




LSC VIRGO

Gravitational waves – Experiments and sources
II PART

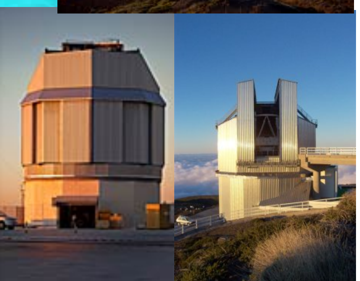
1506 UNIVERSITÀ DEGLI STUDI DI URBINO CARLO BO

INFN

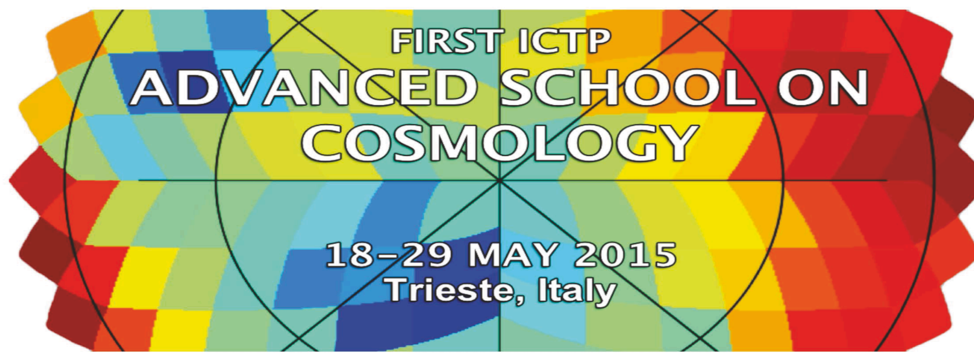
M.Branchesi

FUTURO IN RICERCA

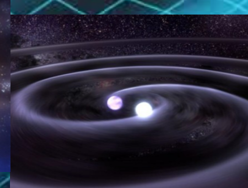
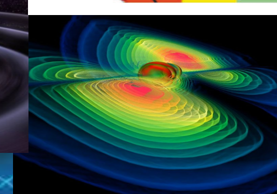
(Università di Urbino/INFN Sezione di Firenze)


The Abdus Salam International Centre for Theoretical Physics www.ictp.it






Outline – II part

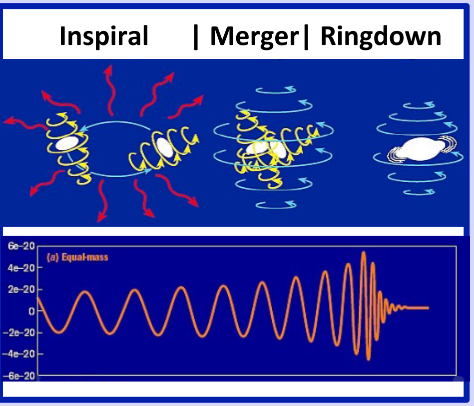
- **Multi-messenger astronomy**
  - Opportunities and challenges

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

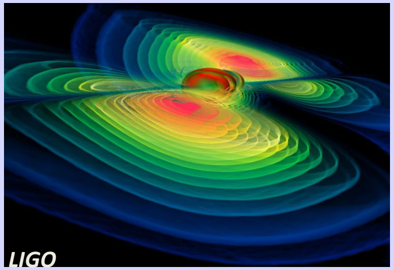
Coalescence of Compact Objects

Neutron-Stars and/or Black-Holes

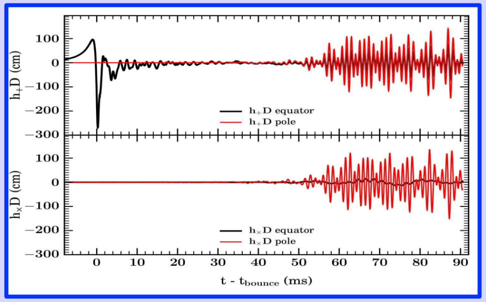


Binary containing a NS:
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz) **< 20 s before merger**
- **Energy emitted in GW: ~$10^{-2} M_o c^2$**

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



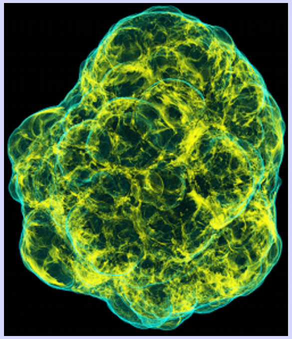
Core-collapse of Massive Stars



Ott, C. 2009, CQG, 26

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

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



Ott et al. 2013, ApJ, 768

Advanced Era GW-detectors (ADE)

LIGO-H

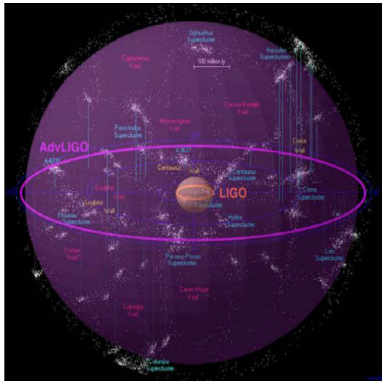
LIGO-L

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

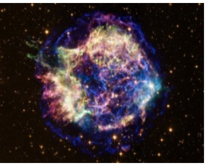
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(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)

Optimistic models **10 - 100 Mpc** (Piro & Pfahl 2007)
(Fryer & New 2011)

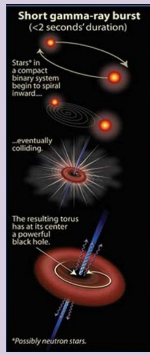
Electromagnetic emission

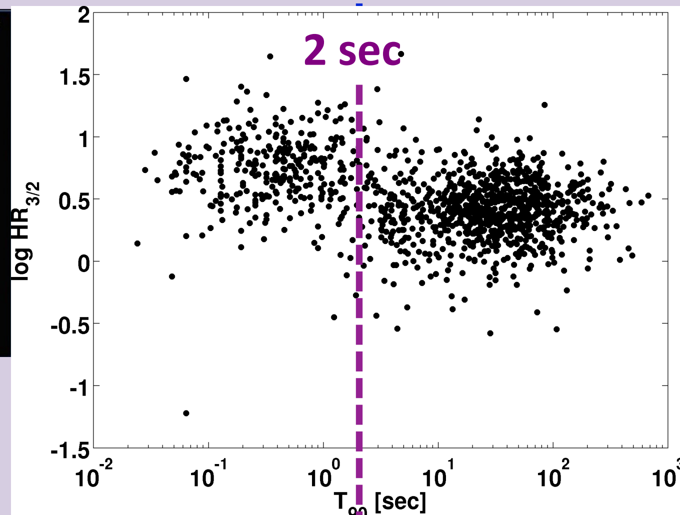
Merger of NS-NS / NS-BH

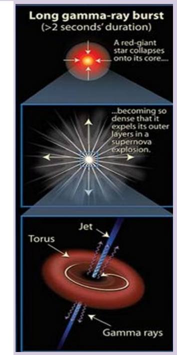
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB







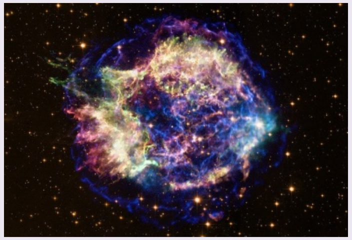
Long Soft GRB

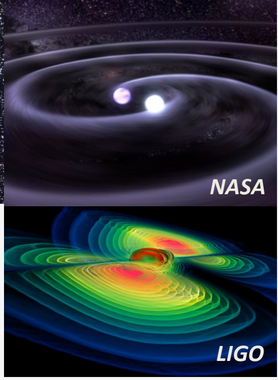
Kilonovae

(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c





Why the discovery of the EM counterpart signal of a GW candidate event will be a key ingredient for maximizing the science return of GW observations?

- **To consider the GW signal in its astrophysical context**
- **To give a precise (arcsecond) localization, identify host galaxy**
- **For a complete multi-messenger 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..)**
- **To fix location, distance, system orientation and gain sensitivity on intrinsic parameters like spin and mass estimates**
- **To constrain the NS equation of state** (Maselli et al. 2014, Pannarale et al. 2014)
- **To start the multi-messenger (GW and photon) astronomy**

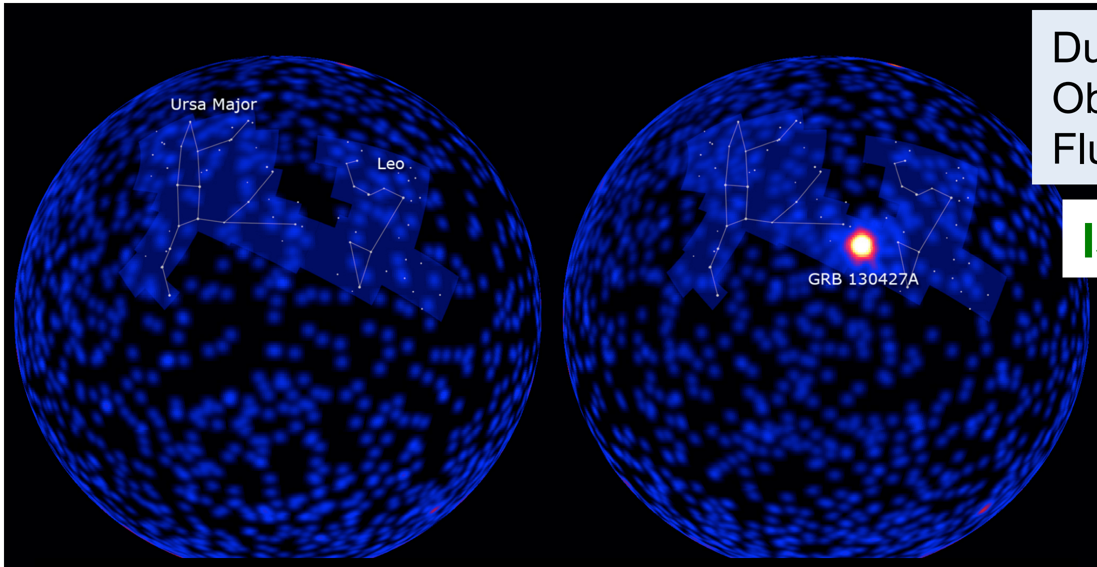




EM emission from transient GW sources

What is a Gamma-Ray Burst?

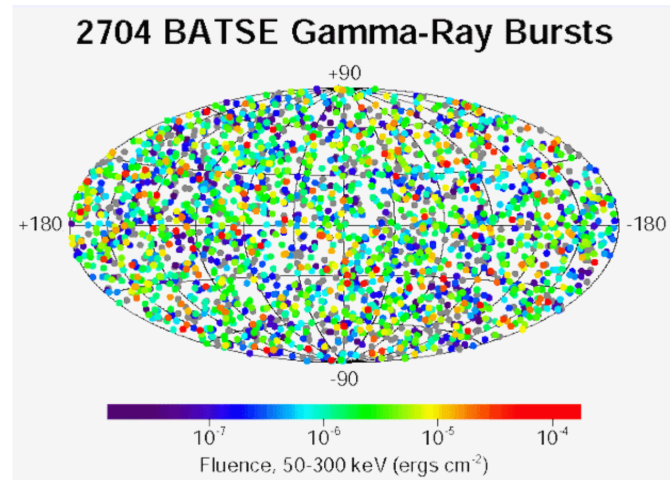
Brief, sudden, intense flash of gamma-ray radiation



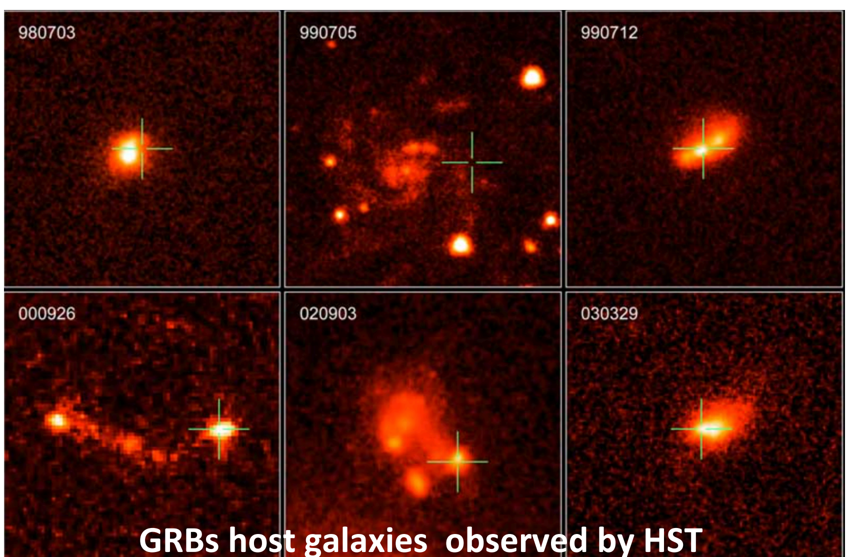
Before and after Fermi LAT observation of GRB 130427A

Duration: **from few ms to hundreds of s**
Observational band: **10 keV – 1 MeV**
Flux: **10^{-8} - 10^{-4} erg cm^{-2} s^{-1}**

Isotropic distribution of the GRBs



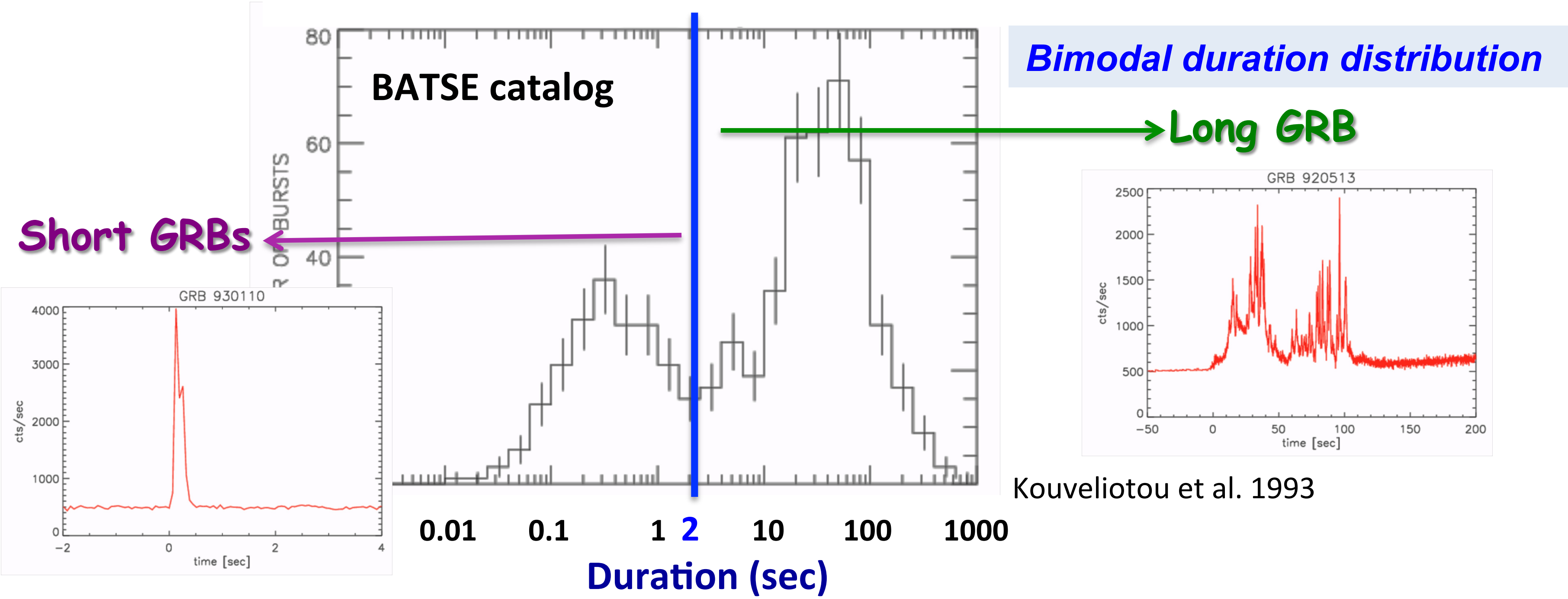
GRBs are extragalctic , cosmological, and occur in galaxies



GRBs host galaxies observed by HST

Huge amount of energy
up to **~ 10^{53} erg**
(isotropic-equivalent)

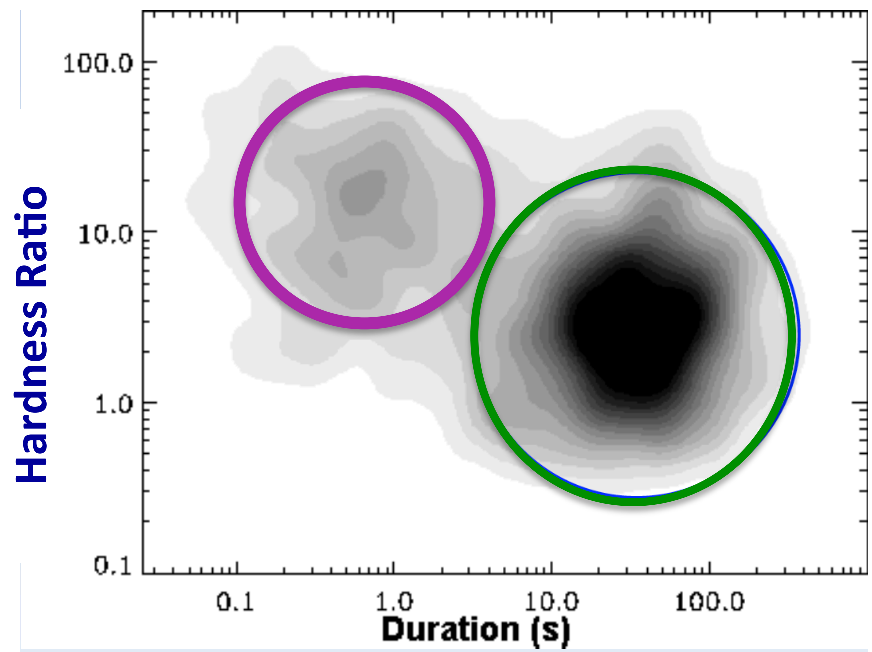
Two classes of GRBs



Kouveliotou et al. 1993

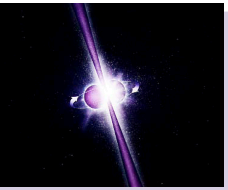
Hardness ratio = $\frac{\text{(100-300 keV) counts}}{\text{(50-100 keV) counts}}$

