Expected evolution of Advanced LIGO sensitivity

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(in part on behalf of the
LIGO Scientific Collaboration)

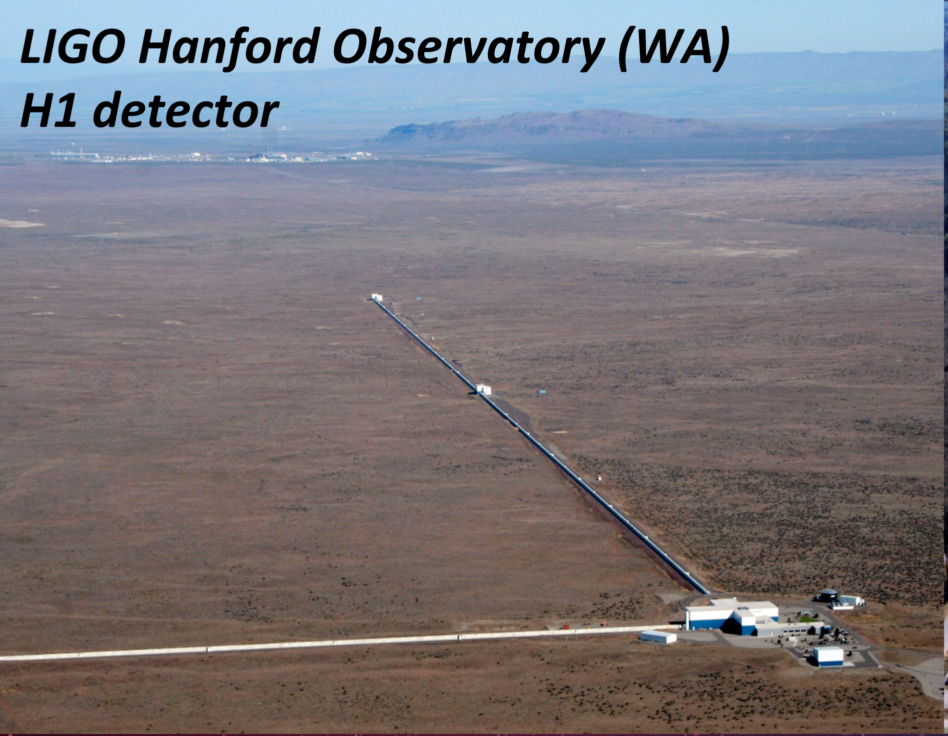
LIGO Document **G1700581**

Outline

- Advanced LIGO detectors performance during the first and second observing runs (O1 & O2)
  - on behalf of the LIGO Scientific Collaboration

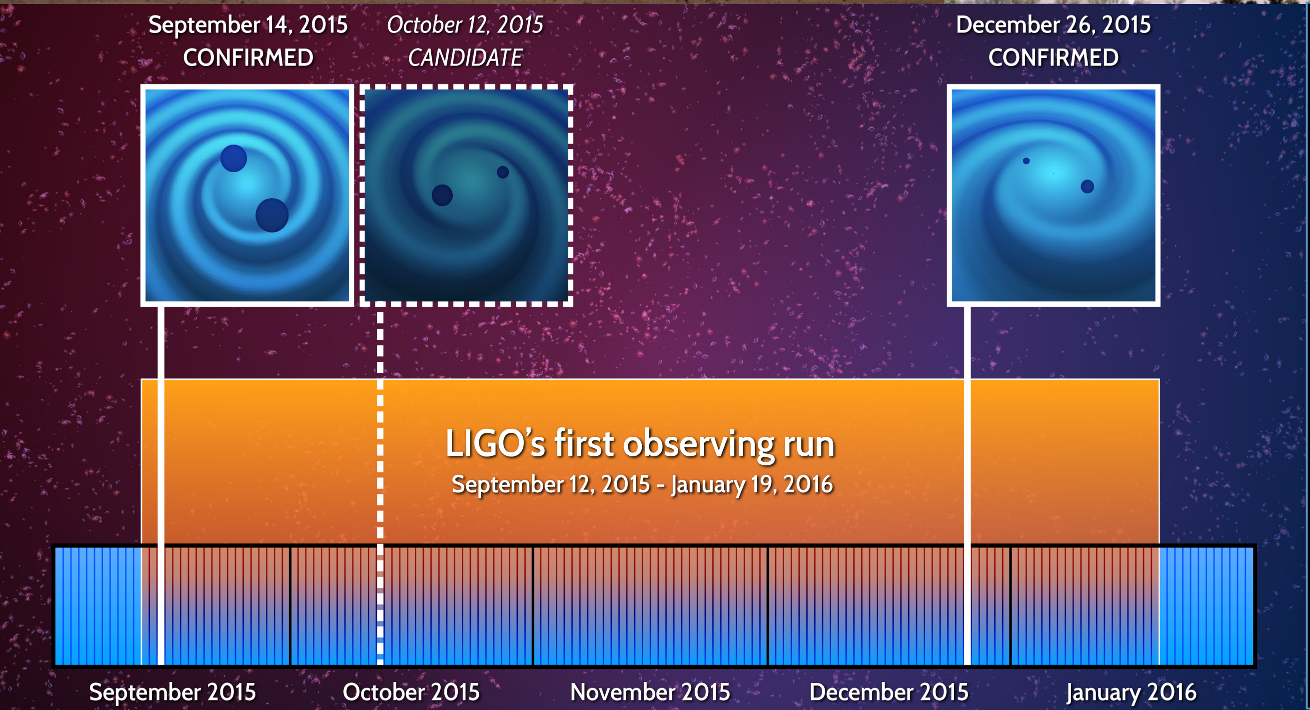
- Plausible scenario of Advanced LIGO sensitivity evolution in the upcoming years

- Beyond Advanced LIGO



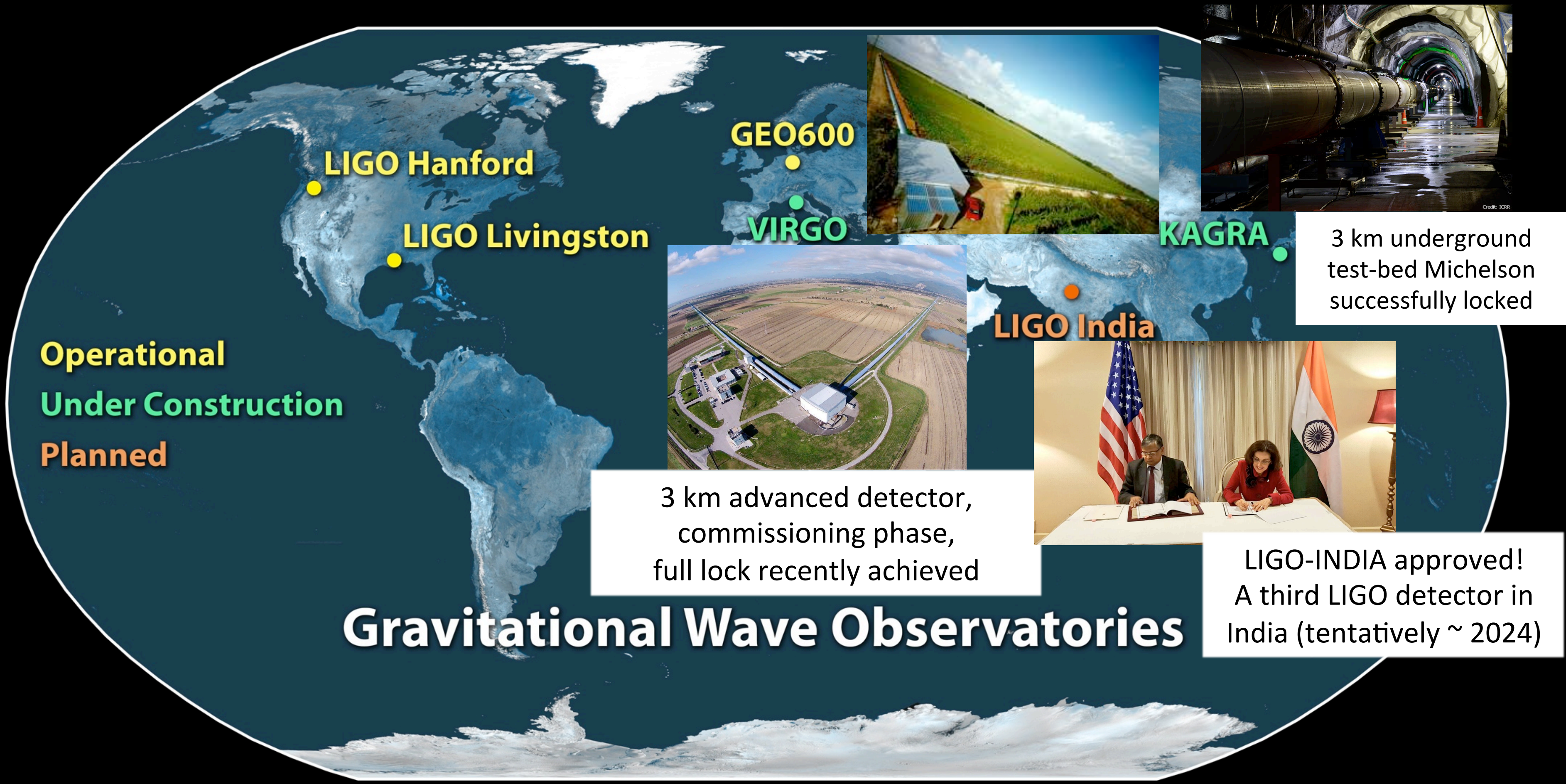
LIGO Hanford Observatory (WA)
H1 detector

LIGO Livingston Observatory (LA)
L1 detector



2 confirmed
black hole binary
mergers
in the first aLIGO
observing run O1
(Sep 2015 – Jan 2016)

The upcoming world-wide network



Credit: ICRR

3 km underground
test-bed Michelson
successfully locked

3 km advanced detector,
commissioning phase,
full lock recently achieved

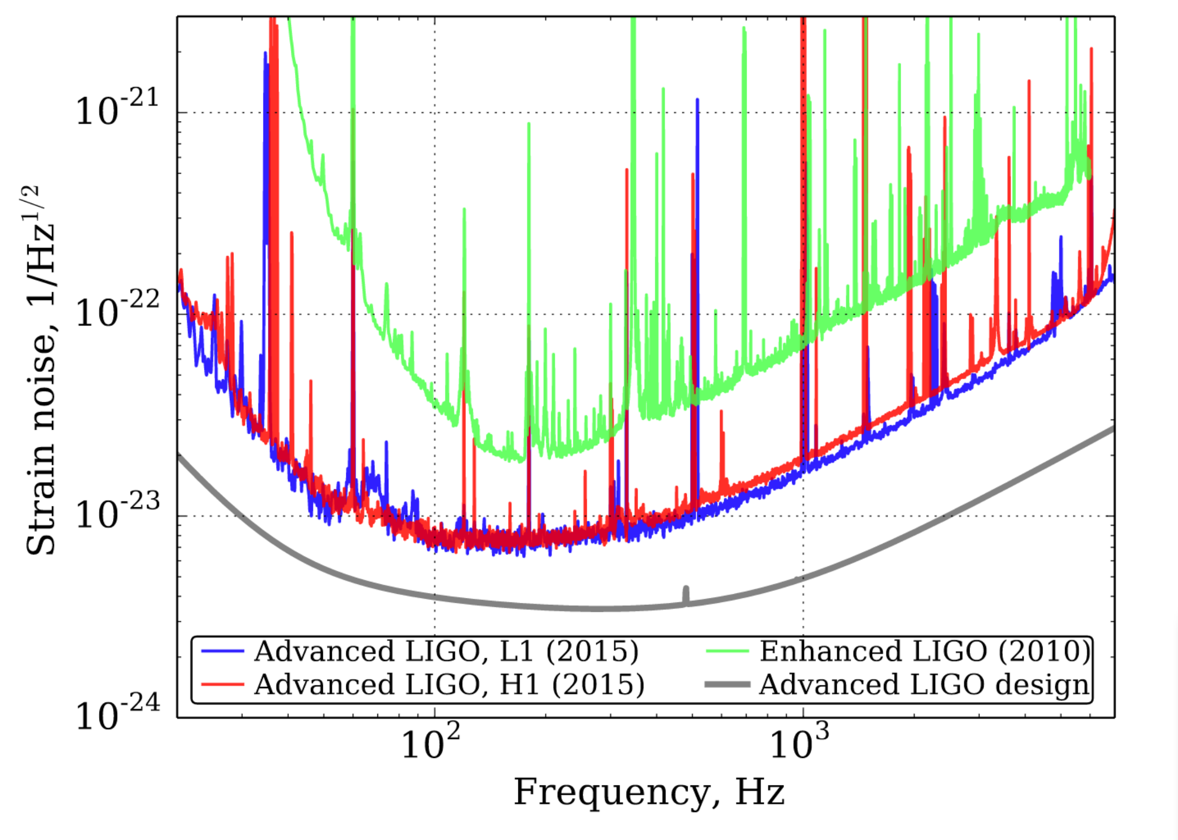
LIGO-INDIA approved!
A third LIGO detector in
India (tentatively ~ 2024)

Next talk by Duncan Brown

Strain noise during O1:

better than ever, not at design sensitivity yet

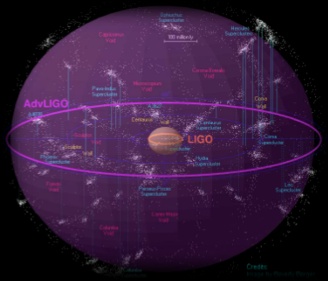
"Strain Noise"
=
Detector noise
expressed as
equivalent
GW strain, h



Initial LIGO (2010)

O1 (2015)

