

Localization and broadband follow-up of the Gravitational-Wave Transients

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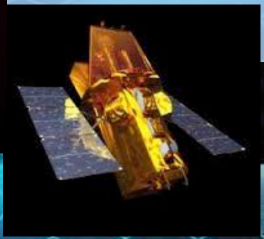
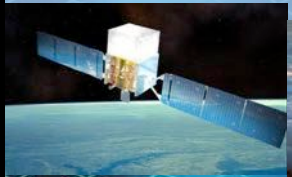
(Università di Urbino/INFN Sezione di Firenze)

on behalf of the LIGO Scientific collaboration and Virgo collaboration

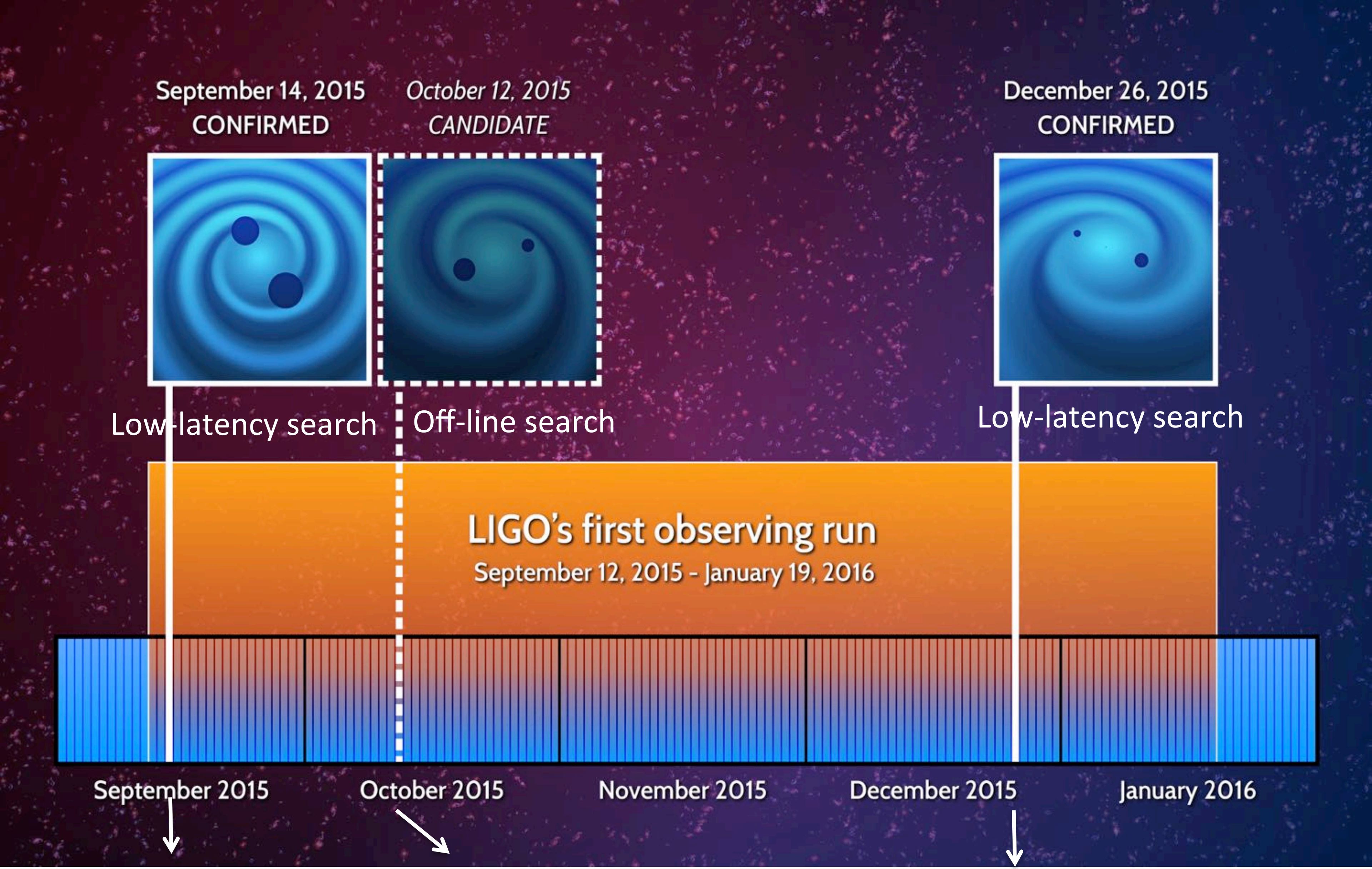


RICAP 16

6th Roma International Conference on AstroParticle Physics

INFN Istituto Nazionale di Fisica Nucleare · Università degli Studi di Roma Tor Vergata · Sapienza Università di Roma · Roma Tre Università degli Studi Dipartimento di Fisica

Futuro in Ricerca

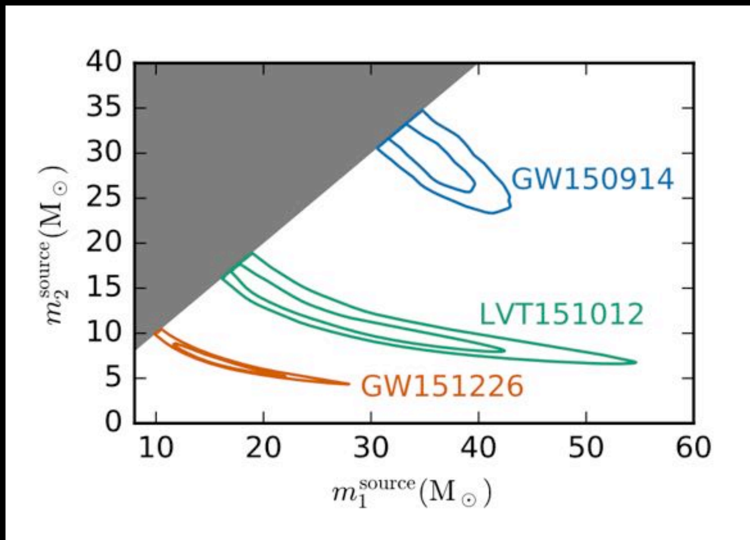


SNR=24
FAR < 6 x 10^{-7} yr^{-1}
Significance > 5.3 σ

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

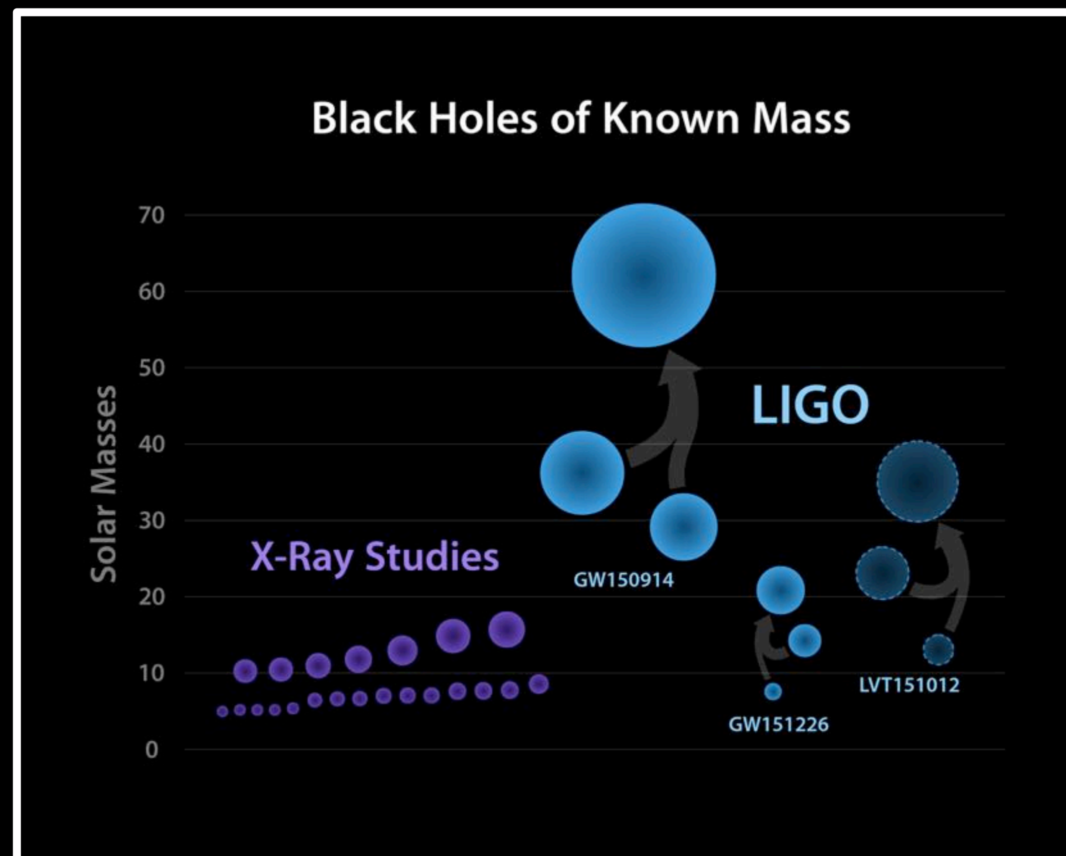
SNR=13
FAR < 6 x 10^{-7}
Significance > 5.3 σ

Parameters of the BBH 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}



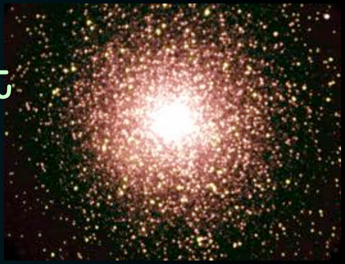
LVC arXiv:1606.04856

LVC 2016 Phys. Rev. Lett. 116, 241103

Where black holes form?

Galaxy field
R~10 kpc,
N ~ 10^{10} stars

Dense enviroment
star clusters
R~1-10 pc,
N ~ 10^{3-7} stars



How do they form binary system?

Isolated binary

Dynamical interactions

Both formation paths are consistent with
GW150914 and GW151226
For GW150914, low metallicities are necessary

Where black holes form?

Galaxy field
R~10 kpc,
N ~ 10^{10} stars

Dense enviroment
star clusters
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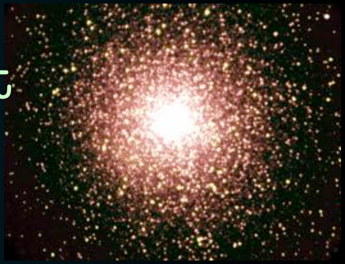
N ~ 10^{3-7} stars



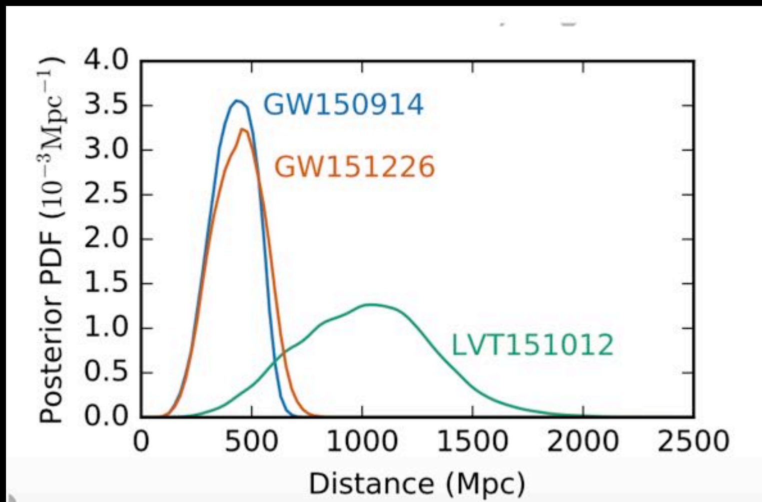
How do they form binary system?

