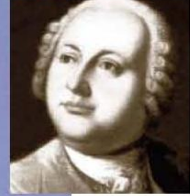


Mikhail Lomonosov
1711-1765

SIXTEENTH LOMONOSOV CONFERENCE
ON ELEMENTARY PARTICLE PHYSICS

Moscow, August 22-28, 2013

Electromagnetic counterparts of gravitational wave transients

INFN

M.Branchesi

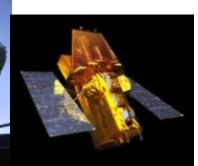
1506 UNIVERSITÀ DEGLI STUDI DI URBINO CARLO BO

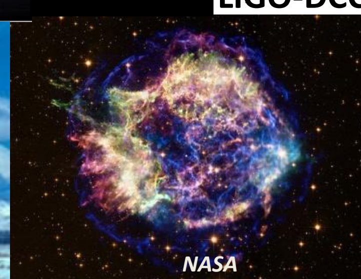
(Università di Urbino/INFN Sezione di Firenze)

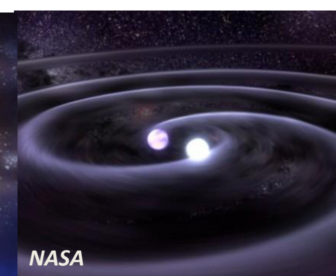
on behalf of the LIGO Scientific Collaboration and Virgo Collaboration

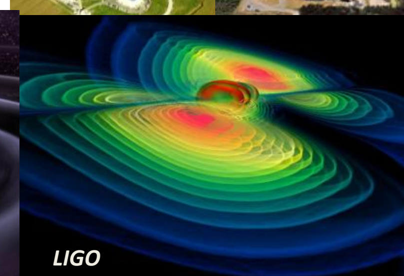
LSC VIRGO

LIGO-DCC G1300486







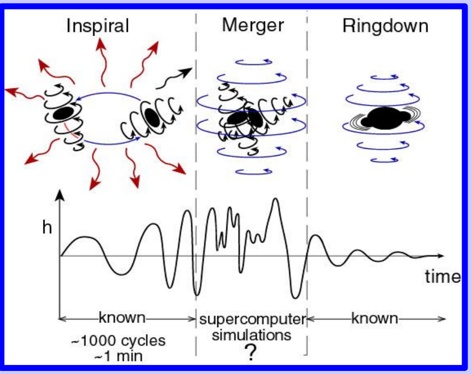


Expected "transient" GW sources detectable by LIGO/Virgo

"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

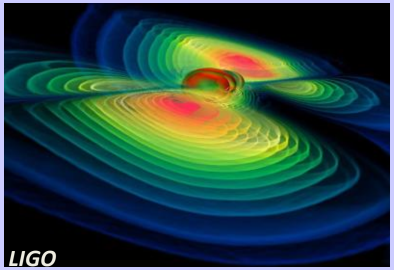


Binary containing a NS:

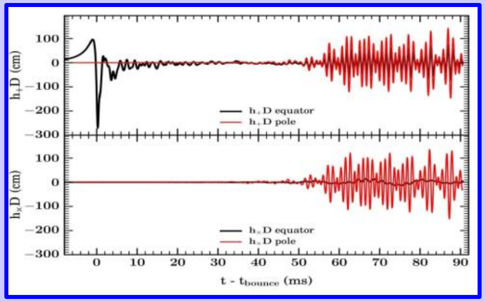
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz) **< 20 s before merger**
- **Energy emitted in GW: $\sim 10^{-2} M_o c^2$**

Initial LIGO/Virgo

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



Core-collapse of Massive Stars



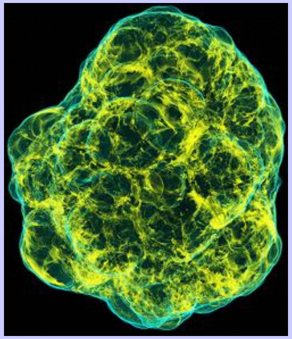
Ott, C. 2009, CQG, 26

Energy emitted in GW uncertain:

- Likely $\mathbf{10^{-8} M_o c^2}$
- Optimistic $10^{-4} M_o c^2$

Initial LIGO/Virgo

Detectable within a fraction of the Milky Way (10 kpc)



Ott et al. 2013, ApJ, 768

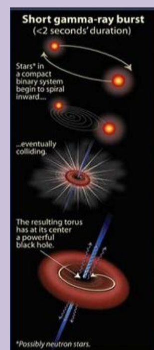
NASA

These energetic astrophysical events are expected to emit EM radiation

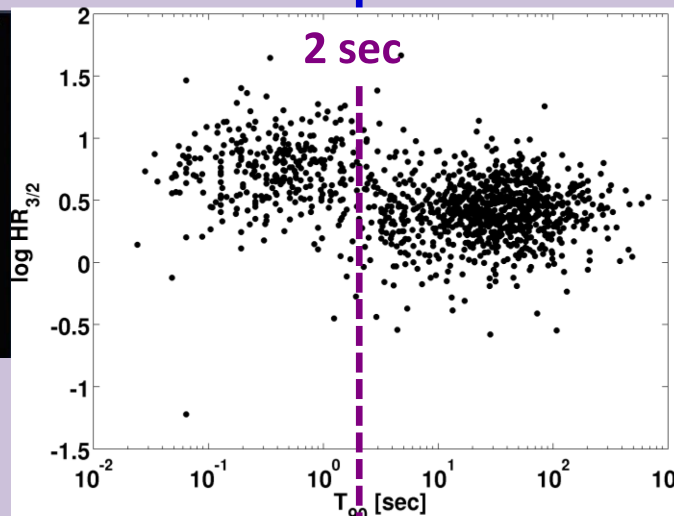
Merger of NS-NS / NS-BH | **Core collapse of massive star**

Gamma-Ray Burst: intense flashes of gamma-rays
isotropic-equivalent energy up to 10^{53} erg

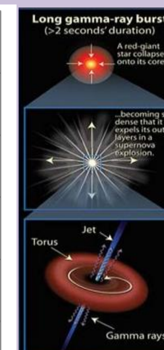
Short Hard GRB



Progenitor indications:
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)

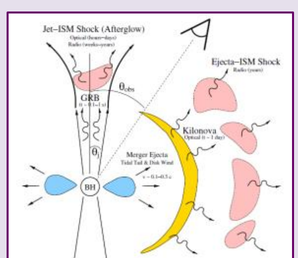


Long Soft GRB



Progenitor strong evidence: observed Type Ic SN spectrum

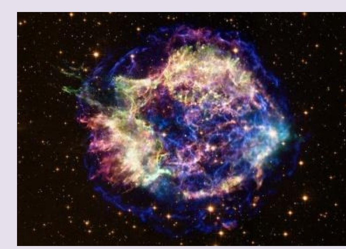
Optical Kilonovae
Radio Remnant



Metzger & Berger 2011

Supernovae

Type II, Ib/c



Advanced Era GW-detectors (ADE)

LIGO-H

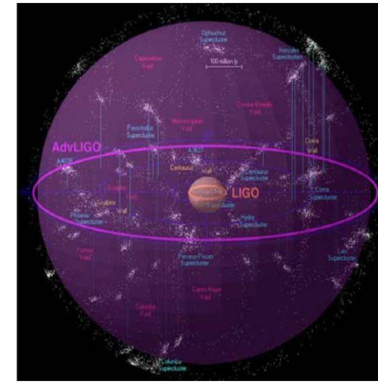
LIGO-L

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

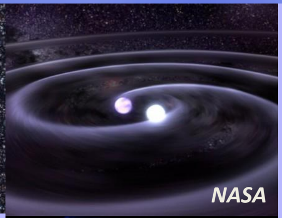
2-4 yr^{-1} EM-observed within **20 Mpc**

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

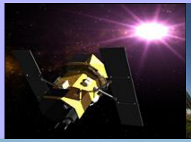


- **Consider the GW signal in its astrophysical context**
- **Give a precise (arcsecond) localization, identify host galaxy**
- **Multi-messenger picture for a complete knowledge of the most energetic events in the Universe**
- **GW and EM provide insight into the physics of the progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)**
- **Start the GW astronomy to answer a plethora of open questions on:**

  - connection between short GRBs and compact object mergers
  - the birth and evolution of black holes
  - equation of state of nuclear matter
  - in the long term cosmology

  ……………



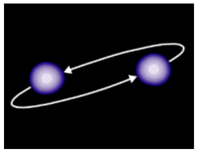



EM emission from transient GW sources

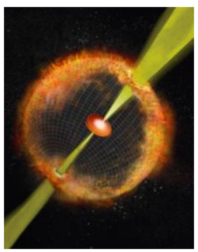
GRBs emission - Fireball Model

Cataclysmic event

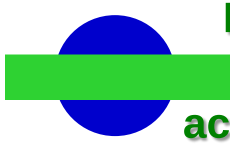
NS-NS NS-BH merger



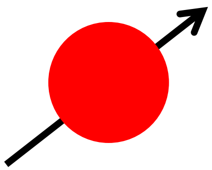
Collapsar



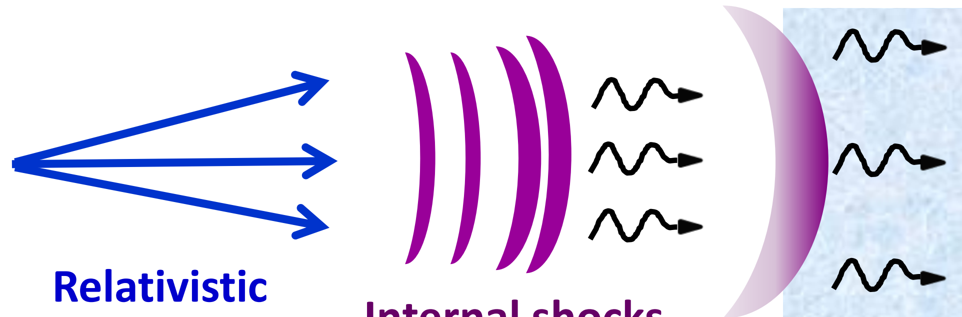
Central engine



Black Hole + accretion disk



"Magnetar" millisecond magnetized ($B > 10^{11}$ T) **Neutron Star**



Relativistic Outflow

Internal shocks

Surrounding medium

External Shocks

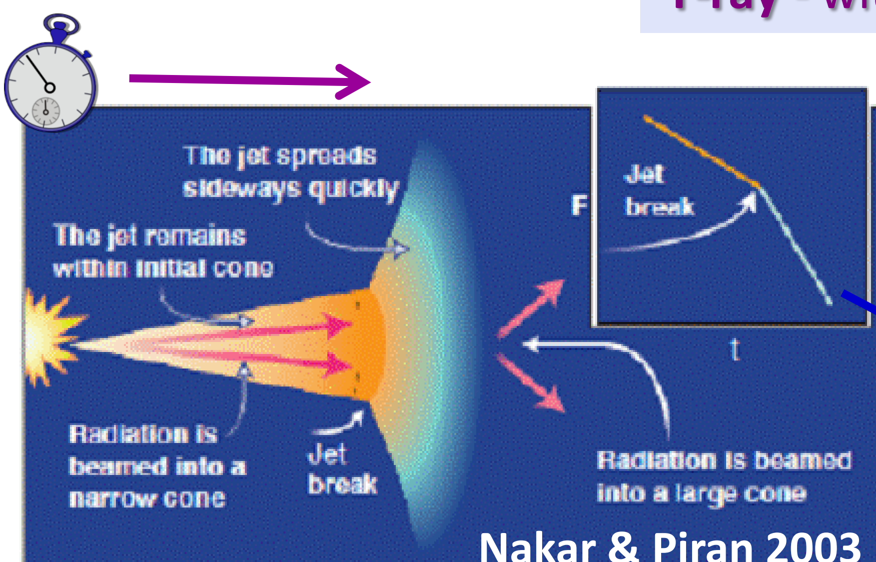
Prompt emission

ϒ-ray - within seconds

Afterglow emission

Optical, X-ray, radio

hours, days, months



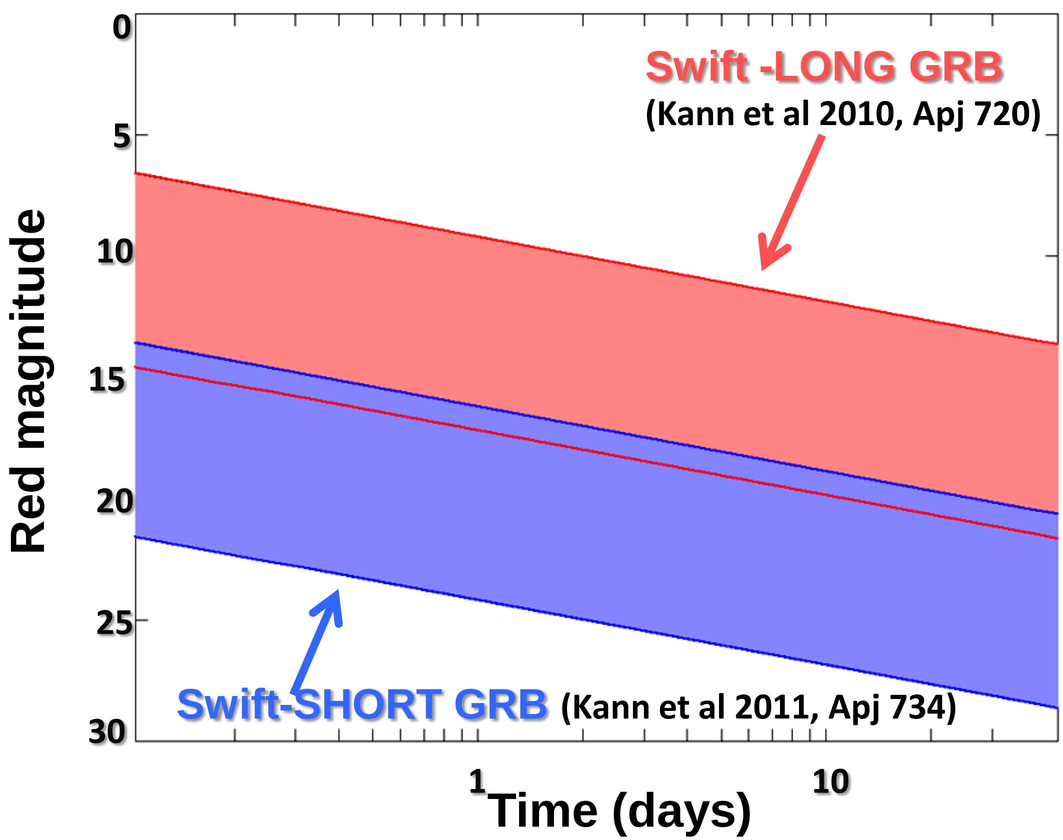
Nakar & Piran 2003

Jet temporal evolution

Light curve (Flux vs time)

