

Electromagnetic Counterparts Follow up of GW Sources

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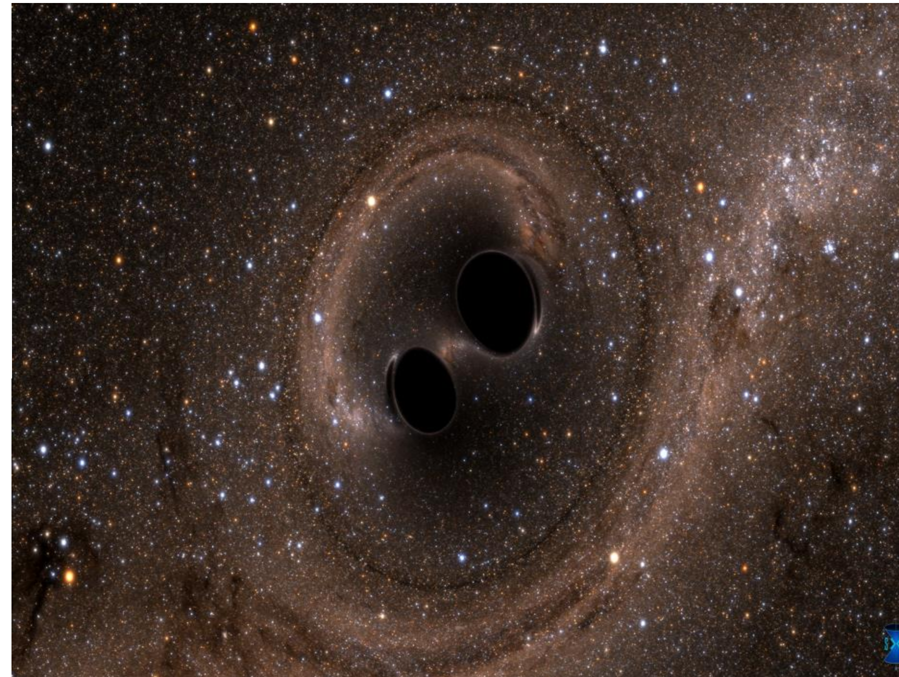
The birth of the GW astronomy….

On ***September 14, 2015 09:50:45 UTC***
the Advanced LIGOs detected the GW signal
GW150914*, originating from the coalescence of*
a ***binary black hole system***



Source parameters

Primary black hole mass	36^{+5}_{-4} *Mo*
Secondary black hole mass	29^{+4}_{-4} *Mo*
Final black hole mass	62^{+4}_{-4} *Mo*
Luminosity distance	410^{+160}_{-180} *Mpc*
Sky Localization	$590\,\mathrm{deg}^2$

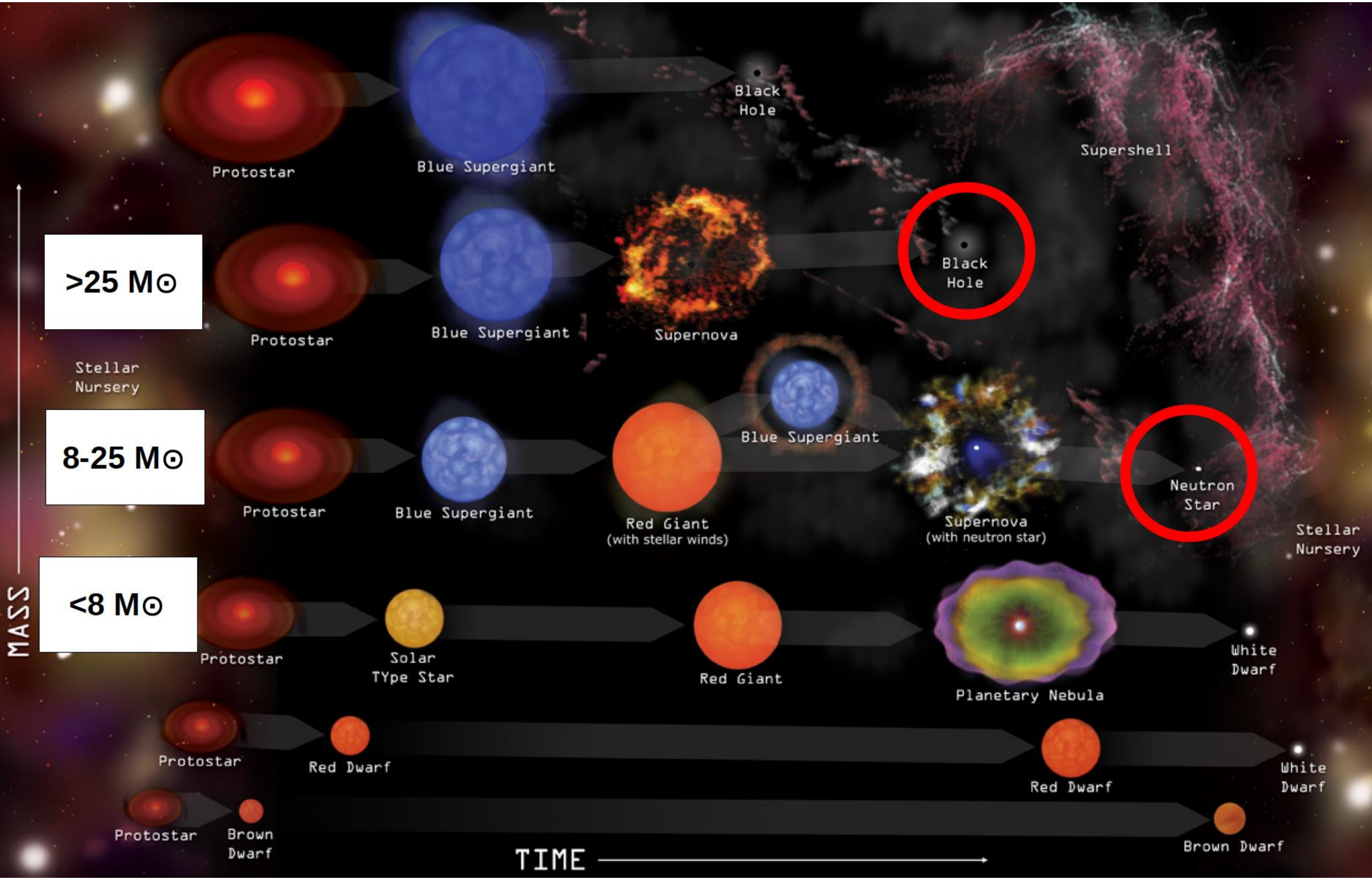
Abbott et al. 2016, PhRvL, 116

Provides the **first robust confirmation** that:

- *"Heavy" stellar-mass BHs exist*
- *Binary BHs (BBH) form in nature*
- *BBHs inspiral and merge within the age of the Universe*

How do black holes and neutron stars form?

Credits: Chandra



Can massive black holes (>25 Mo) form?

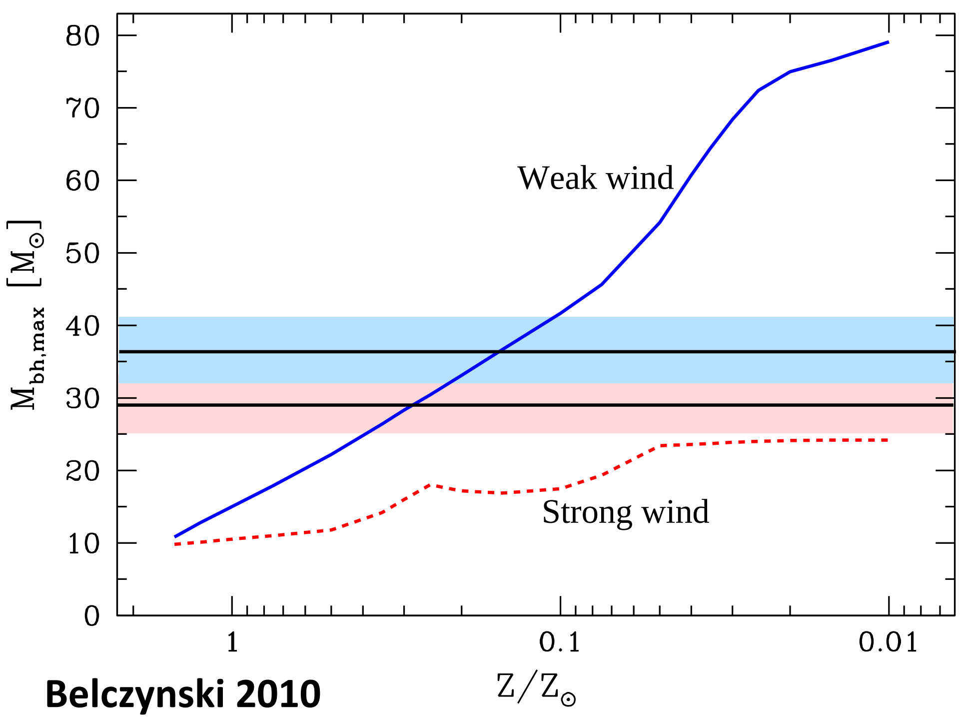
Abbott et al. 2016, ApJL, 818L

BH mass depends on:

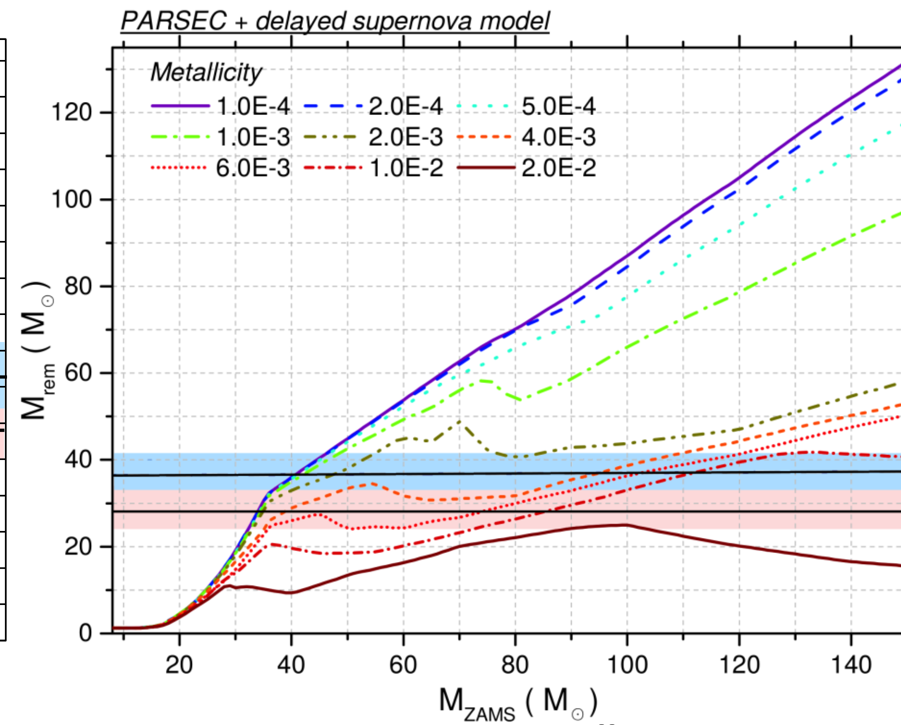
- Stellar progenitor mass
- Stellar wind mass loss
- Metallicity
- Rotation
- SN mechanism

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

weaker winds



Belczynski 2010

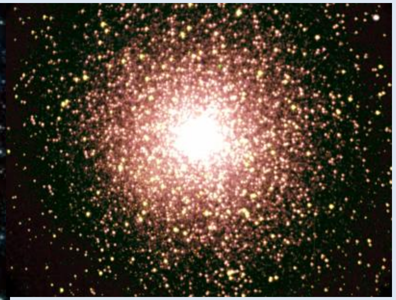


Mapelli 2013, Ziosi 2014

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

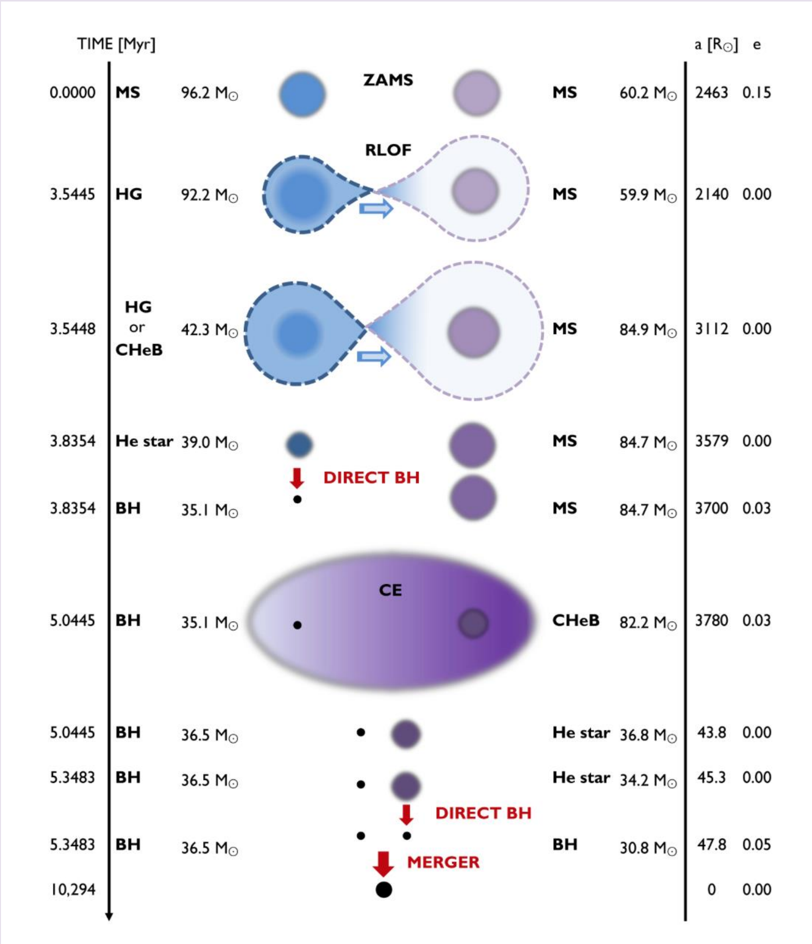
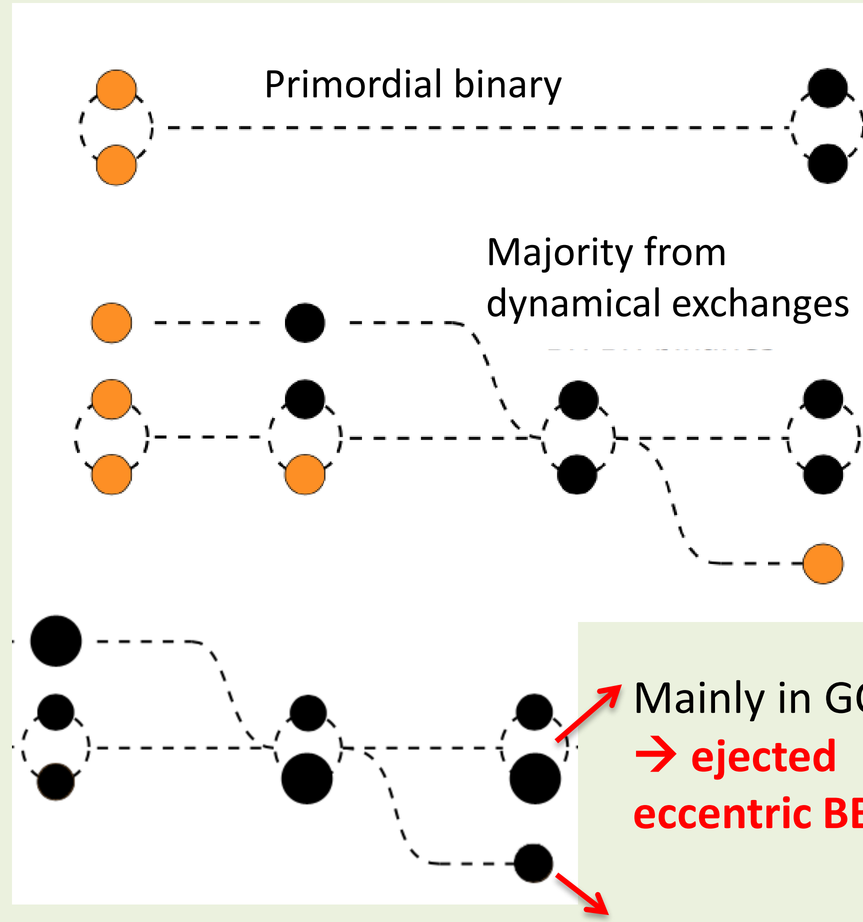


