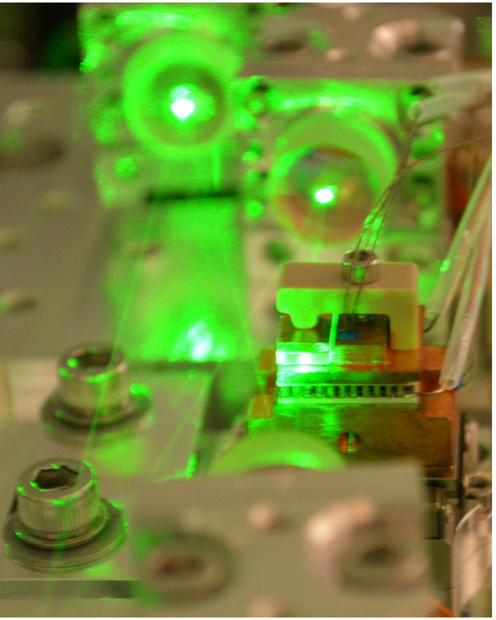
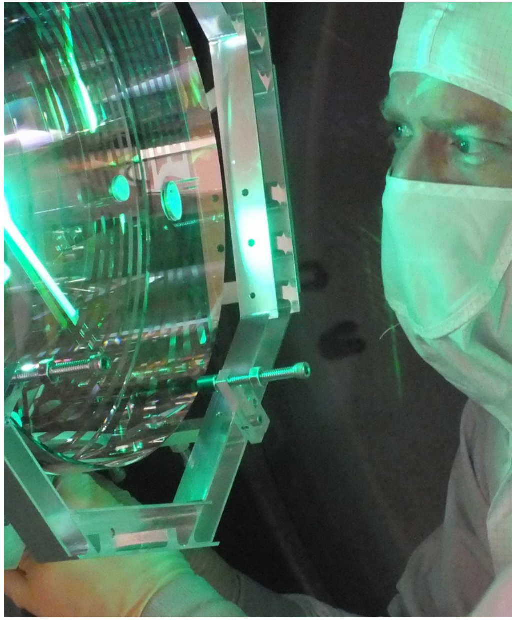
Quantum Squeezing and Quantum Correlations in advanced LIGO

Lee McCuller, MIT
for the SQZ team
(LIGO Laboratory, in collaboration with ANU)

Fermilab Colloquium
17 Feb. 2020



LIGO's optical
Parametric amplifier

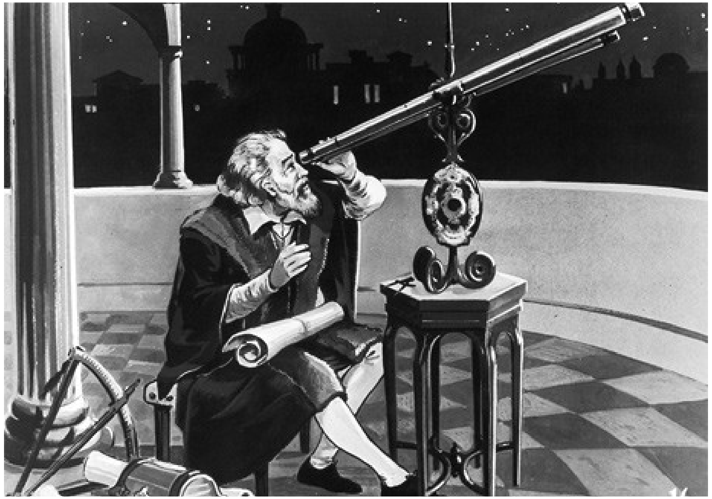


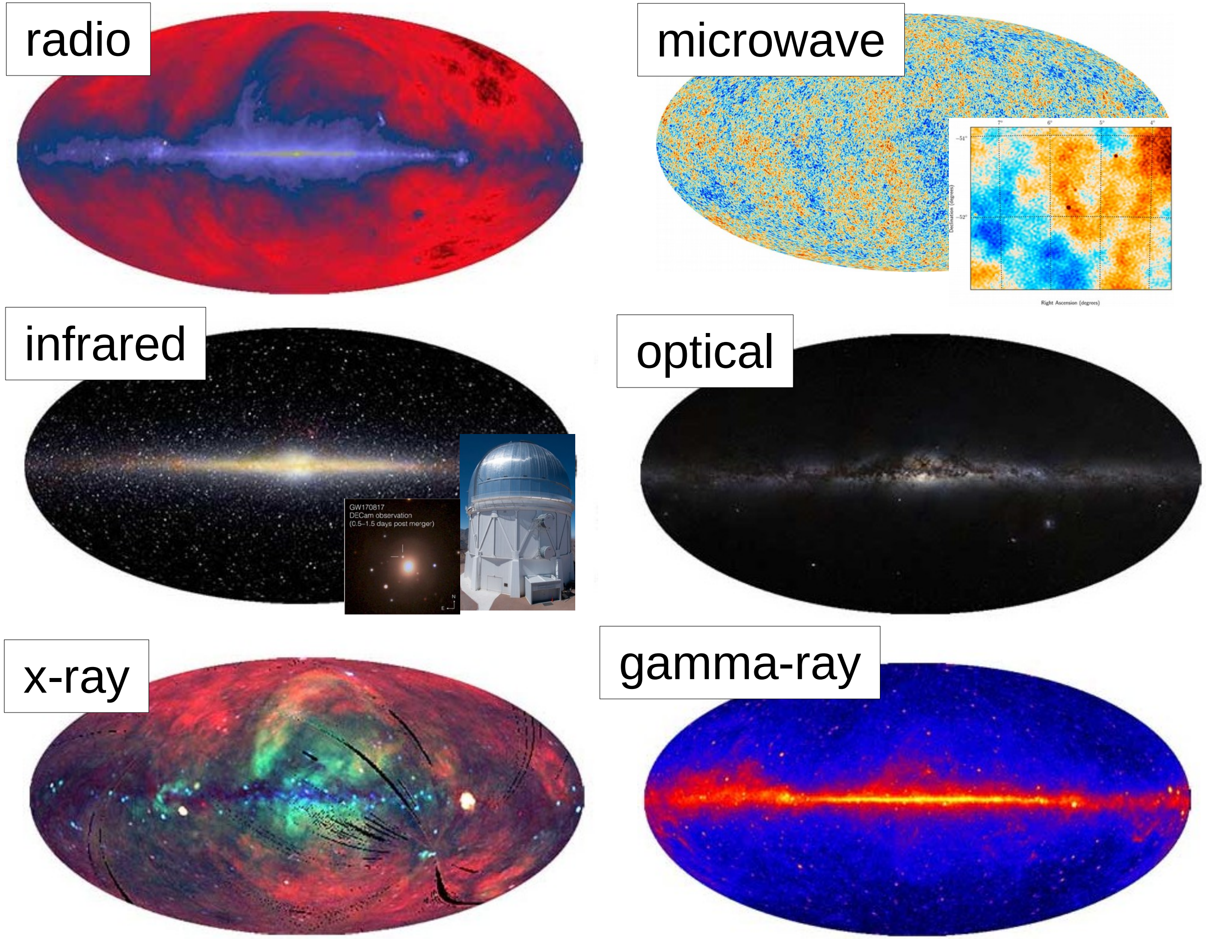
How strongly can we
probe the LIGO mirrors?

Every New *Wavelength*

In 1610, Galileo pointed a telescope to the sky, and changed the way we learn about our Universe

Since then, every new wavelength
discovers new objects,
maps new populations,
probes new physics

