Electromagnetic counterparts to gravitational wave sources

INFN

FUTURO IN RICERCA

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(Università di Urbino/INFN Sezione di Firenze)

Nicolaus Copernicus Astronomical Center

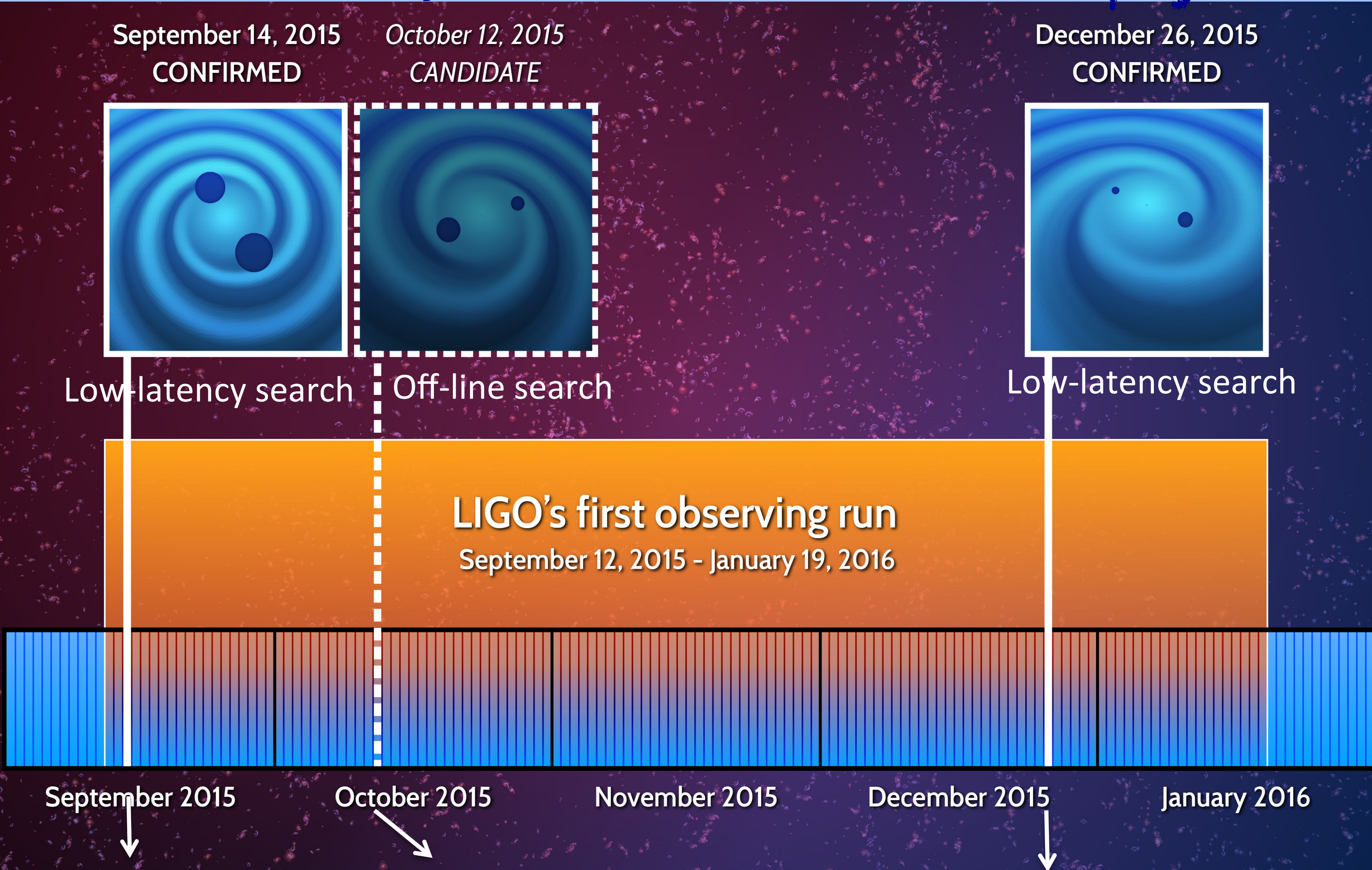
IASF

Tribhuvan University

INTERNATIONAL CONFERENCE ON
SHINING FROM THE HEART OF DARKNESS: BLACK HOLE ACCRETION AND JETS

Kathmandu, Nepal, October 16 - 21, 2016

The era of gravitational wave astrophysics

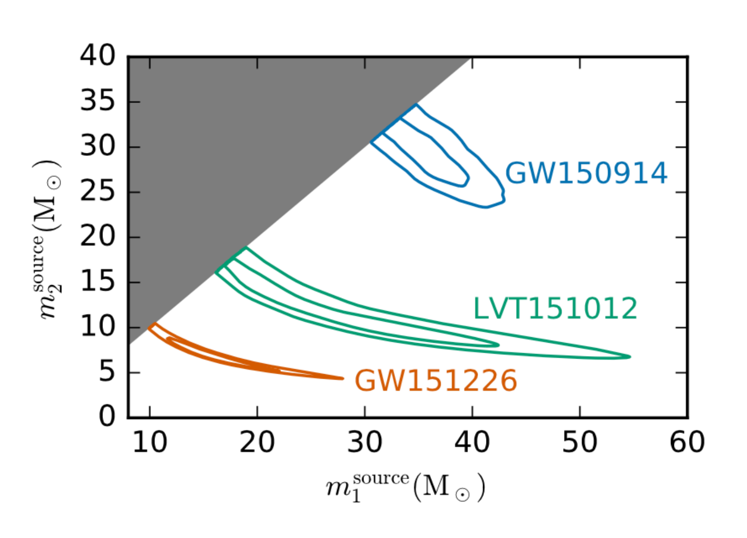


SNR=24
FAR < 6 x 10^{-7} yr^{-1}
Significance > 5.3 σ

SNR=9
FAR 0.37 yr^{-1}
Significance = 1.7 σ

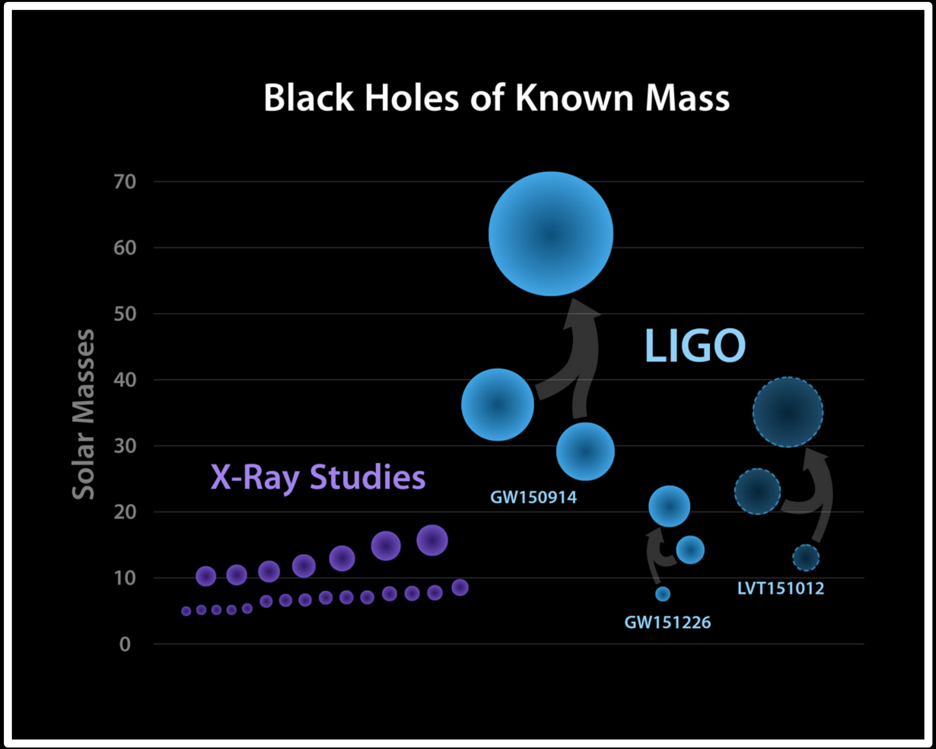
SNR=13
FAR < 6 x 10^{-7}
Significance > 5.3 σ

Parameters of the binary stellar-mass BH systems



Component masses

Event	GW150914	GW151226	LVT151012
Primary mass $m_1^{source}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{source}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}



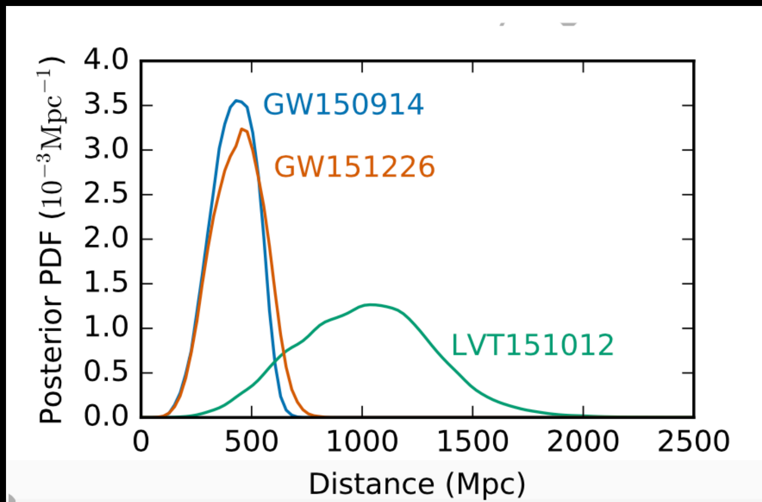
LVC arXiv:1606.04856

LVC 2016 Phys. Rev. Lett. 116, 241103

LVC 2016 ApJL, 818, 22

To understand how BBH systems form and evolve crucial to identify the host galaxy and study the GW source environment

Challenges to identify the host galaxy



Distances

LVC arXiv:1606.04856

Event	GW150914	GW151226	LVT151012
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

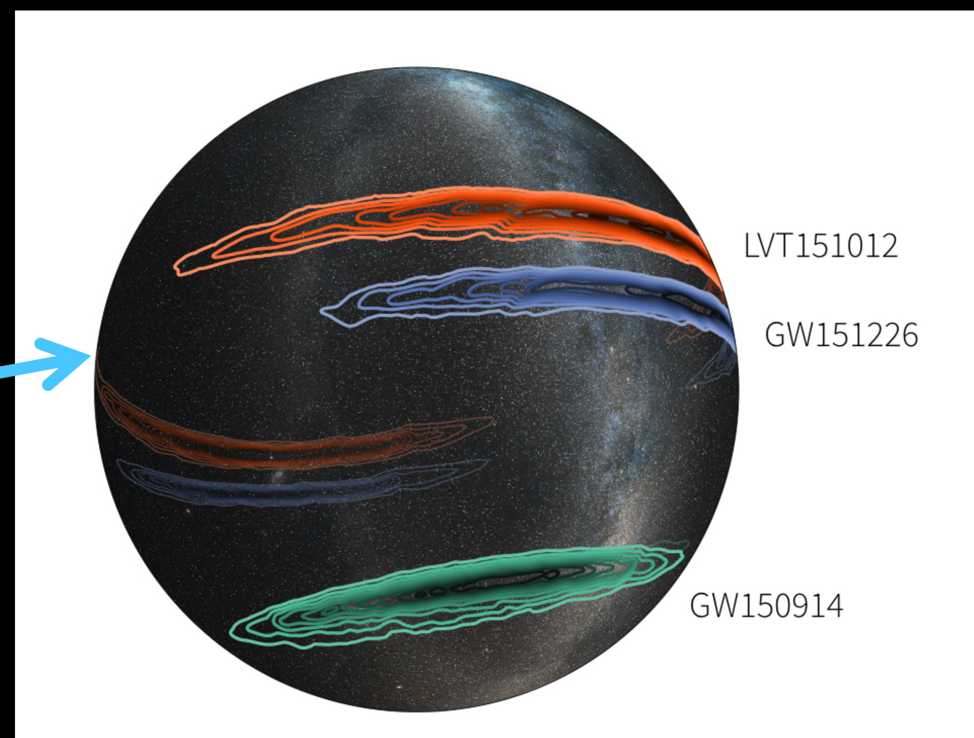
Sky localizations

90% credible areas of about

600 deg^2 GW150914

1600 deg^2 LVT15012

1000 deg^2 GW151226

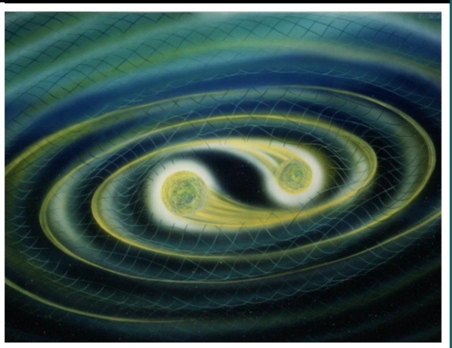


In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 there are 10^5-10^6 galaxies

The multi-messenger astronomy is required...