Figure: Belczynsky arXiv:1602.04531

Dense stellar environments – dynamical origin

Figure: Ziosi et al. 2014



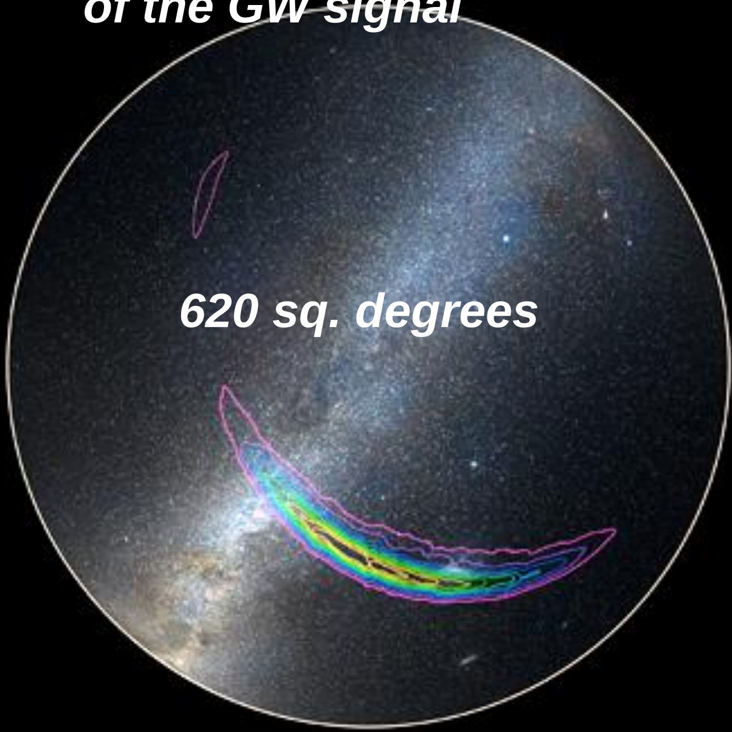
Mainly in GC → **ejected eccentric BBH**

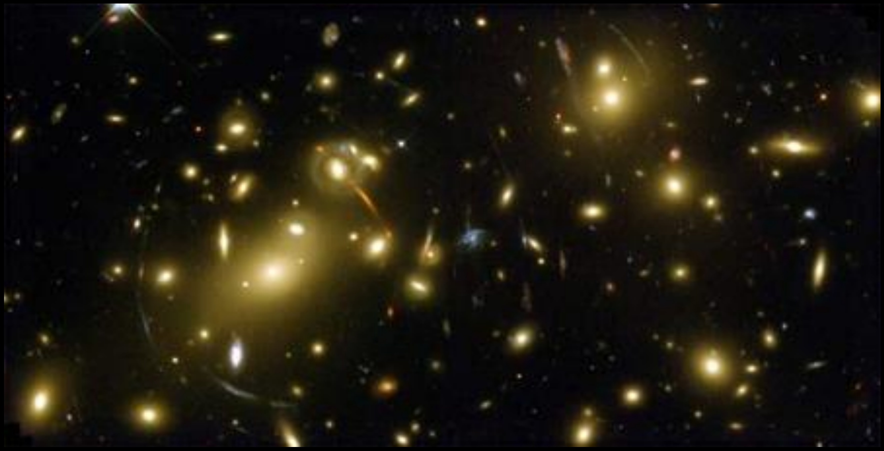
Both scenarios consistent with GW150914 provided metallicities lower than 1/2 Zo

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

GW150914: two challenges to identify the host galaxies…

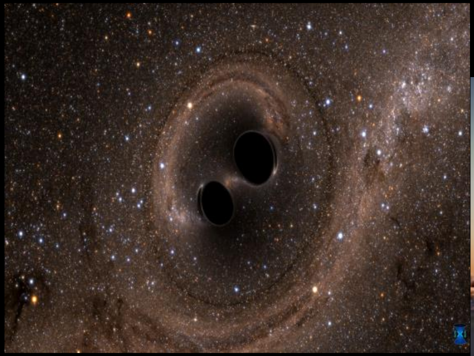
1) ***The poor sky localization of the GW signal***

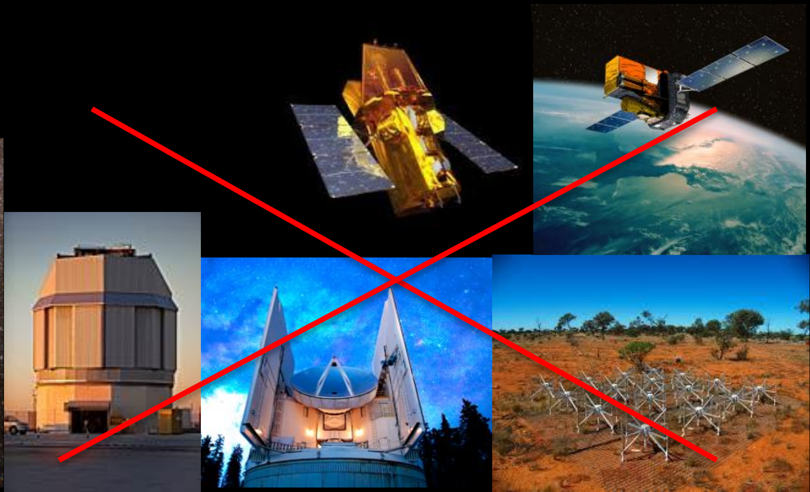




In the volume of the Universe corresponding to GW150914 there are 100000 galaxies

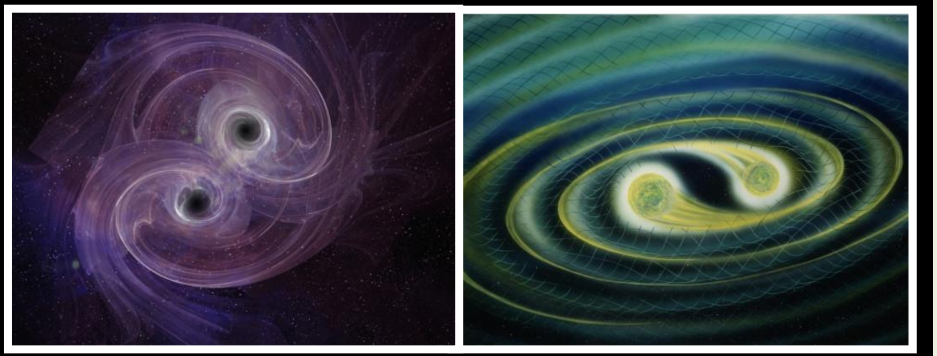
2) ***No significant EM emission is expected from stellar-mass BBH mergers***





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

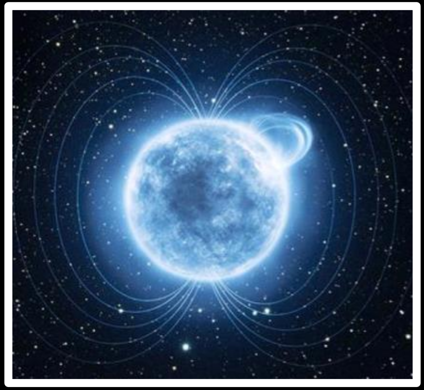
Coalescence of binary system of neutron stars (NS) and/or stellar-mass black-hole (BH)



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

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

Advanced detectors Rate and Range (design sensitivity)

Compact binary coalescence

	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

About **2 per century** in a Milky way equivalent galaxy **(Li 2011, Cappellaro 1999)**
2 per year within **20 Mpc (Li 2011)**

Rate of GW-detectable events unknown

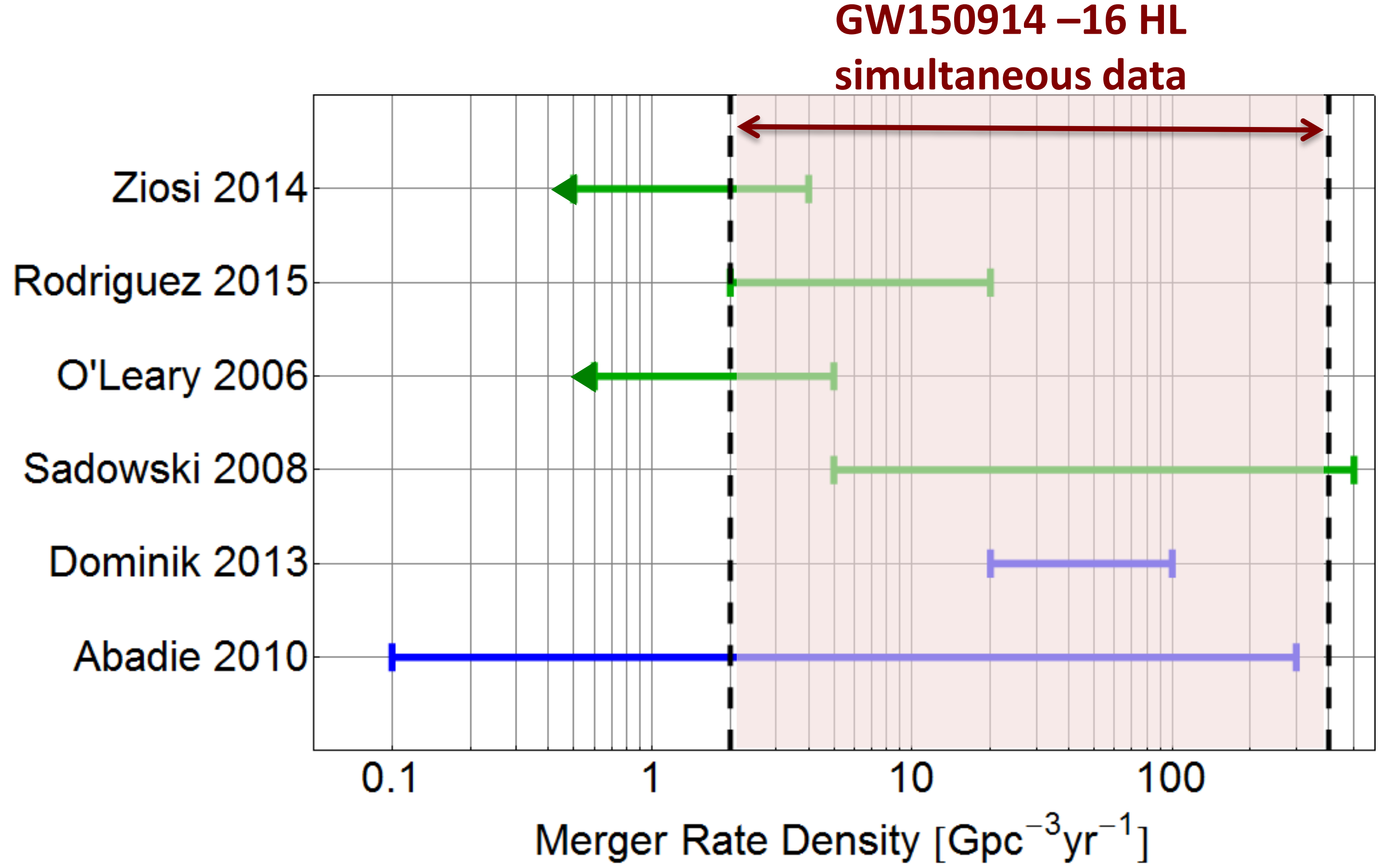
GW-signal detectable **Milky Way (Ott et al. 2012)**

Optimistic models **Tens of Mpc (Fryer & New 2011)**

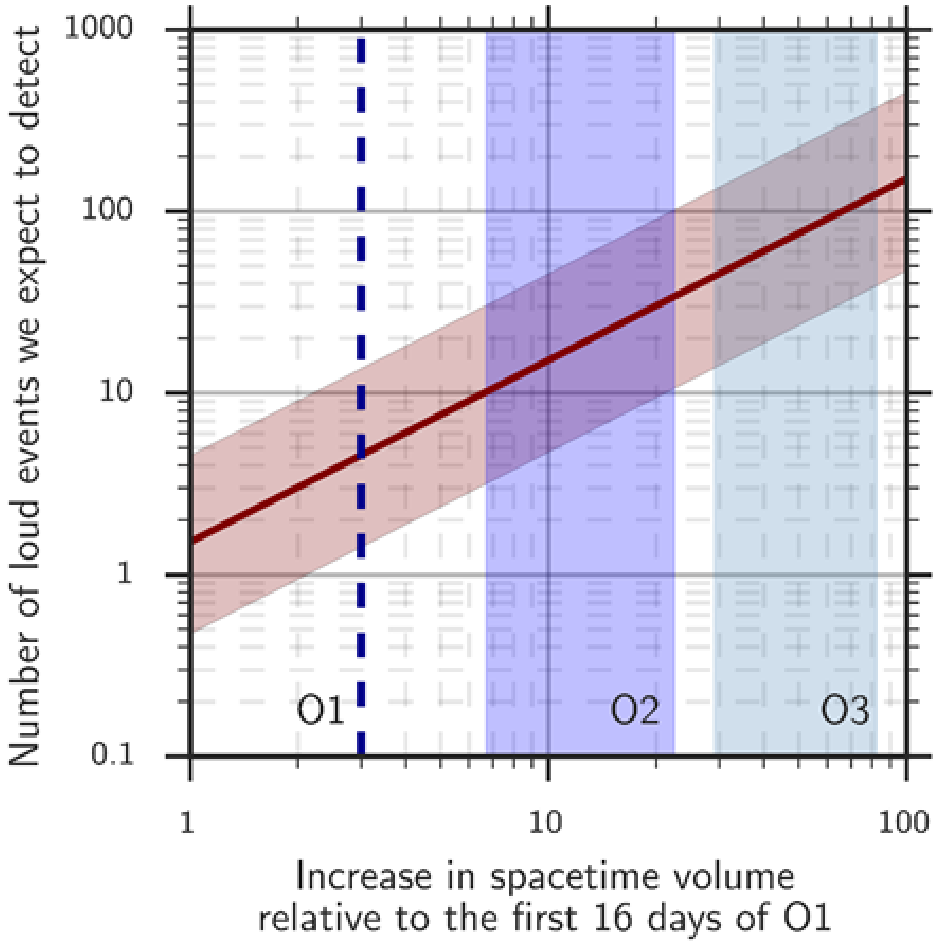
Binary Black-Hole merger rates

BBH merger rate 2 - 400 Gpc^{-3} yr^{-1} **(LVC 2016 arXiv:1602.03842)**

The rate is consistent with most BBH rate predictions.
Only the lowest can be excluded.



Expected number of highly significant BBH events (FARs <1/century)

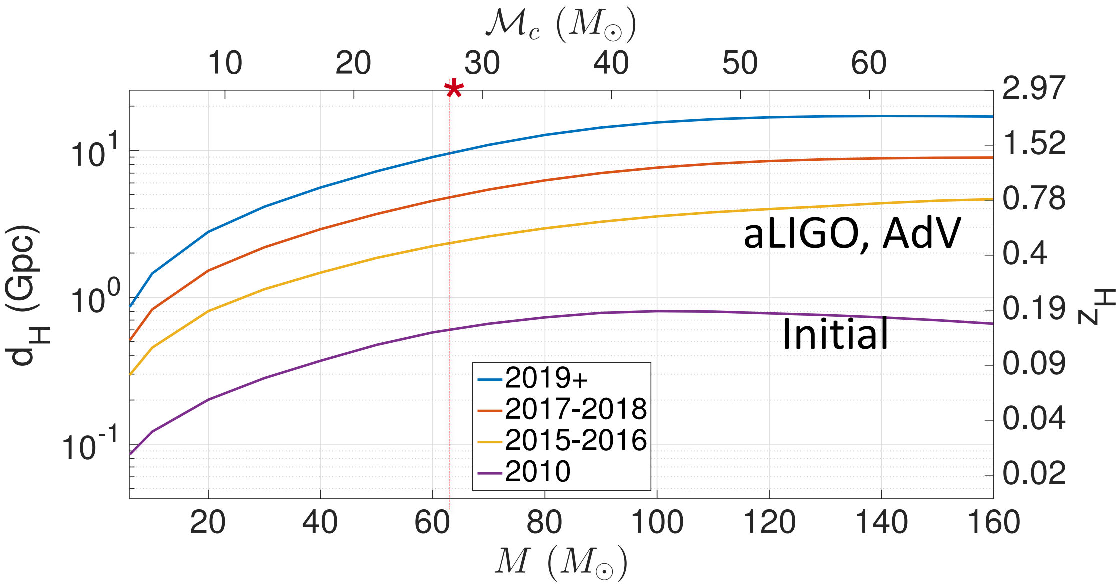


Number of events based on the first O1 16 days of simultaneous two-detector observational data

O2 → 3-100 BBH events
O3 → 13-450 BBH events

LVC arXiv:1602.03842

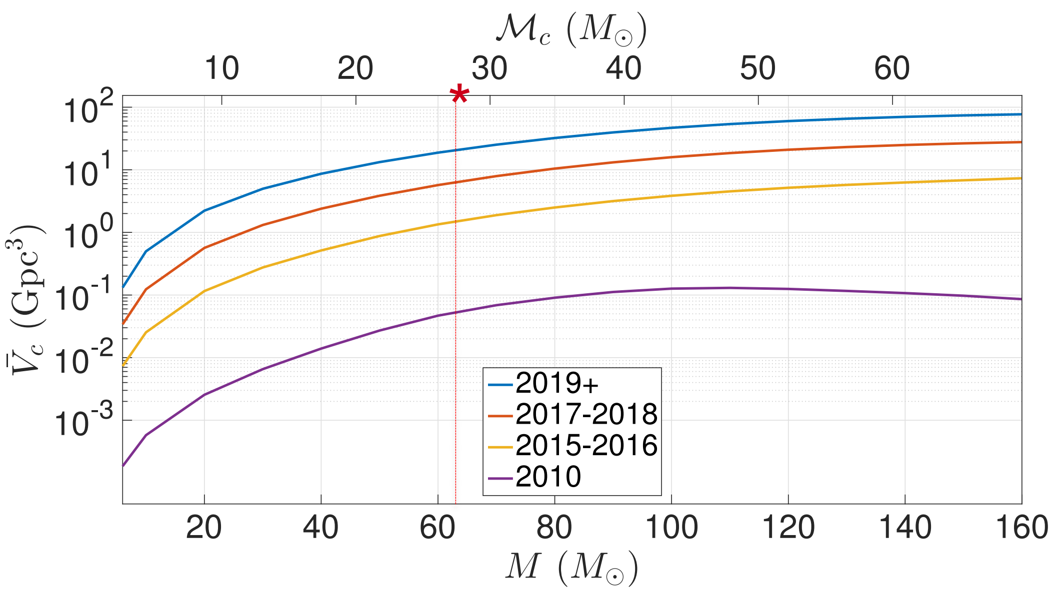
Binary Black-Hole horizon and surveyed volume



