VULCANO Workshop 2014

Frontier Objects in Astrophysics and Particle Physics

18th - 24th, May 2014

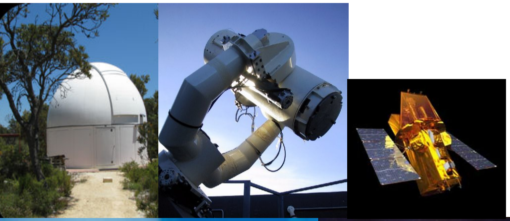
Vulcano Island, Sicily, Italy

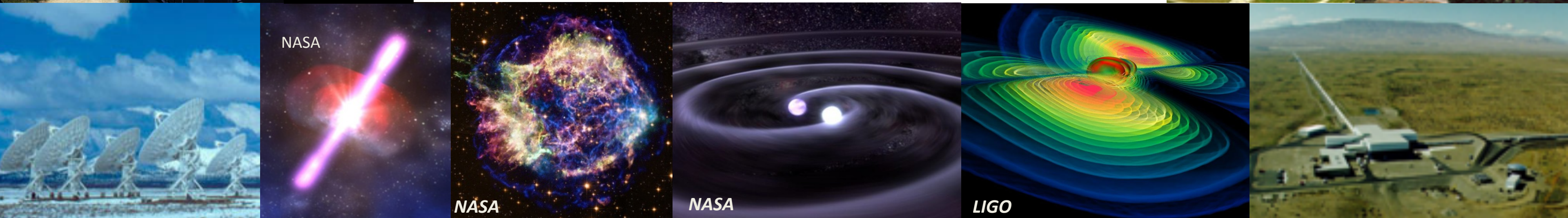
Observational prospects in the electromagnetic domain of the gravitational wave sources

M.Branchesi

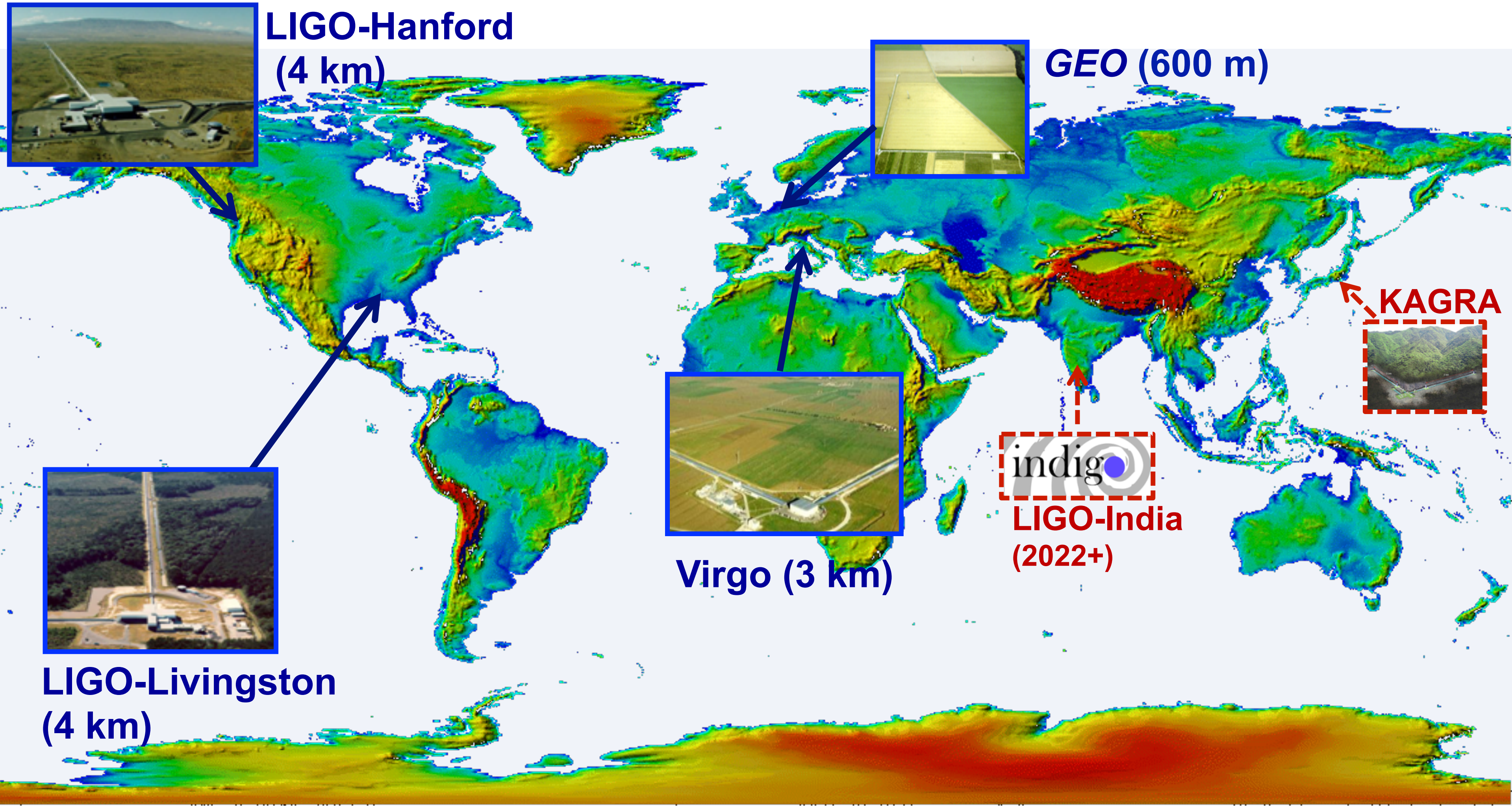
(Università di Urbino/INFN Sezione di Firenze)

on behalf of the LIGO Scientific Collaboration and Virgo Collaboration





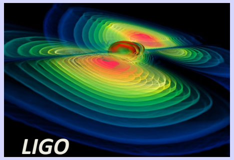
Ground-based Gravitational Wave Detectors



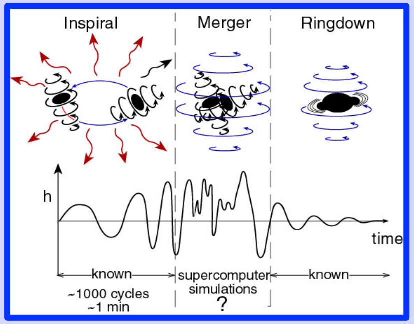
LIGO and **Virgo** detectors are currently being upgraded and will observe the sky (10-1000 Hz) as a single network aiming at **the first direct detection of GWs**

Expected GW sources detectable by LIGO/Virgo

Coalescence of Compact Objects
Neutron-Stars and/or Black-Holes

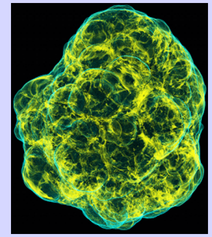


- Known waveform
- Energy emitted in GW: $\mathbf{10^{-2} M_{o} c^{2}}$



Initial LIGO/Virgo
detectable to **50 Mpc**
likely rate $\mathbf{0.02\ yr^{-1}}$

Core-collapse of Massive Stars

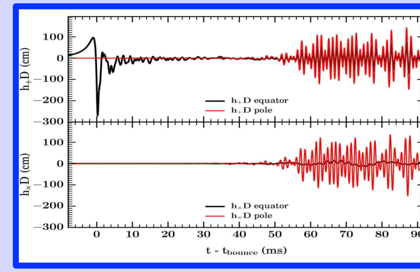


Ott et al. 2013

Waveform and energy emitted in GW uncertain:

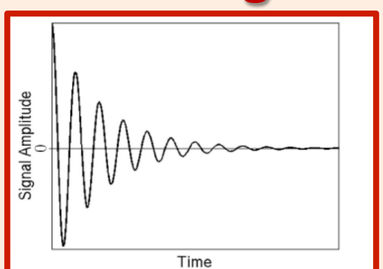
- Likely $\mathbf{10^{-8} M_{o} c^{2}}$
- Optimistic $\mathbf{10^{-4} M_{o} c^{2}}$

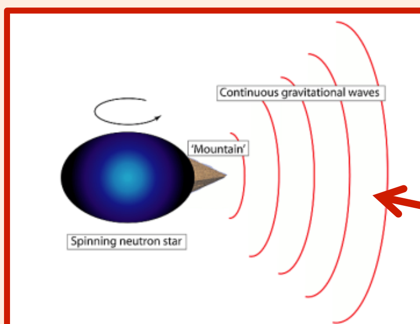
Initial LIGO/Virgo
detectable within our Galaxy (10 kpc)

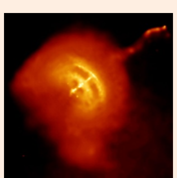


Ott, C. 2009

Single Neutron Star



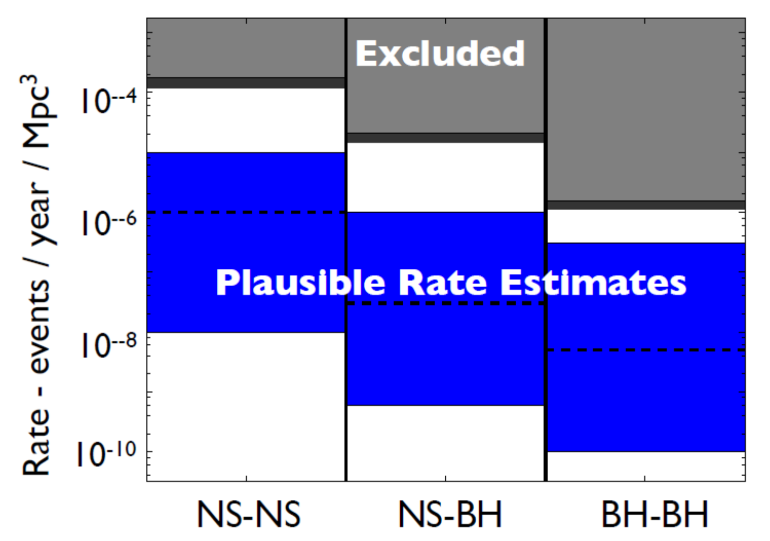




"Transient GW signals"

" Continuous GW signal"

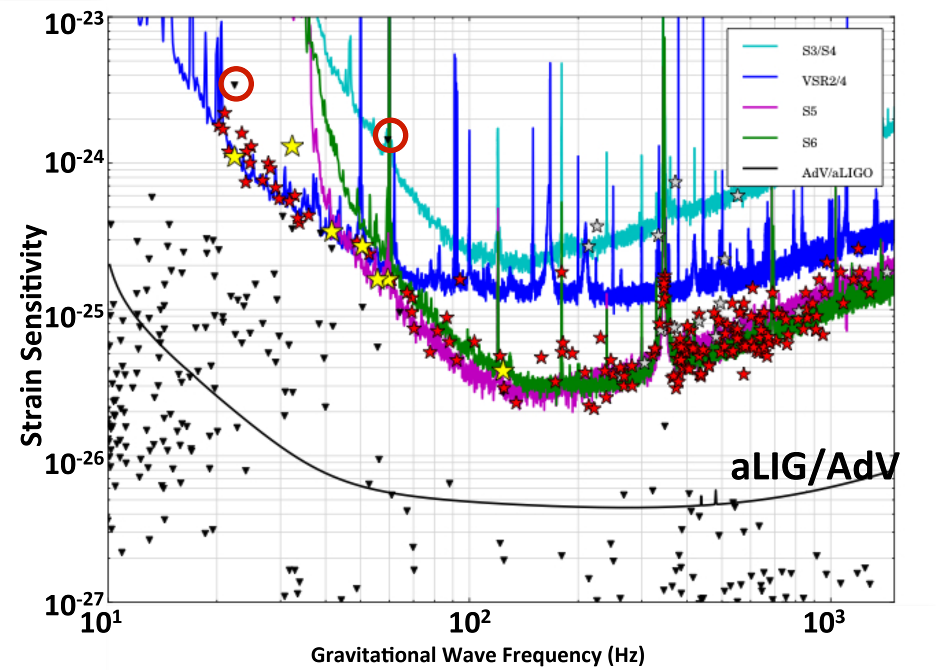
Some Example of GW Science from Initial LIGO/Virgo(2005-2010)



Upper limits on the rate of low mass compact binary coalescence total mass 2-25 Mo

Abadie et al. 2012, *Phys. Rev. D*, 85

GW amplitude upper limits from 195 known Pulsars



Crab limit *at 1% of total energy loss!*

Vela limit *at 10% of total energy loss!*

Aasi et al. 2014, ApJ, 785

Advanced Era GW-detectors (ADE)

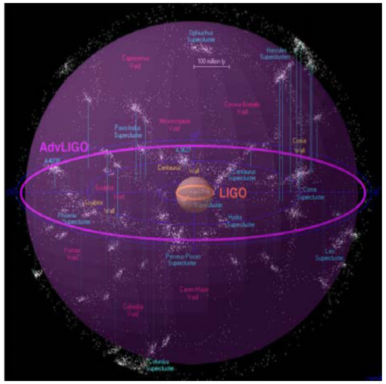
LIGO-H

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)



Advanced era
Detection rates of compact binary coalescences

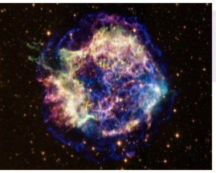
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(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



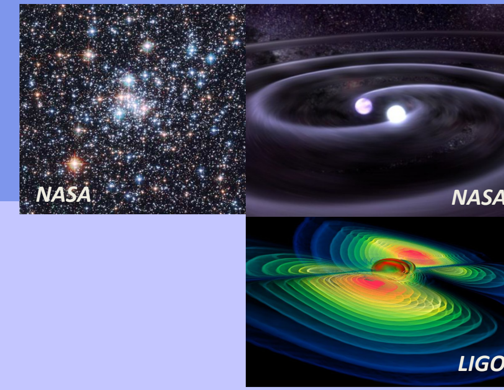
Core-Collapse Supernovae

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 - 100 Mpc** (Piro & Pfahl 2007)



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 multi-messenger (GW and photon) astronomy

EM emission from transient GW sources

Electromagnetic emission

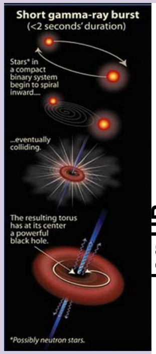
Merger of NS-NS / NS-BH

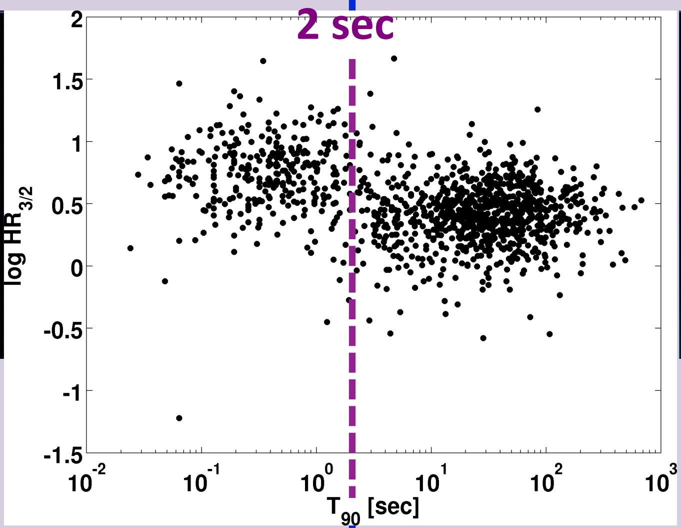
Core collapse of massive star

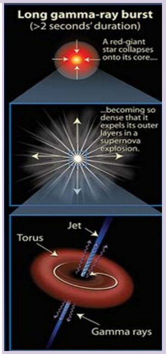
Gamma-Ray Burst: flashes of gamma-rays
isotropic-equivalent energy up to 10^{53} erg

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

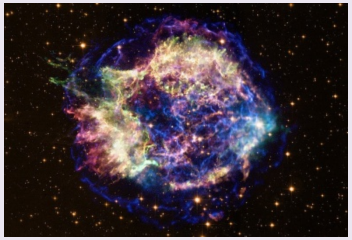
Progenitor strong evidence: observed Type Ic SN spectrum

