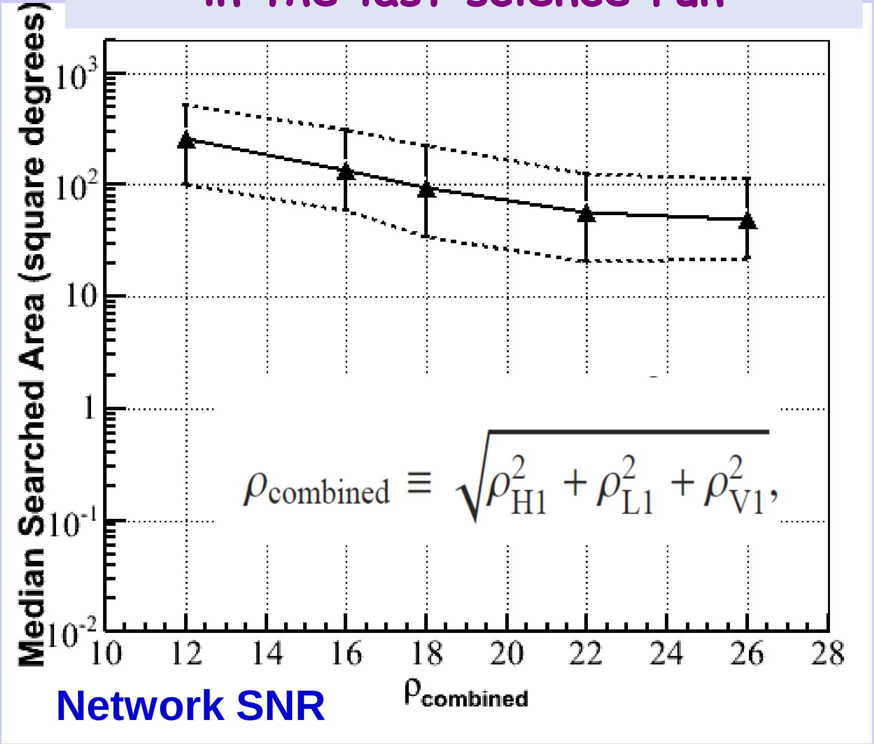

The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**

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

⬇

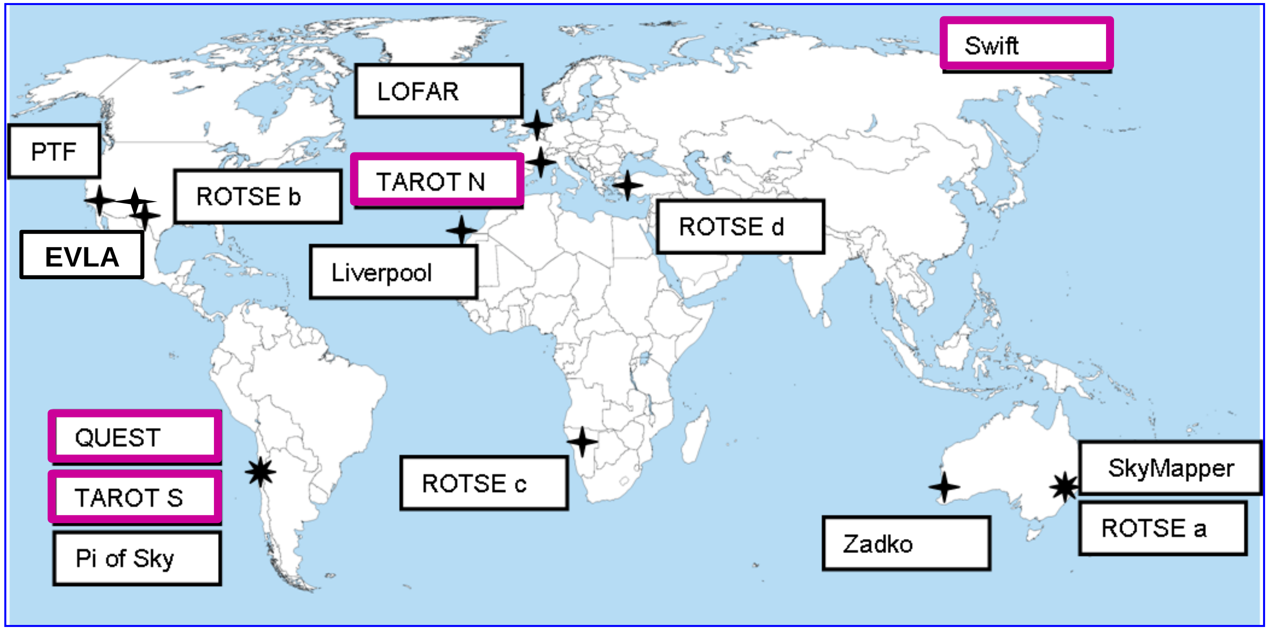
**Necessity of wide field of view EM telescopes**

