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Searches for gravitational waves with LIGO and Virgo – O1 and O2 results –

Florent Robinet
on behalf of the LIGO scientific collaboration and the Virgo collaboration

Third SVOM Scientific Workshop – May. 2018

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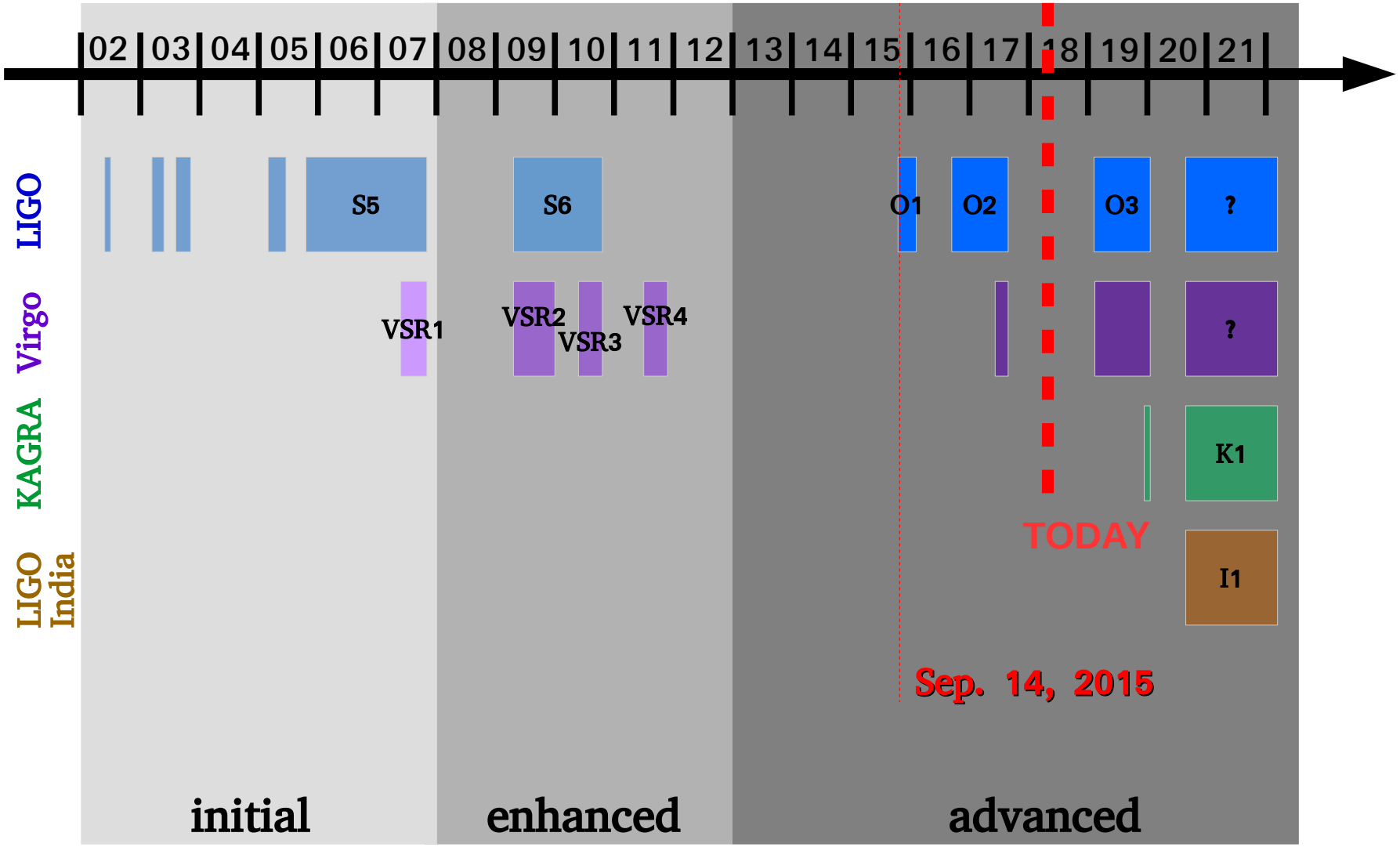
Searches for gravitational waves with LIGO and Virgo – O1 and O2 results –

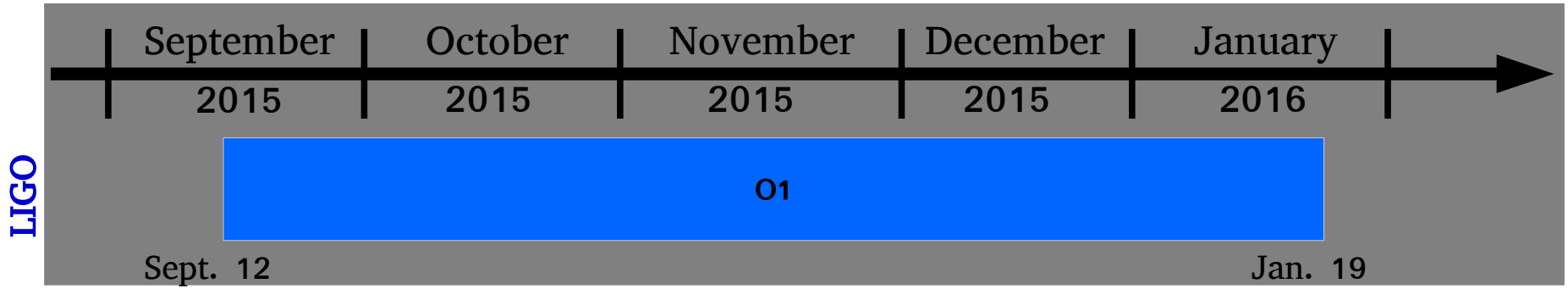
- Overview
- Binary black hole detections
- Other results

Third SVOM Scientific Workshop – May. 2018

20 years of searches



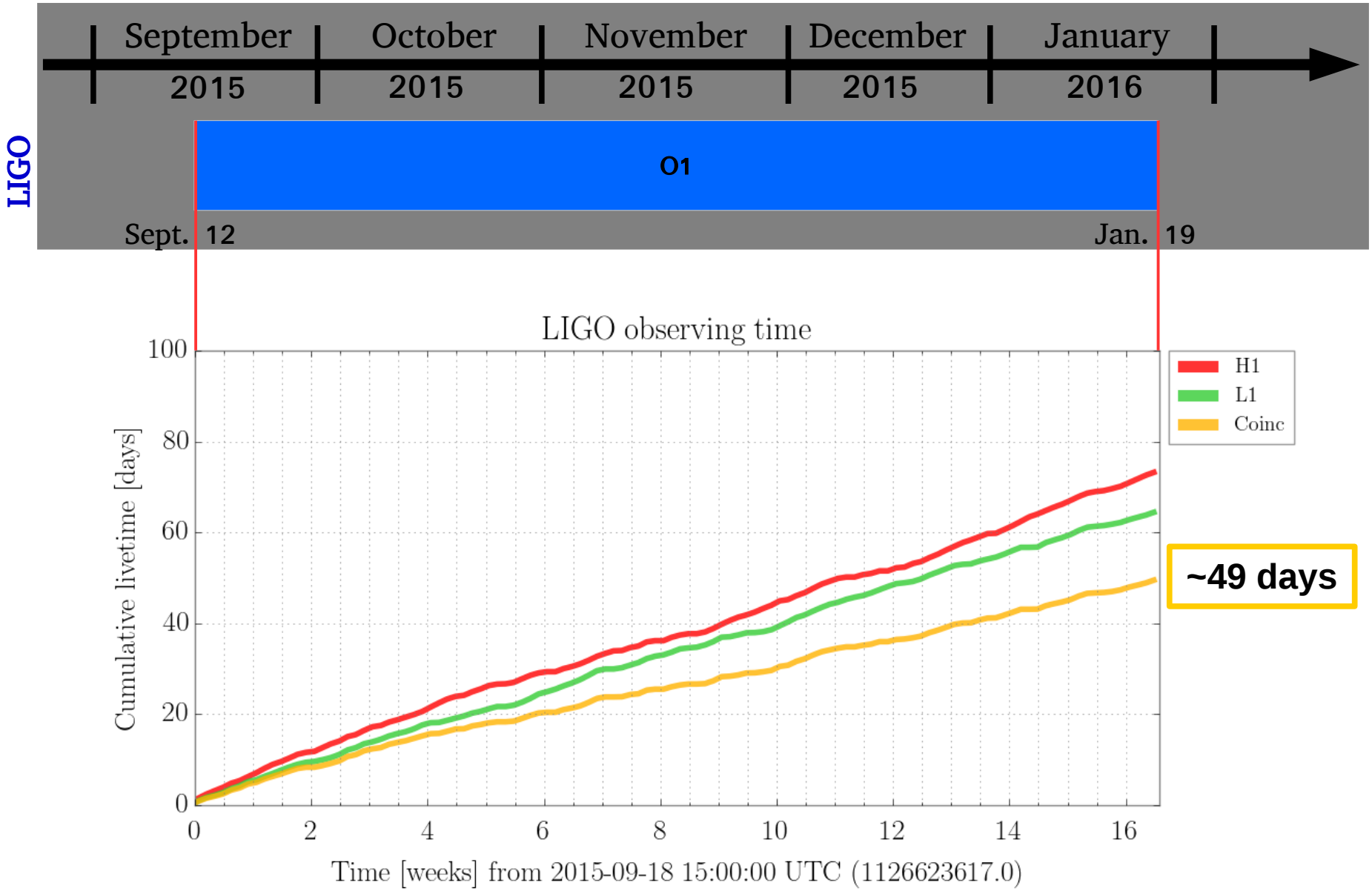
LIGO detectors



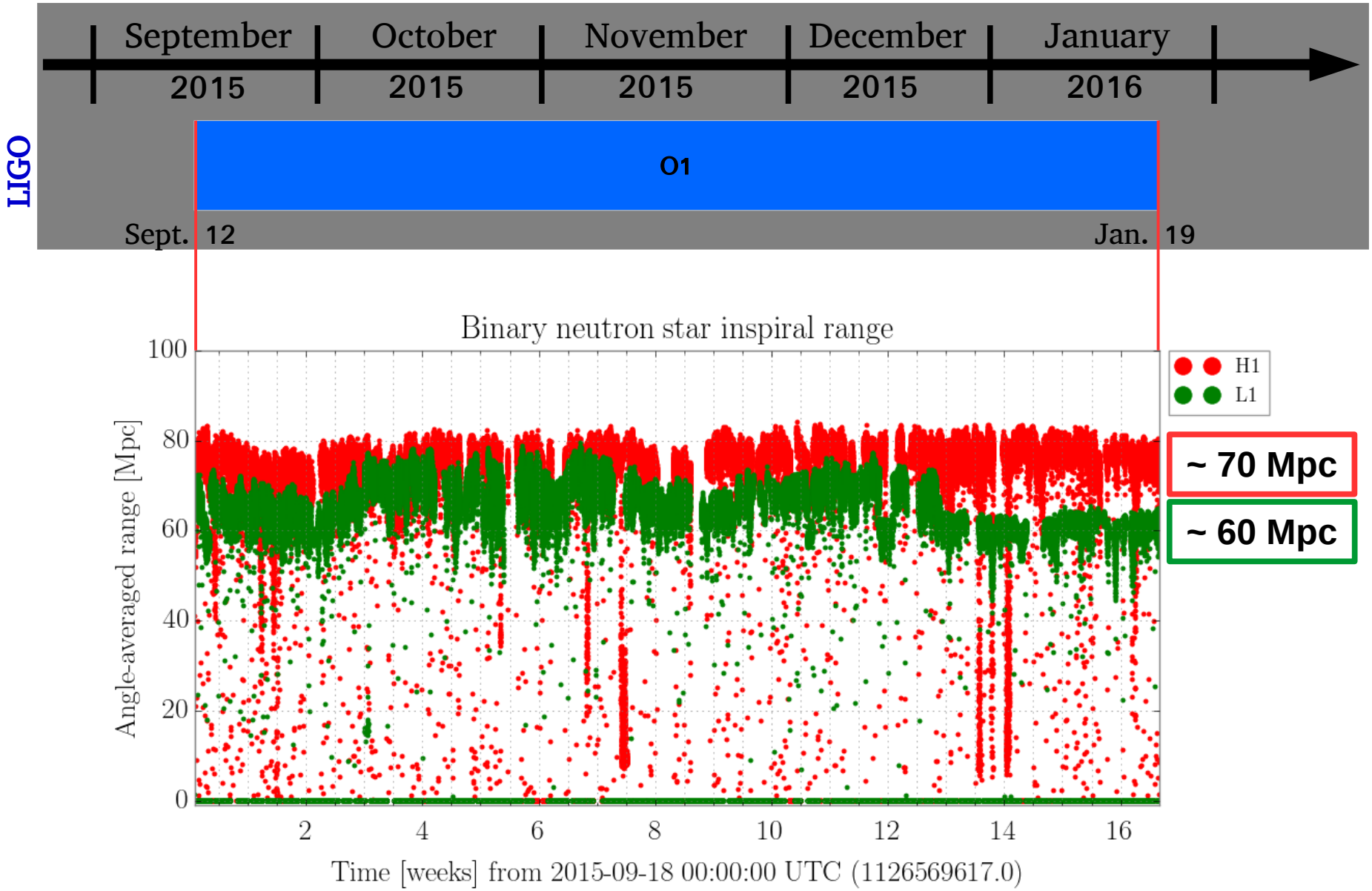
LIGO Hanford, WA

LIGO Livingston, LA

O1 observing time

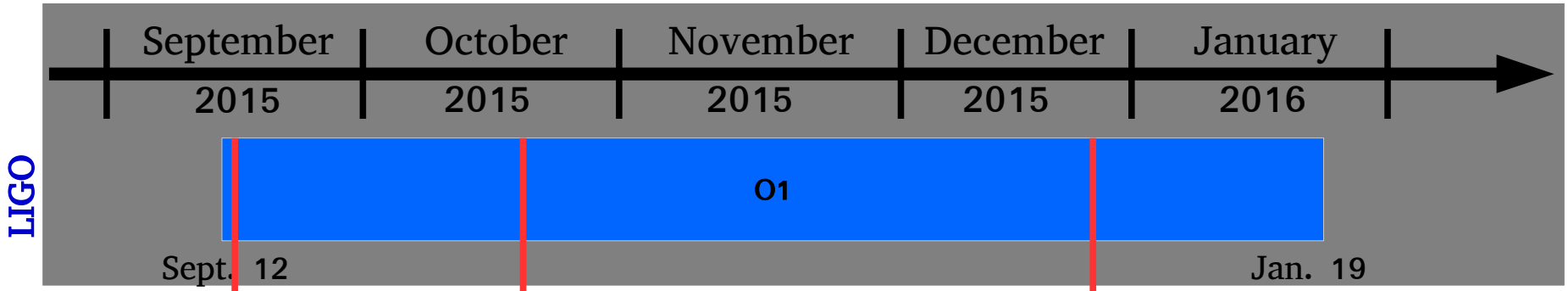


O1 LIGO sensitivity



range = distance up to which a binary neutron star merger can be detected with a signal-to-noise ratio of 8, averaging over the position and orientation of the binary system.

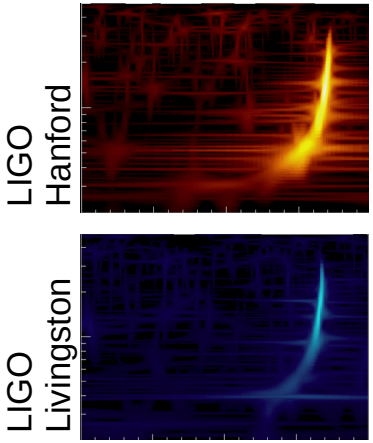
O1 GW detections



LVT151012

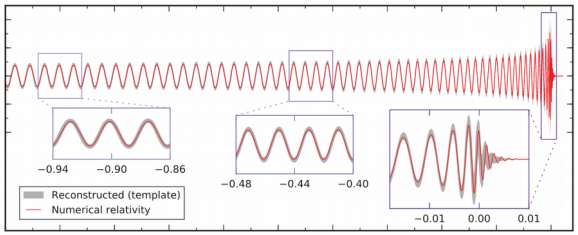
Marginal signal (~2σ)

GW150914



First gravitational wave detection
The signal is off the charts !

