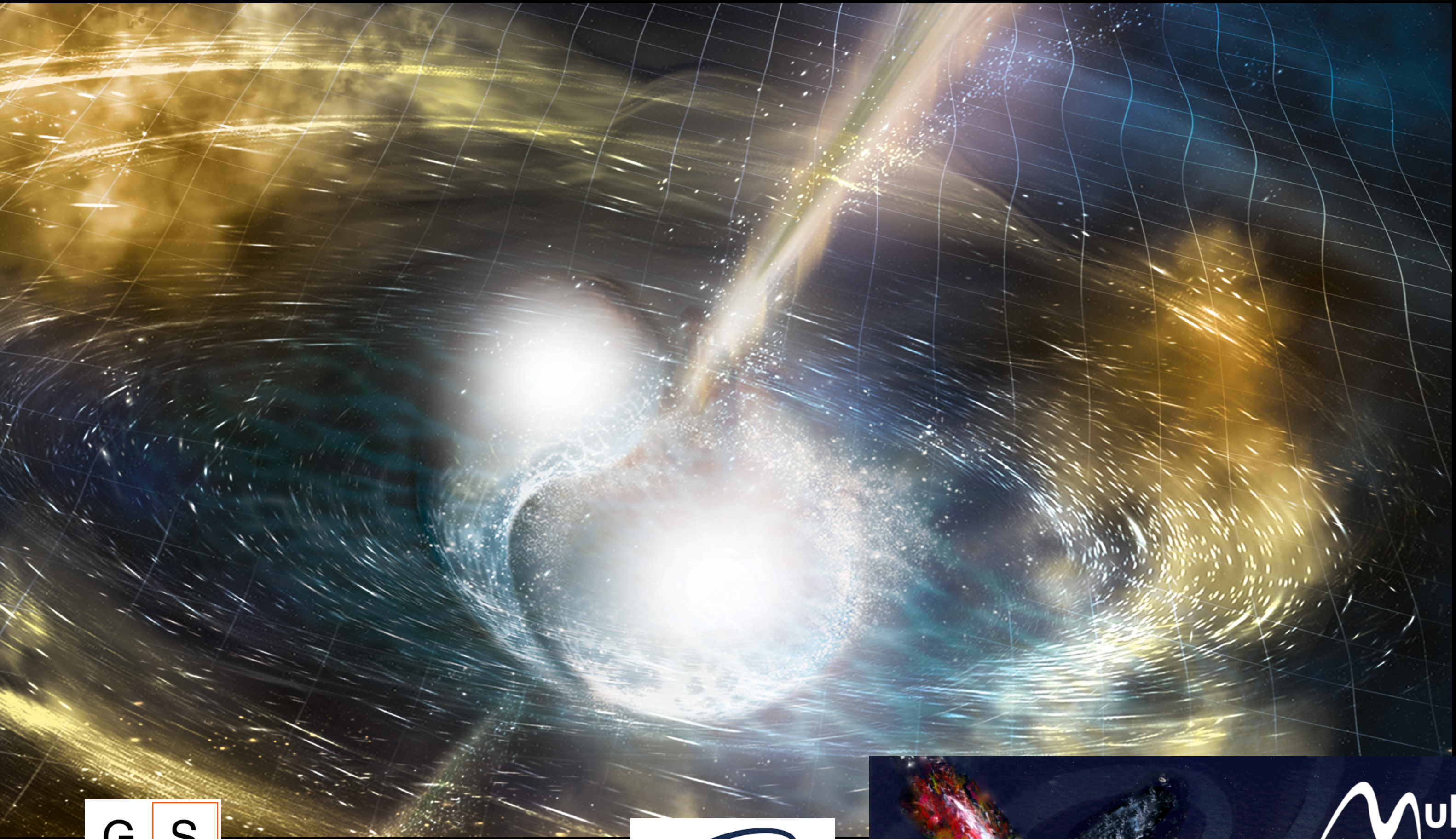
Multi-messenger Astrophysics and Gravitational Waves



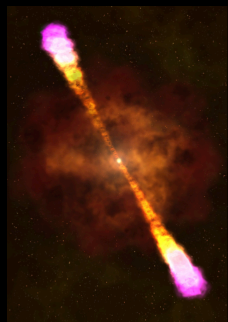
M. Branchesi

Gran Sasso Science Institute

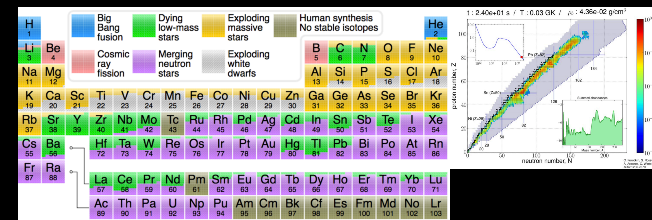
INFN/LNGS and INAF

Radioactively powered transients

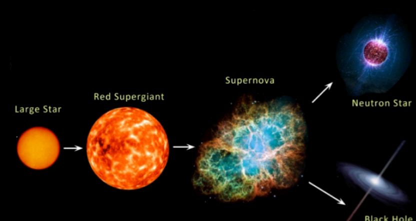
Relativistic astrophysics



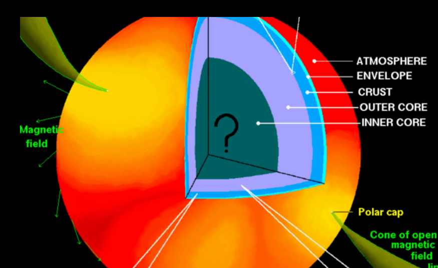
Nucleosynthesis and enrichment of the Universe



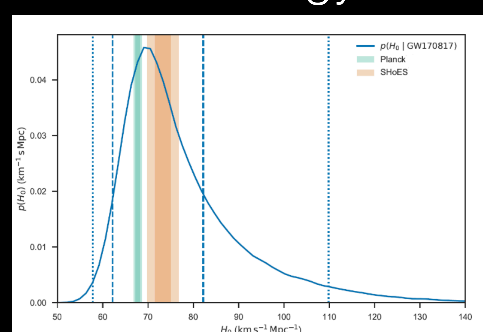
Compact object formation and evolution



Nuclear matter physics

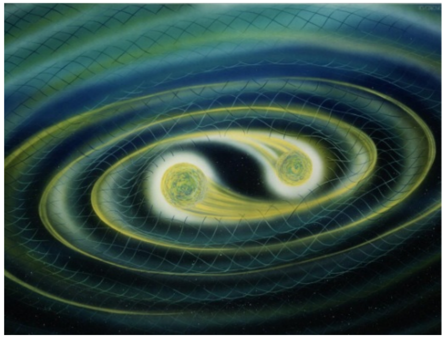


Cosmology



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

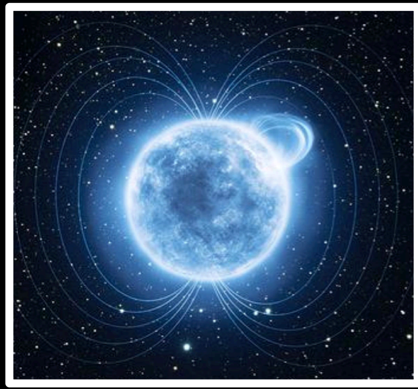
Coalescence of binary system of neutron stars (BNS) and NS-BH



- 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



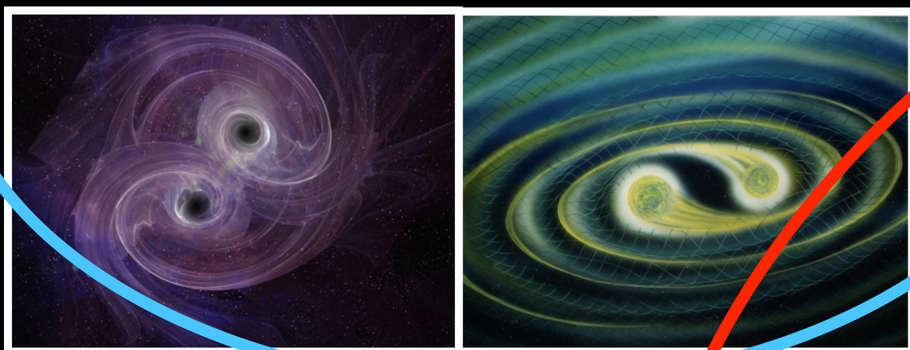
- Modeling of the GW shape and strength is complicated → **uncertain waveforms**
- **Energy emitted in GWs:**

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

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

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

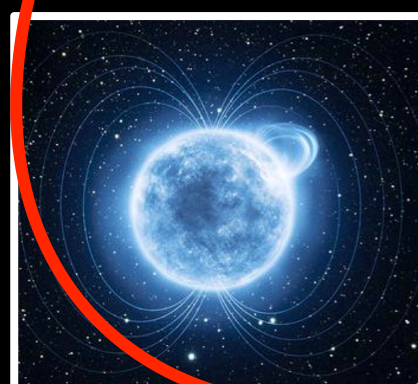
Coalescence of binary system of neutron stars and/or stellar-mass black-hole



→ MATCHED-FILTER MODEL SEARCHES

Core-collapse of massive stars

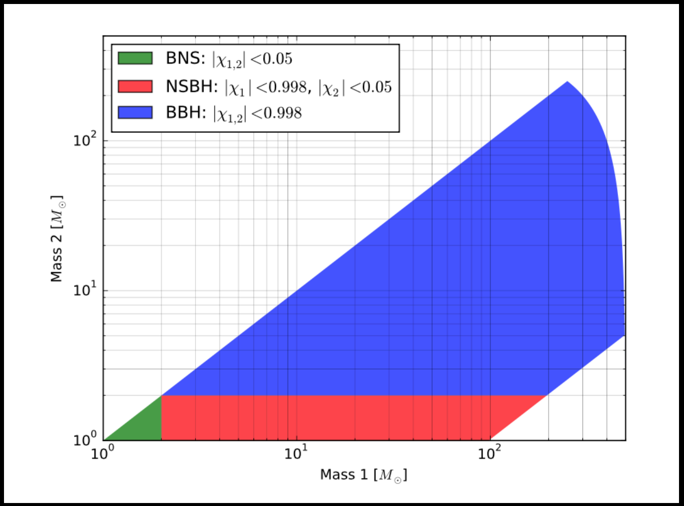
Isolated neutron-star



UNMODELED SEARCHES

Matched filtering searches

Template bank



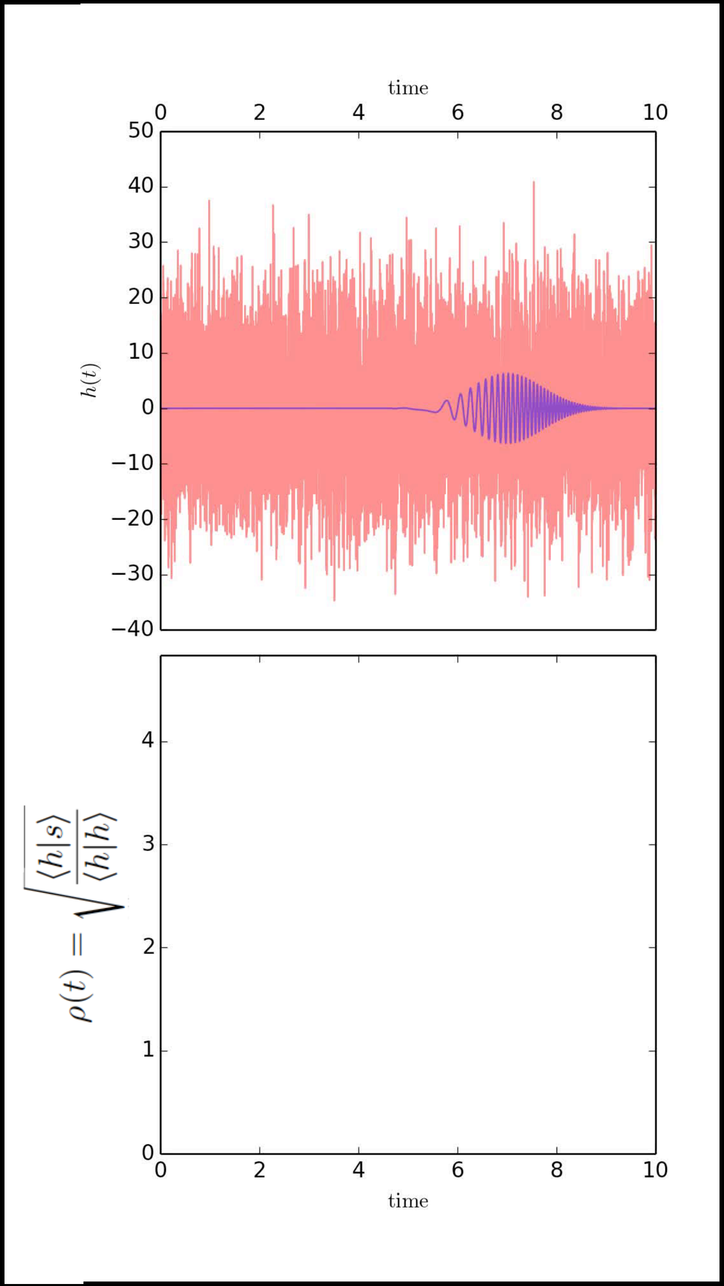
LVC Phys. Rev. X 6 (2016)