**Binary coalescence localization in the last science run**




Abadie et al. 2012, A&A 539

# Ground-based and space EM facilities observing the sky in the Optical, X-ray and Radio bands 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

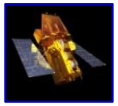
### Pi of the Sky
**400** sq. degree FOV

### Palomar Transient Factory
**7.8** sq.degree FOV

### Liverpool telescope
**21** sq. arcminute FOV

## X-ray and UV/Optical Telescope

### Swift Satellite
**0.16** sq. degree FOV



## Radio Interferometer

### LOFAR
30 - 80 MHz
110 - 240 MHz
Maximum **25** sq. degree FOV

### EVLA

5 GHz - **7** arcminute FOV

# Additional priors to improve the localization accuracy and increase the chance to observe the EM counterpart

## LIGO/Virgo horizon:

a binary inspiral containing a NS detected out to **50 Mpc**

⬇

**EM-observation was restricted to the regions occupied by galaxies within 50 Mpc and Galactic globular clusters**

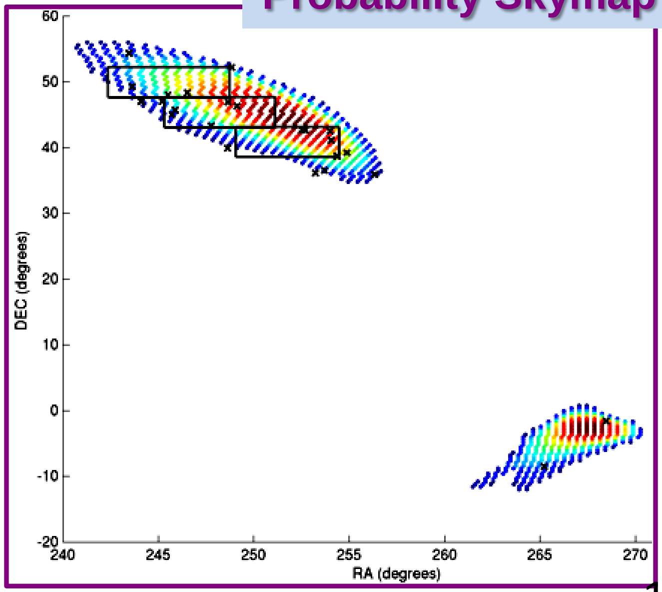
(GWGC catalog White et al. 2011, CQG 28, 085016)

