# LIGO-Virgo observational results with the O1 run and the expectations for the O2 run



GRavitational-wave Astronomy Meeting in PAris

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On behalf of the LIGO Scientific Collaboration & the Virgo Collaboration

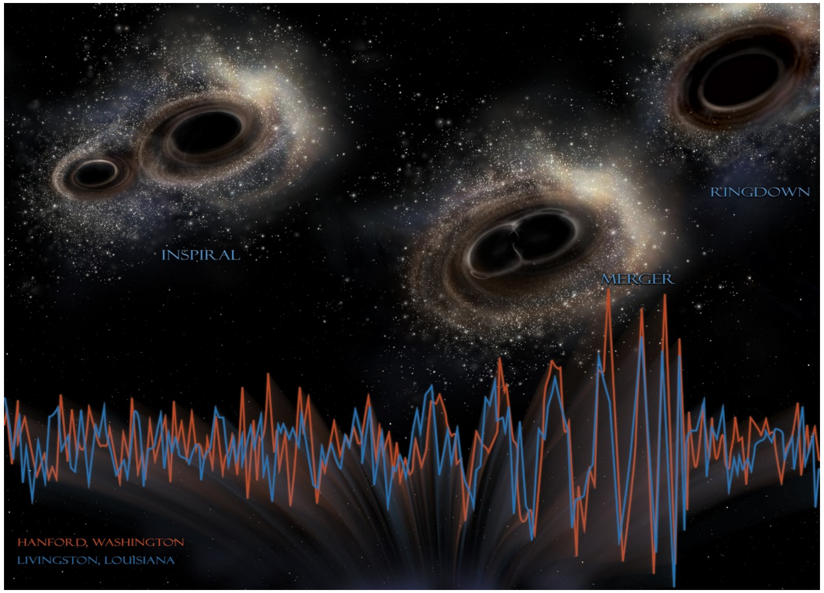
29/08/2016

# Outline

**Introduction**

**O1 results**

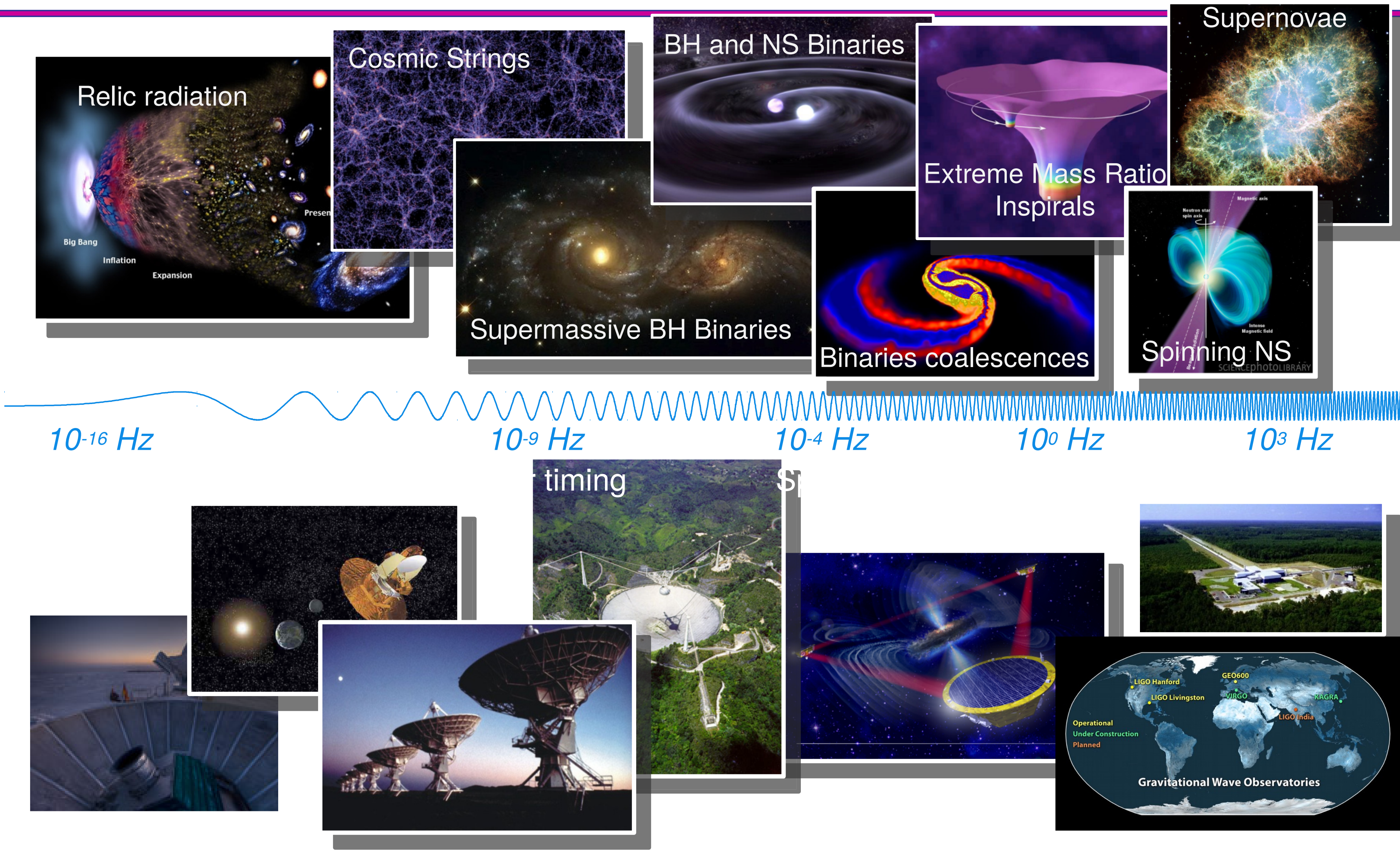
- Binary black holes discovery
- Other transient searches
- Stochastic background searches




**O2 preparation**

- LIGO detectors readiness
- Virgo detector status
- O2 science expectations

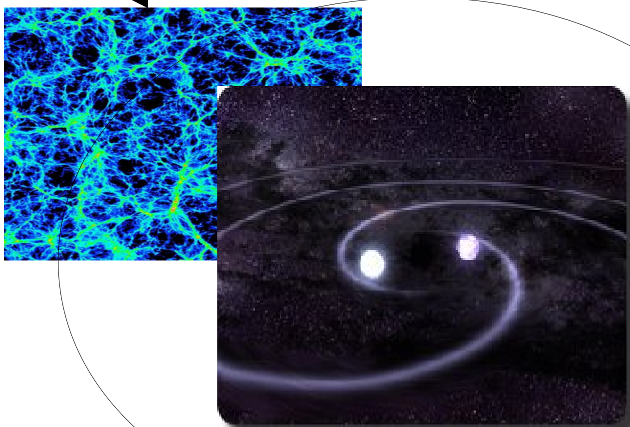
# The gravitational wave spectrum

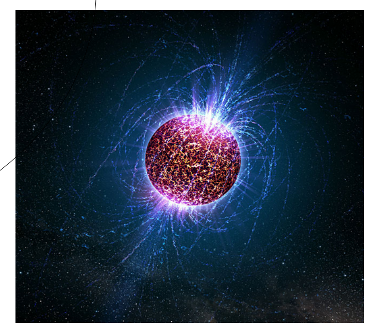


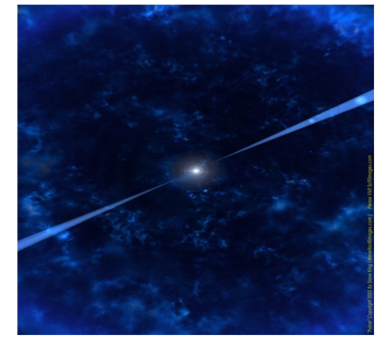
# LIGO-Virgo GW searches zoology

Short duration (~1s) | Long duration (∞)

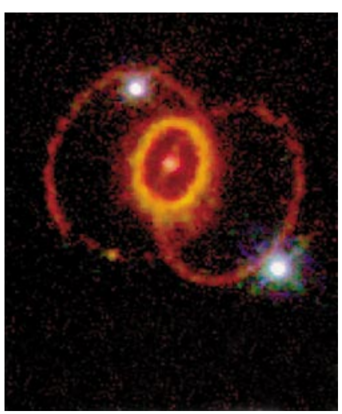
Waveform known







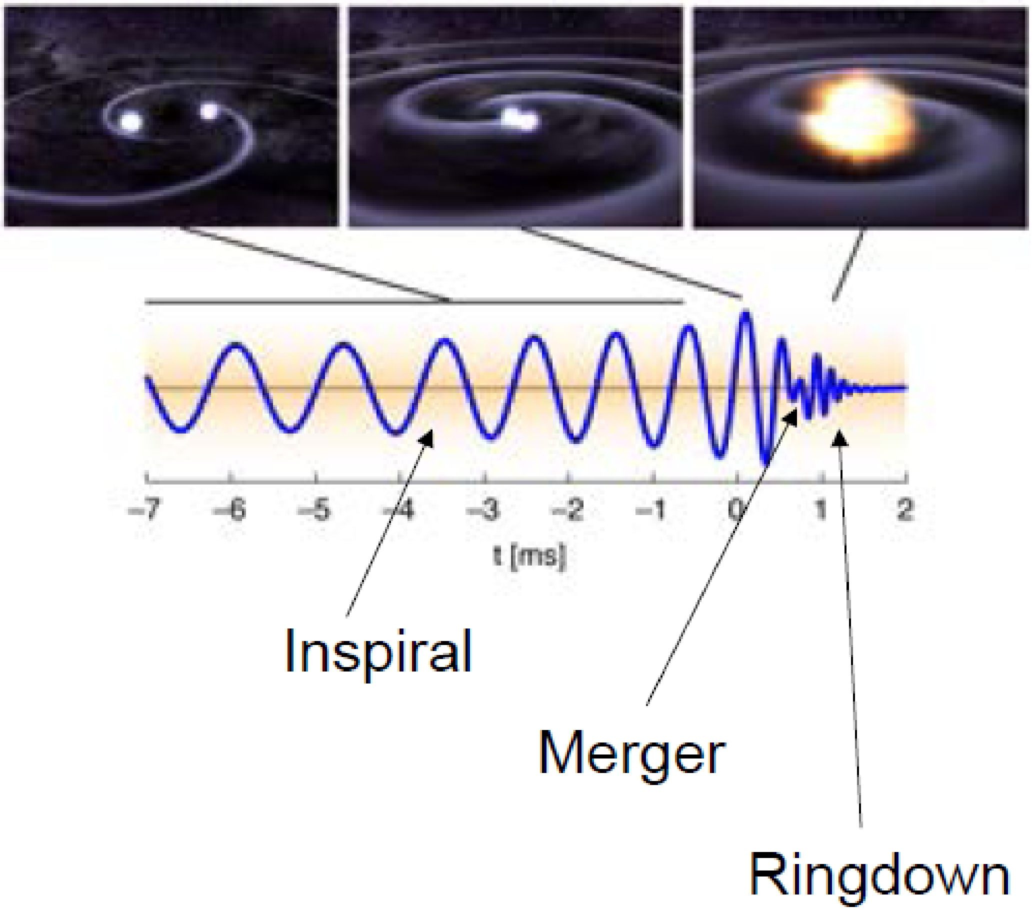
Waveform unknown



?

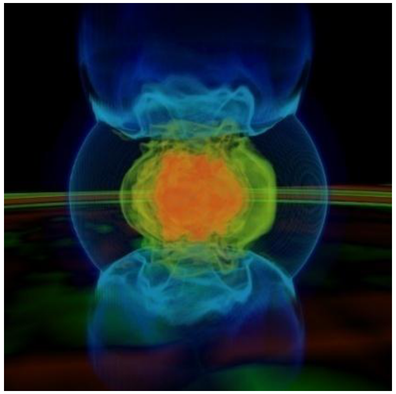
# Compact Binary Coalescence

- Compact binary objects:
  - » Two neutron stars and/or black holes.
- Inspiral toward each other.
  - » Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform well understood, matched template searches.

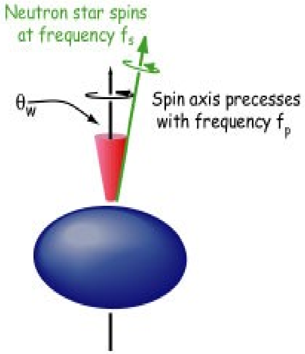


# Other sources

- Transient
  - Stellar core collapse (probe the supernova mechanism)
  - Pulsar glitches
  - Magnetars
  - Cosmic string cusps



- Stochastic background
  - Cosmological (inflation reheating, phase transitions, cosmic strings, ...)
  - Astrophysical (compact binary coalescence, neutron star instablities, …)
- Periodic
  - Rotating neutron star with small mass non uniformity



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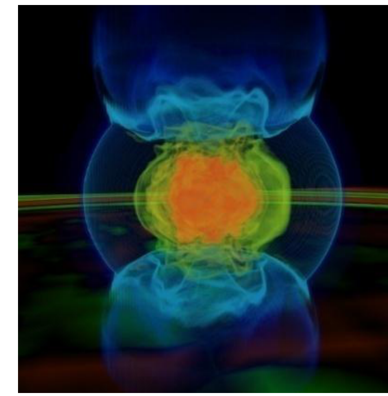

- Stochastic background
  - Cosmological (inflation reheating, phase transitions, cosmic strings, ...)
  - Astrophysical (compact binary coalescence, neutron star instablities, …)

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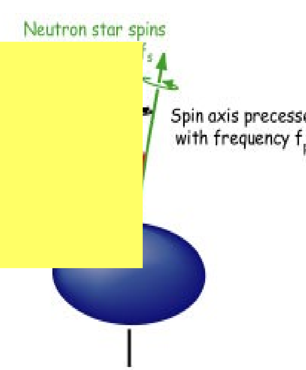
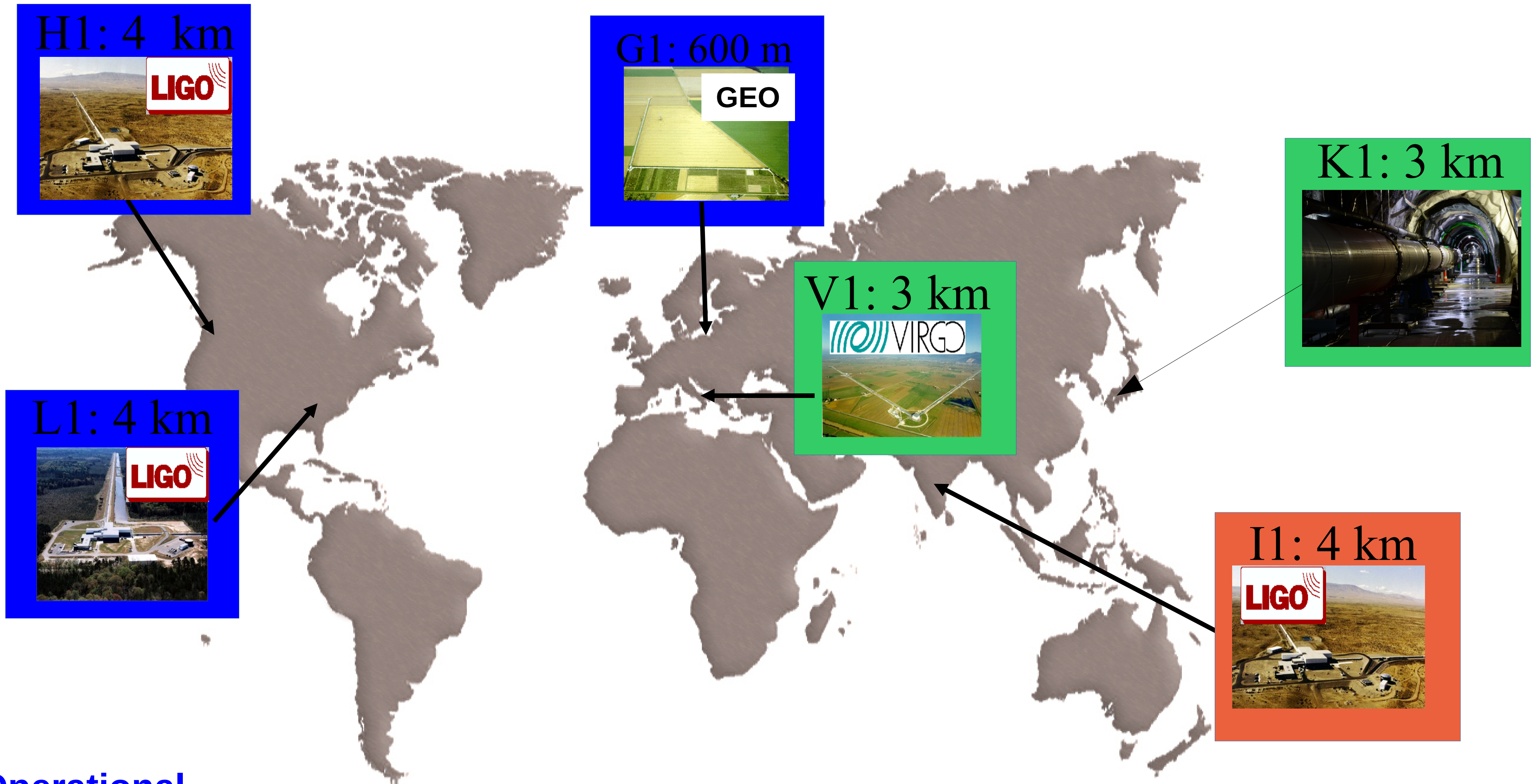
NO RESULTS FROM O1
YET AVAILABLE



