Ondes gravitationnelles
Dernières nouvelles

Benoit Mours
(IPHC)

9 octobre 2019

Gravitational waves

- A prediction of General Relativity
- Perturbations in space-time metric
- Mass acceleration → gravitational waves

$$h \approx \frac{G}{c^4} \frac{E_{ns}}{r}$$

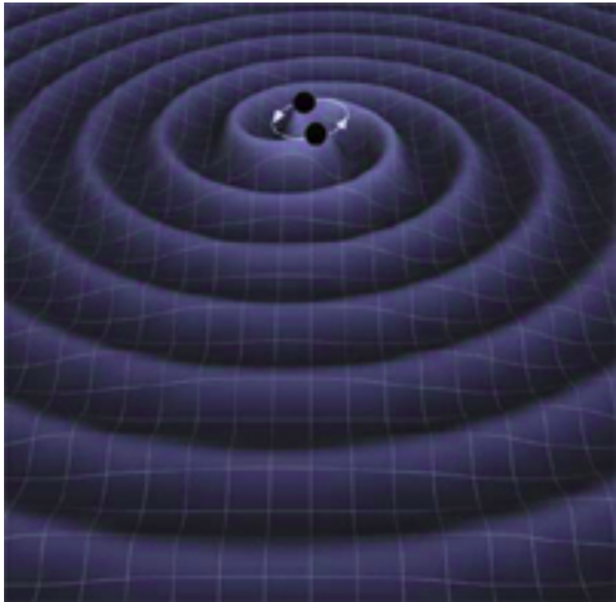
"Non symmetrical" energy

Distance to the source

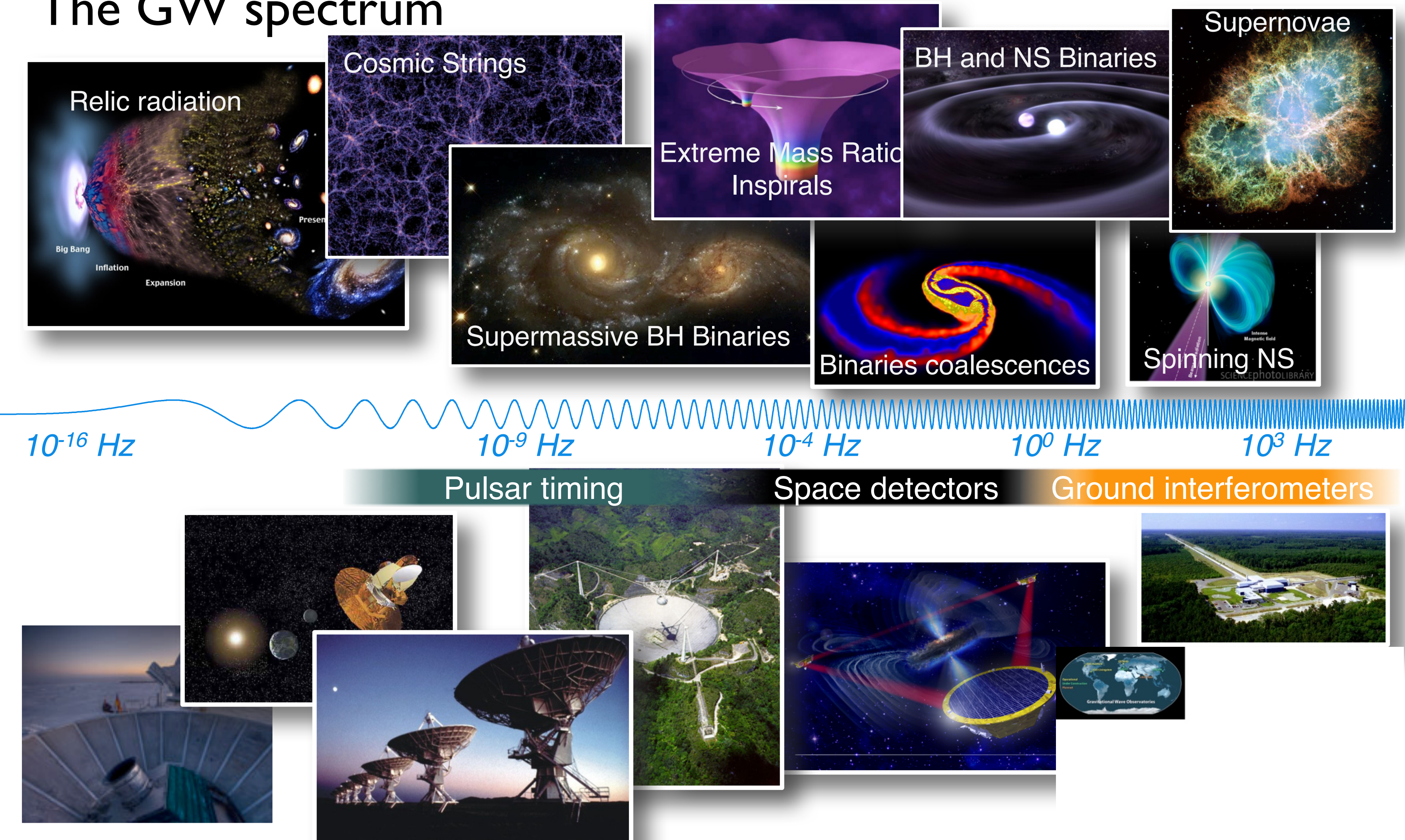
$\sim 10^{-44}\ m^{-1}\ kg^{-1}\ s^{2}$

- Require very large energy

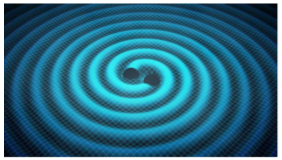
→ Astrophysical sources
  - Like two heavy orbiting objects
- GWs come directly from the central engine
  - Direct probe of the dynamic of the system
  - Not obscured or scattered by material



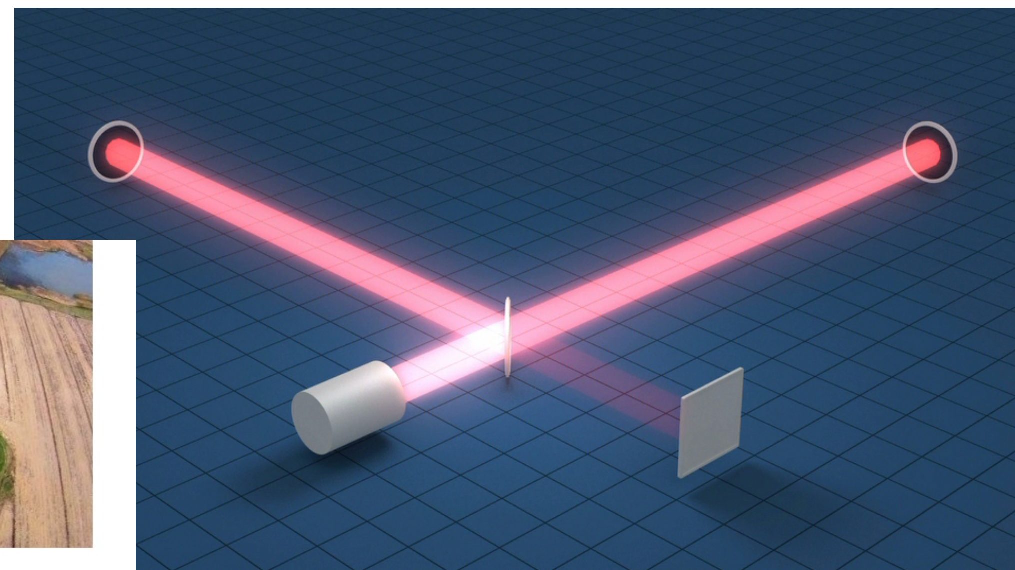
The GW spectrum

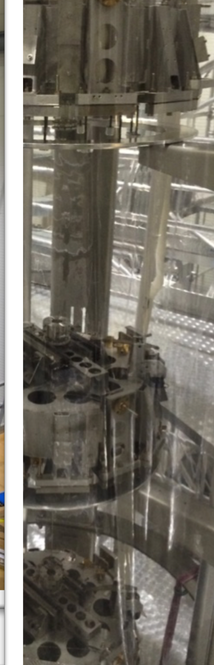


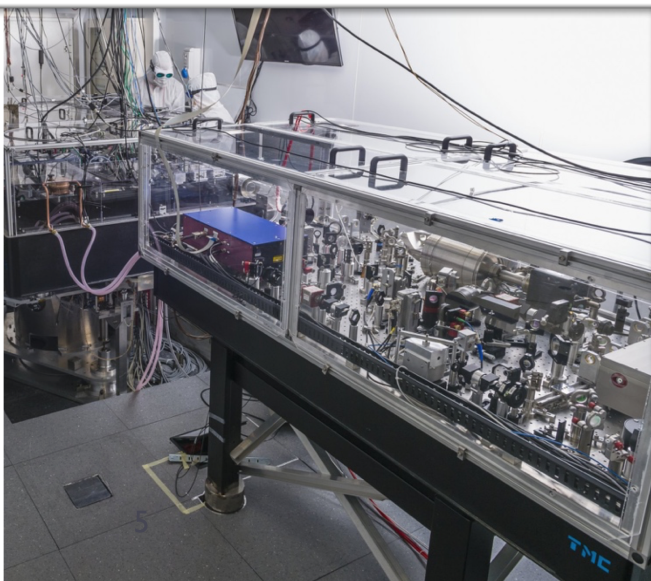
Détecter les ondes gravitationnelles

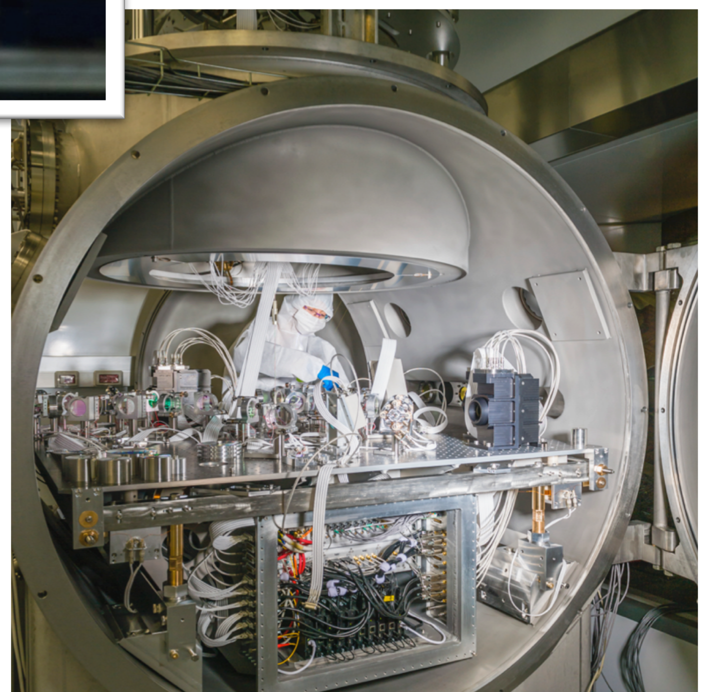


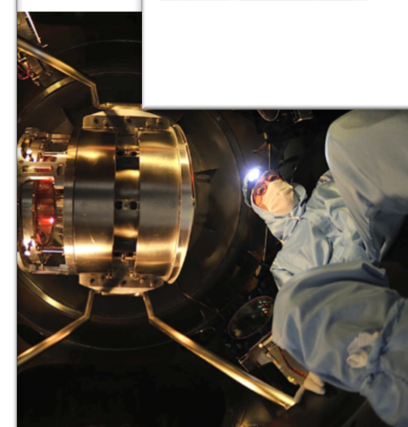
- Ondes gravitationnelles : des effets très faibles sur terre
  - Sensibilité : $h = \frac{\delta L}{L} \leq 10^{-21}$
  - Mesurer des petits déplacements sur de grandes longueurs



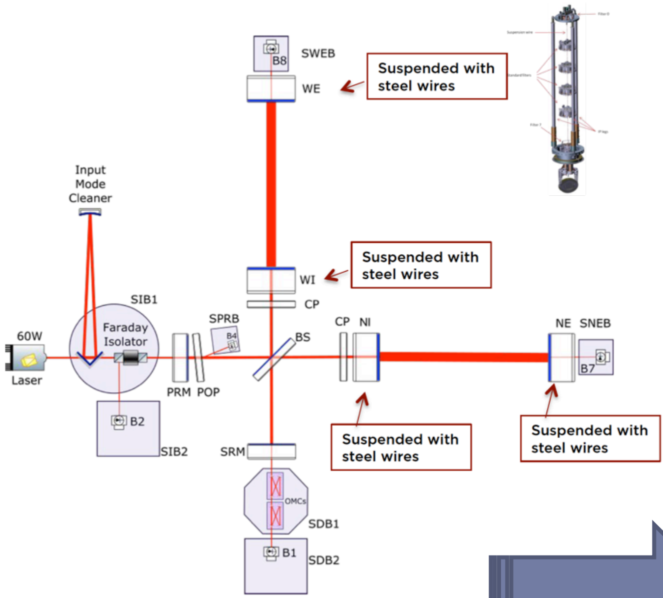


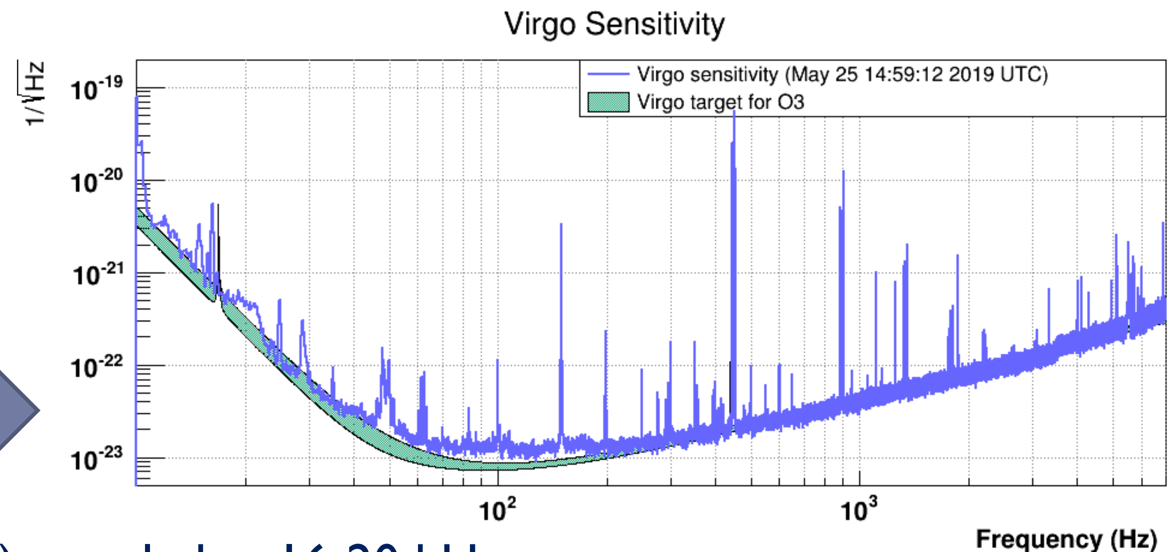

TMC





Sensitivity

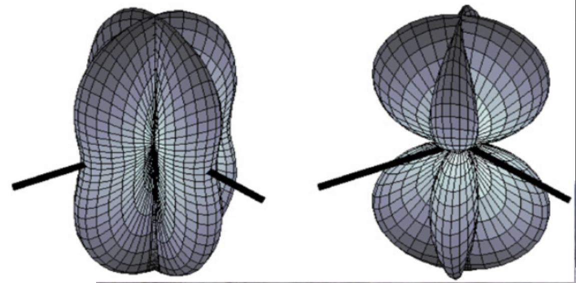


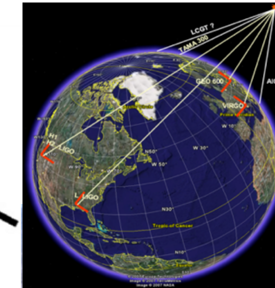


- The detector output is h(t) sampled at 16-20 kHz
- Noise floor is dominated by:
  - Low freq.: control/technical noises
  - Mid freq.: quantum noises (radiation pressure, mirrors coating)
  - High freq.: quantum noises (shot noise)