TEMPLATE

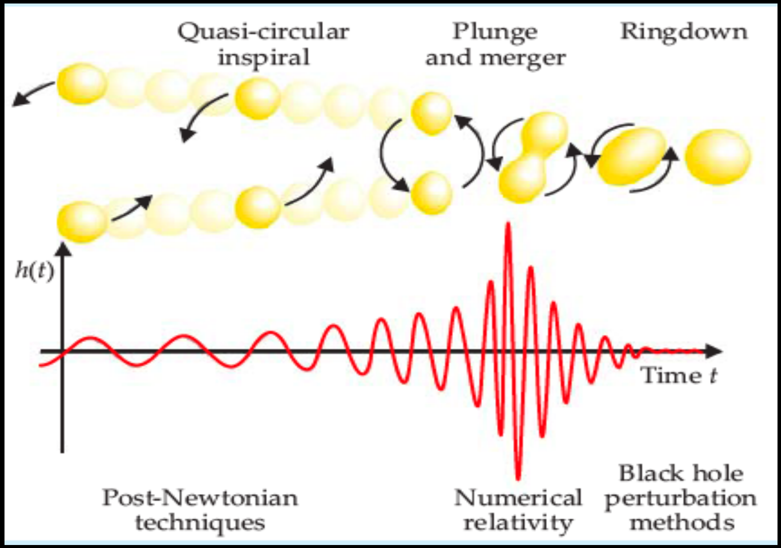
OBSERVATIONS

$$\langle h|s\rangle(t) = 4\Re \int_0^\infty \frac{\tilde{h}^*(f)\tilde{s}(f)e^{2\pi i f t}}{S_{\rm n}(f)} df$$

NOISE MODEL



Modelled compact binary coalescence searches



Waveforms depend on

- ***intrinsic parameters**: **masses** and **spins** of the binary system (plus eccentricity, NS compactness, tidal deformability)*
- ***extrinsic parameters** that describe location, distance, merger time and system orientation with respect to an observer*

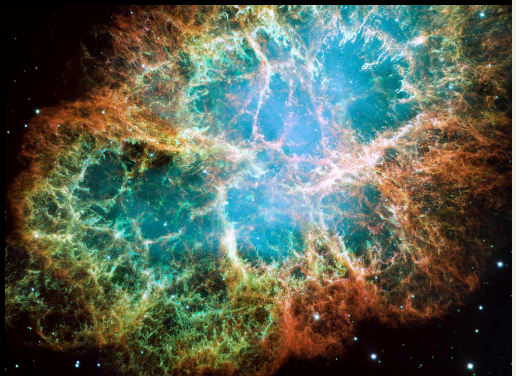
Detection phase: known waveforms → **MATCHED FILTERING**

- ➢ Using waveform templates for a range of intrinsic parameters (masses and spin)
- ➢ "Extrinsic" parameters absorbed in overall amplitude

After detection → ***Source PARAMETER RECONSTRUCTION:***

- ➢ Algorithms to explore the full-parameter space and find most likely values for sky location, masses, distance, orientation, spin…

Unmodeled GW transient searches



Transient sources:

- Core-collapse of massive stars
- Cosmic strings
- Neutron star instabilities
- Intermediate Massive BH
- ... the unknown

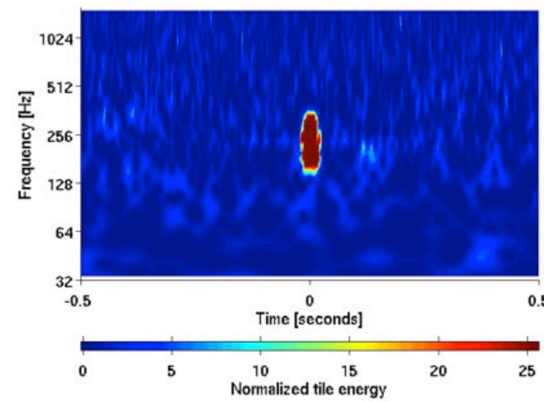
Poorly modelled
→ Can’t use matched filtering

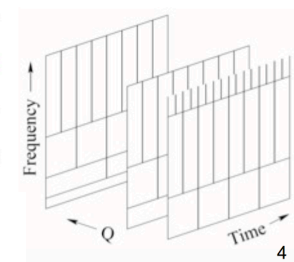
Detection without unknown waveform
→ **LOOK FOR “EXCESS POWER”**

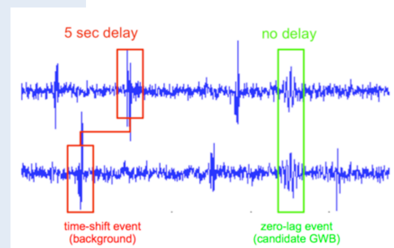
All-sky, all-time search for transient as increase in power (hot pixels) in time-frequency map, minimal assumptions:

1. Duration: 1 ms to 1 s (characteristic time scale for stellar mass objects) → now also to a few hundreds of sec
2. Frequency: 10 to 5000 Hz (determined by detector's sensitivity)
3. **Signal appears coherently** in multiple detectors, consistent with antenna pattern → coincidence, coherent statistics, sky location

Noise fluctuations can be eliminated based on their non-correlation between detectors







Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alerts

GW candidates

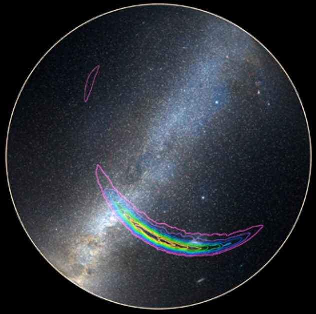
Sky Localization

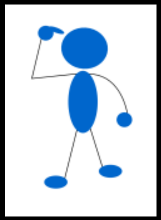
EM facilities

LIGO-H

LIGO-L

Virgo



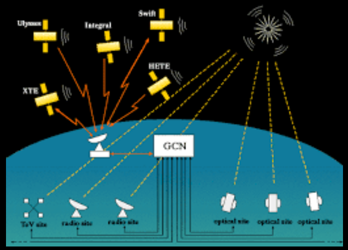


Event validation

Low-latency search
to identify the GW-candidates

Software to

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



a few min → 30 min

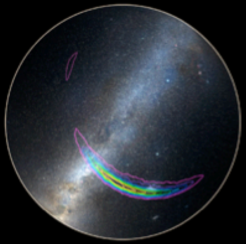
O3 run started in April

LIGO-H LIGO-L

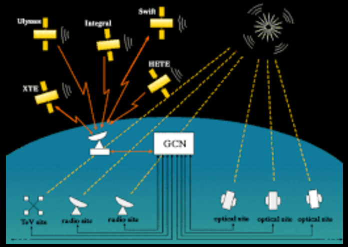
Virgo

GW candidates

Sky Localization



EM facilities



Event validation
RETRACTION
or
CONFIRMATION
GCN

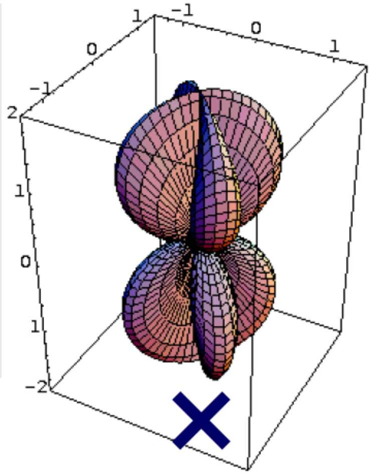
→ a few min → 30 min- few hrs

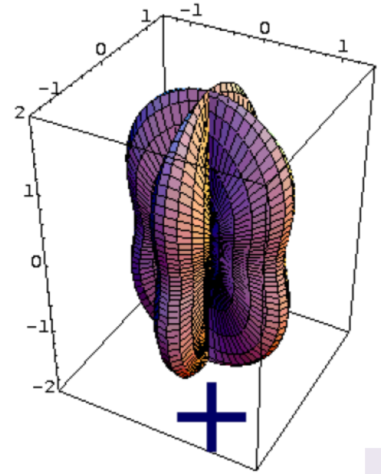
Parameter estimation codes → Hours,days → GW candidate updates

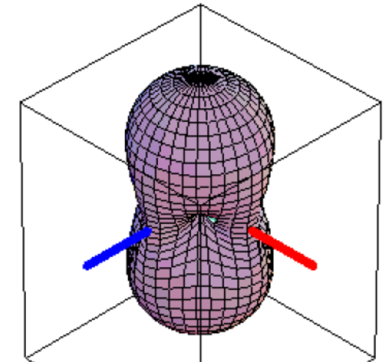
Sky location - single GW detector directional sensitivity

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

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

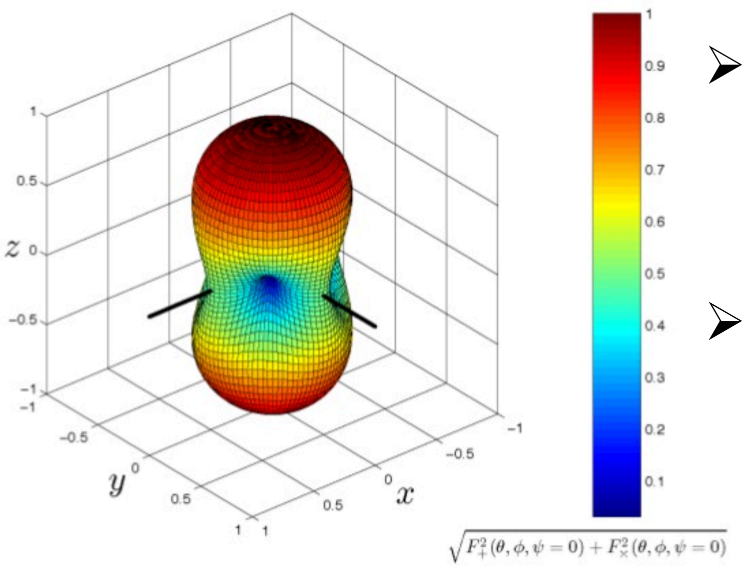






RMS sensitivity

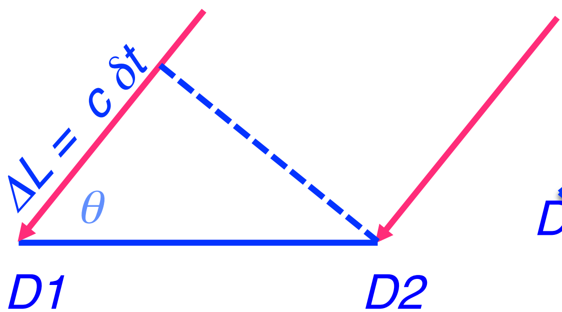
$$\sqrt{F_+(\theta,\phi)^2 + F_x(\theta,\phi)^2}$$

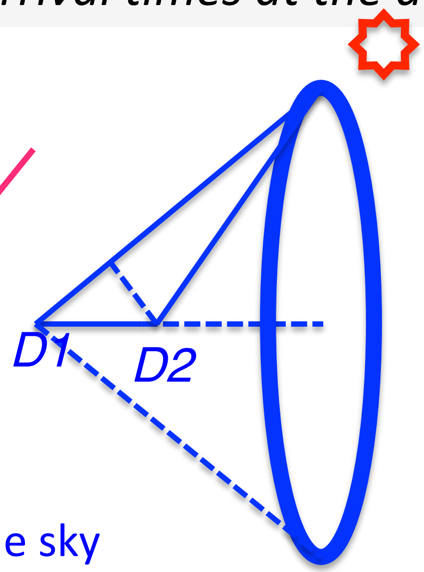


- Single GW detector is a **good all-sky monitor**, nearly omni-directional (the transparency of Earth to GWs)
- But does not have good directional sensitivity, **not a pointing instrument!** It has a very poor angular resolution (about 100 deg)

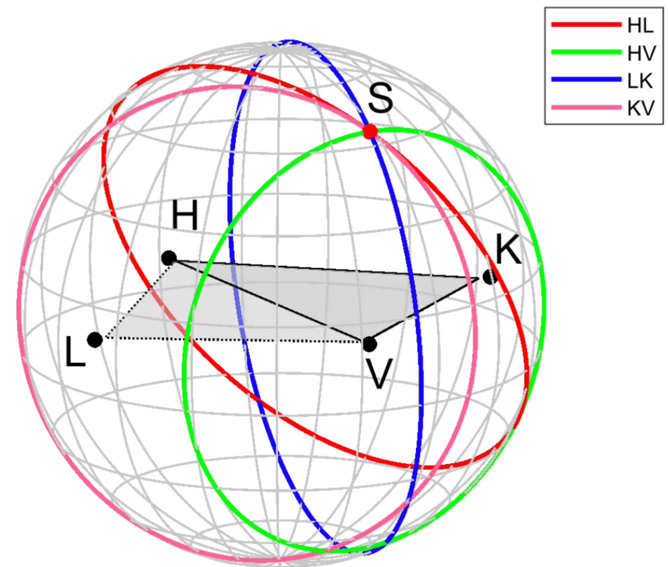
The source localization requires a network of GW detectors

*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



4-detectors → localize

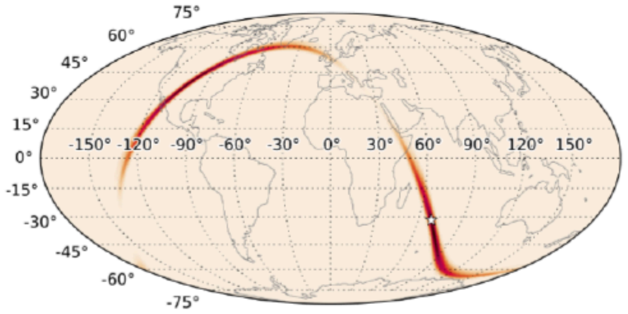
The localization capabilty improves with signal SNR → the sky localization area scales inversely with the square of the SNR