GW151226



Long-lasting signal (~1s)

2+1 binary black hole (BBH) mergers were detected in O1 data

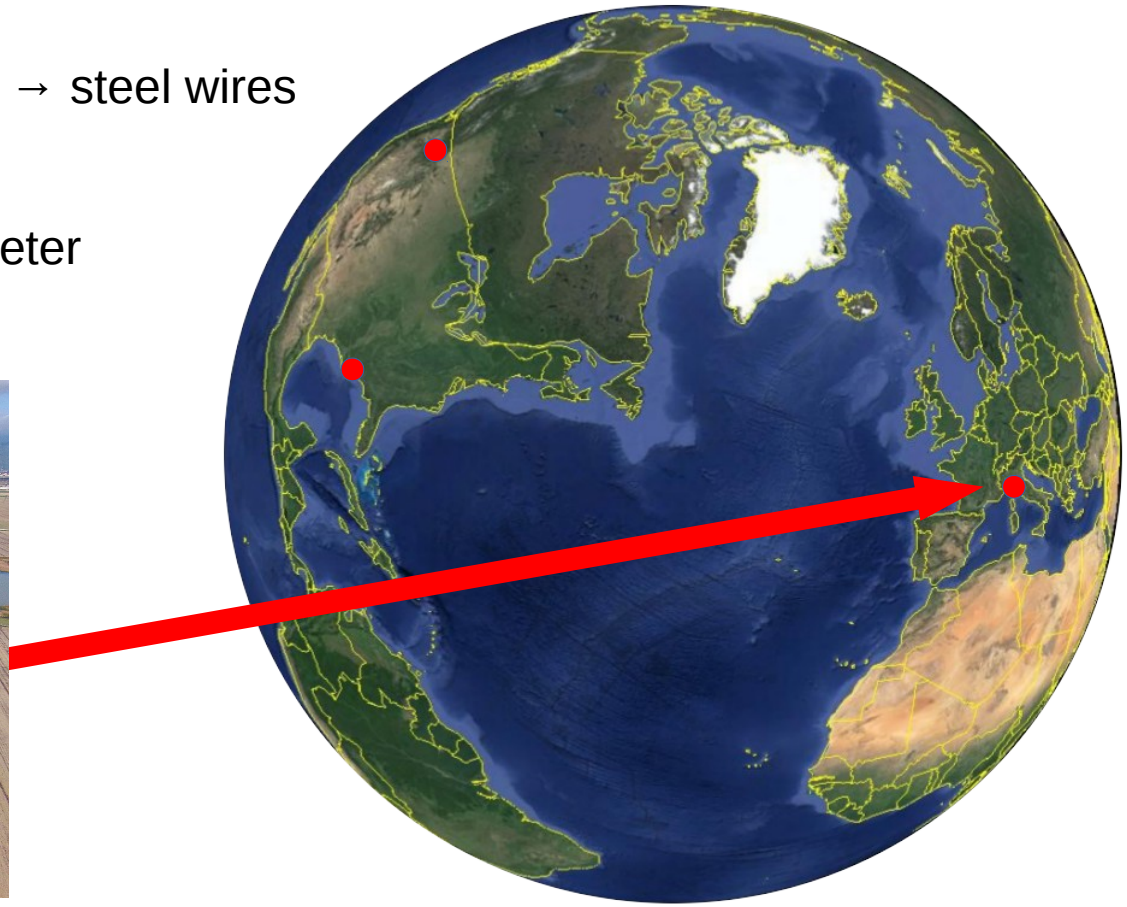
O1 → O2 upgrades

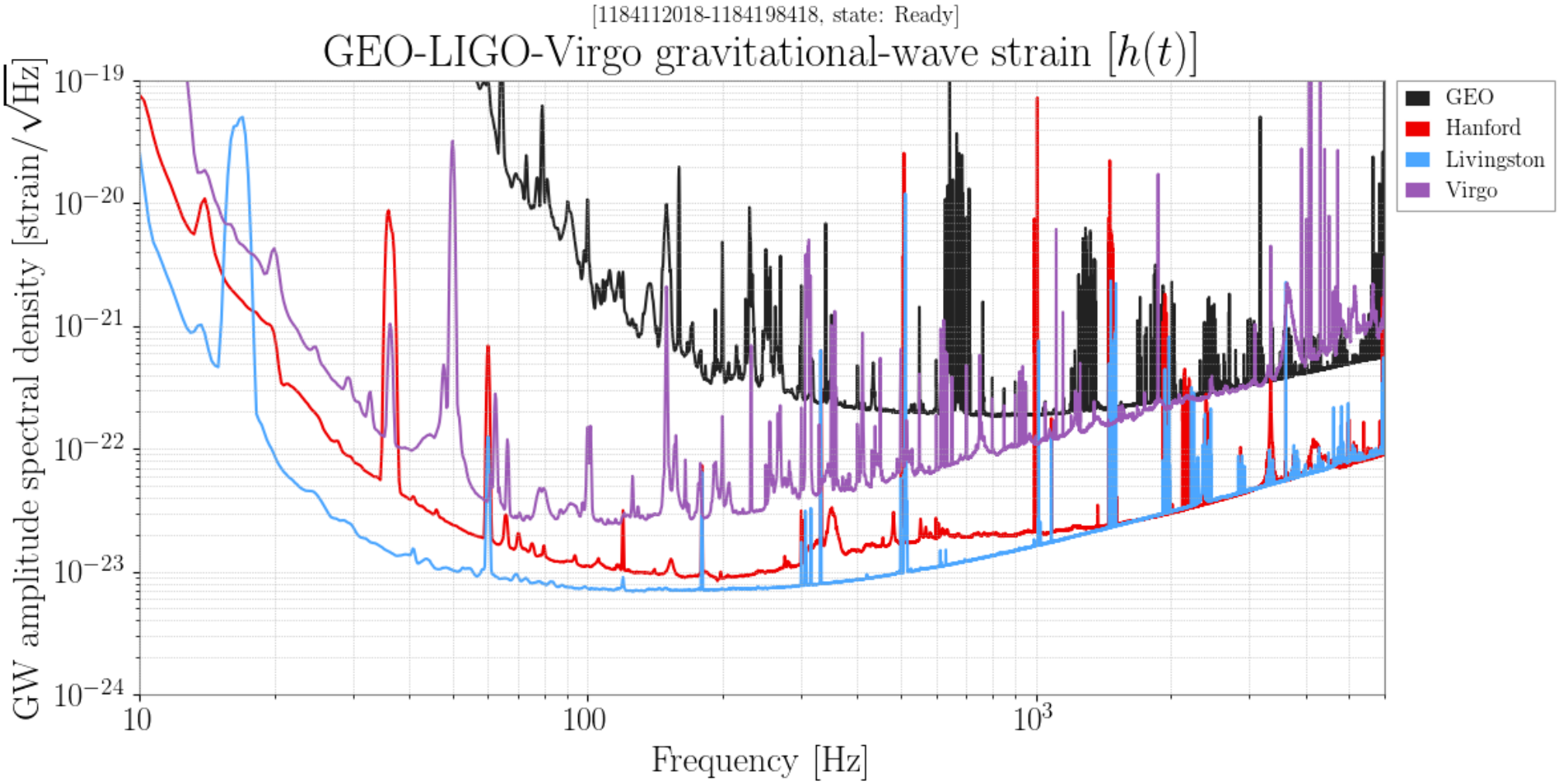
Advanced LIGO: 6 months of commissioning

- Increased laser power at Hanford (22W→30W)
- Reduction of scattered-light noise at Livingston

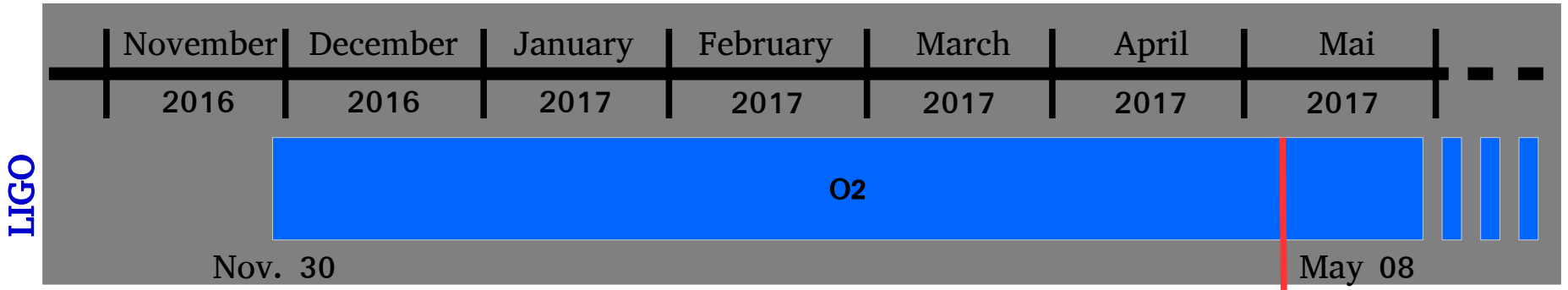
Advanced Virgo upgrades

- New injection system. Input laser power = 14 W
- New mirrors: arm cavity finesse = 450
- Failure of fused silica suspension wires → steel wires
- New suspended detection benches
- March 2017: First lock of the interferometer
- End of July 2017: join O2

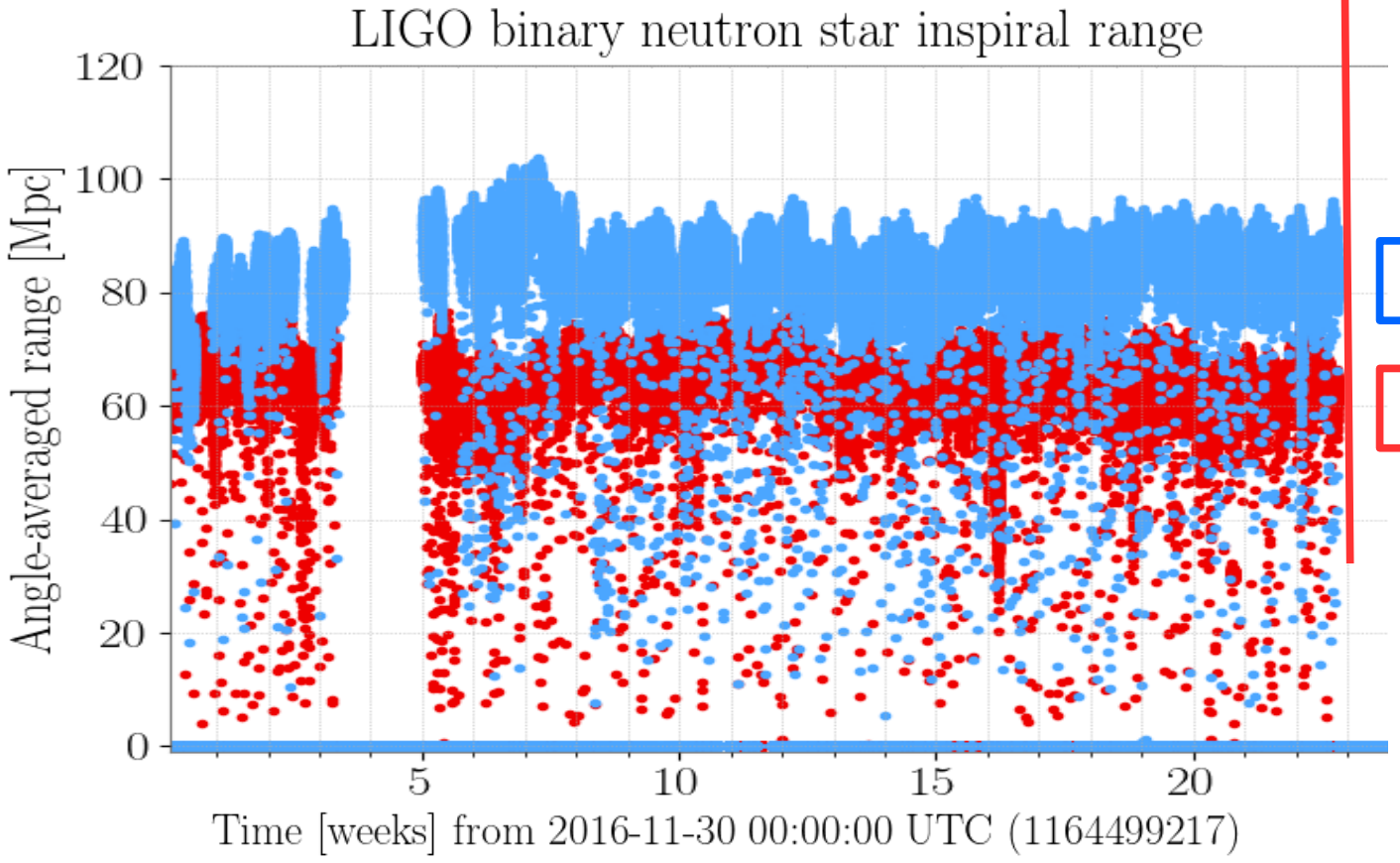



[1184112018-1184198418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain $[h(t)]$
GW amplitude spectral density [strain/$\sqrt{\text{Hz}}$]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
10^3
Frequency [Hz]
GEO
Hanford
Livingston
Virgo

O2 sensitivity (LIGO only)



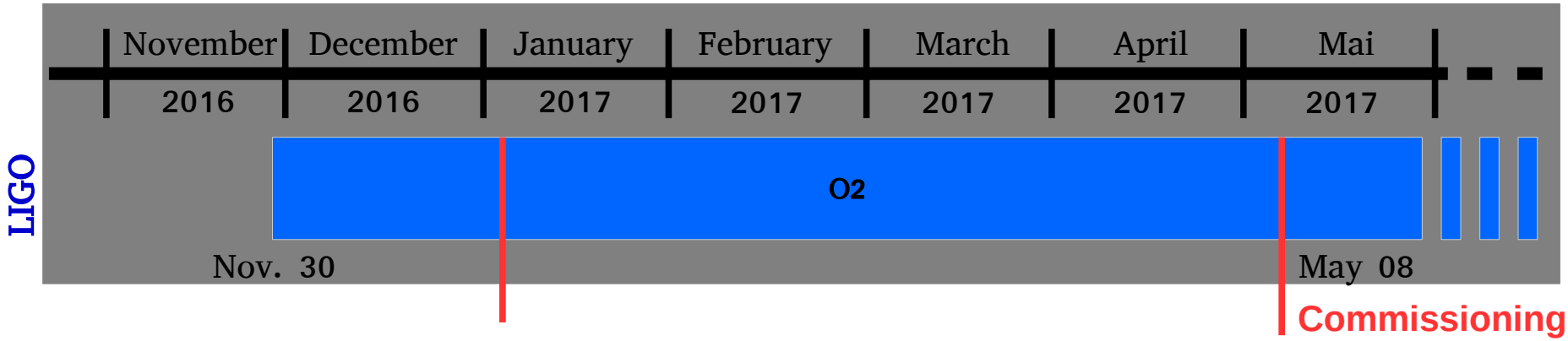
Commissioning break

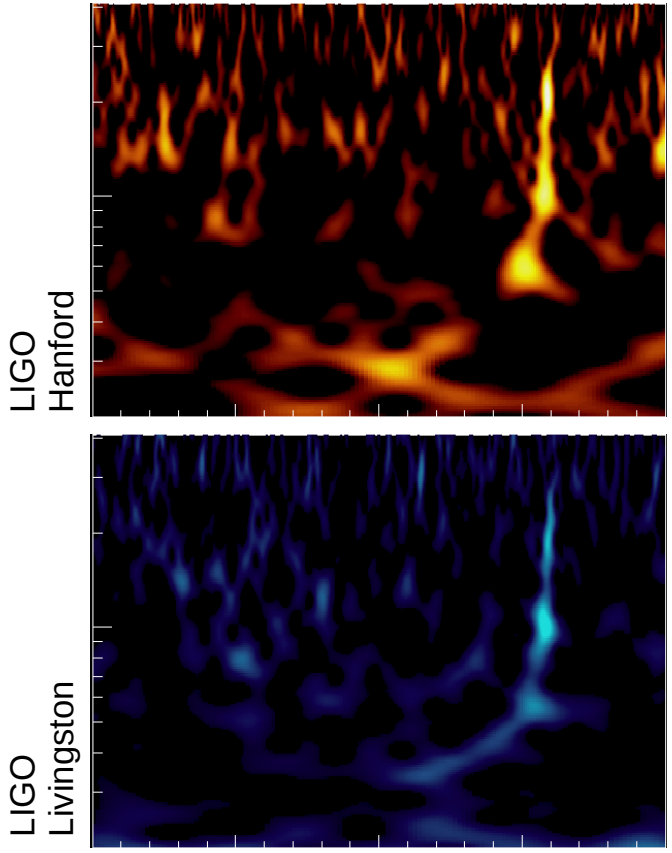


~ 80 Mpc

~ 60 Mpc

O2 detections (LIGO only)