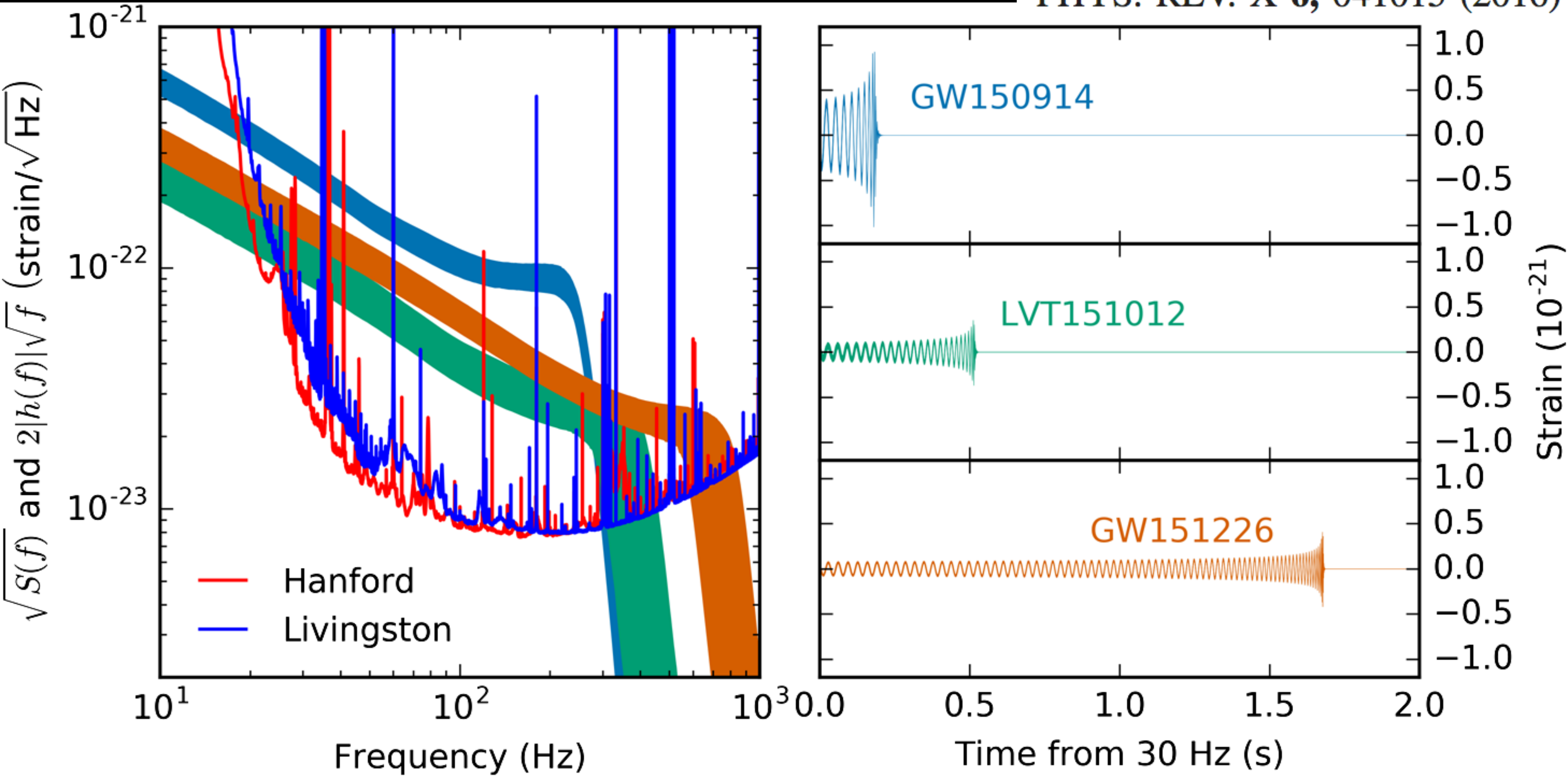
Advanced LIGO Design



Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy D. V. Martynov et al. Phys. Rev. D 93, 112004

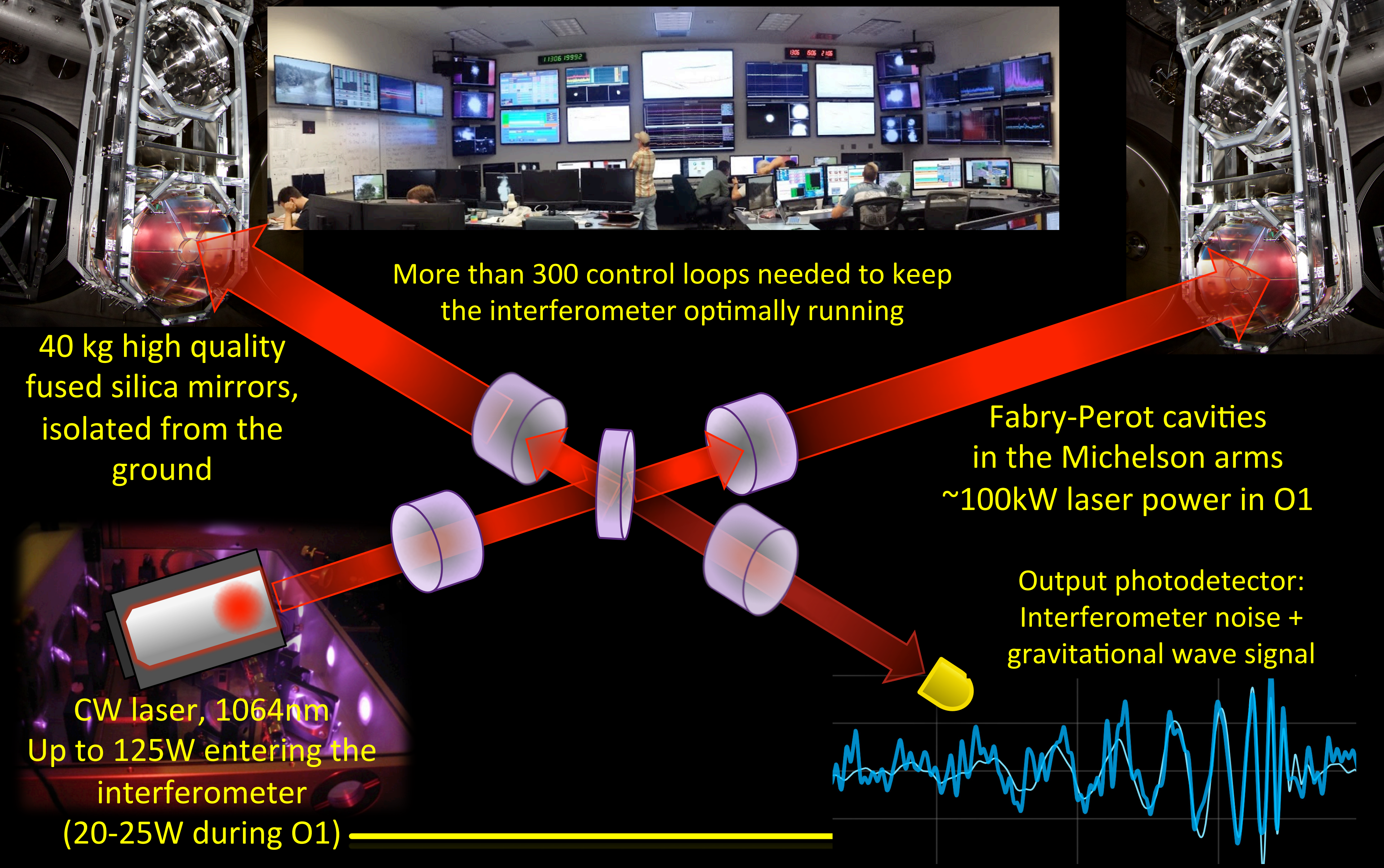
Summary of Observing Run O1 results

PHYS. REV. X **6,** 041015 (2016)



Vicky Kalogera's talk on Monday

The Advanced LIGO detectors



More than 300 control loops needed to keep the interferometer optimally running

40 kg high quality fused silica mirrors, isolated from the ground

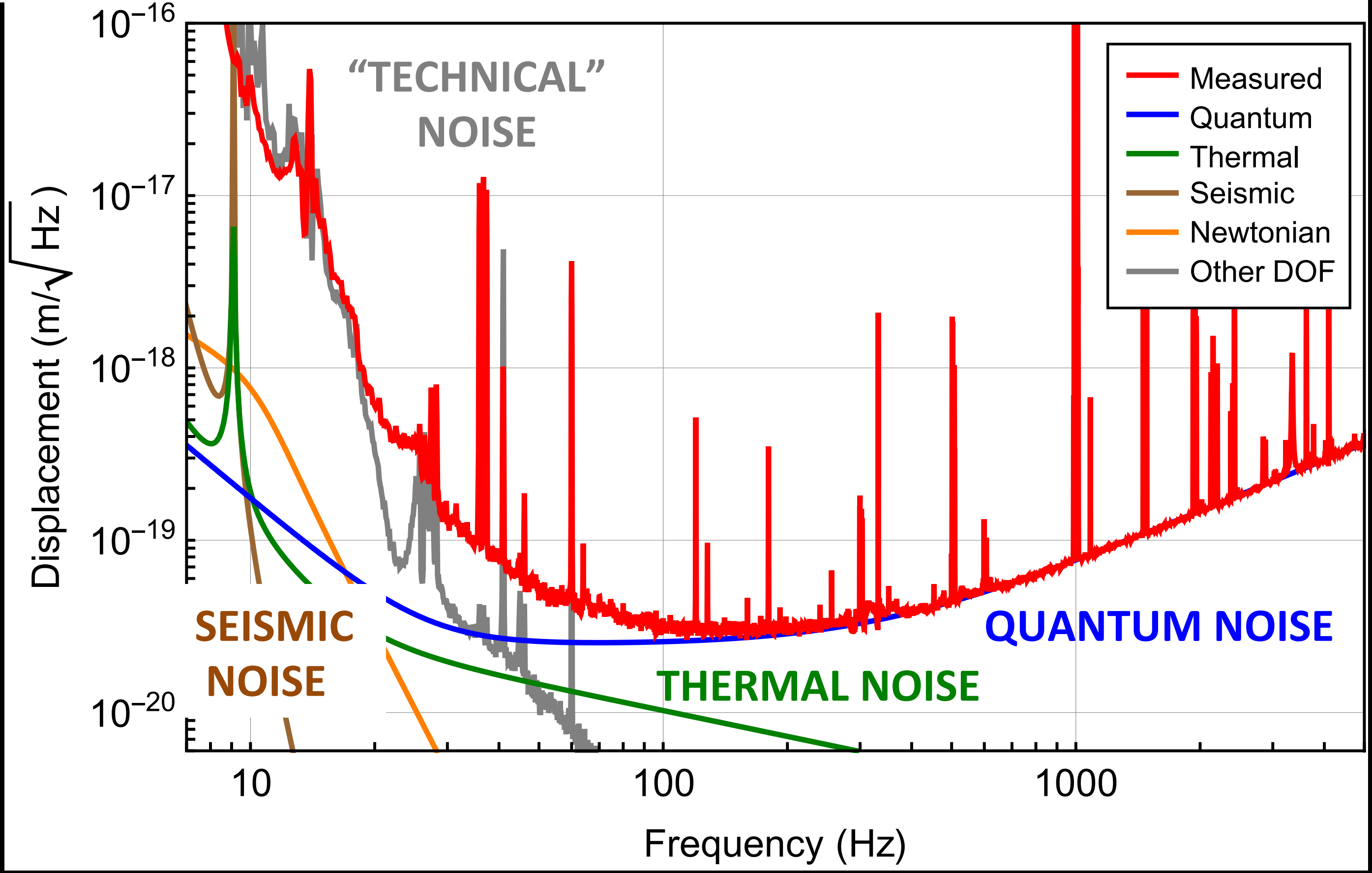
Fabry-Perot cavities
in the Michelson arms
~100kW laser power in O1

Output photodetector:
Interferometer noise +
gravitational wave signal

CW laser, 1064nm
Up to 125W entering the interferometer
(20-25W during O1)

Interferometer Displacement Noise (H1 in O1)

$$h\left[\frac{1}{\sqrt{Hz}}\right]=\frac{\Delta L}{L}\,\frac{[m/\sqrt{Hz}]}{[m]}$$



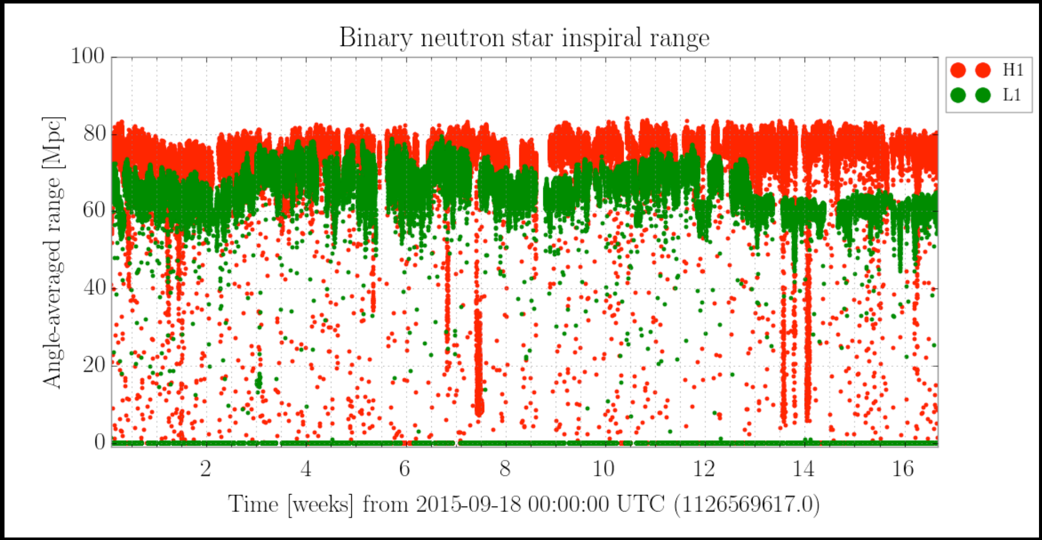
GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (Phys. Rev. Lett. 116, 131103)