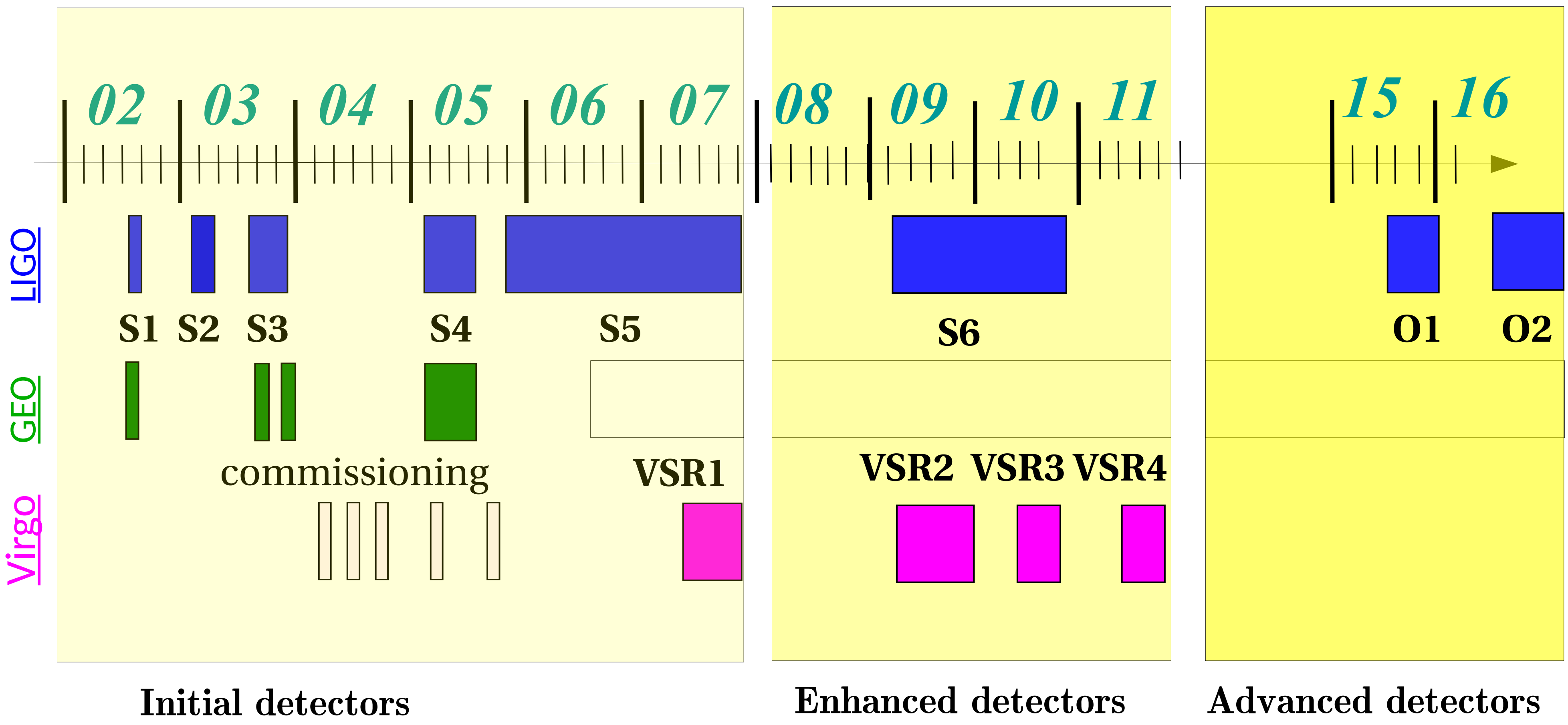
# Network of ground based advanced detectors




Operational
Commissioning/construction
Planned

**Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.**

# LIGO-GEO-Virgo joint runs

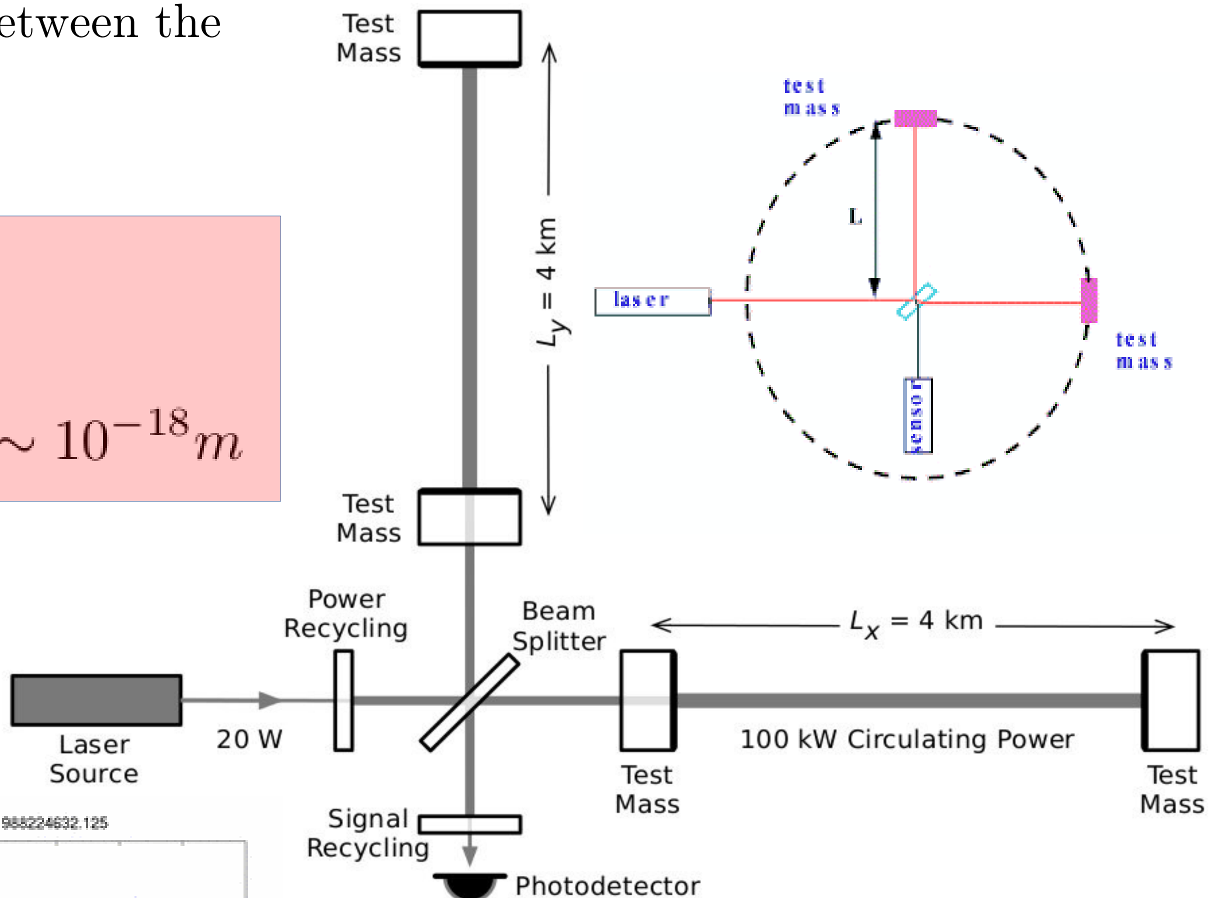


# GW detection with ground based laser interferometry detectors

Passing GWs modulate the distance between the end test mass and the beam splitter

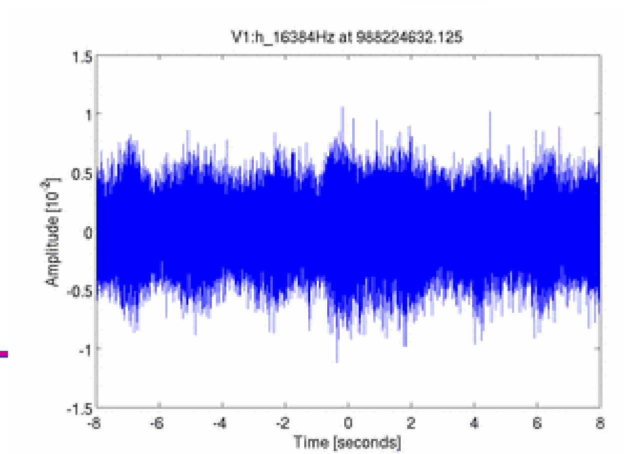
$$\frac{\Delta L}{L} = \frac{h}{2}$$

$$L = 4\ km\ ,\ h \sim 10^{-21} \rightarrow \Delta L \sim 10^{-18} m$$



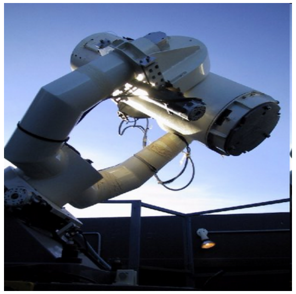

$$h(t) = F_+ \times h_+(t) + F_\times \times h_\times(t)$$

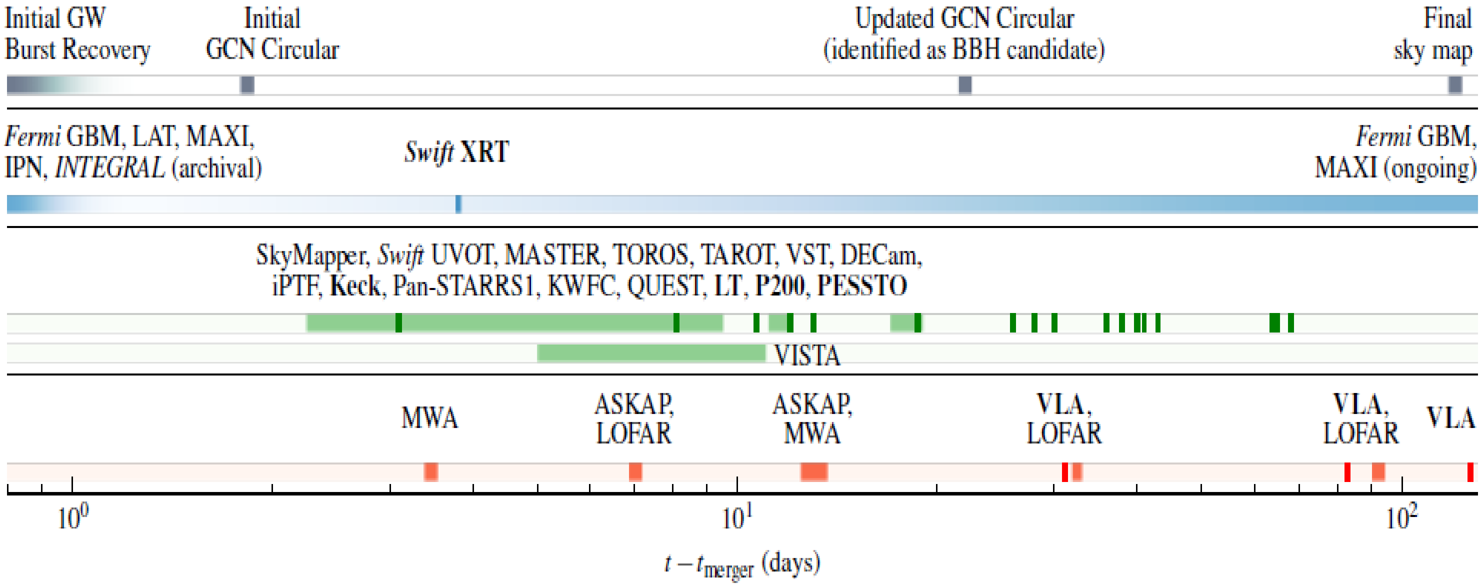
$$s(t) = n(t) + h(t)$$



# O1 data set

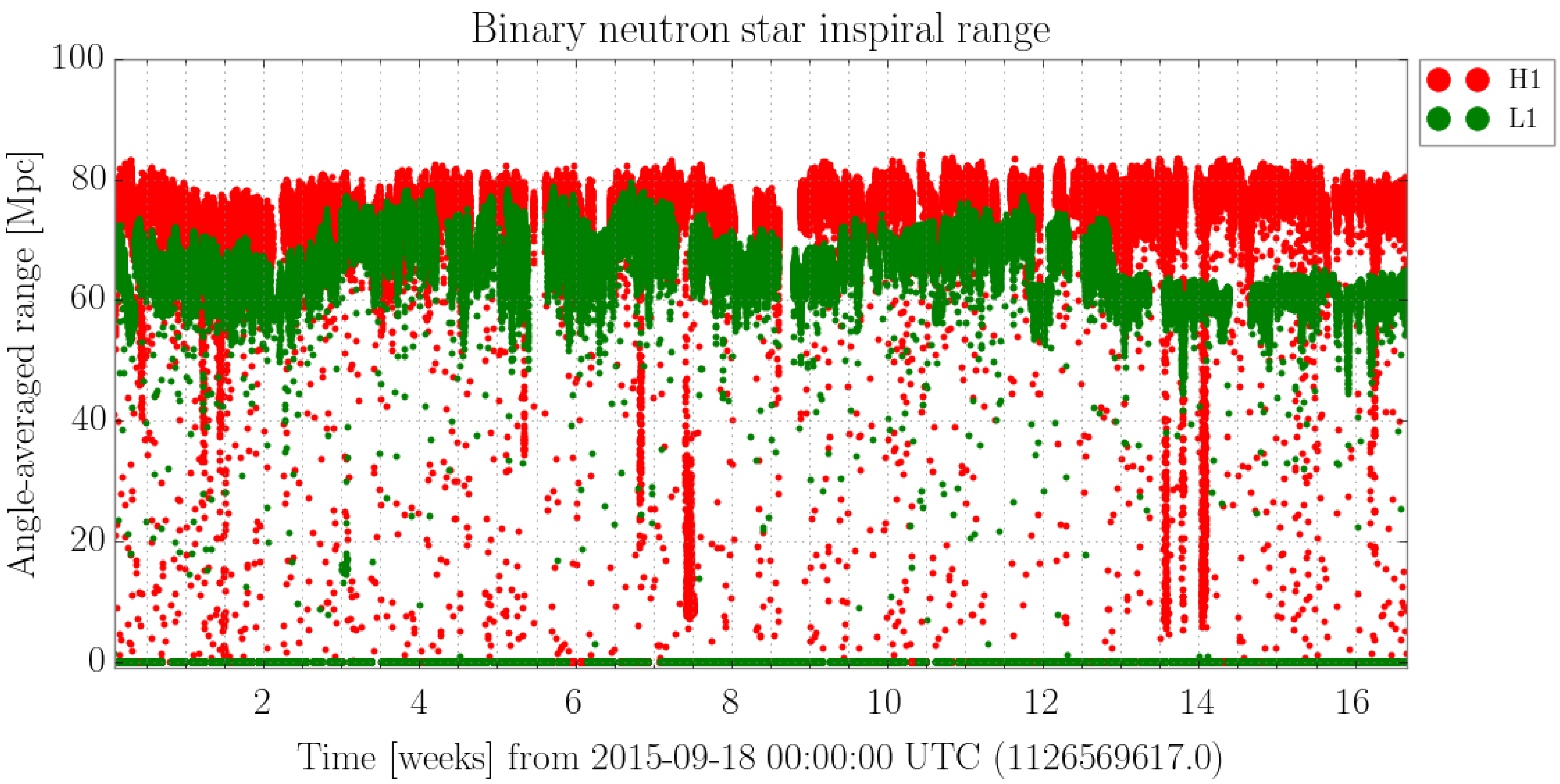
- Observation run O1 : September 12, 2015 – January 19, 2016
- Only LIGO Hanford (62%) & LIGO Livingston (55%) online
- ~50 days of coincident data to be analyzed
- Online transient searches & electro-magnetic follow-up program
    - Matched filtering CBC searches & un-modelled short transient searches
    - 62 MOUs (radio, optical, IR, X-ray and γ-ray).
    - 20 groups reacted to the first alert





