SEARCHING FOR GAMMA-RAY COUNTERPARTS TO GRAVITATIONAL WAVE SOURCES

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Gamma Ray Astrophysics with CTA
July 24-28, 2017
Sexten

on behalf of
the LIGO Scientific Collaboration
and the Virgo Collaboration

LIGO's GW detections

The era of GW astronomy has begun!

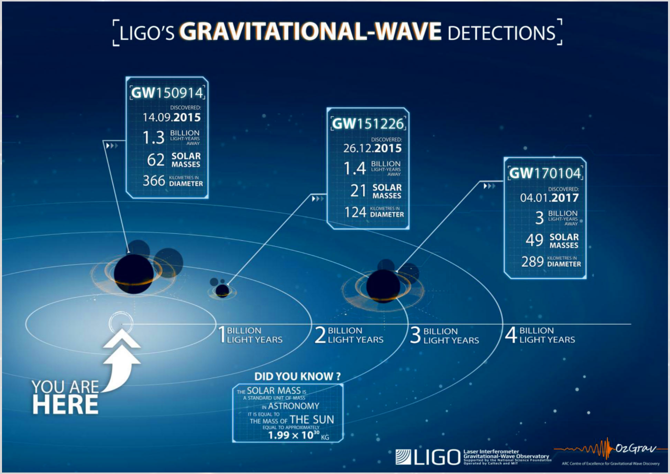


Image credit: LIGO, ARC Centre of Excellence for Gravitational Wave Discovery

Physical parameters of the BBH systems

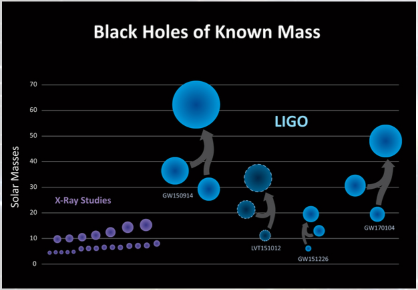


Image credit:
LIGO/Caltech/Sonoma State (A. Simonnet)

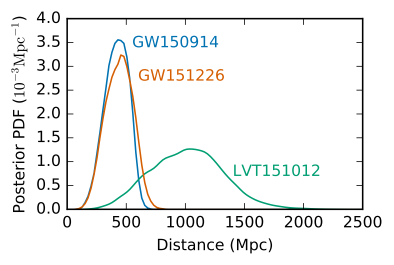
Event \ Mass	m_1 ($M_\odot$)	m_2 ($M_\odot$)
GW150914	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$
GW151226	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$
LVT151012	23^{+18}_{-6}	13^{+4}_{-5}
GW170104	$31.2^{+8.4}_{-6.0}$	$19.4^{+5.3}_{-5.9}$

Abbott et al. 2016, PRX, 6, 041015
Abbott et al. 2017, PRL, 118, 221101

How do BBH systems form and evolve? → identification of the host galaxy and study of the source environment

Where did the BBH mergers occur?

Luminosity distance



Event	GW150914	GW151226	LVT151012	GW170104
D_L (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}	880^{+450}_{-390}

Abbott et al. 2016, PRX, 6, 041015
Abbott et al. 2017, PRL, 118, 221101

Final sky localization

Event	GW150914	GW151226	LVT151012	GW170104
$\Delta\Omega$ (deg^2)	230	850	1600	1200

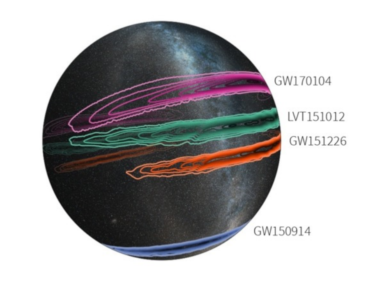


Image credit: LIGO/CALTECH/MIT/ L. Singer/A. Mellinger

$\longrightarrow$ **Multi-messenger astronomy is needed!**

Why multi-messenger astronomy?