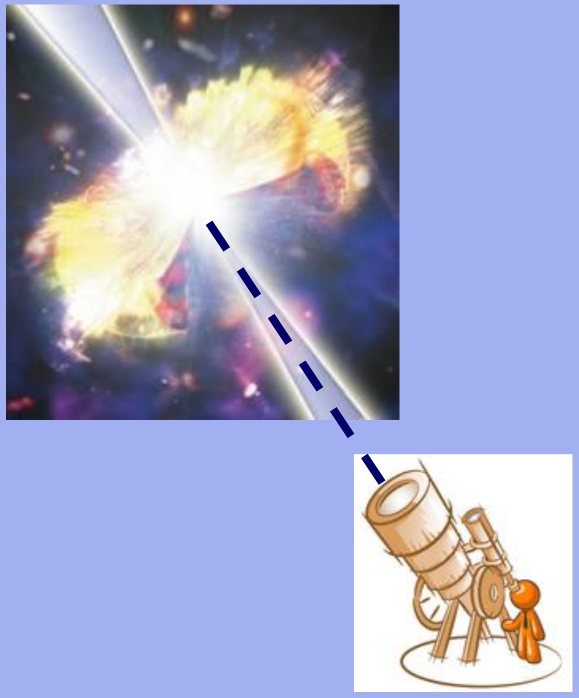
Optical afterglow ON-AXIS GRB

Source at distance of 200 Mpc



Observer along the jet axis

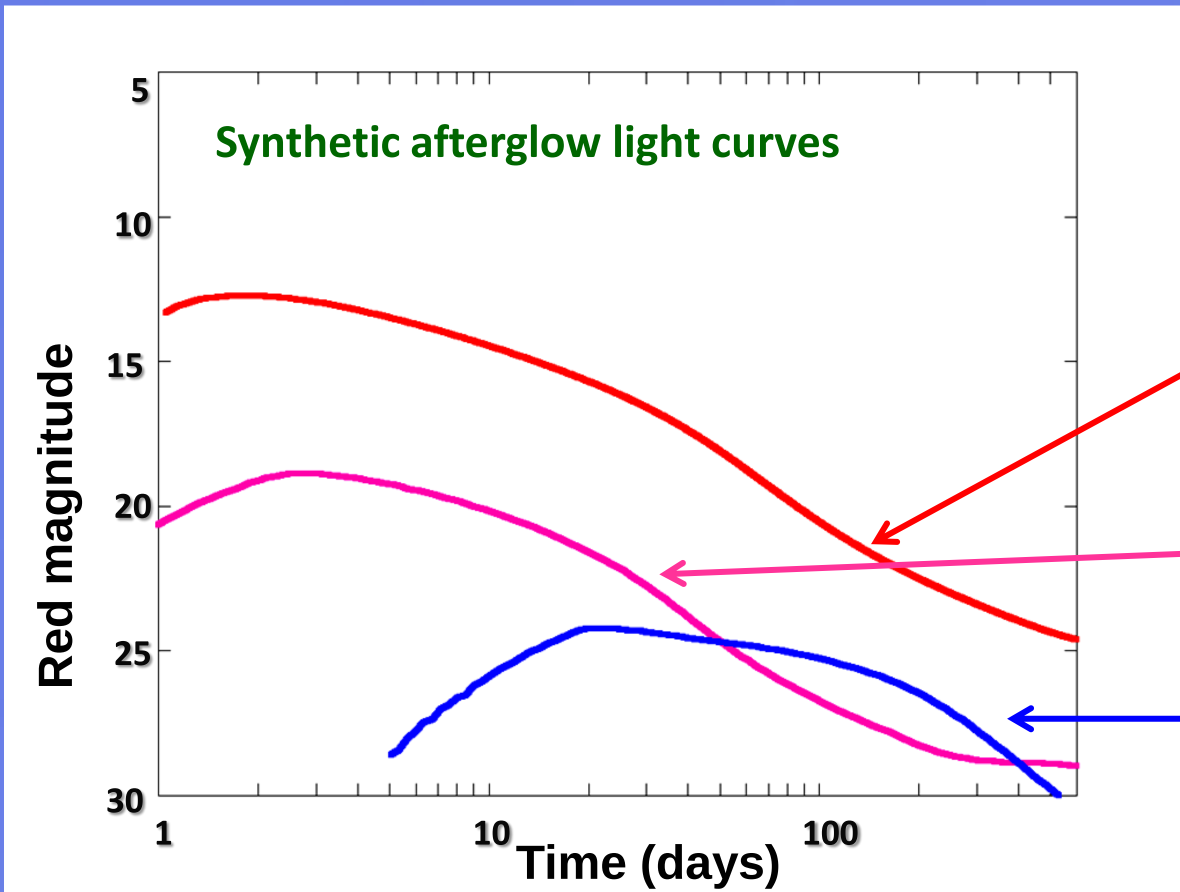
$\theta_{obs} < \theta_{Jet}$



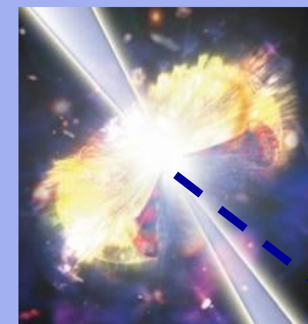
Power-law luminosity decay with time $t^{-\beta} \rightarrow \beta = 1 \div 1.5$

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

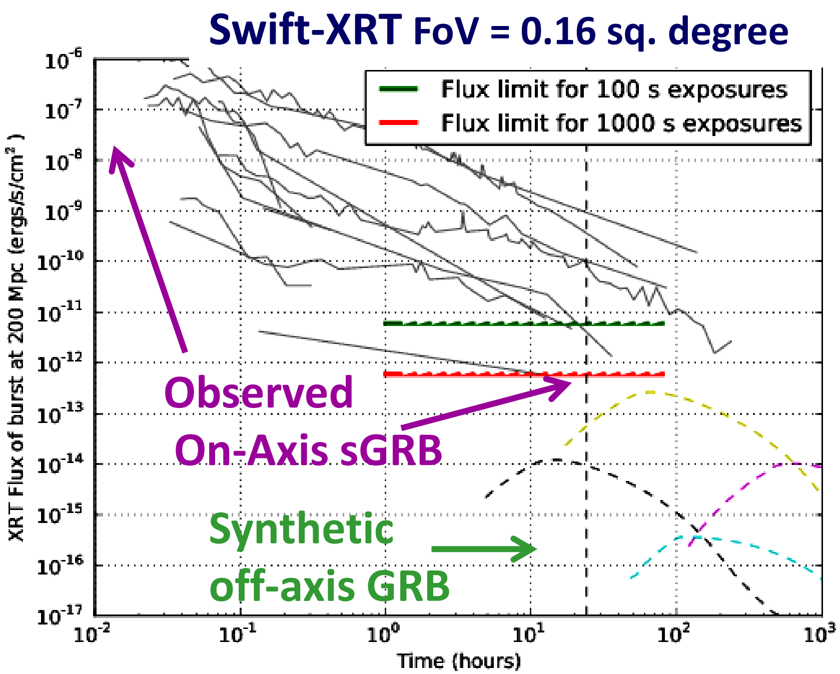
LONG low-luminosity GRB
$\theta_{obs} = 0.4$ rad

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

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

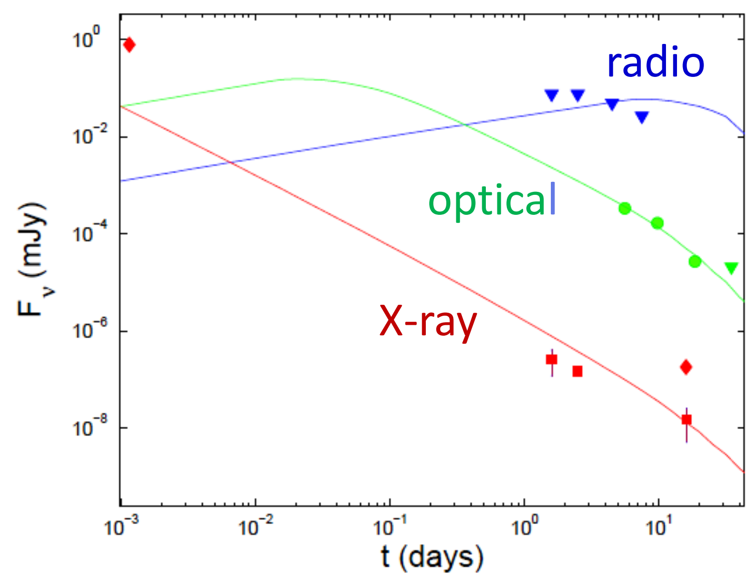
X-RAY and Radio GRB Afterglow

X-RAY: GRB at distance of 200 Mpc



Kanner et al. 2013, ApJ, 759

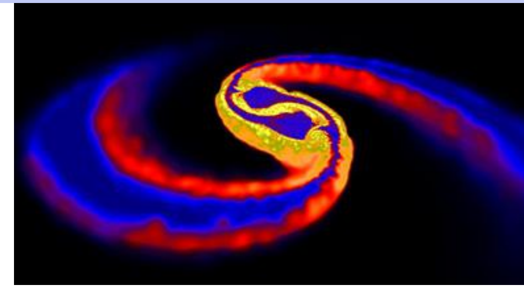
Short GRB 050709:



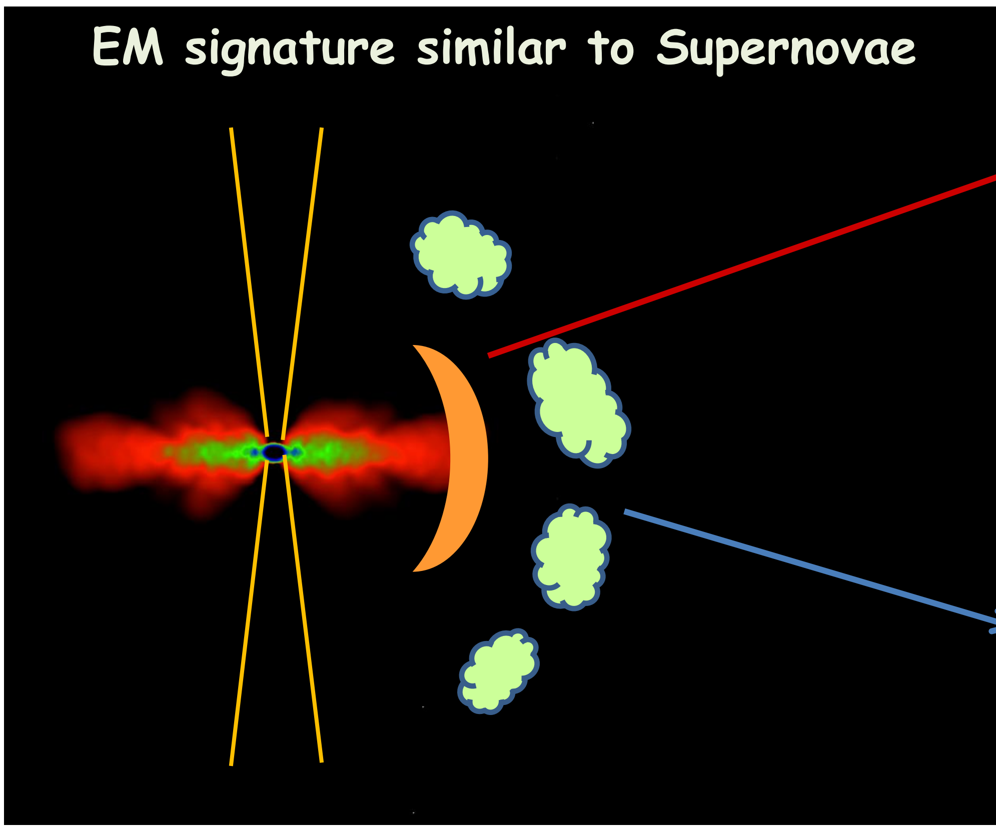
Fox et al. 2005, Nature 437

Kilonovae and Radio Flares

Significant **mass (0.01-0.1 m_o)** is **dynamically ejected**
during **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 radioactive decay of heavy elements synthesized in the ejected outflow

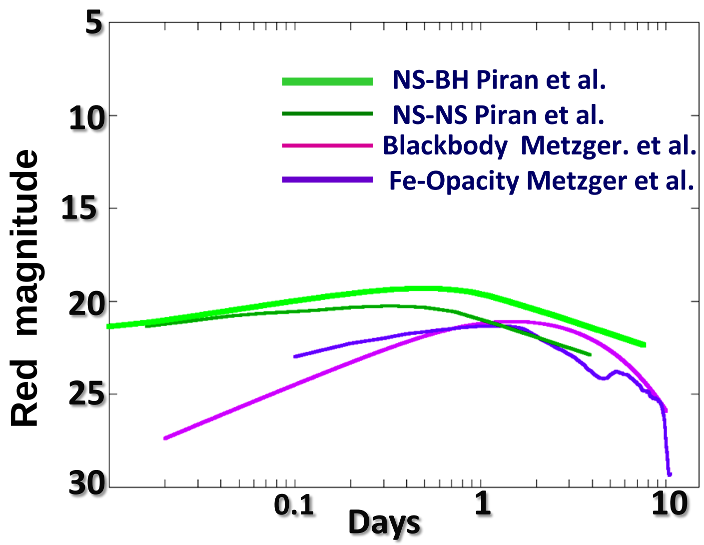
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;
Piran et al. 2013, MNRAS, 430