Horizon distance *as function of chirp mass/total mass for a 8 SNR detection of equal mass, non spinning BBH mergers*

Surveyed comoving volume

R = constant merger rate → **expected number of detections** during an observing run of duration *T* is given by ***(R*V*T)***



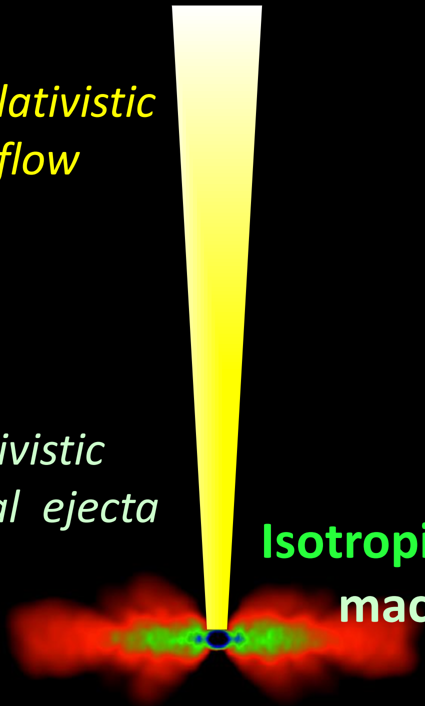
Abbott et al. 2016, ApJL, 818L

EM emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)

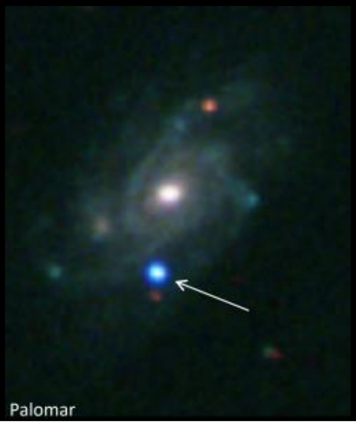
Ultra-relativistic outflow



Sub-relativistic dynamical ejecta

Isotropic emission
macronova

Core-collapse



SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Radio
(years)

+ Long GRB

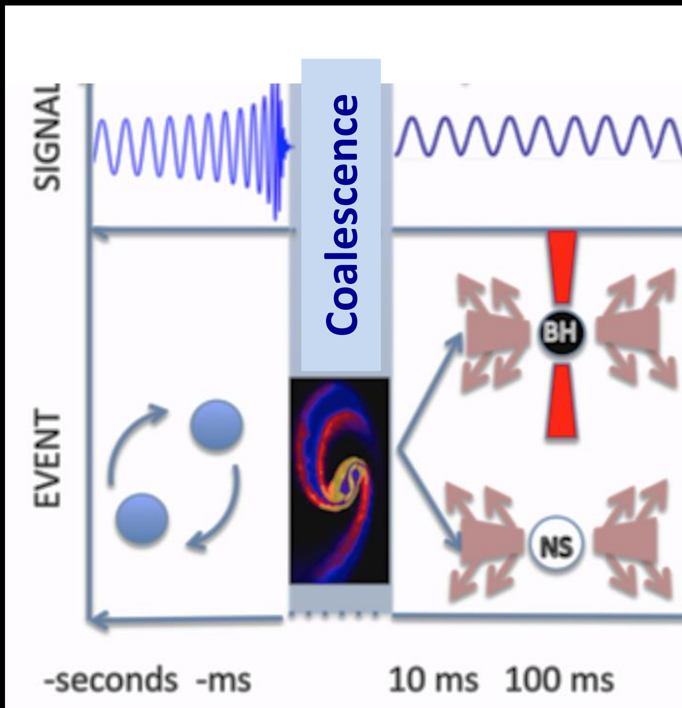
Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray
Pulsar glitches

BH-BH mergers ?

NS-NS and NS-BH inspiral and merger



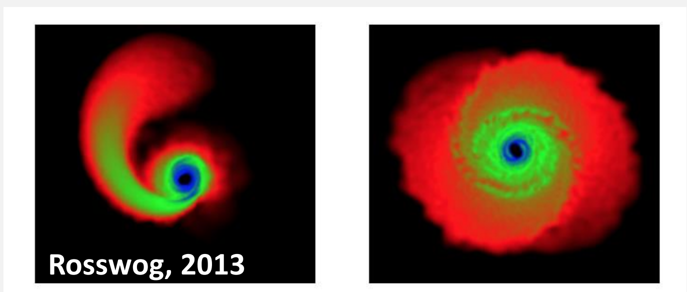
Final remnant contains most (>90%) of the mass initially in the binary

- Ejected mass by tidal forces → dynamically unbound matter
- Mass not gravitationally unbound from the central remnant can posses enough angular momentum to circularize into an accretion disk

1) Dynamical Phase:

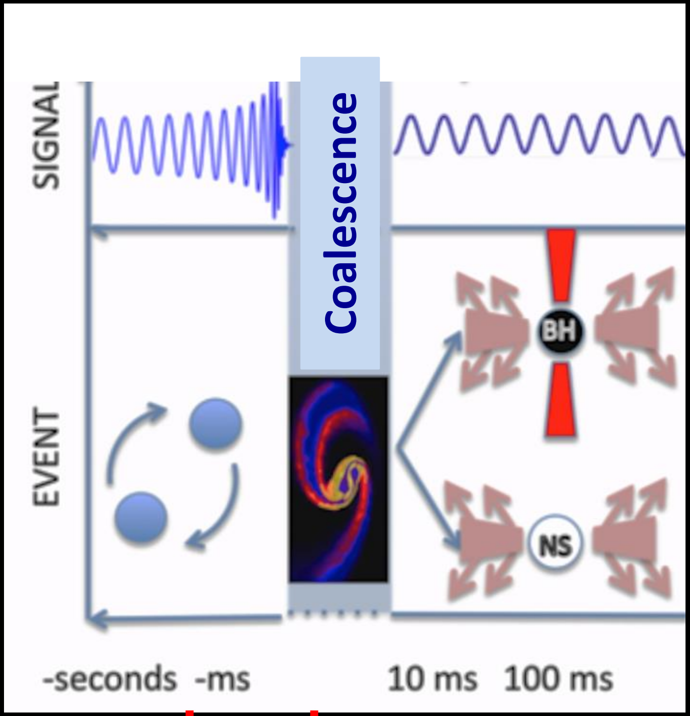
- when the tidal effects become important, few to several orbits before merger (separation ~50 km)
- last several tens of ms

BNS binary → unbound mass of 10^{-4} -10^{-2} Mo ejected at 0.1-0.3c depends on total mass, mass ratio, EOS and eccentricity



Fernandez & Metzger arXiv:1512.05435

NS-NS and NS-BH inspiral and merger



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1) Dynamical Phase:

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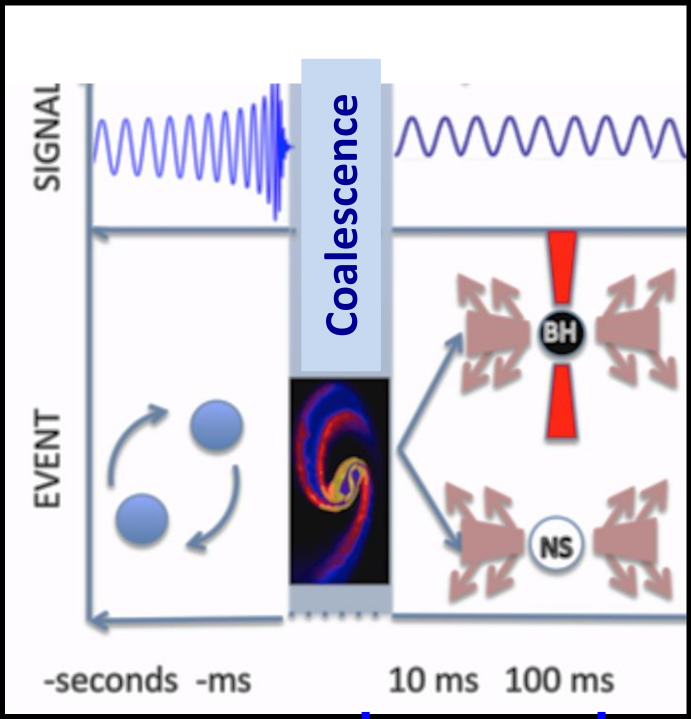
- last several tens of ms

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

NS-NS and NS-BH inspiral and merger



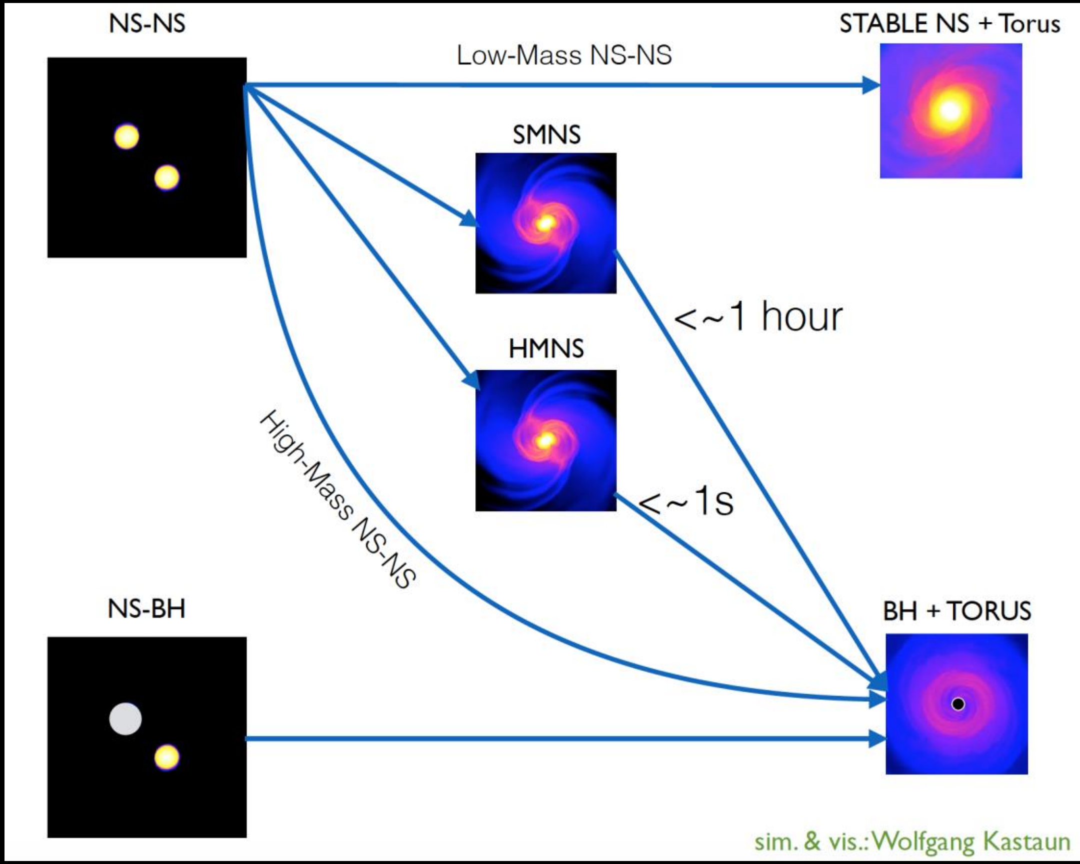
- Ejected material not gravitationally unbound from the central remnant can fall back or circularizes into an accretion disk

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 binary mass**

2) Accretion phase:
within **100 ms after the merger, BH-torus system forms** that can **power a transient relativistic jet through accretion**

Outflow mass and geometry influence the EM emission

The central remnant influences the EM emission

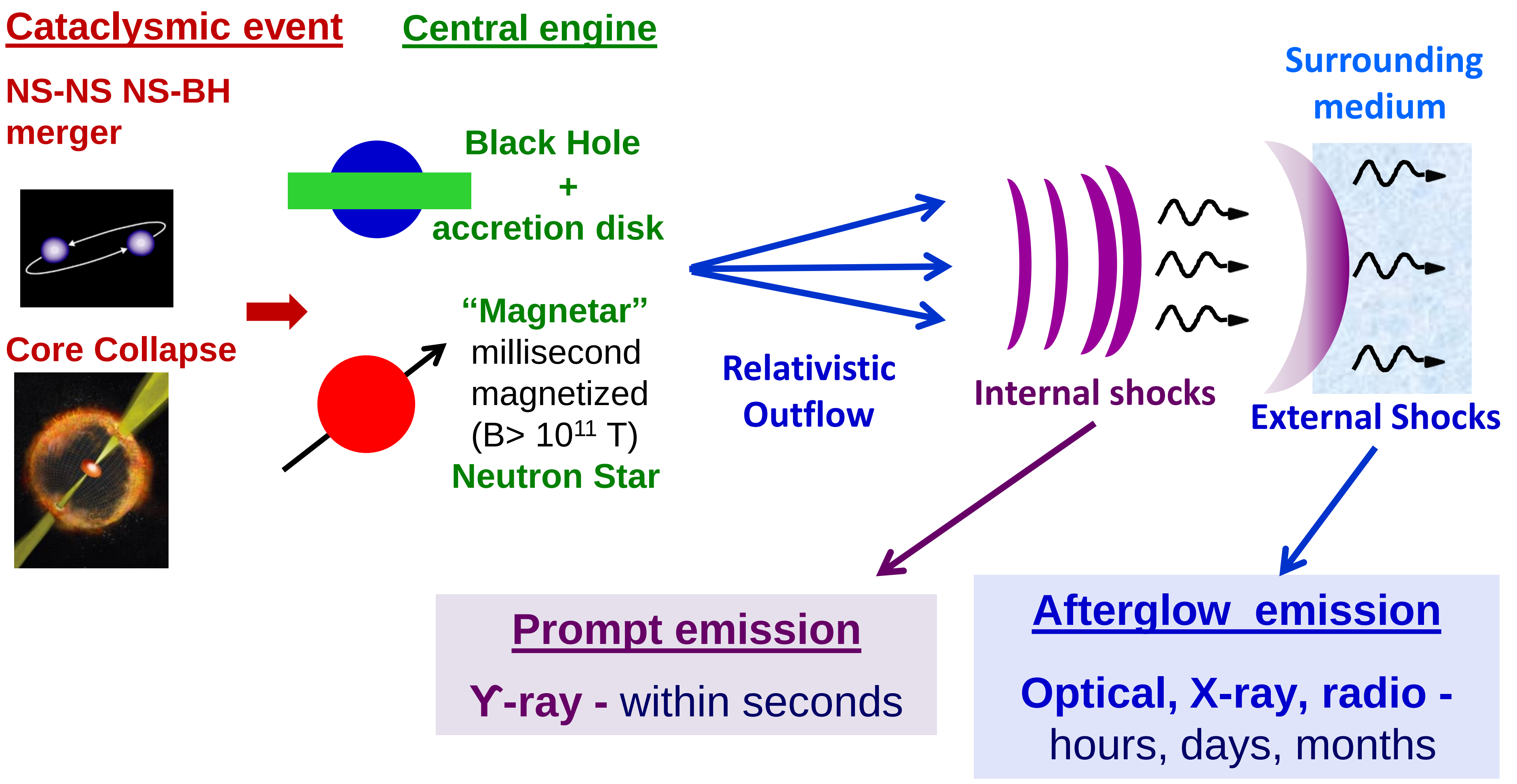


The central remnant influences GW and EM emission

What is central remnant?