GWs and photons provide complementary information about the physics of the sources and their environments

GW

- *mass*
- *spin*
- *eccentricity*
- *system orientation*
- *luminosity distance*
- *compact object binary merger rate*

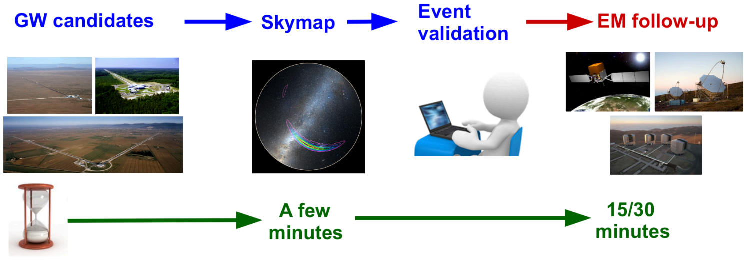
EM

- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *local environment*
- *emission processes*
- *acceleration mechanisms*

Joint GW and EM detections

Two possible scenarios:

- **EM follow-up:** low-latency GW data analysis pipelines promptly identify GW candidates and send GW alerts to trigger prompt EM observations and start archival searches[1]



- **Externally-triggered GW searches:** an EM transient event is detected and GW data are analyzed to look for possible associated GW events (see, e.g., Abbott et al. 2017, ApJ 841, 89).

[1] including searches for high-energy neutrino counterparts

EM follow-up of GW transients

EM follow-up challenges:

- Poor sky localization of GW events

  - large FoV telescopes and/or optimized observational strategies are needed to cover the GW error box

  - broadband observations and spectroscopy are needed to identify the EM counterparts among many transient contaminants

- Latency to send the GW alert ($\sim$ tens of minutes)

  - very sensitive instruments and/or long monitoring periods are needed to detect faint and fading sources

The first multi messenger campaign including GWs

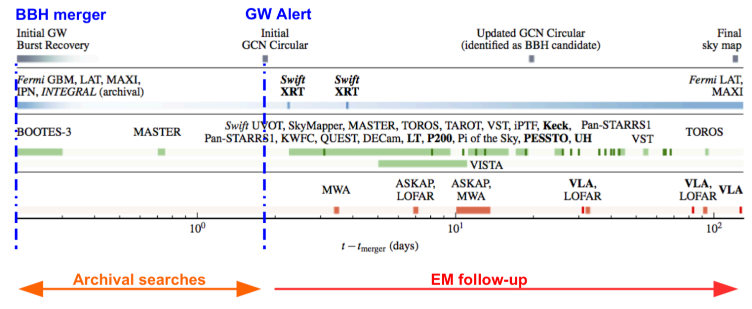
EM follow-up: GW150914

Twenty-five teams of observers responded to the GW alert!

High energy

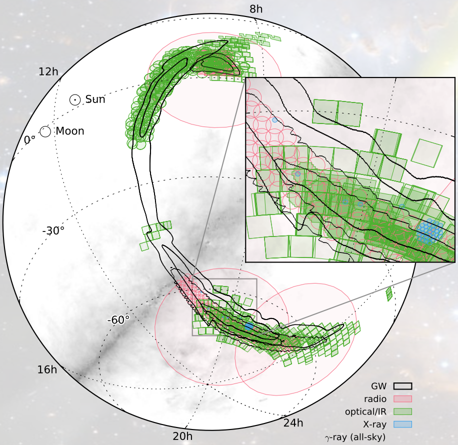
Optical

Radio



Abbott et al. 2016, ApJ Letters, 826, L13

GW150914 sky map coverage



Covered sky map contained probabilty:

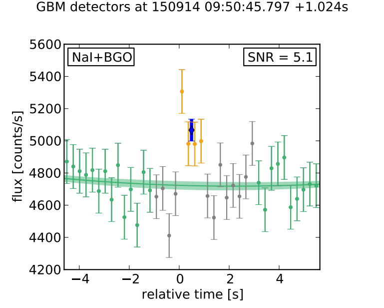
- Gamma-ray: 100 %
- Optical: over 50 %
- Radio: 86 %
- X-ray: ∼ 90 %
  (MAXI + *Swift*-XRT)

Several candidate counterparts have been found in optical, all identified to be normal population SNe, dwarf novae and AGN unrelated to GW150914. But...