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

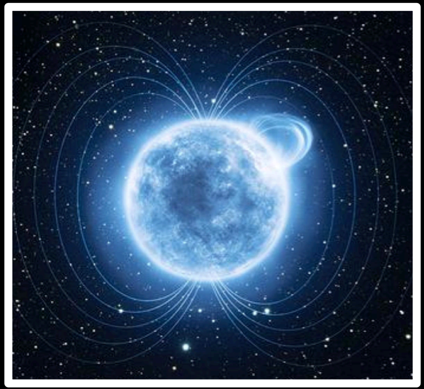
Coalescence of binary system of neutron stars (BNS) and NS-BH



- Orbital evolution and GW signals accurately modeled by post-Newtonian approximation and numerical simulations
  → precise waveforms
- **Energy emitted in GWs (BNS): ~$10^{-2} M_o c^2$**

Core-collapse of massive stars

Isolated NSs instabilties



- Modeling of the GW shape and strength is complicated → **uncertain waveforms**
- **Energy emitted in GWs:**

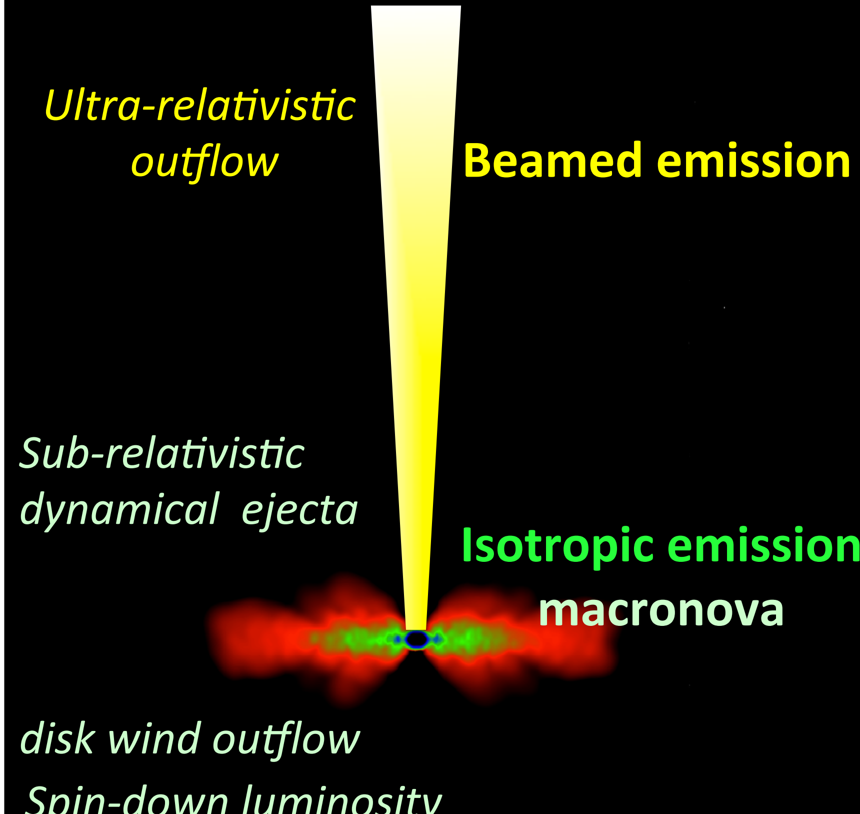
~10^{-8} – 10^{-5} $M_o c^2$ for the core-collapse

~10^{-16} – 10^{-6} $M_o c^2$ for isolated NSs

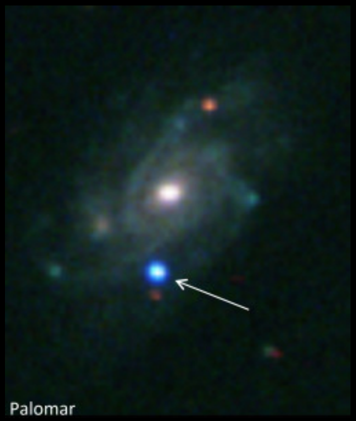
Electromagnetic emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)



Core-collapse of massive stars



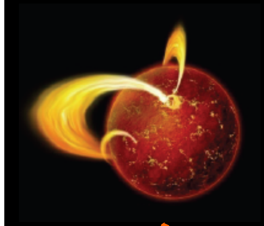
X-ray/UV SBO

Optical

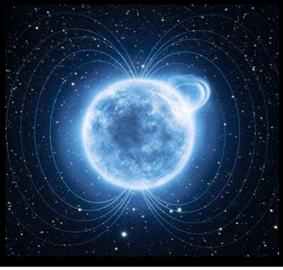
Radio

+ Long GRB

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

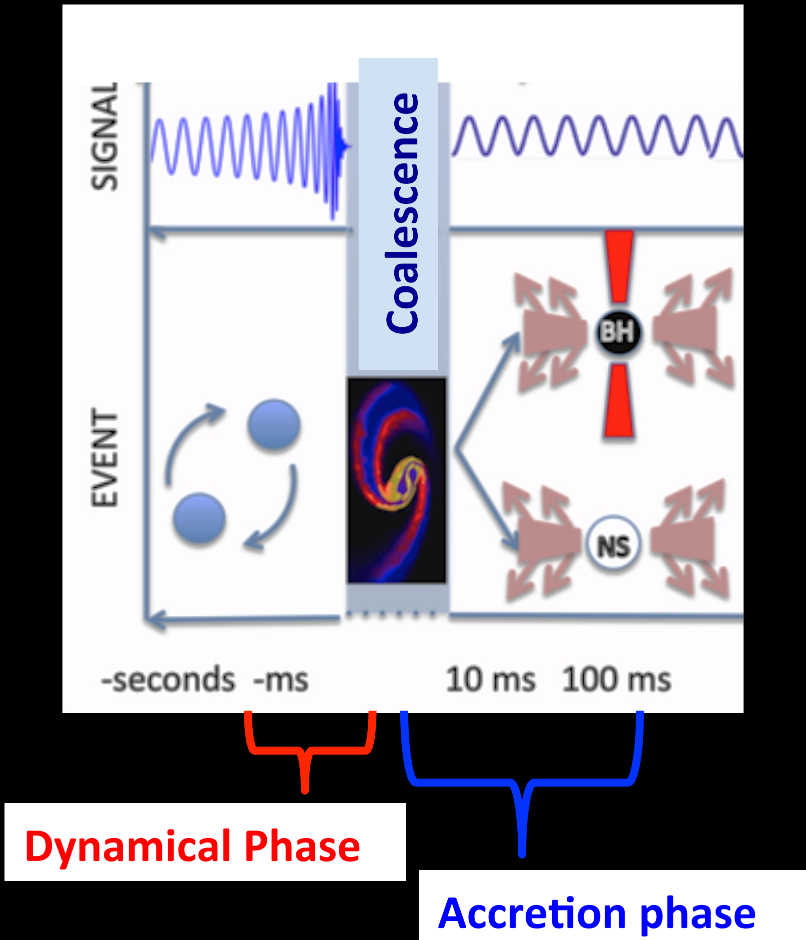


Radio/gamma-ray Pulsar glitches

BH-BH mergers

some mechanisms for EM emission recently discussed **Loeb 2016 ; Perna et al. 2016 ; Zhang et al. 2016**

NS-NS and NS-BH inspiral and merger

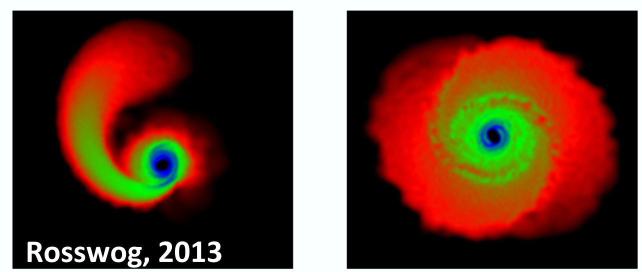


Fernandez & Metzger 2016, ARNPS, 66

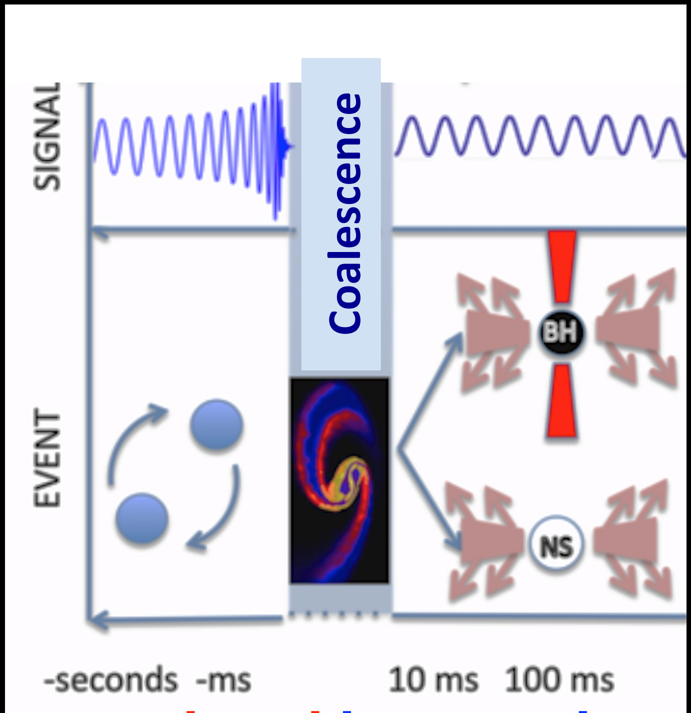
The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound from the central remnant either falls back or circularizes into an accretion disk

NS-NS binary → **<u>unbound mass</u> of 10^{-4} -10^{-2} Mo ejected at 0.1-0.3c,** which depends on **total mass, mass ratio, EOS NS and binary eccentricity**



NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound from the central remnant either falls back or circularizes into an accretion disk