Isolated binary

Dynamical interactions

Crucial: 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

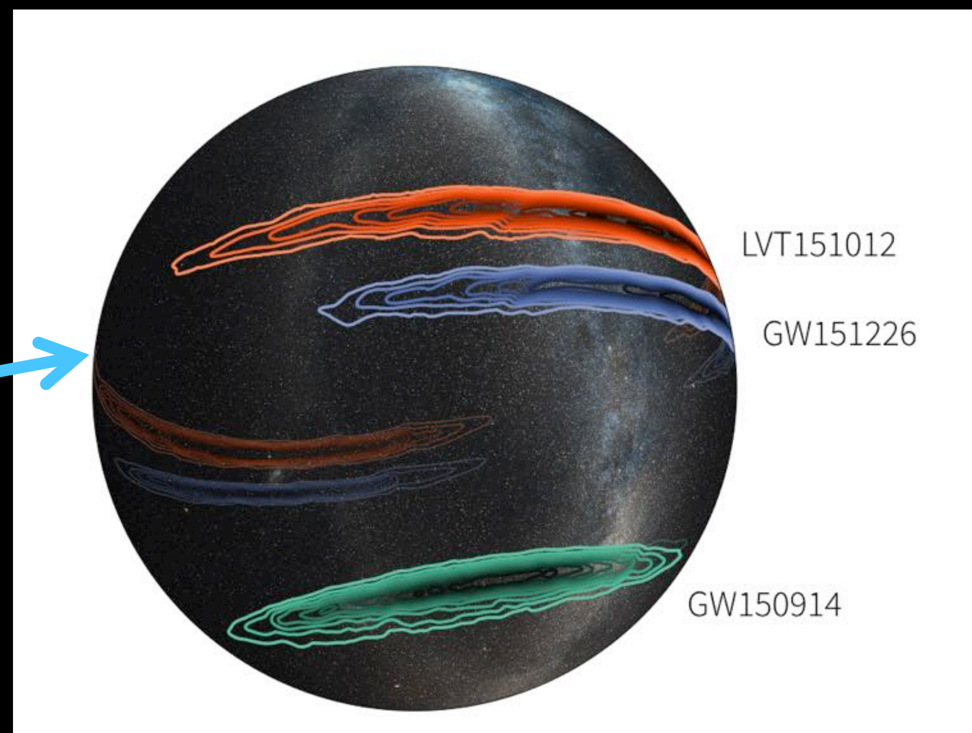


Image credit: LIGO/L. Singer/A. Mellinger

Final Sky localizations

Event	GW150914	GW151226	LVT151012
Sky localization $\Delta\Omega$/deg^2	230	850	1600

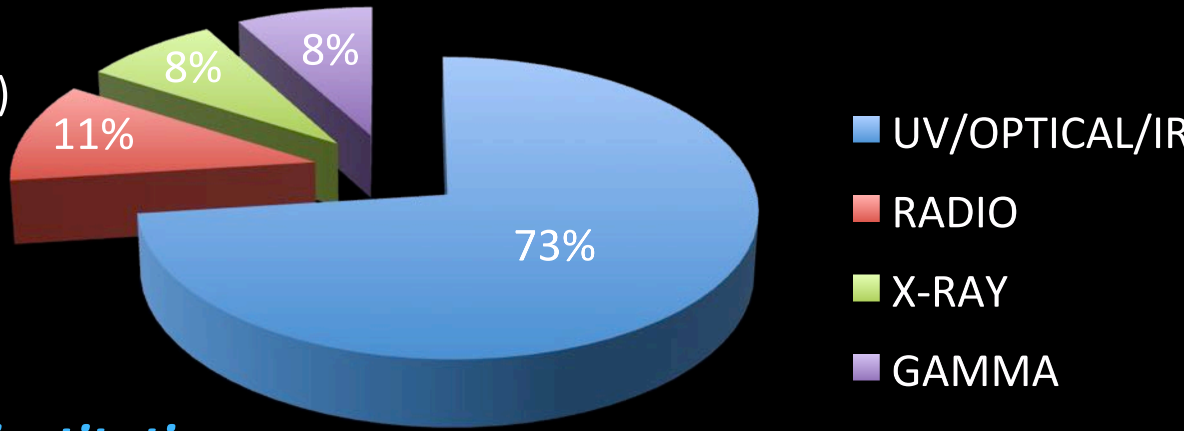
LVC GW-EM follow-up program

80 MoUs involving

- **170 instruments**

(satellites/ground-based telescopes)

covering the full spectrum from radio to very high-energy gamma-rays!



- *Worldwide astronomical institutions, agencies and large/small teams of astronomers*

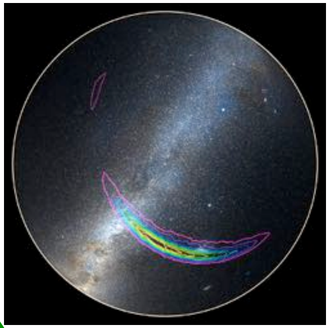
65 teams of astronomers were ready to observe during O1 (September 2015 – January 2016)!