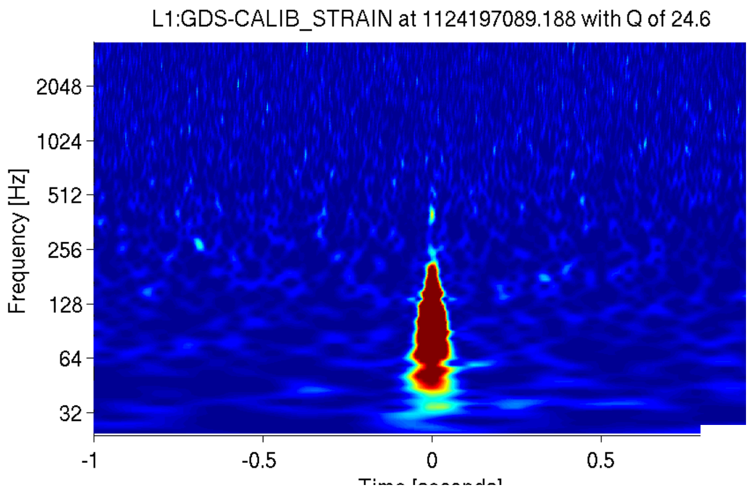
# O1 data quality

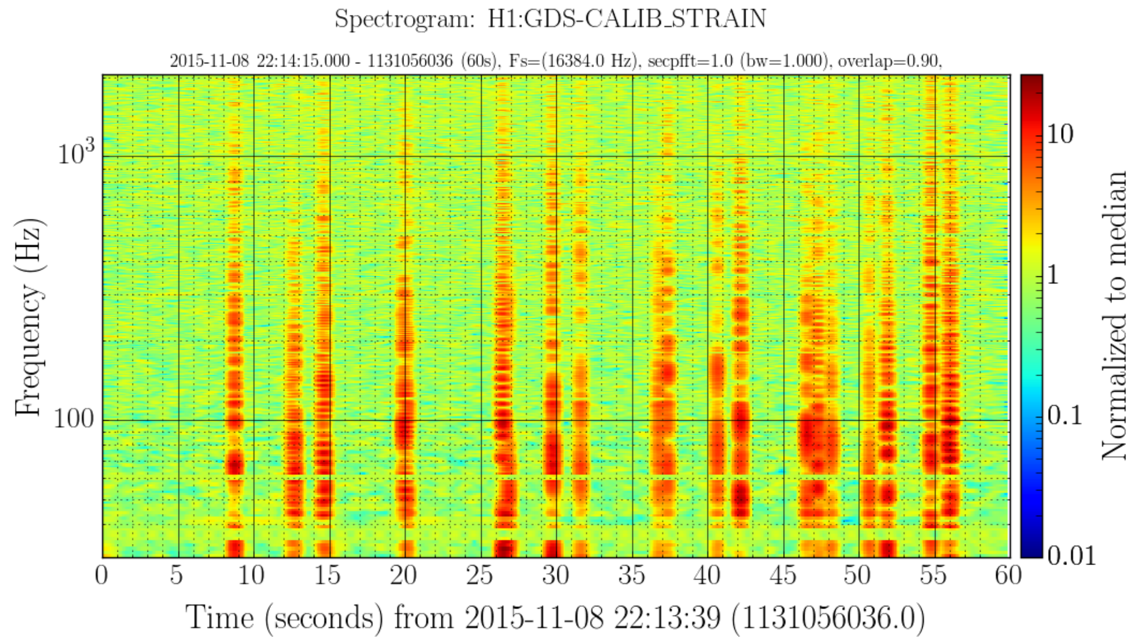
- Stable performance of both detectors during O1
- The product of observation volume X time exceeded that of previous runs after 16 coincident days in O1.

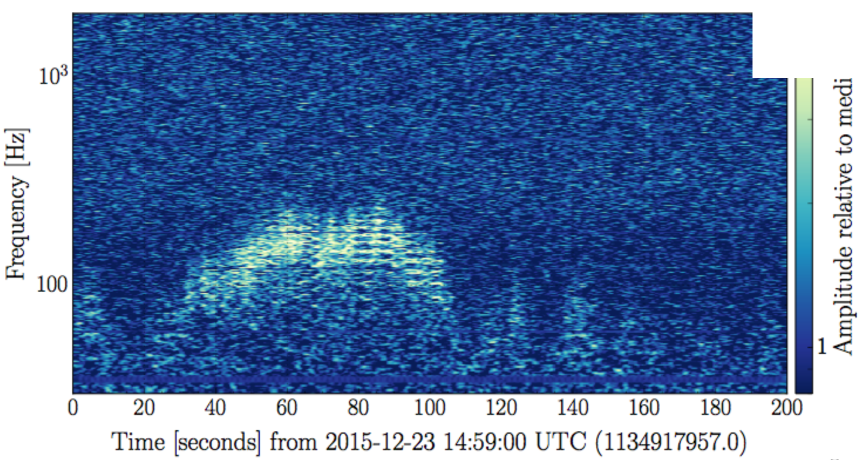


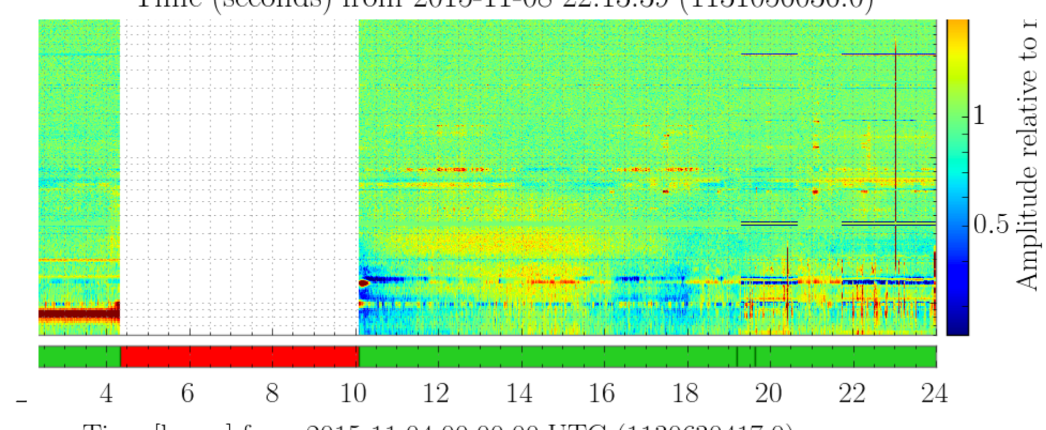
# O1 data quality

- Many glitch sources (RF-modulation electronics fault, « blip » glitches, …) : either correlation in auxiliary channels → vetoes
- Spectral lines : wandering, 1Hz combs, breathing effects



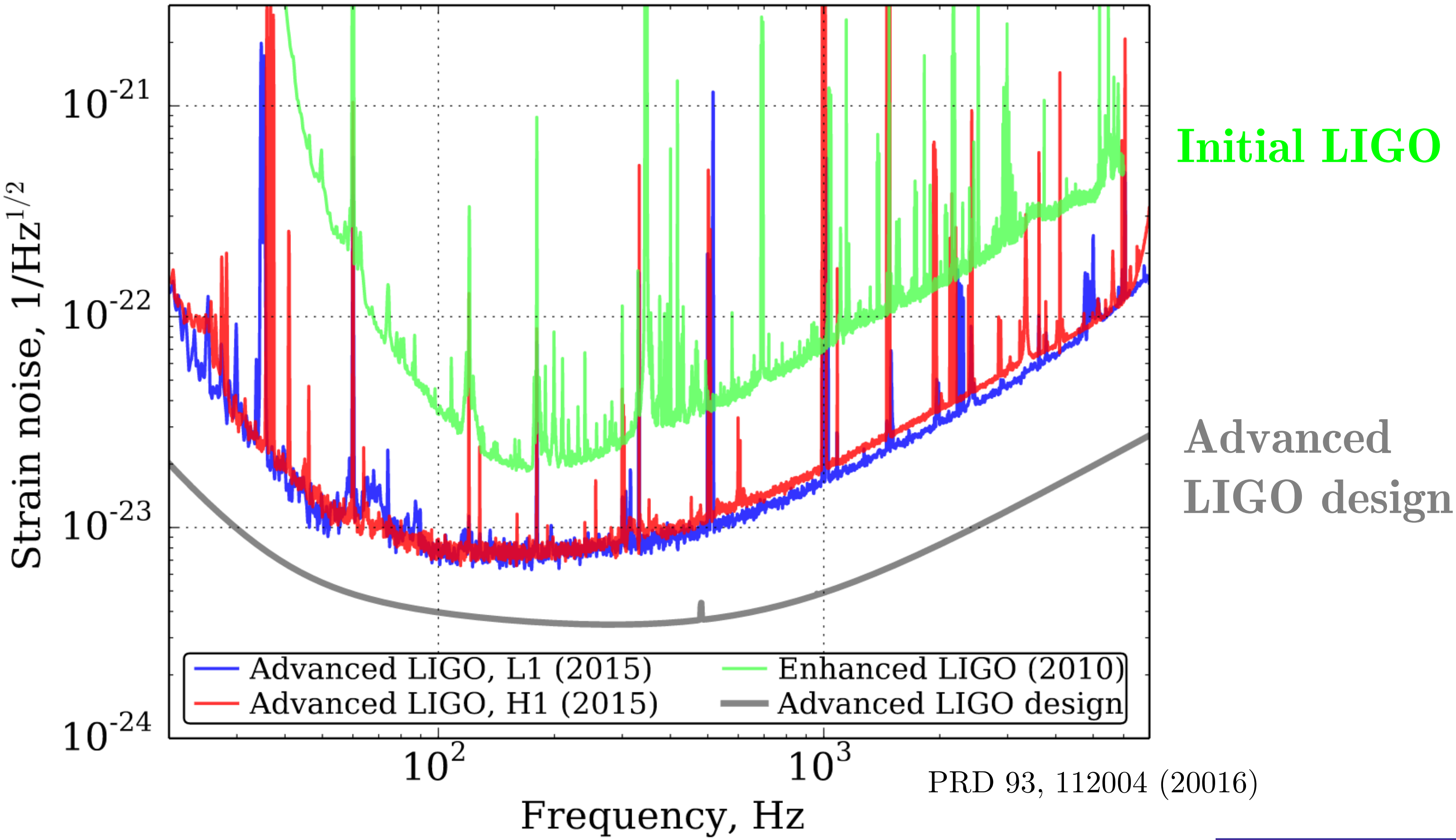



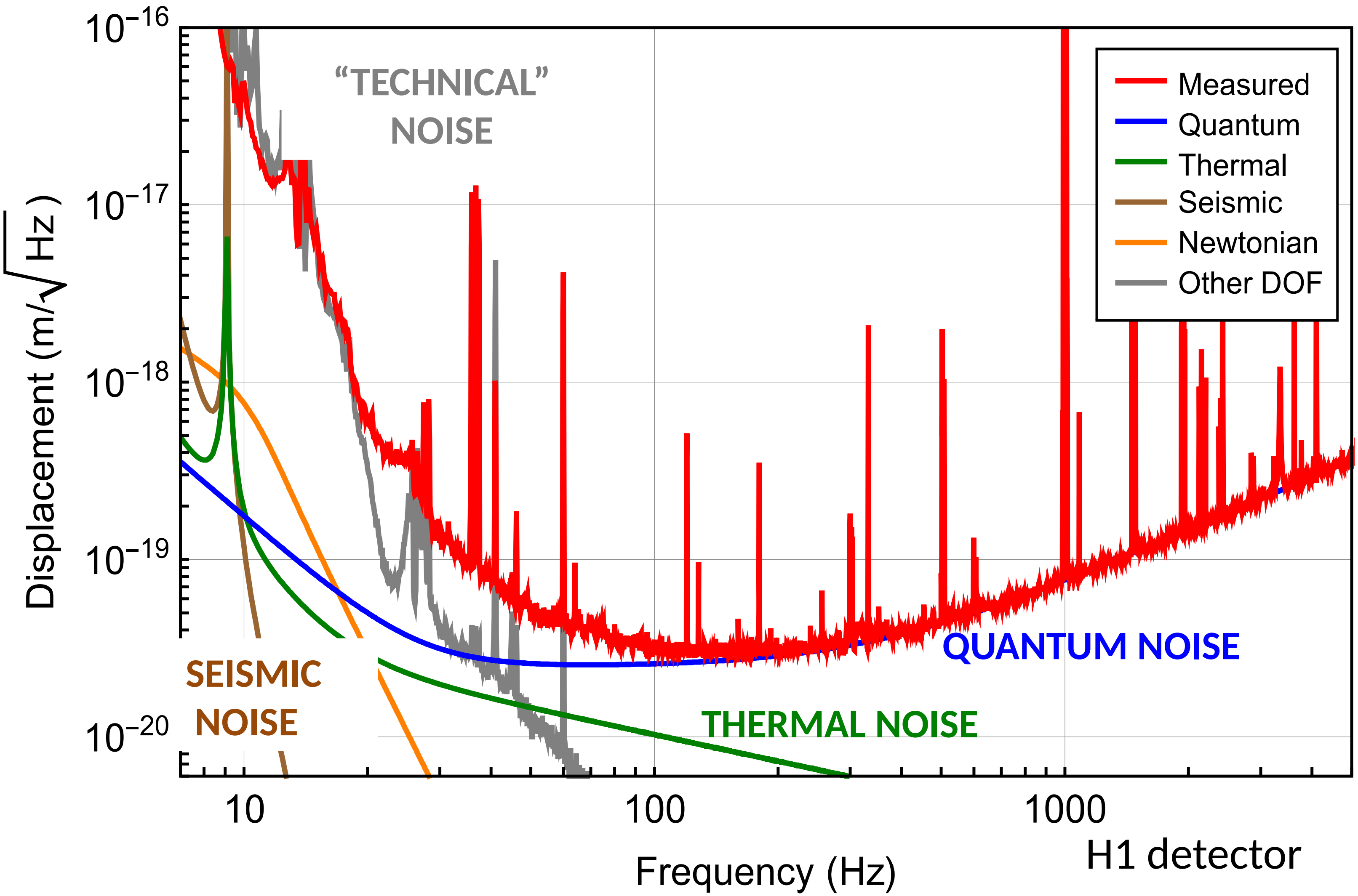
# Strain noise during O1

**Better than ever not yet at sensitivity !**

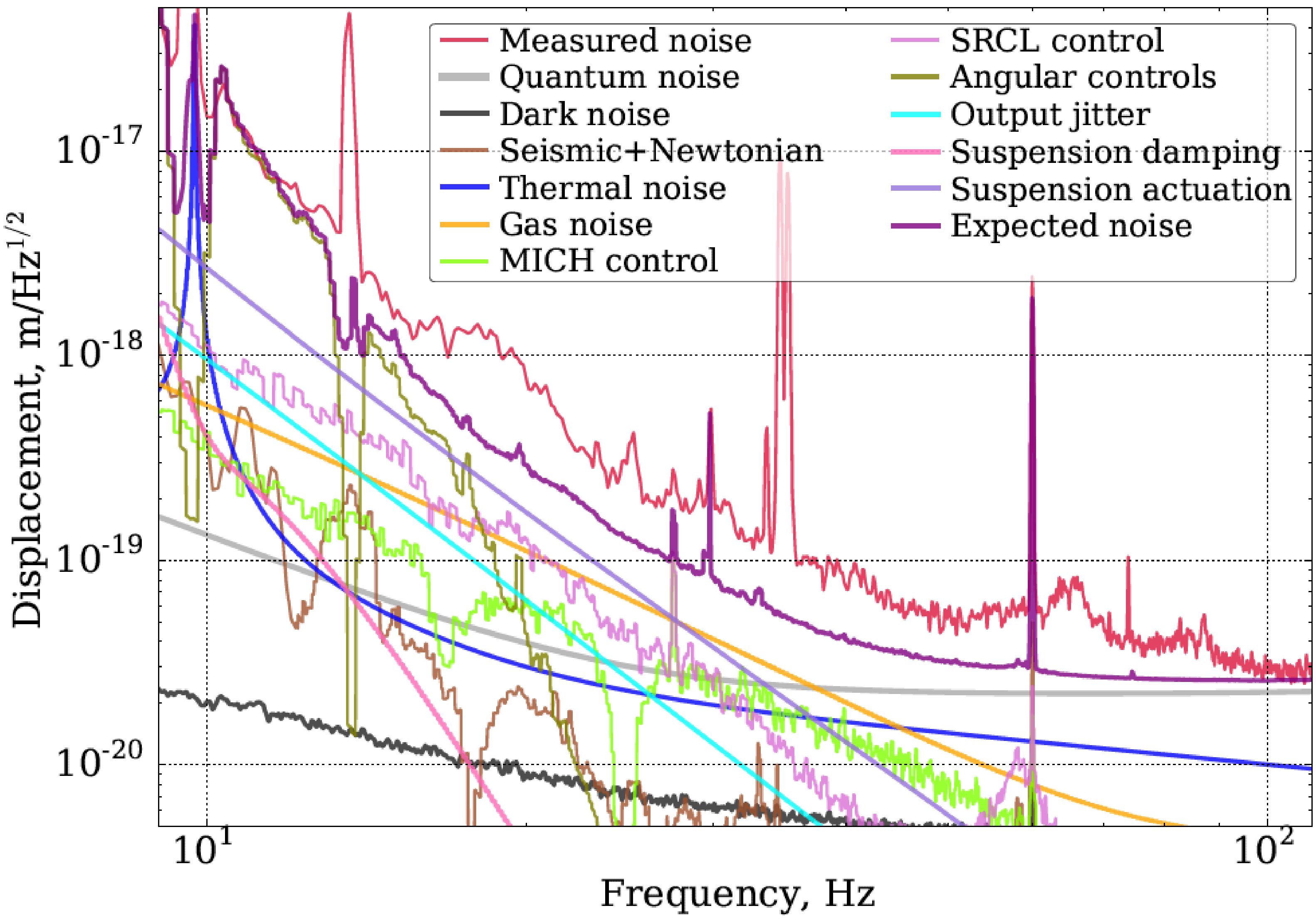



PRD 93, 112004 (20016)