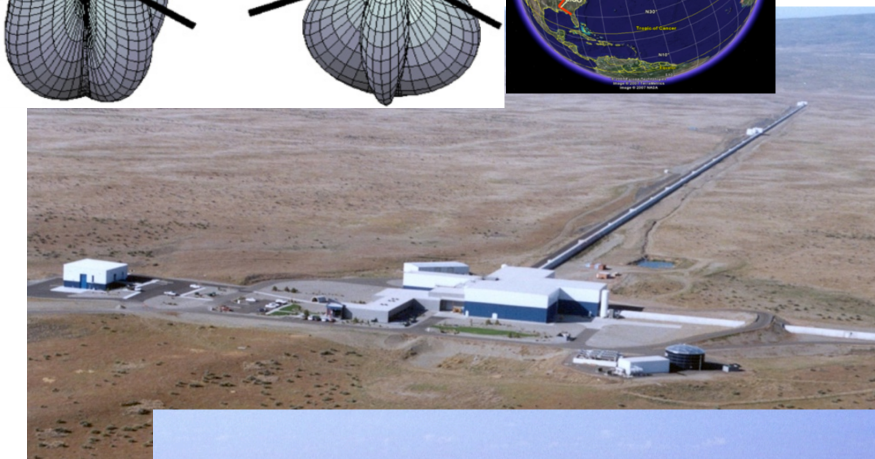
- BNS range: average luminosity distance at which the merger of two 1.4 $M_\odot$ objects would be detectable with a signal to noise ratio of 8.
- BBH range is larger by one order of magnitude

LIGO-Virgo : a global network



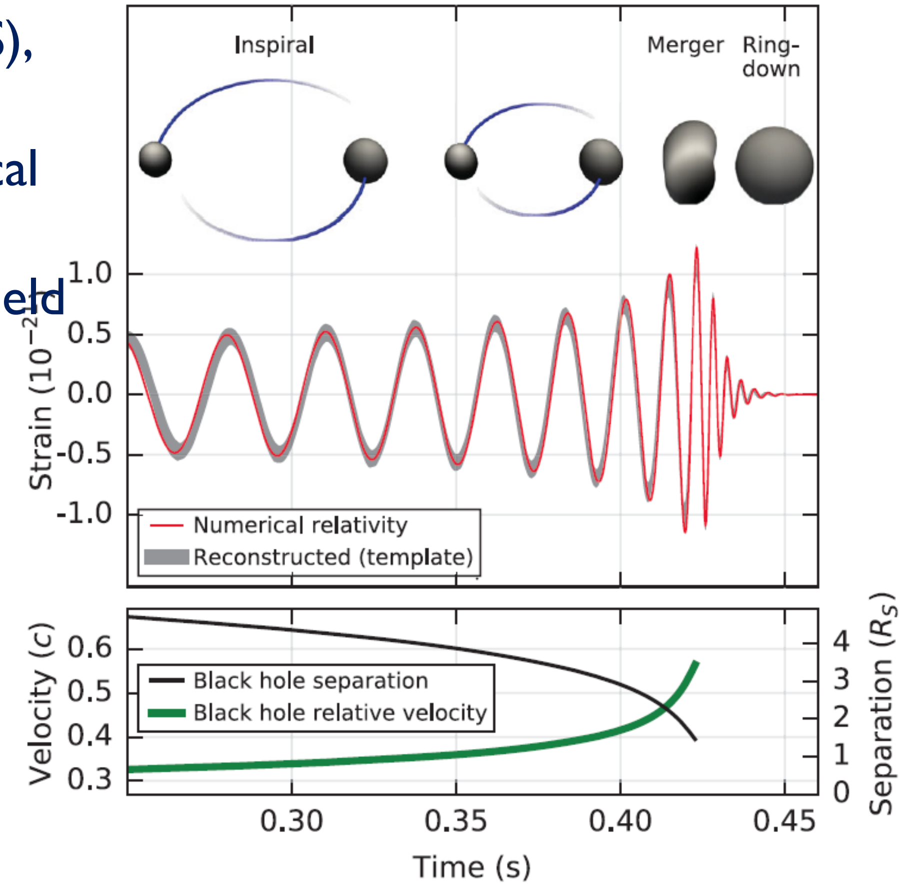


- Detectors have wide antenna pattern
  - →Network for source localization, duty cycle, polarization test…
- 2007: LIGO - Virgo collaboration agreement
  - Full data sharing; joint data analysis
- Common data taking

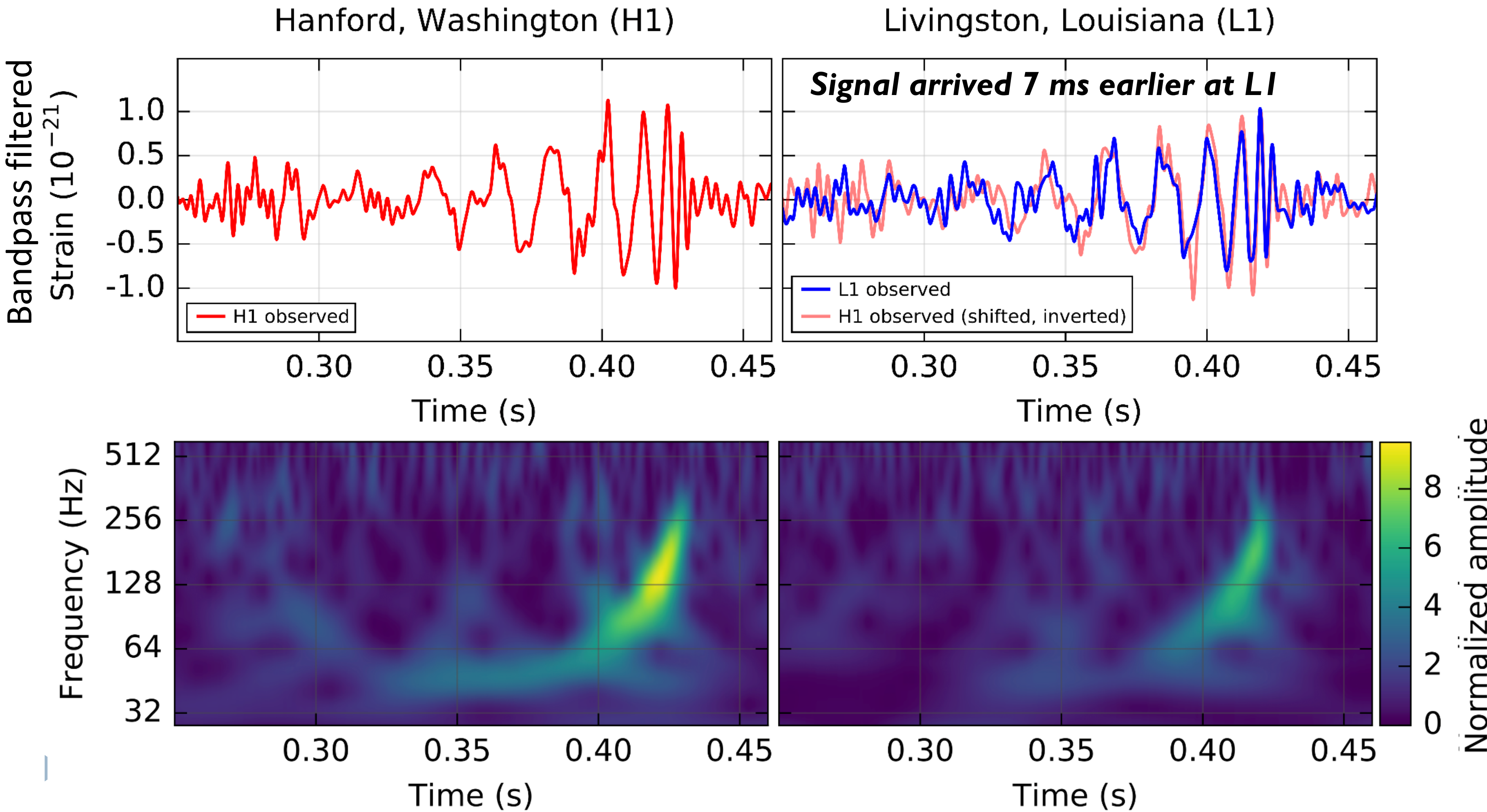


Compact Binary Coalescences

- BH + BH (BBH), NS + NS (BNS), NS + BH (NSBH) systems
- Waveform models from analytical and numerical relativity
- Event dynamics probes strong field gravity
- Standard candles
- Rare events
  - Rates now measured
  - R_{BBH} = 9.7 - 101 Gpc^{-3} yr^{-1}
  - R_{BNS} = 110 - 3840 Gpc^{-3} yr^{-1}
  - R_{NSBH} < 610 Gpc^{-3} yr^{-1}

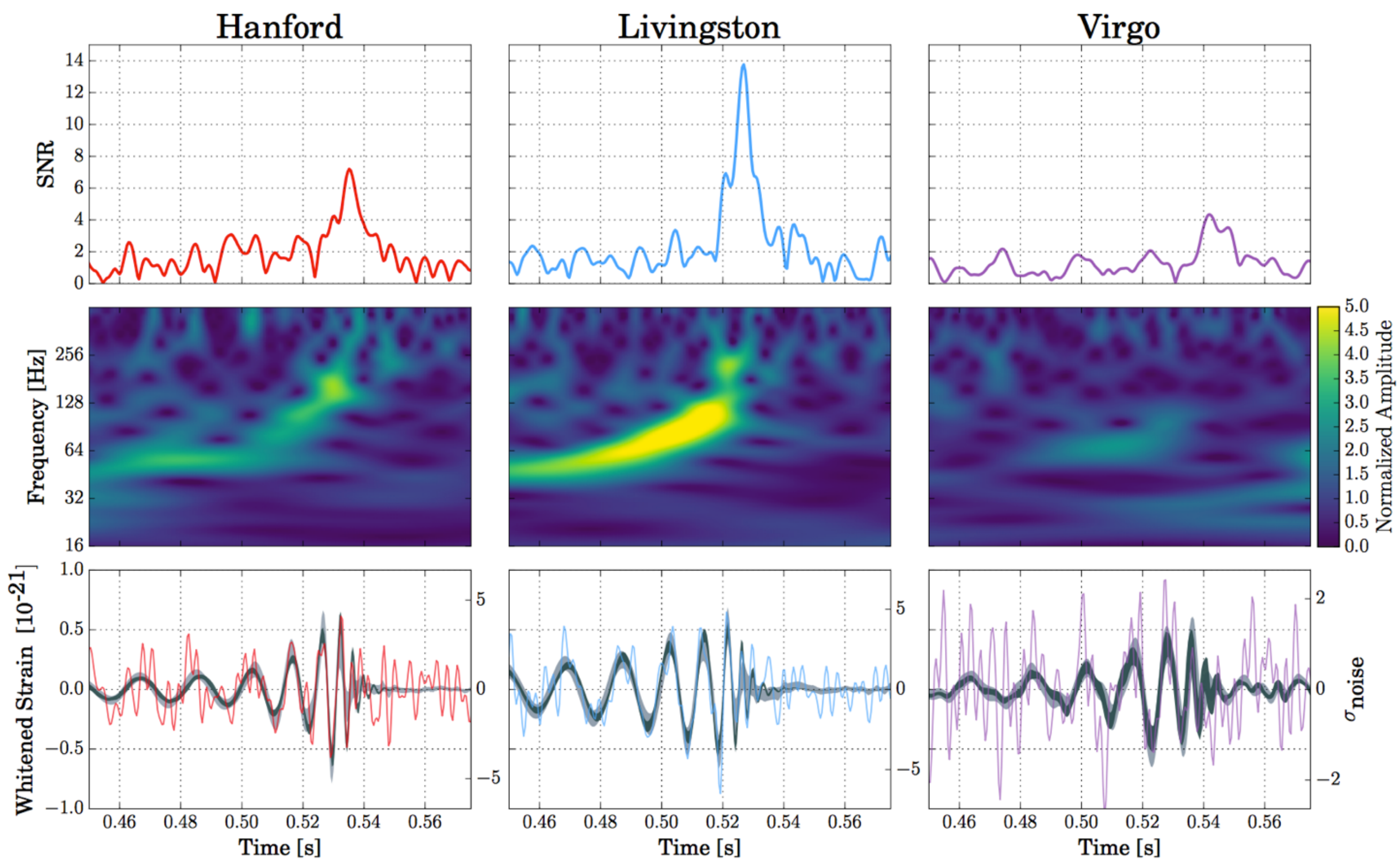


GW150914



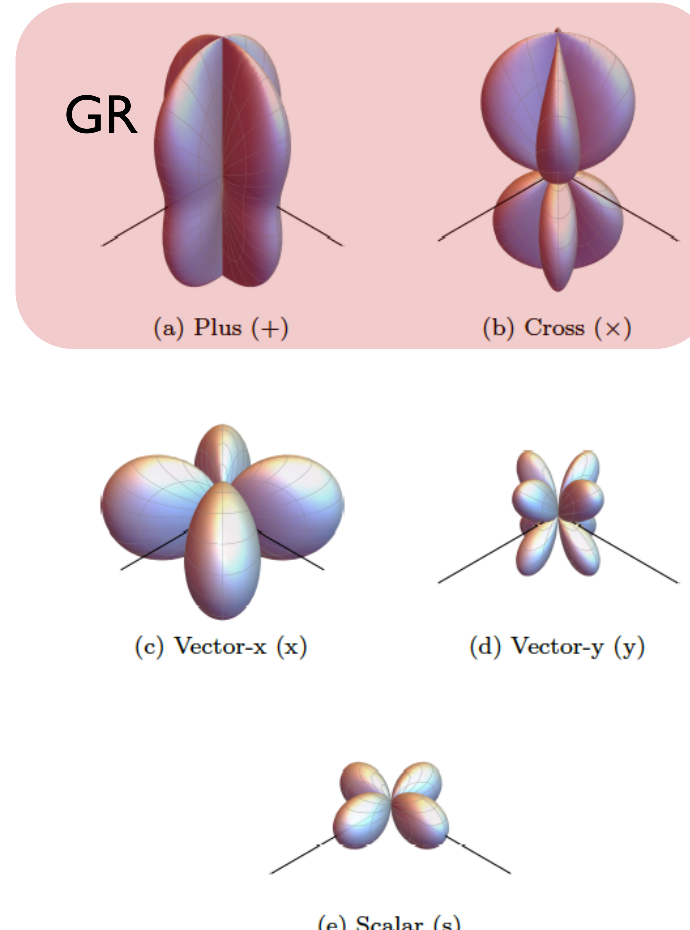
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Signal arrived 7 ms earlier at L1
Bandpass filtered Strain (10^−21)
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
0.30
0.35
0.40
0.45
Time (s)
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
8
6
4
2
0