Observing Run O1

(from mid-September 2015 to mid-January 2016)

- ✓ During O1: H1 and L1 operational for ~4 calendar months
- ✓ Duty cycle: H1 = 62%, L1 = 55% → H1&L1 = 43%
- ✓ 51.5 days of coincident time, 48.6 days after data quality process

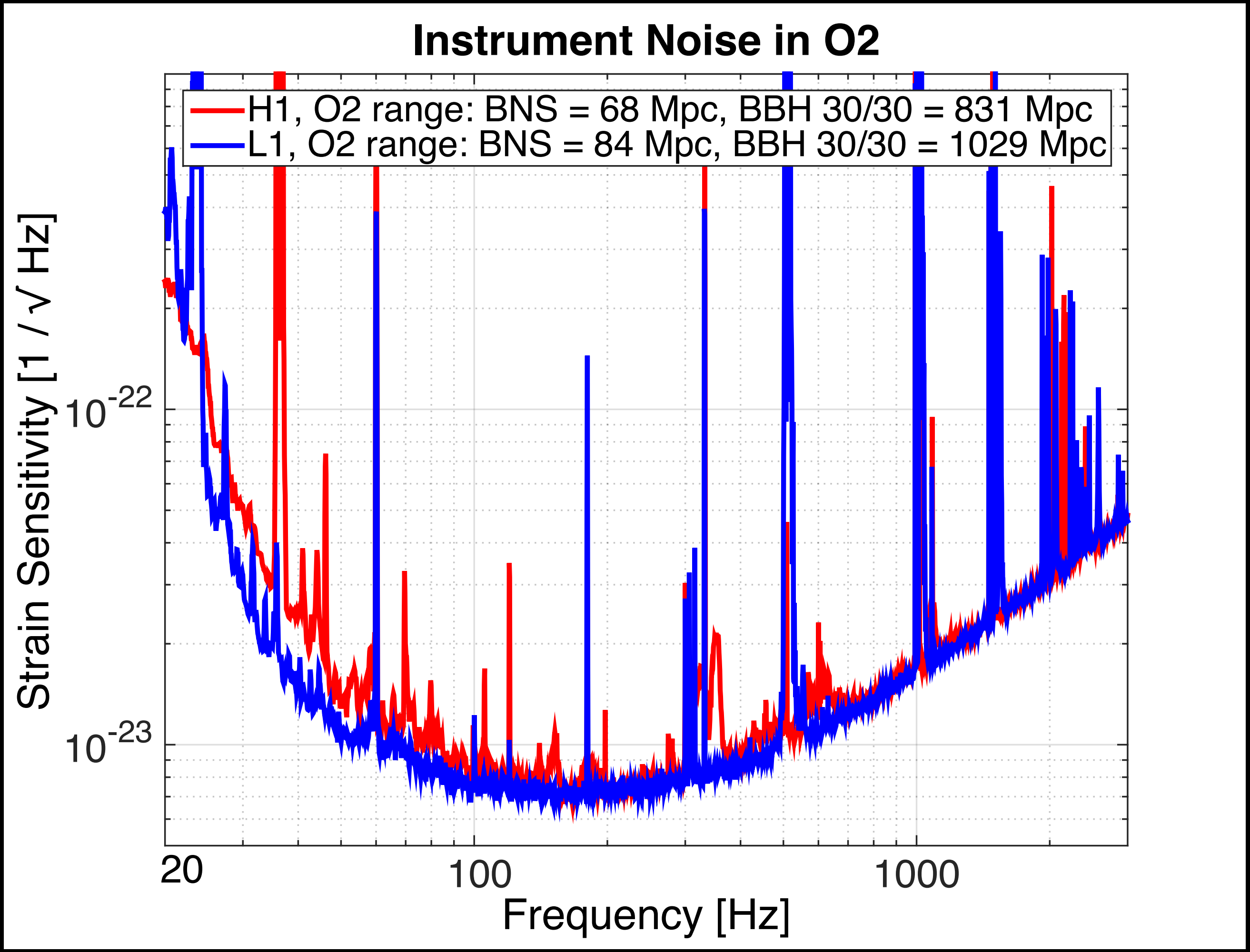
The product of observable volume and measurement time exceeded that of all previous runs within the first 16 days of coincident observation



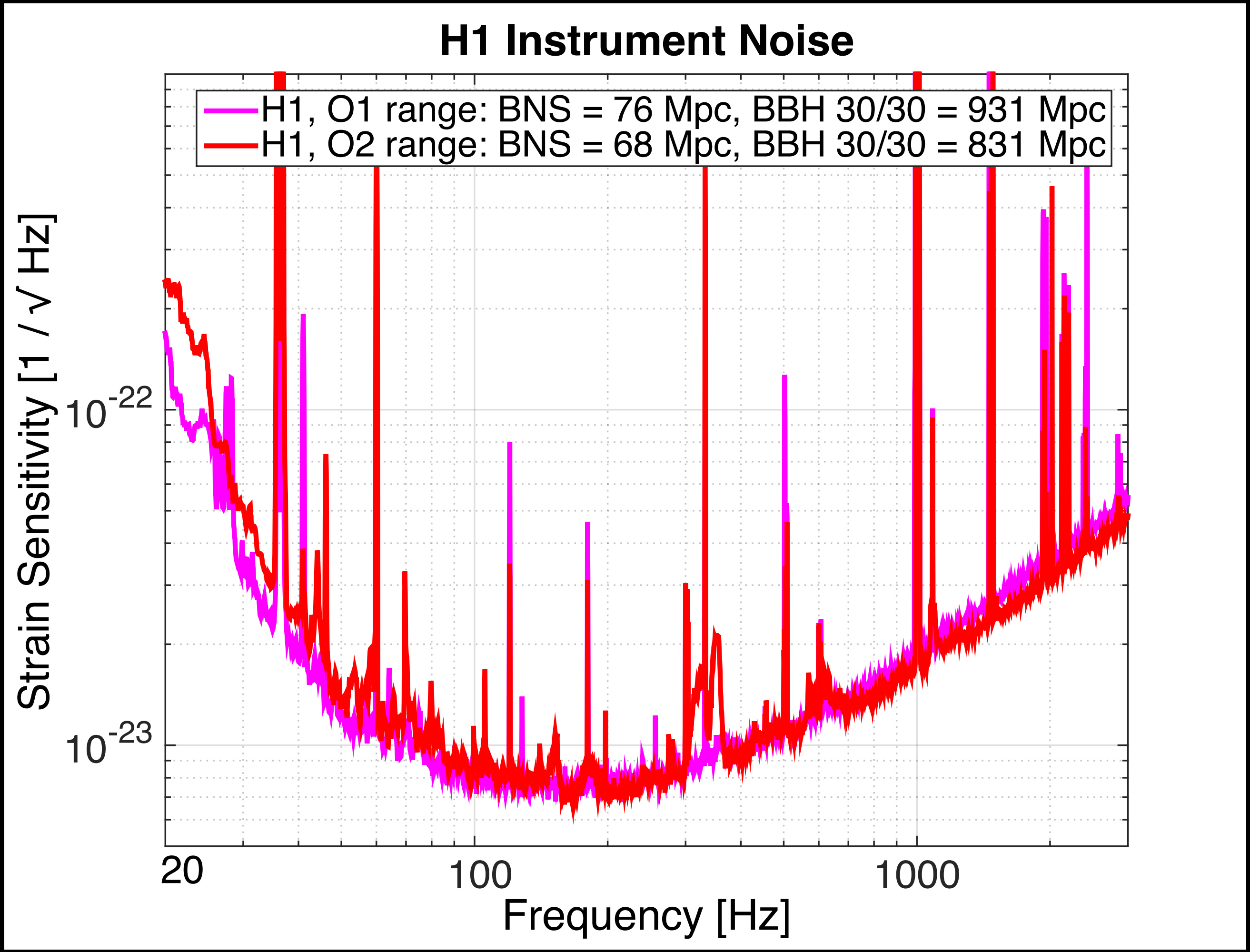
Since the end of the first Observing Run O1

- 10 months (January – October 2016) of work on both Livingston and Hanford detectors to reduce detector noise, improve duty cycle and data quality
- Main activities:
  - H1: laser power increase
    - Required commissioning of high power laser and improvements in interferometer control
  - L1: mitigation of scattered light noise, interferometer robustness, (failed) attempt to laser power increase
    - Required hardware changes inside the vacuum chambers
- Transition into engineering run in November 2016

Observing Run O2: typical sensitivity



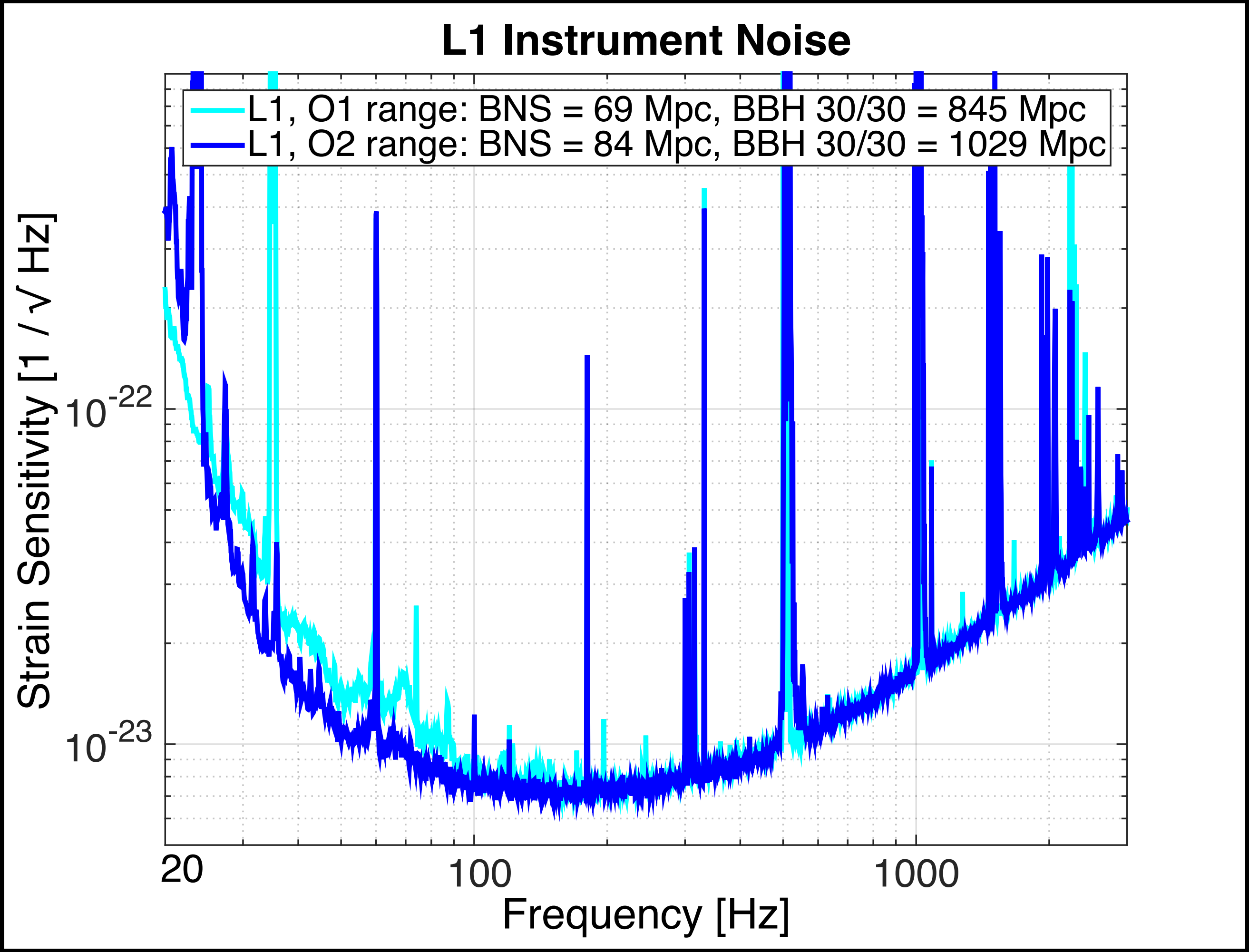
Comparison O2 vs O1: H1 detector



Noise improvement at high frequency due to 30% higher power

Overall range slightly worse (by 10%) due to not fully understood higher noise at low frequency

