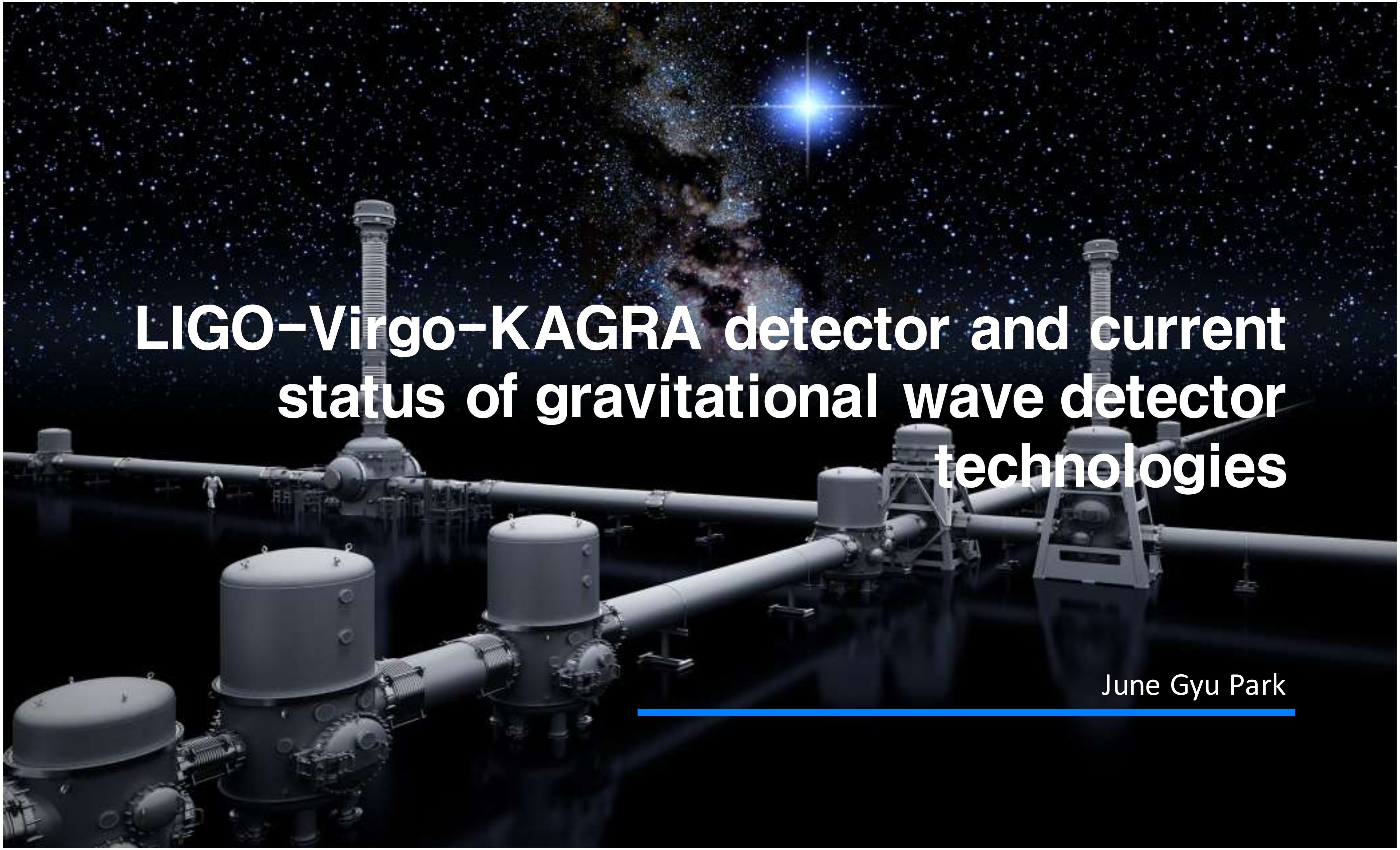


LIGO-Virgo-KAGRA detector and current status of gravitational wave detector technologies

June Gyu Park

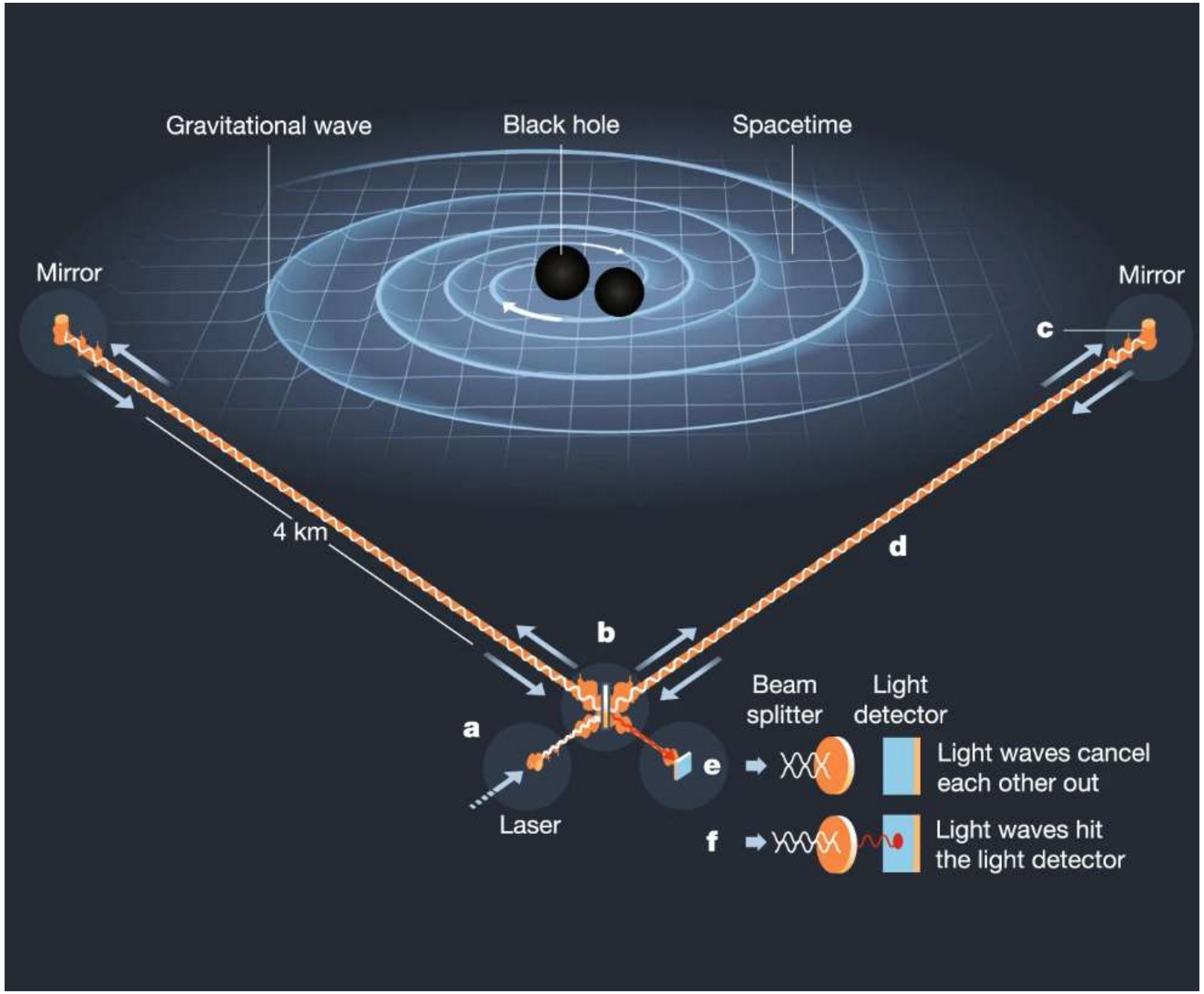
Korea Astronomy and Space Science Institute

Contents

1. Gravitational wave detector and status of LVK
2. Quantum noise of gravitational wave detector
3. Squeezed vacuum injection

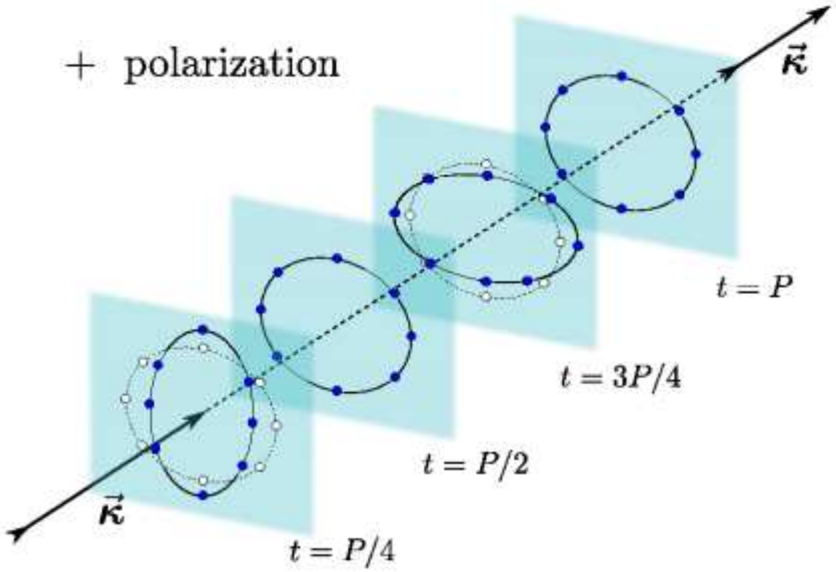
Gravitational wave detector and status of LVK

Gravitational wave and GW detector



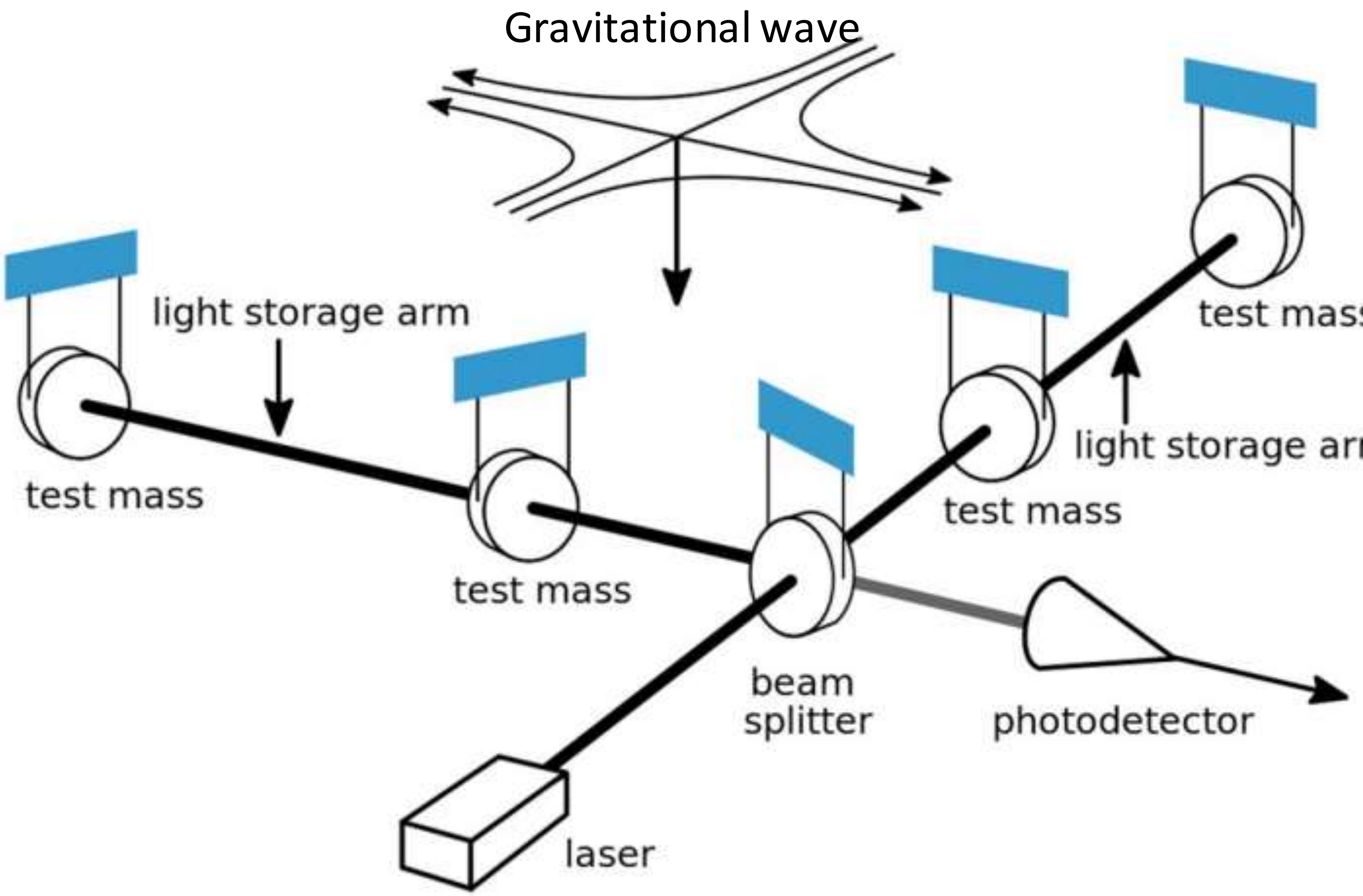
Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568,** 469–476 (2019)

Gravitational wave



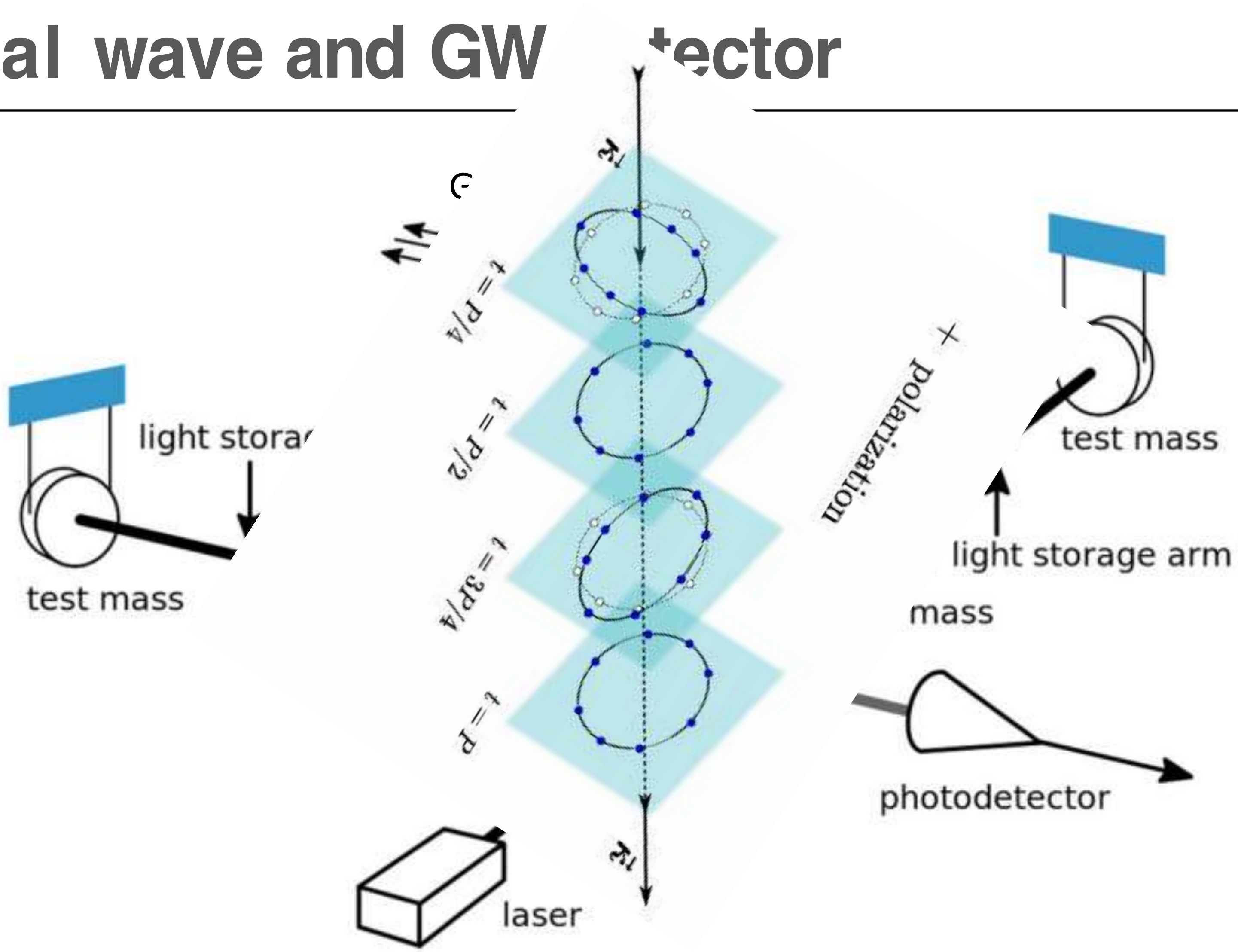
MPA Lectures on Gravitational Waves in Cosmology
Azadeh Maleknejad
Max-Planck-Institute for Astrophysics

Gravitational wave and GW detector



https://www.ligo.caltech.edu/

Gravitational wave and GW detector



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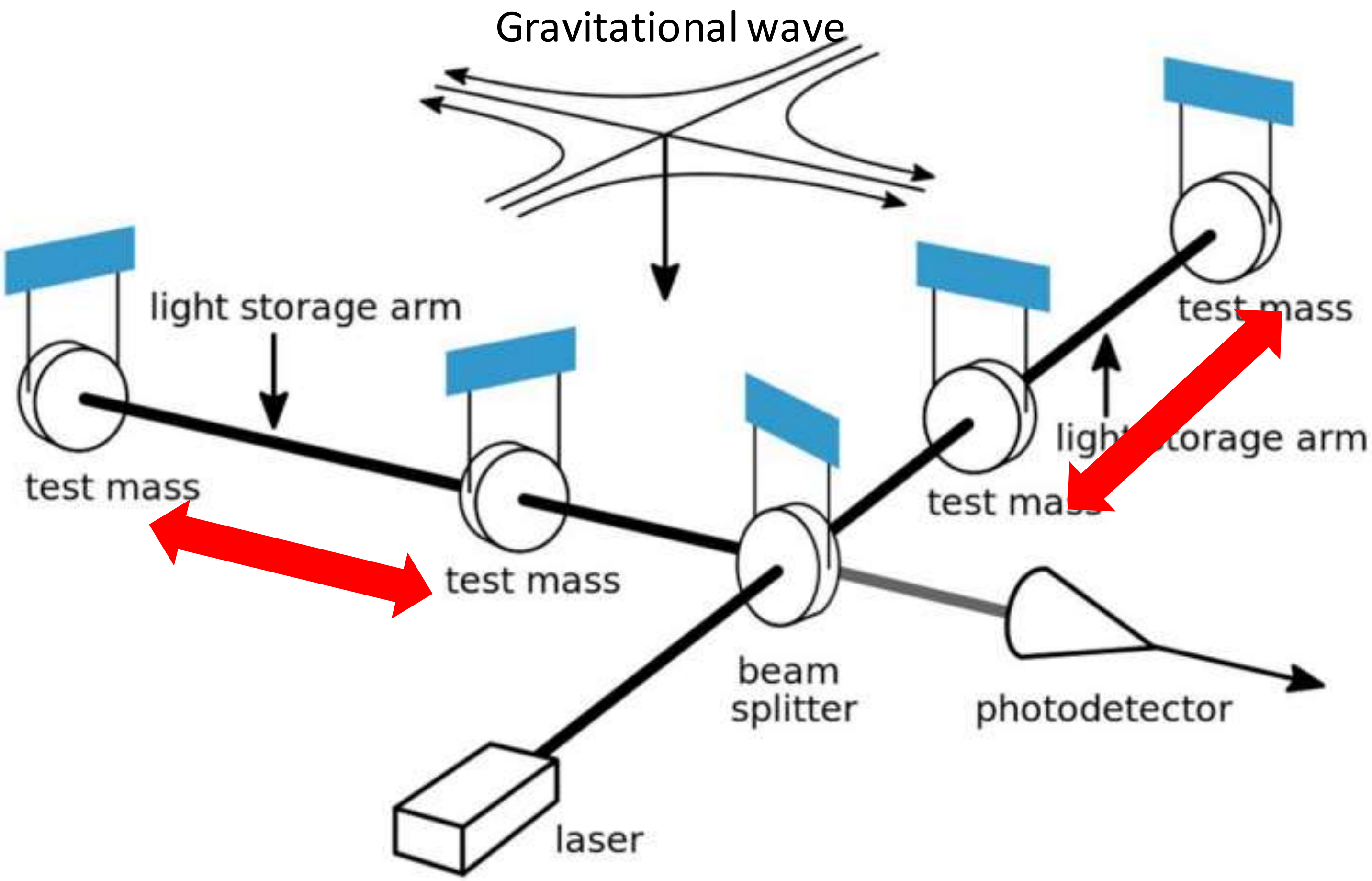

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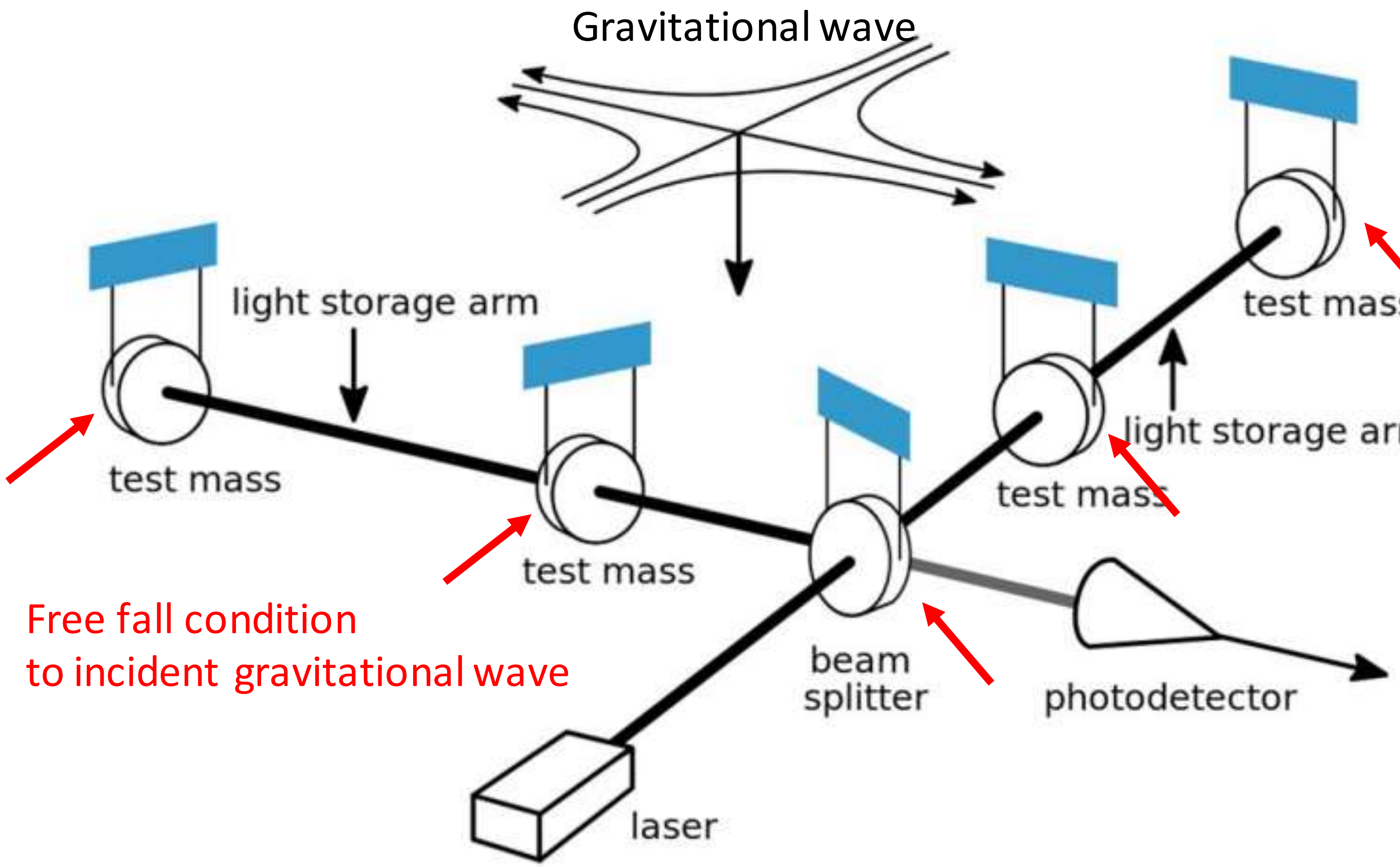
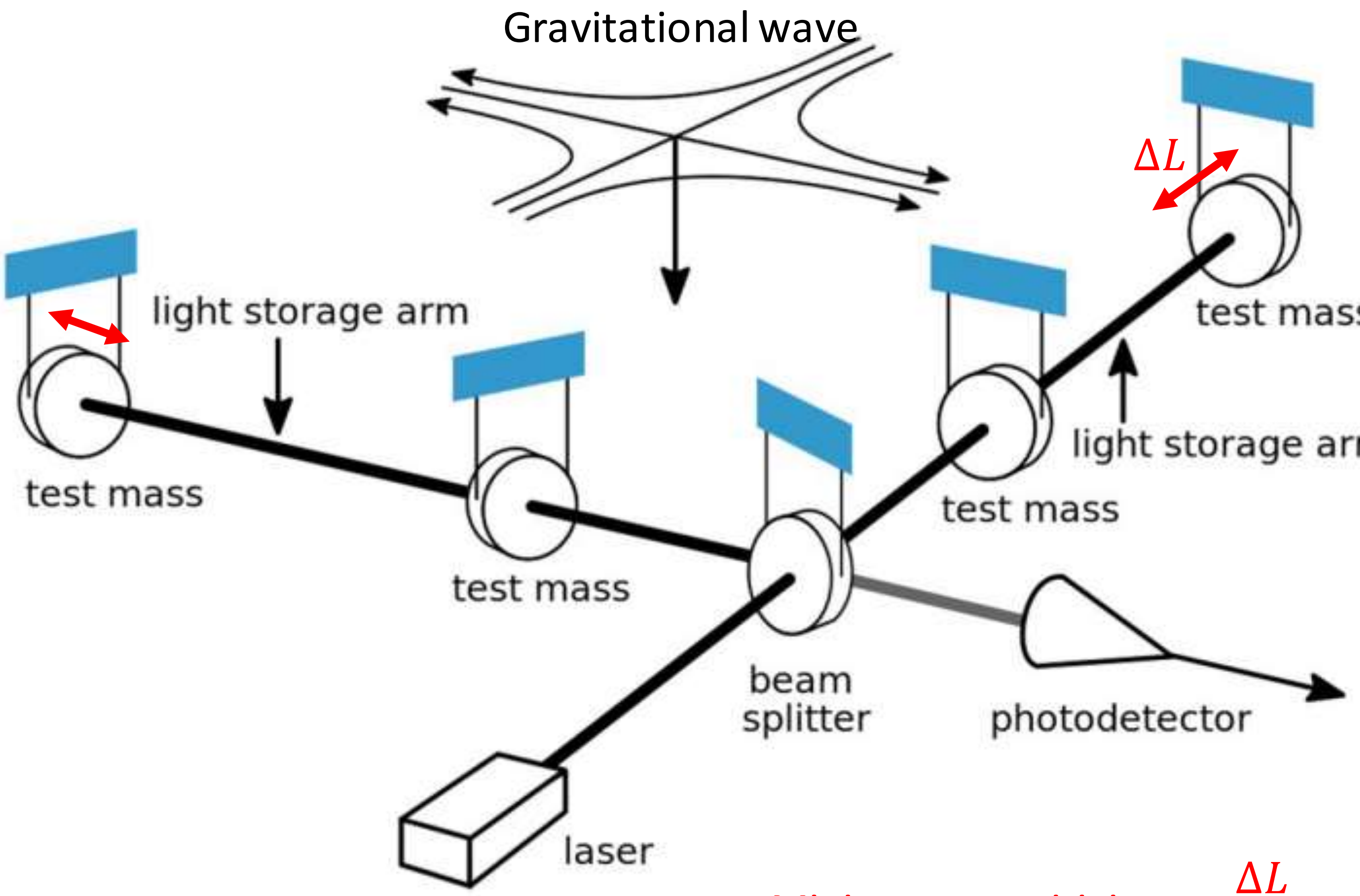


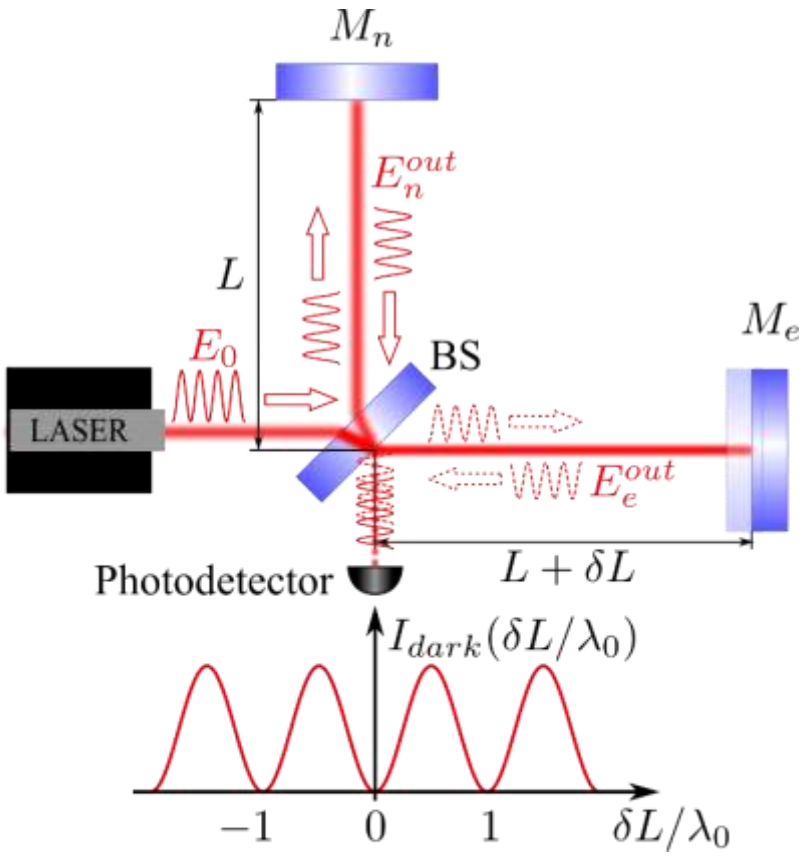
Free fall condition
to incident gravitational wave