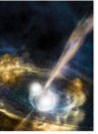
GW170814: BBH seen in 3 detectors



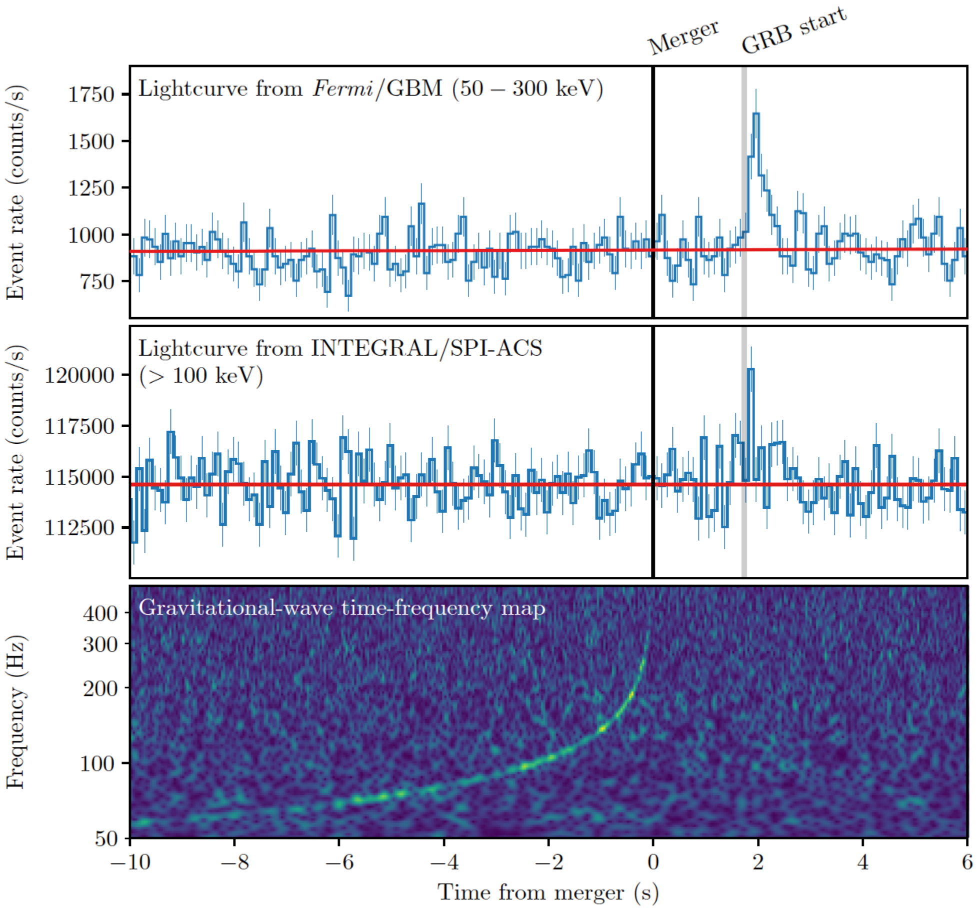
Testing GR with GW170814: GW Polarizations

- Generic metric theories of gravity allow up to six polarizations
  - GR allows two tensor polarizations, + and x
- LIGO instruments have similar orientation
  - ➔ record same combination of polarizations
- Virgo has different orientation
  - ➔ breaks degeneracy
- GW geometry probed directly through projection of metric perturbation onto detector network
- GW170814: pure tensor polarization strongly favored over
  - pure vector polarizations (200:1)
  - pure scalar (1000:1)

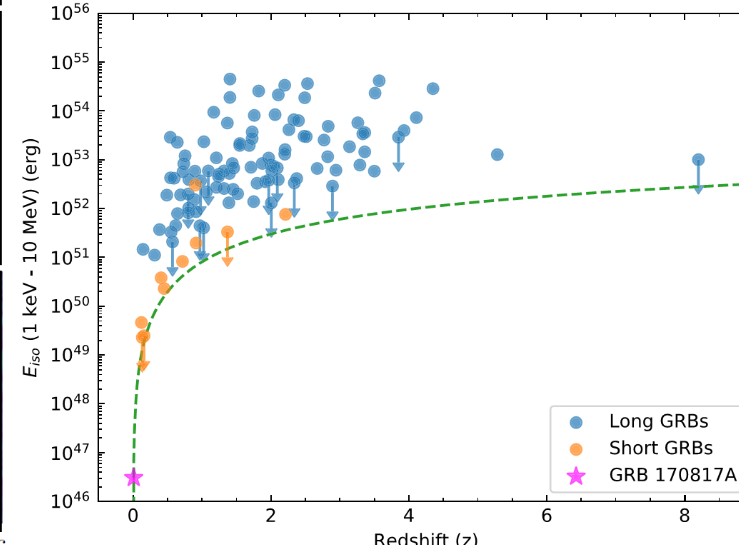


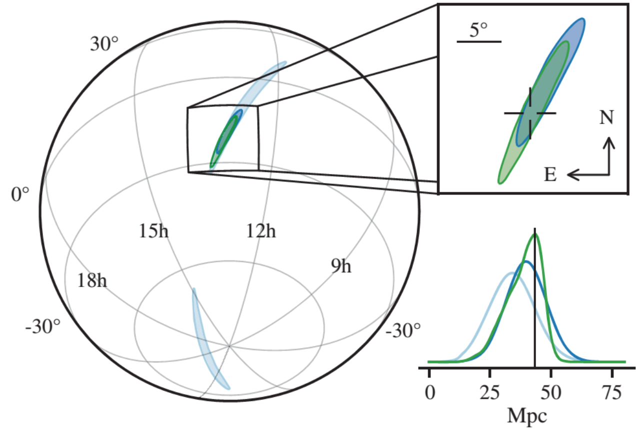


GW170817 + GRB170817A: First BNS merger



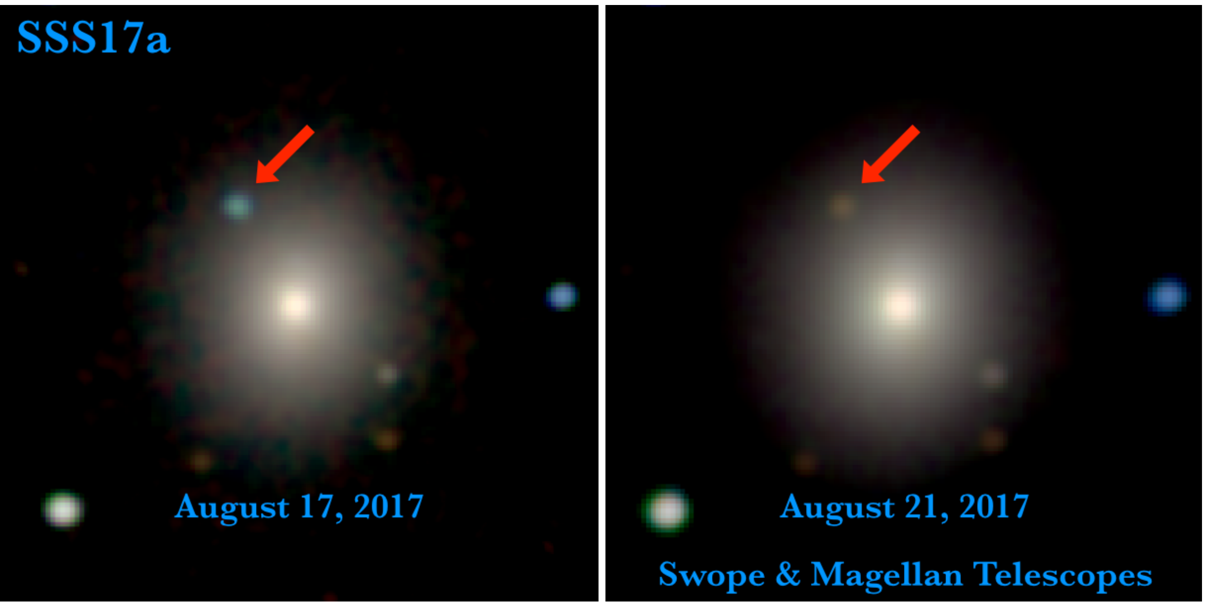
- Off axis GRB?

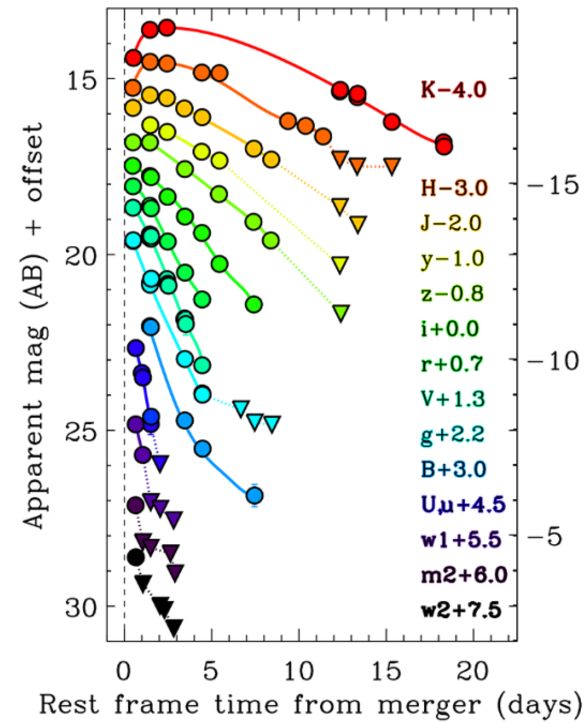




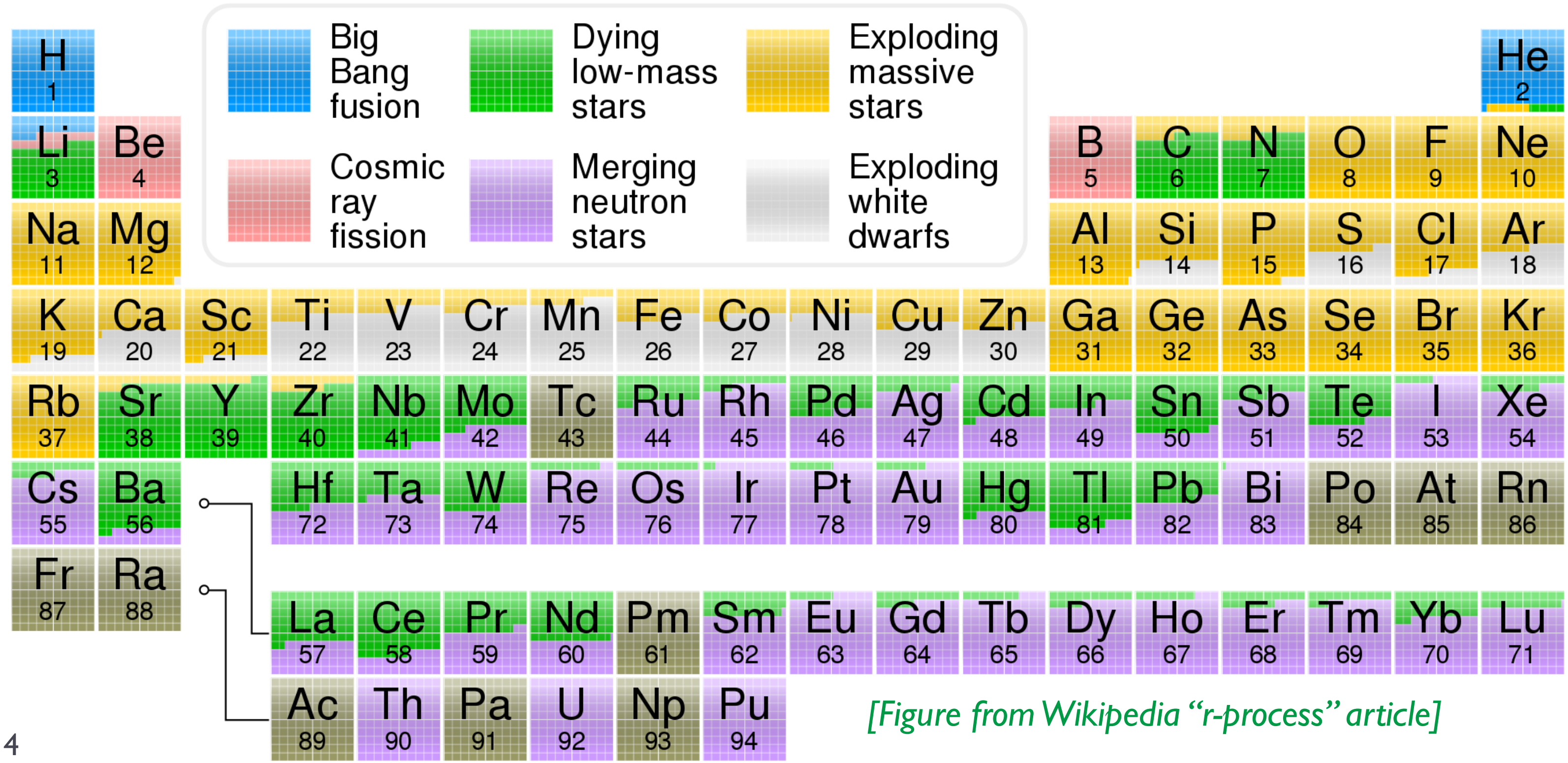
GW170817 + AT2017gfo: a kilonova

- Sky map after 5 hours (31 deg^2 at 90% prob.)
- → ATF2017gfo
- From blue to red in a few days → "Kilonova"