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

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

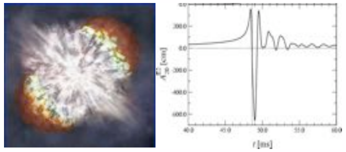
LIGO-H LIGO-L

Virgo

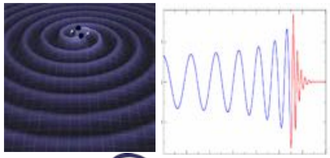


Event validation

Low-latency Search
to identify the GW-candidates



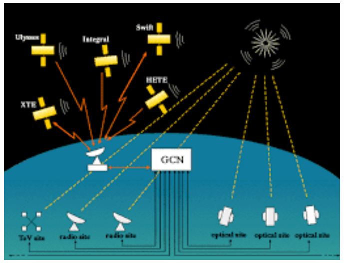
Unmodeled GW burst search



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

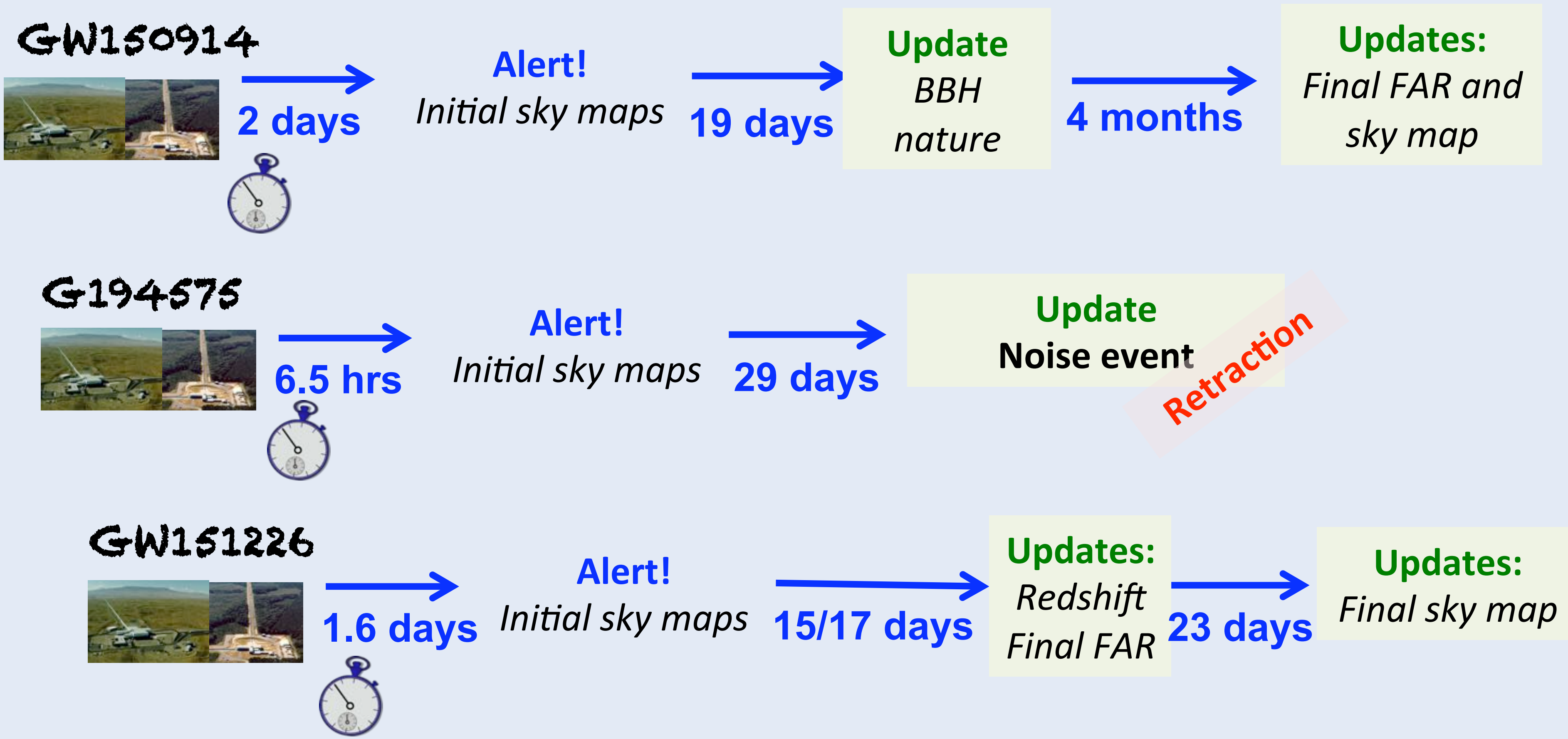


→ **a few min** → **15/30 min**

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

EM follow-up program - O1 run

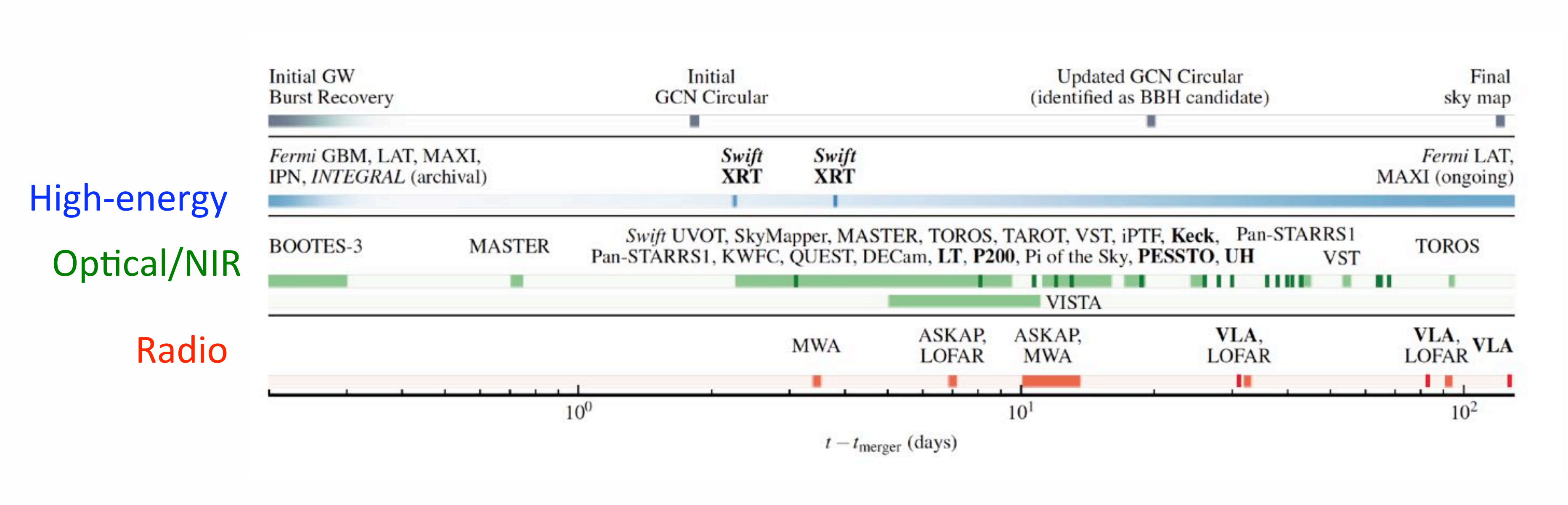
- **Three alerts** sent to 65 groups of astronomers with observational capabilities
- **About 40 groups followed-up at least one alert** giving a broadband coverage of the sky maps and the rapid characterization of the candidate counterparts



GW150914

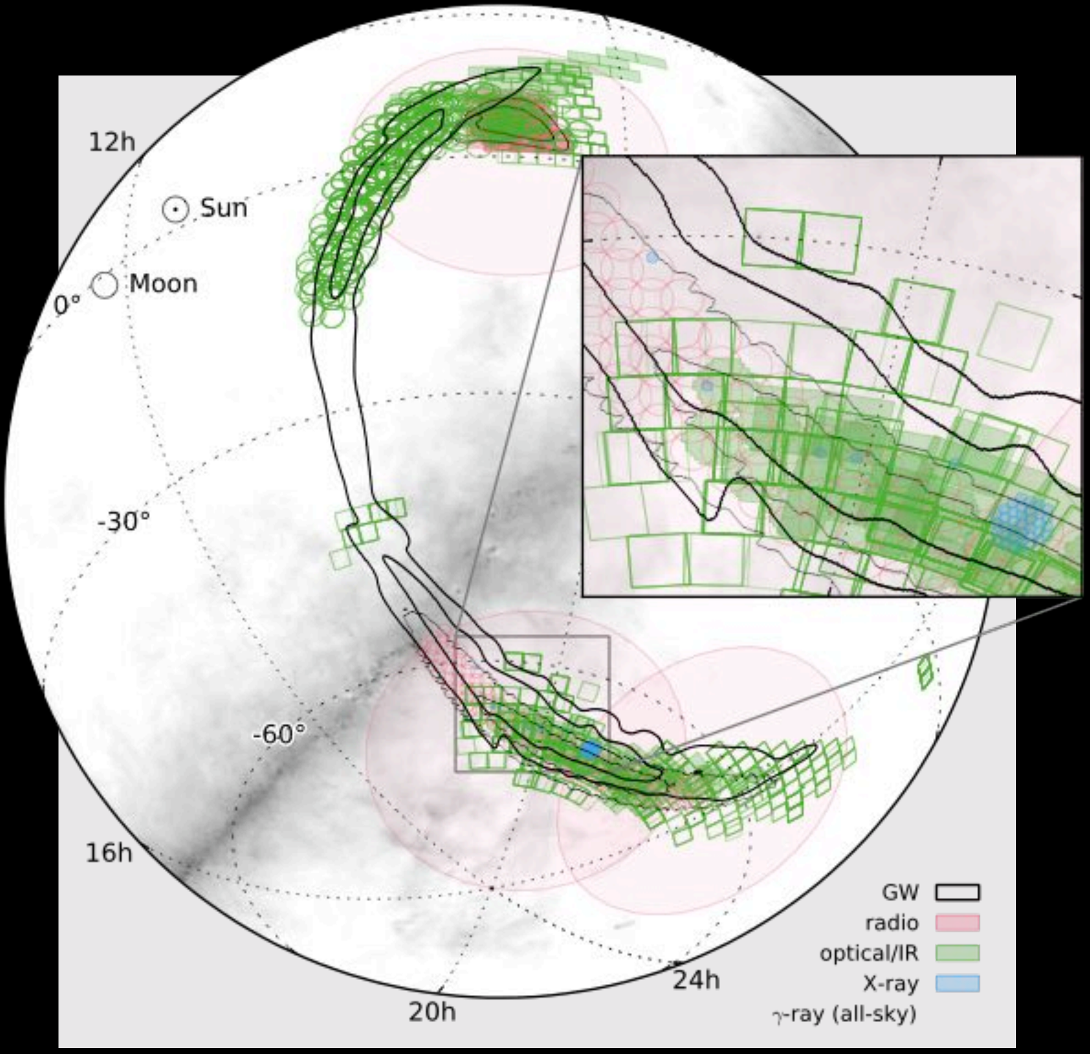
EM follow up observations and archival searches

- ***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 arXiv1602.08492
LVC+astronomers arXiv1604.07864
Connaughton et al. arXiv:1602.03920
Savchenko et al. 2016 ApJL 820, 36
Smartt et al. arXiv160204156S
Evans et al. MNRAS 460, L40
Annis et al. arXiv:1602.04199
Kasliwal et al. arXiv:1602.08764
Morokuma et al. arXiv:1605.03216
Fermi-LAT collaboration APJL, 823,2
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. arXiv:1602.04198

Sky map coverage



Skymap coverage/Depth and Results Summary

Most complete coverage in the **gamma-ray down to 10^{-7} erg cm^{-2} s^{-1}**

X-rays coverage complete down to 10^{-9} erg cm^{-2} s^{-1} (MAXI),
relatively **sparse at fainter flux** with the Swift XRT

Fermi-GBM sub-threshold search → **weak signal** of 1 sec 0.4 s after the event
fluence (1 keV - 10 MeV) = 2.4×10^{-7} erg cm^{-2}
FAR 4.79×10^{-4} Hz, FAP 0.0022
(**Connaughton et al. arXiv:1602.03920**)

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

No signal detected by **AGILE** (**Tavani et al. arXiv:1604.00955**) and **MAXI**

Optical facilities together tiled about **900 deg^2** with a **contained probability of over 50% of the initial sky map** and slightly less **of the refined sky map**

The **depth varies widely** among these facilities, **DES** and **VST** deepest surveys **22.5**

Deep photometry, broadband observations and spectroscopy → candidates to be normal population type Ia and type II SNe, dwarf novae and active galactic nuclei, all very likely unrelated to GW150914

The **radio coverage is also extensive**, with the contained probability of 86%, dominated by **MWA** down to **200 mJy**

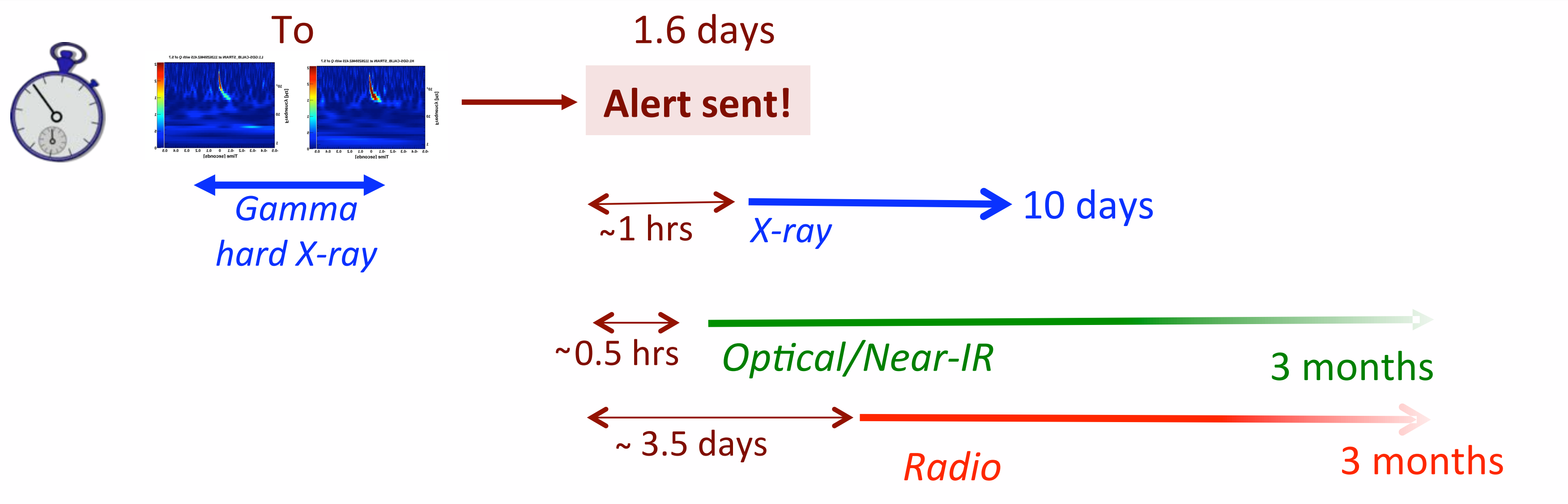
GW151226

***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

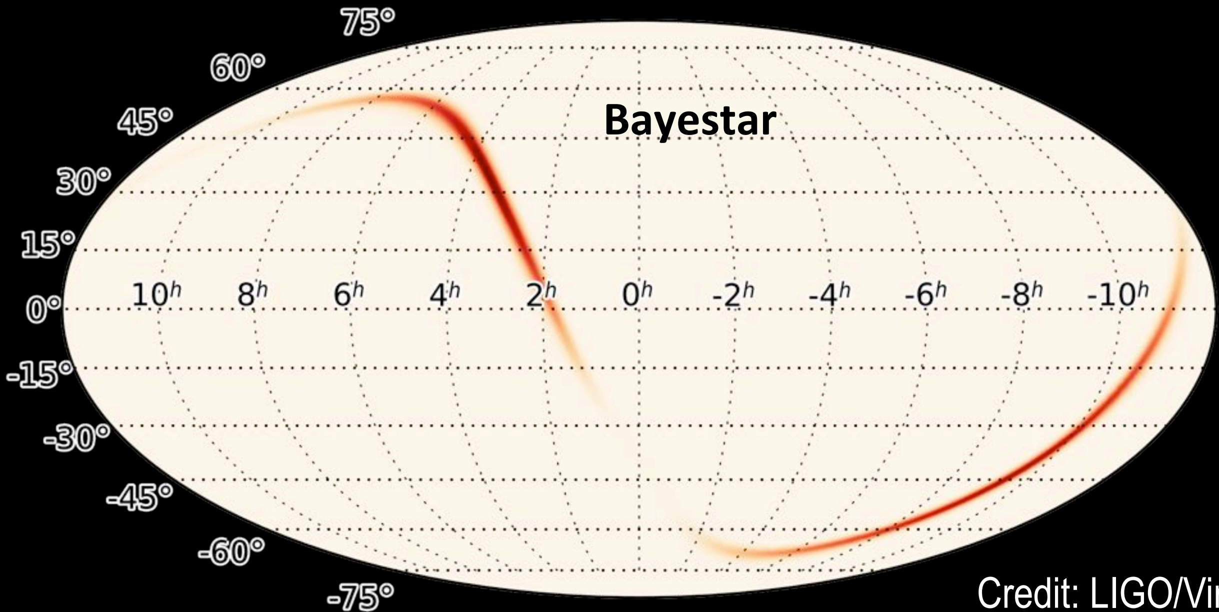
Optical-NIR → MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla–QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky observations, LCOGT/UCSB, CSS/CRTS, GTC

