Multi-messenger exploration of the transient sky with LIGO and the VLA

Alessandra Corsi, for the LSC

Fifteenth Synthesis Imaging Workshop

1-8 June 2016

Key topics

- Time-domain astronomy, Gravitational Waves (GWs), and the start of a new era in multi-messenger astrophysics.

- ElectroMagnetic (EM) follow-up of GWs: Sources and observational facilities (or at least some of them…).

- Practical considerations for VLA follow-up.

Transient Astronomy

- A **transient astronomical event** is an astronomical object or phenomenon whose **duration may be from seconds to days, weeks or even several years**.

- These timescales are **much shorter than the millions or billions of years** during which galaxies and their component stars in our universe have evolved.

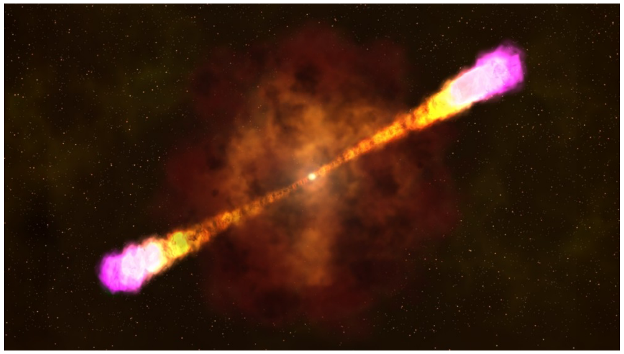
- When we talk about transient astronomy in connection with GWs and ground-based GW detectors, we are mostly interested in the EM counterparts of **EXPLOSIVE events marking the birth of NSs or BHs**.

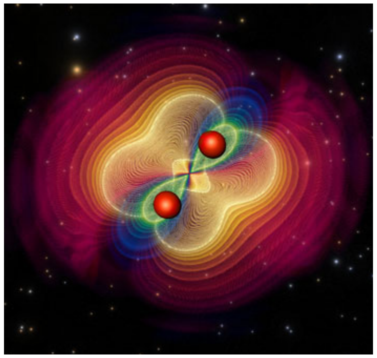
Why Transient Astronomy & GWs?

Highly energetic astrophysical transients are promising **GW transients**.

- GW emission only **weakly beamed: we don't need to worry too much about source inclination.**

NASA GSFC





W. Benger, LSU

- GW detectors **weakly directional:** can basically monitor the whole sky! (BUT, poor localization compared to EM telescopes…)

- GWs come **directly from the central engine**: Not obscured or scattered by material, complement photon diagnostics of surface, outflows, CSM, and astronomical context.

Why multi-messenger astrophysics?

Complete astrophysical picture

GWs

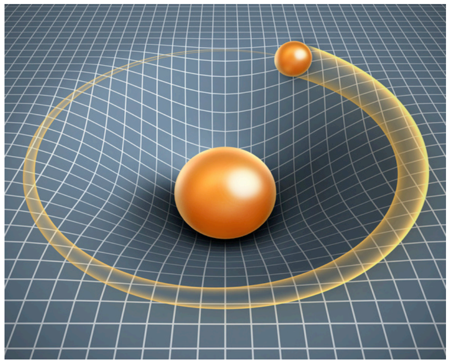
- Masses.
- Spins.
- Rates and implications on progenitor formation scenarios.
- Geometric properties of the progenitor:
  - "Position"
  - Distance
  - Inclination angle
  - …

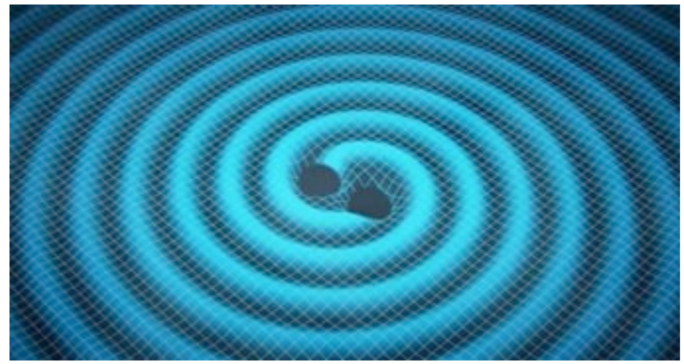
EM

- Enhance confidence of low-SNR GW detections.
- Nucleosynthesis.
- Ejecta properties:
  - Energetics
  - Velocity
  - Geometry
- Redshift.
- Environment properties (especially density).
- …

Gravitational waves

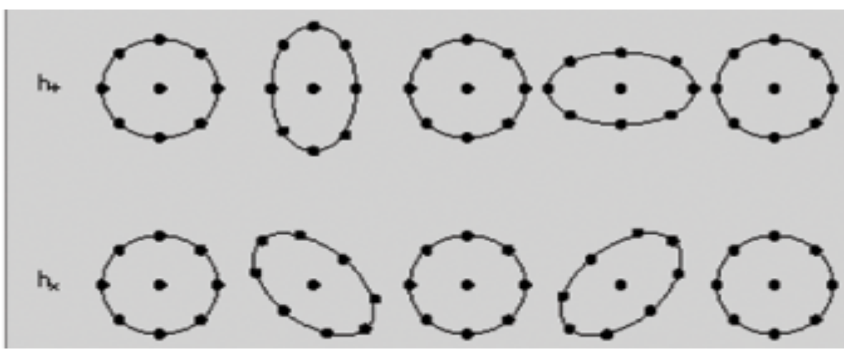
- In Einstein's view of gravity, "spacetime tells matter how to move; matter tells spacetime how to curve" (J.A. Wheeler).

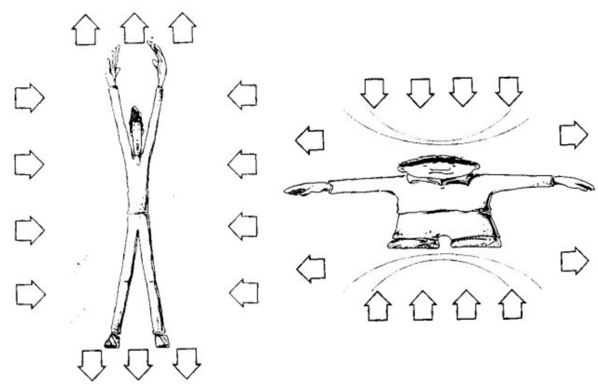




Swinburne Astronomy Productions

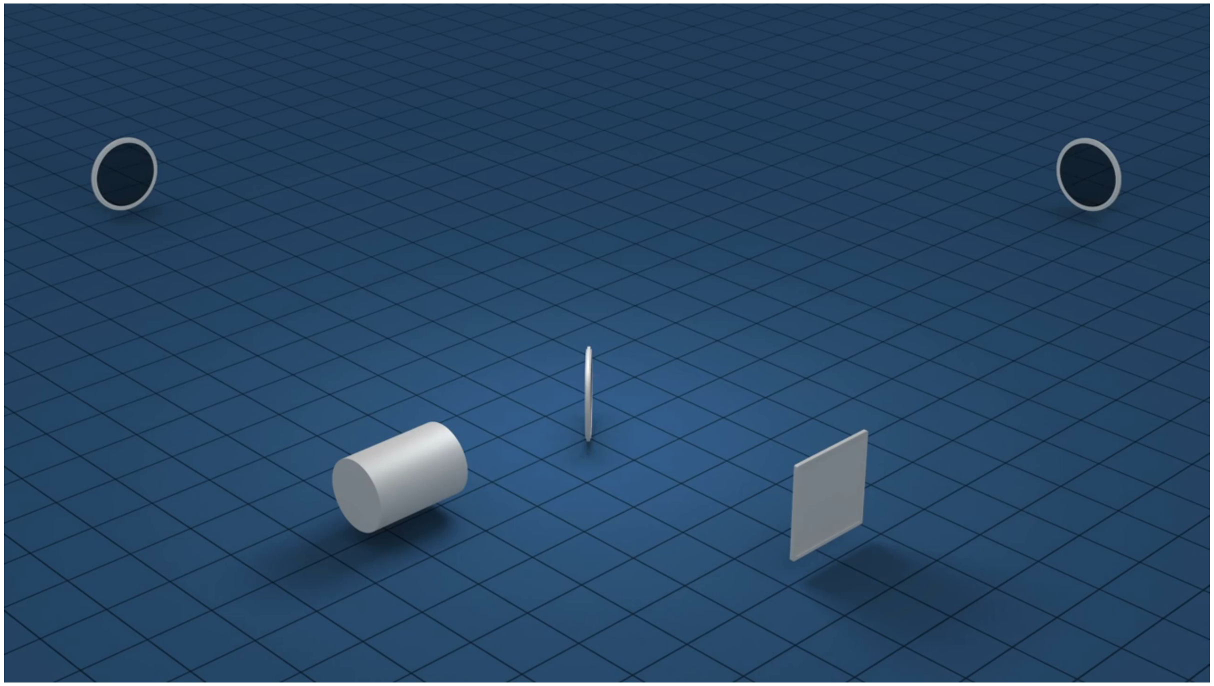
- GWs are 'ripples' in the fabric of space-time that change the distance between free falling masses. They come in two polarizations + and x.