Compact binary Coalescence (CBC) Sky localization map

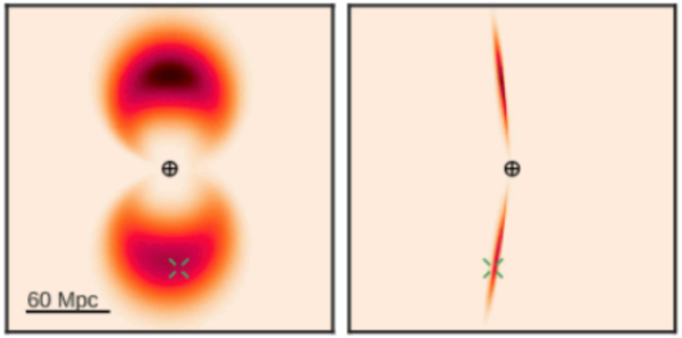
Arrival time Amplitudes Phase

→ sky location
→ distance to the source
→ binary orientation

Sky location also in 3 D



Sky direction



Projections of 3d location

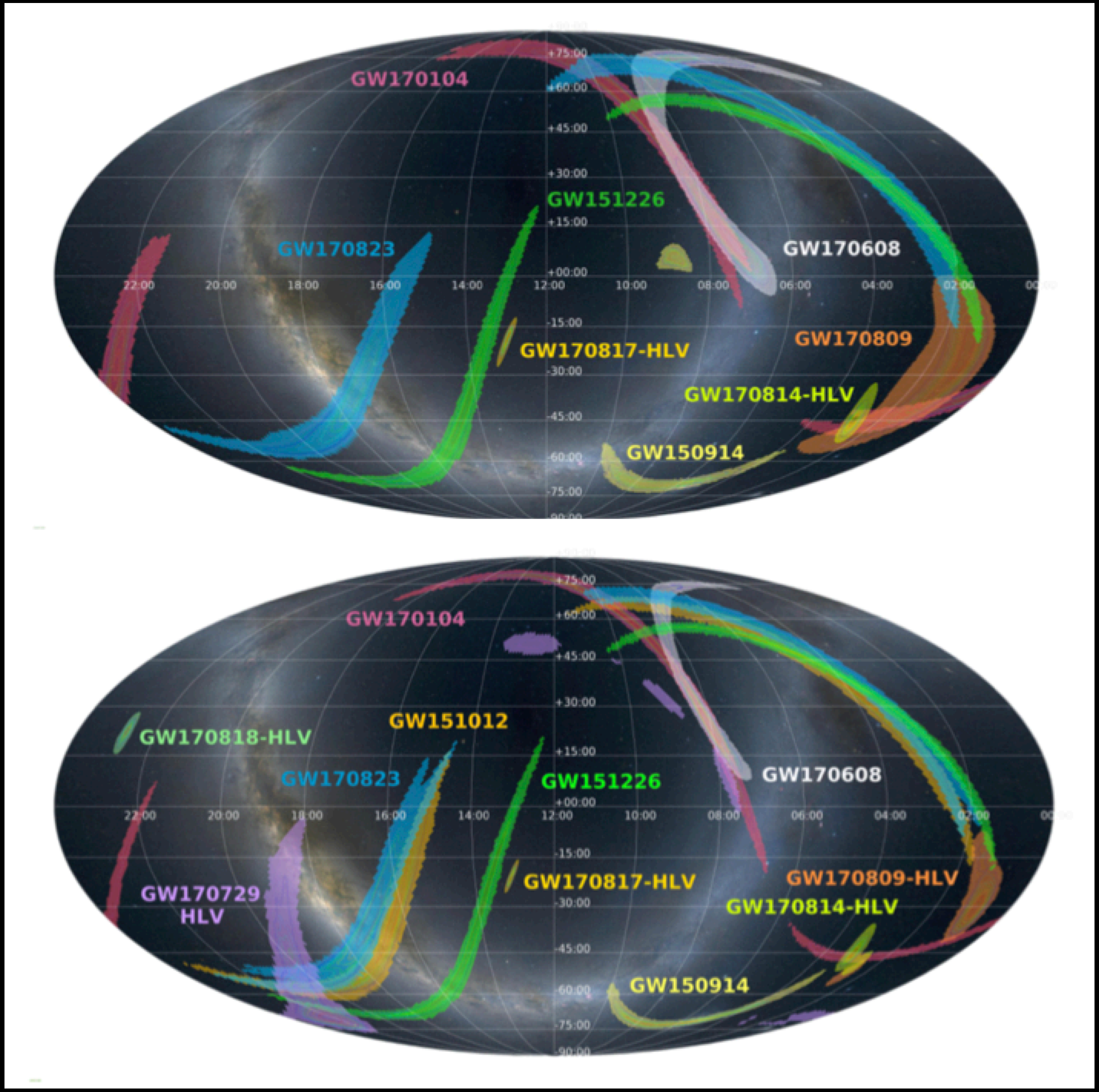
Online pipelines estimate → arrival time, phase, signal amplitude at each detector

These estimates + template masses : constrain direction of GW arrival and distance to the source

→ **BAYESTAR (Singer et al 2014, ApJ, 795, 2016 ApJL, 829)**: estimate 3D location in <1 minute

→ **LALInference**, **full PE Bayesian MCMC** **(Veitch 2015; Berry et al. 2015)**, modeling the inspiral-merger-ring down phase and taking into account the calibration uncertainty

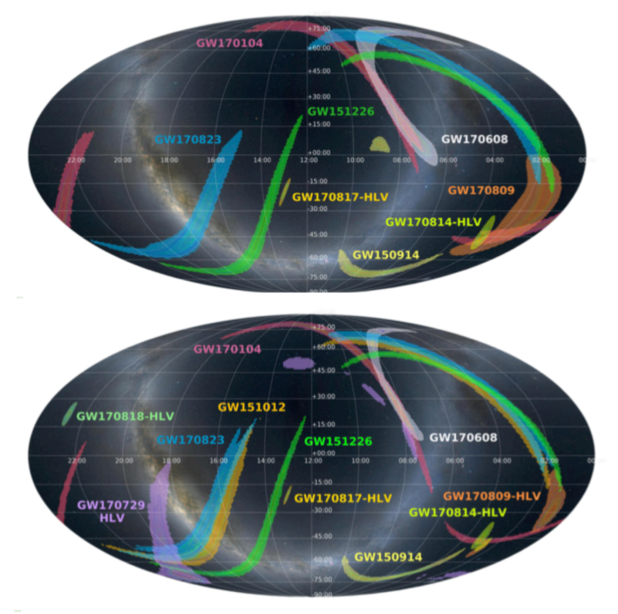
O1 and O2 → 17 ALERTS



11 confident detections

8 sent in low-latency

LVK arXiv:1304.0670

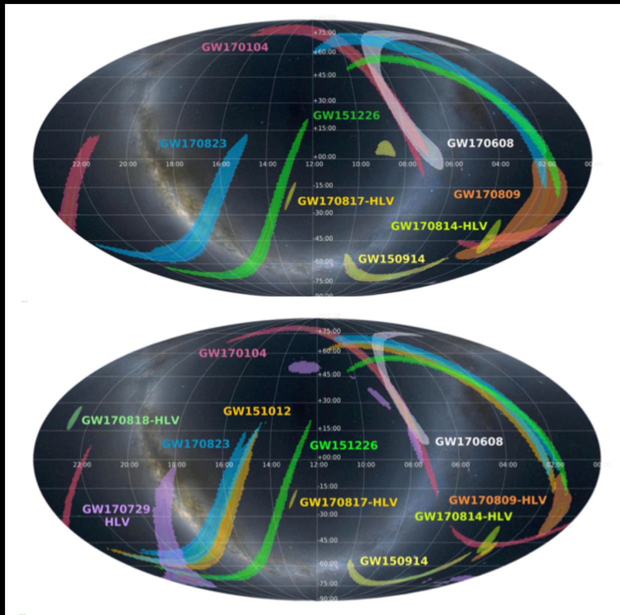


Low-latency sky localization

- a few thousands of sq. deg for 2-site detector network,
- a few tens of sq. deg for 3-site dtector network

	Low-latency analyisis			Refined analysis		
Event	d_L(Mpc)	$\Delta\Omega(\mathrm{deg}^2)$	IFOs	d_L(Mpc)	$\Delta\Omega(\mathrm{deg}^2)$	IFOs
GW150914	—	307	HL	440^{+150}_{-170}	182	HL
GW151012	—	—	—	1080^{+550}_{-490}	1523	HL
GW151226	—	1337	HL	490^{+180}_{-190}	1033	HL
GW170104	730^{+340}_{-320}	1632	HL	990^{+440}_{-430}	921	HL
GW170608	310^{+200}_{-120}	864	HL	320^{+120}_{-110}	392	HL
GW170729	—	—	—	2840^{+1400}_{-1360}	1041	HLV
GW170809	1080^{+520}_{-470}	1155	HL	1030^{+320}_{-390}	308	HLV
GW170814	480^{+190}_{-170}	97	HLV	600^{+150}_{-220}	87	HLV
GW170817	40^{+10}_{-10}	31	HLV	40^{+7}_{-15}	16	HLV
GW170818	—	—	—	1060^{+420}_{-380}	39	HLV
GW170823	1380^{+700}_{-670}	2145	HL	1940^{+970}_{-900}	1666	HL

LVK arXiv:1304.0670



Virgo in O2

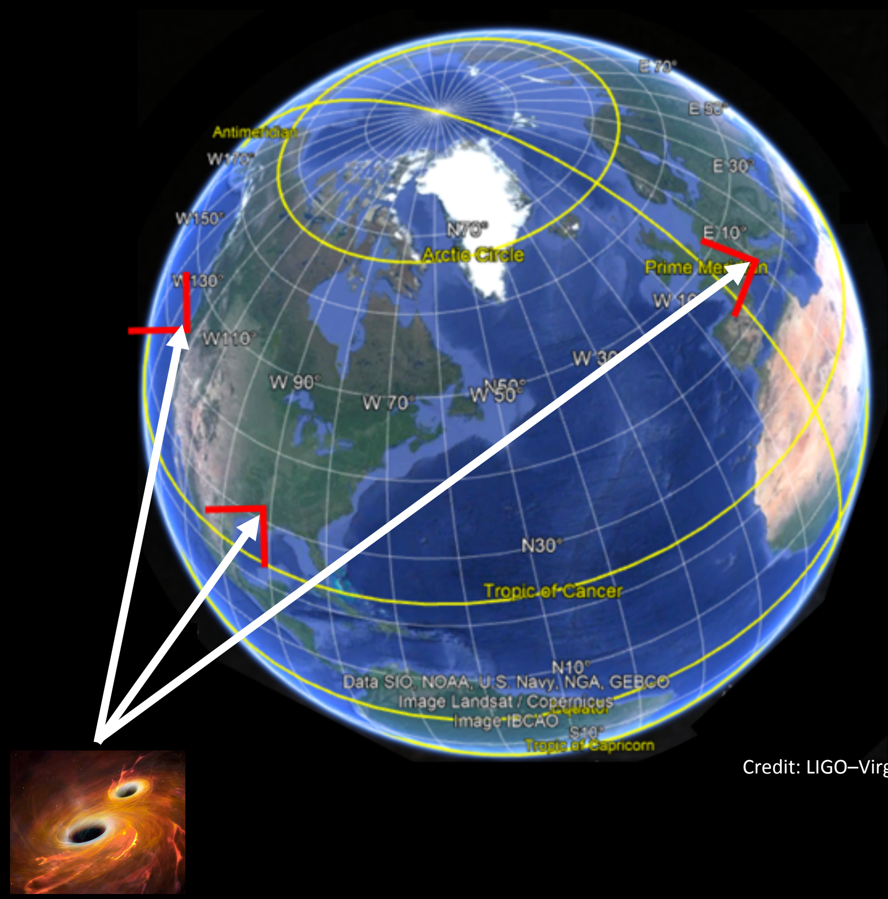
- Virgo data used in low-latency for the initial localization of 2 events
- Virgo data used for the final localizion of 5 events

	Low-latency analiysis			Refined analysis		
Event	d_L(Mpc)	$\Delta\Omega$(deg^2)	IFOs	d_L(Mpc)	$\Delta\Omega$(deg^2)	IFOs
GW150914	—	307	HL	440^{+150}_{-170}	182	HL
GW151012	—	—	—	1080^{+550}_{-490}	1523	HL
GW151226	—	1337	HL	490^{+180}_{-190}	1033	HL
GW170104	730^{+340}_{-320}	1632	HL	990^{+440}_{-430}	921	HL
GW170608	310^{+200}_{-120}	864	HL	320^{+120}_{-110}	392	HL
GW170729	—	—	—	2840^{+1400}_{-1360}	1041	HLV
GW170809	1080^{+520}_{-470}	1155	HL	1030^{+320}_{-390}	308	HLV
GW170814	480^{+190}_{-170}	97	HLV	600^{+150}_{-220}	87	HLV
GW170817	40^{+10}_{-10}	31	HLV	40^{+7}_{-15}	16	HLV
GW170818	—	—	—	1060^{+420}_{-380}	39	HLV
GW170823	1380^{+700}_{-670}	2145	HL	1940^{+970}_{-900}	1666	HL

The contribution from Virgo significantly shrink the localization to a few tens of square degrees for 3 events