Gravitational wave and GW detector



Minimum sensitivity $\frac{\Delta L}{L} \approx 10^{-21}$

Sensitivity of michelson interferometer



Danilishin, Stefan L. et al. Living Rev.Rel. 15 (2012) 5 arXiv:1203.1706

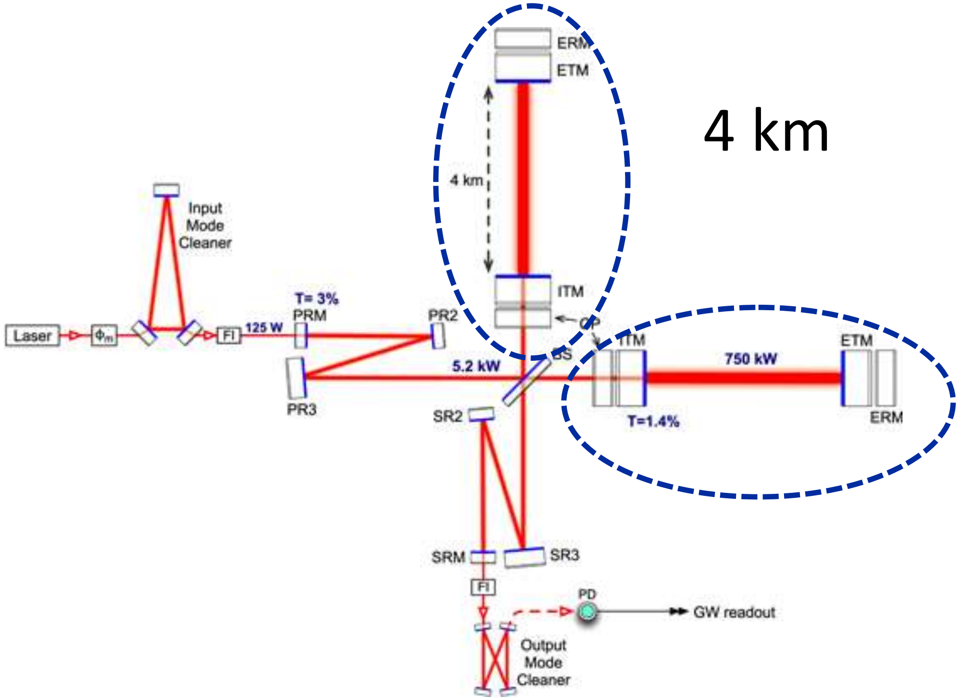
When L = 1 m

$$\frac{\Delta L}{L} \approx 10^{-16} m$$

IF L = 1000 km

$$\frac{\Delta L}{L} \approx 10^{-21} m$$

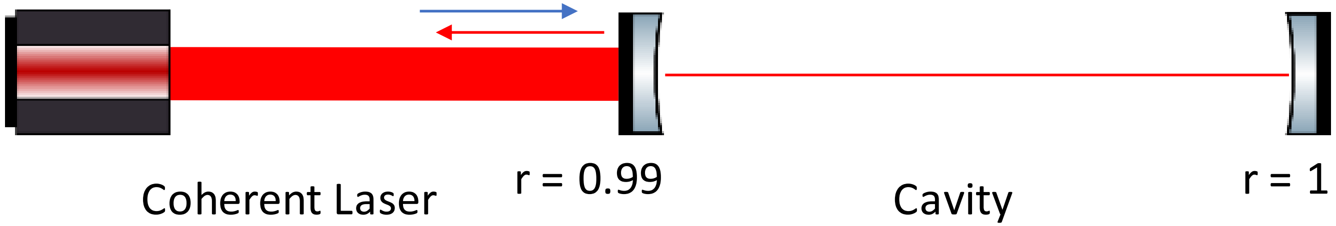
Interferometer of GW detector



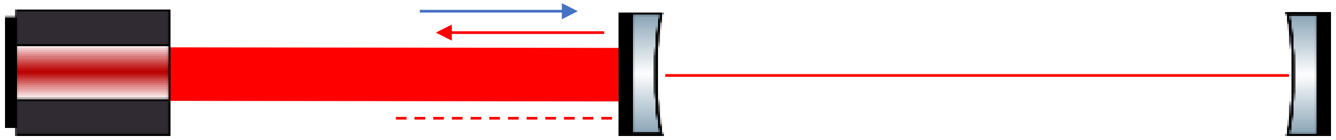
4 km

Fabry-Perot cavity

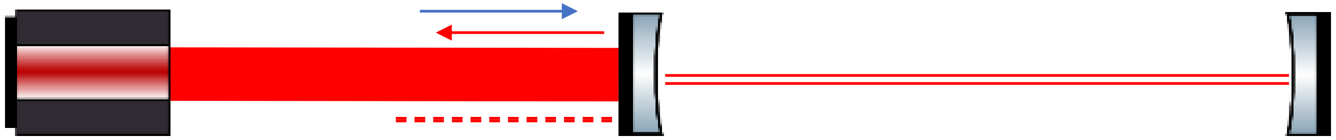
Fabry–Perot cavity



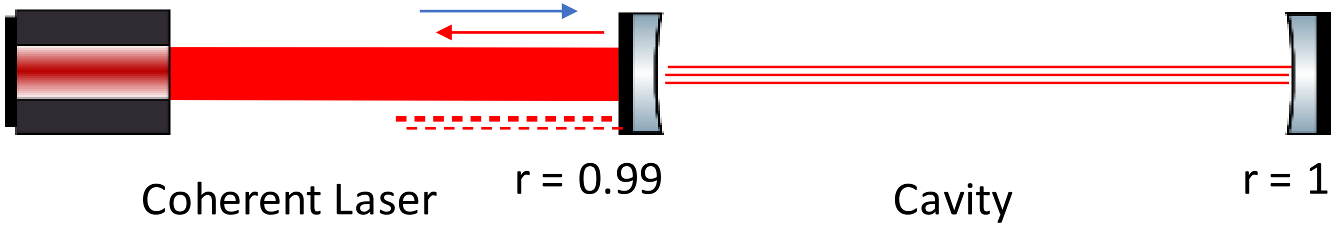
Fabry-Perot cavity



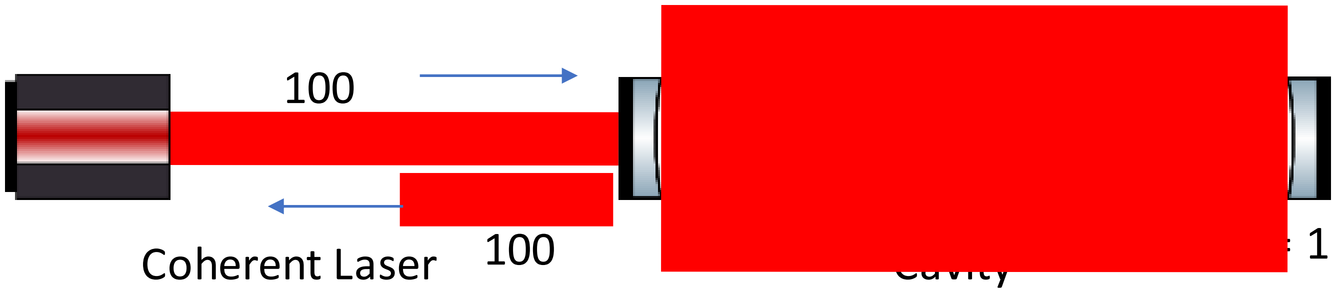
Fabry-Perot cavity



Fabry-Perot cavity

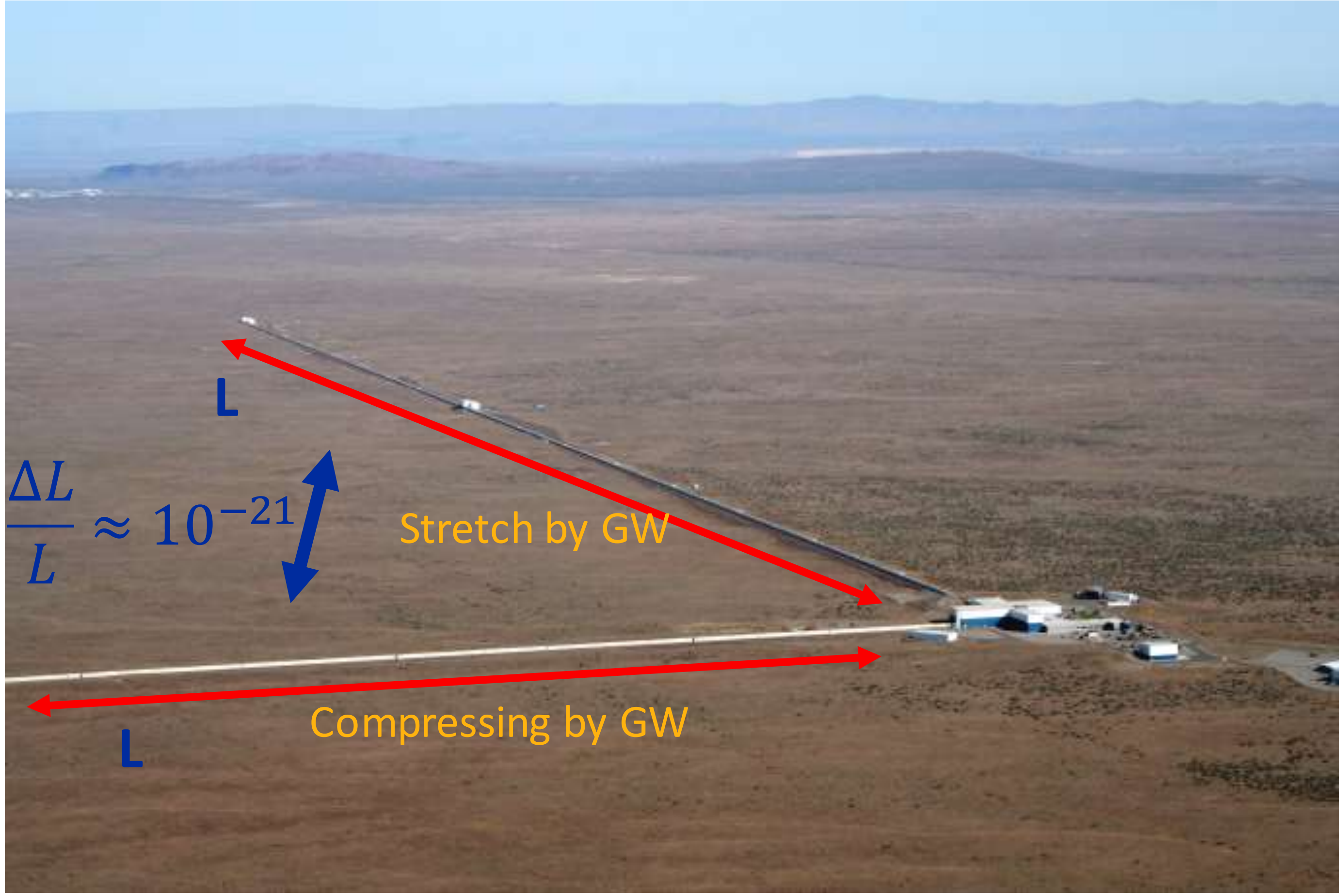


Fabry-Perot cavity

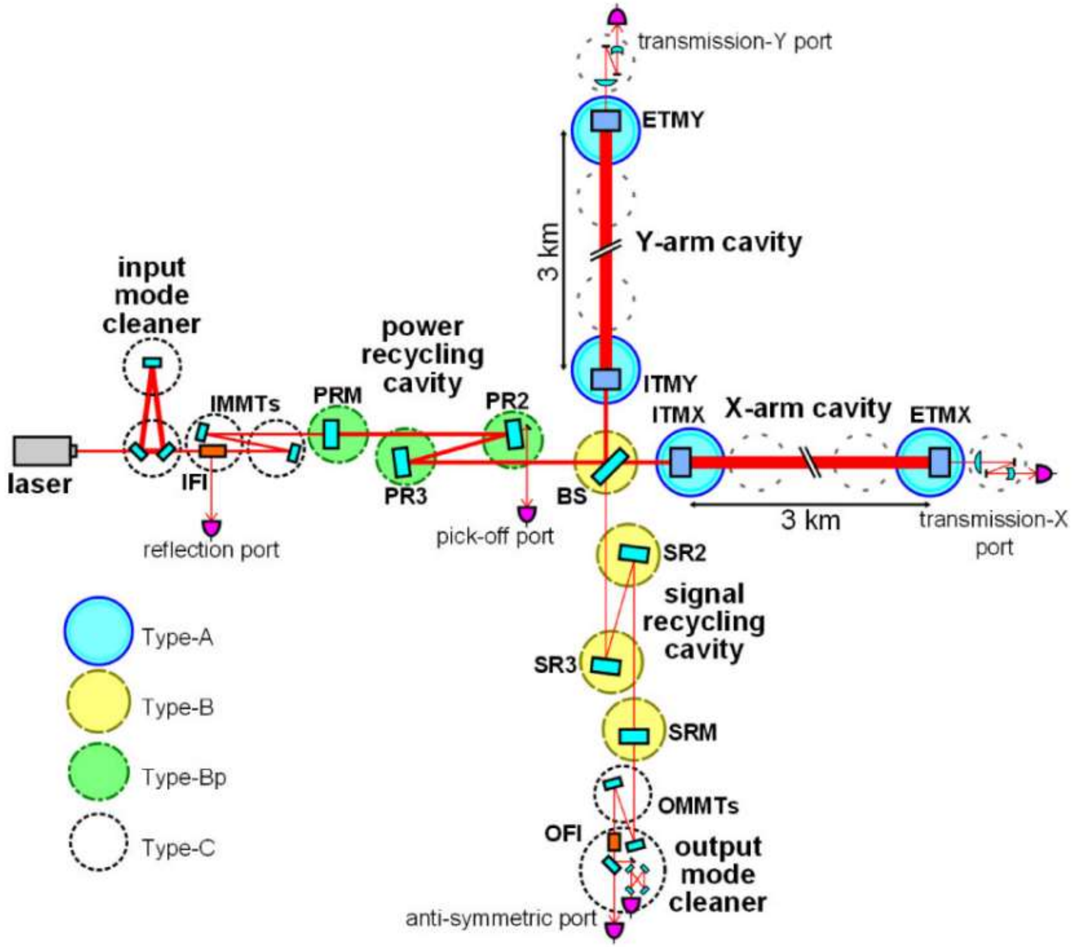


Fabry–Perot cavity

Strain sensitivity



Interferometer of GW detector



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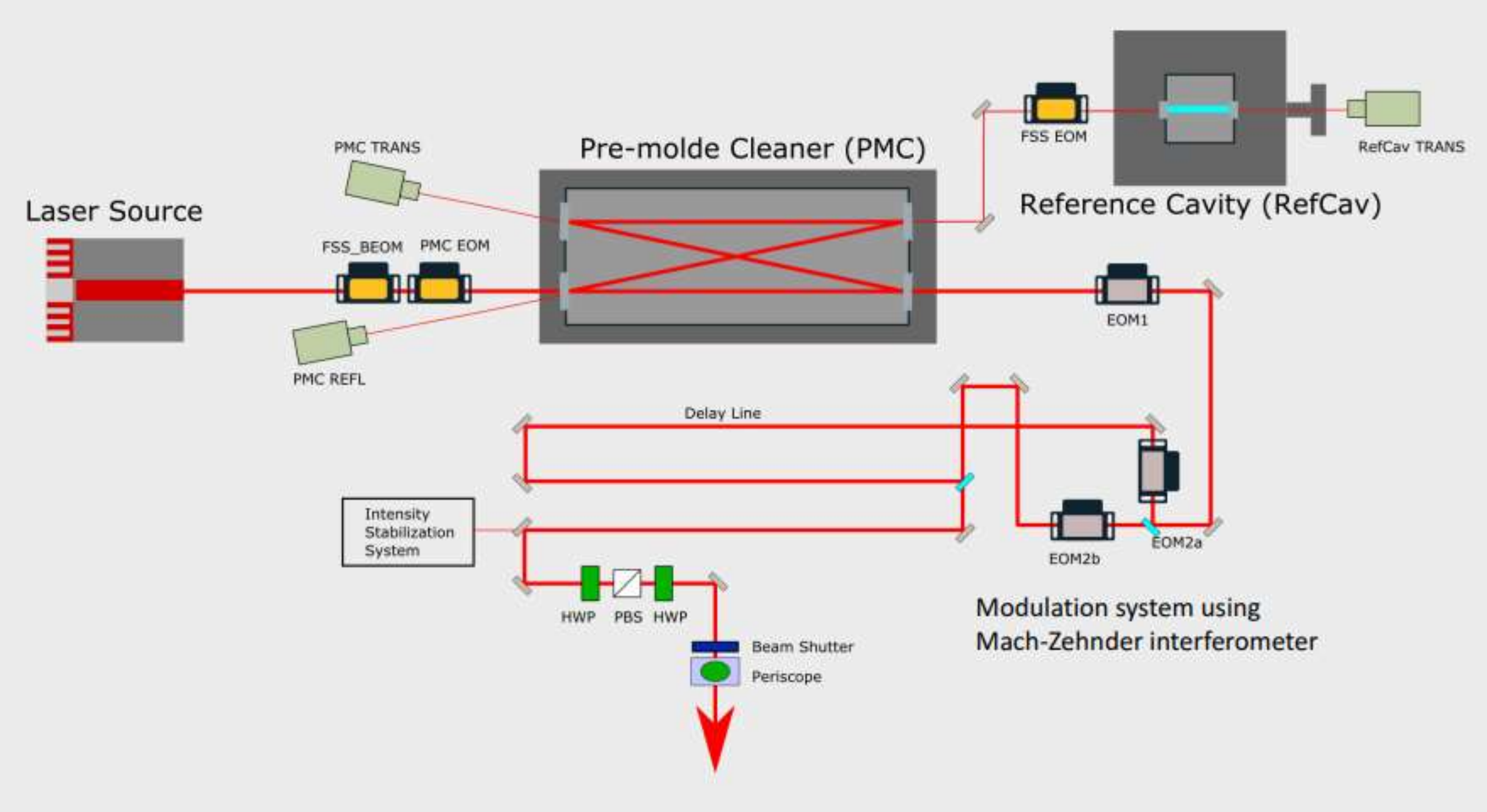
SRM : Signal recycling mirror

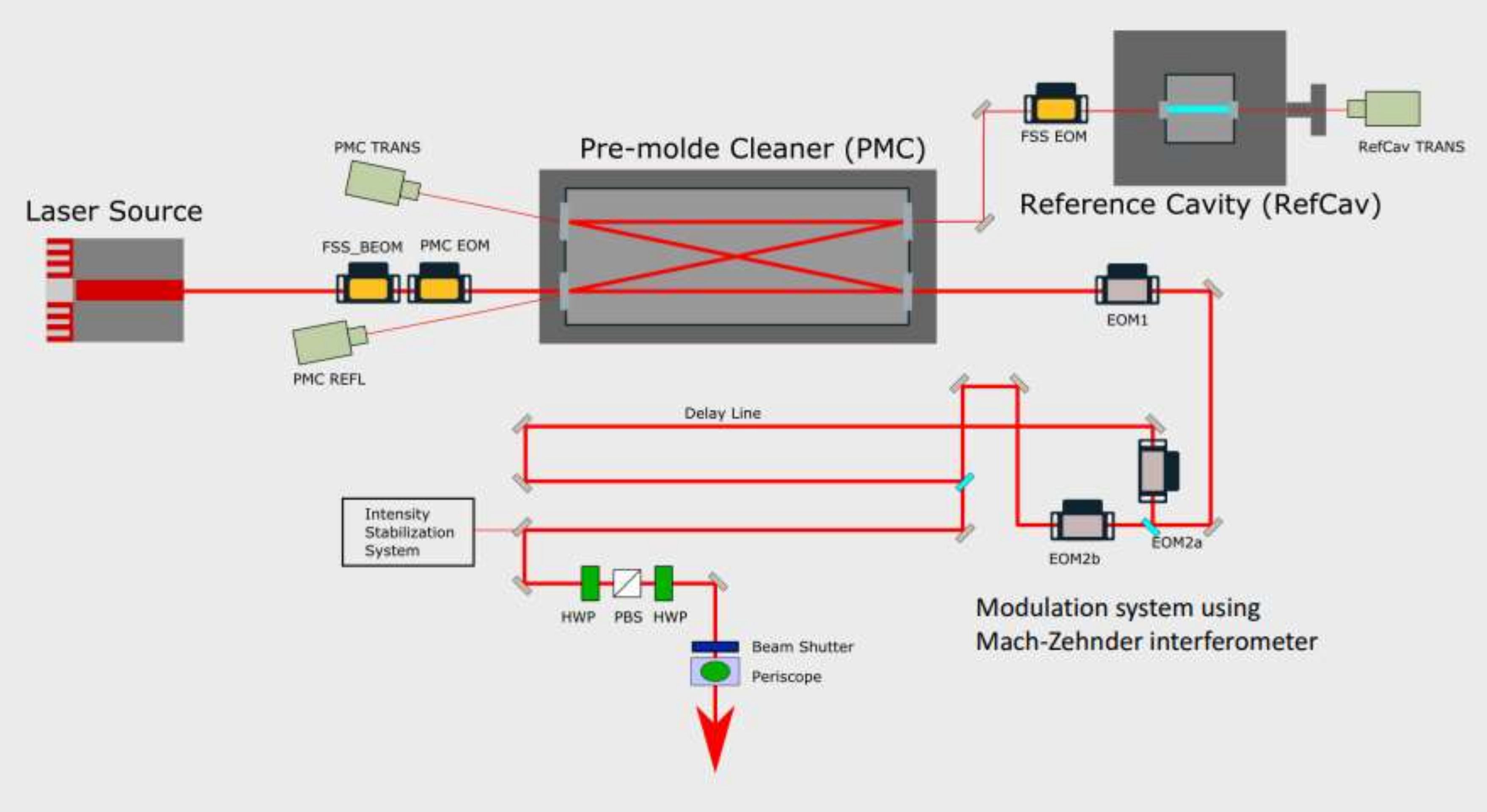
PSL room



JGW-G1808402-v6

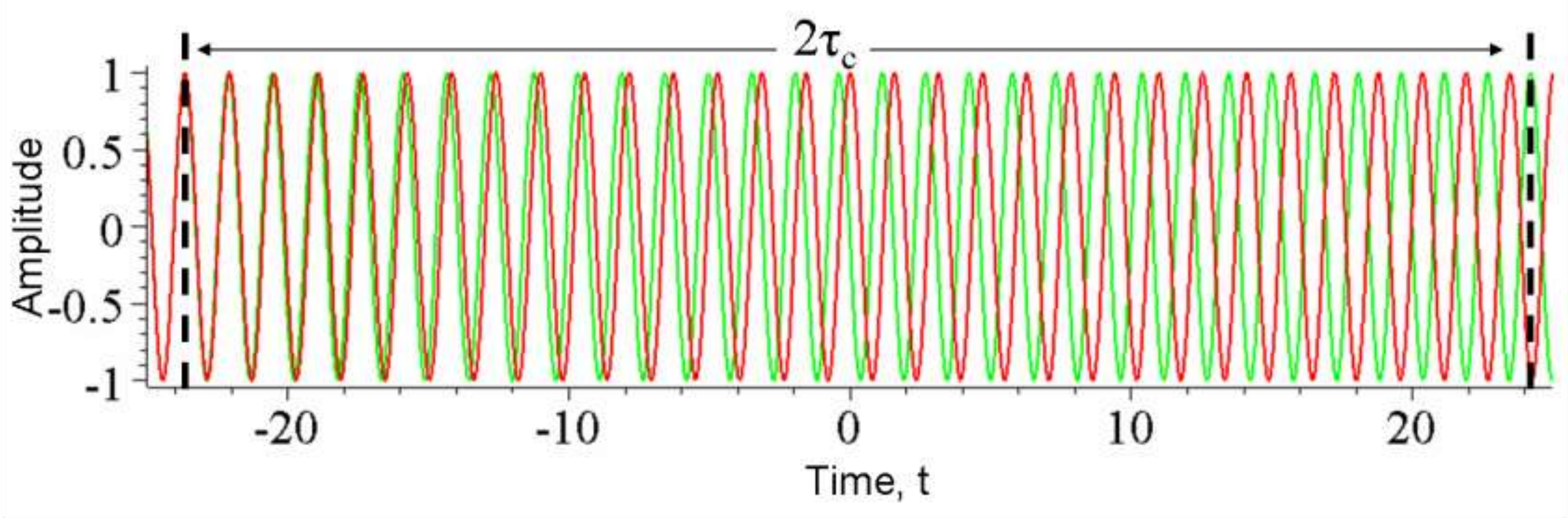

PMC
ISS
MZM
FSS

PSL room

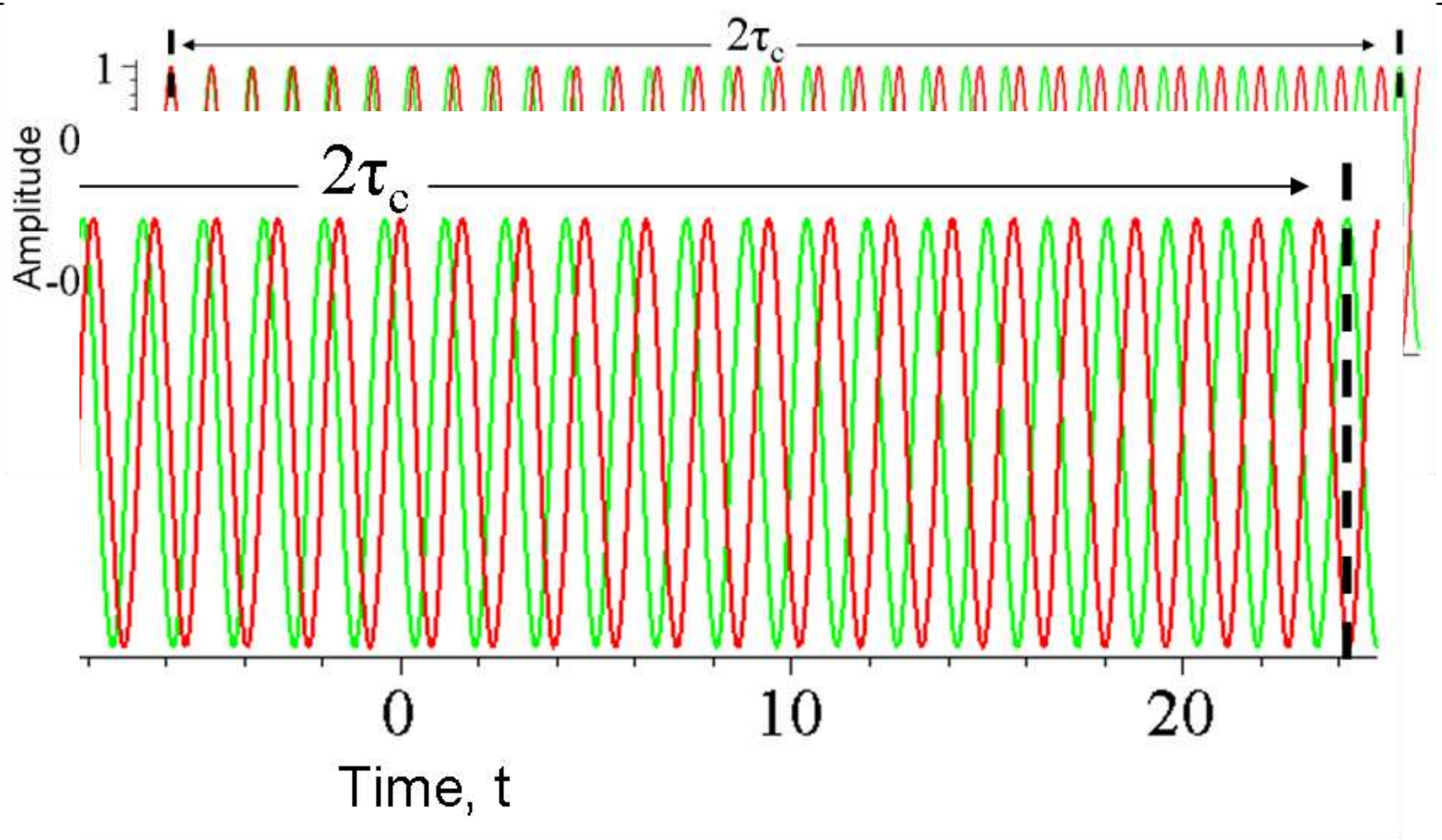


JGW-G1808402-v6

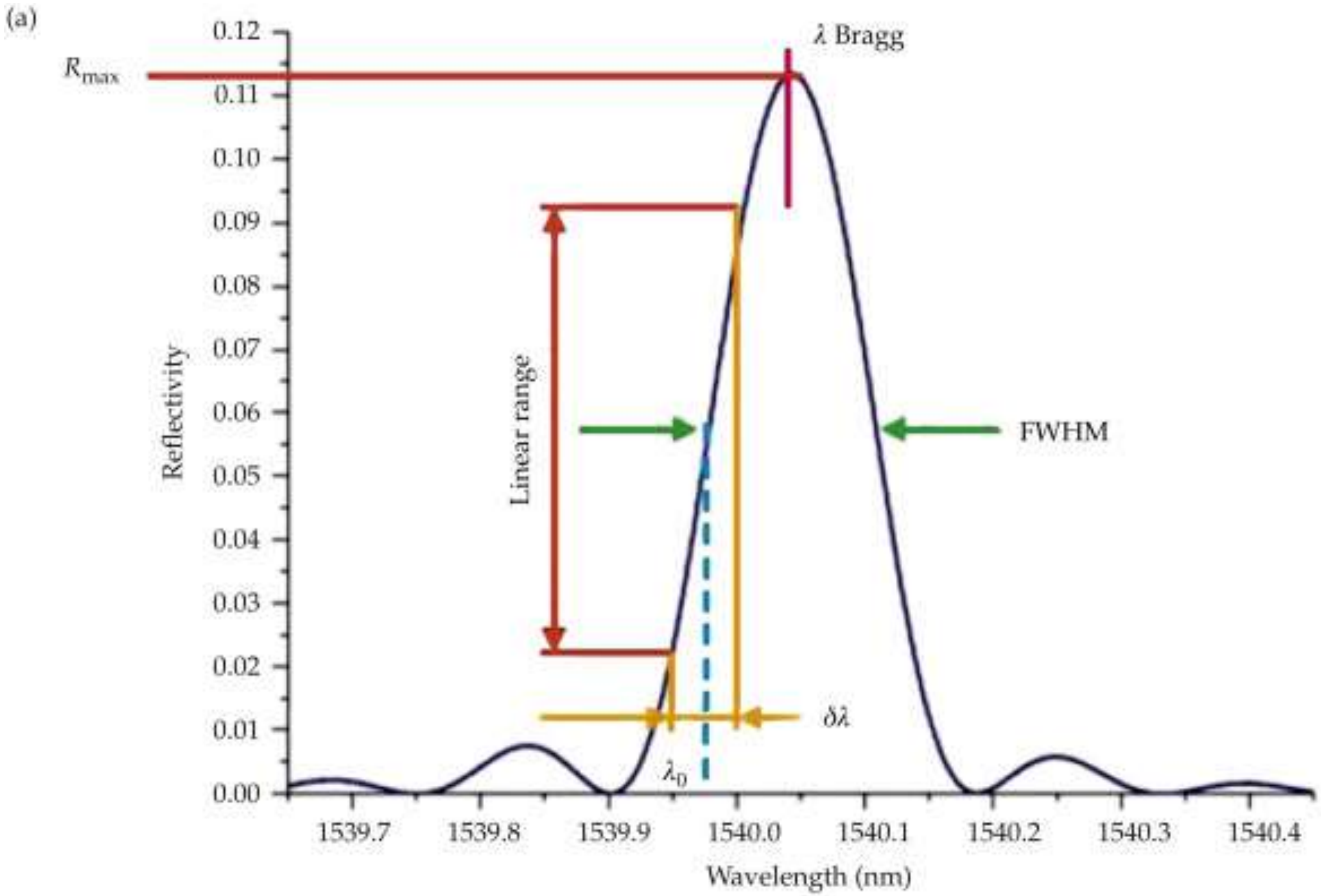
Coherence



Coherence



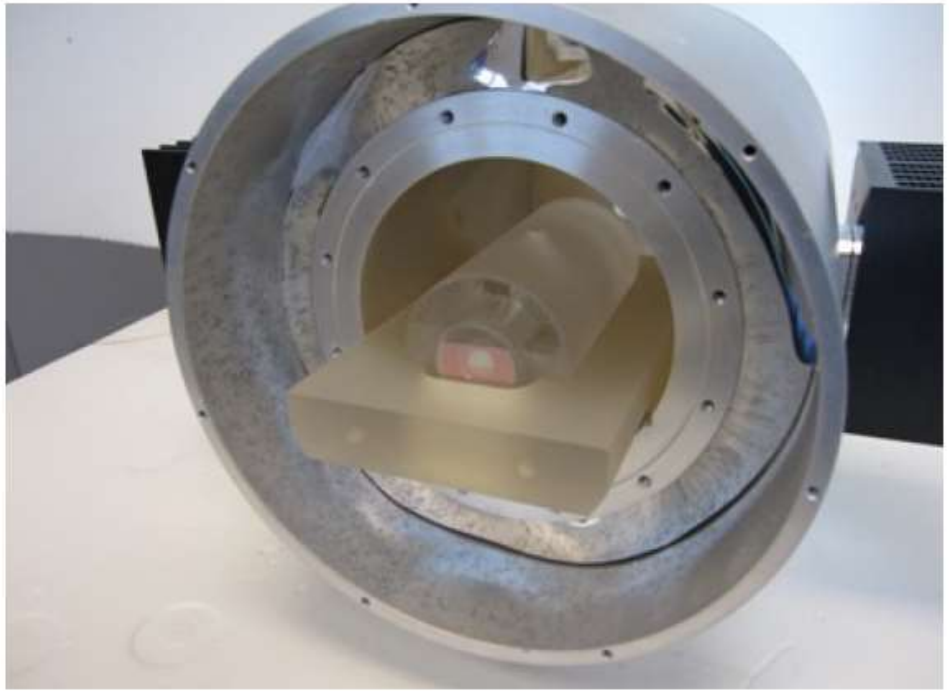
Linewidth of laser



Transmitter and Receiver Design for Amplified Lightwave Systems
Daniel A. Fishman, B. Scott Jackson, in Optical Fiber Telecommunications (Third Edition), Volume B, 1997

PSL room

Reference Cavity



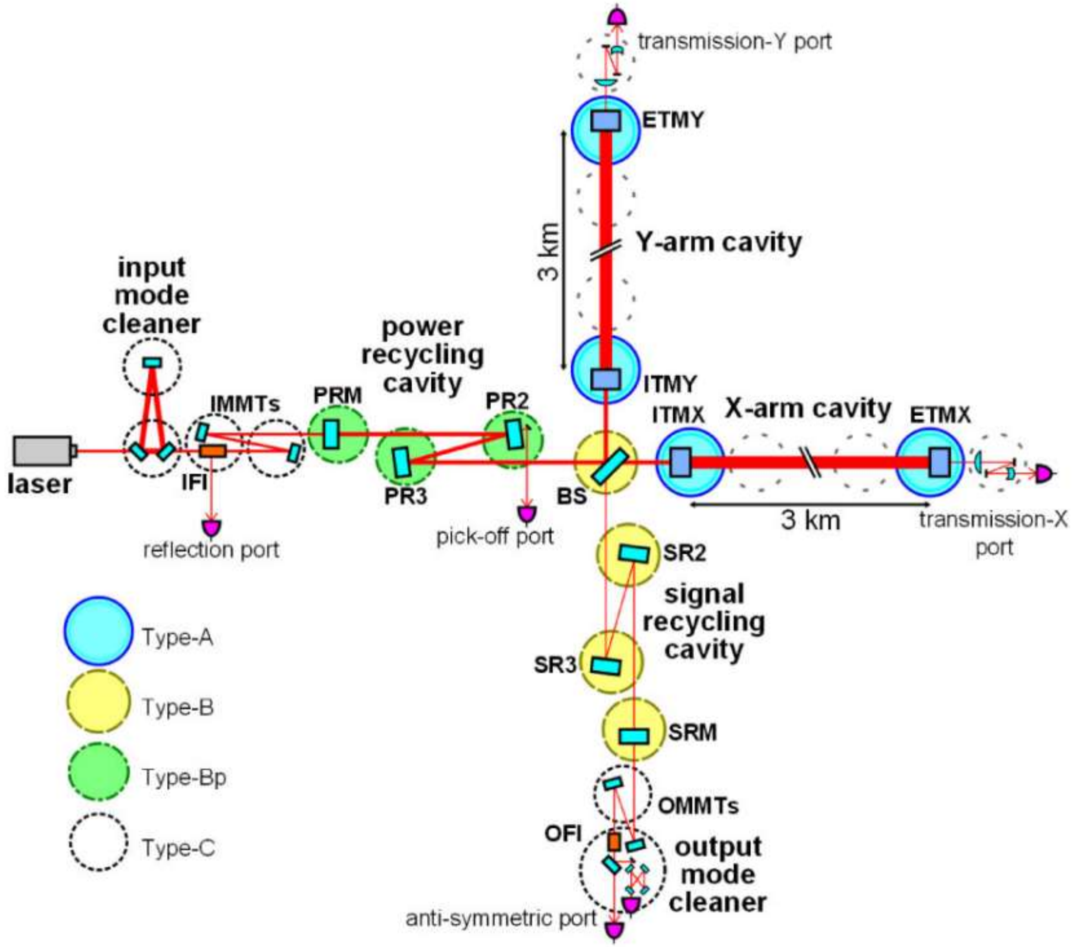
Status:

Installed and automated in air

Details:

- A very stable cavity for the frequency reference using the ultra-low expansion (ULE) glass spacer
- Requrement < 100mHz/sec
- Vacuum chamber had a leak; preparing for the repair
- Spacer length 100.71mm (catalog)
- Finesse 30000 (PhD thesis, Nakano)
- Controls: laser thermal, laser PZT, BB EOM
- UGF ~ 500 kHz

Interferometer of GW detector



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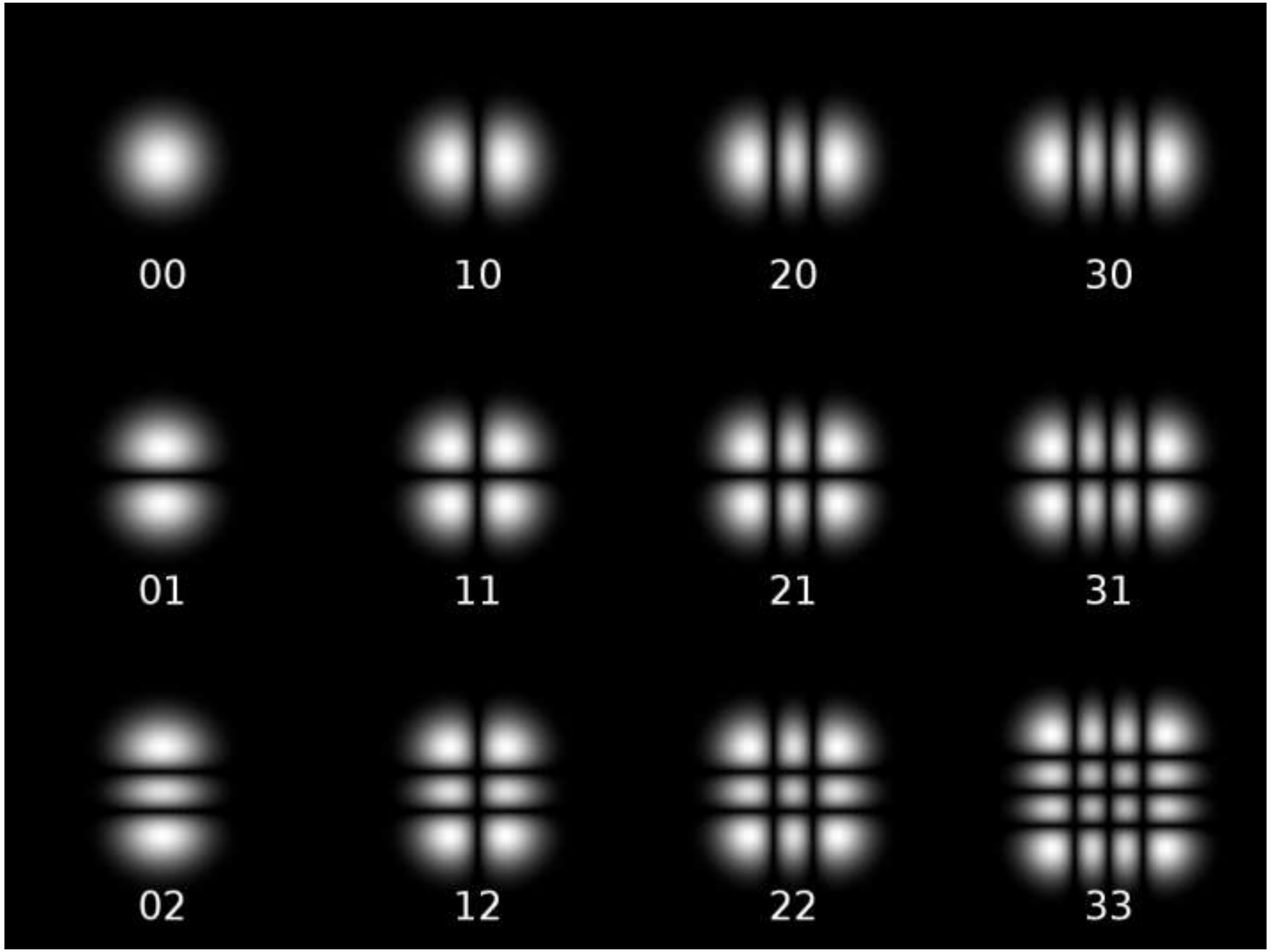
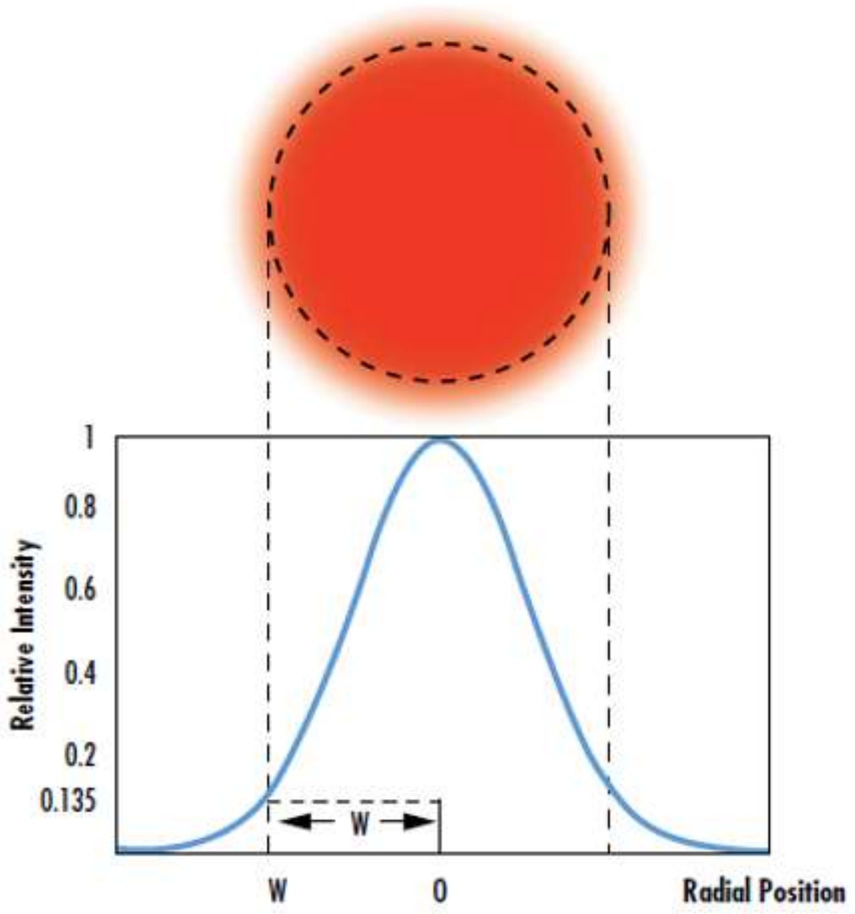
Spatial mode of gaussian beam

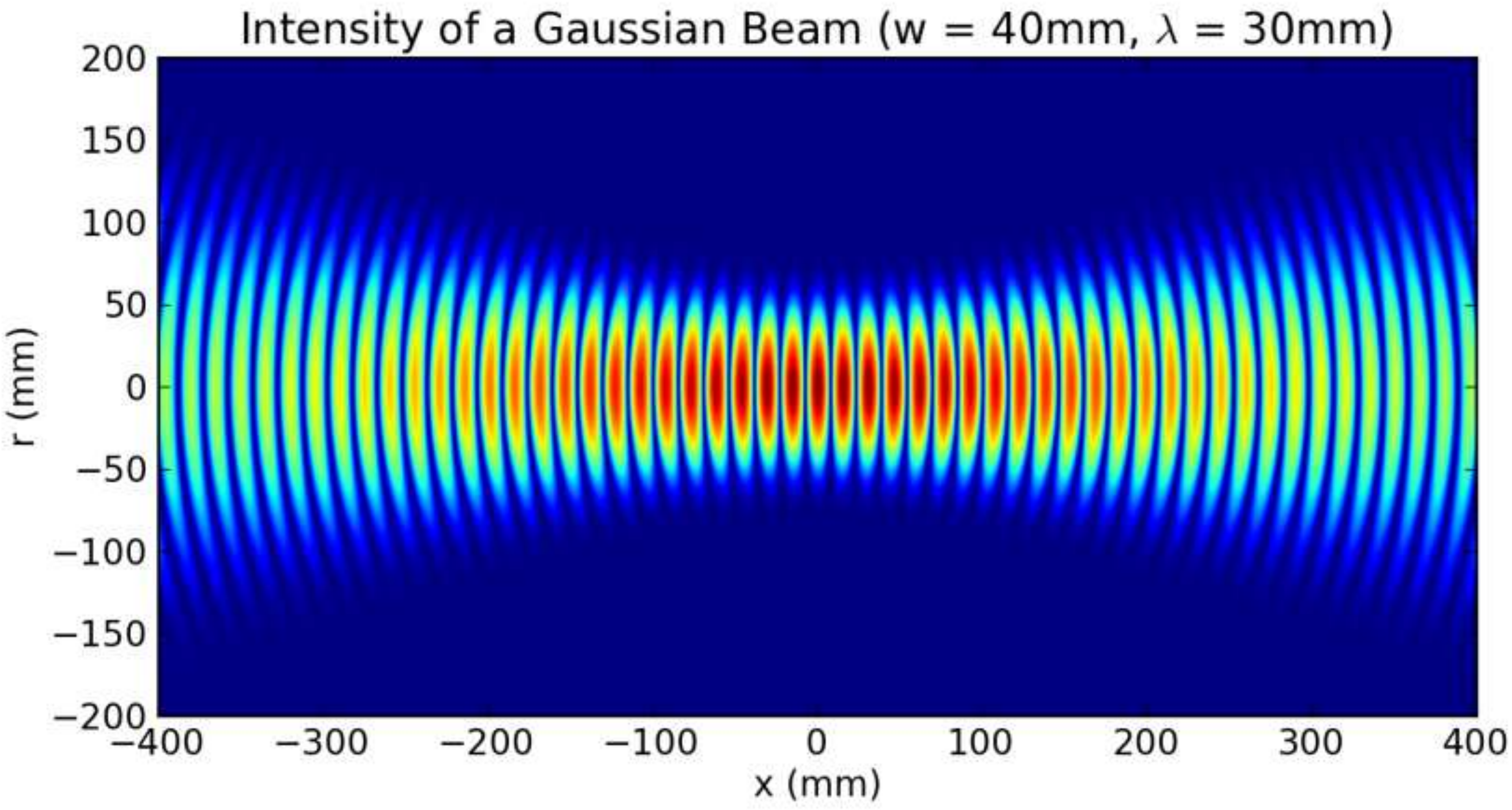


Gaussian beam

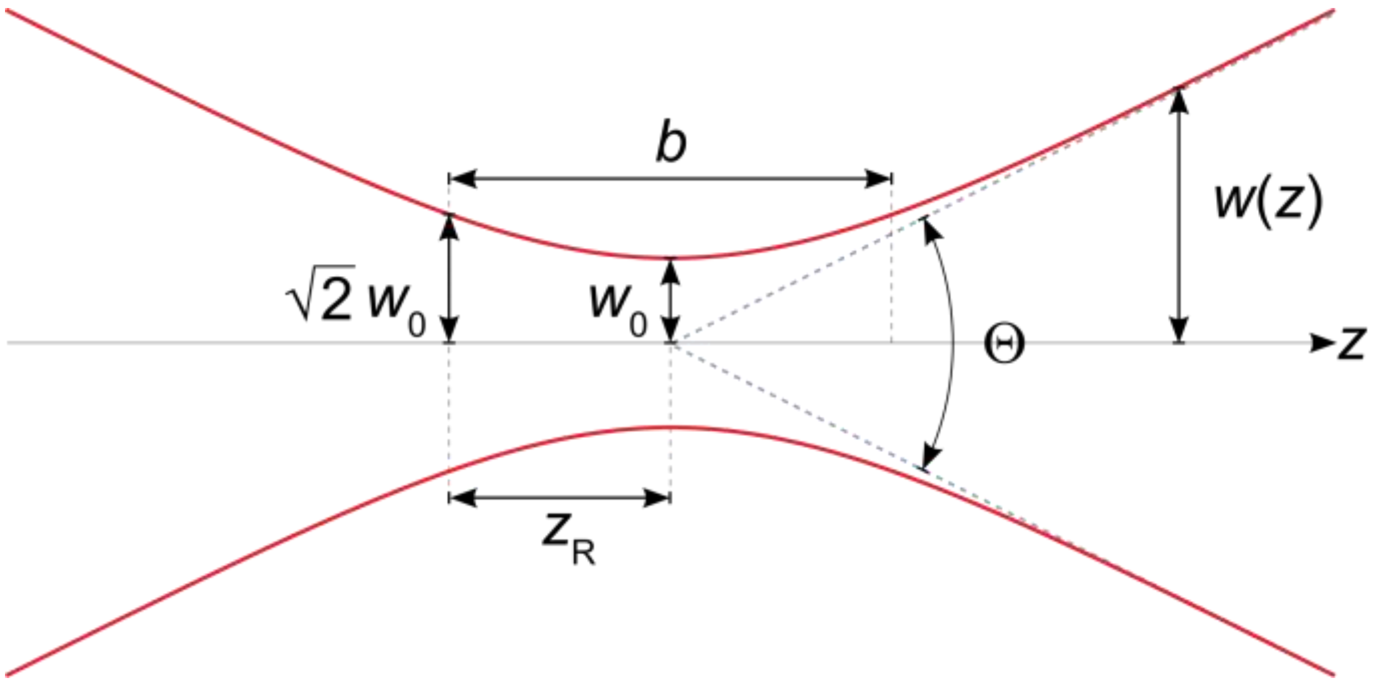


https://www.edmundoptics.co.kr/knowledge-center/application-notes/lasers/gaussian-beam-propagation/