Kilonovae

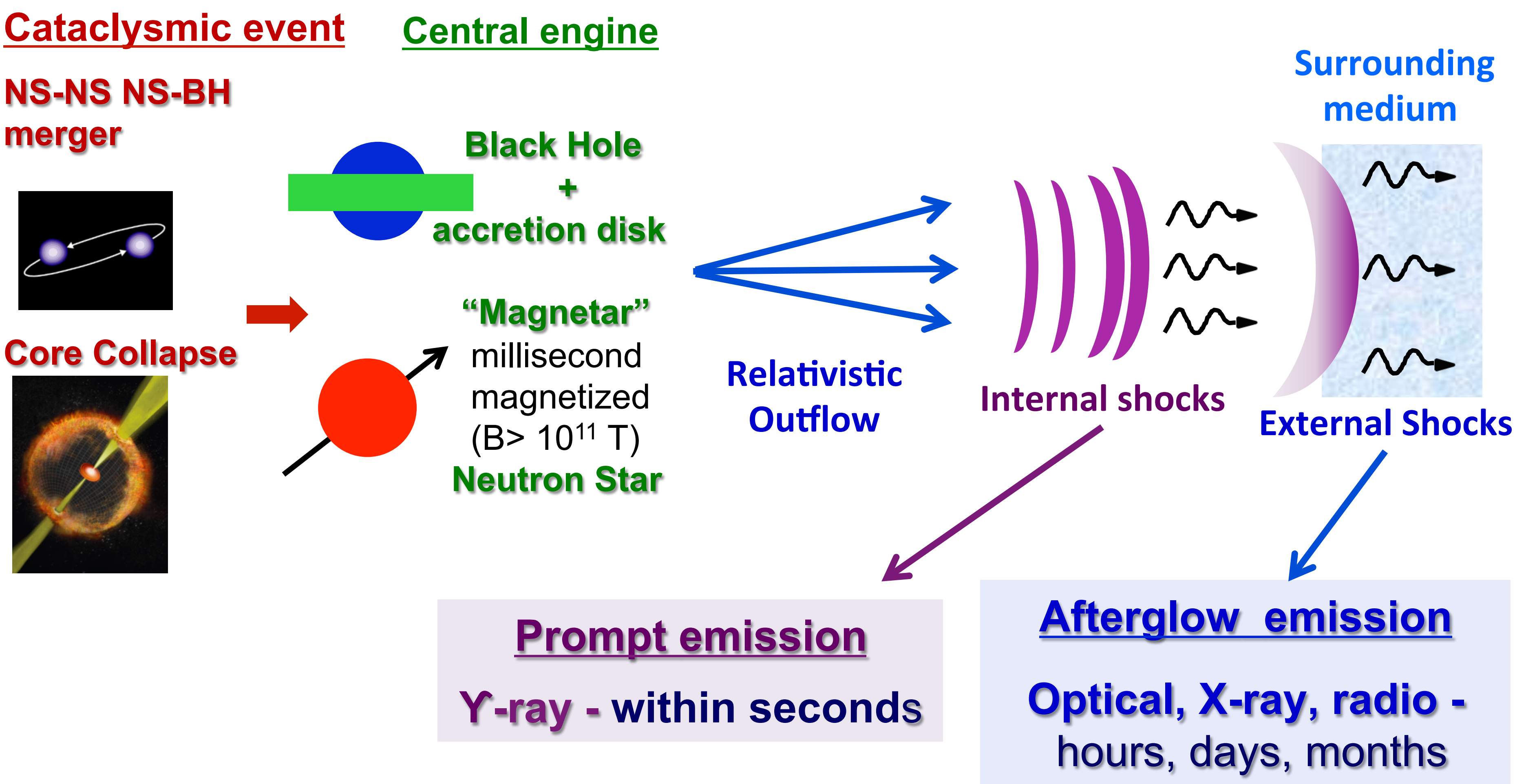
(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c

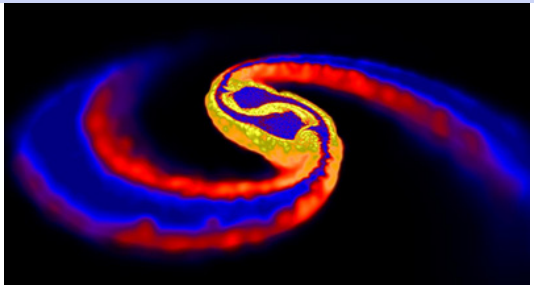


GRBs emission - Fireball Model

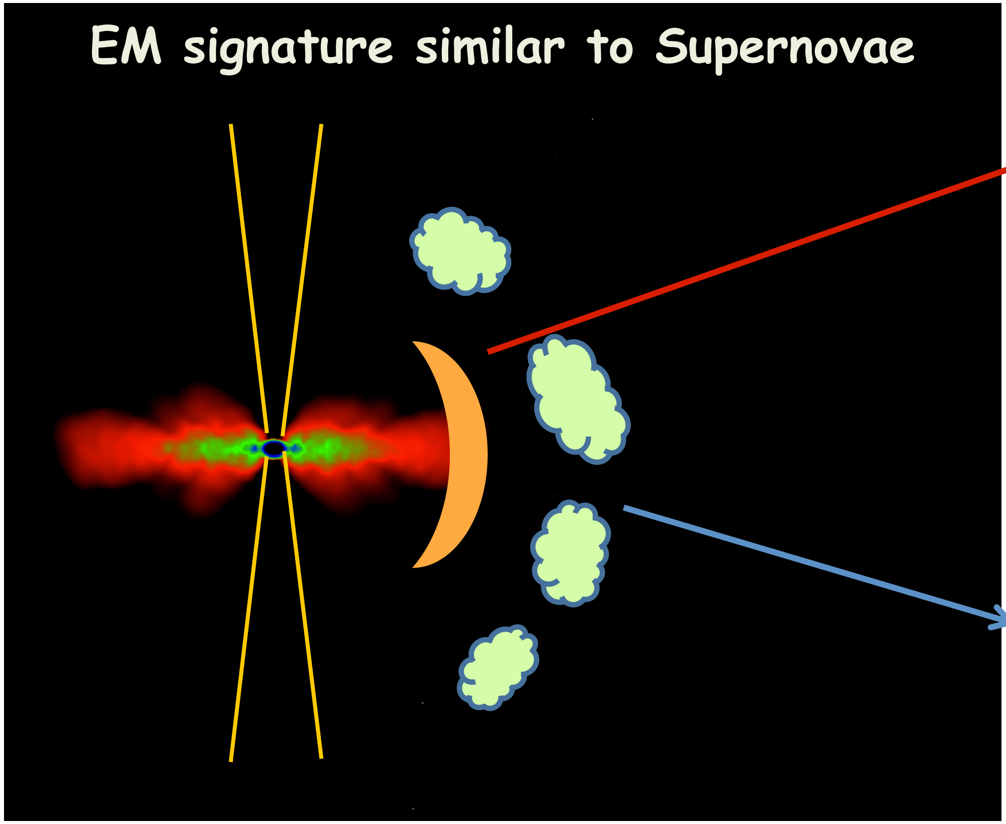


Kilonovae and Radio Flares

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; Rosswog et al. 2013 , MNRAS, 430)



Macronova – Kilonova

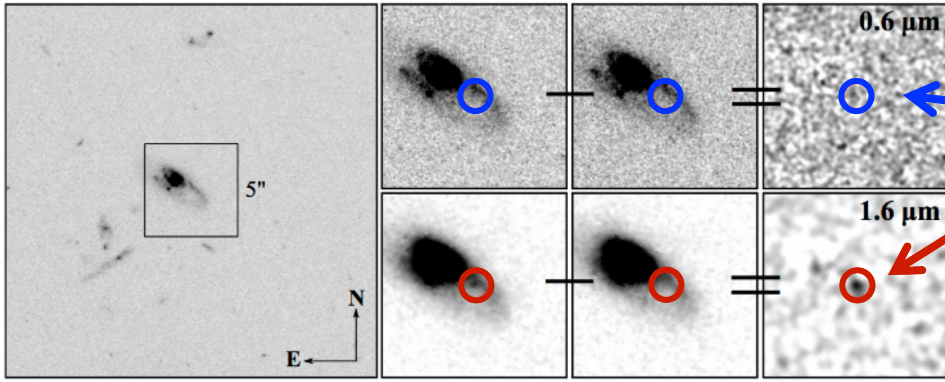
short lived IR-UV signal (days) powered by the radioactive decay of heavy elements synthesized in the ejected outflow **Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507; Metzger et al. 2010, MNRAS, 406; Barnes & Kasen 2013, ApJ, 775**

RADIO REMNANT

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

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

Tanvir et al. 2013, Nature ,500



Afterglow and host galaxy z=0.356

HST two epochs (9d, 30d) observations

F606W/optical

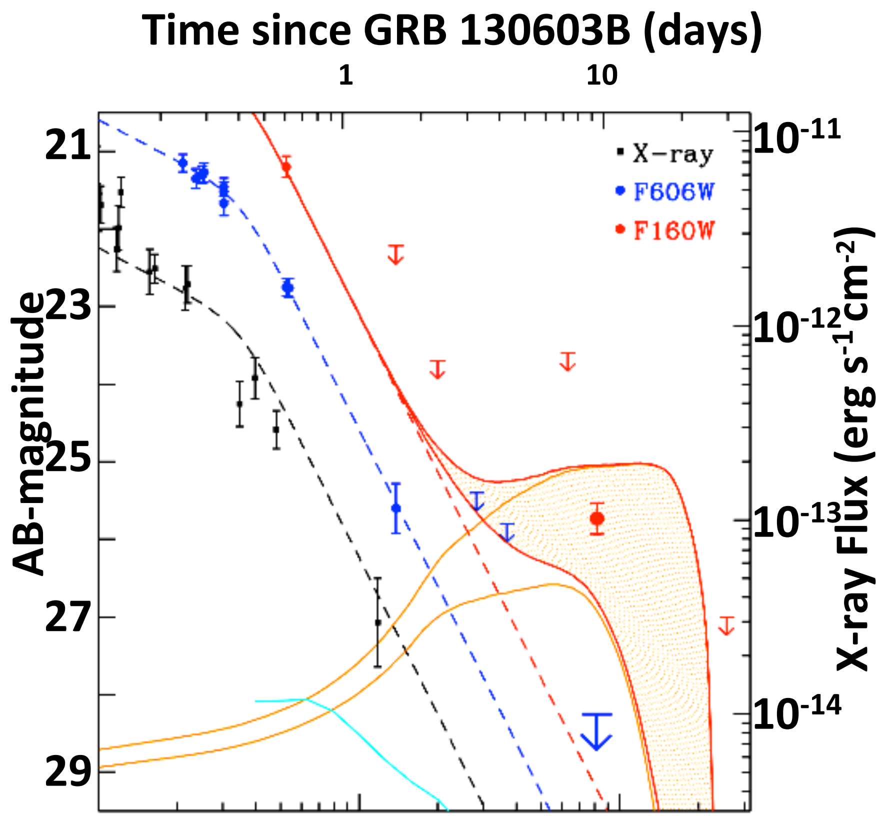
NIR/F160W

Orange curves → kilonova NIR model

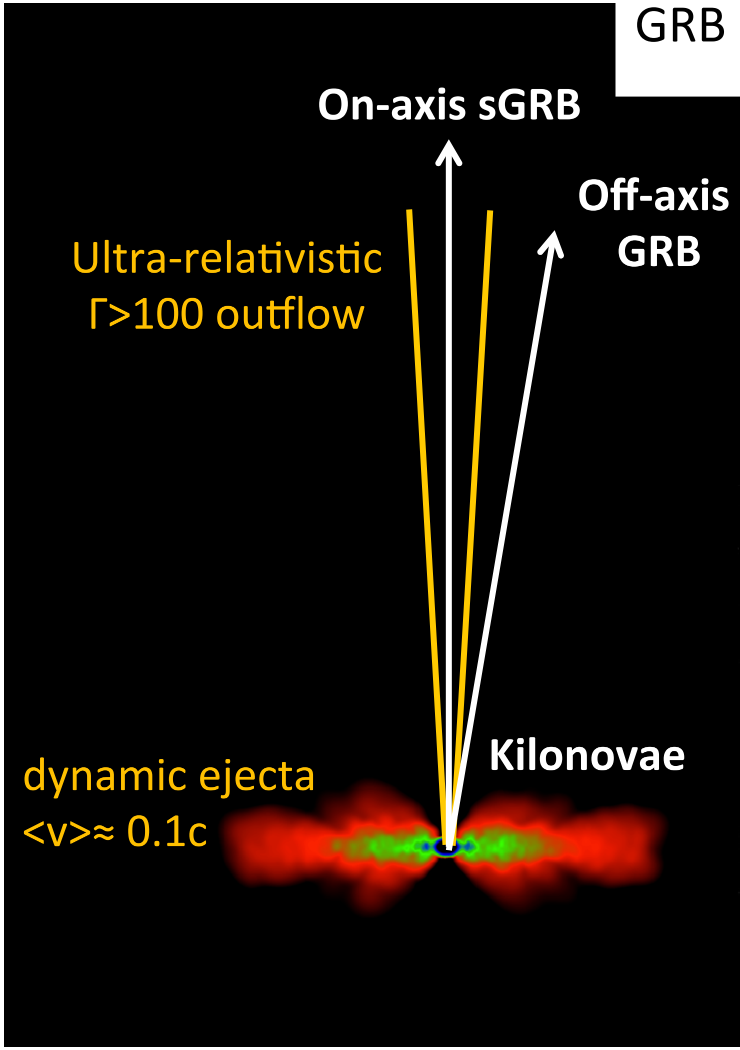
ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model



EM signals from NS-NS/NS-BH merger and massive star core-collapse



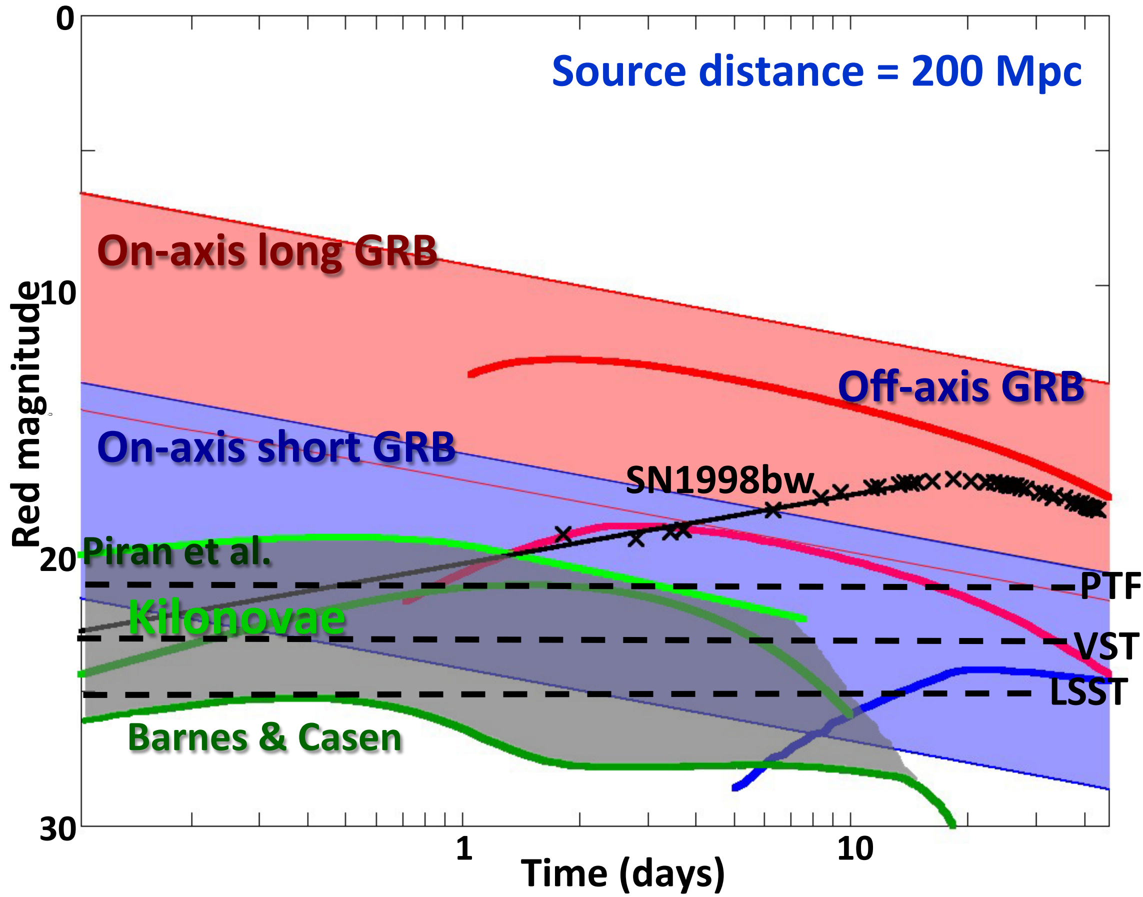
❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"GRB Triggered analysis"**