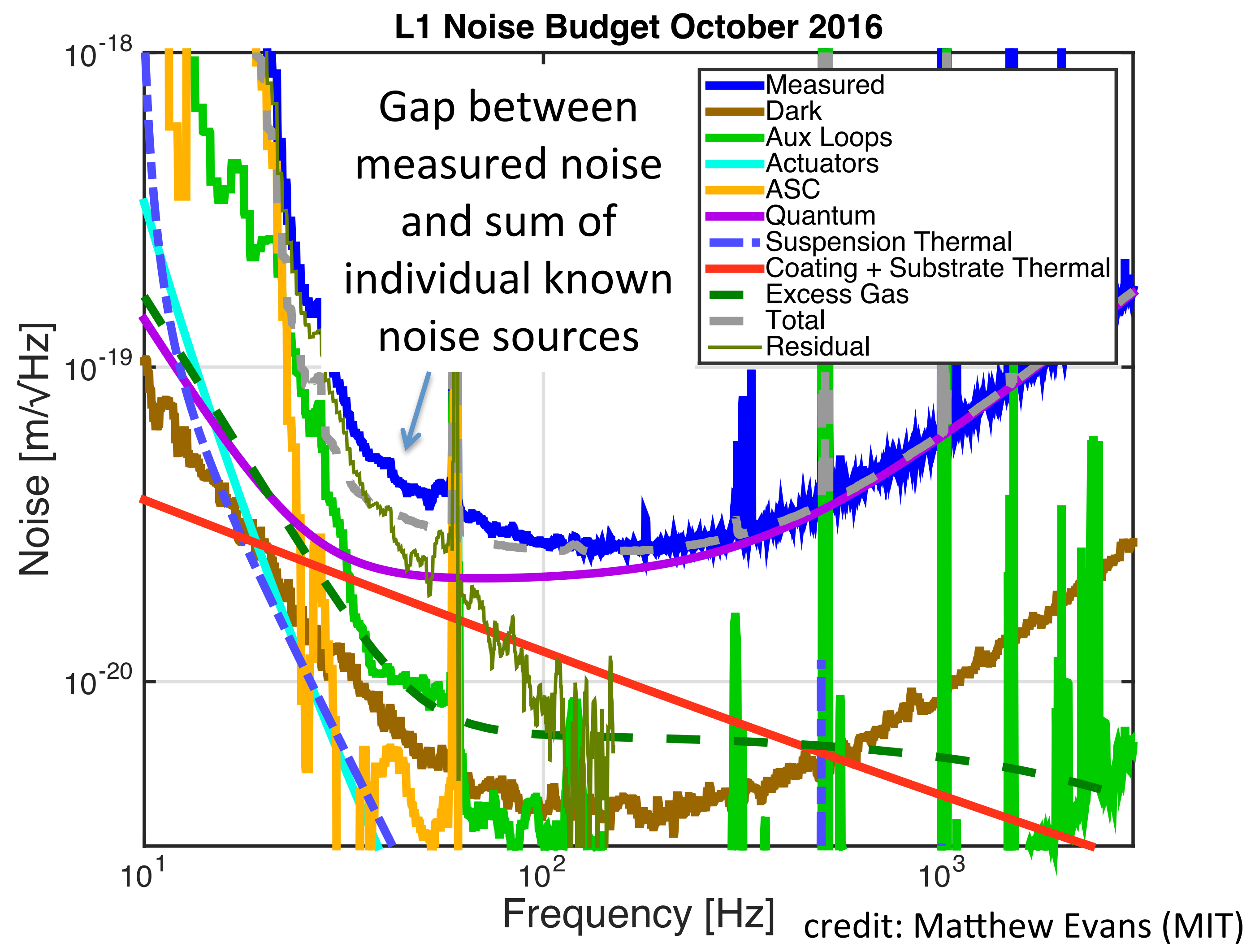
Comparison O2 vs O1: L1 detector



Improvement at low frequency mostly due to mitigated scatter light noise

Significant range improvement (+20%)

L1 noise budget



Gap between measured noise and sum of individual known noise sources

credit: Matthew Evans (MIT)

On-going Observing Run O2

- Started on November 30, 2016
- Scheduled break: Dec 22 – Jan 4
- 30 days of coincident data collected up to Feb 23
  - Significantly improved duty cycle of the two LIGO detectors in the last two months
- 3 event candidates have been identified by online analysis up to Feb 23 using a *loose false-alarm-rate threshold of one per month*, and shared with astronomer partners
  - Off-line analysis of the data in progress

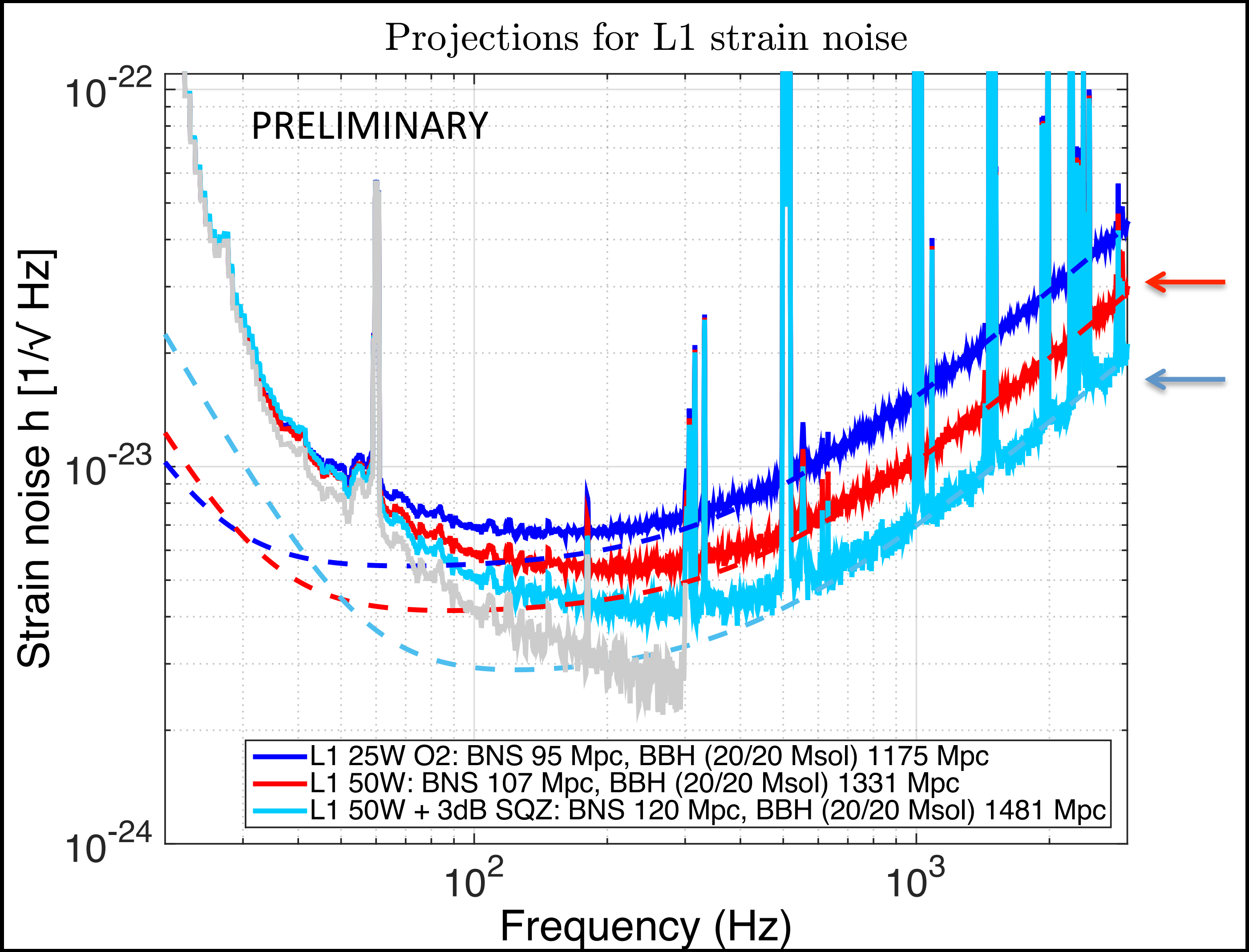
Observing Run O2 duration

- Proposal to extend O2 through the end of August
  - Pending final decision by the LIGO Operations Management Team
  - If proposal accepted, O2 will collect about 9 calendar months of data
- Transition from 2 LIGO detector network to 3 detector network including Virgo in early summer (depending on Virgo status, final decision expected in a few weeks)

What's coming after O2?

- Commissioning will start right after the end of O2 for about a calendar year, possibly longer
- Main commissioning activities:
  - Further mitigation of scattered light
  - Laser power increase at both sites
  - Squeezed vacuum injection: quantum noise reduction similar to laser power increase, but using quantum optics technologies instead