# O1 displacement noise



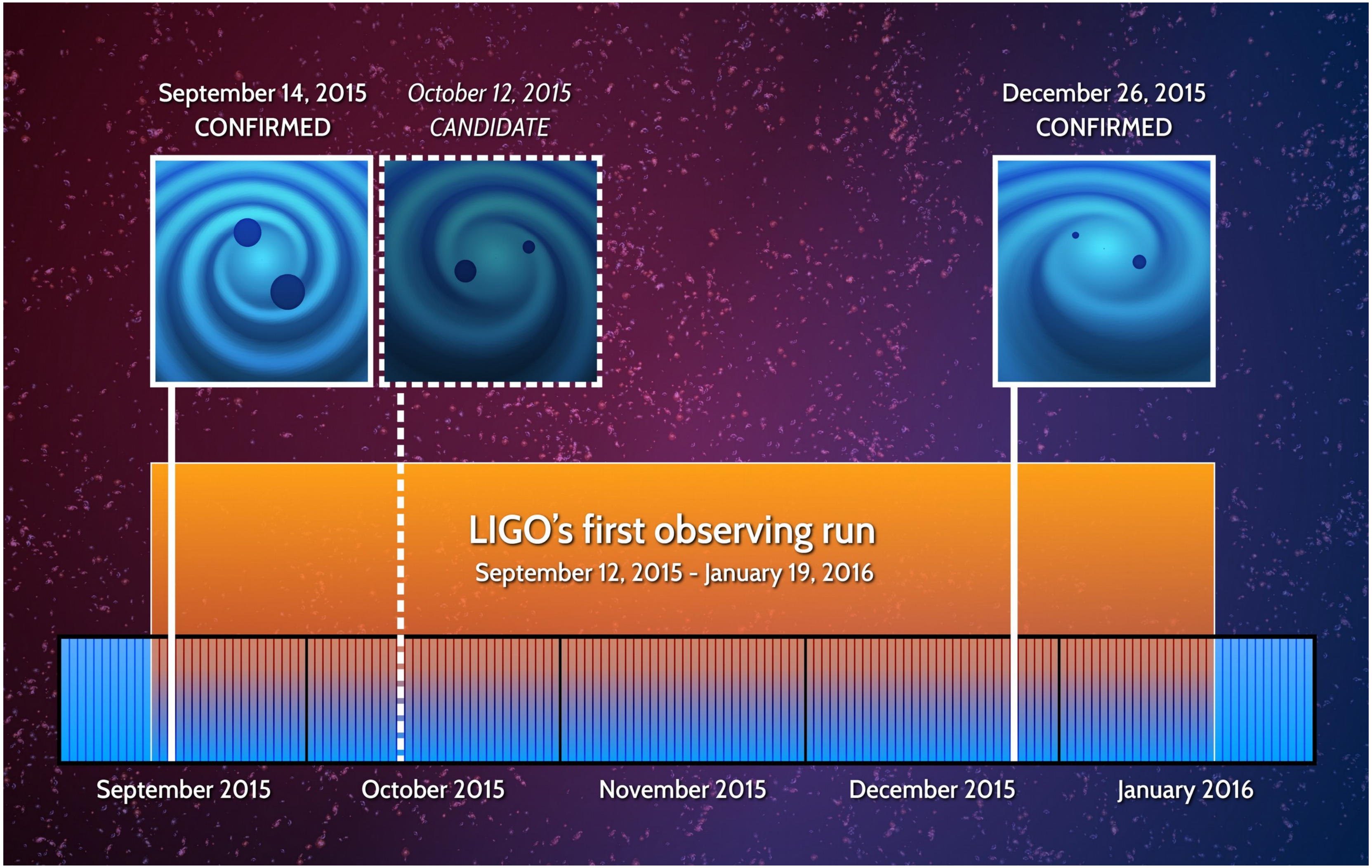
# Low-frequency noise sources




(a) LIGO Livingston Observatory

# O1 results

# Binary black holes discovery : a summary

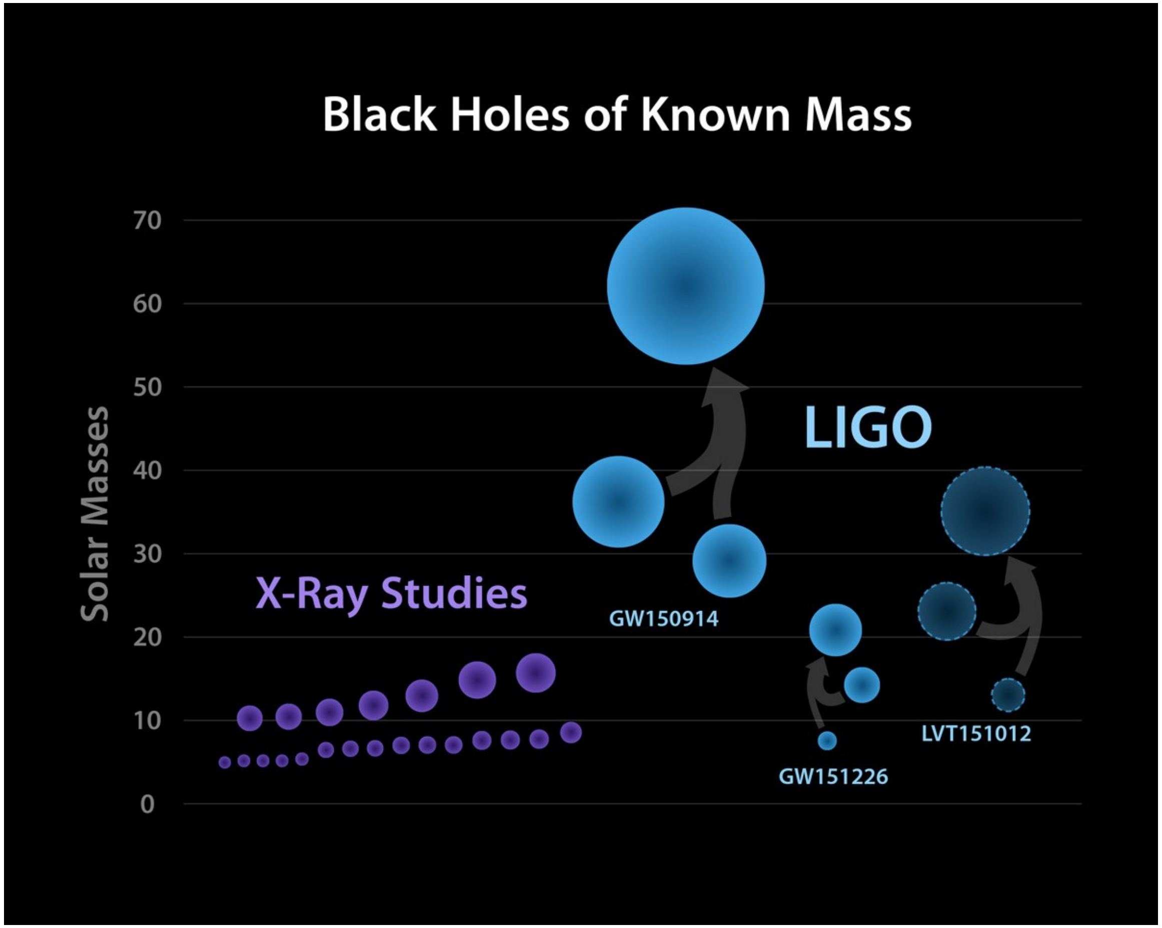


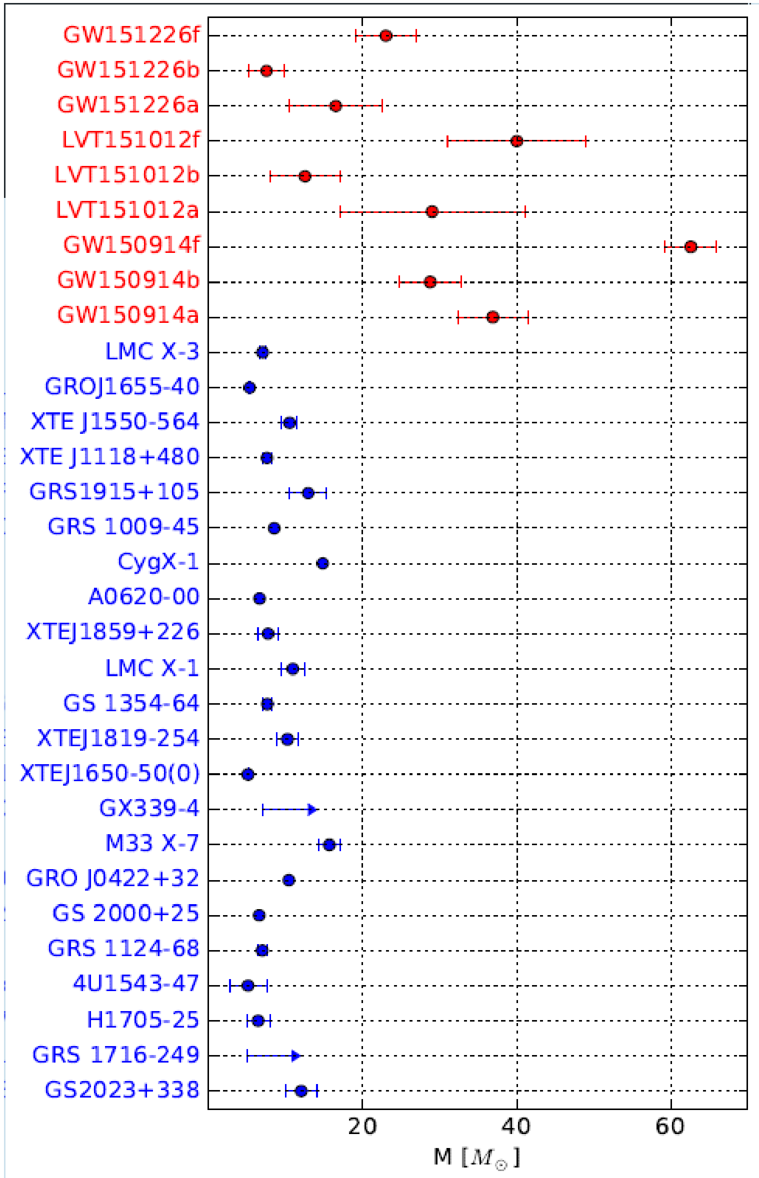
# O1 BBH: Two Golds and a Silver

[gr-qc:1606.04856]

| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Signal-to-noise ratio $\rho$ | 23.7 | 13.0 | 9.7 |
| False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$ | $< 6.0 \times 10^{-7}$ | $< 6.0 \times 10^{-7}$ | 0.37 |
| p-value | $7.5 \times 10^{-8}$ | $7.5 \times 10^{-8}$ | 0.045 |
| Significance | $> 5.3\,\sigma$ | $> 5.3\,\sigma$ | $1.7\sigma$ |
| Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$ | $36.2^{+5.2}_{-3.8}$ | $14.2^{+8.3}_{-3.7}$ | $23^{+18}_{-6}$ |
| Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$ | $29.1^{+3.7}_{-4.4}$ | $7.5^{+2.3}_{-2.3}$ | $13^{+4}_{-5}$ |
| Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$ | $28.1^{+1.8}_{-1.5}$ | $8.9^{+0.3}_{-0.3}$ | $15.1^{+1.4}_{-1.1}$ |
| Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$ | $65.3^{+4.1}_{-3.4}$ | $21.8^{+5.9}_{-1.7}$ | $37^{+13}_{-4}$ |
| Effective inspiral spin $\chi_{\mathrm{eff}}$ | $-0.06^{+0.14}_{-0.14}$ | $0.21^{+0.20}_{-0.10}$ | $0.0^{+0.3}_{-0.2}$ |
| Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$ | $62.3^{+3.7}_{-3.1}$ | $20.8^{+6.1}_{-1.7}$ | $35^{+14}_{-4}$ |
| Final spin $a_{\mathrm{f}}$ | $0.68^{+0.05}_{-0.06}$ | $0.74^{+0.06}_{-0.06}$ | $0.66^{+0.09}_{-0.10}$ |
| Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$ | $3.0^{+0.5}_{-0.4}$ | $1.0^{+0.1}_{-0.2}$ | $1.5^{+0.3}_{-0.4}$ |
| Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$ | $3.6^{+0.5}_{-0.4} \times 10^{56}$ | $3.3^{+0.8}_{-1.6} \times 10^{56}$ | $3.1^{+0.8}_{-1.8} \times 10^{56}$ |
| Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$ | $420^{+150}_{-180}$ | $440^{+180}_{-190}$ | $1000^{+500}_{-500}$ |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ | $0.09^{+0.03}_{-0.04}$ | $0.20^{+0.09}_{-0.09}$ |
| Sky localization $\Delta\Omega/\mathrm{deg}^2$ | 230 | 850 | 1600 |