NS-BH binary → unbound mass up to 0.1 Mo depends on **ratio of the tidal disruption radius to the innermost stable circular orbit**

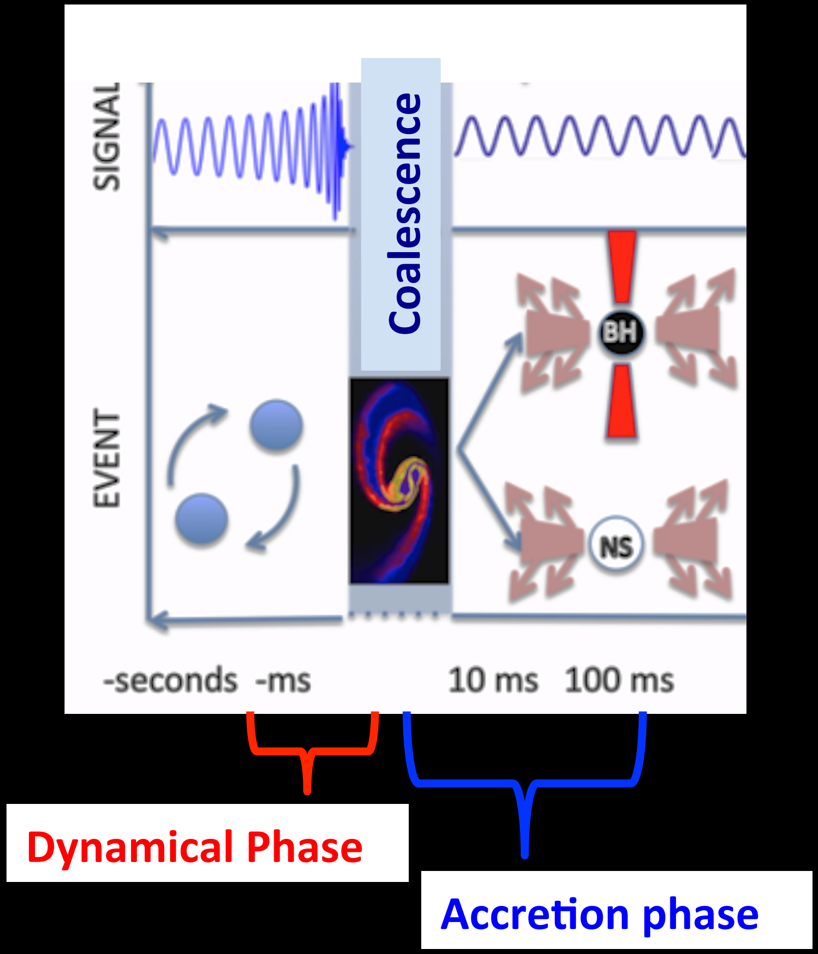
If < 1 → NS swallowed by the BH no mass ejection

If > 1 NS → tidally disrupted, long spiral arms

which depends on **the mass ratio, the BH spin and the NS compactness**

See Kawaguchi et al. 2016,ApJ, 825, 52

NS-NS and NS-BH inspiral and merger



Fernandez & Metzger 2016, ARNPS, 66

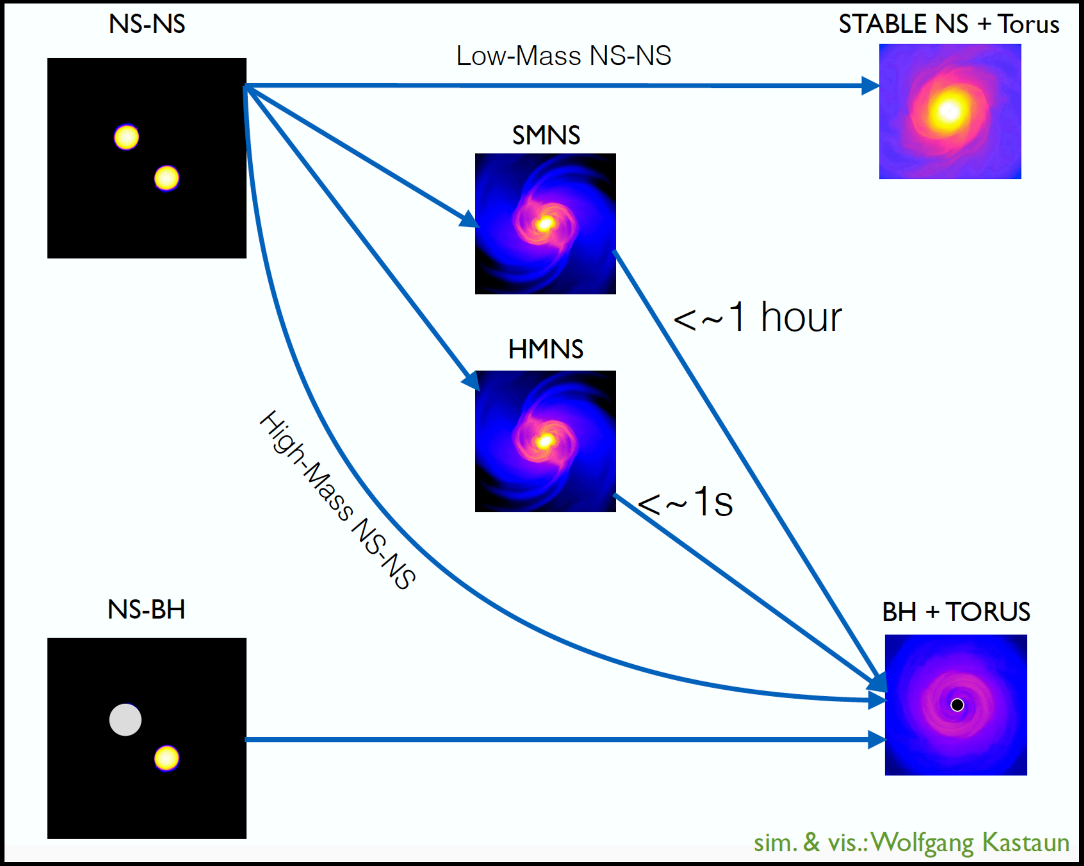
- Ejected material gravitationally bound from the central remnant can fall back or circularizes into an accretion disk

Disk mass up to ~ **0.3Mo**
Disk mass depends on the **mass ratio of the binary, the spins of the binary components, the EOS, and the total mass of the binary**

For NS-BH see e.g. Foucart 2012, PhRvD, 86;
Maselli & Ferrari, PhRvD, 89;
Pannarale & Ohme, ApJL, 791

Outflow mass and geometry influence the EM emission

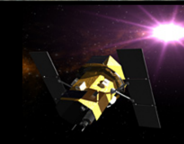
Central remnant of NS-NS or NS-BH merger



The central remnant influences GW and EM emission

What is central remnant?

- It depends on the total mass of the binary
- The mass threshold above which a BH forms directly depends on EOS



GWs and photons provide complementary insight into the physics of the progenitors and their environment

GWs

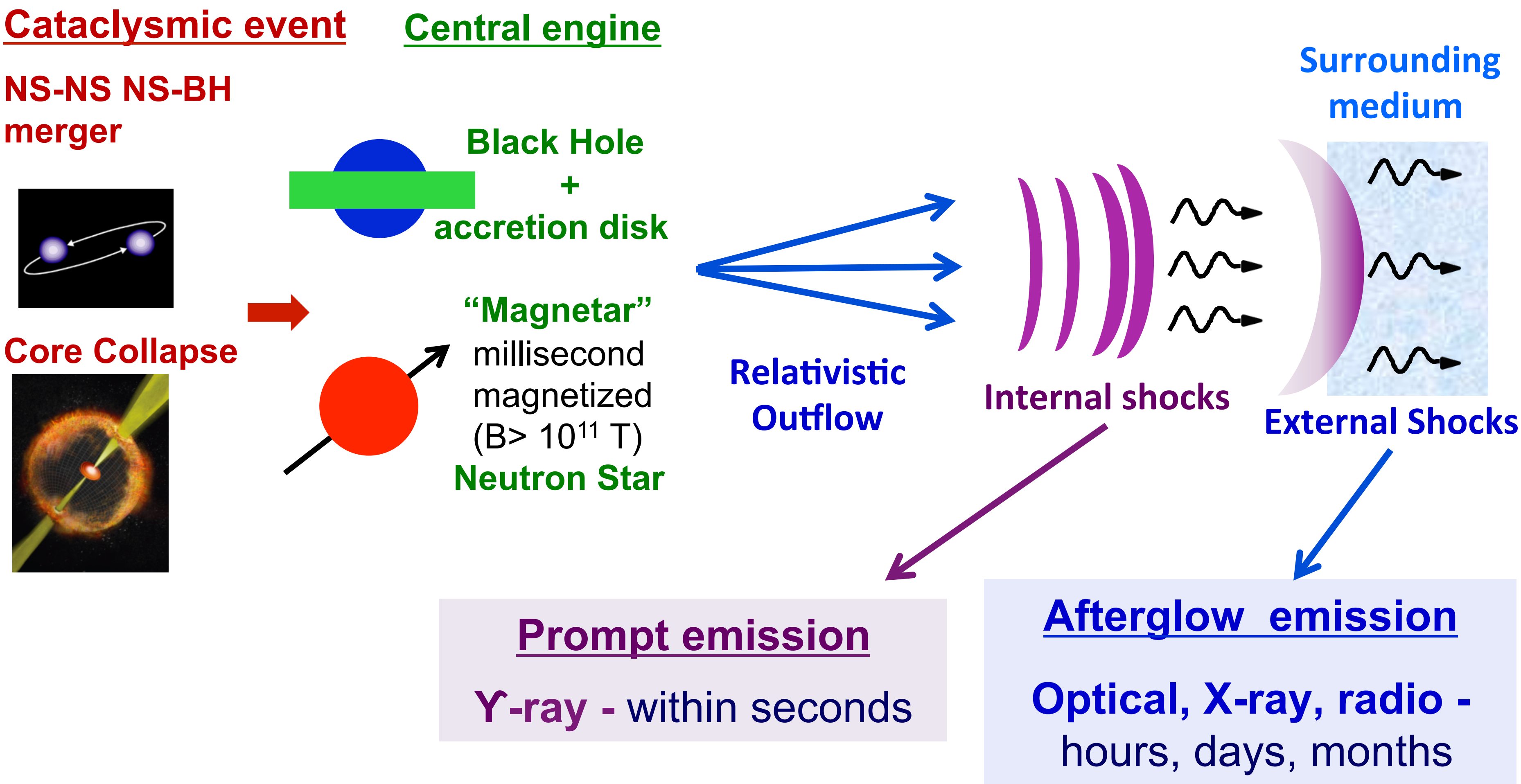
- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance

→

EM emission

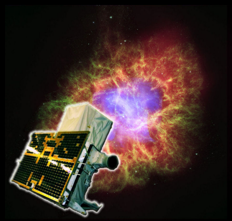
- Beamed and isotropic EM emissions
- Energetics
- Nuclear astrophysics
- Source enviroment
- Precise (arcsec) sky localization
- Host galaxy
- Redshift

GRBs emission - Fireball Model



Kinetic energy of the relativistic jet converted into radiation
Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

How many on-axis/off-axis short GRB?