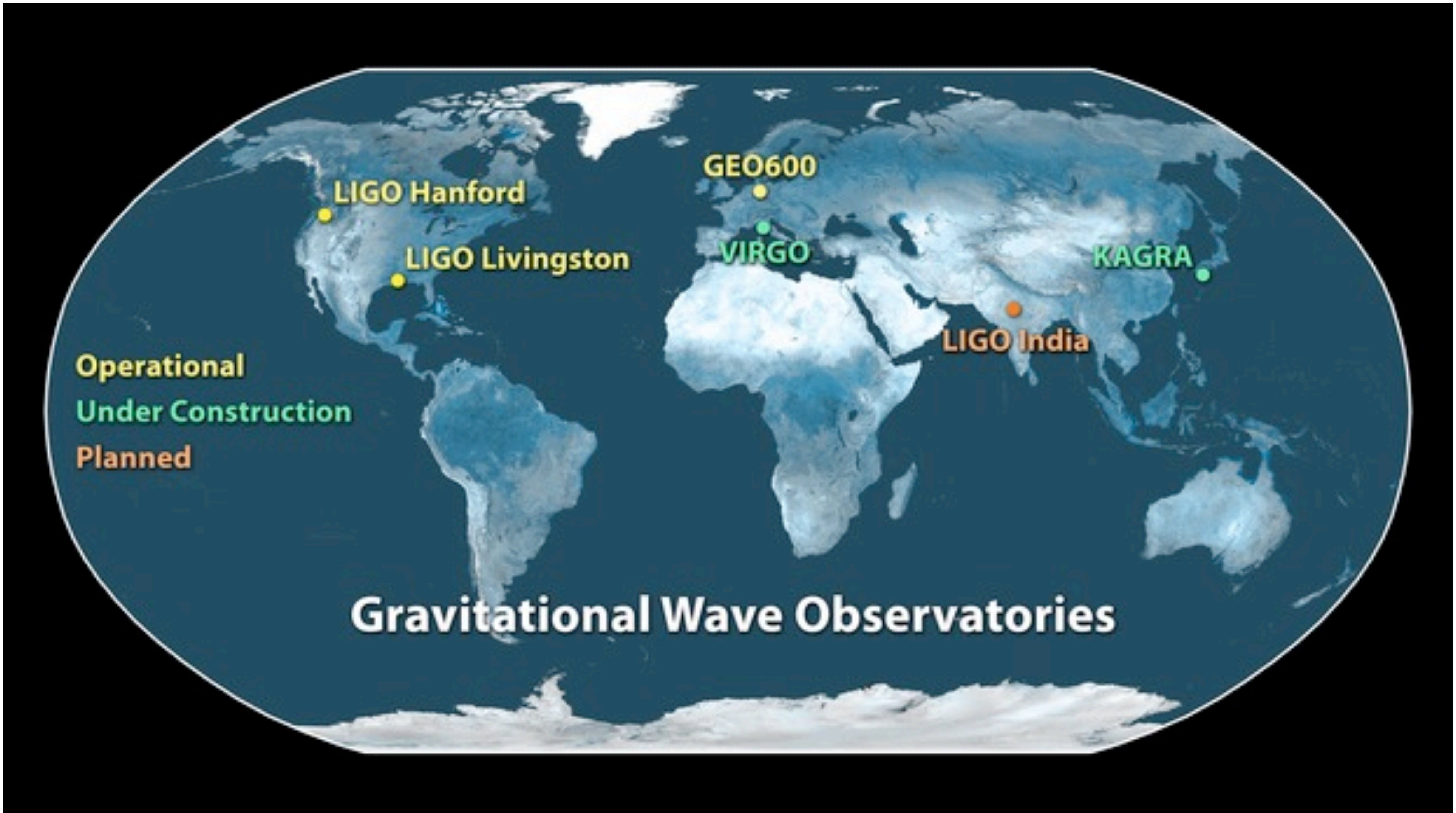
Detecting gravitational waves

- Fire a light beam through an L-shaper detector…
- GWs cause an arm length difference by stretching one arm and compressing the other, thus changing the amount of light collected on the output photodetector.



$\Delta L/L \sim h \sim 10^{-21}$ → for L=4km →$\Delta L \sim 10^{-18}$ m!