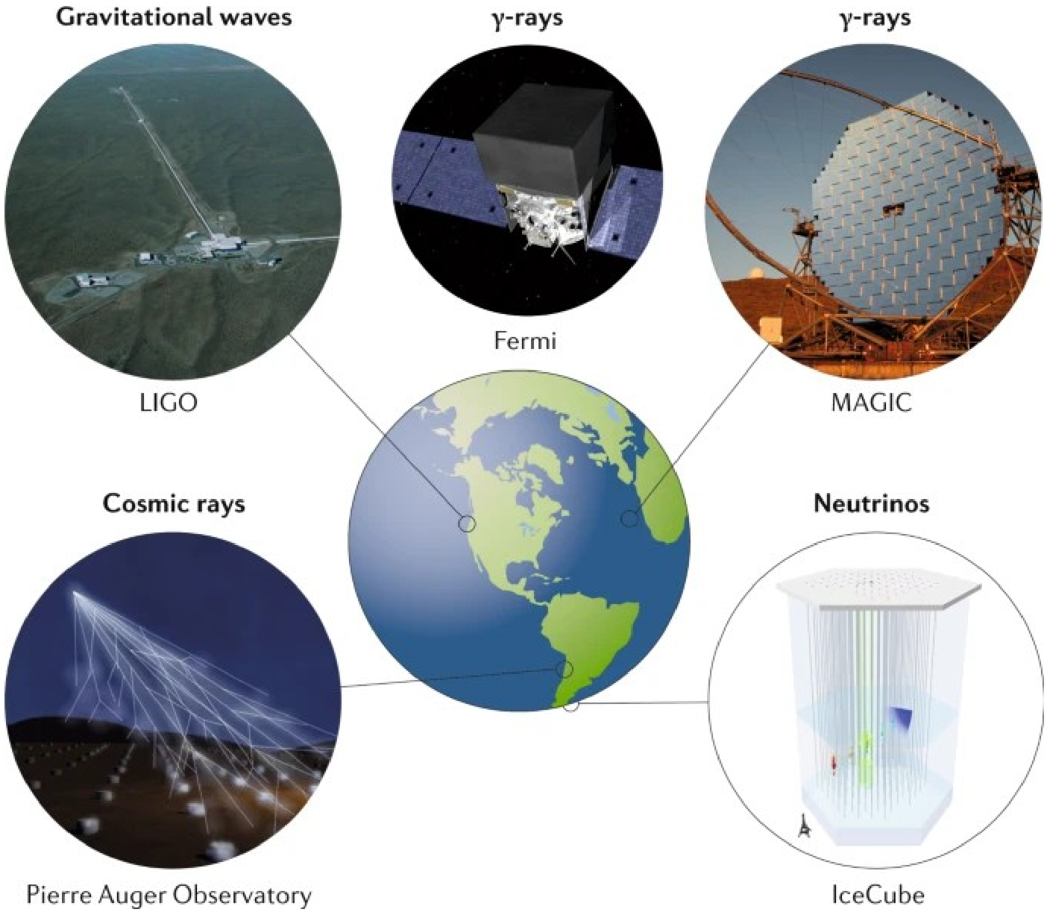




Credits: CMB: Planck, South Pole Telescope; radio: Haslam et al. 1982; infrared: NASA, DESGW; optical: ESO/S. Brunier; X-ray: Max Planck Institute for Extraterrestrial Physics and S. L. Snowden; gamma-ray: NASA/DOE/Fermi LAT Collaboration

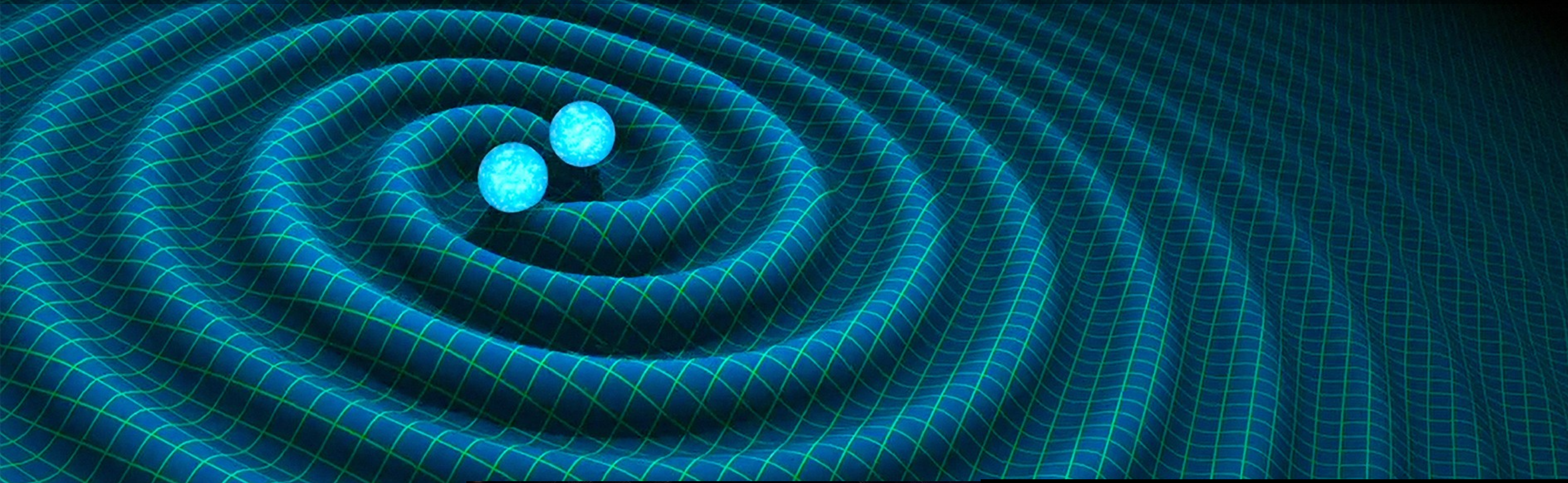
Every new *Messenger*

- New *modalities* from astro-particle physics and gravitational waves
- Each modality observes in a new way, is a new *messenger*
- *Complementary observations* with electromagnetic imaging
- The dawn of multi-messenger astrophysics



Mészáros, P., Fox, D. B., Hanna, C. & Murase, K.
Multi-messenger astrophysics. Nature Reviews Physics 1, 585–599 (2019).

Gravitational Waves from the Cosmic Collider



Binary black holes

Image: NASA's Goddard Space Flight Center.

Gravitational transients in spacetime

Image: MIT, CC BY-NC-ND 3.0

Neutron Star "atom smashing"

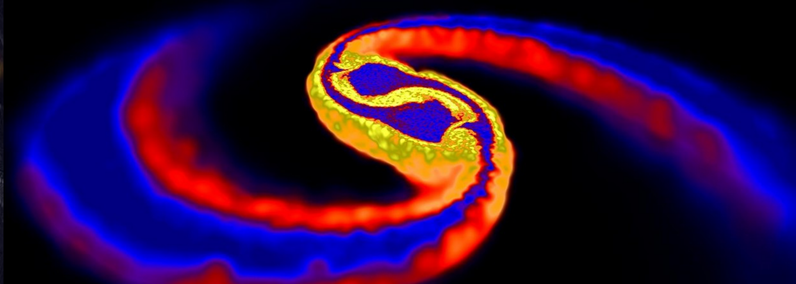
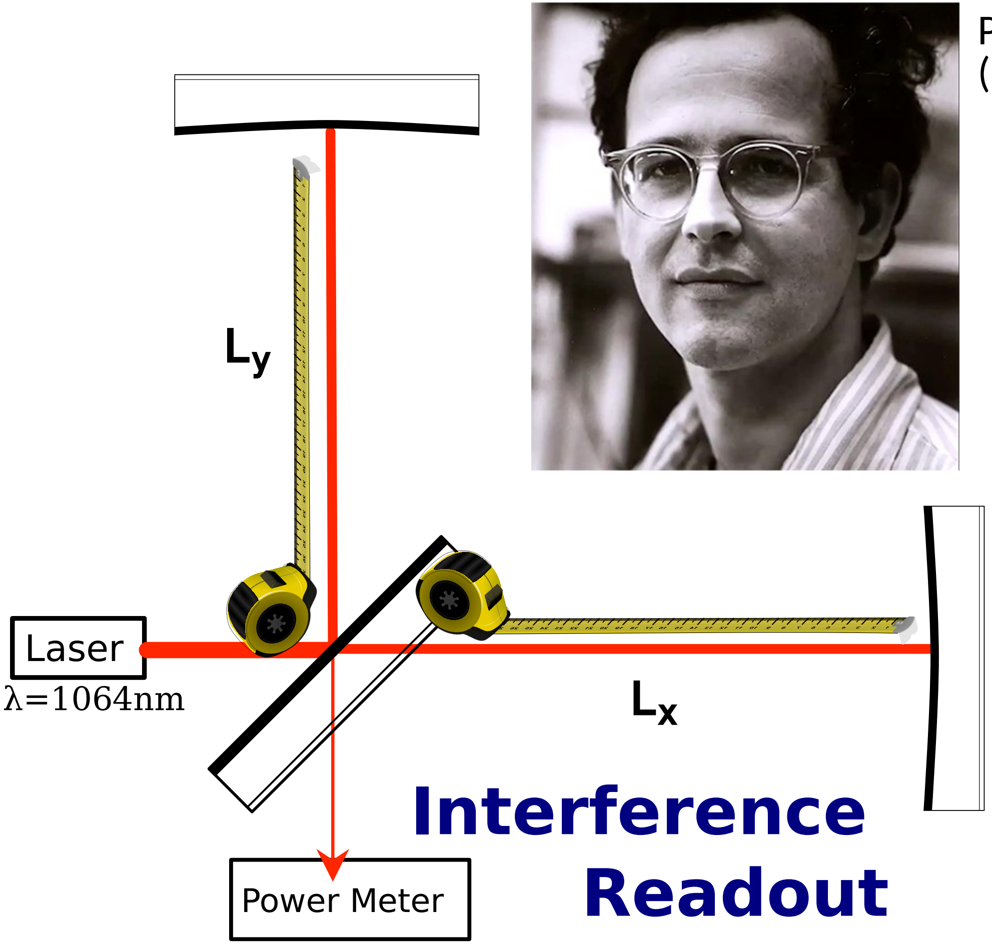


Image: Daniel Price (University of Exeter) and
Stephan Rosswog (International University Bremen), Science 2006