Abbott et al. 2016, ApJ Letters, 826, L13

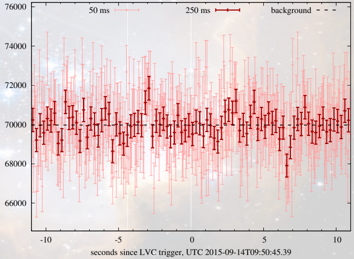
An EM counterpart for GW150914?

Fermi-GBM:
sub-threshold **weak signal above 50 keV 0.4 s after GW150914** (at 2.9 σ), consistent with the direction of GW 150914



Duration and spectrum consistent with a weak short GRB (Connaughton et al. 2016).

But...
no signal detected by INTEGRAL (Savchenko et al. 2016), AGILE (Tavani et al. 2016) and *Fermi*-LAT (Ackermann et al. 2016); see also Greiner et al. 2016



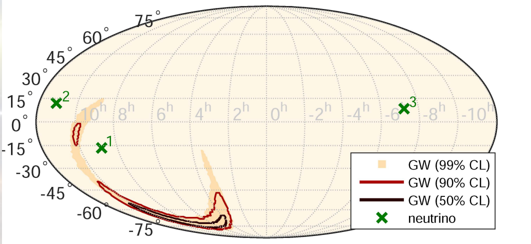
INTEGRAL data, Savchenko et al. 2016

High-Energy neutrino follow-up of GW150914

Search for coincident neutrino candidates with data of IceCube and ANTARES

Within $\pm$ 500 s of GW150914:

- ANTARES neutrino candidates: 0
- IceCube neutrino candidates: 3
    - All consistent with the expected atmospheric background
    - **No one directionally coincident with GW150914**



Adrián-Martínez et al. 2016

EM follow-up: GW151226

Thirty-one teams of observers responded to the GW alert!

Swift, XMM-Slew, MAXI, AGILE, Fermi, CALET, CZTI, IPN, MAGIC, HAWC

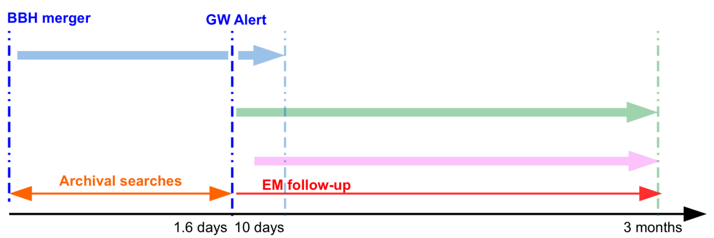
MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla-QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky, LCOGT/UCSB, CSS/CRTS, GTC

VLA, LOFAR, MWA

HE and VHE

Optical

Radio



Several candidate counterparts have been found in optical, all identified to be normal population SNe, dwarf novae and AGN unrelated to GW151226

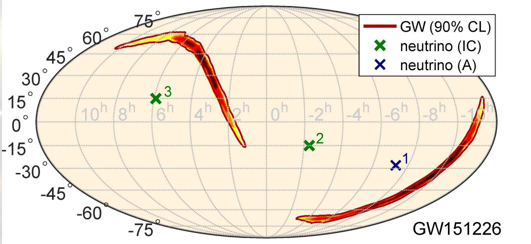
All the informations from public GCNs: `http://gcn.gsfc.nasa.gov/gcn3_archive.html`

High-Energy neutrino follow-up of GW151226

Search for coincident neutrino candidates with data of IceCube and ANTARES

Within ± 500 s of GW151226:

- ANTARES neutrino candidates: 1
- IceCube neutrino candidates: 2
  - All consistent with the expected atmospheric background
  - **No one directionally coincident with GW151226**



Adrián-Martínez et al. 2017

EM follow-up of GW150914 and GW151226 demonstrated the capability to cover large areas, to identify candidates, and to rapidly activate large telescopes

BBH mergers are not expected to have an EM counterpart due to the absence of accreting material ...