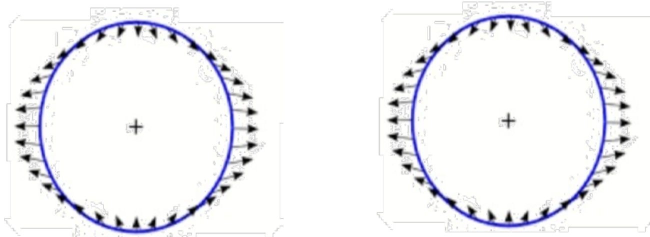




GW170817 and heavy elements

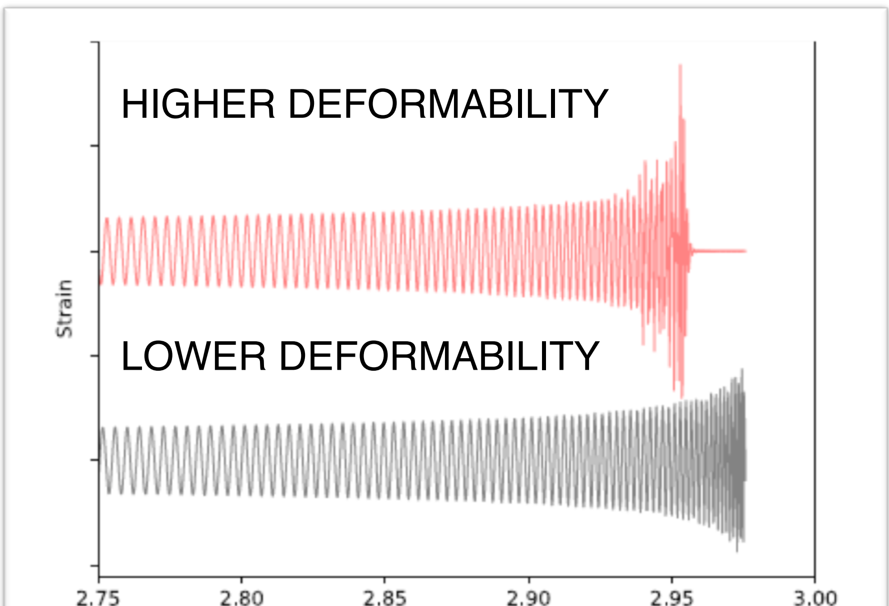
- Consistent with the picture that neutron star mergers produce most of the heaviest elements
- 

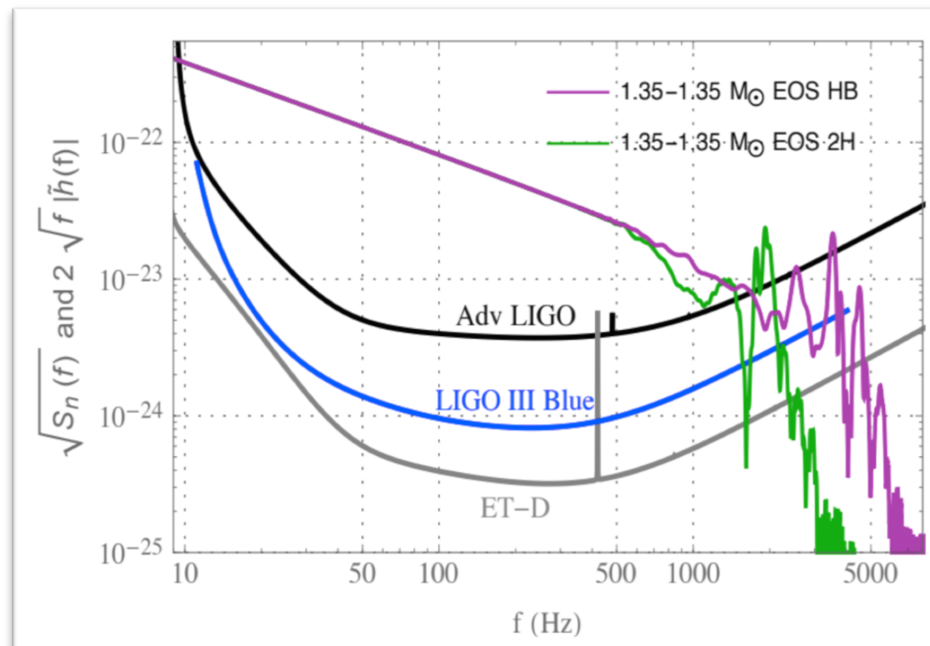
[Figure from Wikipedia "r-process" article]



BNS and tide effects: NS EOS

- Tidal effects in BNS signal
  - Point particle approximation breaks down before end of inspiral
  - Companion tidal field induces mass-quadrupole moment and accelerates coalescence
  - Ratio of induced quadrupole moment to tidal field ∝ tidal deformability Λ





NS Tidal Deformability & Radius

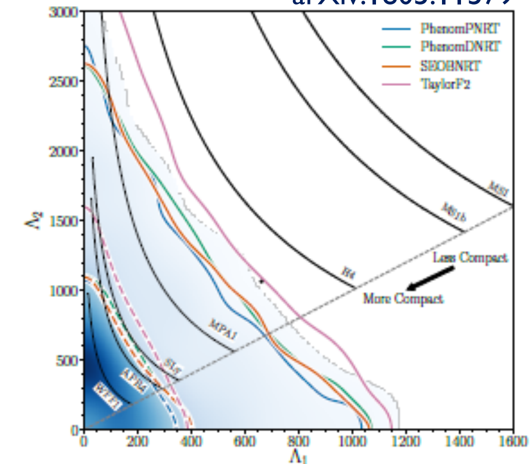
- Minimal assumption analysis
  - NS EoS predicting less compact stars disfavored
- More constraining analysis under additional assumptions
  - Both bodies are NS
  - Both NS have same EoS
  - Spins within range of Galactic binary NS

$$R_1 = 10.8^{+2.0}_{-1.7}\,\mathrm{km} \quad \text{and } R_2 = 10.7^{+2.1}_{-1.5}\,\mathrm{km}$$

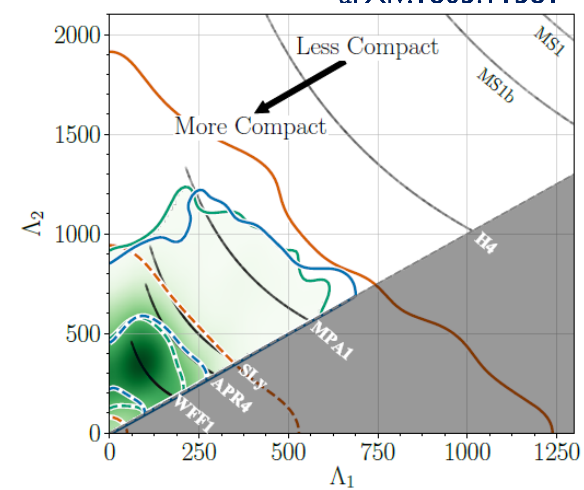
  - + EoS supports $M_{NS} > 1.97\ M_{\odot}$

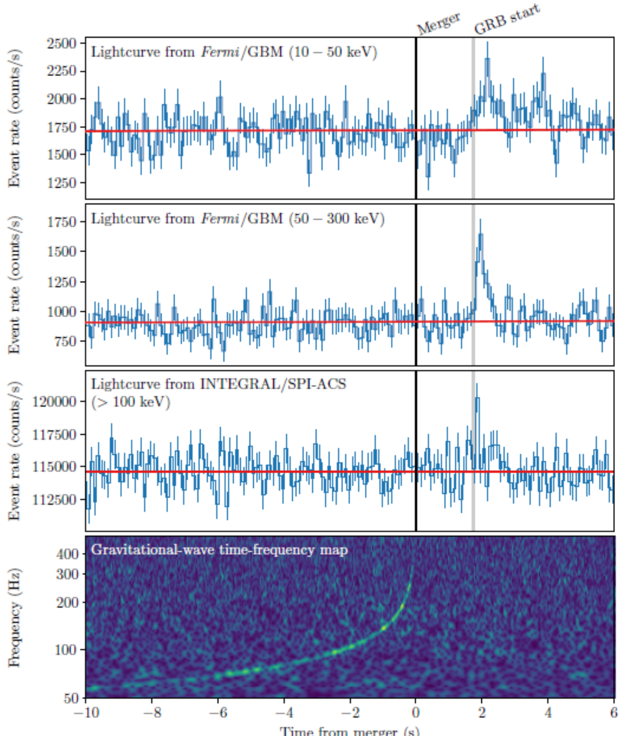
$$R_1 = 11.9^{+1.4}_{-1.4}\,\mathrm{km} \text{ and } R_2 = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$

arXiv:1805.11579



arXiv:1805.11581





Testing GR with GW170817

- GW propagation speed
  - GW170817 – GRB 170817A: delay of 1.74 ± 0.05 s over > 85 million years propagation
    - Assume Gamma emission delayed by [0,10]s

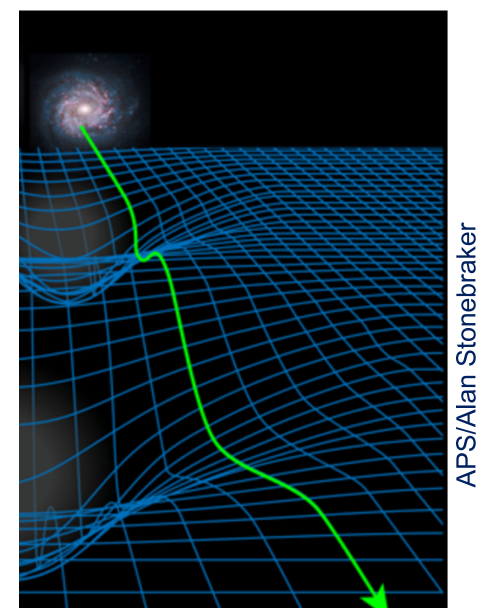
$$-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

- Equivalence principle
  - EM radiation and GWs affected by background gravitational potentials in the same way ?
  - Shapiro delay

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3} \int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))dl$$

$$-2.6 \times 10^{-7} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 1.2 \times 10^{-6}$$

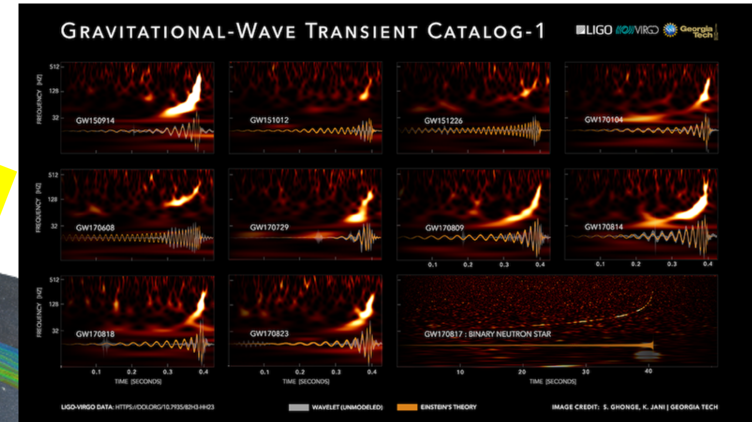
- Many alternative theories of gravity ruled out

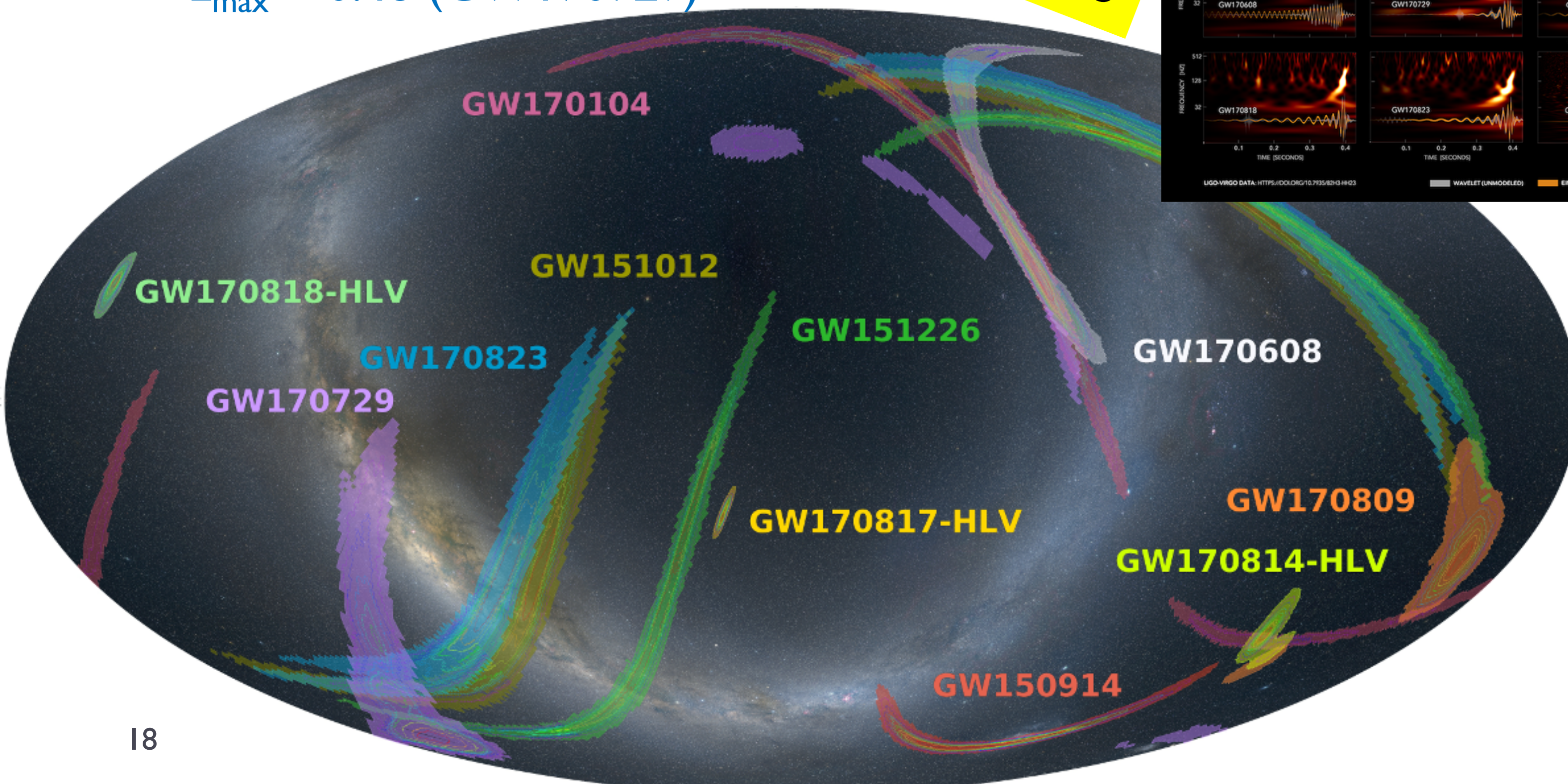


GWTC-1: Catalog of Compact Binary Mergers (O1+O2)

- 10 BBH and 1 BNS
  - 4 new BBH
  - z_{max} = 0.48 (GW170729)