**To determine the telescope pointing position:**

⬇

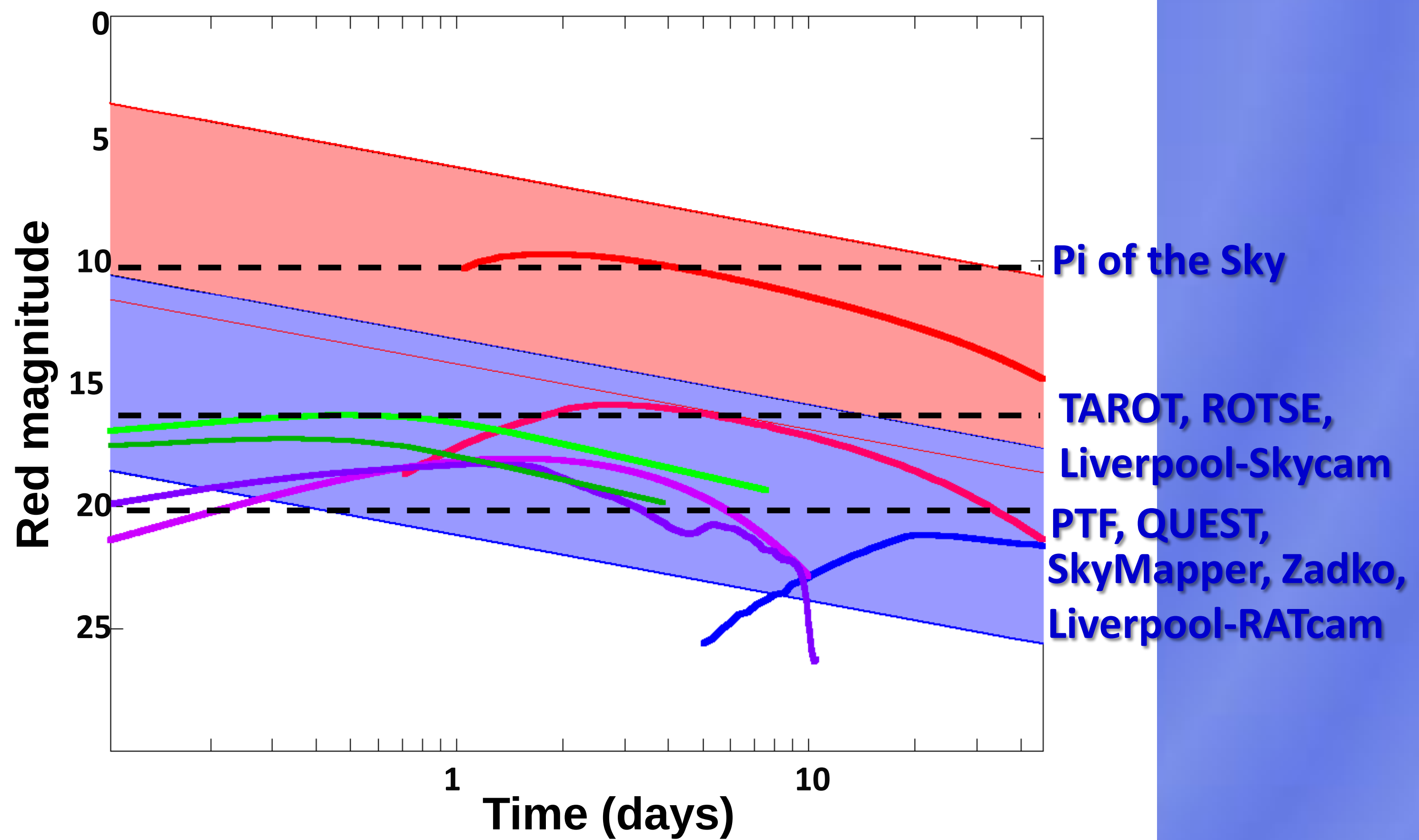
**The probability skymap of each GW trigger was 'weighted'** taken into account **luminosity** and **distance** of nearby galaxies and globular clusters

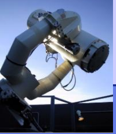
**Probability Skymap**



# Optical Afterglow Light Curves
## for GRBs and kilonovae

Source at distance 50 Mpc



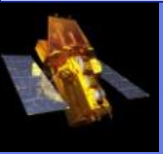


# Optical Telescopes

**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



Evans et al. 2012, ApjS, 203

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

# Radio Interferometers

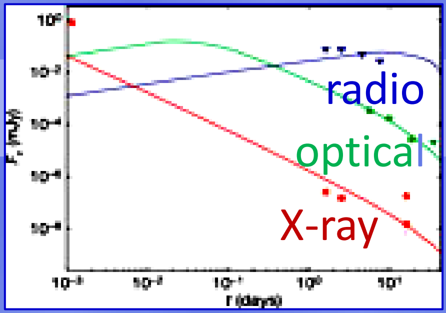

## LOFAR

**5 GW alerts sent and observed**

## Expanded-VLA

Lazio et al. , 2012 IAUS, 285

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



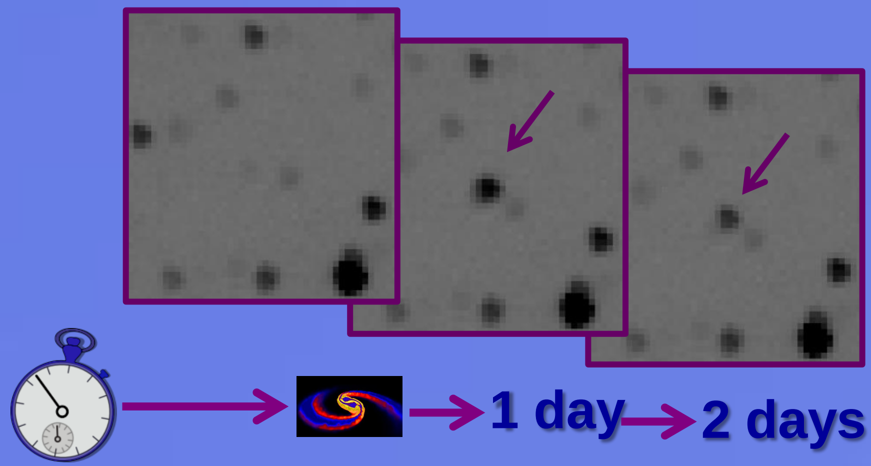

Fox et al. 2005, Nature 437,835

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

3 weeks, 5 weeks + 8 months later

# EM Image Analysis Procedure

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




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 challenge** due to the **"large sky area"** to analyze