LVK arXiv:1304.0670

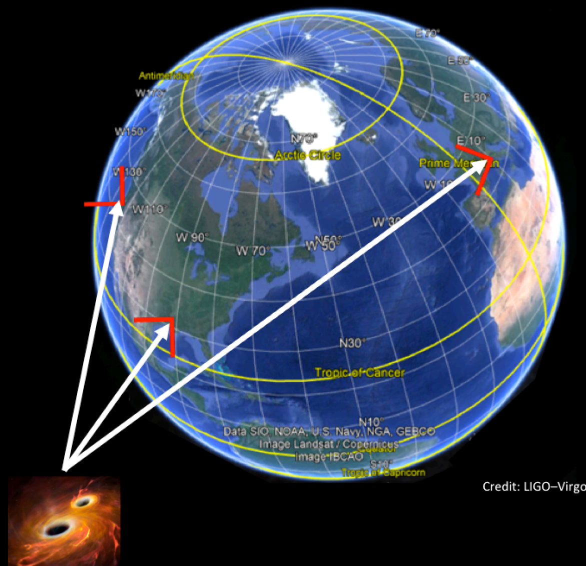
2017 August 14, 10:30:43 UT



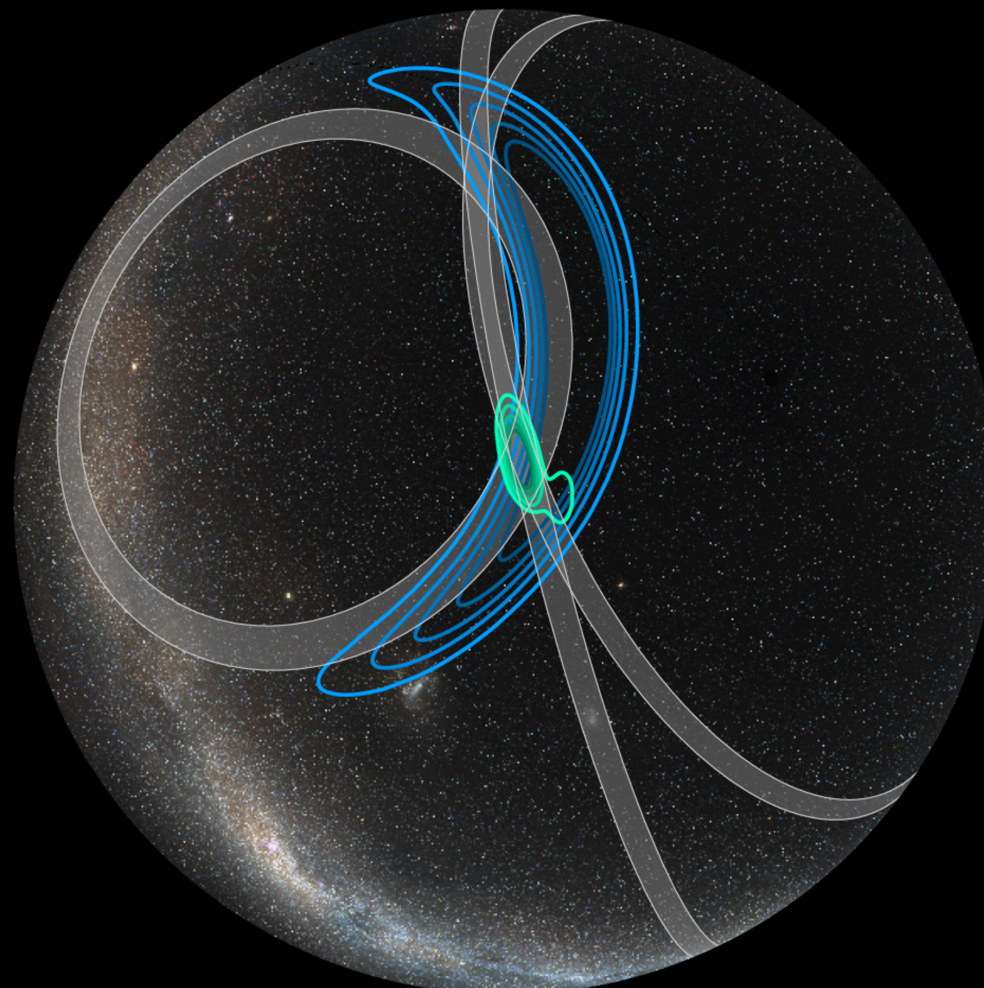
Credit: LIGO–Virgo

Virgo observed its first BBH coalescence, GW170814

2017 August 14

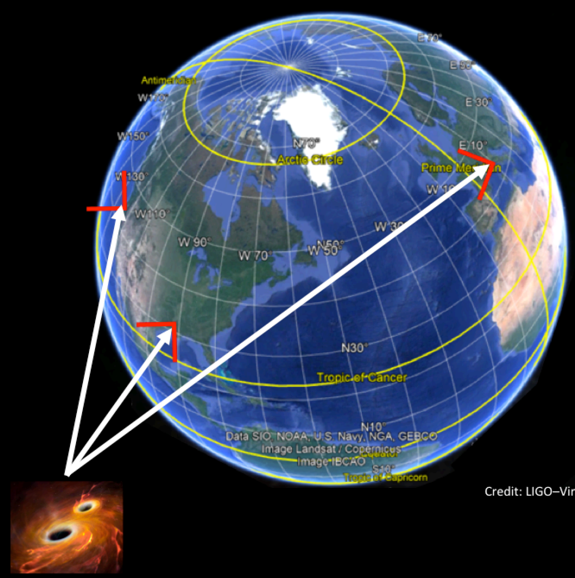


Credit: LIGO–Virgo

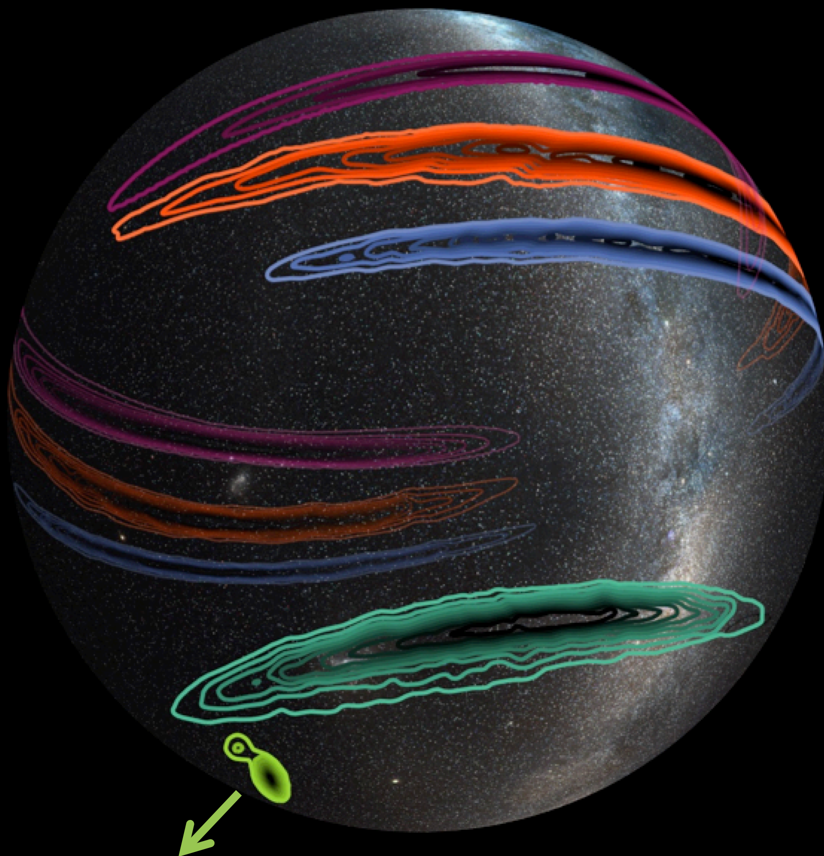


Credit: Leo Singer

2017 August 14



Credit: LIGO–Virgo

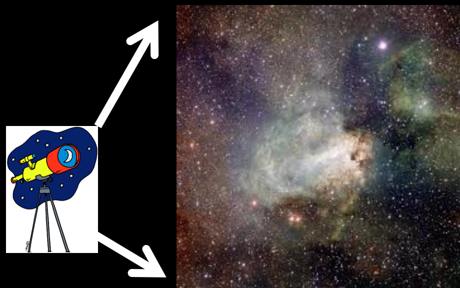


GW170814

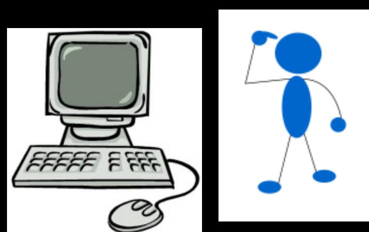
Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

LH 1160 square degrees
LHV 60 square degrees

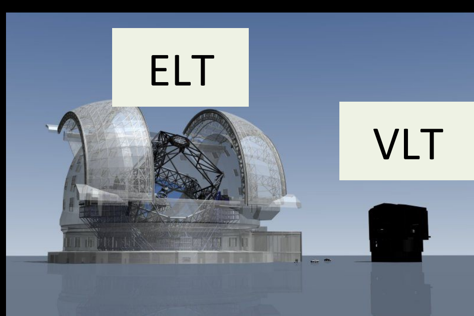
Hunt the elusive EM-counterpart!



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

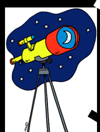
The EM Counterpart!

to cover hundreds/thousands of square degrees

to remove transients contaminants

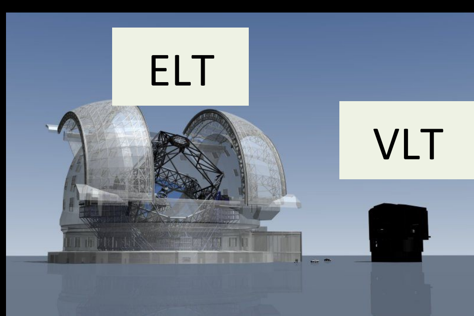
To obtain observational time for the characterization

Hunt the elusive EM-counterpart!

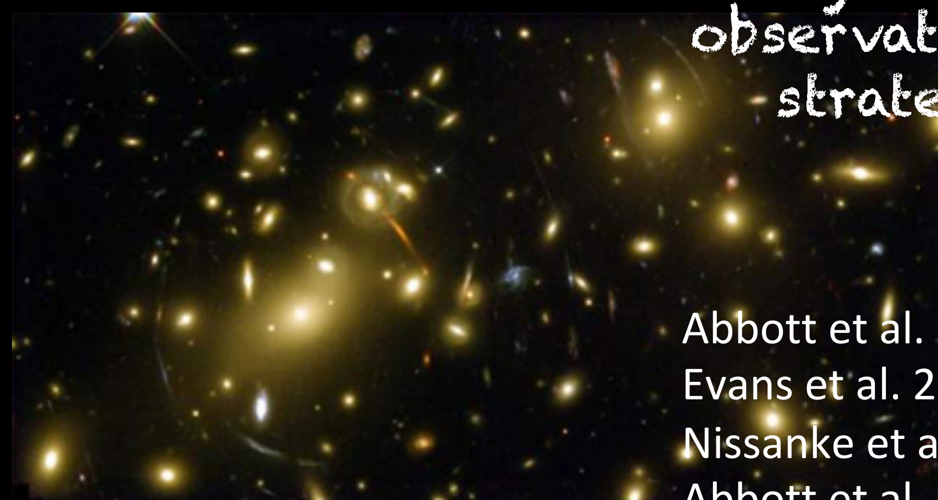


Wide-field telescope
FOV >1 sq.degree

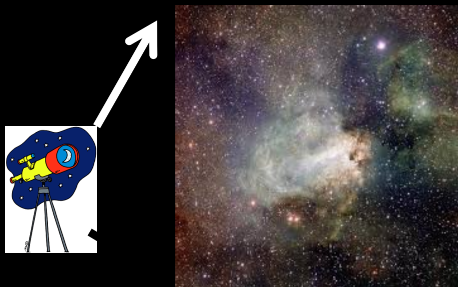
to cover hundreds/thousands of square degrees

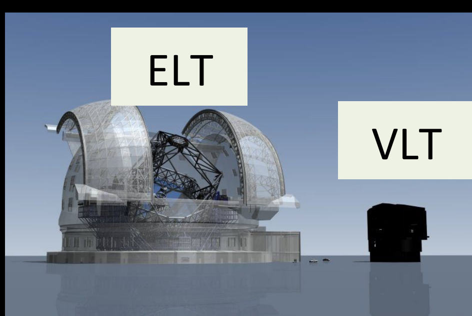


Galaxy-targeting observational strategy



Abbott et al. 2012 A&A
Evans et al. 2012
Nissanke et al. 2013
Abbott et al. 2014 ApJS
Gehrels et al. 2016





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

Optical/NIR band

10^4-10^5 variable objects over 100 sq. degrees

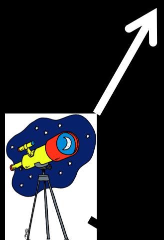
Artifacts and many astrophysical contaminants

M-dwarf flares (min to hrs)
3 (0.3) deg^{-2} up to red mag 24
at 20 (80) deg latitude
(Ridgway et al., 2014)

Supernovae (days to month)
7 deg^{-2} up to red mag 24
(Graur et al., 2014; Dahlen et al., 2012; Cappellaro, 2014)

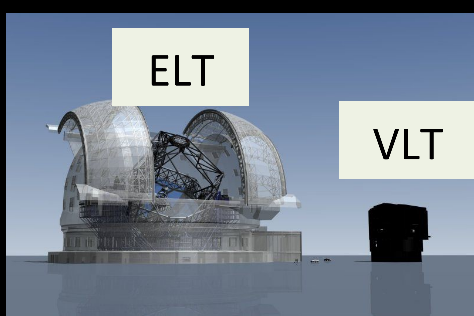
A few tens of candidate counterparts

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!

X-rays

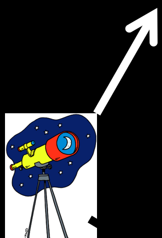
✓ less contaminants

Transient rate **2.5×10^{-3} deg^{-2}**
flux$_{0.2\text{-}2KeV}$ > 3×10^{-12}ergs^{-1}cm^{-2}
(Kanner et al. 2013)

x no wide-field telescope

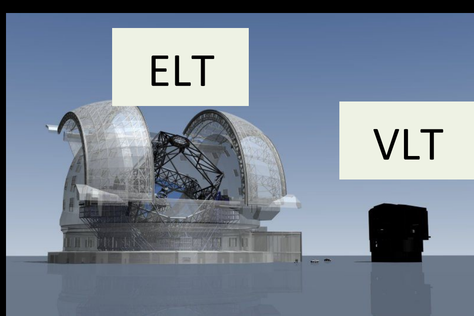
Gamma-rays

✓ less contaminants
✓ all-sky monitors
x beamed emission



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!