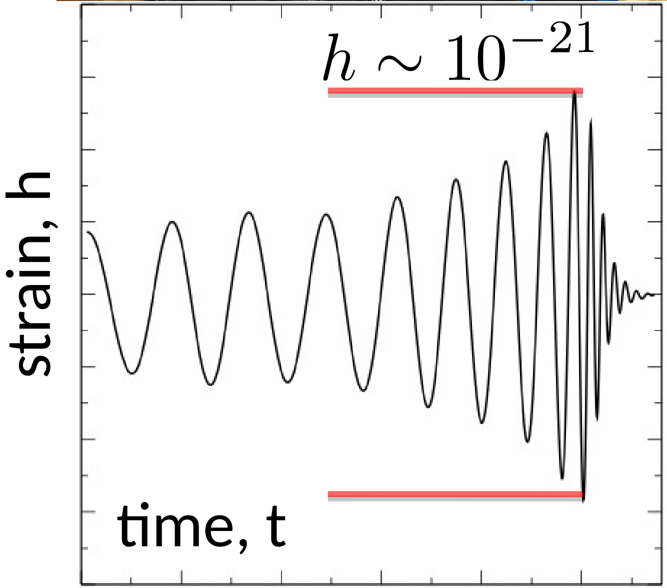
Gravitational Wave Detectives



Interference Readout

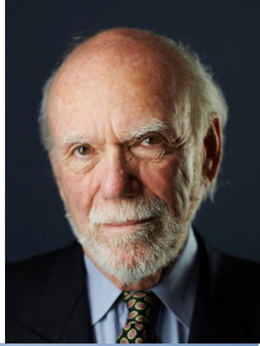
Prof. Rainer Weiss (MIT)

Prof. Kip Thorne (Caltech)