... but some mechanisms that could explain an EM signature have been recently proposed (see, e.g., Loeb et al. 2016, Perna et al. 2016, Zhang 2016...)

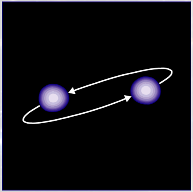
Future EM follow-ups of GWs will shed light on the presence or absence of EM counterparts for BBH mergers

Besides BBH mergers, which are the other transient GW sources detectable by LIGO and Virgo?

Do they have an EM counterpart?

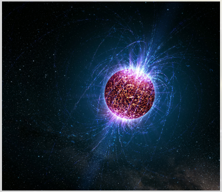
Other transient GW sources

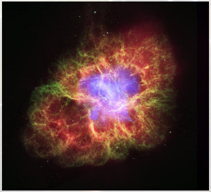
Coalescence of binary systems of NSs and/or BHs



- GW signals accurately modeled by post-Newtonian approximation and numerical simulations → **Matched filter modeled searches**
- Energy emitted in GWs (NS-NS): $\sim 10^{-2}$ $M_{\odot}c^2$

Isolated neutron stars and Core collapse of massive stars





- The modeling of the GW signal is complicated → **Unmodeled searches**
- Energy emitted in GWs:

  $\sim 10^{-8}$- 10^{-5} $M_{\odot}c^2$ for core collapse
  $\sim 10^{-16}$- 10^{-6} $M_{\odot}c^2$ for isolated NSs

Associated multi-wavelength EM emission

NS-NS and NS-BH mergers

- Short GRBs:
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

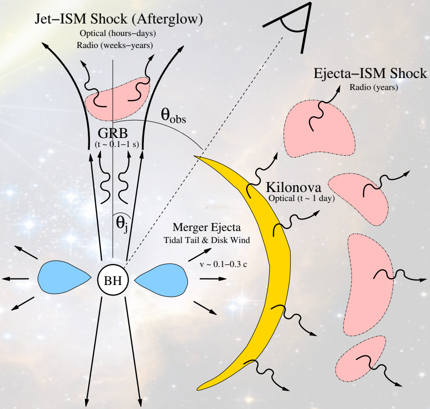


Image credit: Metzger & Berger 2012

Associated multi-wavelength EM emission

Core collapse of massive stars

- supernovae:
  - SBO X-rays, UV (minutes, days)
  - optical (week, months)
  - radio (years)

Image Credit: Avishay Gal-Yam

- long GRBs

Isolated neutron stars

- soft γ-ray repeaters
- radio/X-ray pulsar glitches

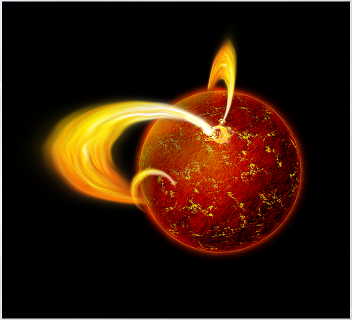
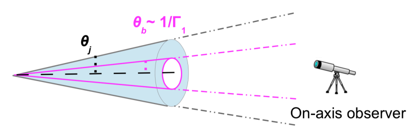


Image Credit: NASA, CXC, M. Weiss

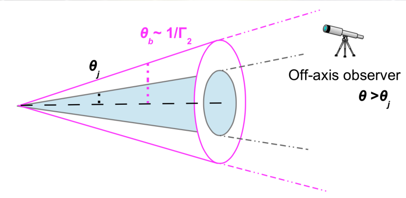
Gamma Ray Bursts:
why joint GW and EM observations?