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

GRBs emission - Fireball Model

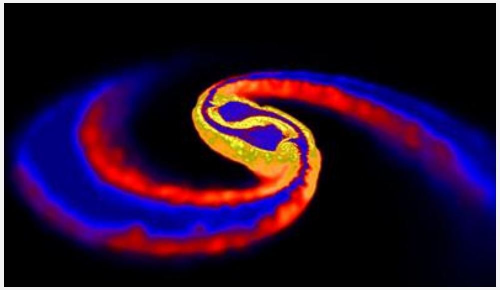


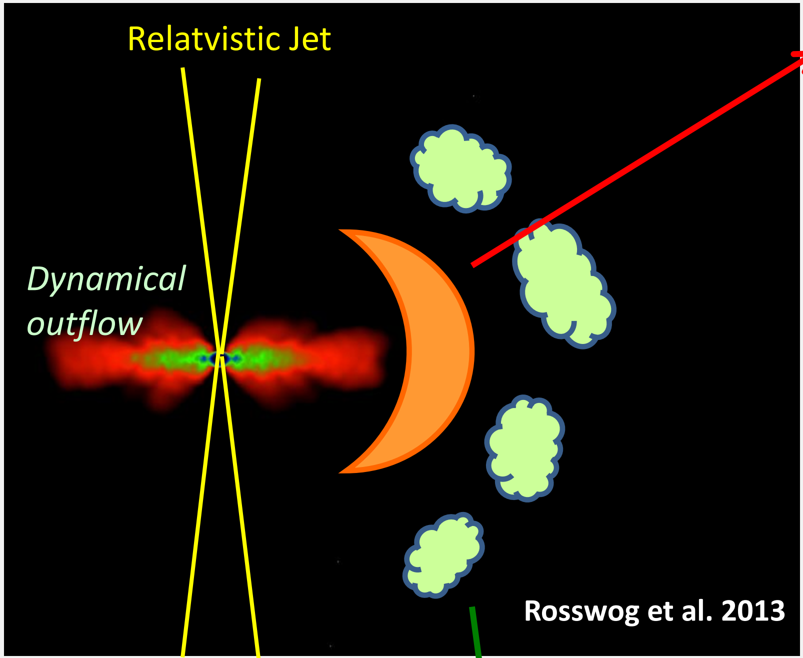
Kinetic energy of the relativistic jet converted in radiation

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)

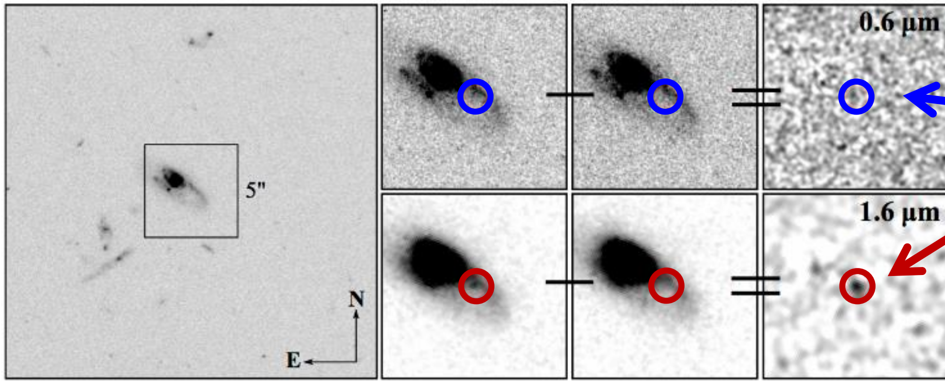
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;

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

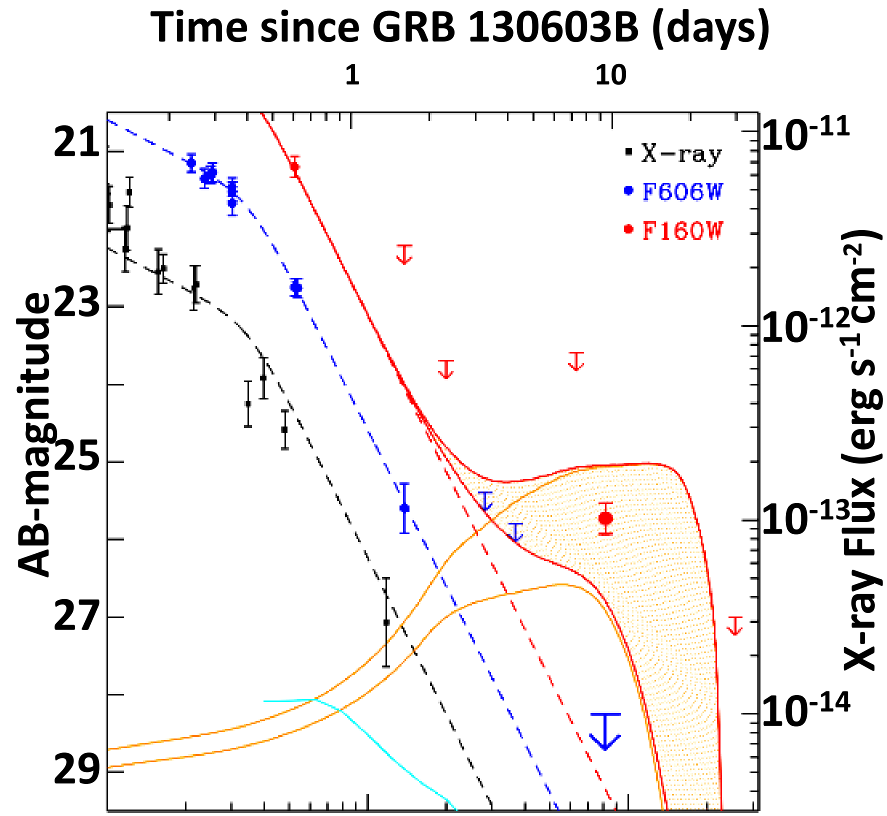


HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

Afterglow and host galaxy z=0.356



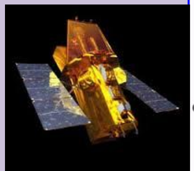
Orange curves → kilonova NIR model

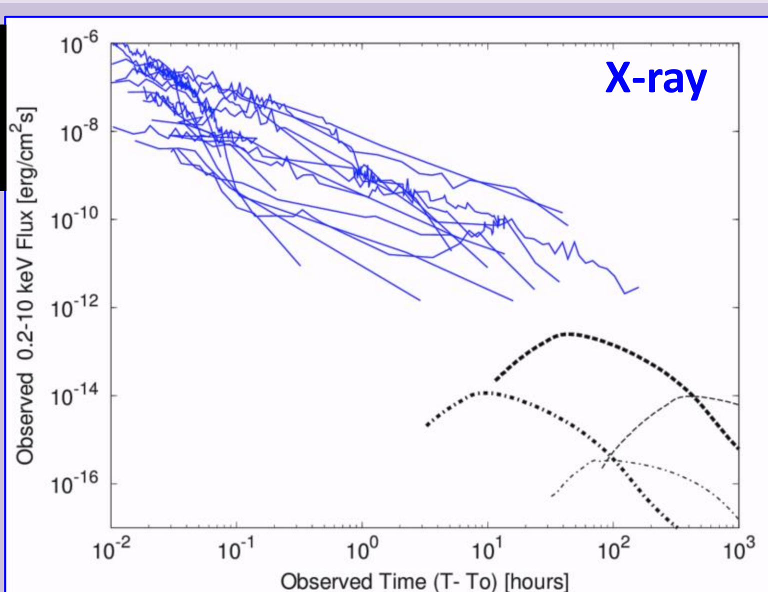
ejected masses of 10^{-2} Mo and 10^{-1}Mo

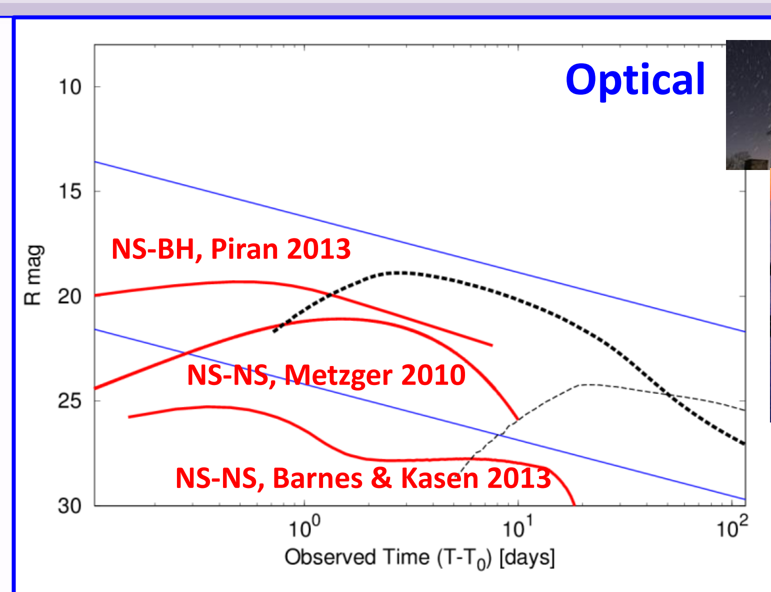
Solid red curves → afterglow +kilonova

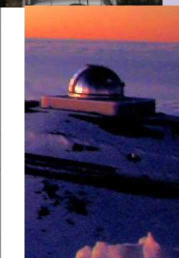
Cyan curve → kilonova optical model

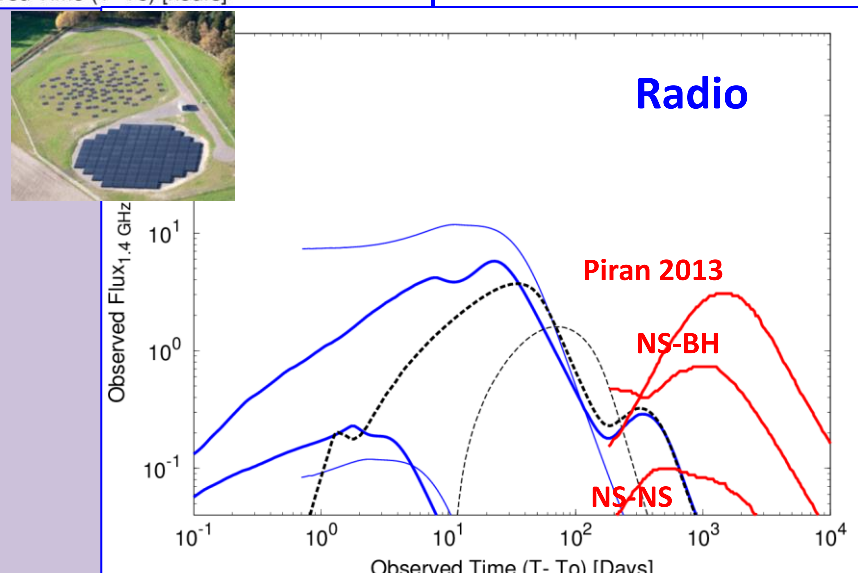
NS-NS and NS-BH merger EM-emissions





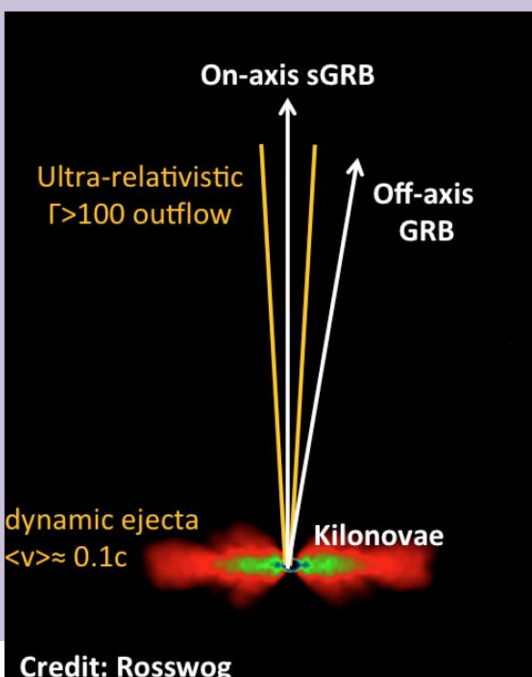






Source at 200 Mpc

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



- *Different emissions*
- *Different timescales*

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

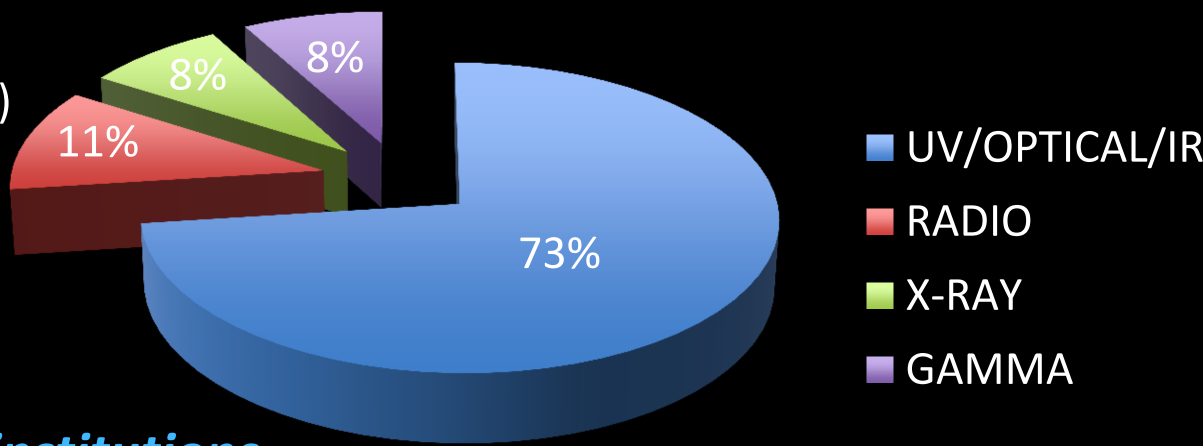
LVC GW-EM follow-up program

Seventy-four MoUs involving

➢ **160 instruments**

(satellites/ground-based telescopes)

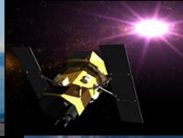
covering the full spectrum *from radio to very high-energy gamma-rays!*



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

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

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

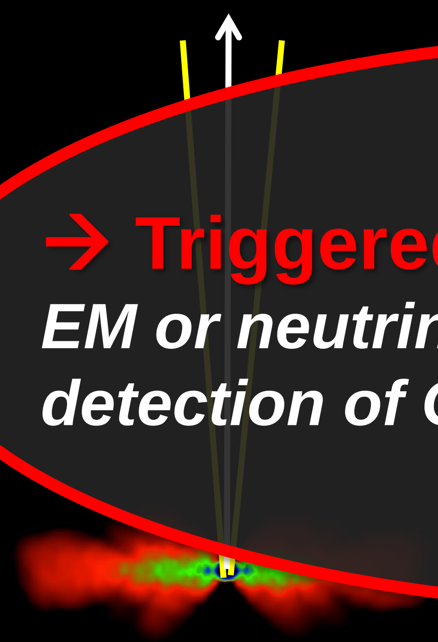
To shed light on birth and evolution of BH

To constrain geometry of the systems and emssion models

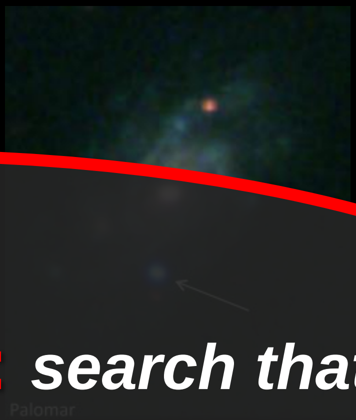
EM emissions

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)



Core-collapse of massive stars



SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

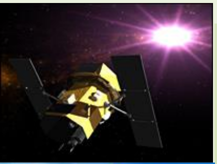
Isolated NS instabilities

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

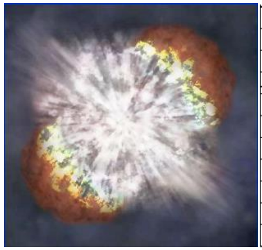
Aasi et al. 2014,PhRvL, 113

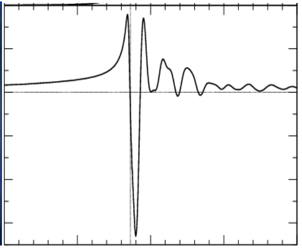
Abadie et al. 2012, ApJ, 755

Adrián-Martínez et al. 2013, JCAP

Aartsen et al, PhysRevD, 90, 102002

GW transient searches



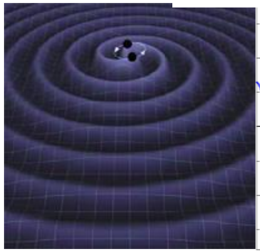


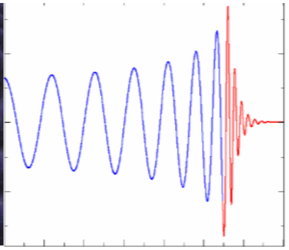
Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

→ Excess power

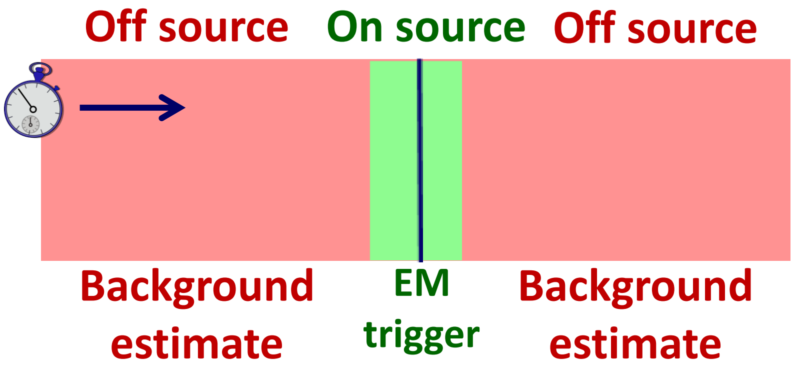




Compact Binary Coalescence

Known waveform

→ Matched filter



What is time delay between the GW and EM emissions?

What is the time window to search for GWs?

EM emissions

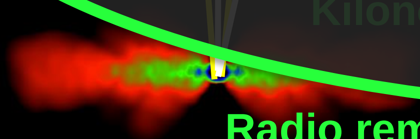
NS-NS and NS-BH mergers

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)

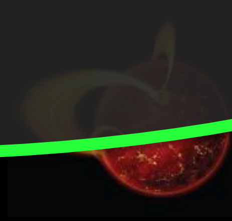
Core-collapse of massive stars

SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Radio
(years)

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray
Pulsar glitches

BH-BH mergers ?