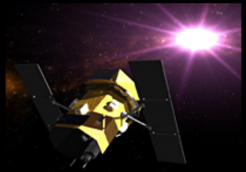
Short GRB rate → GW/sGRB detections by aLIGO/Virgo in full sensitivity

R_{GRB} = 0.2-10 $Gpc^{-3}\ yr^{-1}$ (e.g. Ghirlanda et al 2016, Wanderman & Piran 2015)

→ $R_{GRB/GW}$ (300* Mpc) = 0.02-1 yr^{-1}

→ $R_{GRB/GW}$ (600* Mpc) = 0.2-10 yr^{-1}

(*Distance range for NS-NS 200 Mpc and for NS-BH 400 Mpc expected times 1.5 for face-on systems)



sGRB rate → NS-NS aLIGO/Virgo detection rate

Assuming NS-NS progenitor of short GRB:

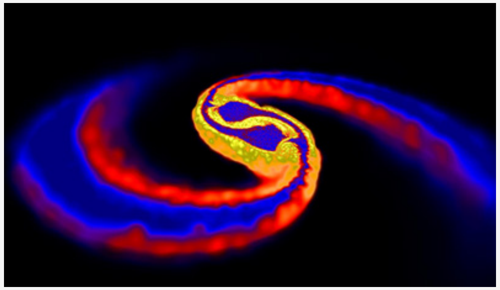
$$R_{NS-NS}=R_{GRB}/(1-\cos(\theta j))$$

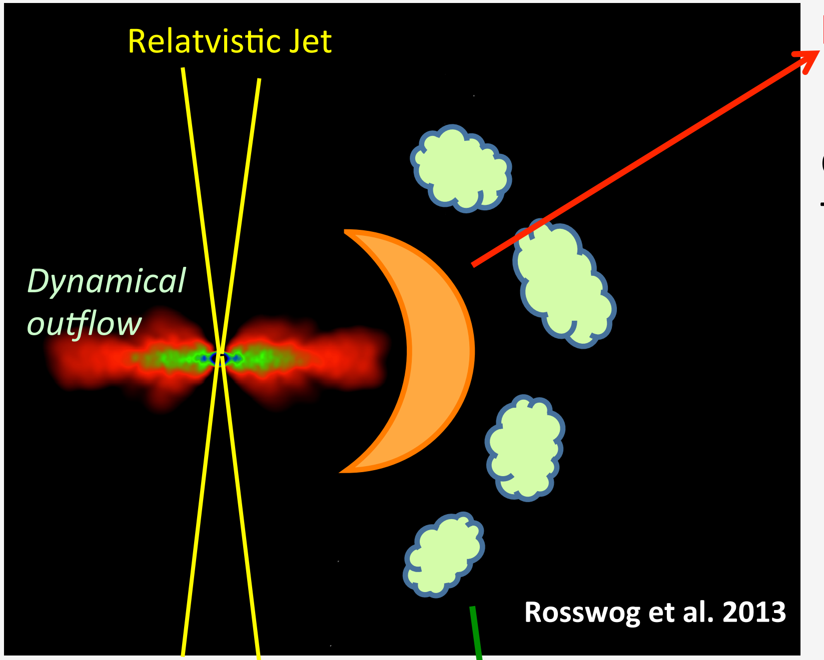
For θj = 10 deg → R_{NS-NS} (200* Mpc) = 0.4-20 yr^{-1}

For θj = 30 deg → R_{NS-NS} (200* Mpc) = 0.04-2 yr^{-1}

Macronova/Kilonova-Radio remnant

Dynamically unbound ejected mass
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.3 c)**





r-process

Neutron capture rate much faster than decay, special conditions:
T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

↓

radioactive decay of heavy elements

↓

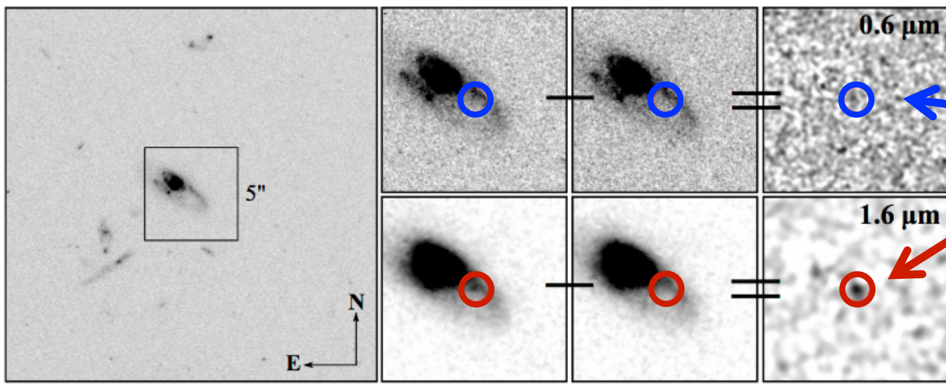
Power MACRONOVA
short lived IR-UV signal (days)

Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507 Metzger et al. 2010, MNRAS, 406; Tanaka et al. 2014 ApJ, 780; Barnes & Kasen 2013, ApJ, 775. See Kasen et al. 2015, MNRAS, 450 for the accretion disk wind outflow component.

RADIO REMNANT
long lasting radio signals (years)
produced by interaction of sub-relativistic outflow with surrounding matter

Hotokezaka arXiv:1605.09395; Piran et al. 2013, MNRAS, 430

Possible HST kilonova detection for short GRB130603B after 9.4 days (Tanvir et al. 2013, Nature ,500)

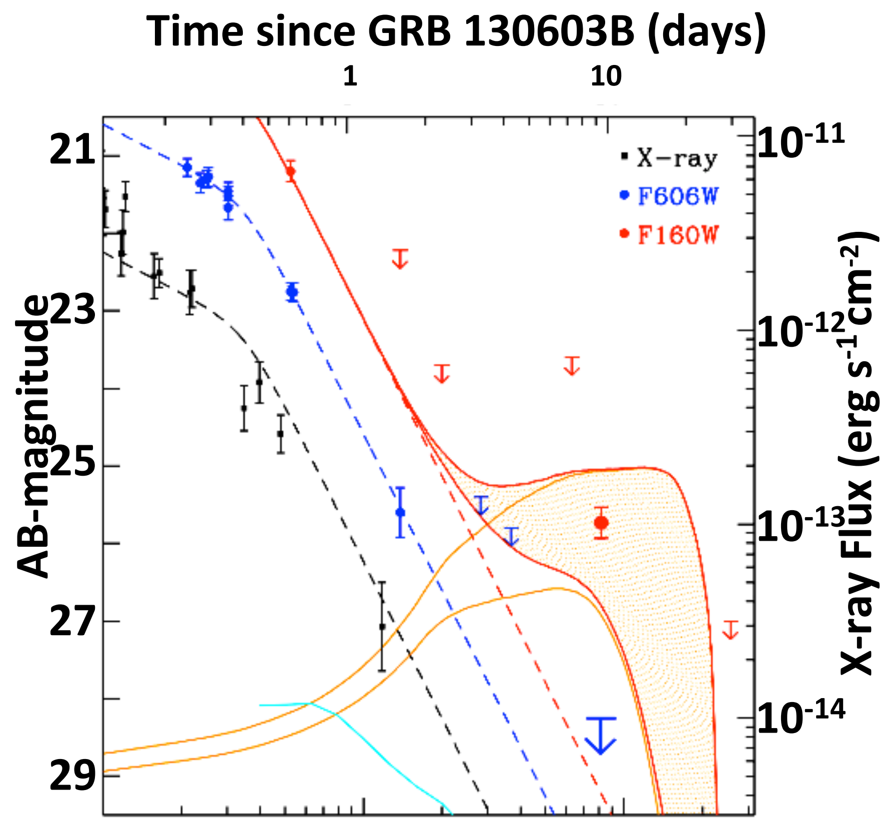


Afterglow and host galaxy z=0.356

HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

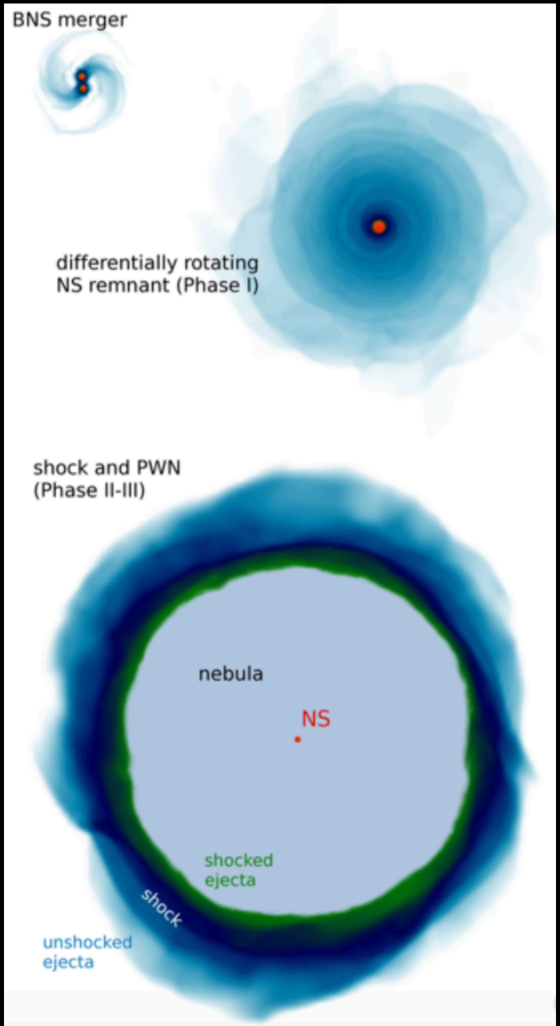


Orange curves → kilonova NIR model ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model

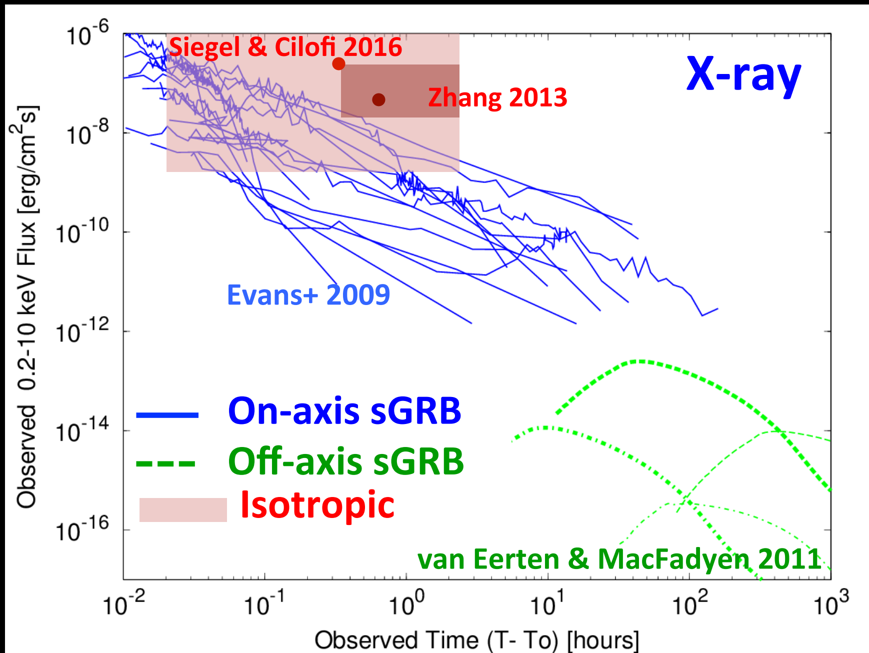
X-ray emission from the long-lived NS remnant