❖ **GRB afterglow emission, kilonovae:**

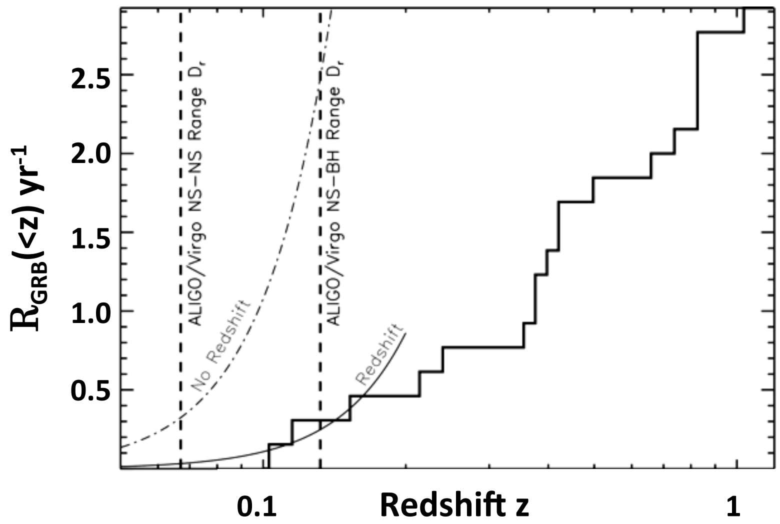
GW trigger → EM search

"Low-latency EM follow-up"



GW detection rate based on short GRB observations

GW/on-axis short GRB detection rate



All-sky gamma-ray monitor

→ **0.3 short GRBs per year** (NS-NS range)

→**3 short GRBs per year** (NS-BH range)

Metzger & Berger 2012, ApJ 746

aLIGO and Virgo NS-NS detection rate

Short GRB observations → NS-NS merger rate

$$R_{NS\text{-}NS}=R_{GRB}/(1-\cos(\theta))$$

$R_{NS\text{-}NS}$

8 -1100 $Gpc^{-3}yr^{-1}$ (Coward et al. 2012)

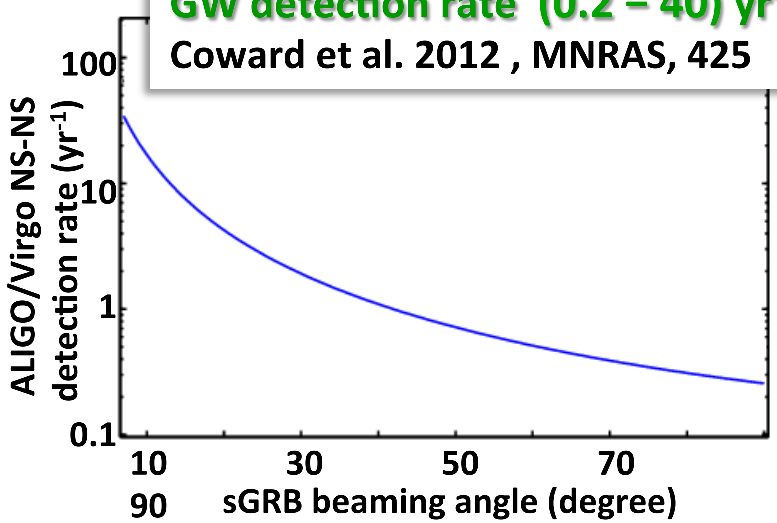
92–1154 $Gpc^{-3}\ yr^{-1}$ (Siellez et al. 2013)

Theoretical prediction

10-10000 $Gpc^{-3}\ yr^{-1}$ (Abadie et al. 2010)

GW detection rate (0.2 – 40) yr^{-1}

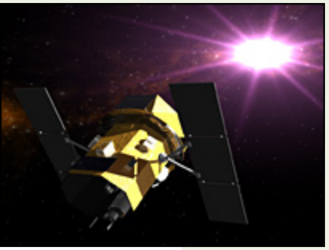
Coward et al. 2012 , MNRAS, 425



Triggered analysis

EM observations → GW analysis

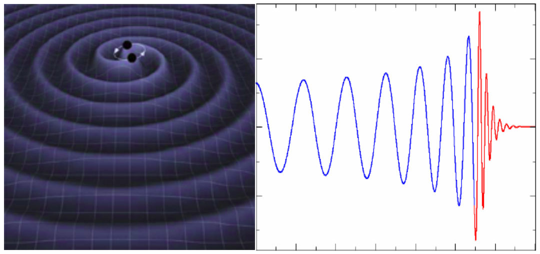
GRB prompt emission → TRIGGERED GW SEARCH



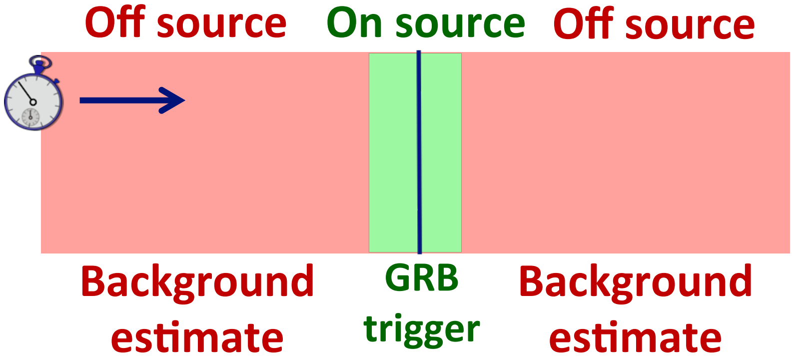
Known **GRB event time** and **sky position:**

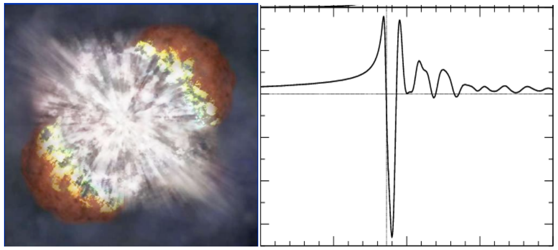
→ **reduction in search parameter space**
→ **gain in search sensitivity**

GW transient searches



Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ **Excess power**





Compact Binary Coalescence
Known waveform
→ **Matched filter**

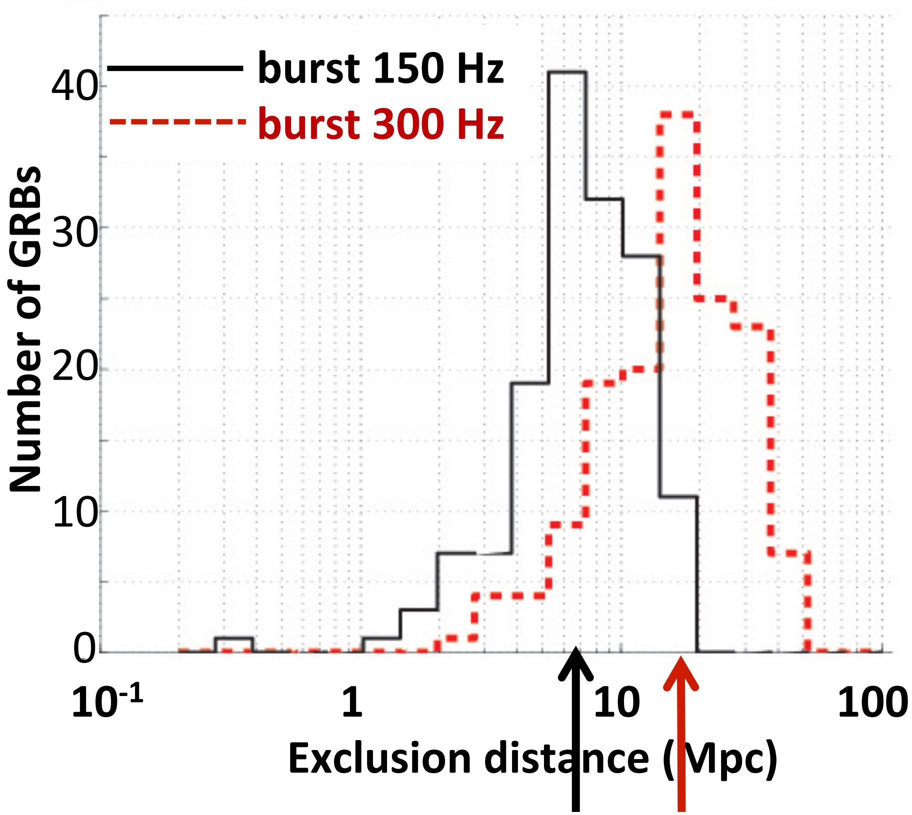
Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010**
while 2 or 3 LIGO/Virgo detectors were taken good data
No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

GRB prompt emission - TRIGGERED SEARCH

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

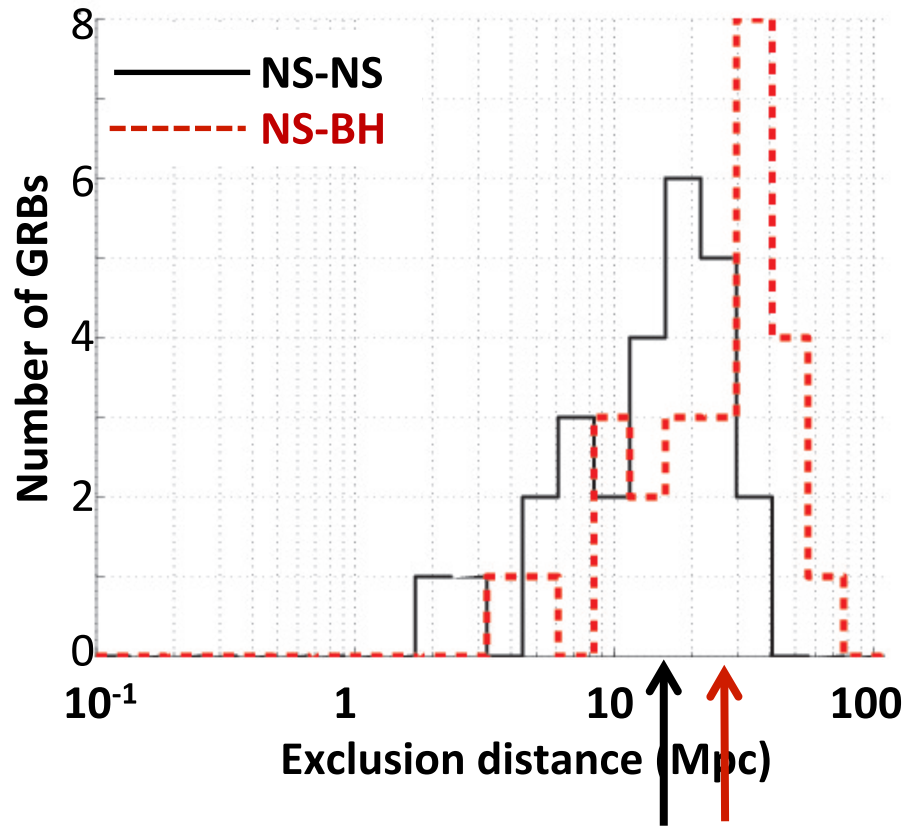
Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (150 GRBs)
with **10^{-2} Moc^{2} energy in GW** (optimistic)



Median distances: 7 17 Mpc

Binary system coalescence
(26 short GRBs)



Median distances: 16 28 Mpc

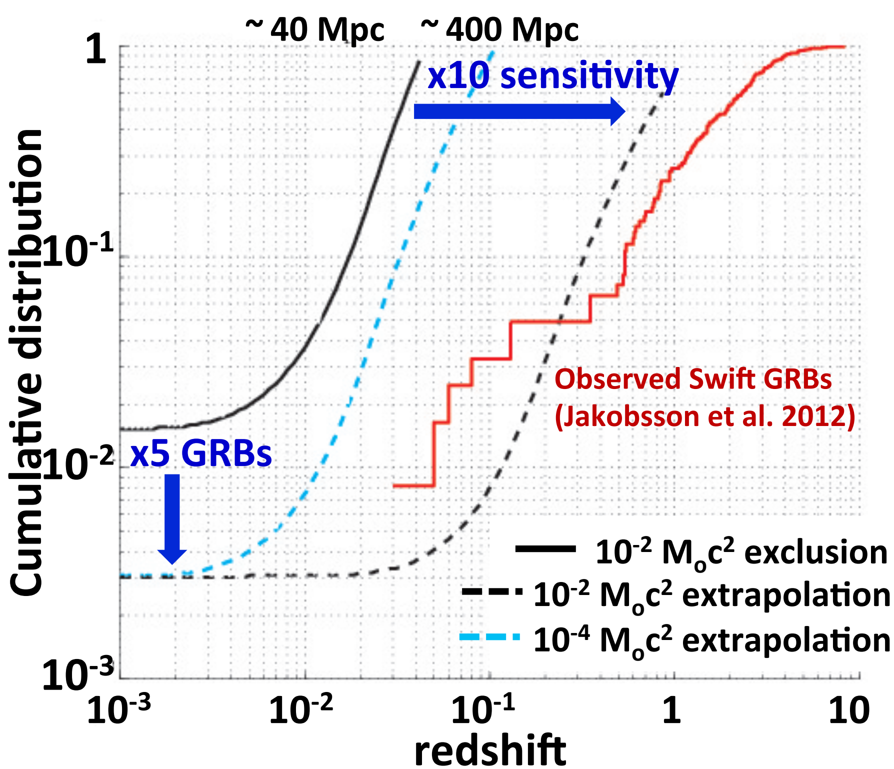
GRB prompt emission - TRIGGERED SEARCH

Population exclusion on cumulative redshift distribution

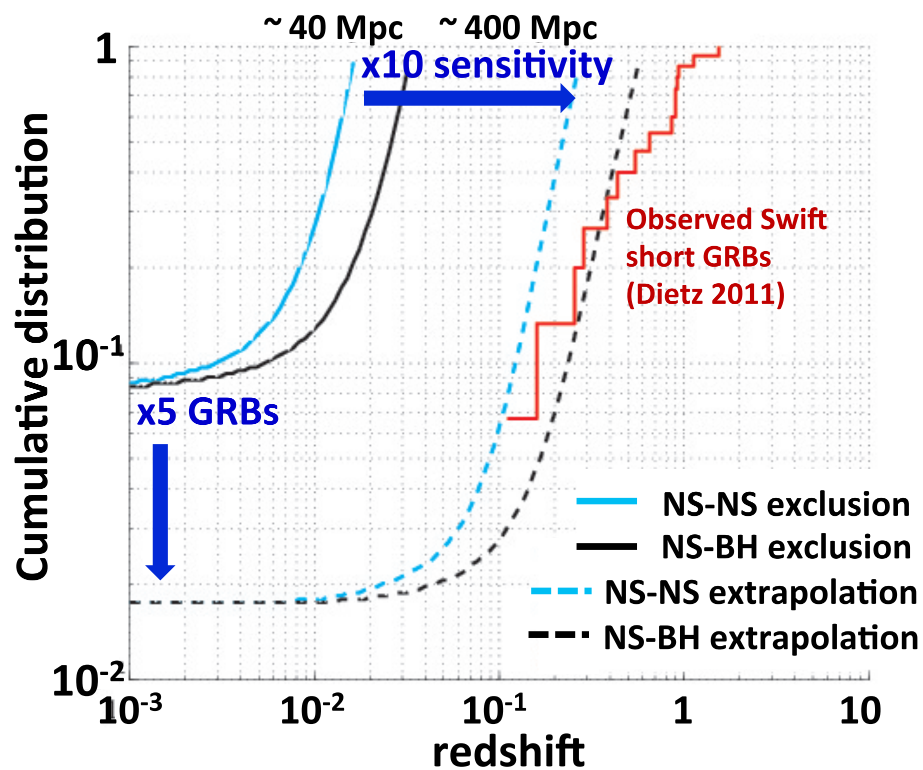
Results 2009-2010 & prospects for Advanced LIGO/Virgo

Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (150 GRBs)



Binary system coalescence (26 GRBs)



→ 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

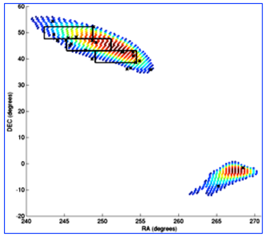
GW triggers

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:

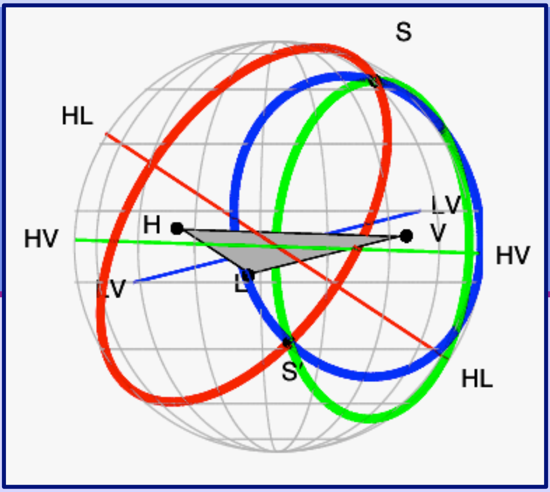
- select statistically significant triggers wrt background
- determine telescope pointing

~ 10 min. → **~ 30 min.**

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

ADE latency expected to be improved!