Radio

✓ less contaminants

Transient rate < 0.37 deg^{-2}
peak-flux_1.4 GHz > 0.21 mJy
timescales 1 d – 3 m
(Mooley et al., 2013)

✓ wide-field array at low frequencies (MHz)

x faint sources

x long delay GW → radio emission

ALERT CONTENTS to support observing startegy

- Estimate of FALSE ALARM RATE (FAR) of the event candidate
  FAR=Rate of noise events louder than the candidate event

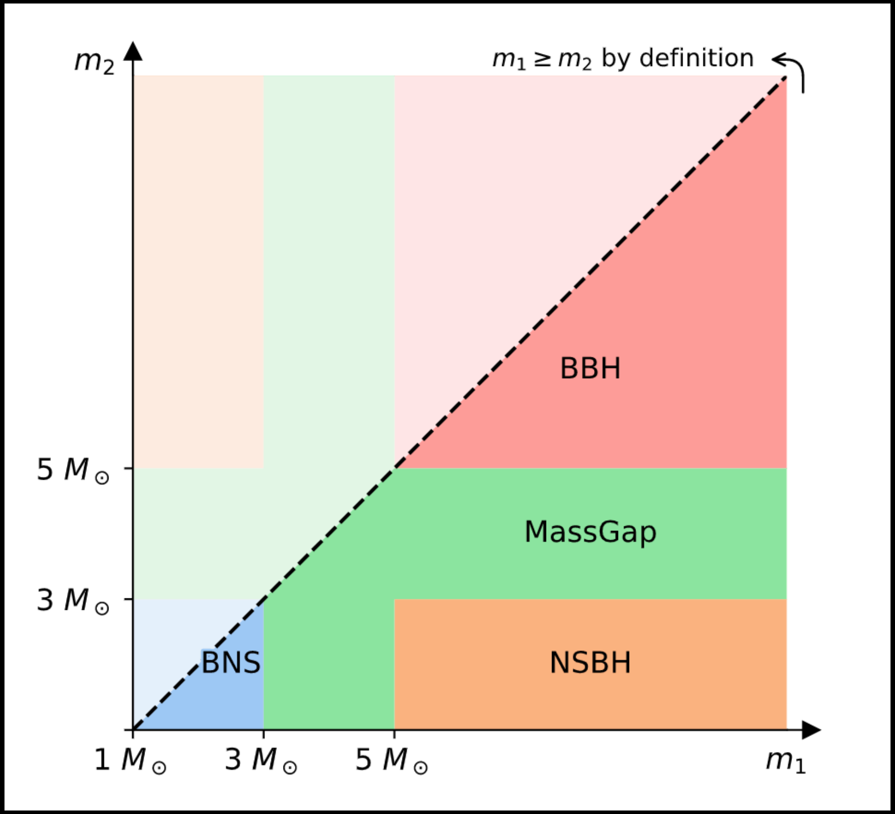
- Event TIME and LOCALIZATION given as a posterior probability distribution of the source's sky position(HEALPix FITS file)

For CBC candidates:

- 3-D skymap (Singer et al. 2016, ApJL 829, L15), with direction dependent luminosity distance
- Luminosity distance marginalized over whole sky (mean+/-standard deviation)

ALERT CONTENTS

- For CBC candidates, CLASSIFICATION and PROPERTIES



Credit: User Guide

Categories in terms of component masses

CLASSIFICATION:

→ P_astro probability that the signal is astrophyiscal

This probability evaluates whether the source belongs to one of five categories: BNS, mass gap, NSBH, BBH, Terrestrial

Based on our knowledge of trigger distribution, assumptions about signal distribution (such as that sources are uniformly distributed involume), and knowledge and assumptions about merger rate per unit volume fo reach class of sources

(See Kapadia et al 2019)

PROPERTIES

- HasNS → probability that the mass of one or more of the binary's two companion compact objects is consistent with a neutron star.

- **HasRemnant** → probability that a non-zero amount of neutron star material remained outside the final remnant compact object (a necessary but not sufficient condition to produce certain kinds of electromagnetic emission such as a short GR or a kilonova)

(Foucart 2012, 2018, PhRvD, Pannarale & Ohme, 2014, ApJ)

LIGO/Virgo Public Alerts User Guide

Getting Started Checklist →

LSC LIGO Scientific Collaboration

VIRGO

Public Alerts User Guide

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Navigation

- Getting Started Checklist
- Observing Capabilities
- Data Analysis
- Alert Contents
- Sample Code

- Change Log
- Glossary

Question? Issues? Feedback?

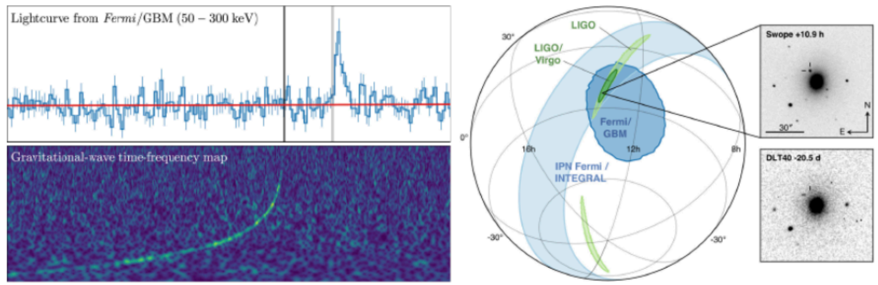
Email emfollow-userguide@support.ligo.org

Quick search

Go

National Science Foundation

LIGO/Virgo Public Alerts User Guide



Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Three sites (LHO, LLO, Virgo) together form a global network of ground-based GW detectors. The LIGO Scientific Collaboration and the Virgo Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

Advanced LIGO and Advanced Virgo began their third observing run (O3) on April 1, 2019. For the first time, **LIGO/Virgo alerts are public**. Alerts are distributed through NASA's Gamma-ray Coordinates Network (GCN). There are two types of alerts: human-readable GCN Circulars and machine-readable GCN Notices. This document provides a brief overview of the procedures for vetting and sending GW alerts, describes their contents and format, and includes instructions and sample code for receiving GCN Notices and decoding GW sky maps.

Contents

https://emfollow.docs.ligo.org/userguide/index.html highly significant FAR = 1/100 yr

significant

low significance FAR = 1/yr

FAR = 1/month

FAR = Rate of noise events louder than the candidate event

Candidates to be observed selected based on the observer's choice of FAR threshold highly significant FAR = 1/100 yr

significant

low significance FAR = 1/yr

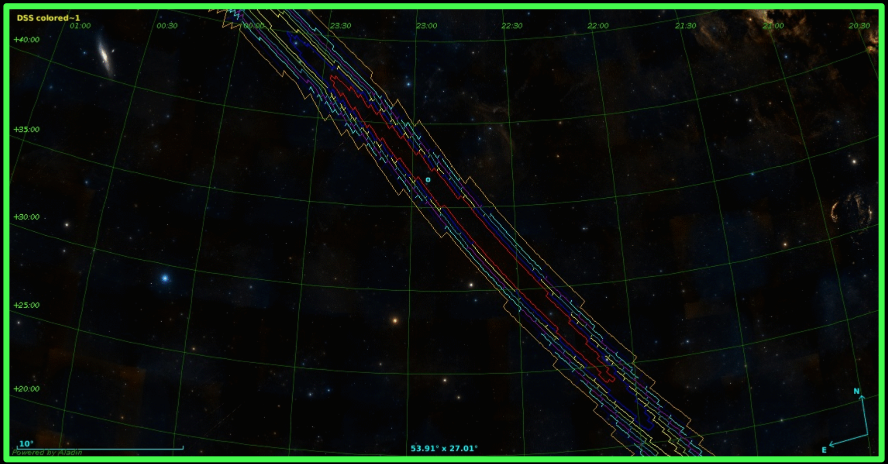
FAR = 1/month

FAR = Rate of noise events louder than the candidate event

Candidates to be observed selected based on the observer's choice of FAR threshold

Sky map + basic source classification

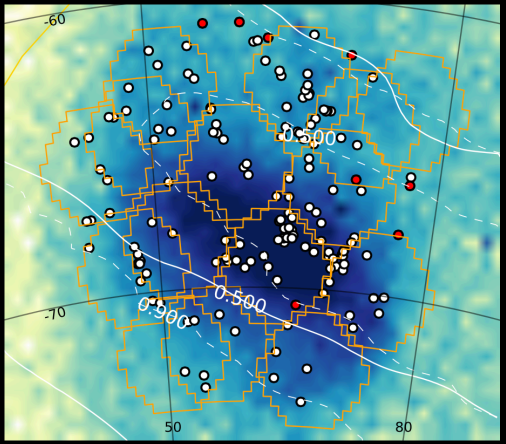
Credit: G. Greco, GWsky https://github.com/ggreco77/GWsky



Tiling the sky map to maximize the enclosed localization probability

To decide the search type

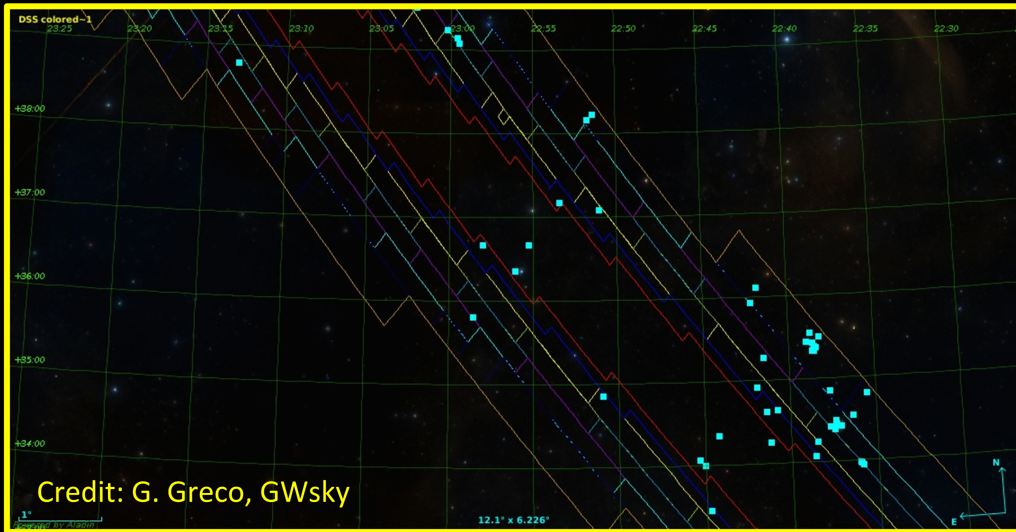
DES, Annis et al. 2016, ApJL



Burst → failed-SNe

Search for missing Supergiants in the LMC

Sky map + source classification + distance

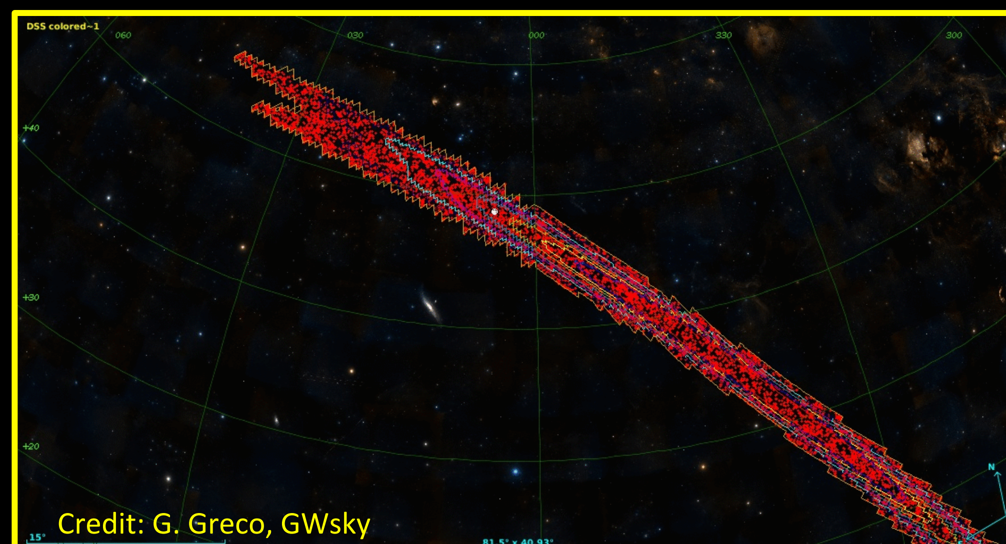


Targeting ranked galaxies

(Small FoV instruments)

Targeting ranked FoV pointings

(Instruments FoV > 1 deg^2)