# Optical Telescopes: Image Analysis

**Different telescopes, observational cadences and sensitivities**

⬇

**heterogeneous dataset of collected images**

**Various approaches** were used to identify the **“transient events”** and reduce the **“false positives”**

For each set of images and procedure the **SEARCH SENSITIVITY**, the capability to detect the expected EM counterpart up to the LIGO/Virgo horizon, was evaluated by adding simulated on-axis GRBs and kilonovae to the data

## Approaches used to identify the “transient events”:

- **Image Subtraction Methods**
  (for Palomar Transient Factory, ROTSE and SkyMapper)
- **Reference Catalog Cross-Check Methods**
  (for TAROT, Zadko, QUEST and Pi of the Sky)

# Optical Telescopes: Image Analysis

**Contaminating Transient Events**:

- **"technical background",** procedure artifacts that mimic transient events
- **"very rapid transients"** like cosmic rays and asteroids
- **foreground astrophysical transients:** M-Dwarf flares, CVs, Galactic variable stars
- **background astrophysical transients:** AGN, Supernovae

  (rate in Rau et al. 2009, PASP, 121)

## False positives rejection:

❖ by **comparing the light curves of each event** with the expected EM counterpart luminosity evolution

❖ **"on-source analysis":** by limiting the analysis to the regions occupied by the most likely GW source host galaxies and taking into account the possible offset between the galaxy center and the binary systems

❖ **"whole-field analysis":** by limiting the analysis to bright object

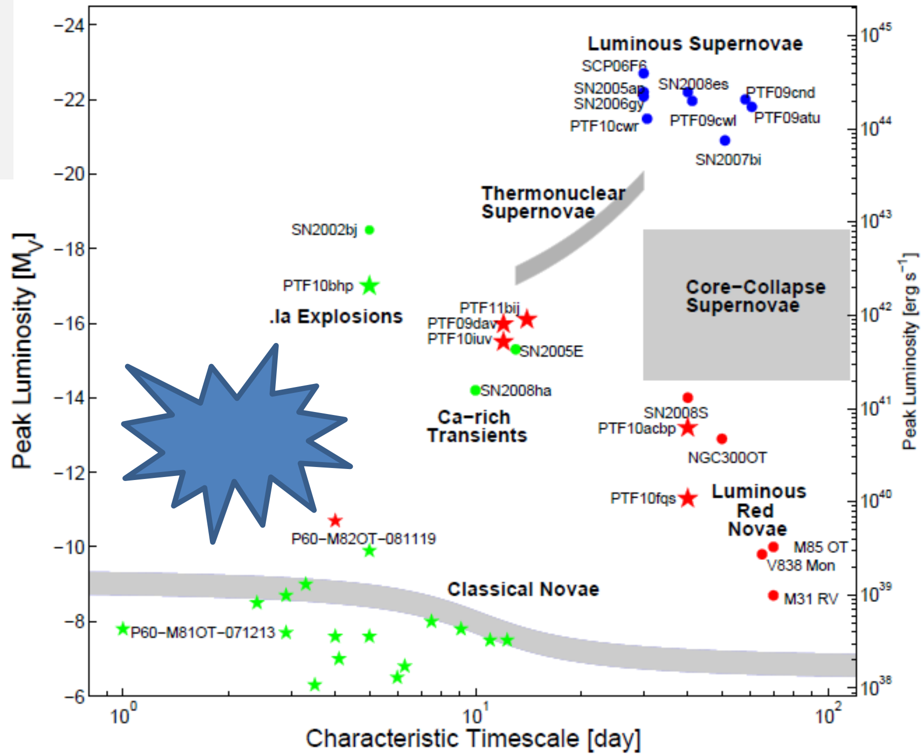
# Optical Astrophysical background

Exploration of **the optical transient sky** at faint magnitudes and short timescale has started recently, but **it is still largely unknown..**