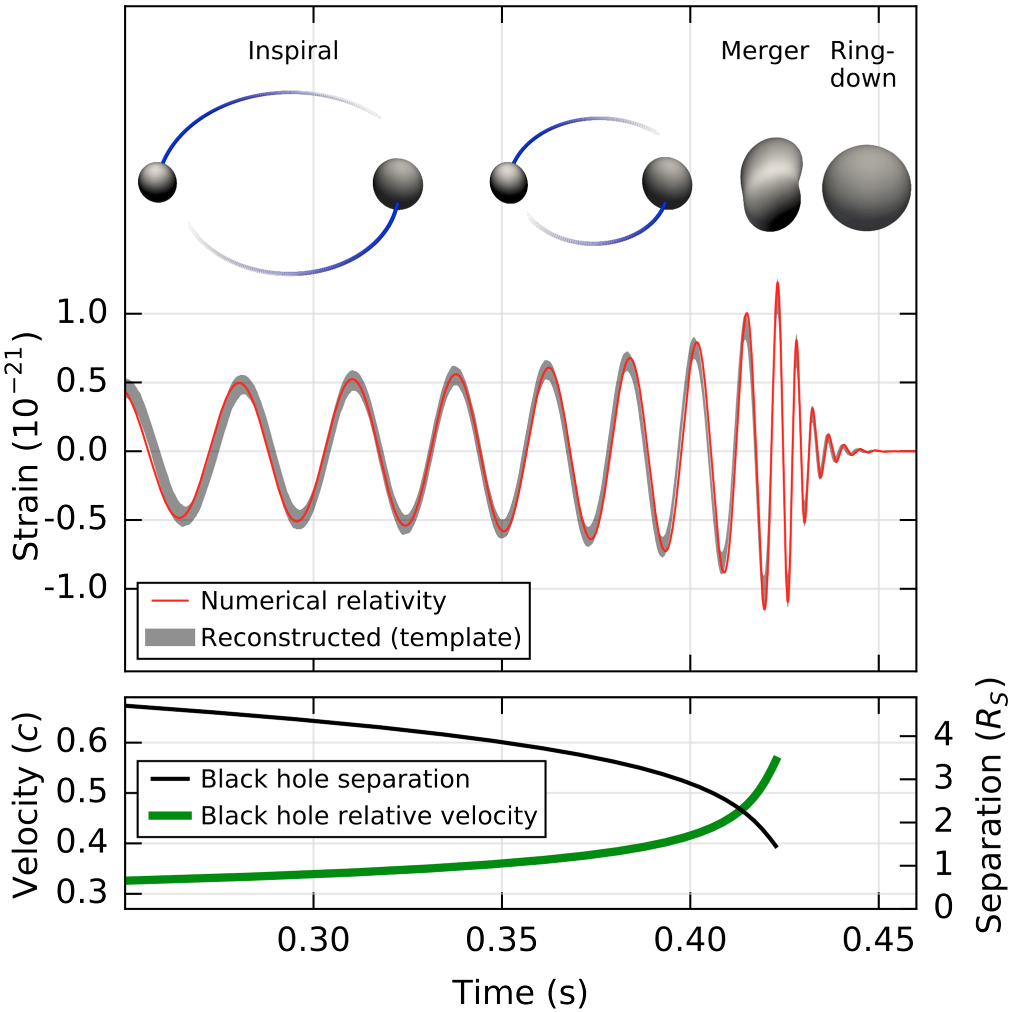
Ground-based GW detectors network



Credit: Caltech/MIT/LIGO Lab

The discovery: GWs from a BBH

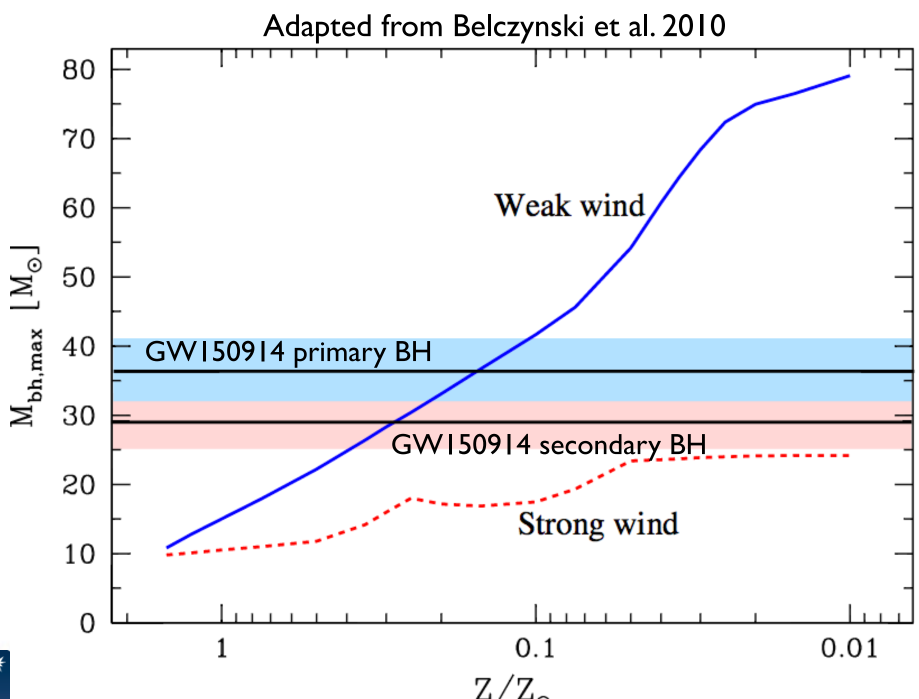
Abbott et al. 2016, PRL, 116, 6, 061102

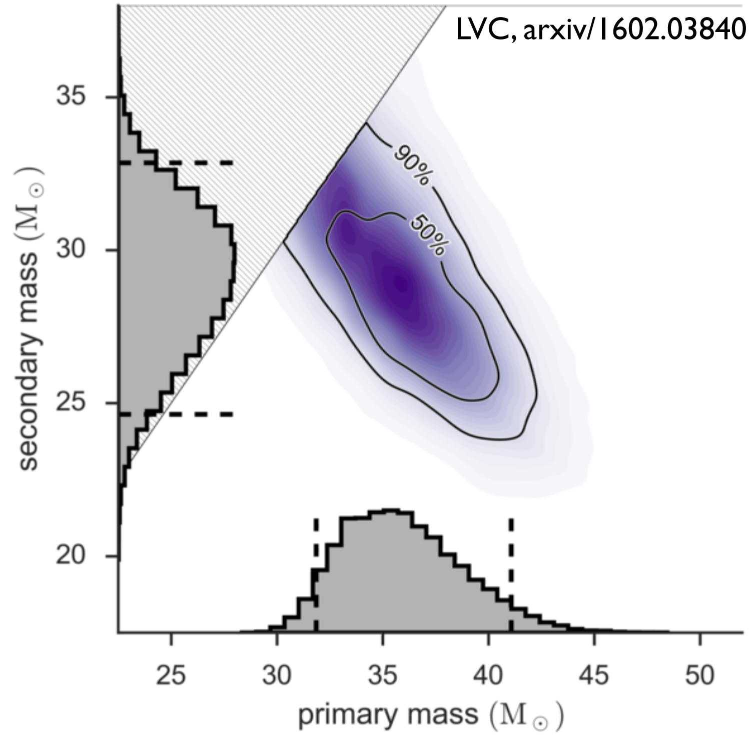


Credit: LIGO Lab.

New Astrophysical Implications

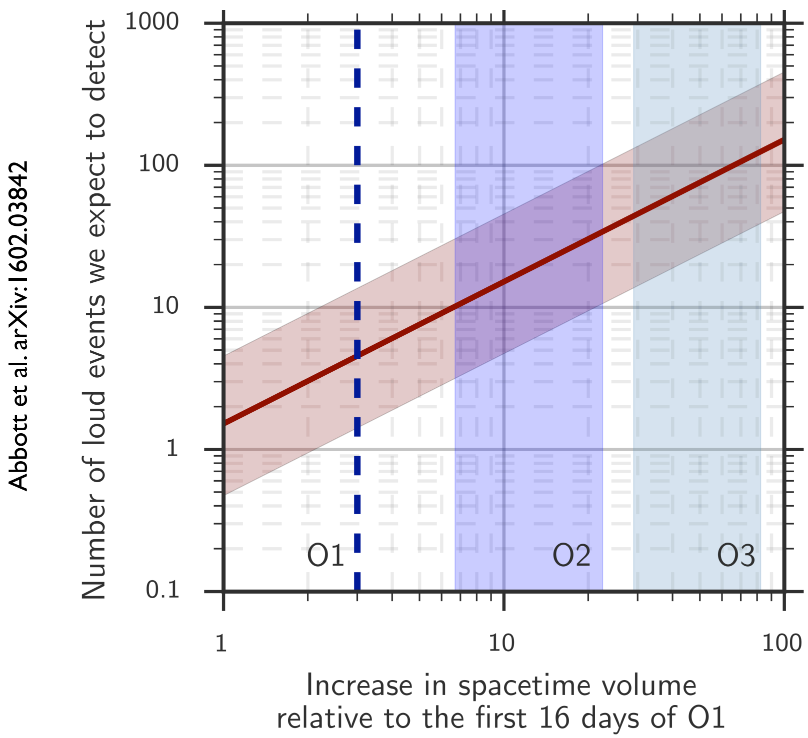
- Unexpectedly massive (29-36 $M_{\odot}$) stellar-mass BH exist and merge.
- Low-metallicity environment or formation in dense cluster required (Abbott et al. 2016).