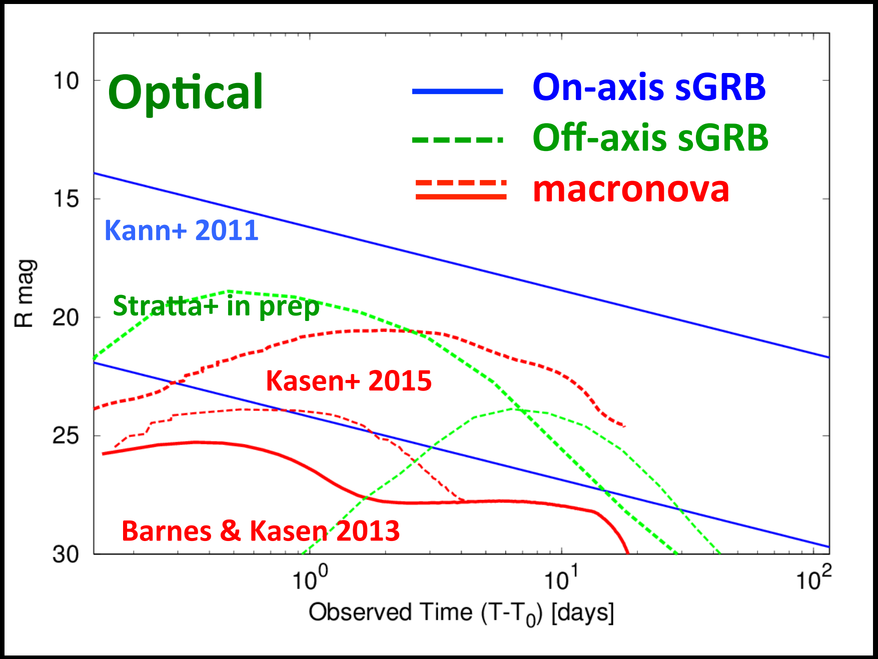


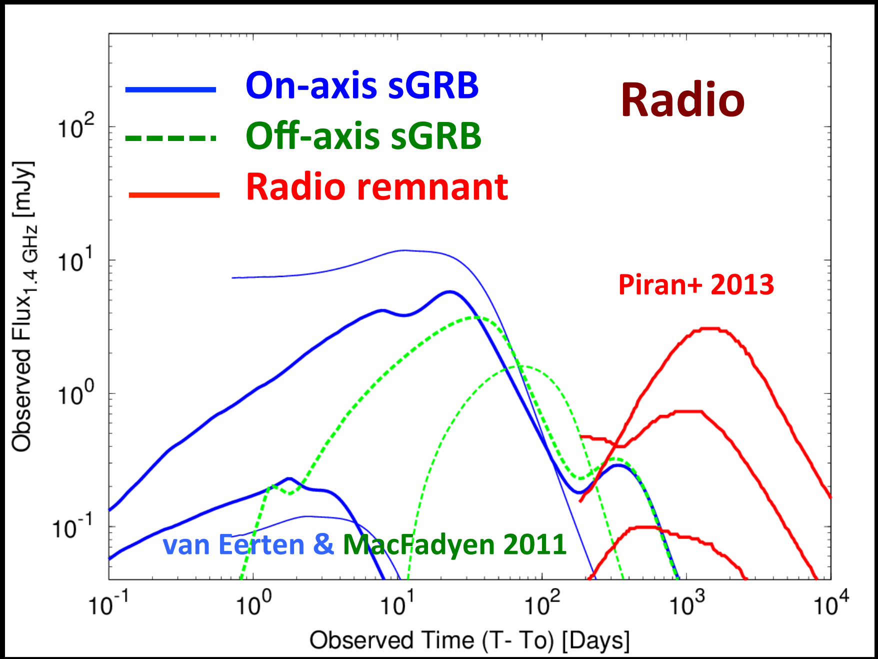
- X-ray afterglow radiation produced by spin-down energy extracted from the NS prior to collapse, slowly diffusing through optically thick environment composed of a pulsar wind nebula (PWN) and outer shell of ejected material
- signal peaks at 10^2-10^4 s after the merger
- luminosities 10^{46}-10^{49} erg/s
- mostly in the soft X-rays (0.2-10 keV)

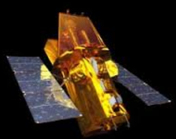
Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

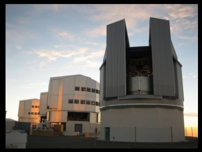
NS-NS merger EM-emissions











Source at 200 Mpc

Different timescale

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio

(minutes, hours, days, months)

Off-axis afterglow

Kilonovae

(days)

ssion

Radio remnants

(months, years)

Core-collapse

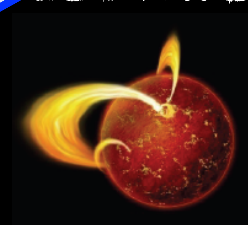
SBO X-

(mi

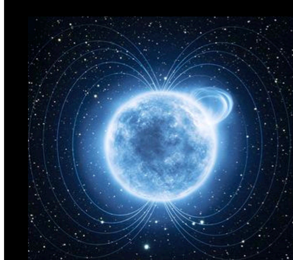
ears)

+ Long GRB

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

Request for network of multi-wavelength high sensitivity observatories which cover huge region of the sky and repeat observations over different timescales...

Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma

HEN Neutrinos

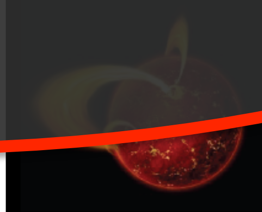
Core-collapse of massive stars

SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Low-energy Neutrinos

Isolated NS instabilities



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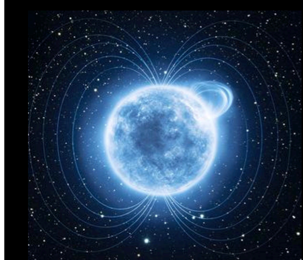
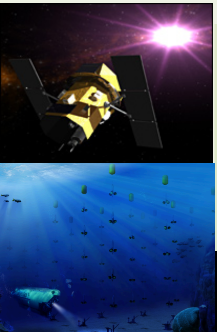


Radio/gamma-ray Pulsar glitches

→ GW Triggered Analysis: *search that uses EM or neutrino observations to drive the detection of GWs*

GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino → GW TRIGGERED ANALYSIS



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

→ reduction in search parameter space

→ gain in search sensitivity

Kochanek and Piran 1993, ApJL, 417

Abadie et al. 2012, ApJ, 760

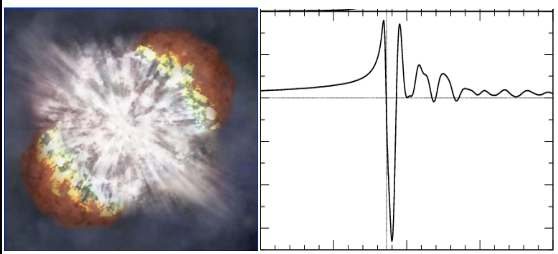
Aasi et al. 2014,PhRvL, 113

Abadie et al. 2012, ApJ, 755

Adrián-Martínez et al. 2013, JCAP

Aartsen et al, PhysRevD, 90, 102002

GW transient searches

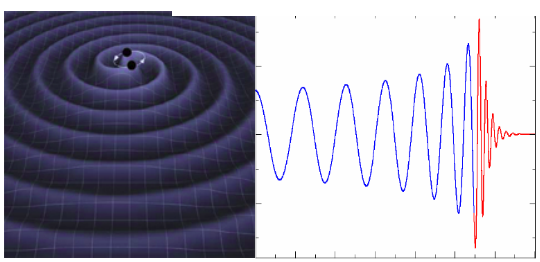


Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

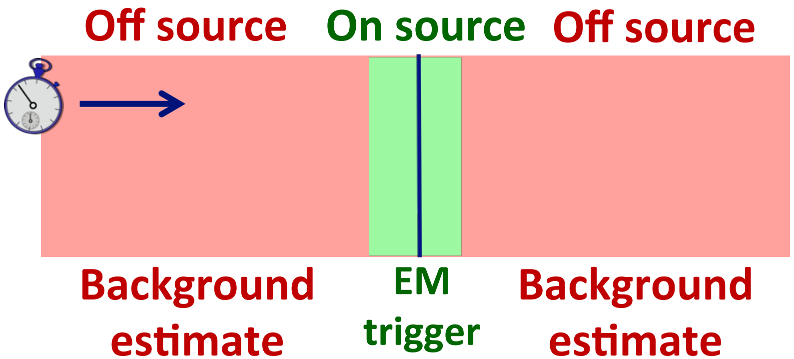
→ **Excess power**



Compact Binary Coalescence

Known waveform

→ **Matched filter**



Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)
→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)

Radio remnants
(months, years)

Siegel & Ciolfi 2016, ApJ → X-ray (min, hrs)

Core-collapse of massive stars

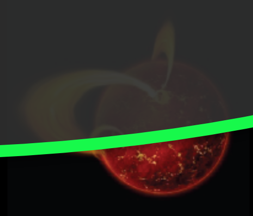
SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Radio
(years)

→ **EM follow-up:** *low-latency GW candidate events to trigger prompt EM observations and* archival searches

Isolated NS instabilities



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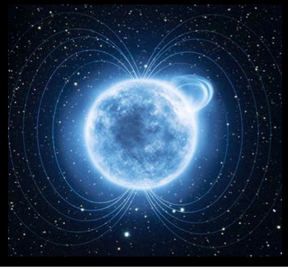
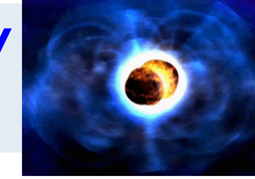


Radio/gamma-ray Pulsar glitches

BH-BH mergers ?

Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alert to obtain EM observations

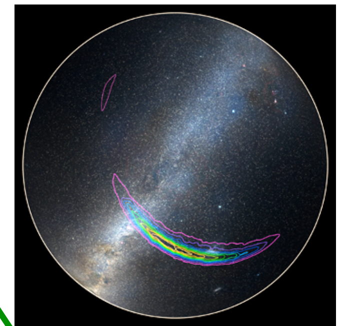


LSC VIRGO

GW candidates **Sky Localization** **EM facilities**

LIGO-H LIGO-L

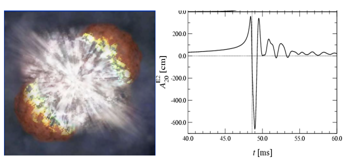
Virgo



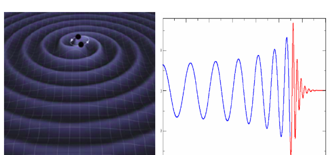
Event validation

Low-latency Search

to identify the GW-candidates



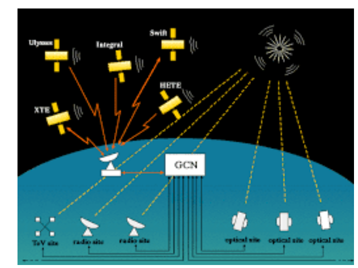
Unmodeled GW burst search



Matched filter with waveforms of compact binary coalescence

Software to

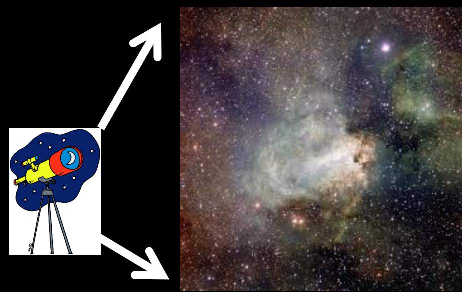
- select statistically significant triggers wrt background
- check detector sanity and data quality
- determine source localization



→ **a few min** → **15/30 min**

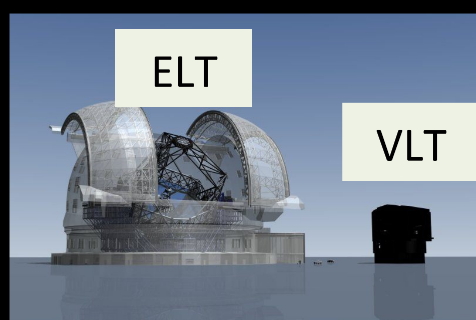
Parameter estimation codes → **Hours,days** → **GW candidate updates**

Hunt the elusive EM-counterpart!