**Extremely valuable**

- ➢ **optical survey to study the astrophysical transients** in the space-time search region but not directly associated with a GW event
- ➢ **algorithms for a rapid discovery and classification of transients over a wide sky area** (**"machine-learning"**, Bloom et al. 2012, PASP, 124)

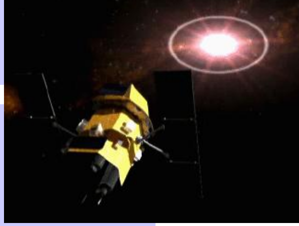
**Kasliwal 2011, BASI, 39**

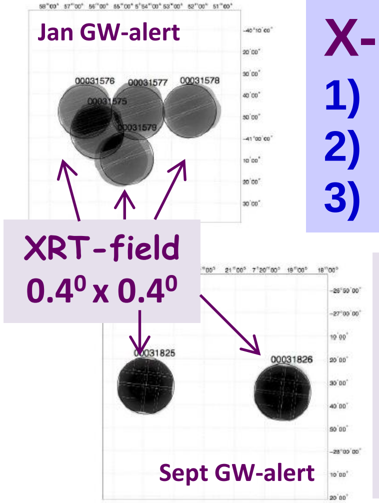



to select a **small number of counterpart candidates** that can be **promptly followed-up spectroscopically**

→**uniquely** identify **the optical counterpart** of the GW trigger

# Swift Satellite: analysis and results






## X-ray and Optical/UV image analysis

1) detection of the sources in the FOV
2) comparison with the number of serendipitous sources
3) variability analysis

**RESULTS:**

XRT-analysis **20 detections** (1.5σ)

UV/OP-analysis **6800 detections**

- **ALL consistent with EXPECTED SERENDIPITOUS sources**
- **NO single source with significant variability**

### Joint GW/X-ray search sensitivity improvement

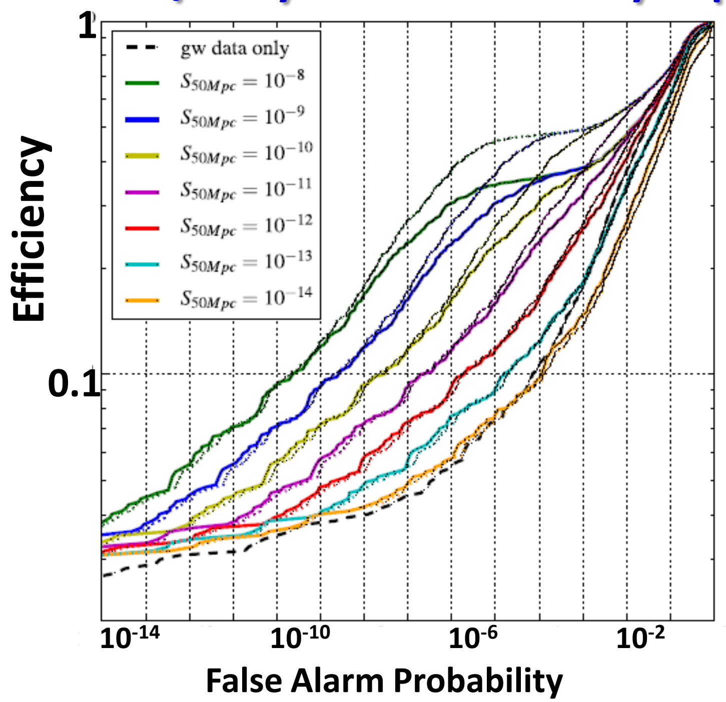



**Figure shows**

- an efficiency increase with the X-ray counterpart flux
- an efficiency gain observing with 10 (dashed) wrt 5 (solid) Swift fields

⬇

**An X-ray telescope with wide FOV increases the chance to observe the counterpart despite the larger serendipitous X-ray background**