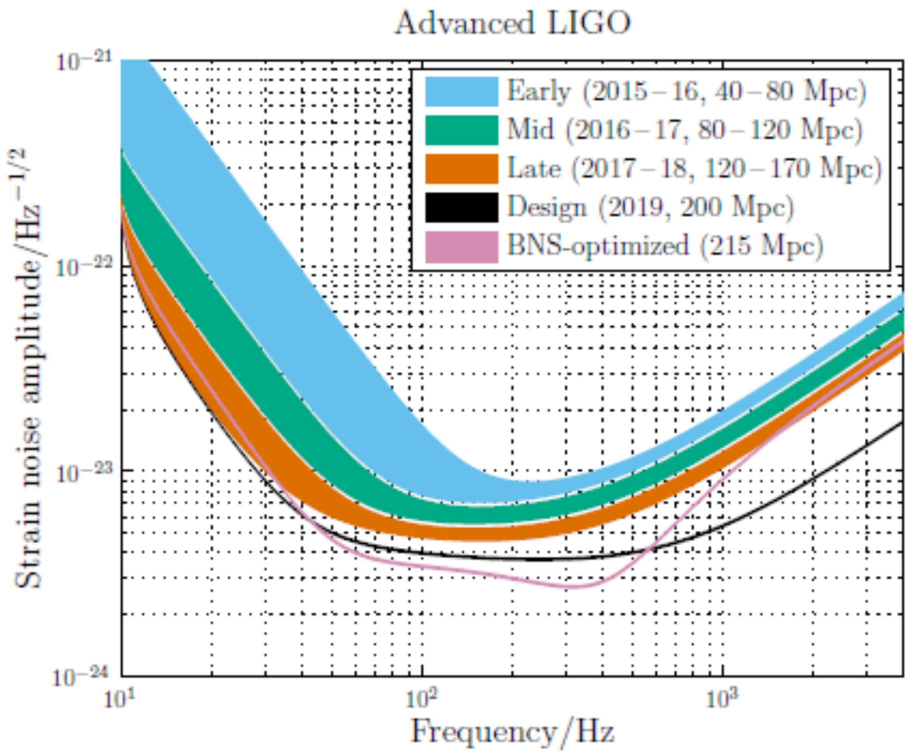




BBH: Rates and Future prospects

- Local rate of BBH mergers: 2-400 yr^{-1} Gpc^{-3} (LVC, arXiv:1602.03842). Previously: 0.1–300 Gpc^{-3} yr^{-1} (Abadie et al. 2010).



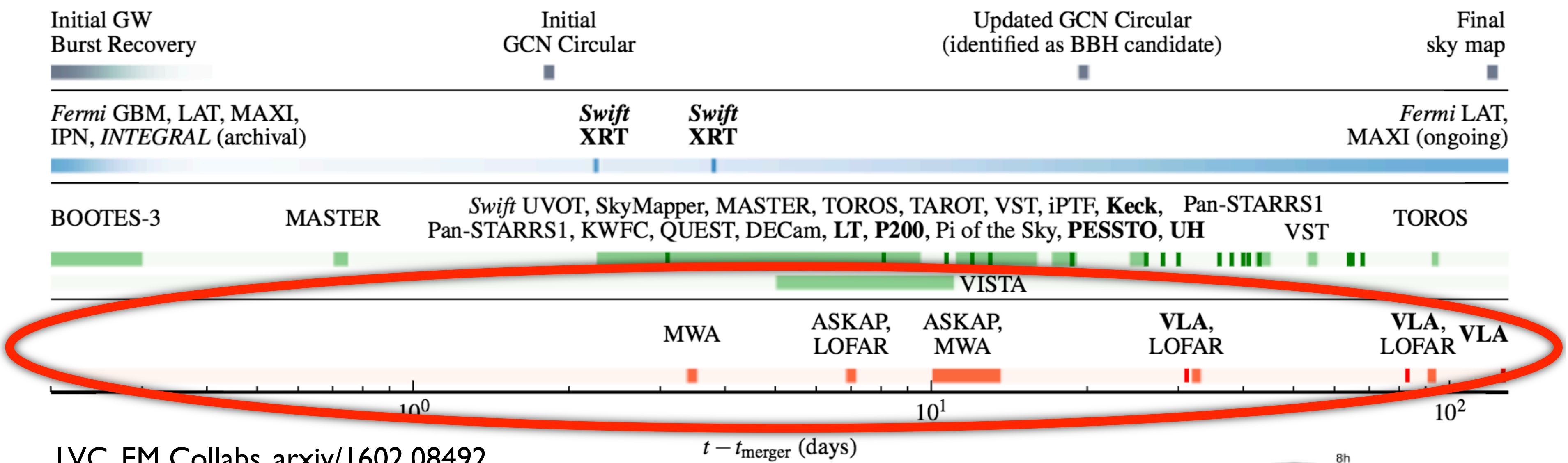


Abbott et al., Living Reviews in Relativity 19, 1 (2016)

With more detections:

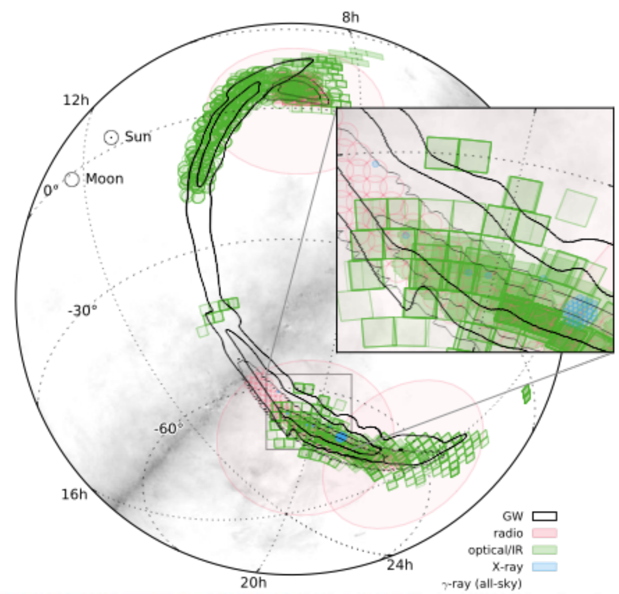
- Pin down the rate at which BBH merge in the Universe;
- Learn new/finer details on BBHs in the universe (e.g., mass distribution).

Panchromatic EM follow-up



LVC, EM Collabs, arxiv/1602.08492

- Consortium between LIGO-Virgo and 63 teams using ground and space facilities.
- Gamma-ray, X-ray, optical, infrared, and radio wavelengths.
- Localization area ~600 deg^2 (90% conf.)



BHs are nice but NS matter…

- Binary neutron stars (NSs)
- BH-NS star binaries
- Individual NSs and magnetars
- Supernovae (and engine-driven SNe)


Credit: Bill Saxton, NRAO/AUI/NSF


Credit: NASA

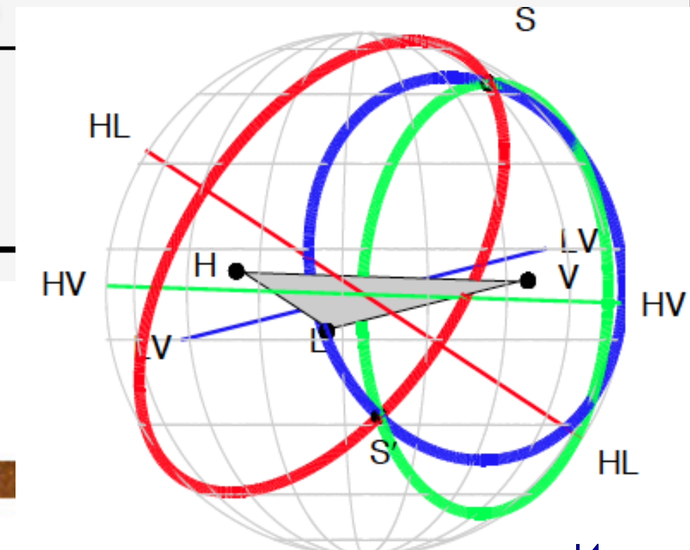

Credit: NASA/CXC/ASU/Hester et al.