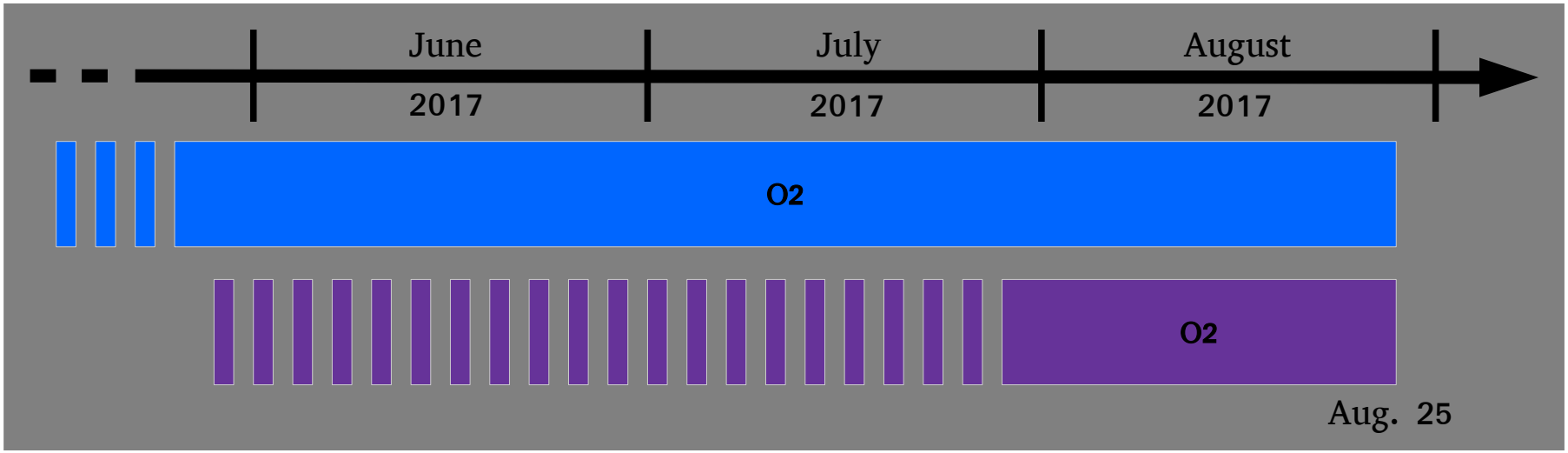


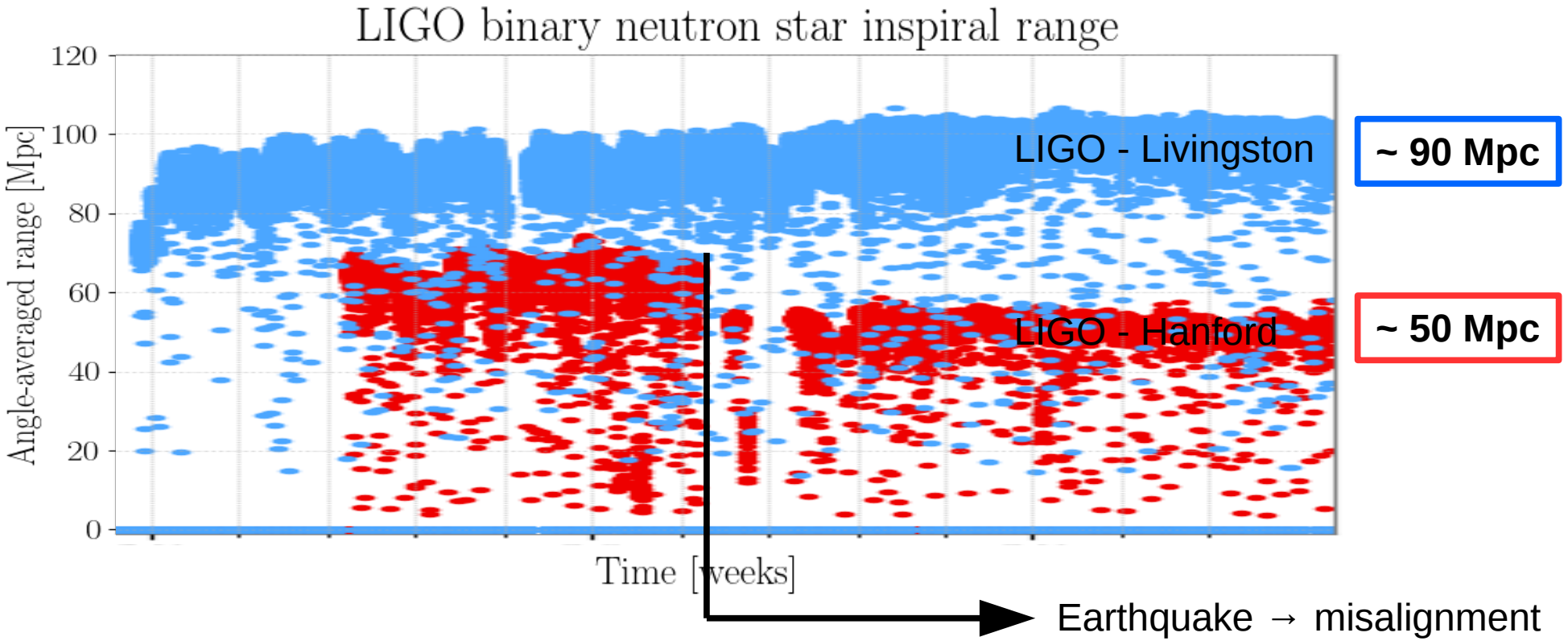


1 BBH event detected by LIGO in January 2017

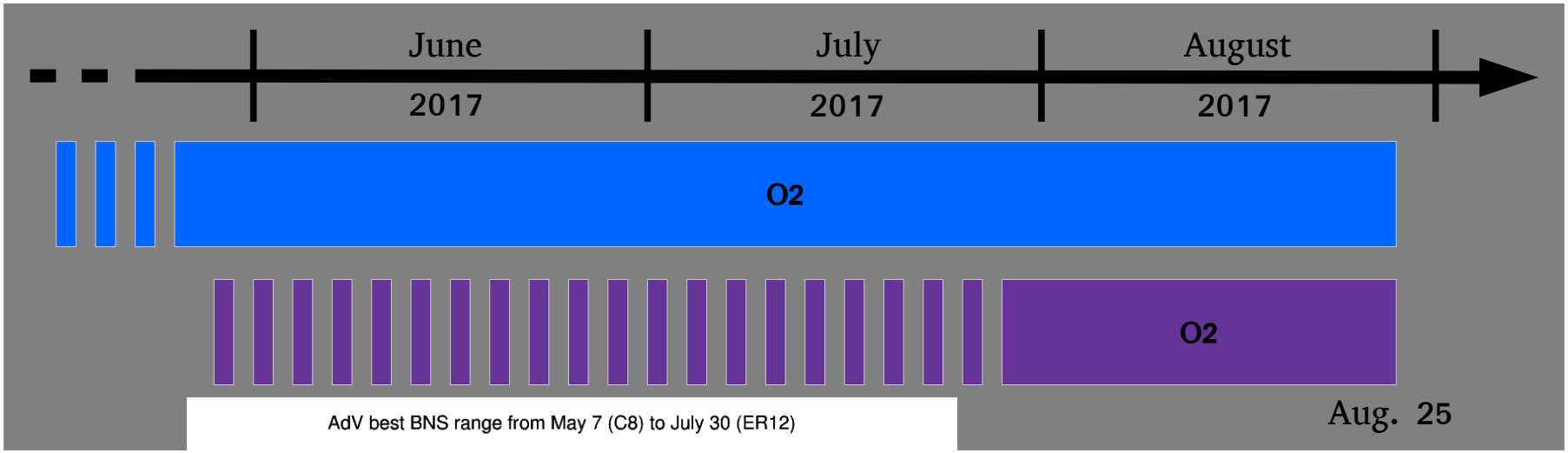
Phys.Rev.Lett. 118 (2017) no.22, 221101

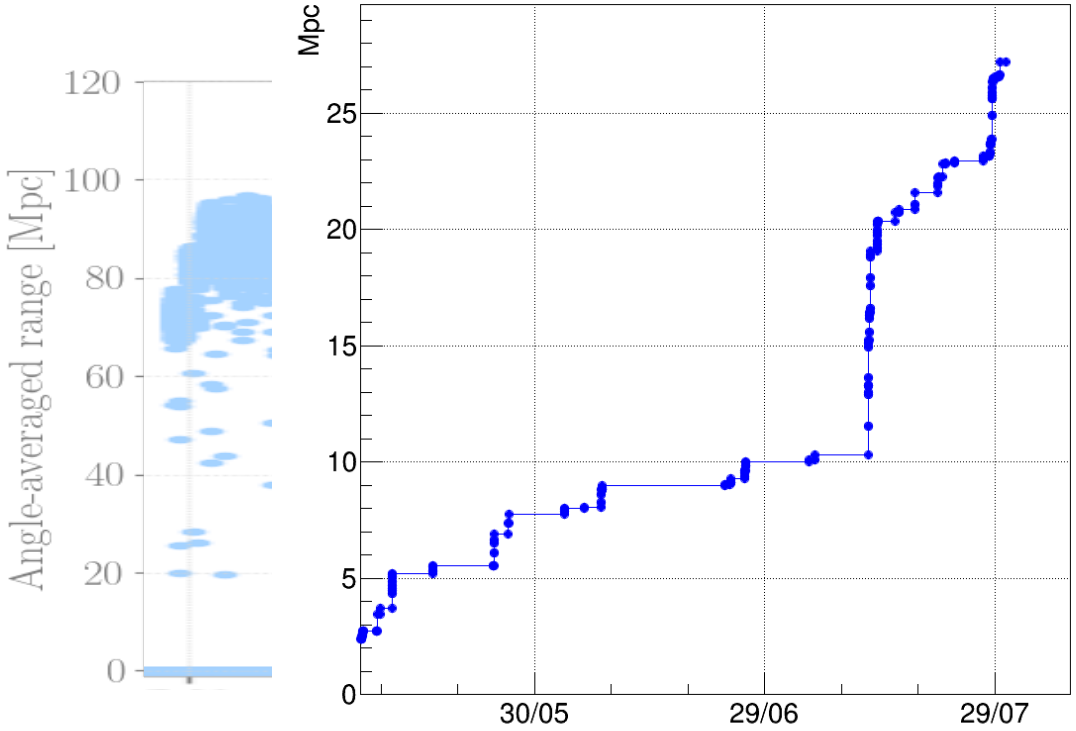
O2 sensitivity (LIGO and Virgo)

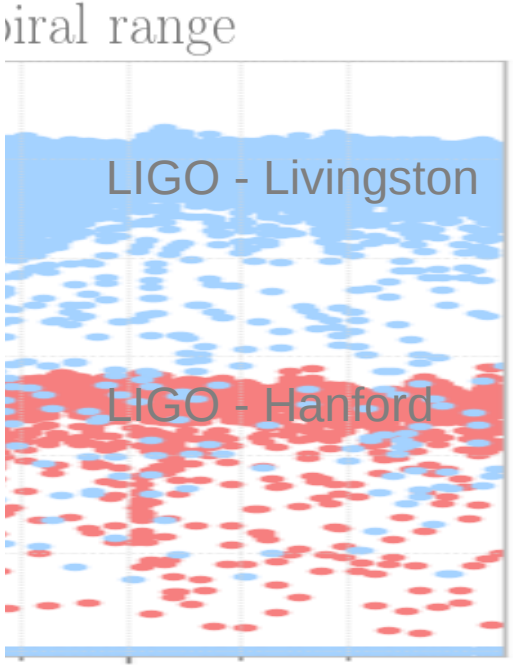




O2 sensitivity (LIGO and Virgo)