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

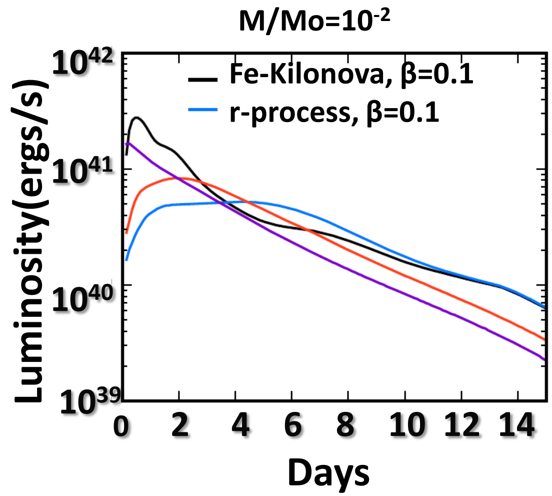


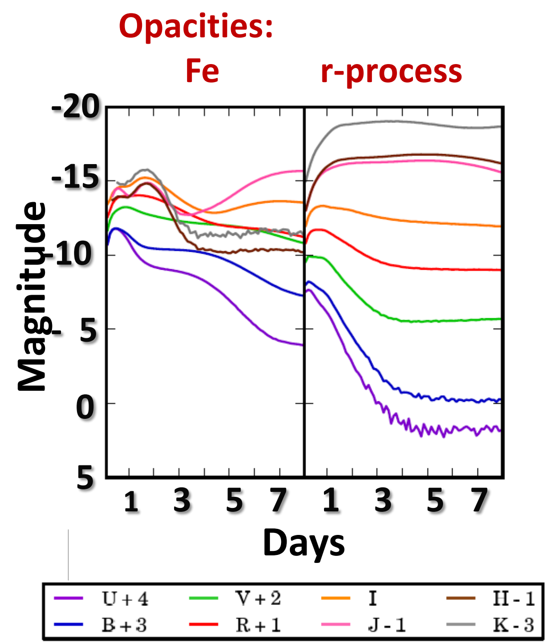
***Kilonova* model afterglow** peaks about **a *day* after** the merger/GW event

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

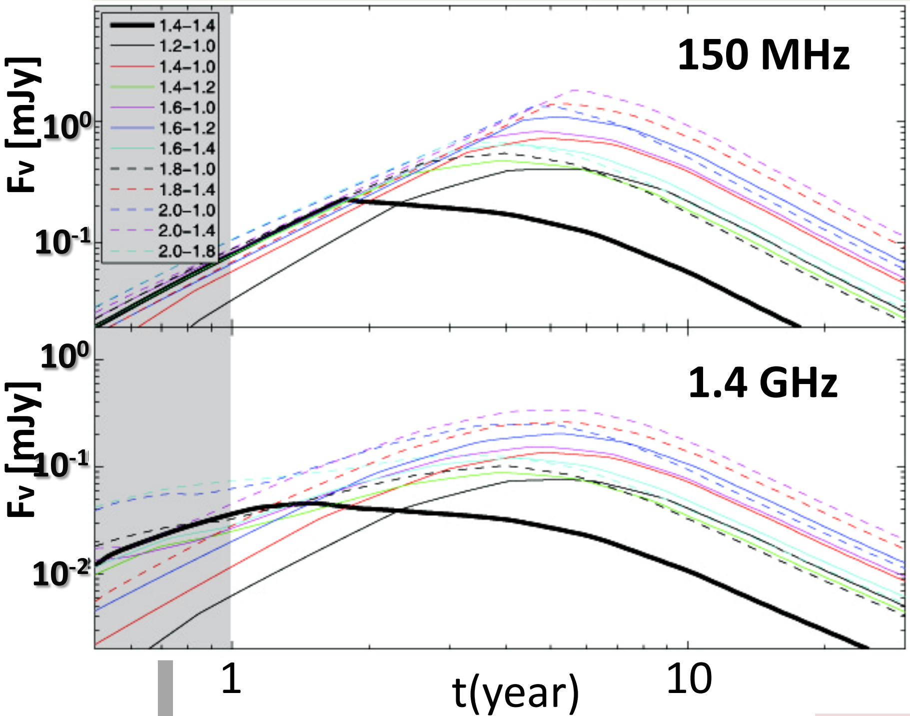
Possible HST kilonova detection for short GRB 130603B after 9.4 days

Berger & Fong arXiv:1306.3960, Tanvir et al. 2013, Nature/12505

Radio Flare Light Curves

Source at distance of 300

External ambient density n= 1cm^{-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

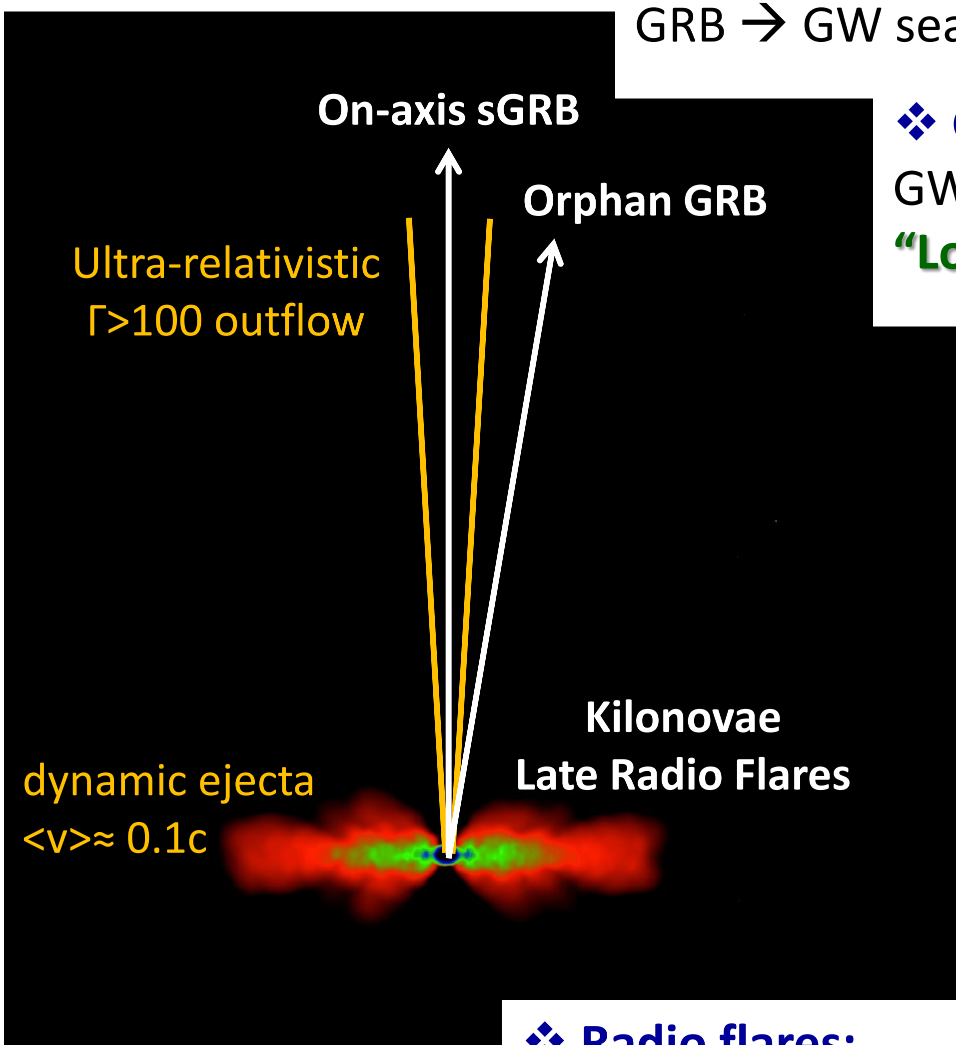
Piran et al. 2013, MNRAS, 430

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 and massive star core-collapse



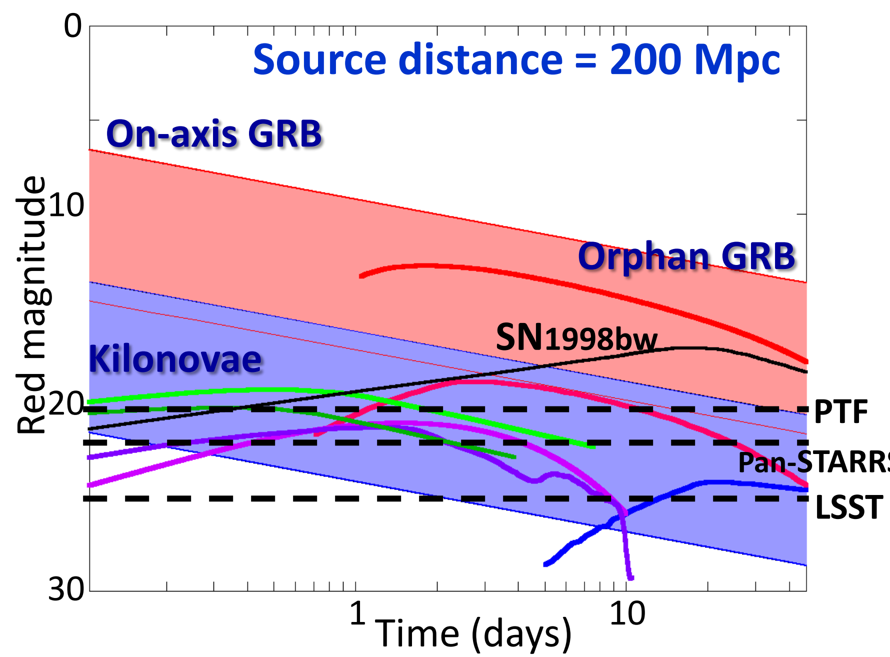
❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"Triggered 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"**

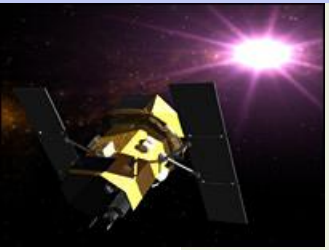
Blind radio search → GW search **"Triggered off-line analysis"**

Triggered analysis

EM observations → GW analysis

15

GRB prompt emission - TRIGGERED SEARCH



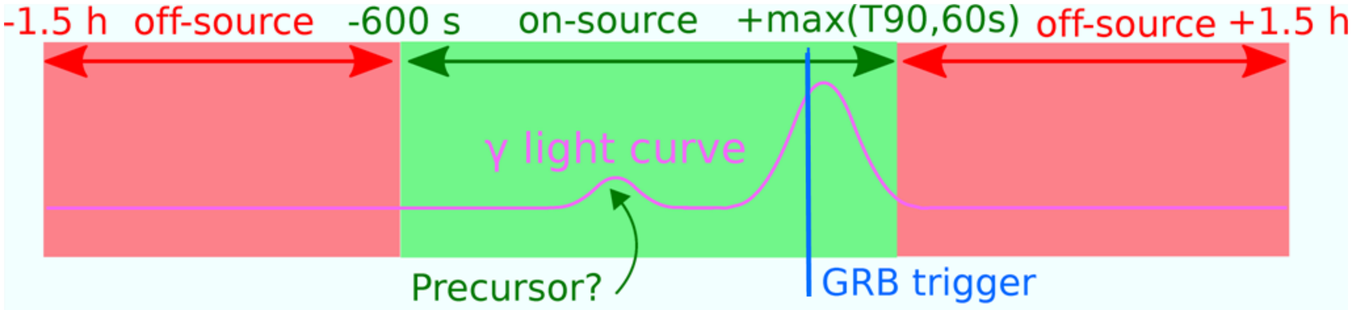
EM observations guide GW analysis

Known **GRB event time** and **sky position:**

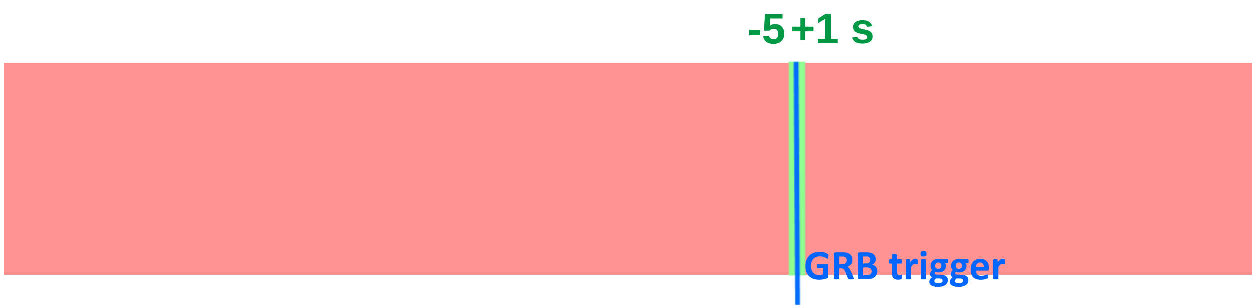
→ **reduction in search parameter space**
→ **gain in search sensitivity**

Analyzed 154 GRBs detected by gamma-ray satellites (most from Fermi GBM and Swift BAT) during **2009-2010** while 2 or 3 LIGO/Virgo detectors were taken good data