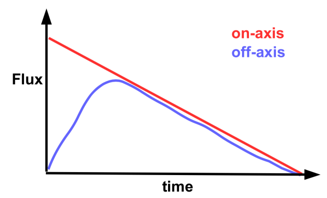
GRB emission - on/off axis

The **prompt** emission can be observed only if the GRB is on-axis



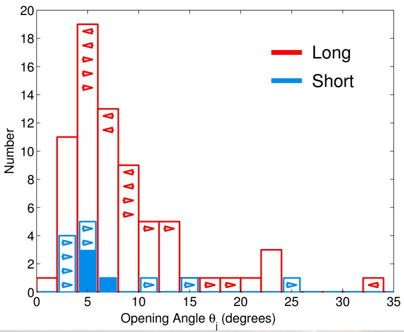
The **afterglow** emission can be potentially observed also if the GRB is off-axis





GRB jet opening angle

- GRB jet opening angle is not well constrained by observations (see, e.g., Berger et al. 2014):



- Numerical studies suggest that $\theta_j \leq 30^\circ$ (see, e.g., Rezzolla et al. 2011)

How many on-axis/off-axis short GRBs in the local universe?

Local (on-axis) short GRB rate:

$\rho_{\rm GRB}$=0.1-40 Gpc^{-3} yr^{-1} (e.g., Ghirlanda et al. 2016, Wanderman & Piran 2015)

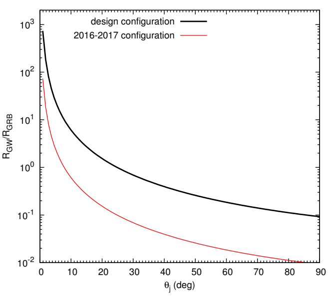
$\Rightarrow$R$_{\rm GRB}$ (300 Mpc*)=0.01-4.5 yr^{-1}

short GRB rate $\Rightarrow$ NS-NS merger rate

Assuming that all NS-NS mergers are progenitors of short GRBs:

$$\boxed{R_{\rm NS-NS} = \frac{R_{\rm GRB}}{1-\cos(\theta_j)}}$$

- θ_j=10°: R$_{\rm NS-NS}$(200 Mpc)=0.2-90 yr^{-1}
- θ_j=30°: R$_{\rm NS-NS}$(200 Mpc)=0.02-10 yr^{-1}



Patricelli et al. 2016, JCAP, 11, 56

Joint GW and EM observations will help to constrain the jet opening angle and the fraction of NS-NS progenitors

*The distance range for NS-NS of 200 Mpc is expected to be a factor 1.5 greater for face-on systems

Do GRBs have GeV-TeV emission?

Before Fermi:

limited knowledge about GRB emission above 100 MeV

- A 18 GeV photon was detected by EGRET from the long GRB 940217 (Hurley et al. 94)
- high energy emission (up to 200 MeV) was detected by EGRET from the long GRB 941017 (González et al. 2003)
- A hint of $\sim$ TeV emission was detected by Milagrito (500 GeV-20 TeV) from the long GRB 970417A (Atkins et al. 2000)

with Fermi:

- tenths of GRBs with high energy emission ($>$ 100 MeV)
- among them, six are short GRBs, two with emission above 1 GeV:
  - GRB 081024b (highest energy $\sim$ 3 GeV)
  - GRB 090510 (highest energy $\sim$ 30 GeV)

Fermi represents a very promising instrument to detect short GRBs associated to GW transient events (see, e.g., Clark et al. 2015, Patricelli et al. 2016)

How can we do better?