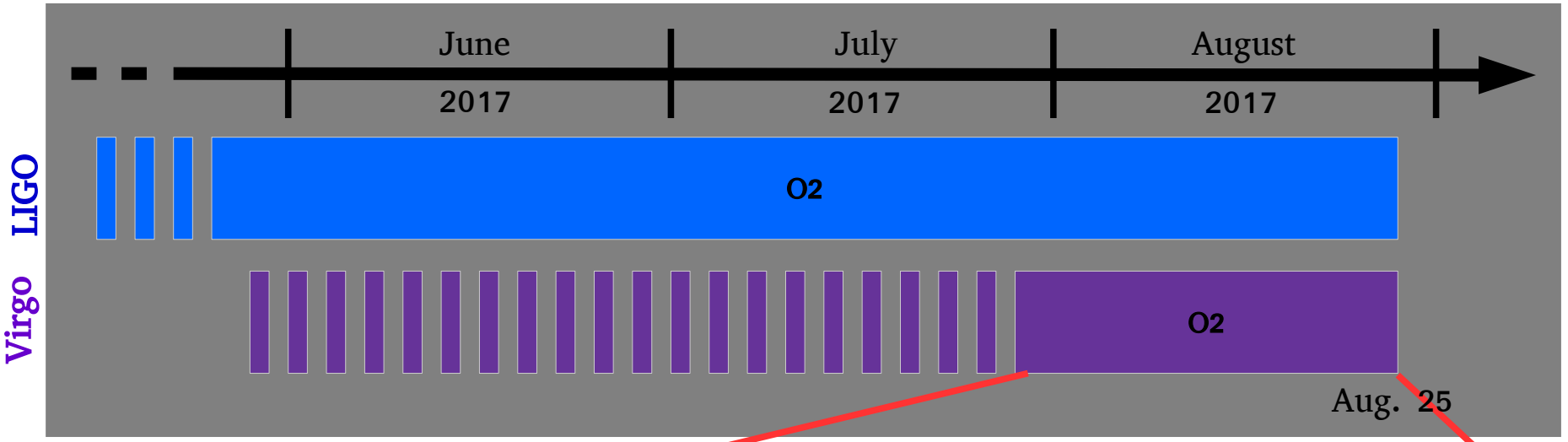


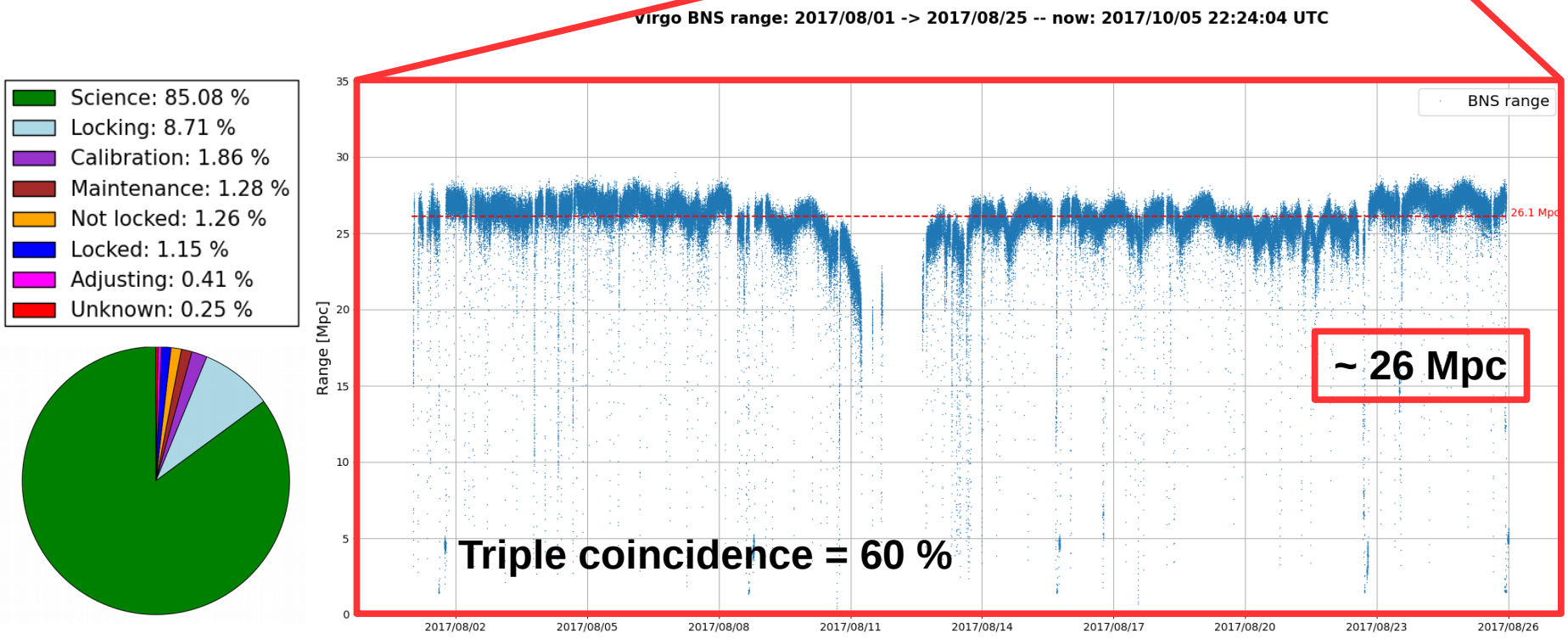
~ 90 Mpc

~ 50 Mpc

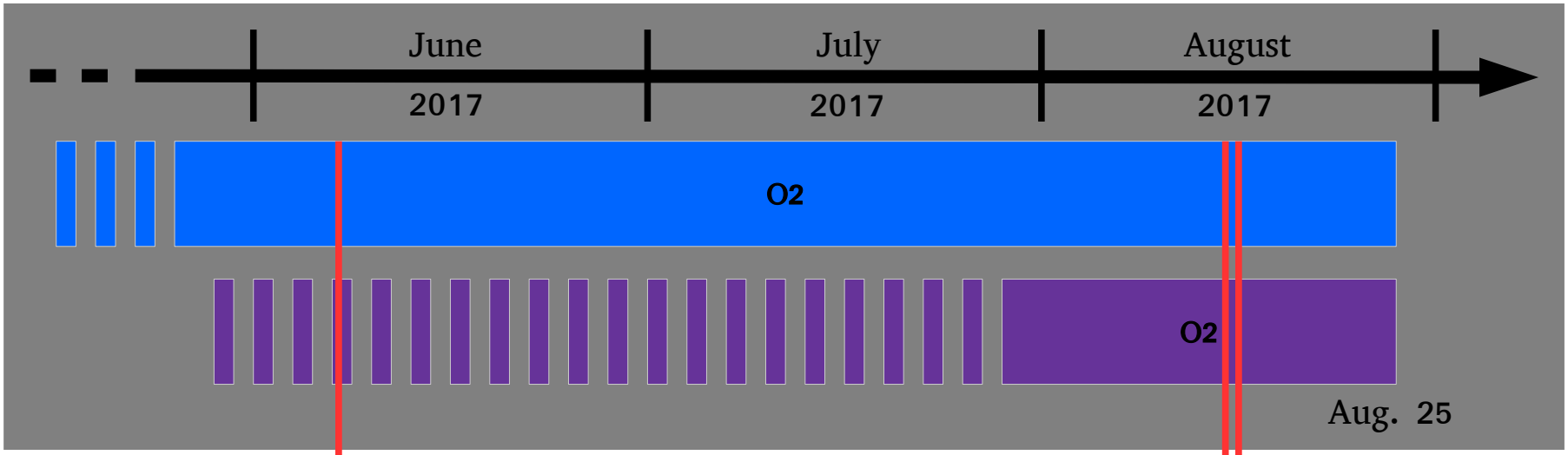
Earthquake → misalignment

O2 sensitivity (LIGO and Virgo)

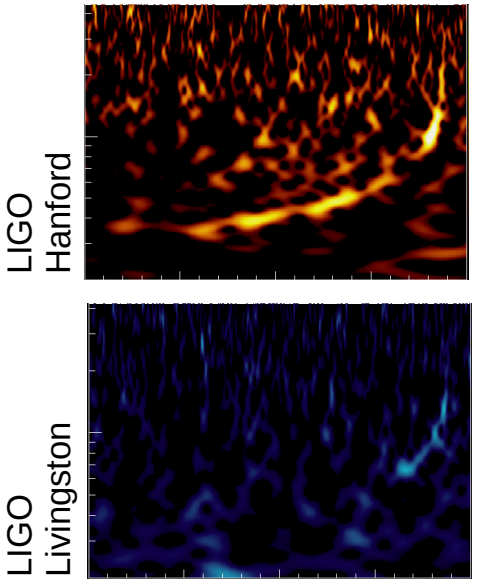




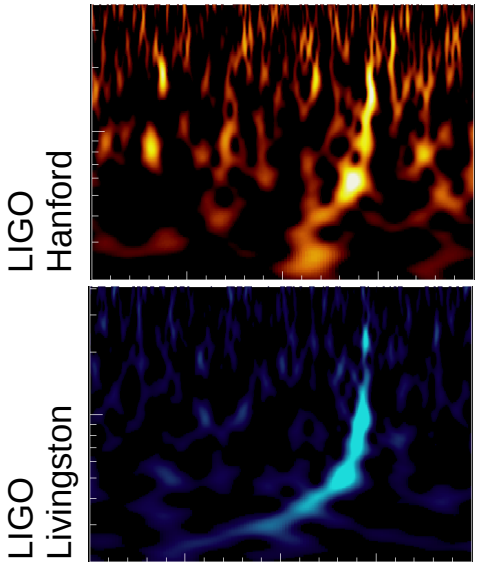
O2 detections (LIGO and Virgo)



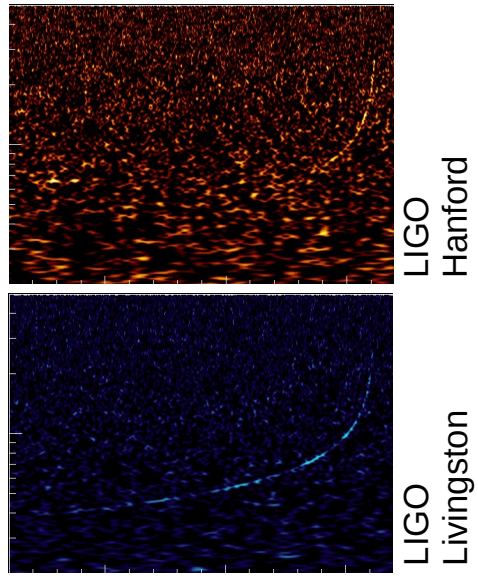
GW170608



GW170814



GW170817



BNS: see Eric Chassande-Mottin's talk

BBH summary

		Total mass (M_{sun})	q=m2/m1 (M_{sun}/M_{sun})	radiated energy (M_{sun})	effective inspiral spin	redshift	SNR
O1	GW150914	$65.3^{+4.1}_{-3.4}$	$\frac{29.1^{+3.7}_{-4.4}}{36.2^{+5.2}_{-3.8}}$	$3.0^{+0.5}_{-0.4}$	$-0.06^{+0.14}_{-0.14}$	$0.09^{+0.03}_{-0.04}$	23.7
O2	GW170814	$55.9^{+3.4}_{-2.7}$	$\frac{25.3^{+2.8}_{-4.2}}{30.5^{+5.7}_{-3.0}}$	$2.7^{+0.4}_{-0.3}$	$0.06^{+0.12}_{-0.12}$	$0.11^{+0.03}_{-0.04}$	15.0
O2	GW170104	$50.7^{+5.9}_{-5.0}$	$\frac{19.4^{+5.3}_{-5.9}}{31.2^{+8.4}_{-6.0}}$	$2.0^{+0.6}_{-0.7}$	$-0.12^{+0.21}_{-0.30}$	$0.176^{+0.078}_{-0.074}$	13.3
O1	GW151226	$21.8^{+5.9}_{-1.7}$	$\frac{7.5^{+2.3}_{-2.3}}{14.2^{+8.3}_{-3.7}}$	$1.0^{+0.1}_{-0.2}$	$0.21^{+0.20}_{-0.10}$	$0.09^{+0.03}_{-0.04}$	13.0
O2	GW170608	19^{+5}_{-1}	$\frac{7^{+2}_{-2}}{12^{+7}_{-2}}$	$0.85^{+0.07}_{-0.17}$	$0.07^{+0.23}_{-0.09}$	$0.07^{+0.03}_{-0.03}$	13.0

Parameter estimation

	Total mass (M_{sun})	q=m2/m1 (M_{sun}/M_{sun})	radiated energy (M_{sun})	effective inspiral spin	redshift	SNR
GW						
GW						
GW						
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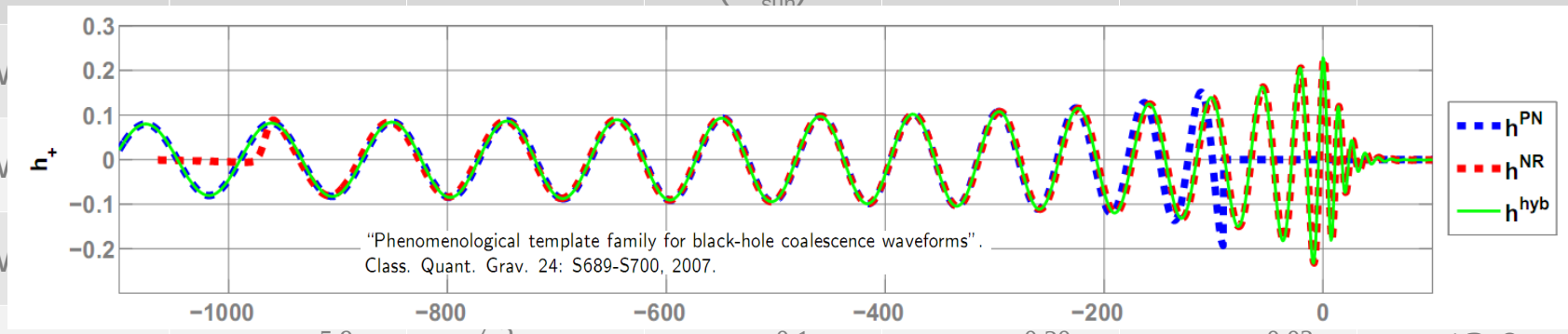

Full analysis of the data surrounding the event → coherent Bayesian analysis
→ only input from searches: time of the event
→ fully explore the parameter space
→ include calibration uncertainty

8 intrinsic parameters (masses and spins)
9 extrinsic parameters (distance, position, orientation, coalescence time and phase)
Orbital ellipticity is neglected

Dimensionless spin: $a = \frac{c\,|\vec{S}|}{Gm^2} \leq 1$

Frequency is redshifted → masses must be rescaled by a factor (1+z)

Parameter estimation

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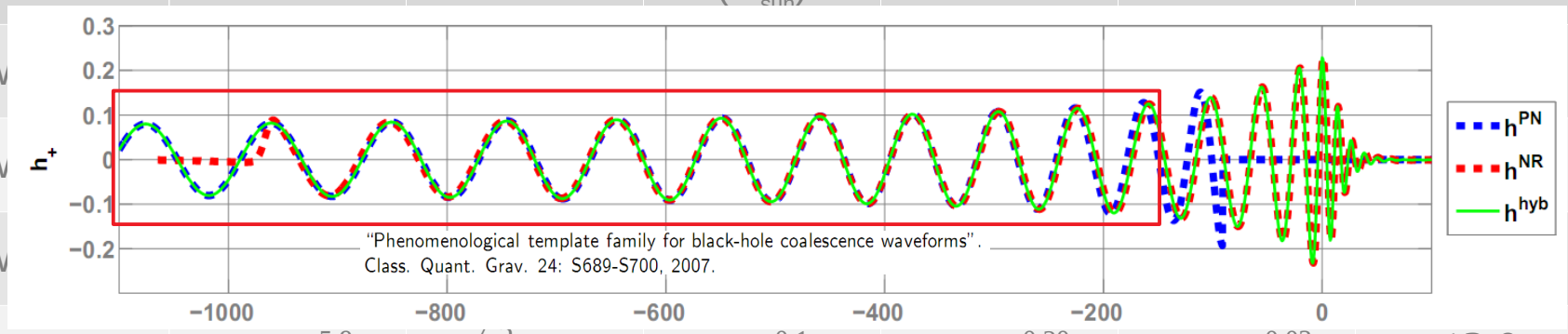

Inspiral phase: PN perturbative expansion (v/c)

Leading order → phase evolution driven by the chirp mass (tight constraints)
Next order → m2/m1 and spins // **L**
Next orders → full spins

Late inspiral – merger – ringdown: numerical relativity waveforms
Late inspiral → total mass (+chirp mass + m1/m2) → individual masses
Ringdown → final BH mass and spin

Amplitude → distance

Parameter estimation

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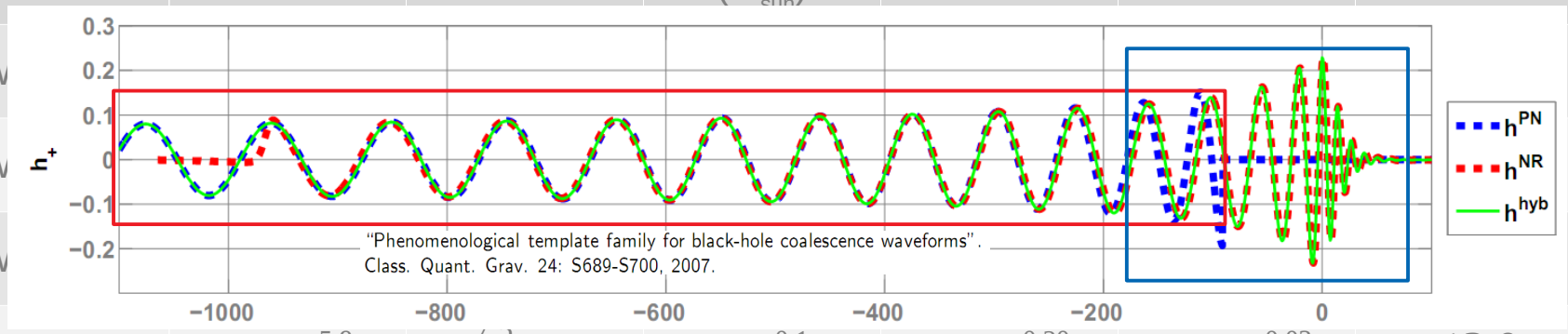

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Late inspiral → total mass (+chirp mass + m1/m²) → individual masses
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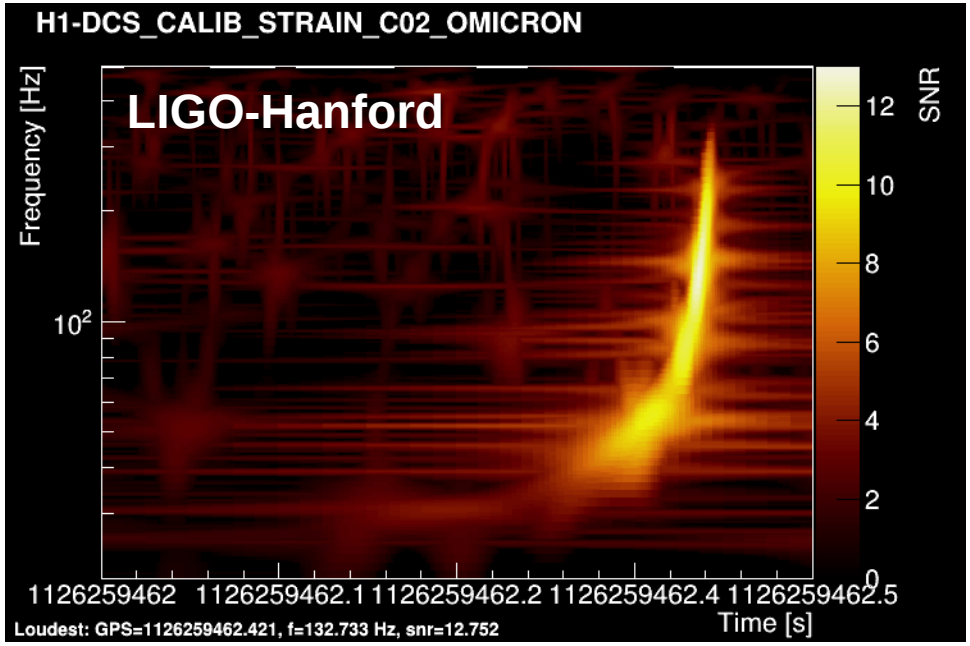