Wide-field telescope
FOV >1 sq.degree

“Fast” and “smart” software to select a sample of candidate counterparts

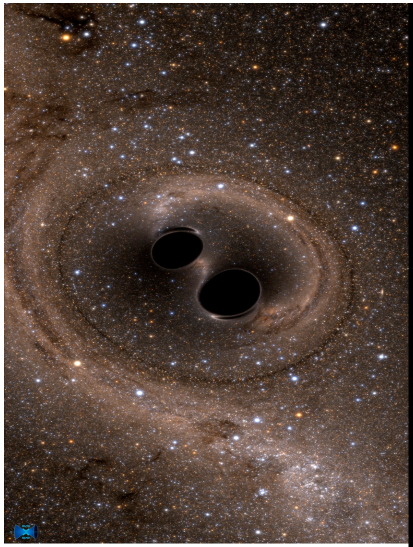


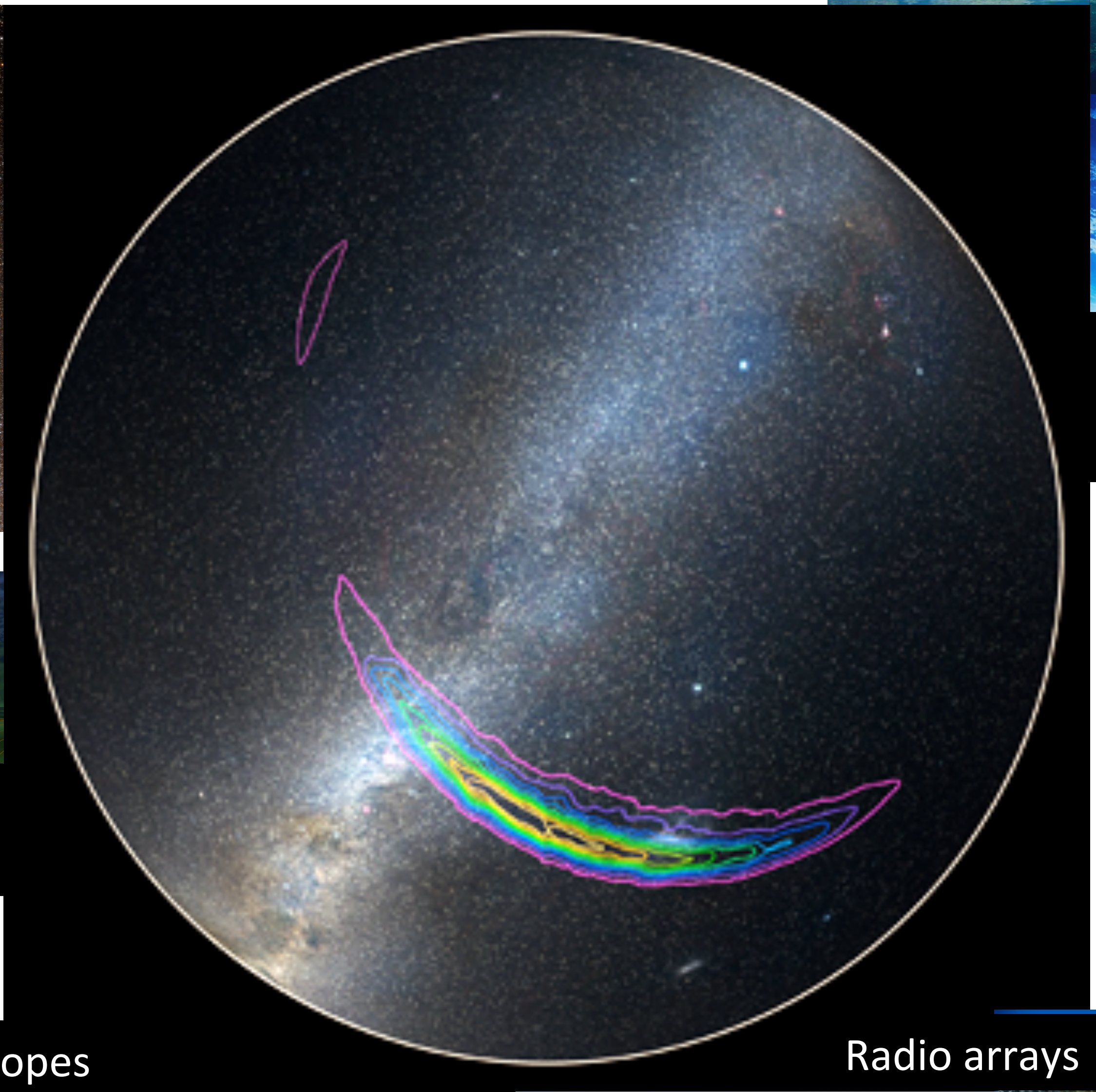
Larger telescope to **characterize** the candidate nature

The EM Counterpart!

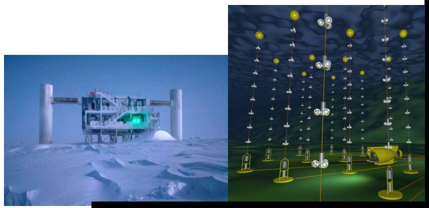
See Palazzi’s talk

The first multi-messenger campaign including GW observations

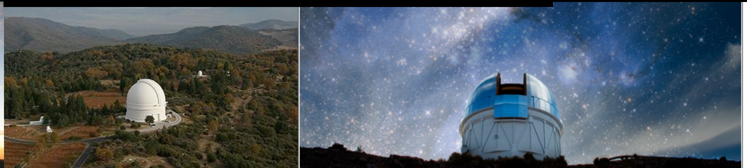




Gamma and X-ray satellites



Neutrino observatories



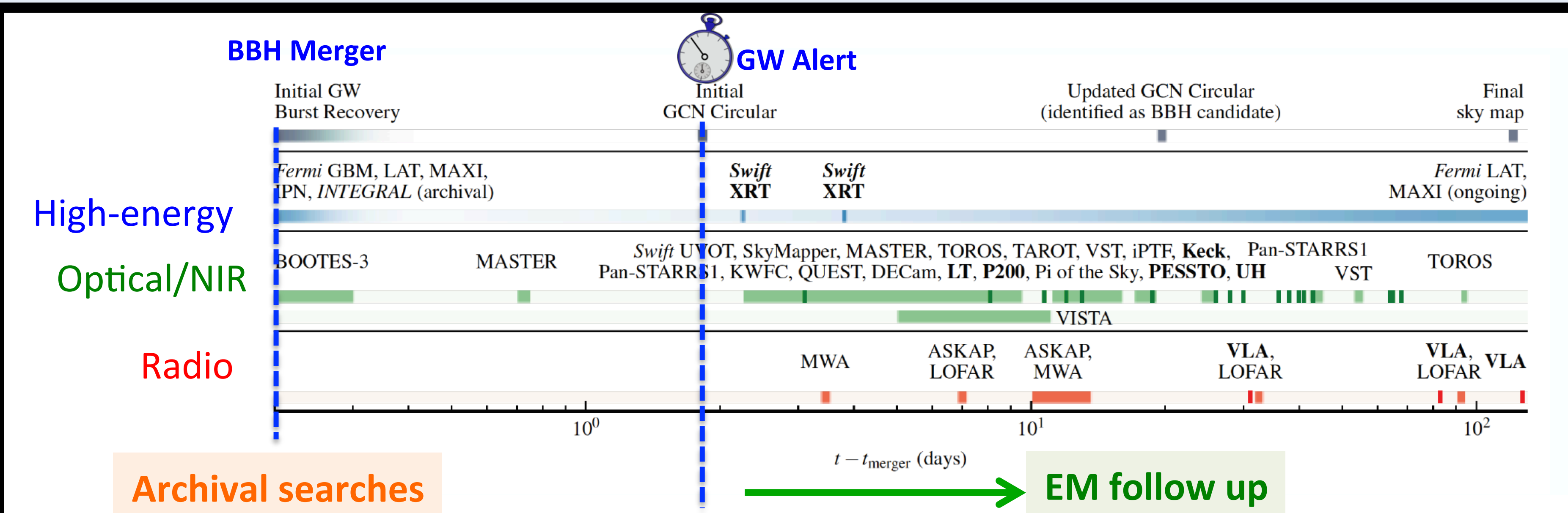
Optical telescopes

Radio arrays

GW150914

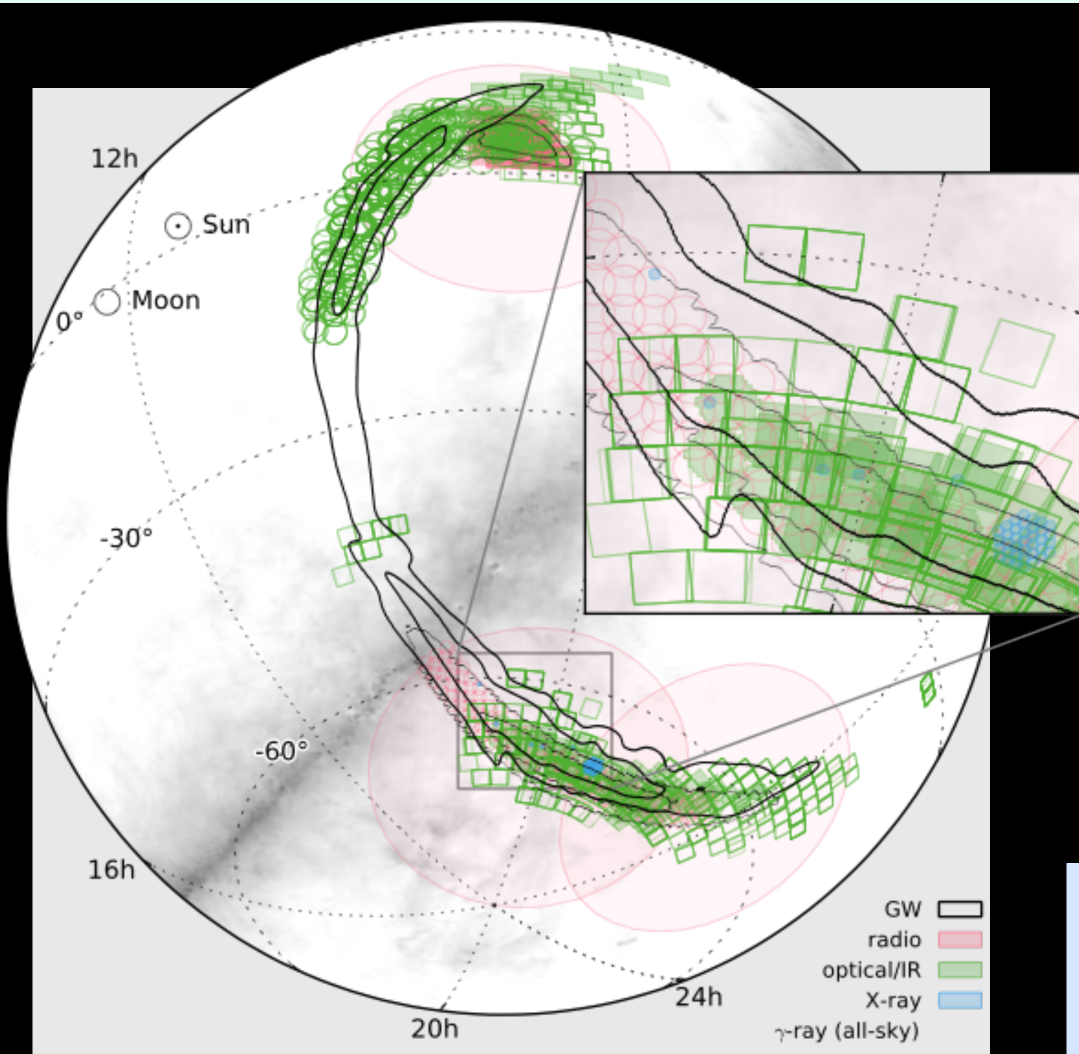
EM follow up observations and archival searches