Sky map weighted by galaxy luminosity

For each FoV →

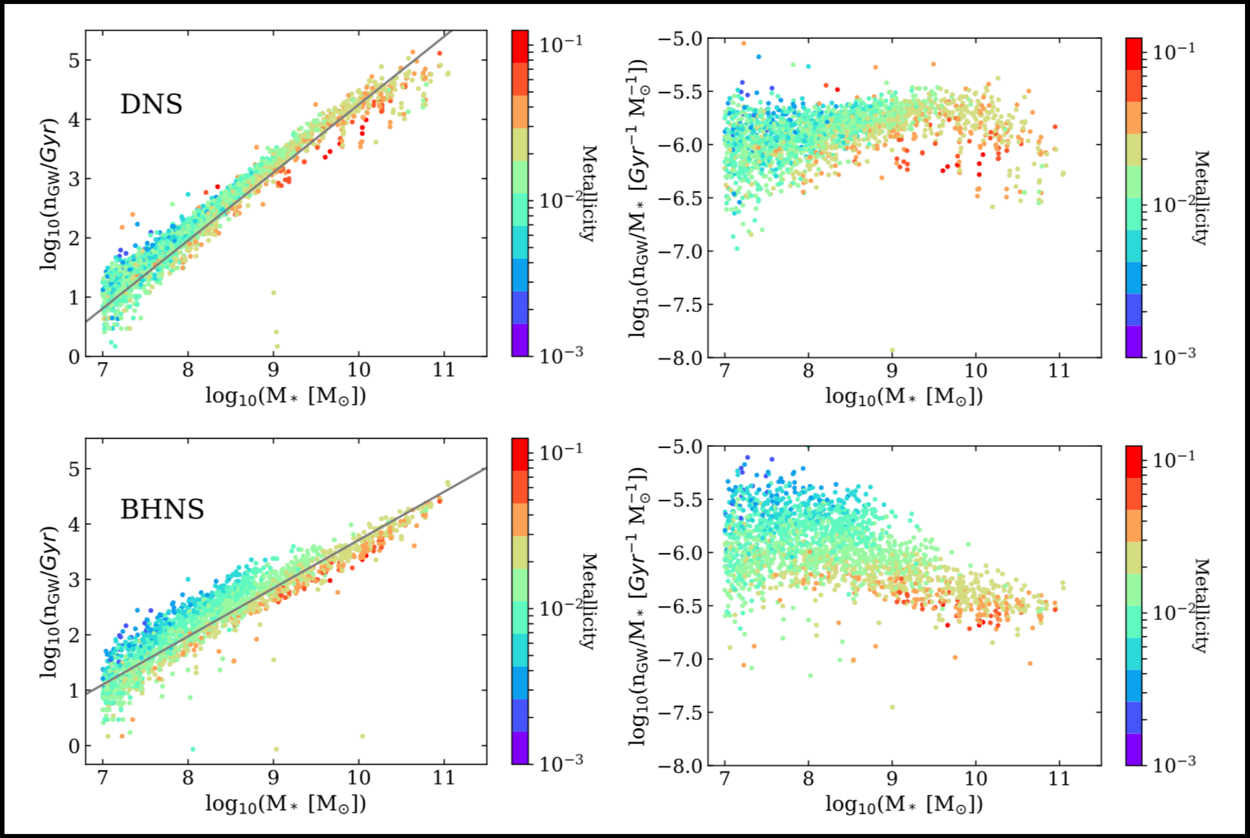
$$P = \sum \frac{L_i}{L_{tot}} P_{GW}$$

P_{GW} = probability that GW candidate lies within the FoV

See e.g Evans et al. 2016, MNRAS

HOW TO RANK THE GALAXIES?

From theoretical simulations: identify the most probable host
by combining the results of population-synthesis models together with galaxy catalogs from galaxy cosmological simulation



Artale et al. 2019 MNRAS

- strong correlation between host galaxy mass and merger rate
- low mass galaxies have a more efficient merger rate per galaxy of NSBH systems

REAL OBSERVATIONS → GALAXY CATALOG + 3D SKY LOCALIZATION MAP

The overall probability of the merger occurring in a galaxy is given by

1) Localization probability

$$P_{loc} = P_{(RA,DEC)} P_{(D_l)}$$

$$\Rightarrow P = P_{loc} P_{lum}$$

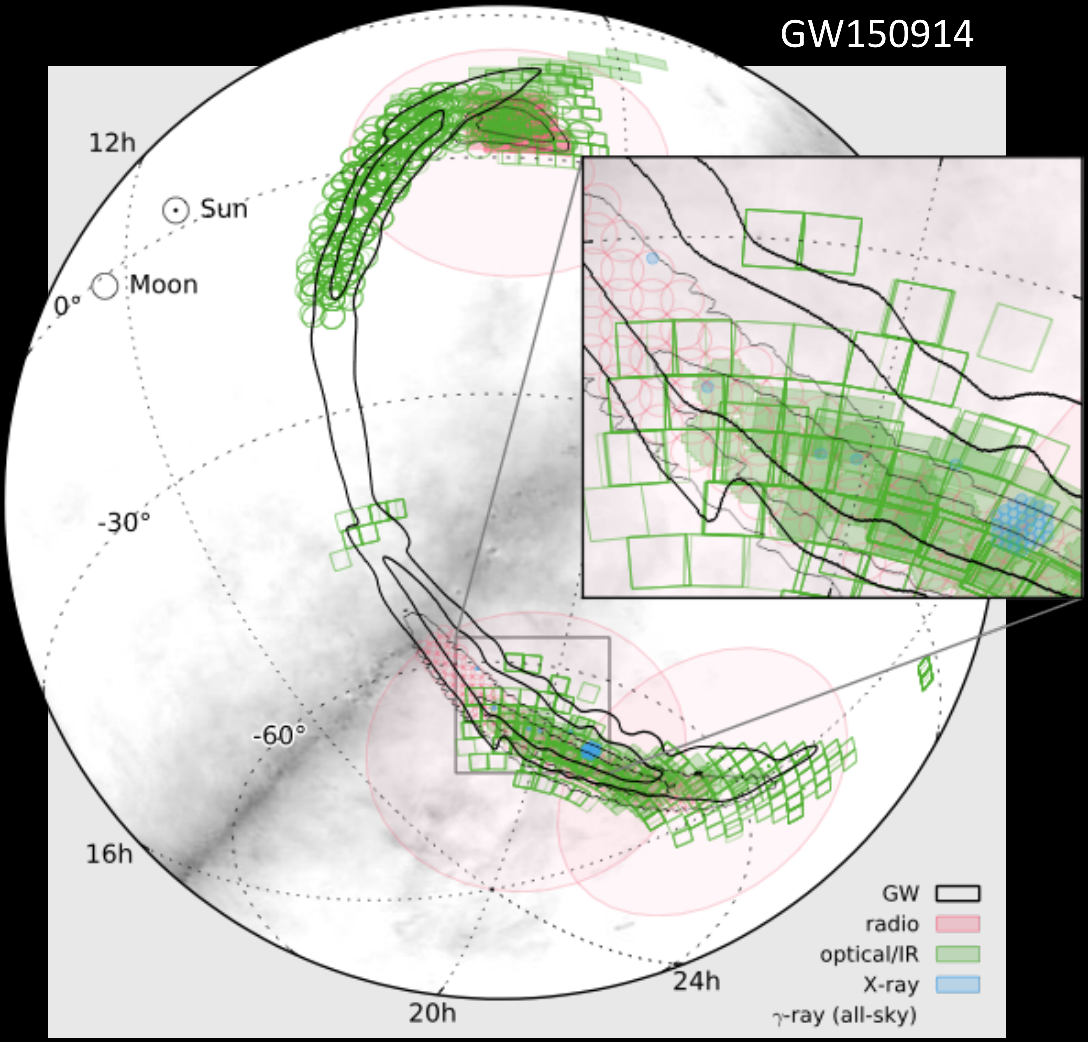
2) Mass/SFR probability

$$P_{lum} = \frac{L_{K,B}}{L_{tot}} = \frac{L_{K,B}}{\sum L_{K,B}}$$

After the observations the same formalism is used to evaluate the probability covered by the galaxy targeted search (including catalog incompleteness)

See e.g. Gehrels et al. 2016, Arcavi et al. 2017, Salmon 2019

Counterpart search



For all the detected BBH
no firm electromagnetic counterpart found!

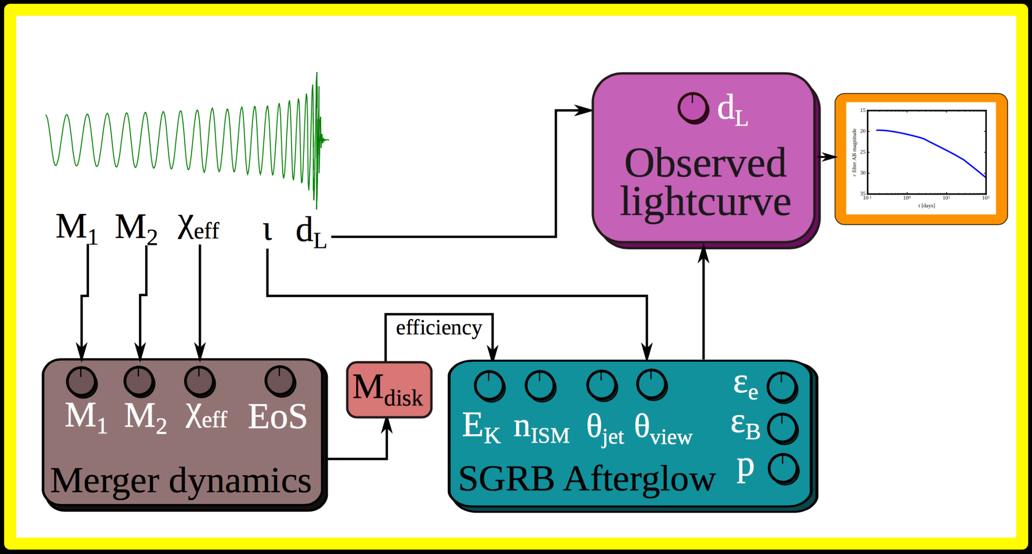
Abbott et al. 2016, ApJL, 826, 13
Abbott et al. 2016, ApJS, 225, 8

Optimizing the observational strategy: when and where?

GWs

- Mass
- Spins
- EOS

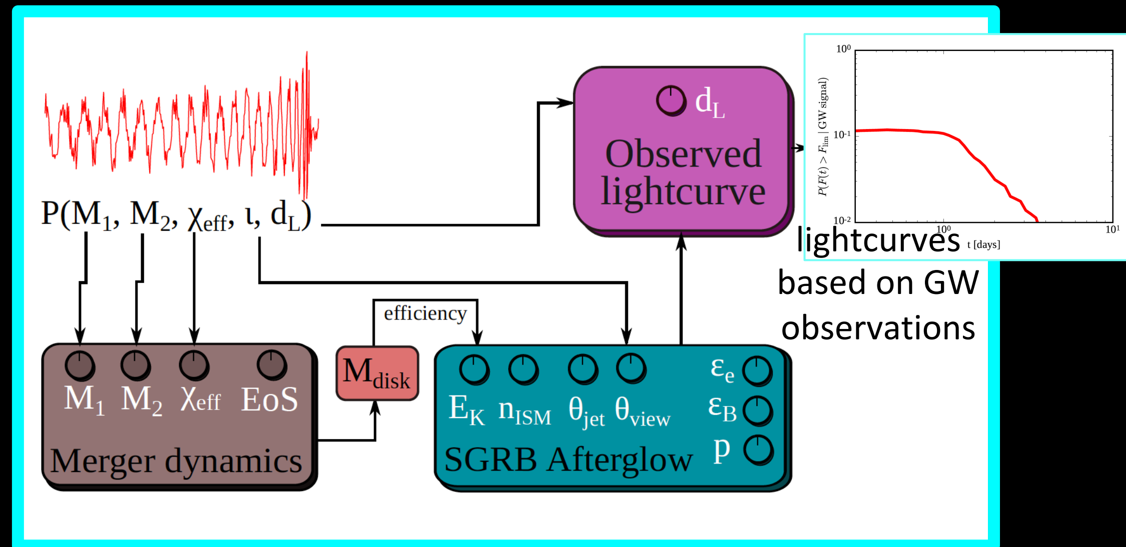
EM emission



Optimizing the observational strategy: when and where?

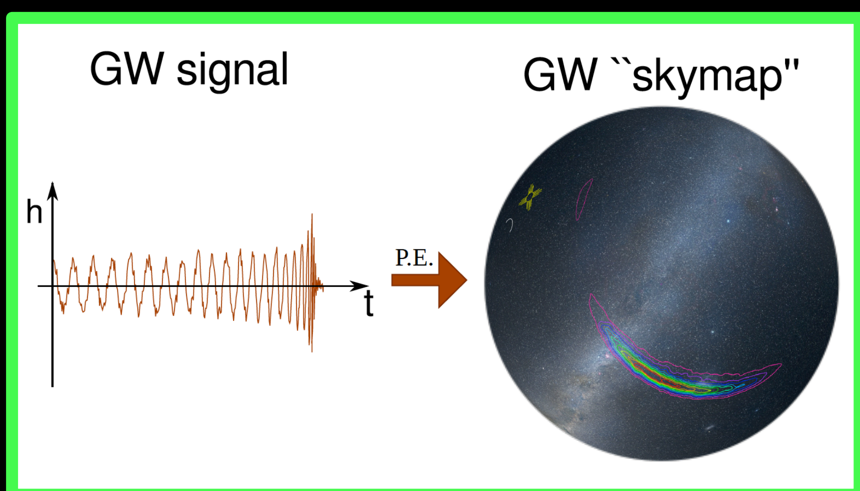
Posterior distributions of GW parameters

The same signal can be produced by different combinations of the parameter values