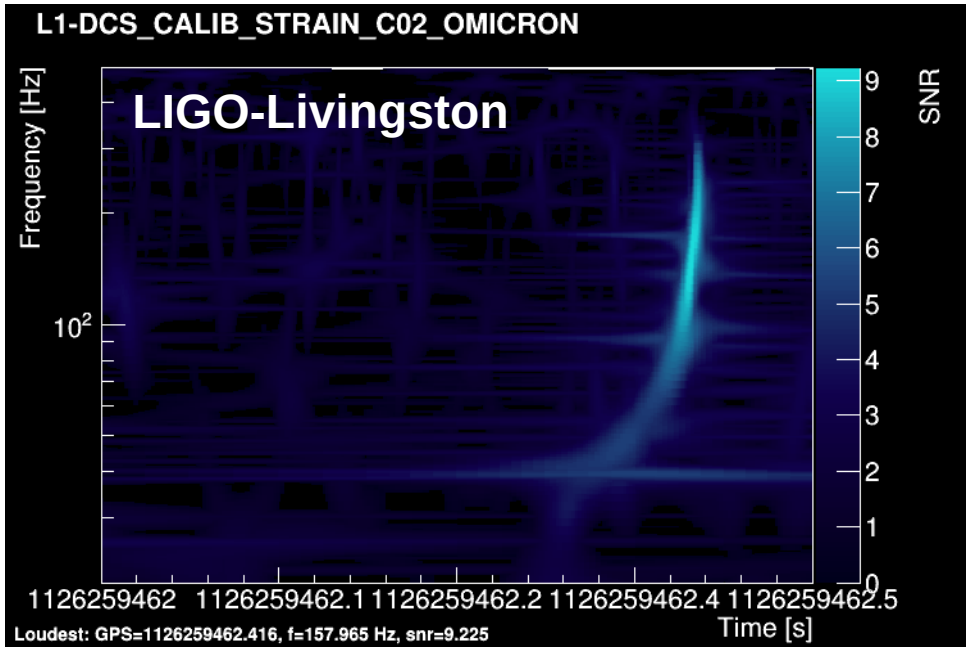

GW150914 : Most powerful and heaviest BBH event ever detected

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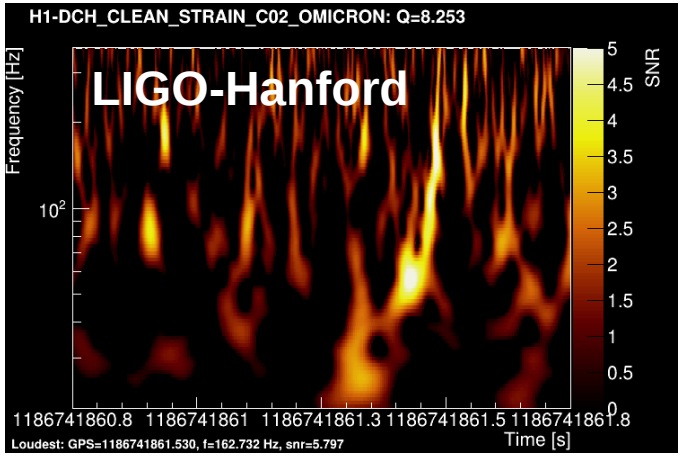

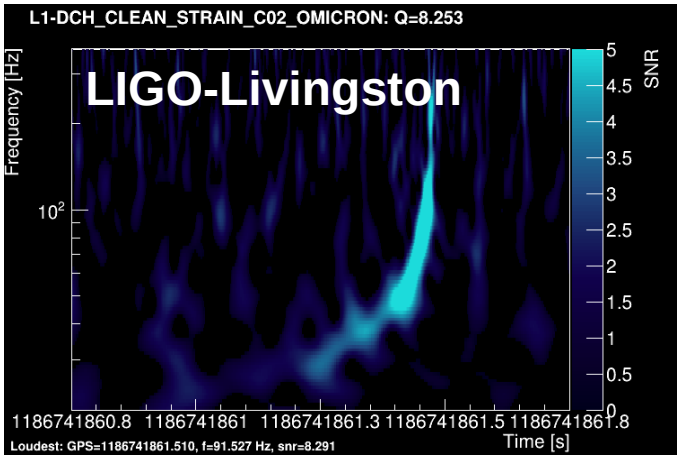

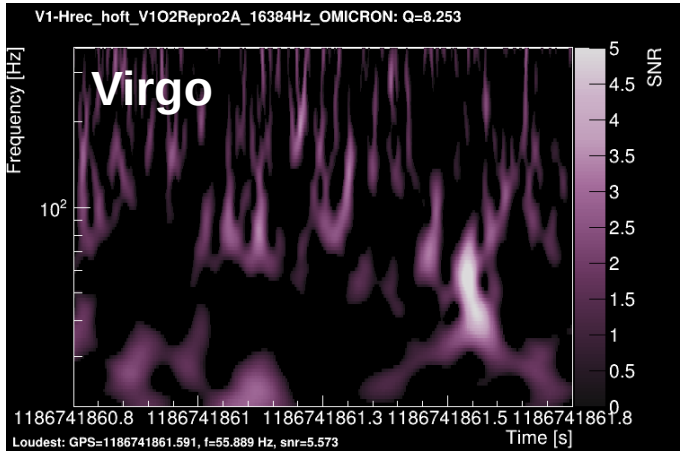

GW170814 : First BBH event detected in Virgo data

Source localization

Phys.Rev.Lett. 119 (2017) no.14, 141101

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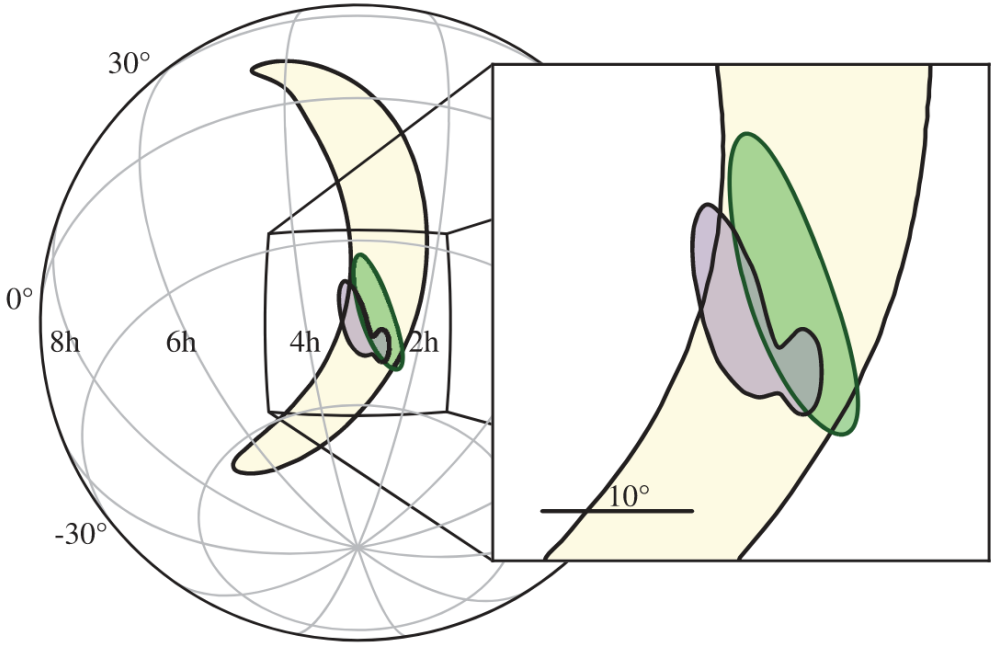
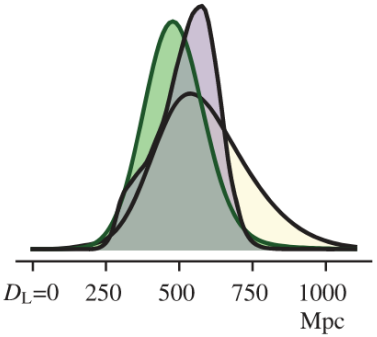


3 detectors → triangulation using time differences, phase differences and amplitude ratios



~1000 deg² (LIGO)

~60 deg² (LIGO+Virgo)

Luminosity distance = 540^{+130}_{-210} Mpc

	Total mass (M_{sun})	q=m2/m1 (M_{sun}/M_{sun})	radiated energy (M_{sun})	effective inspiral spin	redshift	SNR
GW150914	$65.3^{+4.1}_{-3.4}$	$\frac{29.1^{+3.7}_{-4.4}}{36.2^{+5.2}_{-3.8}}$	$3.0^{+0.5}_{-0.4}$	$-0.06^{+0.14}_{-0.14}$	$0.09^{+0.03}_{-0.04}$	23.7
GW170814	$55.9^{+3.4}_{-2.7}$	$\frac{25.3^{+2.8}_{-4.2}}{30.5^{+5.7}_{-3.0}}$	$2.7^{+0.4}_{-0.3}$	$0.06^{+0.12}_{-0.12}$	$0.11^{+0.03}_{-0.04}$	15.0
GW170104	$50.7^{+5.9}_{-5.0}$	$\frac{19.4^{+5.3}_{-5.9}}{31.2^{+8.4}_{-6.0}}$	$2.0^{+0.6}_{-0.7}$	$-0.12^{+0.21}_{-0.30}$	$0.176^{+0.078}_{-0.074}$	13.3
GW151226	$21.8^{+5.9}_{-1.7}$	$\frac{7.5^{+2.3}_{-2.3}}{14.2^{+8.3}_{-3.7}}$	$1.0^{+0.1}_{-0.2}$	$0.21^{+0.20}_{-0.10}$	$0.09^{+0.03}_{-0.04}$	13.0
GW170608	19^{+5}_{-1}	$\frac{7^{+2}_{-2}}{12^{+7}_{-2}}$	$0.85^{+0.07}_{-0.17}$	$0.07^{+0.23}_{-0.09}$	$0.07^{+0.03}_{-0.03}$	13.0

3 detectors → gravitational-wave polarizations

GR: 2 tensor degrees of freedom

Generic metric theories: combination of **scalar**, **vector** and **tensor** polarizations

→ Project polarization onto the detector network
→ test purely tensor, purely vector and purely scalar polarizations

→ **Bayes factor for purely tensor polarization: 200 (/vector) 1000 (/scalar)**

See also arXiv:1802.10194 (stochastic background search)

	Total mass (M_{sun})	q=m2/m1 (M_{sun}/M_{sun})	radiated energy (M_{sun})	effective inspiral spin	redshift	SNR
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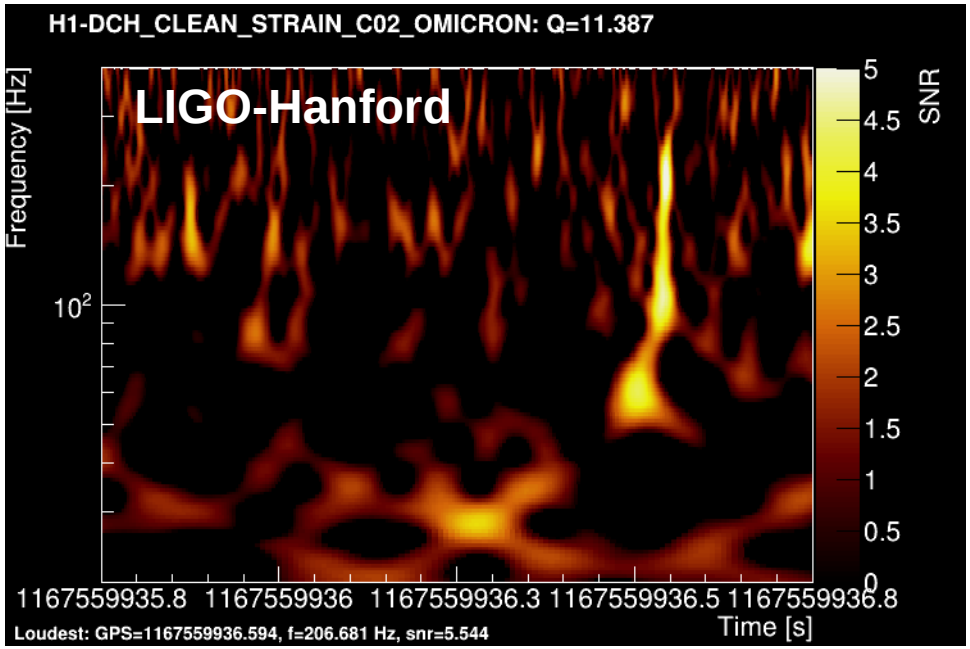

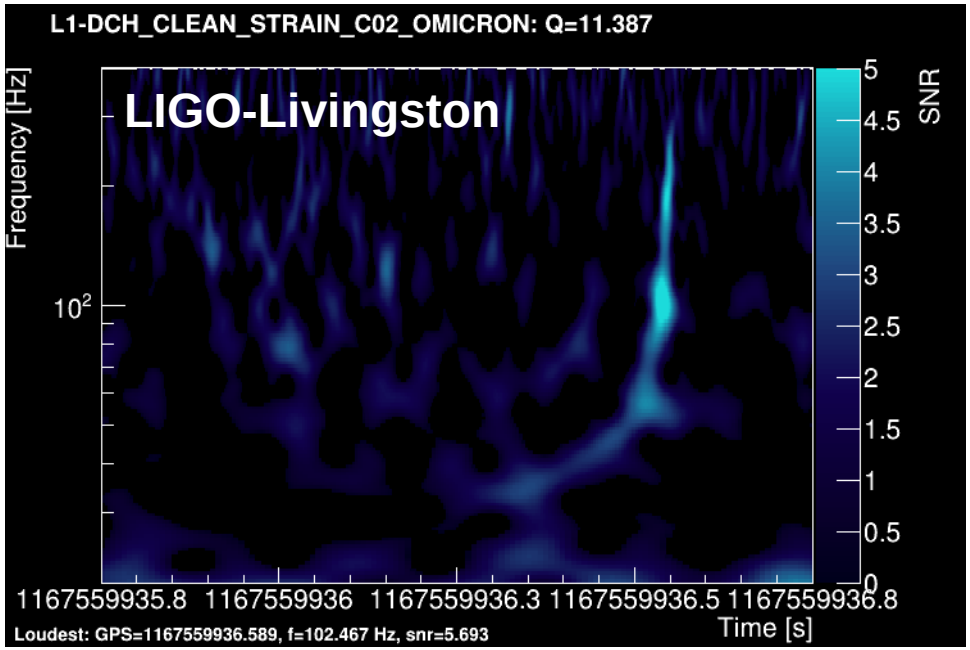

Phys.Rev.Lett. 118 (2017) no.22, 221101

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Testing General Relativity

Modified dispersion relation (ex: LIV theories): $E^2 = p^2 c^2 + A^\alpha c^\alpha$

massive graviton: $\alpha = 0$
multifractal theories: $\alpha = 2.5$
doubly special relativity: $\alpha = 3$
extra-dimensions: $\alpha = 4$

→ modified propagation velocity: $\frac{v_g}{c} = 1 + (\alpha - 1)\frac{AE^{\alpha-2}}{2}$

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Testing General Relativity

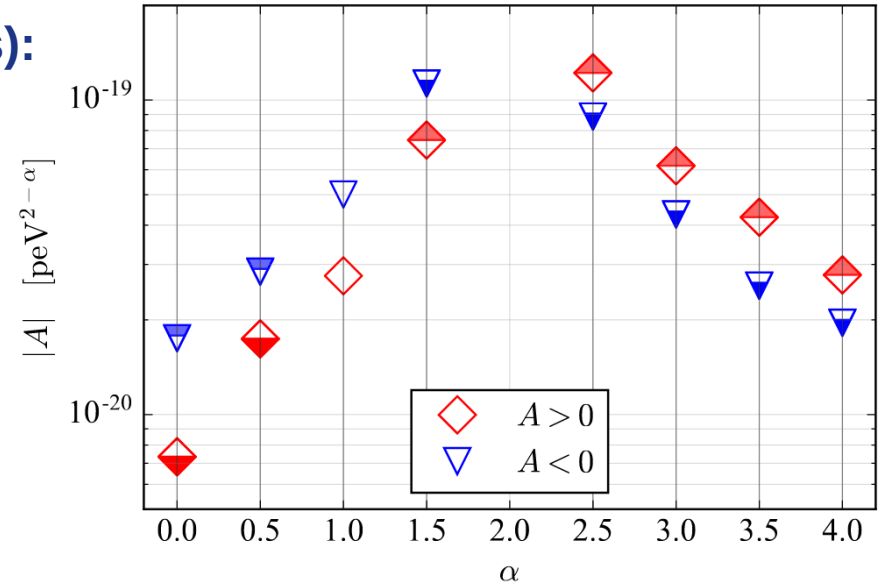
Modified dispersion relation (ex: LIV theories):