- ***Twenty-five teams*** *of observers responded to the GW alert*
- *The EM observations involved* ***satellites and ground-based telescopes*** *around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*



LVC+astronomers, ApJL, 826, 13
LVC+astronomers ApJS, 225,8
Connaughton et al. ApJL, 826, 6
Savchenko et al. 2016 ApJL 820, 36
Fermi-LAT collaboration ApJL, 823,2
Hurley et al. ApJL, 829, 12
Evans et al. MNRAS 460, L40
Morokuma et al. PASJL, 68, 9
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. ApJL, 823, 33
Annis et al. ApJL, 823, 34
Smartt et al. MNRAS, 462, 4094
Kasliwal et al. ApJL, 824, 24
Diaz et al. ApL 828, 16
Greiner et al. ApJL, 827, 38
Tavani et al. ApJL, 825, 4
Troja et al. ApJL, 827, 102

Sky map coverage



- *Covered sky map contained probabilty:*
  100% gamma-ray
  86% radio
  50% optical
- *Candidate counterparts rapidly characterized*
- *In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN*

LVC+astronomers ApJL, 826, 13
LVC+astronomers ApJS, 225, 8

Fermi-GBM → **weak signal**
of 1 sec 0.4 s after GW15014
fluence(1 keV-10 MeV) = 2.4×10^{-7} erg cm^{-2}
FAR 4.79×10^{-4} Hz, FAP 0.0022
(**Connaughton et al. 2016 ApJL, 826**)

INTEGRAL → no signal but
stringent upper limit
(**Savchenko et al. 2016 ApJL, 820**)

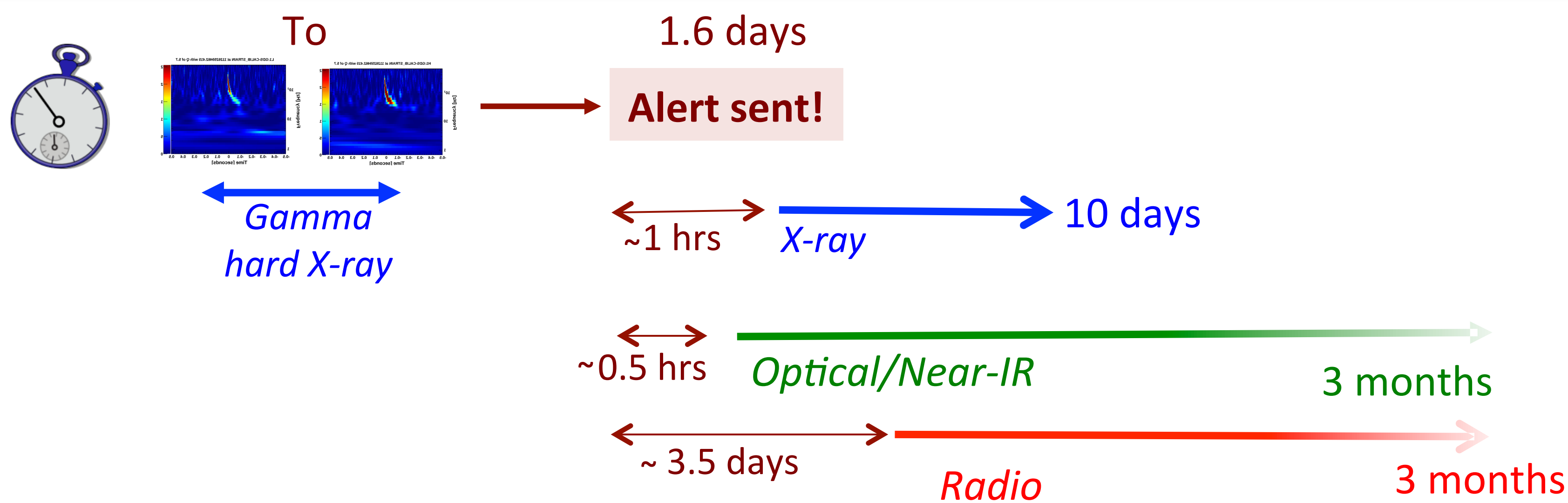
GW151226

***Thirty-one groups** responded to the GW alert:*

High-energy and Very high-energy → Swift, XMM-Slew, MAXI, AGILE, Fermi, CALET, CZTI, IPN, MAGIC, HAWC

Optical-NIR → MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla–QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky observations, LCOGT/UCSB, CSS/CRTS, GTC

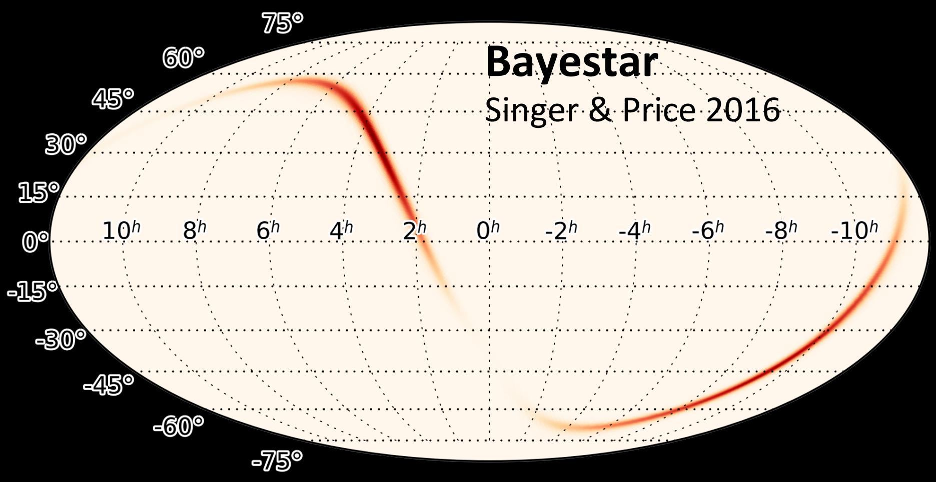
Radio → VLA-Corsi, LOFAR, MWA



All the info from public GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html

Racusin et al. arXiv:1606.04901
Smartt et al. arXiv:1606.04795
Copperwheat et al. MNRAS, 462, 3528
Cowperthwaite et al., ApJL, 826, 29
Evans et al. MNRAS, 462, 1591
Adriani et al.ApJL, 829, 20
Palliyaguru et al. ApJL, 829, 28

GW151226



Credit: LIGO/Virgo

- *Large portions of the GW sky map observed*
- *Candidate counterparts rapidly characterized*
- *In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN*
- ***No EM counterpart reported***

GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html

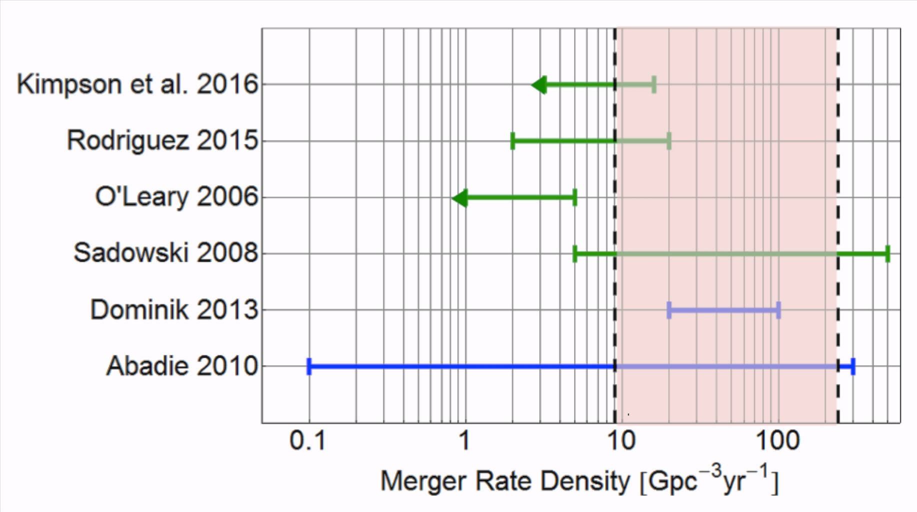
The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range

The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

Prospects of observing and localizing GWs in the next LIGO and VIRGO scientific runs



BBH merger rate based on O1 observations



9-240 Gpc^{-3} yr^{-1}

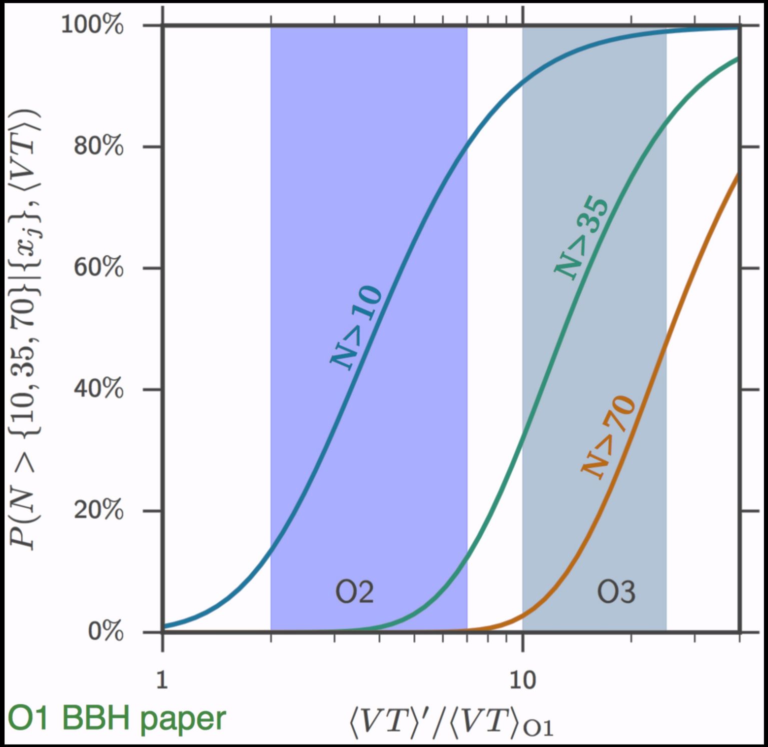
Number of expected highly significant detections (FAR < 1/century)