# Black hole population



# Three BBH GW signals

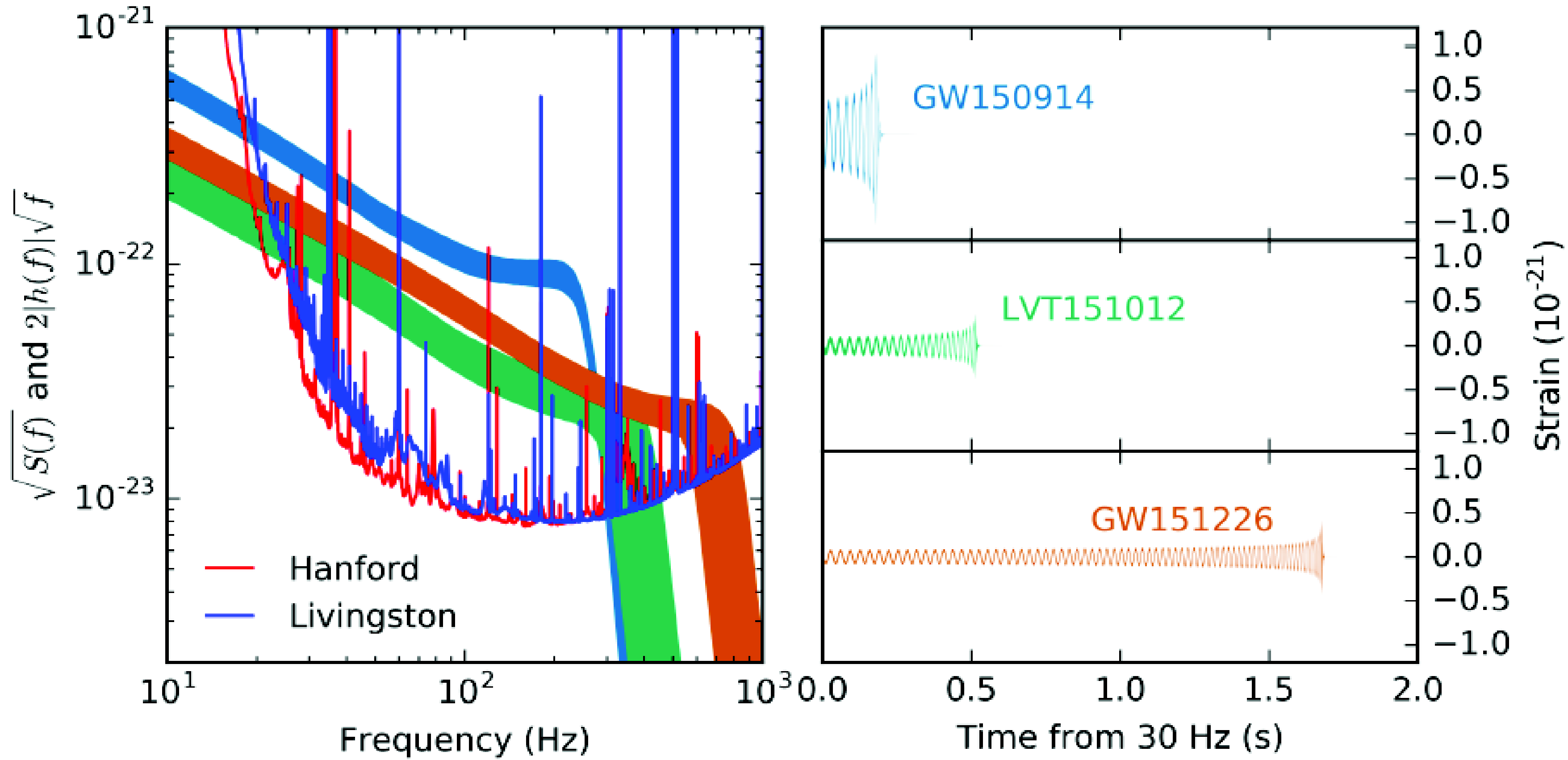
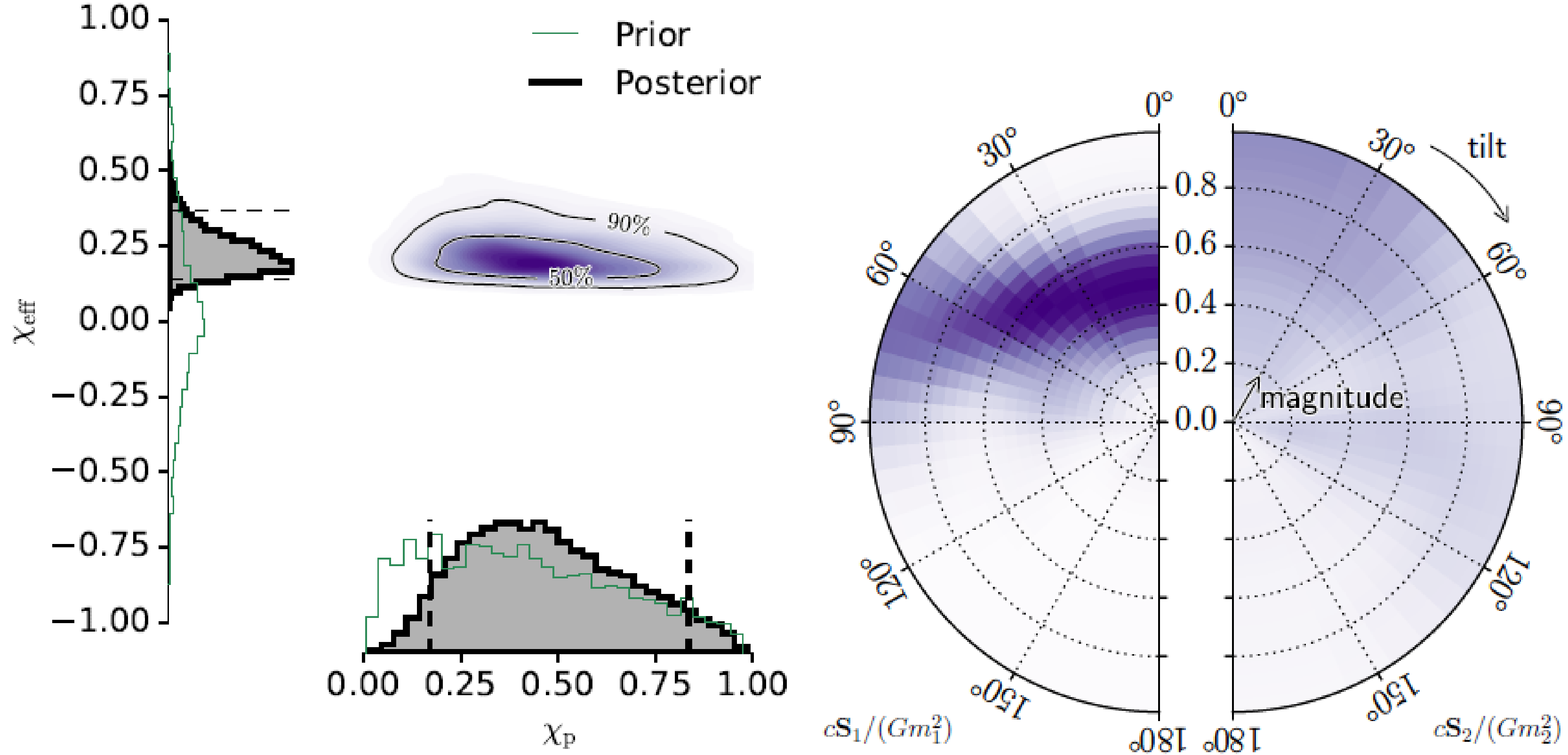



FIG. 1. Left: amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226 and LVT151012 plotted so that the relative amplitudes can be directly related to the SNR of the signal (as described in the text). Right: the time evolution of the waveforms from when they enter the detectors' sensitive band at 30 Hz. All bands show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model [44].

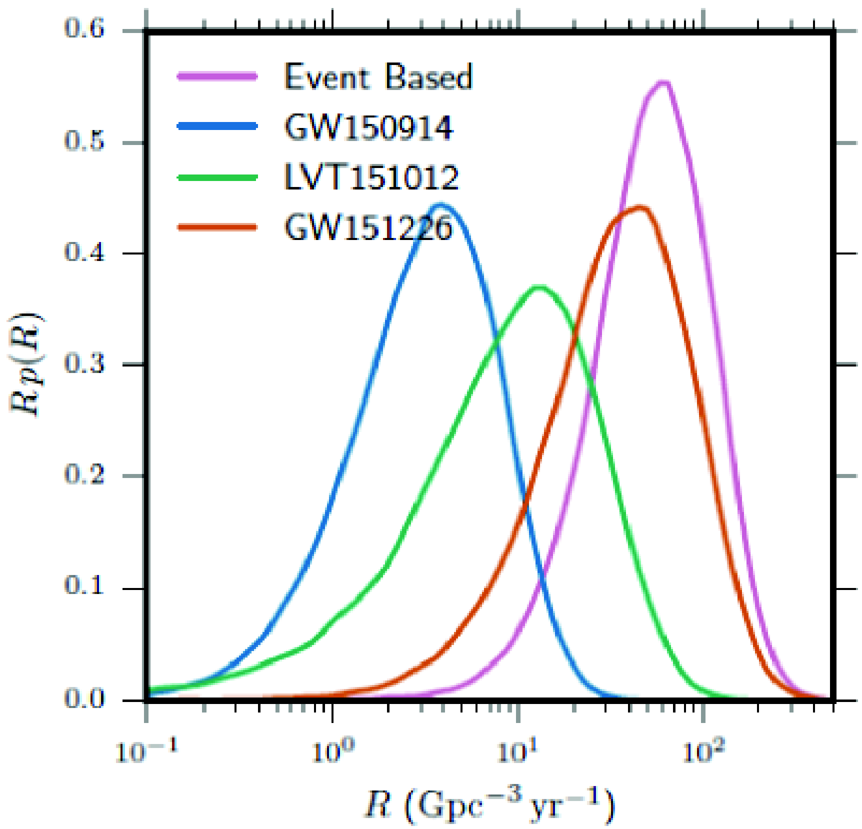
# GW151226 – At least one BH had spin

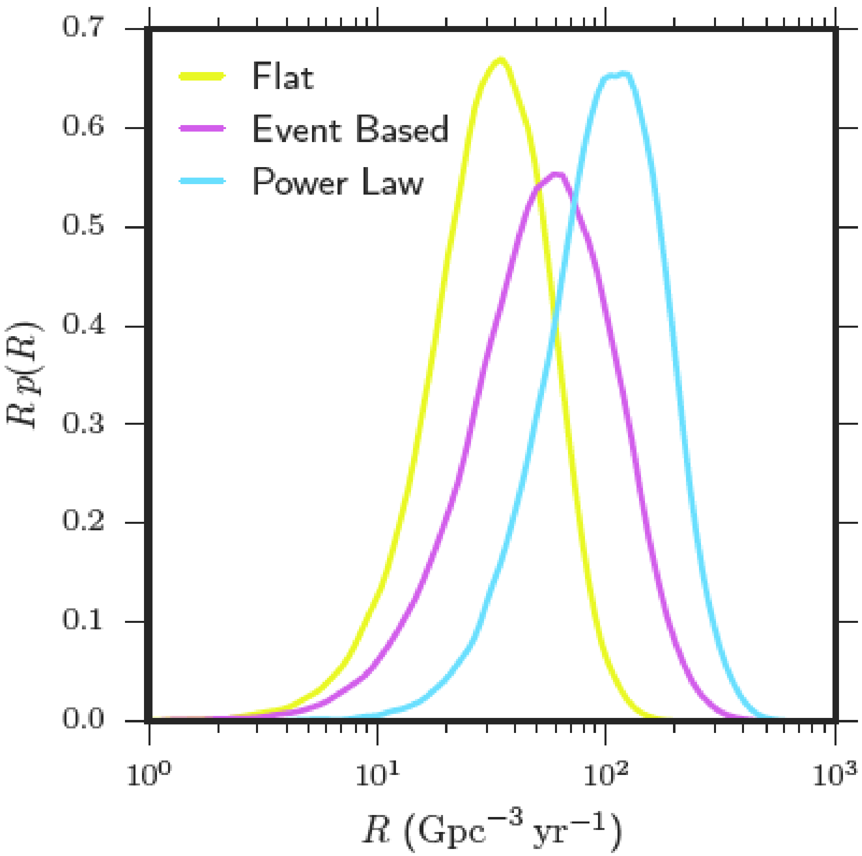



At least one black hole has spin greater than 0.2. Spins of the primary and secondary black holes are constrained to be positive.

Mass-weighted combinations of orbit-aligned spins $\chi_{\mathrm{eff}}$ and in-plane spins $\chi_{\mathrm{p}}$ (weak constraints only, non-informative).

# Binary Black Hole Merger Rate




90% allowed range: [9-240] /Gpc$^3$/yr

# Binary black hole merger rate

- Assuming that all binaries are like these 3 events is not realistic.
- Try two alternative models:
  Flat distribution in log m1 – log m2
  - (m1) $\propto m_1^{-2.35}$ with a uniform distribution for the second mass.
- Significantly different rate estimates.
- Altogether: 9 – 240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.
- Lower limit comes from the flat in log mass population and the upper limit from the power law population distribution.

- Rules out <9 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, which were previously allowed.

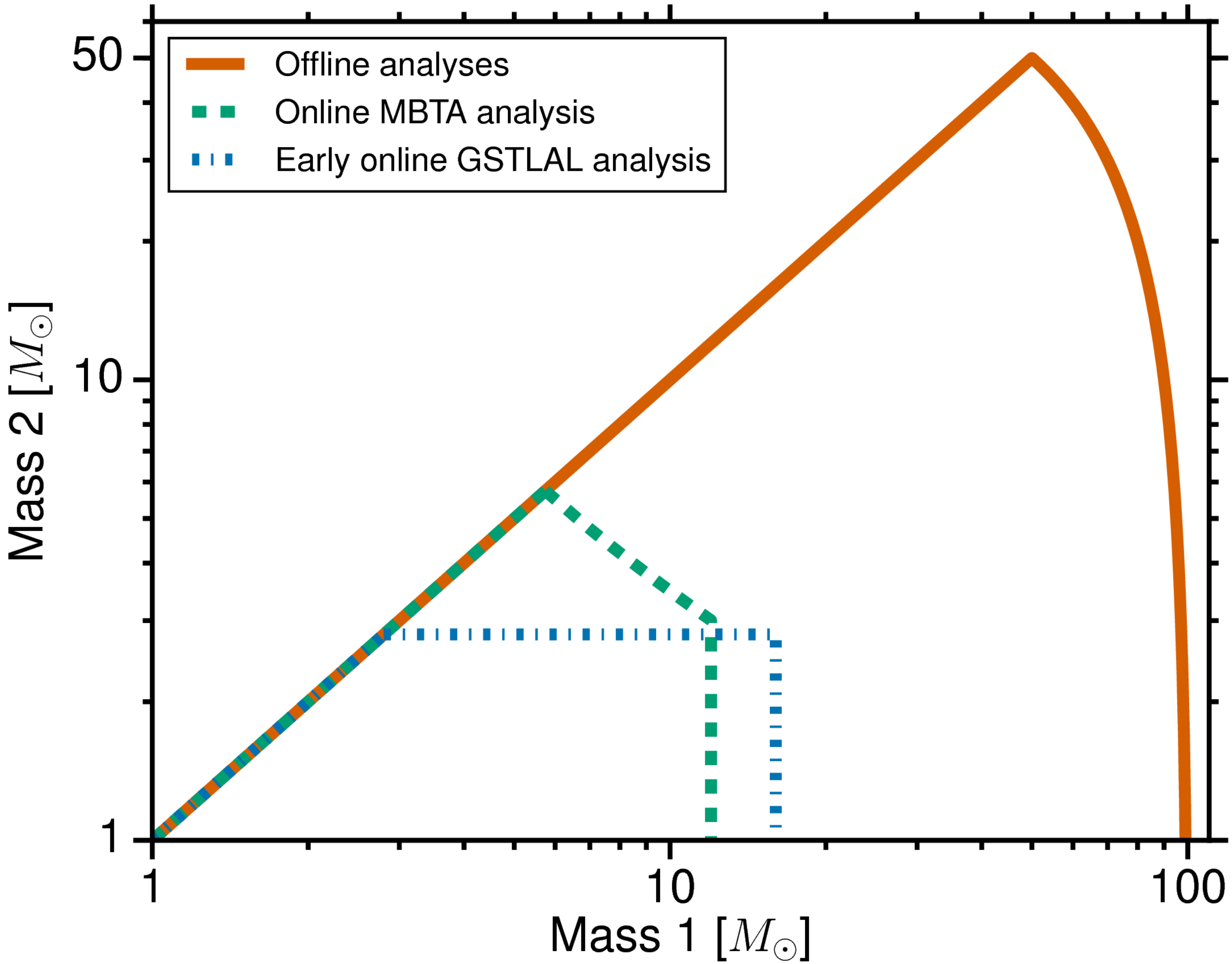
# The birth of GW astronomy

- Testing GR in strong field regime
- Unveiling the black hole merger dynamics and the post-merger phase
- Checking consistency between waveform predictions (analytical/numerical)
- Understanding binary black hole formation mechanisms

- More information in this week's talks :
  - Monday : Alberto Vecchio
  - Tuesday : Stas Babak, Ian Hinder, Christopher Berry
  - Thursday : Selma De Mink, Ilya Mandel
  - Friday : Samaya Nissanke