Credit: NASA

Rates and localization areas

Abbott et al., Living Reviews in Relativity 19, 1 (2016)

Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	*> 1–2*	*> 3–8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8–30*	*> 50*
		median/deg^2	480	230			
searched area	% within	5 deg^2	6	20			
		20 deg^2	16	44			
		median/deg^2	88	29			

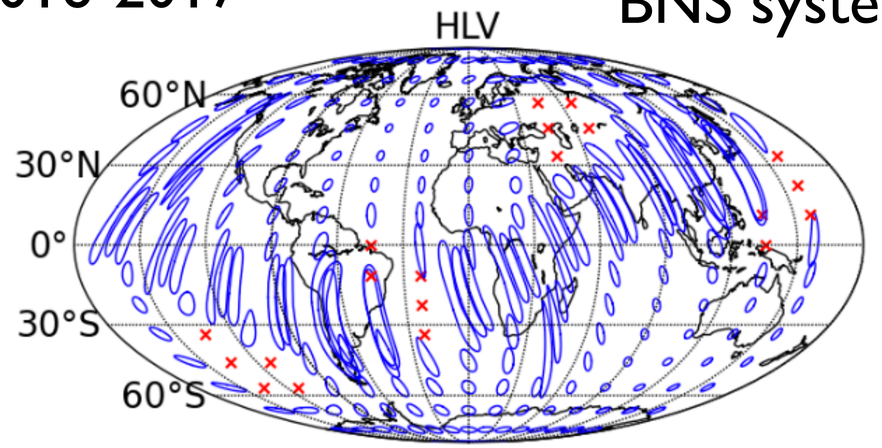


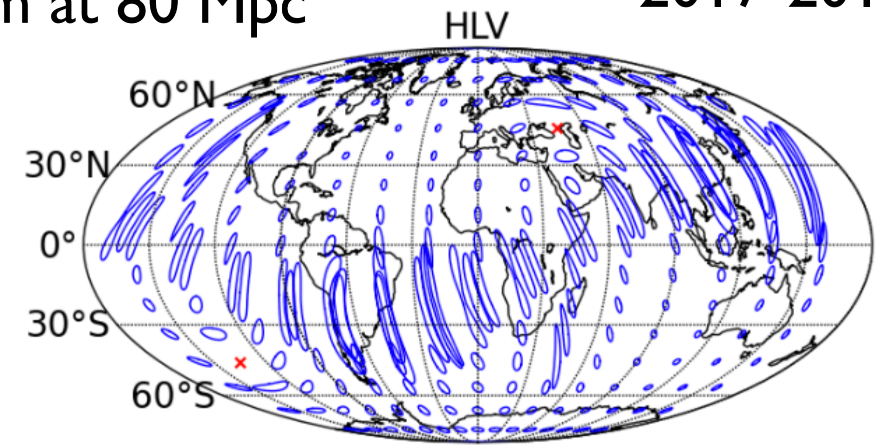
Localization areas

2016-2017

BNS system at 80 Mpc

2017-2018

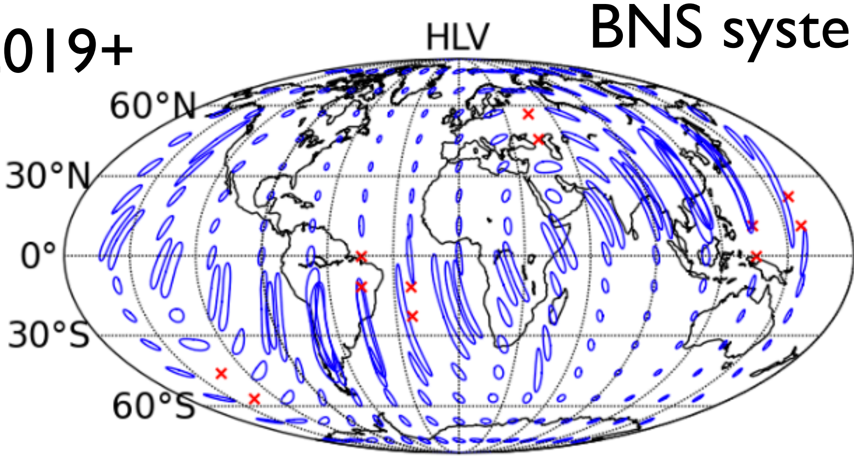


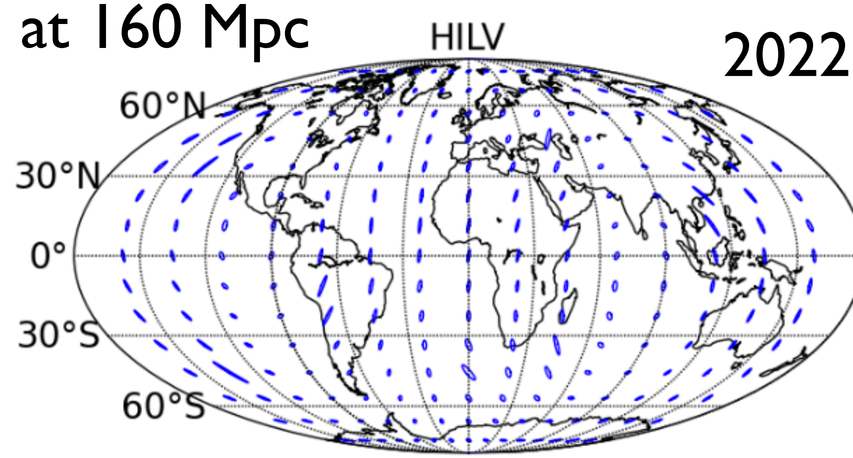


2019+

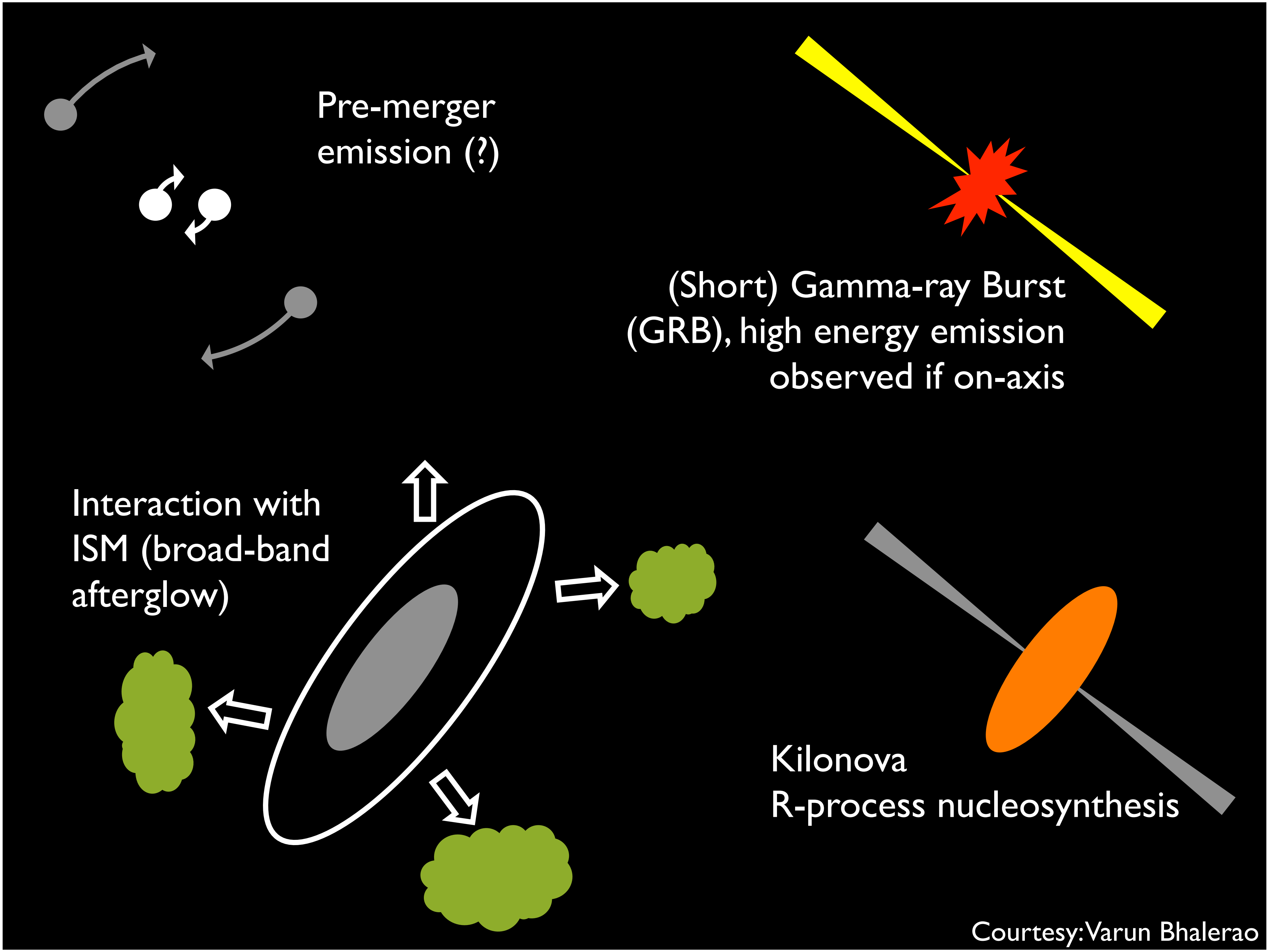
BNS system at 160 Mpc

2022+





Abbott et al., Living Reviews in Relativity 19, 1 (2016)