O2 → ~10 BBH events

(O2 observing run 2016-2017 6 months)

O3 → ~ 35 BBH events

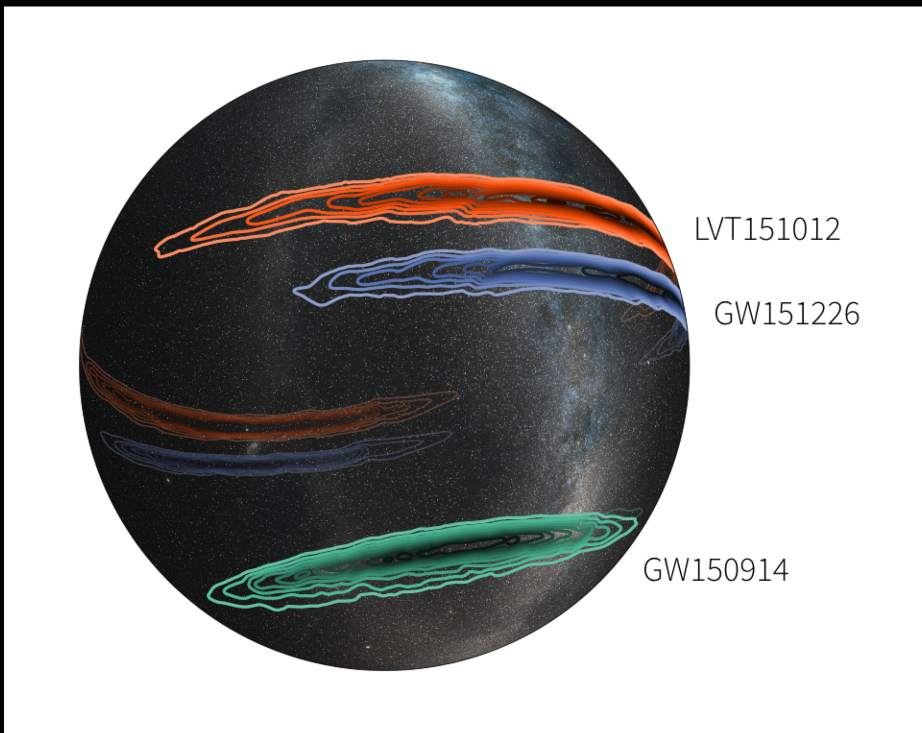
(O3 observing run 2017-2018 9 months)



LVC arXiv:1606.04856

Sky localization with Virgo

Actual estimates



Simulated estimates with Virgo

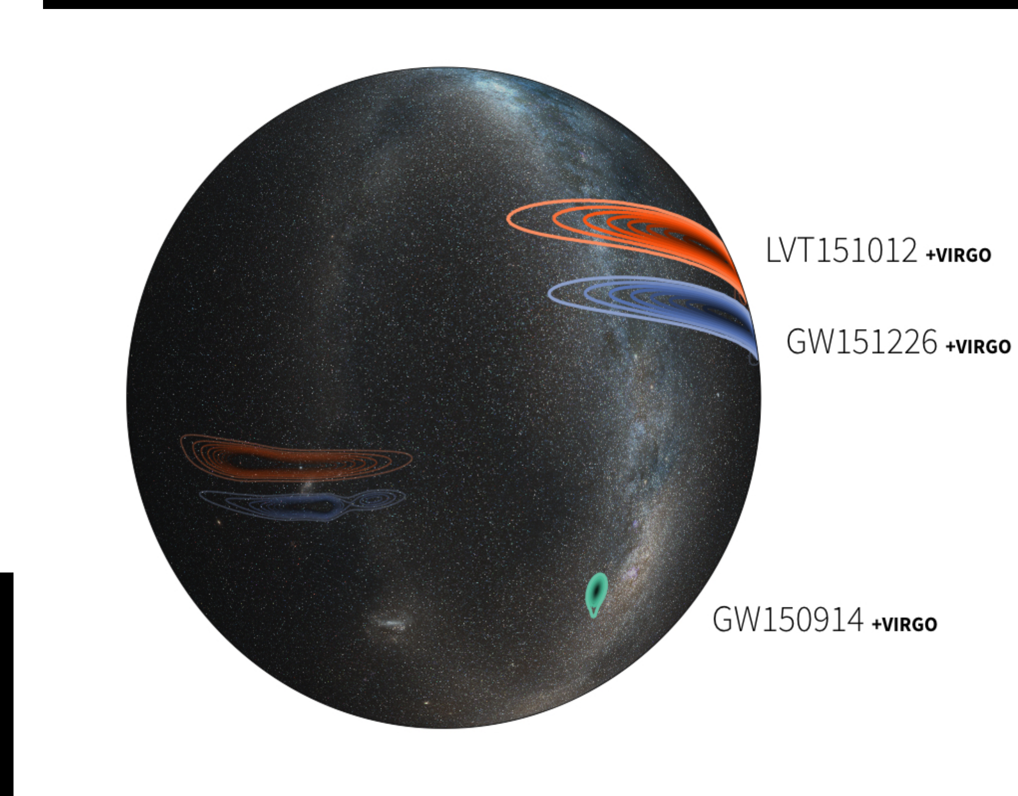


Image credit: LIGO/L. Singer/A. Mellinger

No detection of either NS-NS or NS-BH mergers in O1

Reached distance range:

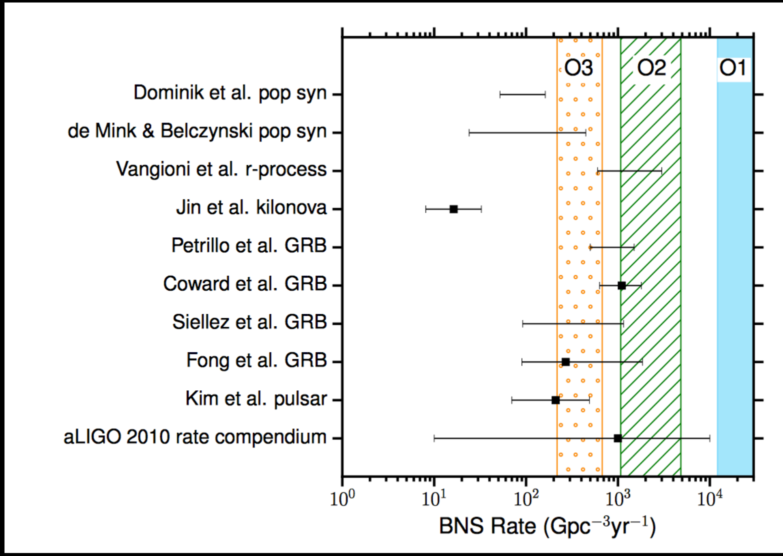
- **70 Mpc** for NS-NS 1.35±0.13 $M_\odot$
- **110 Mpc** for NS 1.4 $M_\odot$ -BH 5 $M_\odot$

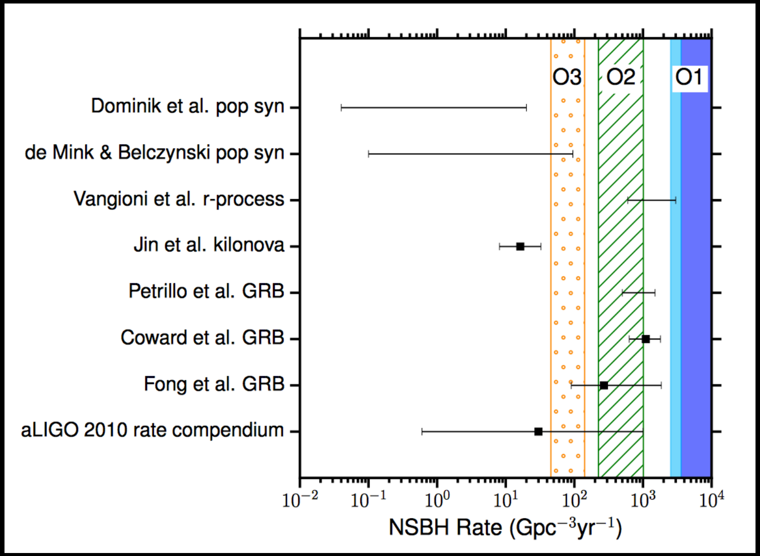
LVC 2016, arXiv:1607.07456

Upper limits on the merger rates in the local Universe:

- **< 12600** $Gpc^{-3} yr^{-1}$ for NS-NS 1.35±0.13 $M_\odot$
- **< 3600** $Gpc^{-3} yr^{-1}$ for NS 1.4 $M_\odot$ -BH 5 $M_\odot$

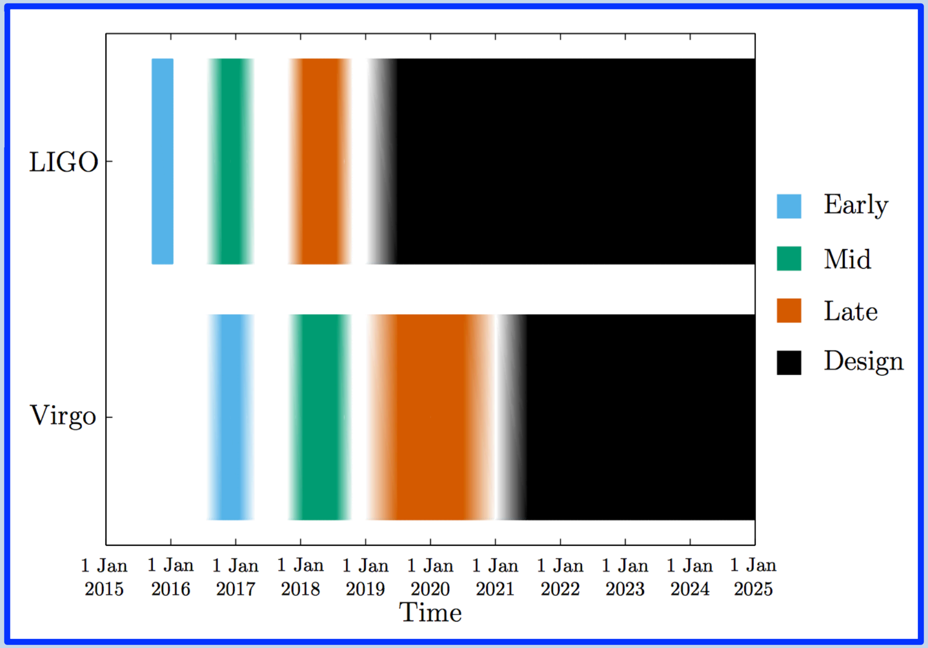
The upcoming Advanced LIGO and Virgo observing runs would place significant constraints on the merger rates





Prospects of Observing and Localizing GWs

Sensitivity evolution and observing runs

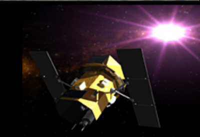


LVC 2016, LRR, 19, 1

Observing schedule, sensitivities, and source localization for BNS

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	—	—	—

Multi-messenger astronomy with the advanced GW detectors



GWs

- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance
- Compact object binary rate

EM emission

- Energetics
- Magnetic field strength
- Precise (arcsec) sky localization
- Host galaxy
- Redshift
- Nuclear astrophyisics

→ **To confirm the short GRB progenitor**

→ **To probe geometry of the systems and emission models**

→ **To probe birth and evolution of compact objects**

→ **To investigate the origin of the heavy elements in the Universe**

→ **To probe the NS equation of state**