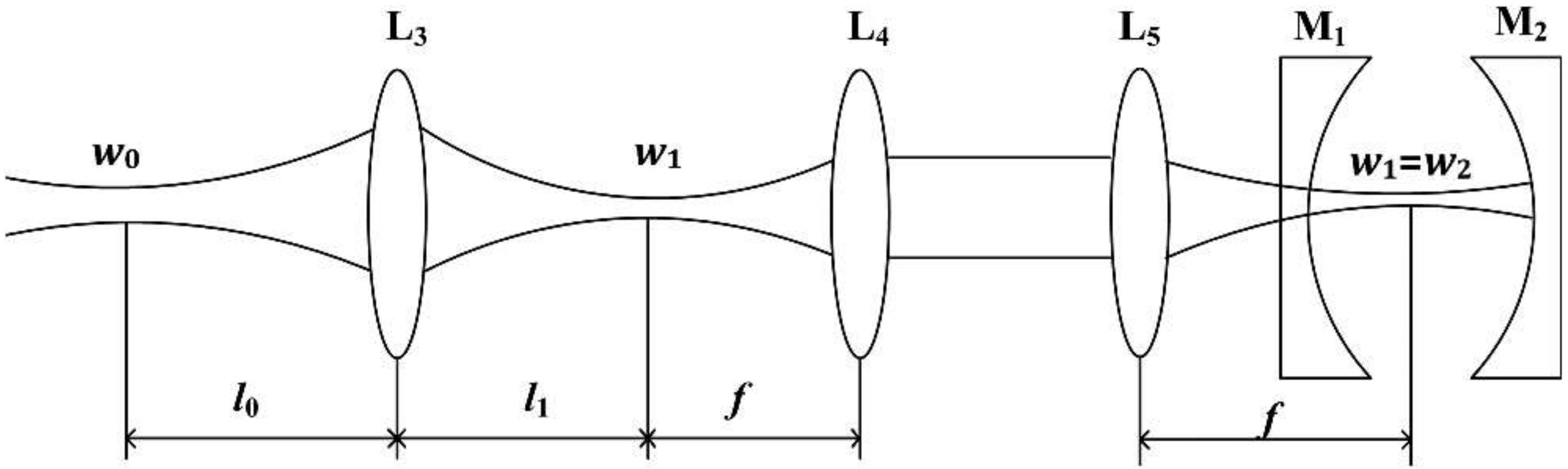
Gaussian beam



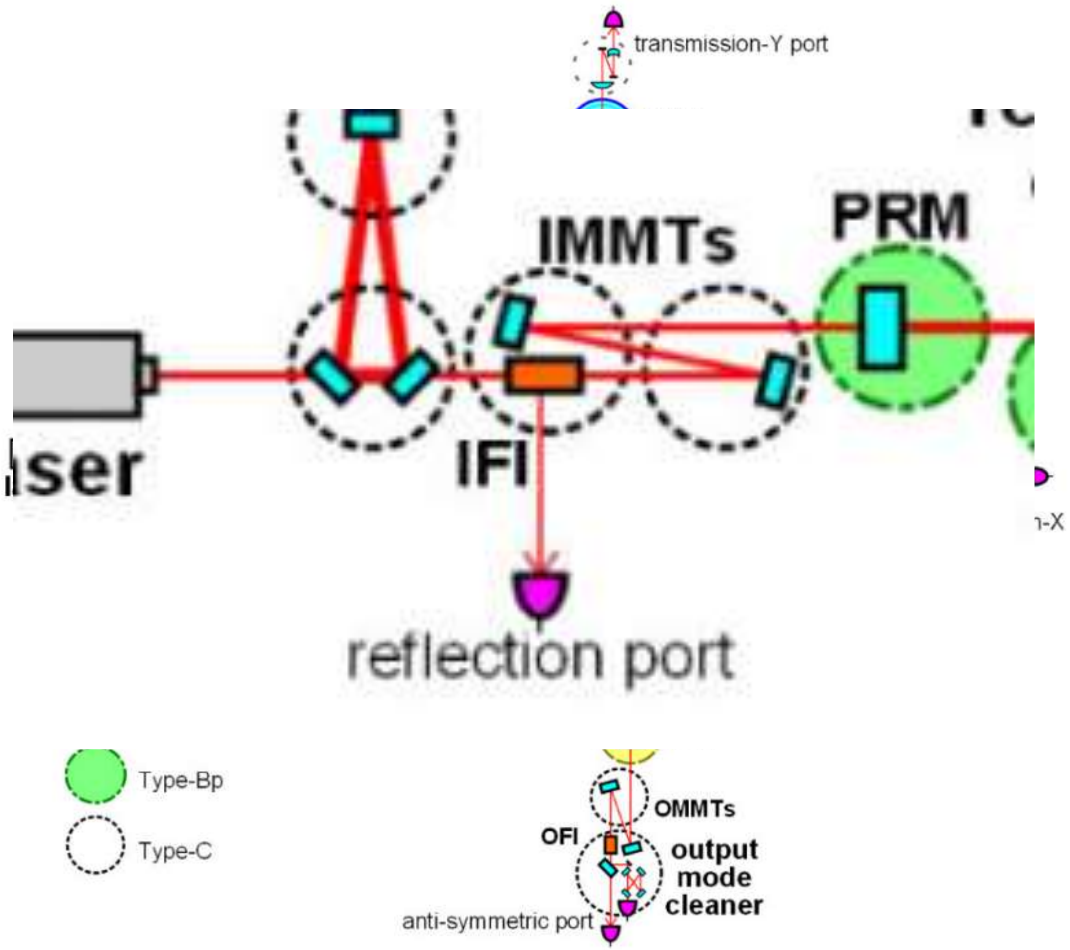
Gaussian beam



Gaussian beam mode matching



Interferometer of GW detector



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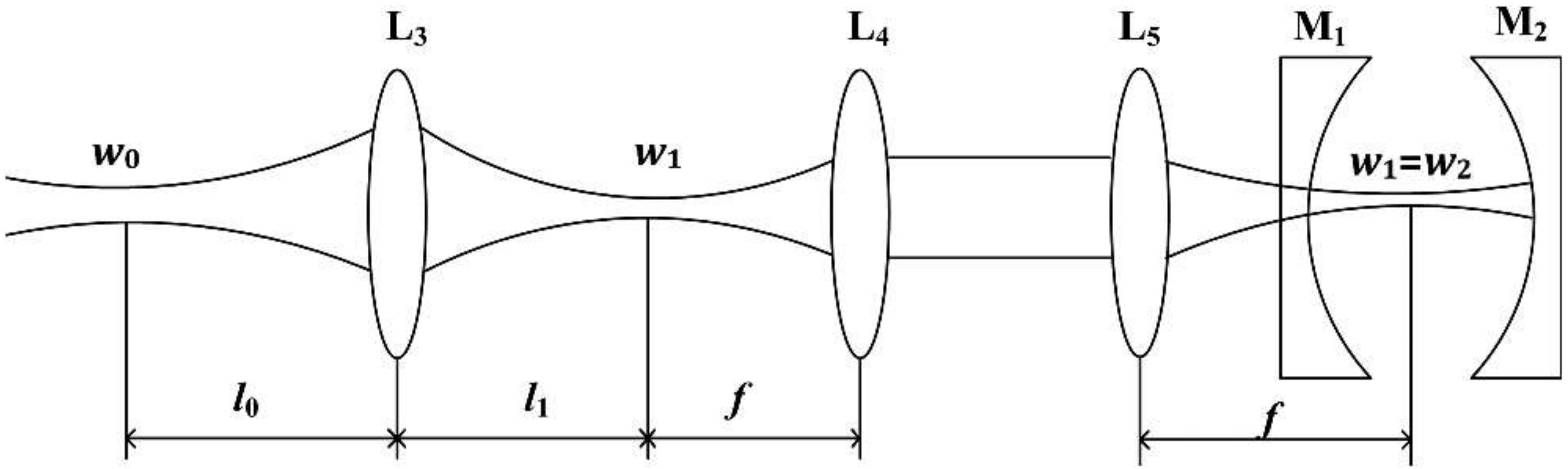
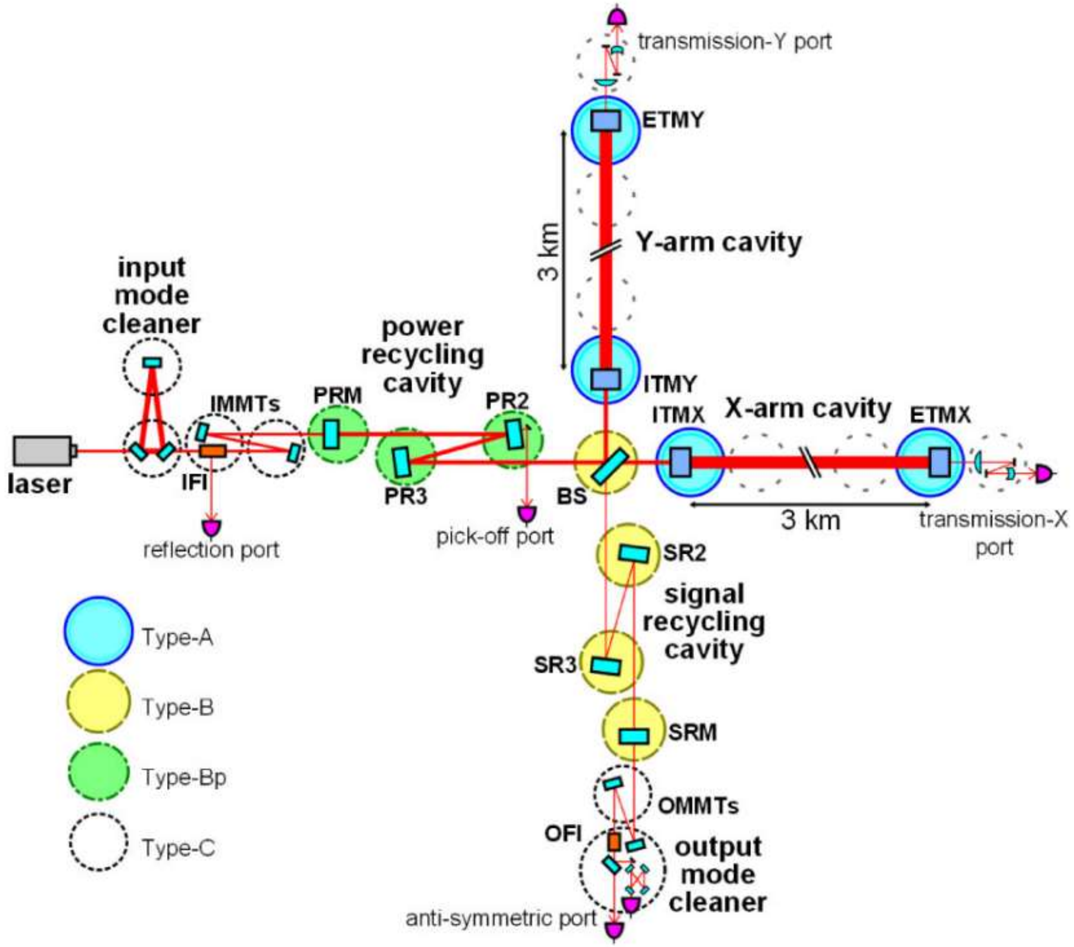
Gaussian beam mode matching



Interferometer of GW detector



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MMT : Mode matching telescope

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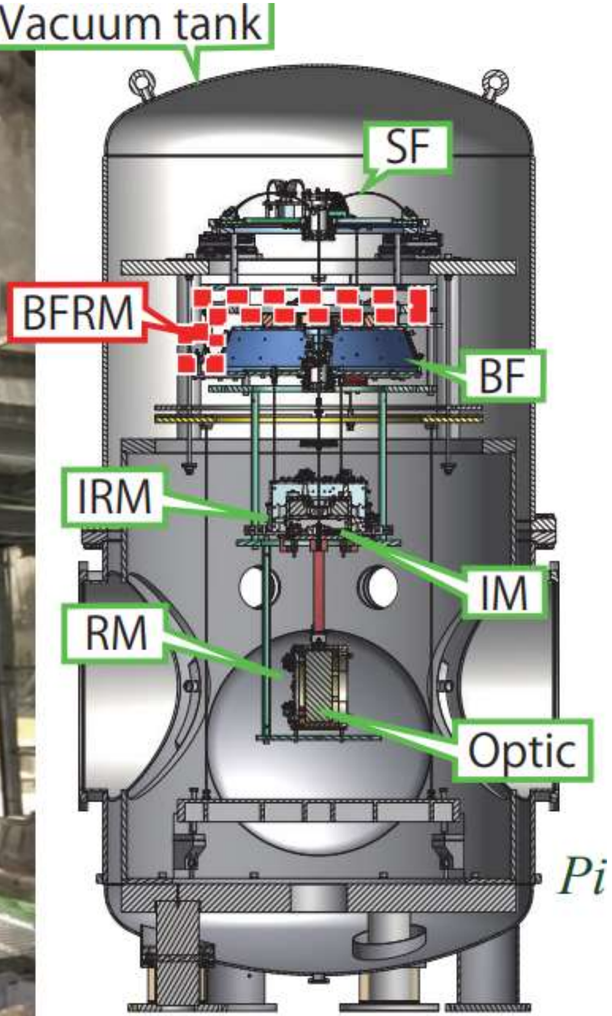
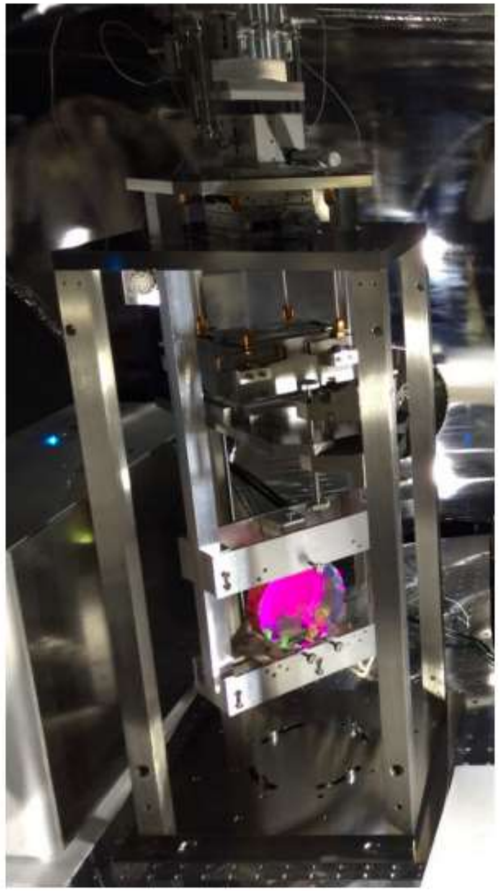
KAGRA chamber

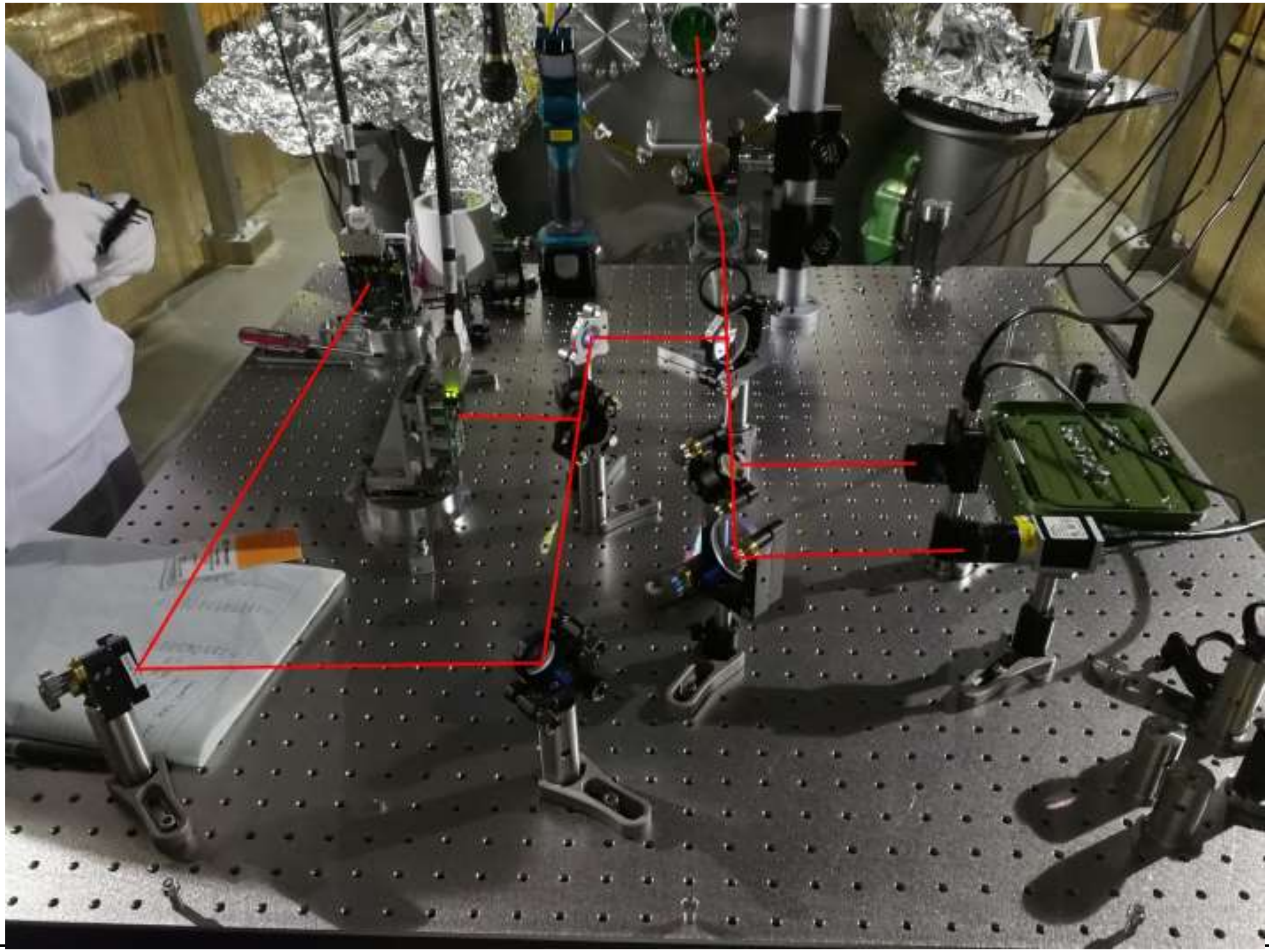


https://authors.library.caltech.edu/94680/2/1901.03053.pdf

Mirror of IMC



Wavefront sensor MCE_TRANS



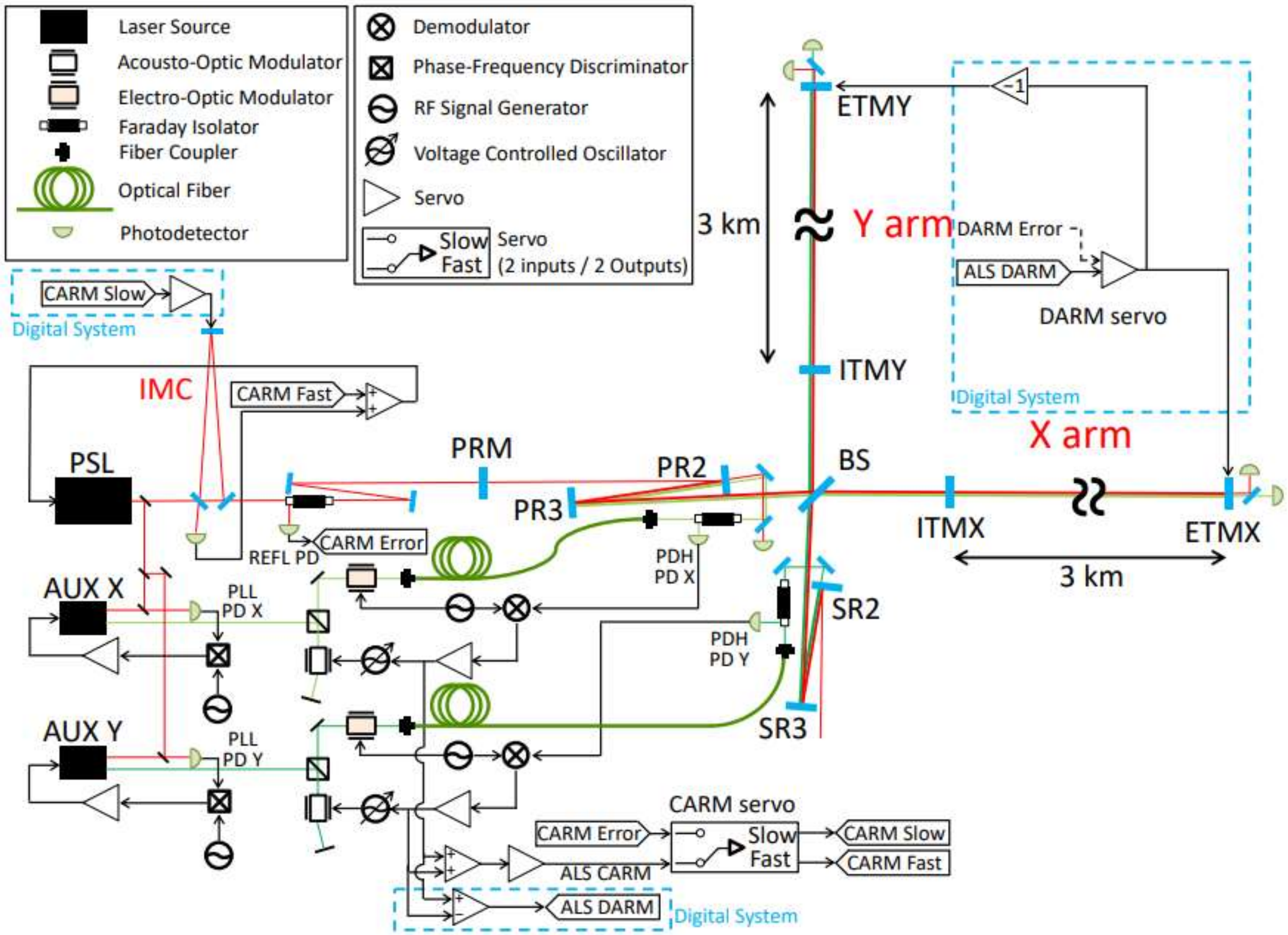
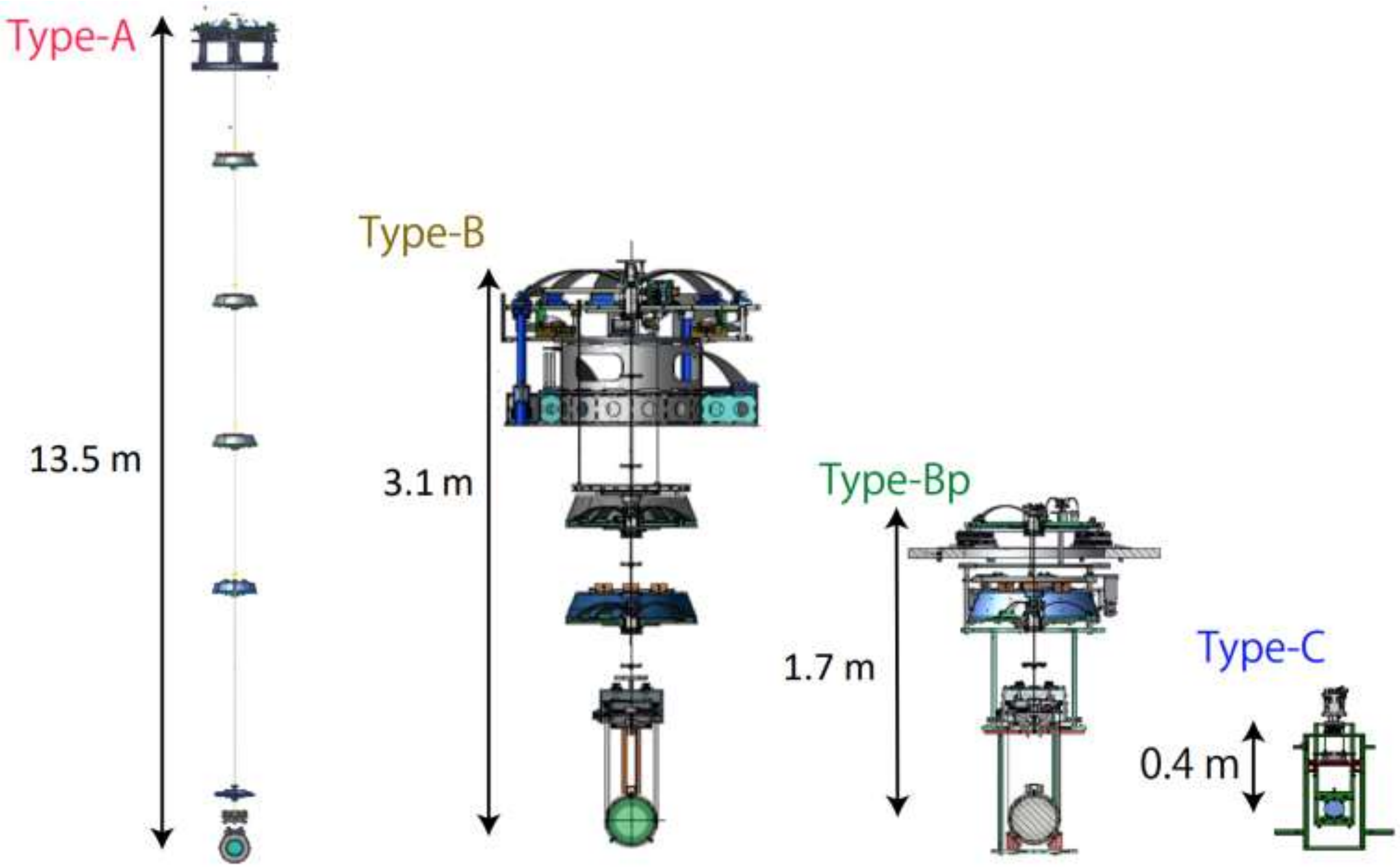
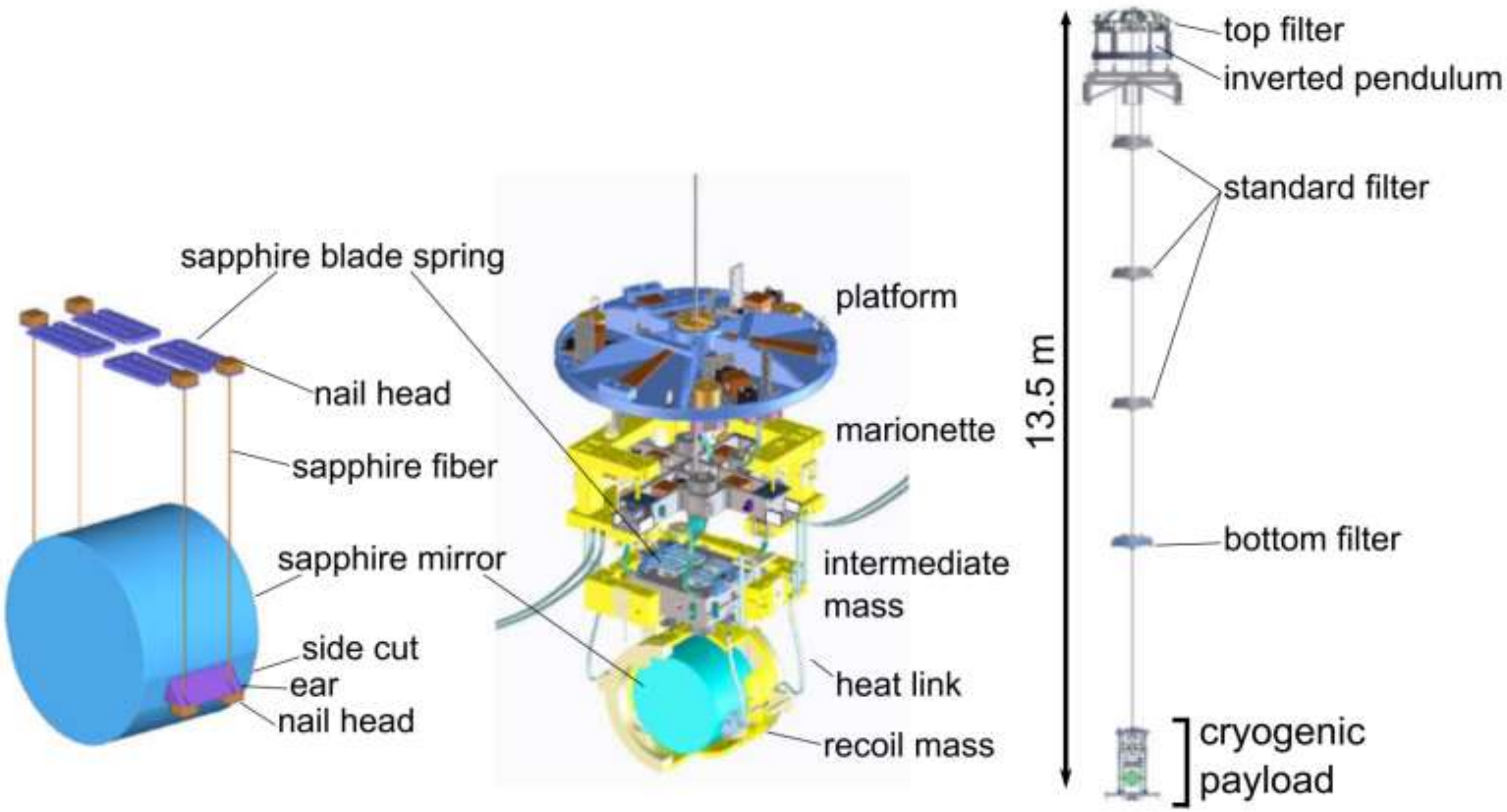


Figure 2. Overview of the arm length stabilization system of KAGRA. The frequencies of the two auxiliary lasers are phase-locked to that of PSL. The frequency of the each green laser is controlled by the combination of a double-path acousto-optic

Vibration isolation system of KAGRA

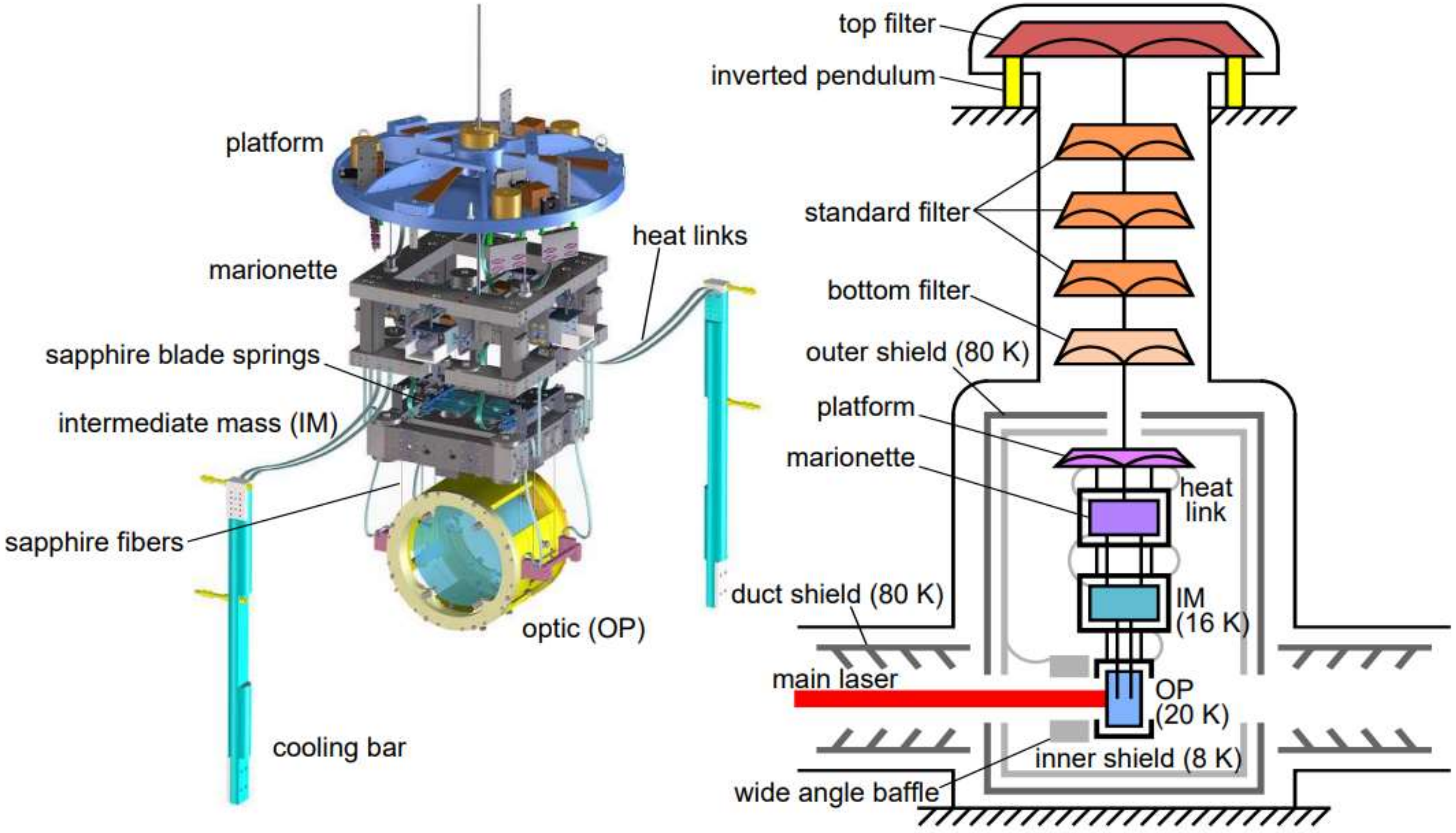


Cryogenic system of KAGRA



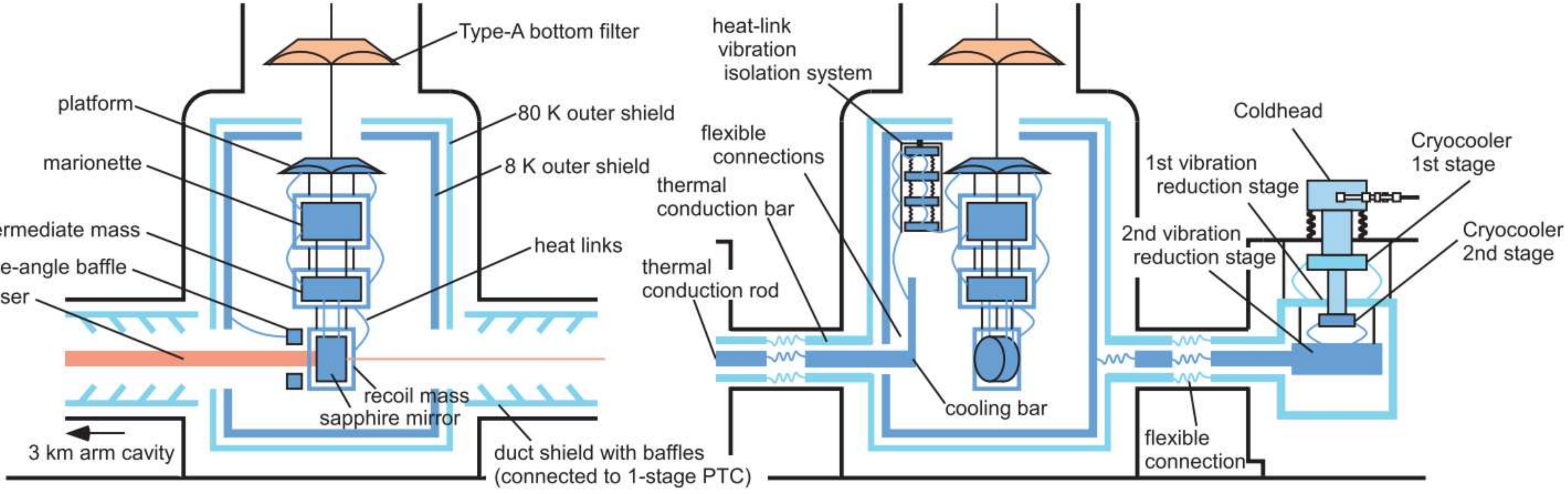
T. Akutsu et al.
PTEP 2020, 05A101

Cryogenic system of KAGRA



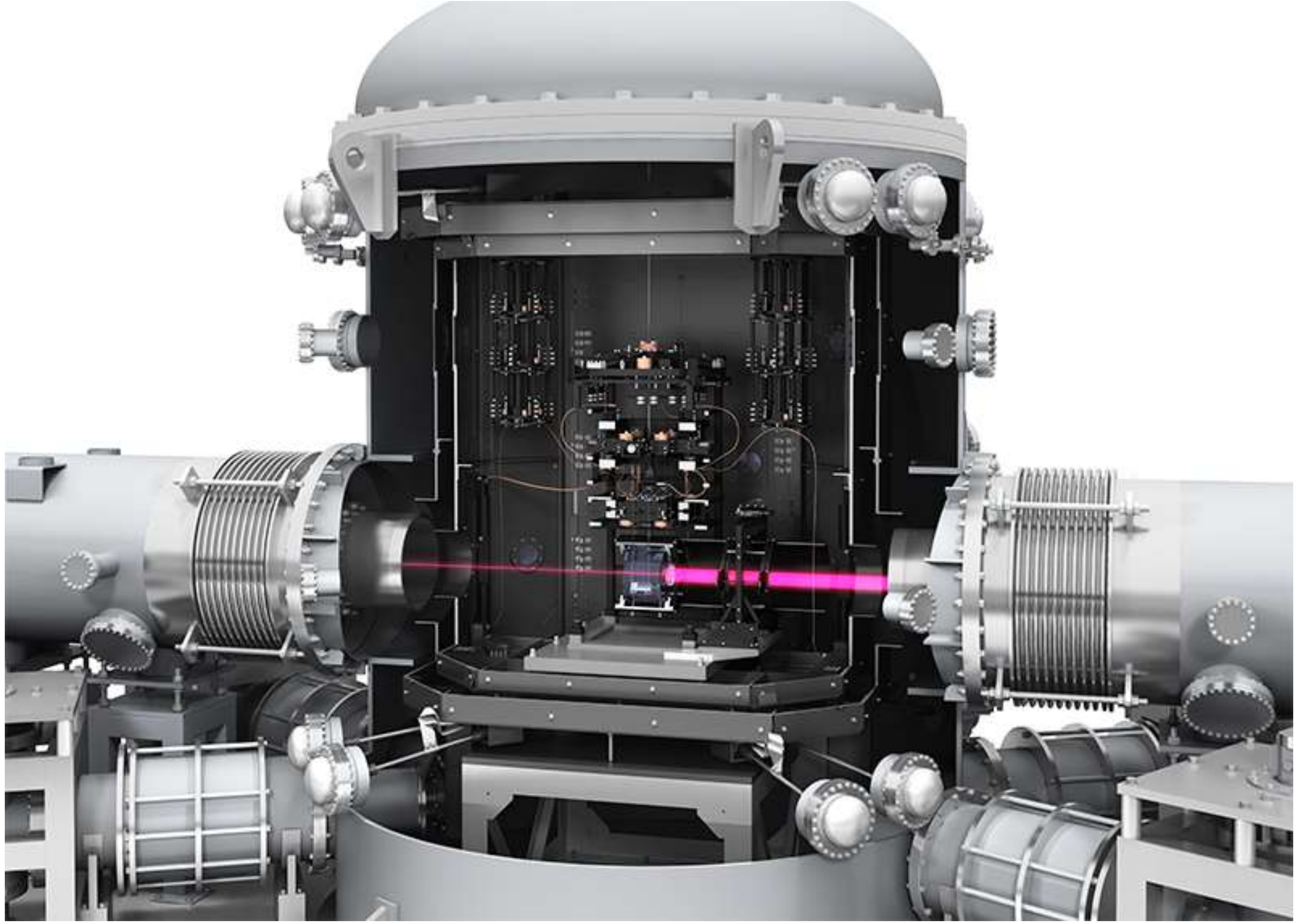
Class. Quant. Grav. 36 (2019) 165008

Cryogenic system of KAGRA



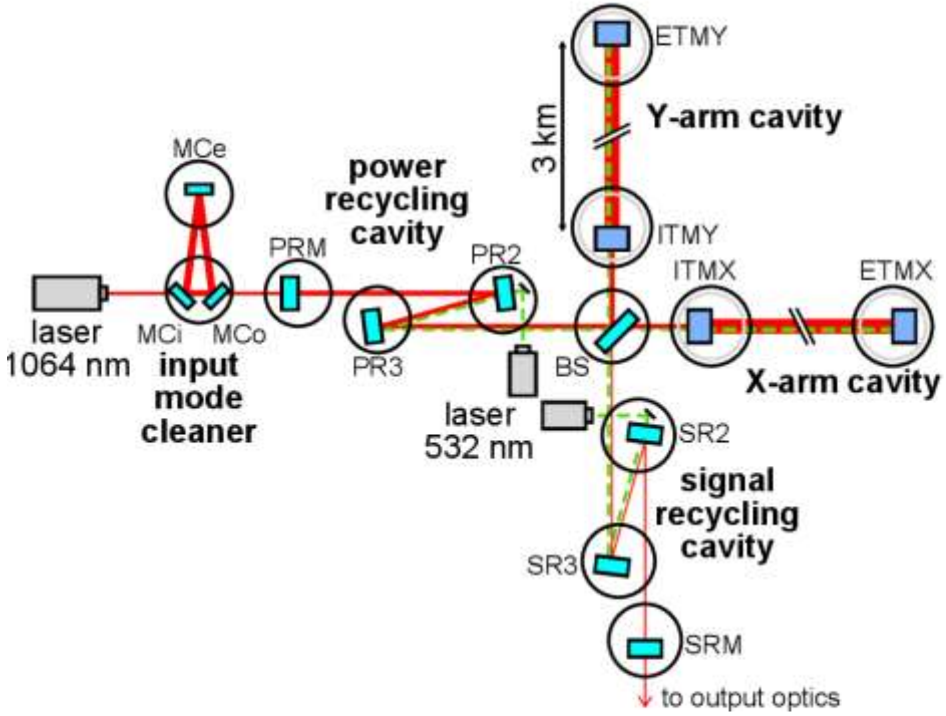
T. Akutsu et al.
PTEP 2020, 05A101

Test mass chamber



Rey.Hori

Power and Signal recycling mirror



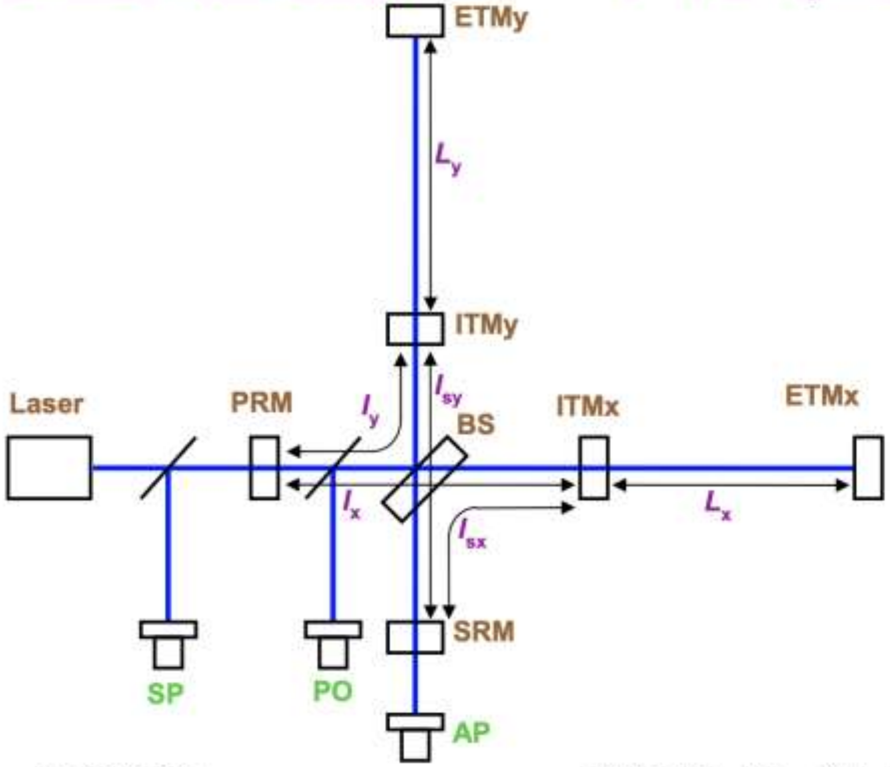
Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