Unmodeled GW burst search



Binary system coalescence search



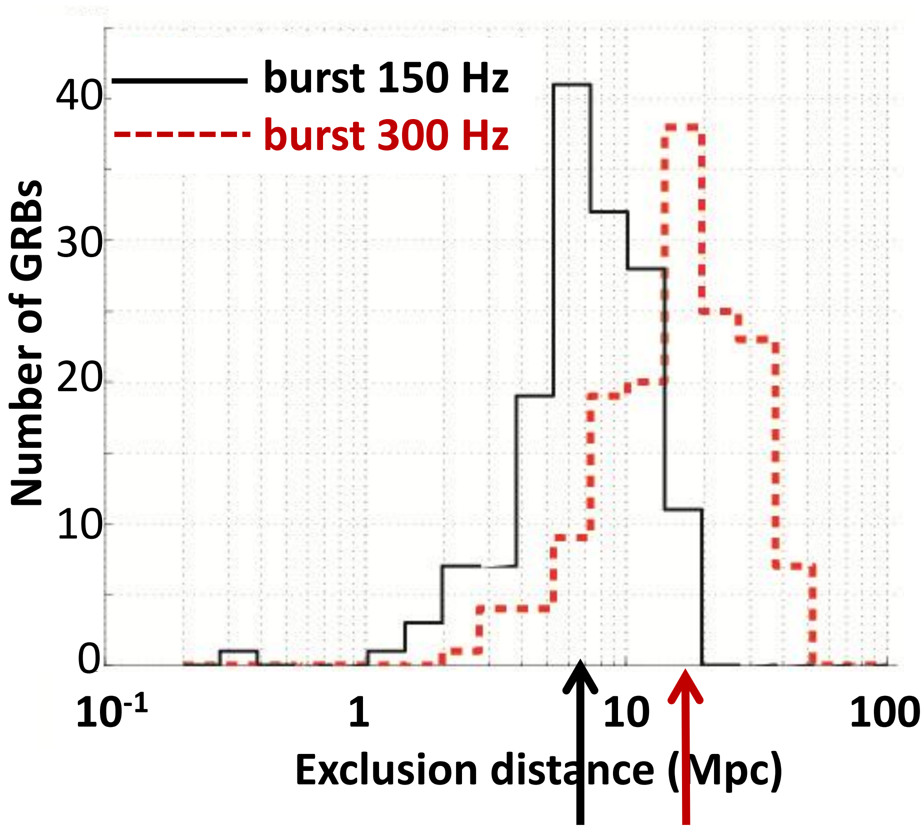
No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

GRB prompt emission - TRIGGERED SEARCH

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

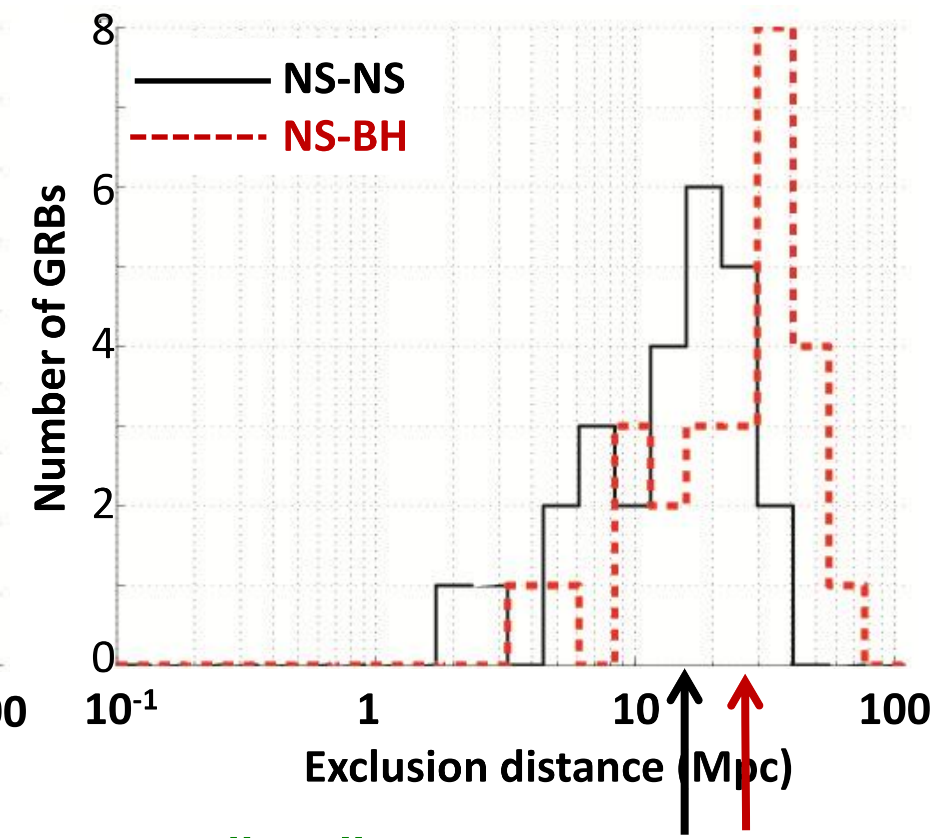
Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (150 GRBs)
with **10^{-2} $M_{\odot}c^2$ energy in GW** (optimistic)



Median distances: 7 17 Mpc

Binary system coalescence
(26 short GRBs)



Median distances: 16 28 Mpc

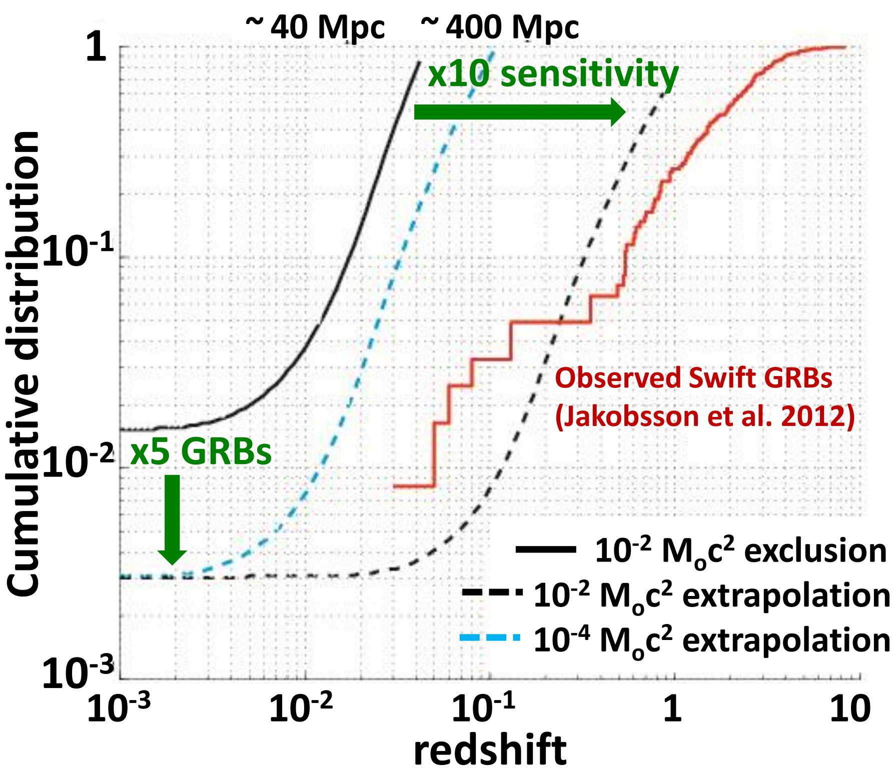
GRB prompt emission - TRIGGERED SEARCH

Population exclusion on cumulative redshift distribution

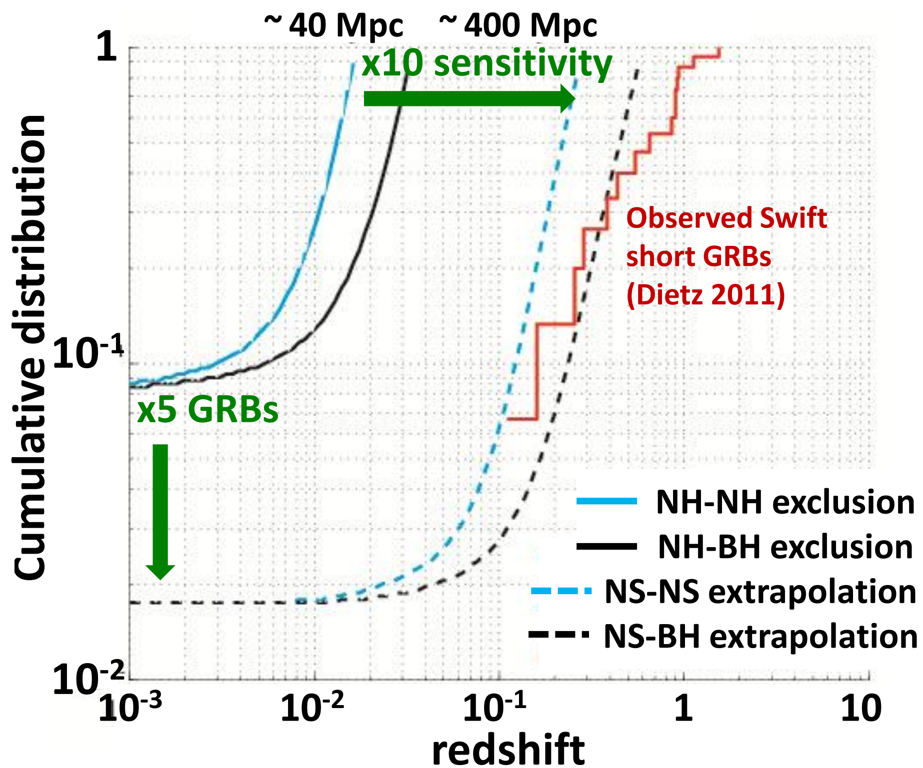
Results 2009-2010 & prospects for Advanced LIGO/Virgo

Abadie et al. 2012, ApJ, 760

Unmodeled GW burst



Binary system coalescence



→ Detection is quite possible in the advanced detector era

→ No detection will place relevant constraints on GRB population models

Electromagnetic follow-up

GW → prompt EM observations

2009-2010 first EM follow-up of candidate GW events

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

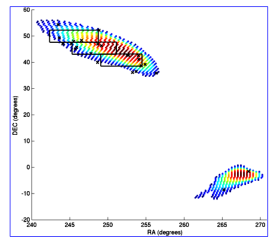
GW triggers

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

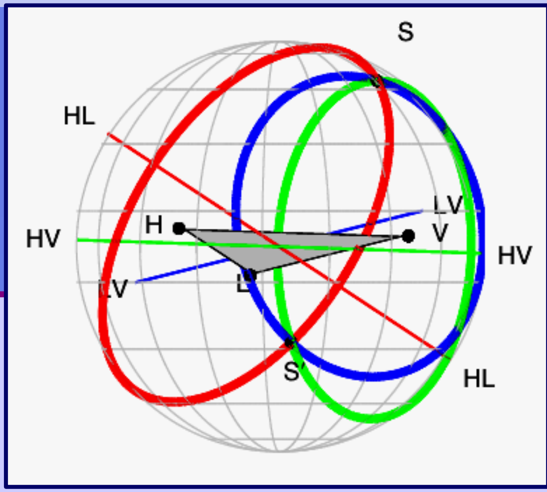
"Software" to identify GW-trigger for the EM follow-up:
- select statistically significant GW triggers
- determine telescope pointing

~ 10 min. → **~ 30 min.**

ADE latency expected to be improved!

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

Sky Localization of GW transients



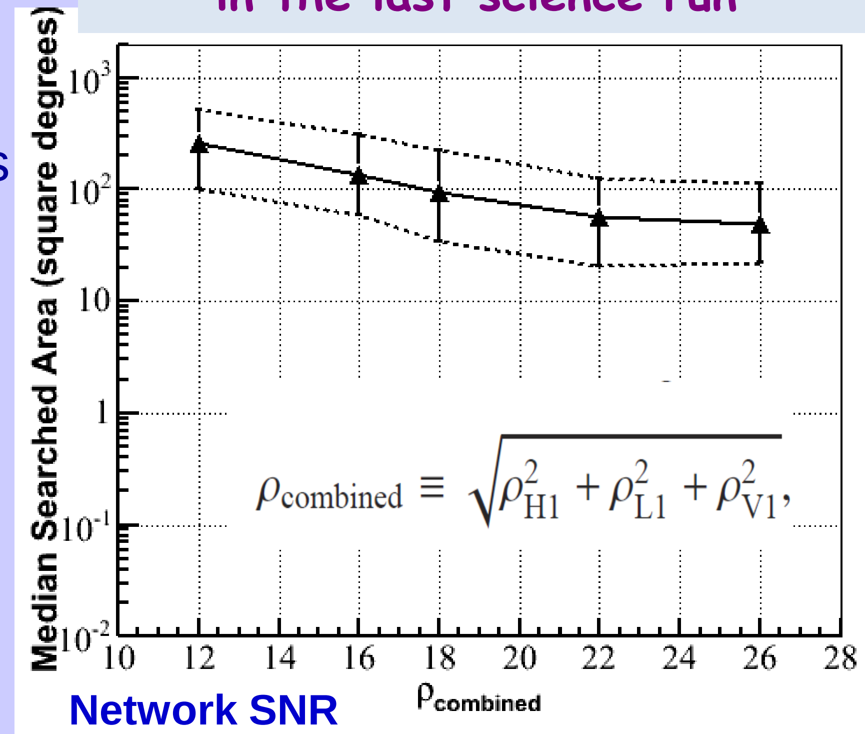
The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**

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

⬇

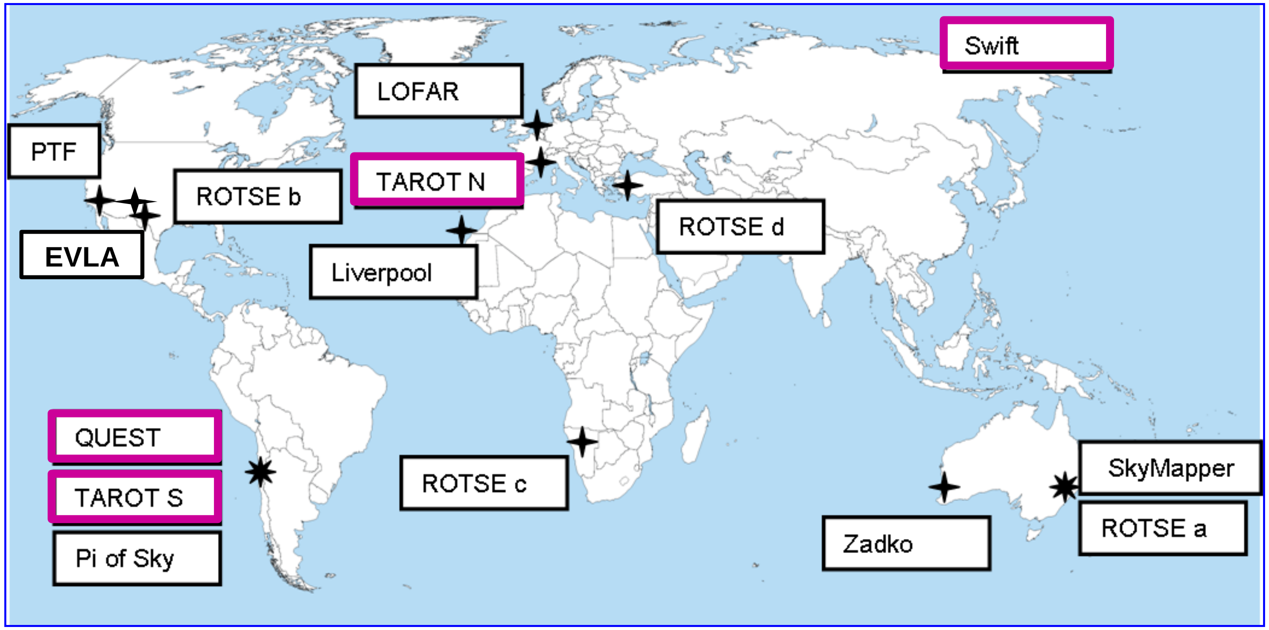
Necessity of wide field of view EM telescopes