Pre-merger
emission (?)
(Short) Gamma-ray Burst
(GRB), high energy emission
observed if on-axis
Interaction with
ISM (broad-band
afterglow)
Kilonova
R-process nucleosynthesis
Courtesy: Varun Bhalerao

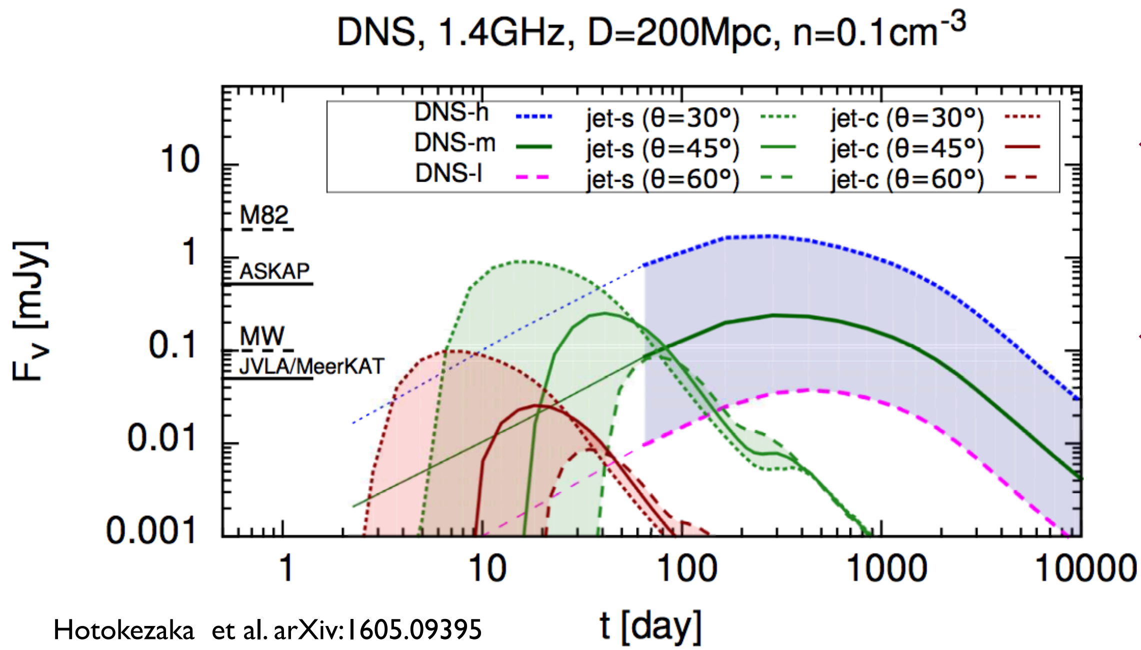
DNS/BH-NS in radio: timescales and counterparts

- **<100 s since merger: ??** →Models include: prompt radio pulse from magnetically-driven relativistic plasma, FRB, …(e.g., Chu et al 2015 and refs. therein).

- **Days-weeks: Ultra-relativistic radio afterglow**
  - ***If on-axis***, prompt high-energy counterpart and bright optical counterpart (on-axis afterglow, hrs-day).
  - ***If moderately off-axis*** (~2x jet opening angle), faint optical counterpart (off-axis afterglow, ~day).
  - ***If largely off-axis***, may have faint optical/IR counterpart (kilonova, hrs-day, r≥20.5mag @ 100 Mpc depending on source parameters (e.g. Berger et al. 2013, Metzger et al. 2015).

- **Weeks-months: Slower radio remnant**
  - May have faint optical/IR counterpart (kilonova, hrs-day, r≥20.5mag @ 100 Mpc depending on source parameters, e.g. Metzger et al. 2015).

Radio counterparts to DNS and BH-NS with no γ−ray trigger



Hotokezaka et al. arXiv:1605.09395

- Horizontal solid bars are 7σ detection limits in 1 hr.
- Radio flux densities of M82 and MW also indicated.

Model	E_K [erg]	$\langle\beta_0\rangle$ [c]	$L^{n=1}_{1.4\mathrm{GHz}}$ [erg s^{-1}Hz^{-1}]	$L^{n=0.1}_{1.4\mathrm{GHz}}$	$L^{n=0.01}_{1.4\mathrm{GHz}}$
DNS$_h$	10^{51}	0.3	$4\cdot10^{29}$	$8\cdot10^{28}$	10^{28}
DNS$_m$	$3\cdot10^{50}$	0.25	$8\cdot10^{28}$	10^{28}	$2\cdot10^{27}$
DNS$_l$	10^{50}	0.2	10^{28}	$2\cdot10^{27}$	$3\cdot10^{26}$
BH-NS$_h$	$5\cdot10^{51}$	0.3	$2\cdot10^{30}$	$5\cdot10^{29}$	$7\cdot10^{28}$
BH-NS$_m$	$2\cdot10^{51}$	0.25	$5\cdot10^{29}$	$8\cdot10^{28}$	10^{28}
BH-NS$_l$	$5\cdot10^{50}$	0.2	$7\cdot10^{28}$	$9\cdot10^{27}$	10^{27}
strong-jet	10^{49}	~1	$3\cdot10^{28}$	10^{28}	$2\cdot10^{27}$
canonical-jet	10^{48}	~1	$4\cdot10^{27}$	10^{27}	$2\cdot10^{26}$

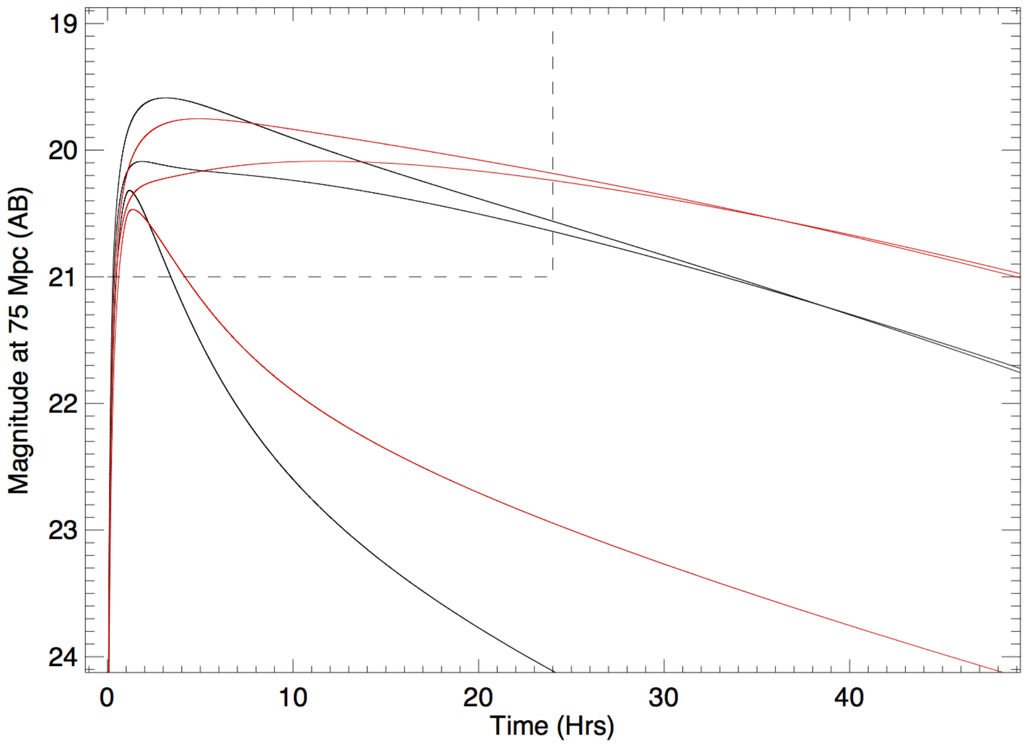
VLA Observing strategy (i): map GW error area