Sky Localization of GW transients



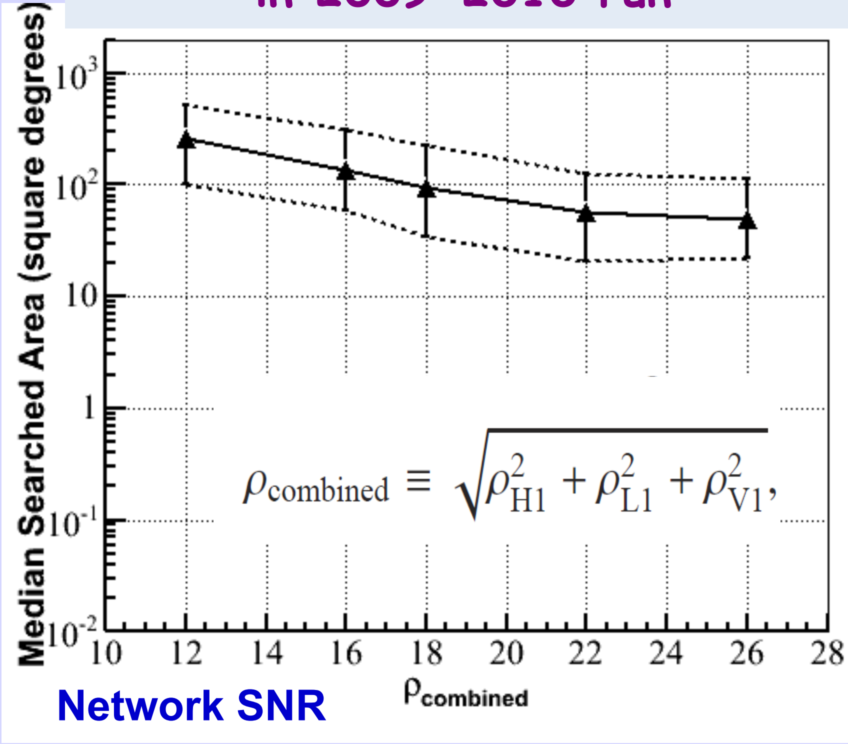
The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**

low SNR signals were localized into regions of **tens to hundreds of sq. degrees** possibly in several disconnected patches

⬇

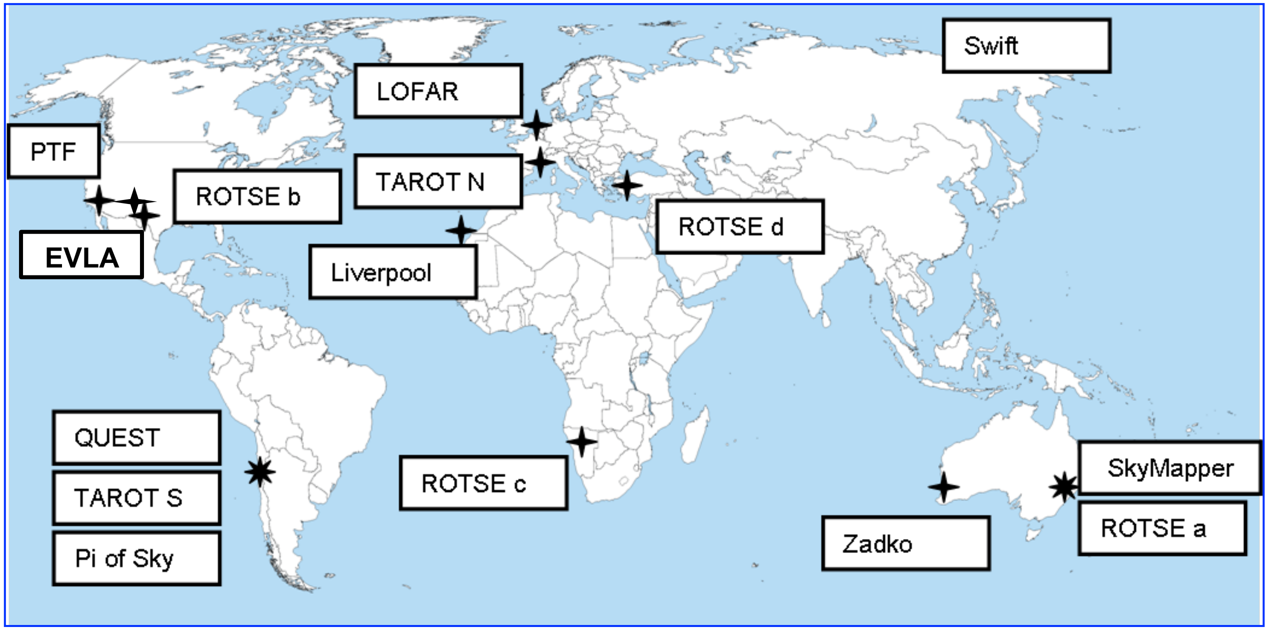
Necessity of wide field of view EM telescopes

Binary coalescence localization in 2009-2010 run



Abadie et al. 2012, A&A 539

Ground-based and space EM facilities involved in 2009-2010 follow-up program



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

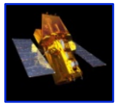

5.7 deg^2 , **21** mag

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

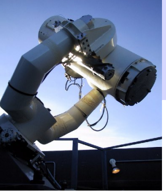

30 - 80 MHz

110 - 240 MHz

Maximum **25** deg^2

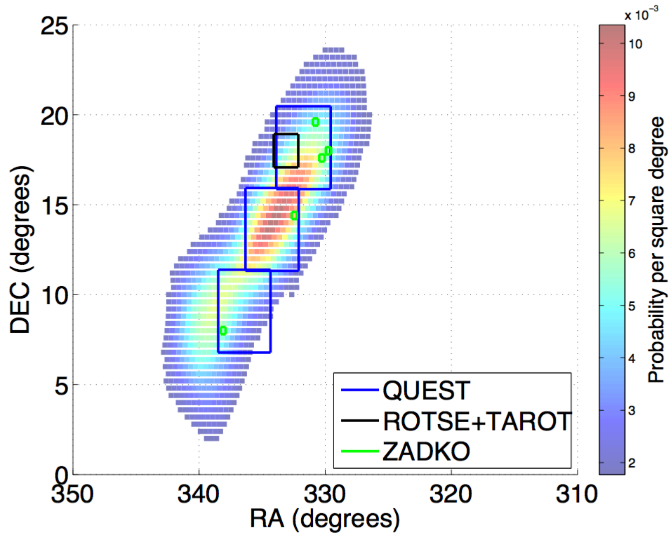
EVLA

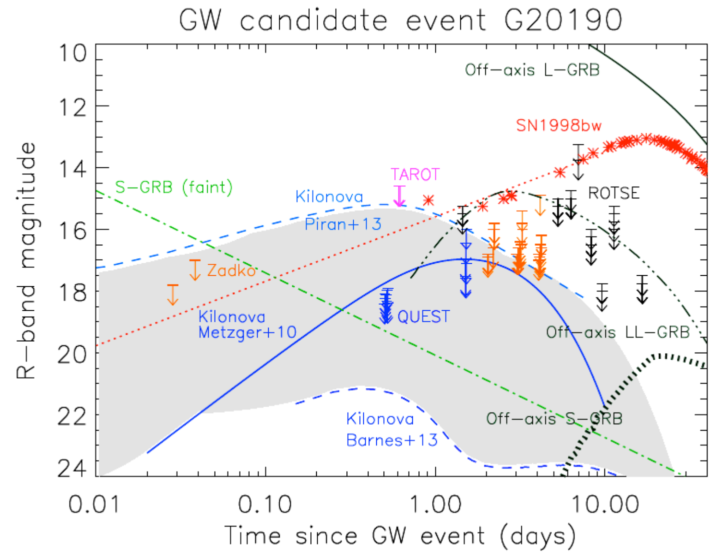

5 GHz - **7** arcmin^2



Optical telescope 8 GW alerts

Aasi et al. 2014, ApJS, 211





Swift Satellite: XRT-UVOT

2 GW alerts

Evans et al. 2012, ApjS, 203

Radio Interferometers

LOFAR

5 GW alerts

E-VLA

2 GW alerts

Lazio et al. , 2012 IAUS, 285

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**

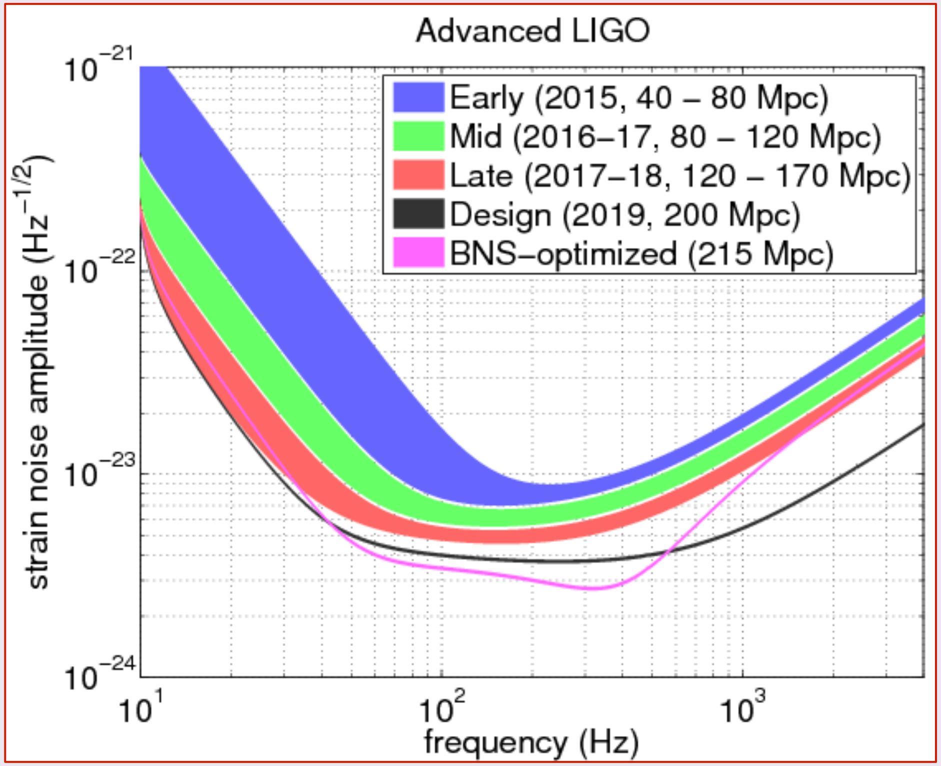
Advanced detector era observing scenario

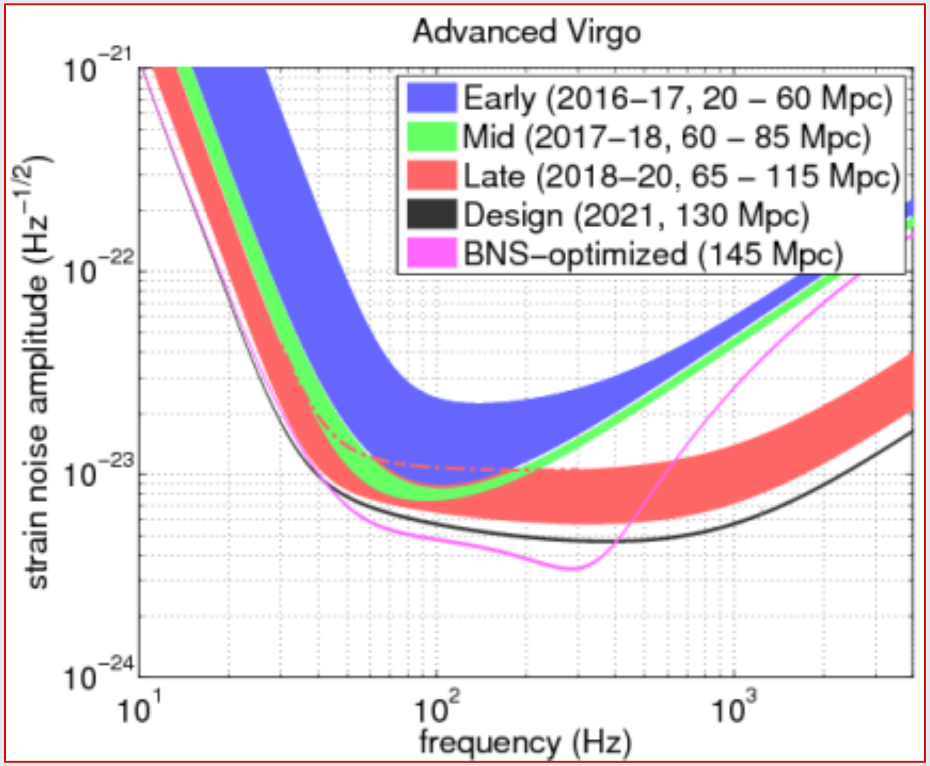
LSC & Virgo Collaborations, arXiv:1304.0670

Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

Progression of sensitivity and range for Binary Neutron Stars

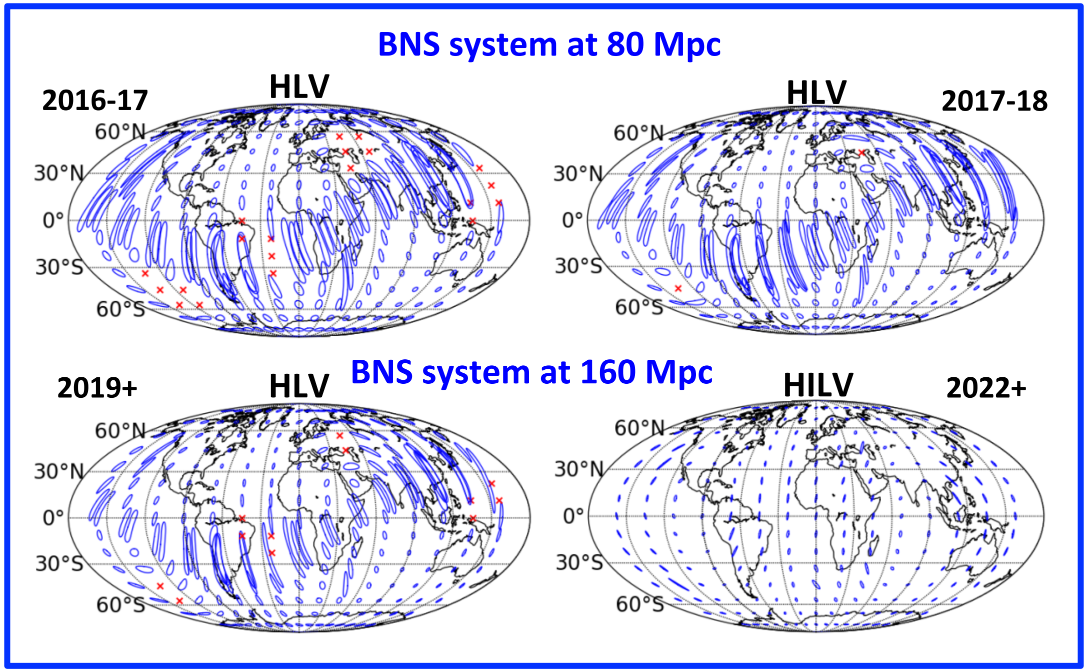




Larger GW-detectable Universe

Sky Localization of Gravitational-Wave Transients

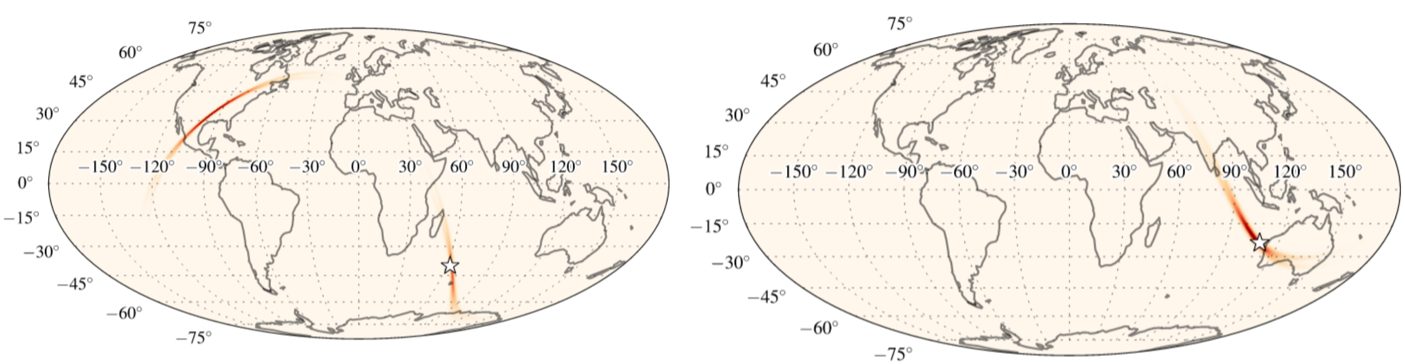
Position uncertainties with areas of **tens to hundreds of sq. degrees**



⬭ → **90% confidence localization areas**

X → **signal not confidently detected**

Example of skymaps for the first two years of operation, 2015 through 2016



Median 90% CR of:
about **500 deg²** in 2015
about **200 deg²** in 2016

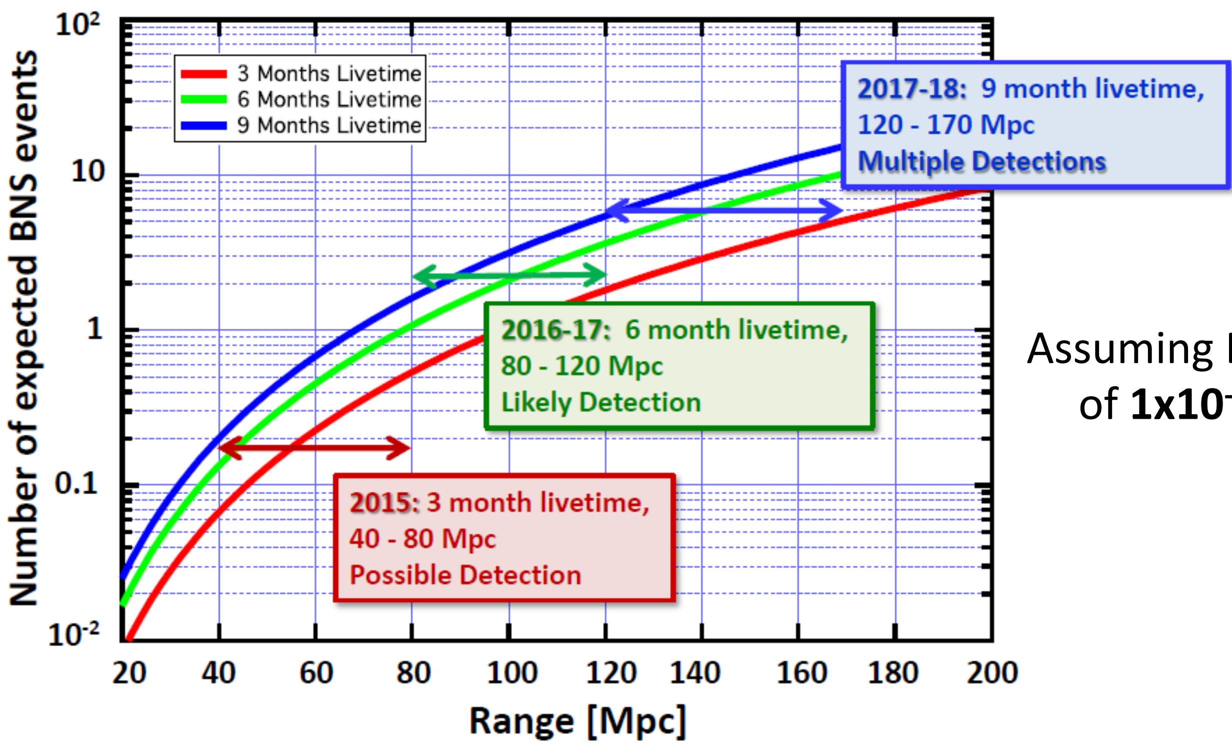
Singer et al. arXiv:1404.5623 http://www.ligo.org/science/first2years

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	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



Assuming BNS merger rate of **1x10^{-6}** Mpc^{-3} year^{-1}

EM-follow up challenges:

- **Fast faint transient counterparts**
- **Large GW error box → difficult to be covered**
  → many transient contaminants
- **Larger Universe observed by LIGO/Virgo**

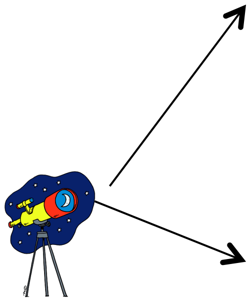
EM-follow up key points:

- **How to set up an optimal observational strategy? to image the whole GW error box or the most propable galaxy hosts?**
- **How to uniquely identify the EM counterpart?**

TIGHT LINK is required between GW/EM/Theoretical COMMUNITIES!!

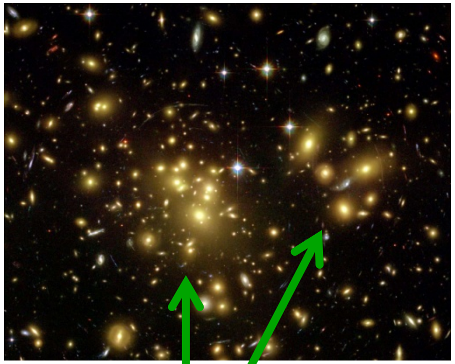
Hierachical EM-follow up Search

Aasi et al. 2014, ApJS, 211
Singer et al. 2013, ApJ, 776L

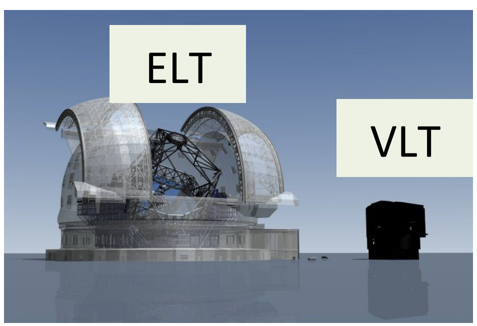



Wide-field telescope
FOV 10 sq.degree


"Fast" and "smart" software to select a sample of candidate counterparts



Galaxy targeting?



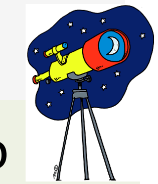
Larger telescope to **characterize** the candidates

The EM Counterpart!

LIGO-Virgo EM-follow up plan

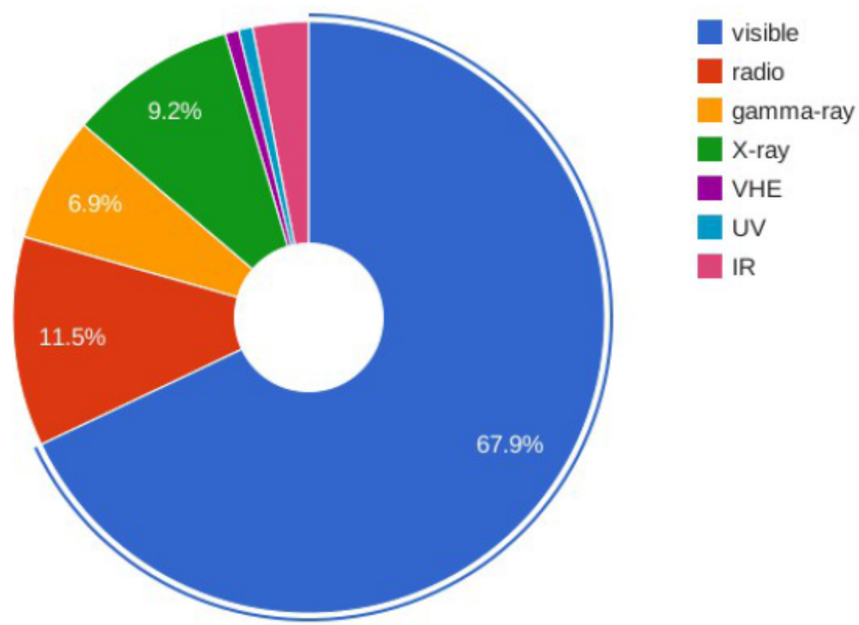
➢ **Agreed LVC Policy for releasing GW triggers** **(dcc.ligo.org/M1200055, VIR-0173A-12)**

"**Until first four GW events** have been published, **triggers will be shared** promptly only with astronomy partners who have signed an **MoU** with LVC "

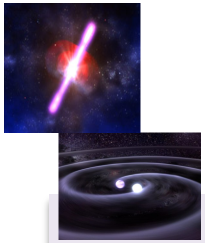


➢ **Opened call to sign MoU** for the identification of EM counterparts to GW triggers found in the next science runs of aLIGO/Virgo, which will start in 2015 **Deadline 16 Feb, 2014**

➢ More than **sixty MoU applications** from **19 countries** about **150 instruments** **covering the full spectrum** from radio to very high-energy gamma-rays!



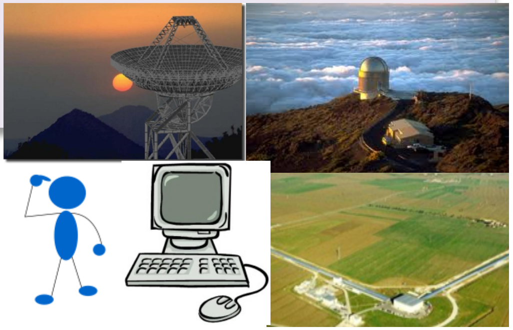
EXTRA SLIDES



Some (Astro)Physical open questions

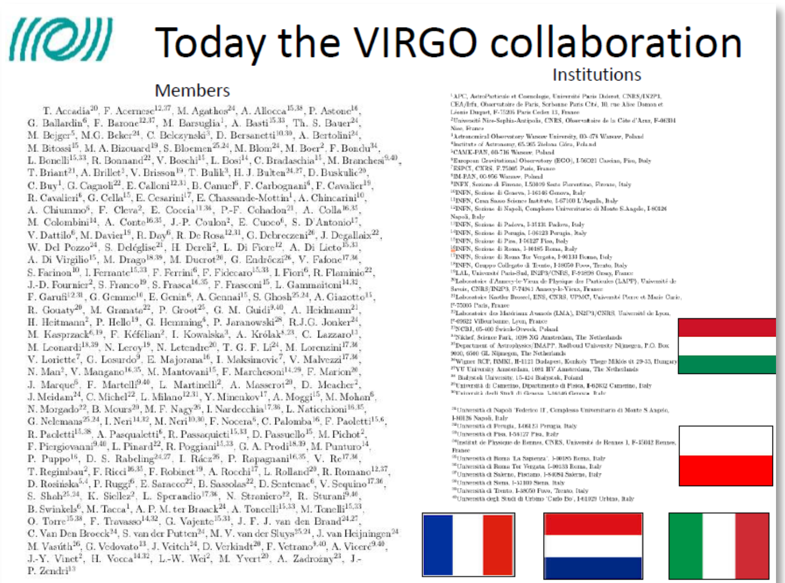
……..that need GWs, photons and theory to be answered:

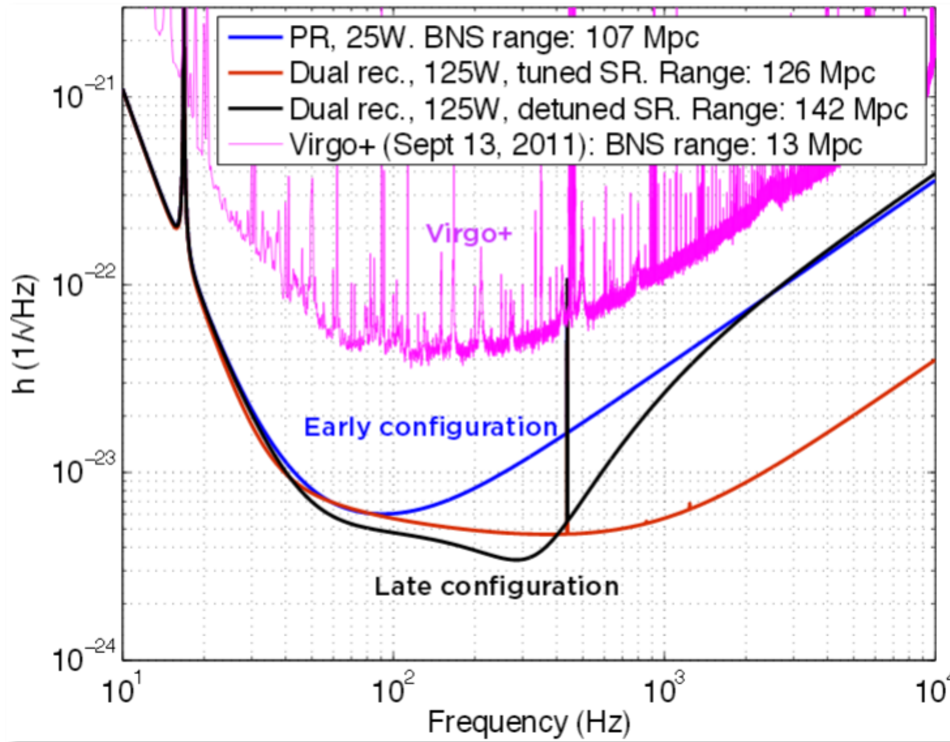
- Are NS-NS and/or NS-BH merger progenitors of Short GRBs?
- What are the beaming angle of the GRB prompt emission, and the details of the energy radiation processes?
- Are NS mergers/kilonova able to explain the presence of elements heavier than iron in the Universe?
- How are BHs born and how do they evolve?
- What are the details of the mechanism through which SN explode?
- What is the EoS of matter in the interior of NS?