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

(FOV, limiting magnitude)

TAROT SOUTH/NORTH

3.4 deg^2 , **17.5** mag

Zadko

0.17 deg^2, **20.5** mag

ROTSE

3.4 deg^2 , **17.5** mag

QUEST

9.4 deg^2 , **20.5** mag

SkyMapper

5.7 deg^2 , **21** mag

Pi of the Sky

400 deg^2 , **11.5** mag

Palomar Transient Factory

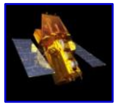
7.8 deg^2 , **20.5** mag

Liverpool telescope

21 arcmin^2 , **21** mag

X-ray and UV/Optical Telescope

Swift Satellite



XRT-FOV **0.16** deg^2

Flux **10^{-13}** ergs/cm^2/s

Radio Interferometer

LOFAR

30 - 80 MHz

110 - 240 MHz

Maximum **25** deg^2

EVLA

5 GHz - **7** arcmin^2

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

Initial 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

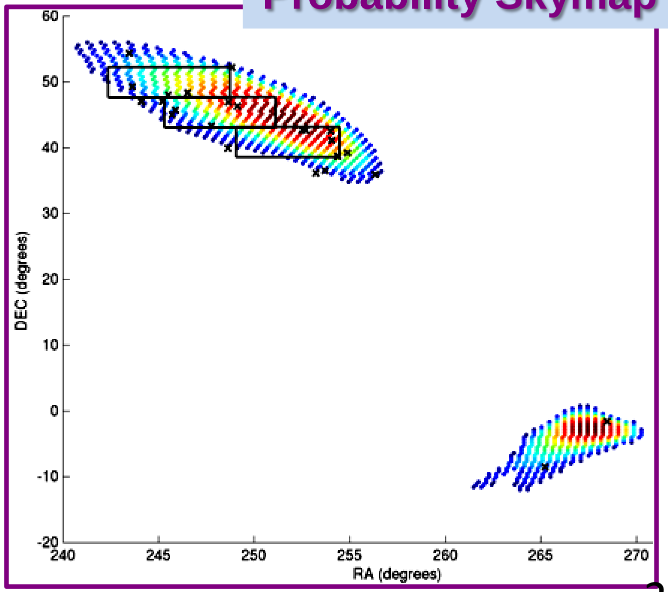
(GWGC catalog White et al. 2011, CQG 28, 085016)

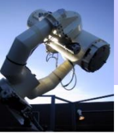
To determine the telescope pointing position:

⬇

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

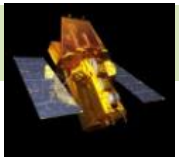
Probability Skymap





Optical telescope

14 GW alerts ➡ 9 followed by at least one telescope



Swift Satellite: X-ray and UV/Optical telescope

2 GW alerts sent and followed

Evans et al. 2012, ApjS, 203

Radio Interferometers

LOFAR

5 GW alerts sent and followed

Expanded-VLA

Lazio et al. , 2012 IAUS, 285

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

3 weeks, 5 weeks + 8 months later

GW/EM transient data analysis results:

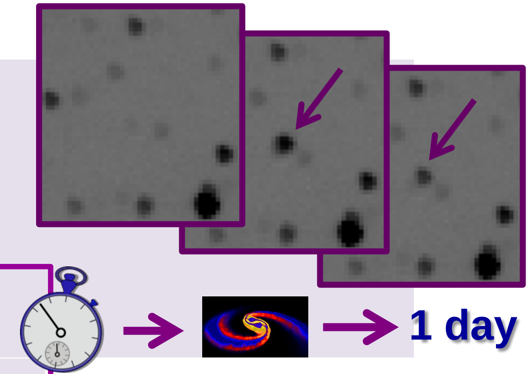
- **Off-line analysis of the GW data** alone → GW candidates show **no evidence of an astrophysical origin**
- **EM transients** detected in the images **consistent with the EM background**

(optical analysis results under internal LIGO/Virgo review)

EM analysis procedure to identify a GW counterpart

Main steps:

1) **Identification** of all **"Transient Objects"** in the images



2) **Removal of "Contaminating Transients"**

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

"Contaminating transients" rejection:

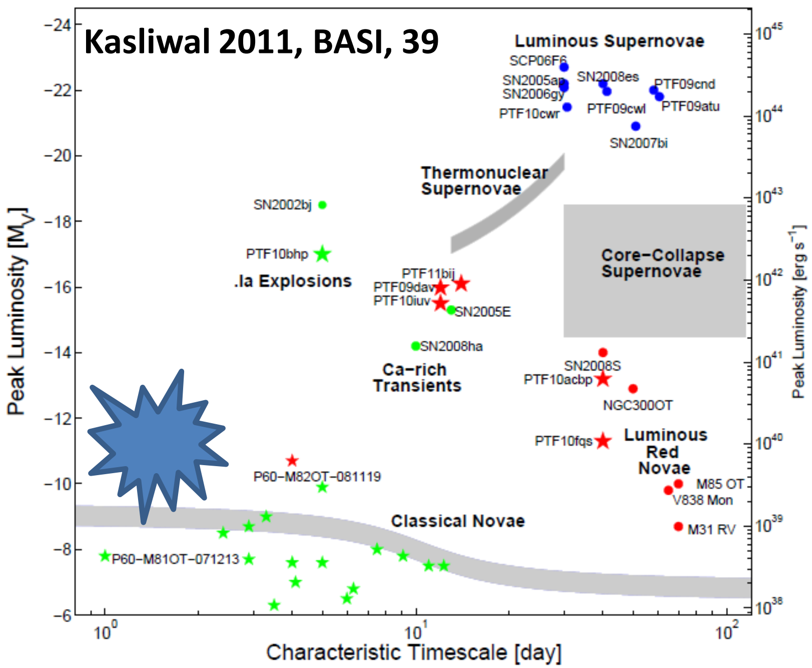
- by limiting the analysis to the **regions occupied by the most likely GW source host galaxies**
- by a **rapid transient discovery** and (light curve/color/shape) **classification** over wide sky areas

3) **Multi-wavelength** and **spectroscopic follow-up** of a small number of counterpart candidates **to uniquely identify a counterpart** of the GW trigger

Very promising result: discovery and redshift of **optical afterglow** for the long GRB 130702 over **71 sq. degree**
Singer et al. 2013, arXiv1307.5851

ElectromagneticTransient Sky

Exploration of **the optical transient sky at faint magnitudes and short timescale** has started recently



Pan-STARRS searching for **fast optical transient (0.5 hr – 1d)** brighter **22.5 mag:**

→ **primary contaminants: M-dwarf flares** and **asteroids** (19/19 transient detections)

→ **upper limit on extragalactic fast transients** (no detection): **rate 0.12 deg^{-2} d^{-1}** (0.5 hrs)

rate < 2.4 10^{-3} deg^{-2} d^{-1} (1d)

Berger et al. 2013, arXiv 1307.5324

Transient X-ray and radio sky is emptier than in the optical band

X-ray transients in the Advanced LIGO/VIRGO horizon

Systematic search in the **XMM-Newton Slew Survey** covering 32800 deg^2 above a **flux threshold of 3 X 10^{-12}** (erg s^{-1}cm^{-2})

→ **4 x 10^{-4} transients per sq. degree**

Kanner et al. 2013, arXiv 1305.5874

Radio transients

(1.4 GHz and 150 MHz)

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

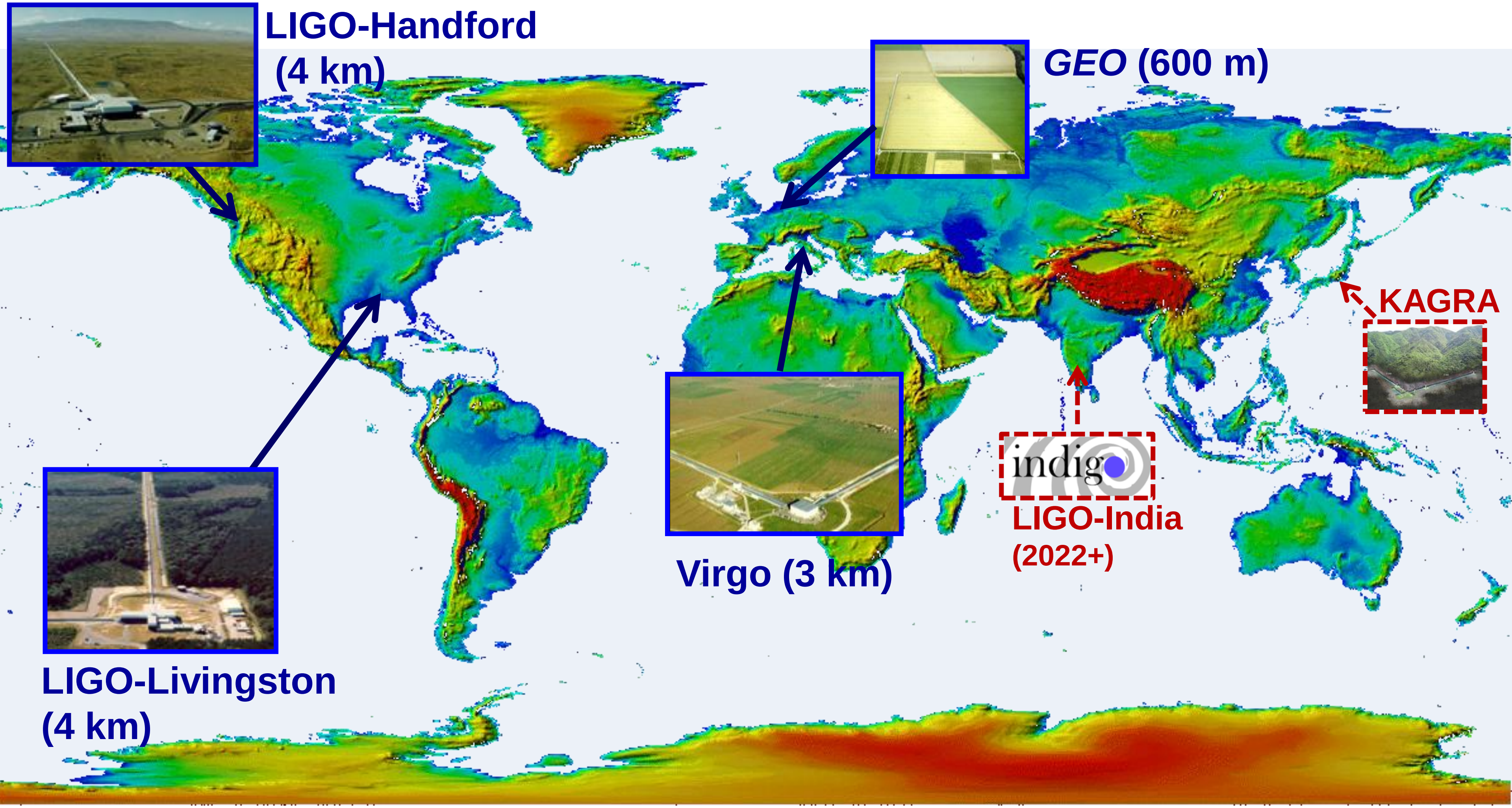
→ **transient density < 0.37 deg^{-2} above 0.21 mJy**