- **Short Hard GRB**
- **Long Soft GRB**



Two classes of GRBs/Different Progenitors

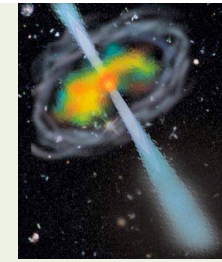
Merger of NS-NS / NS-BH

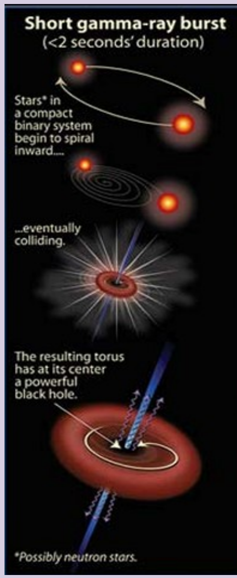


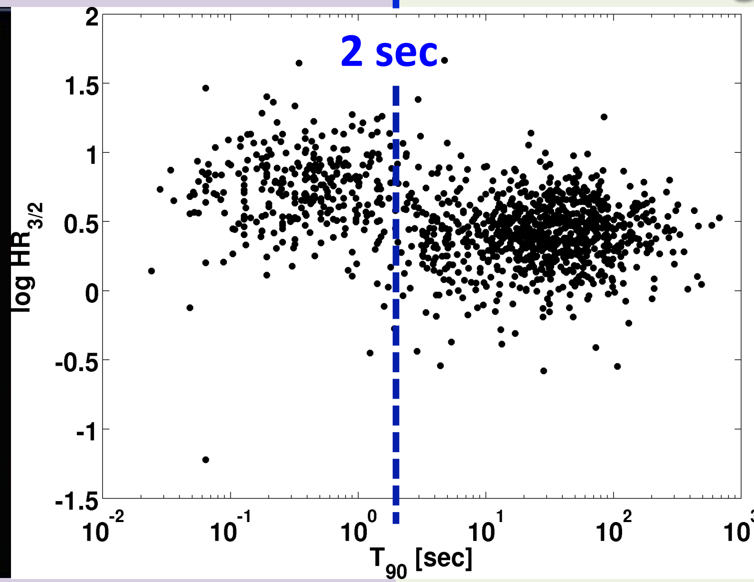
Short Hard GRB

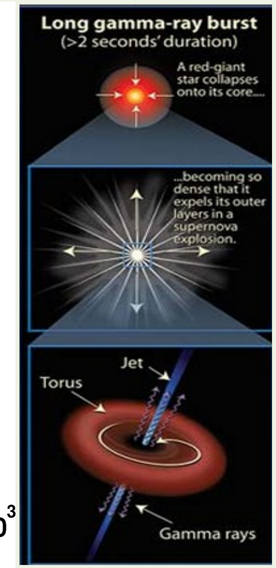
Core collapse of massive star

Long Soft GRB









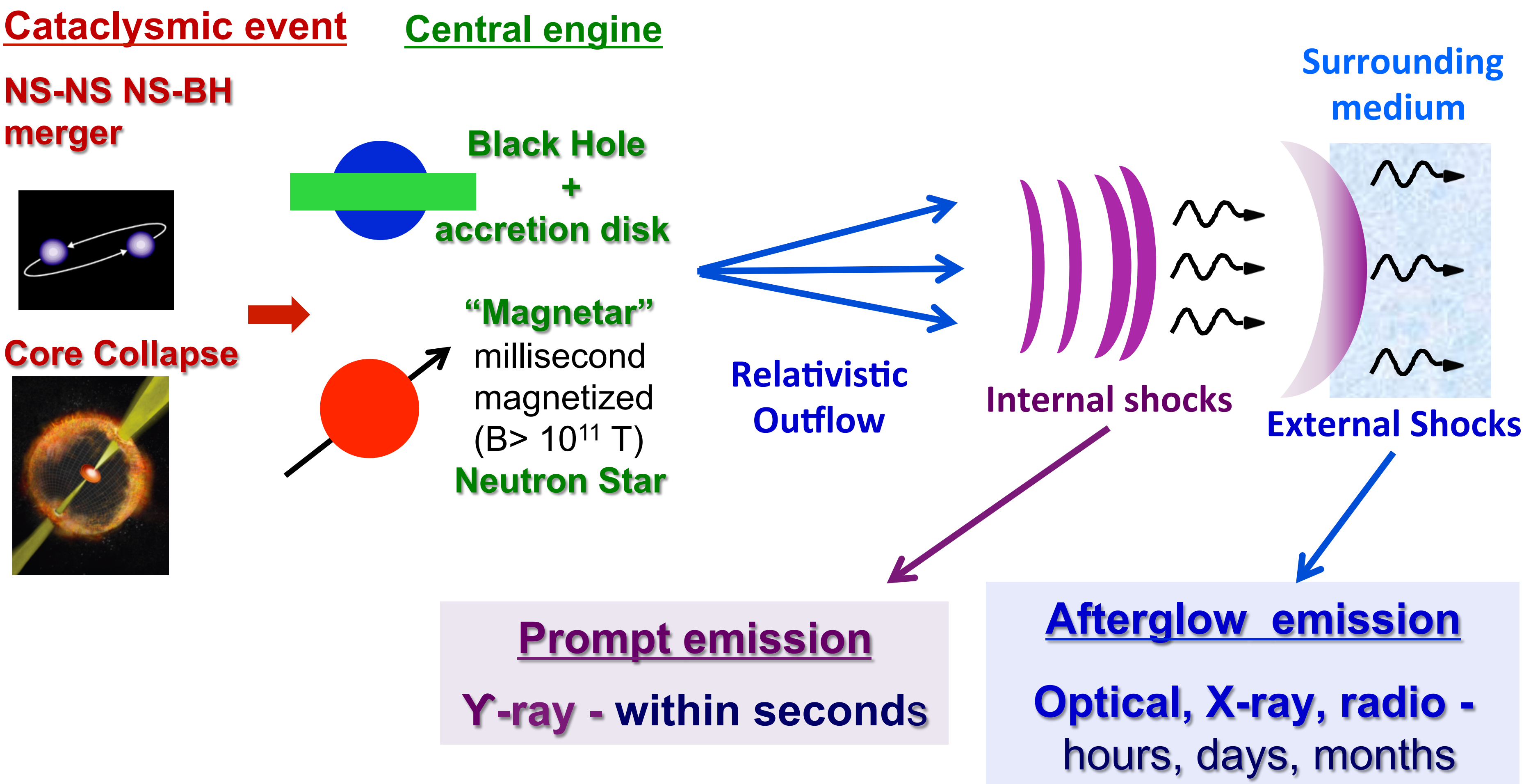
Progenitor indications:

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

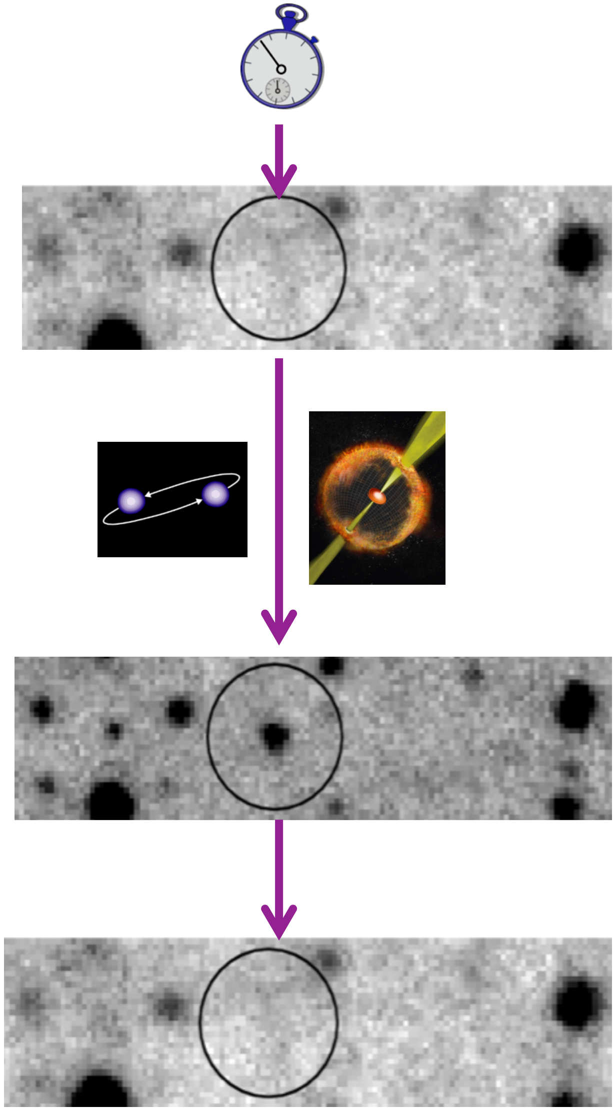
Progenitor strong evidence:

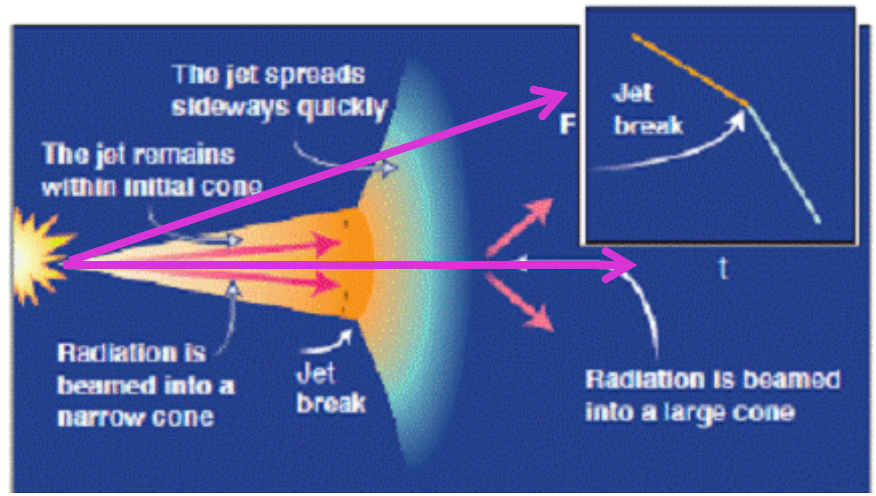
- observed Type Ic SN spectrum

GRBs emission - Fireball Model



GRBs emission – Transient events

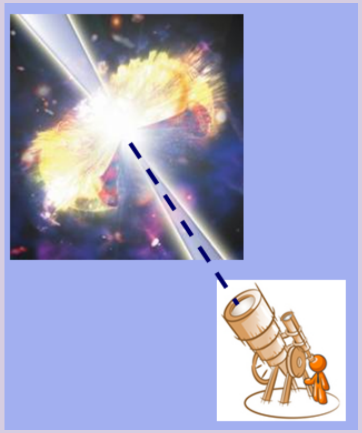




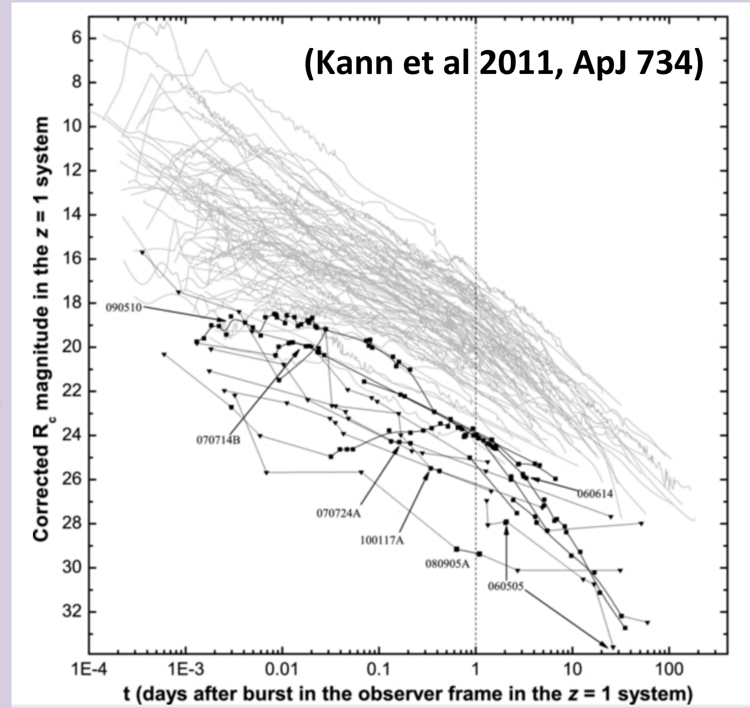
Nakar & Piran 2003

Optical afterglows of On-axis GRBs

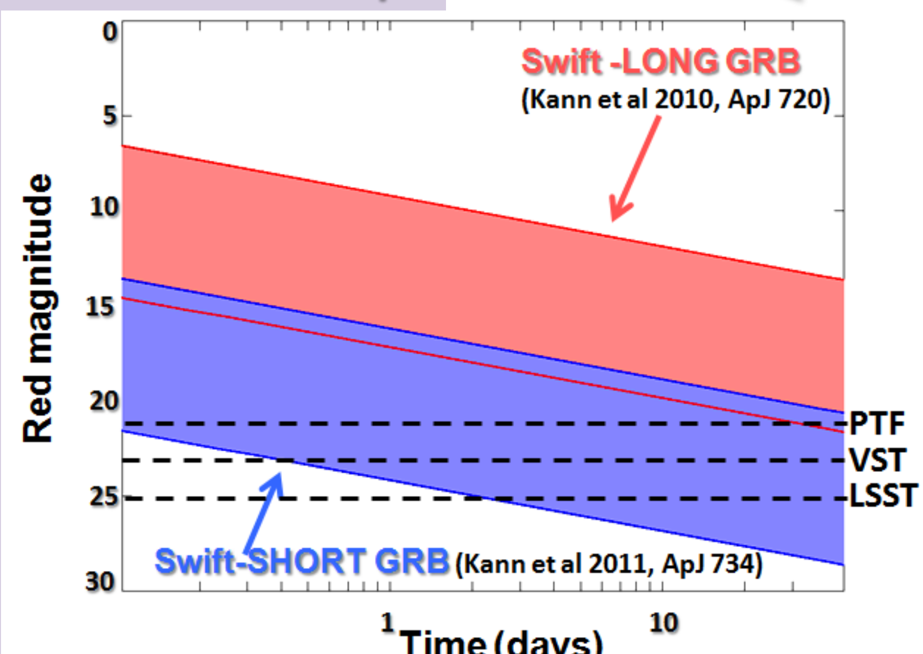
On-axis GRBs



Observed GRB optical afterglows



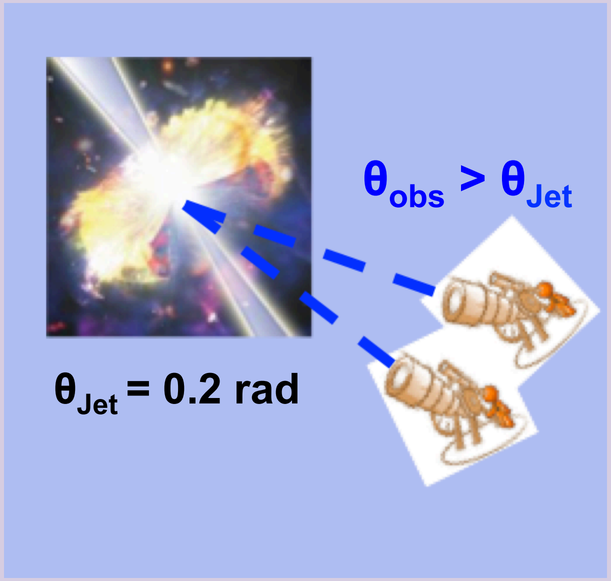
Source at 200 Mpc



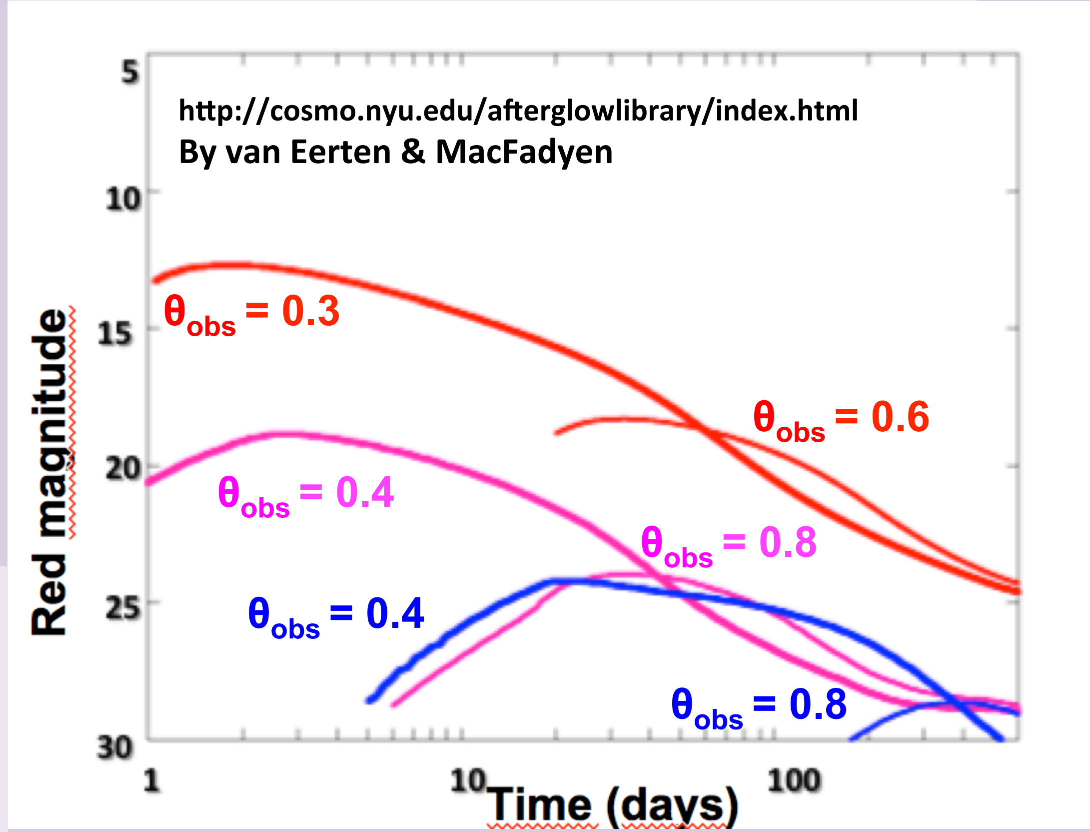
On average the optical afterglow decays as a **power law time$^{-\alpha}$** with **α in the range 1 to 1.5**