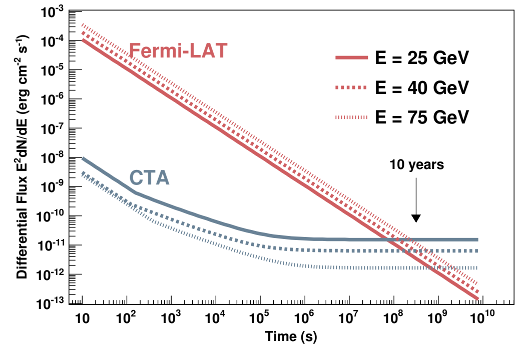
↓

Higher sensitivity is needed:

- to increase the probability of detecting the EM counterparts also when observations are delayed by minutes (EM follow-up)
- to identify and characterize the GeV emission from the less energetic short GRBs
- to possibly localize the off-axis sources

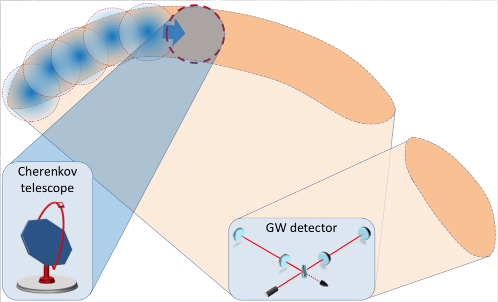
Why CTA?

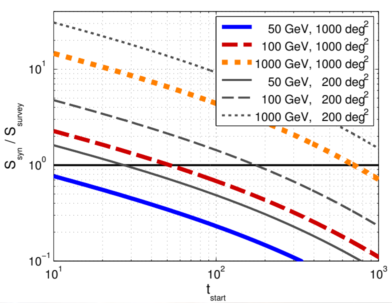
- coincident observational schedule with GW detectors at design sensitivity
- large FoV (LST: 4.5 deg)
- survey mode
- **Rapid response ($\leq$ 30 s) of LST**
- **Very high sensitivity**



Funk et al. 2013

Why CTA?





Short GRBs occurring in the local universe (300 Mpc) with HE emission extending up to $\sim$ 100 GeV can be detected by CTA, even if CTA observations are delayed by $\sim$100 s

Bartos et al. 2014, MNRAS, 443, 738

Summary

We are at the dawn of multi-messenger astronomy, many discoveries are expected in the near future!

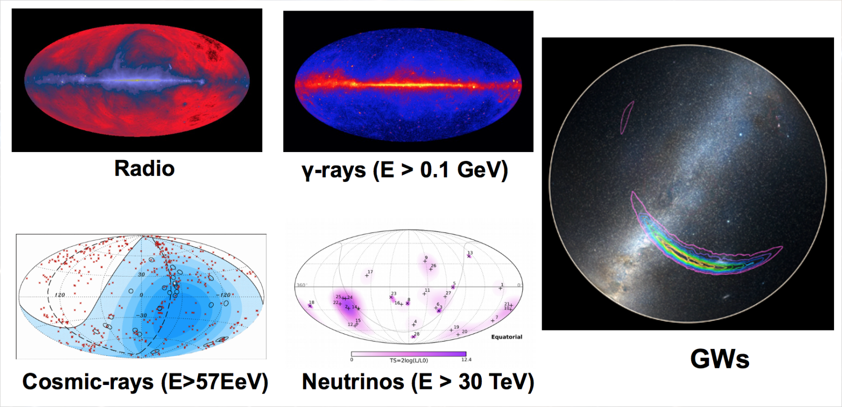
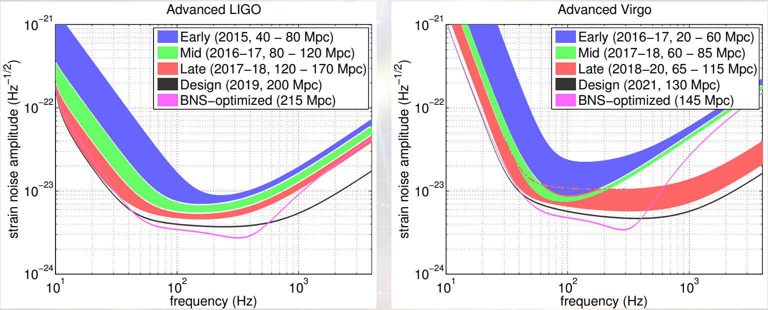