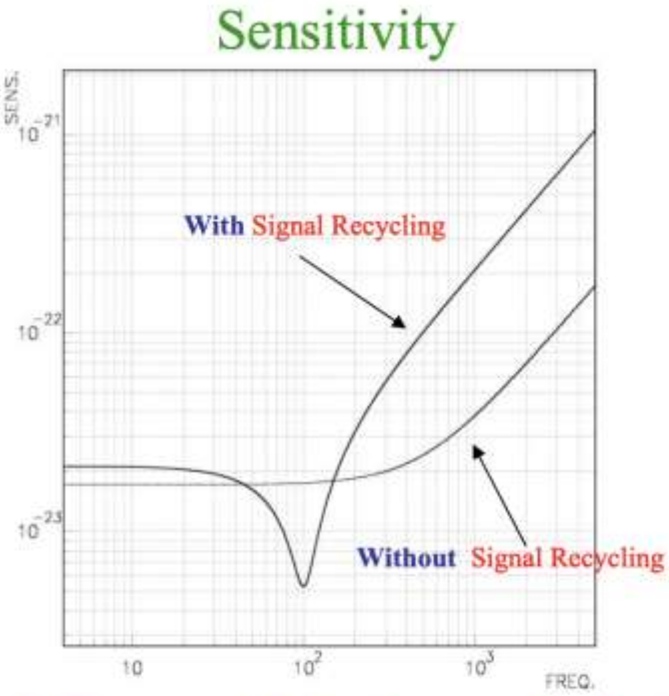
MC : Mode Cleaner
ITMX : Input Test Mass X
ITMY : Input Test Mass Y
REFL : Reflection Port
PRM : Power Recycling Mirror
OMC : Output Mode Cleaner
AS_DC : Anti Symmetric DC
SRM : Signal Recycling Mirror
POP : Pick-off-in-the-PRC
ETMX : End Test Mass X
ETMY : End Test Mass Y
AS_RF : Anti Symmetric RF

Power and Signal recycling mirror

DUAL-RECYCLED INTERFEROMETER

Common of arms : $L_+ = (L_x + L_y) / 2$
Differential of arms : $L_- = (L_x - L_y) / 2$
Power recycling cavity : $l_+ = (l_x + l_y) / 2$
Michelson : $l_- = (l_x - l_y) / 2$
Signal recycling cavity : $l_s = (l_{sx} + l_{sy}) / 2$

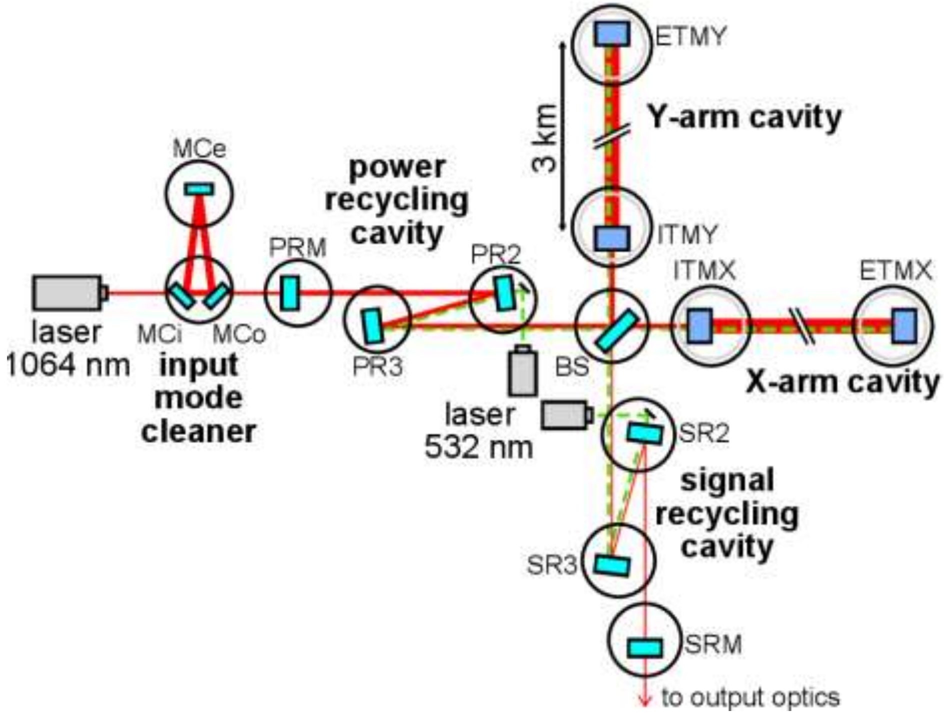




better sensitivity in an optimized frequency band

(naive view)

Power and Signal recycling mirror



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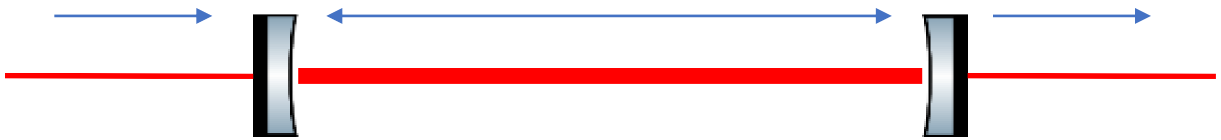

Power and Signal recycling mirror

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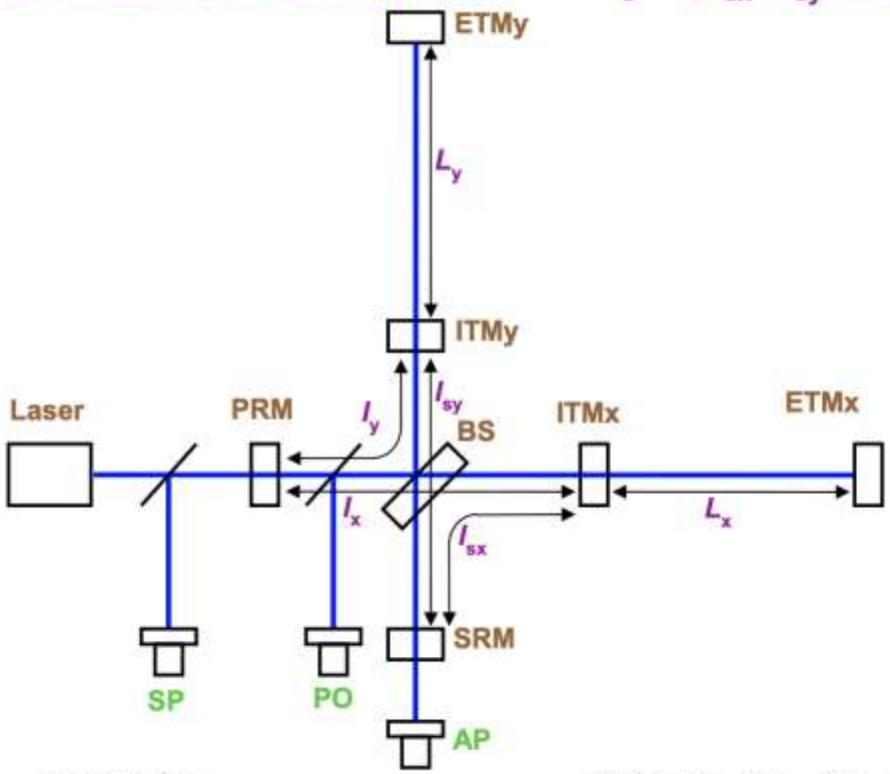
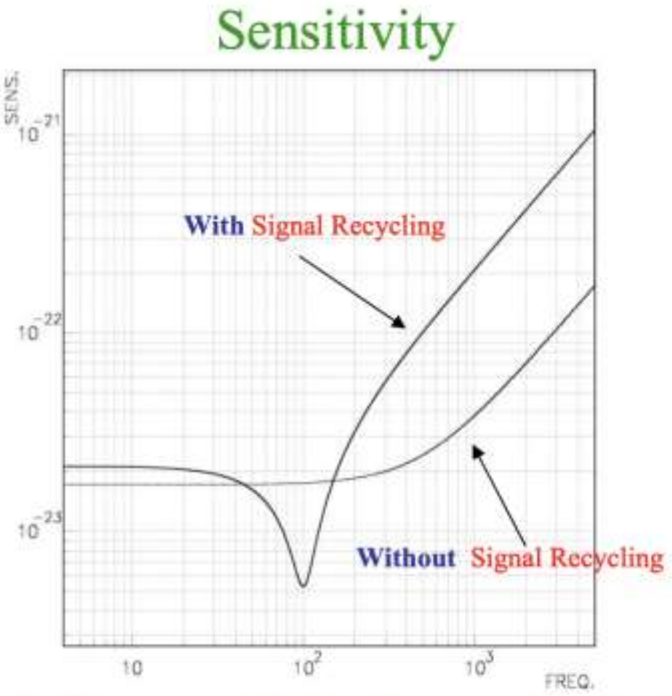
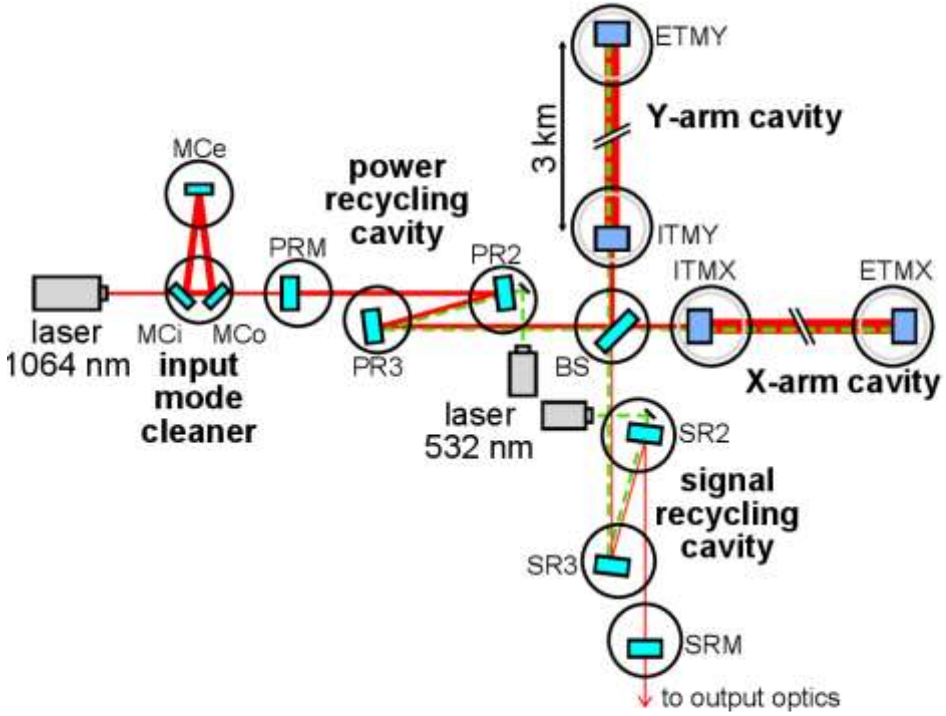




better sensitivity in an optimized frequency band
(naive view)

Power and Signal recycling mirror



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LIGO status

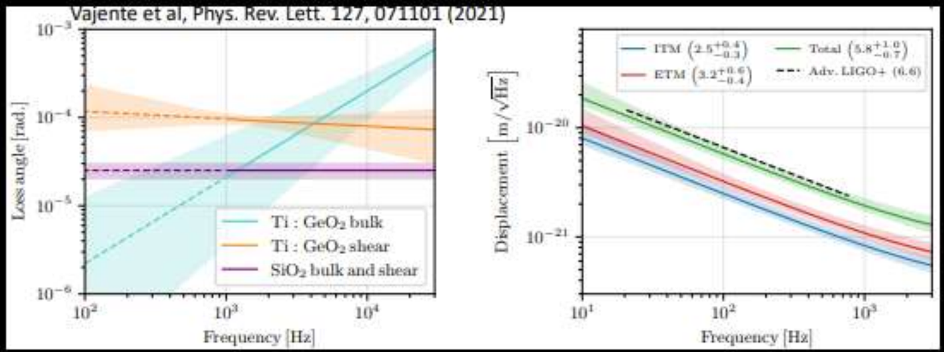
LIGO

A+ Upgrade: Toward O4

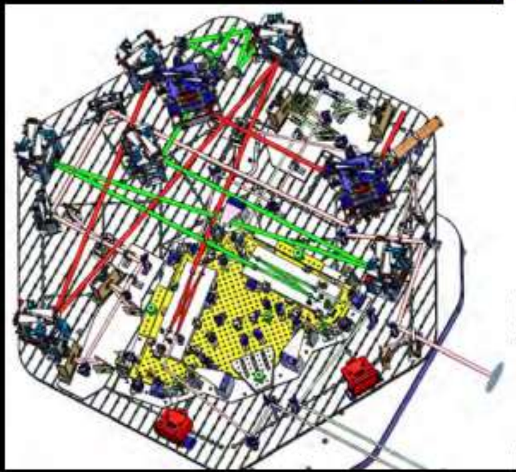
- Target: 190 Mpc BNS range
  - Improved Faraday isolators (UF/Montclair)
  - Adaptive wavefront control (LIGO/Adelaide/Syracuse)
  - High-dynamic-range photodetectors (LIGO/Cardiff)
  - Frequency-dependent squeezing
    - Upgraded squeezer & dark port
    - New end station labs & filter cavity tube enclosure buildings
    - New vacuum chambers & filter cavity beamtubes
  - [+ concurrent detector improvements, not A+: high laser power, point-defect-free TM's, scattered light control, …]

A+ Upgrade: Toward O5

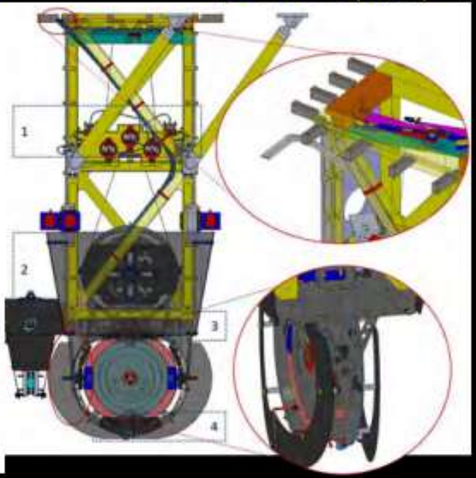
- A+ O5 Target: 325 Mpc BNS range
- Low-CTN coatings
  - A+ and AdV+ will pursue Ti:GeO_2 material for O5; LIGO has procured required deposition targets
    - LIGO/Virgo joint working group appointed to guide full-aperture development & QA
    - *Bubble formation risk during annealing is not yet resolved;* R&D is underway
  - A+ substrates all in hand, now polishing (UK/Glasgow + US)
  - Coating production readiness review planned for end of calendar '22
- Large-aperture beamsplitter and relay triple suspension designs complete, fabrication reviews imminent (UK/RAL)
- Balanced Homodyne Readout (BHR) in final design, FDR pending (UK/Glasgow & Cardiff)
  - O5 start paced by post-O4 A+ installation
  - Estimated ~11 months after post-run cal, not including commissioning



BHR raytrace in HAM6, G2101467 (Glasgow)

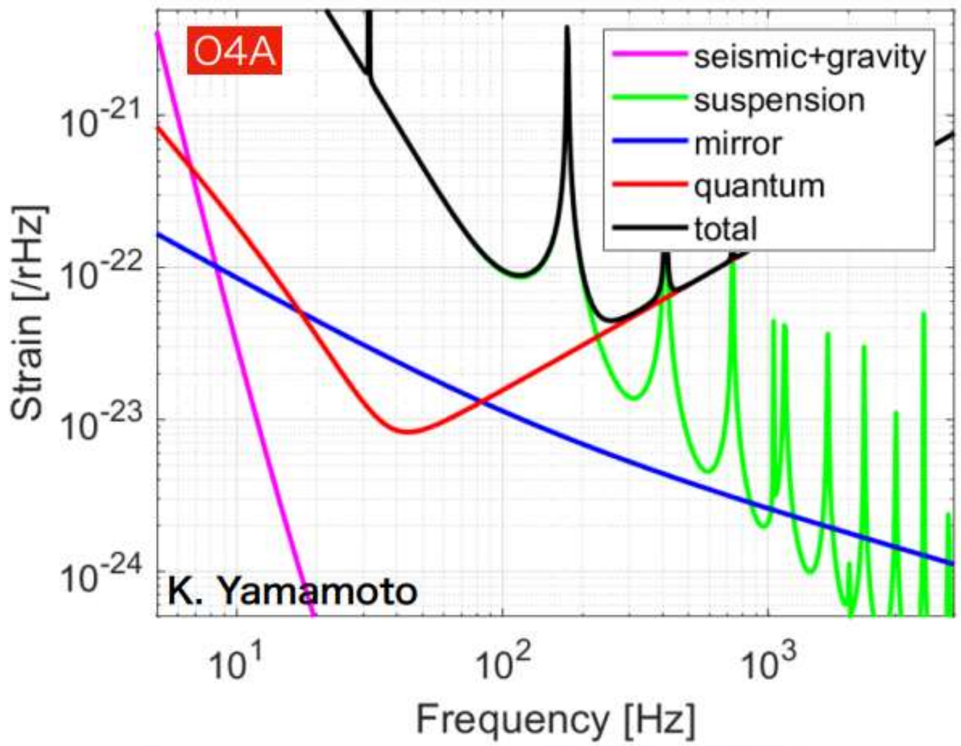


BBSS Final Design, T2000503 (RAL)

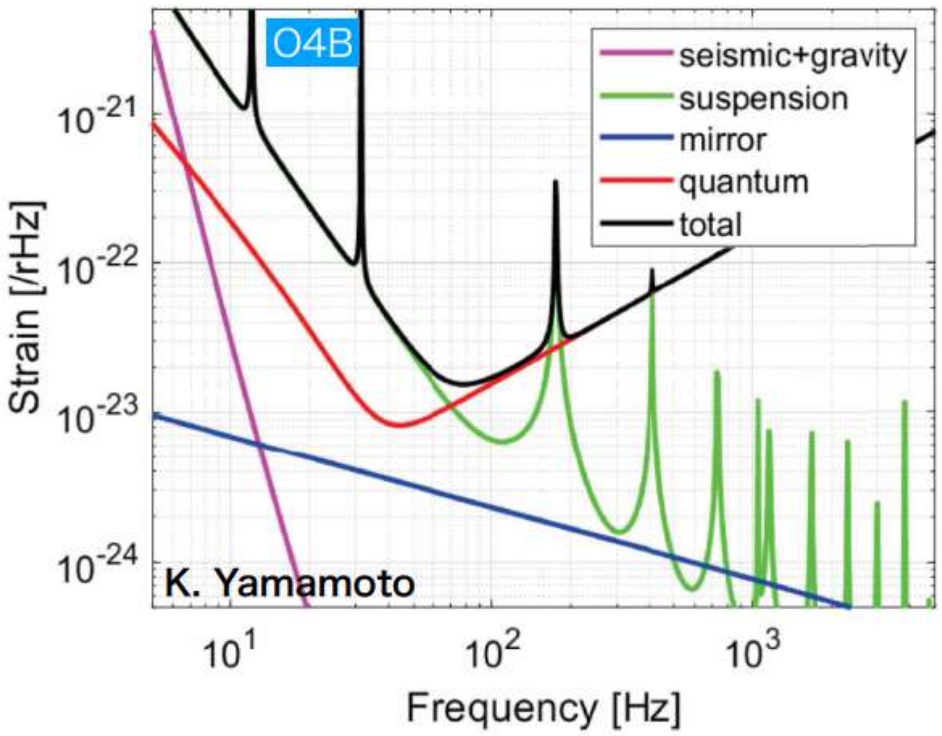


KAGRA status

Fundamental noises in O4

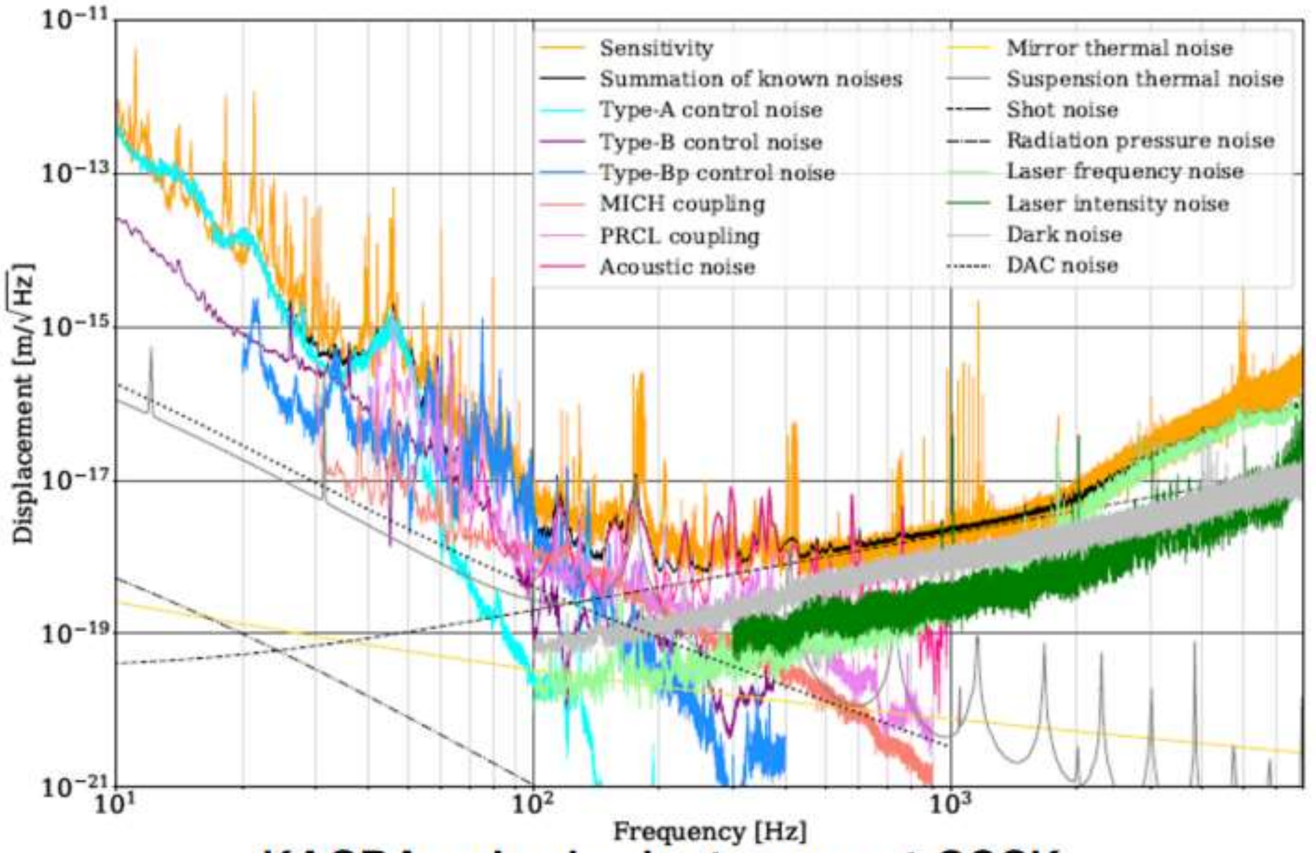


- Mirror temperature: 250K ~ 300K
- Laser power at BS: 58W (same as O3GK)
- PRFPMI
- Observation range limit: 6Mpc
- Target: 1Mpc



- Mirror temperature: ~20K
- Laser power at BS: 58W
- PRFPMI
- Observation range limit: 35Mpc
- Target: 10Mpc

Noise budget at O3GK

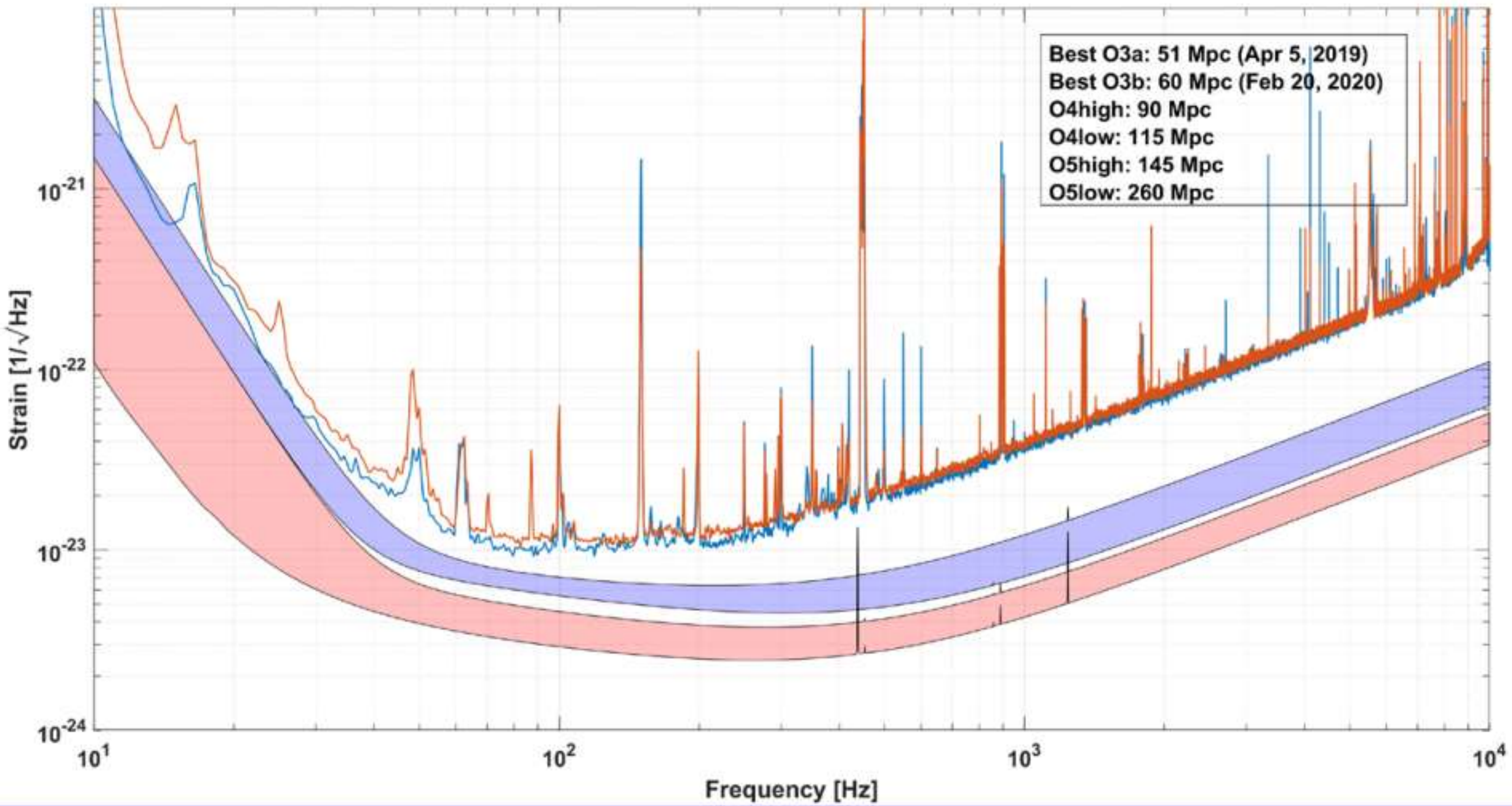


KAGRA noise budget curve at O3GK
https://arxiv.org/abs/2203.07011

- Noise sources limiting the sensitivity at O3GK were well identified.
  - The noise budget paper has just been submitted to the archive.
- Low frequency (< 100Hz): Suspension control noise.
- Mid-frequency (100Hz-400Hz): Scattering light noise excited by acoustic noise.
- High frequency (400Hz<): Shot noise, optical loss between BS and AS detection port (70% reflection SRM and so on).

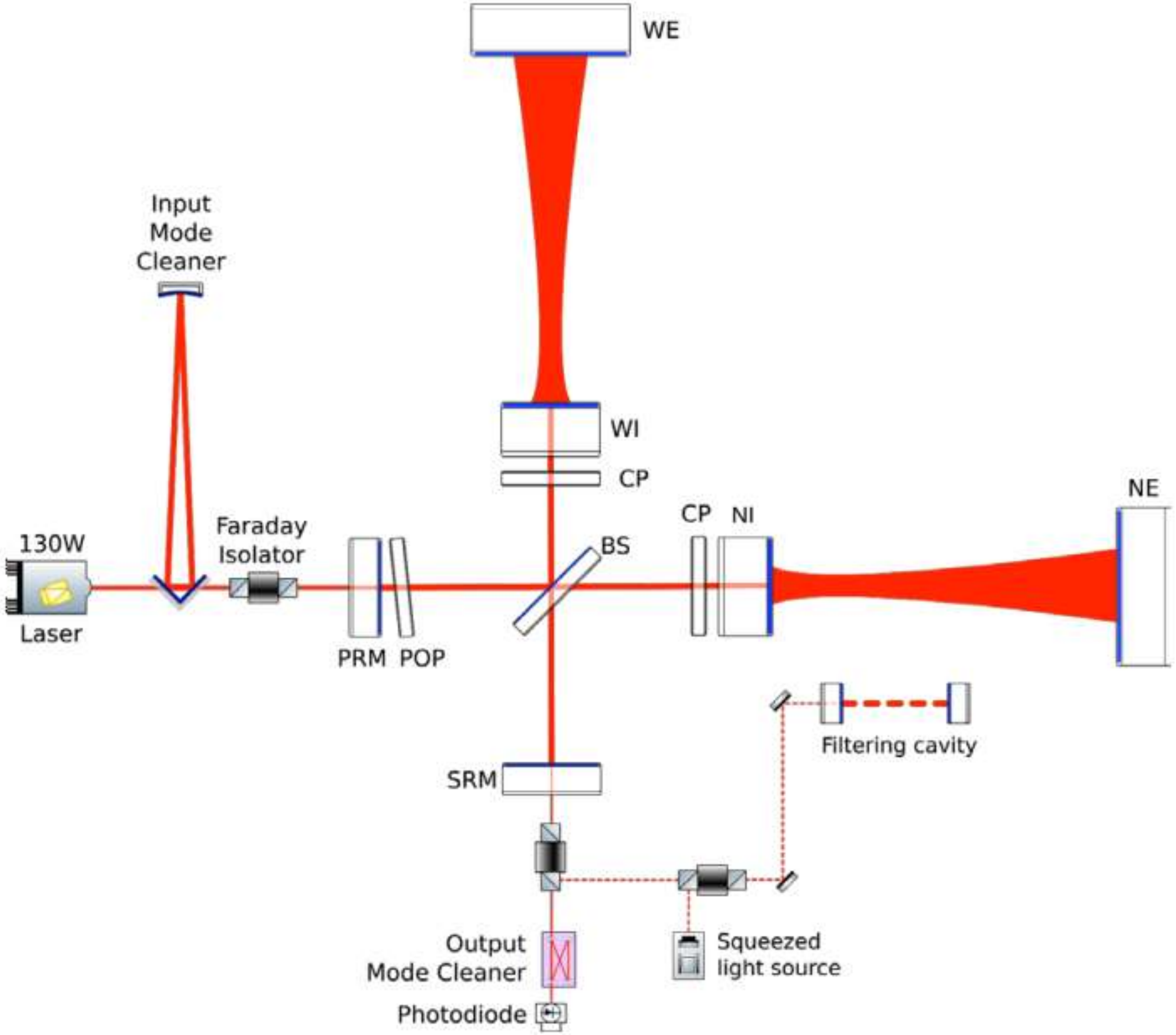
Advanced Virgo+ design sensitivity

- Phase I: reduce quantum noise, hit against thermal noise. BNS range: 100 Mpc's
- Phase II: lower the thermal noise wall. BNS range: 200 Mpc's or more



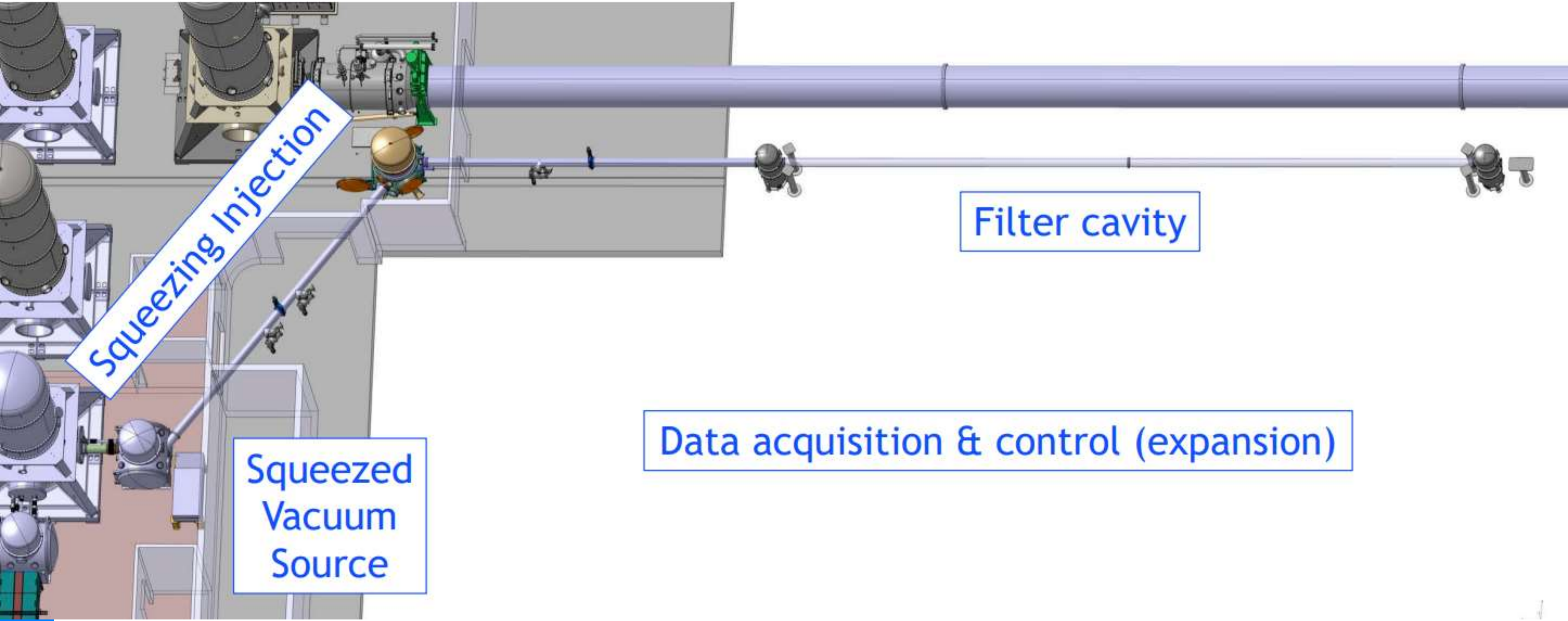
Advanced Virgo+ Phase II

- Main changes
  - Larger beams on end test masses
    - » 6 cm radius ⇒ 10 cm radius
  - Larger end mirrors
    - » 40 kg ⇒ 100 kg
  - Better mirror coatings
    - » Lower mechanical losses, less point defects, better uniformity
  - New suspensions/seismic isolators for large mirrors
  - Further increase of laser power
    - » 40W ⇒ 60W ⇒ 80 W

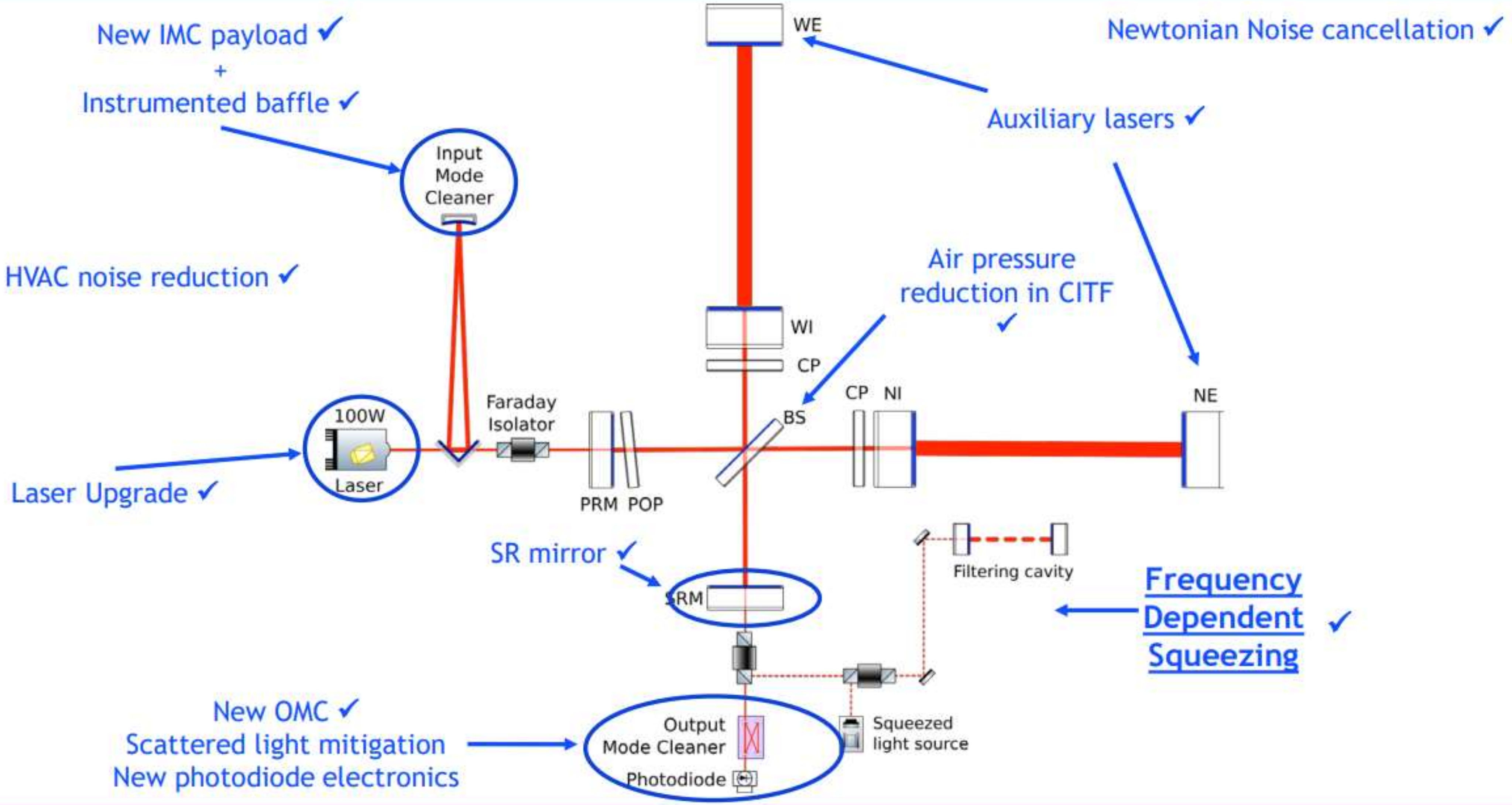


Quantum noise reduction system (QNR)

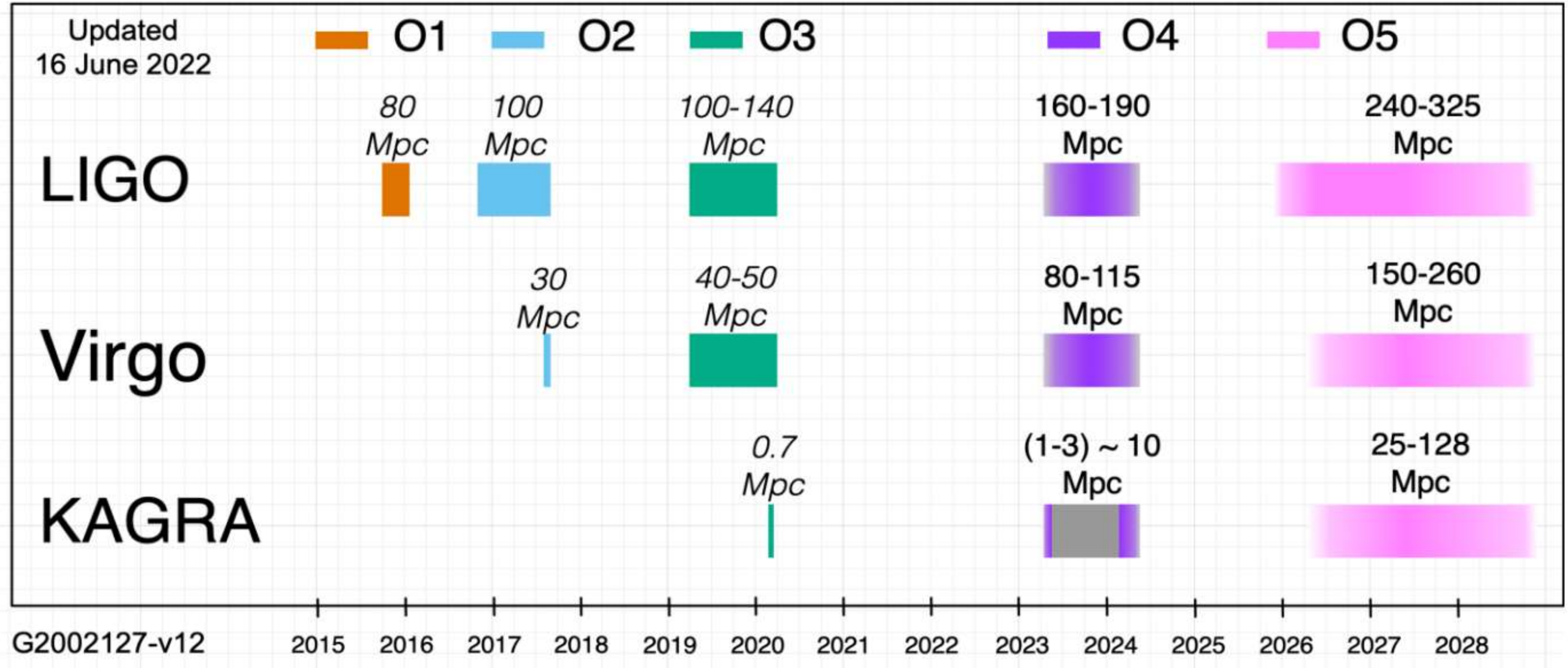
- Goal: use frequency dependent squeezing in AdV+ Phase I
  - System design compatible with FIS as well