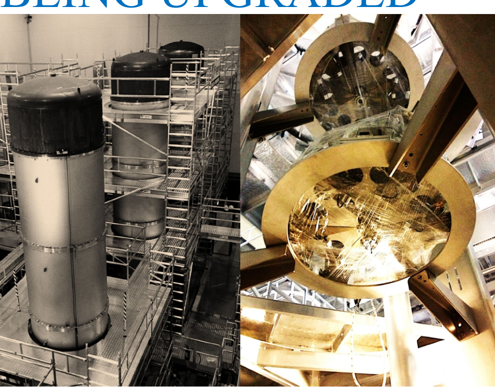
From VIRGO+ to ADVANCED VIRGO (AdV)

Goal → to realize a competitive detector joining the international network made by the two aLIGO and AdV



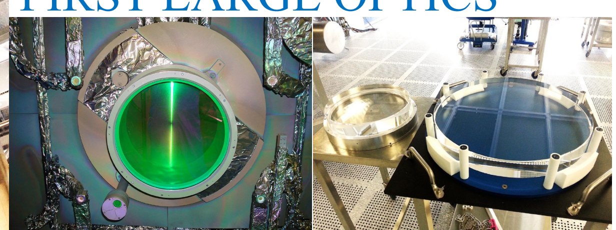


SUPERATTENUATORS BEING UPGRADED



Status of the AdV project → construction well on track

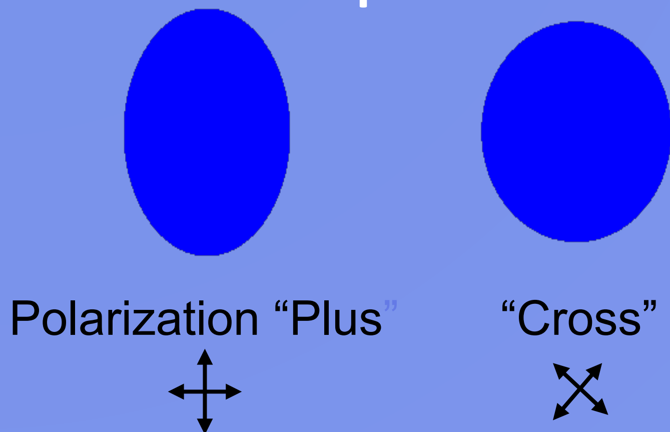
FIRST LARGE OPTICS



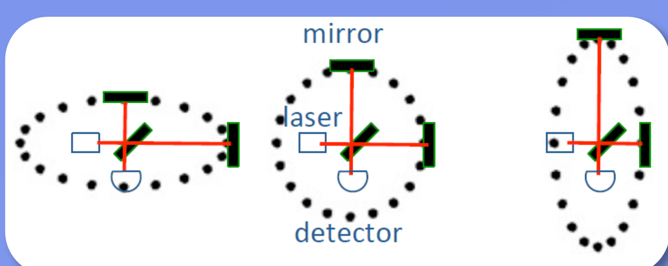
First science data in 2016

Gravitational Wave Interferometers

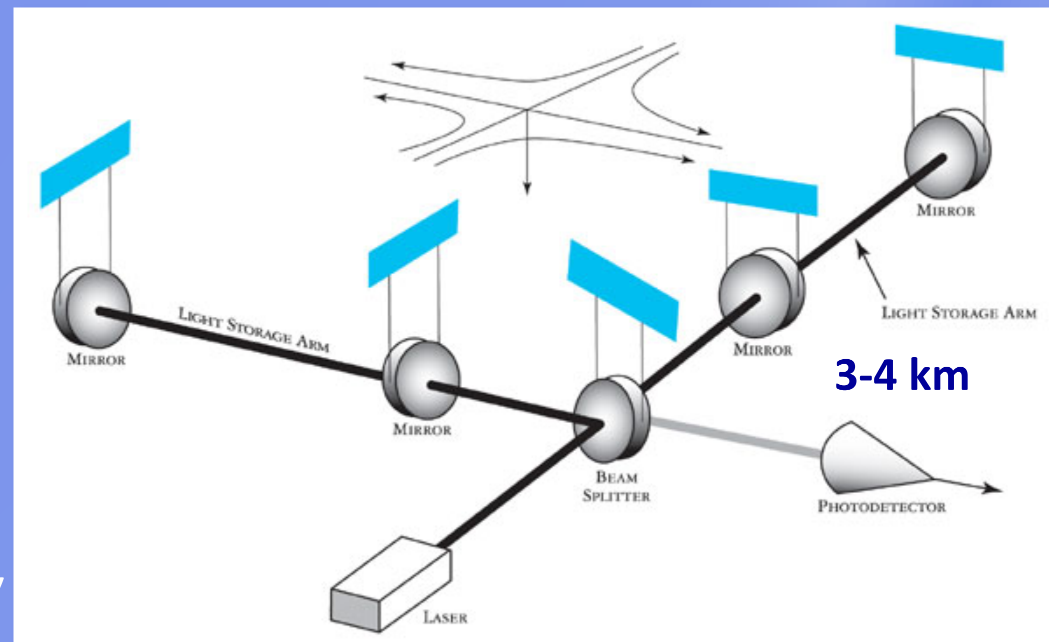
Spatial distortion from a ***plus and a cross*** **polarized GW**



The length change is measured interferometrically by using a ***laser light beam***



Suspended mirrors as test mass



Goal: to measure length change of 1 part in 10^{22} or 10^{-19} meters

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**

⬇

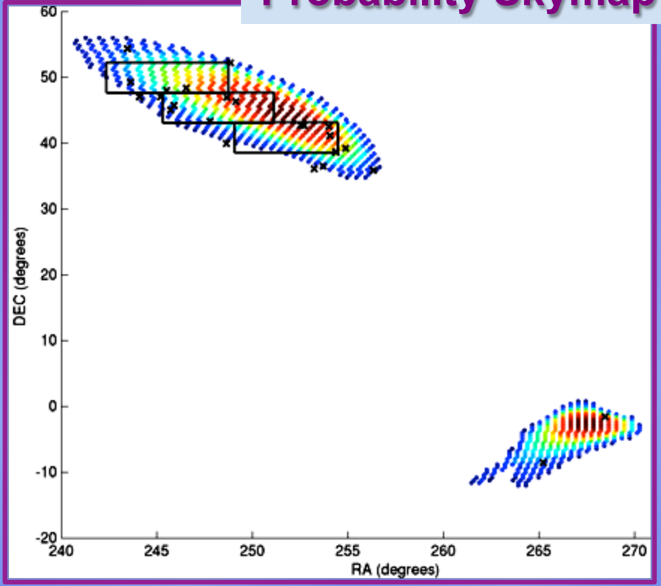
EM-observation was restricted to the regions occupied by galaxies within 50 Mpc and Galactic globular clusters
(GWGC catalog White et al. 2011, CQG 28, 085016)

To determine the telescope pointing position:

⬇

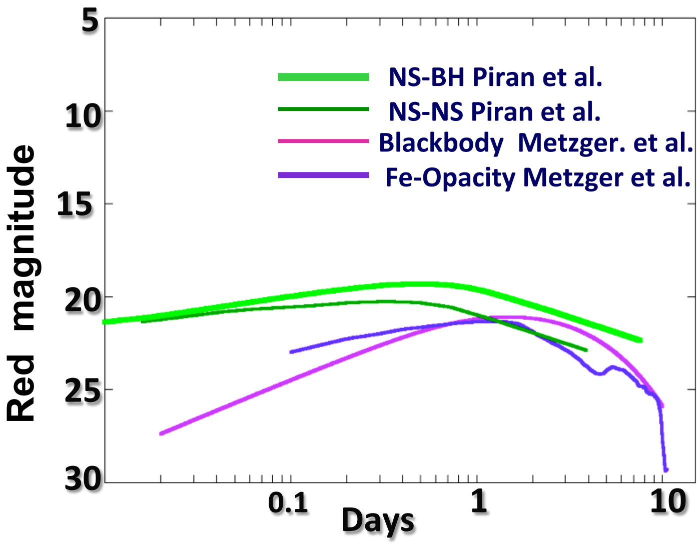
The probability skymap of each GW trigger was 'weighted' taking into account **luminosity** and **distance** of nearby galaxies and globular clusters

Probability Skymap



Kilonovae Light Curves

Source at distance of 200 Mpc

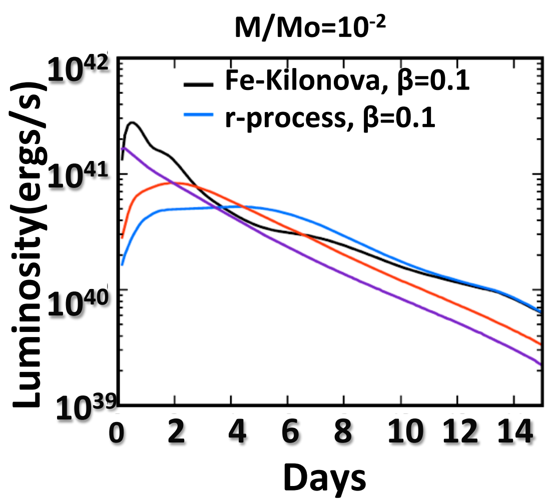


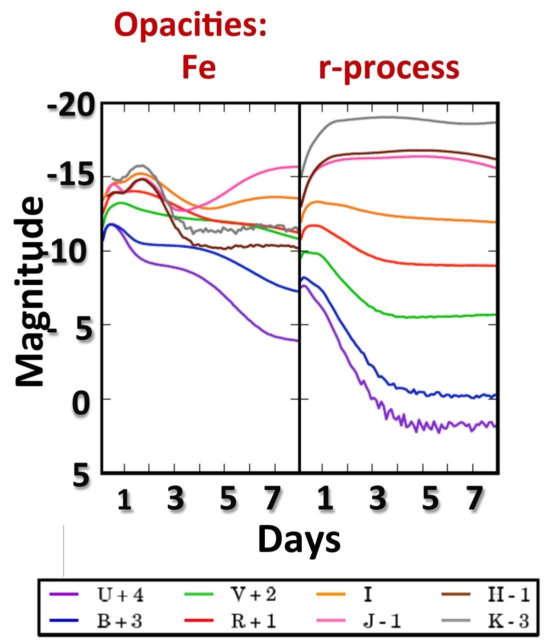
***Kilonova* model afterglow** peaks about **a *day* after** the merger/GW event

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**





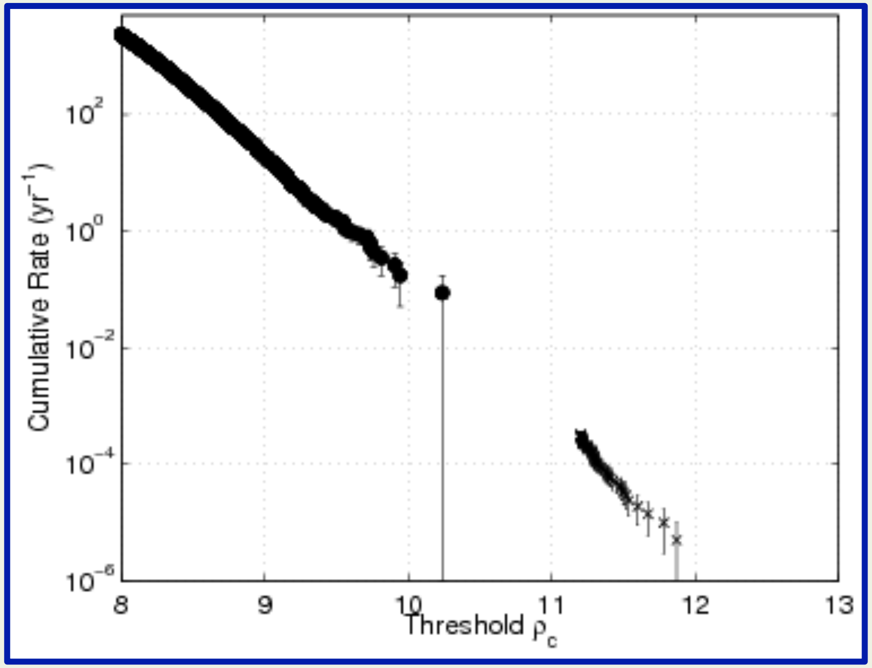
Barnes & Kasen 2013, ApJ, 775

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

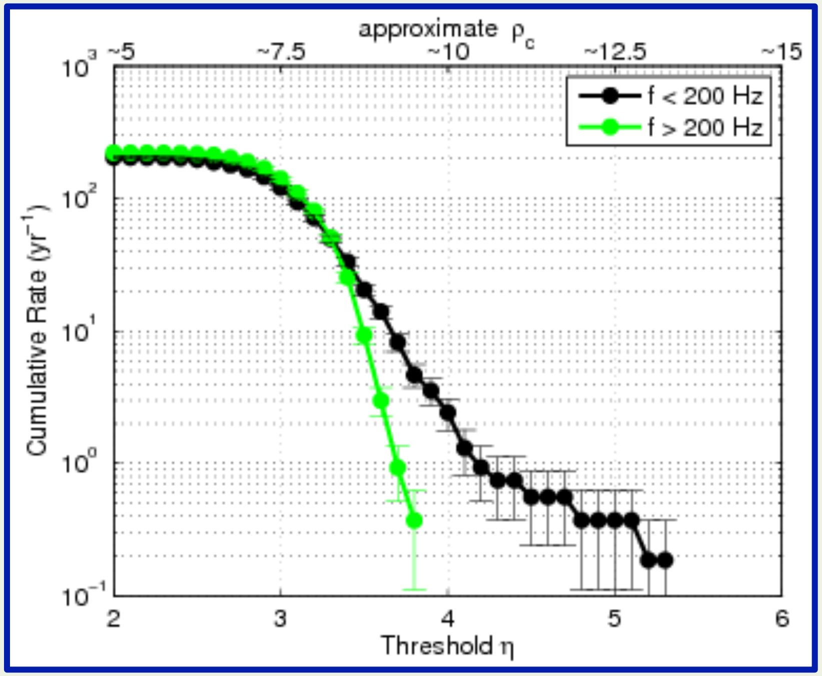
2009-2010 LIGO-Virgo data

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

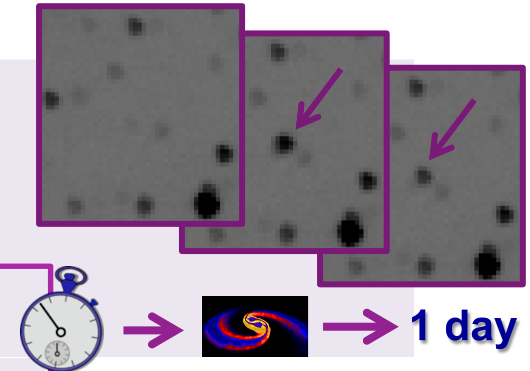
Burst search



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

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:

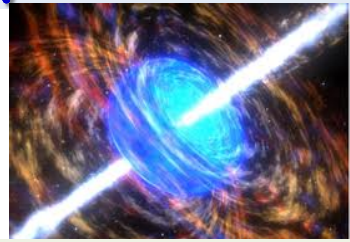
- by limiting the analysis to the **regions occupied by the most likely GW source host galaxies**
- by a **rapid transient discovery** and (light curve/color/shape) **classification** over wide sky areas

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

Promising result: discovery and redshift of **optical afterglow** for the long GRB 130702 over **71 sq. degree**

Singer et al. 2013, ApJ, 776L

Observational galaxy priors to identify the most likely GW-host



Useful:

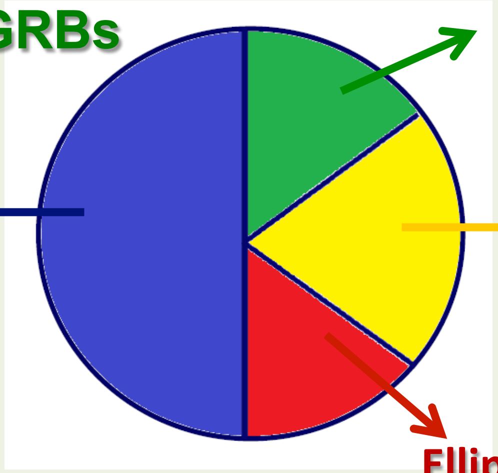
- to define an optimal observational strategy
- to identify the image region to be analyzed

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:

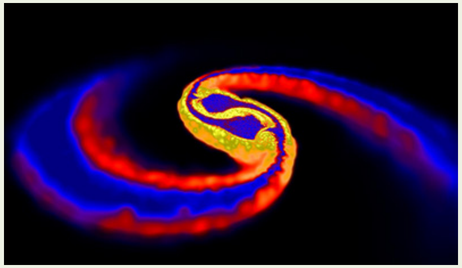
Sample: 36 short GRBs



(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)



Optical transient sky

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

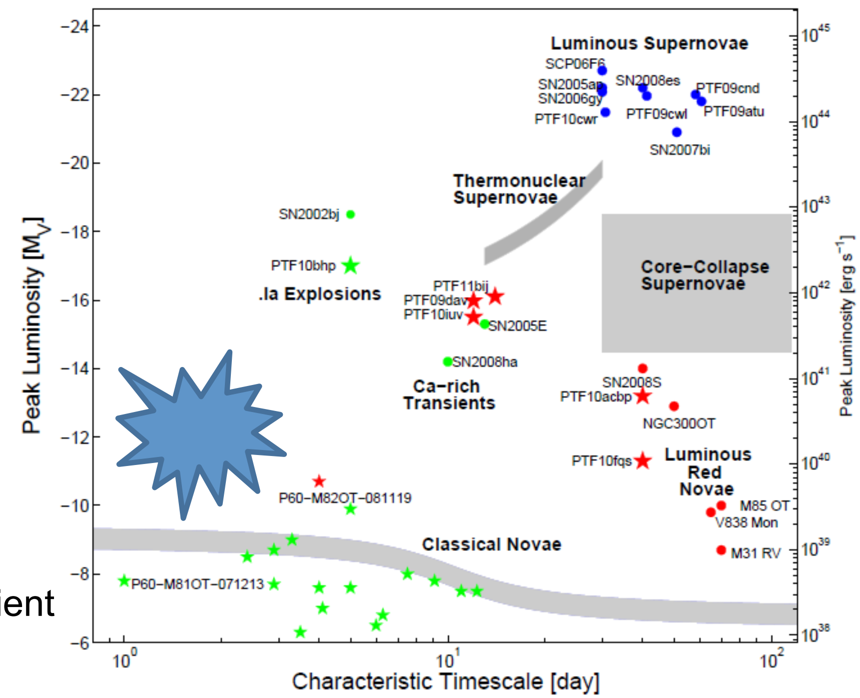
Optical contaminating transients:

foreground - asteroids, M-dwarf flares, CVs, Galactic variable stars

background - AGN, Supernovae

For rate see **Rau et al. 2009, PASP, 121** and for fast transient (0.5 hr – 1d) see **Berger et al. 2013, ApJ, 779**

Kasliwal 2011, BASI, 39



Transient X-ray and radio sky is less populated than the optical sky

X-ray contaminating transients:

tidal disruption events, AGN variability Ultra-luminous X-ray Source variability, background GRBs

For rate in the Advanced LIGO/Virgo Horizon see **Kanner et al. 2013, ApJ, 774**

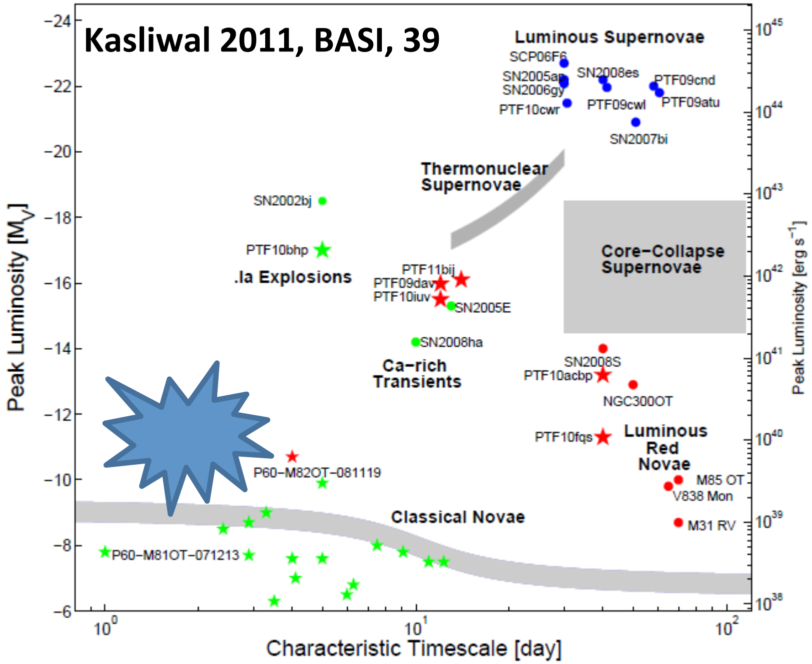
Radio contaminating transients:

Supernovae, AGN variability

For rate see **Mooley et al. 2013, ApJ,768**

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, ApJ, 774

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

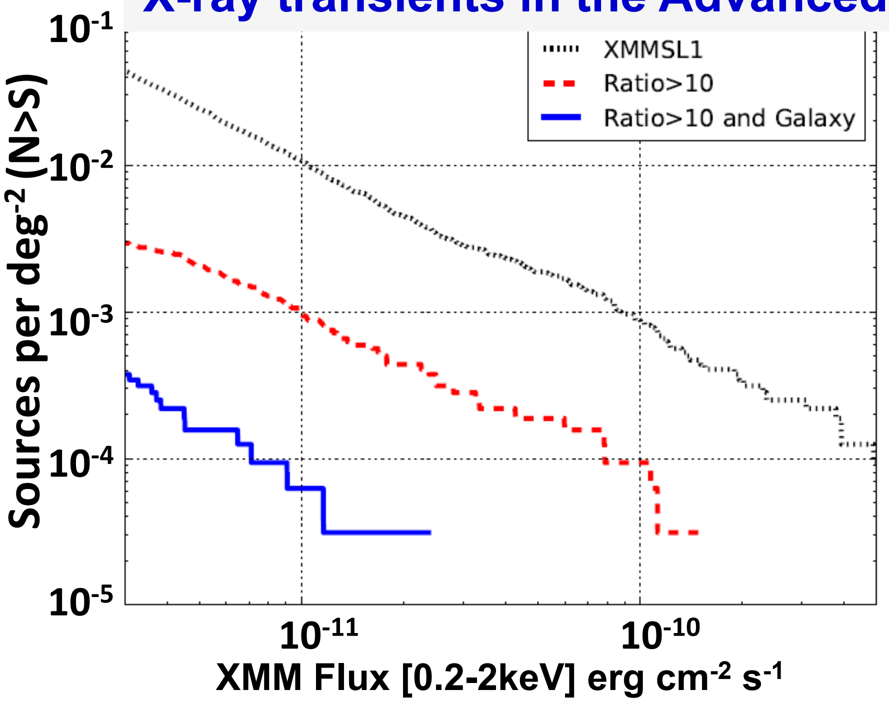
Summary of promising EM counterparts

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

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

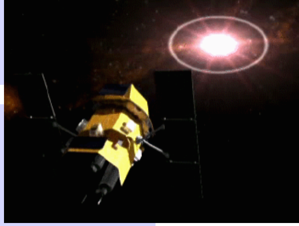
Transient contaminants (1.4 GHz and 150 MHz)

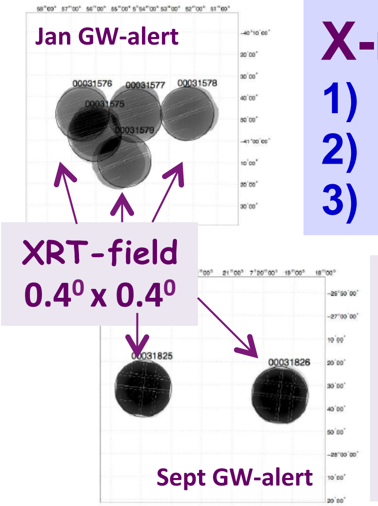
49 epochs of E-CDFS VLA observations on timescale **1 day – 3 months** show:

- **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

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

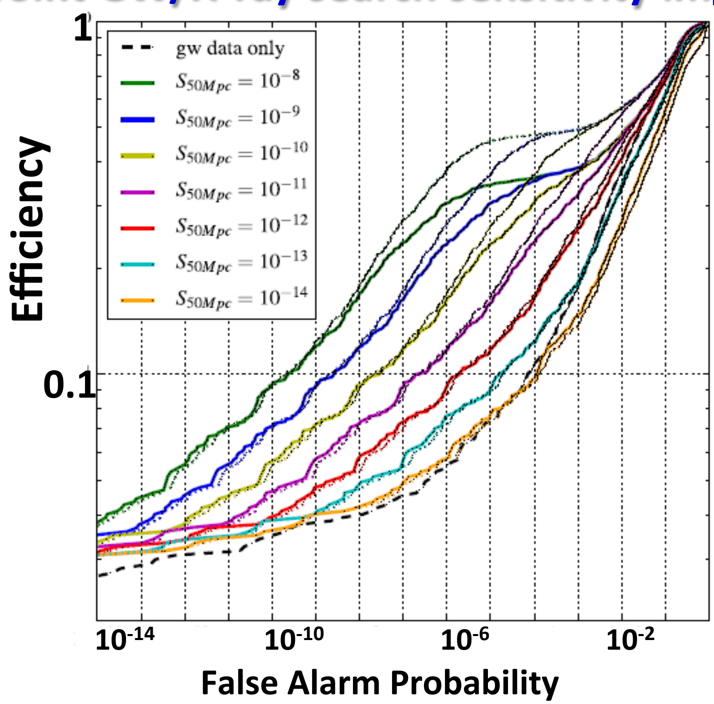


Figure shows

- 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**

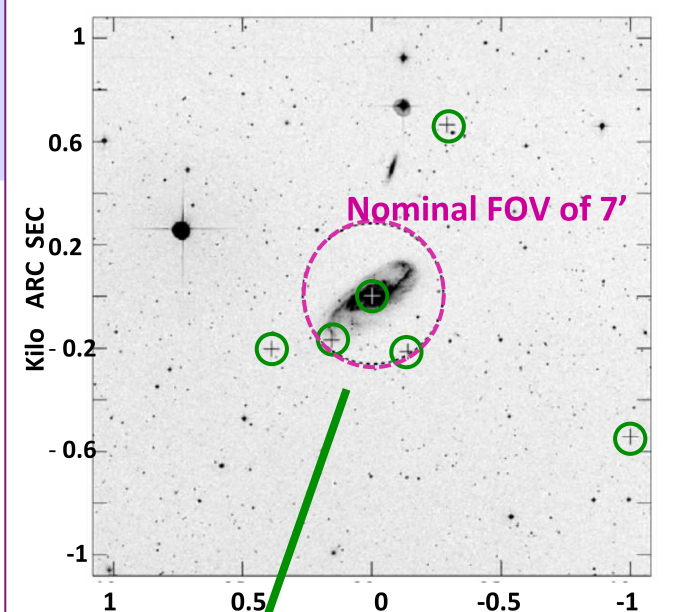
For each of the two GW-candidates observed ➡ **3 most probable host galaxies**

Image Analysis:

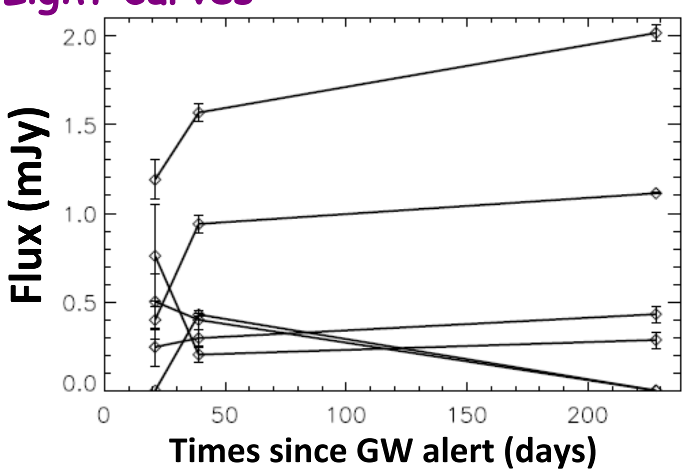
1) radio source detection
2) variability analysis
3) identification of contaminating transients

variability of AGN emission caused by interstellar medium scintillation of Galaxy

Imaged region (≈ 30') around one galaxy



Light curves



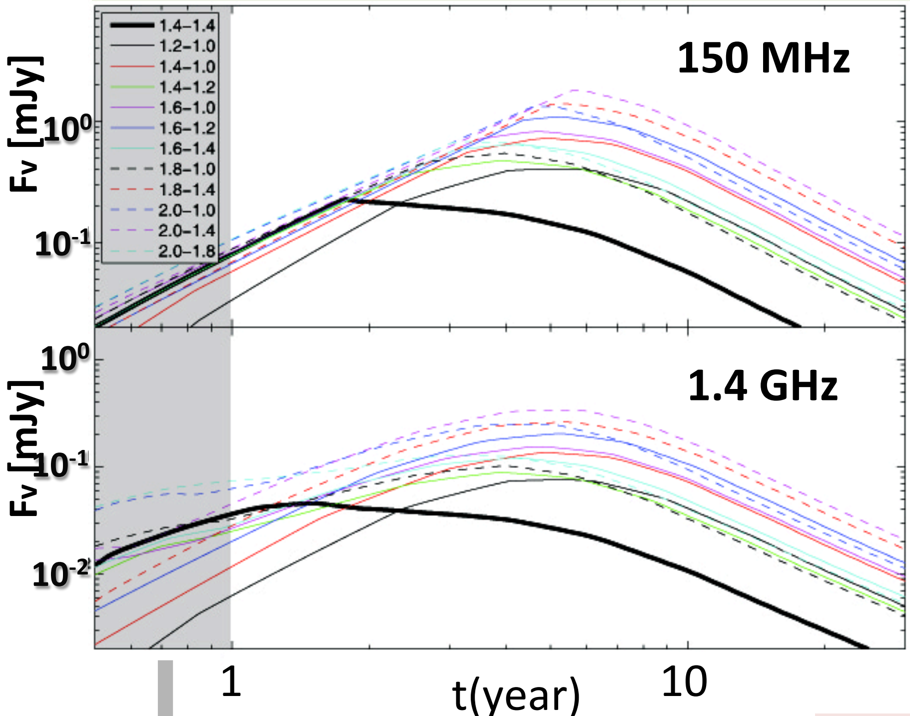
About **6 sources** in the field of each galaxy **consistent** with number of **expected serendipitous sources** (Windhorst 2003)

Lazio et al. , 2012 IAUS, 285

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**

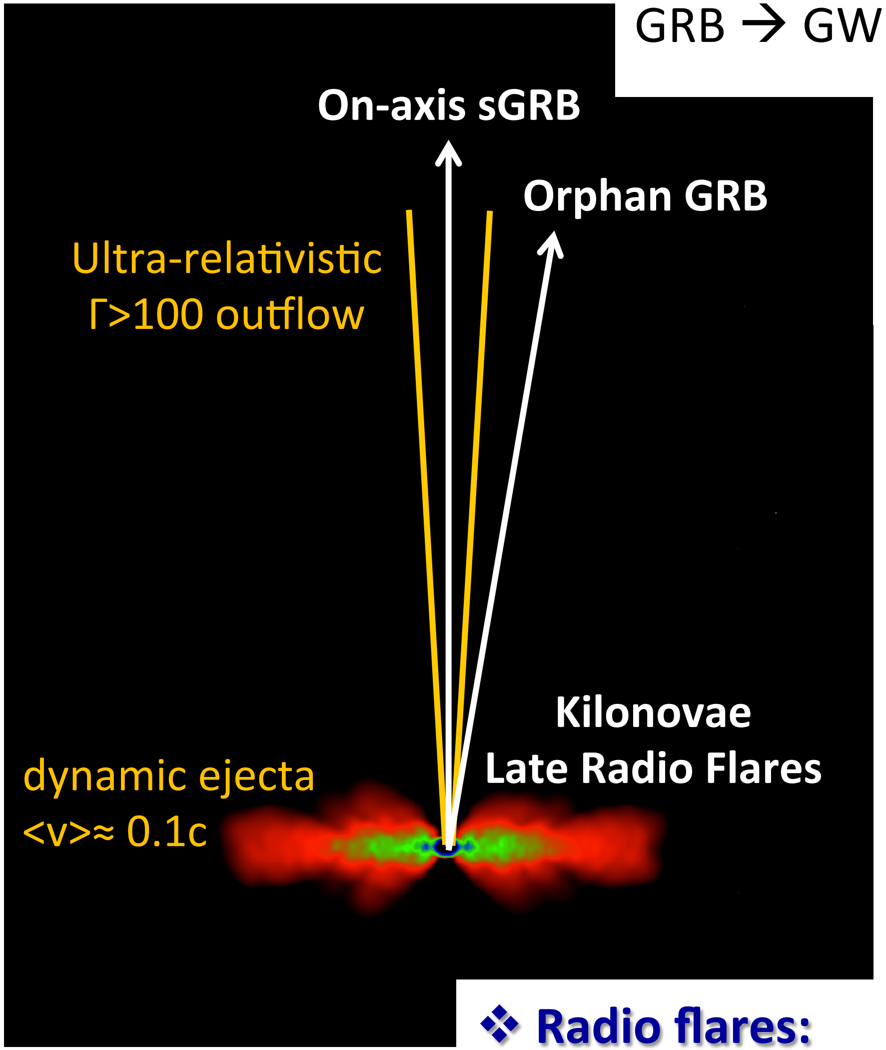
External ambient density critical parameter