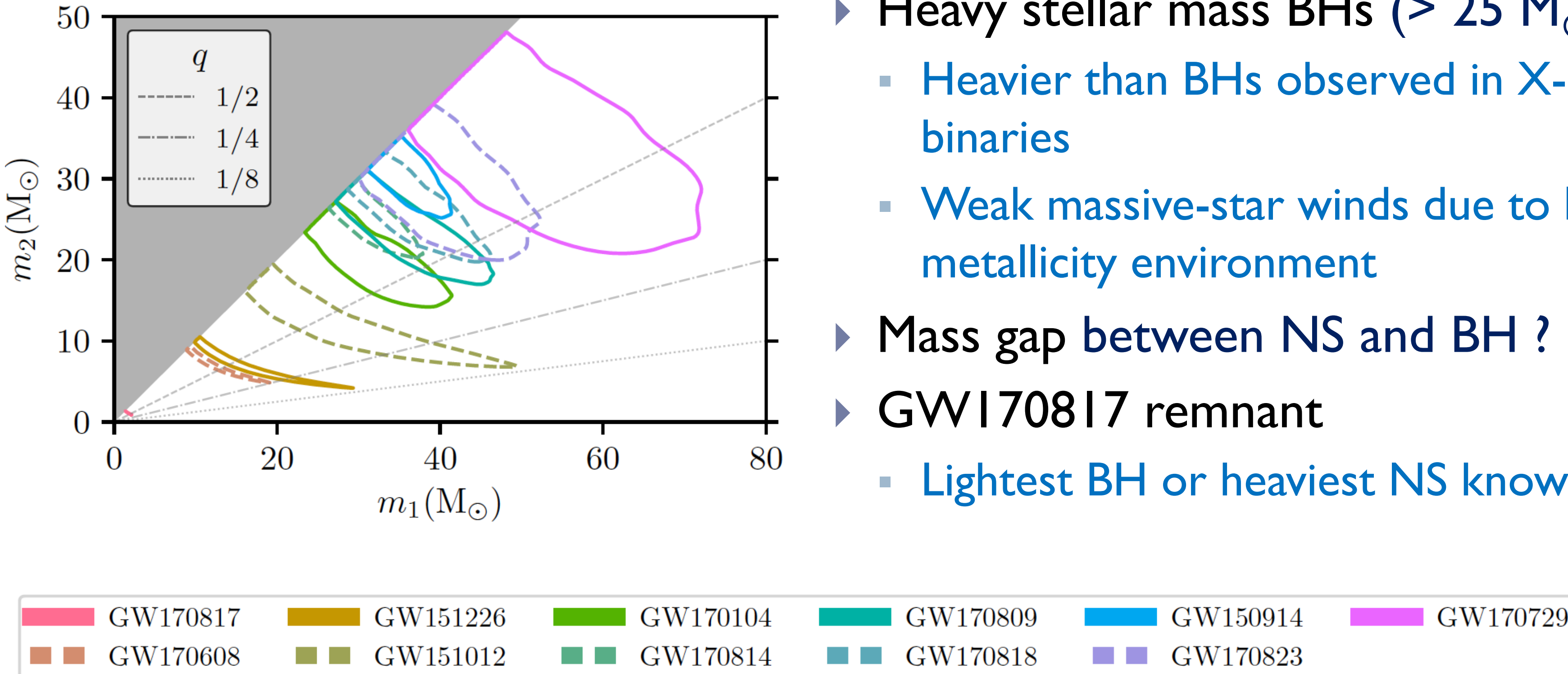
December 2018





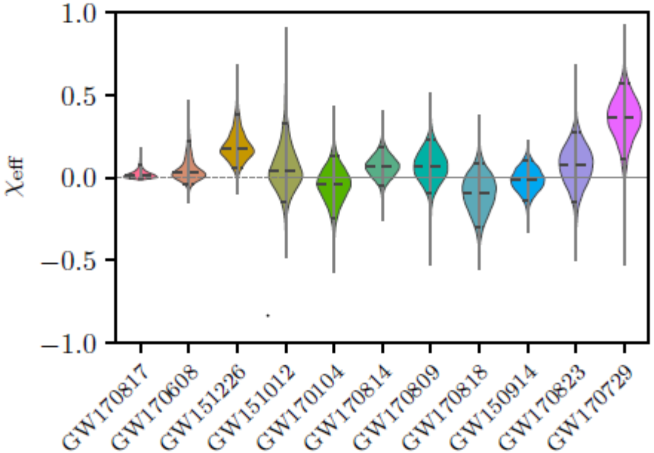
Masses from O1+O2 catalogue

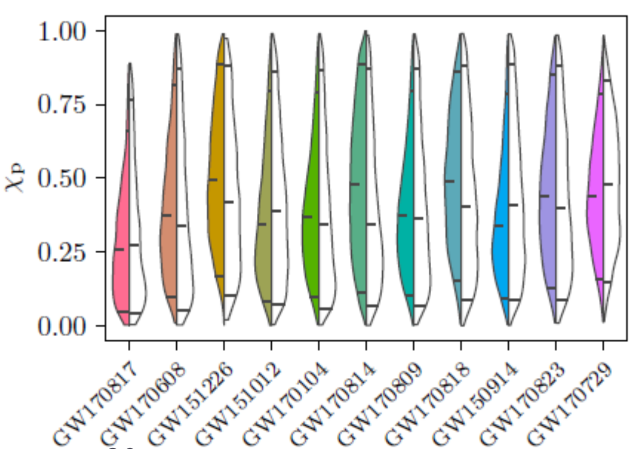
arXiv:1811.12940



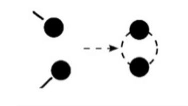
- Heavy stellar mass BHs (> 25 $M_\odot$)
  - Heavier than BHs observed in X-ray binaries
  - Weak massive-star winds due to low-metallicity environment
- Mass gap between NS and BH ?
- GW170817 remnant
  - Lightest BH or heaviest NS known

Spins

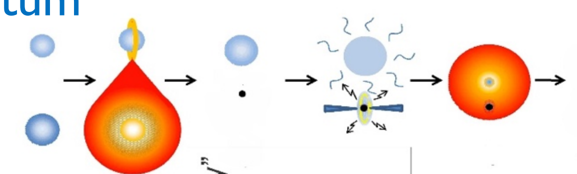




- Spins difficult to measure
  - Sub-dominant effect on waveforms
- Possible discriminator for BBH formation history
  - BHs in dynamically formed binaries in dense stellar environments expected to have spins distributed isotropically



  - Field populations: stellar evolution expected to induce BH spins preferentially aligned with the orbital angular momentum



- Current sample disfavors large spins aligned with the binary's orbital angular momentum

arXiv:1811.12907

Testing GR with CBC

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity

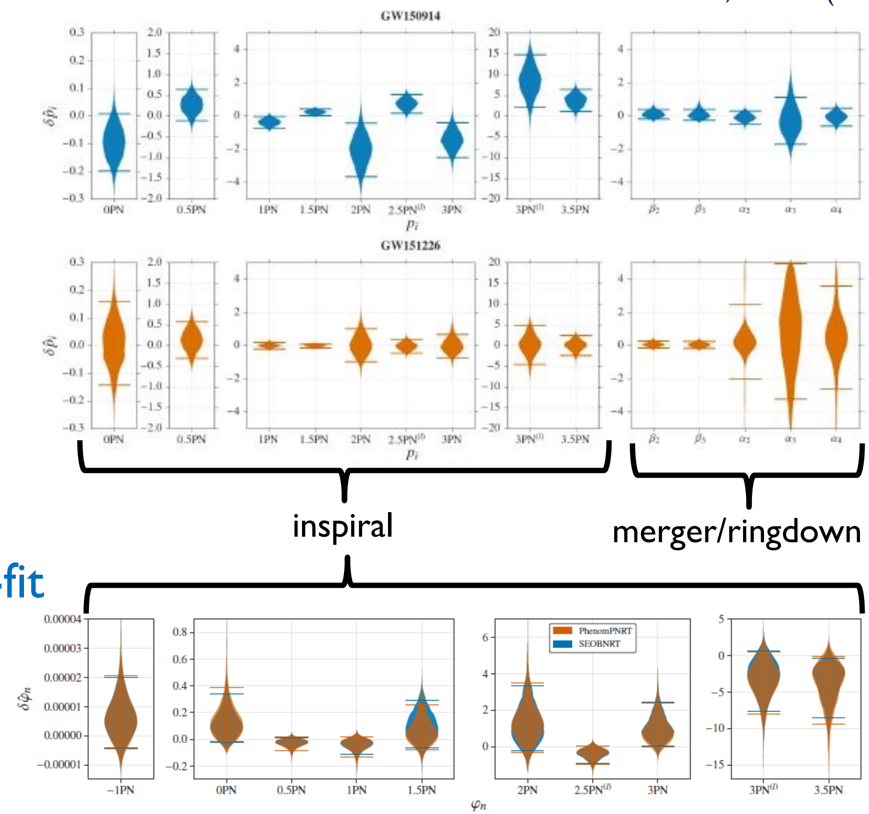
    $$v/c \sim 2 \times 10^{-3}$$

- BBH / BNS mergers
  - Strong field, non linear, high velocity regime

    $$v/c$$

- Several tests performed
  - Check residuals after subtracting best-fit waveform
  - Check consistency of low- and high-frequency parts of signal
  - Check that phenomenological deviations in waveform model are consistent with zero

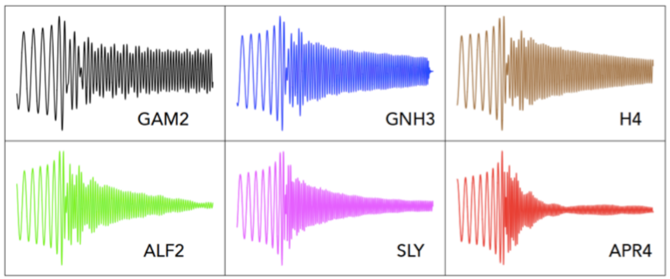
PHYSICAL REVIEW X 6, 041015 (2016)

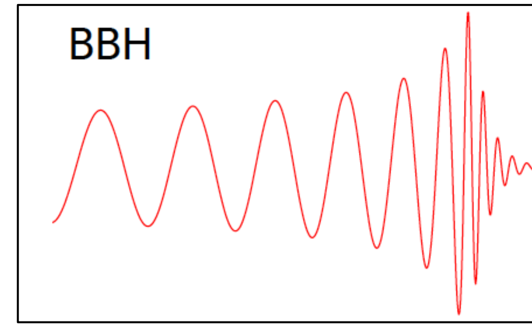


GW170817

arXiv:1811.00364

Ring down: BNS are very different from BBH



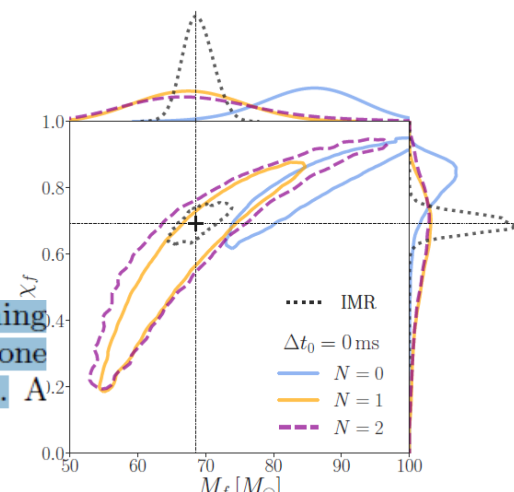


- BNS: depend on the EOS
- BBH: quasi normal mode predicted by GR

Testing the no-hair theorem with GW150914

Maximiliano Isi,[1,*] Matthew Giesler,[2] Will M. Farr,[3,4] Mark A. Scheel,[2] and Saul A. Teukolsky[2,5]
[1]*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(GW150914) in search of the ringdown of the remnant black hole. Using observations beginning at the peak of the signal, we find evidence of the fundamental quasinormal mode and at least one overtone, both associated with the dominant angular mode ($\ell = m = 2$), with 3.6σ confidence. A



Measuring the Hubble Constant

$$v_H = H_0 d$$

Hubble flow velocity from host galaxy NGC4993

Distance from GW

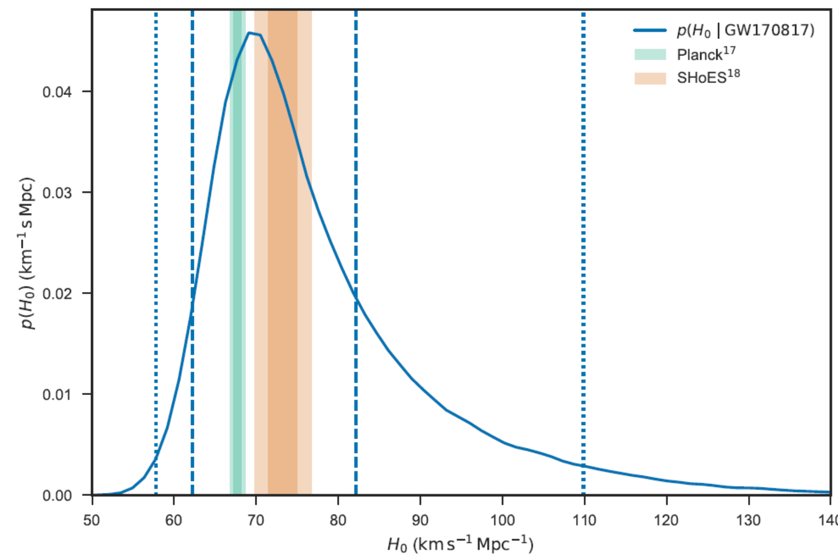
- GW170817 – AT2017gfo
  - GW only; d = 40^{+8}_{-14} Mpc at 90% CL
  - Assuming sky position of AT2017gfo
    - $d = 43.8^{+2.9}_{-6.9}$ Mpc at 68% CL
  - H_0 uncertainty from statistics, geometrical degeneracy with system inclination, and galaxy peculiar velocity
- With additional information on the viewing angle from high resolution imaging of the radio counterpart:

$$H_0 = 64.8^{+7.3}_{-7.2}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

arxiv/1909.00587

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

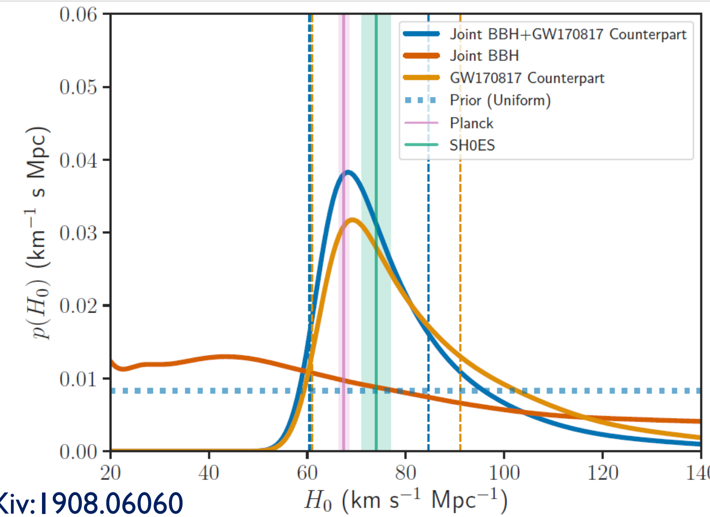
Independent of any cosmic distance ladder



Nature 551, 85 (2017)