Radio → VLA-Corsi, LOFAR, MWA



Racusin et al. arXiv:1606.04901
Smartt et al. arXiv:1606.04795
Copperwheat et al. arXiv:1606.04574
Cowperthwaite et al. arXiv:1606.04538
Evans et al. arXiv:1606.05001

GW151226



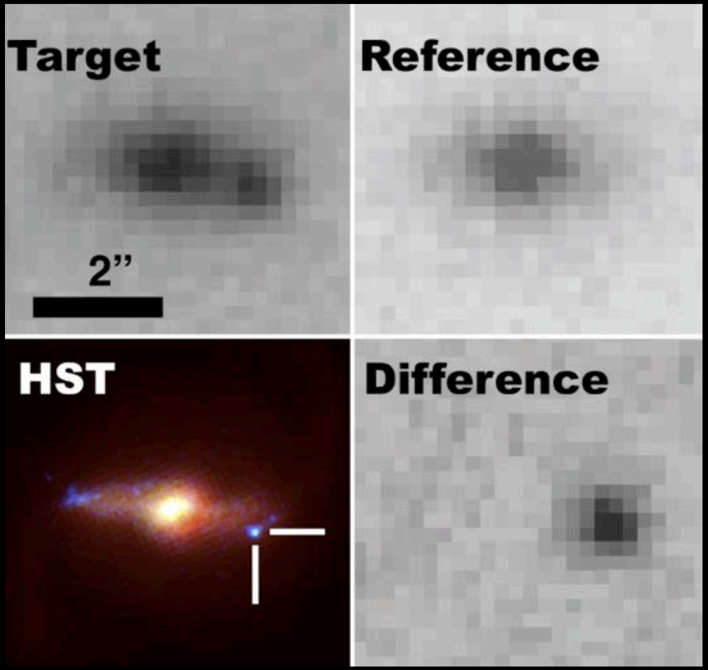
- *Large portions of the GW sky map observed*
- *Candidate counterparts rapidly characterized*
- *In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN*
- ***No EM counterpart reported***

PS15dpn → unusual transient with an explosion temporally coincident with GW151226

- rising light curve and very blue spectrum
- Hα, HeI and HeII lines
- host galaxy at z=0.175
  (Pan-STARRS/PESSTO GCNs 18786,18811)
- no Swift detection **(Swift team 18849)**
- VLA radio detection (but no variability)
  (TTU GCNs 18873)
- light curve coverage and optical/NIR spectra over months **(Smartt et al. arXiv: 1606.04795)**

→Identified as Type Ibn supernova
(GRAWITA GCN 19145)

See also iPTF GCN* 18848 and *GTC GCN 19258



Smartt et al. arXiv:1606.04795

EXCLUDED as counterpart → luminosity distance of the transient has a zero probability of being consistent with that of GW151226
(see LVC GCN 18850)

*EM follow-up of GW150914 and GW151226 demonstrates the **capability to cover large area**, to **identify candidates**, and to rapidly **activate larger telescopes***

No stellar-BBH EM emission due to the absence of the accreting material
…but some mechanisms that could produce unusual presence of matter around BHs recently discussed

Loeb 2016 ; Perna et al. 2016 ; Zhang et al. 2016

Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

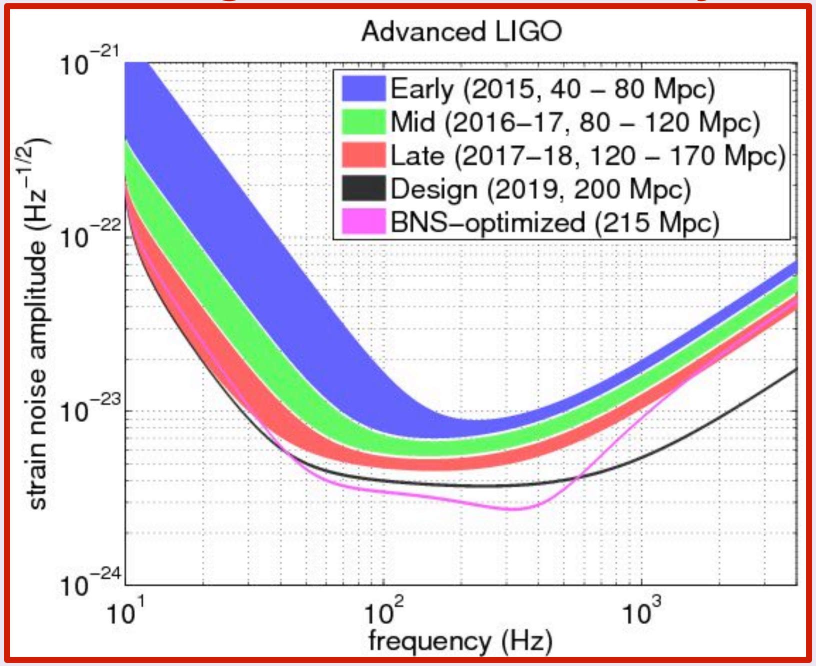
The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range
The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

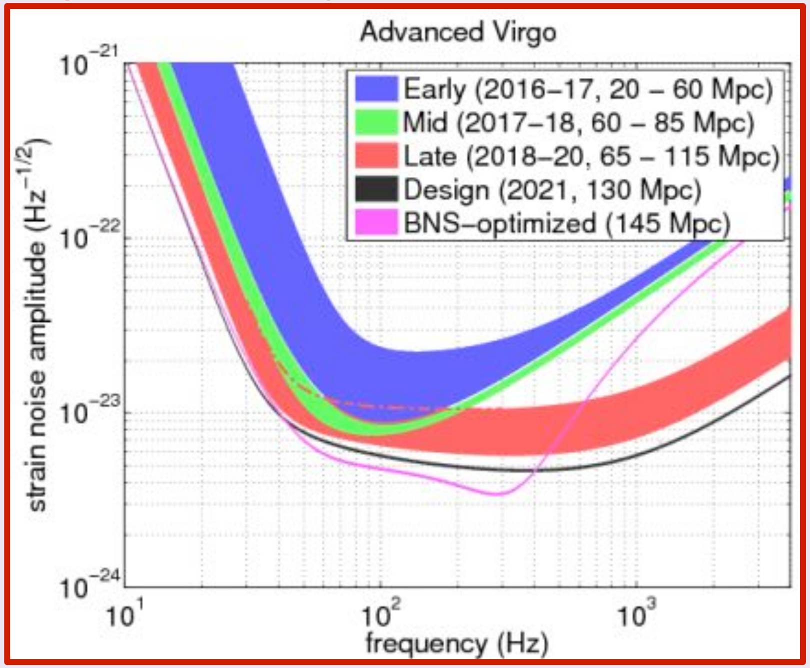
Prospects of observing and localizing GWs in the next LIGO and VIRGO scientific runs