Optical afterglows of Off-axis GRBs

Off-axis GRB



Modelled afterglows - Source at 200 Mpc



LONG bright GRB

E_jet = 2e51 erg, n = 1 cm^{-3}

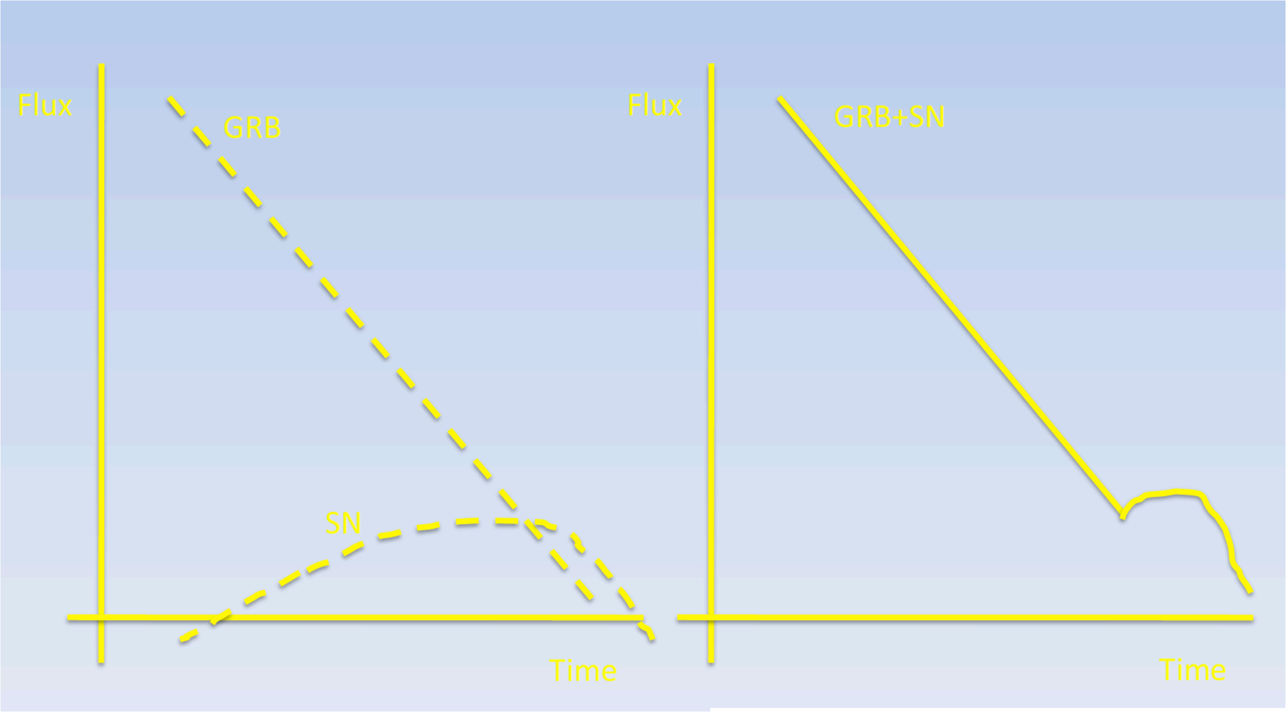
LONG faint/ SHORT bright GRB

E_jet = 1e50 erg , n=1 cm-3

SHORT GRB

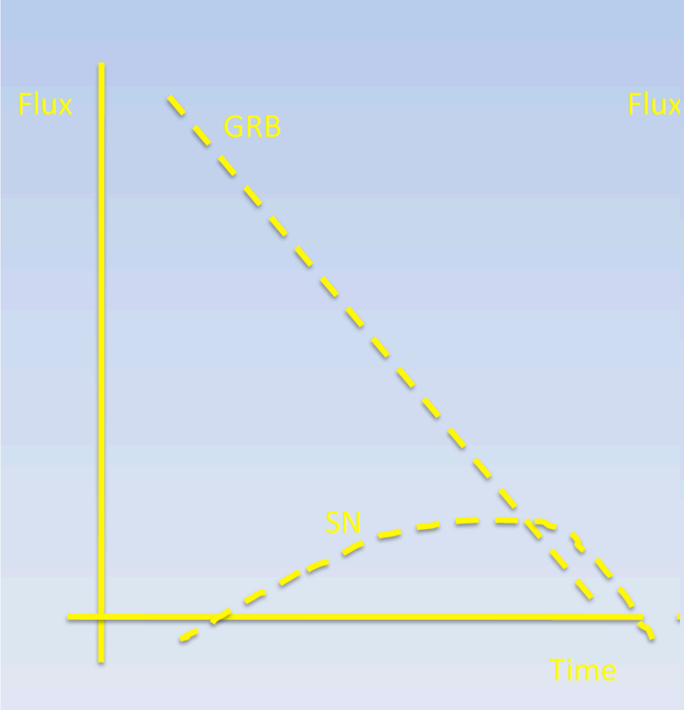
E_jet = 1e50 erg , n=10^{-3} cm^{-3}

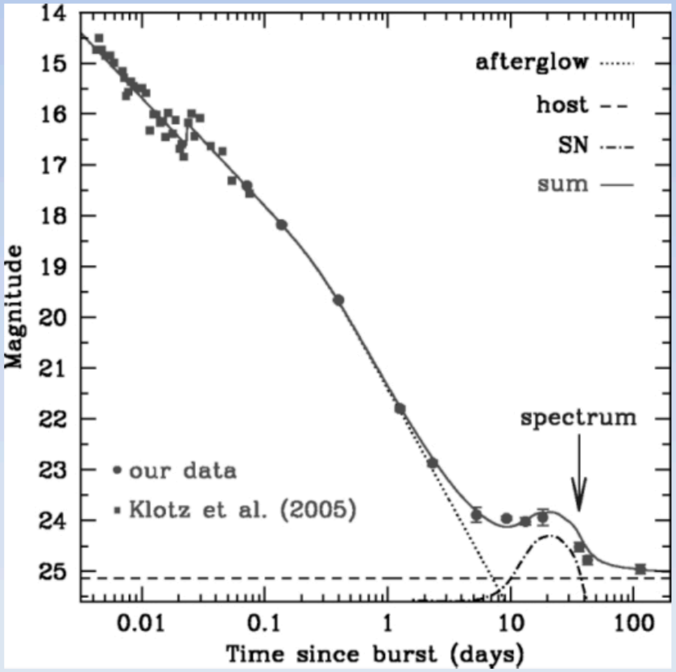
Long GRB and Supernovae



From D'Avanzo Talk

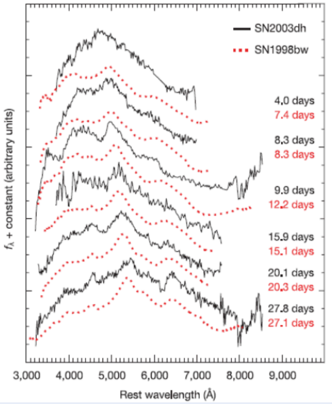
Long GRB and Supernovae

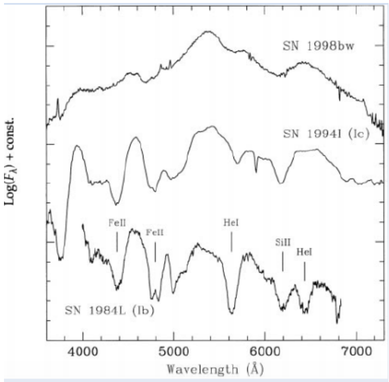




From D'Avanzo Talk

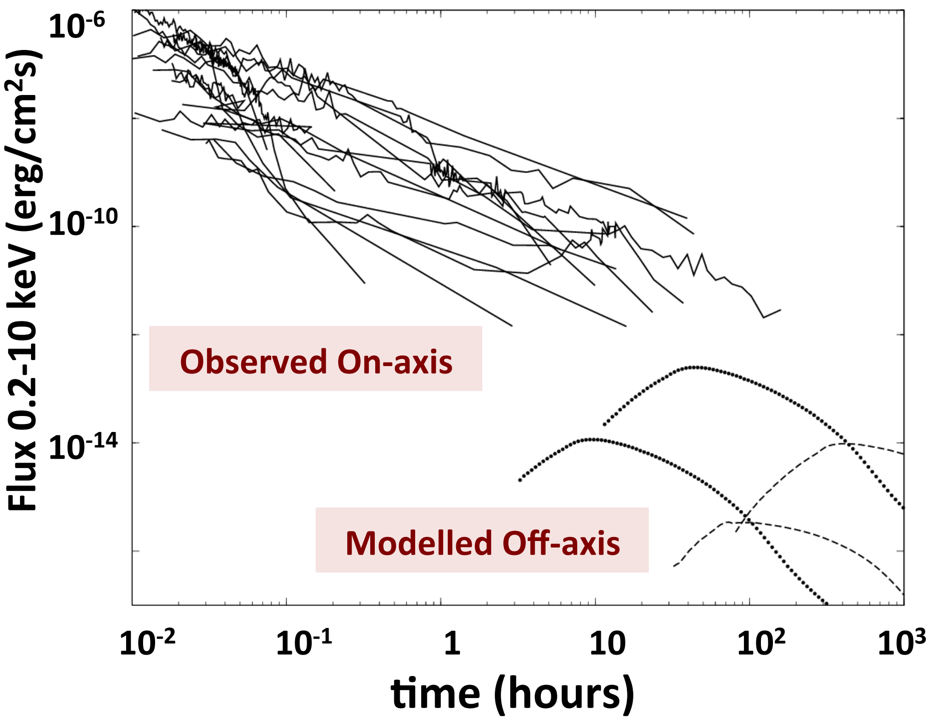
Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melnadri et al. 2014 and others…



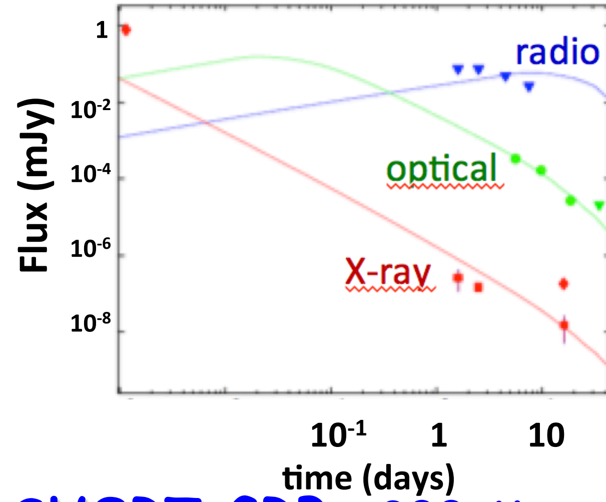


X-RAY and Radio bands

SHORT GRBs at distance of 200 Mpc

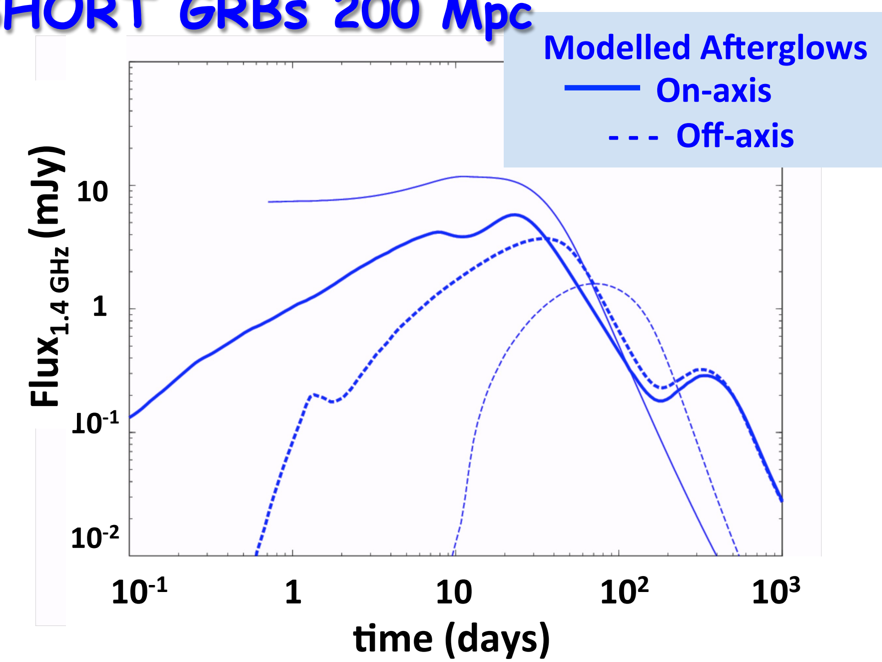


SHORT GRB 050709



Fox et al. 2005, Nature

SHORT GRBs 200 Mpc



Long GRBs and SN

Shock breakout in SN

Short (up to a few thousands seconds) and long (several days) **X-ray flashes**

Also model of **radio precursor** at low radio frequencies (Pshirkov & Postnov 2010)

Short GRBs: how many on-axis/off-axis

Observed on-axis SHORT GRBs

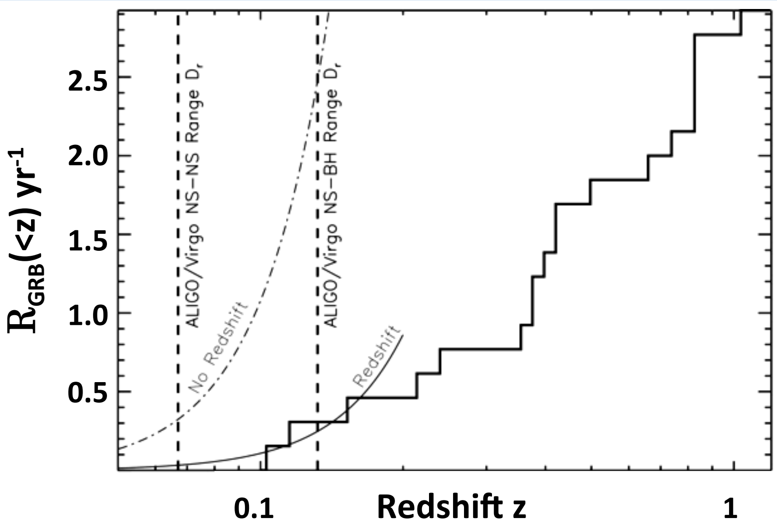
So far **~100** of which **~20** at known distance

<z>=0.5 = 3 Gpc

zmin = 0.12 = 560 Mpc

Energy = 10^{48-52} erg

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

*The **number of off-axis wrt on-axis** short GRB depend on the **beaming angle** that is very poorly constrained: **only two measures** → 7 and 14 degree*

Advanced LIGO and Virgo NS-NS detection rate based on short GRB observations

Assuming that the progenitor of all the short GRBs observed are NS-NS merger:

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)

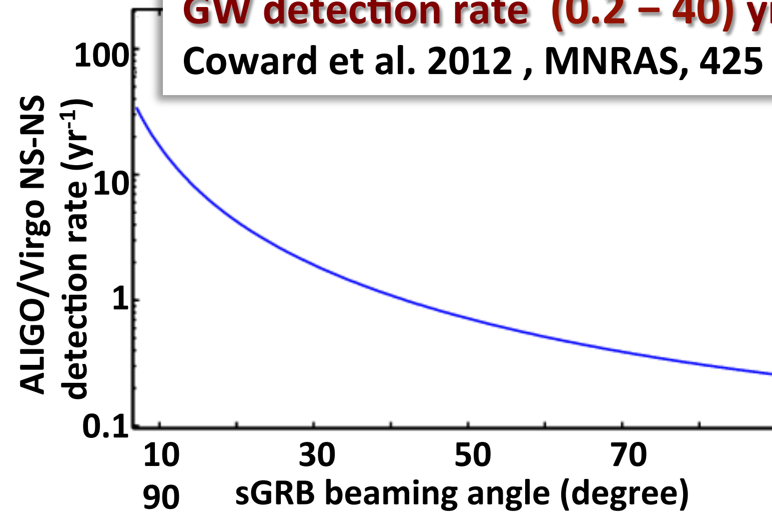
92–1154 $Gpc^{-3}\ yr^{-1}$ (Siellez et al. 2013)