Evans et al. 2012, ApJS 203

# Expanded Very Large Array: analysis and results

**Three epochs** (3,5 weeks,8 months after the GW alert) **of 6 cm observations**

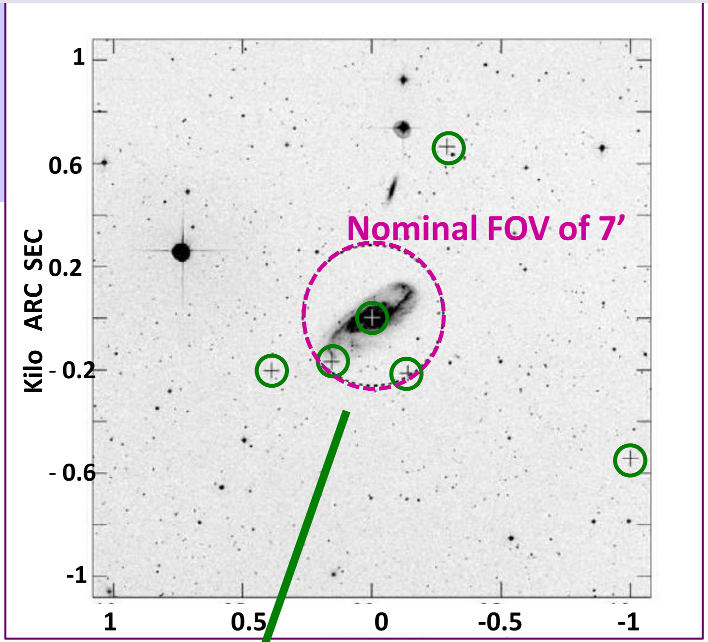
For each of the two GW-candidates observed ➡ **3 most probable host galaxies**

**Image Analysis:**

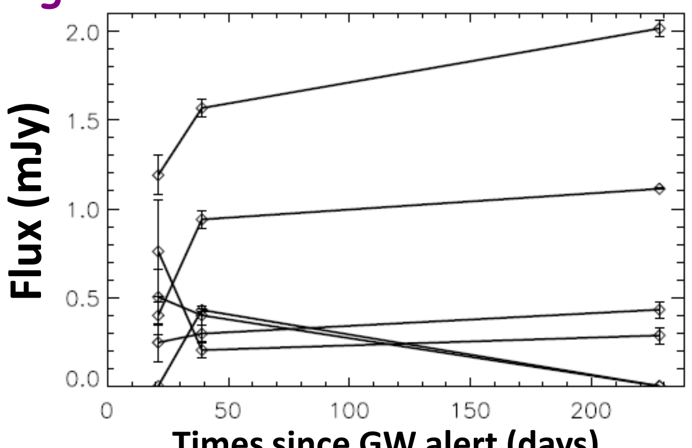
1) radio source detection
2) variability analysis
3) identification of contaminating transients

variability of AGN emission caused by interstellar medium scintillation of Galaxy

**Imaged region (≈ 30')** around **one galaxy**




**Light curves**



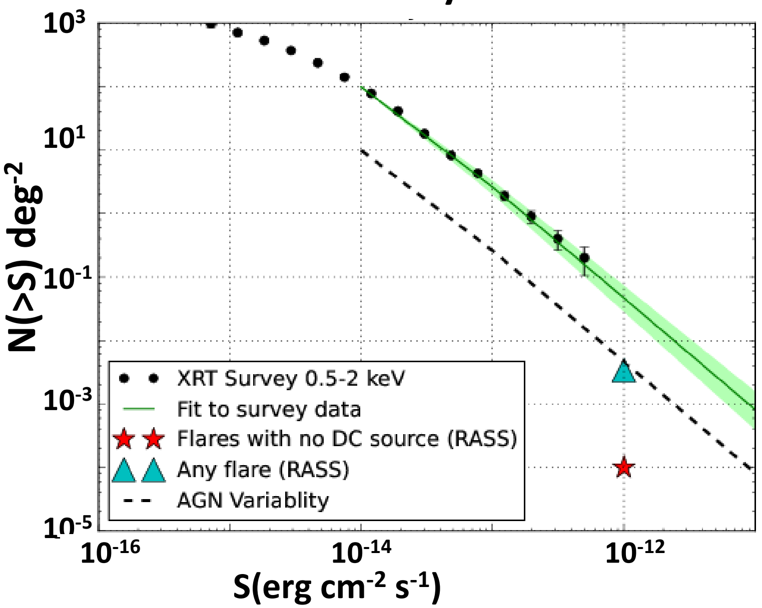

About **6 sources** in the field of each galaxy **consistent** with number of **expected serendipitous sources** (Windhorst 2003)

Lazio et al. , 2012 IAUS, 285

# X-ray and radio background

**Transient X-ray and radio sky is more empty** than the optical at the expected fluxes of the EM counterparts

Number density of sourses




Kanner et al. 2012, ApJ, 759

## X-ray sky

At a sensitivity of **2 x 10$^{-12}$** (erg s$^{-1}$cm$^{-2}$) and a GW localization **area of 100 sq. degrees**