Prospects of Observing and Localizing GWs

Progression of sensitivity and range for Binary Neutron Stars

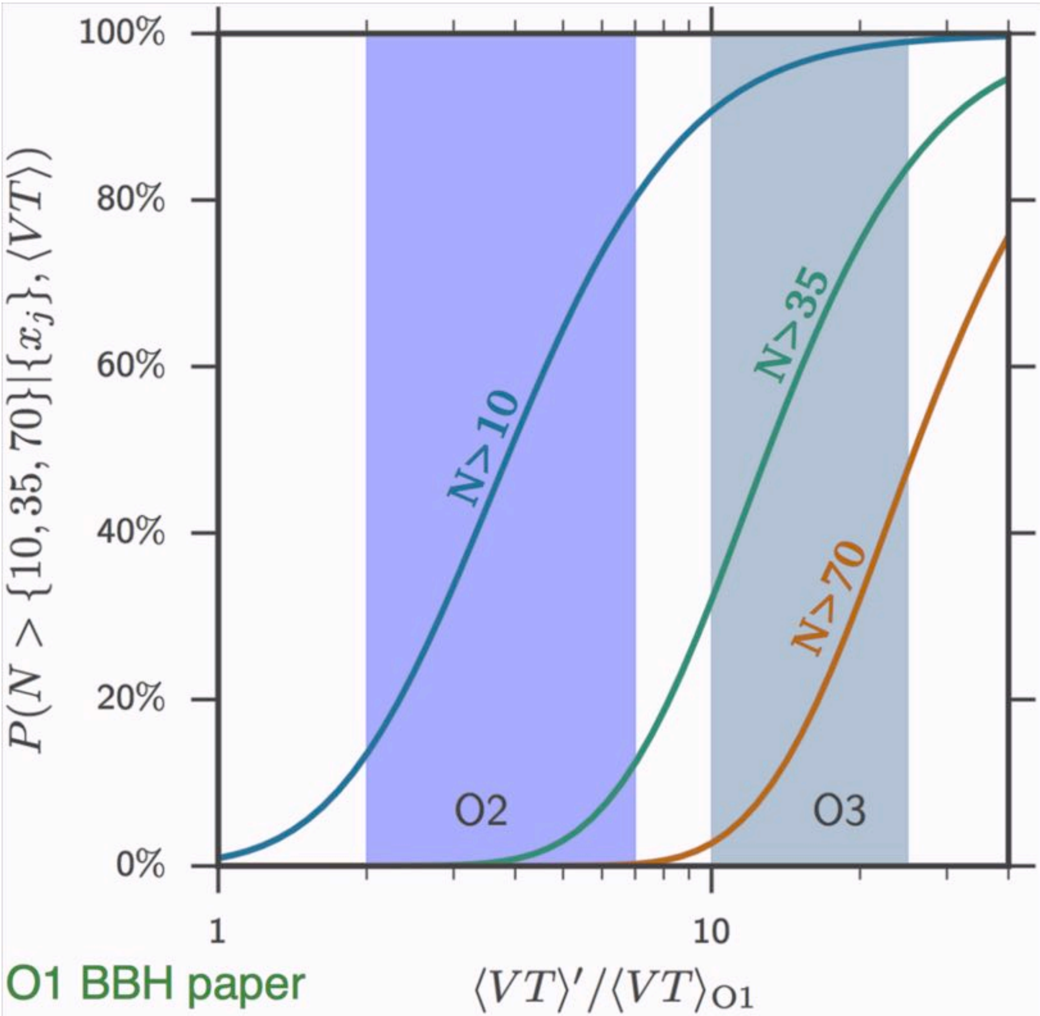




Larger GW-detectable Universe

LVC 2016, Living Reviews in Relativity, 19

BBH merger rate based on O1 observations 9-240 Gpc^{-3} yr^{-1}



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

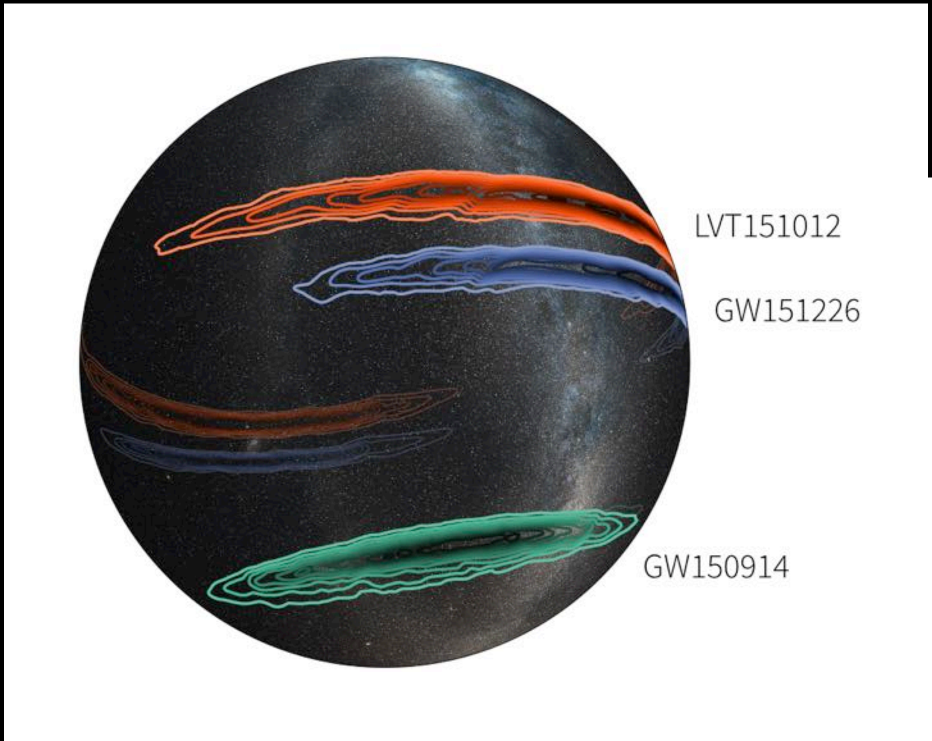
O2 → ~ 10 BBH events

O3 → ~ 35 BBH events

LVC arXiv:1606.04856

Sky localization with Virgo

Actual estimates



Simulated estimates with Virgo

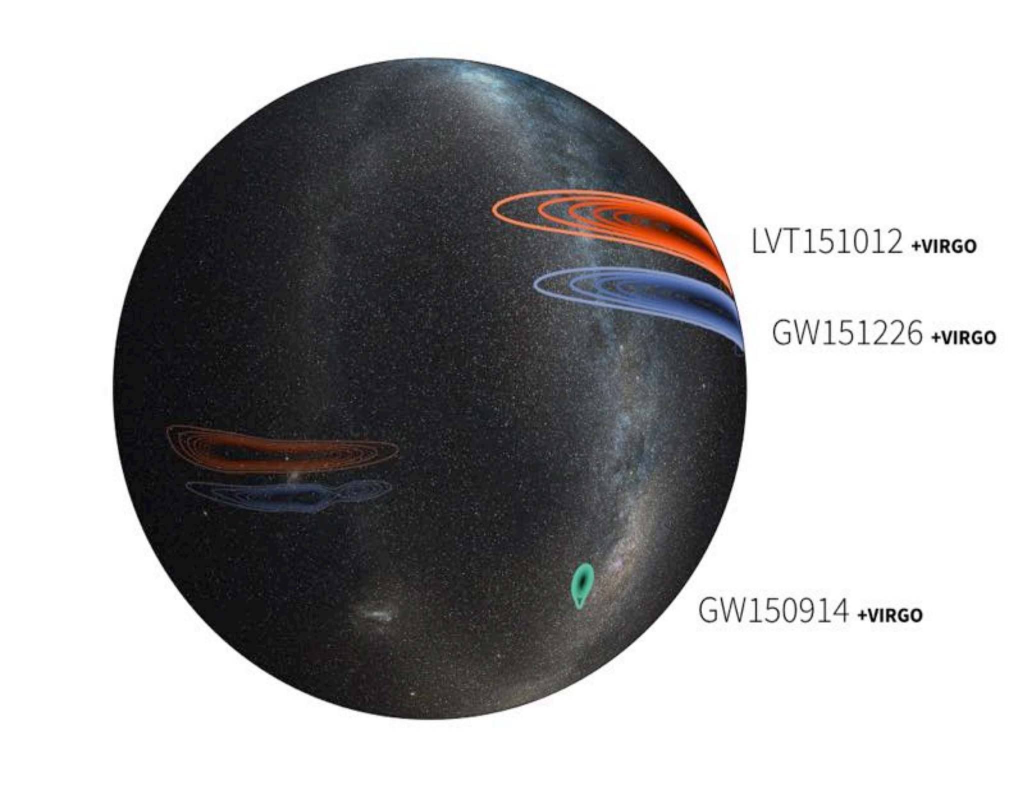
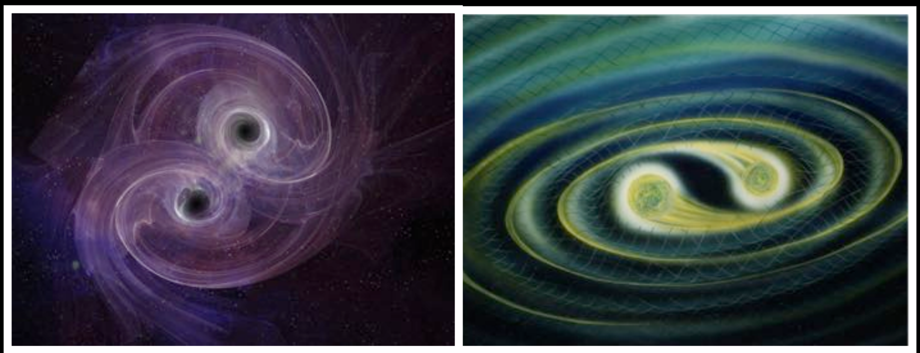


Image credit: LIGO/L. Singer/A. Mellinger

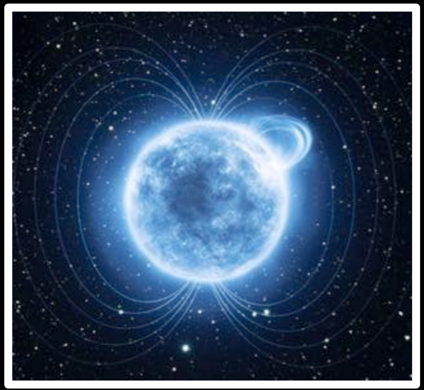
OTHER ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

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



Core-collapse of massive stars

Isolated neutron-star

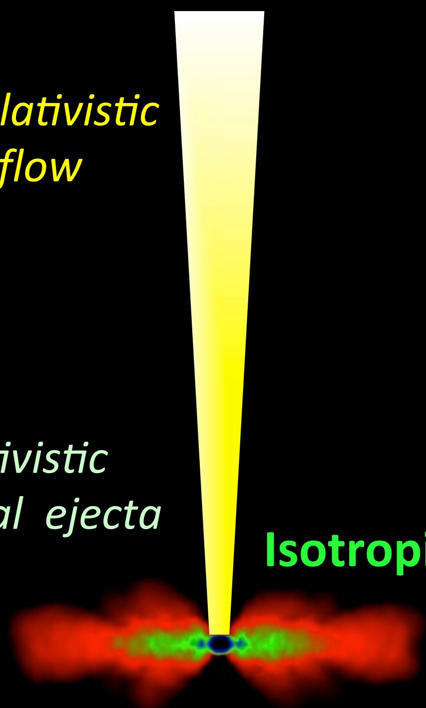


EM emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)

Ultra-relativistic outflow

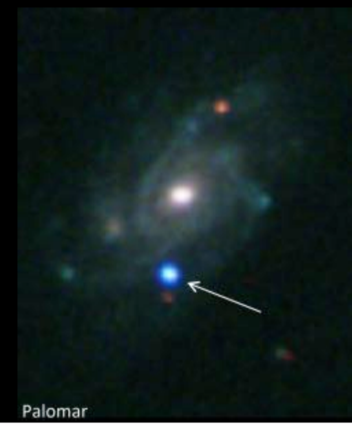


Sub-relativistic dynamical ejecta

Isotropic emission

disk wind outflow
Spin-down luminosity

Core-collapse



SBO X-ray/UV

Optical

Radio

+ Long GRB

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

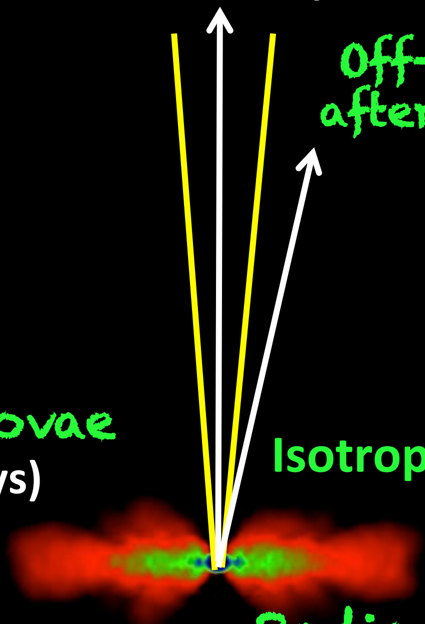
Radio/gamma-ray Pulsar glitches

EM emissions

NS-NS and NS-BH mergers

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

Off-axis afterglow



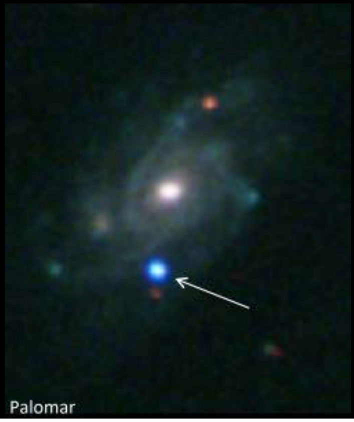
Kilonovae
(days)