→ extra term in the evolution of the gravitational-wave phase

→ **Upper limits on A**

$\alpha = 0$ $A > 0$: limit on the graviton mass:

$$m_g < 7.7 \times 10^{-23} eV/c^2$$



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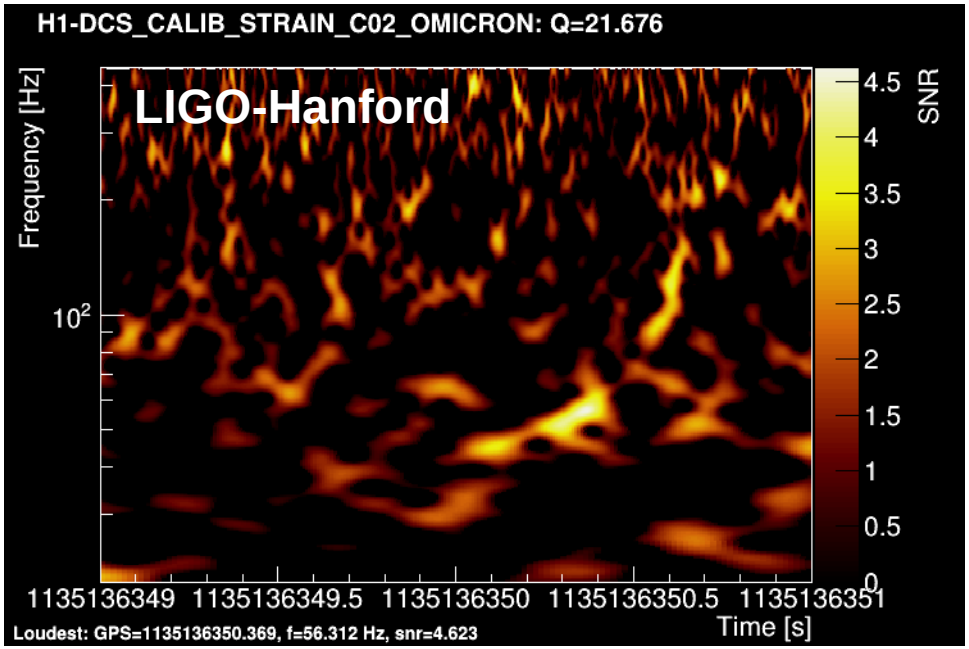

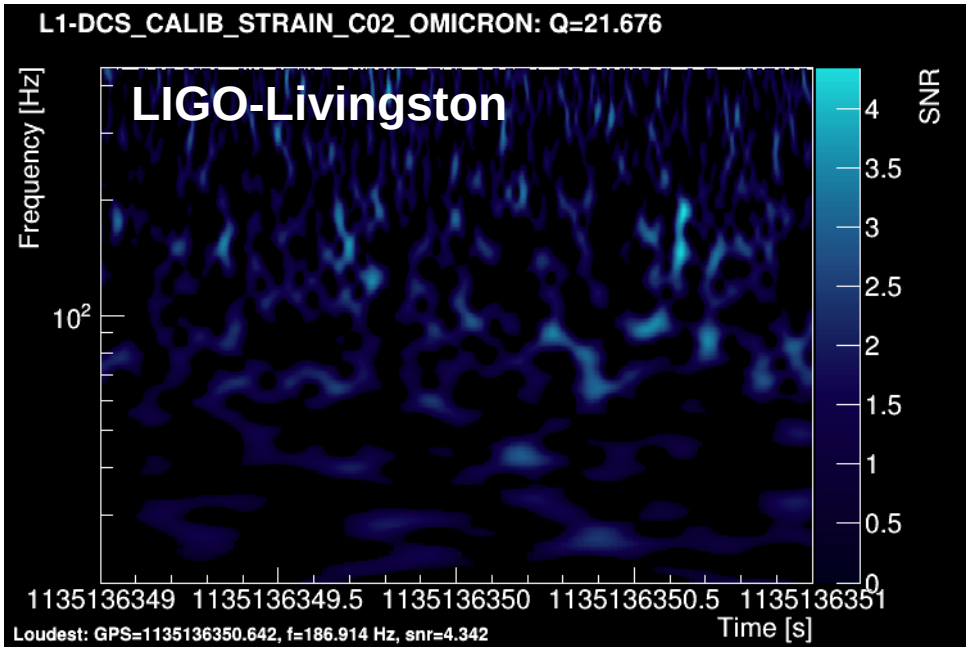

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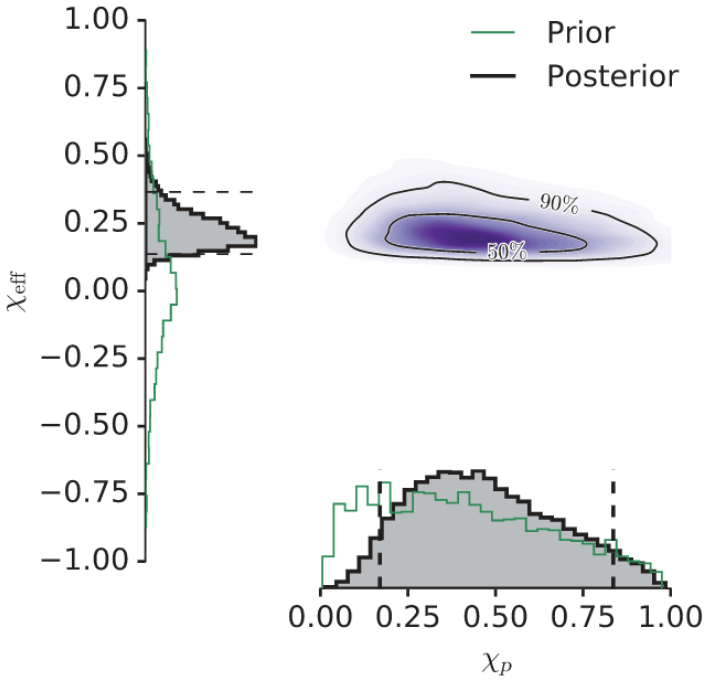
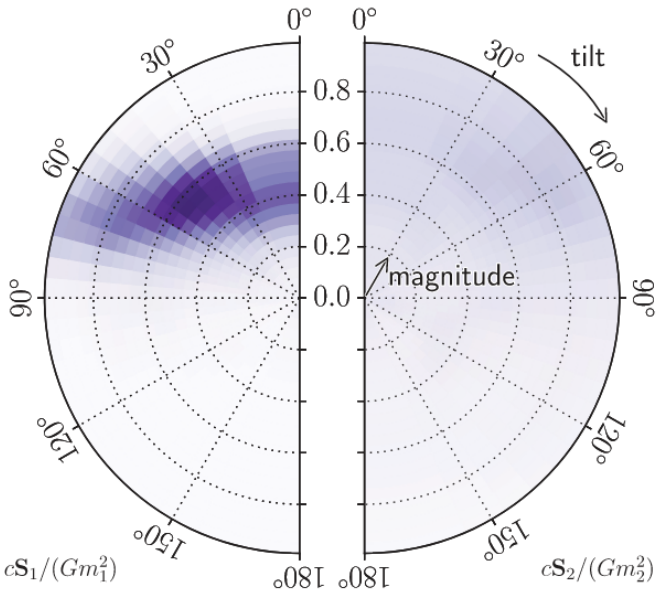
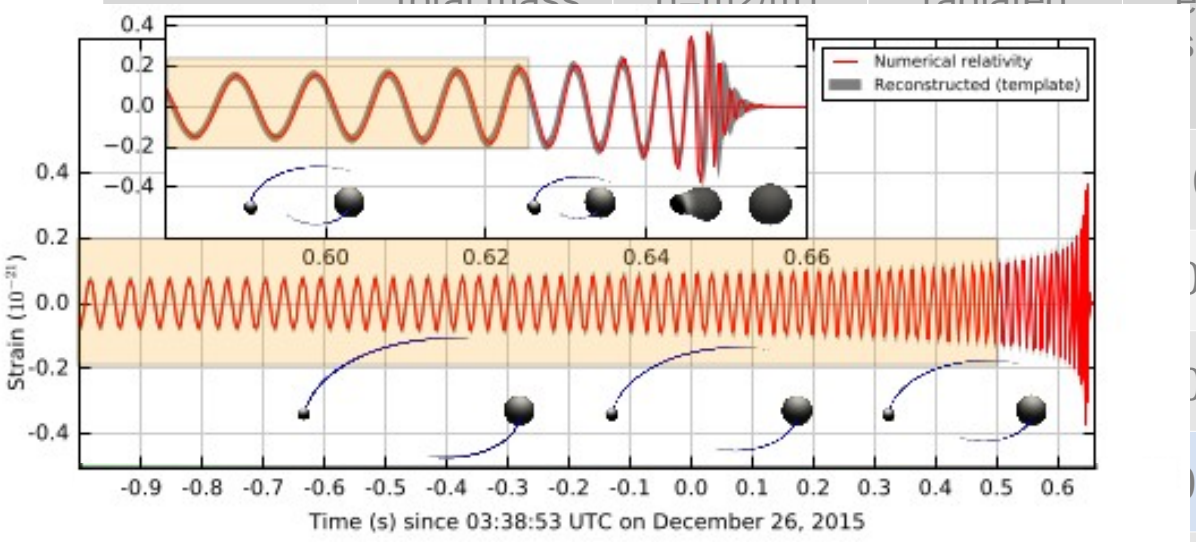


One of the initial black hole has spin





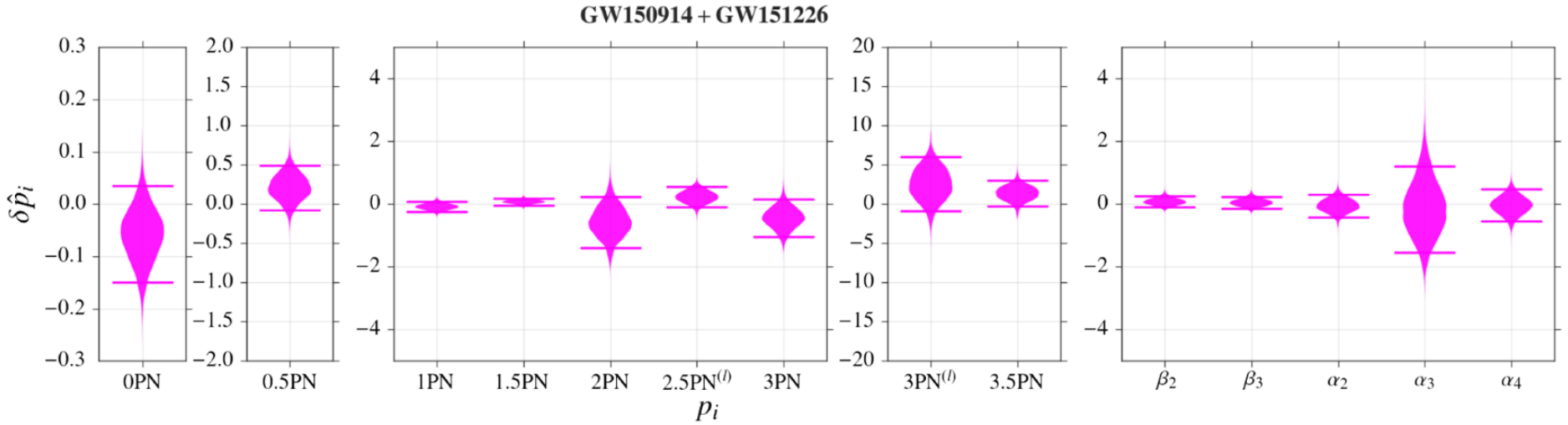
	Total mass	q=m2/m1	radiated	effective spiral spin	redshift	SNR
				$0.06^{+0.14}_{-0.14}$	$0.09^{+0.03}_{-0.04}$	23.7
				$0.06^{+0.12}_{-0.12}$	$0.11^{+0.03}_{-0.04}$	15.0
				$0.12^{+0.21}_{-0.30}$	$0.176^{+0.078}_{-0.074}$	13.3
				$0.21^{+0.}_{-0}$		
GW170608	19^{+5}_{-1}	$\frac{7^{+}_{-2}}{12^{+7}_{-2}}$	$0.85^{+0.07}_{-0.17}$	0.07^{+0}_{-0}		

Testing General Relativity

- Waveform: $h(f,\theta) = A(f;\theta)e^{i\phi(f;\theta)}$,
- $\phi = \phi_o + \sum \phi_k(\theta)(\pi M f)^{(k-5)}$
  $\theta = \{m_1, m_2, \mathbf{s_1}, \mathbf{s_2}\}$
- $\phi_k = \phi_k^{GR}(1 + \delta\phi_k)$

[LVC PRL(2016), PRX(2016), PRL(2017)]

Post-Newtonian coefficients:



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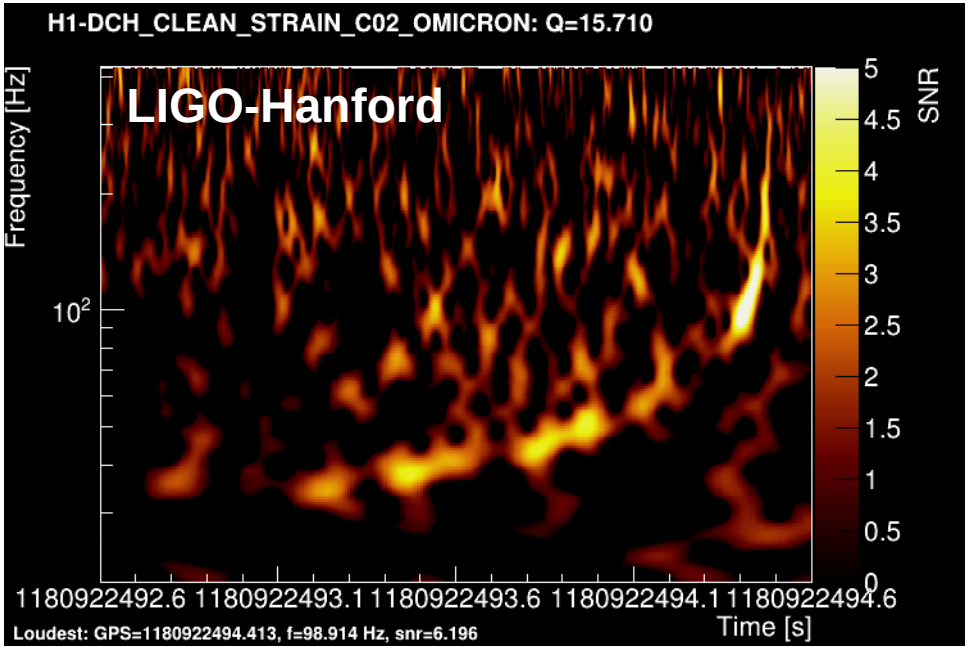

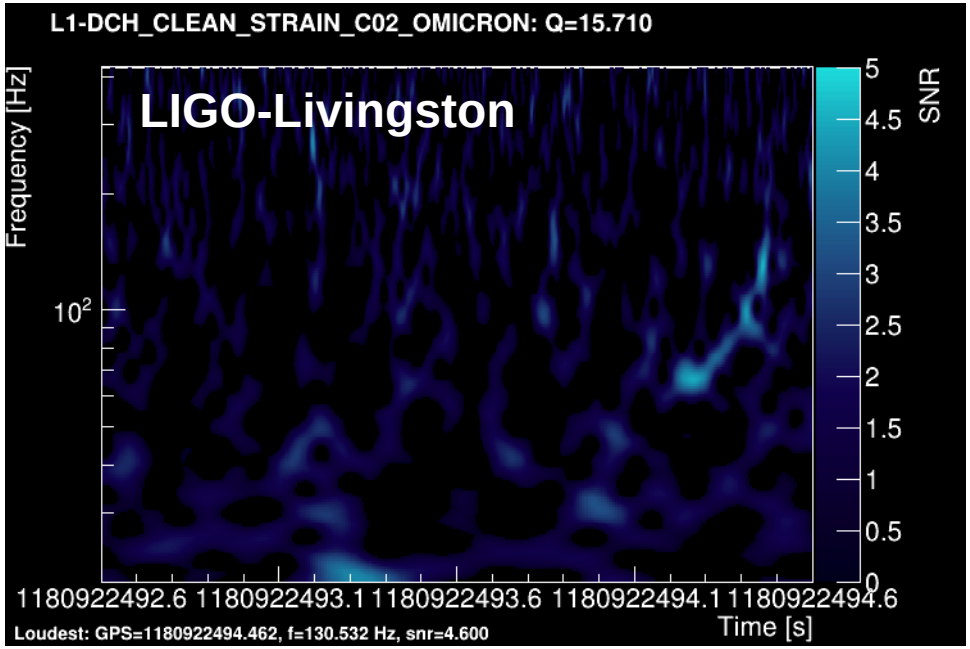

→ low mass BHs, compatible with the known population of low-mass X-ray binaries

Online searches

Several GW searches are performed online:
– **gstLAL**: gstreamer-based search for CBC signals
– **pyCBC**: CBC search
– **MBTA**: CBC search running at Virgo
– **coherent wave-burst**: coherent search for unmodeled transient signals
– **oLIB**: coincident search for unmodeled transient signals