• • • only a few extragalactic sources **(Puccetti et al. 2011)**

Demanding variability

- - - AGN variability **(based on Gibson & Brandt, 2011)**

▲▲ RASS data for variable “flare-like” sources **(Fuhrmeister & Schmitt 2003)**

★★ RASS study to seek GRB “orphan afterglows” **(Greiner et al. 2000)**

## Radio sky

**Transient contaminants** (1.4 GHz and 150 MHz)

**AGN variability** → location wrt to the galaxy center

**Supernovae** → optical light curve, spectral studies

**49 epochs of E-CDFS VLA observations** on timescale **1 day - 3months** show:

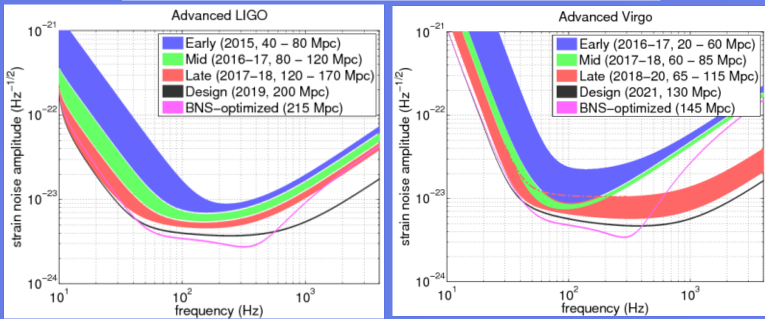
- **1% of unresolved sources show variability above 40 µJy**
- **density of transients is less than 0.37 deg$^{-2}$ above 0.21 mJy**

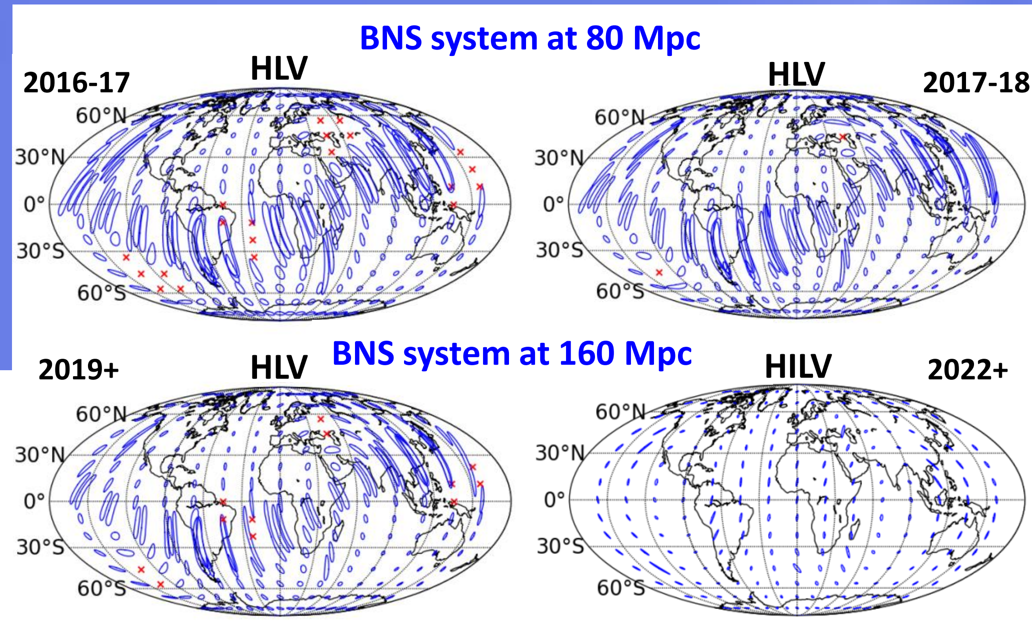
**(Mooley 2013, arXiv1303.6282)**

# Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

**Sensitivity vs frequency**




**Localization:**
large position uncertainities → areas of many **tens to thousands of sq. degrees**

| | | LIGO/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 deg$^2$ | % BNS Localized within 20 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 |

# Advanced Era EM-Follow-up

**GW Sky-localization of few tens of square degrees** (until a 4th detector KAGRA, LIGO-India will observe, 2022+) **+ Larger GW-Detectable Universe**