Model	n (cm^{-3})	JVLA (1.4 GHz)
DNS$_h$	0.1	86 (93)
DNS$_m$	0.1	21 (31)
DNS$_l$	0.1	6 (4)
BH-NS$_h$	0.1	98 (97)
BH-NS$_m$	0.1	44 (44)
BH-NS$_l$	0.1	4 (6)
strong-jet	0.1	36 (41)
canonical-jet	0.1	8 (8)

Hotokezaka et al. arXiv:1605.09395

- Radio-GW detection likelihood (%) for each radio telescope and a network of 3 GW detectors (or 5). 2x smaller if we account for Northern/Southern hemisphere.
- At least a 7σ detection **during at least 1 of 5 observation epochs** (10 d, 30 d, 100 d, 300 d, or 1000 d after GW detection).
- A total observation time of **30 hr is assumed in each observation epoch** → 150 hr per GW trigger for 5 epochs.

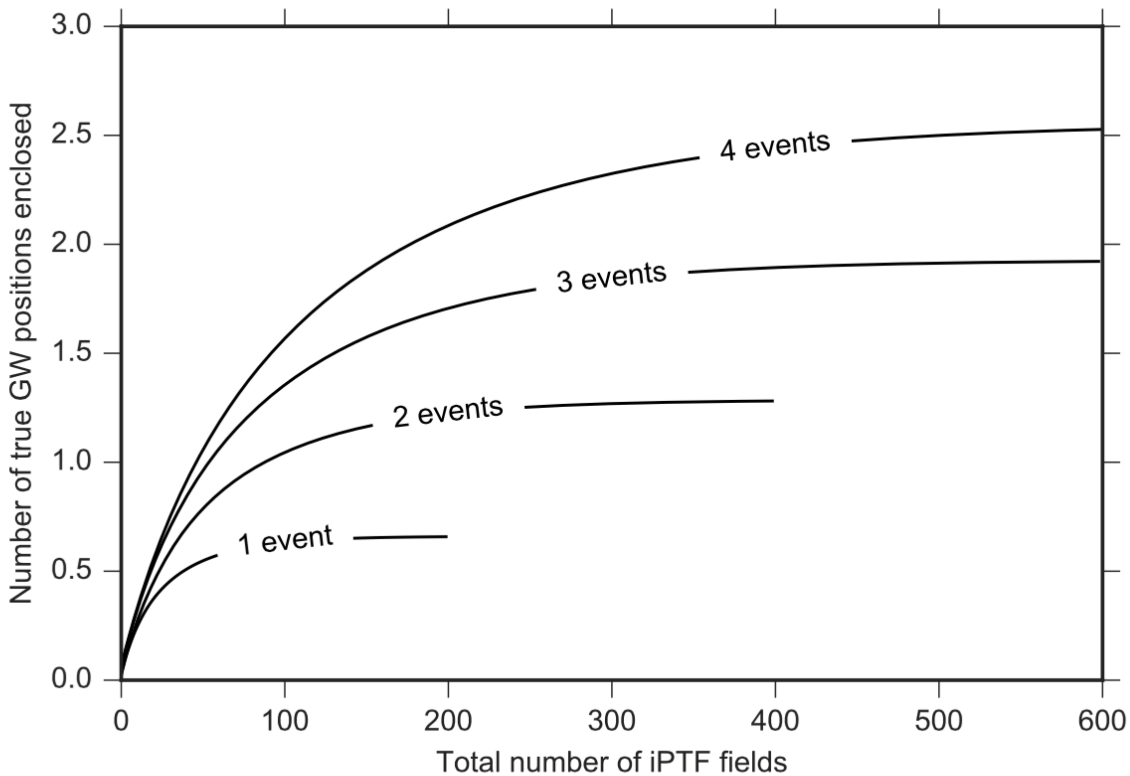
VLA Obs. strategy (ii): coordinate with optical telescopes



Kasliwal et al. arXiv:1602.08764

- **Minimizes required VLA time** for discovery, enables time spent on multi-band radio follow-up to constrain radio spectral properties.
- **Detectability in optical is key (provides arcsec localization)**.
- g-band (black) and r-band (red) kilonova model light curves for different values of opacities and remnant mass (Metzger 2015). iPTF limiting r~21mag in 60 s.

VLA Obs. strategy (ii): iPTF example



Kasliwal et al. arXiv:1602.08764

- Average # of times true GW position is enclosed as a function of # of imaged iPTF fields ($7.1 deg^2$ each).
- Two 60s images of 150 iPTF fields can be obtained in 1 night.
- **2 GW events follow-ups needed to have at least 1 in the area.**

Background and false positives

- Optical/IR false positives @ 24 mag: ~ 60 deg^{-2} (Nissanke et al. 2013). Hard problem but tractable via machine learning techniques (e.g., Kasliwal et al. 2016).

- Extragalactic radio transient false positives: <~1 deg^{-2} for f>0.1mJy @ 1.4GHz on weeks-months timescales (Mooley et al. 2013, 2016; Hotokezaka et al. 2016).

- AGN (i.e., persistent extragalactic radio sources) inside the GW localization volume or outside the GW localization volume but behind the candidate host galaxy: ~10 x(Area/100 deg^2) @ 0.1mJy assuming <1% varies more than 30% (Hotokezaka et al. 2016).

- CAVEAT: population of radio variable sources depends on sensitivity and still (mostly) unexplored at flux densities of GW radio counterparts. Combining optical and multi-band/multi-epoch radio observations will be most effective.

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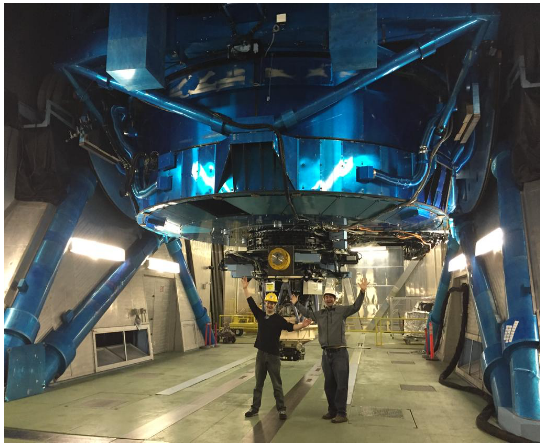

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- Gravitational waves from GRBs, pulsars, and magnetars using advanced LIGO.
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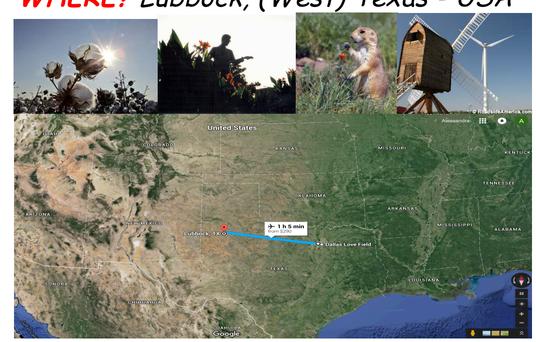
Instrumentation / Big Science Projects
- FLOYDS – a pair of spectrographs for the Faulkes Telescopes.
- We are contributing to several big science projects: CTA, iPTF, LIGO, LSST, WINGS (WFIRST IR nearby Galaxy Survey).