Theoretical prediction

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

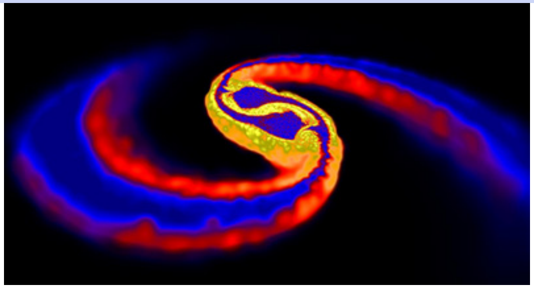
GW detection rate (0.2 – 40) yr^{-1}

Coward et al. 2012 , MNRAS, 425

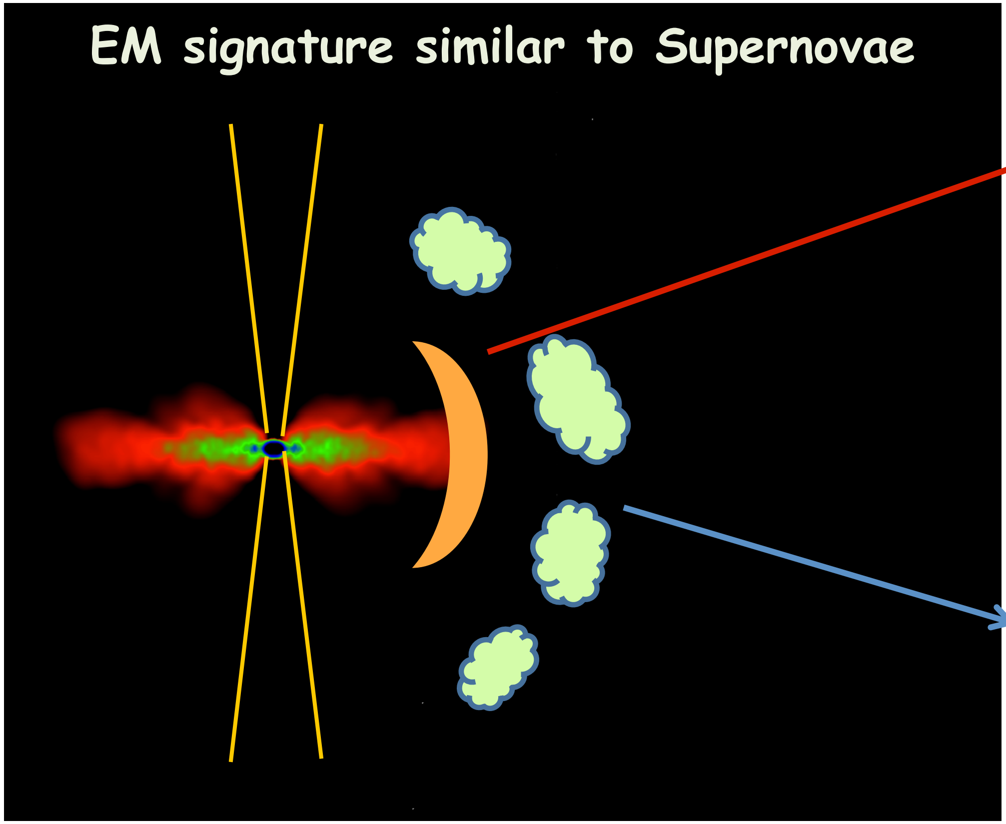


Kilonovae

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

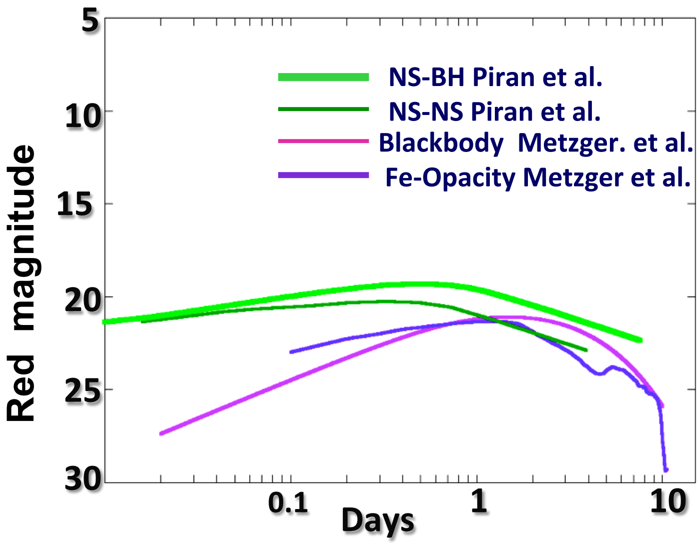
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;
Piran et al. 2013, MNRAS, 430

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

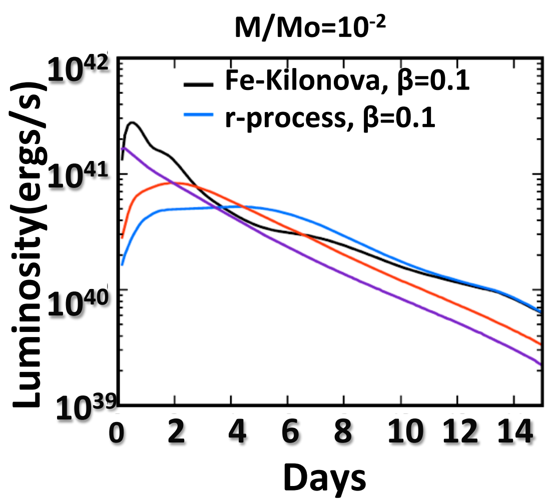


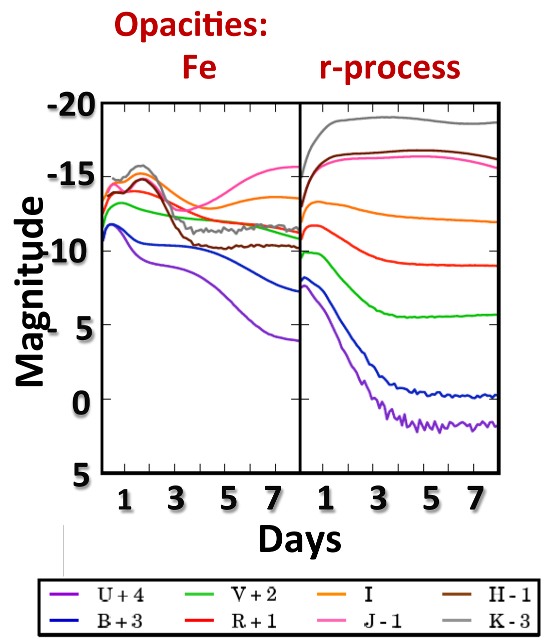
***Kilonova* model afterglow** peaks about a ***day* after** the merger/GW event

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**

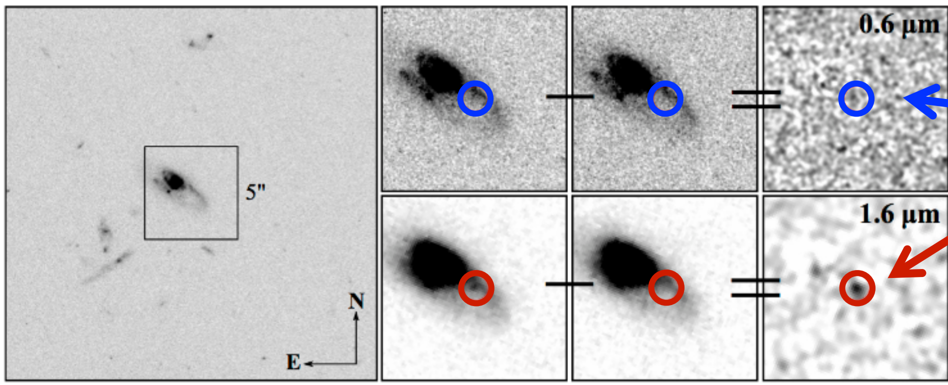




Barnes & Kasen 2013, ApJ, 775

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

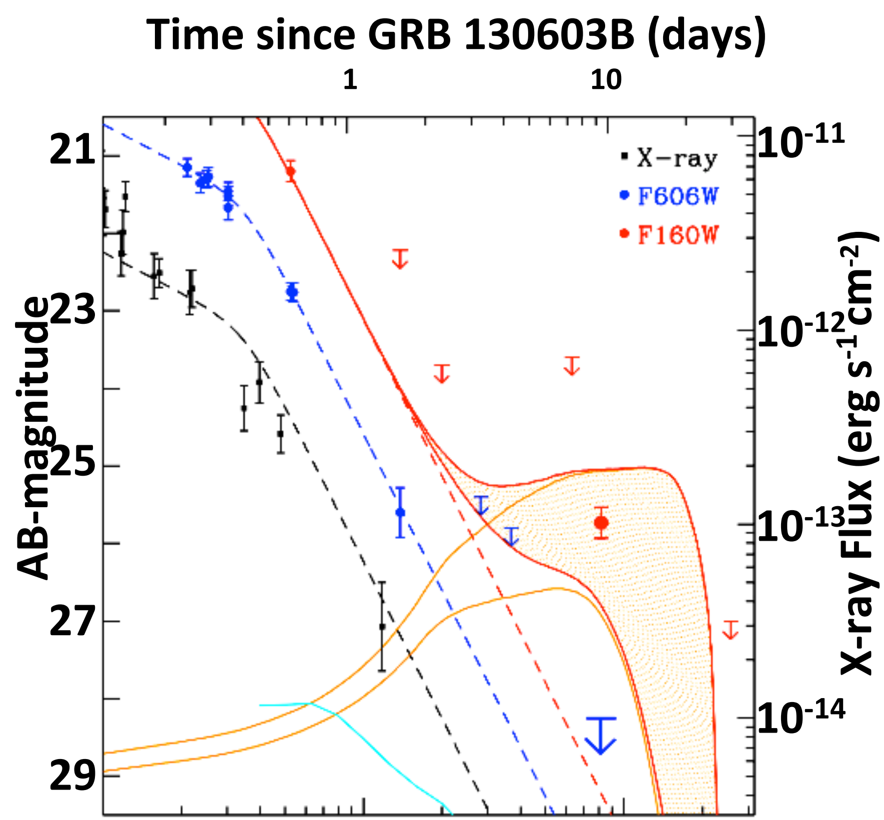
NIR/F160W

Orange curves → kilonova NIR model

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

Solid red curves → afterglow +kilonova

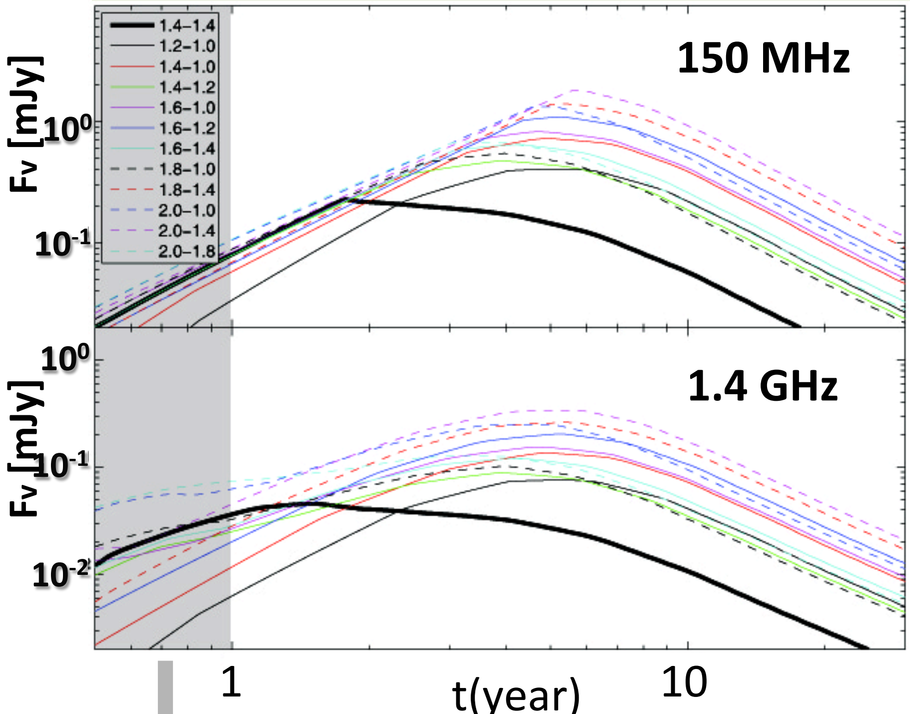
Cyan curve → kilonova optical model



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

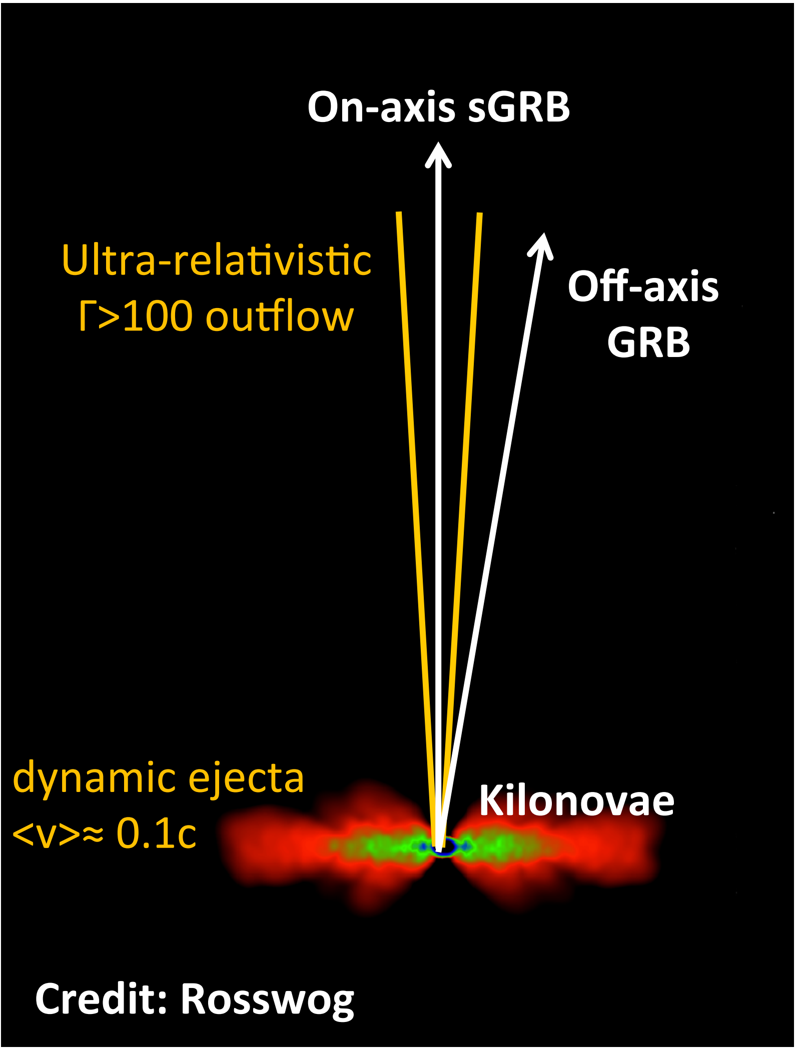
Piran et al. 2013, MNRAS, 430

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} ⟶ one order of magnitude fainter signals

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



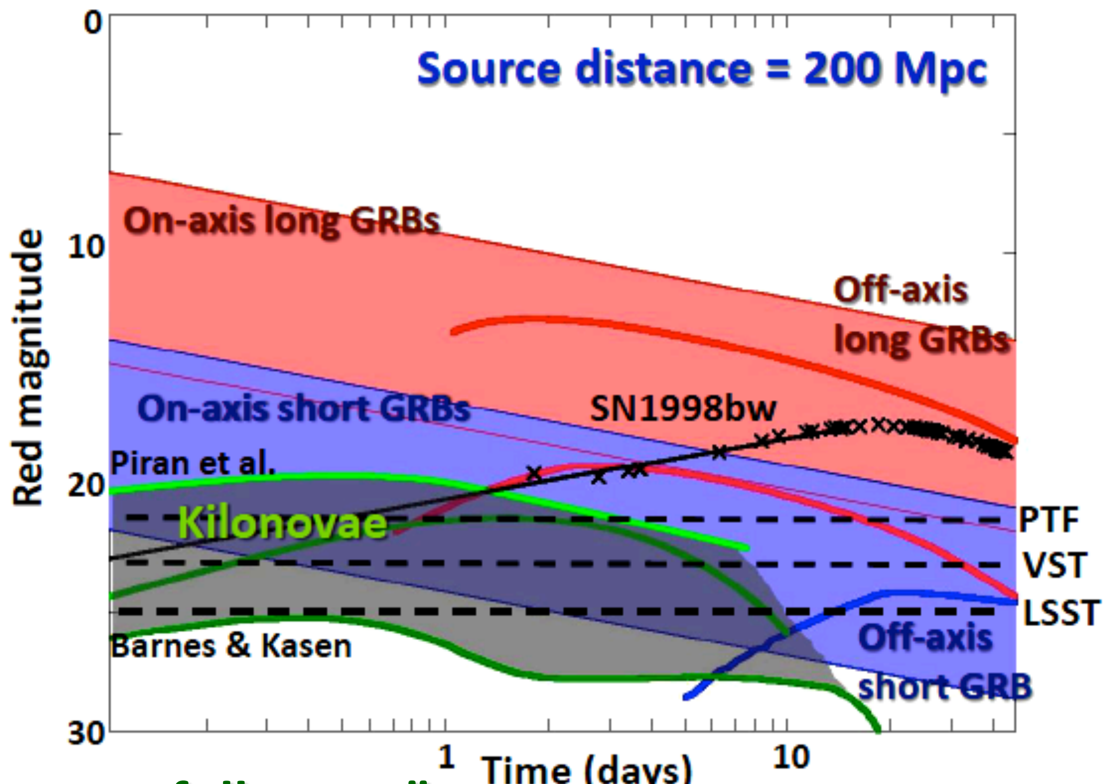
❖ **Prompt ϒ-ray emission (beamed):**

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

❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

"Low-latency EM follow-up"



❖ **Radio:**

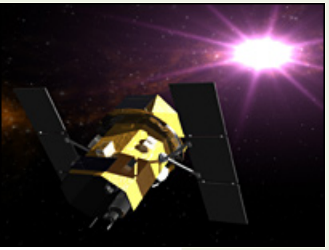
GW trigger → radio search **"High-latency follow-up"**