H_0 with GW170817 + BBH

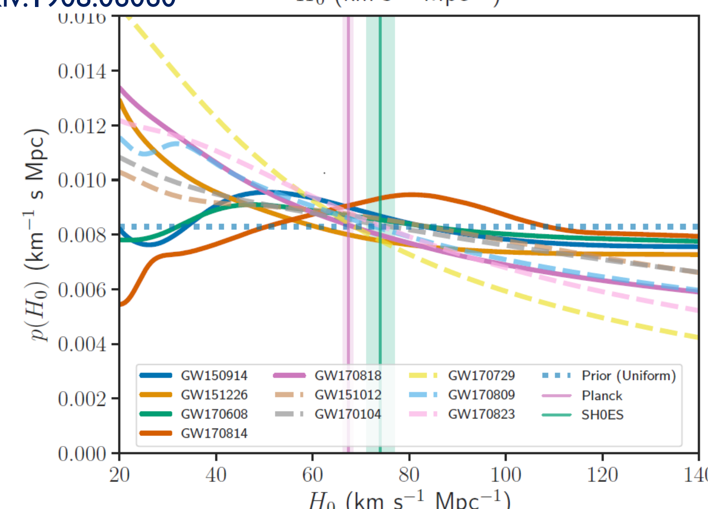
- Statistical method for BBH
- Include all galaxies with the error box
  - Weighted by Galaxy luminosity
- Require catalogue
- Less powerful but complementary



arXiv:1908.06060

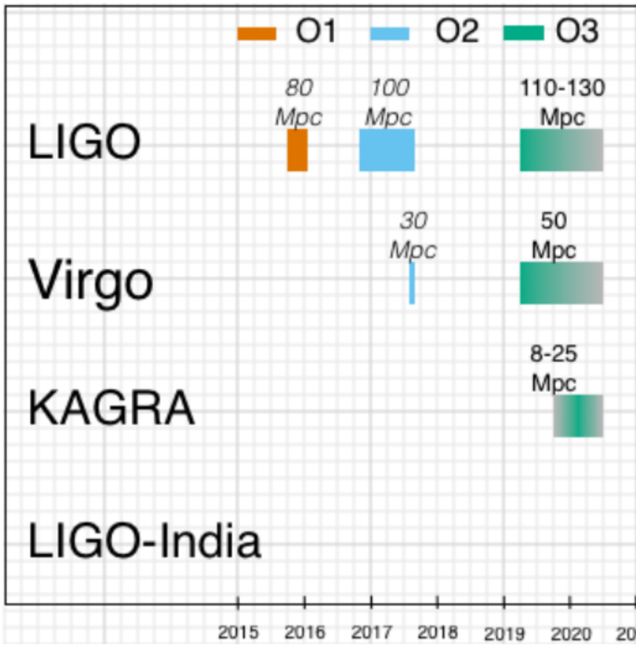
BBH O1+O2

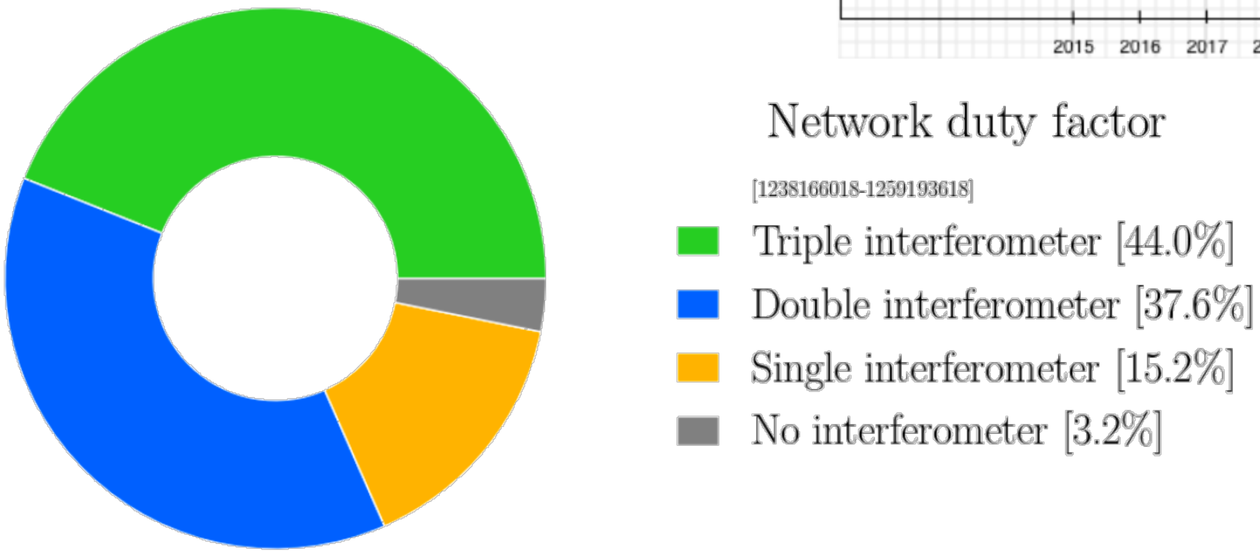
Event	$\Delta\Omega/\mathrm{deg}^2$	d_L/Mpc	z_{event}	V/Mpc^3	Galaxy catalog	Number of galaxies	$p(G \mid z_{\mathrm{event}}, D_{\mathrm{GW}})$
GW150914	182	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	3.5×10^6	GLADE	4944	0.61
GW151012	1523	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	5.8×10^8	GLADE	45214	0.06
GW151226	1033	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	2.4×10^7	GLADE	39387	0.60
GW170104	921	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	2.4×10^8	GLADE	48786	0.10
GW170608	392	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	3.4×10^6	GLADE	20883	0.76
GW170729	1041	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	8.7×10^9	GLADE	34100	< 0.01
GW170809	308	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	9.1×10^7	GLADE	23031	0.08
GW170814	87	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	4.0×10^6	DES-Y1	4392112	> 0.99
GW170817	16	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	227	–	–	–
GW170818	39	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	1.5×10^7	GWENS	134040	0.94
GW170823	1666	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	3.5×10^9	GLADE	54786	< 0.01



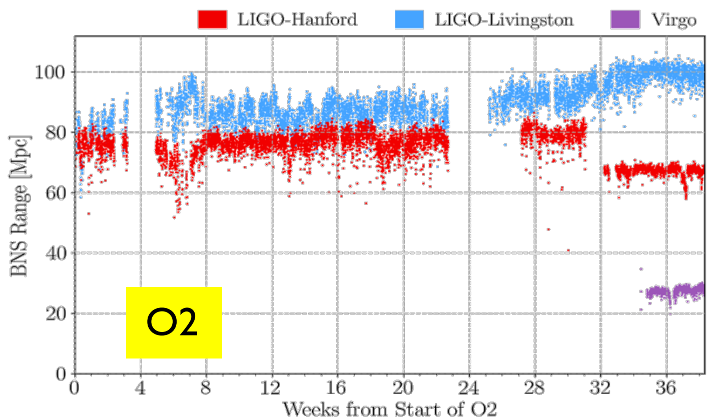
O3 run

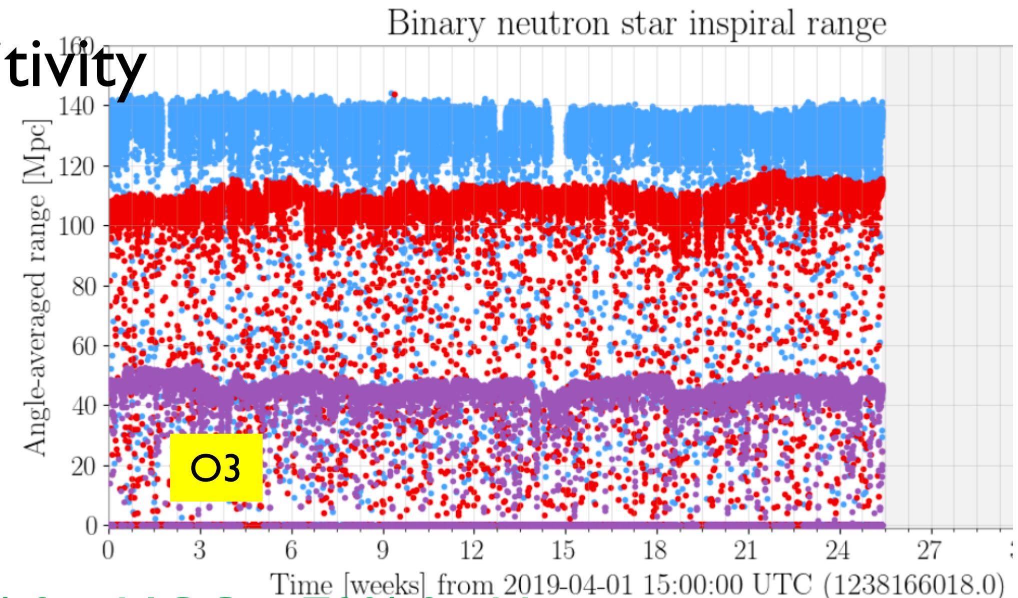
- Split in two six months periods:
  - OA3: April 1st to October 1st
  - O3B: Start on November 1st
  - Single ITF duty cycle: 71% (H1), 76 % (L1,V1)



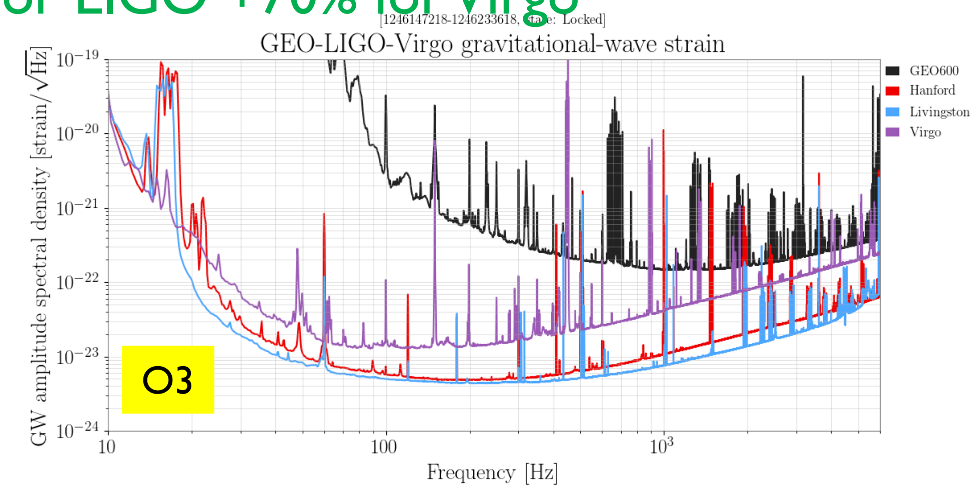


Run O3: BNS range & sensitivity





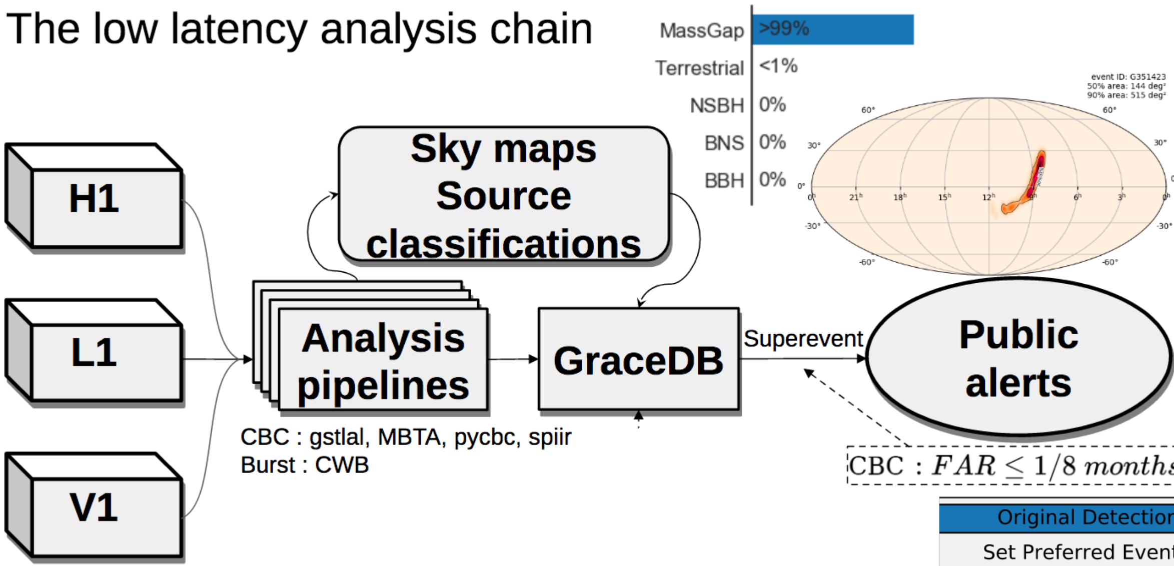
- 03/02 range improvement ~: +40% for LIGO +70% for Virgo

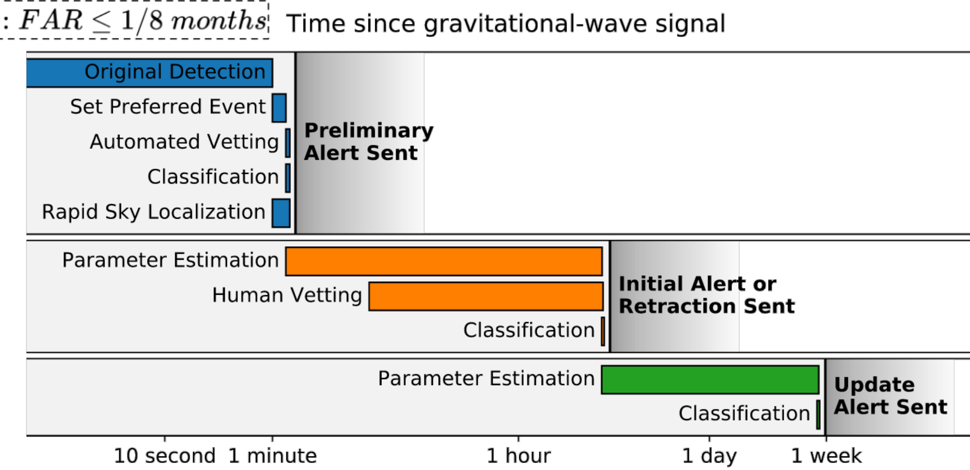


- BNS range: average luminosity distance at which the merger of two 1.4 $M_{\odot}$ objects would be detectable with a signal to noise ratio of 8.
- BBH range is larger by one order of magnitude