Projections post-O2



x2 Higher power

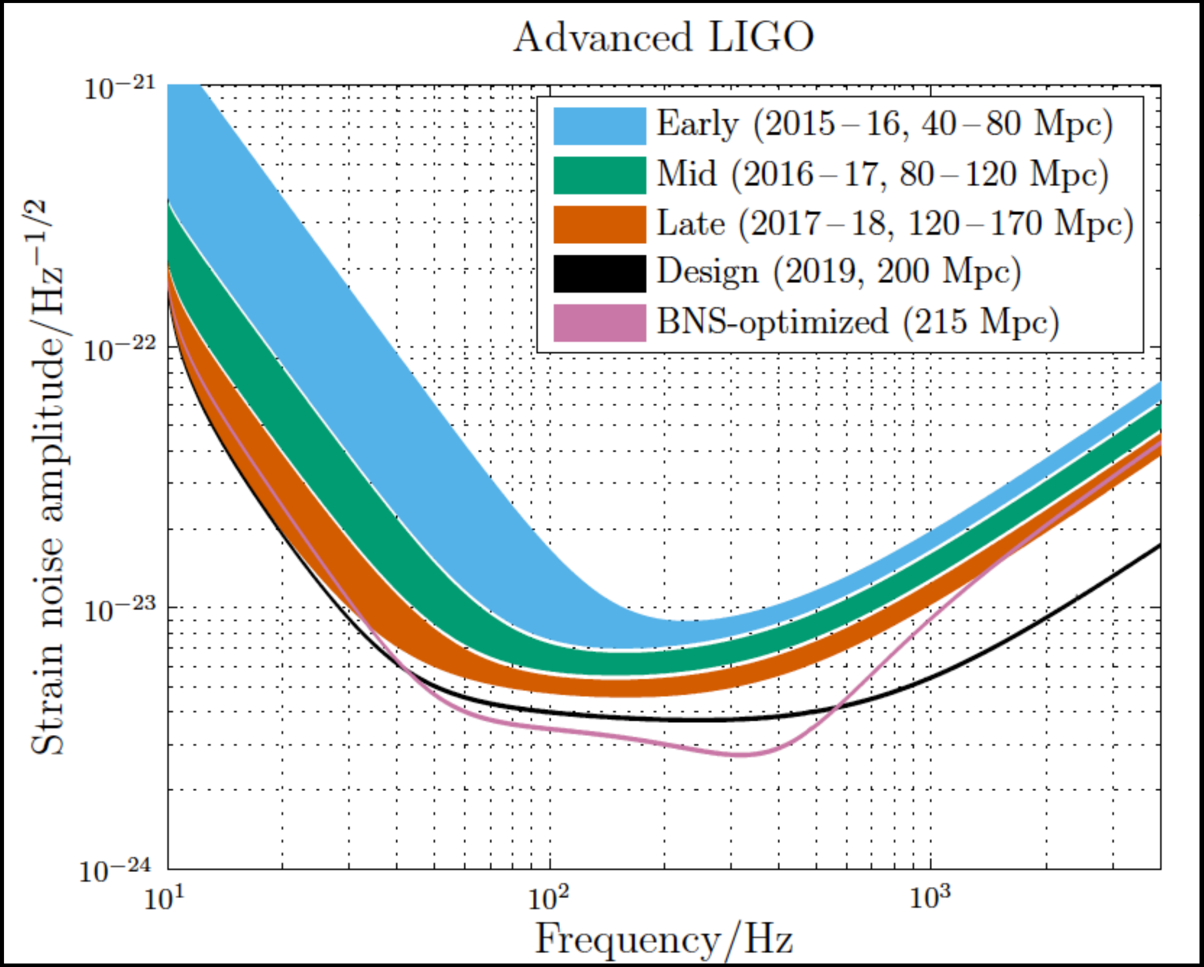
x2 Higher power + squeezing

No further reduction of low frequency noise assumed in this plot

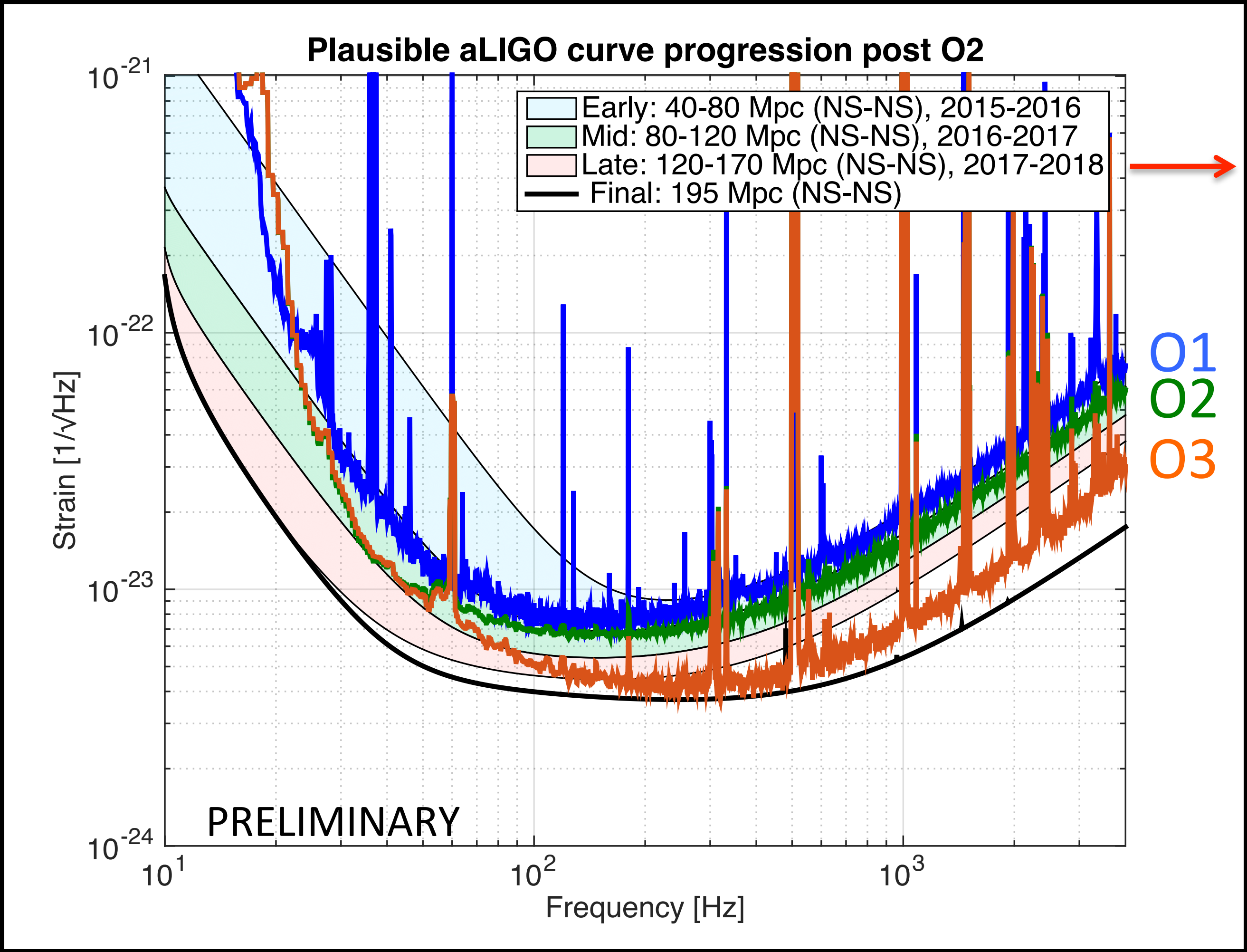
LIGO-Virgo Observing Plan

Live Observing document http://arxiv.org/abs/1304.0670

Working on an updated version including O2 plans



O3 projection with higher laser power and squeezing

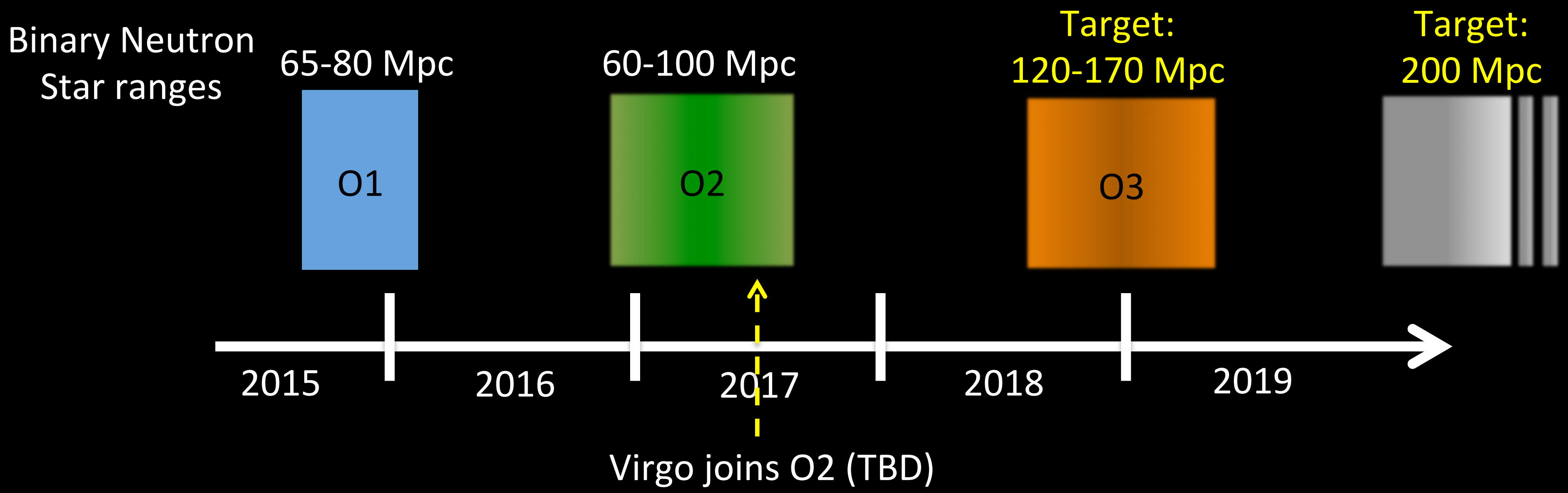


2018-2019

O1
O2
O3

Plausible Observing Run Timeline

(still under development within the LIGO and Virgo Collaborations)



Binary Neutron Star ranges

65-80 Mpc

O1

60-100 Mpc

O2

Target: 120-170 Mpc

O3

Target: 200 Mpc

2015

2016

2017

2018

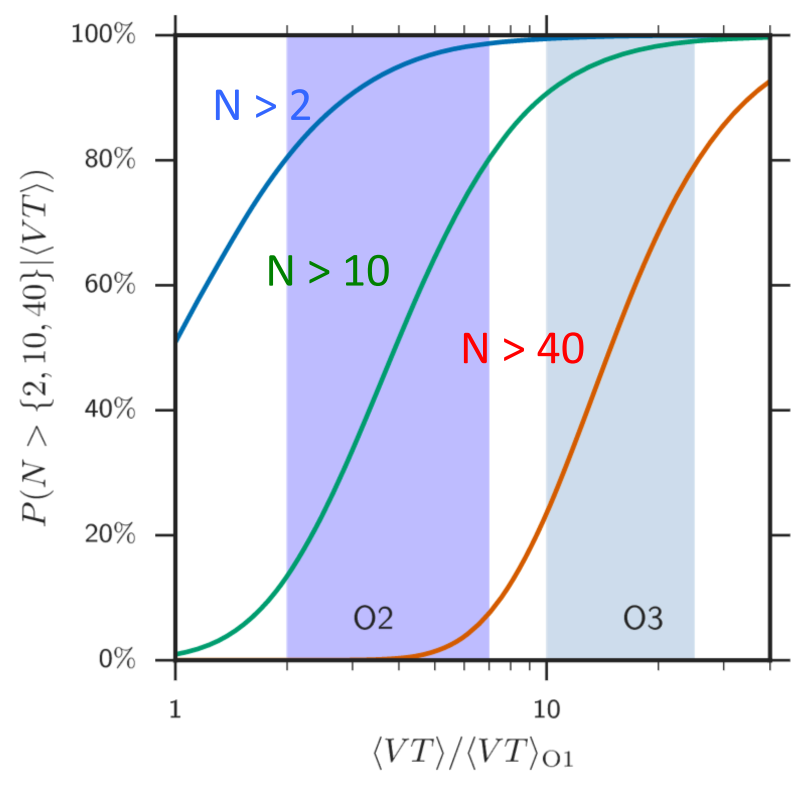
2019

Virgo joins O2 (TBD)

Conclusions - part I

- O2 is progressing well, it will possibly extend through the end of August
- Sensitivity improvement over O1 overall not as large as hoped for, but promising directions identified during commissioning work
  - Many activities to improve the detectors planned post-O2, commissioning period will be about 1 year long
  - We target a significant sensitivity improvement for O3

Binary Black Holes Rates



surveyed time-volume
(shown as multiple of VT during O1)

- Expect to see (at least) a few significant events by the end of O2
- Ten(s) of events by the end of O3

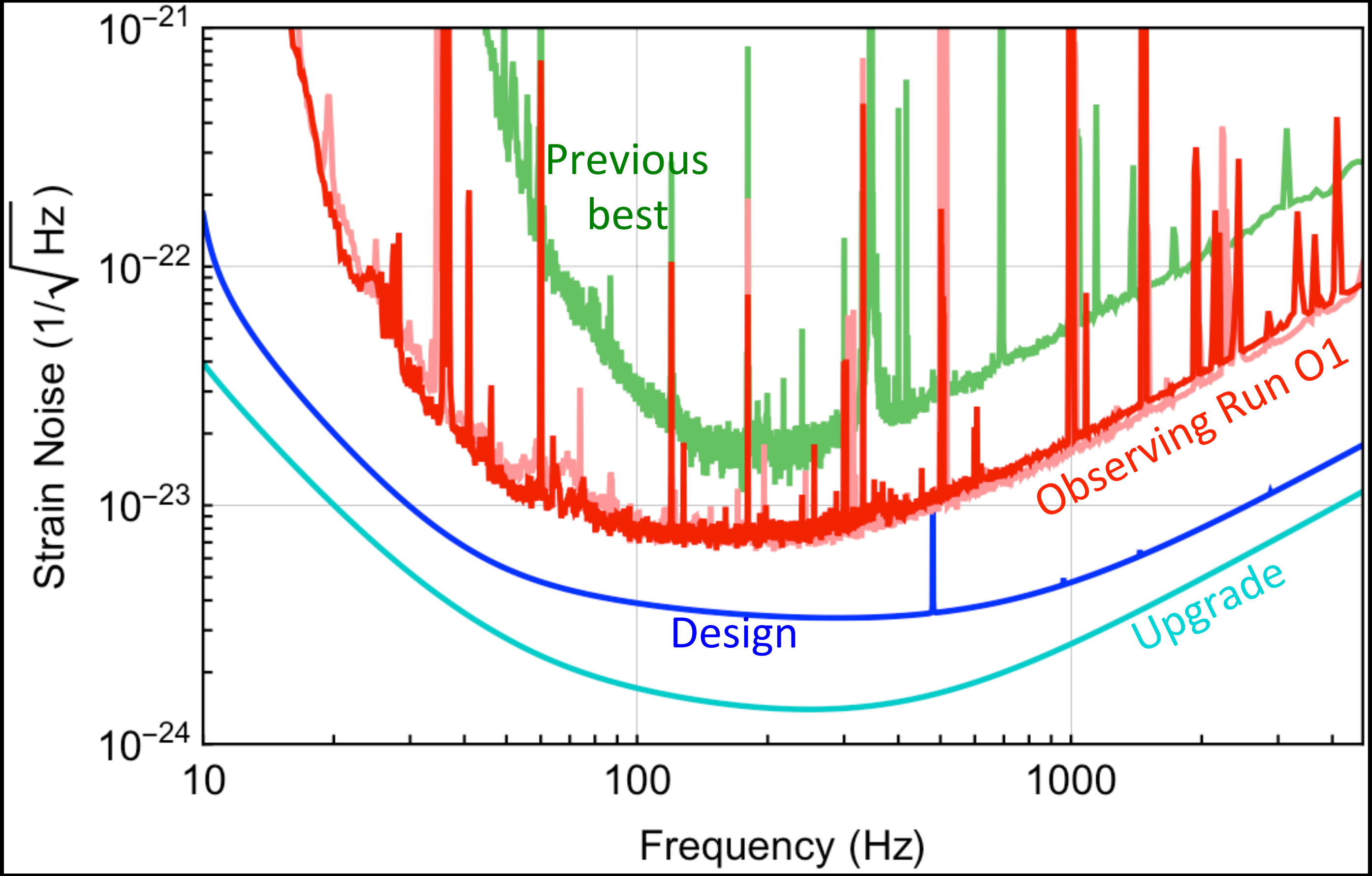
Current BBH rate: 9–240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

PHYS. REV. X **6,** 041015 (2016)

Near term vision beyond Advanced LIGO: A+

- Incremental upgrade to aLIGO that leverages existing technology and infrastructure
- Minimal new investment and moderate risk
  - ➔ More and “better” squeezing, improved mirror coatings to reduce thermal noise
  - ➔ Target: a factor of 1.7 increase in range over aLIGO design; about a factor of 5 greater event rate
- Plans are ramping up, A+ could be operational mid-2022 (with prompt funding)

A+: near term Advanced LIGO upgrade



GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (Phys. Rev. Lett. 116, 131103)

Looking further ahead:

new technologies IN current facilities

- New technologies in current facilities
  - goal is to reach the sensitivity limit allowed by current facilities (3-4 times better sensitivity than Advanced LIGO design)
  - might require changing wavelength of laser light, new materials for mirrors and coatings, cryogenics operations

- R&D on-going, envisioned as post-A+ upgrade

Ultimately, we need new technologies AND new facilities for x10-20 better sensitivity than Advanced LIGO

Einstein gravitational wave Telescope

Conceptual Design Study

http://www.et-gw.eu/

10km triangular shape, underground, multiple co-located detectors

Cosmic Explorer (CE):

- on the surface
- L-shaped
- up to 40 km

Ultimately, we need new technologies AND new facilities for x10-20 better sensitivity than Advanced LIGO