Isotropic emission

X-ray (min, hrs)

Radio remnants
(months, years)

Core-collapse



SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Radio
(years)

+ Long GRB

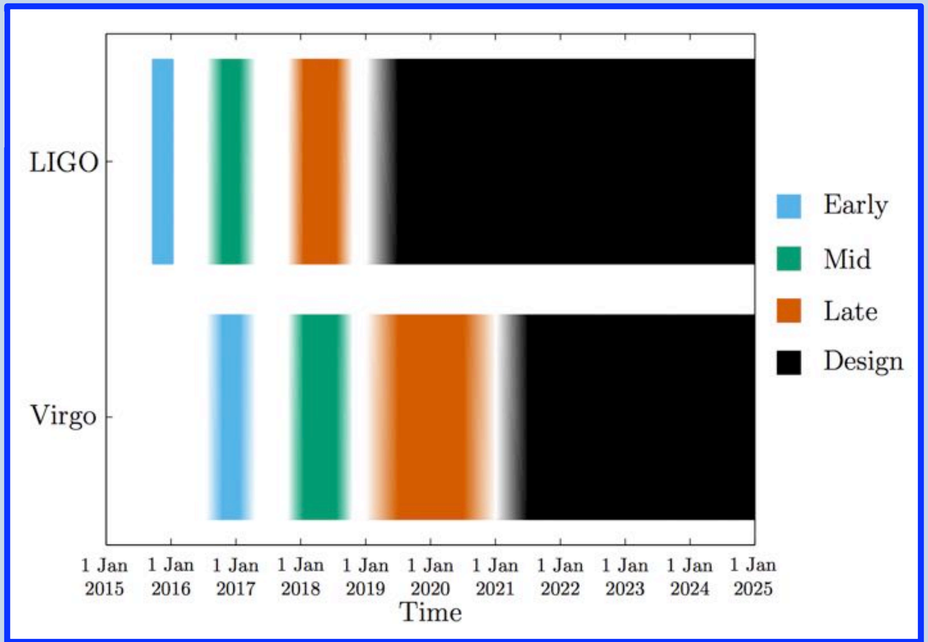
Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray Pulsar glitches

Prospects of Observing and Localizing GWs

Sensitivity evolution and observing runs

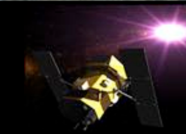


LVC 2016, LRR, 19, 1

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	—	—	—

The era of multi-messenger astronomy including GWs started!



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
- Explosion asymmetry

EM emission

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

To constrain the NS equation of state
To shed light on birth and evolution of BH
To constrain geometry of the systems and emission models

EXTRA SLIDE

Can massive black holes (>25 Mo) form?

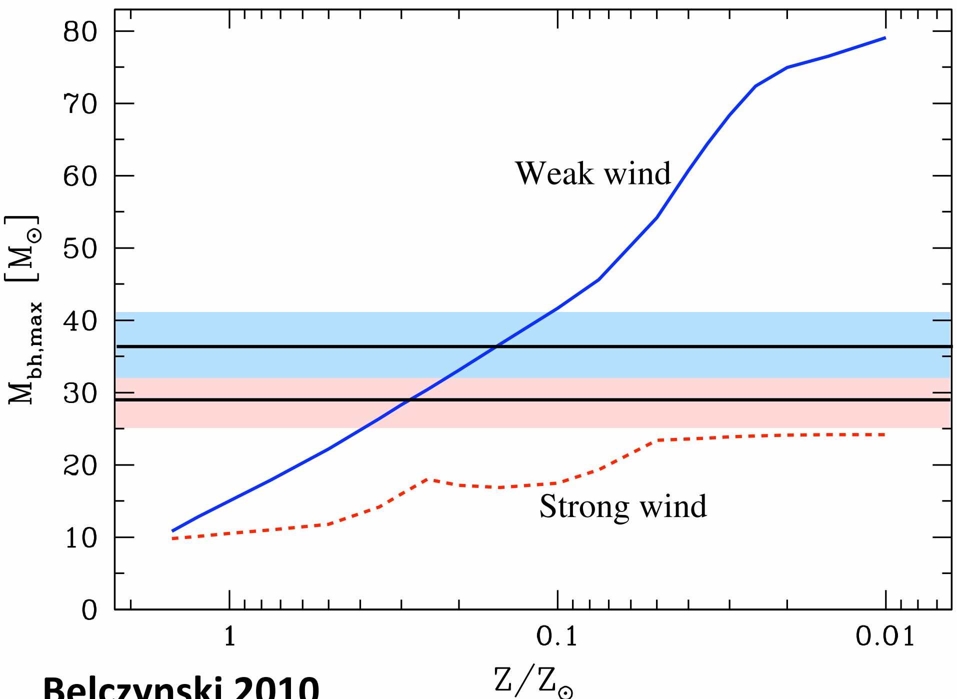
Abbott et al. 2016, ApJL, 818L

BH mass depends on:

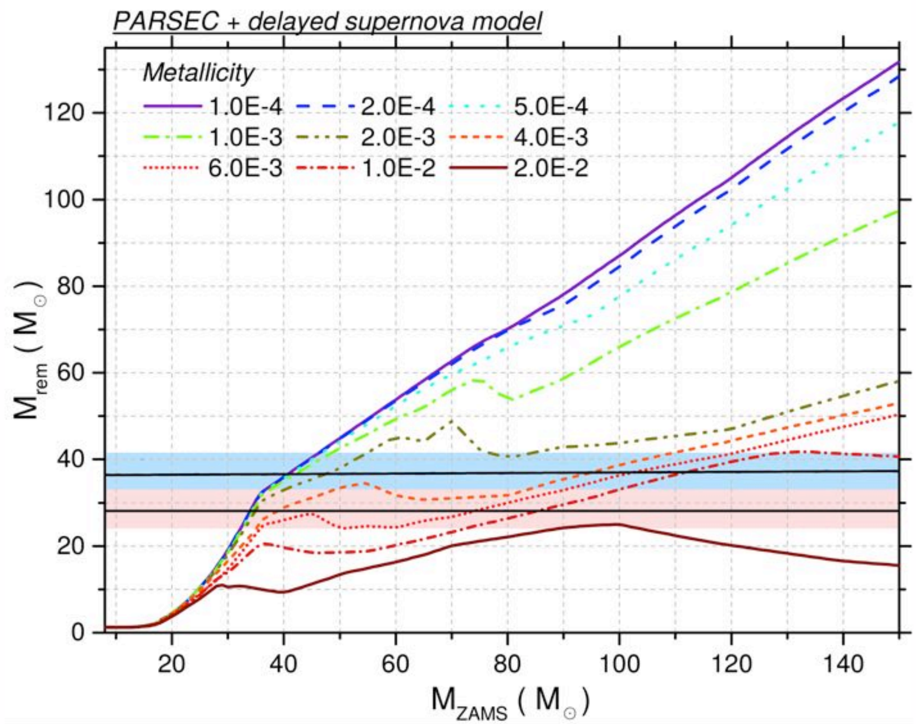
- Stellar progenitor mass
- Stellar wind mass loss
- Metallicity
- Rotation
- SN mechanism

Lower metallicity → reduced opacity, easier radiation transport and reduced momentum transfer→ reduced mass loss from stellar surface

weaker winds



Belczynski 2010



Mapelli 2013, Ziosi 2014

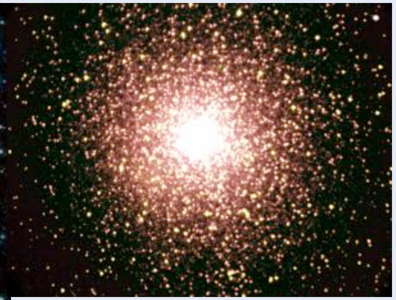
The GW150914 BBH formed in a low-metallicity environment below 1/2 Zo and possibly 1/4 Zo

Formation pathways to form massive black holes (>25 Mo)

BHs can form in dense environment or in the galaxy field:

- Globular Cluster/Young Star Cluster

R ~ 1-10 pc, N ~ 10^{3-7} stars



- Galaxy field

R~10 kpc, N ~10^{10} stars

Massive BHs form:

1) from direct collapse in metal-poor environment
   (BOTH CLUSTER AND FIELD)
2) dynamically triggered mergers of lower mass BHs or BH-star favored by three-body encounters(CLUSTER ONLY)