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

Triggered analysis

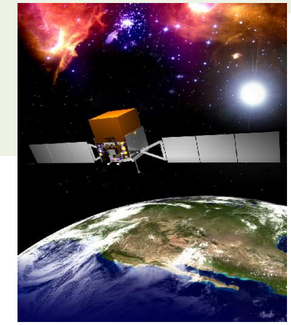
EM observations → GW analysis

GRB prompt emission → TRIGGERED GW SEARCH

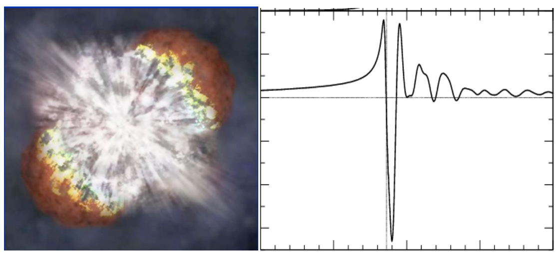


Known **GRB event time** and **sky position:**

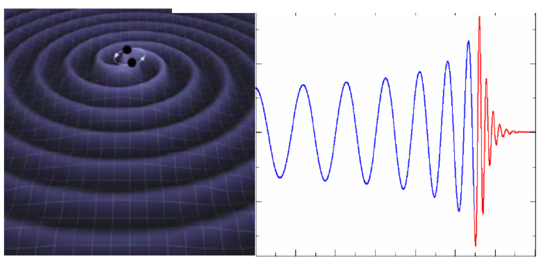
→ **reduction in search parameter space**
→ **gain in search sensitivity**



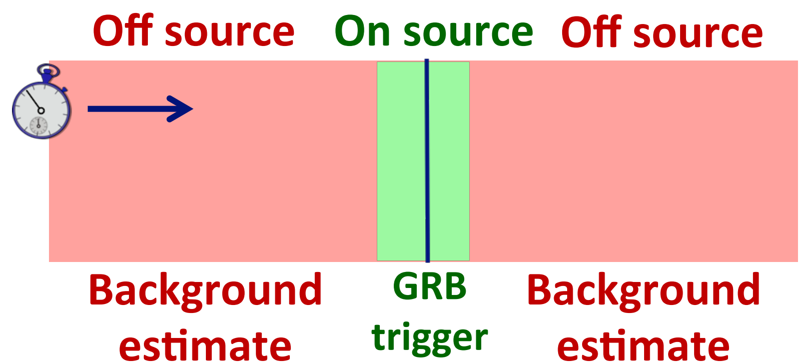
GW transient searches



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



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



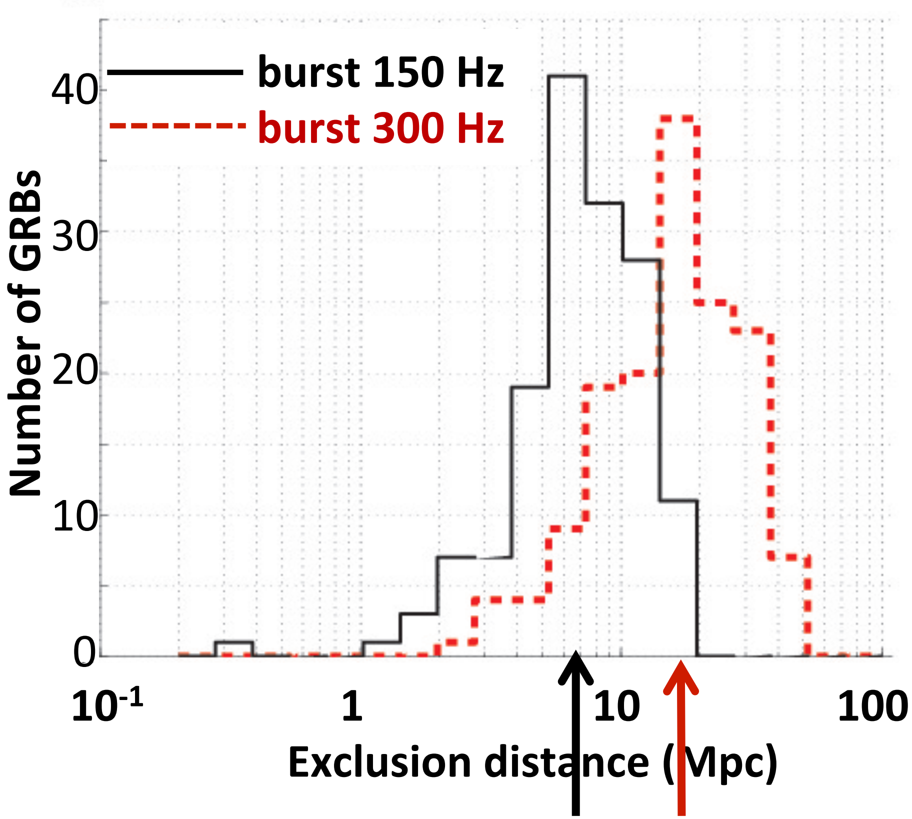
Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010**
while 2 or 3 LIGO/Virgo detectors were taken good data
No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

GRB prompt emission - TRIGGERED SEARCH

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

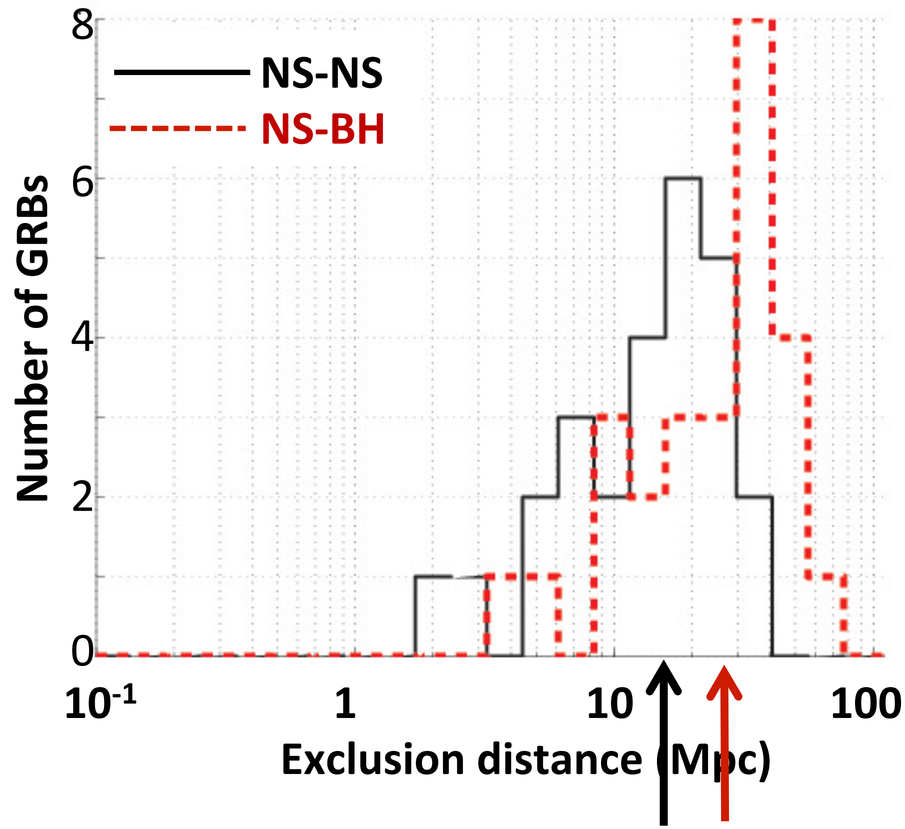
Abadie et al. 2012, ApJ, 760

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



Median distances: 7 17 Mpc

Binary system coalescence
(26 short GRBs)



Median distances: 16 28 Mpc

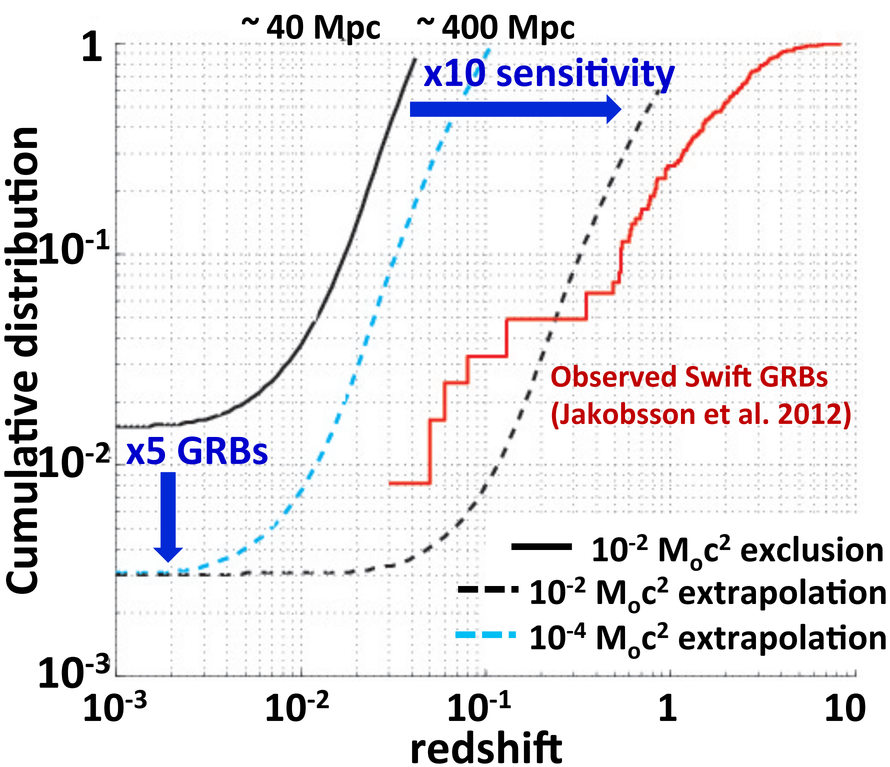
GRB prompt emission - TRIGGERED SEARCH

Population exclusion on cumulative redshift distribution

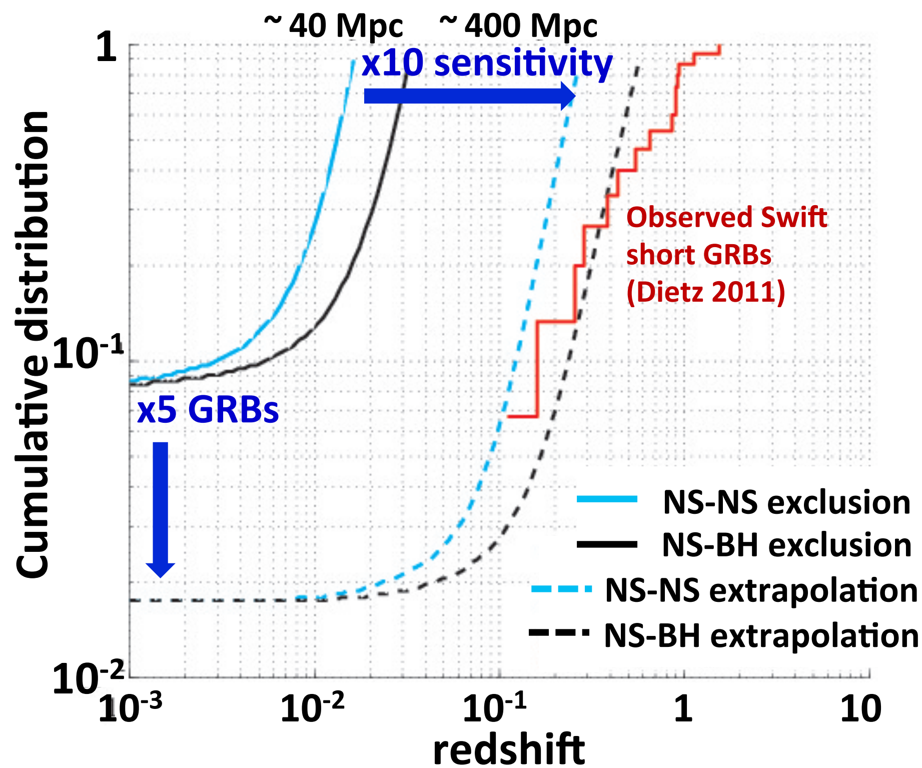
Results 2009-2010 & prospects for Advanced LIGO/Virgo

Abadie et al. 2012, ApJ, 760

Unmodeled GW burst (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

See also Aasi et al. 2014, PhRvL, 113

Astrophysical non-detection results for single events

Short GRB070201 / GRB051103

- **gamma-ray emission:**

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

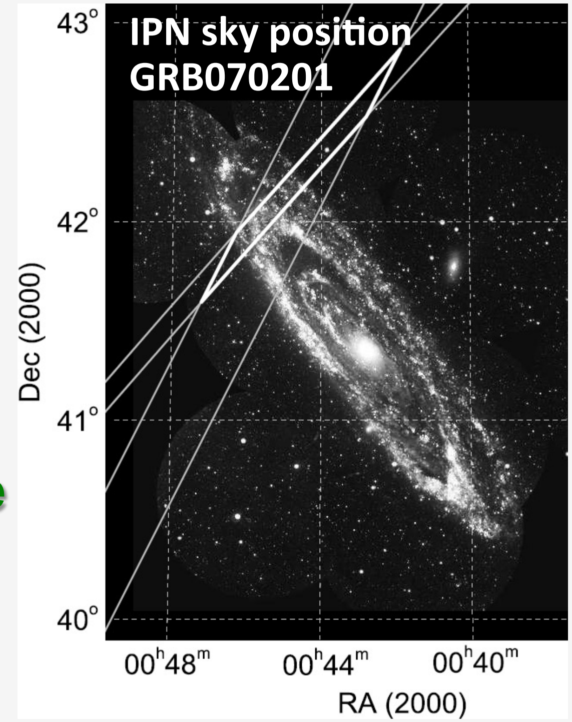
- **Non detection of GWs from binary coalescence**

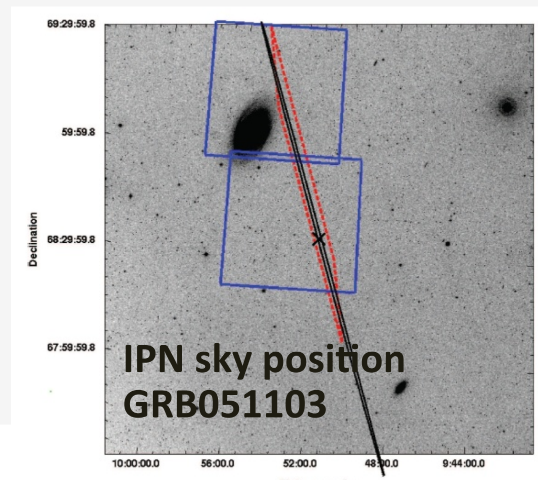
→ compact binary progenitor in M31excluded at 99% c.l.
→ comapct binary progenitor in M81excluded at 98% c.l.

- **Non detection of GW burst sets limits on emitted energy compatible with:**

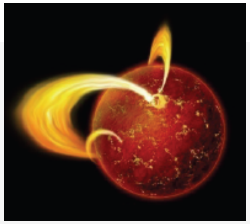
→ **soft gamma-ray repeater giant flare**
→ **coalescence in galaxy more distant than M31/M81**

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





Other EM Triggered GW Searches



Soft Gamma Ray Repeaters & Anomalous X-ray Pulsars

- Magnetars which emit **hard X-ray/gamma repetitive 0.1 sec flares** (10^{42} erg/s) & **giant flares** (10^{47} erg/s)
- Maximum **energy available for GWs:**

→ Crust-cracking **10^{-7} -10^{-4} $M_o c^2$**

→ Magnetic rearrangement **10^{-9}-10^{-6} $M_o c^2$**

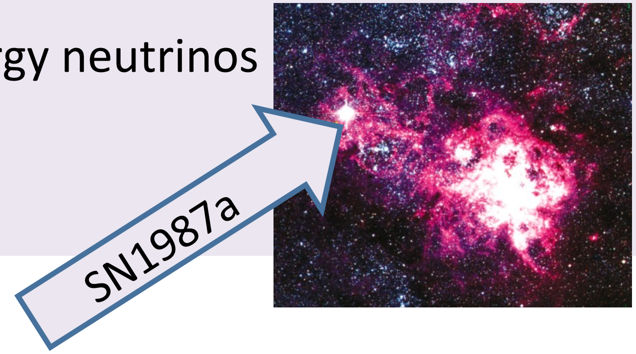
Abbott et al. 2008, PRL, 21110

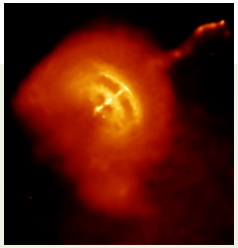
Abbott et al. 2009, ApJ, 701

Abadie et al. 2011, ApJ, 734

Core-Collapse Supernovae

- Energy in GW **10^{-8} -10^{-4} $M_o c^2$**
- 2-4 yr^{-1} EM-observed within 20 Mpc
- Challenges in EM: **nightly/weekly optical/X-ray survey** of nearby galaxies
- Low-energy neutrinos





Pulsar glitches:

sudden increase in the NS rotational phase, frequency or frequency derivatives observable in **radio and gamma-ray pulsars**

Expected energy in GW: **10^{-16} -10^{-12} $M_o c^2$**

Abadie et al.2011PhRvD,83

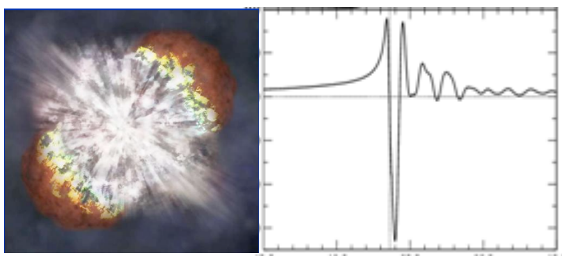
Electromagnetic follow-up

GW → prompt EM observations

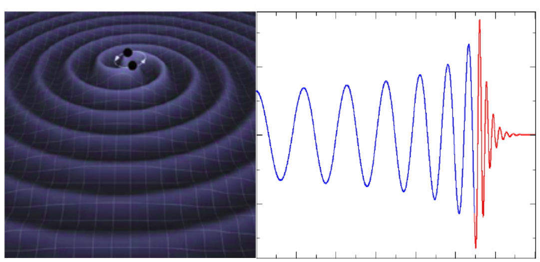
2009-2010 first Electromagnetic follow-up of candidate GW events