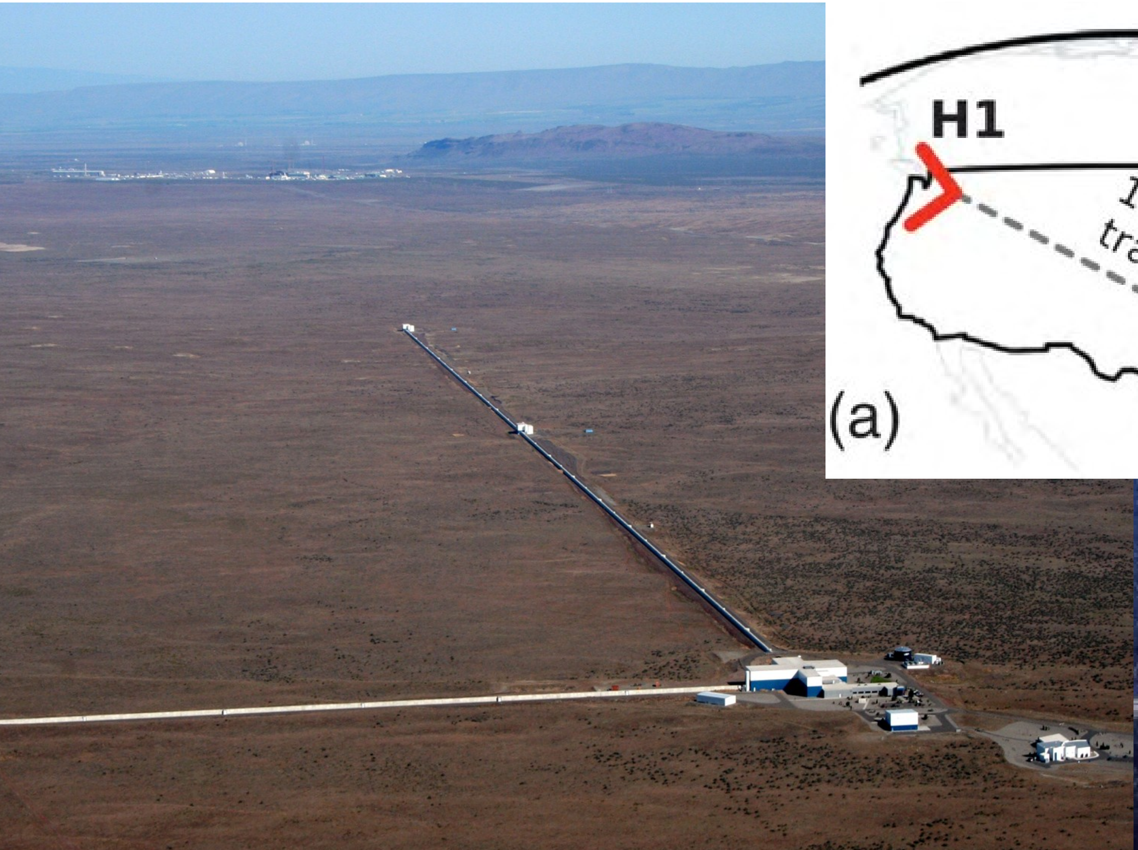


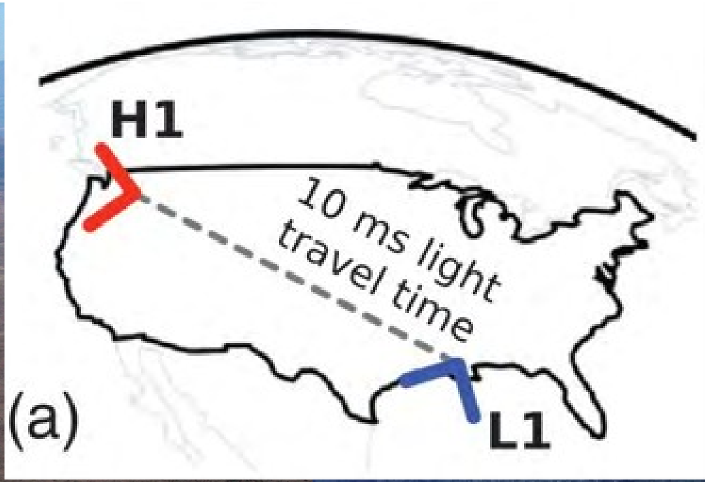
Two LIGO Observatories

each one a
laser interferometer with 4 km arms

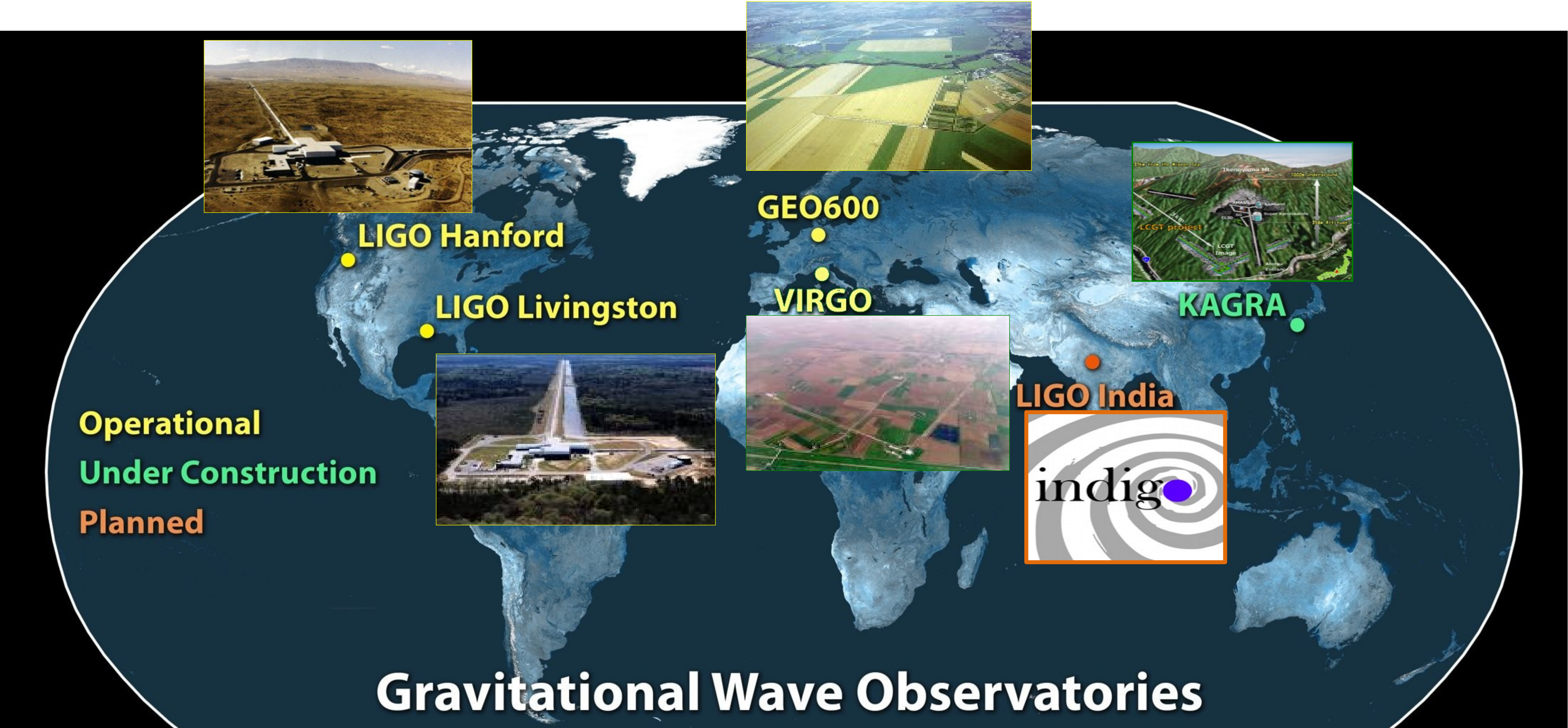


Prof. Barry Barish (Caltech)
Image Credit: Nobel





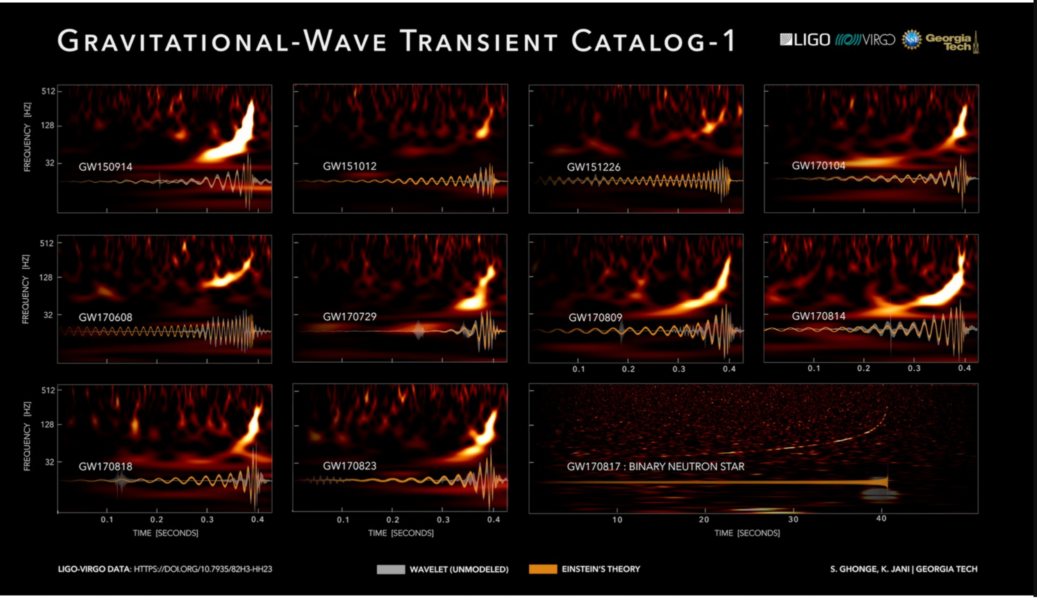
Observatory Network



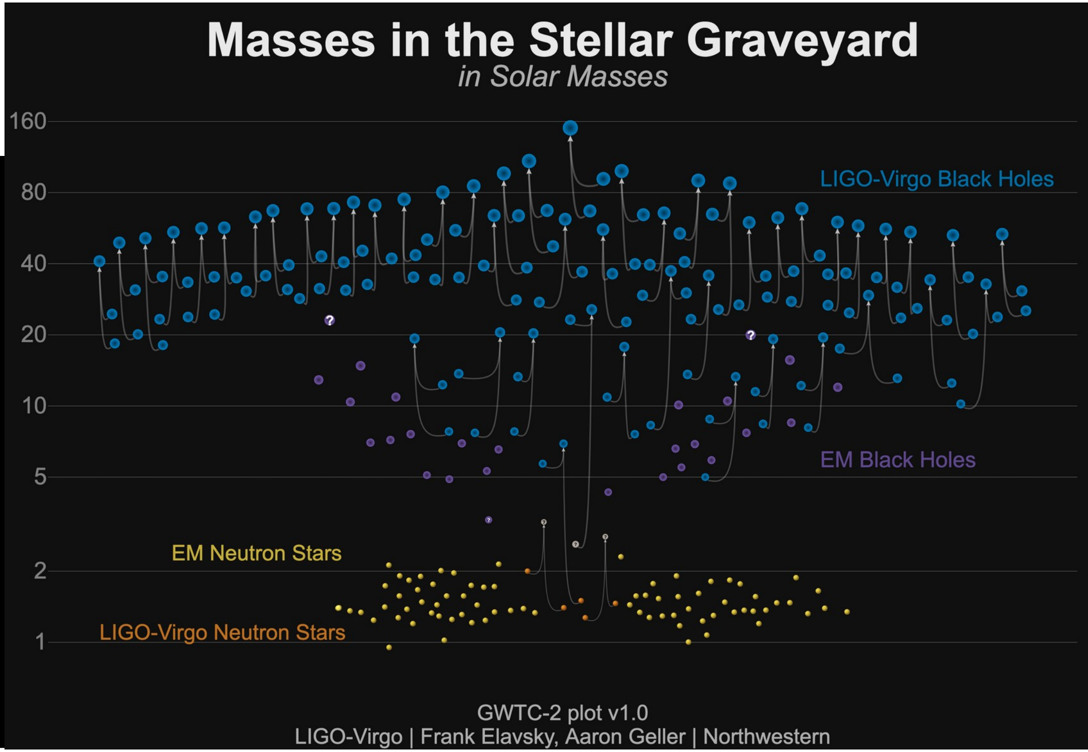
Detections, Physics, Astrophysics

The zoo or orrery exhibits a population.

The population is made of individuals.
each is exciting!



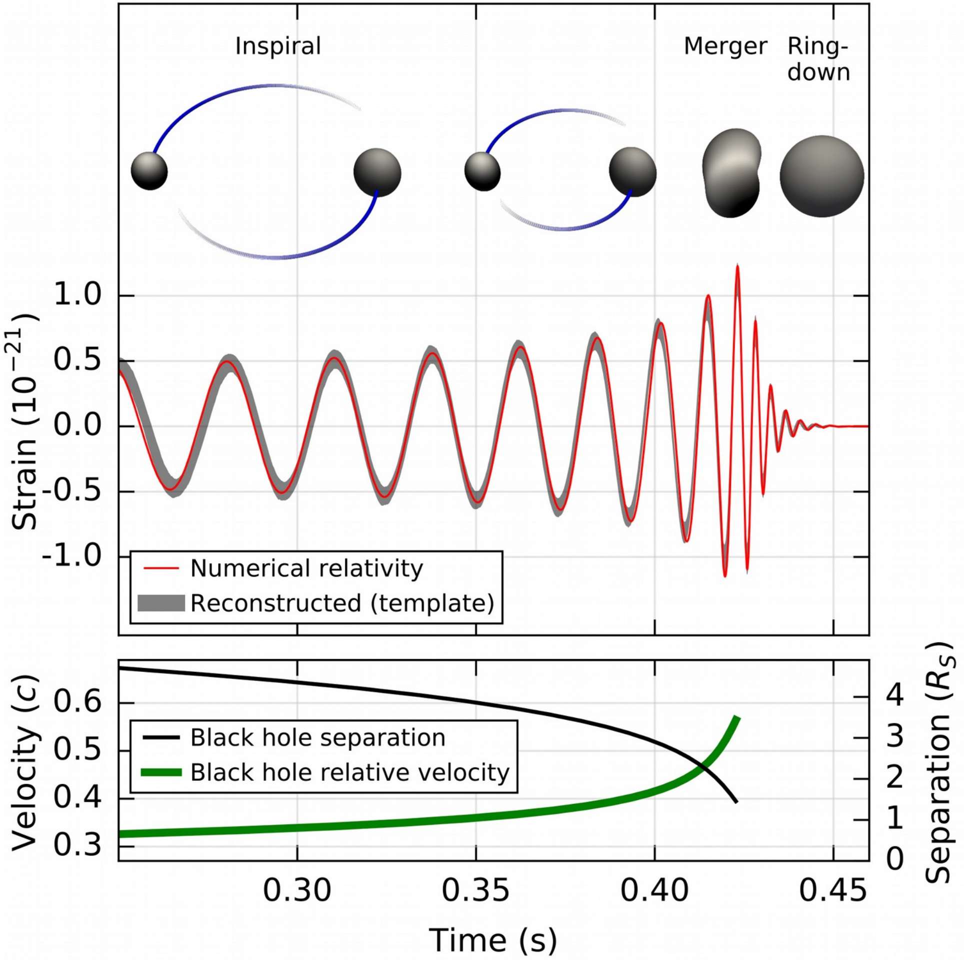
Observing Run 2 Catalog GWTC-1
Phys. Rev. X 9, 031040