The low latency analysis chain

O3: Public alerts

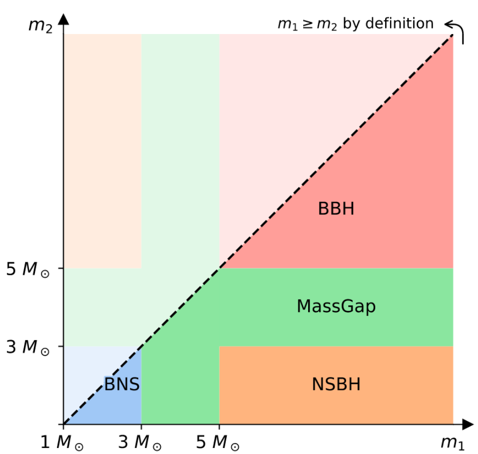


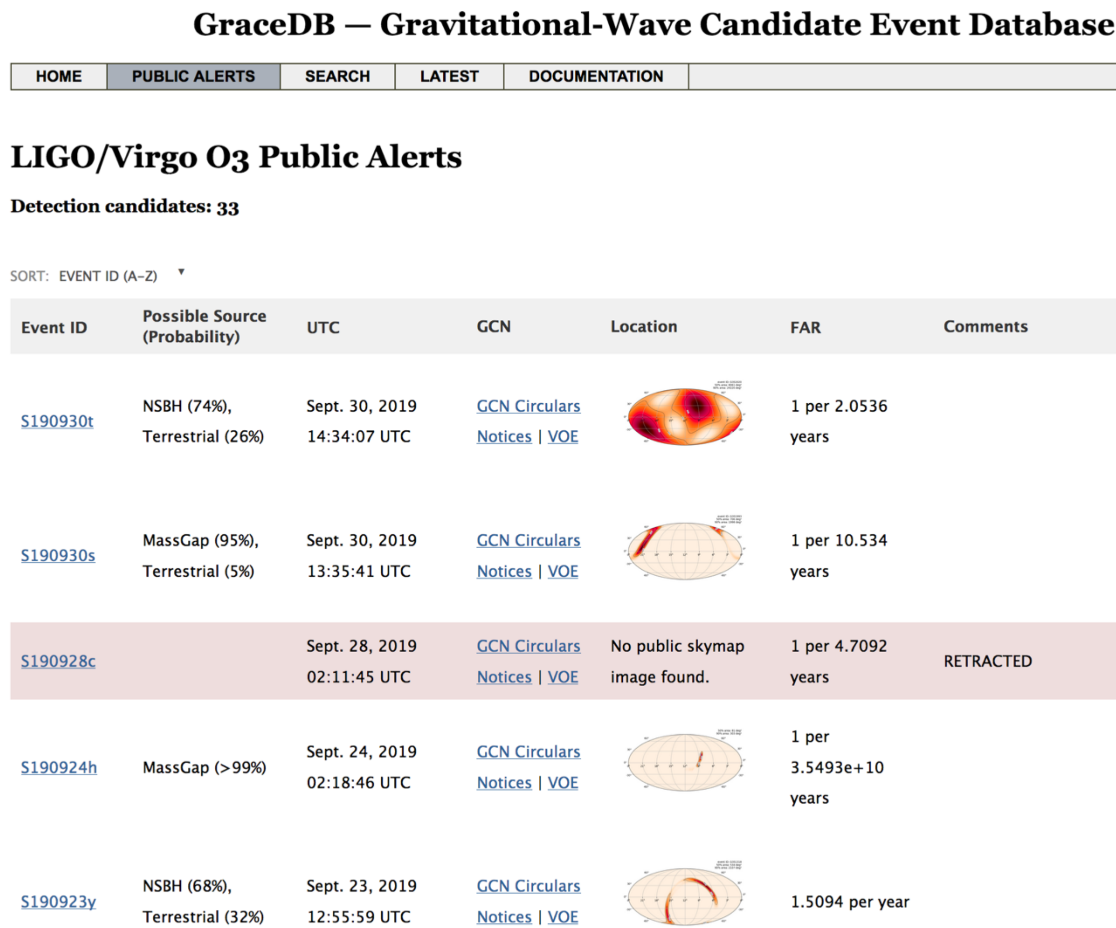


- CBC threshold: FAR < 1/8 months
- 1–10 minutes after GW time: automated preliminary notice
- Within 24 hours: Initial notice and circular to confirm or retract it.
  - Human validation.

O3 run: open alerts

- 33 candidates for O3A
  - 21 BBH
  - 6 BNS
  - 4 NSBH
  - 2 MassGap
  - + 8 retracted alerts





GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION

LIGO/Virgo O3 Public Alerts

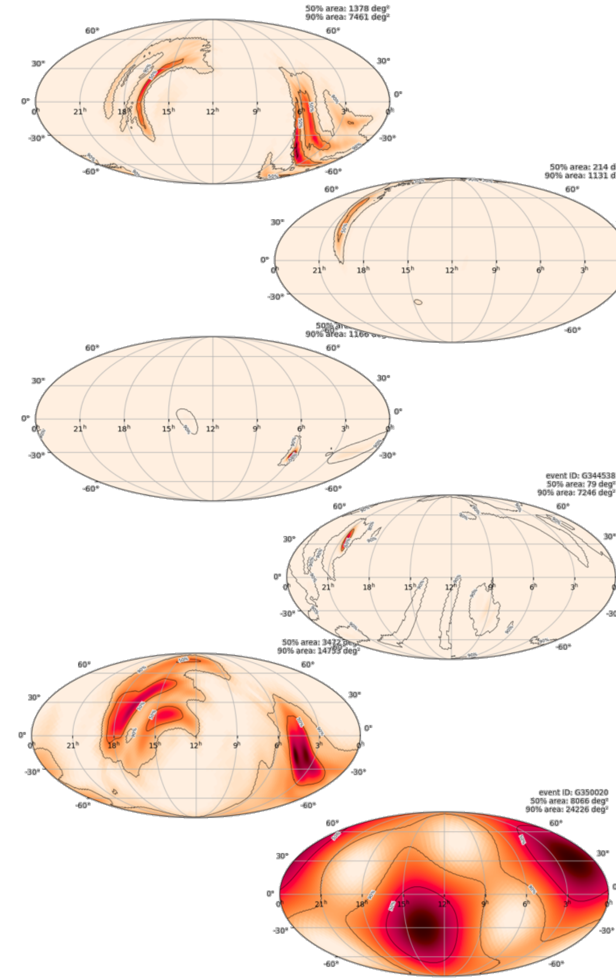
Detection candidates: 33

SORT: EVENT ID (A–Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190930t	NSBH (74%), Terrestrial (26%)	Sept. 30, 2019 14:34:07 UTC	GCN Circulars Notices | VOE		1 per 2.0536 years	
S190930s	MassGap (95%), Terrestrial (5%)	Sept. 30, 2019 13:35:41 UTC	GCN Circulars Notices | VOE		1 per 10.534 years	
S190928c		Sept. 28, 2019 02:11:45 UTC	GCN Circulars Notices | VOE	No public skymap image found.	1 per 4.7092 years	RETRACTED
S190924h	MassGap (>99%)	Sept. 24, 2019 02:18:46 UTC	GCN Circulars Notices | VOE		1 per 3.5493e+10 years	
S190923y	NSBH (68%), Terrestrial (32%)	Sept. 23, 2019 12:55:59 UTC	GCN Circulars Notices | VOE		1.5094 per year	

6 BNS candidates during O3A

- S190425z FAR = 1 per 70k years
  - 90% area: 7461 deg^2; 156+-40 Mpc
- S190426c FAR = 1 per 1.6 years
  - 90% area: 1131 deg^2
- S190510g FAR = 1 per 3.6 years
  - 90% area: 1166 deg^2
- S190718y FAR = 1.2 per year
  - 90% area: 7246 deg^2
- S190901ap FAR = 1 per 4.5 year
  - 90% area: 14753 deg^2
- S190910h FAR = 1.3 per year
  - 90% area: 24226 deg^2

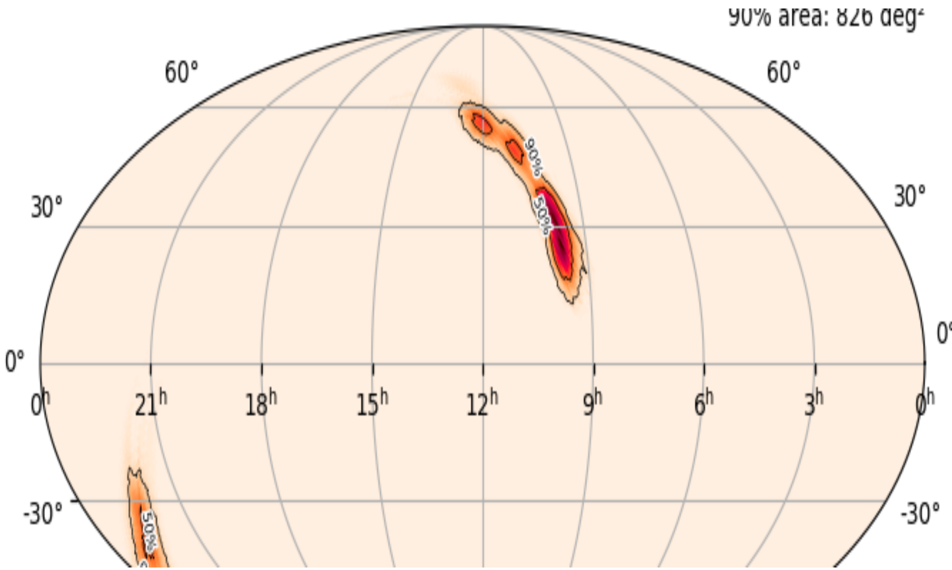


4 NSBH candidates during O3A

- S190330t FAR = 1 per 2 years
- S190923y FAR = 1.5 per year
- S190910d FAR = 1 per 8 years
- S190814bv FAR = 1 per 10^{25} years
  - Very well localized
  - 90 % area: 23 deg^2
  - ~ 7 further away than GW170817

21 BBH candidates during O3A

- 16 with a False Alarm Rate < 1 per 10 years
- S190706ai
  - FAR =1 per 17 years
  - Largest distance: 5.3 Gpc = 18 Gly → z ~ 1
    - Observed masses are rescaled by a factor 2

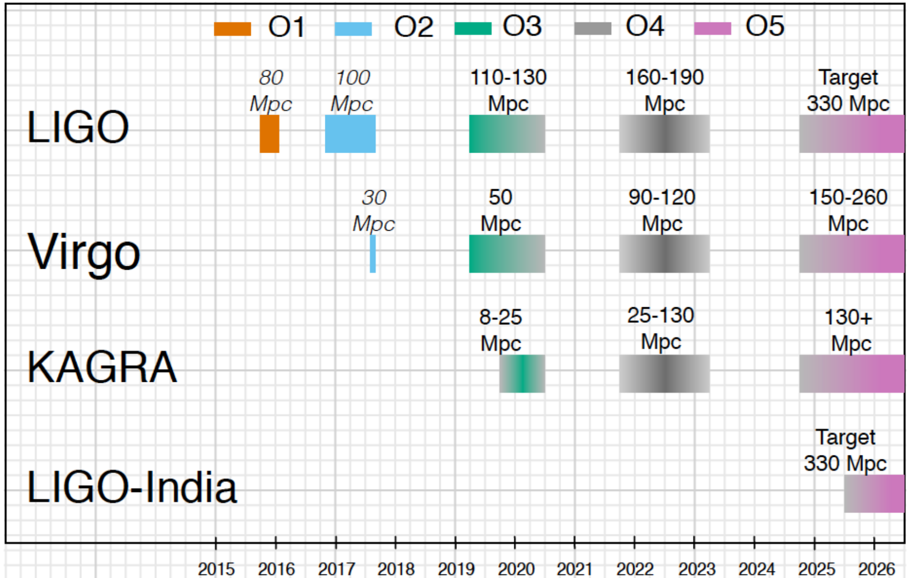


https://gcn.gsfc.nasa.gov/gcn3_archive.html#tc1

- 25884 LIGO/Virgo S190930s: no counterpart candidates in AGILE-GRID observations
- 25883 LIGO/Virgo S190928c: Retraction of GW unmodeled transient candidate
- 25882 LIGO/Virgo S190930t : no neutrino counterpart candidate in ANTARES search
- 25881 LIGO/Virgo S190930s : no neutrino counterpart candidate in ANTARES search
- 25880 LIGO/Virgo S190930t: No counterpart candidates in INTEGRAL SPI-ACS prompt observation
- 25879 GRB 190928A: Insight-HXMT/HE detection
- 25878 LIGO/Virgo S190930s: No counterpart candidates in AGILE-MCAL observations
- 25877 LIGO/Virgo S190930s: Coverage and upper limits from MAXI/GSC observations
- 25876 LIGO/Virgo S190930t: Identification of a GW compact binary merger candidate
- 25875 LIGO/Virgo S190930t: Global MASTER-Net observations report
- 25874 LIGO/Virgo S190930t: Upper limits from IceCube neutrino searches
- 25873 LIGO/Virgo S190930s: Upper limits from IceCube neutrino searches
- 25872 LIGO/Virgo S190930s: No counterpart candidates in INTEGRAL SPI-ACS prompt observation
- 25871 LIGO/Virgo S190930s: Identification of a GW compact binary merger candidate
- 25870 LIGO/Virgo S190930s: Global MA
- 25869 Fermi trigger No 591532362: Glob
- 25868 Konus-Wind observation of GRB 1
- 25867 GRB 190928A: MASTER optical o
- 25866 GRB 190930A: Fermi GBM Final I
- 25865 GRB 190928A: CALET Gamma-R
- 25864 IPN triangulation of GRB 190928A
- 25863 Fermi trigger No 591391412: Glob
- 25862 GRB 190926A: AbAO upper optic
- 25861 LIGO/Virgo S190828j: Updated Sk
- 25860 GRB 190926A: Swift-BAT refined
- 25859 GRB 190928A: AGILE/MCAL det
- 25858 Baksan Neutrino Observatory Alert
- 25857 Fermi trigger No 591321287: Glob
- 25856 GRB 190926A: Upper Limit from
- 25855 LIGO/Virgo S190923y: MASTER
- 25854 GRB 190926A: MITSuME Akeno
- 25853 GRB 190926A: Swift/UVOT Uppe
- 25852 GRB 190926A: KAIT Optical Upper Limit
- 25851 GRB 190926A: Swift-XRT refined Analysis
- 25850 GRB 190926A: Enhanced Swift-XRT position
- 25849 Swift GRB190926.41: Global MASTER-Net observations report
- 25848 GRB 190926A: Swift detection of a burst
- 25847 LIGO/Virgo S190923y: No significant candidates in TAROT-GRANDMA observations
- 25846 LIGO/Virgo S190923y: no counterpart candidates in the Swift/BAT observations
- 25845 LIGO/Virgo S190924h: No counterpart candidates in Fermi-LAT observations
- 25844 LIGO/Virgo S190924h: Not observable by CALET
- 25843 LIGO/Virgo S190924h: no counterpart candidates in the Swift/BAT observations
- 25842 LIGO/Virgo S190923y: No neutrino candidates at Pierre Auger Observatory
- 25841 LIGO/Virgo S190924h: Upper limits from Fermi-GBM Observations
- 25840 LIGO/Virgo S190924h: no counterpart candidates in AGILE-GRID observations
- 25839 LIGO/Virgo S190924h: No counterpart candidates in AGILE-MCAL observations