Low-latency GW data analysis pipelines

GW transient searches



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



Compact Binary Coalescence
Known waveform
→ Matched filter

enabled us to:

1) identify GW candidates in "real time"

2) obtain prompt EM observations

Abadie et al. 2012, A&A 539

Abadie et al. 2012, A&A 541

GW triggers

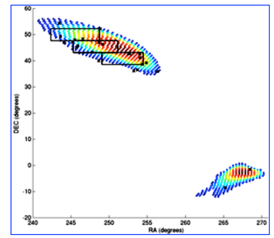
Sky Pointing Position

EM facilities

LIGO-H

LIGO-L

Virgo



Event validation

"Search Algorithms" to identify the GW-triggers

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

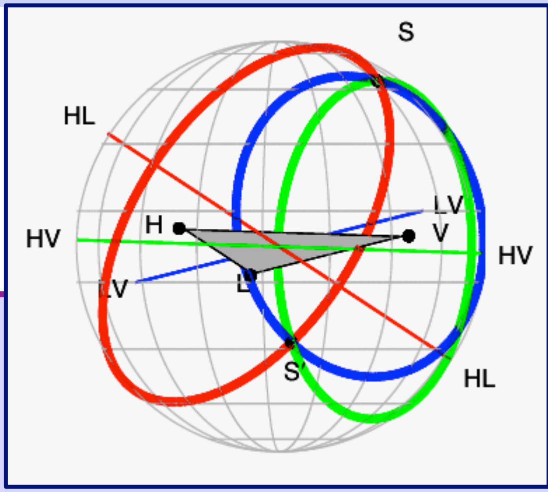
- select statistically significant triggers wrt background
- determine telescope pointing

~ 10 min. → **~ 30 min.**

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

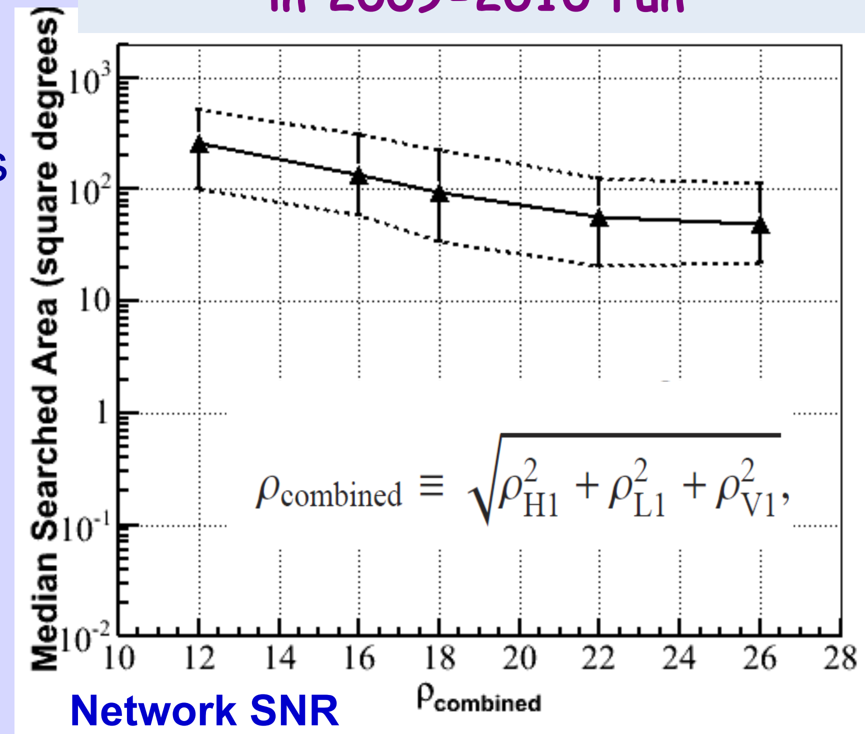
Advanced detector era latency expected to be improved to few minutes!

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**

Binary coalescence localization in 2009-2010 run

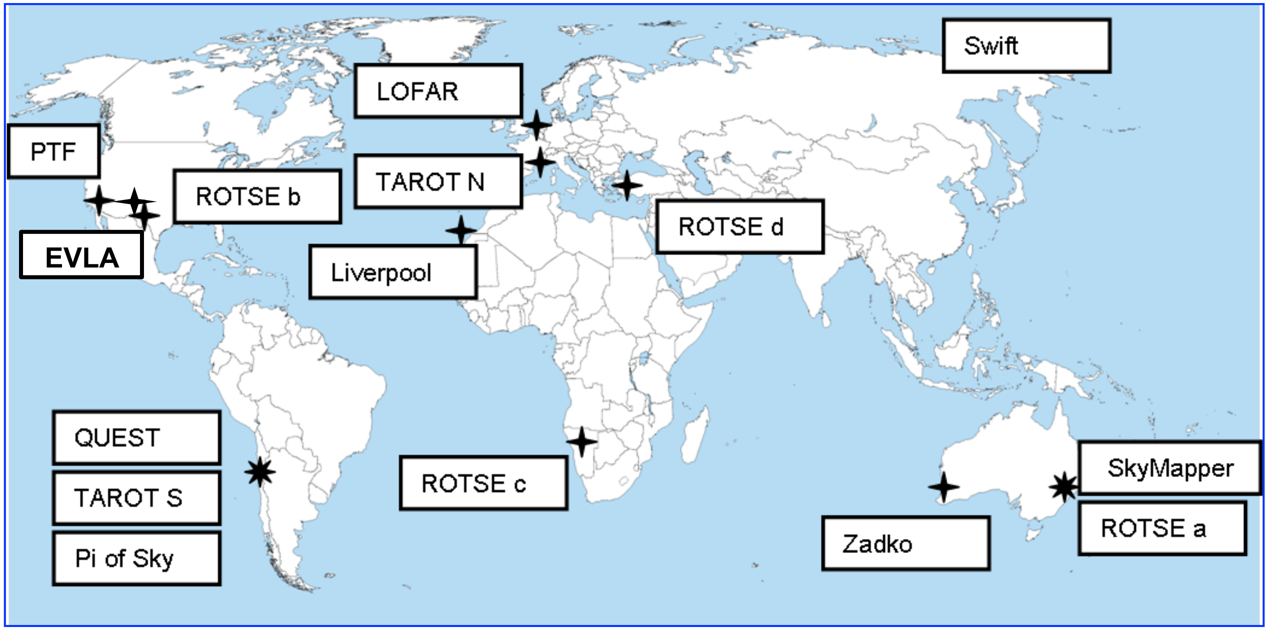


Abadie et al. 2012, A&A 539

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

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

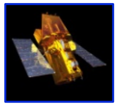
7.8 deg^2 , **20.5** mag

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

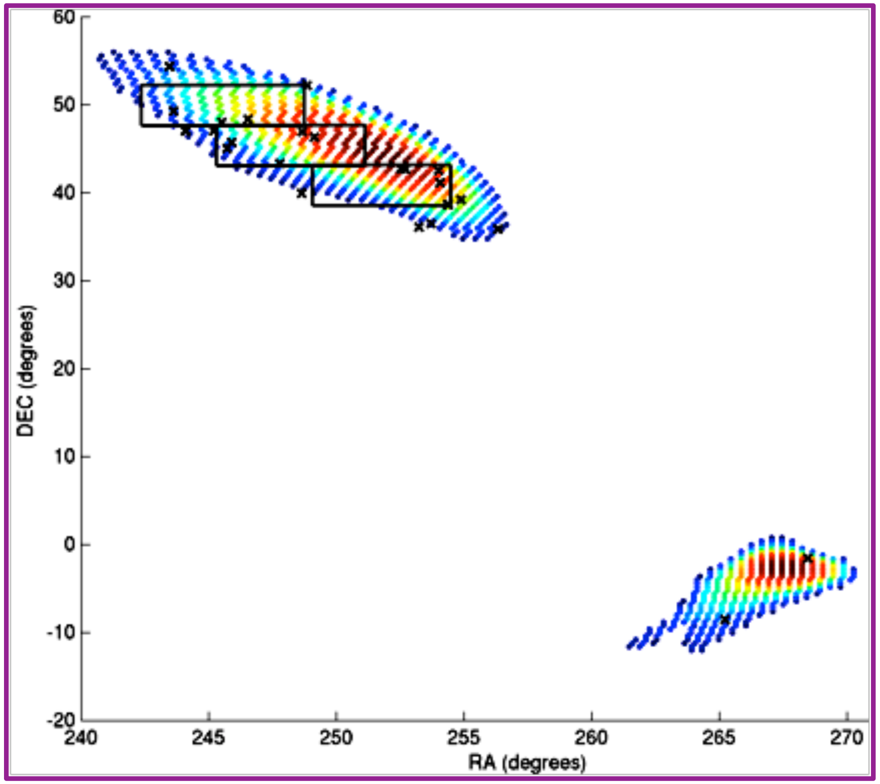
EVLA

5 GHz - **7** arcmin^2

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

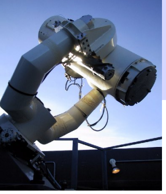
To determine each telescope pointing position:

The probability skymap of each GW trigger was 'weighted'



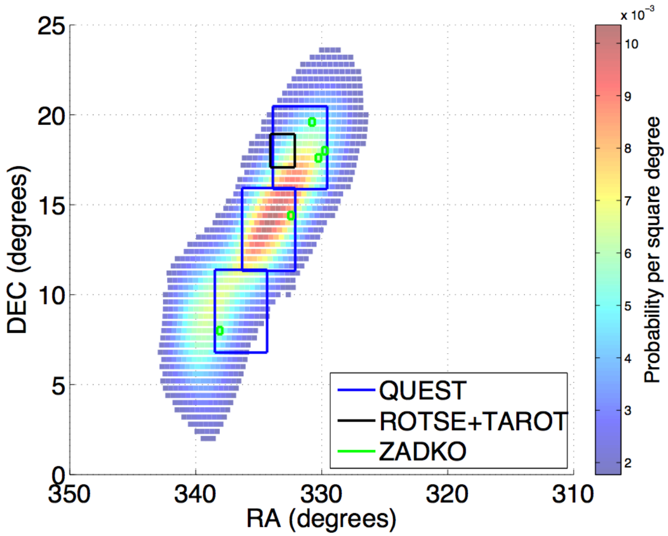
→ taking into account **luminosity** and **distance of galaxies within the LIGO/Virgo horizon** for binary containing a NS 50 Mpc

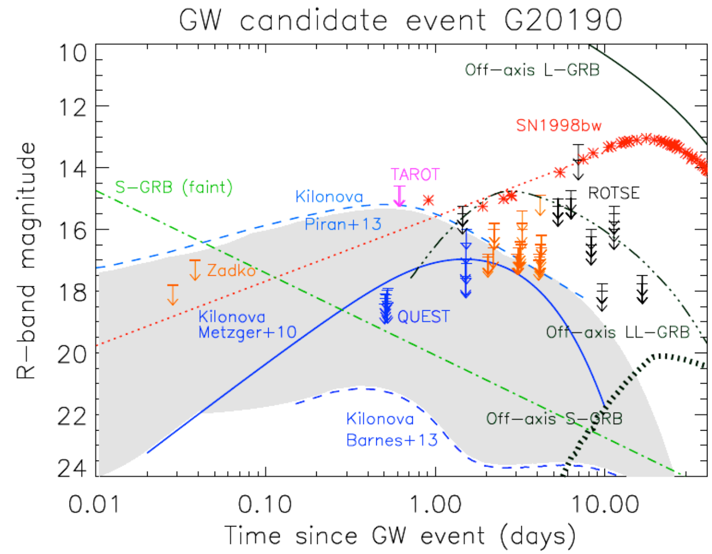
Galaxy targeting strategy



Optical telescope 8 GW alerts

Aasi et al. 2014, ApJS, 211



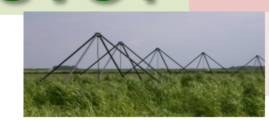


Swift Satellite: XRT-UVOT

2 GW alerts

Evans et al. 2012, ApjS, 203

Radio Interferometers



LOFAR

5 GW alerts

E-VLA

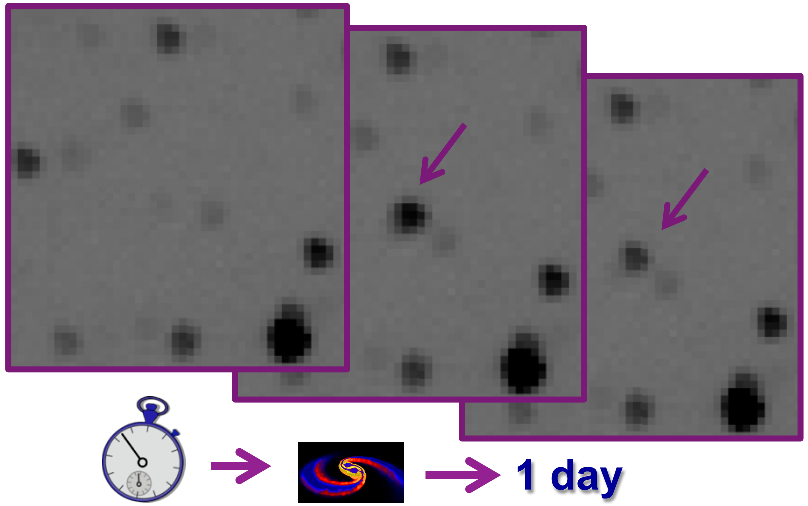
2 GW alerts

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**

EM counterpart search – Time domain astronomy



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

This requires **a detailed knowledge of the transient sky** for a **rapid transient discovery** and **classification** based on light curve/color/shape/..

Optical transient sky

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

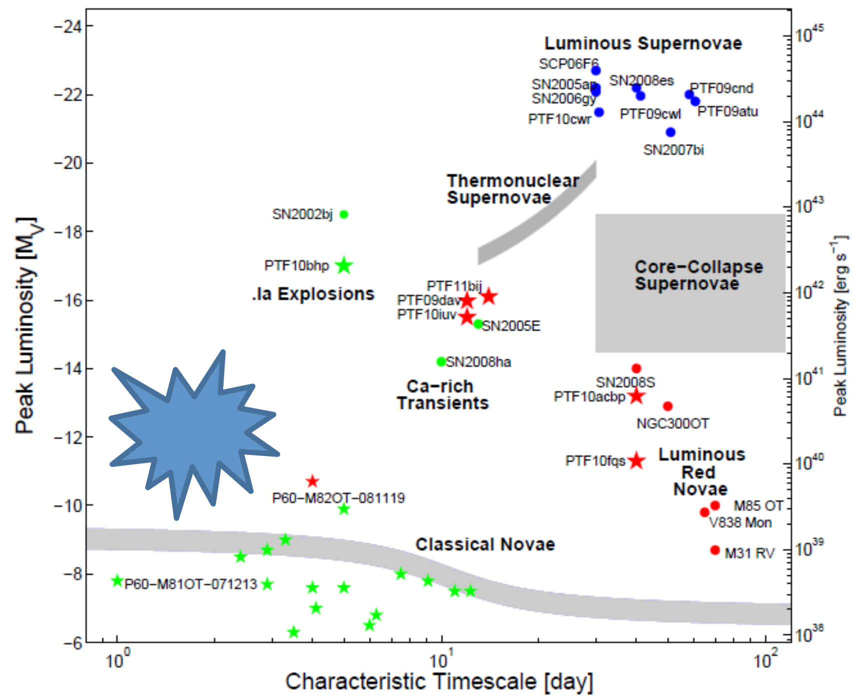
Optical contaminating transients:

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

background - AGN, Supernovae

Per image of 10 sq. degrees:
timescale **minutes – hours, ~ 30 M-dwarf flares** at 20 degree latitude **(Ridgway et al., 2014)**
timescale **days – months, ~ 70 Type I and CC SN** (up to mag_R 24) **(Cappellaro, 2014)**

Kasliwal 2011, BASI, 39



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

X-ray contaminating transients:

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

2.5×10^{-2} transients per 10 sq. degrees
above fux threshold of 3×10^{-12} erg s^{-1} cm^{-2}
(Kanner et al. 2013)

Radio contaminating transients:

Supernovae, AGN variability

Timescales 1 day - 3 months, **< 3.7 per 10 sq. degrees**
above 0.21 mJy at 1.4 GHz
(Mooley et al. 2013)

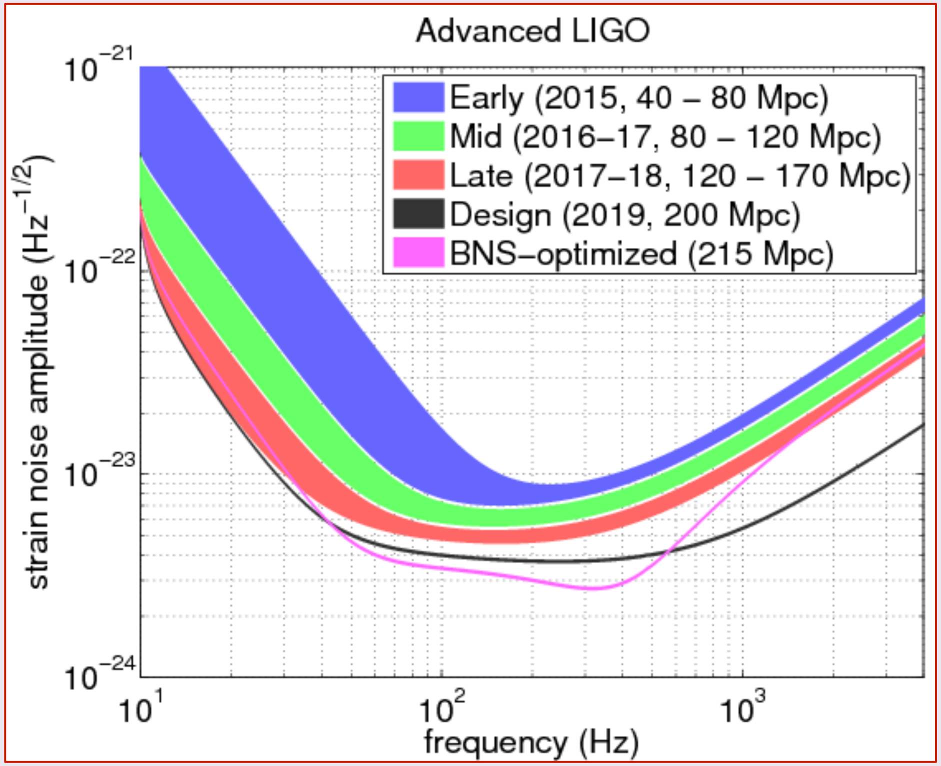
Advanced detector era observing scenario