Mooley et al. 2013, ApJ,768

Advanced detector era observing scenario

LSC & Virgo Collaborations, arXiv:1304.0670

Ground-based Gravitational Wave Detectors

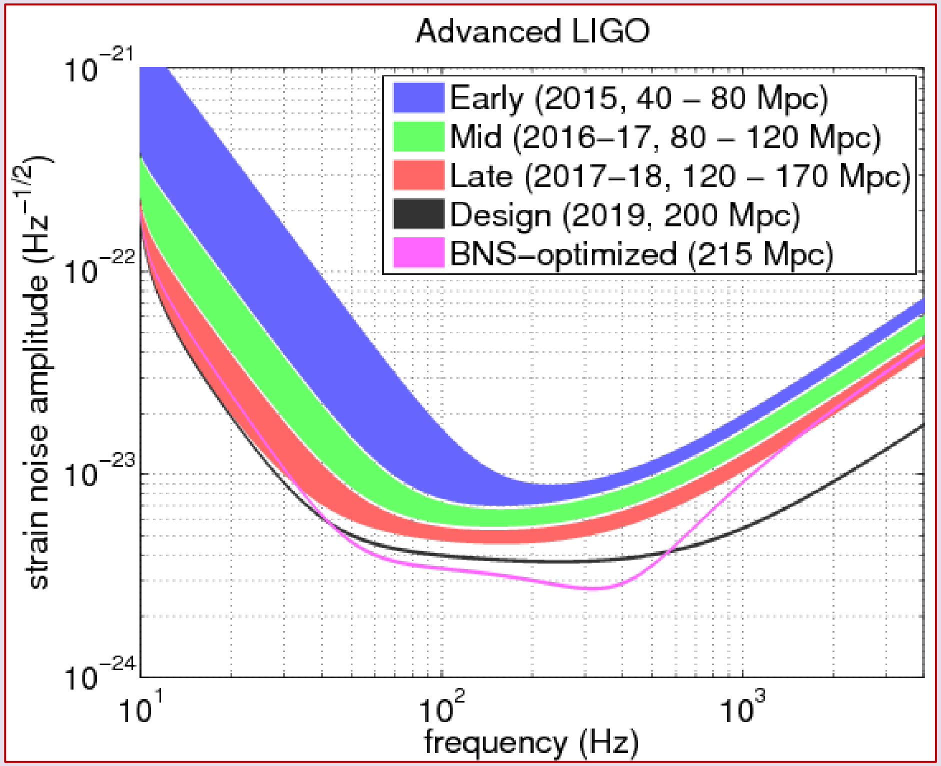


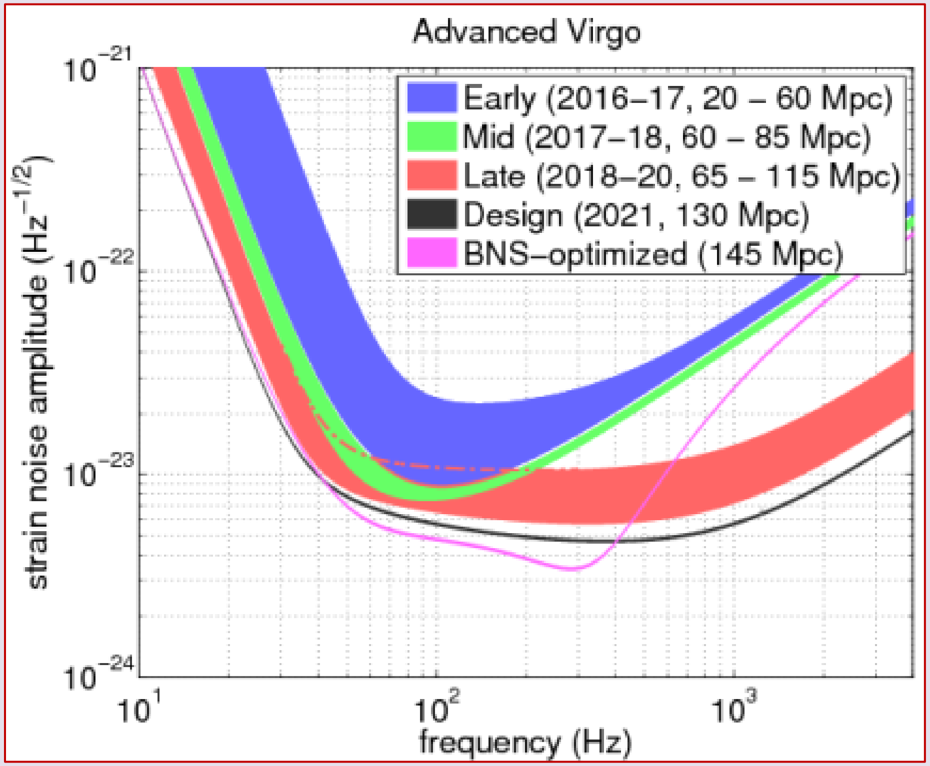
The **advanced LIGO** and **Virgo** will observe the sky (10-1000 Hz) as a single network aiming at the **first direct detection of GWs**

Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

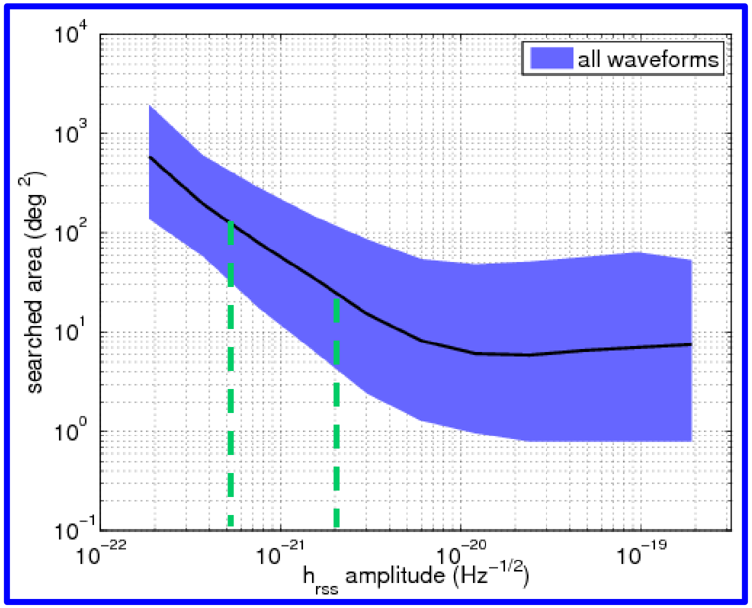
Progression of sensitivity and range for Binary Neutron Stars





Larger GW-detectable Universe

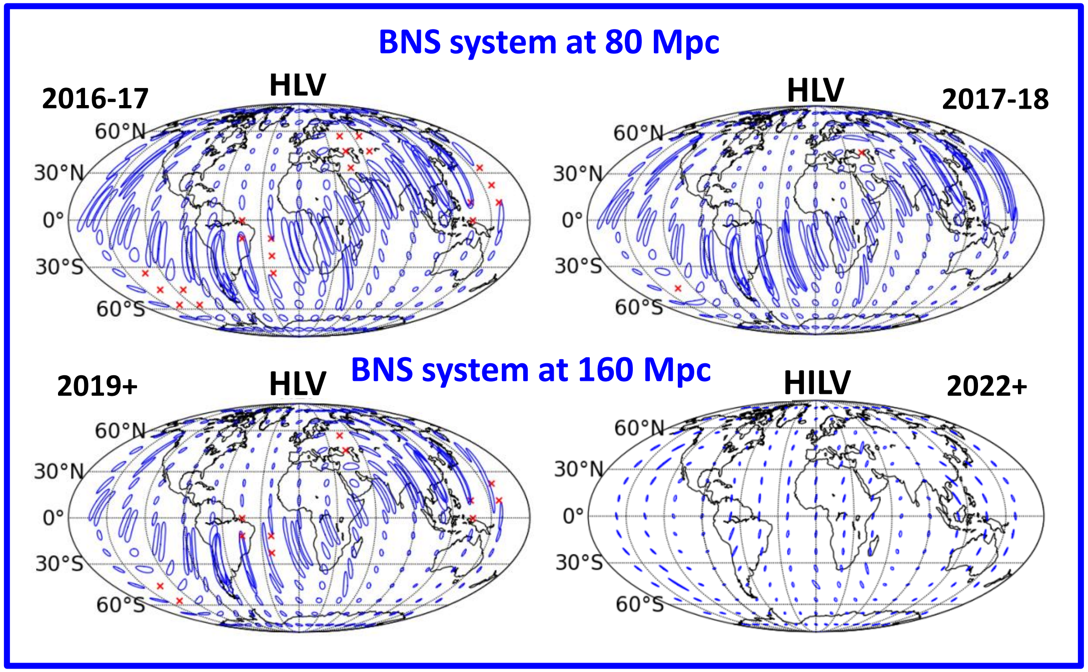
Sky Localization of Gravitational-Wave Transients



Burst search "uncertainty region size"

ρ_c **≥ 15** median region of **30 deg² - 200 deg²**

Network sensitivity /Localization accuracy for Binary Neutron Stars



→ **90% confidence localization areas**

X → **Regions of the sky where the signal would not be confidently detected**

Follow-ups would need to deal with large position uncertainties with areas of many **tens of sq. degrees**

Summary of plausible observing scenario

LSC & Virgo collaboration
arXiv:1304.0670

LIGO/Virgo Range	Rate	Localization

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	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

Observational strategies for each epoch..key points:

- **Image the whole GW error box:**
  - → Large "etendue surveys" (PTF, Pan-STARRS, LSST)?
  - → Wide-medium FOV telescope networks?
- **Galaxy targeting:** → is still useful to point small-FOV telescope?
  → to reduce the EM FAR?
  Galaxy priors to sample GW source population?
- **Identify uniquely the EM counterpart**: survey the explore the "transient sky"? multi-wavelength observations? larger telescope and spectroscopic-follow up?
- ………

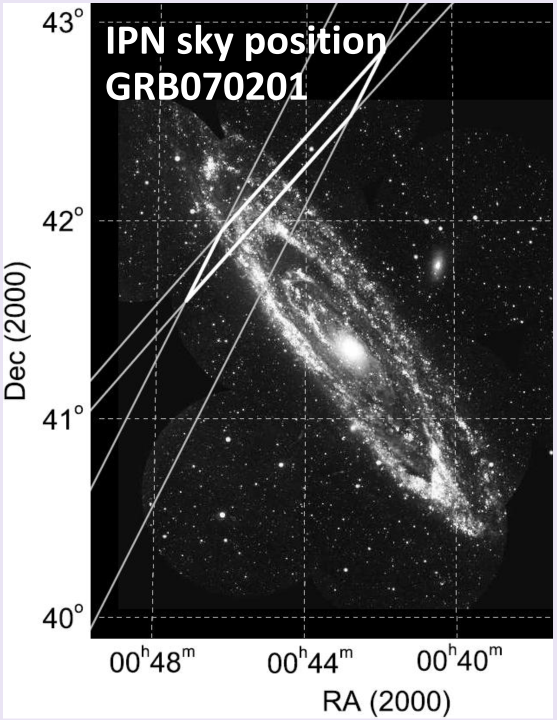
TIGHT LINK is required between GW/EM COMMUNITIES
to be ready for the UPCOMING GW-TRANSIENT ASTRONOMY!!

Summary of promising EM counterparts

EM Band	Sources	Analysis	Strength	Weakness	Example Facilities
γ-rays	On-axis GRB	EM→GW "off-line"	→ strong EM signal → temporal coincidence	→ beamed emission/small % of events	Fermi-GBM Swift-BAT
X-ray	On-axis and "orphan" GRB	GW →EM Low-latency	→ few false positive	→lack of wide FoV facilities	Swift-XRT ISS-Lobster
UV/O/IR	On-axis and "orphan" GRB Kilonova	GW →EM low-latency	→ Transient "survey" facilities →Isotropic	→numerous false positive → Faint in UV/O	PTF, PanStarrs, VISTA, LSST
Radio	GRB Radio flares	GW→EM high-latency EM→GW "Off-line"	→ few false positive →isotropic	→long time delay →Dependence on ambient density	ASKAP Apertif LOFAR

EXTRA SLIDES

Short hard GRB070201 / GRB051103



➢ γ-ray emission:

→GRB070201 sky position overlaps with M31 (Andromeda, 770 kpc)
→ GRB051103 sky position overlaps with M81 (3.6 Mpc)

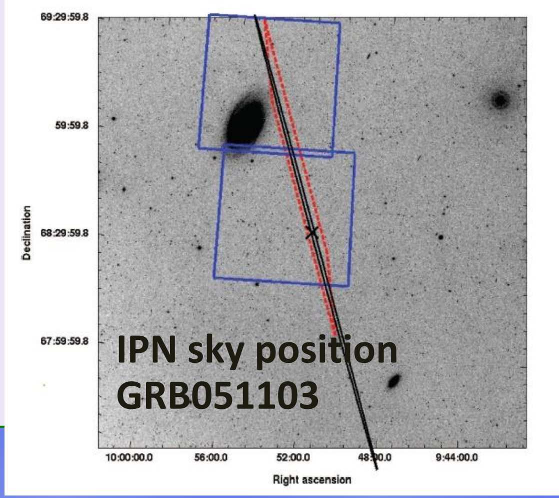
➢ No binary coalescence GW detection

→ compact binary progenitor in M31excluded at 99% c.l.
→ comapct binary progenitor in M81excluded at 98% c.l.

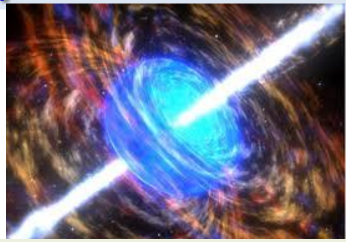
➢ No burst GW detection set emitted energy limits compatible with:

→ soft gamma-repeater giant flare
→ coalescence in galaxy more distant than M31/M81

Abbott et al 2008, ApJ, 681; Abadie et al. 2012, ApJ, 755



Observational galaxy priors to identify the most likely GW-host



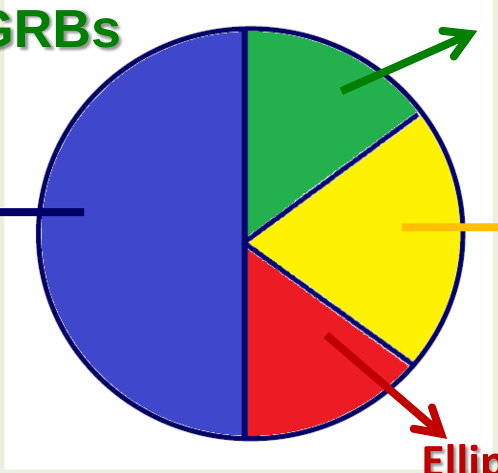
Useful:
- **to define an optimal observational strategy**
- **to identify the image region to be analyzed**

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**

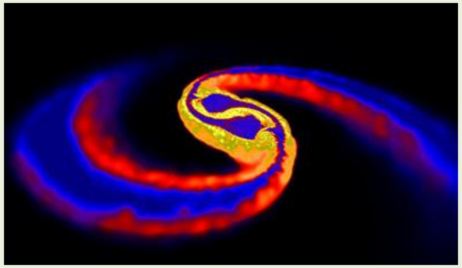
❑ Assuming that the short GRBs trace the binary neutron star mergers:

Sample: 36 short GRBs

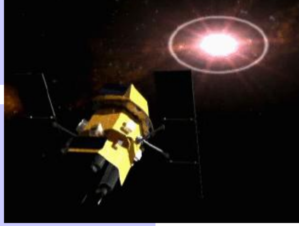


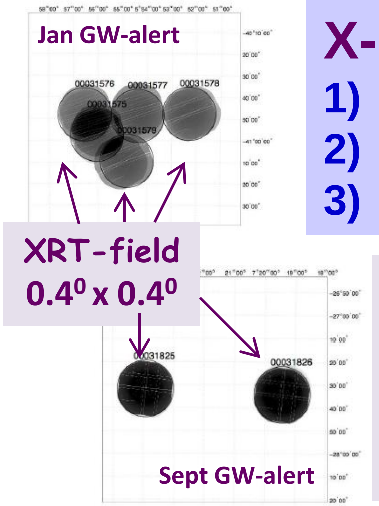
(Fong et al. 2013, ApJ, 769)

❑ **Population synthesis models** indicate a **relevant fraction (20 − 50%) of elliptical galaxy hosts** at z=0
(O'Shaughnessy et al. 2008, ApJ, 675)



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

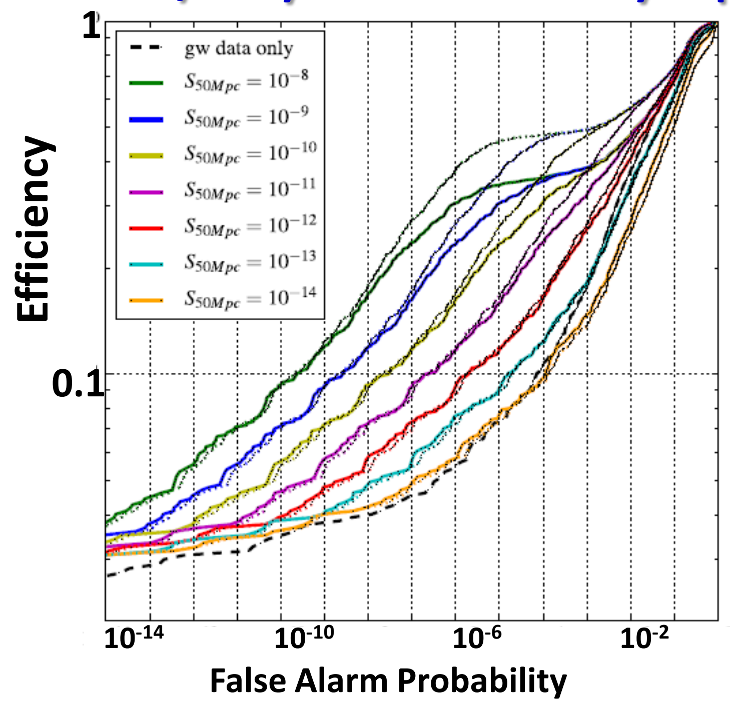


Figure shows

- 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**

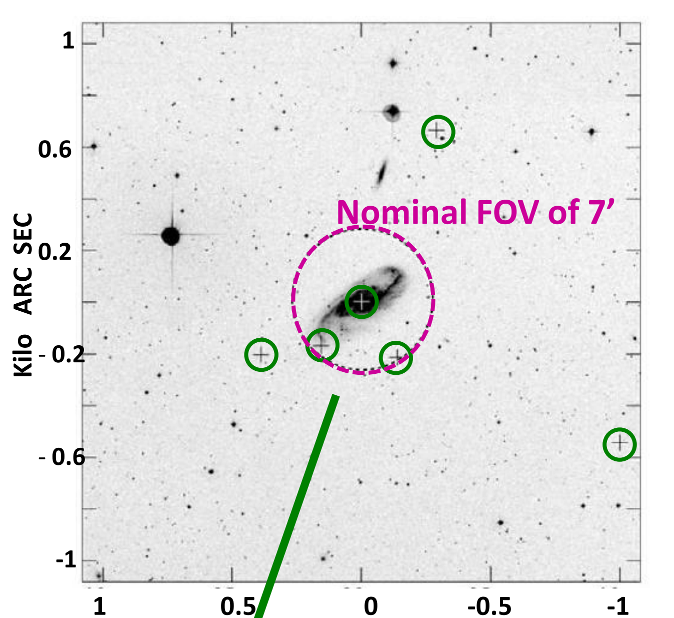
For each of the two GW-candidates observed ➡ **3 most probable host galaxies**

Image Analysis:

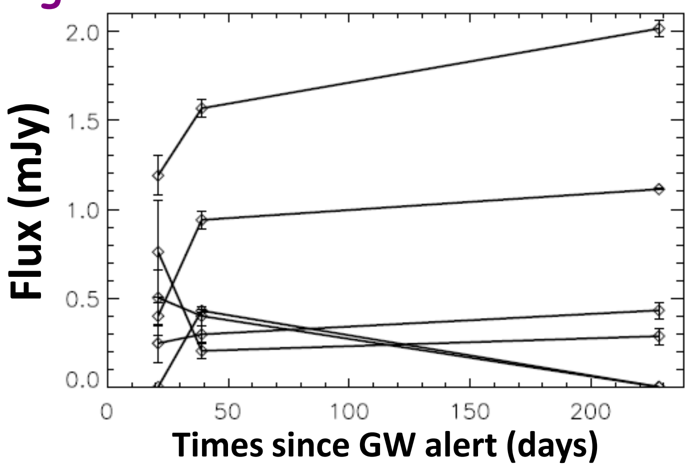
1) radio source detection
2) variability analysis
3) identification of contaminating transients

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)

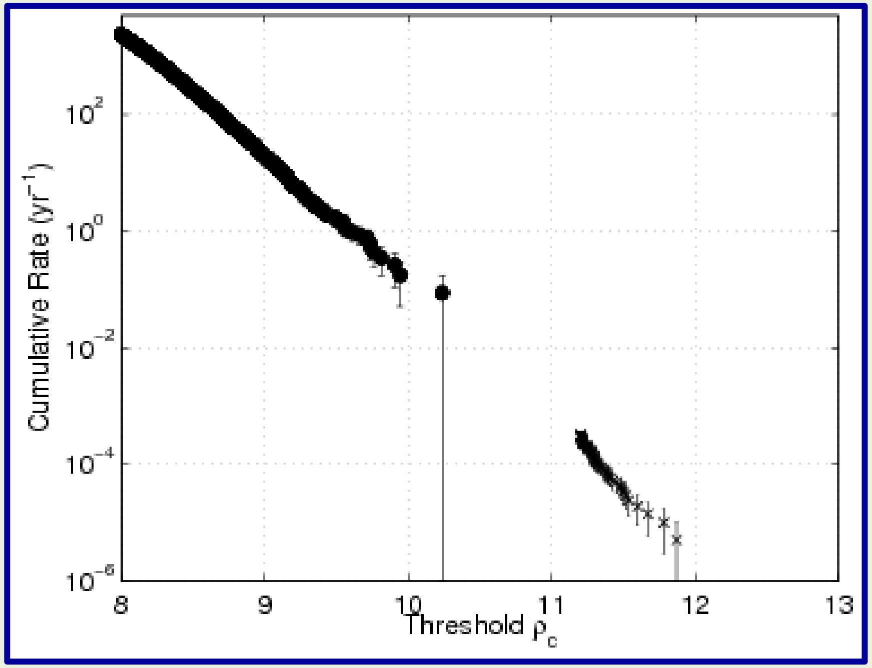
Lazio et al. , 2012 IAUS, 285

Rate of False Alarm GW triggers

FAR will depend on the data quality of the advanced detectors
"instrumental glitches" will produce an elevated background of loud triggers

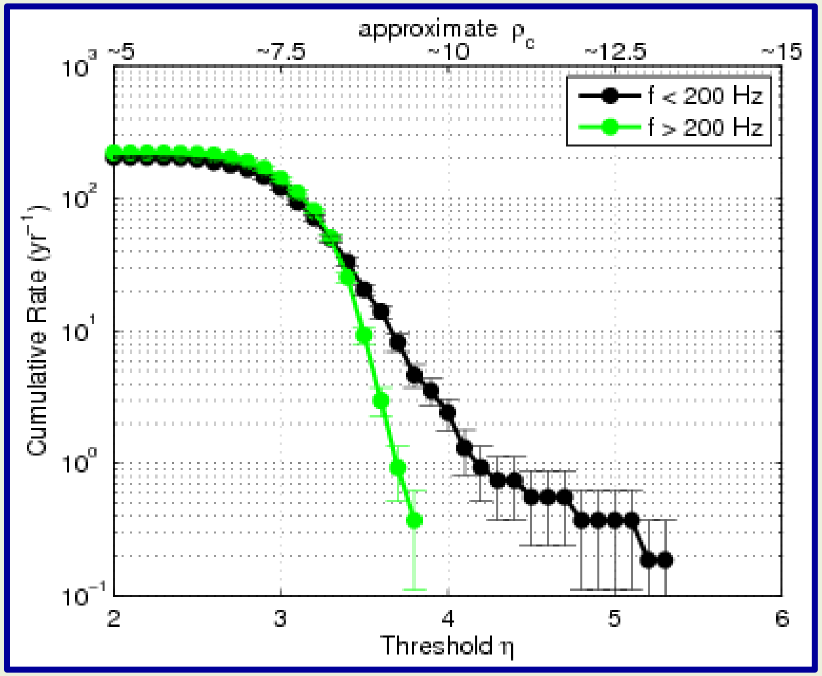
2009-2010 LIGO-Virgo data

Compact Binary Coalescence search



Modelled-search reduces the background
→ conservatively, **ρ_C of 12** is required for a **FAR 10^{-2} yr^{-1}** in aLIGO and aVirgo

Burst search

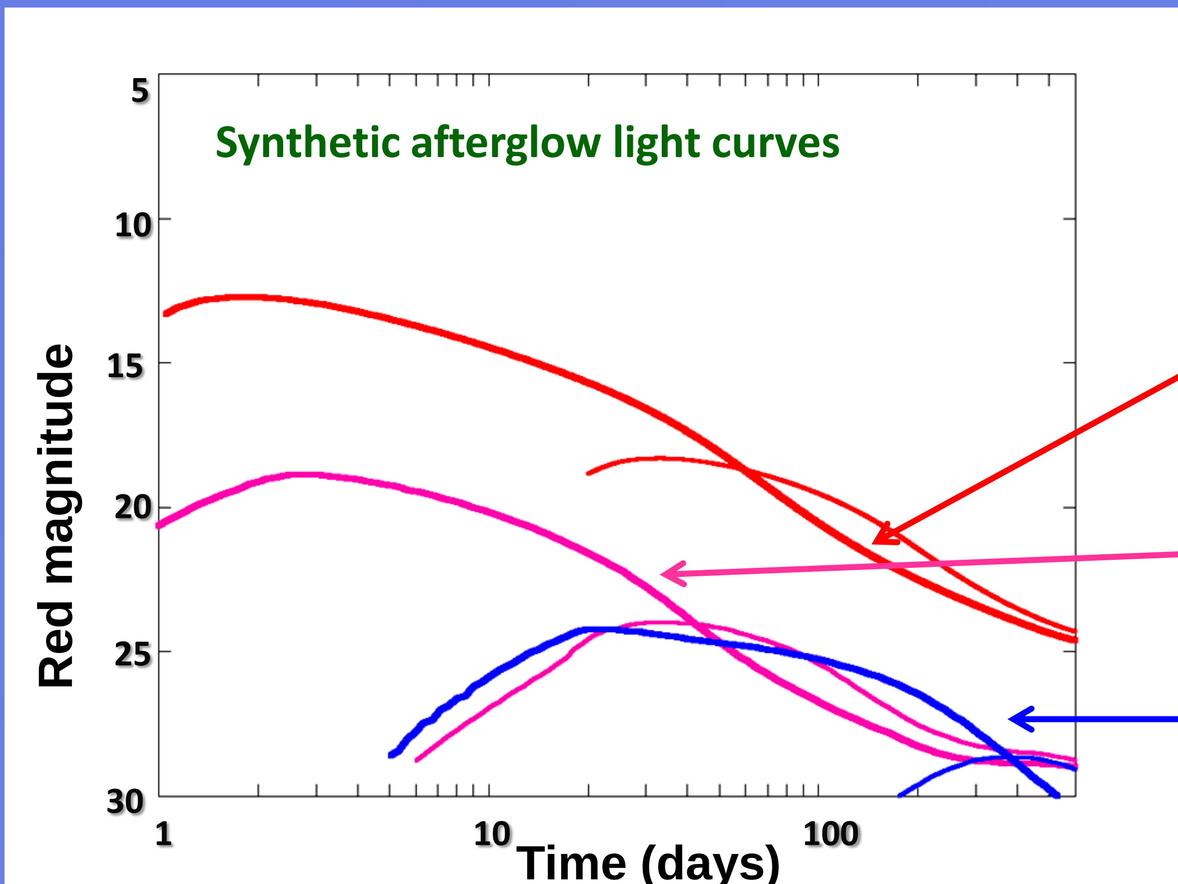


Unmodelled search →more difficult to distinguish signal from glitches. At frequencies below 200 Hz significant tails of loud bkg events

LSC & Virgo Collaborations, arXiv:1304.0670

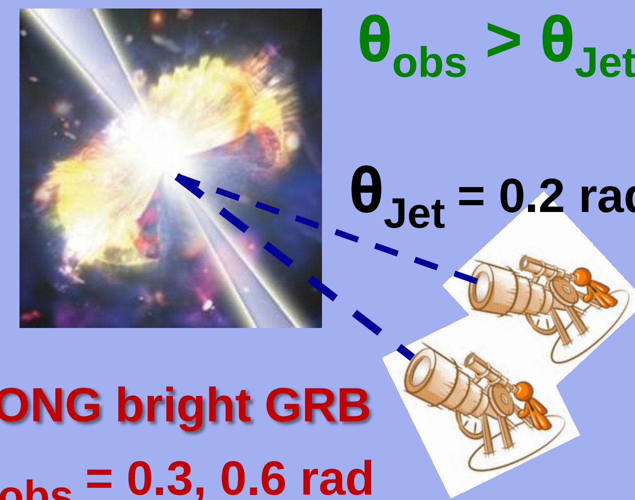
Optical afterglow “Orphan GRB”