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

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

LSC VIRGO

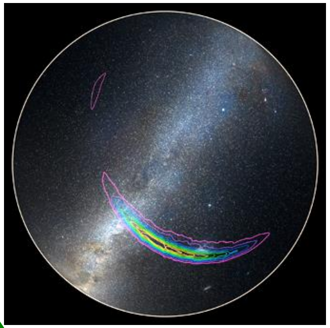
GW candidates

Sky Localization

EM facilities

LIGO-H LIGO-L

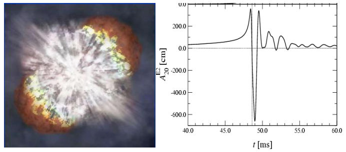
Virgo



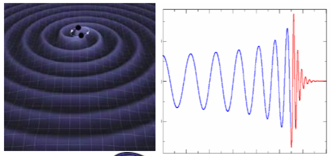
Event validation

Low-latency Search

to identify the GW-candidates



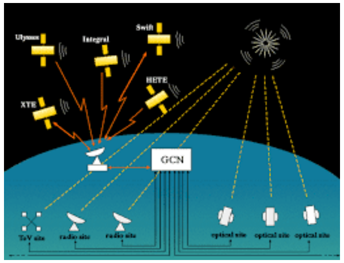
Unmodeled GW burst search



Matched filter with waveforms of compact binary coalescence

Software to

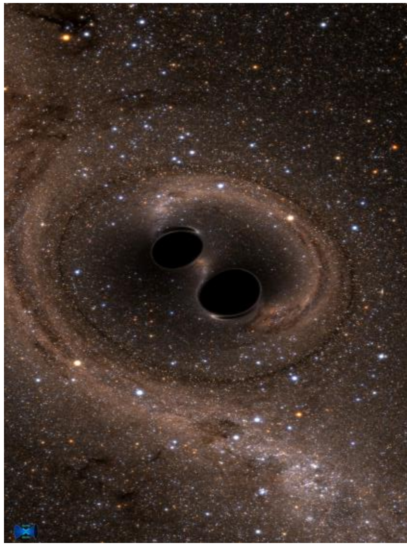
- select statistically significant triggers wrt background
- Check detector sanity and data quality
- determine source localization

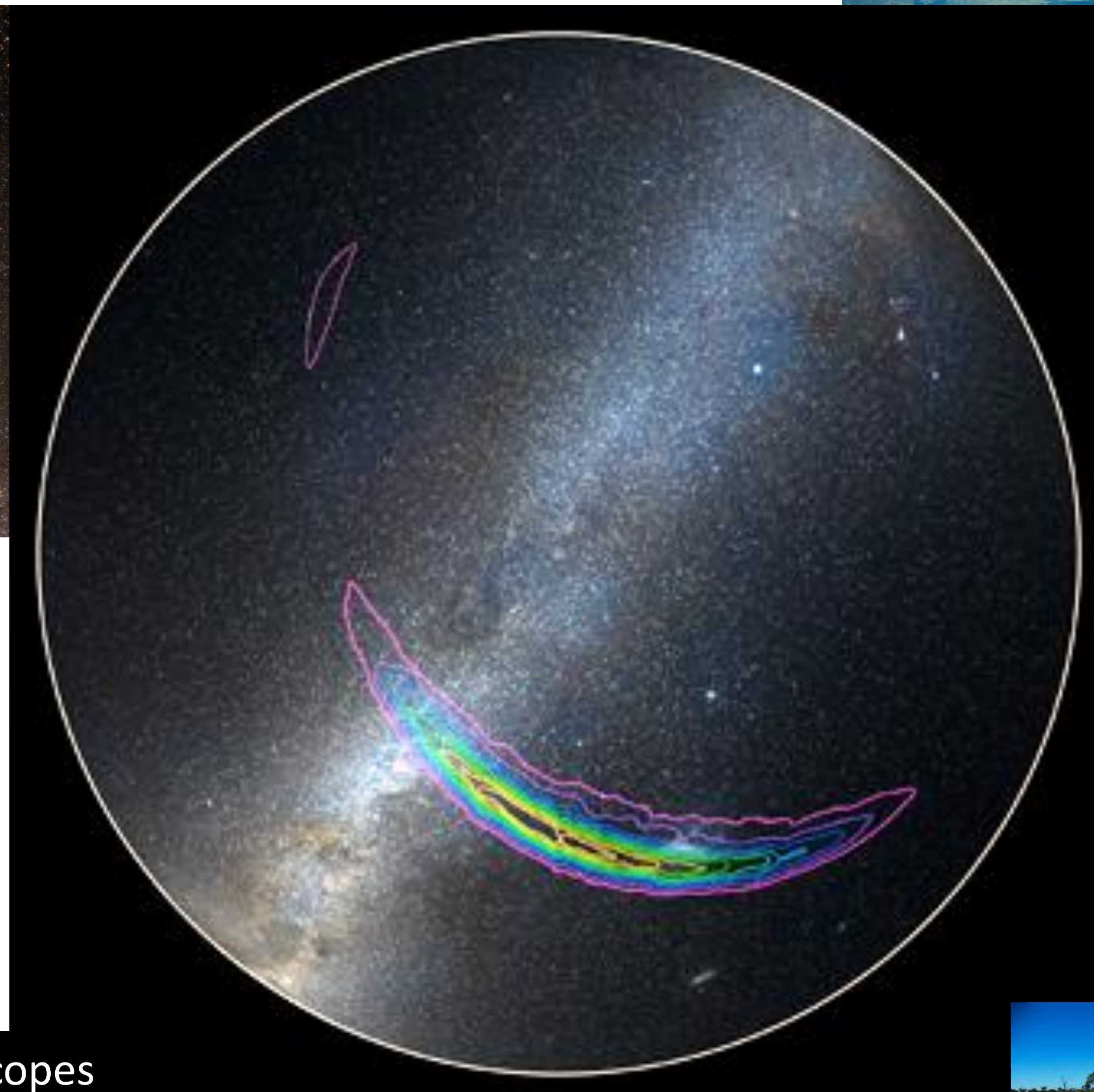


a few min → **15/30 min**

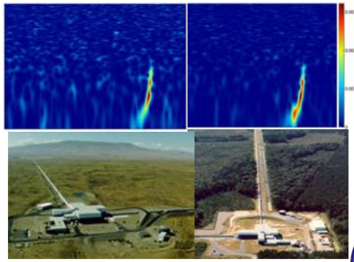
Parameter estimation codes → **Hours,days** → **GW candidate updates**

GW150914, the first multi-messenger campaign including GWs….



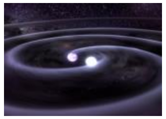


Optical telescopes

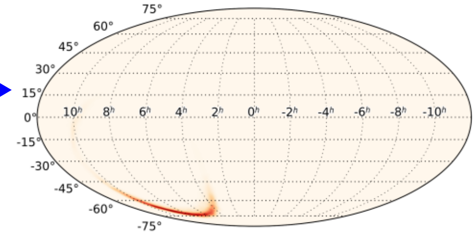


2 days

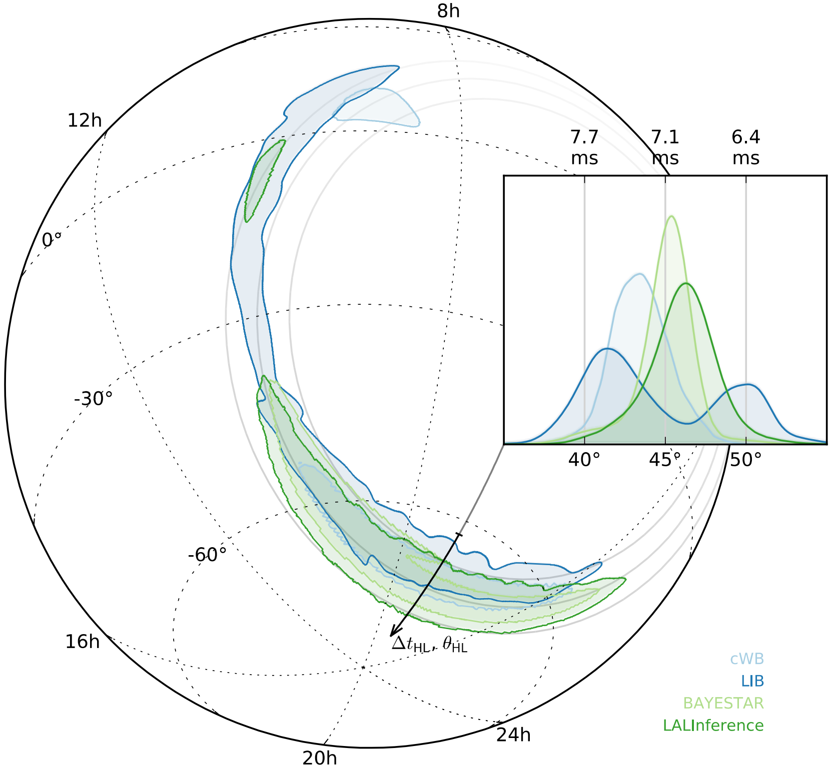
19 days



4 months



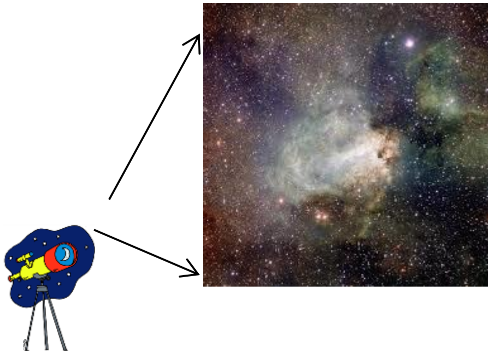
Final Skymap



	Area[a]		
	10%	50%	90%
cWB	10	100	310
LIB	30	210	750
BSTR	10	90	400
LALInf	20	150	620

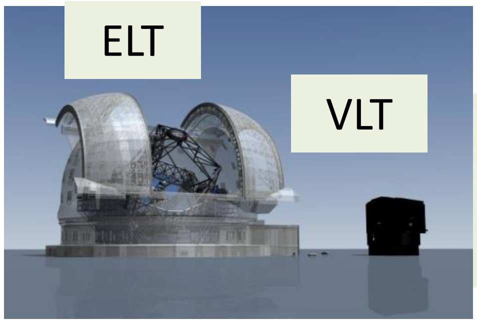
LVC+astronomers, acepted by ApJL
arXiv:1602.08492

Hierachical EM-follow up Search



Wide-field telescope
FOV > 1 sq.degree

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

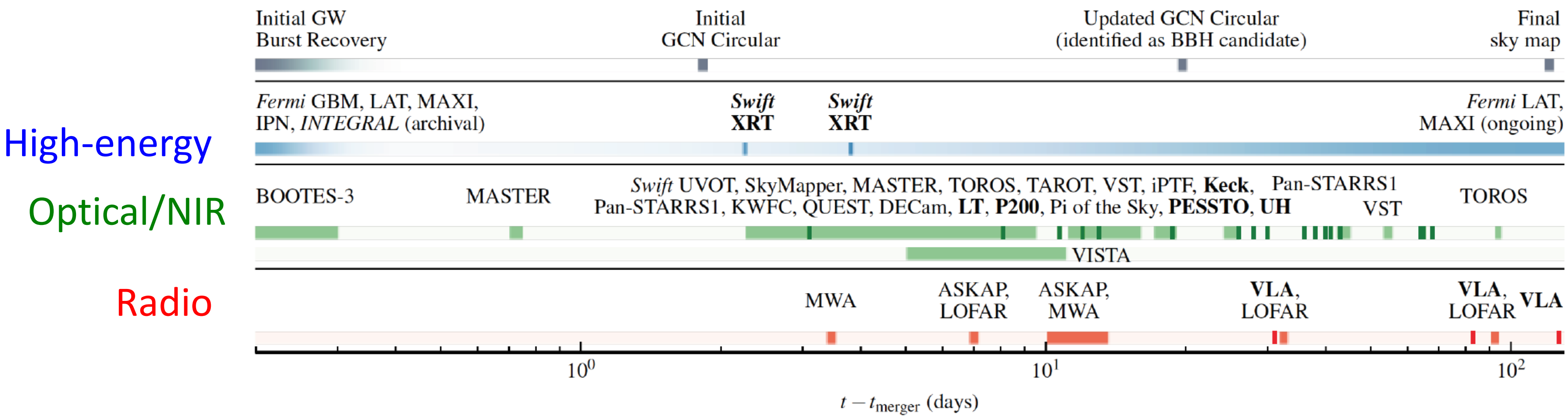


Larger telescope to **characterize** the candidate nature

The EM Counterpart!

EM follow up observations and archival searches

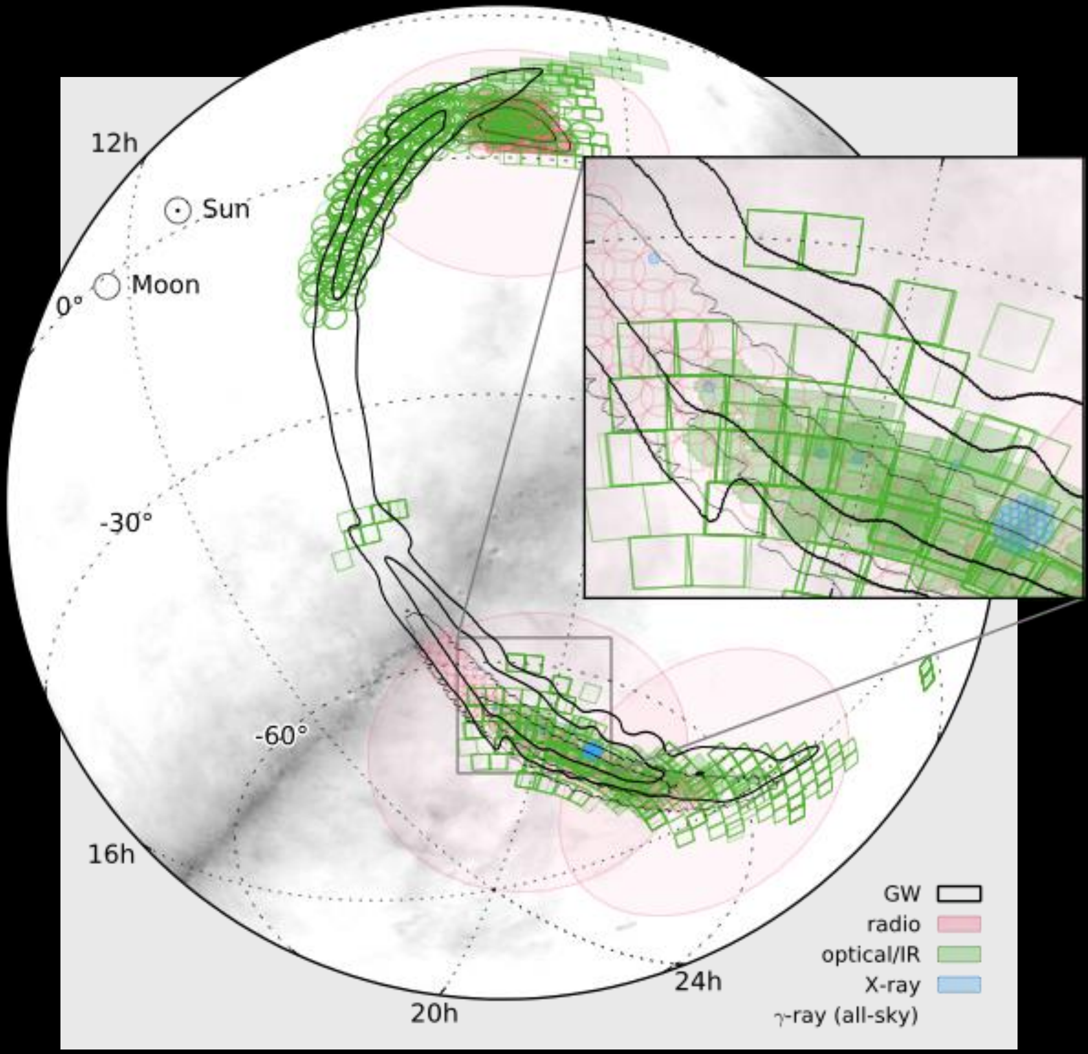
- ***Twenty-five teams*** *of observers responded to the GW alert*
- *The EM observations involved* ***satellites and ground-based telescopes*** *around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*



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
Soares-Santos et al. arXiv:1602.04198
Kasliwal et al. arXiv:1602.08764
Morokuma et al. arXiv:1605.03216
Fermi-LAT collaboration APJL, 823,2
Lipunov et al. arXiv:1605.01607

Sky map coverage



- *The astronomer teams tiled large portions of the GW sky maps*
- *some groups, considering the possibility of a NS merger or core-collapse SN, selected fields based on nearby galaxies or pointed at the Large Magellanic Cloud*

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)**

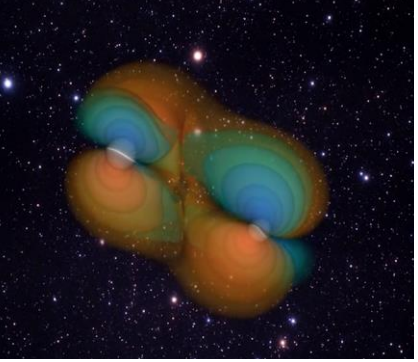
No signal detected by **AGILE** (Tavani et al. arXiv:1604.00955) and **MAXI**

Optical facilities together tiled about **870 deg^2** with a **contained probability of 57% of the initial sky map** and only **36% 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**



*EM follow-up of GW150914 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

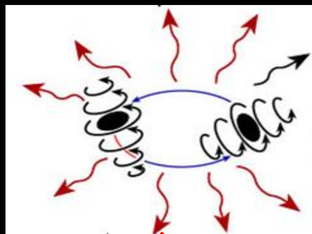
Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