Advanced Virgo+ Phase I

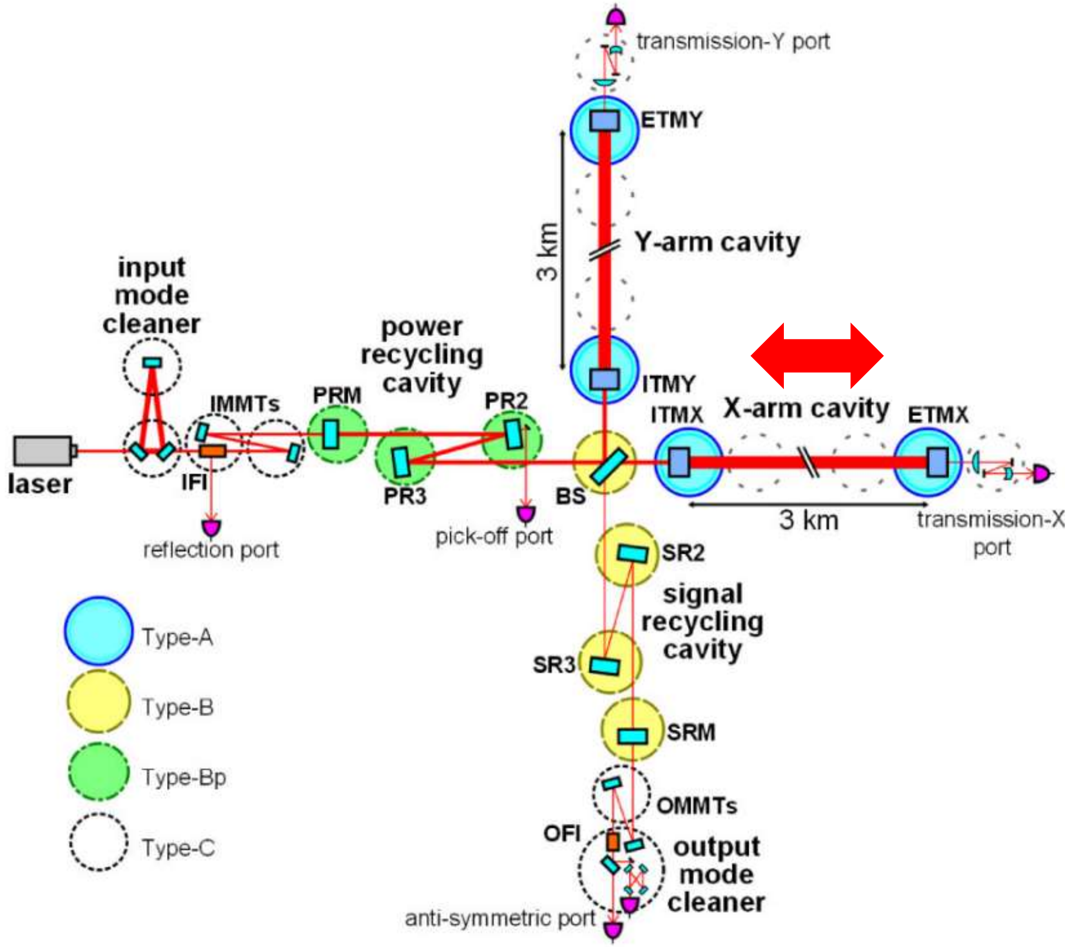


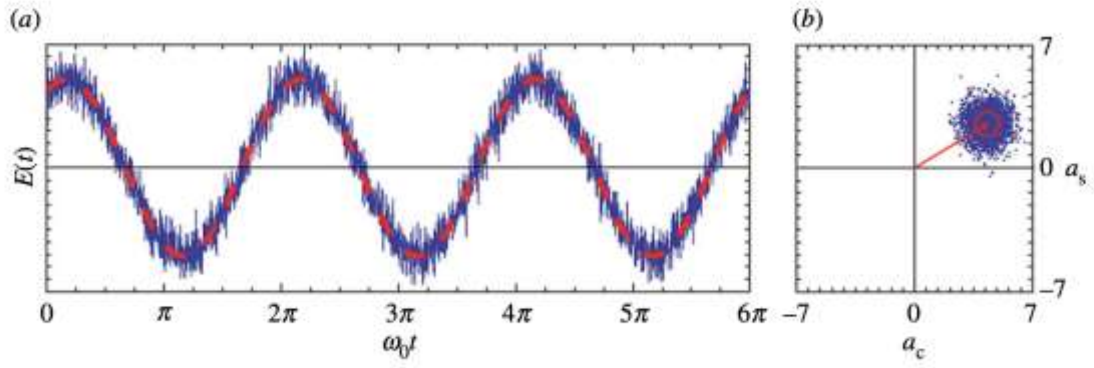
LIGO status


Updated
16 June 2022
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
80-115 Mpc
150-260 Mpc
KAGRA
0.7 Mpc
(1-3) ~ 10 Mpc
25-128 Mpc
G2002127-v12
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028

Quantum noise of gravitational wave detector

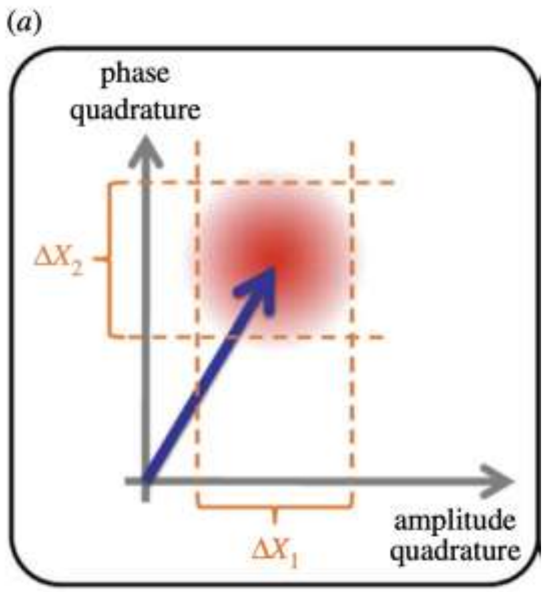
Quantum noise of coherent light





Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit. Phil. Trans. R. Soc. A 376: 20170289.

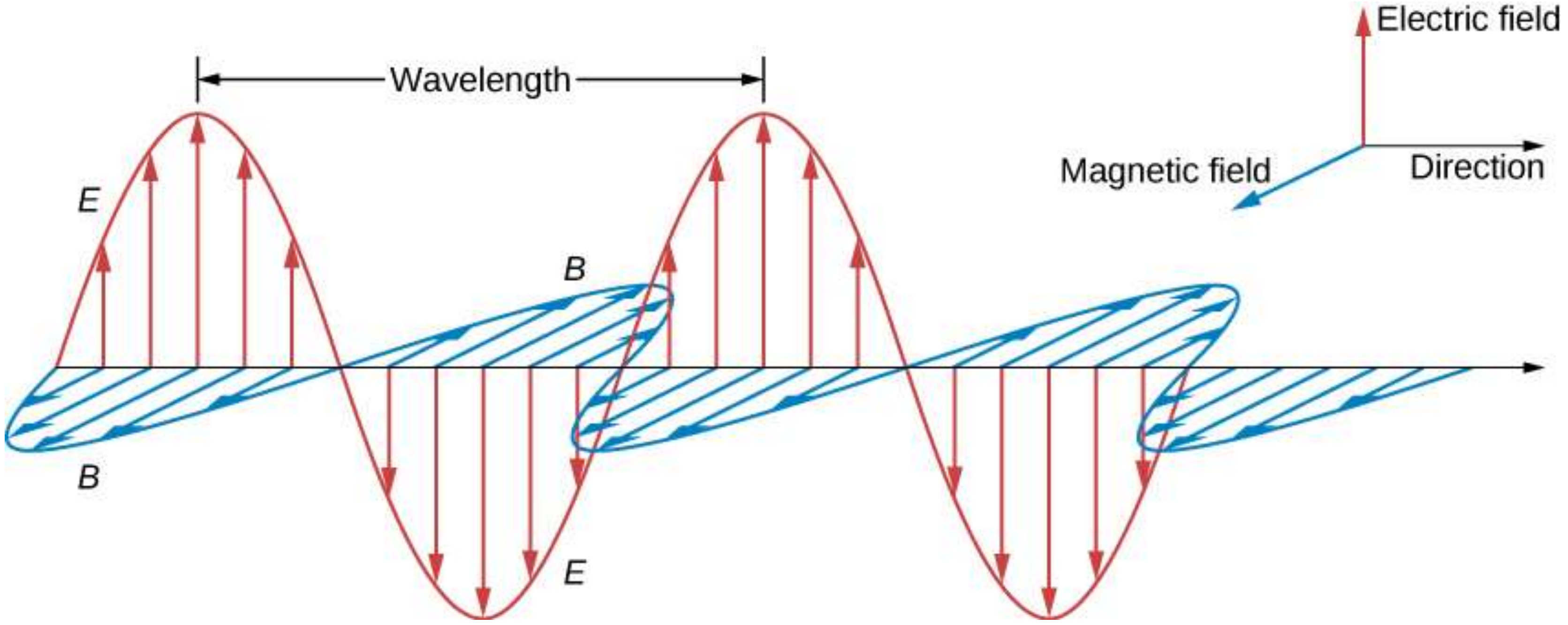
Phase and amplitude noise of light



$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

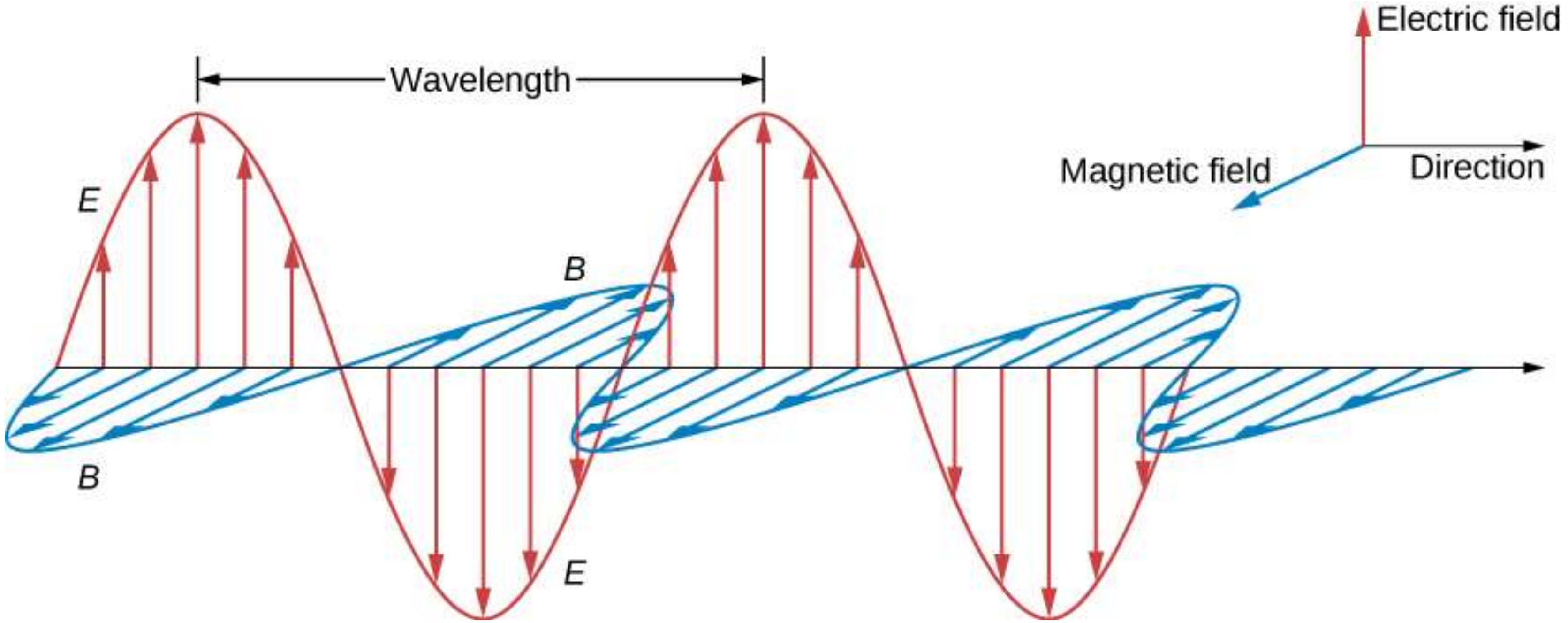
Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Classical electromagnetic wave



Measuring the electromagnetic wave

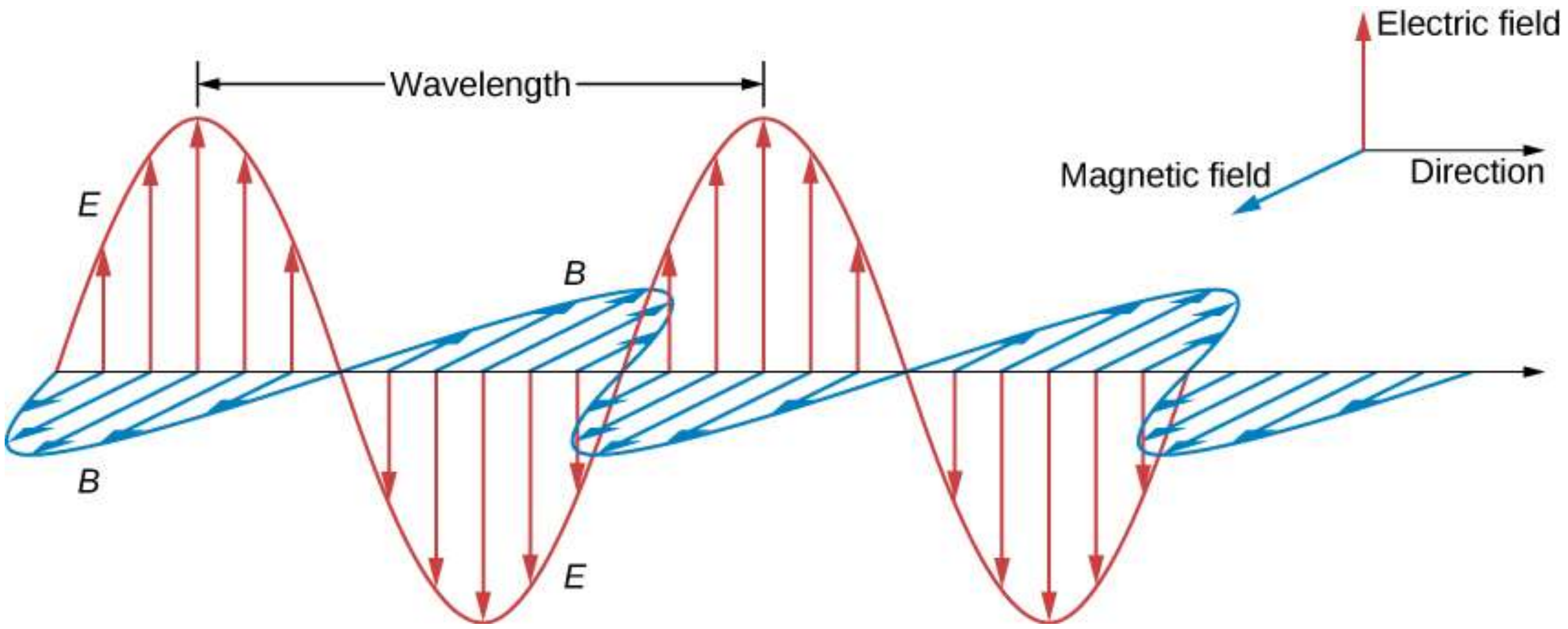
$$Itensity \rightarrow |\vec{E}|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$



$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

Measuring the electromagnetic wave

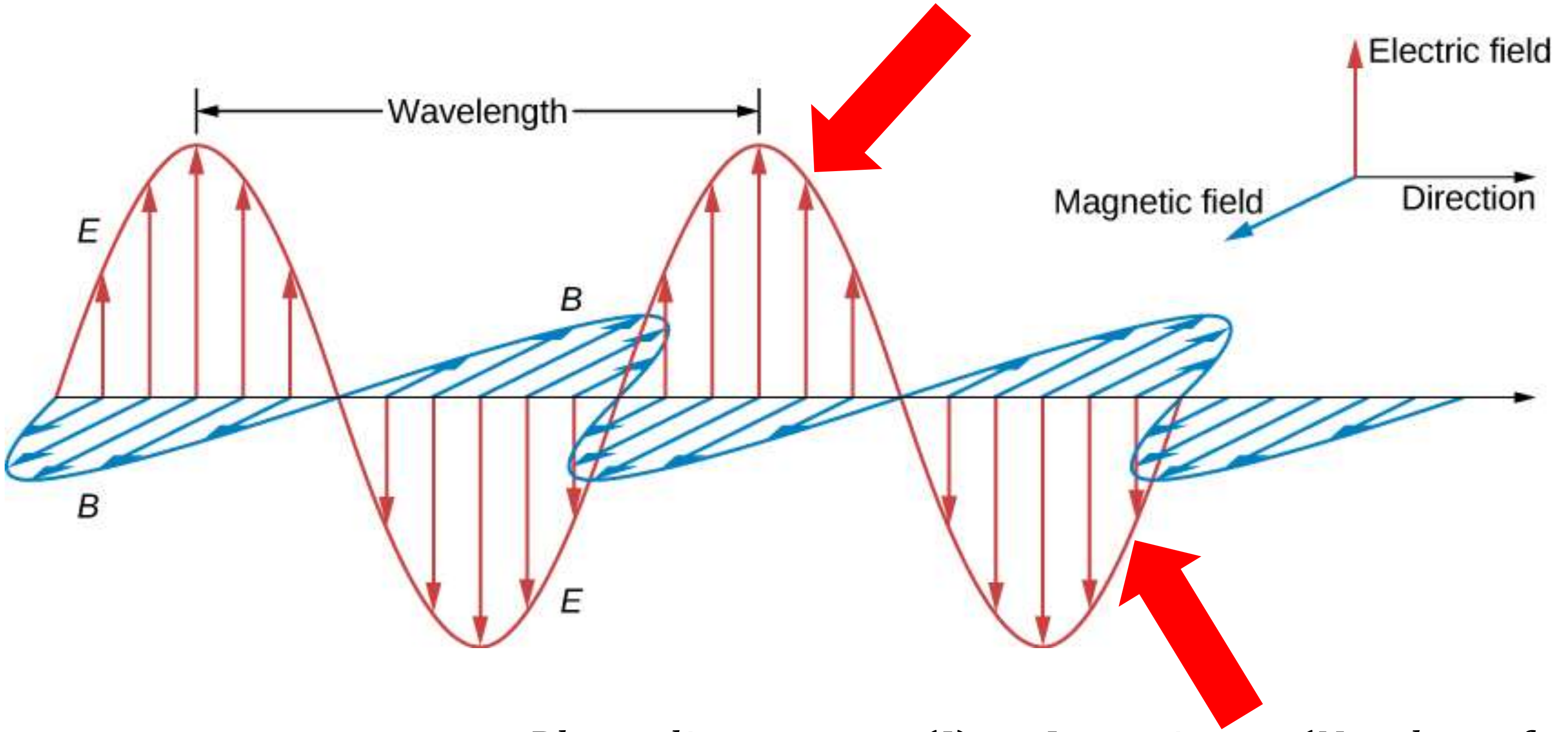
$$Itensity \rightarrow \left|\vec{E}\right|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$



$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

Measuring the electromagnetic wave

$$Itensity \rightarrow |\vec{E}|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$



$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

Measuring the electromagnetic wave

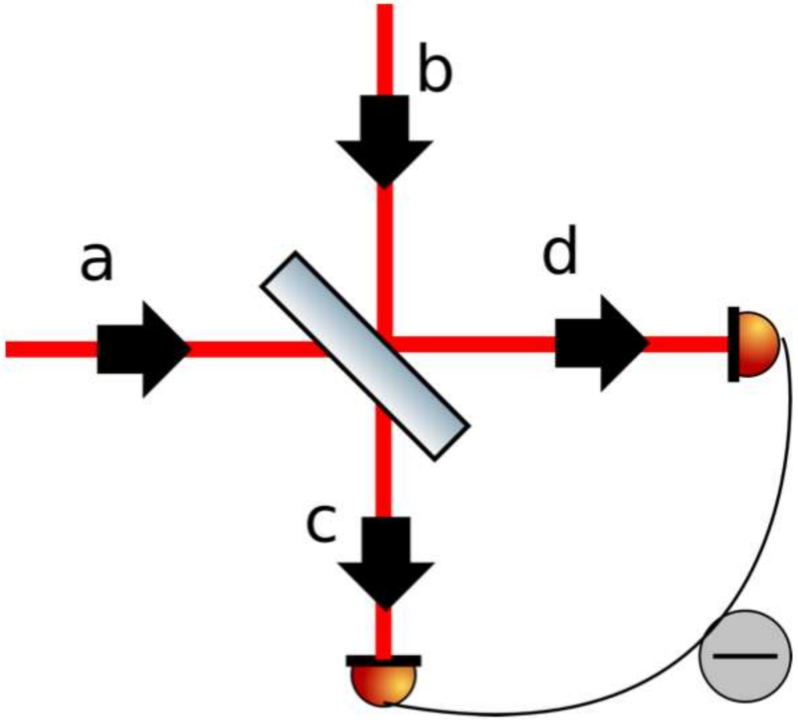
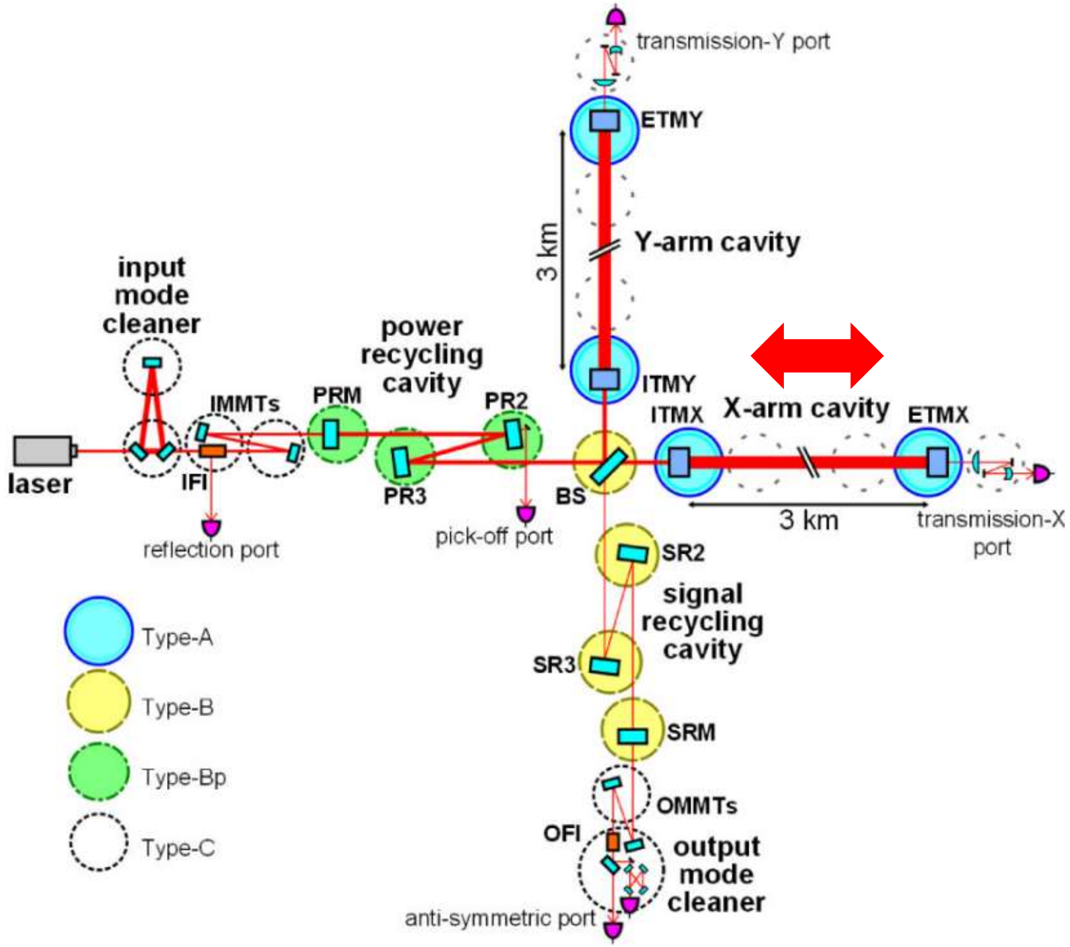
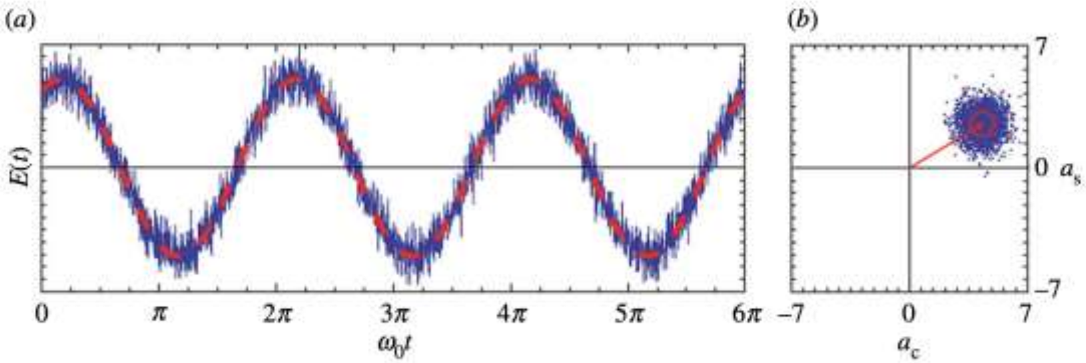


Figure 2-3: Balanced homodyne readout.

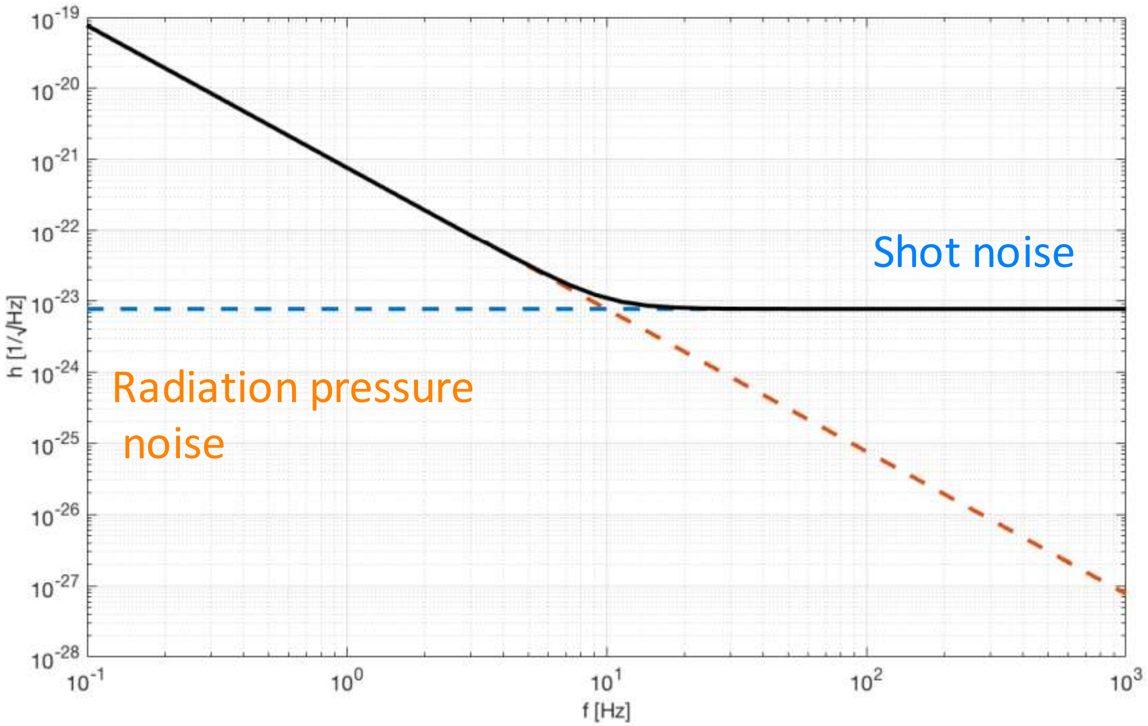
Quantum noise of coherent light





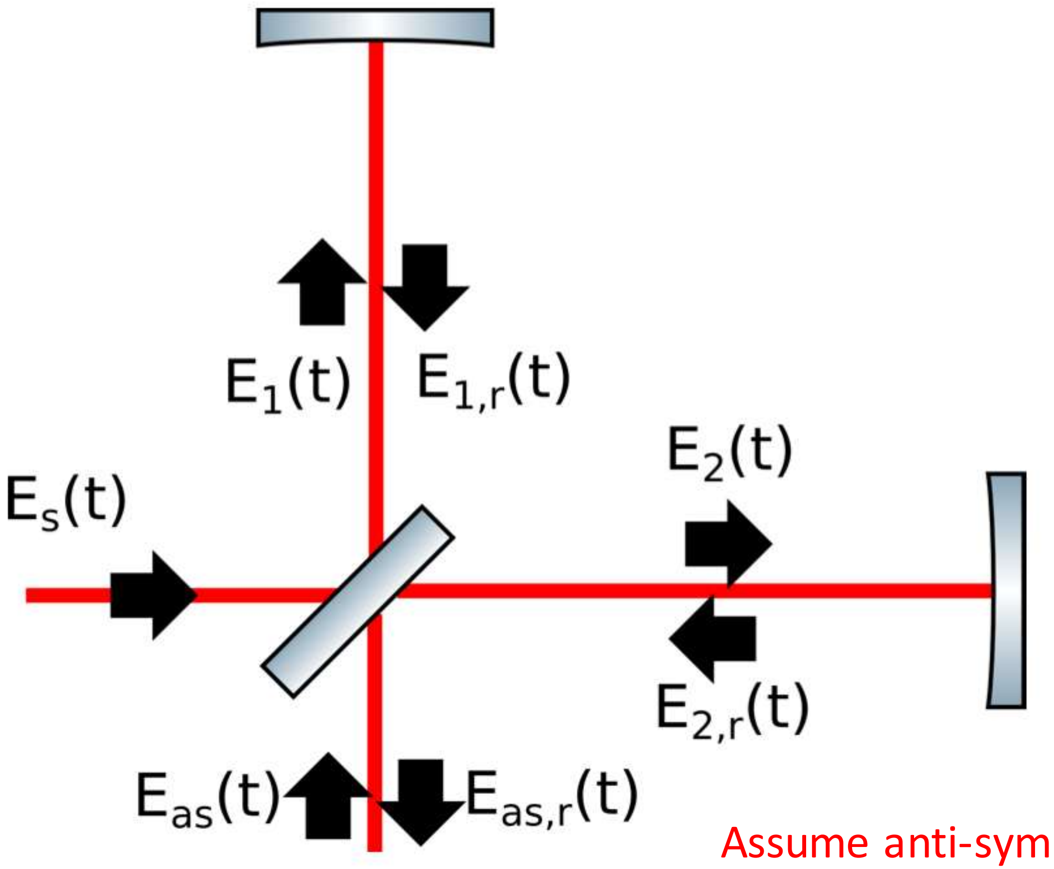
Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Standard quantum limit of GW detector



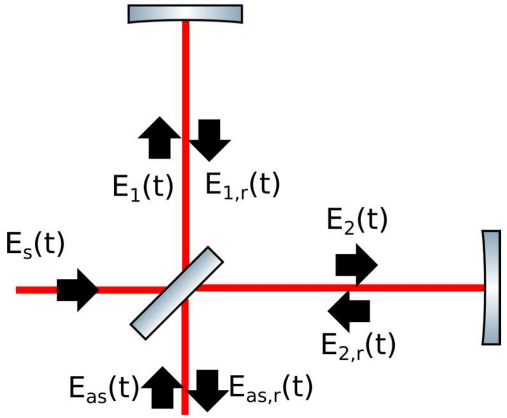
Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

Quantum noise of interferometer



Assume anti-symmetric port is dark port

Quantum noise of interferometer



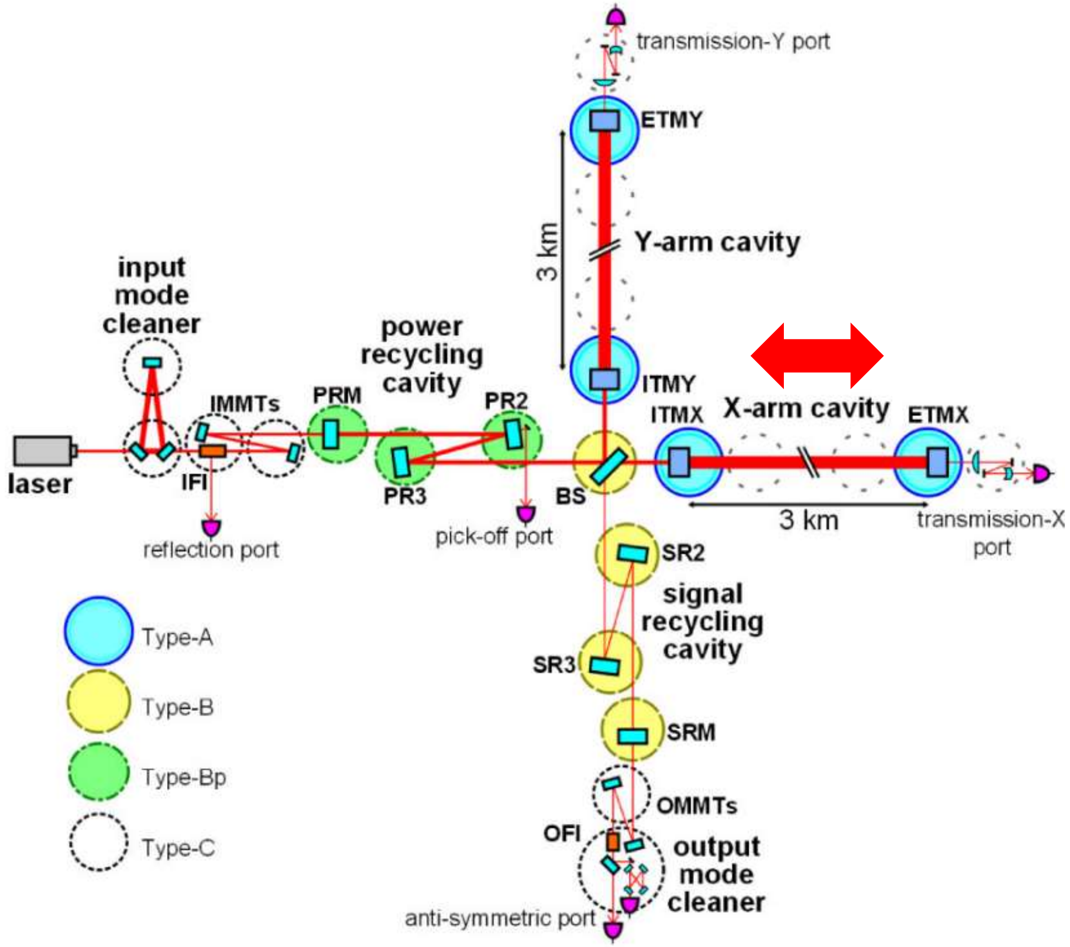
Assume anti-symmetric port is dark port

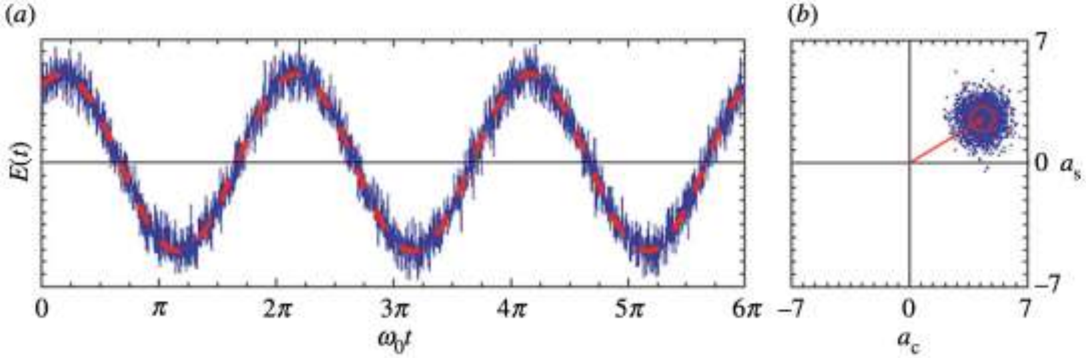
$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$
$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Quantum noise of coherent light