A posteriori detectability
$P\,(F(t) > F_{lim}\,|\text{GWsignal})$

Salafia et al. 2017 ApJ



3D sky map

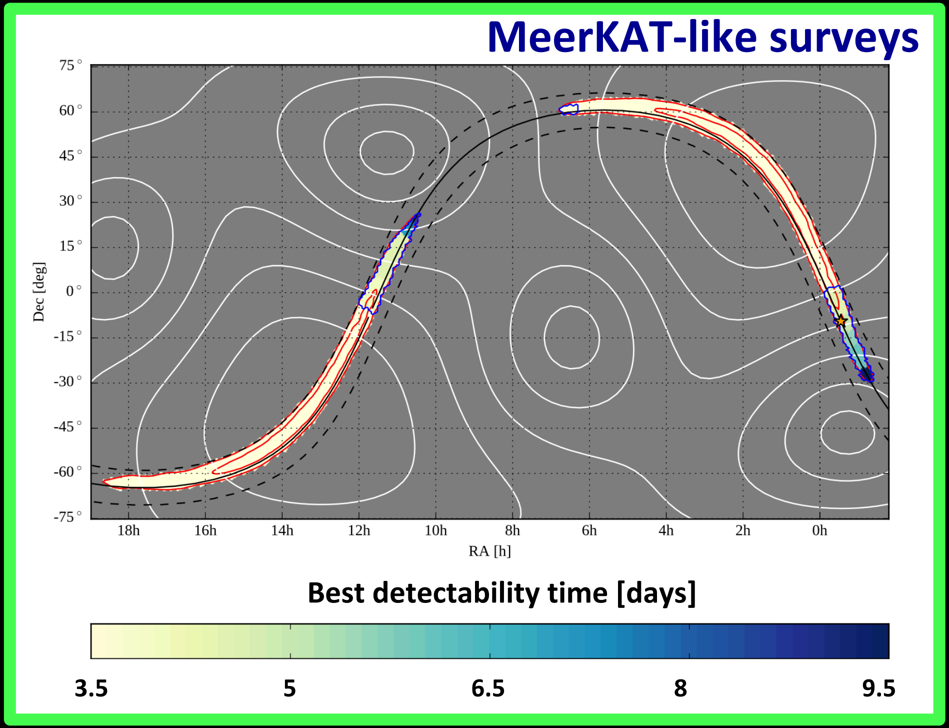
Sky localization probability with direction-dependent distance and its distribution

Singer et al. 2016 ApJL, ApJS

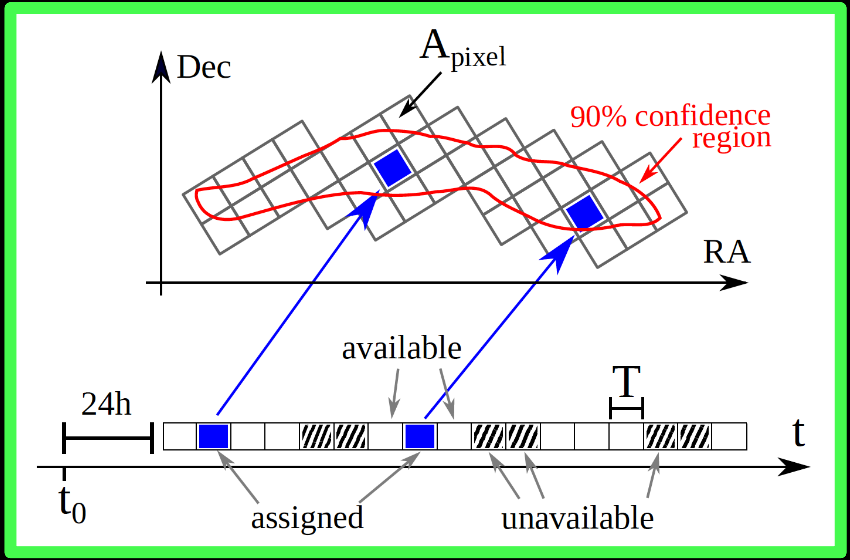
Detectability map
$P\,(F(t) > \text{Flim}\,|\text{RA,DEC}, D_L)$

Sky-position-conditional posterior distribution

→ Detectability map P (F(t) > Flim |RA,DEC, GW signal)



Observing strategies based on the detectability map



Salafia et al. 2017 ApJ

→ Optimize the sequence of tiles and observational epochs

→ Reduce area to be observed and telescope time

Electromagnetic emissions from gravitational wave sources detectable by ground-based detectors (10-1000 Hz)

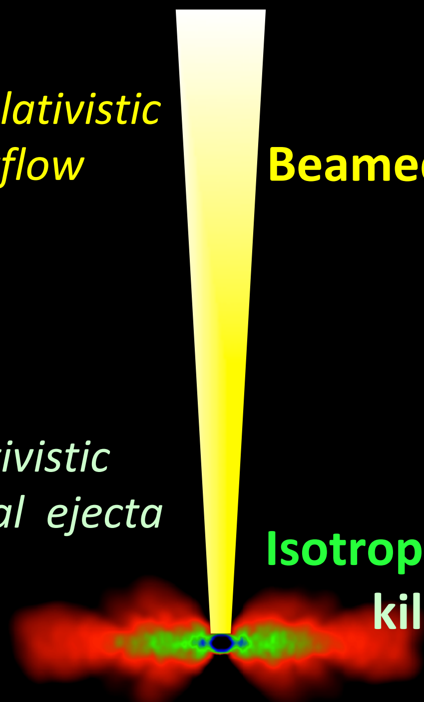
EM emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)

Ultra-relativistic outflow

Beamed emission



Sub-relativistic dynamical ejecta

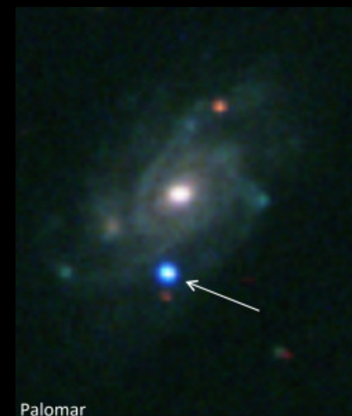
Isotropic emission

kilonova

disk wind outflow

spin-down luminosity

Core-collapse of massive stars



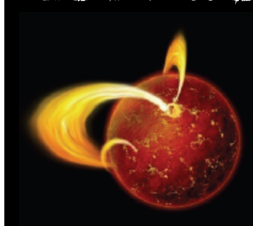
SBO X-ray/UV

Optical

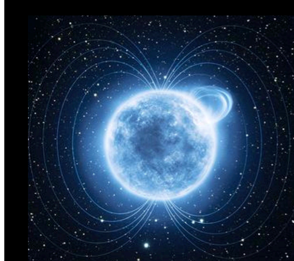
Radio

+ Long GRB

Isolated NS instabilities

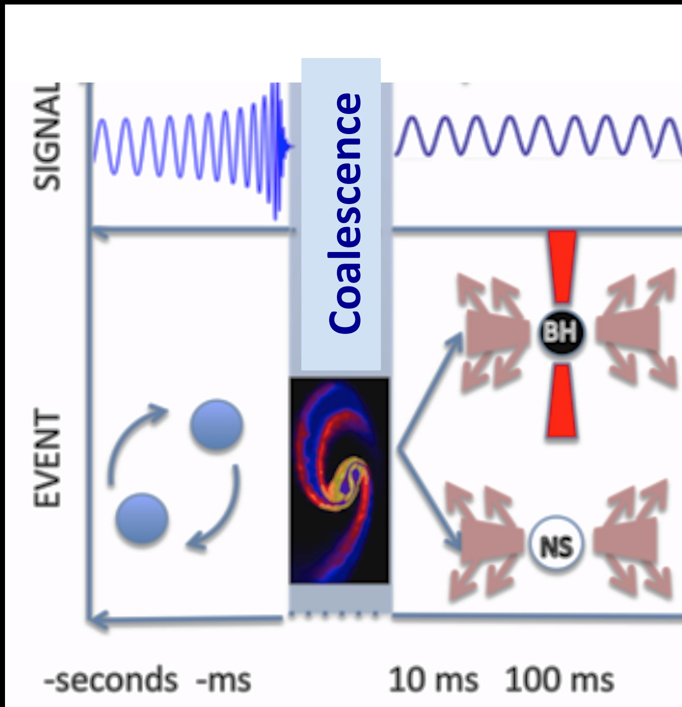


Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

NS-NS and NS-BH inspiral and merger



Dynamical Phase

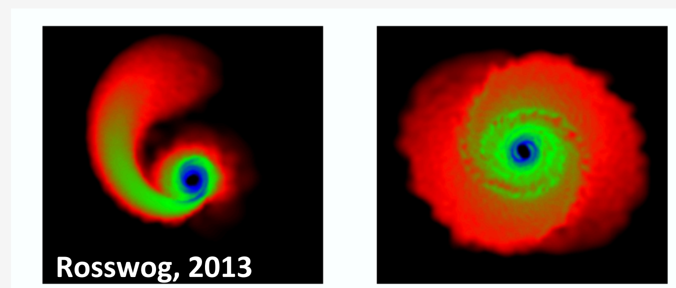
Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

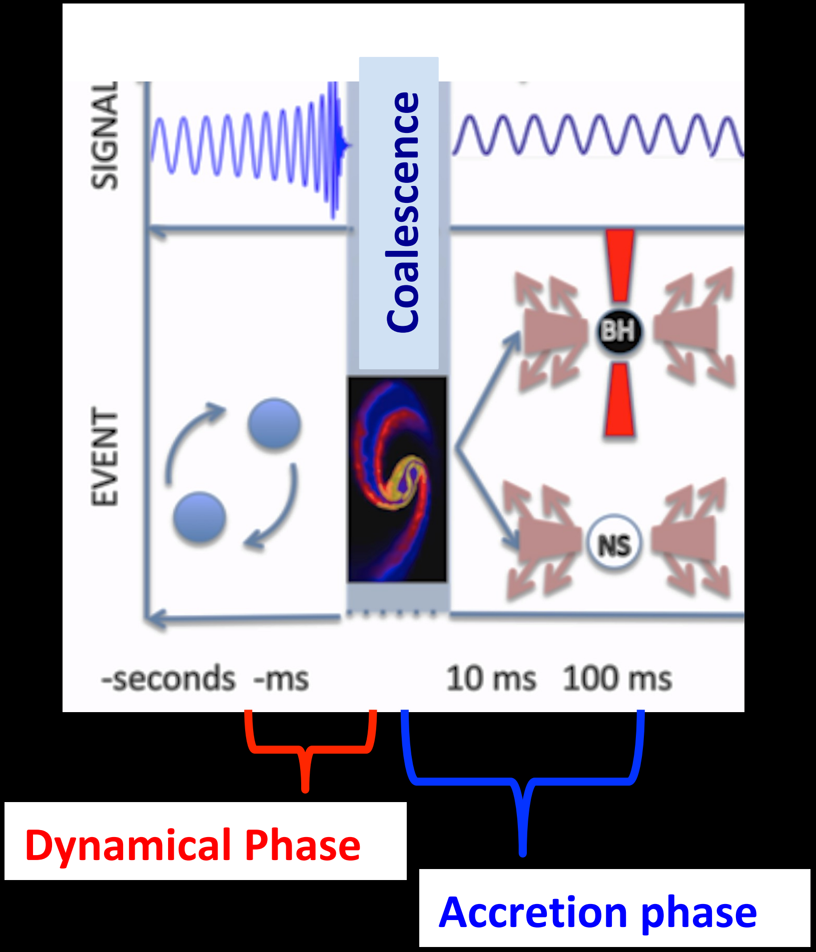
The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound to 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



Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

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

NS-BH binary → <u>unbound mass</u> 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

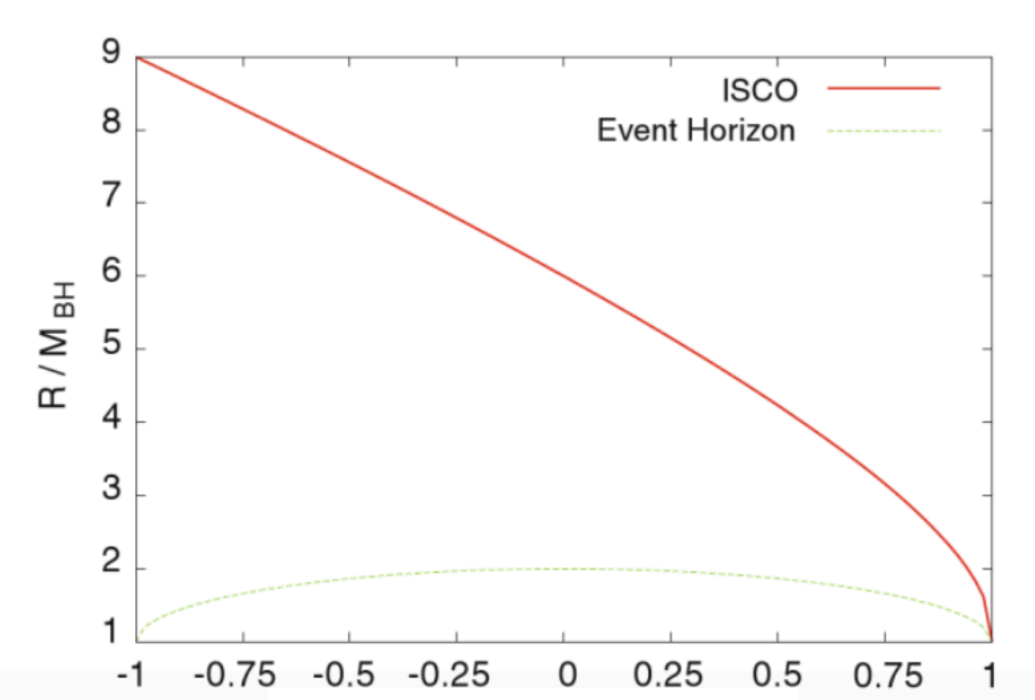
which depends on **the mass ratio, the BH spin and the NS compactness**

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

ISCO = innermost stable circular orbit of the BH, inside which no material have a stable circular orbit around the BH