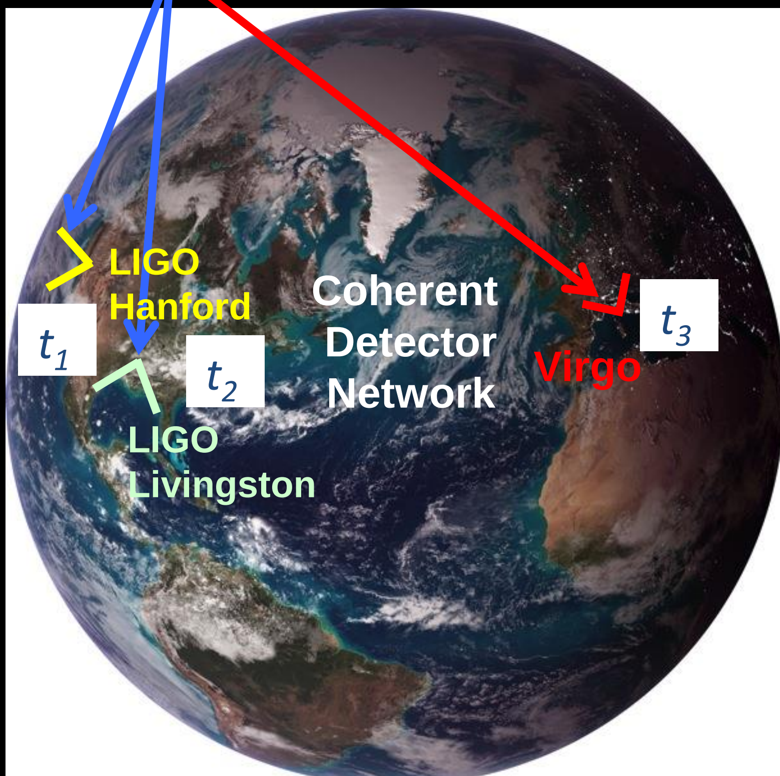
The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range

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

GW150914

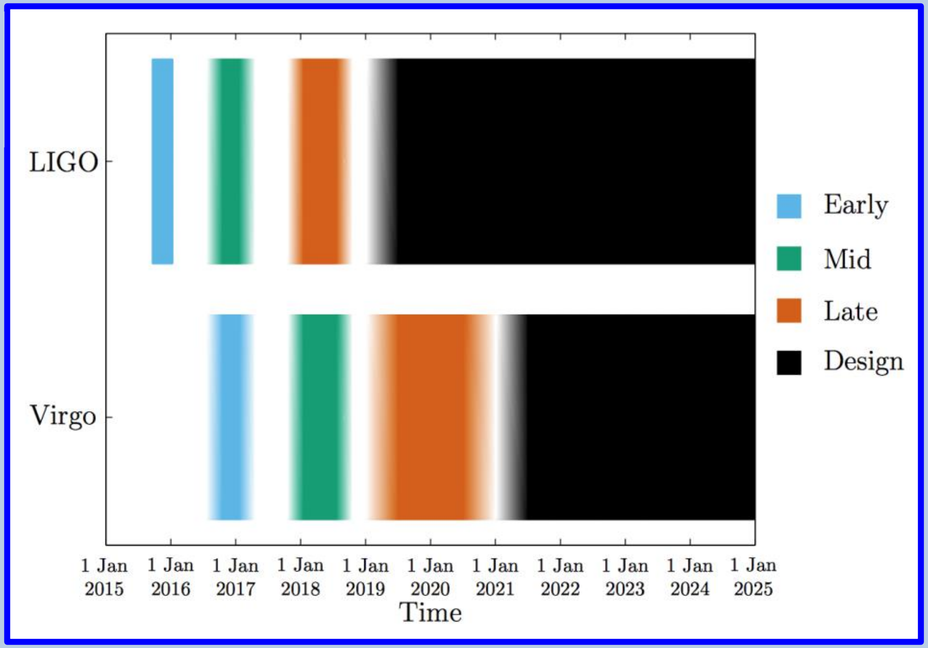
LIGO is expected to start the **second** osbserving run in **Autumn, Virgo** to join the run **before the end of 2016!**





The sky localization of GW150914 with Virgo ***few tens of square degrees***
Virgo will significantly improve the efficiency of the EM searches!

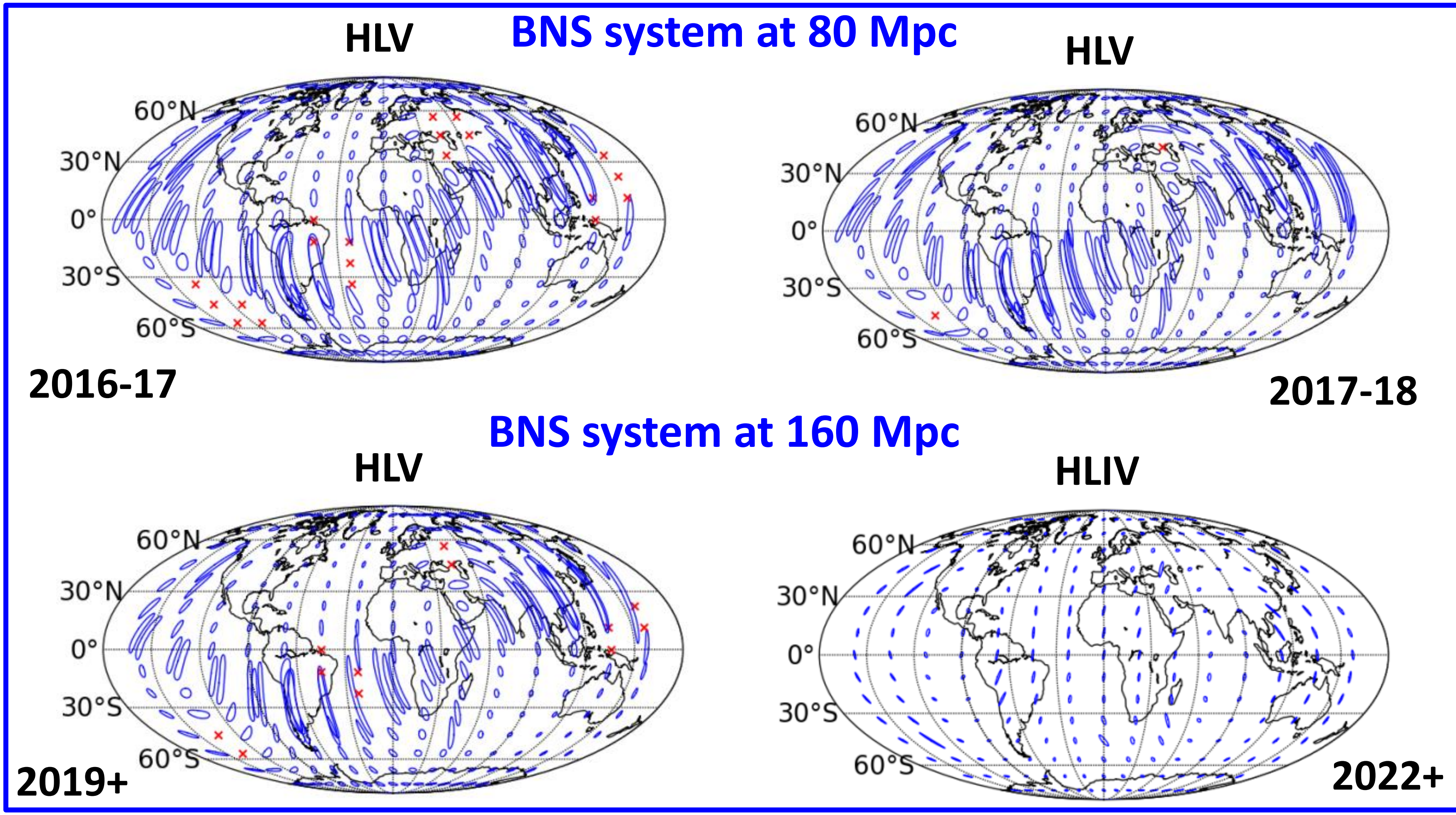
Sensitivity evolution and observing runs



Observing schedule, sensitivities, and source localization

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*
	% within 20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
	median/deg^2	480	230	—	—	—
searched area	% within 5 deg^2	6	20	—	—	—
	% within 20 deg^2	16	44	—	—	—
	median/deg^2	88	29	—	—	—

Sky Localization of Gravitational-Wave Transients



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

→ 90% confidence localization areas

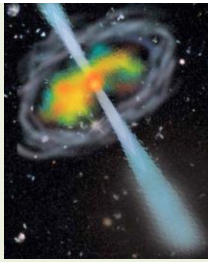
X → signal not confidently detected

Two classes of GRBs/Different Progenitors

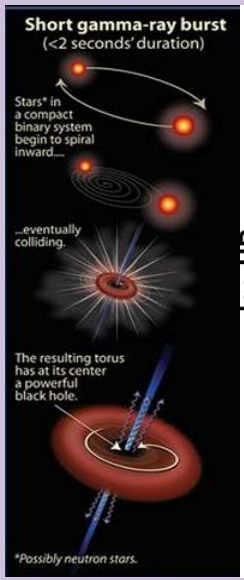
Merger of NS-NS / NS-BH

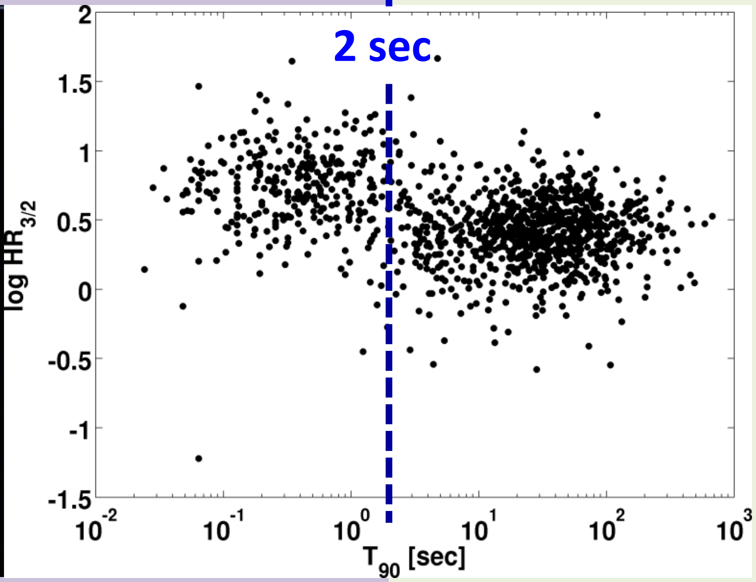
Short Hard GRB

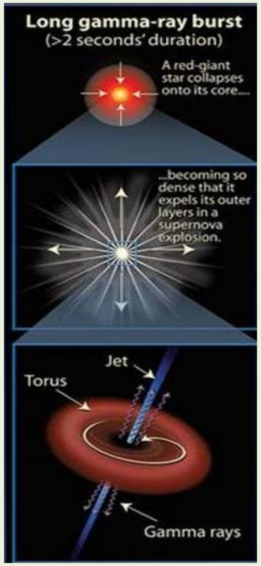
Core collapse of massive star



Long Soft GRB







Progenitor indications:

- accretion timescale of disk in binary merger model is short (t ~ 1s)
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)

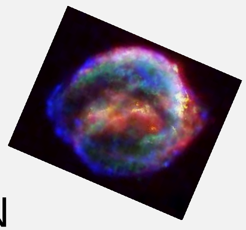
Progenitor strong evidence:

- accretion disk is fed by fallback of SN material onto disk, timescale t ~ 10-100s
- observed Type Ic SN spectrum

Multi-messenger astronomy

The most energetic emission mechanisms

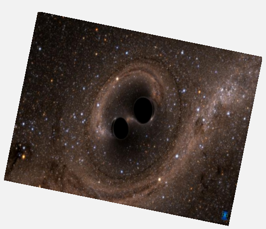
GRB/kilonovae



Pulsar SN

SGR

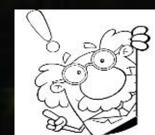
BBH



GWs/photons/neutrinos

Necessary to probe…

+ theory



Necessary to unveil …

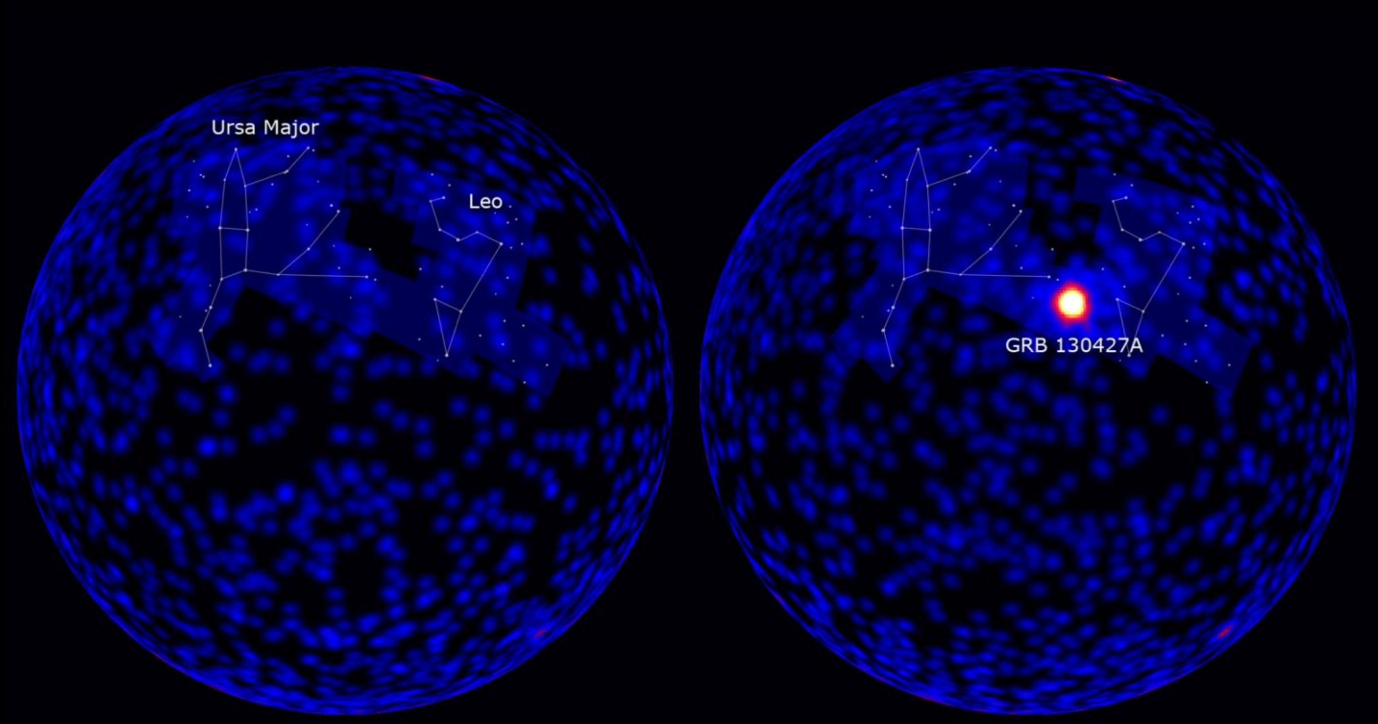
Rates, demography and enviroment of compact objects

The nature and structure of compact objects

To reveal the unknown… exotic sources, new physics

To constrain models of their birth and evolution

Gamma-Ray Bursts



Before and after Fermi LAT observation of GRB 130427A

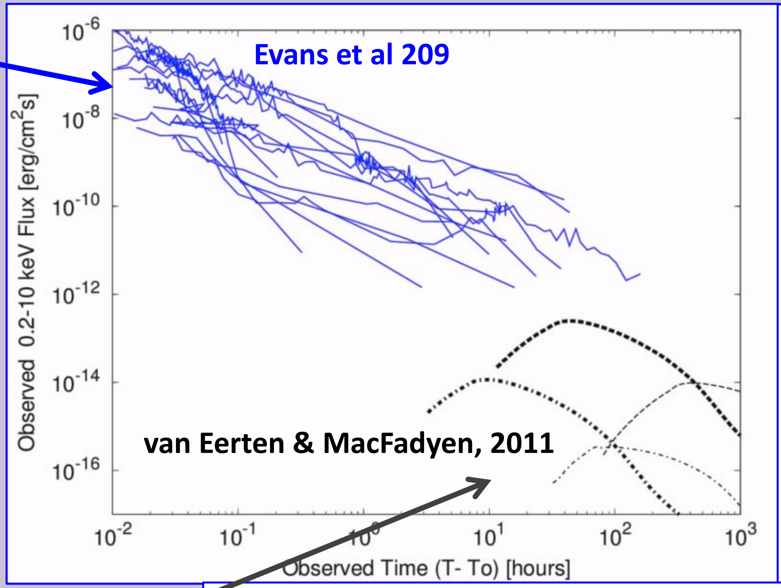
Brief, sudden, intense flashes of gamma ray radiation which release energy up to **~ 10^{53} erg** (isotropic-equivalent)

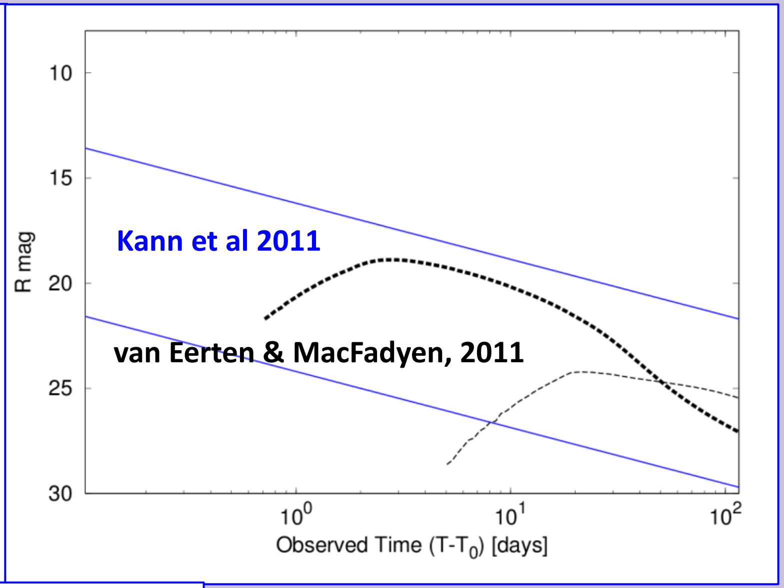
Duration: **from few ms to hundreds of s**
Observational band: **10 keV – 1 MeV**
Flux: **10^{-8} - 10^{-4} erg cm^{-2} s^{-1}**