→ in GC unlikely since BBH ejected from host cluster before merger

→ in YSC low rate

Pathways to form "heavy" binary BHs

Isolated binary systems

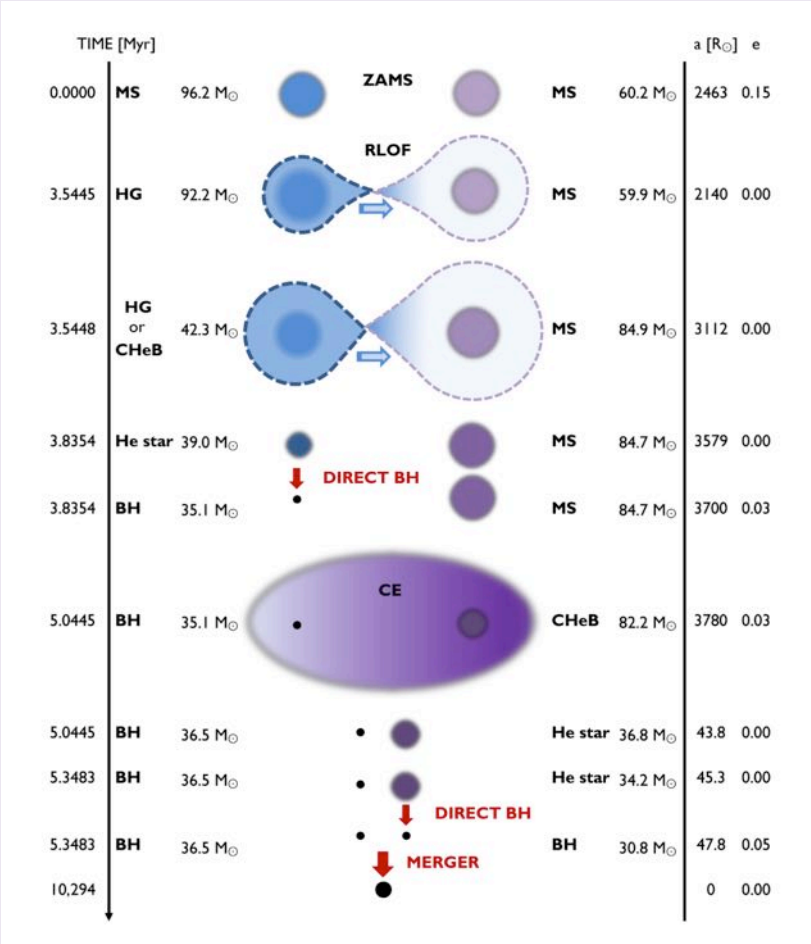
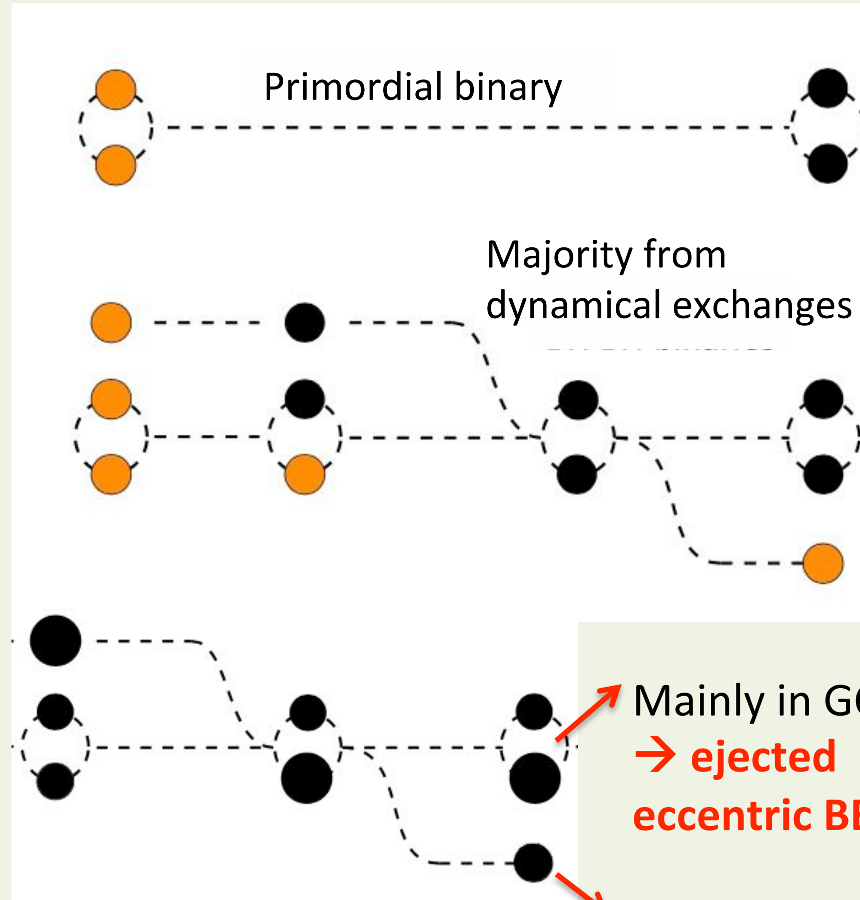


Figure: Belczynsky arXiv:1602.04531

Dense stellar environments – dynamical origin

Figure: Ziosi et al. 2014

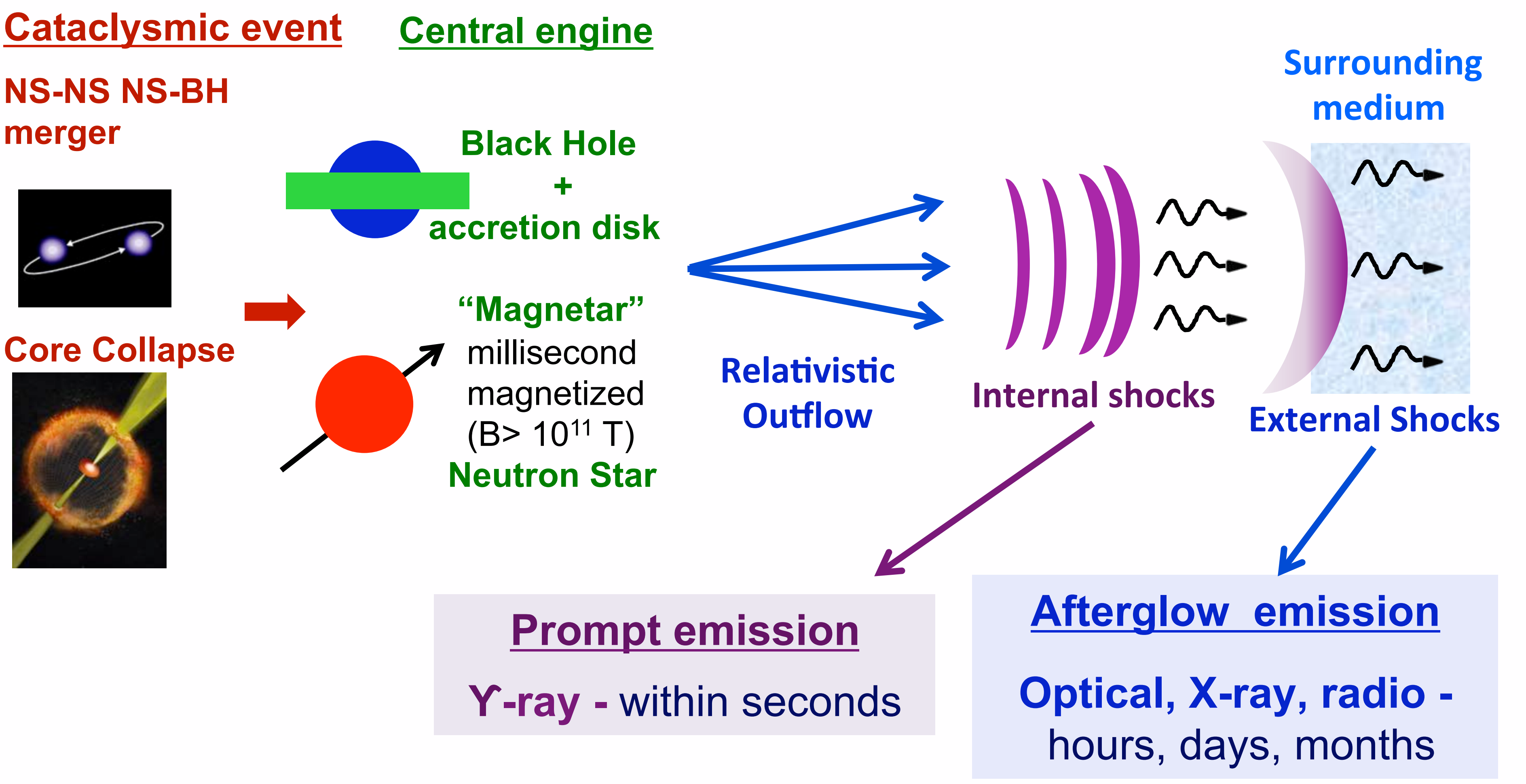


Mainly in GC
→ ejected eccentric BBH

Both scenarios consistent with GW150914 provided metallicities lower than 1/2 Zo

Crucial: identify the **host galaxy** and **study the GW source environment** through the EM counterpart discovery!

GRBs emission - Fireball Model

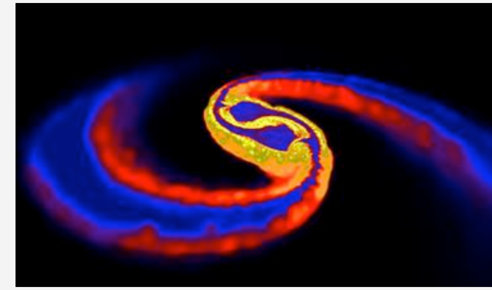


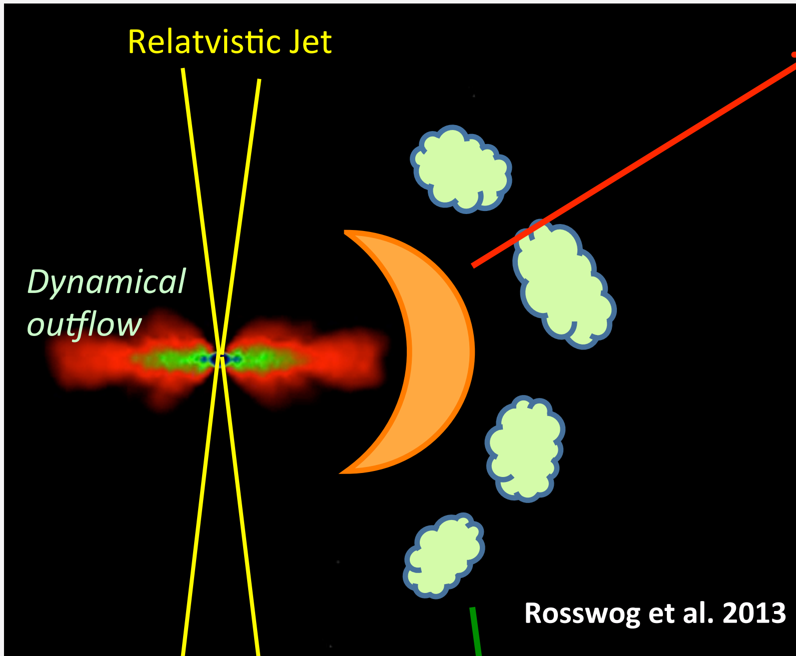
Kinetic energy of the relativistic jet converted in radiation

Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

Macronova/Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected** 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)

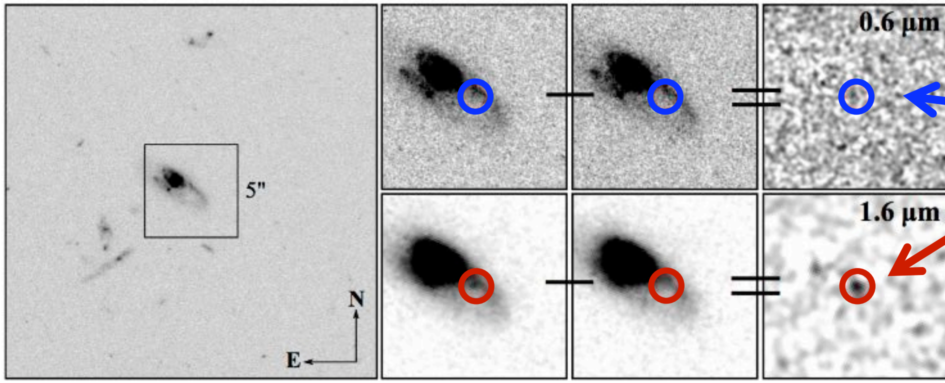
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;

RADIO REMNANT
long lasting radio signals (years)
produced by interaction of 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