Einstein gravitational wave Telescope

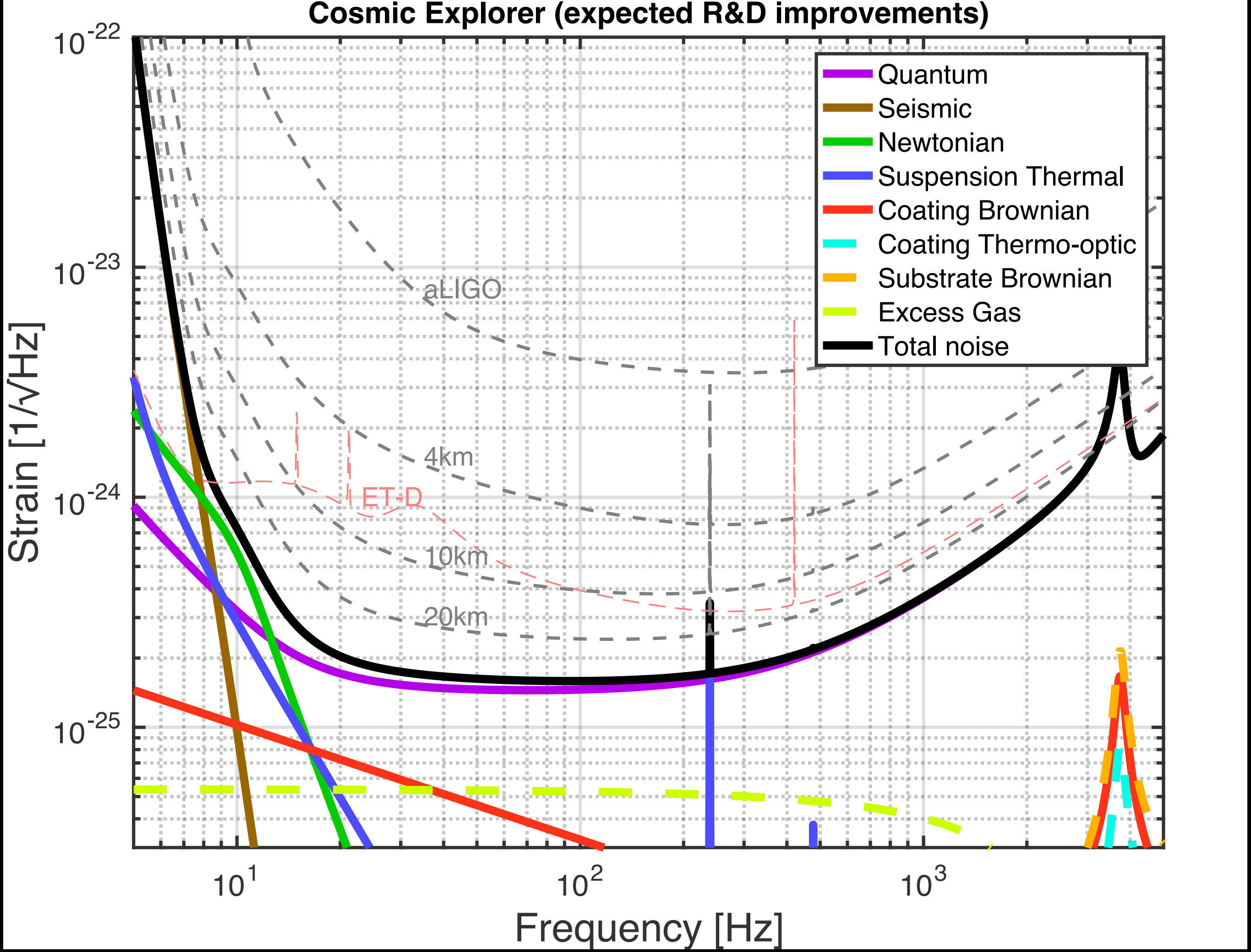
Conceptual Design Study

http://www.et-gw.eu/

10km triangular shape, underground, multiple co-located detectors

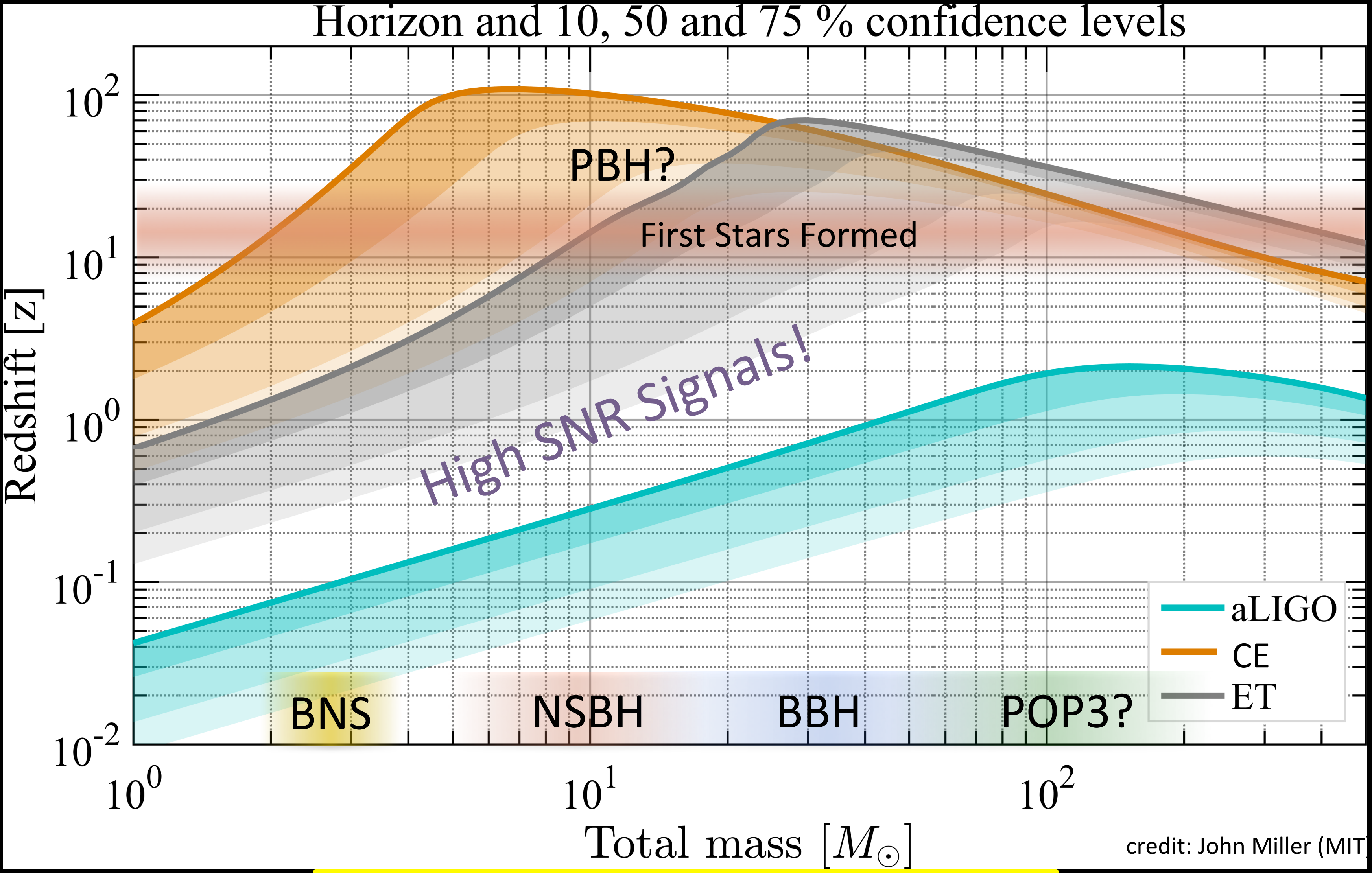
Picture is photo-shopped!
Credit: Stefan Ballmer (Syracuse)

Looking further ahead:
new technologies, new facilities



Class. Quantum Grav. 34 (2017) 044001

Cosmic Explorer could detect all of the compact binaries in the Universe



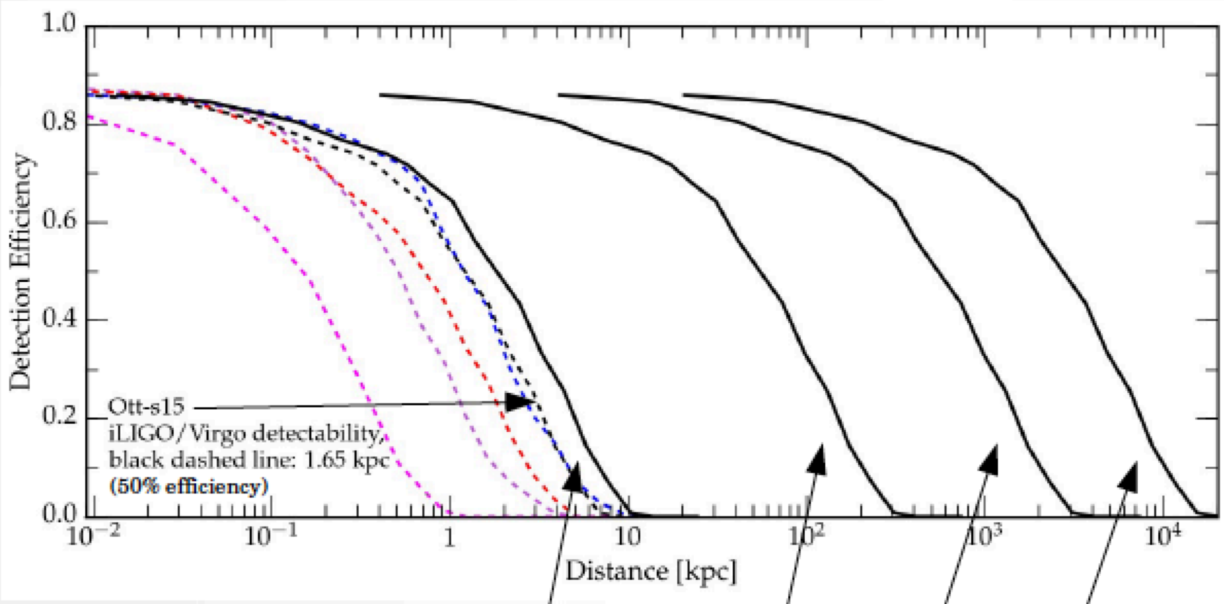
credit: John Miller (MIT)

Conclusions – part II

- New technologies and new facilities could give us access to gravitational waves from all of the compact binaries in the Universe
- International community working now to shape the future of ground base gravitational wave astronomy

3G detectors (Cosmic Explorer, Einstein Telescope) Presented in Valencia 2016 (Szczepańczyk)

From iLIGO/Virgo SN search, PRD 94, 102001 (2016):



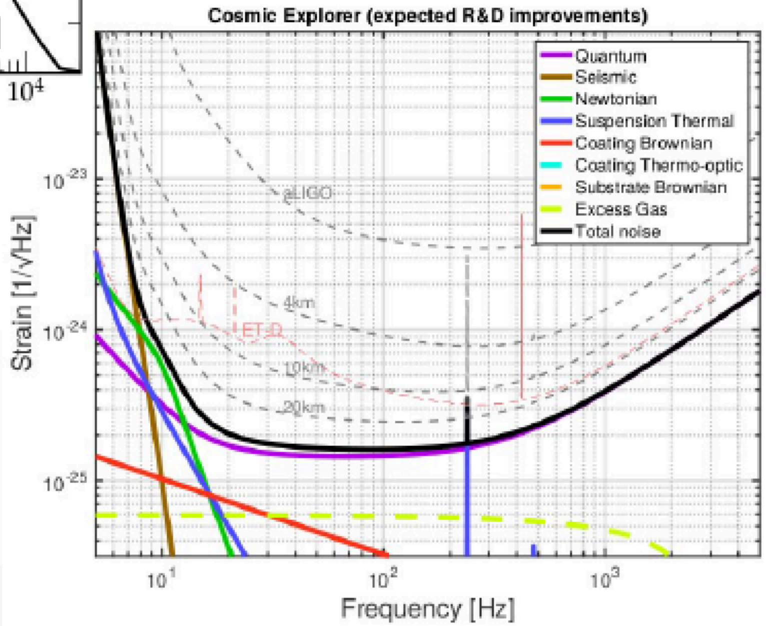
Can we achieve sensitivity to reach 1SN/year rate?

1SN/year → ~13Mpc
4SN/year → ~20Mpc

Improvements:

- x1.5 (algorithm + BW+ denoising)
- x30 (advanced LIGO design sensitivity)
- x10 (vanilla 3rd generation improvement)
- x5 counting techniques and distributional methods

arXiv:1067.08697



GW from CCSNs

- current best estimates for aLIGO-like detectors predict the ability of detecting GW from CCSN only from nearby sources, D < 1-100 kpc, only within the Milky way → Rates are therefore very low (2-3 every 100 years);

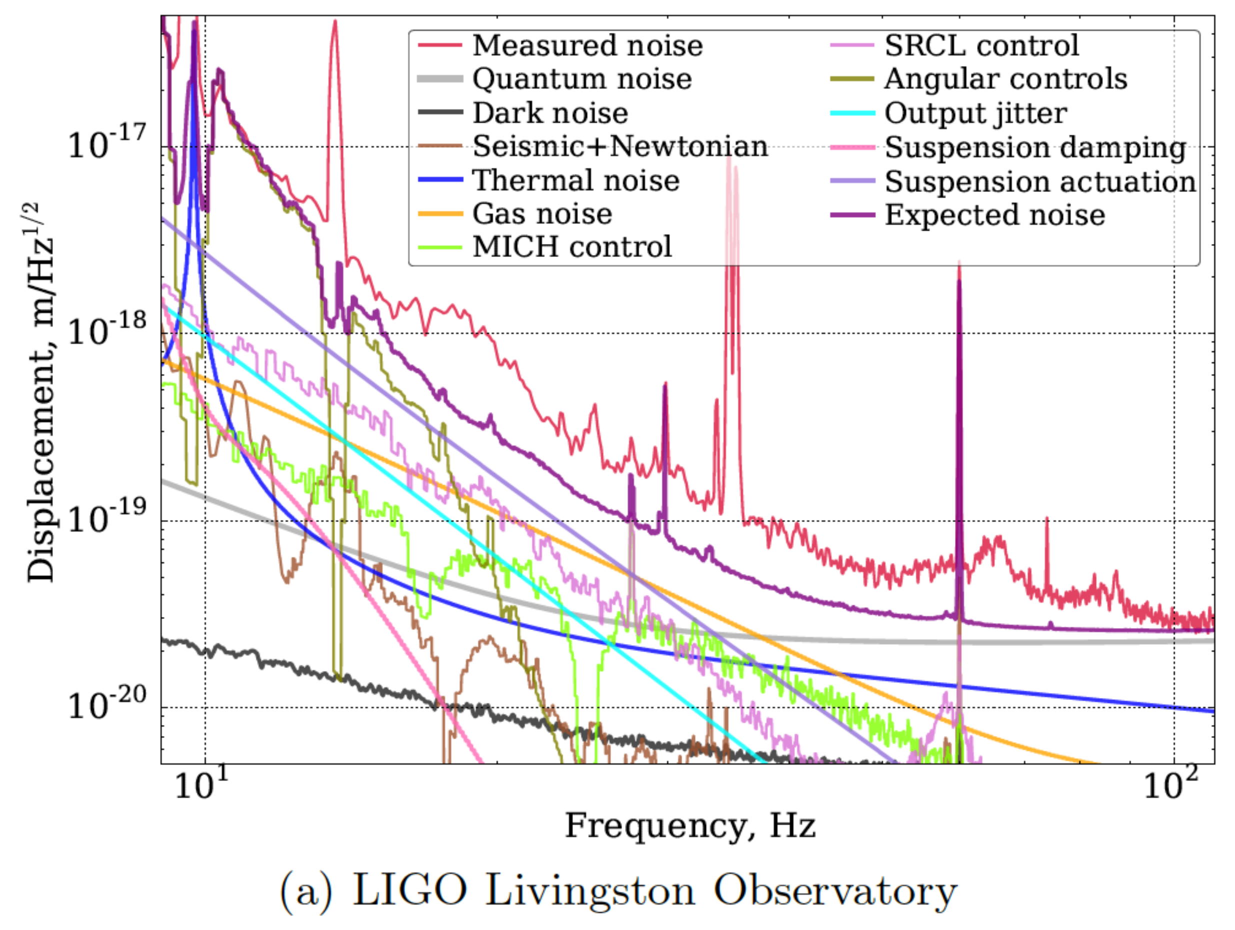
- 3G detectors could reach high detection efficiency up to 1 Mpc