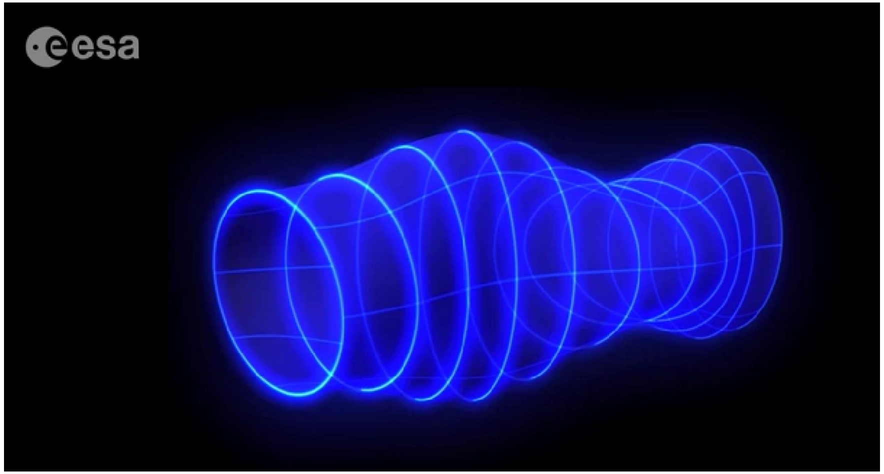


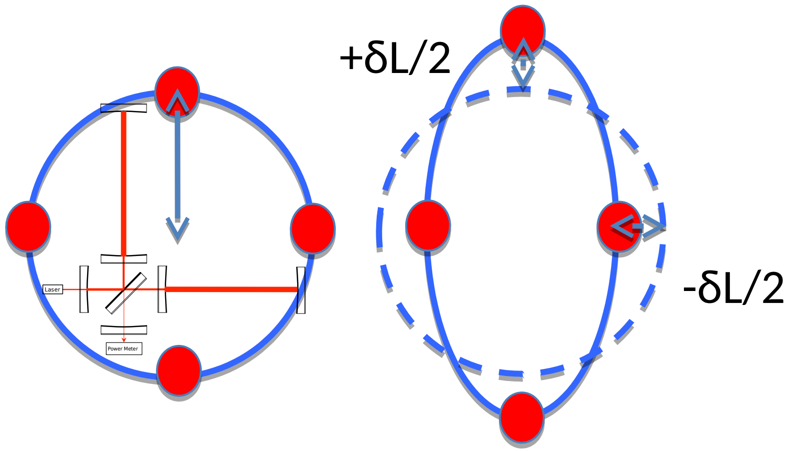
Observing Run 3a Catalog: GWTC-2
arXiv:2010.14527 [gr-qc]

Gravitational Strain Transduction

Phys. Rev. Lett. 116, 061102







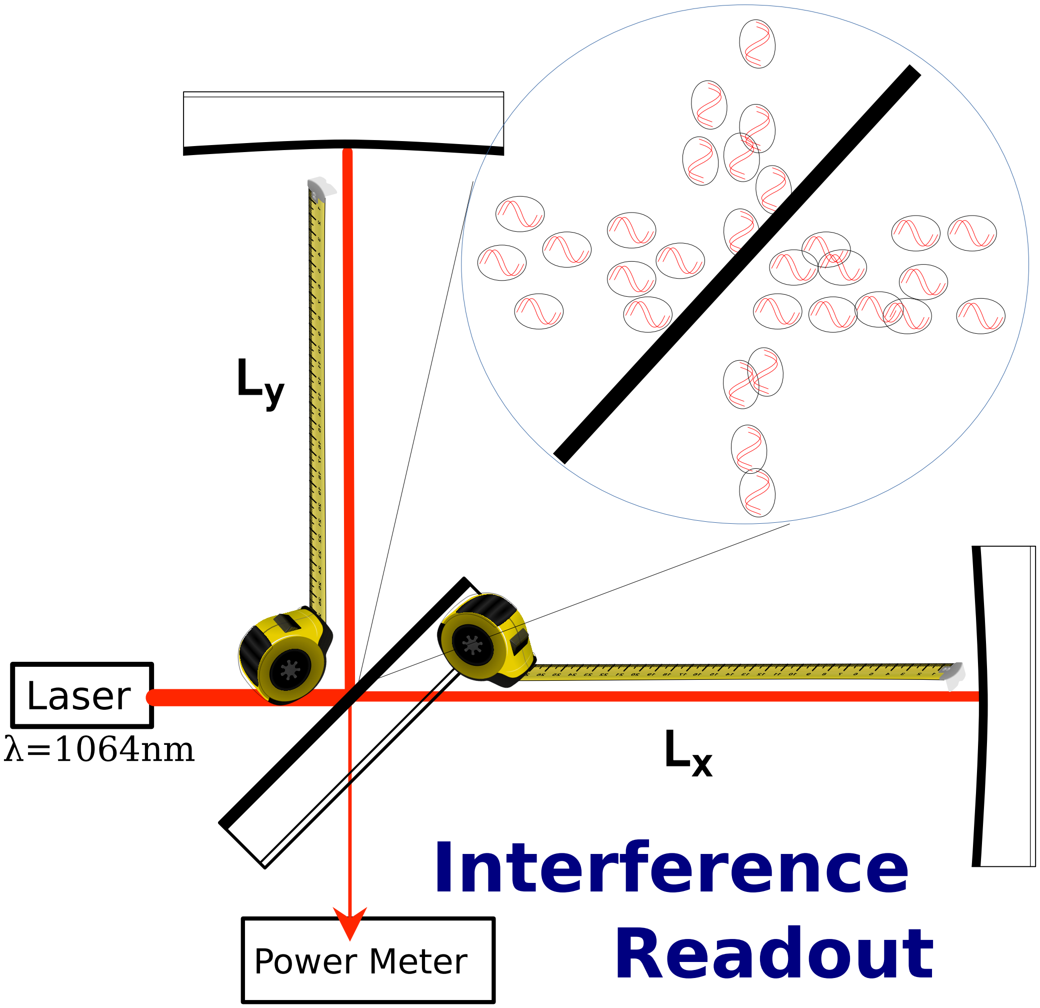
The Michelson Interferometer

Each photon gives
1064nm/2π measurement

minimum measurable length
variance from counting photons

$$\Delta x \propto \frac{1}{\sqrt{N_{\text{photons}}}}$$

~ 10^{19} photons/s in
1 Watt of 1064nm light

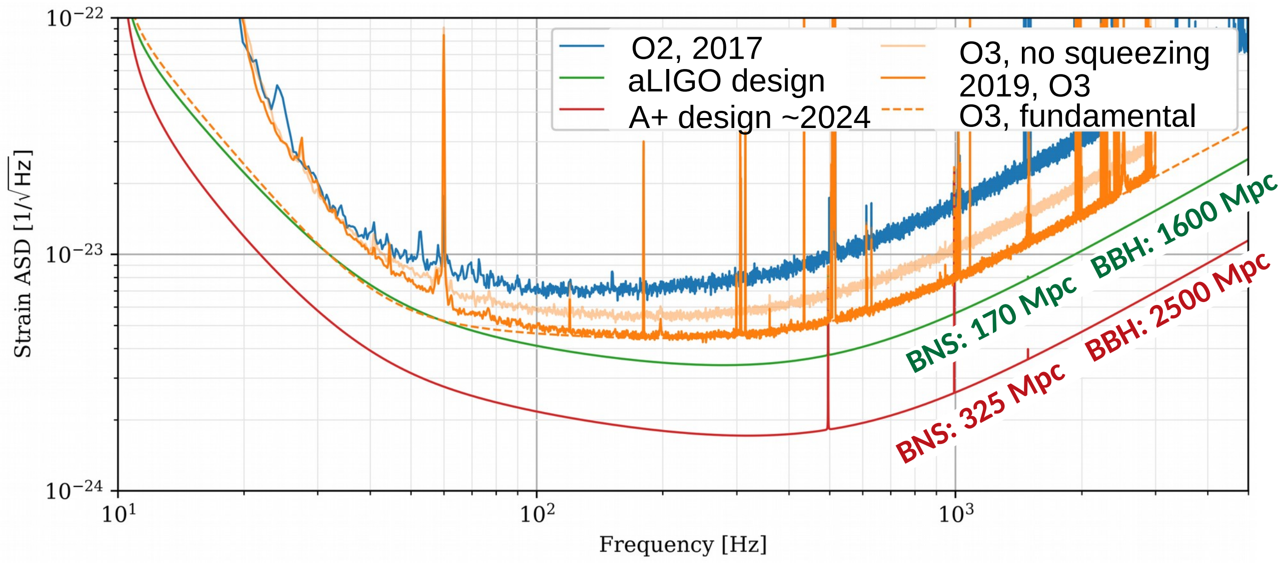


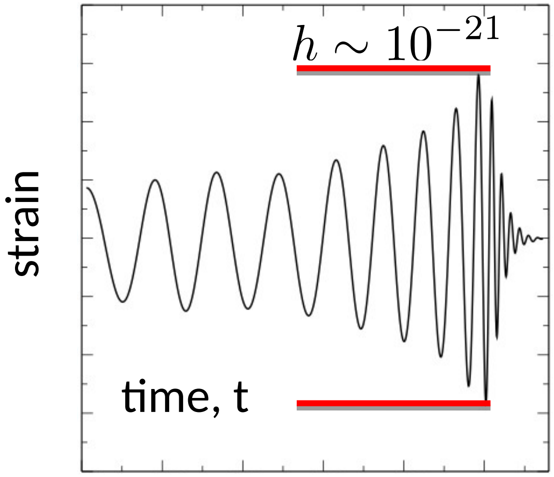
advanced LIGO Sensitivity

1) **Strain Noise Spectrum:** Interferometers measure GW timeseries chirping through frequency. this is the **standard deviation error *density,*** at each frequency
2) **Inspiral Range:** The distance to which fiducial 1.4/1.4 Msol binary neutron star coalescence is detectable, on average.