Short GRB multi-wavelength afterglow emissions

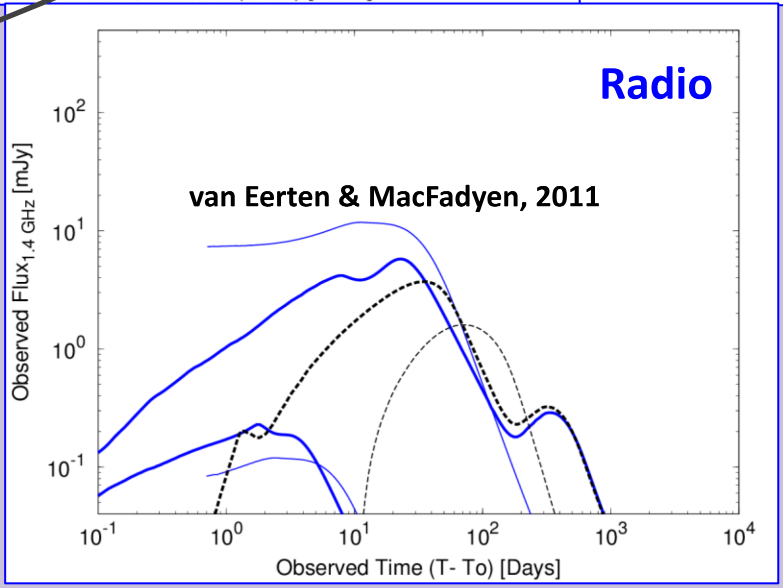
Source at 200 Mpc

On-axis GRBs





Off-axis GRB



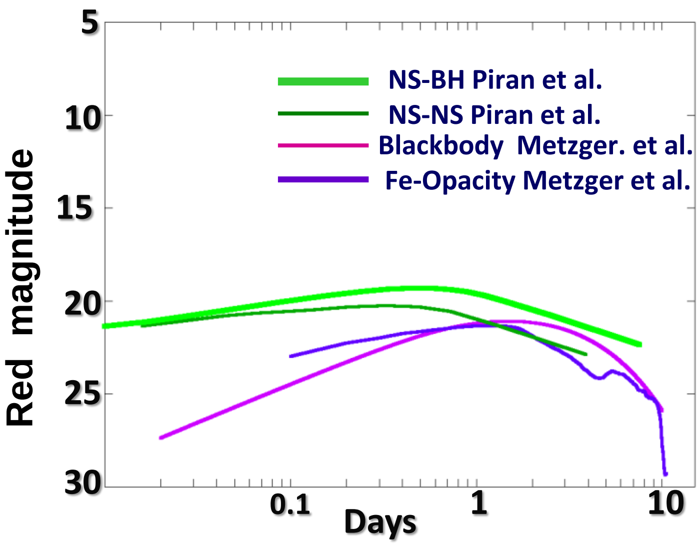
Observed and Modelled Afterglows

- On-axis (solid line)
- Off-axis (dashed line)

→ X-ray → Optical → Radio

Kilonovae Light Curves

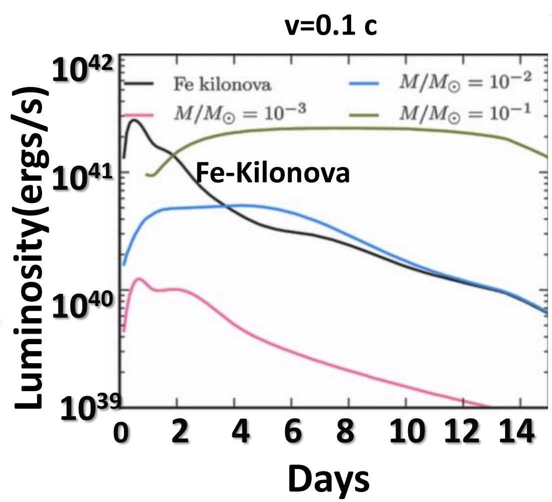
Source at distance of 200 Mpc



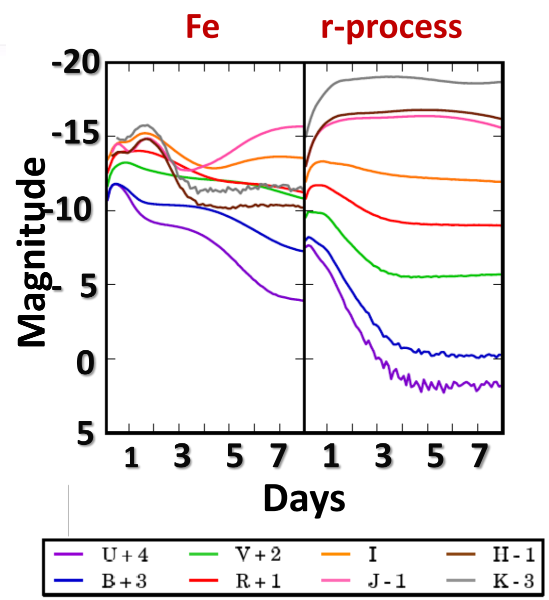
***Kilonova* model afterglow** peaks about **a *day* after** the merger/GW event

OPACITY of "heavy r-process elements"

Barnes & Kasen 2013, ApJ, 775

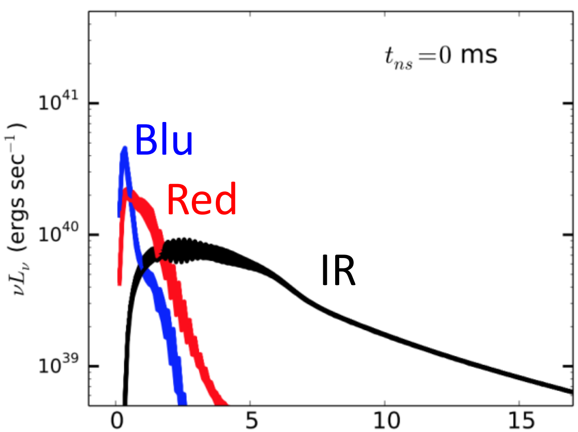


Opacities:



- **broader light curve**
- **suppression of UV/O** emission and **shift to infrared bands**

Accretion disk wind outflow

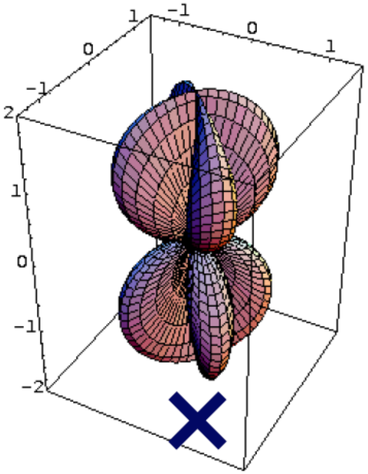


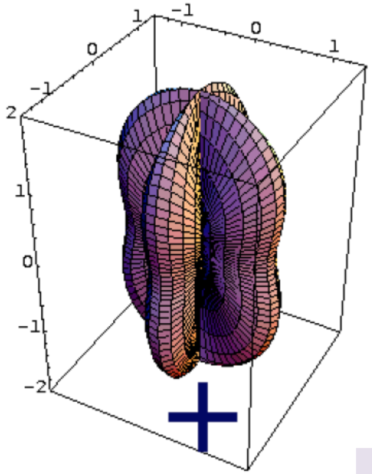
Kasen et al. 2015, MNRAS, 450

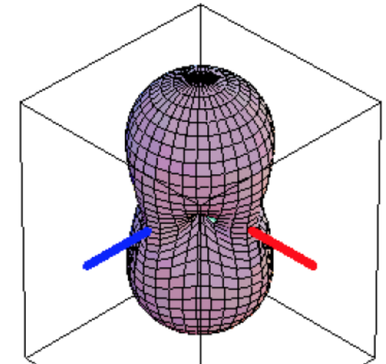
Single GW detector directional sensitivity

$$\frac{DL}{L} = h_{det}(t) = F_+ h_+(t) + F_x h_x(t)$$

The **antenna pattern** depends on the polarization in a certain (x,+) basis

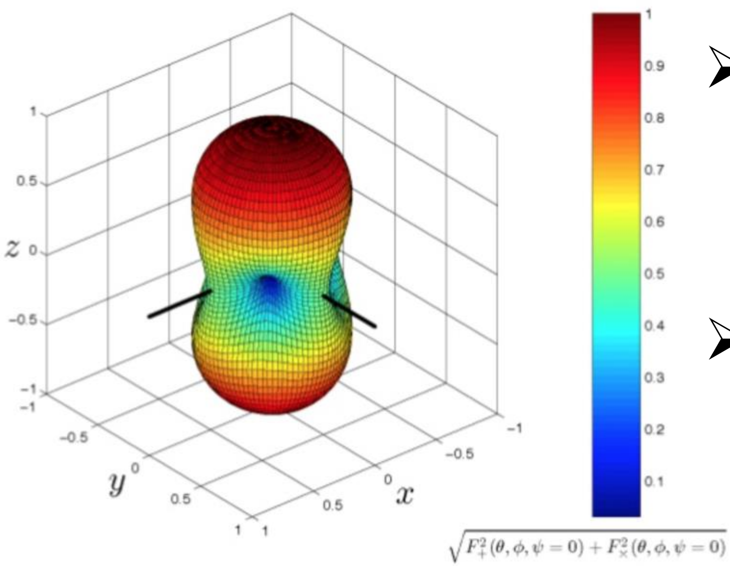






RMS sensitivity

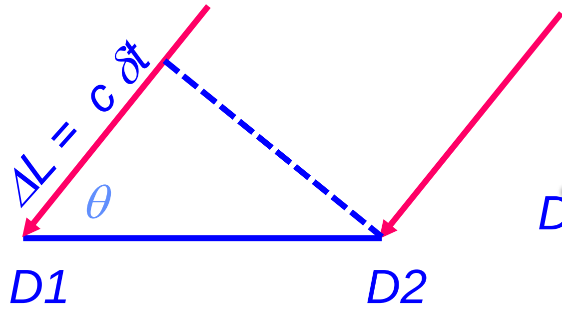
$$\sqrt{F_+(q,f)^2 + F_x(q,f)^2}$$

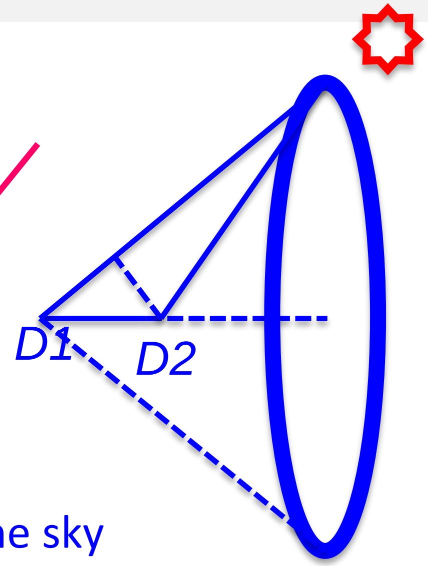


- Single GW detector is a **good all-sky monitor**, nearly omni-directional (the transparency of Earth to GWs)
- But does not have good directional sensitivity, **not a pointing instrument!** It has a very poor angular resolution (about 100 degrees)

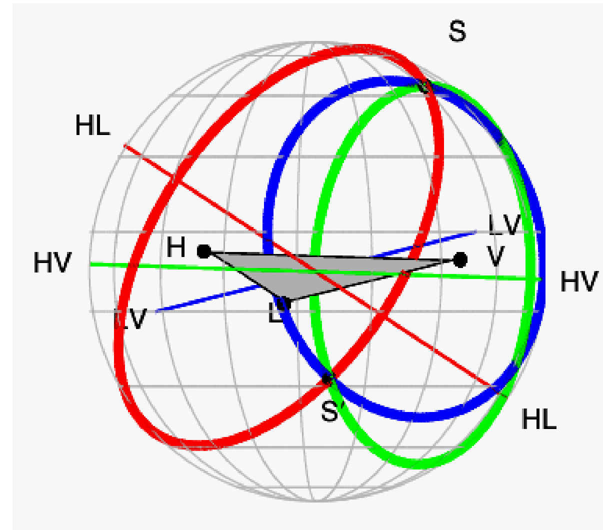
The source localization requires a network of GW detectors

*The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites*

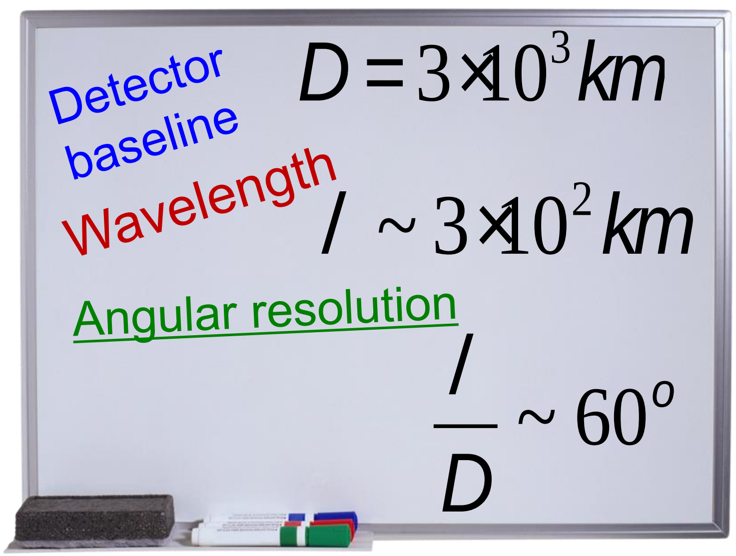




2-detectors → annulus in the sky



3-detectors → localize



The GW lengths are comparable to Earth diameter

→ *longer baseline and greater number of the sites* distributed *worldwide* significantly improve *the sky-localization capabilities!*

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

Observed on-axis SHORT GRBs

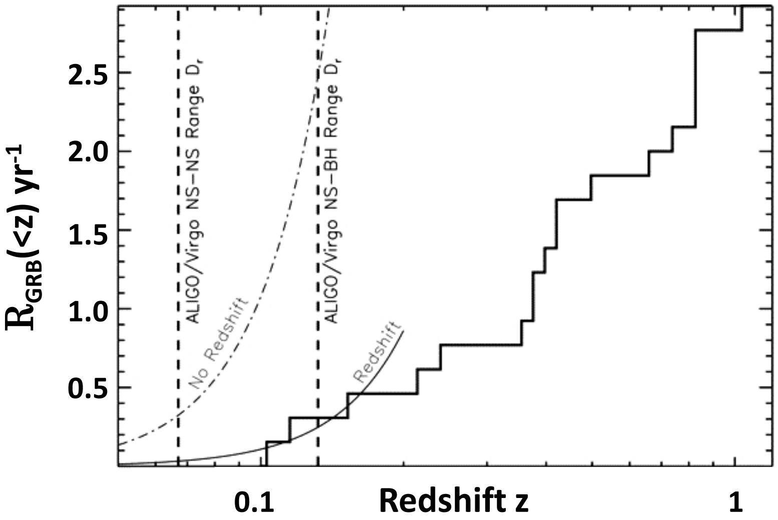
So far **~100** of which **~20** at known distance

<z>=0.5 = 3 Gpc

zmin = 0.12 = 560 Mpc

Energy = $10^{48\text{-}52}$ 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 a few measures***

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)

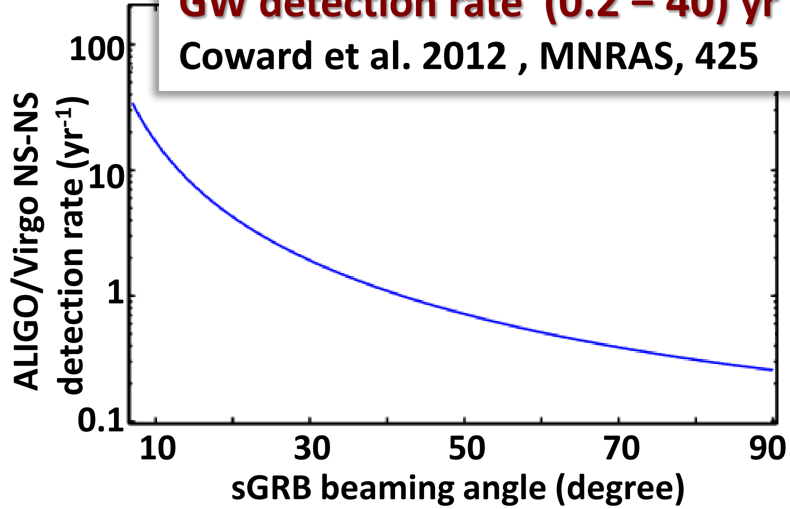
92–1154 $Gpc^{-3} yr^{-1}$ (Siellez et al. 2013)