# Binary neutron stars & neutron star-black hole

gr-qc:1607.07456



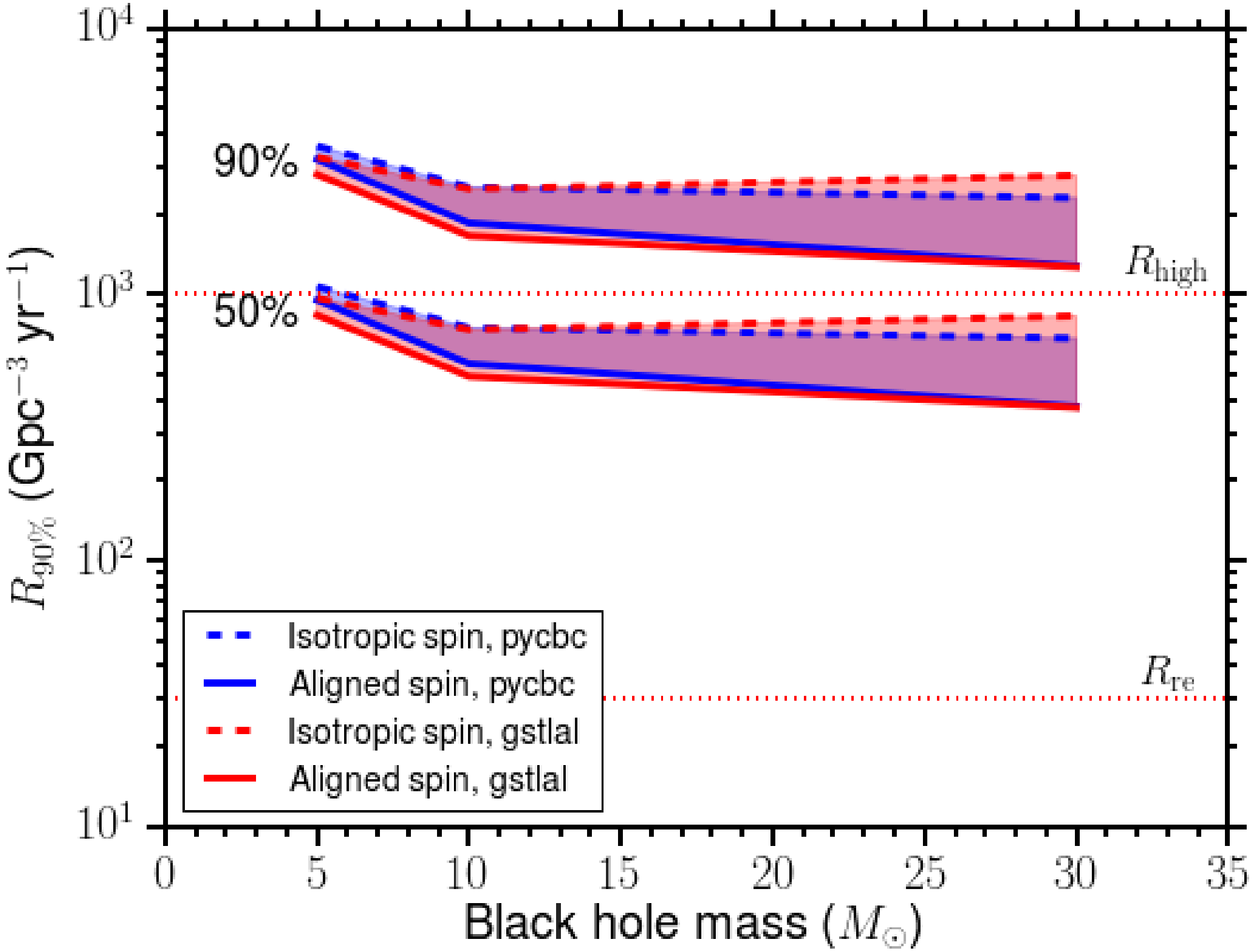

Spins :

Neutron star : $[0 - 0.04]$

Black hole : $[0 - 1]$

# Binary neutron stars & neutron star-black hole

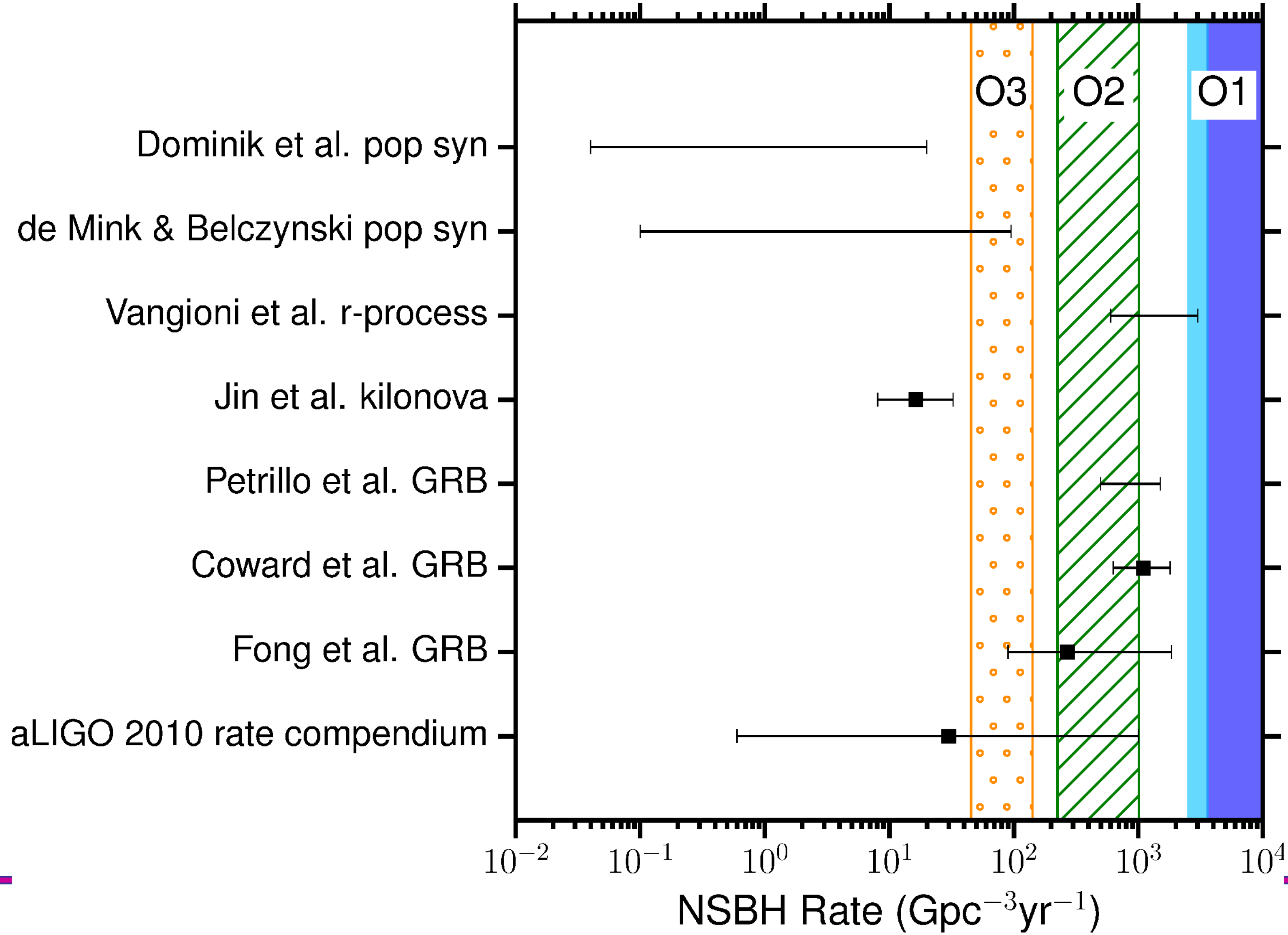
gr-qc:1607.07456



# Binary neutron stars & neutron star-black hole

gr-qc:1607.07456

**NS-BH predictions**



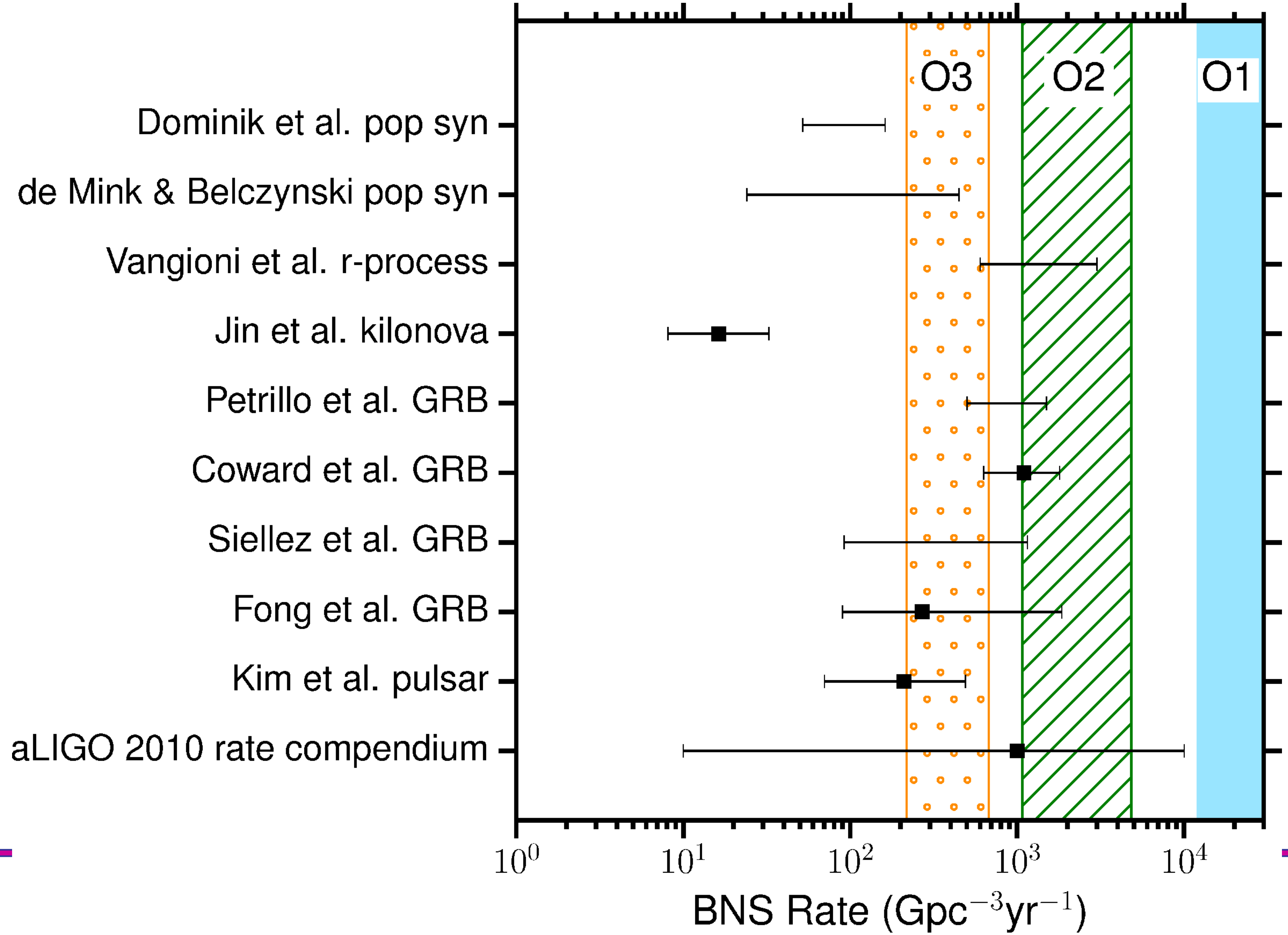

10-1.4 Msun

5-1.4 Msun

# Binary neutron stars & neutron star-black hole

gr-qc:1607.07456

**BNS predictions**



# Implications for a stochastic background of GWs

- For every detected binary merger, there are many more that are too distant and too faint.

- They generate a stochastic background of gravitational waves.

Source Energy Spectrum

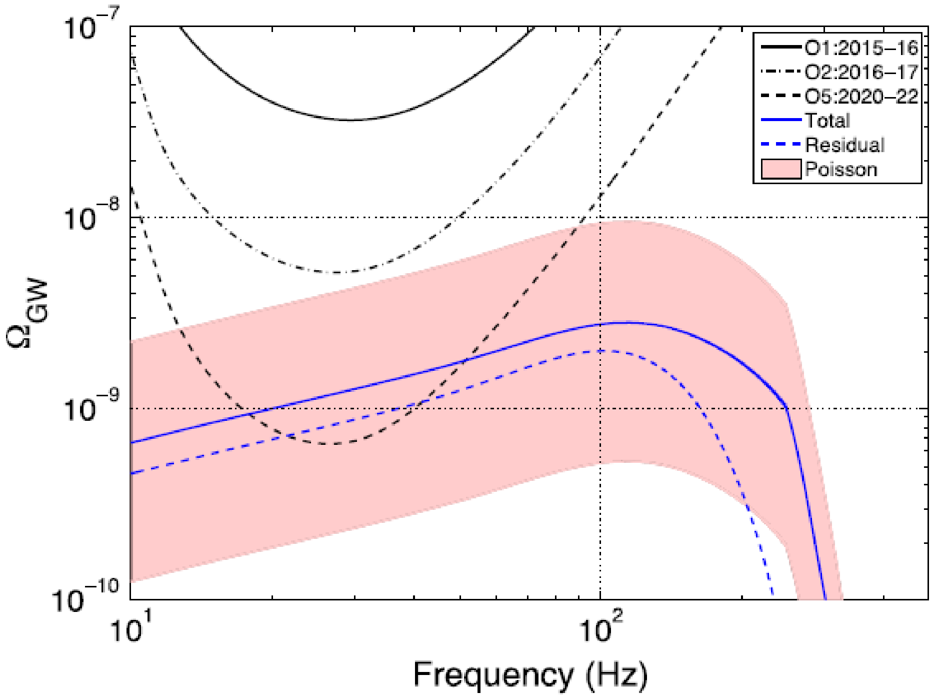
Merger Rate

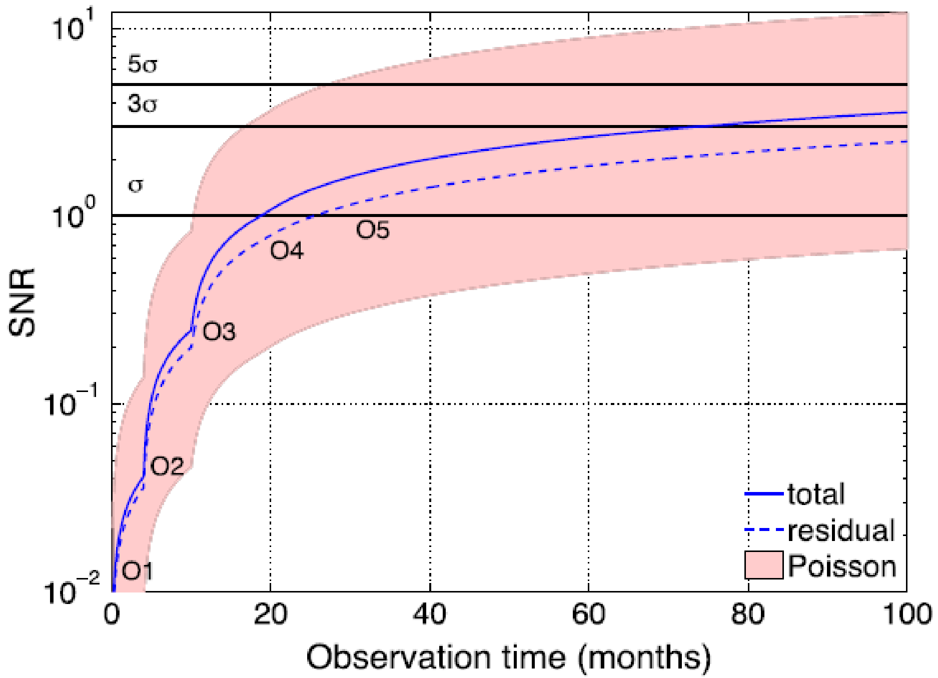
$$\Omega_{\mathrm{GW}}(f;\theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\max}} dz \frac{R_m(z,\theta_k)\frac{dE_{\mathrm{GW}}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_{\mathrm{M}},\Omega_\Lambda,z)}$$

Cosmology

- Relatively high rate and masses of observed systems prefer a relatively strong stochastic background.