- 1 Mpc ≈ 3e6 light-years
- The **event-rate** scales with the ***volume,*** we're talking *cubic giga-parsecs*

3) **RMS Strain or displacement:** the measurement error averaged over the most sensitive band





Reference Curves LIGO T1800042-v5

Rates: LIGO-VIRGO Collab. G1901322

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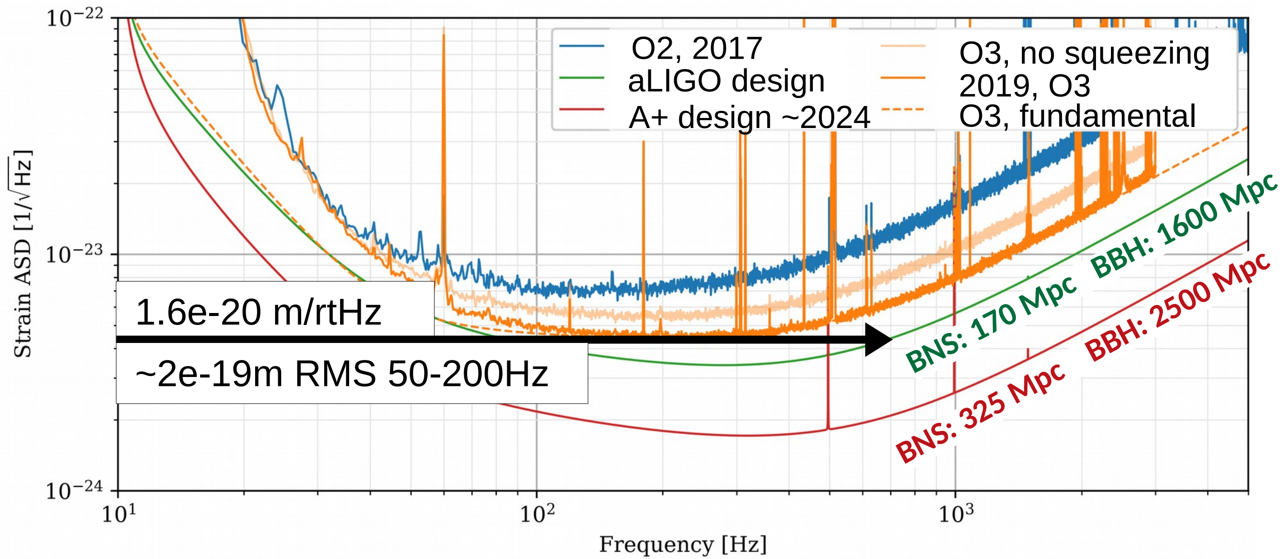
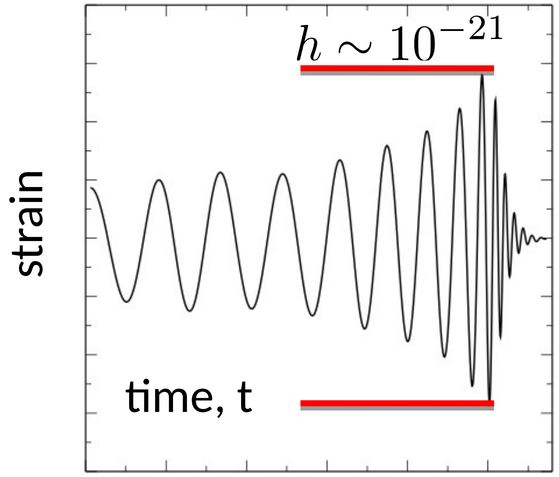


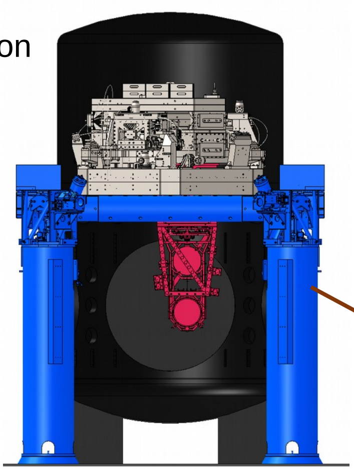


Reference Curves LIGO T1800042-v5

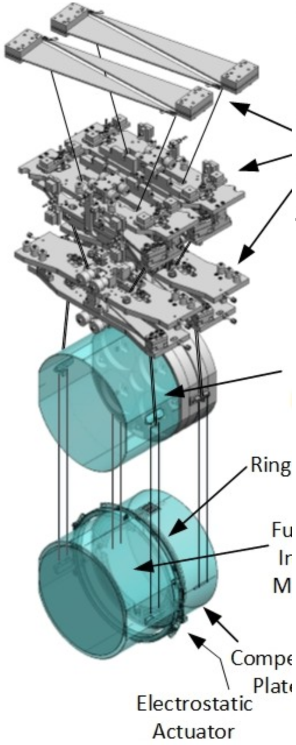
Rates: LIGO-VIRGO Collab. G1901322

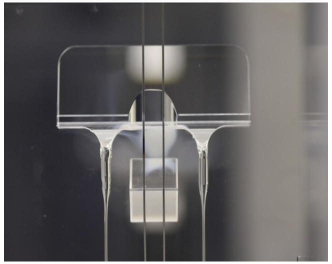
advanced LIGO's noise sources

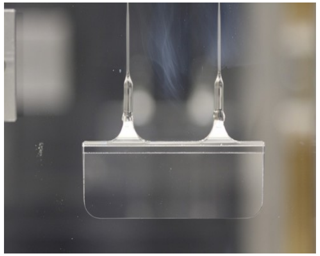
Active inertial isolation



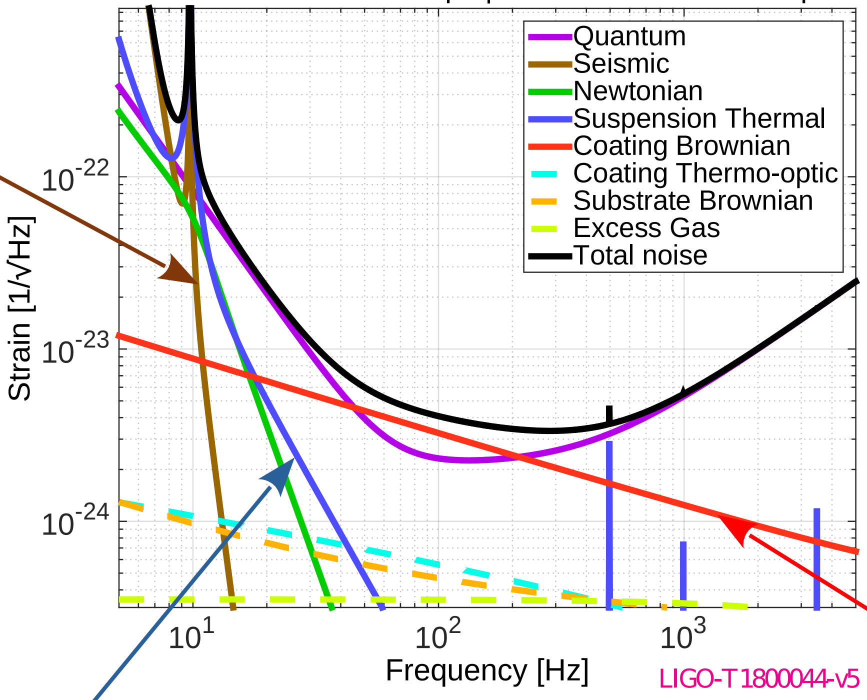
Passive quadruple Suspension





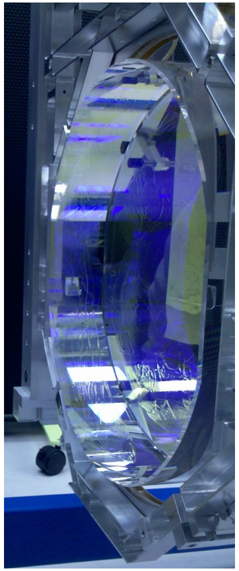


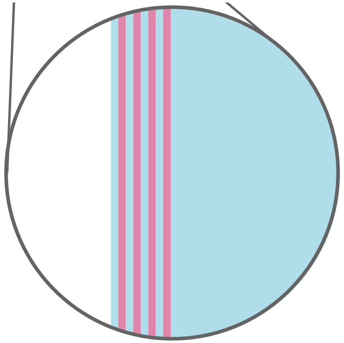
aLIGO Design Curve
1.4:1.4M. NSNS-173 Mpc | 30:30M. BHBH-1600Mpc