Theoretical prediction

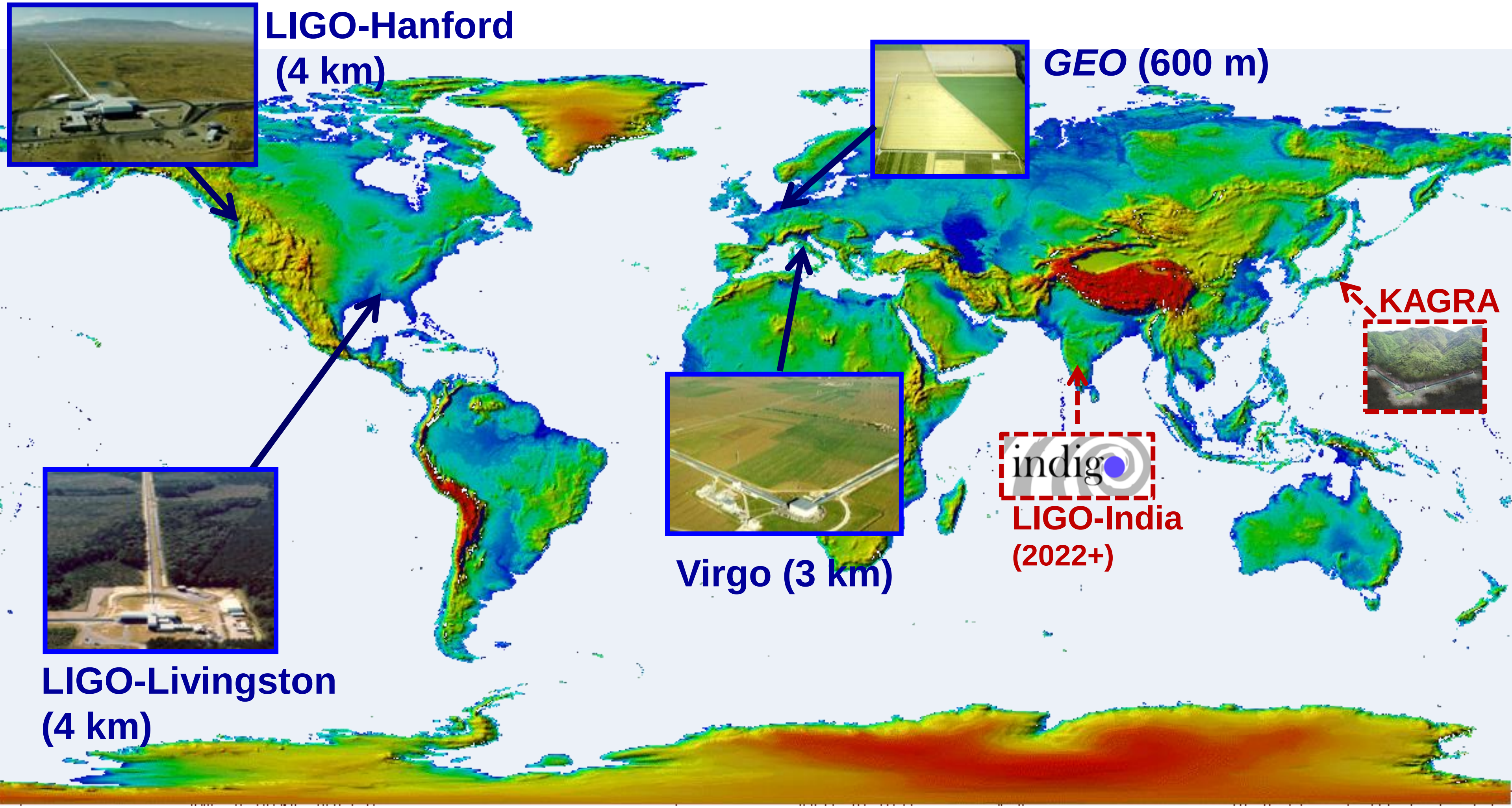
10-10000 $Gpc^{-3} yr^{-1}$ (Abadie et al. 2010)

GW detection rate (0.2 – 40) yr^{-1}

Coward et al. 2012 , MNRAS, 425



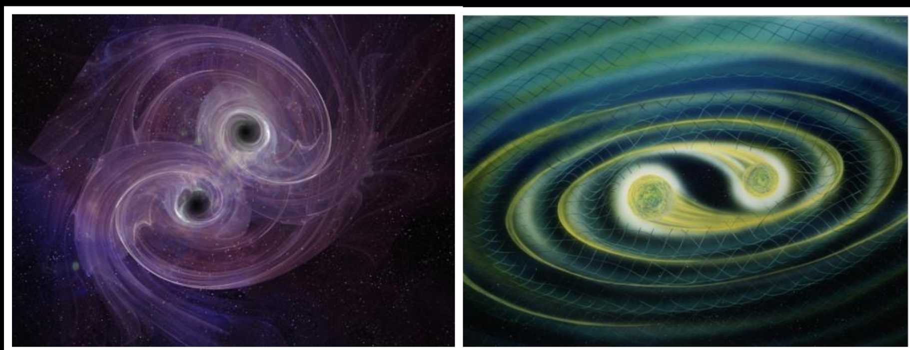
Ground-based GW detector network



Advanced LIGO observed 4 months from September 2015 to January 2016
and will start the **second run of 6 month** osbservations in **Autumn**
Advanced Virgo will join the run **before the end of 2016**

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

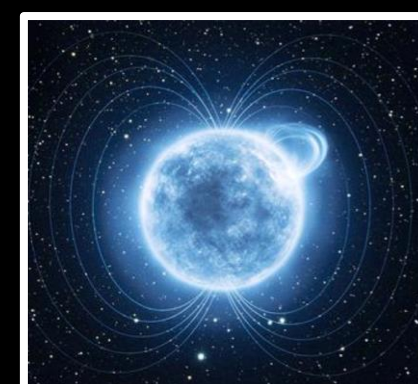
Coalescence of binary system of neutron stars (NS) and/or stellar-mass black-hole (BH)



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

Core-collapse of massive stars

Isolated NSs instabilties

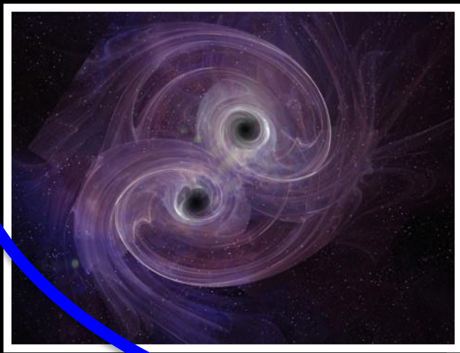


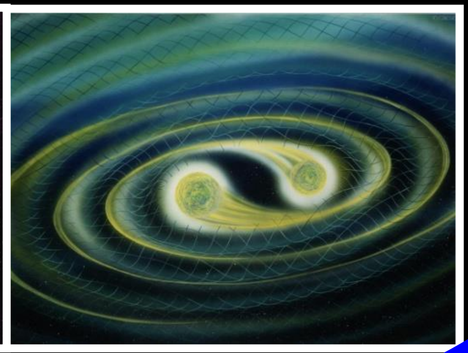
- Modeling of the GW shape and strength is complicated
  → **uncertain waveforms**
- **Energy emitted in GWs:**

~10^{-8} – 10^{-5} $M_o c^2$ for the core-collapse ~10^{-16} – 10^{-6} $M_o c^2$ for isolated NSs

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

Coalescence of binary system of neutron stars (NS) and/or stellar-mass black-hole (BH)

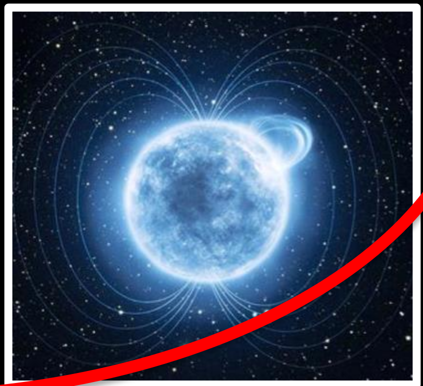




MATCHED-FILTER MODEL GW SEARCHES

Core-collapse of massive stars

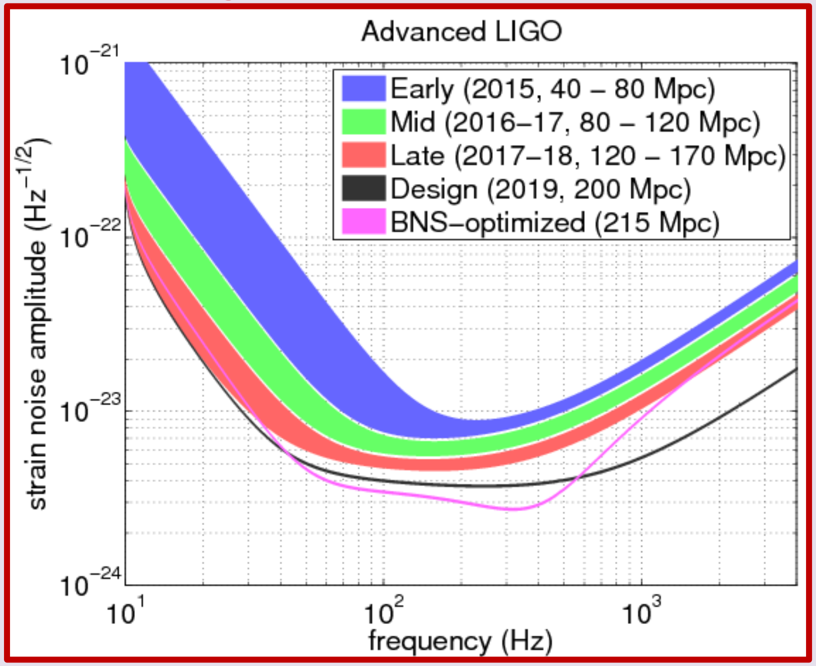
Isolated NSs instabilties

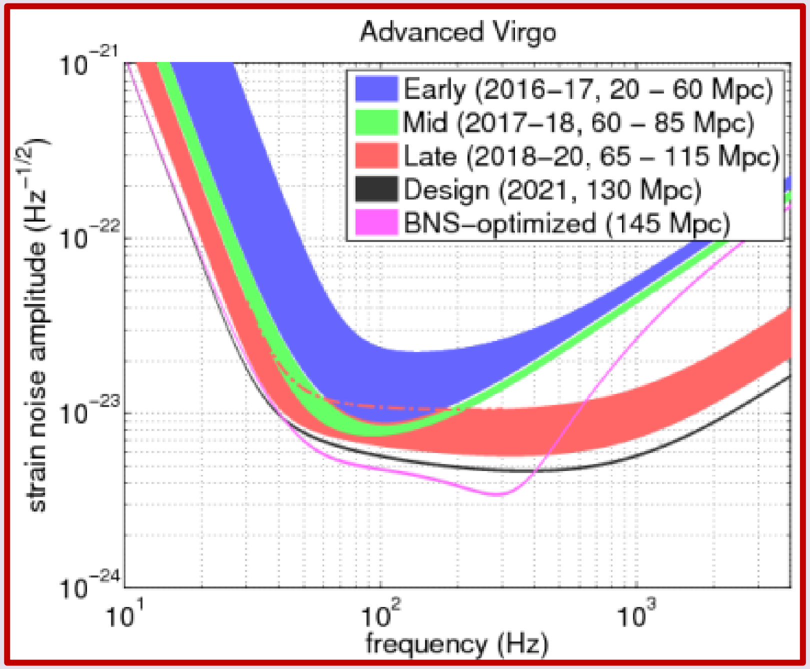


UNMODELED SEARCHES

Prospects of Observing and Localizing GWs

Progression of sensitivity and range for Binary Neutron Stars



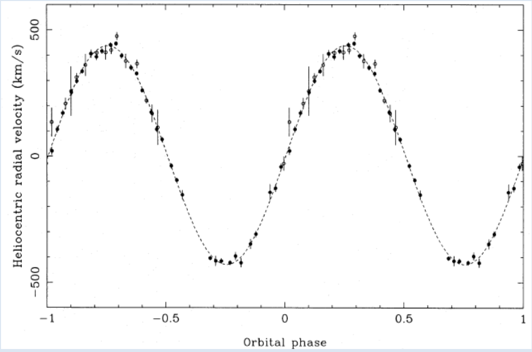


Larger GW-detectable Universe

LVC 2016, Living Reviews in Relativity, 19

Stellar-mass BHs through photons….

Dynamical estimates of BH mass in X-ray binaries



$$\frac{PK^3}{2pG} = \frac{M \sin^3 i}{(1+q)^2}$$

Direct observable:
- system’s orbital period P,
- radial velocity amplitude of the companion K

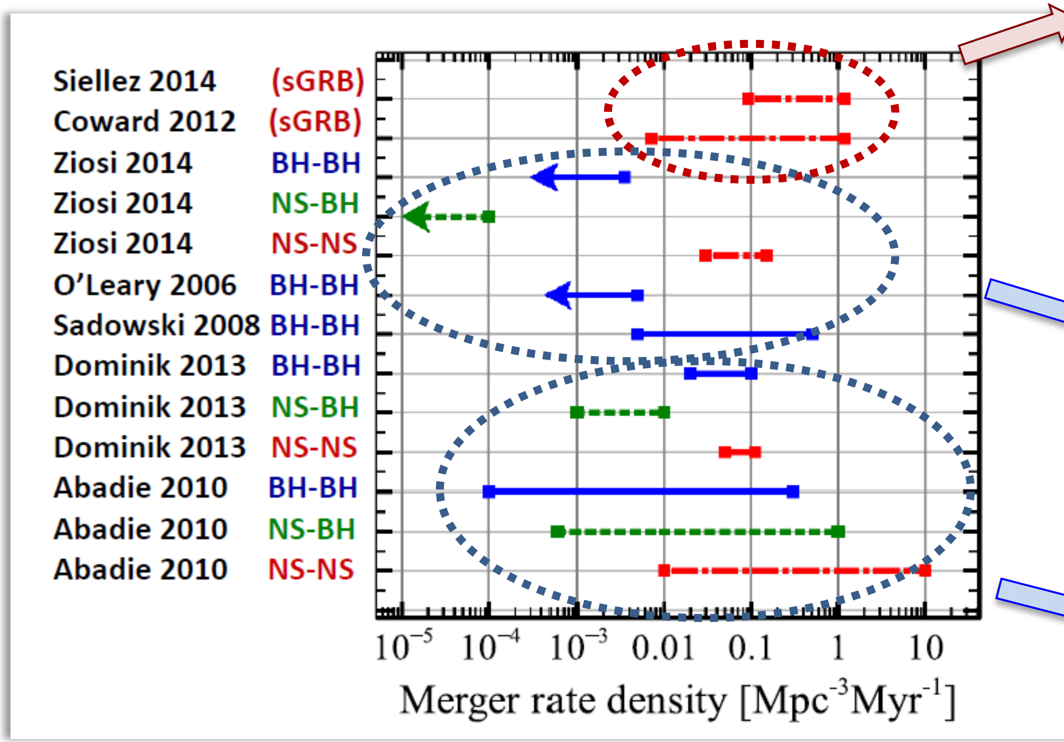
Constraints on:
- binary inclination i
- mass ratio q

MASS ESTIMATES 5-20 Mo

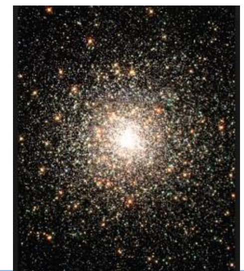
Compact object merger rates

Merger rates of BH-BH, NS-BH, NS-NS

Ziosi et al. 2014, *MNRAS*, 441



Gamma-ray Burst Observations



N-body and Montecarlo

Globular Star cluster

& Young Star Clusters

Population Synthesis Code

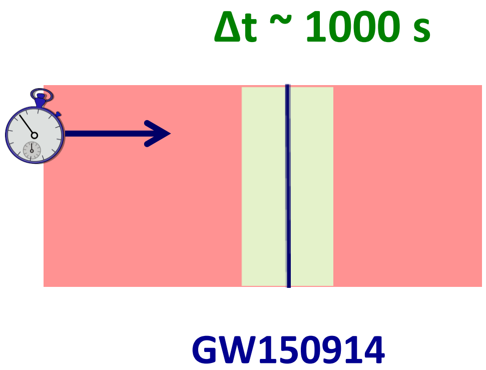
Binaries form and evolve isolated

Rates very poorly constrained:

- only 10 observed binary NS-NS sytems
- never observed NS-BH and BH-BH (now 1 BBH!)

High-Energy Neutrino Follow-up of GW150914

Search for coincident neutrino candidates within data of **IceCube** and **Antares**



Within ±500 s of GW150914:

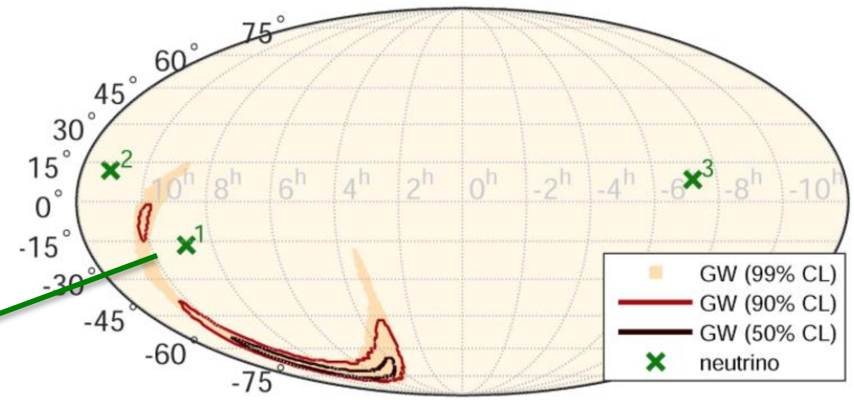
IceCube neutrino candidates **3**

ANTARES neutrino candidate **0**

- Consistent with the expected atmospheric background
- No neutrino candidate directionally coincident with GW150914

#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

Small angular uncertainties



No-detection is consistent with our expectation from a binary black hole merger

A rapid GW/neutrino detection could be used in targeted EM follow-up

Adrián-Martínez arXiv:1602.05411