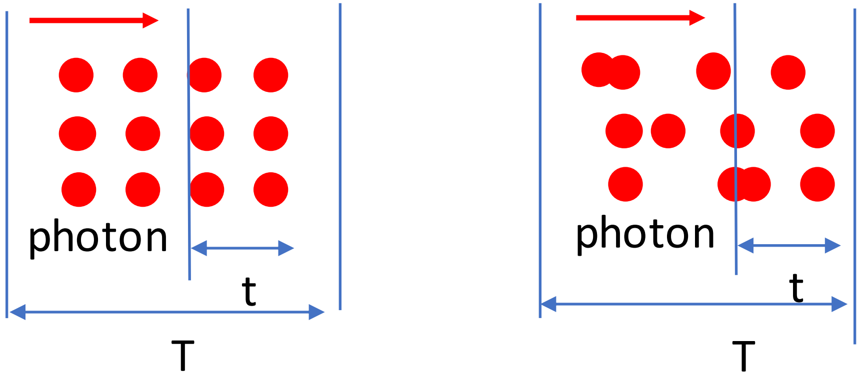




Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

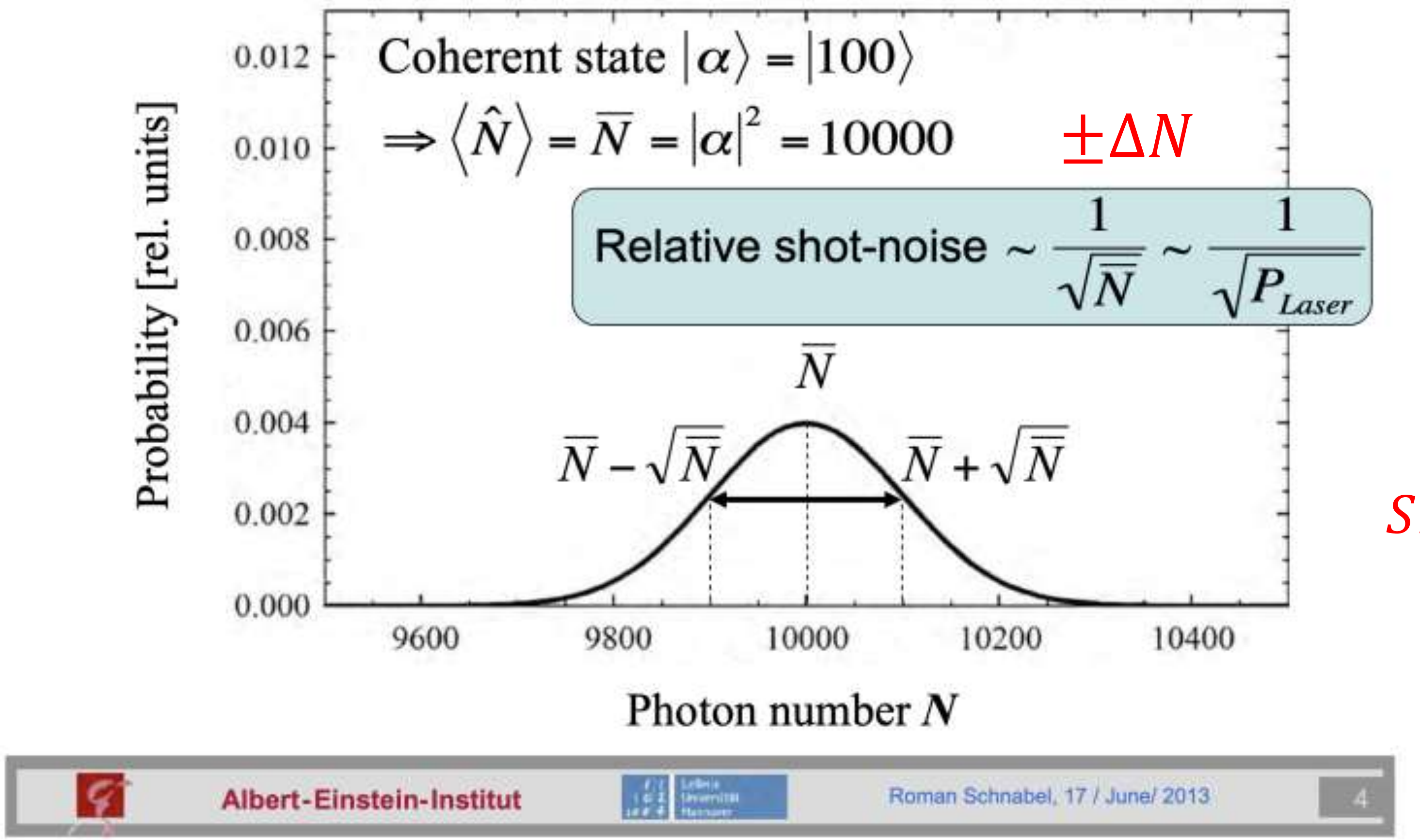
Shot noise of interferometer

Laser power = the number of photon / time



Shot noise

Photon Counting Statistics

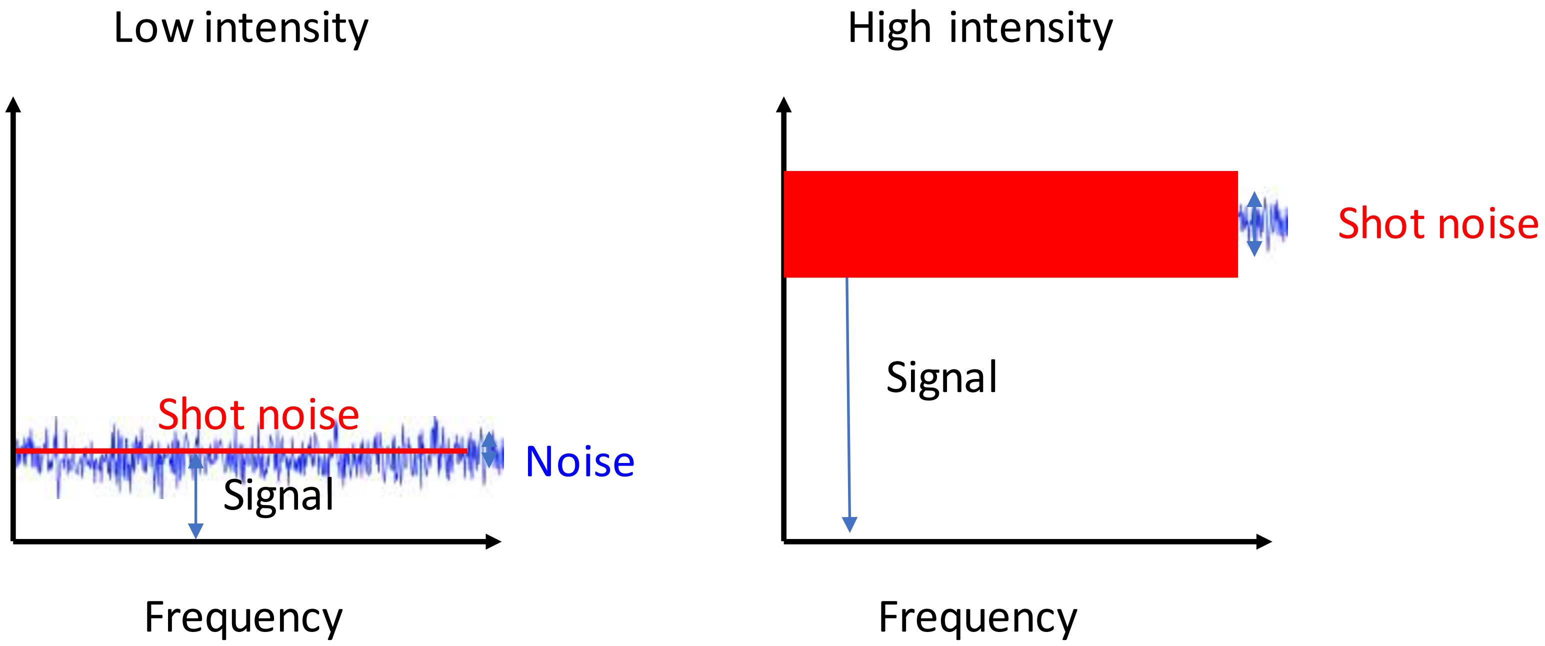


When we have coherent laser source

$$Signal \propto (Number\ of\ photon)$$

$$Shot\ Noise \propto \sqrt{Number\ of\ Photon}$$

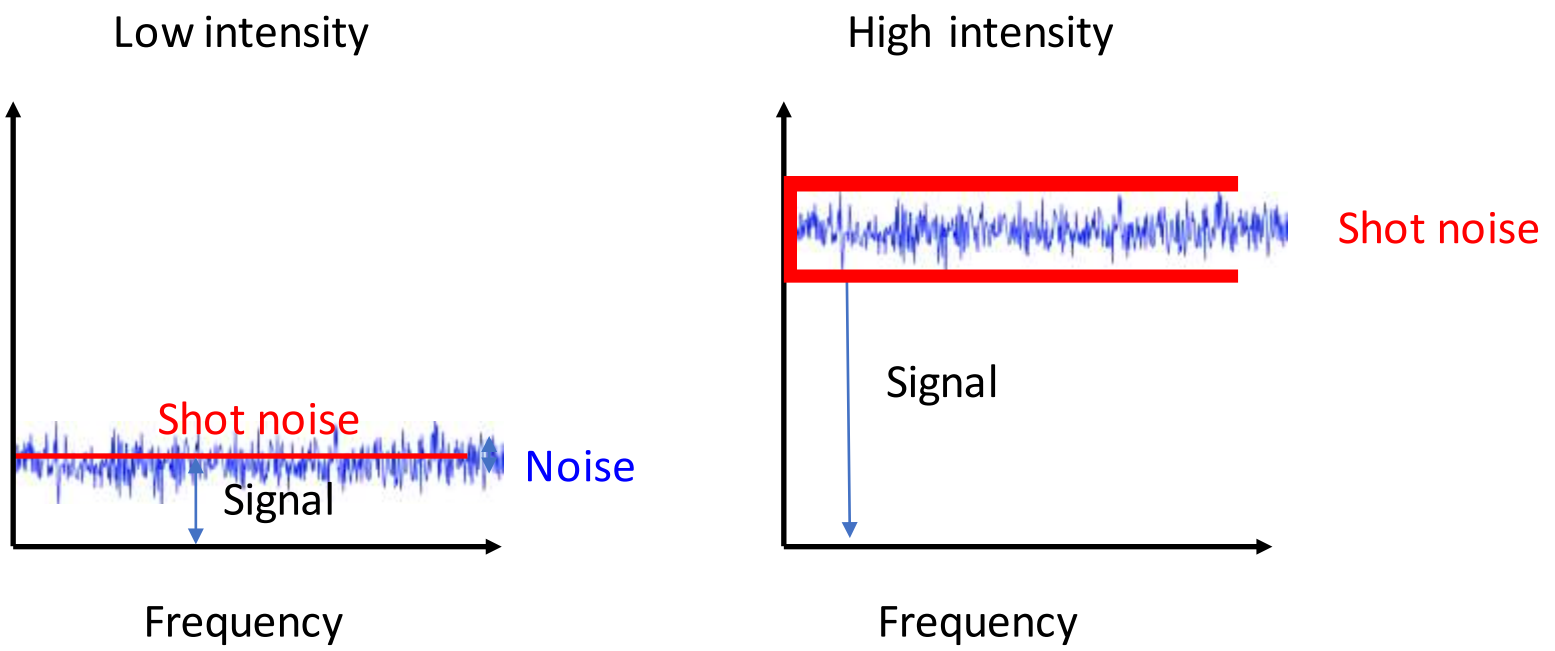
Shot noise of interferometer



$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

If Shot noise is relatively larger than other noise(Thermal, Electric..etc)
We say that it has shot noise limit sensitivity

Shot noise of interferometer



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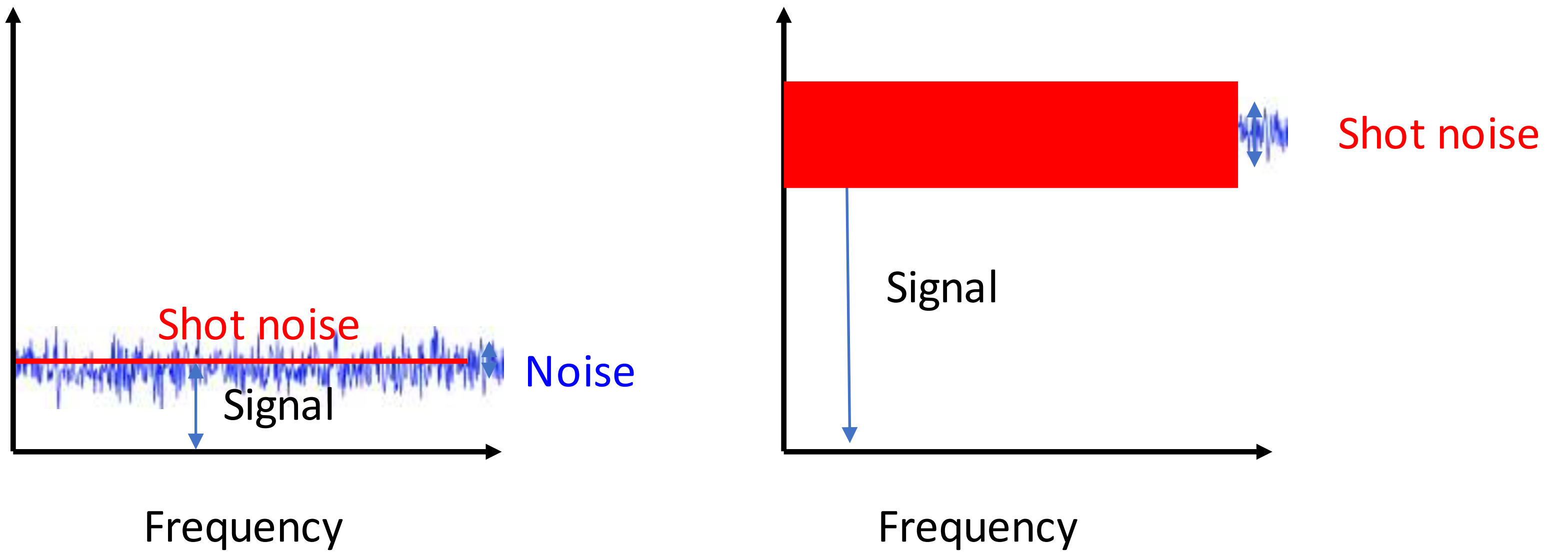
Shot noise of interferometer



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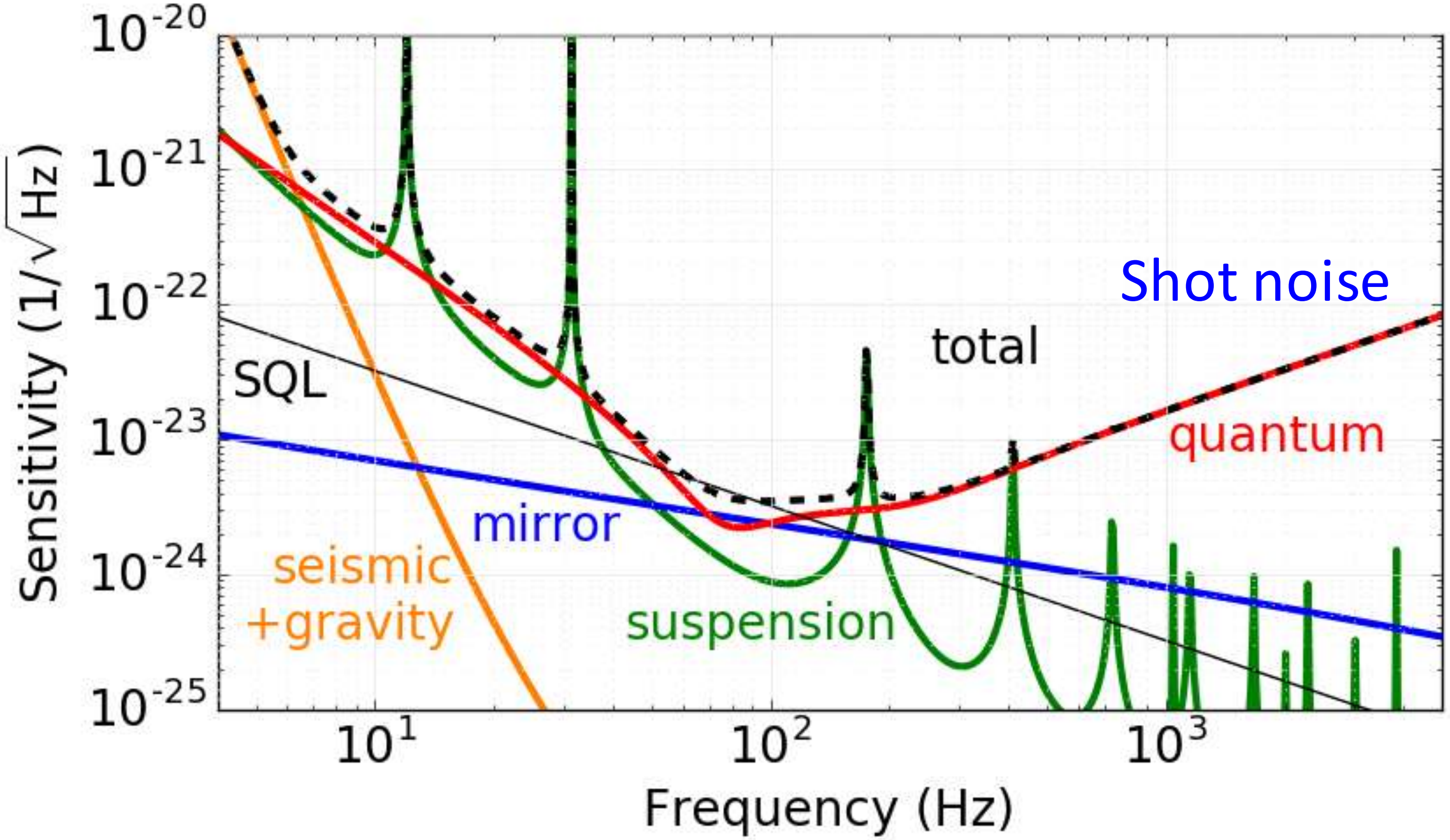
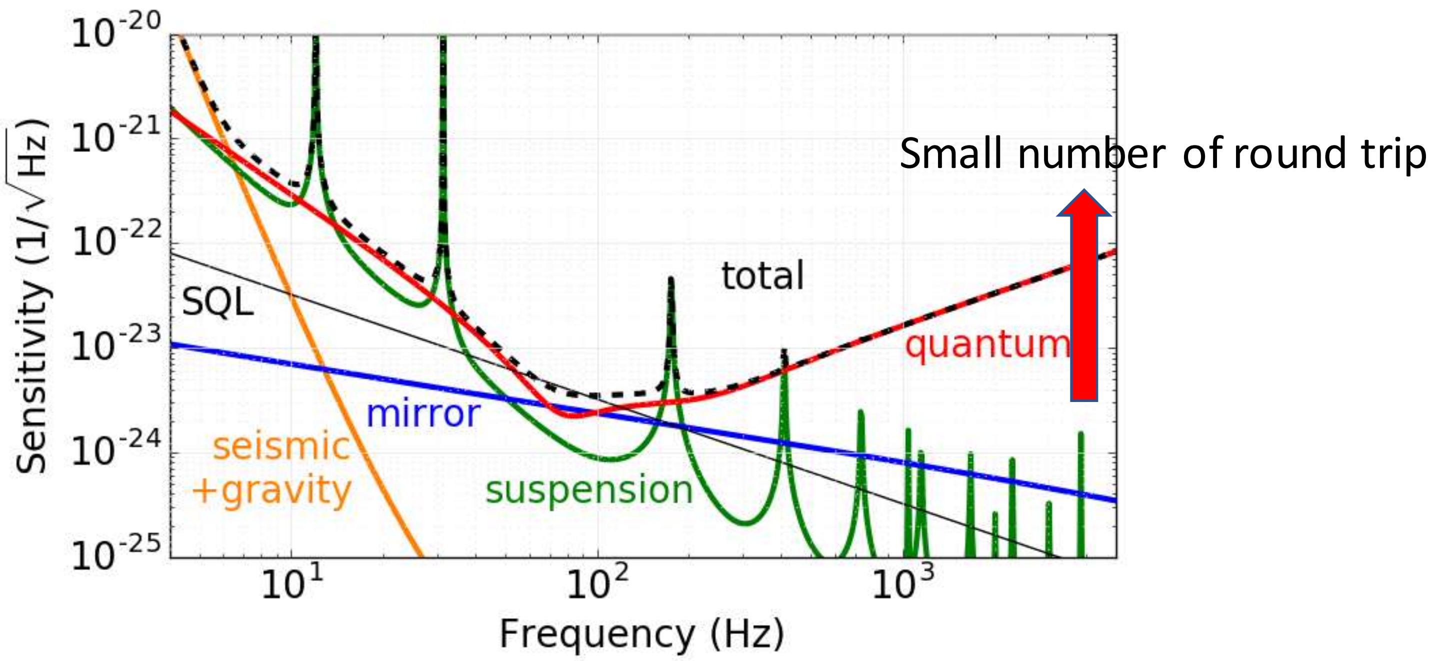
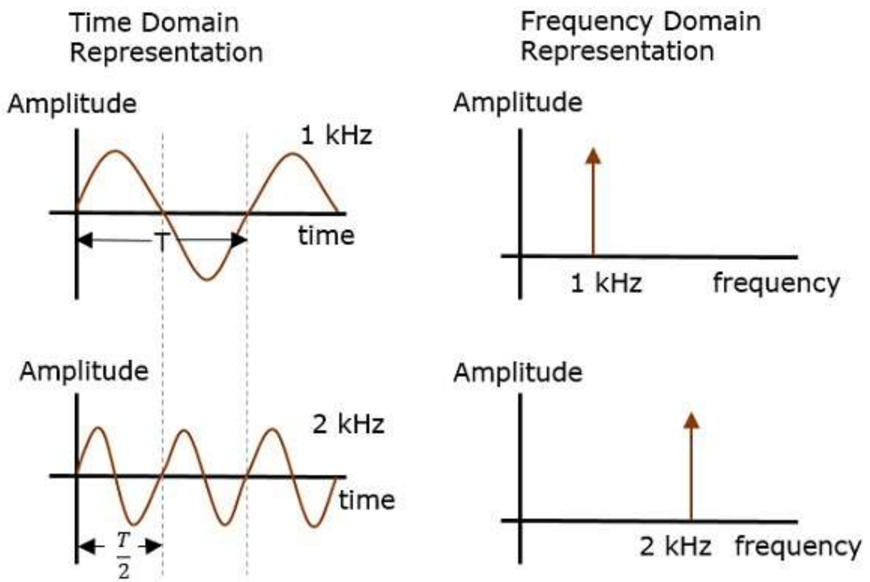
Target sensitivity of KAGRA



Target sensitivity of KAGRA

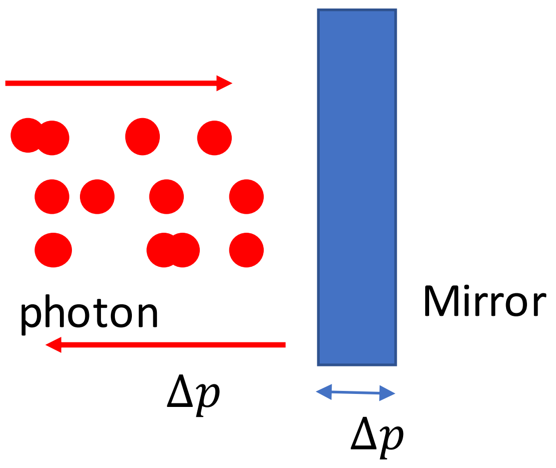


Shot noise curve of GW detector



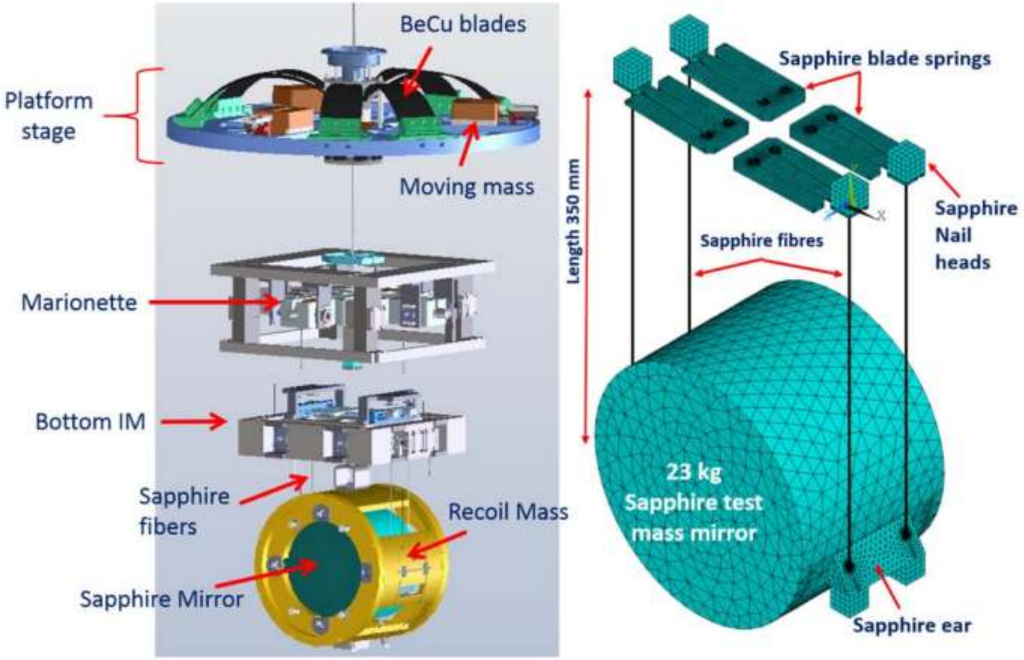
Interaction length ~ Number of round trip x Length

Radiation pressure noise

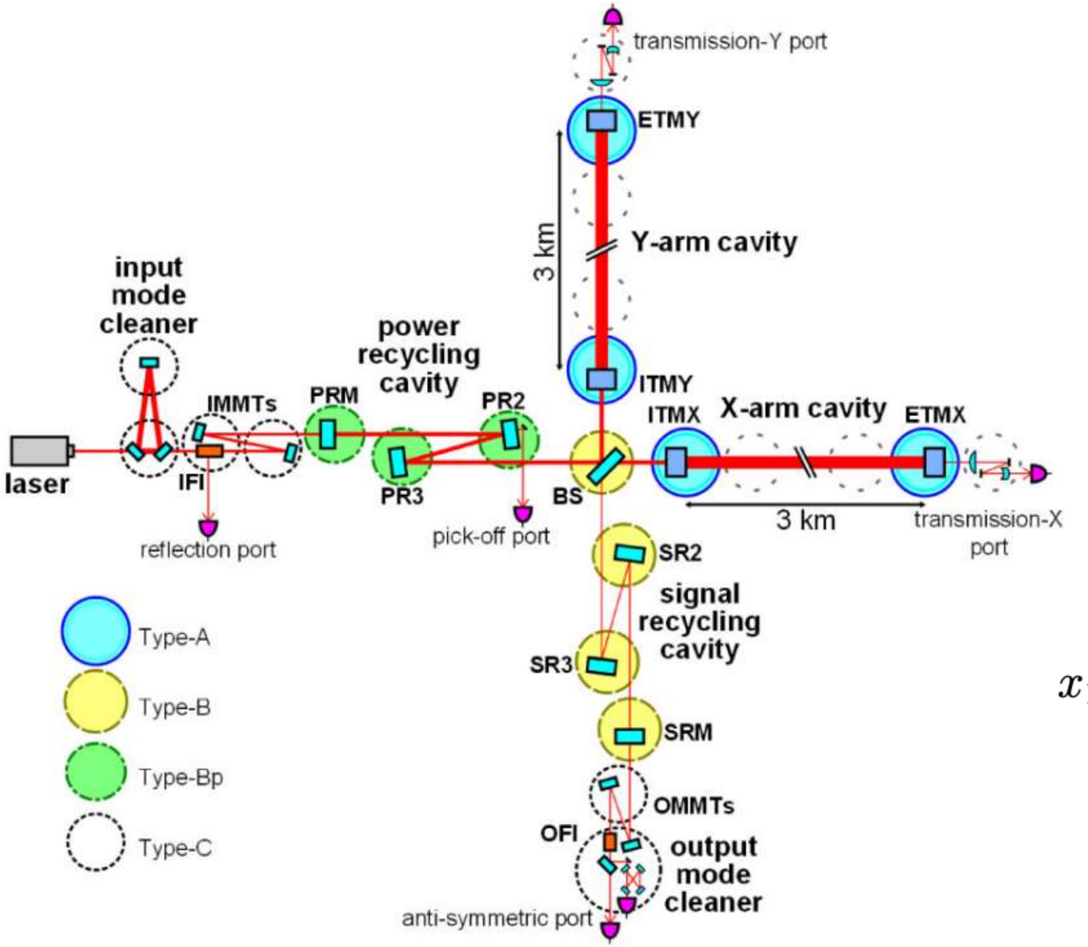


- Stored energy is very high (750 kW)
- Desired sensitivity is very high ($10^{-21} \sim 10^{-24}$)

Test mass of KAGRA



Radiation pressure noise

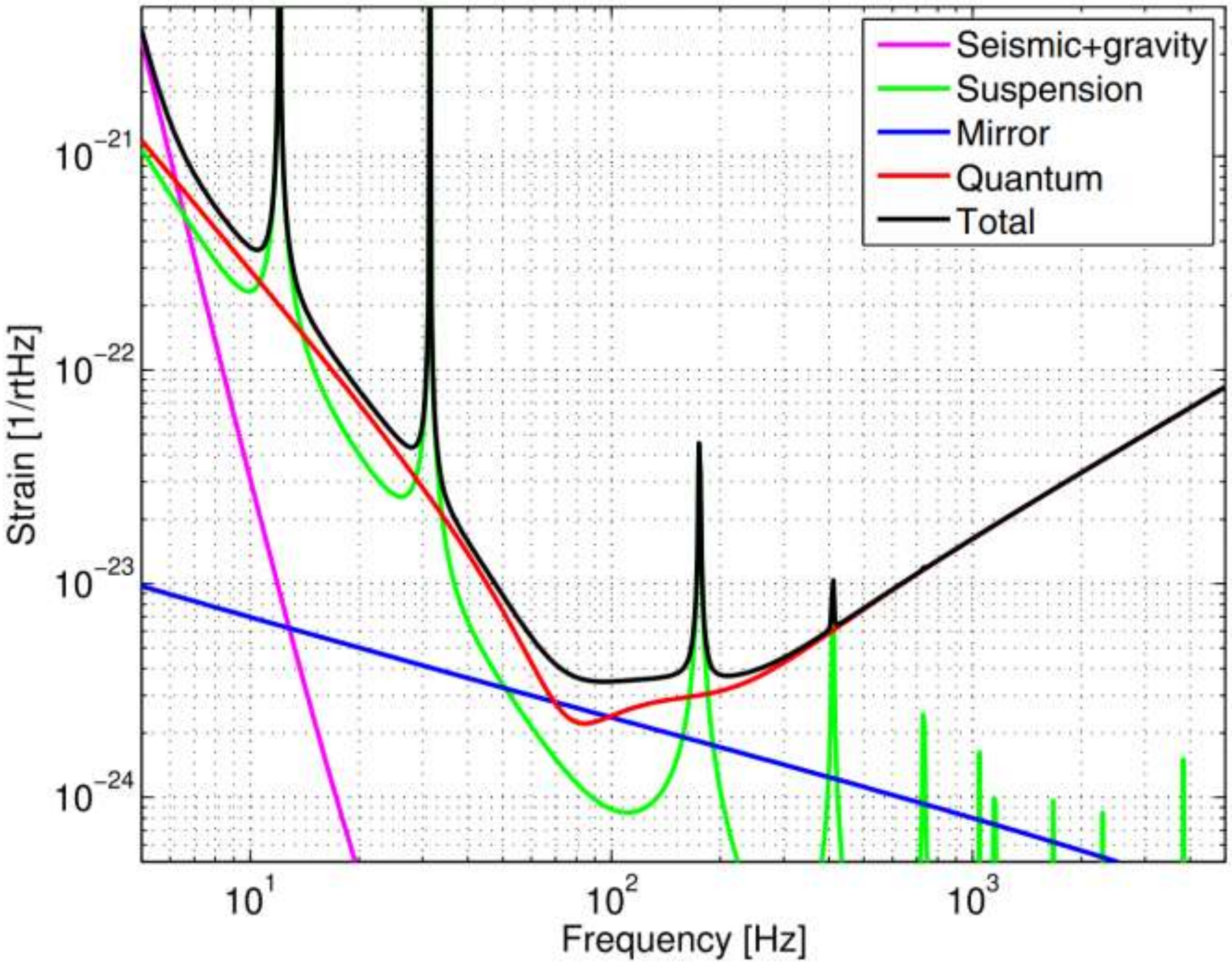


$$E_{as,r}(t) = E_{as} + E_0 \frac{\omega_0 [x_2(t) - x_1(t)]}{c} \sin(\omega_0 t)$$

$$x_1(t) - x_2(t) = x_{cl,1}(t) - x_{cl,2}(t) + \delta\hat{x}_1(t) - \delta\hat{x}_2(t) + Lh(t)$$

Thermal, seismic (slow) — Radiation pressure — GW source

Design sensitivity of KAGRA

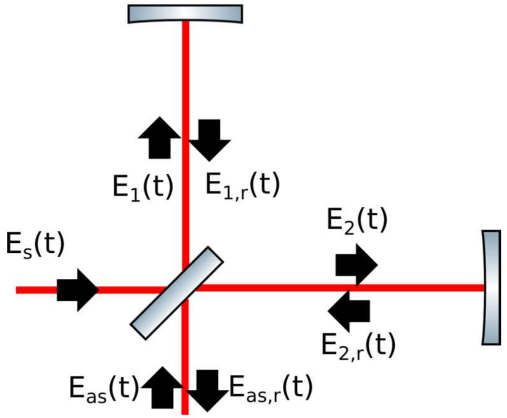


KAGRA

Korea Astronomy and Space Science Institute

Squeezed vacuum injection in GW detector

Quantum noise of interferometer



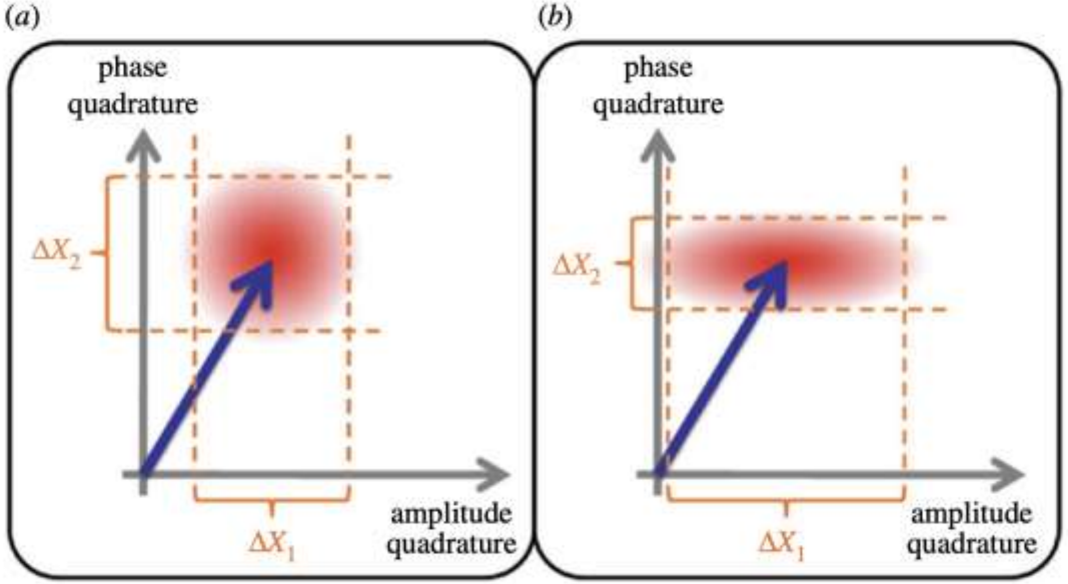
Assume anti-symmetric port is dark port

$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$
$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

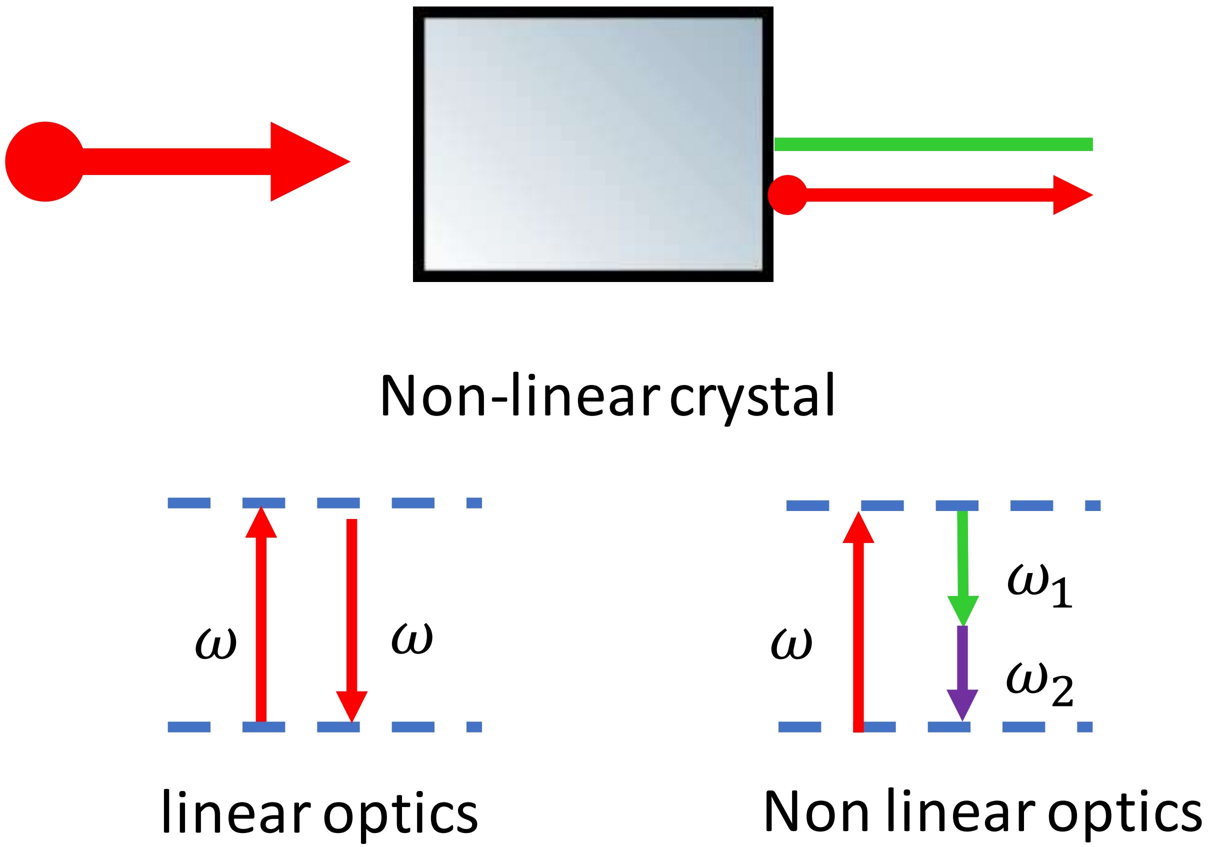
Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Phase and amplitude noise of light