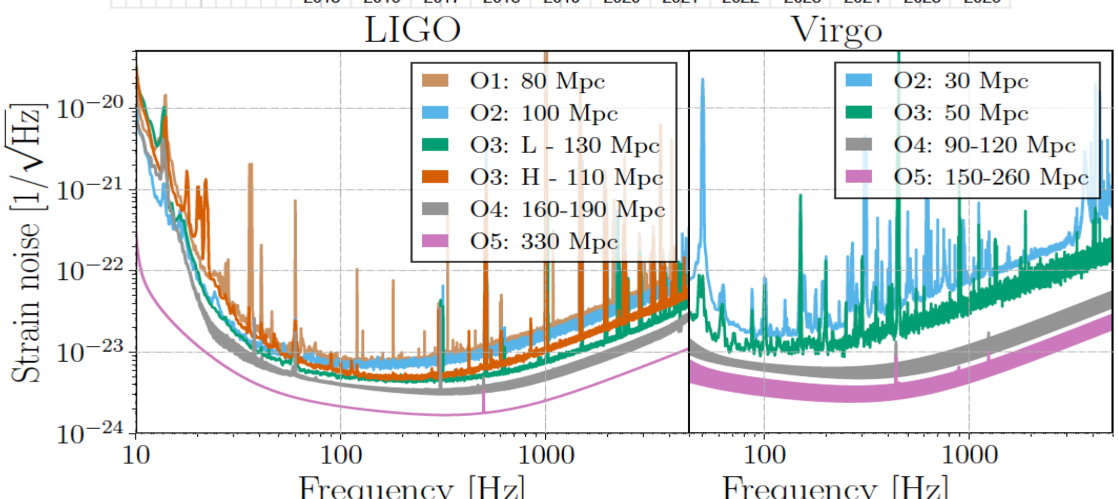
Response of EM/HEN Community

- GCN circular traffic generated:
  - LIGO-Virgo candidates ~50% of total traffic
  - Vanilla BBH candidate typically15-20 circulars
  - S190425z (BNS) and S190814bv (NSBH) ~120 circulars
  - S190426c and S190510g (BNS then terrestrial) ~60-70 circulars
  - S190728q (MassGap then BBH) generated ~40

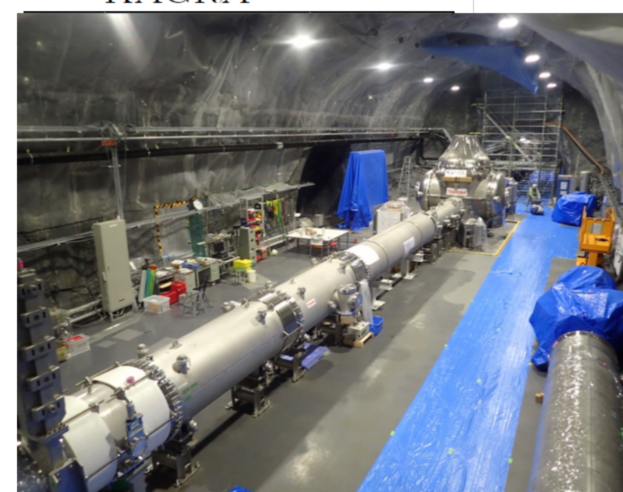


Network evolution

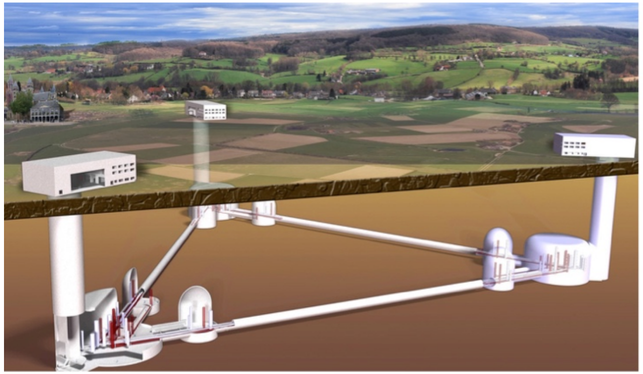
- Expected range increase by 50% for O4 and then O5
- → Rate increase by 3-4
  - Few BNS per month
  - Several BBH per day



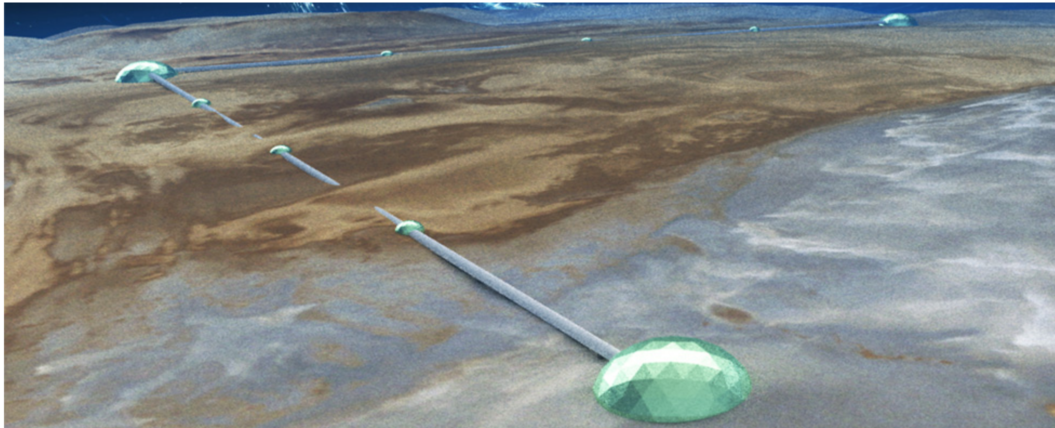
KAGRA



Third generation: ET & Cosmic Explorer



- Einstein Telescope (ET):
  - Underground 10 km triangle
  - European effort
- Cosmic explorer
  - Above ground, L shaped, 40 km
  - US
- Coordination through GWIC (Gravitational Wave International Committee)
  - Science case released



3G (Best) Timelines

Einstein Telescope

- 2010 ET conceptual design
- 2018-2019 **ET collaboration**
- 2019-2021 ESFRI roadmap
- 2021-2022 Site Selection
- 2023 **Full Technical Design**
- 2025 Infrastructure realization start (excavation, ….)
- 2032+: installation / commissioning / operation

Credit: A. Freise

Cosmic Explorer

- 2015 first CE paper
- 2018 NSF grant for US3G study
- 2020-2021 CE white paper
- 2022-2026 Initial Design Phases
- 2027-2029 Final Design
- 2030+ US Congress appropriates funds

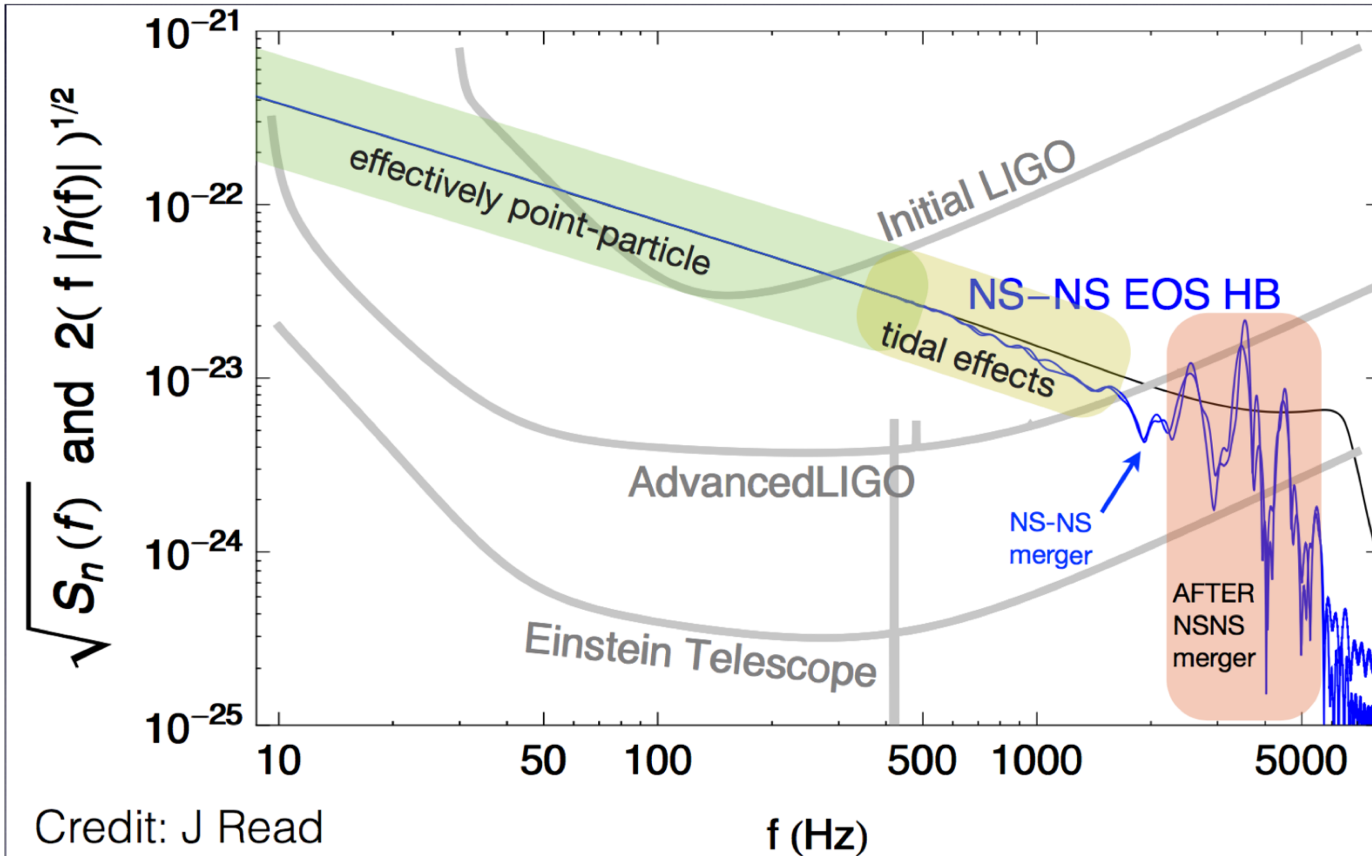
Credit: M. Evans

3G science case

- "Guaranteed science returns"
  - Study the nature of black holes, test the no-hair theorem
    - and gravity in ultra strong fields
  - Explore the state of ultra dense nucleons
    - and the origin of heavy elements
  - Reveal phase transition from nucleons to free quarks
    - and insight into the QCD phase diagram
  - Detect gravitational waves from supernova
    - and determine the physics of core-collapse supernova
  - Determine H0 and the nature of dark energy equation of state
    - and its variation with redshift
  - Provide a new tool for measuring distances to cosmological sources
- + Opportunity for new discovery
- GW: a completely different observational tool compared to EM window

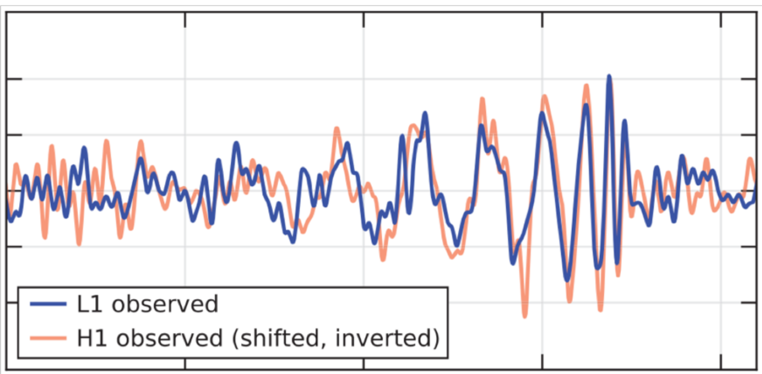
Tests of extreme matter with 3G

- 3G detector could probe NS Equation Of State



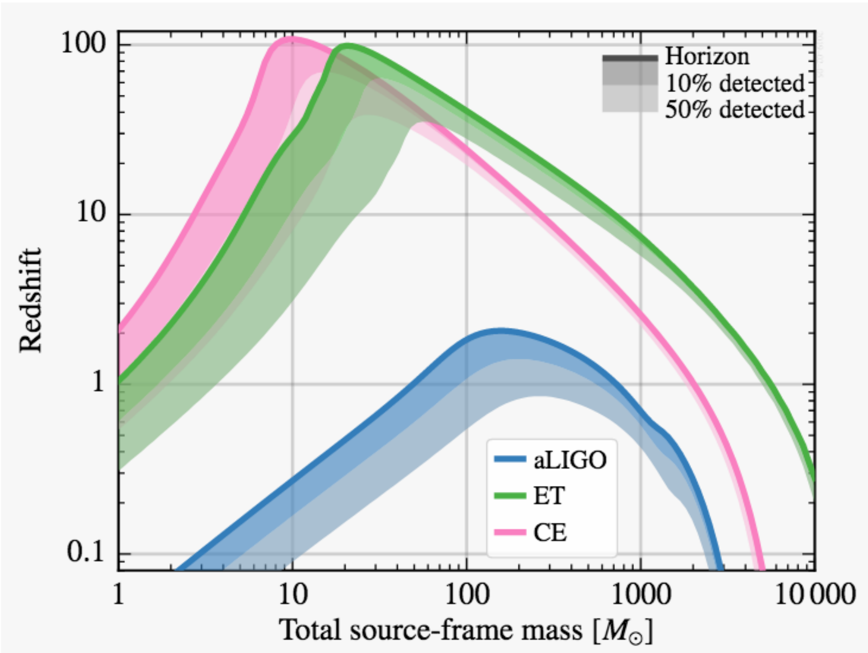
Precision test of GR with 3G detectors

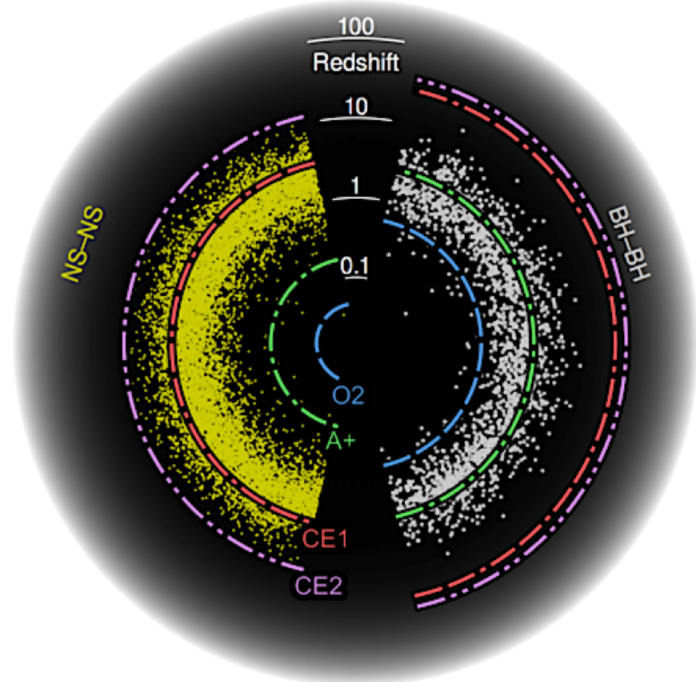
- GW150914



Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800

3G detector: explore the Universe at high redshift





From the first observation to observing all NS and stellar BH mergers in the Universe in a few decades…