Latency:
+20s → local data collection and *h(t)* reconstruction
+1s → data transfer to Caltech
+1s → data distribution to computing centers where analysis pipelines run
+30s → data analysis
+1s → submission to the trigger database (*GraceDB*)

→ total ~ 1min to identify gravitational-wave events

+ ~1 h discussion before sending the alert

GraceDB — Gravitational Wave Candidate Event Database

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Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	Links	UTC Submitted
G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Coinc Tables

End Time (GPS)	1135136350.6478 s
Total Mass	26.3501 $M_\odot$
Chirp Mass	9.5548 $M_\odot$
SNR	11.7103
False Alarm Probability	1.120e-04
Log Likelihood Ratio	22.5996

Single Inspiral Tables

IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_\odot$	19.924686 $M_\odot$
Mass 2	6.4254546 $M_\odot$	6.4254546 $M_\odot$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	2015-12-26 03:38:53 UTC	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

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Basic Info

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G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Low-latency detection

Coinc Tables

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IFO	L1	H1
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G211115		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
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Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_\odot$	19.924686 $M_\odot$
Mass 2	6.4254546 $M_\odot$	6.4254546 $M_\odot$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	2015-12-26 03:38:53 UTC	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

Multiple triggers

Search for unmodeled and short GW signals

SOURCES:

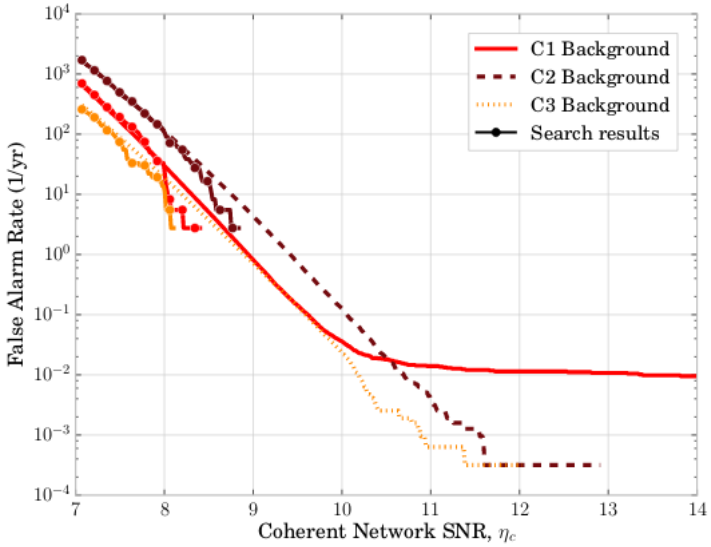
– CBCs

– core-collapse SN

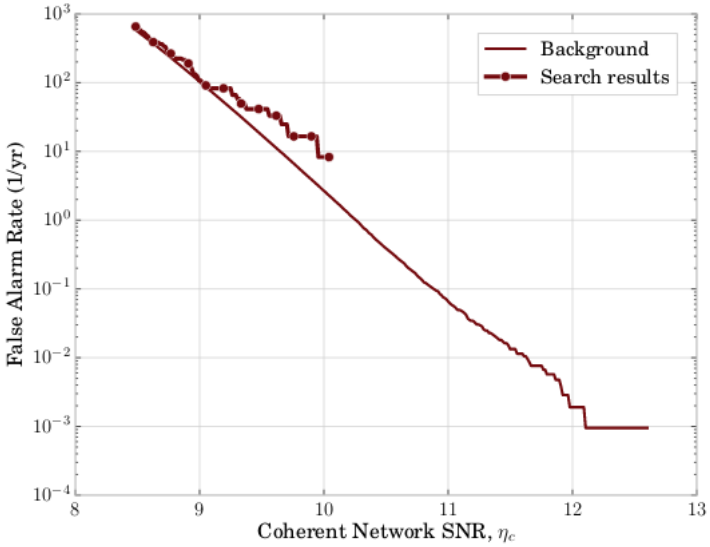
– NSs collapsing to BHs

– Pulsar glitches

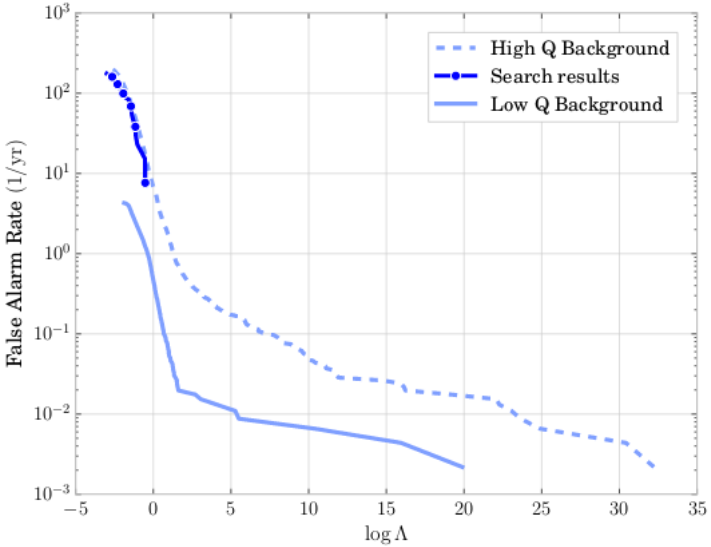
– cosmic strings



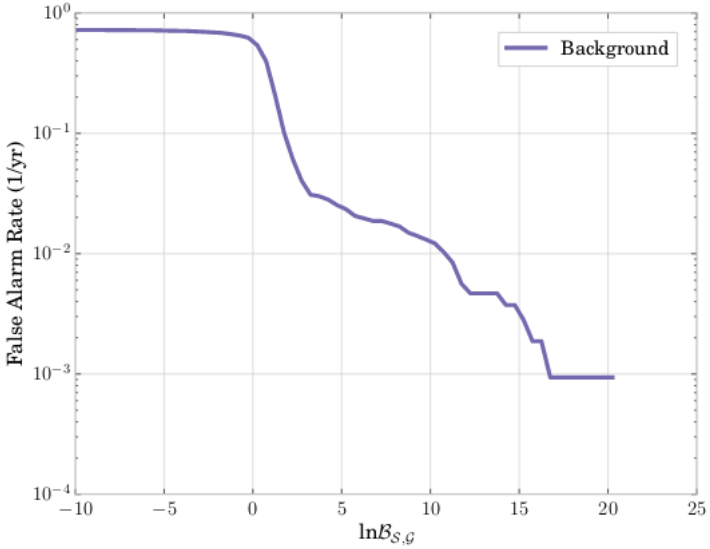
(a) **cWB** 32-1024 Hz search classes: $C1$ (red), $C2$ (brown), $C3$ (yellow).



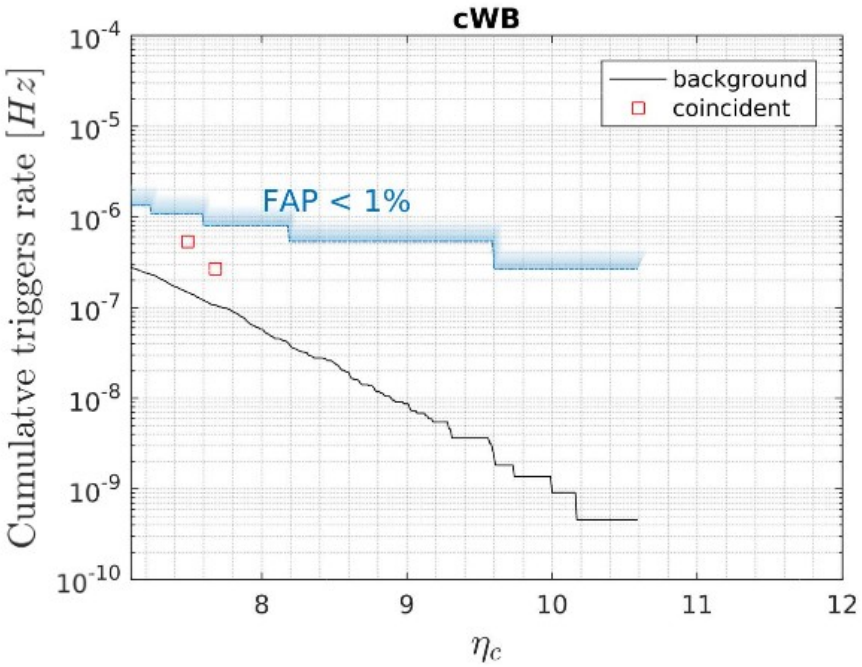
(b) **cWB** 1024-4096 Hz search class.

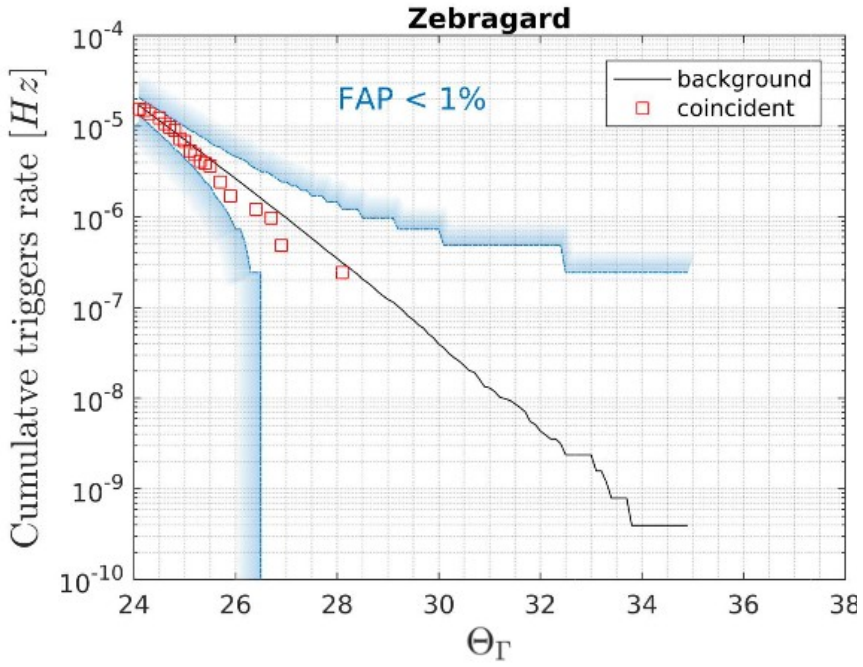


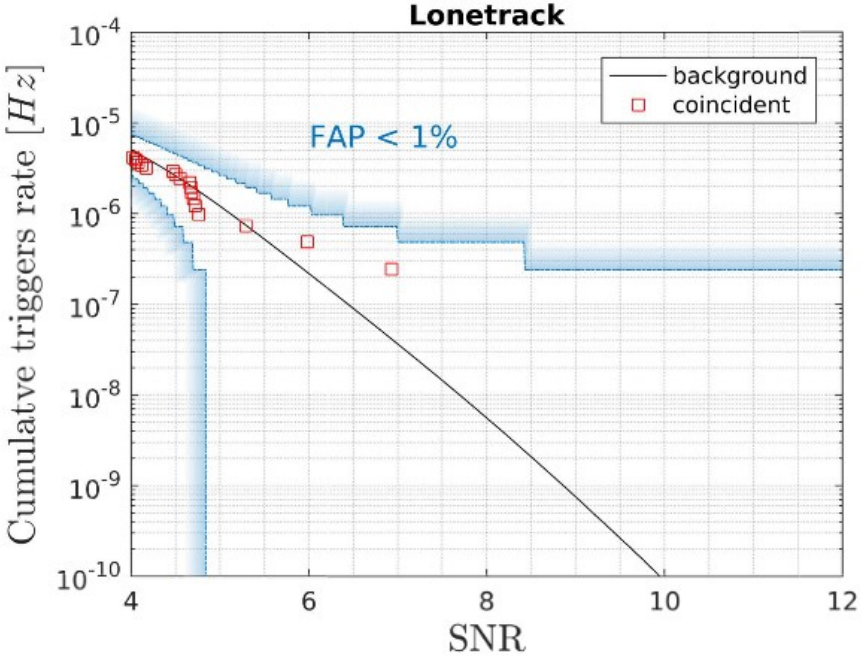
(c) **oLIB** 48-1024 Hz low-Q (dashed) and high-Q (solid) search classes.

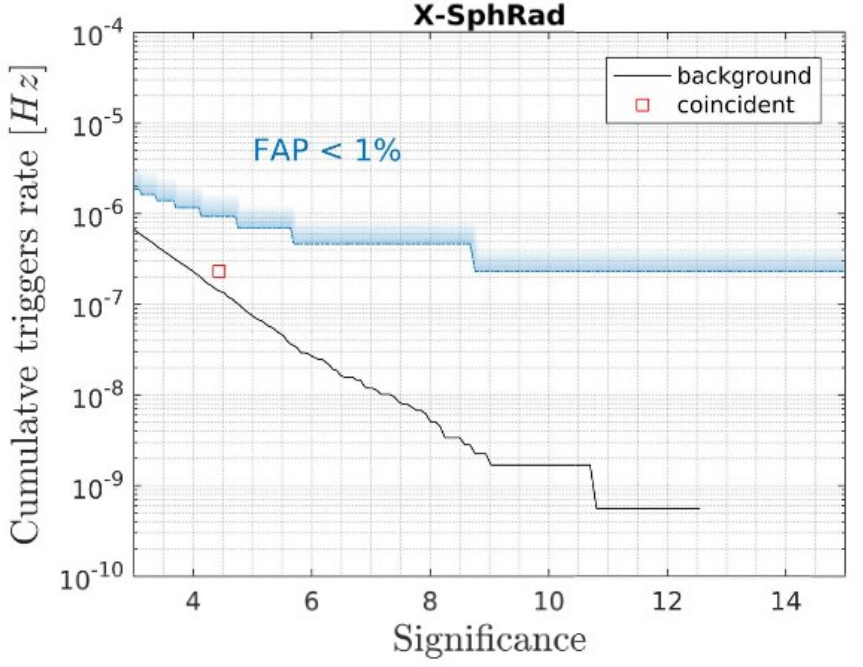


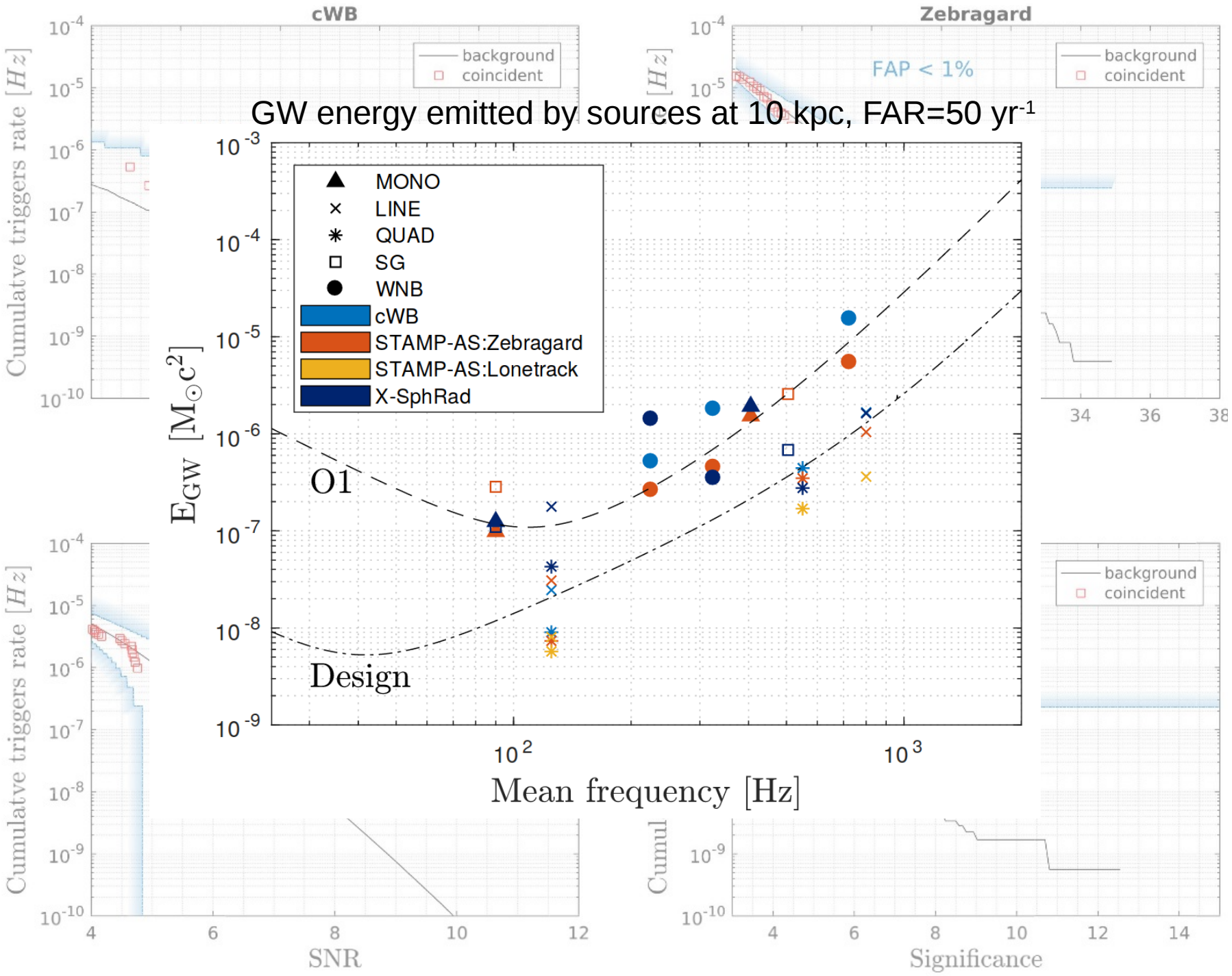
(d) **BayesWave** followup to cWB 32-1024 Hz search class.