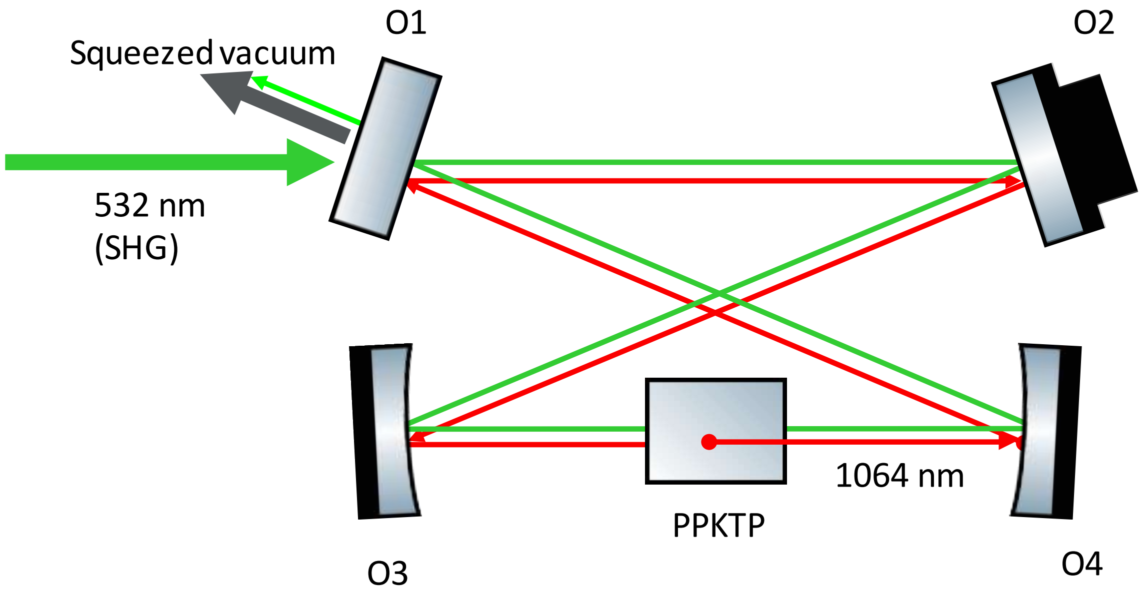


Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Non-linear crystal

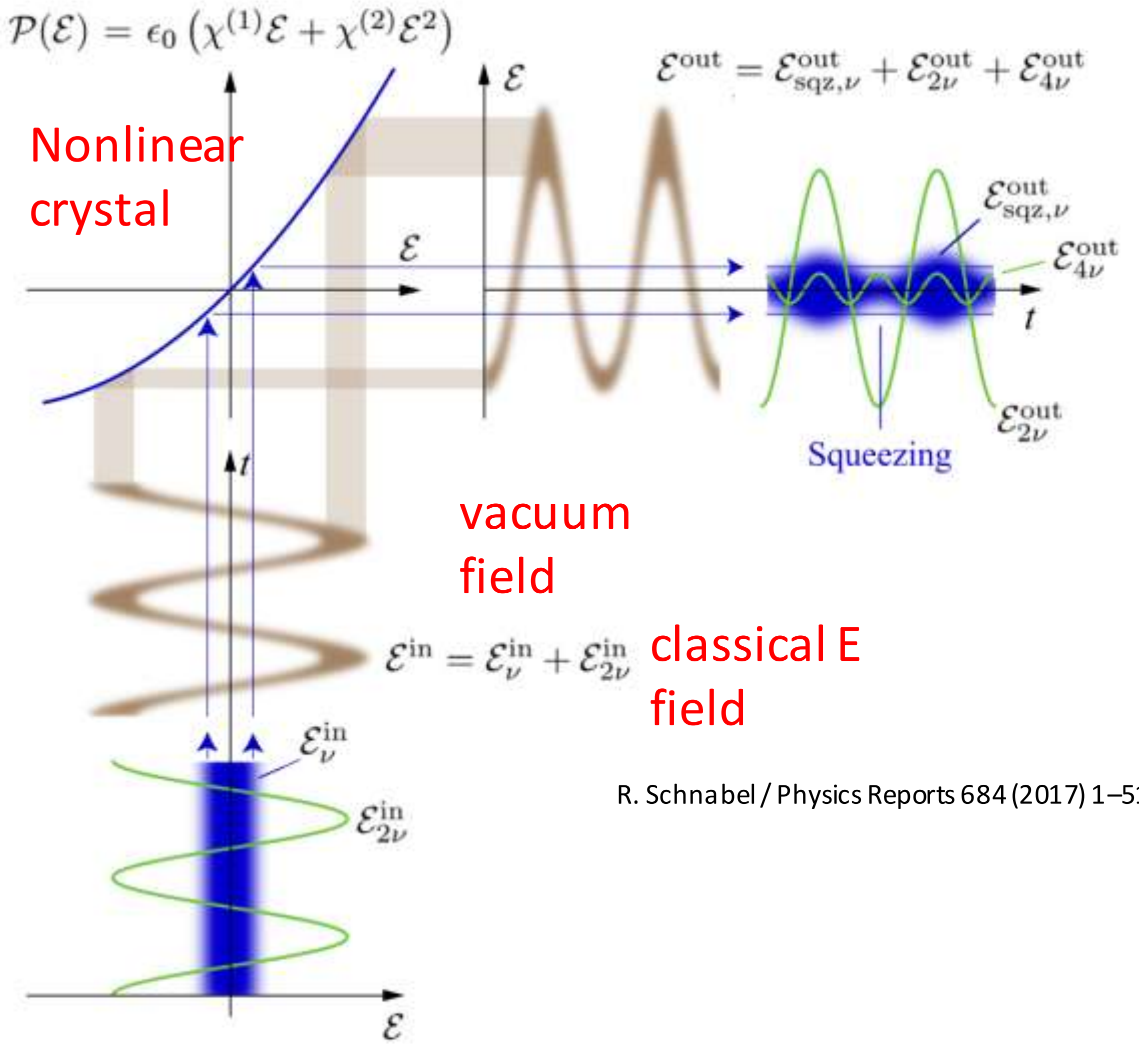


Parametric down conversion



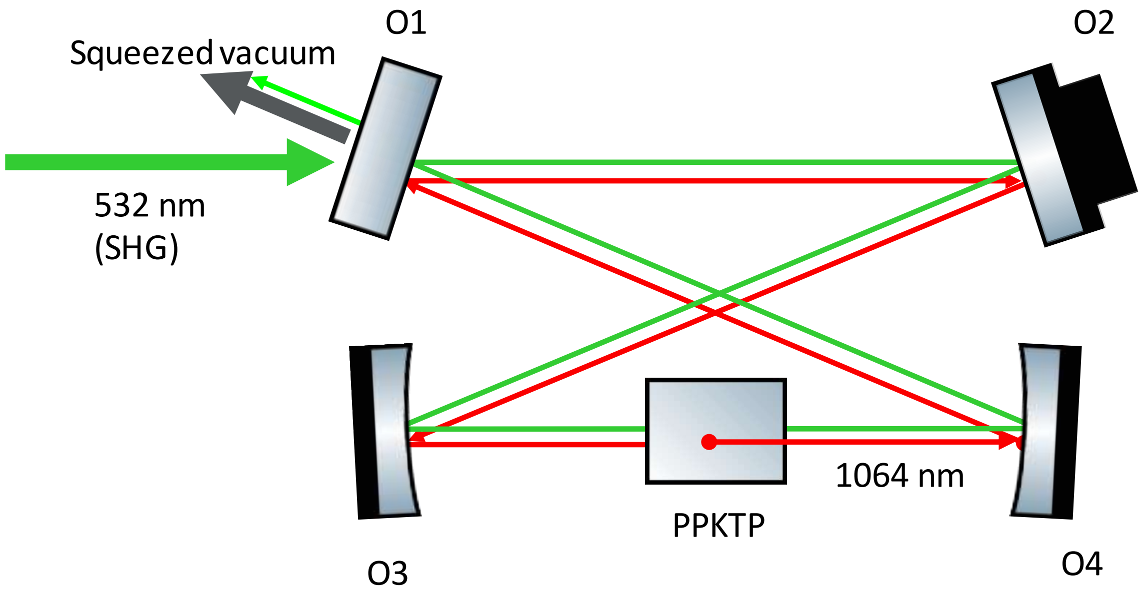
Under threshold operation

Parametric down conversion process



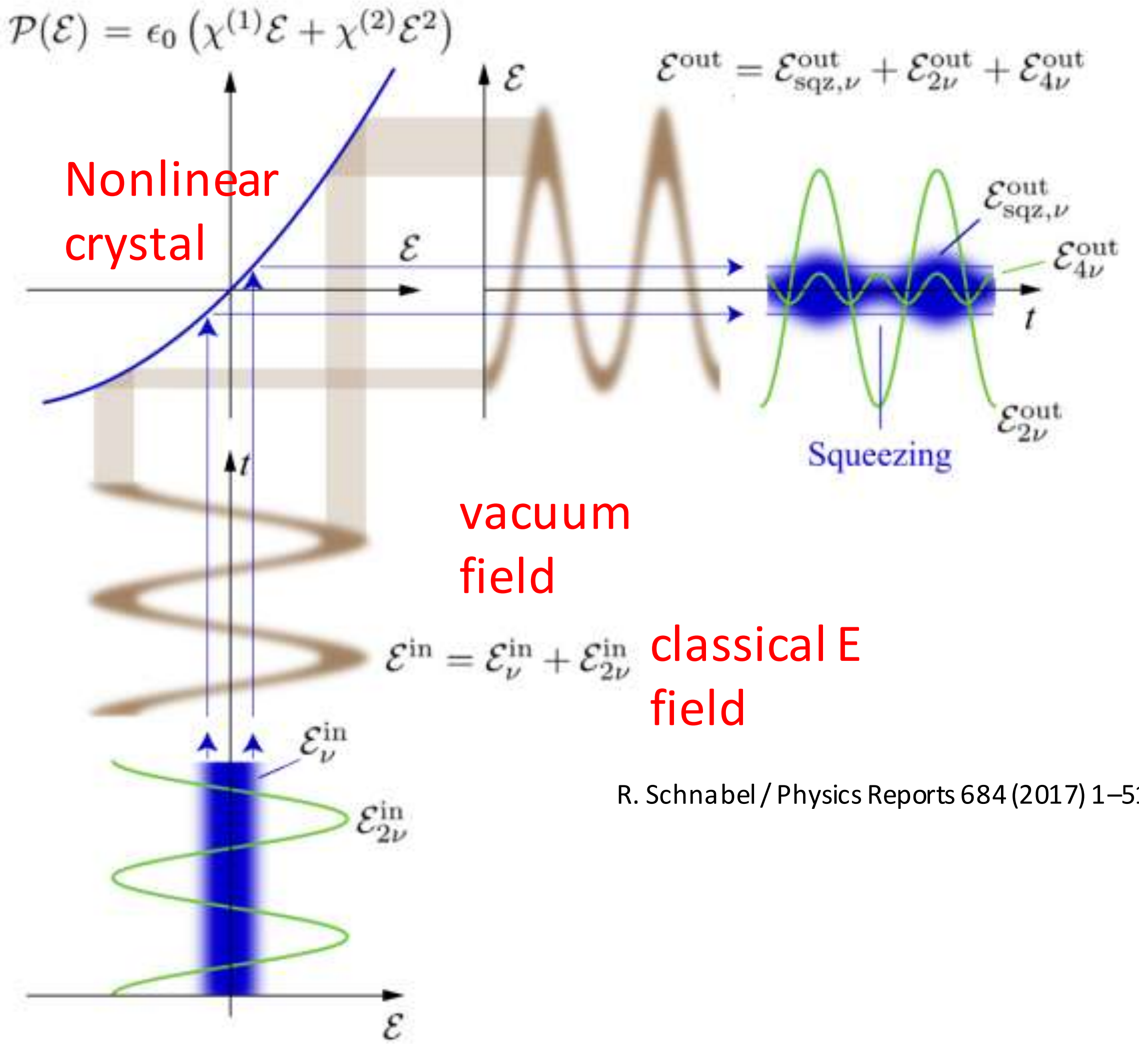
R. Schnabel / Physics Reports 684 (2017) 1–51

Parametric down conversion



Under threshold operation

Parametric down conversion process



R. Schnabel / Physics Reports 684 (2017) 1–51

Squeezed vacuum

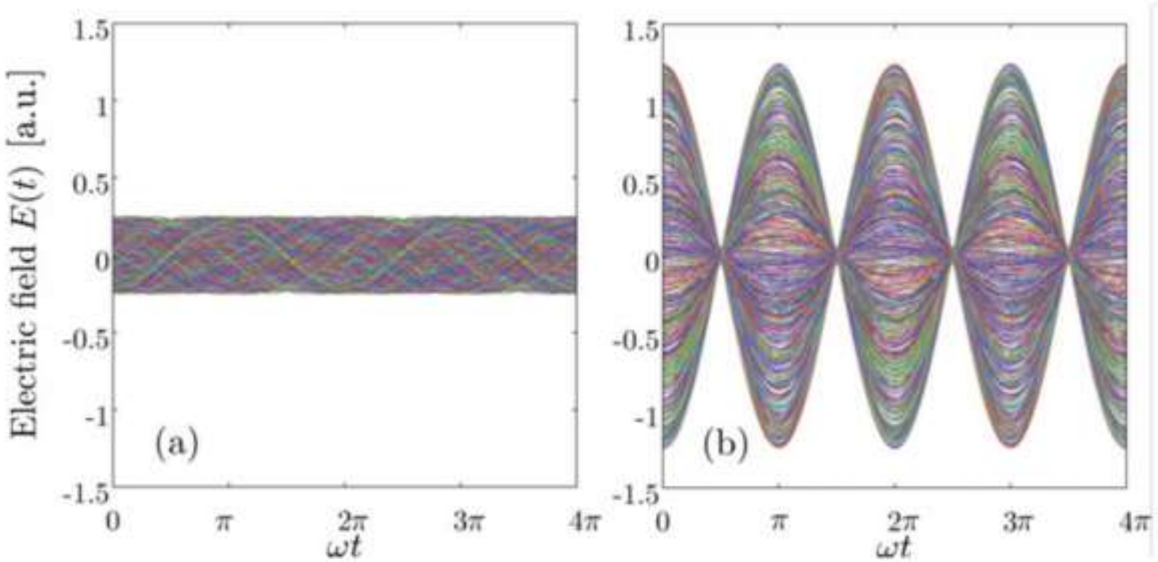
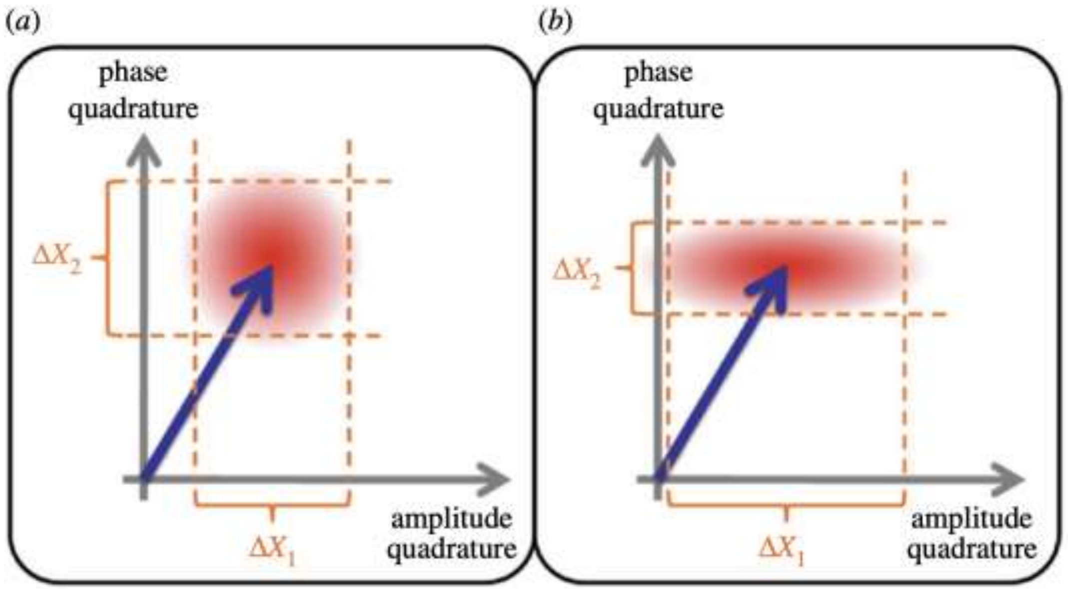


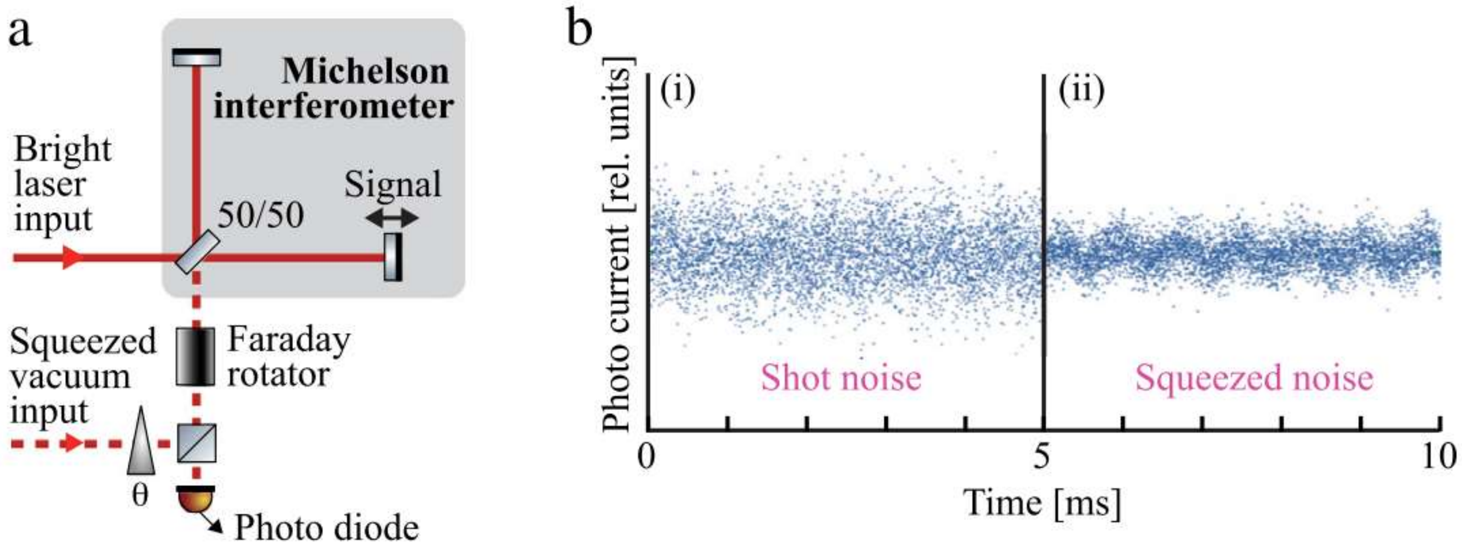
Figure 1.6: Simulation of electric field in time for (a) vacuum state and for (b) squeezed vacuum.

Phase and amplitude noise of light



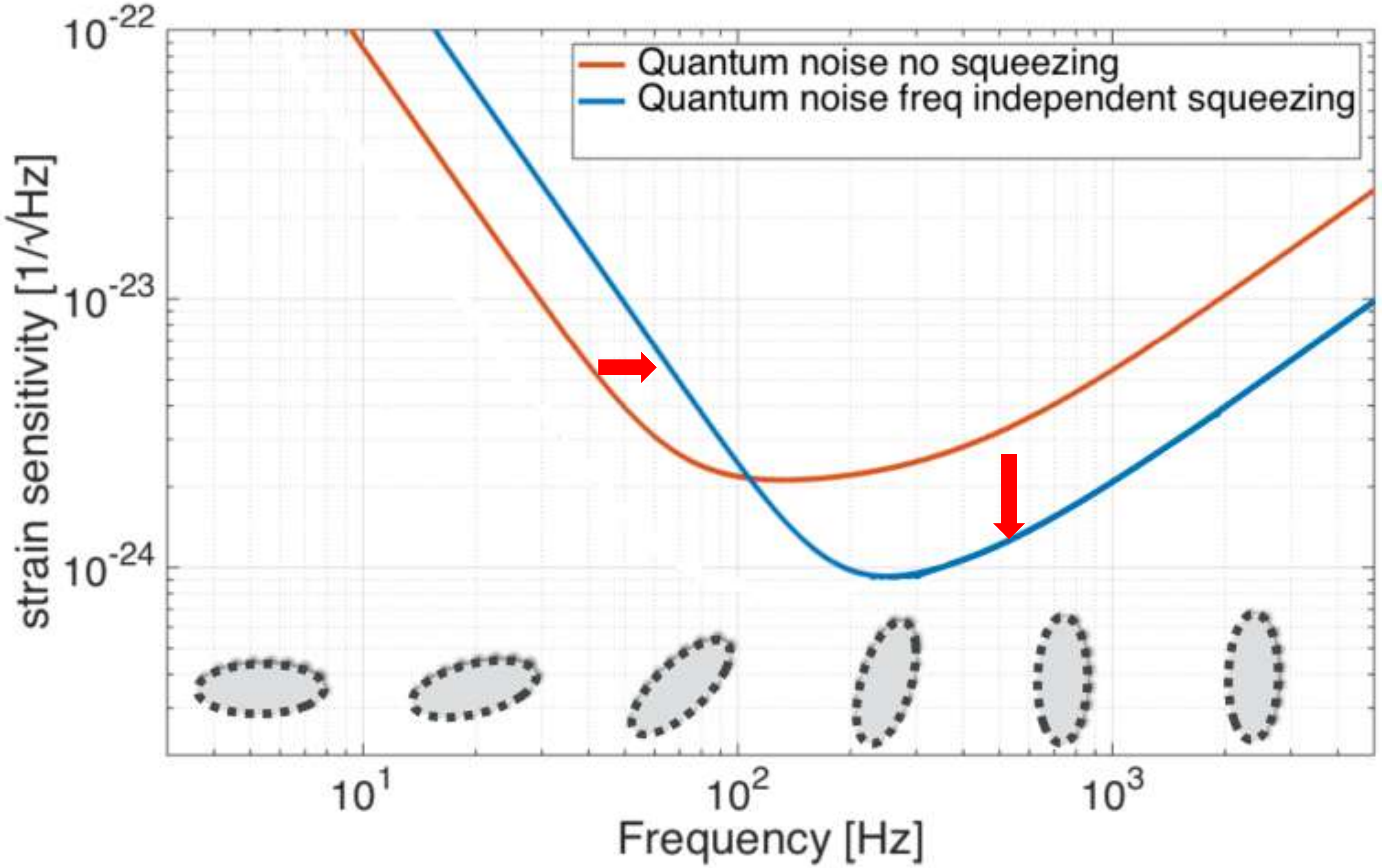
Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Squeezed state of light



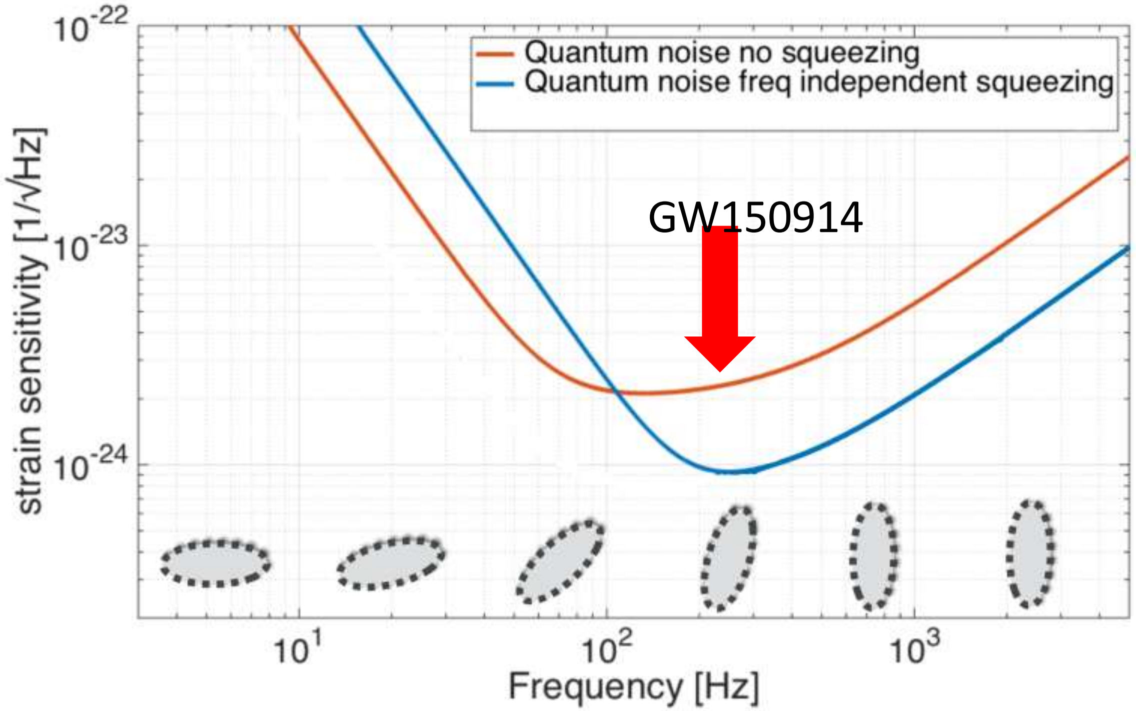
R. Schnabel / Physics Reports 684 (2017) 1–51

Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency independent squeezing



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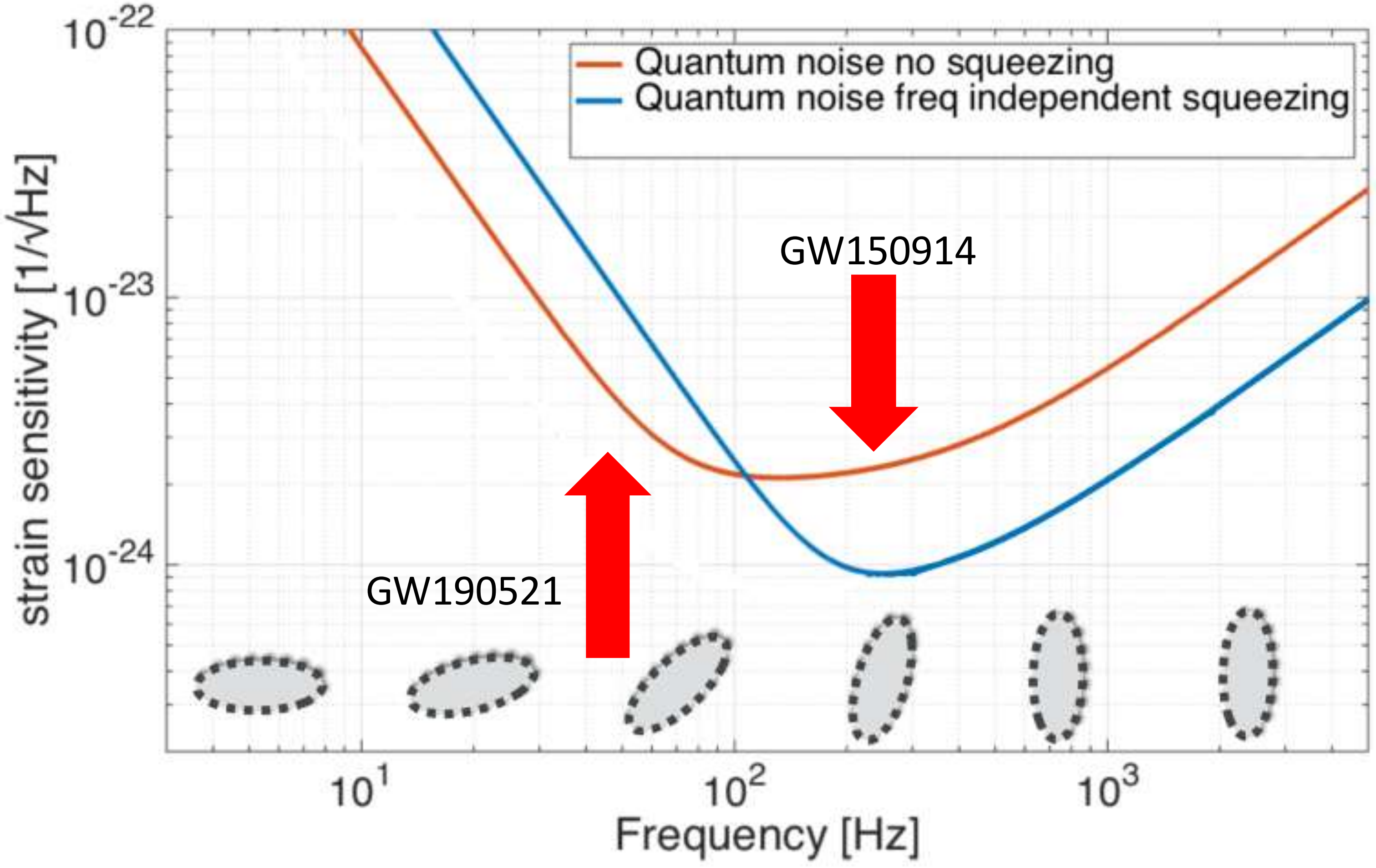
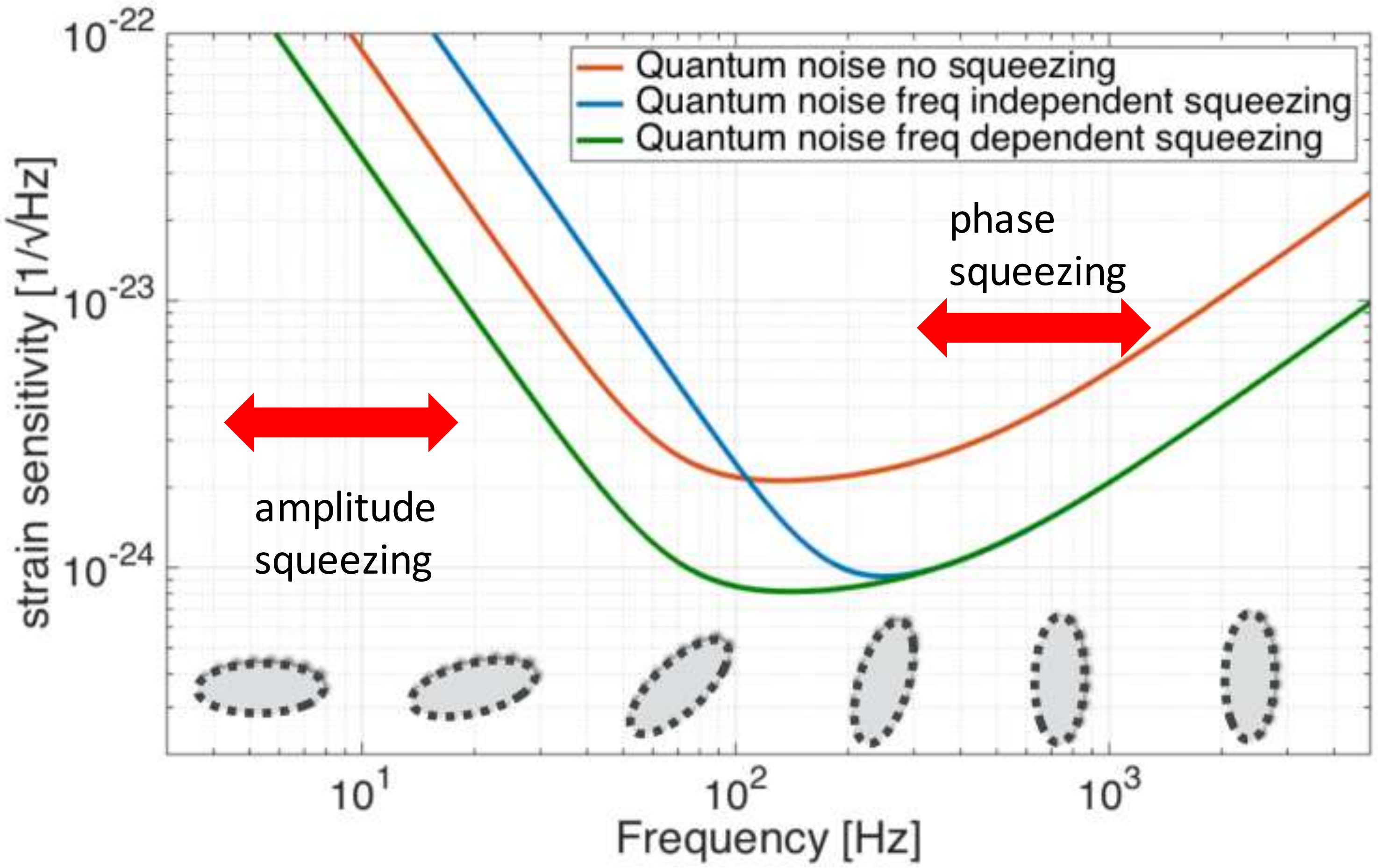
Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency dependent squeezing(FDS)



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

4. Frequency dependent squeezing in GW detector

First suggestion of filter cavity in FD squeezing

Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

H. J. Kimble,[1] Yuri Levin,[2,*] Andrey B. Matsko,[3] Kip S. Thorne,[2] and Sergey P. Vyatchanin[4]
[1]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125*
[2]*Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125*
[3]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242*
[4]*Physics Faculty, Moscow State University, Moscow, 119899, Russia*

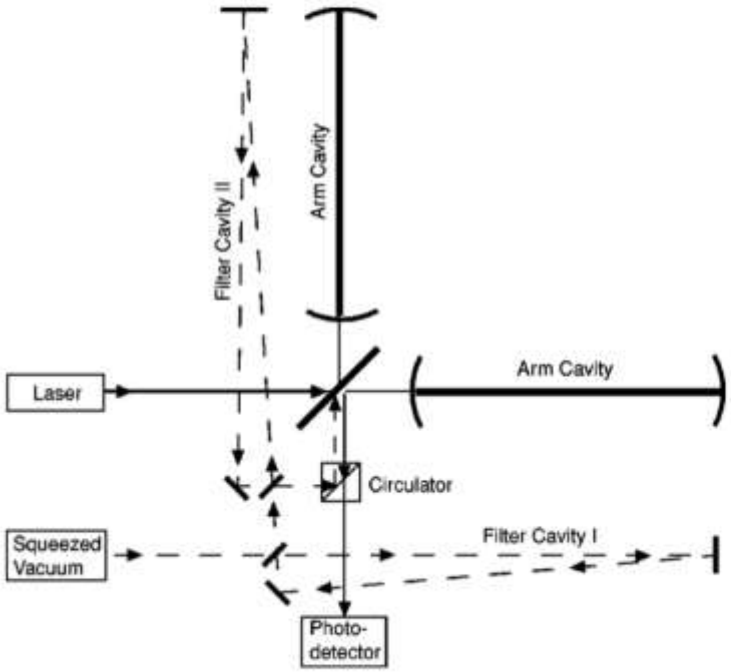
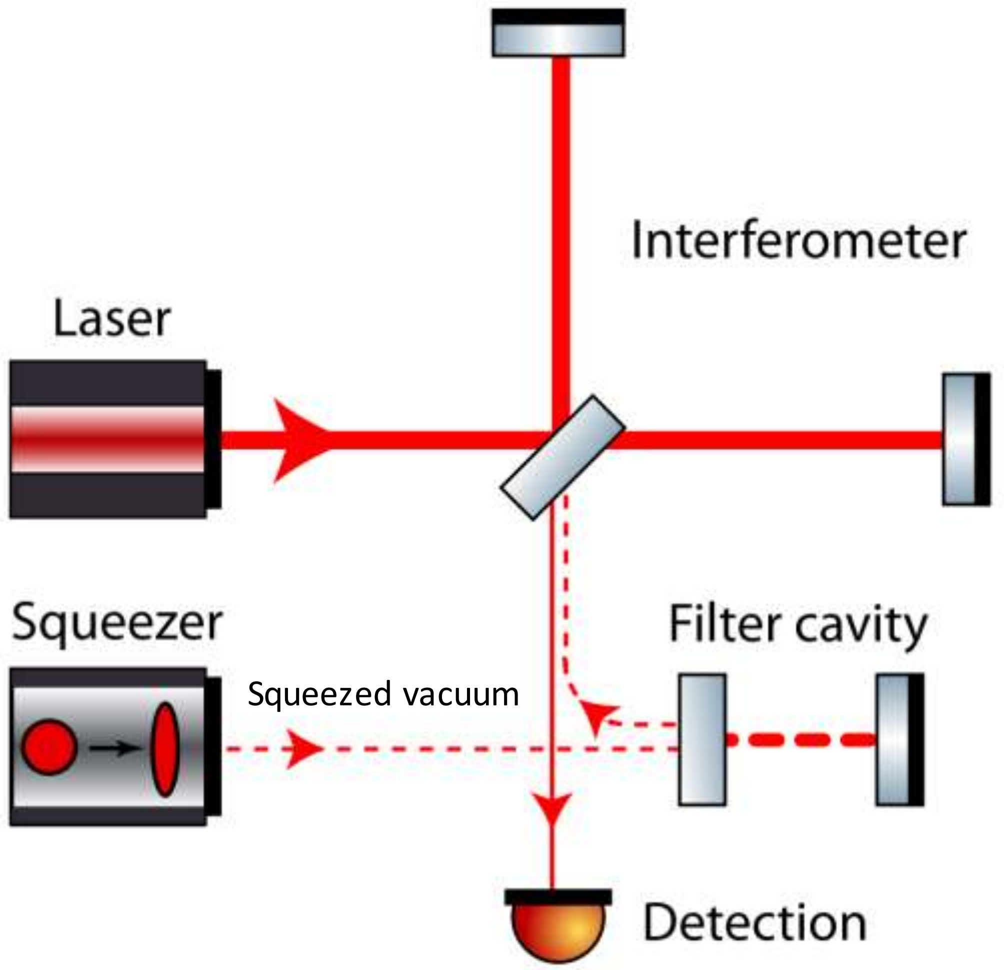


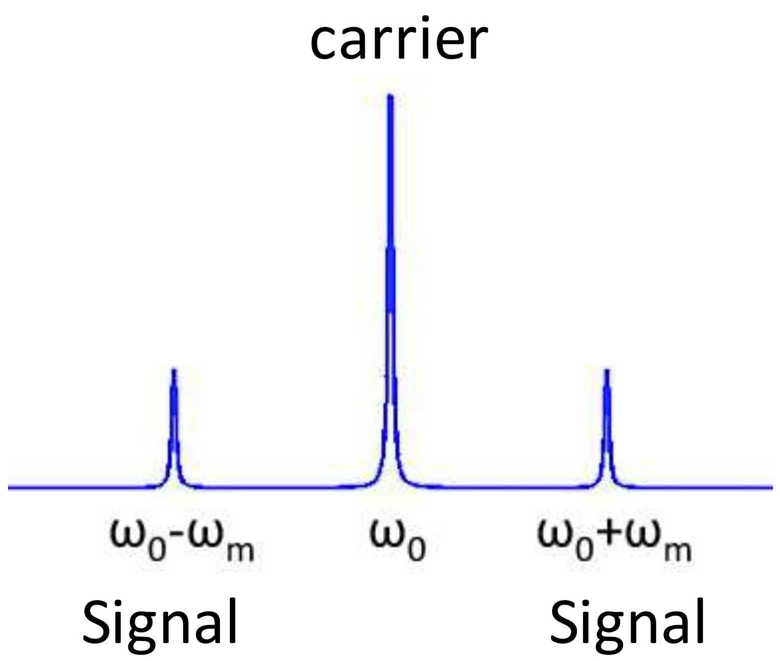
FIG. 1. Schematic diagram of a squeezed-input interferometer.

Squeezed vacuum injection with filter cavity



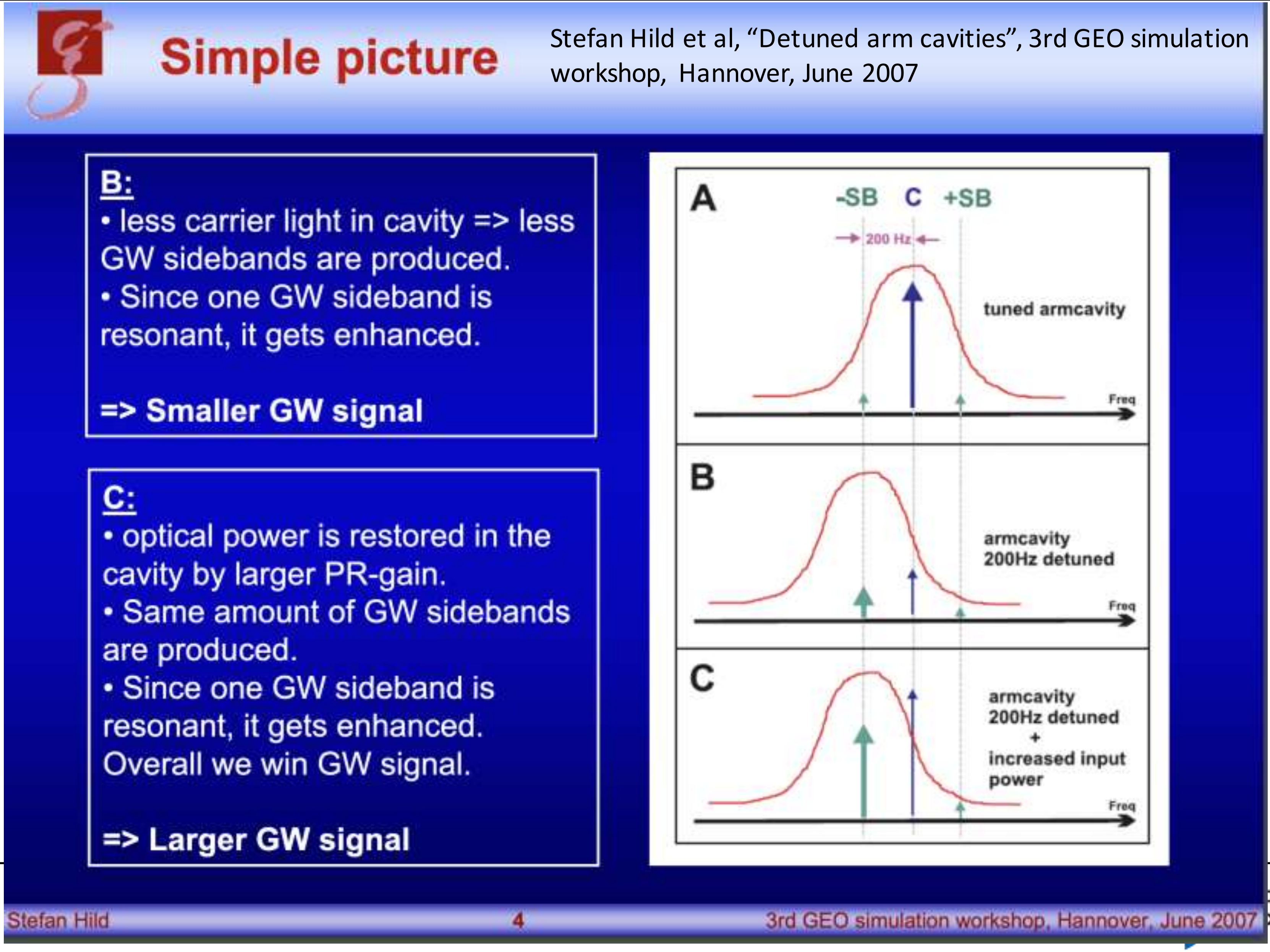
M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

Side band figure

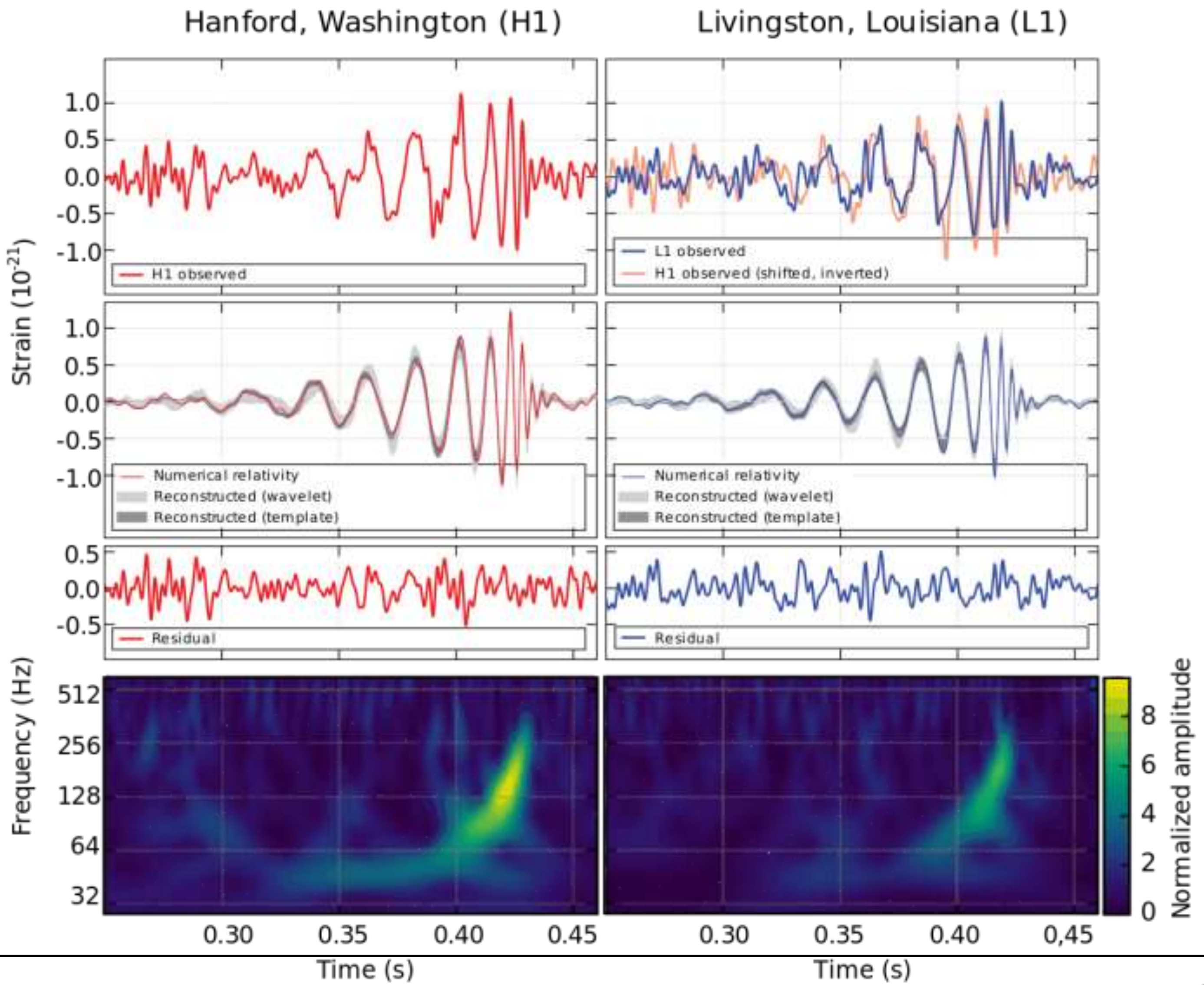


Detuned cavity

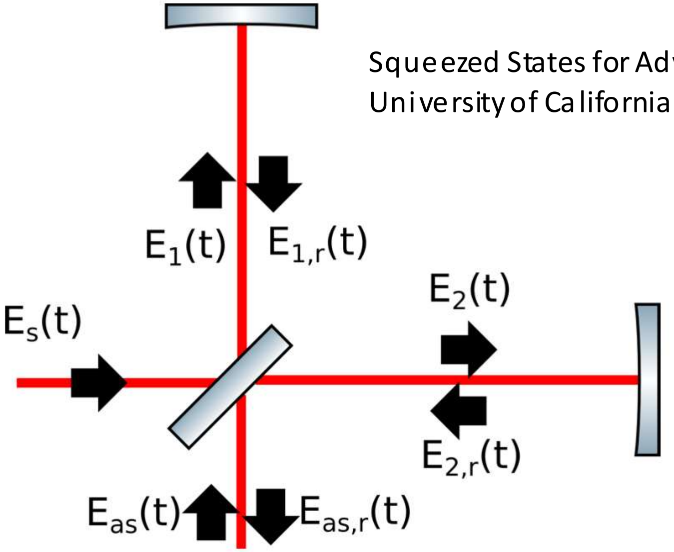
Stefan Hild et al, “Detuned arm cavities”, 3rd GEO simulation workshop, Hannover, June 2007