→ This is not quite enough for achieving the 1 event/year (expected for ~13Mpc) or 4 events/year (expected for ~20Mpc)

- BUT it is close enough that there is hope that improving the way we looks for these events we can actually achieve a high detection efficiency up to those distances: 10% detection efficiency at 10 Mpc, for example;

→ by improving models for the expected GW signal from CCSN searches can be improved, thus making GW from CCSN with 3G detector plausible

Many noise sources in the 10-100 Hz band

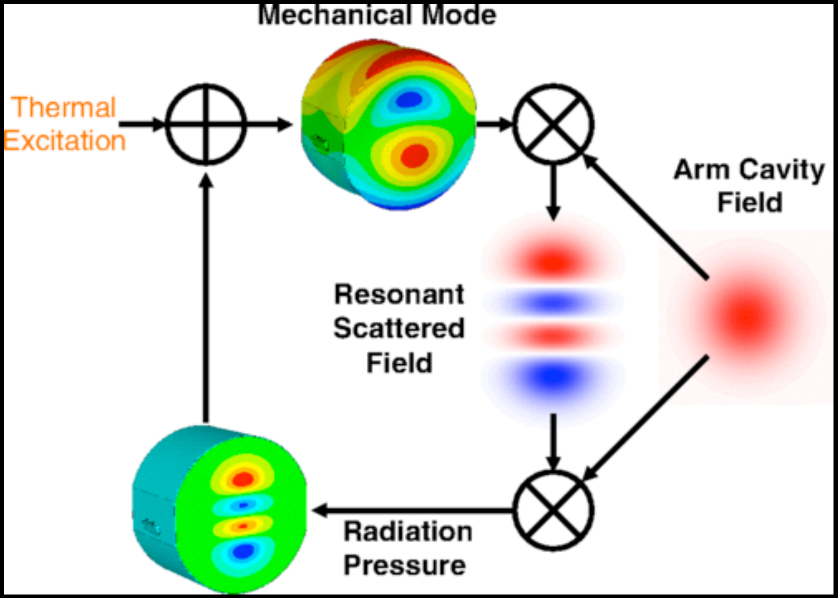


(a) LIGO Livingston Observatory

Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy D. V. Martynov et al. Phys. Rev. D 93, 112004

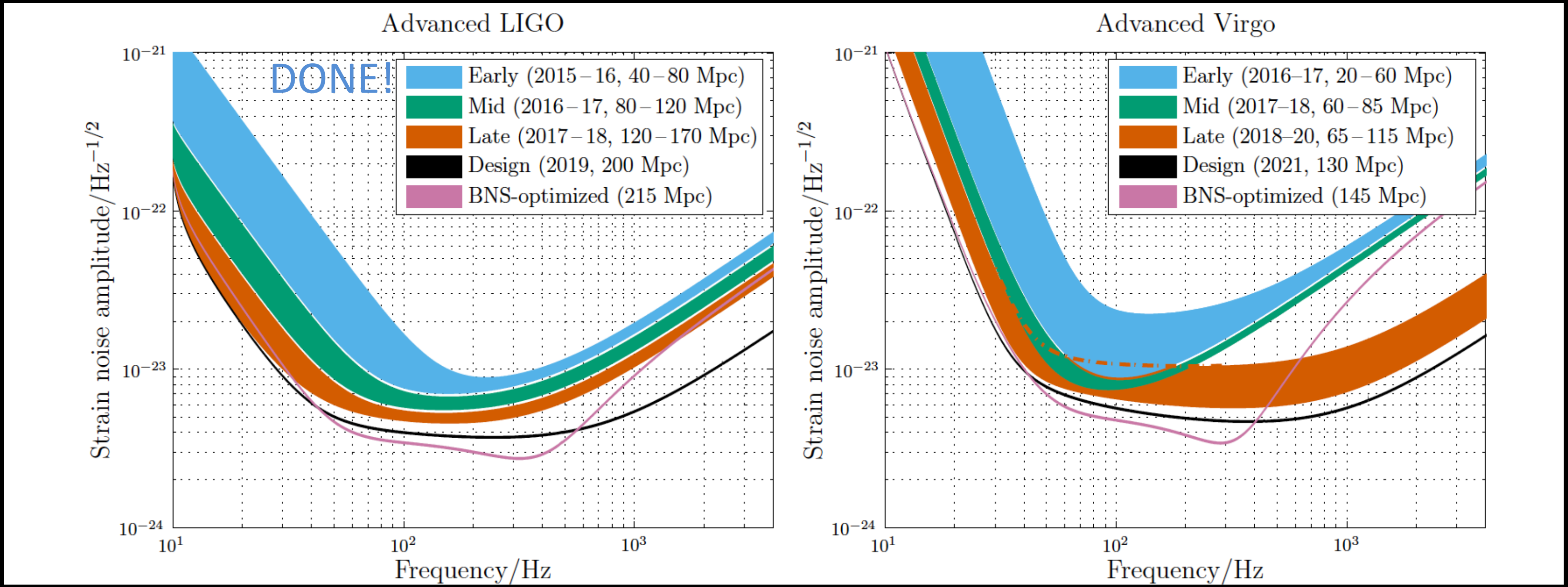
(Some of) the challenges with high circulating laser power

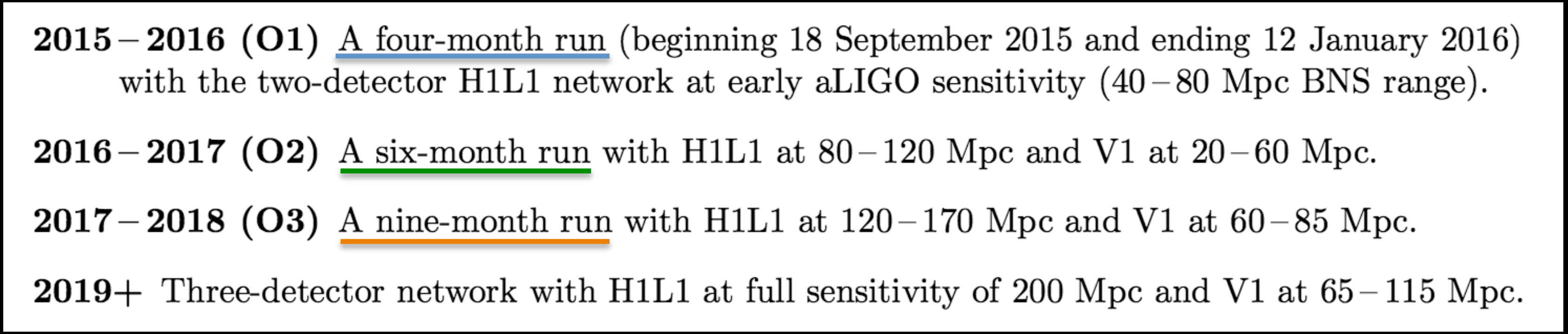
- Thermal lens in the interferometer mirrors induced by high circulating power require active thermal compensation
- Mirror alignment control
- "Parametric" instabilities: acoustic modes of the mirrors get excited and pump light in high order optical modes, that become resonant in the arms



Observation of Parametric Instability in Advanced LIGO
Matthew Evans et al. Phys. Rev. Lett. 114, 161102 (2015)

Observing Plan - Overview




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).

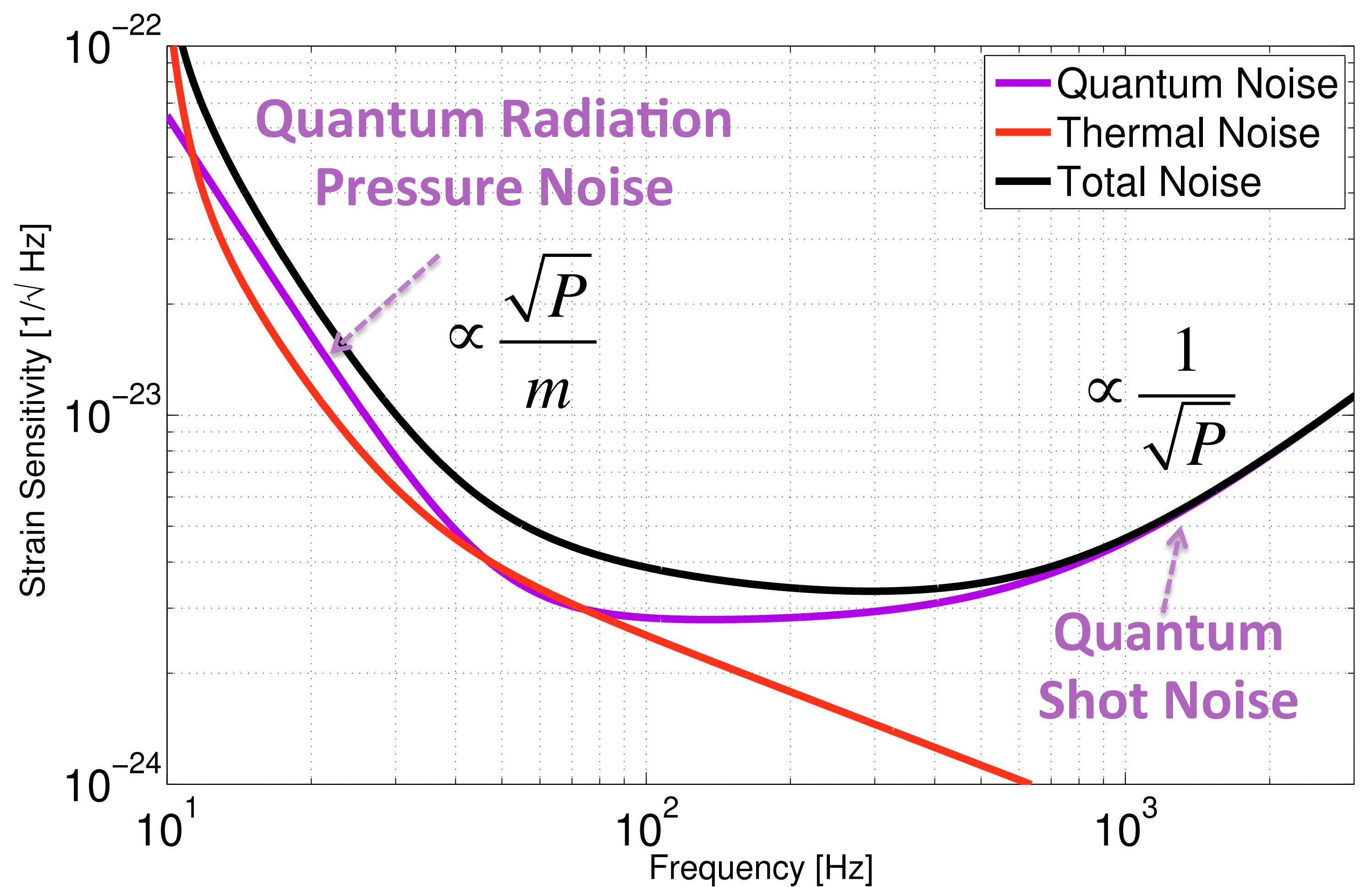
2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

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.

Live Observing document http://arxiv.org/abs/1304.0670

Quantum noise depends on arm power P



Quantum Radiation Pressure Noise

$$\propto \frac{\sqrt{P}}{m}$$

$$\propto \frac{1}{\sqrt{P}}$$

Quantum Shot Noise

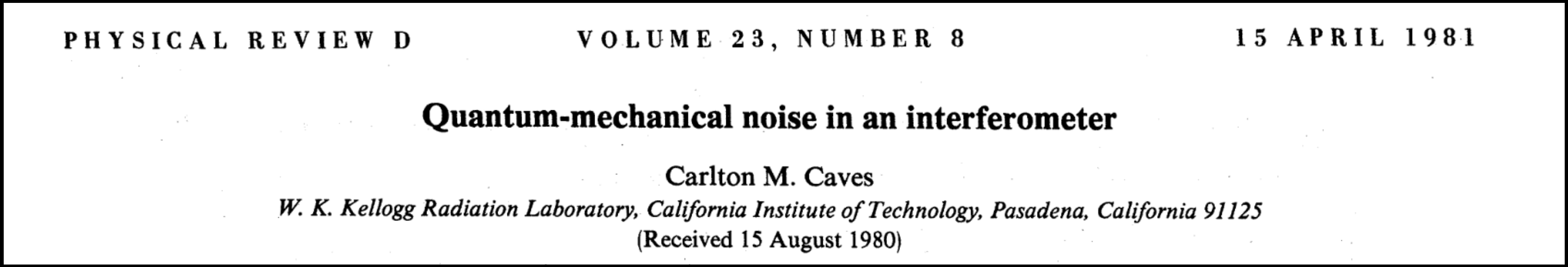
Back-action noise caused by random motion of the mirrors due to fluctuations of the number of photons impinging on the mirrors

➔ *Additional displacement noise*

=

Photon counting noise due to fluctuations in the number of photons detected at the interferometer output