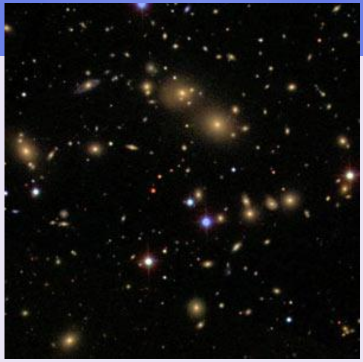
⬇

## New Observational Strategy

- Galaxy targeting still useful? Galaxy priors to sample GW source population?
- Large "etendue surveys" (PTF, Pan-STARRS, LSST)? Wide-medium size FOV telescope coordination?
- What are the optimal EM-bands? All-sky survey or target ToO? Prompt emission or afterglow emission?
- Acceptable GW/EM latency time and optimal observation cadence?
- Optimal EM-facilities? Spectroscopy?
- ……………………

**TIGHT LINK is required between GW/EM COMMUNITIES to be ready for the UPCOMING GW-TRANSIENT ASTRONOMY!!**

# Local Galaxy catalog



**Useful:**

- **To use narrow and medium-FoV (< 1 sq. Degree) telescopes** (Kanner et al. 2012, ApJ, 759)
- **In the post-processing image analysis to reduce the EM false alarm rate (On-source analysis)**

(Kulkarni & Kasliwal 2009, Nissanke et al. 2013, ApJ, 767)

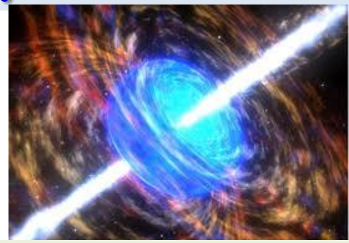
**Main problem: incompleteness**

**Upcoming year observational effort to complete the catalog:**

- **narrow-band H-α survey**
- **HI emission radio line survey** (WALLABY survey - ASKAP)

Metzger et al. 2013, ApJ, 764 ➡ **both surveys should achieve > 50% completeness with respect to the host galaxies of short GRBs** (11 short GRBs host galaxies: 9 star-forming galaxies/2 early type)

# Observational galaxy priors to identify the most likely GW-host



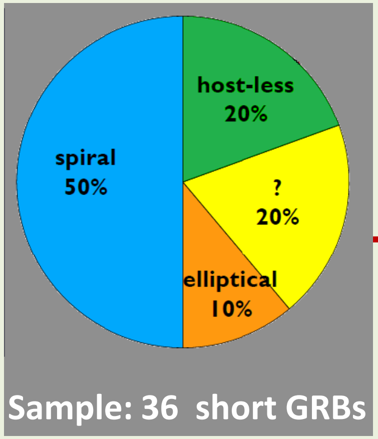
**Useful:**

- to define an optimal observational strategy
- to identify the image region to be analyzed

In the 2009/2010 follow up the **"blue luminosity"** was used to identify the most likely hosts ➡ **actual star formation**

**EM observational results** vs **GW source population numerical simulation**

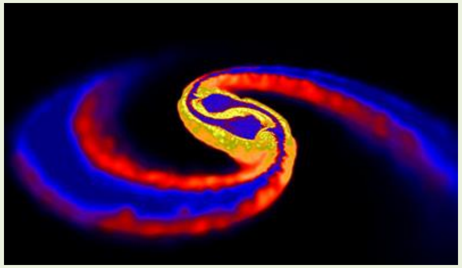
1) Assuming that the short GRBs trace the binary neutron star mergers:




**5 to 1 ratio of spiral to elliptical hosts**
**(Berger 2011)**

→ **Wen-fai Fong's talk**
**(KITP Conference: Rattle and Shine)**

2) **Population synthesis models** indicate a **relevant fraction (20 – 50%) of elliptical galaxy hosts** at z=0
**(O'Shaughnessy et al. 2008)**



# Summary of promising EM counterparts

| EM Band | Sources | Analysis | Strength | Weakness | Example Facilities |
|---|---|---|---|---|---|
| ϒ-rays | On-axis sGRB | EM→GW “off-line” | → strong signal<br><br>→ temporal coincidence | → small % of compact object mergers | Fermi-GBM Swift-BAT |
| X-ray | On-axis and “orphan” sGRB | GW →EM low-latency | → few false positive | →lack of wide FoV facilities | Swift-XRT ISS-Lobster |
| UV/O/IR | On-axis and “orphan” sGRB Kilonova | GW →EM low-latency | → Transient “survey” facilities<br><br>→Isotropic | →numerous false positive<br><br>→ Not yet observed | PTF,PanStarrs LSST,BlackGEM, TOROS,VISTA |
| Radio | sGRB<br><br>Radio flares | GW→EM high-latency EM→GW “Off-line” | → few false positive<br><br>→isotropic | →long time delay<br>→Dependence on ambient density | ASKAP Apertif LOFAR |