# Fiducial models

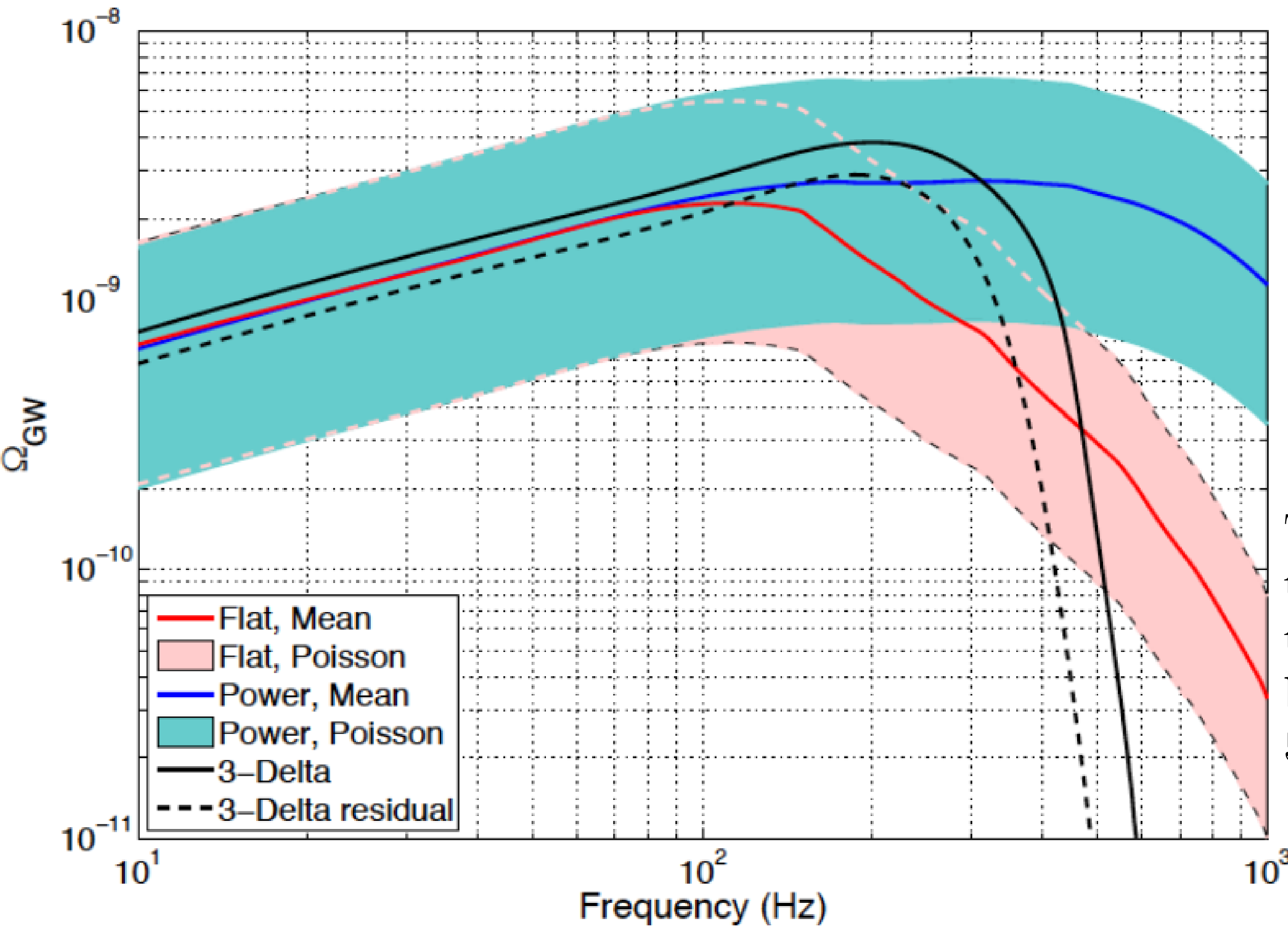



PRL 116, 131102 (2016)

- Many assumptions :
  - Field binary formation mechanism,
  - Assuming only GW150914 parameters.
  - Using chirp mass and merger rate distributions.
  - Formation-merger time delay distribution.
  - Metallicity distribution

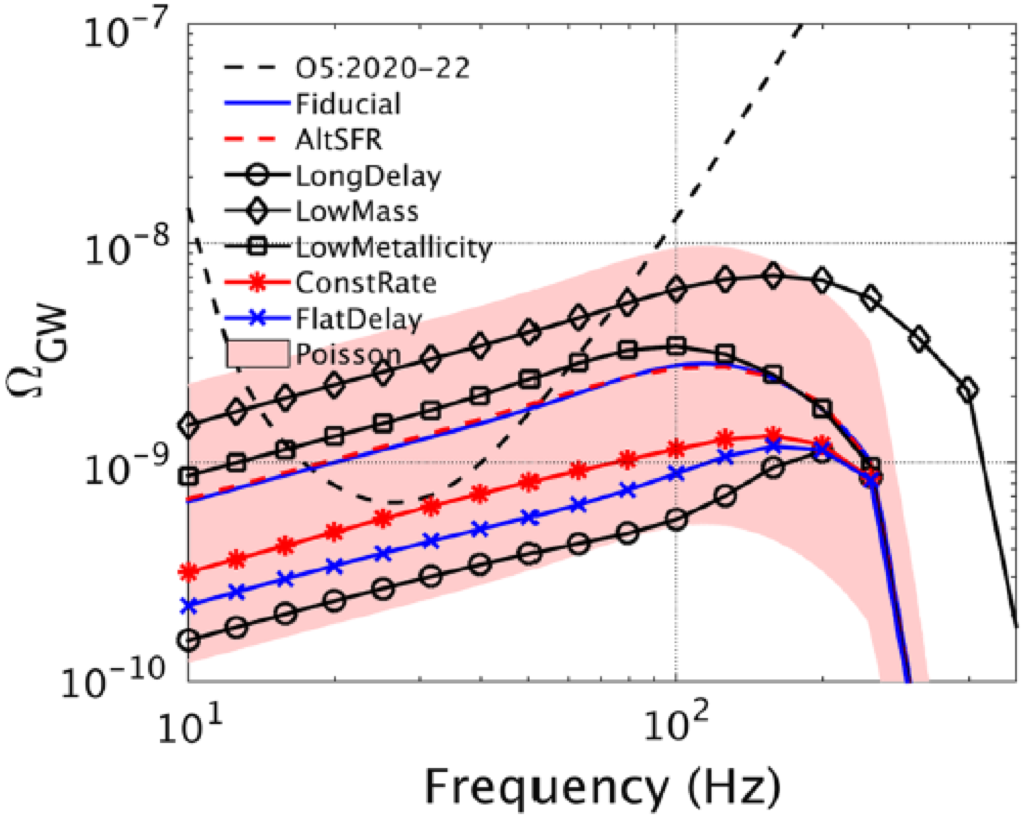
# Fiducial models (all of O1)




- 3 events
- Same mean value $\Omega_{gw}$ (25Hz)~ $10^{-9}$
- Less uncertainty

There is a very real probability that LIGO-Virgo will observe this BBH produced stochastic background in the next 3 to 5 years.

# Alternative models




- Model variations imply relatively small changes in the energy spectrum.
- Large Poisson statistical uncertainty.
- Dominated by z ~1-2 contributions.
- Conservative estimates.
- A foreground to cosmological models of stochastic background.

# O1 stochastic background search

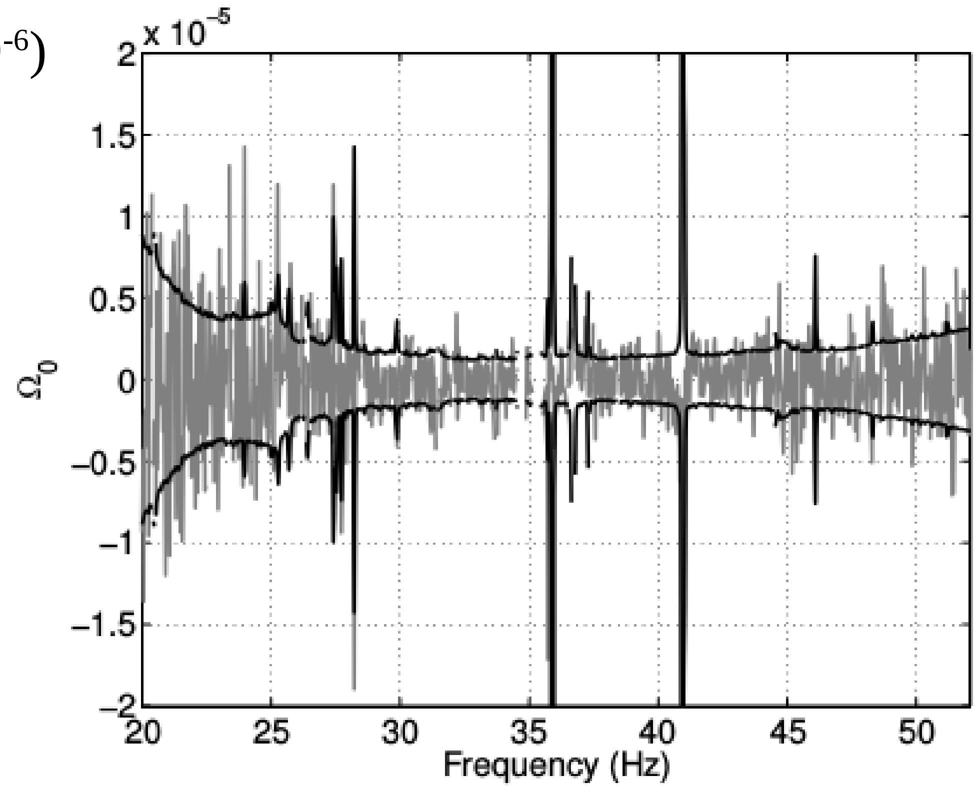
- Cross-correlating H1 & L1
- Preliminary result of the isotropic search :
  - 95 % confidence upper limit :

    $\Omega_o$<1.7 x $10^{-7}$ (previous : 5.6 x $10^{-6}$)
  - 95 % of sensitivity in the 20-55 Hz band

$$Y = \int_{-T/2}^{+T/2} dt_1 \int_{-T/2}^{+T/2} dt_2 \; s_1(t_1)\, s_2(t_2)\, Q(t_2 - t_1)$$

$$\tilde{Q}(f) = \frac{1}{N} \frac{\gamma(f)\, \Omega_t(f)}{f^3\, P_1(f)\, P_2(f)}$$

PRELIMINARY



# O1 un-modelled transient searches

- Have detected first (online) GW150914 because of the large masses.
- O1 data have been search for any un-modelled events in a large parameter space :
  - Short : 1 ms – 10s x 32 Hz – 4 kHz
  - Long : 10s – 500s x 24 Hz – 2kHz
- Search sensitivity estimated : ~3 times better than previous run → an order of magnitude better on the rate of events.
- Papers in preparation

# Towards O2

# Future observing runs

*Living Rev. Relativity*, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

LIVING REVIEWS in relativity

## Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
email: lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it

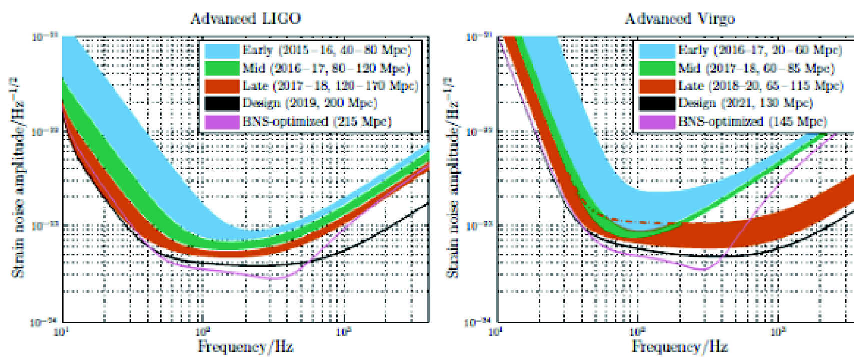




**Figure 1:** aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

**2015 – 2016 (O1)** A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

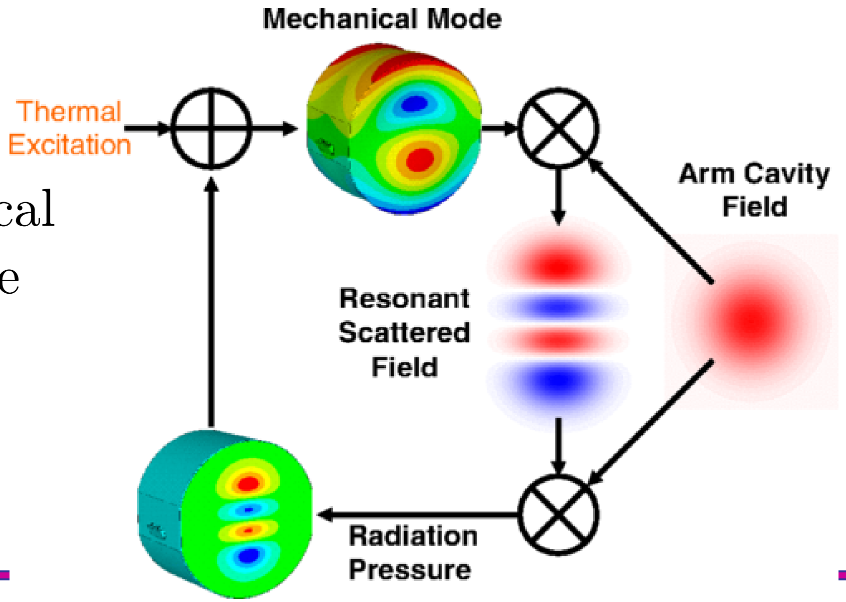
**2016 – 2017 (O2)** A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

**2017 – 2018 (O3)** A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

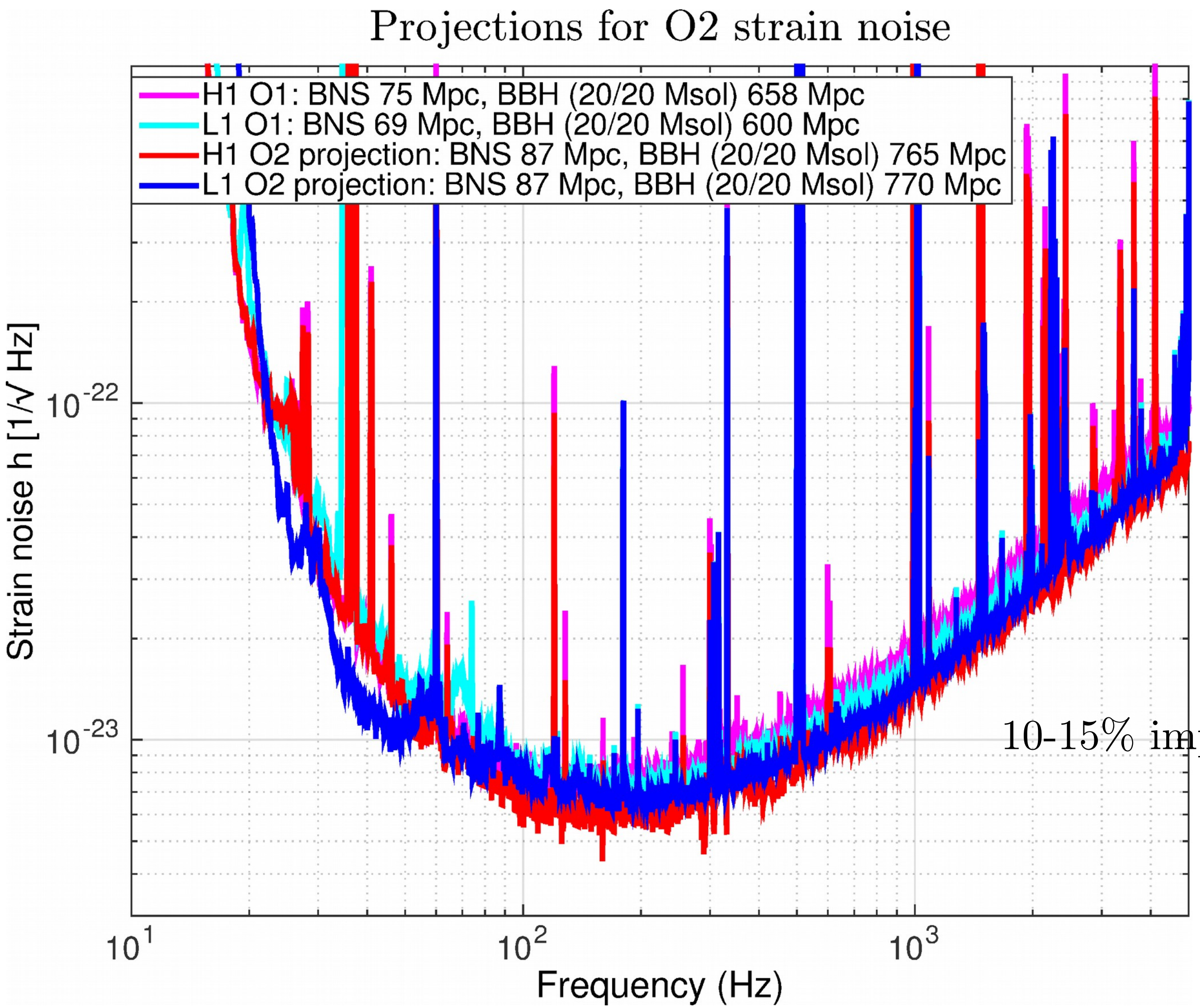
**2019+** Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.

# aLIGO : current activities

- Since O1 :
  - Noise hunting  at low-frequency to reduce « technical » noise
  - Increase laser power (35 W @ L1 – 50 W @ H1)
- Challenges :
  - Thermal lens in mirrors require more active thermal compensation
  - Mirror alignment control
  - Parametric instabilities : acoustic modes of the mirrors get excited and pump light in high order optical modes that become resonant in the arms.