➔ *Limitation of the precision you can measure arm displacement*



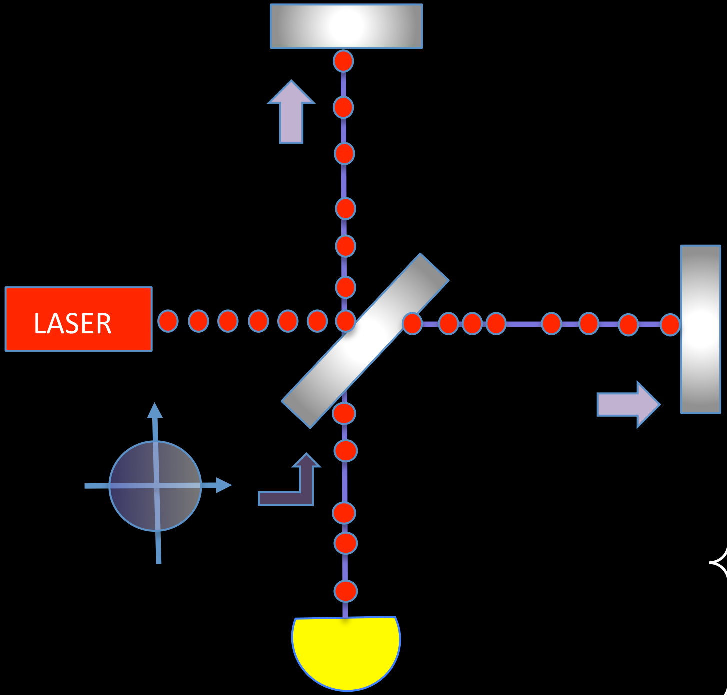
PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

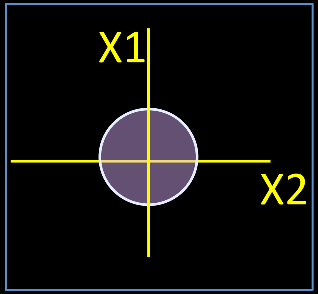
Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 15 August 1980)

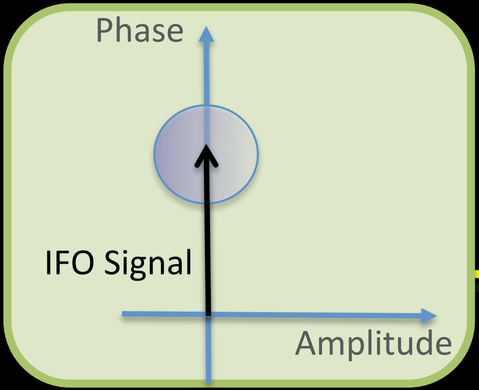


Zero-point energy (vacuum) fluctuations

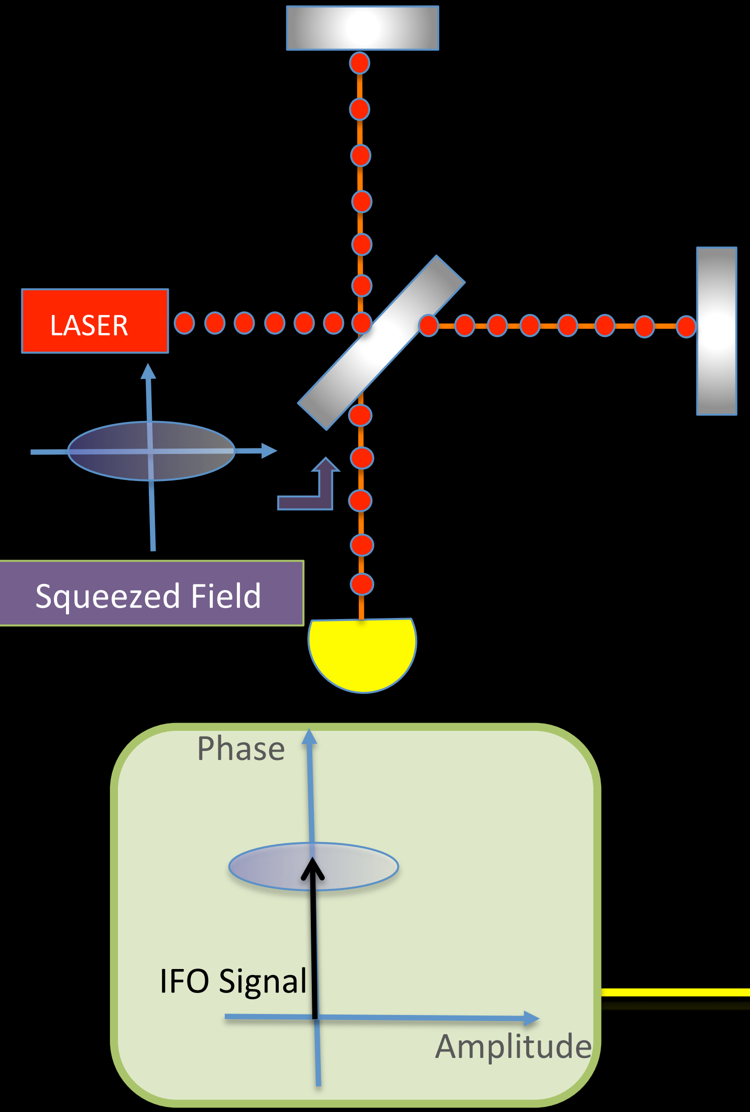


$$\Delta X_1 \, \Delta X_2 \geq 1$$

- ✧ When average amplitude is zero, the variance remains
- ✧ Heisenberg uncertainty principle, quadratures associated with **amplitude** and **phase**
- ✧ They enter the interferometer from all the open ports of the interferometer, but the ones which matter are the one **entering from the anti-symmetric port**!



Replace regular vacuum with squeezed vacuum



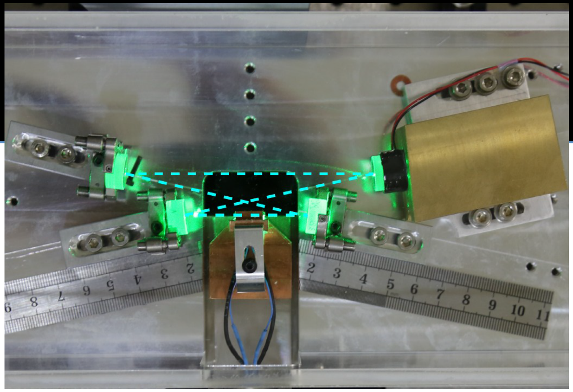
- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures

- Heisenberg uncertainty principle:
  if the noise gets smaller in one quadrature, it gets bigger in the other one

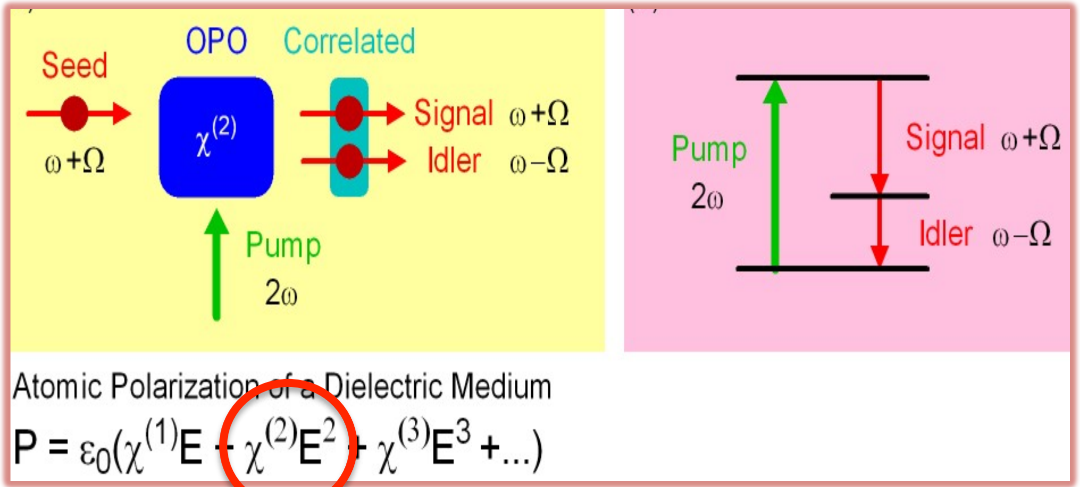
- One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

How to make squeezed fields

- Non linear crystal with a strong second order polarization component, pumped at 2w
- Refractive index depends on intensity of light illumination
- It creates entangled photon pairs by down-conversion



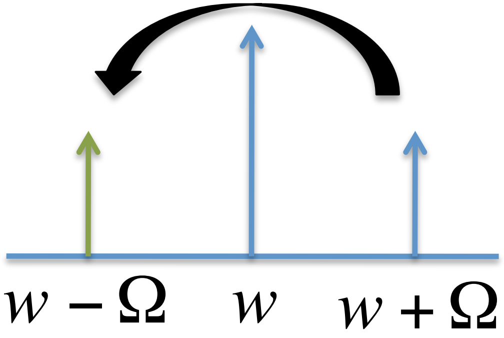
Bow-tie cavity OPO design (ANU)



Atomic Polarization of a Dielectric Medium

$$P = \varepsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots)$$

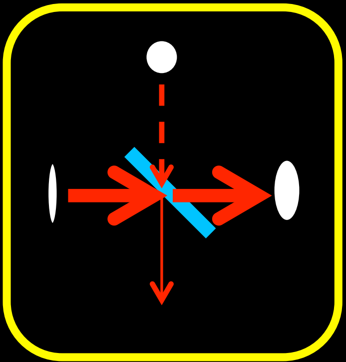
$$P \propto (Ee^{-i2wt} + Ee^{-i(w+\Omega)t})^2 \Rightarrow Ee^{-i(w-\Omega)t}$$



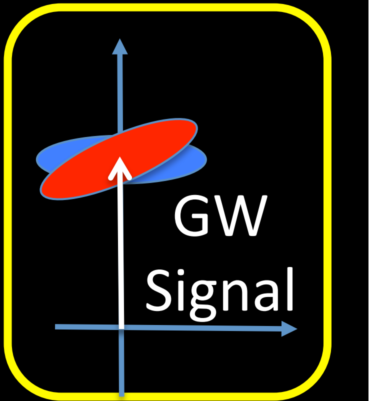
The OPO makes a “copy” of the quantum sideband, and it correlates the sidebands

Squeezing enhancement in LIGO H1 (2011)

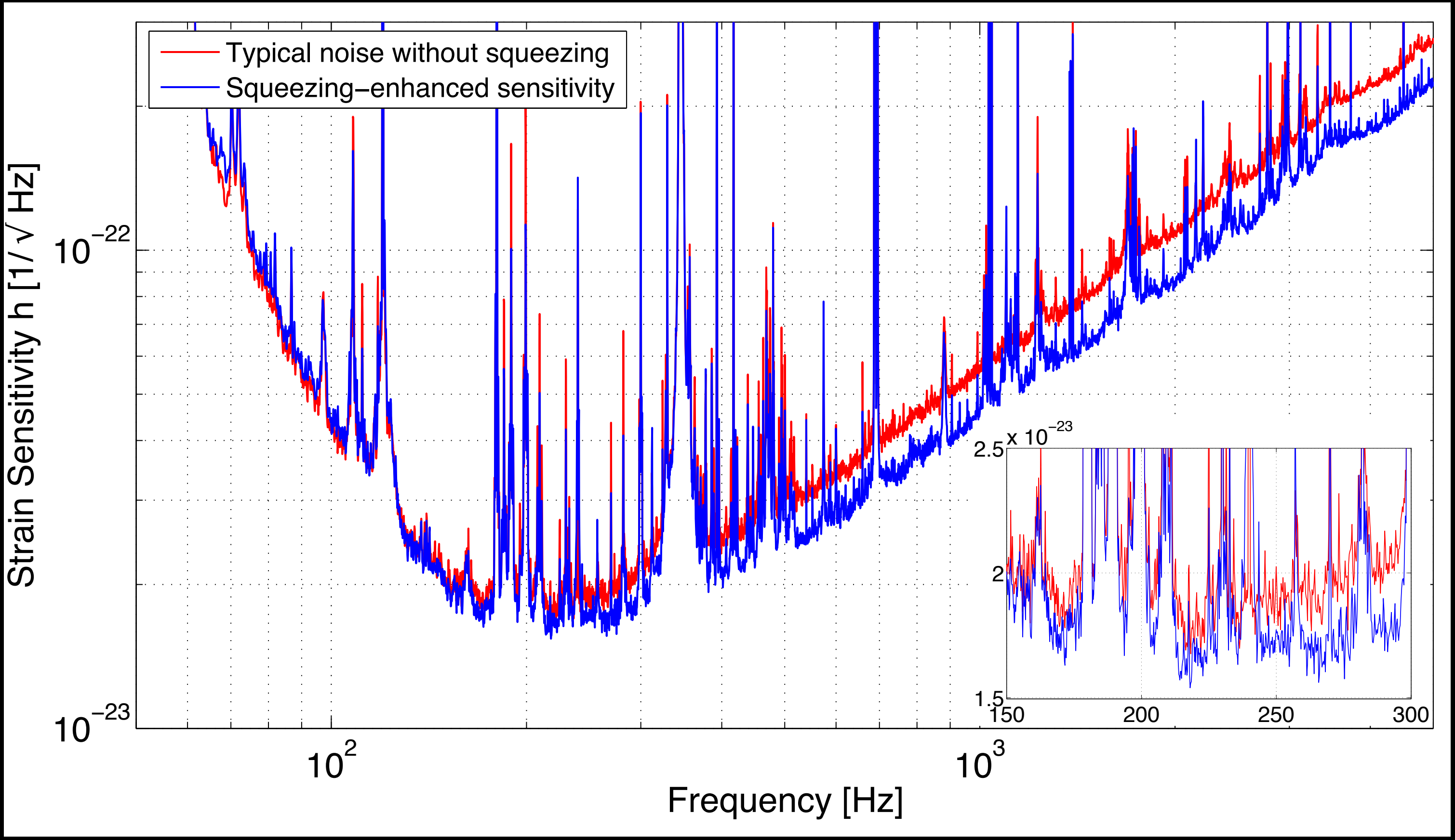
Demonstration on the initial detector before Advanced LIGO upgrade



Losses



Phase noise



Nature Photonics 7, 613–619 (2013)