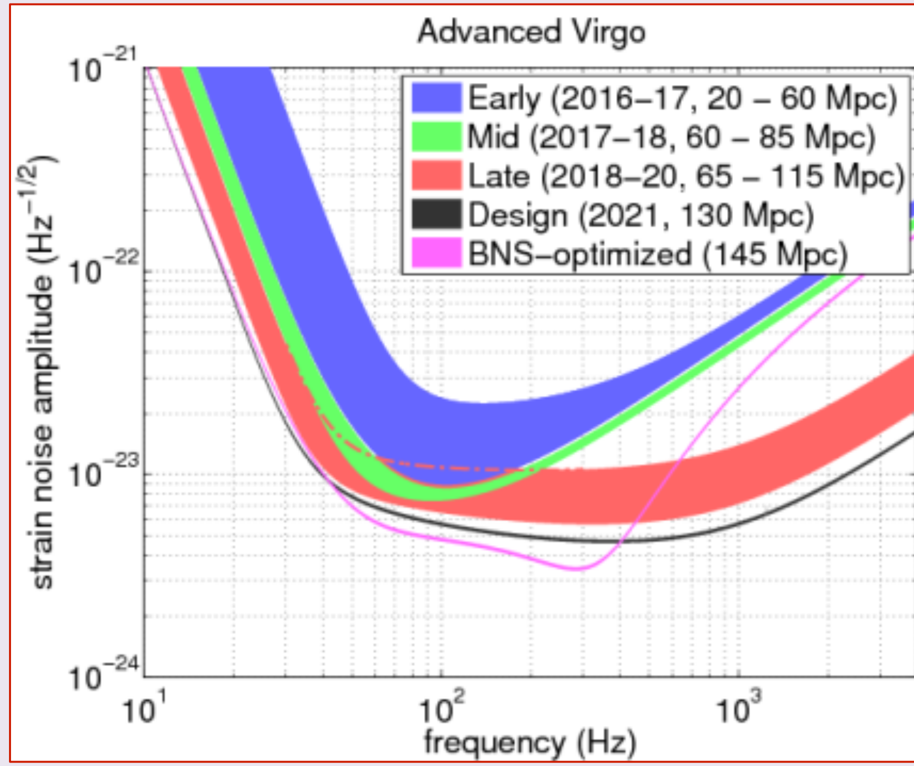
LSC & Virgo Collaborations, arXiv:1304.0670

Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

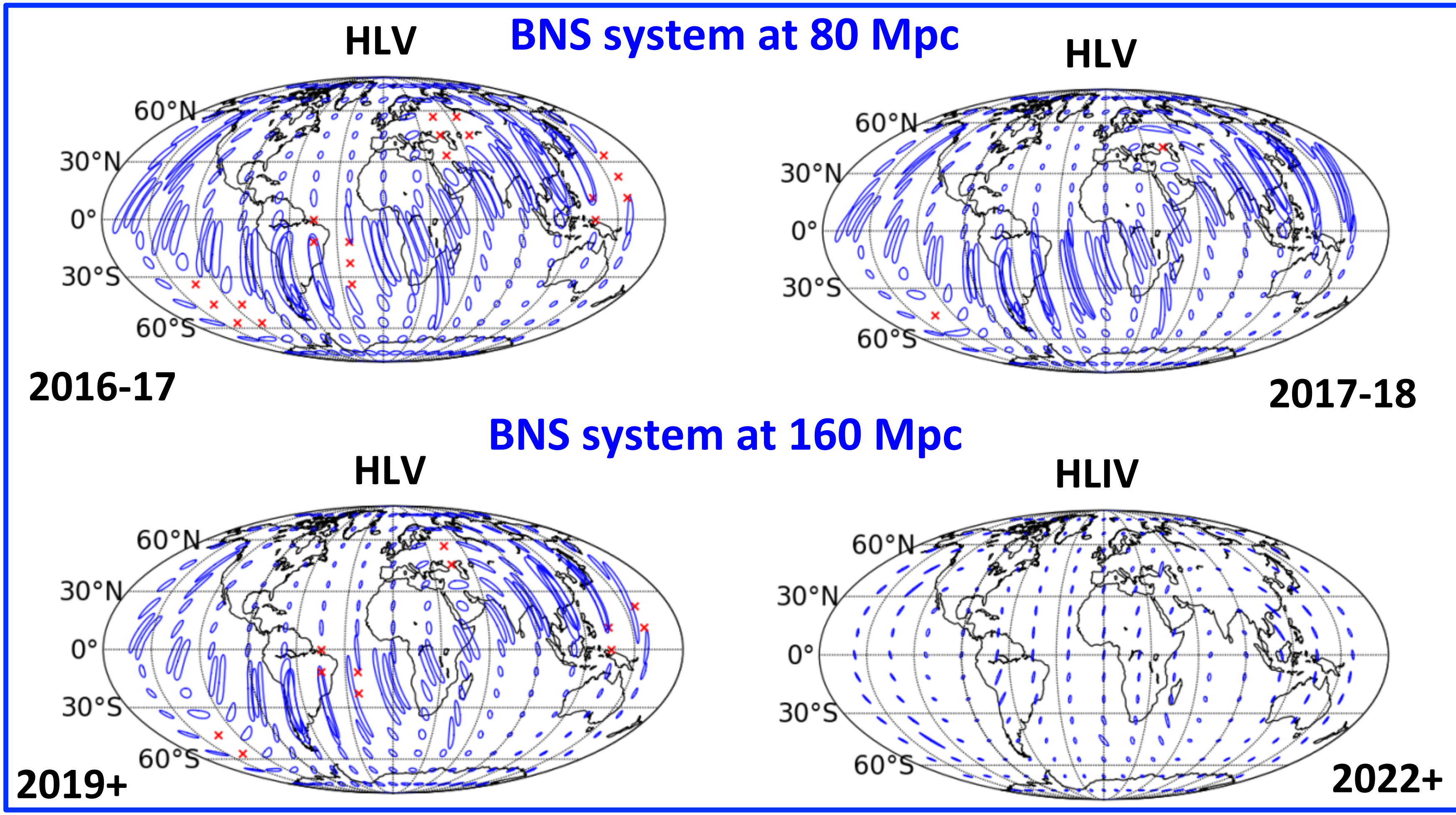
Progression of sensitivity and range for Binary Neutron Stars





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

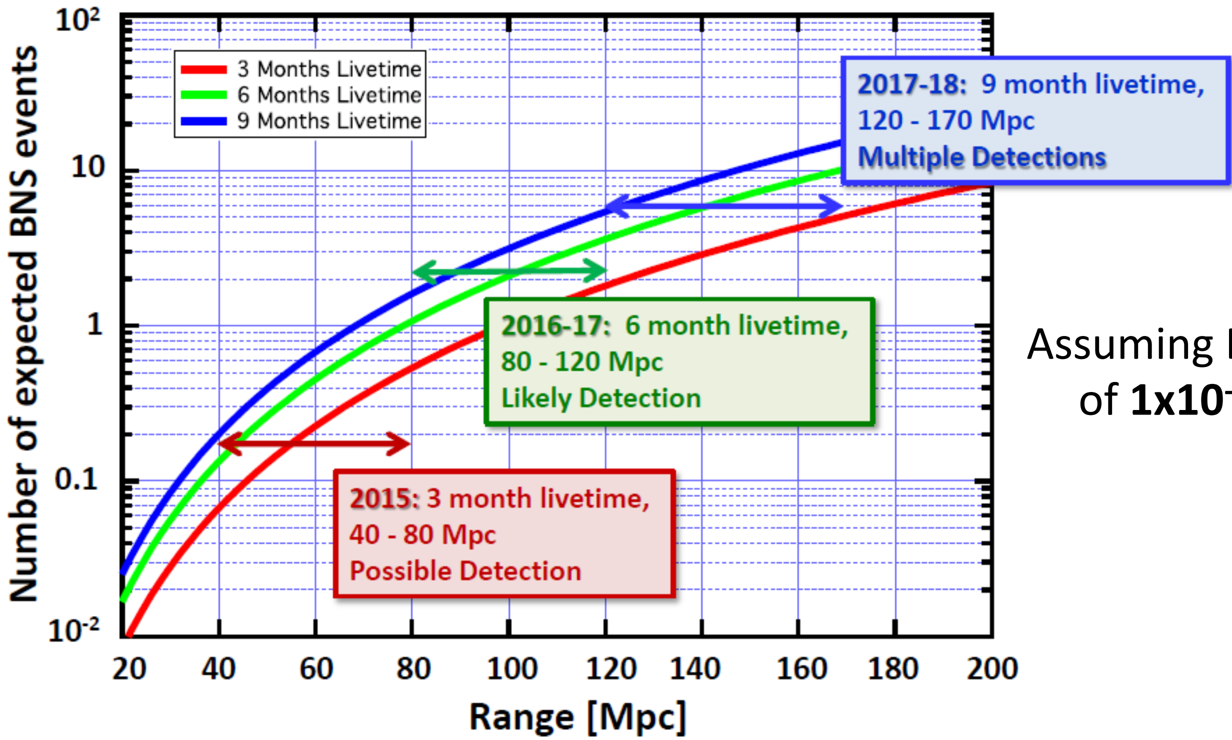
X → signal not confidently detected

Summary of plausible observing scenario

LSC & Virgo collaboration
arXiv:1304.0670

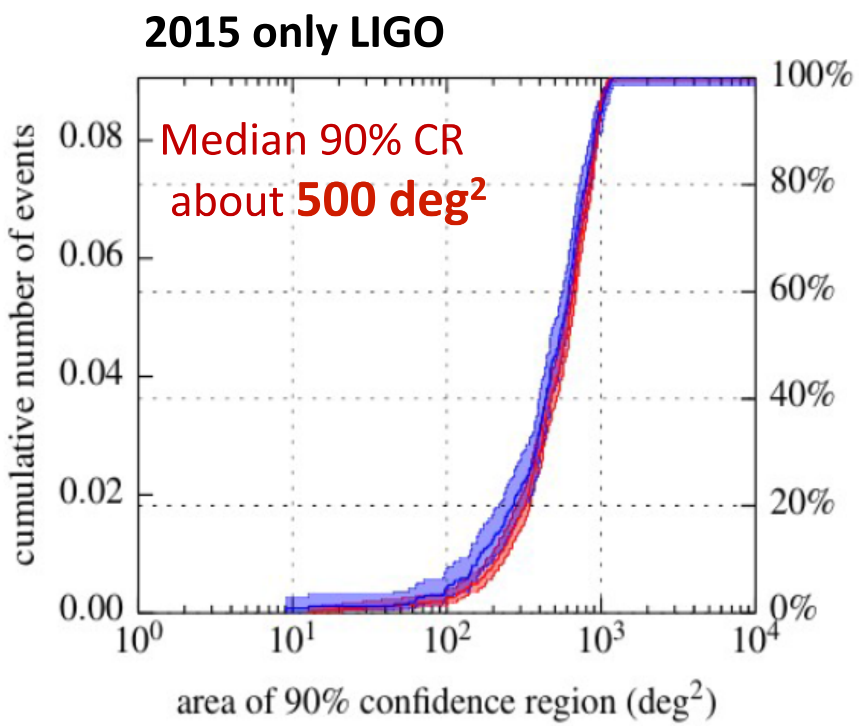
aLIGO/Virgo Range	Rate	Localization

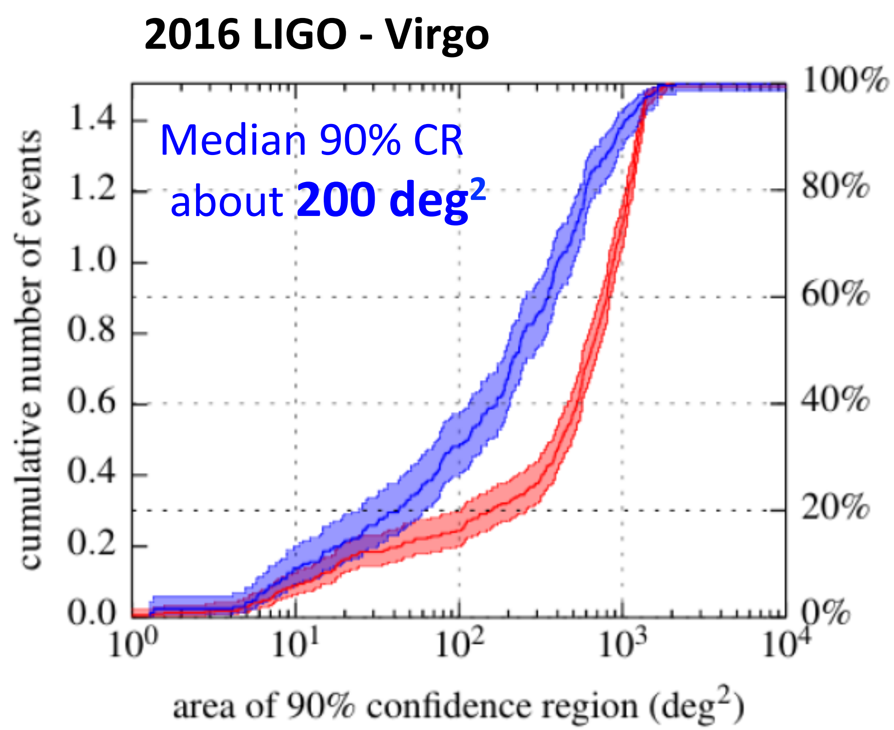
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
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}

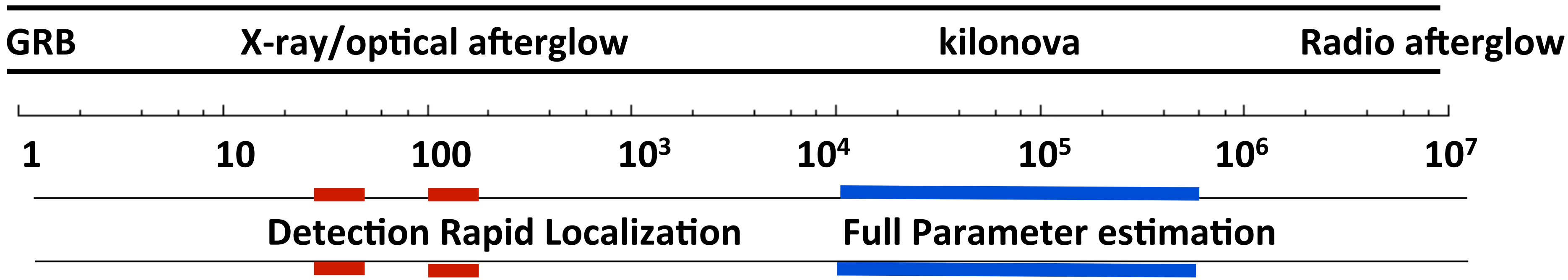
End to end simulation of **GW binary NS search and sky localization in the 2015 and 2016** science runs by **Singer et al. arXiv:1404.5623**





- **Fast sky localization code (~minute scale)**
- **Parameter estimation code (~hours scale)**

See for Burst Search
Essick et al. arXiv:1409.2435



EM-follow up challenges:

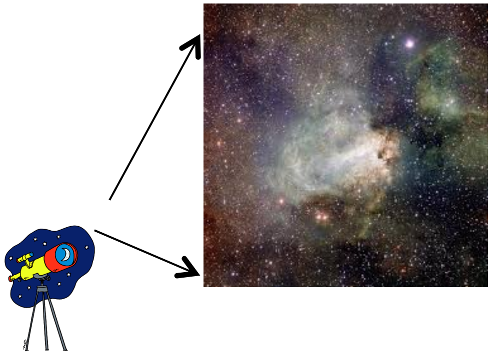
- Fast faint transient counterparts
- Large GW error box → difficult to be entirely observed
  → many transient contaminants
- Larger Universe observed by LIGO/Virgo

EM-follow up key points:

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

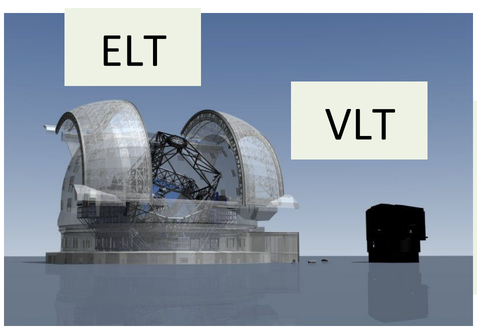
TIGHT LINK is required between GW/EM/Theoretical COMMUNITIES!!

Hierachical EM-follow up Search



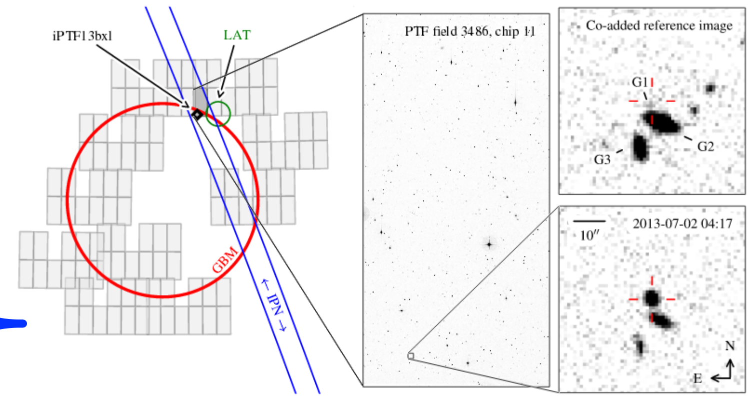
Wide-field telescope
FOV > 1 sq.degree

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



Larger telescope to **characterize** the nature candidates

The EM Counterpart!