Fused Silica Suspension
Q~1 billion, 2 week ringdown

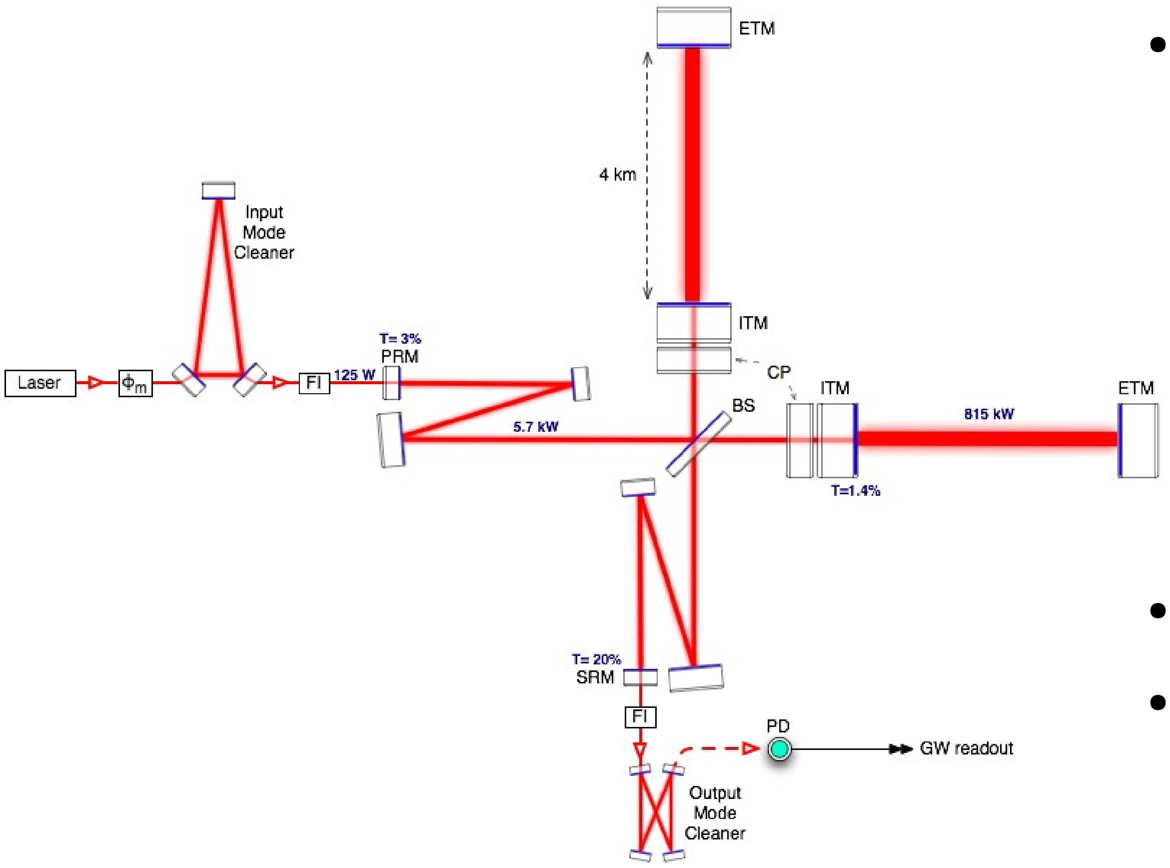
2nm smooth core optics,
~40ppm loss on 6cm beam





Coating materials minimize
Structural loss contributions
To thermal noises

LIGO’s Optical Layout



- Michelson Interferometer with cavity enhancements
  - Power recycling mirror for higher power
  - Arm cavities enhance power *and* signal
  - Signal extraction to enhance bandwidth
- 200W Laser → 4kW → 800kW
- λ = 1064nm from Nd:YAG NPRO seed laser (highly stabilized)

Scales

1m — Human

10^3m — LIGO

10^6m — Earth

10^9m

10^{12}m — 1 a.u

10^{15}m — Alpha Centauri

10^{18}m

10^{21}m — Milky Way

$4{\cdot}10^{24}\text{m}$ — **LIGO BNS 140MPc**

$3{\cdot}10^{25}\text{m}$ — **BBH 1GPc**

$2{\cdot}10^{26}\text{m}$ — Hubble Distance/ Cosmic horizon

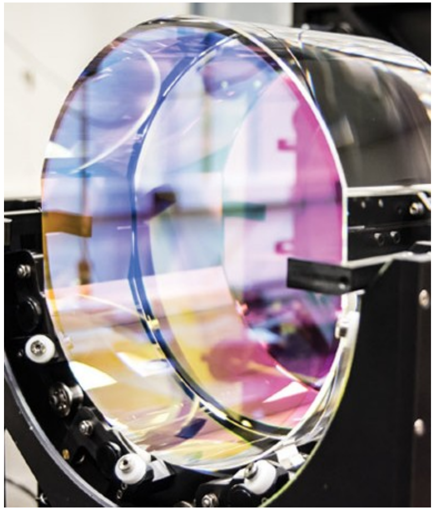
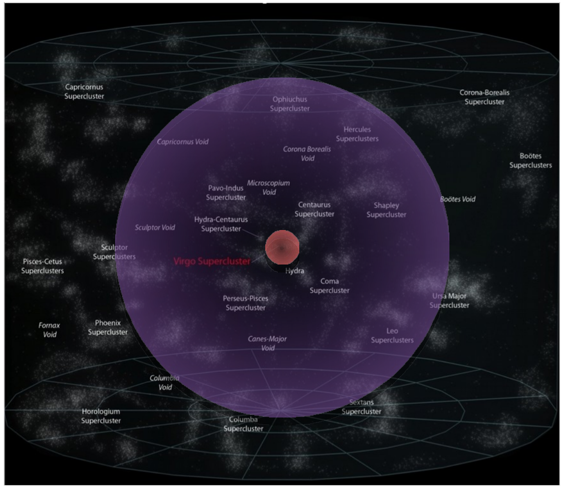


Image: Caltech LIGO Lab



Planck Length, GUT Scale, Compton wavelength of 20 ug — 10^{-34}m ℓ_p

aLIGO Precision 10^{-19}m

10^{-18}m — Electroweak & Higgs

10^{-15}m — Proton

10^{-12}m — Electron

10^{-9}m — Hydrogen Atom

10^{-6}m — LIGO Wavelength

10^{-3}m — “eyeball it”

1m — human

Continuous Measurements

This argument by *Braginsky*

Measurement 1 $\hat{x}(t)$

Measurement 2 $\hat{x}(t+\Delta t)$

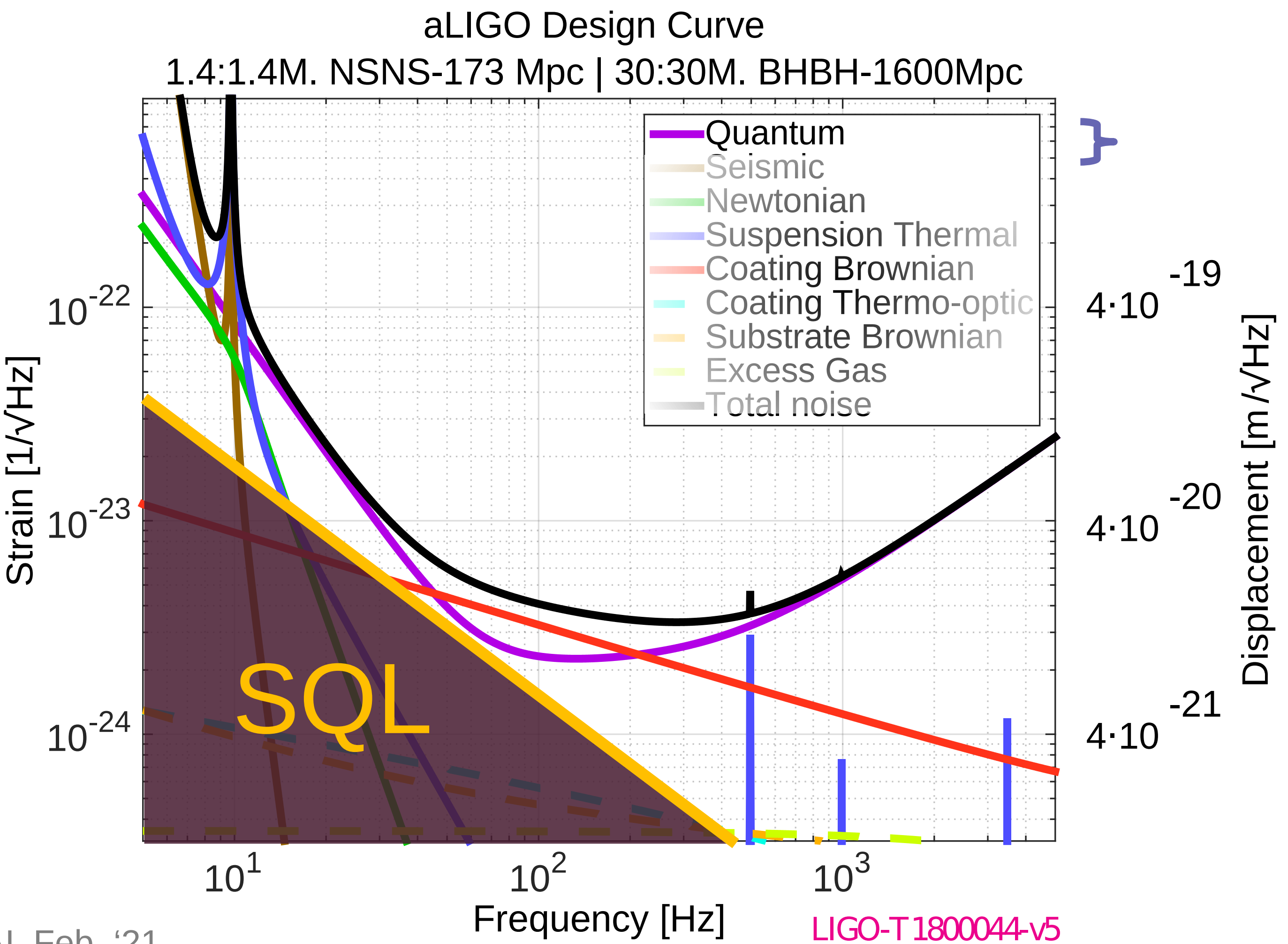
Measurement 2b $\dot{x}(t) \propto \hat{p}$

$$\Delta\hat{x}\Delta\hat{p} \geq \frac{\hbar}{2} \quad \Rightarrow \quad \Delta x_{\text{sys}} = \underbrace{\frac{\hbar}{2\Delta x_{\text{probe}}}}_{\Delta p} \frac{\Delta t}{M}$$