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

EM signals from NS-NS/NS-BH merger and massive star core-collapse

❖ **Prompt ϒ-ray emission (beamed):**

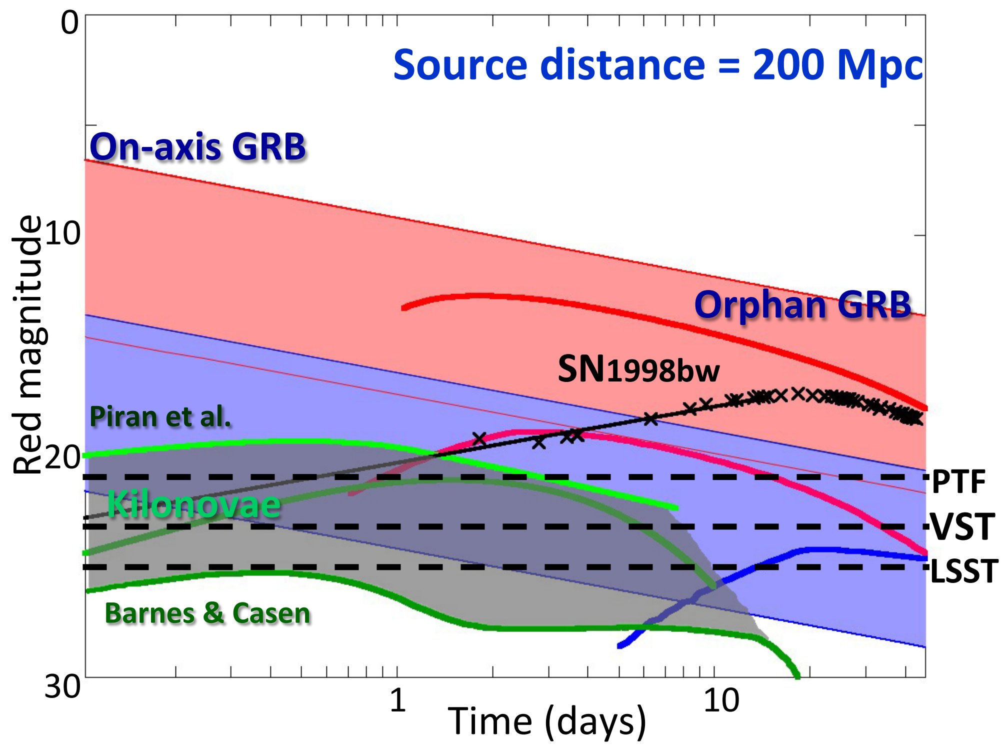
GRB → GW search **"GRB Triggered analysis"**



❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

"Low-latency EM follow-up"



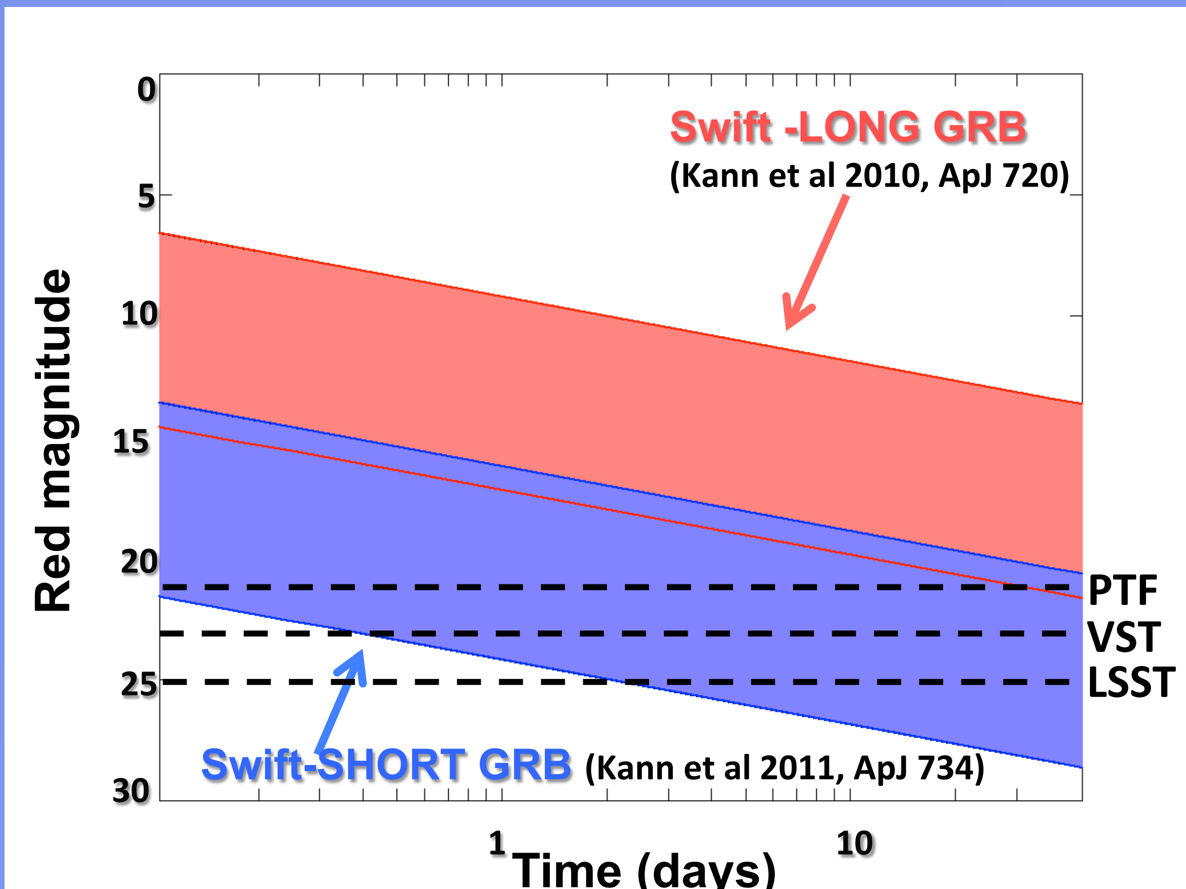
❖ **Radio flares:**

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

Blind radio search → GW search **"Radio Triggered analysis"**

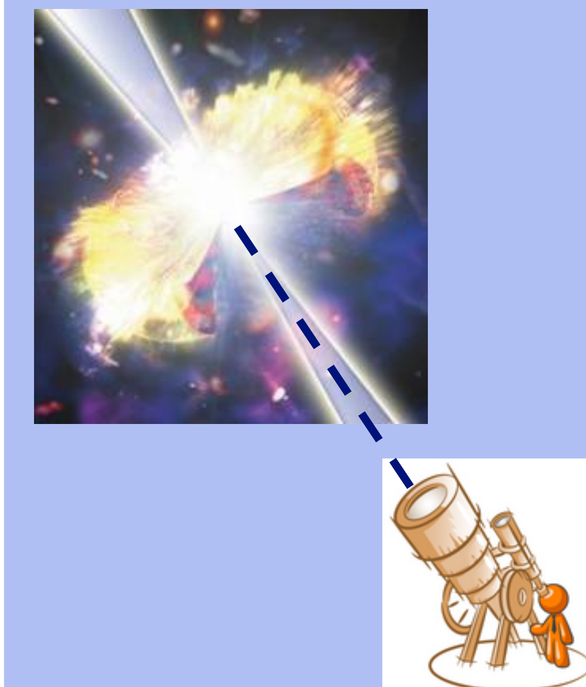
Optical afterglow ON-AXIS GRB

Source at distance of 200 Mpc



Observer along the jet axis

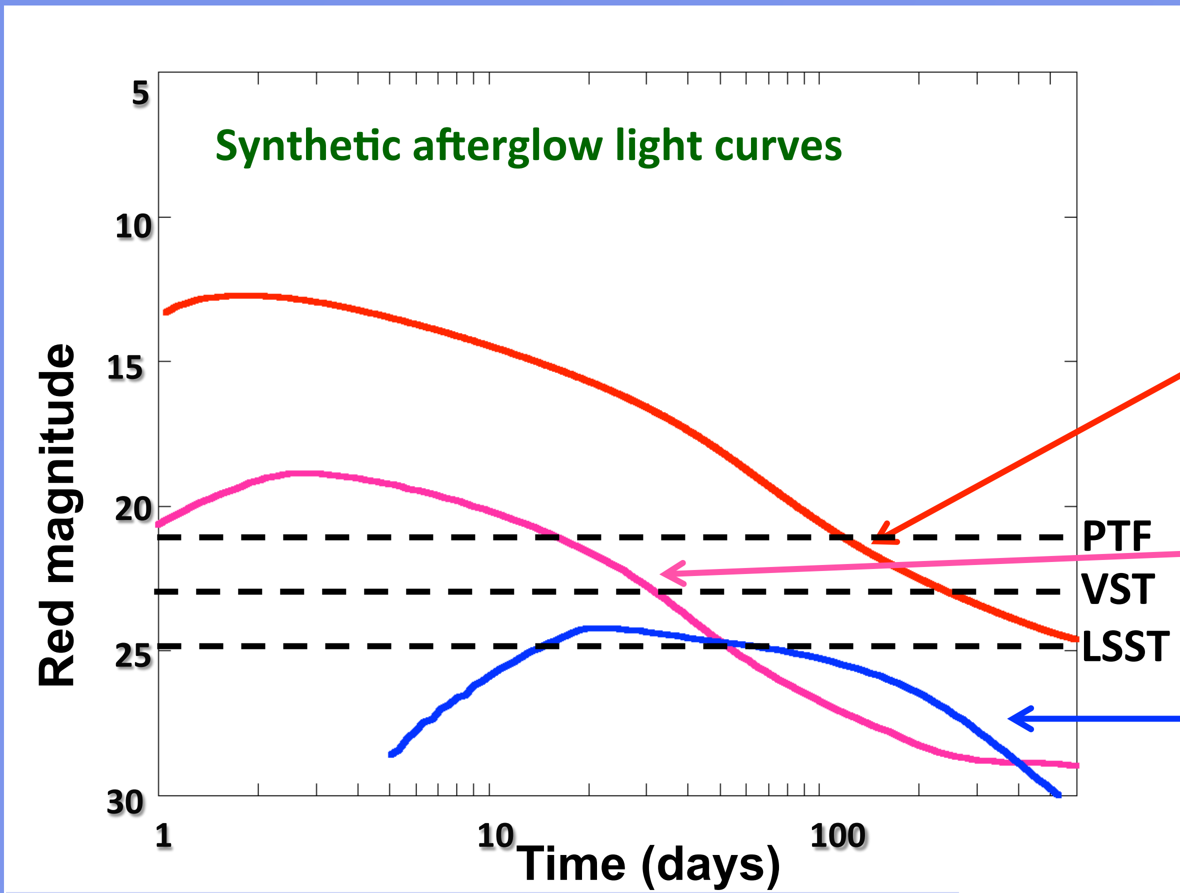
$\theta_{obs} < \theta_{Jet}$



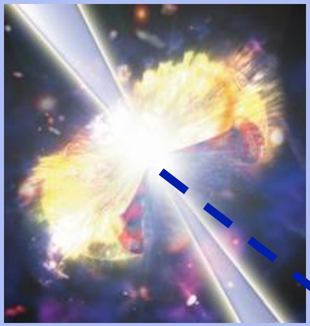
Power-law luminosity decay with time $t^{-\beta} \rightarrow \beta = 1 \div 1.5$

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

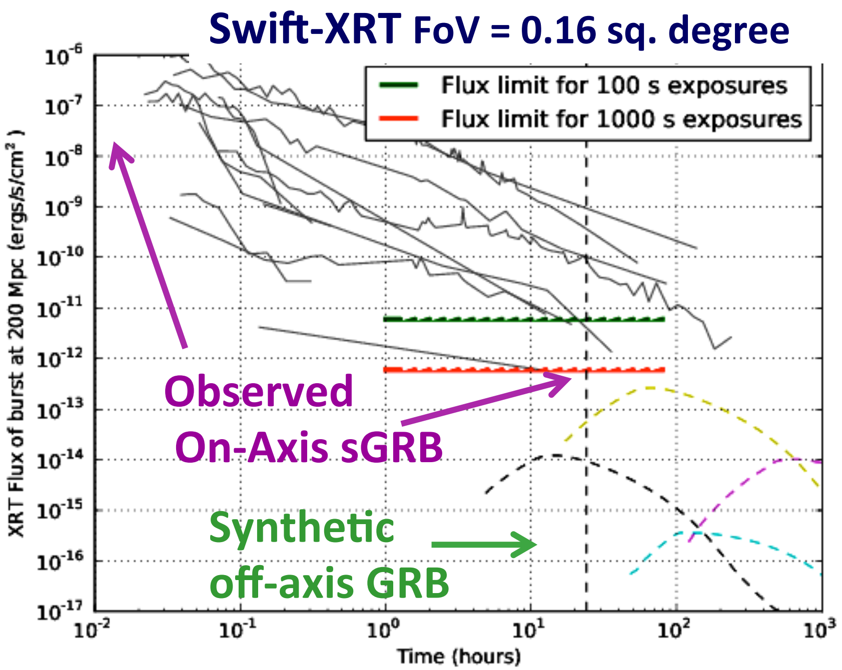
SHORT GRB
$\theta_{obs} = 0.4$ rad

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

By van Eerten & MacFadyen

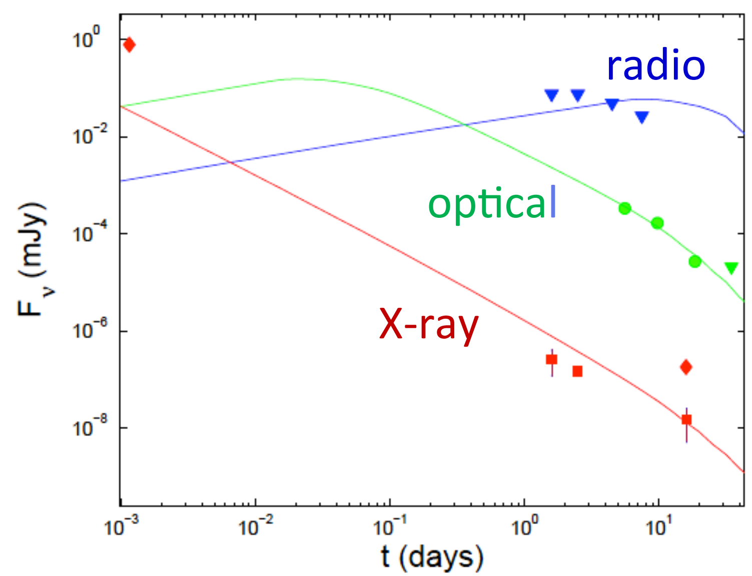
X-RAY and Radio GRB Afterglow

X-RAY: GRB at distance of 200 Mpc



Kanner et al. 2013, ApJ, 759

Short GRB 050709:



Fox et al. 2005, Nature 437