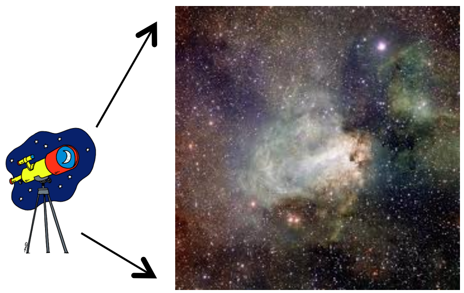


PTF discovery and redshift of **8 optical afterglows** by performing a blind search over areas between **30 to 147 sq. deg**

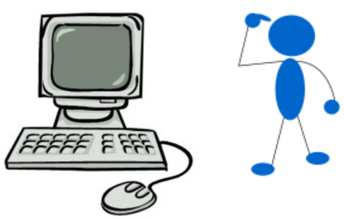
Singer et al. 2013, ApJ, 776L
Singer et al. 2015, arXiv:1501.00495

Hierachical EM-follow up Search

Aasi et al. 2014, ApJS, 211



Wide-field telescope
FOV >1 sq.degree



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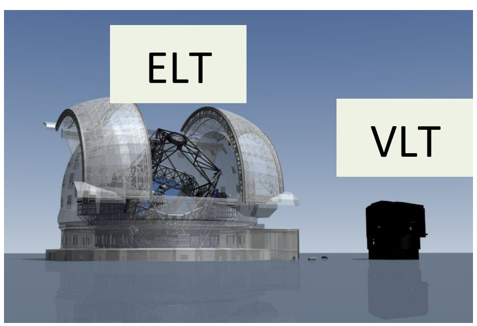

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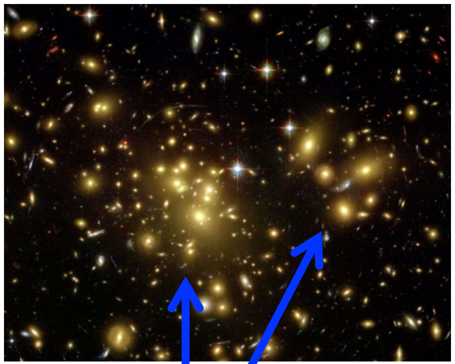


Galaxy targeting?

100 galaxies over 100 sq. degrees within **100 Mpc**

Short GRBs **projected distance from the galaxy center ≈0.5–75 kpc (Fong & Berger 2013)**

Assuming **100 kpc** projected distance the sky area occupied by the galaxies is a **factor 32 smaller** than the entire gravitational-wave sky area

In 2012, **LVC agreed policy on releasing GW alerts**

"Initially, ***triggers*** *(partially-validated event candidates) will be* ***shared promptly only with astronomy partners who have signed a Memorandum of Understanding*** *(MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

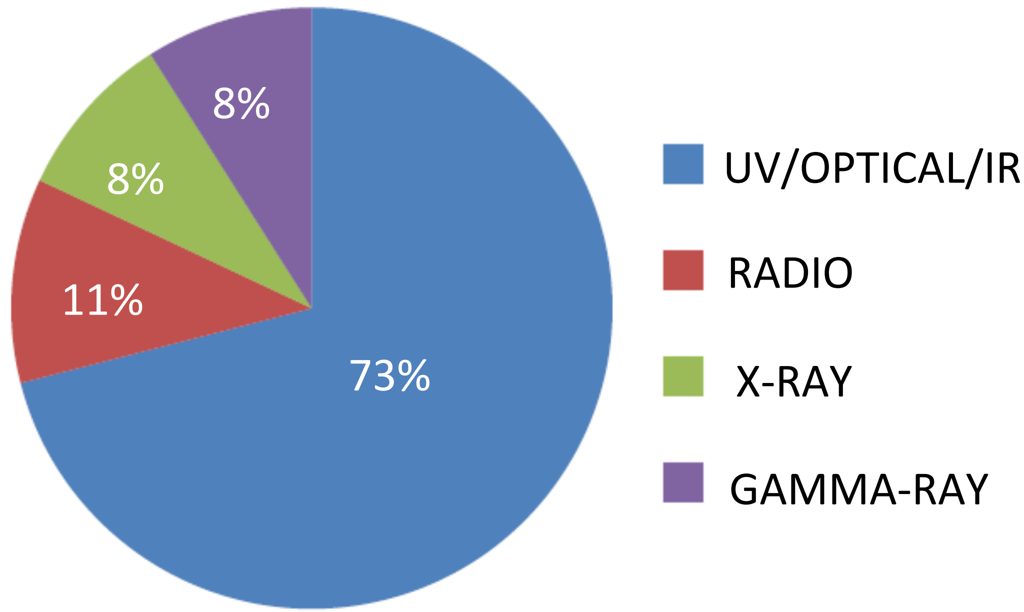
After four GW events have been published*, further event candidates with high confidence will be* ***shared immediately with the entire astronomy community****, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU."*

- The first open call for participation in GW-EM follow-up program (last year) → **60 MoUs signed**
- Second open call (closed in February) → **13 new MoUs**

LVC GW-EM follow-up program

Seventy MoUs involving

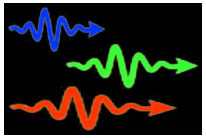
- **150 instruments**
  (satellites/world-wide ground-based)
  covering the full spectrum
  from radio to
  very high-energy gamma-rays!

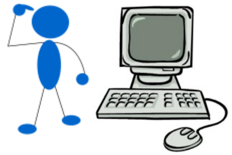


- **Astronomical institutions, agencies and large/small groups of astronomers** from 19 countries

The multi-messenger photon and GW astronomy

Photons + Theory

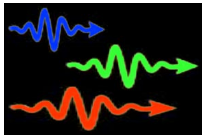


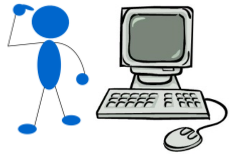


Optimal observational startegies and data analysis to detect the GW source and its EM signal

The multi-messenger photon and GW astronomy

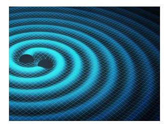
Photons + Theory

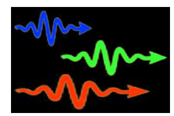




Optimal observational startegies and data analysis to detect the GW source and its EM signal

GWs + photons

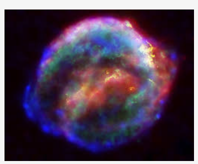




Necessary to probe...

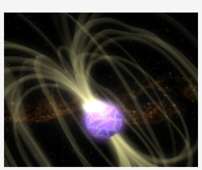
The most energetic emission mechanisms

GRB/kilonovae



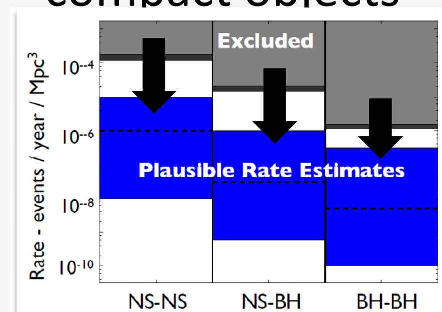
Pulsar

SN



SGR/Magnetars

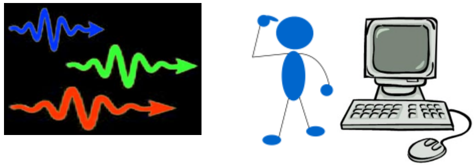
The rates, spatial distribution, and demography of compact objects



Abadie et al. 2012

The multi-messenger photon and GW astronomy

Photons + Theory



Optimal observational startegies and data analysis to detect the GW source and its EM signal

The most energetic emission mechanisms

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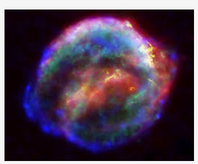

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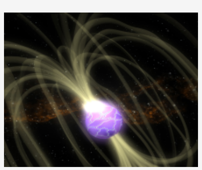
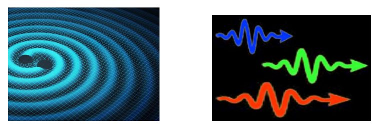


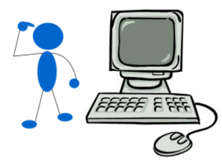
SGR/Magnetars

GWs + photons



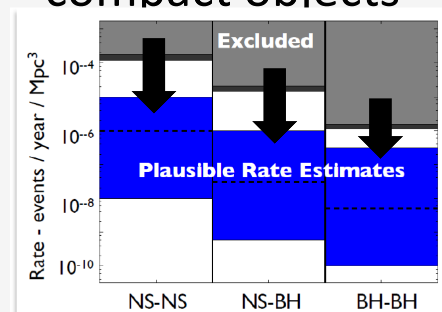
Necessary to probe...

+ theory



Necessary to unveil ...

The rates, spatial distribution, and demography of compact objects

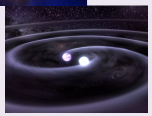


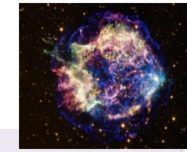
Abadie et al. 2012

The nature and structure of compact objects

To reveal the unknown... exotic sources, new physics

To constrain models of birth and evolution of COs





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?

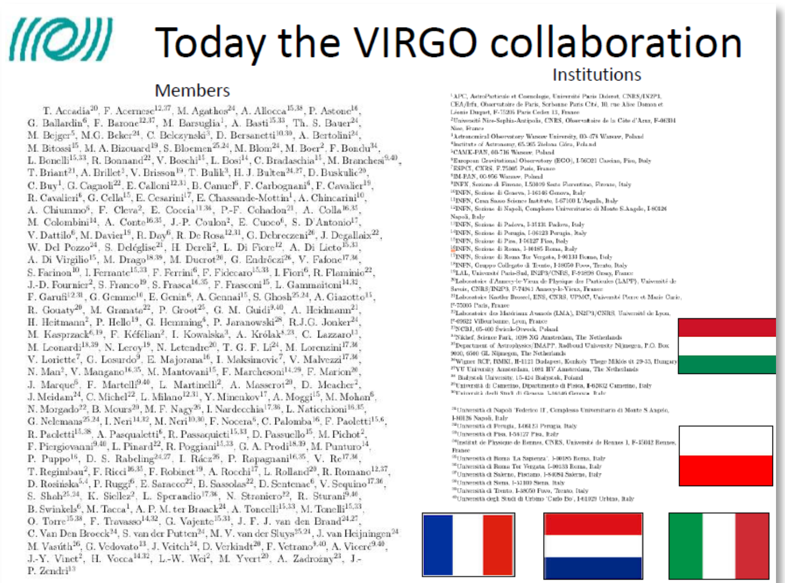
• How are BHs born and how do they evolve? What are their rates, mass and spatial distributions?

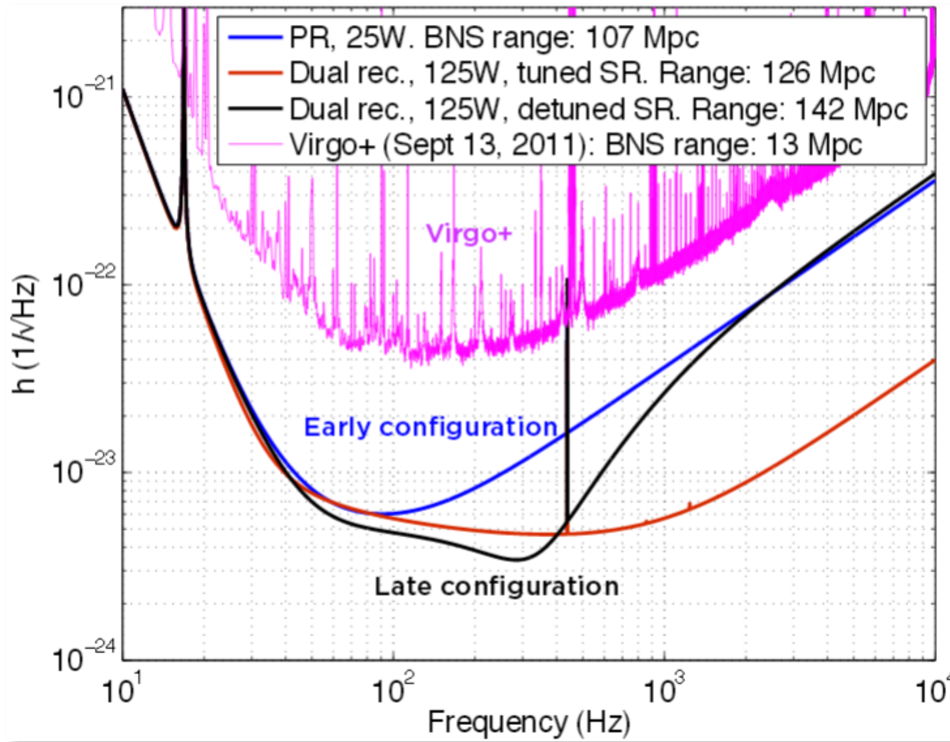
• What are the details of the mechanism through which SN explode?

• What is the EoS of matter in the interior of NS?

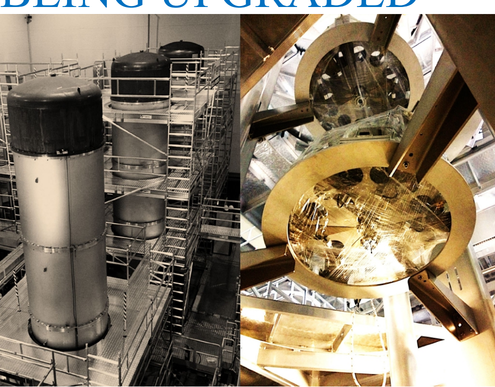
From VIRGO+ to ADVANCED VIRGO (AdV)

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



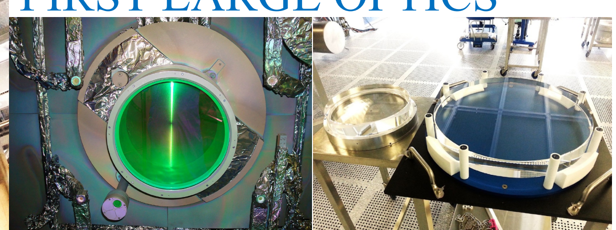


SUPERATTENUATORS BEING UPGRADED



Status of the AdV project → construction well on track

FIRST LARGE OPTICS

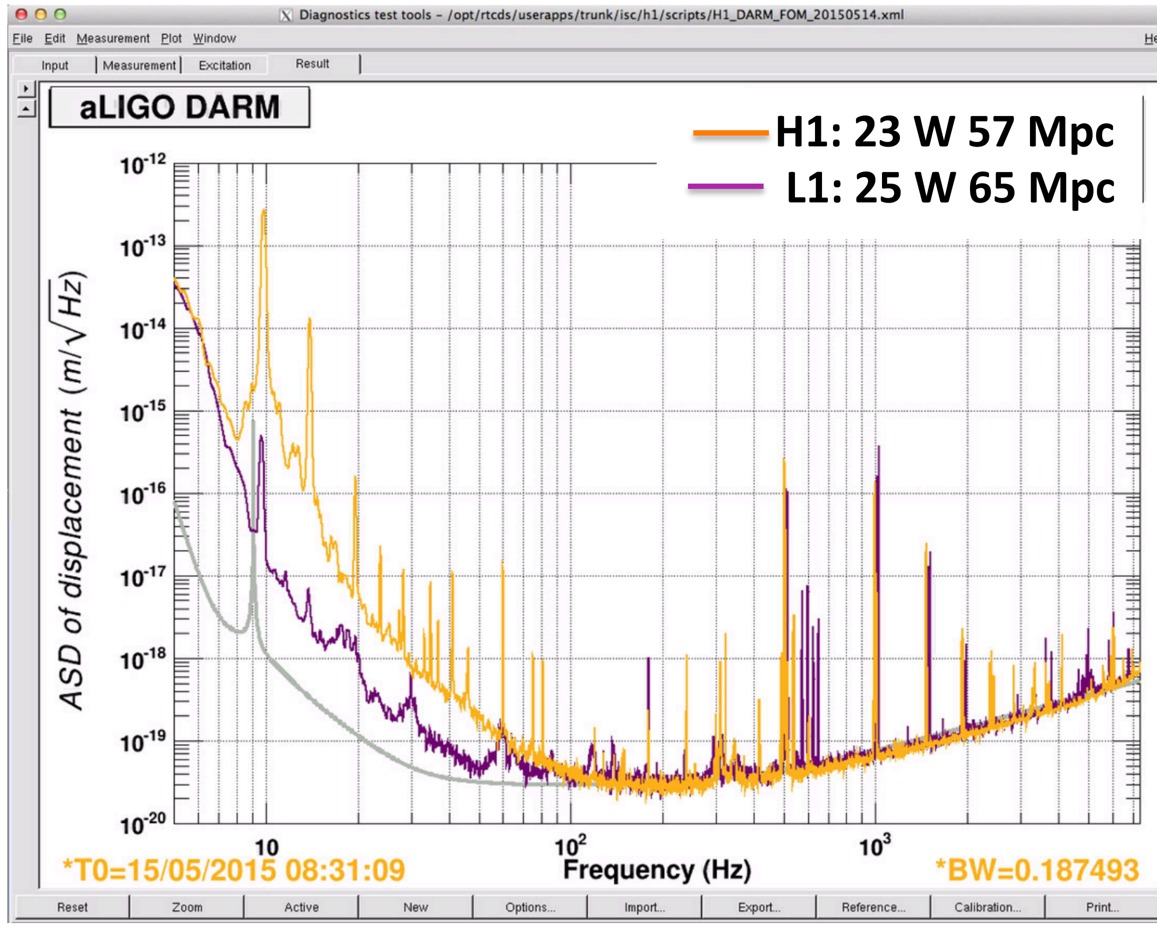


First science data in 2016

LIGO recent progress

Huge steps forward to the advanced LIGO

- First lock of LIGO Livingston in May, first lock of LIGO Hanford in March
- The sensitivity of both detectors surpassed the initial LIGOs
- First observing run expected to start on Septemeber 2015



https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=18442