Gravitational wave signal



Electric field in simple Michelson interferometer



Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

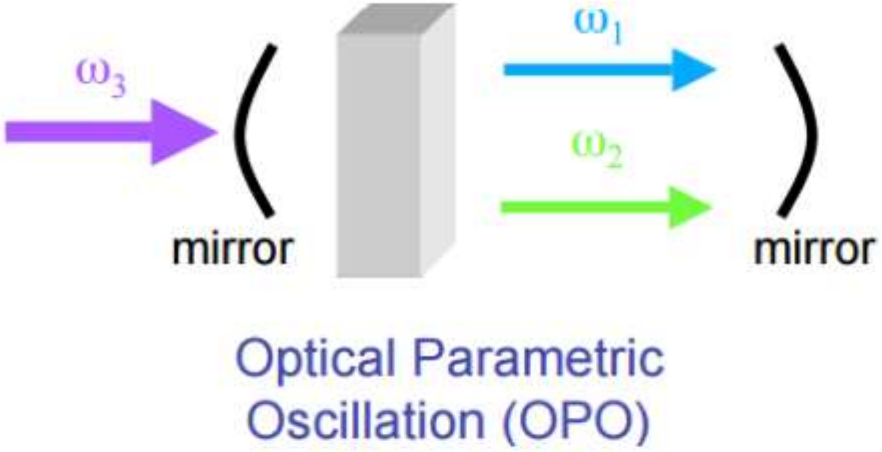
Assume anti-symmetric port is dark port

$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$
$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

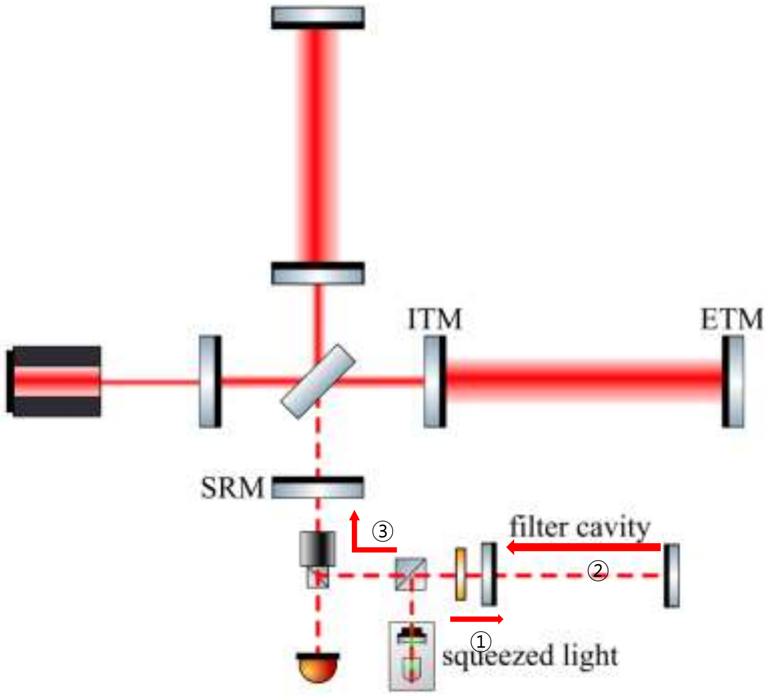
Optical parametric oscillator



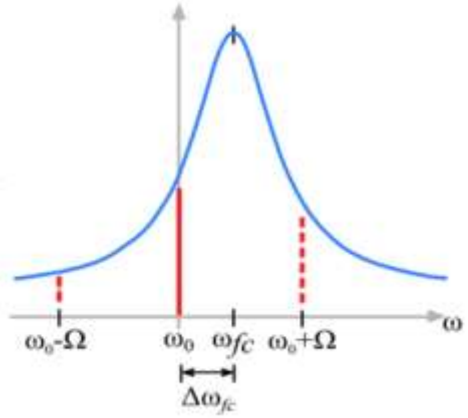
$\omega_1 = \omega_2$: *degenrated OPO*

All-Optical Electron Acceleration with Ultrafast THz Pulses, Wenqian Ronny Huang, MIT(2017)

Filter cavity

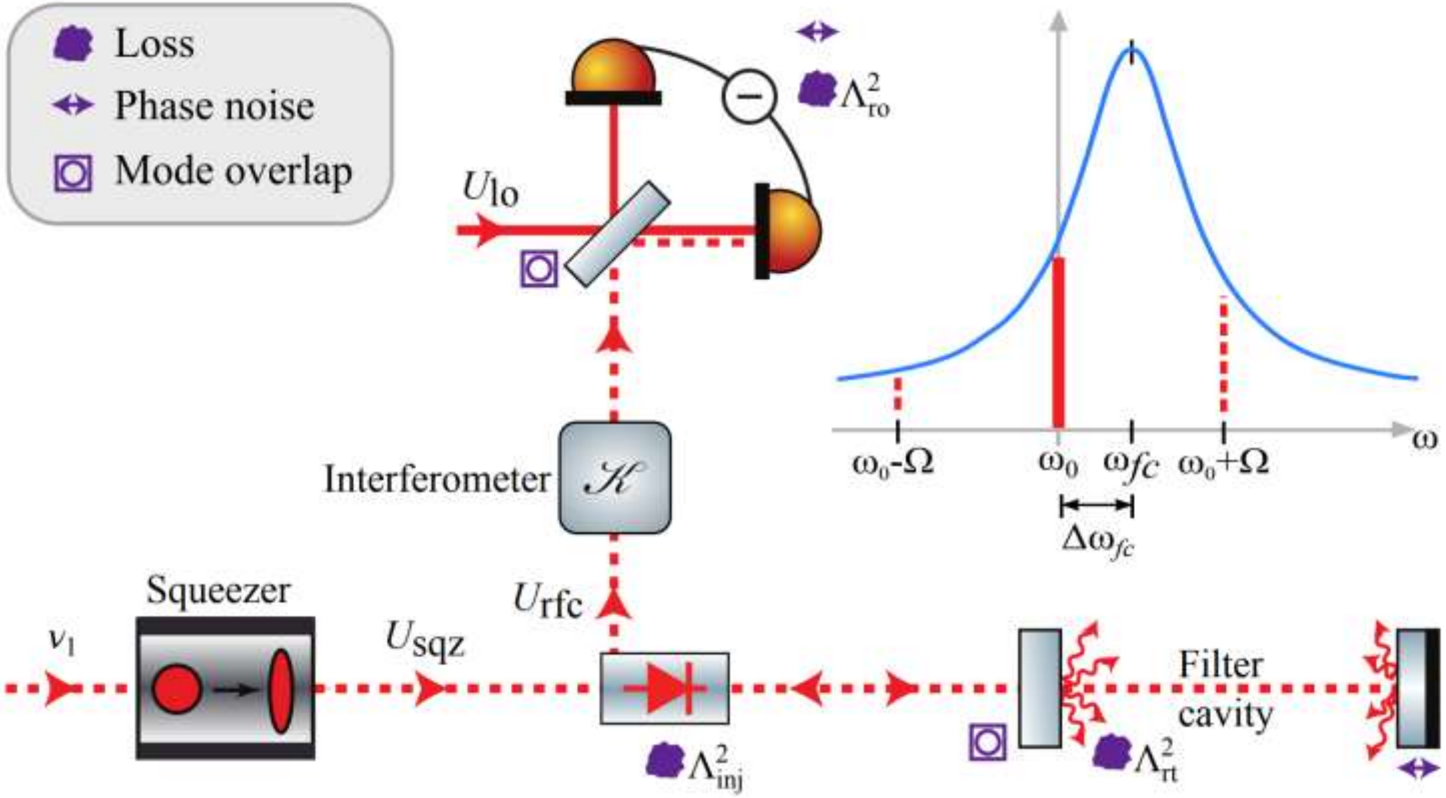


Denis Martynov et al, Phys. Rev. D **99**, 102004



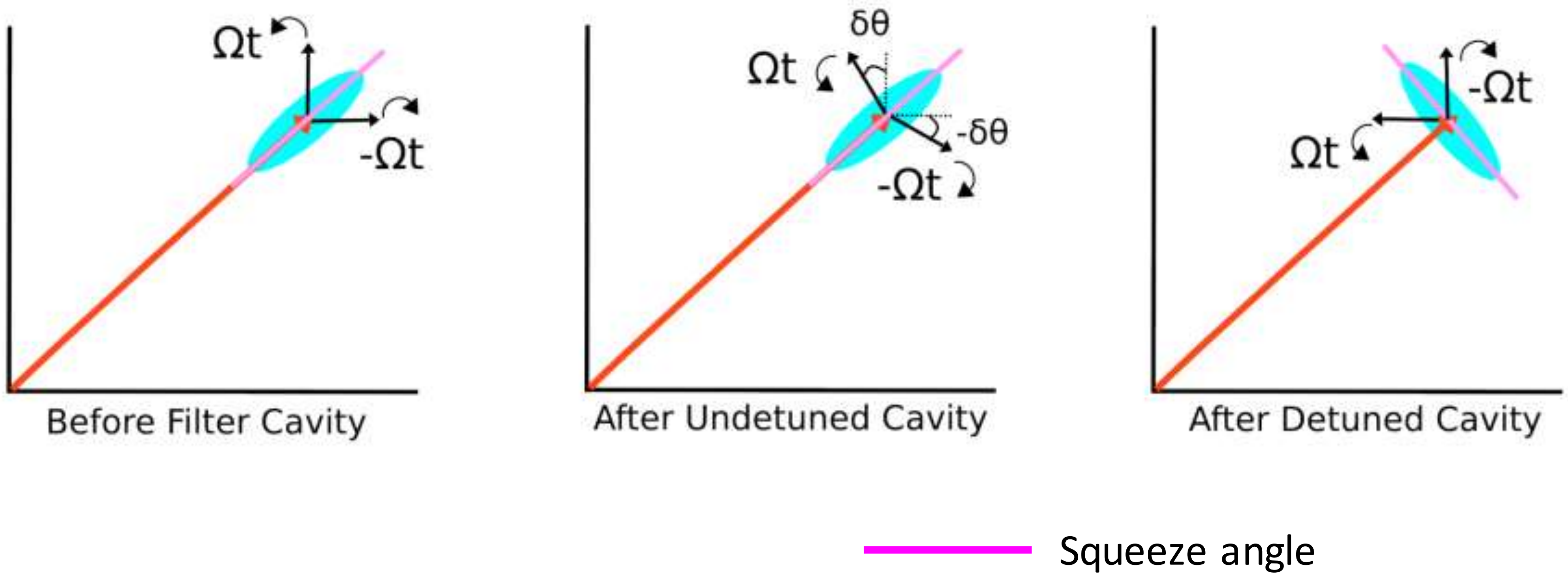
Frequency detuning

Detuned filter cavity



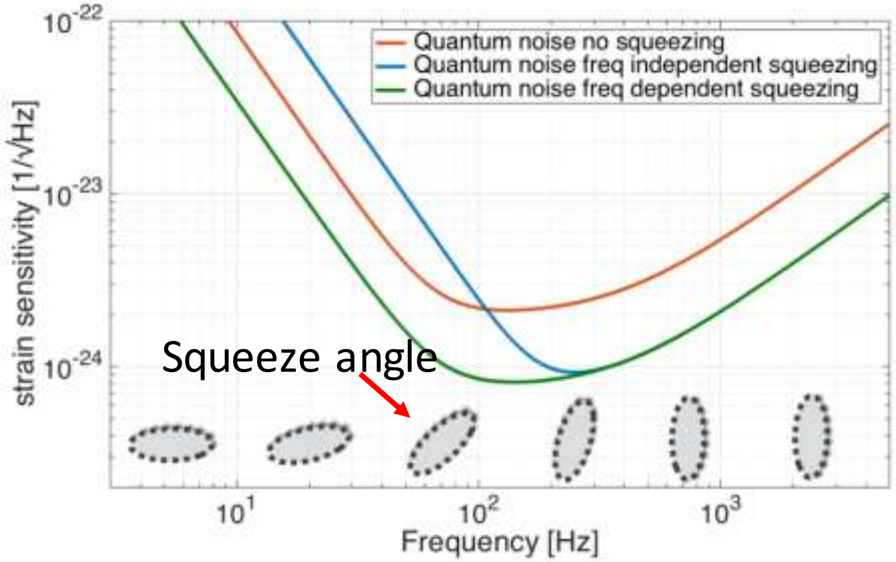
P. Kwee, J. Miller, T. Isogai, L. Barsotti, and M. Evans
Phys. Rev. D 90, 062006 – Published 5 September 2014

Squeeze angle



M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

Squeeze angle



Squeeze angle

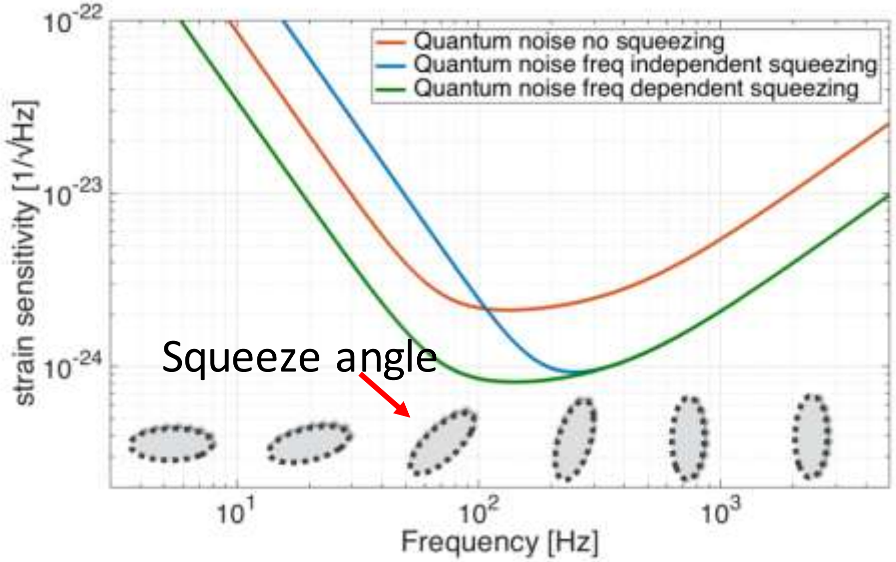
$$\arctan\left(\frac{2\gamma_{\mathrm{fc}}\Delta\omega_{\mathrm{fc}}}{\gamma_{\mathrm{fc}}^2-\Delta\omega_{\mathrm{fc}}^2+\Omega^2}\right)$$

Detuning frequency

< Ω

UNIVERSITÉ PARIS DIDEROT, Eleonora Capocasa (2017)

Squeeze angle



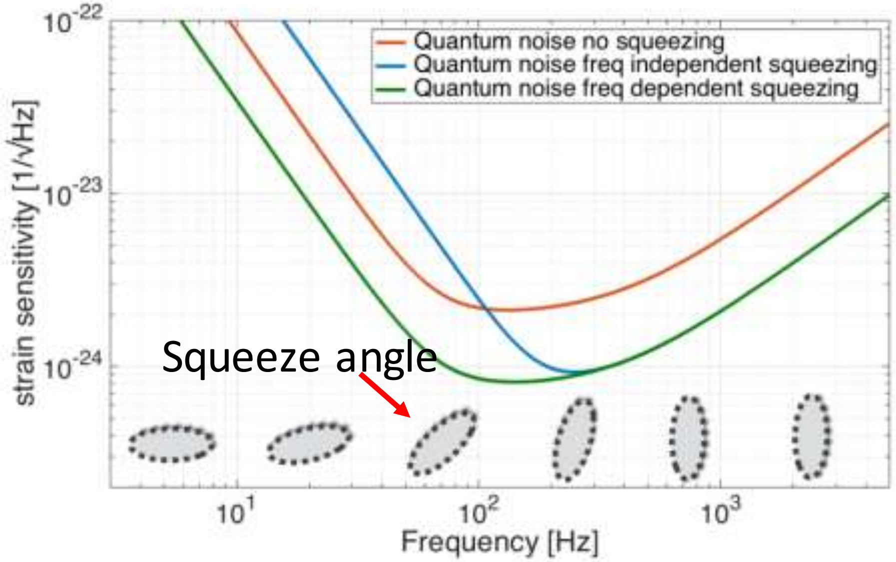
Squeeze angle

$$\arctan\left(\frac{2\gamma_{\rm fc}\Delta\omega_{\rm fc}}{\gamma_{\rm fc}^2-\Delta\omega_{\rm fc}^2+\Omega^2}\right)$$

GW signal side band frequency
~ 100Hz

UNIVERSITÉ PARIS DIDEROT, Eleonora Capocasa (2017)

Squeeze angle



Squeeze angle

$$\arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2}\right)$$

Filter cavity bandwidth

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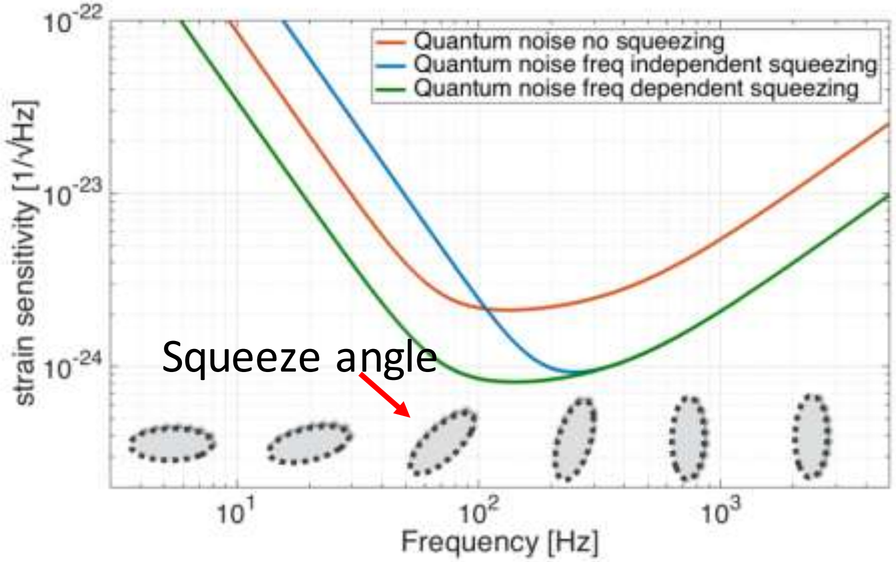
Squeeze angle



Squeeze angle

$$\arctan\left(\frac{2\gamma_{\rm fc}\Delta\omega_{\rm fc}}{\gamma_{\rm fc}^2 - \Delta\omega_{\rm fc}^2 + \Omega^2}\right)$$

$$t_{\rm st} = \frac{1}{\gamma_{\rm fc}} = \frac{\sqrt{2}}{\Omega_{\rm SQL}} \simeq 3\,{\rm ms}$$

Determined by storage time of light

UNIVERSITÉ PARIS DIDEROT, Eleonora Capocasa (2017)

Squeeze angle rotation

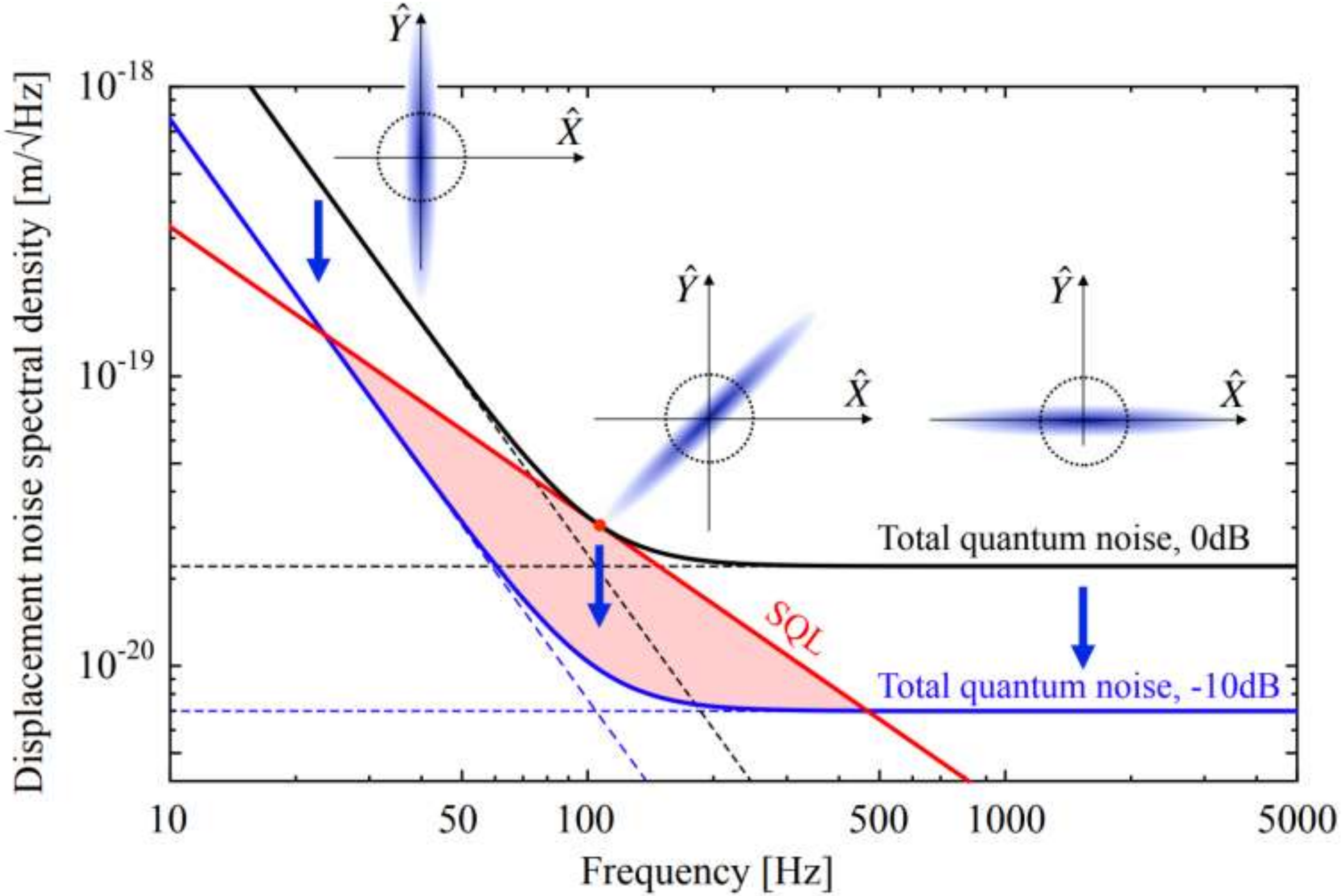
$$\alpha_p = \arctan\left(\frac{2\gamma_{\mathrm{fc}}\Delta\omega_{\mathrm{fc}}}{\gamma_{\mathrm{fc}}^2 - \Delta\omega_{\mathrm{fc}}^2 + \Omega^2}\right)$$

$\gamma = loss\ of\ filter\ cavity$

$\omega_{fc} = detuned\ frequency$

$$t_{\mathrm{st}} = \frac{1}{\gamma_{\mathrm{fc}}} = \frac{\sqrt{2}}{\Omega_{\mathrm{SQL}}} \simeq 3\,\mathrm{ms}$$

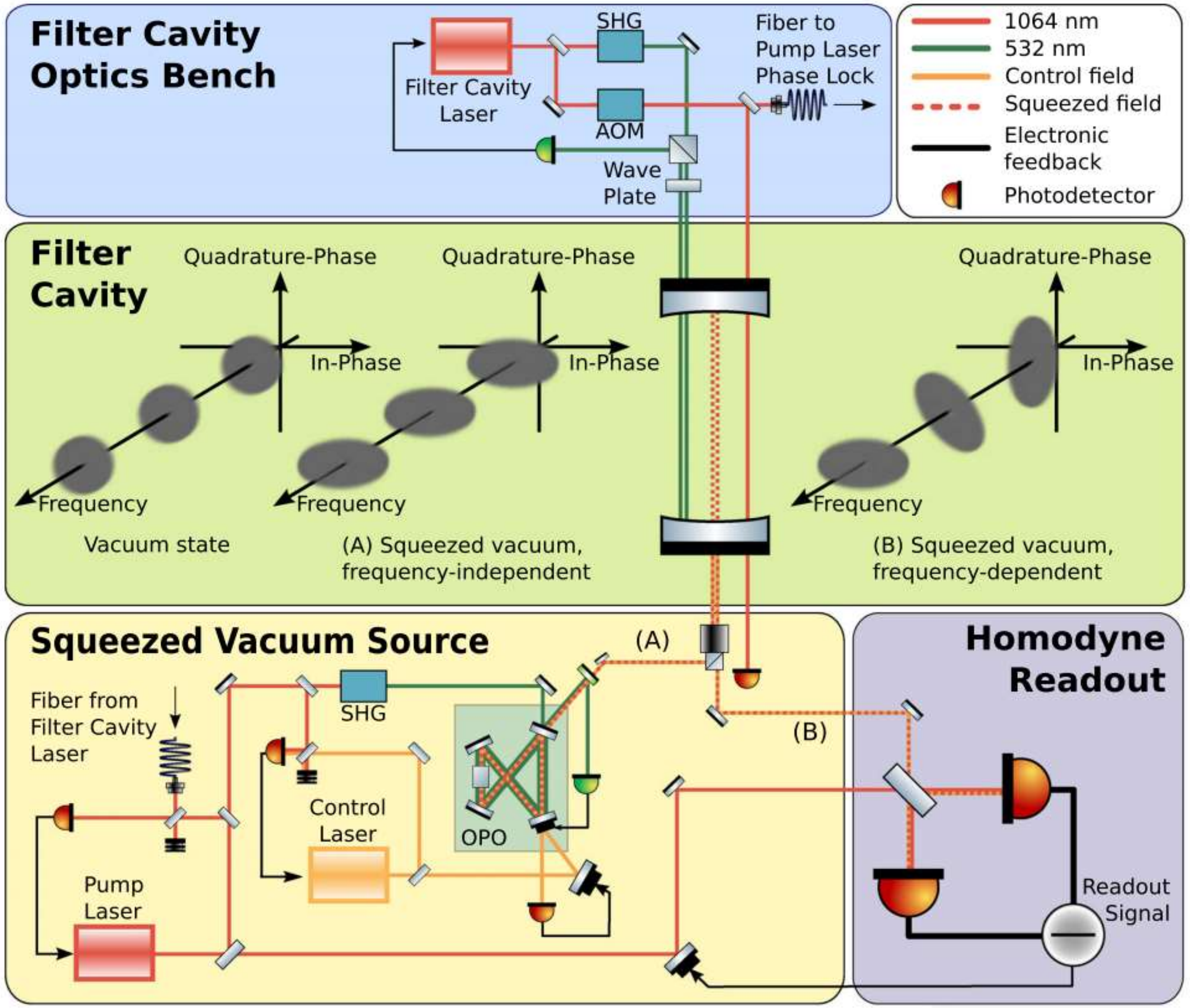
Squeeze angle rotation



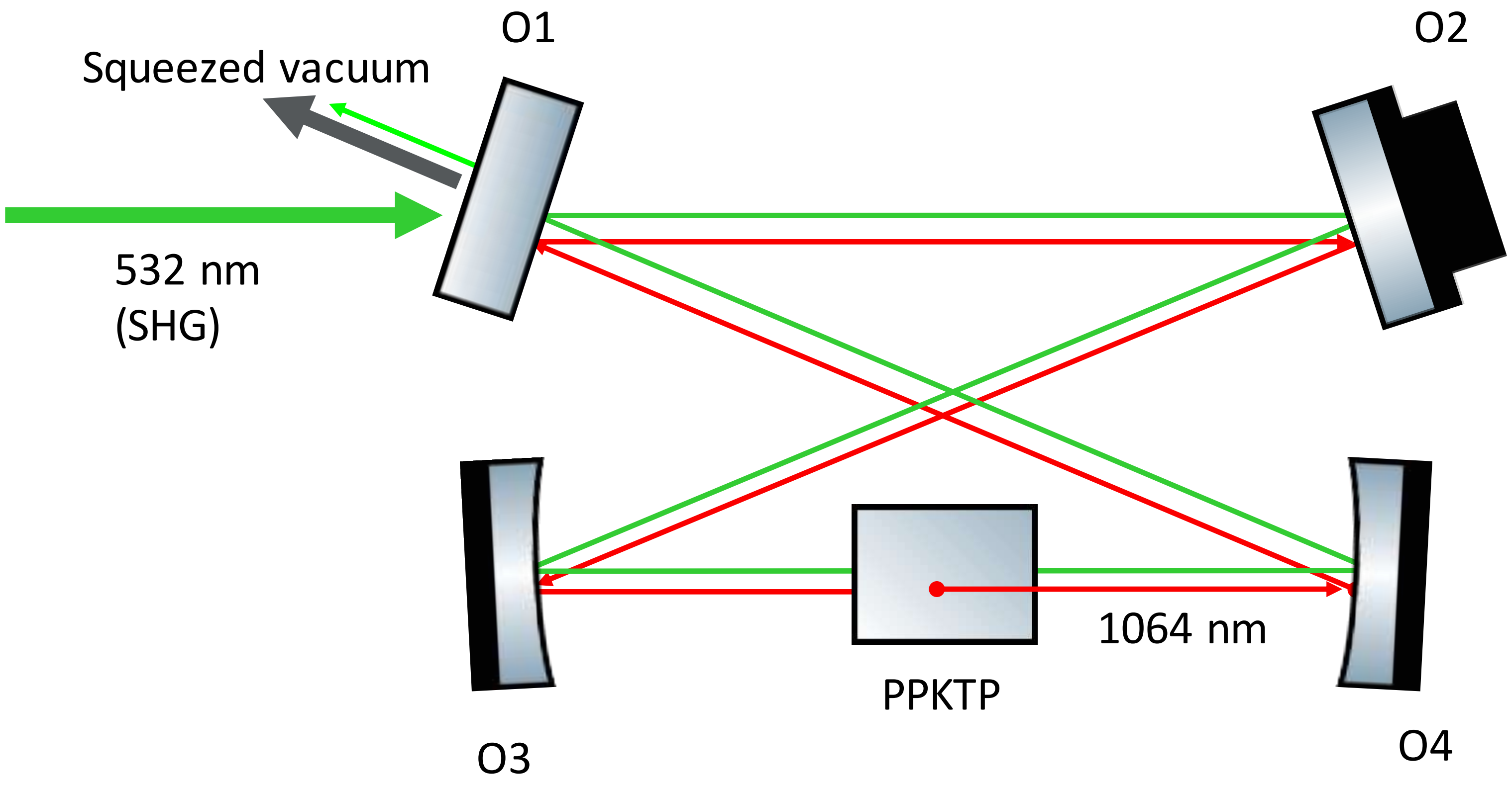
R. Schnabel / Physics Reports 684 (2017) 1–51

LIGO filter cavity

PRL 116, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

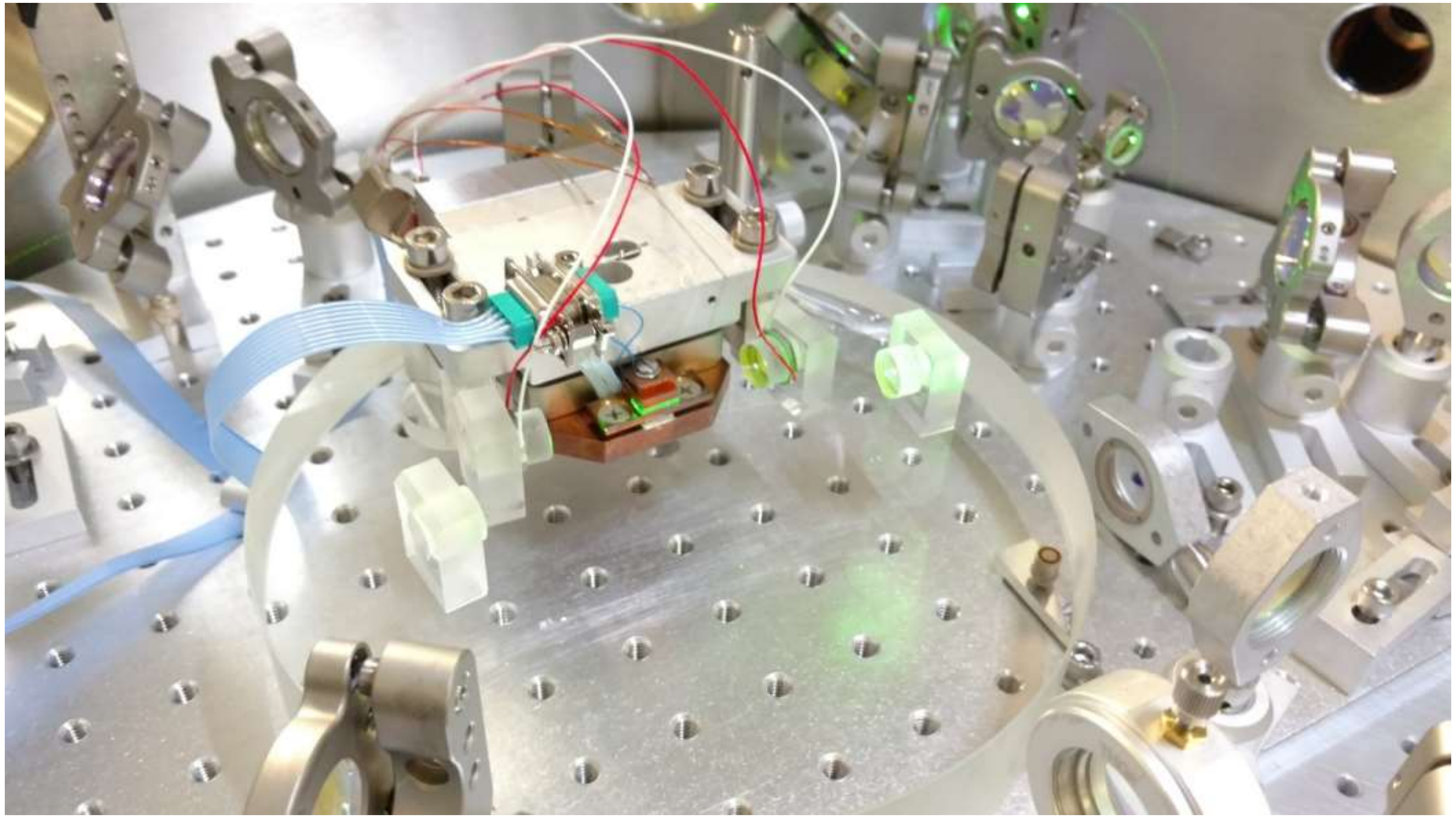


OPO of LIGO squeezer



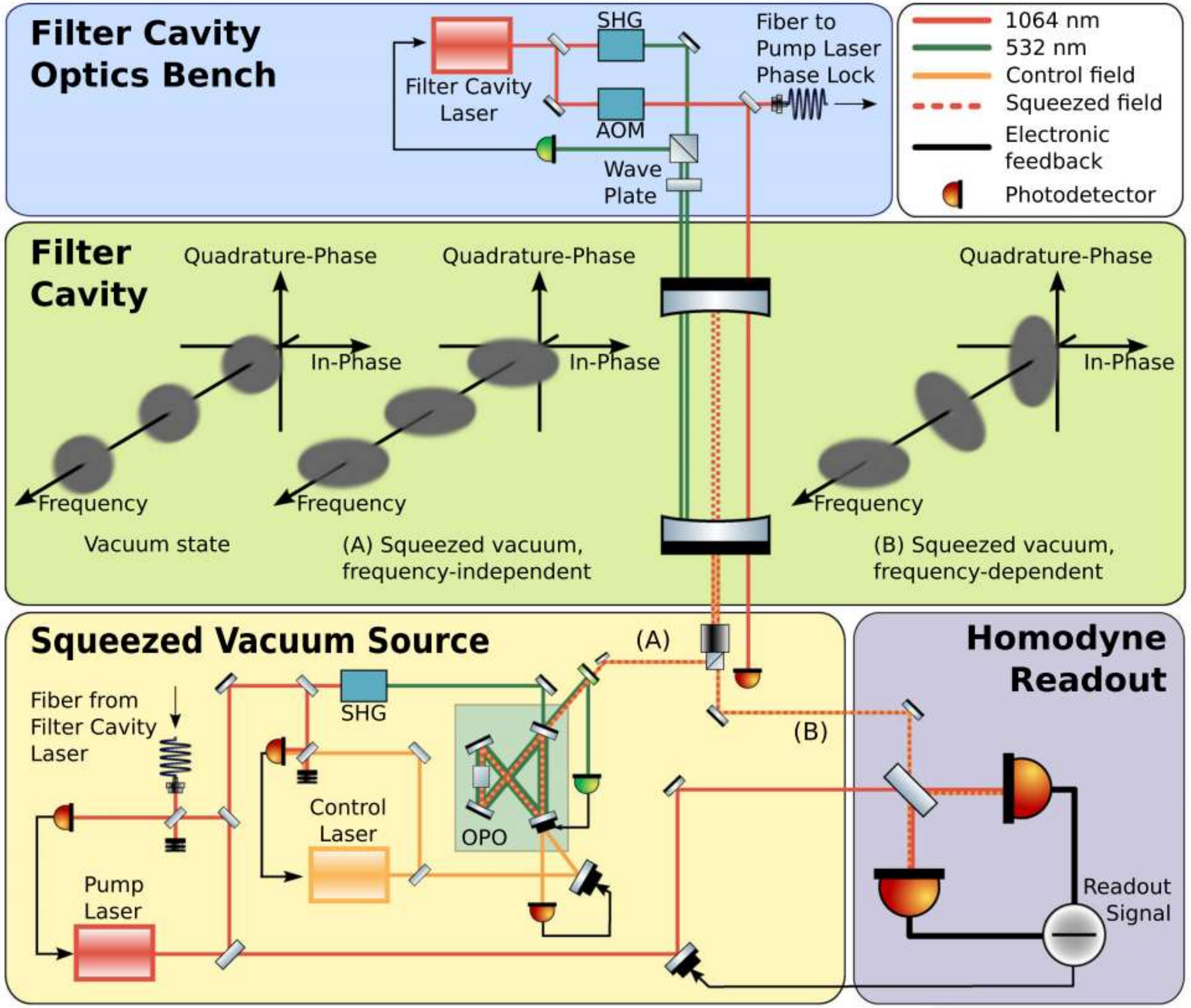
Under threshold operation

LIGO OPO



LIGO filter cavity

PRL 116, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016



ALS with green laser

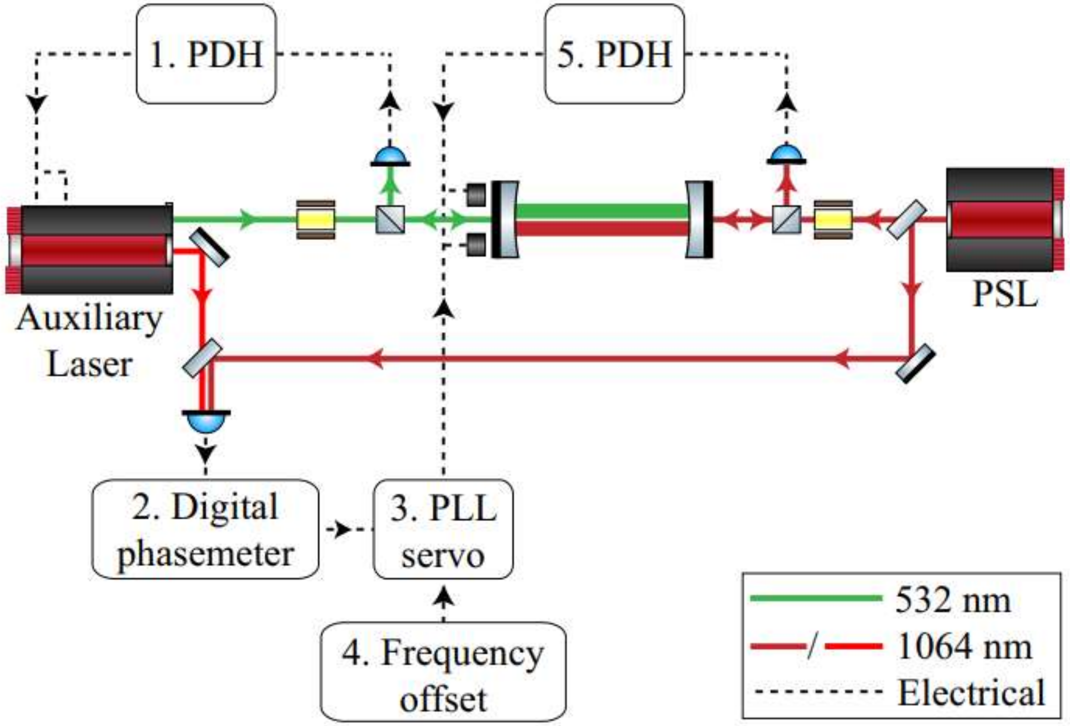


Fig. 2. (Color online) Schematic of the arm-length stabilisation system. The numbering indicates the flow of the lock acquisition process and corresponds to the enumerated list below.

LIGO filter cavity

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