For a non rotating Schwarzchild BH $$R_{ISCO} = 6GM_{BH} / c^2 = 3R_S$$

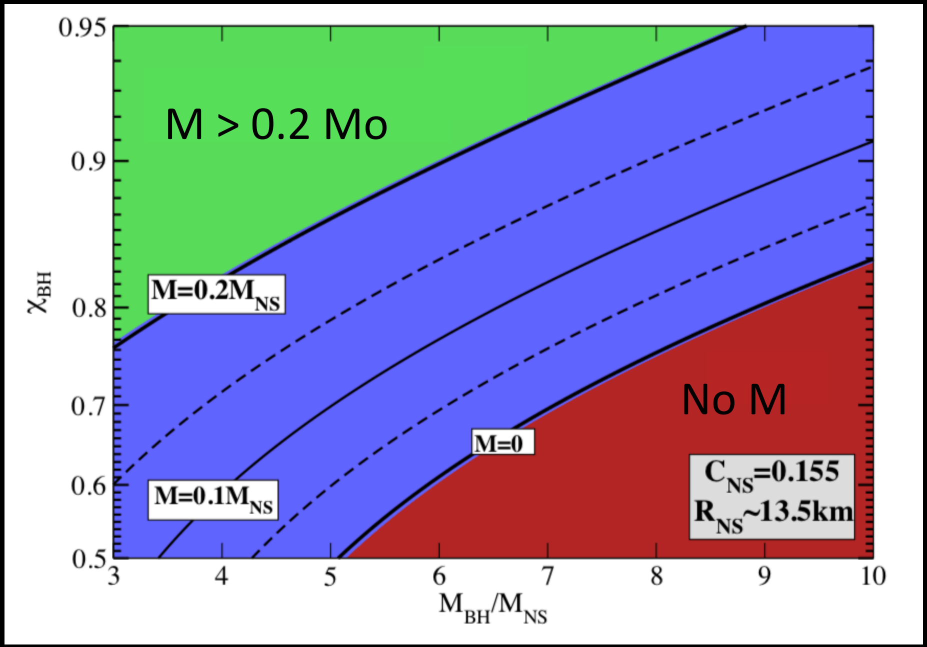
For a rotating BH the equatorial ISCO also depends on the spin angular momentum

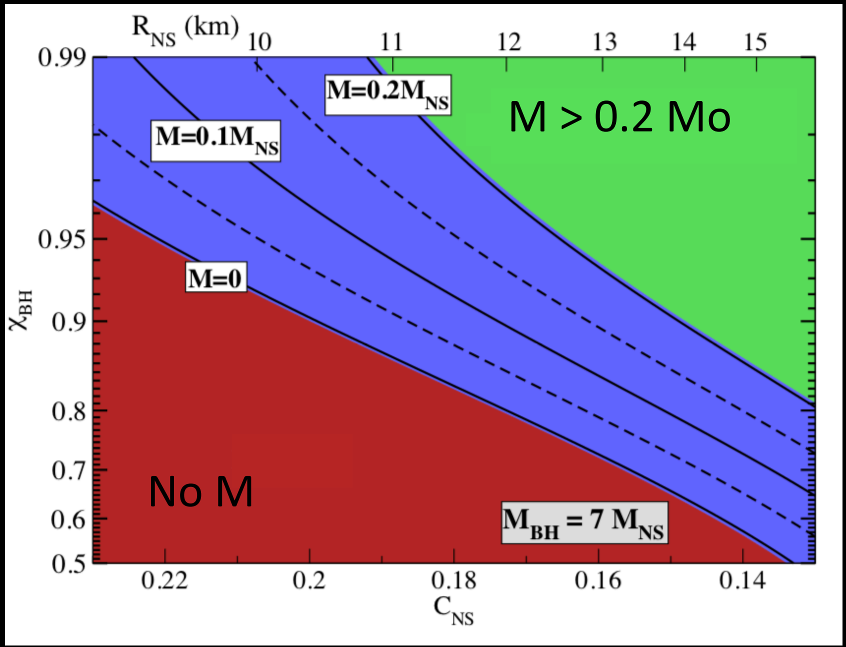


Kyutoku 2013

$$a \equiv cS_{BH} / (M_{BH}^2) \longrightarrow$$ Nondimensional spin parameter

Foucart 2012





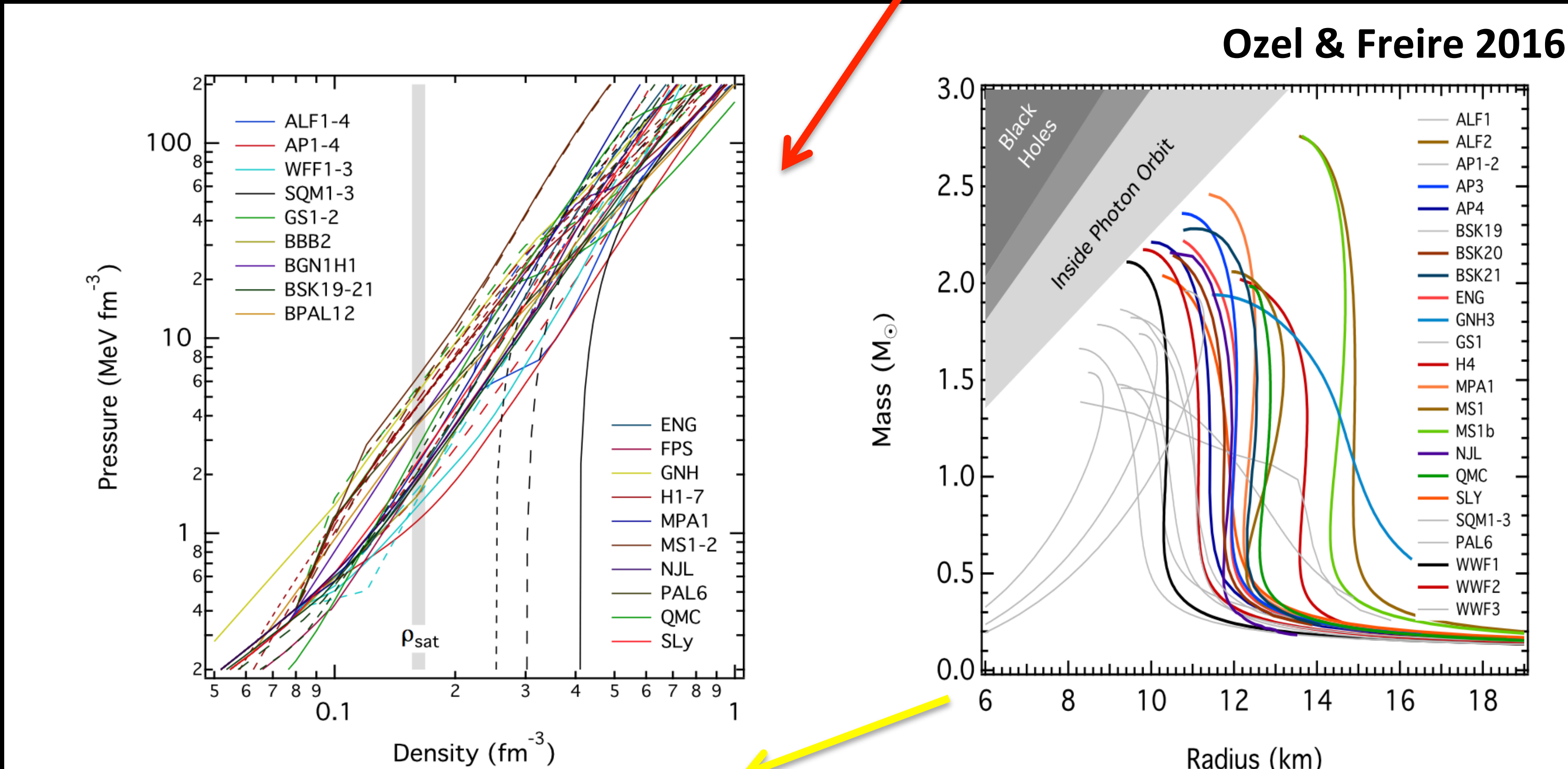
Large baryon mass left outside the merger remnant:

- Mass ratio BH/NS small → small BH mass
- Small NS compactness → large NS radius
- Large BH spin angular momentum

In the degenerate interiors of neutron stars EOS: $P \propto \rho^{\alpha}$

Small α → soft EOS (easier to compress)

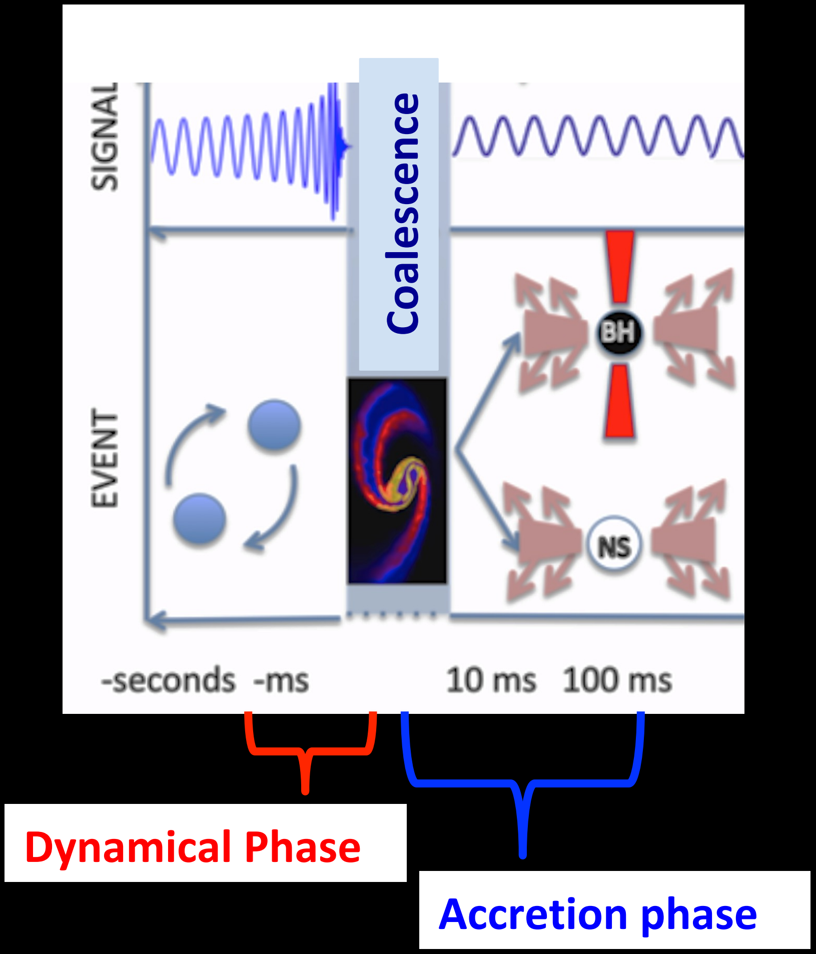
High α → stiff EOS (harder to compress)



Mass-Radius relation is “unique” to the underlying EoS

- Soft EoS: low maximum M and smaller R for the same M (more compact)
- Stiff EoS: high maximum M and larger R for the same M (less compact)

NS-NS and NS-BH inspiral and merger



Fernandez & Metzger 2016, ARNPS, 66

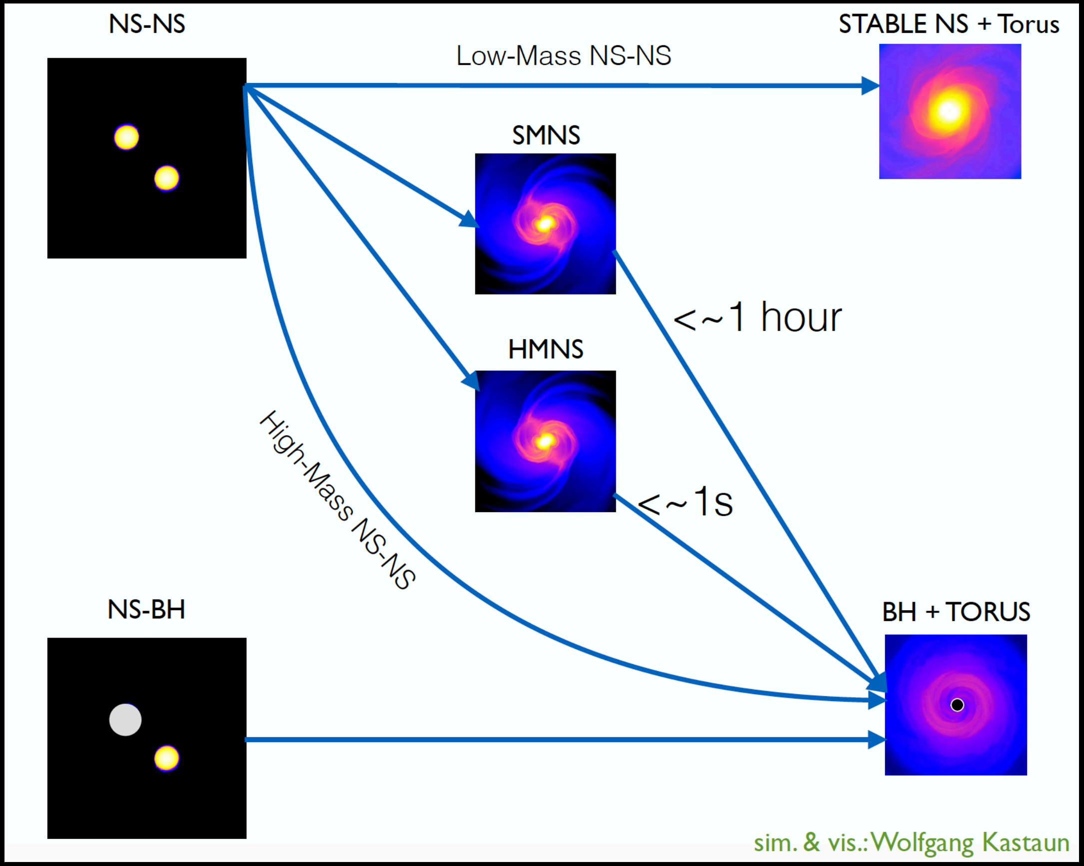
- Ejected material gravitationally bound from the central remnant can fall back or circularizes into an accretion disk

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

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

EM emission

- Beamed and isotropic EM emissions
- Energetics
- Jet astrophysics
- Nucleosynthesis