# O2 LIGO strain prediction




10-15% improvement

# Advanced Virgo preparation

- Accumulated a serie of unexpected problems/accidents
  - Broken suspension blades due to H embrittlement
    - 160/260 blades changed
    - ~ 4 months of delay
  - Monolitic suspensions breaking : anchors culprit
    - Suspected cause : adV anchor glass contains OH that are eliminated through heating generating $H_2$ that migrates and creates bubbles during welding
    - 3/4 replaced with steel wires
    - Several months of delay
- Almost all hardware installed, commissioning has started last spring
  - Individual cavities locked : PR-NI, North arm, West arm
  - Start locking several coupled cavities together

# AdV installatioin in a nutshell

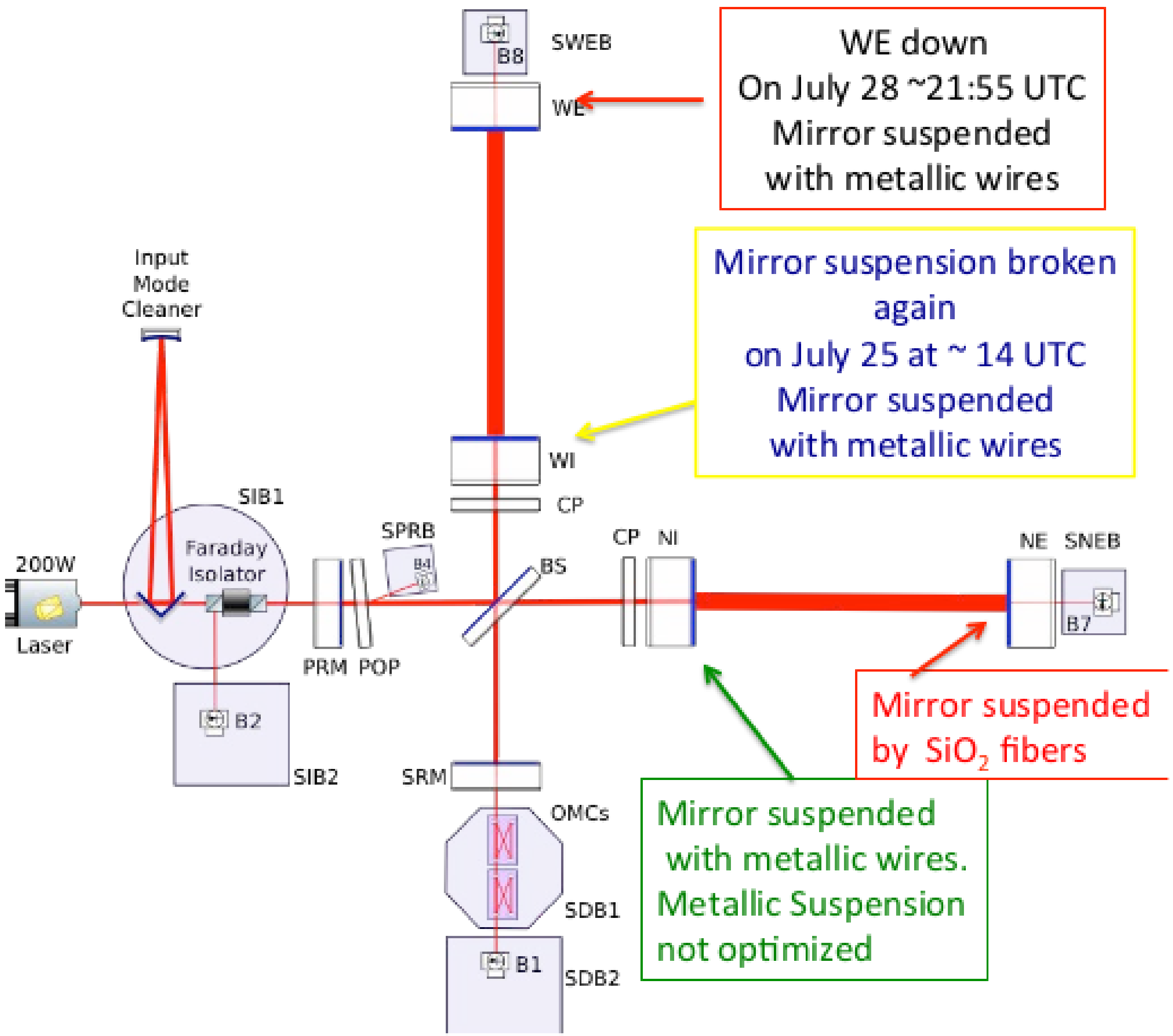
All the main parts of hardware are on-site and are installed

Final NI payload installation TBD soon

Failure of a NIKHEF blade solved promptly

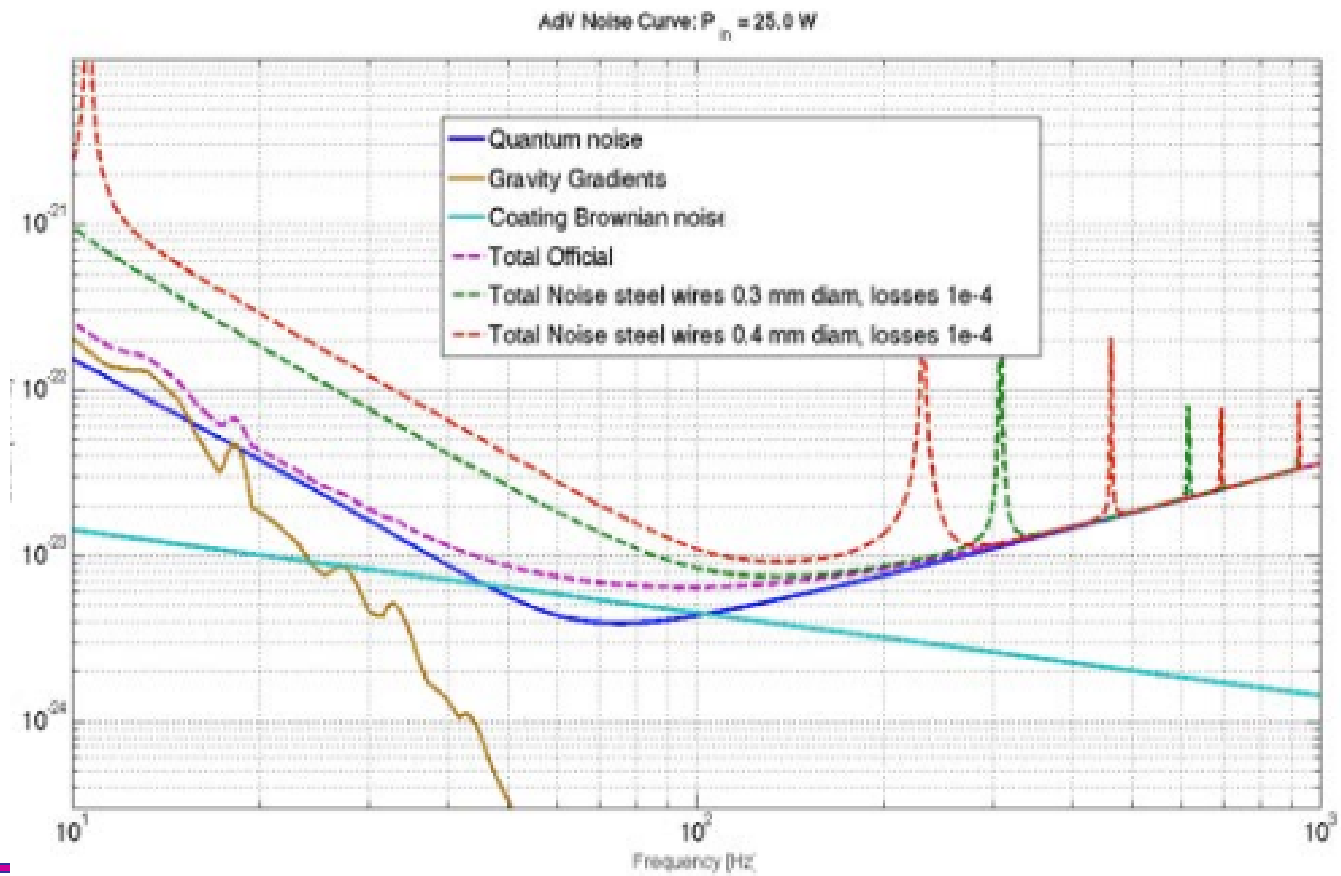
Commissioning of the North arm done. Arm locked. Light circulating also on CITF

West Input down again: action lan TBD



# Which sensitivity for O2 ?

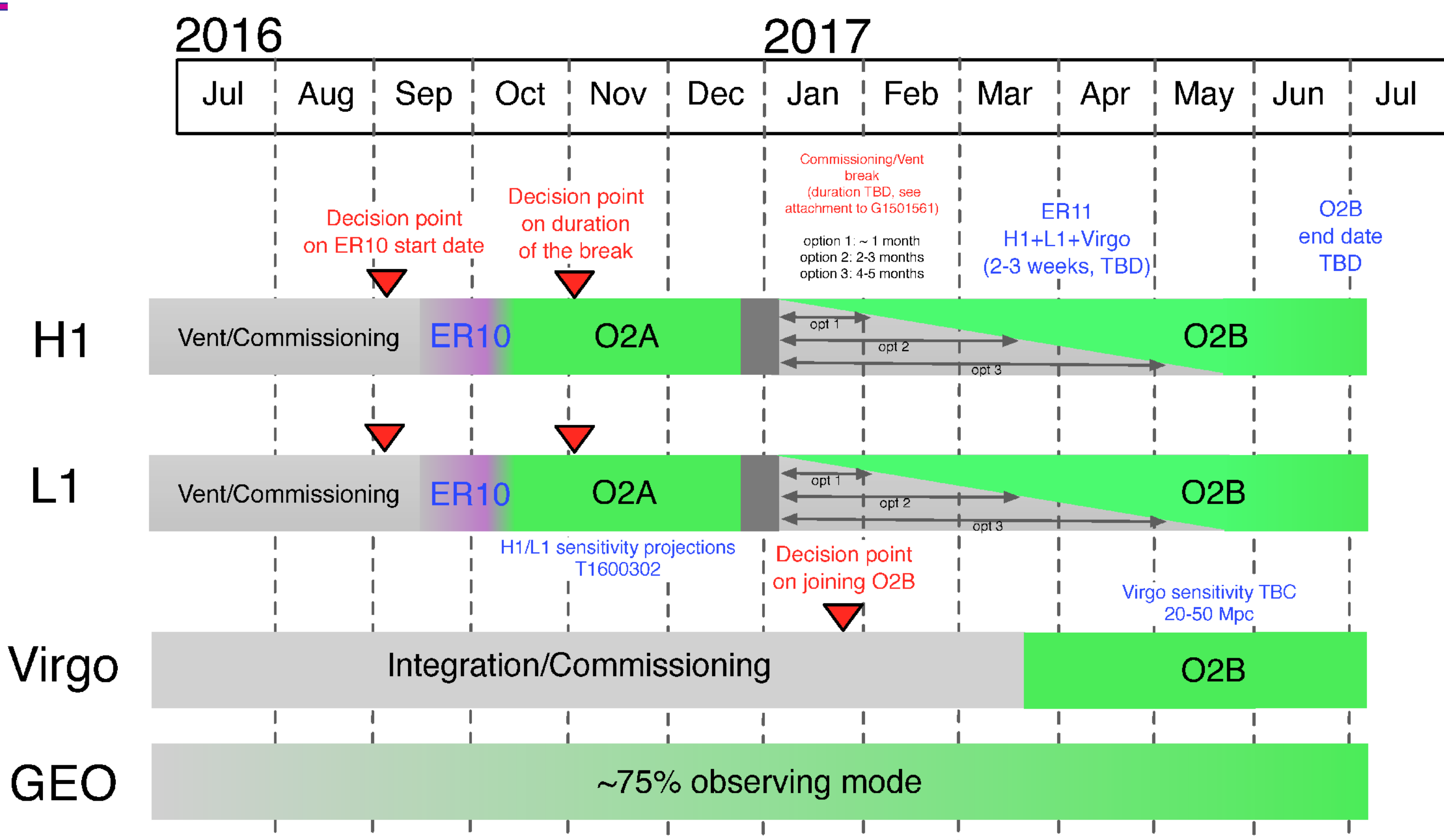
- Keep steel wires suspensions
- Join O2b with « relevant » sensitivity




| | Steel 300 µm $\phi=10^{-4}$ ($\phi=10^{-3}$) |
|---|---|
| Violin [Hz] | 307 |
| Bouncing [Hz] | 8.3 |
| BNS Horizon [Mpc] | 60 (45) |
| **BBH Horizon [Mpc]** | **313 (202)** |

Joint Run Planning Committee

# Working schedule for O2 (G1501561- v8)




Detector operational,commissioning mode (small fraction of observing mode time)

Detector not producing data (Downtime)

Detector in observing mode for a fraction of the time during Engineering Runs (ERs)

24/7 observing mode (Observing Run, EM alerts)

# O2 decision points (@JRPC)

## O2 timeline: decision points for LIGO

- Early August: decision on ER10 starting date, based on:
  - Progress on L1 relock (L1 hasn't yet relocked after major vent, expected to start re-locking full interferometer end of July)
  - H1 noise performance at high power (best O1 low frequency performance not recovered yet below 200 Hz)
- Early October: decision on duration of commissioning/vent break after O2A, based on:
  - L1 and H1 performance during O2A (if exceeding current expectations and sensitivity is around 100 Mpc, best option is to have only a few weeks break to allow maintenance and some commissioning investigations, then keep running)
  - Readiness/installation schedule of new components to be installed in H1/L1 to improve sensitivity/robustness, i.e.: new laser amplifier for LLO

# Unexpected difficulties in Livingston

# Conclusions

- This has been a terrific year !
  - Direct GW discovery
  - First observation of massive black holes
  - First observation of binary black hole mergers
  - Start of :
    - Strong field tests of GR
    - Constrain binary system formation mechanisms
- More observation runs planned 2016-2020 (+KAGRA online 2018)
  - O2 : more BBH events expected and maybe first NSBH event ?
- New call for partnerships with EM partners

# BBHs expectations in next runs

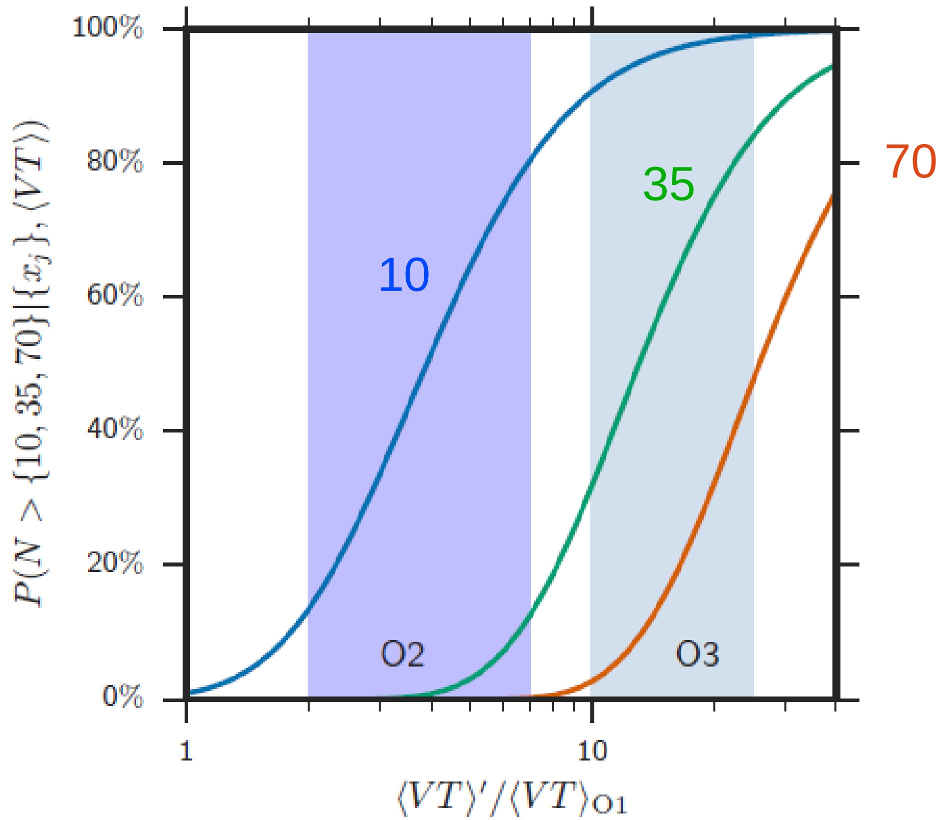



FIG. 12. The probability of observing $N > 10$, $N > 35$, and $N > 70$ highly significant events, as a function of surveyed time-volume. The vertical line and bands show, from left to right, the expected sensitive time-volume for the second (O2) and third (O3) advanced detector observing runs.