QUESTIONS? Contact us:

A. Corsi T. Maccarone B. Owen D. Sand

WHERE? Lubbock, (West) Texas - USA



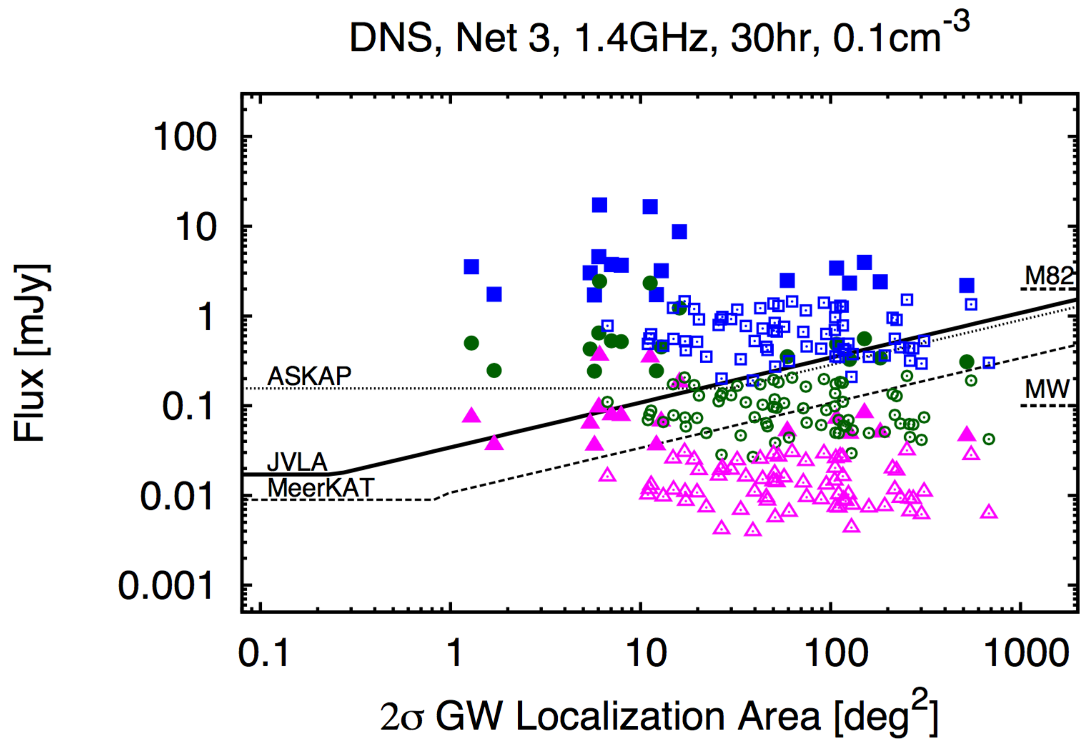
"Easily one of the ten most beautiful campuses" (Stewart Mandel) - "Most beautiful west of the Mississippi until you get to Stanford" (James A. Michener)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^{2}
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Transients	R [Gpc^{-3}yr^{-1}]	$L_{1.4\text{GHz}}$ [erg s^{-1}Hz^{-1}]	T [yr]
Type II radio SN	$3 \cdot 10^4$	$10^{27.5}$	10
Type Ib/c SN	5000	10^{27}	0.3
LLGRB	500	$5 \cdot 10^{27}$	0.1
Orphan LGRB	15	$2 \cdot 10^{29}$	3
TDE (strong jets)	1	10^{31}	3
TDE	200	10^{28}	0.5

VLA Observing strategy (i): radio mapping of GW area



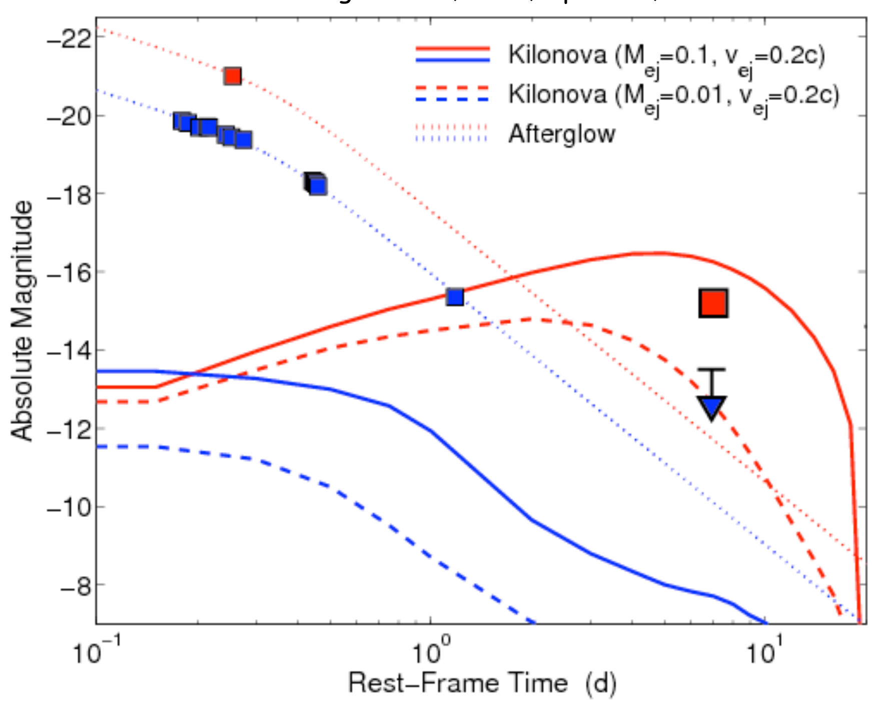
Hotokezaka et al. arXiv:1605.09395

- Example for long-lasting radio remnants.
- Filled squares, circles, triangles: peak flux of high, median, low ejecta model within 200 Mpc. Open symbols are for events beyond 200 Mpc.
- Lines show 7σ sensitivity reached by each instr. to cover the 2σ GW localization area in 30hr.
- VLA: 0.25deg FOV radius @ 1.4GHz.

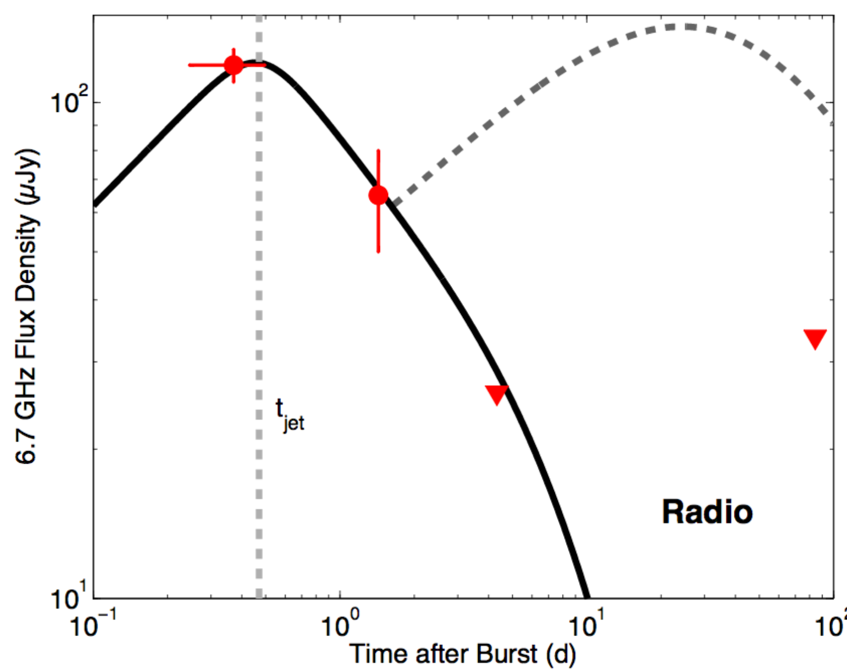
Optical/radio counterparts to DNS/BH-NS (I)

Short-hard GRB130603B at ~ 2 Gpc

Berger et al., 2013, ApJ 774, L23



Fong et al. 2014, ApJ, 780, 118



M_r=-13 → r=22 mag @ 100 Mpc

100 uJy @ 2 Gpc → 40 mJy @ 100 Mpc