Source at distance of 200 Mpc



OFF-AXIS GRB

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



LONG bright GRB
θ_{obs} = 0.3, 0.6 rad

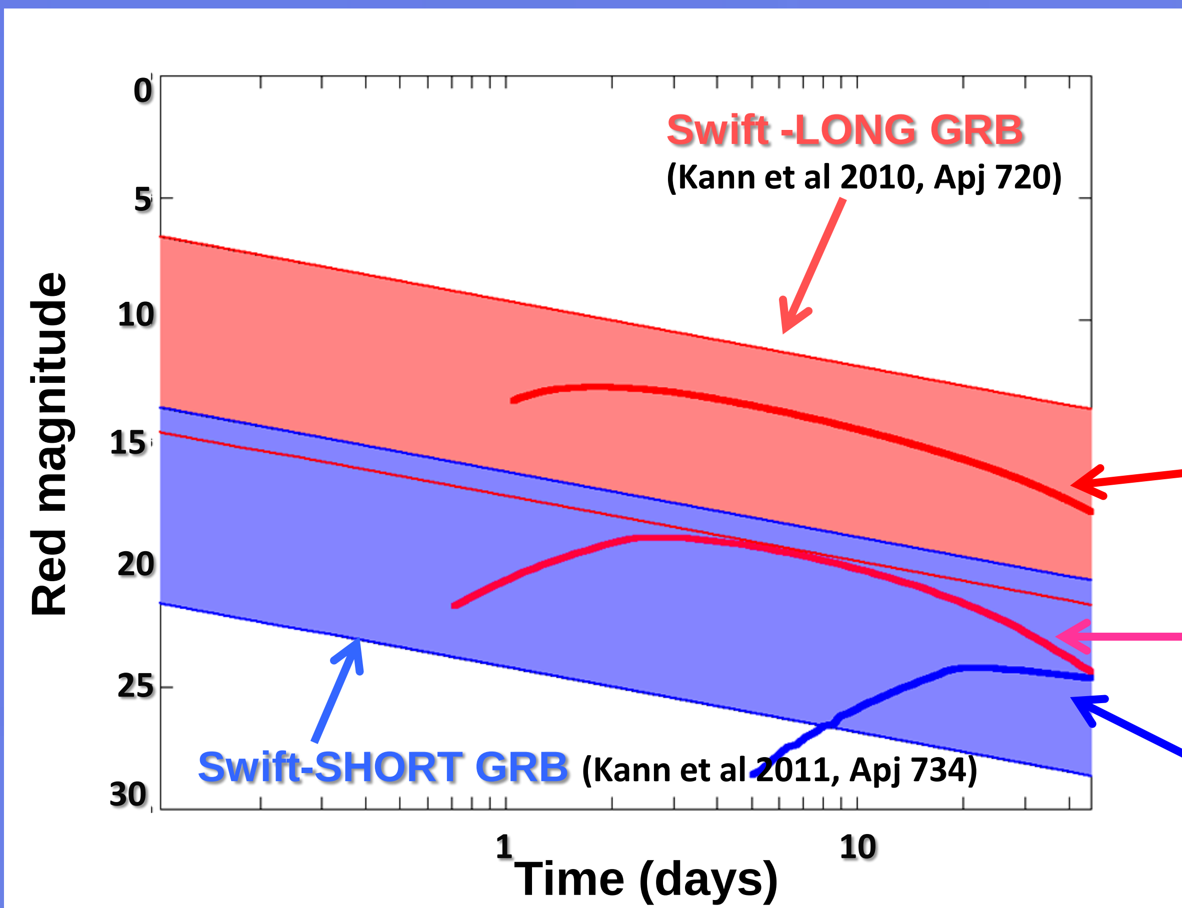
LONG low-luminosity GRB
θ_{obs} = 0.4, 0.8 rad

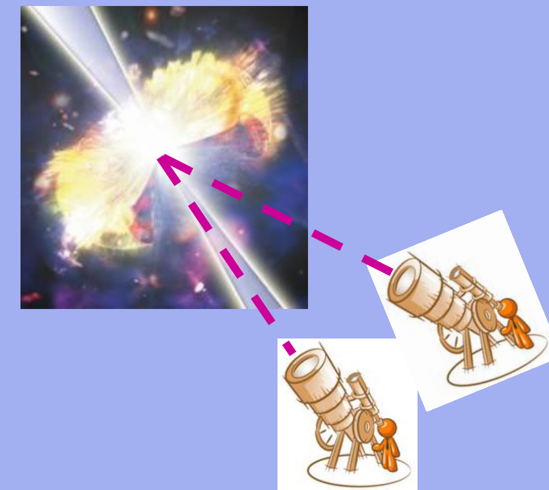
SHORT GRB
θ_{obs} = 0.4, 0.8 rad

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

Gamma Ray Burst Optical afterglow

Source at distance of 200 Mpc





Synthetic afterglow light curves

LONG bright GRB

$\theta_{obs} = 0.3$ rad

LONG low-luminosity GRB

$\theta_{obs} = 0.4$ rad

SHORT GRB

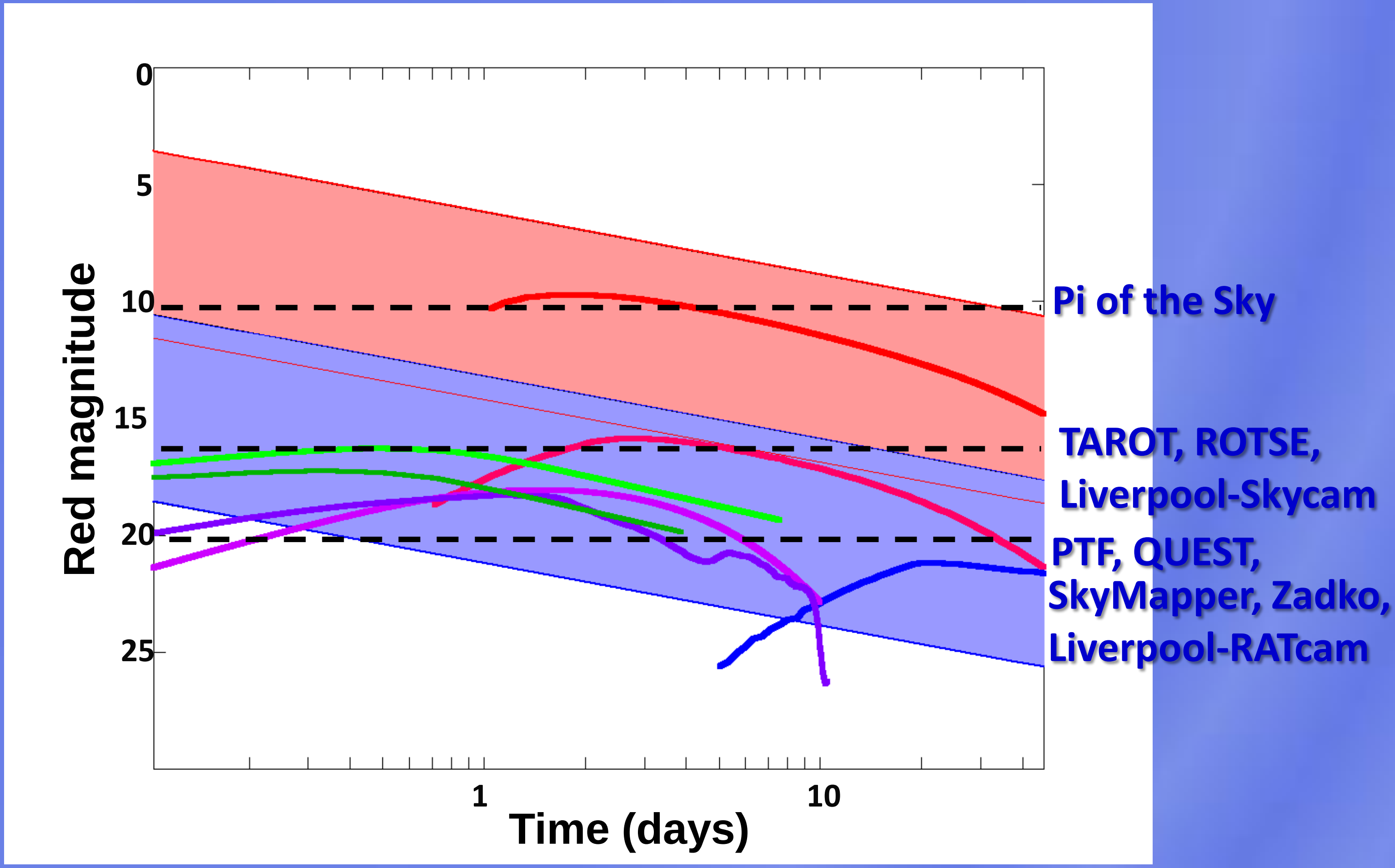
$\theta_{obs} = 0.4$ rad

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

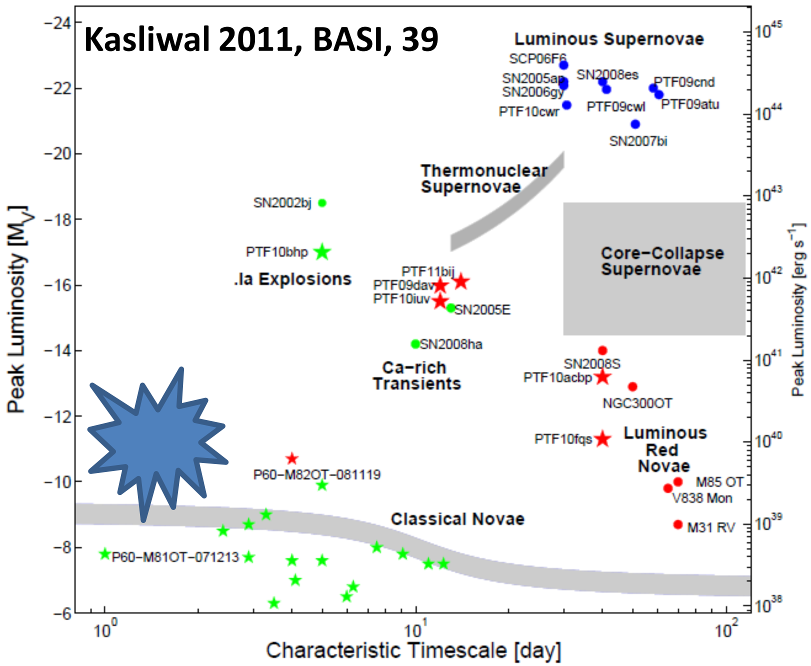
By van Eerten & MacFadyen

Optical Afterglow Light Curves
for GRBs and kilonovae

Source at distance 50 Mpc



Optical Transient Sky



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

Pan-STARRS searching for **fast optical transient (0.5 hr – 1d)** brighter **22.5 mag:**

→ **primary contaminants: M-dwarf flares** and **asteroids** (19/19 transient detections)

→ **upper limit on extragalactic fast transients** (no detection): **rate 0.12 deg^{-2} d^{-1}** (0.5 hrs)
rate < 2.4 10^{-3} deg^{-2} d^{-1} (1d)

Berger et al. 2013, arXiv 1307.5324

Extremely valuable
→ **optical transient survey**

→**algorithms for a rapid transient discovery** and **classification over wide sky areas** **(Bloom et al. 2012, PASP, 124)**

→ to select **small number of counterpart candidates** to be **multi-wavelength** and **spectroscopic followed-up**

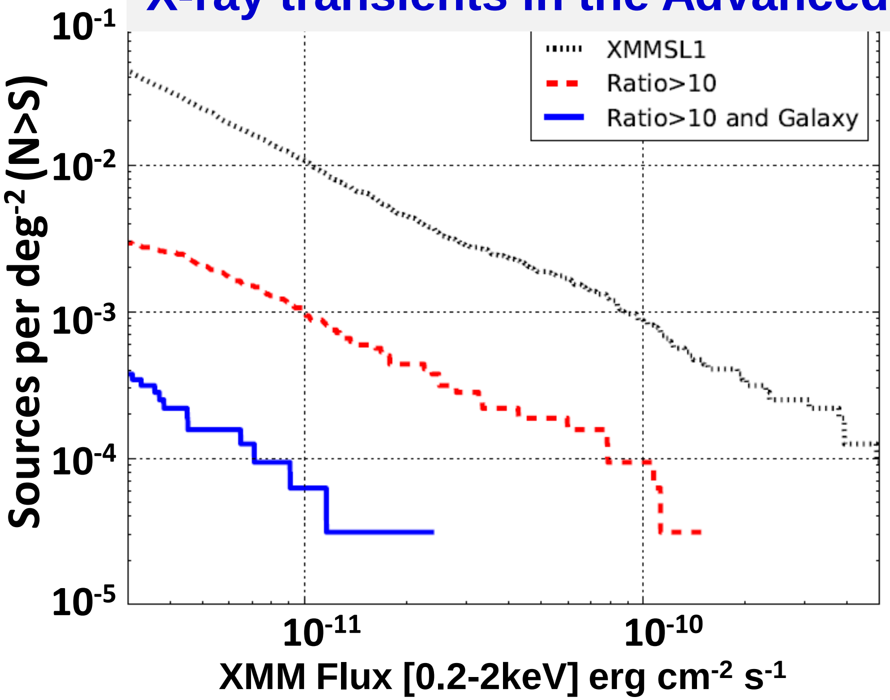
→to **uniquely** identify **a counterpart** of the GW trigger

Very promising result by Singer et al. 2013, arXiv1307.5851
discovery and redshift of **optical afterglow** of long GRB 130702 over **71 sq. degree**

X-ray and radio

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

X-ray transients in the Advanced LIGO/VIRGO horizon



systematic search in the **XMM-Newton Slew Survey** covering 32800 sq. deg

- - - 1411 objects above flux 3 x 10^{-12} erg $s^{-1}cm^{-2}$

- - - 97 transients (> x10 brighter than RASS)

—— 12 transients spatially coincident with known galaxy, after rejecting AGN

Above flux threshold of **3 X 10^{-12}** (erg $s^{-1}cm^{-2}$)

→ **4 x 10^{-4} transients per square degree**

Kanner et al. 2013, arXiv 1305.5874

Radio sky

Transient contaminants (1.4 GHz and 150 MHz)

49 epochs of E-CDFS VLA observations on timescale **1 day – 3 months** 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 et al. 2013, ApJ,768