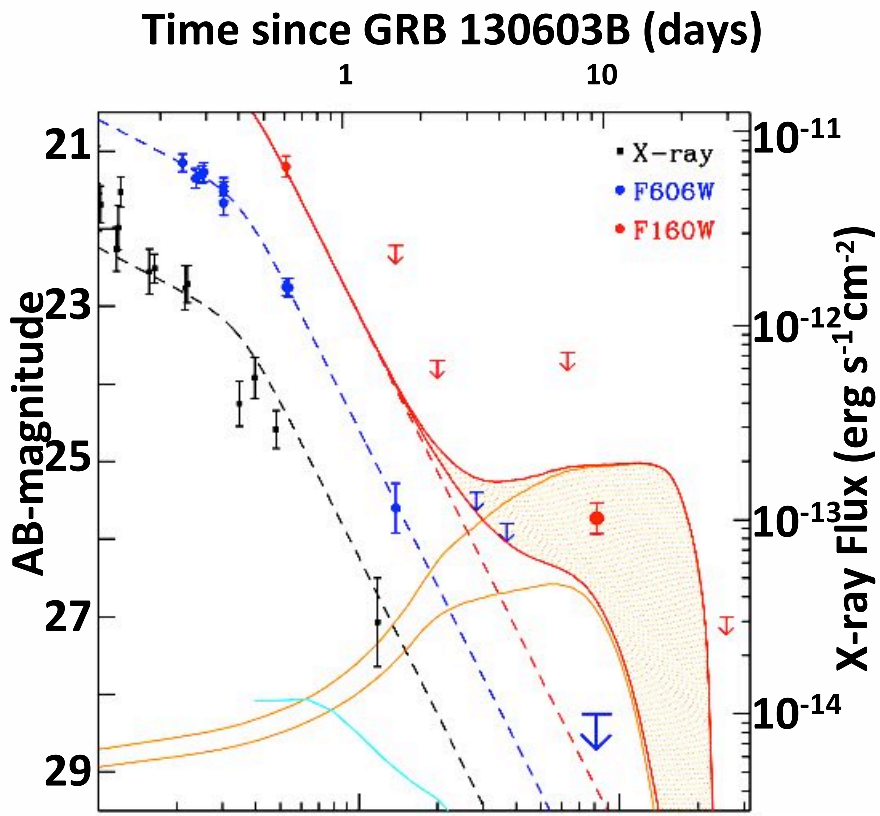


Afterglow and host galaxy z=0.356

HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

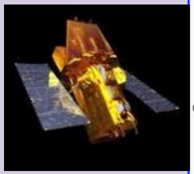


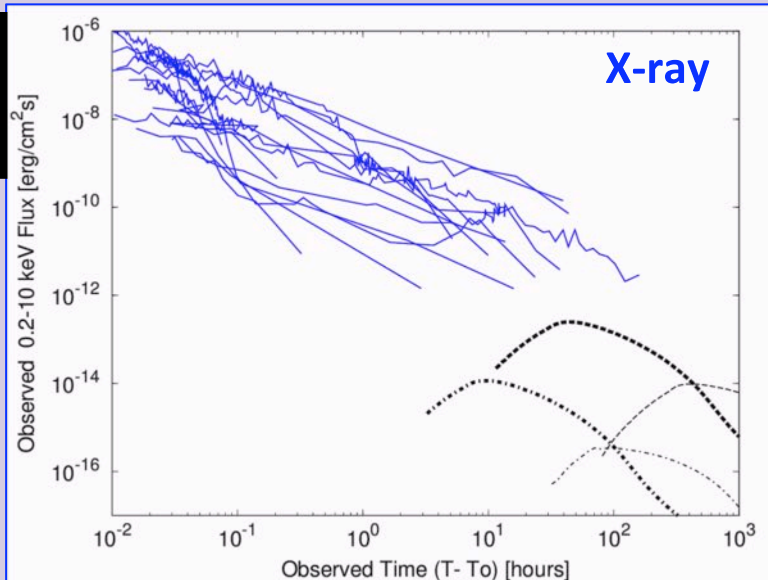
Orange curves → kilonova NIR model
ejected masses of 10^{-2} Mo and 10^{-1}Mo

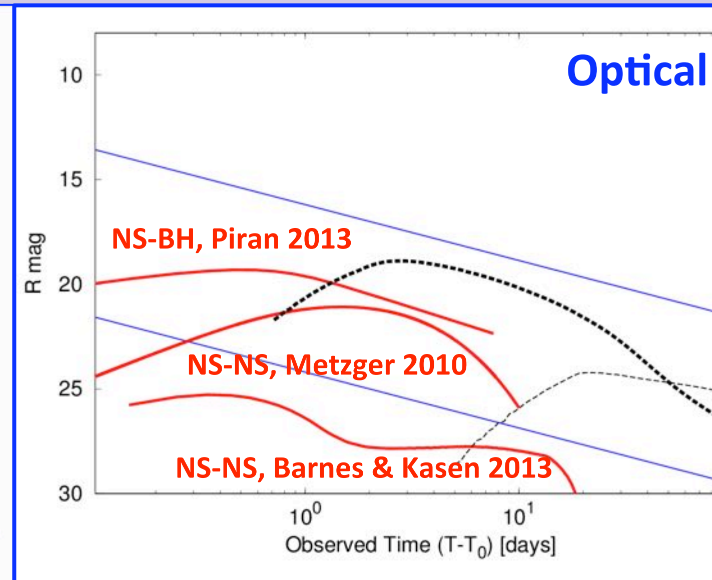
Solid red curves → afterglow +kilonova

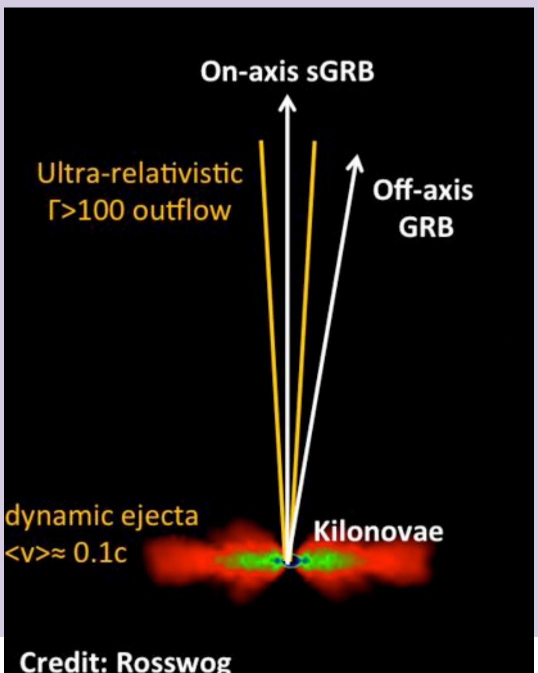
Cyan curve → kilonova optical model

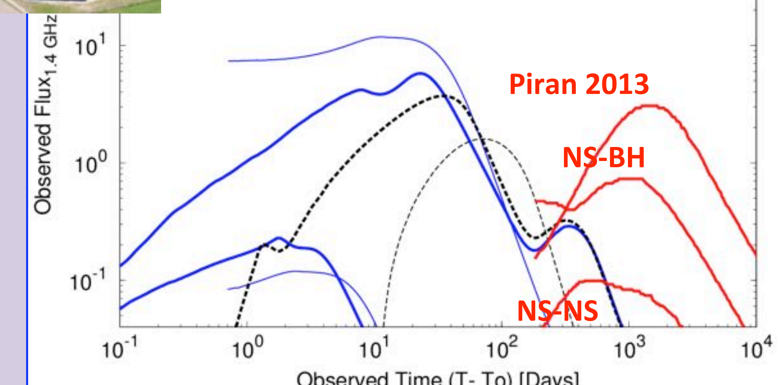
NS-NS and NS-BH merger EM-emissions











Source at 200 Mpc

- On-axis sGRB (solid blue line)
- Off-axis sGRB (dashed line)
- Isotropic kilonova (solid red line)

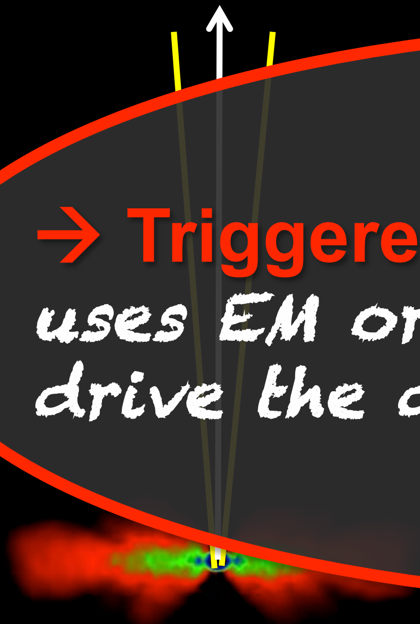
- *Different emissions*
- *Different timescales*

→ ***Global network of multi-wavelength observatories!***

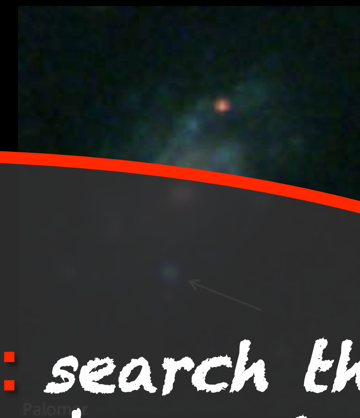
EM emissions

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)



Core-collapse of massive stars



SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray Pulsar glitches

→ 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

Abadie et al. 2012, ApJ, 760

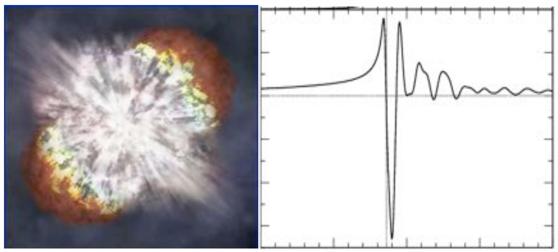
Aasi et al. 2014,PhRvL, 113

Abadie et al. 2012, ApJ, 755

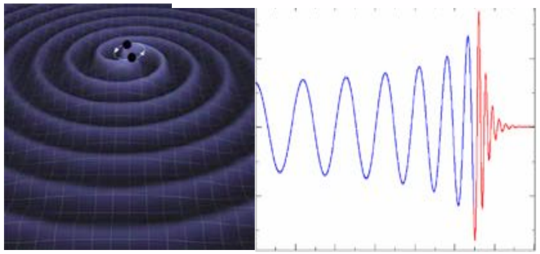
Adrián-Martínez et al. 2013, JCAP

Aartsen et al, PhysRevD, 90, 102002

GW transient searches

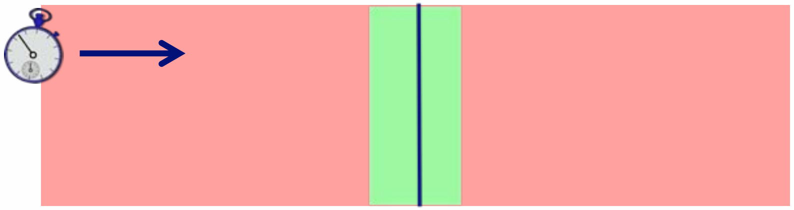


Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ **Excess power**



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

Off source | On source | Off source



Background estimate | EM trigger | Background estimate

What is time delay between the GW and EM emissions?

What is the time window to search for GWs?

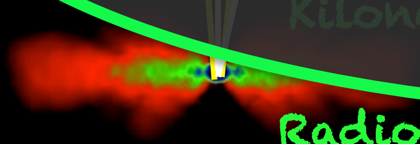
EM emissions

NS-NS and NS-BH mergers

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

Off-axis afterglow

Isotropic emission
Kilonovae (days)



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)

BH-BH mergers ?

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

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray Pulsar glitches