cWB
background
coincident
FAP < 1%
Cumulatve triggers rate [Hz]
η_c

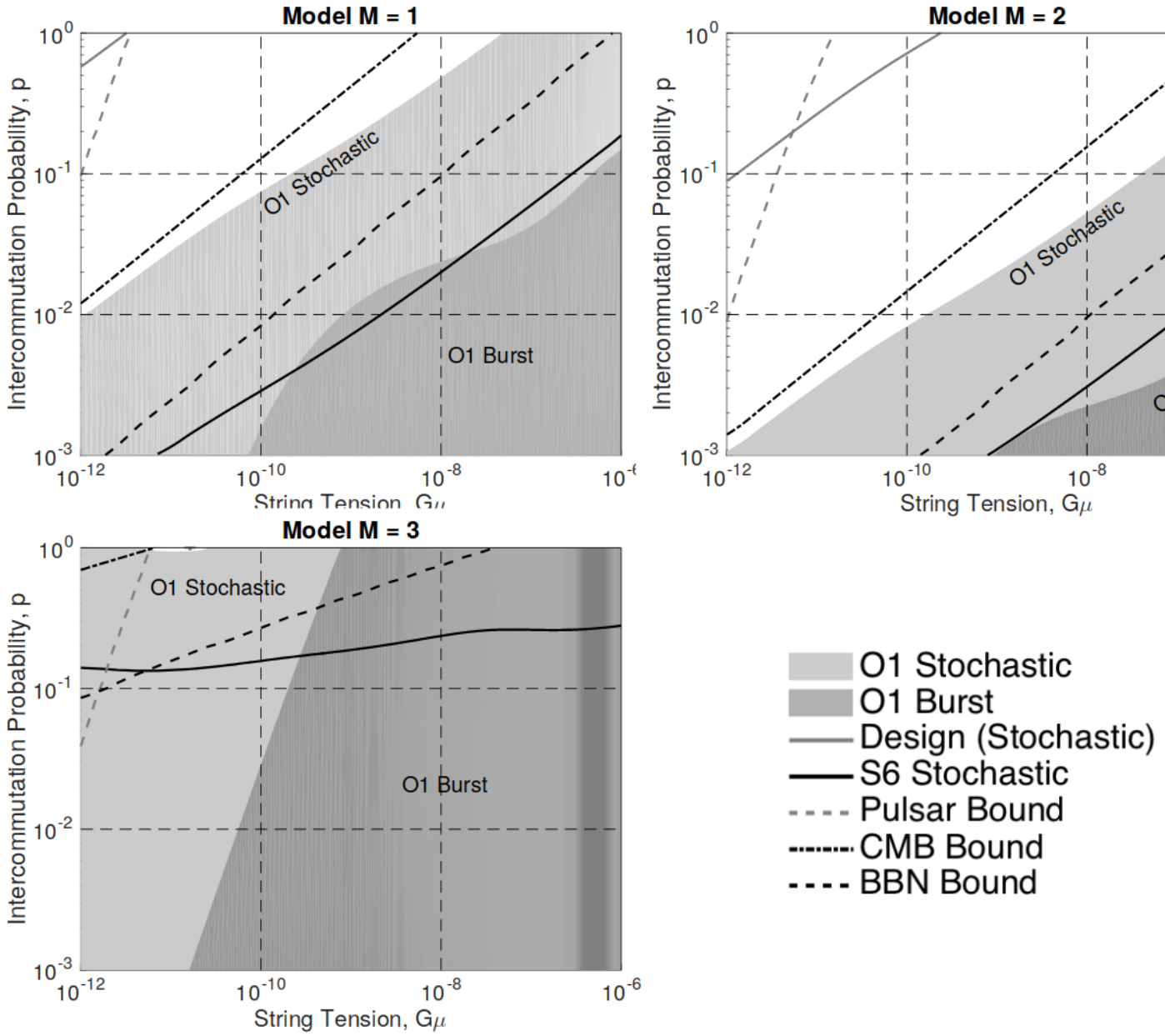

Zebragard
background
coincident
FAP < 1%
Cumulatve triggers rate [Hz]
Θ_Γ

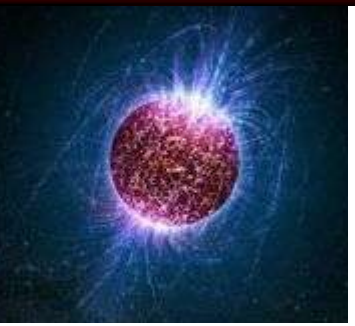

Lonetrack
background
coincident
FAP < 1%
Cumulatve triggers rate [Hz]
SNR


X-SphRad
background
coincident
FAP < 1%
Cumulatve triggers rate [Hz]
Significance

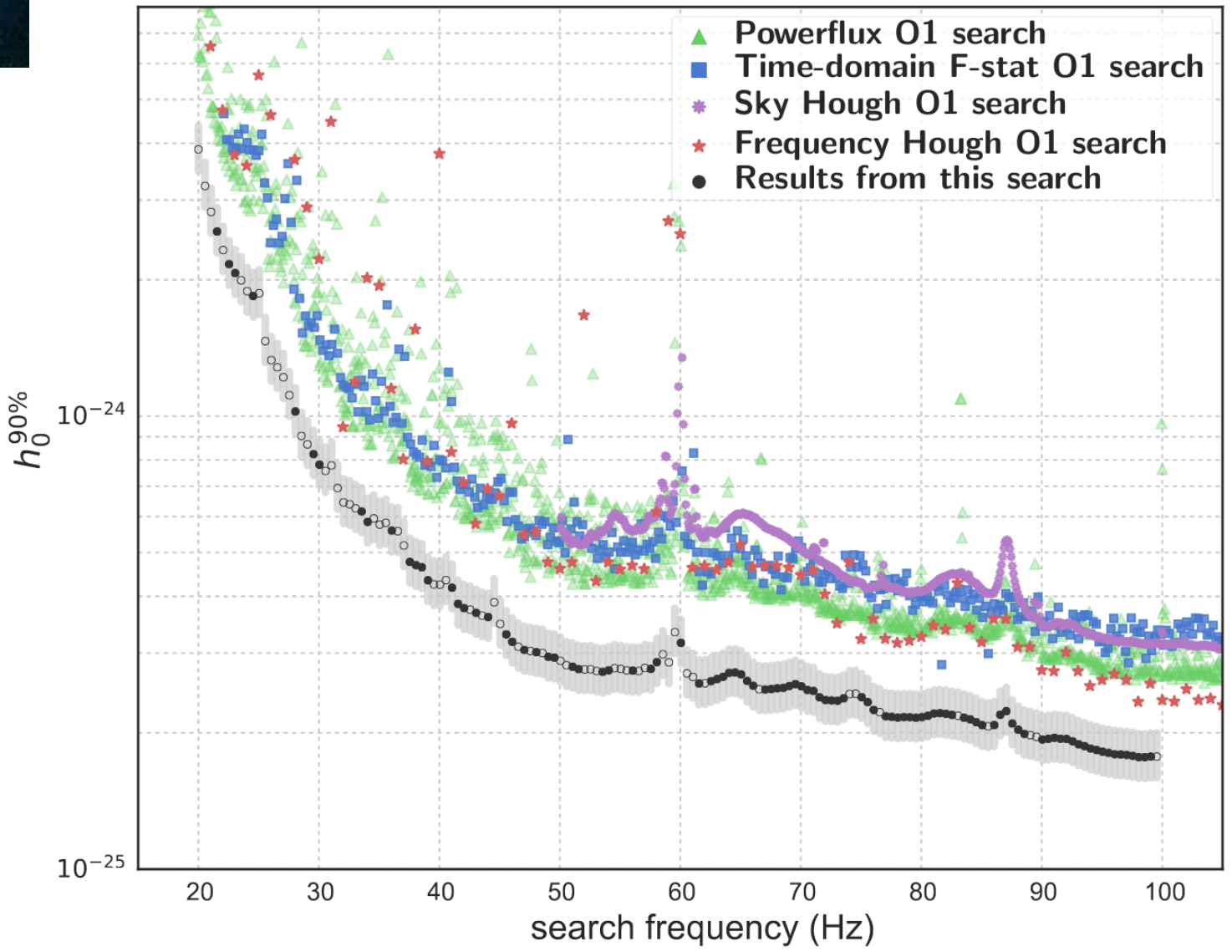

cWB
Zebragard
background
coincident
FAP < 1%
GW energy emitted by sources at 10 kpc, FAR=50 yr-1
MONO
LINE
QUAD
SG
WNB
cWB
STAMP-AS:Zebragard
STAMP-AS:Lonetrack
X-SphRad
O1
Design
E_{GW} [$M_\odot c^2$]
Mean frequency [Hz]
Cumulative triggers rate [Hz]
SNR
Significance

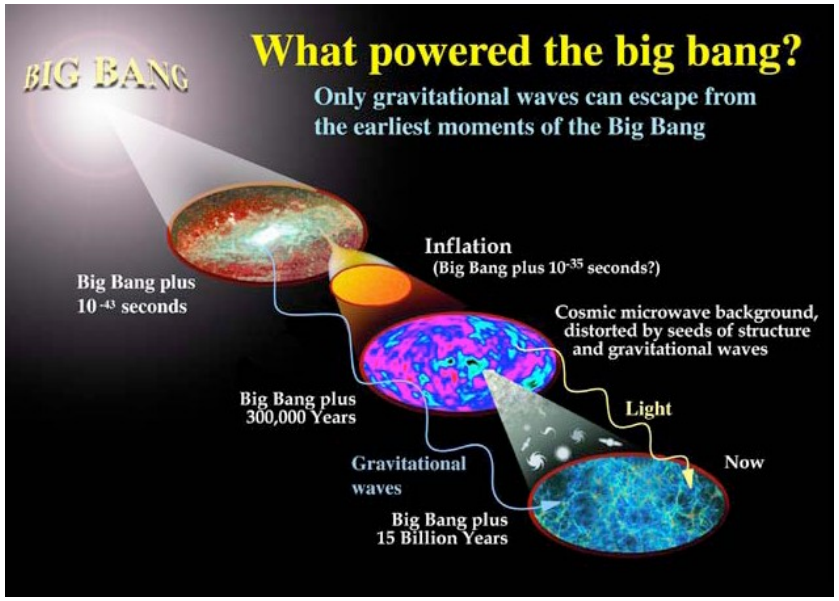
Gravitational-wave bursts produced by cusps and kinks on a cosmic string loop





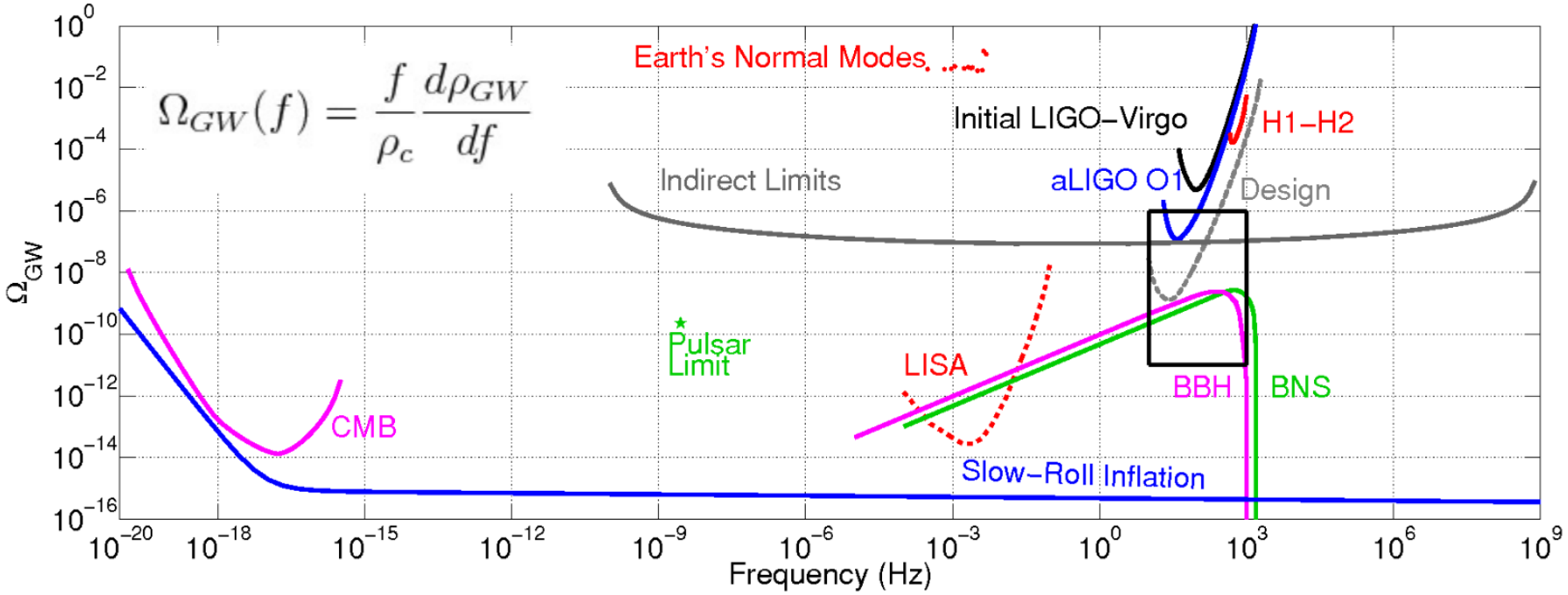
Search for periodic signals from isolated neutron stars
→ Citizen project ''Einstein@home''





O1 isotropic search:

$\Omega_{GW}(25\,Hz) < 1.7\times10^{-7}$



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Plans for O3

→ O3 will start early 2019

→ Improved sensitivity
  – LIGO: ~120 Mpc
  – Virgo: 60-85 Mpc

→ Significant increase of detection rate (1 BBH per week?)

→ Nominal 3-detectors online searches

→ Open public alerts (CBCs and unmodeled bursts)

→ automatic diagnotics (parameter estimation, sky maps, detector characterization, data quality)
  → retractation ~1h