Image credit:
C. Haslam, NASA/DOE/Fermi LAT Collaboration, AUGER Collaboration, IceCube Collaboration, LIGO/Roy Williams & CDS Strasbourg

Backup slides

Sensitivity Improvement

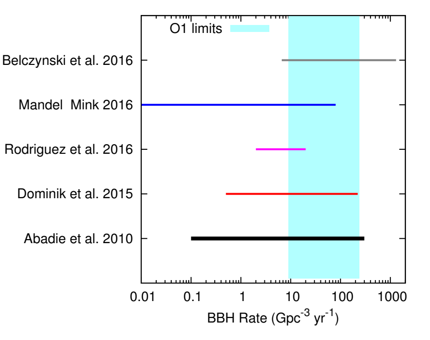


Abbott et al. 2016, Living Reviews in Relativity, 19

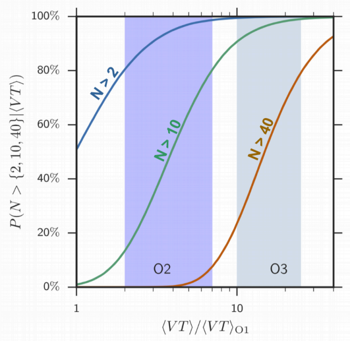
⟶ Larger explorable universe and higher detection rate

Expected BBH rate based on O1 observations

BBH merger rate:
9 - 240 Gpc^{-3} yr^{-1}



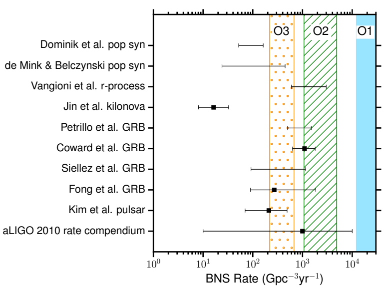
BBH highly significant GW detections
(FAR<1/century)



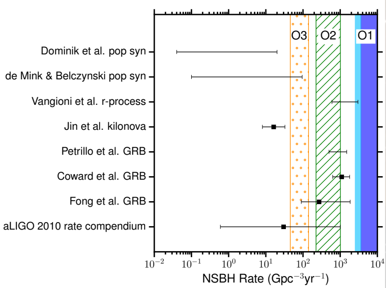
Abbott et al. 2016, PRX, 6, 041015

Upper limits on merger rates based on non-detections

NS-NS



NS-BH

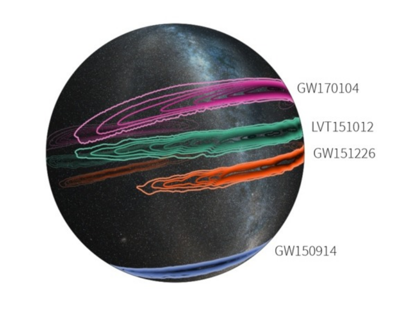


Abbott et al. 2016, ApJ Letters, 832, 2

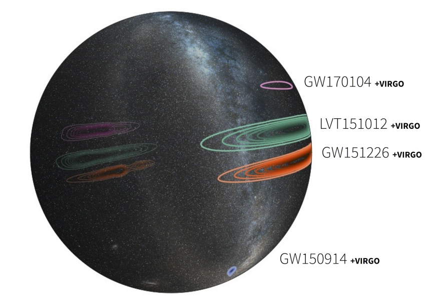
Future Advanced LIGO and Virgo observing runs will help to put significant constraints on these merger rates

Sky localization improvement with Virgo

Sky localizations with LIGO



Simulated estimates with LIGO+Virgo*



Images credit: LIGO/Caltech/MIT/L. Singer/A. Mellinger

Sky localization of GW150914 with Virgo: few tens of deg^2

$\Rightarrow$ **Virgo is expected to significantly improve the efficiency of the EM searches!**

* assuming that Virgo was operating with a NS-NS range of 36 Mpc