Add system and probe uncertainty, convert to frequency domain

$$\Delta x^2_{\text{meas}}(\Omega) \geq \Delta x^2_{\text{probe}}(\Omega) + \Delta x^2_{\text{sys}}(\Omega)$$

The Standard Quantum Limit



What *is* measurement here?

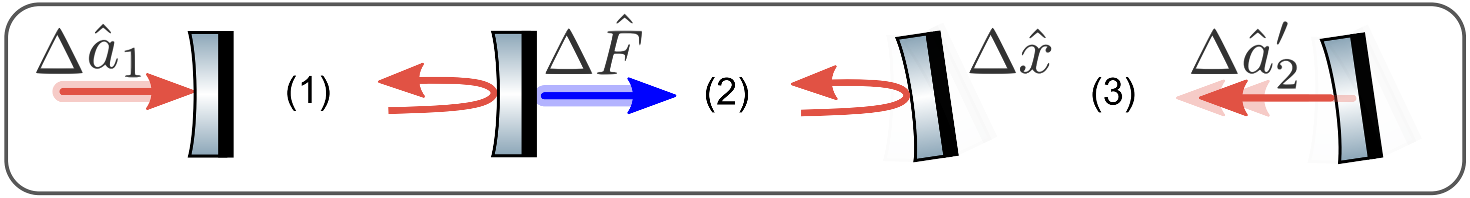
Interferometers measure $\hat{x}$ using optical light.

Light here must be responsible for the noisy consequences of uncertainty + “collapse”

It is the quantization of the optical light that enforces uncertainty for continuous measurement: the <u>Standard Quantum Limit</u>

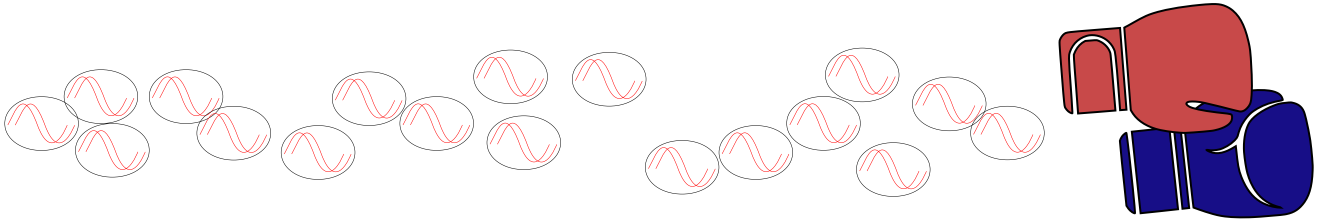
Cartoon: Particle Picture

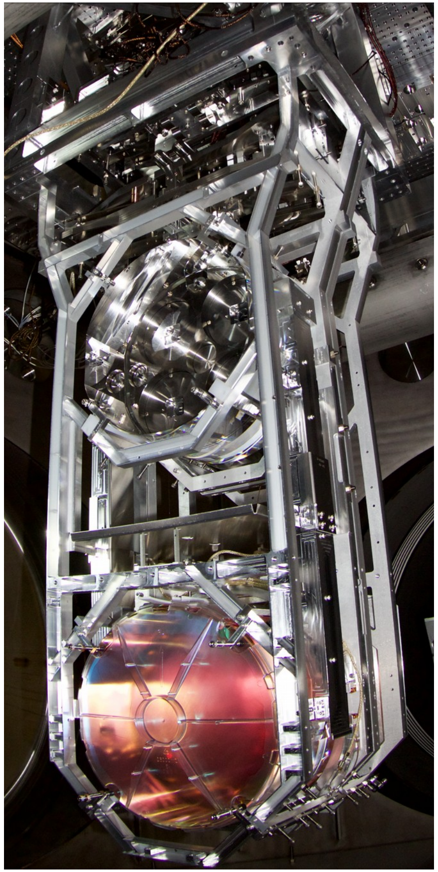
Amplitude → Force → Displacement → Phase:



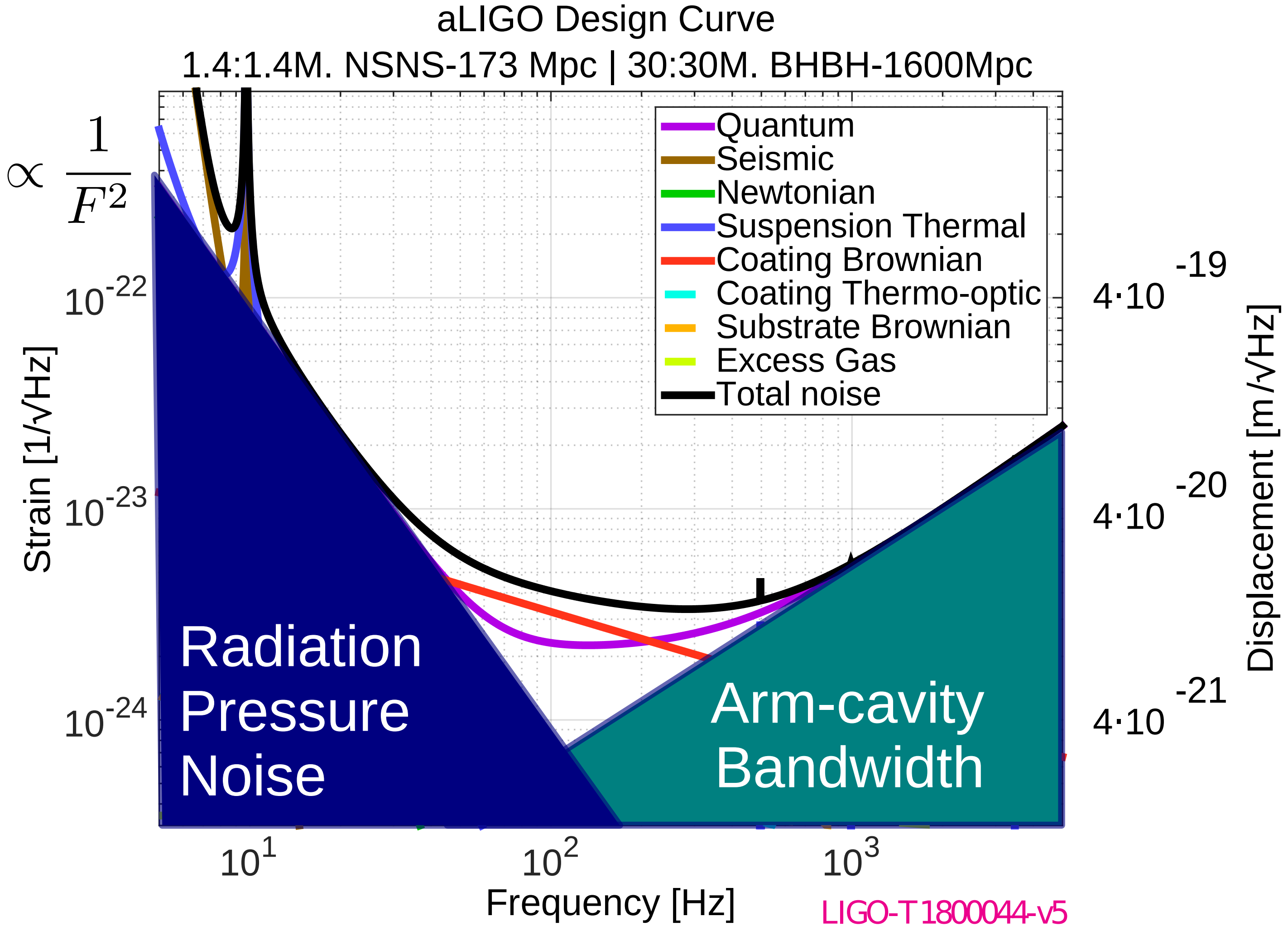
LIGO Mirrors are suspended 40kg glass cylinders

photon shot noise causes *momentum transfer* → femto-N punches



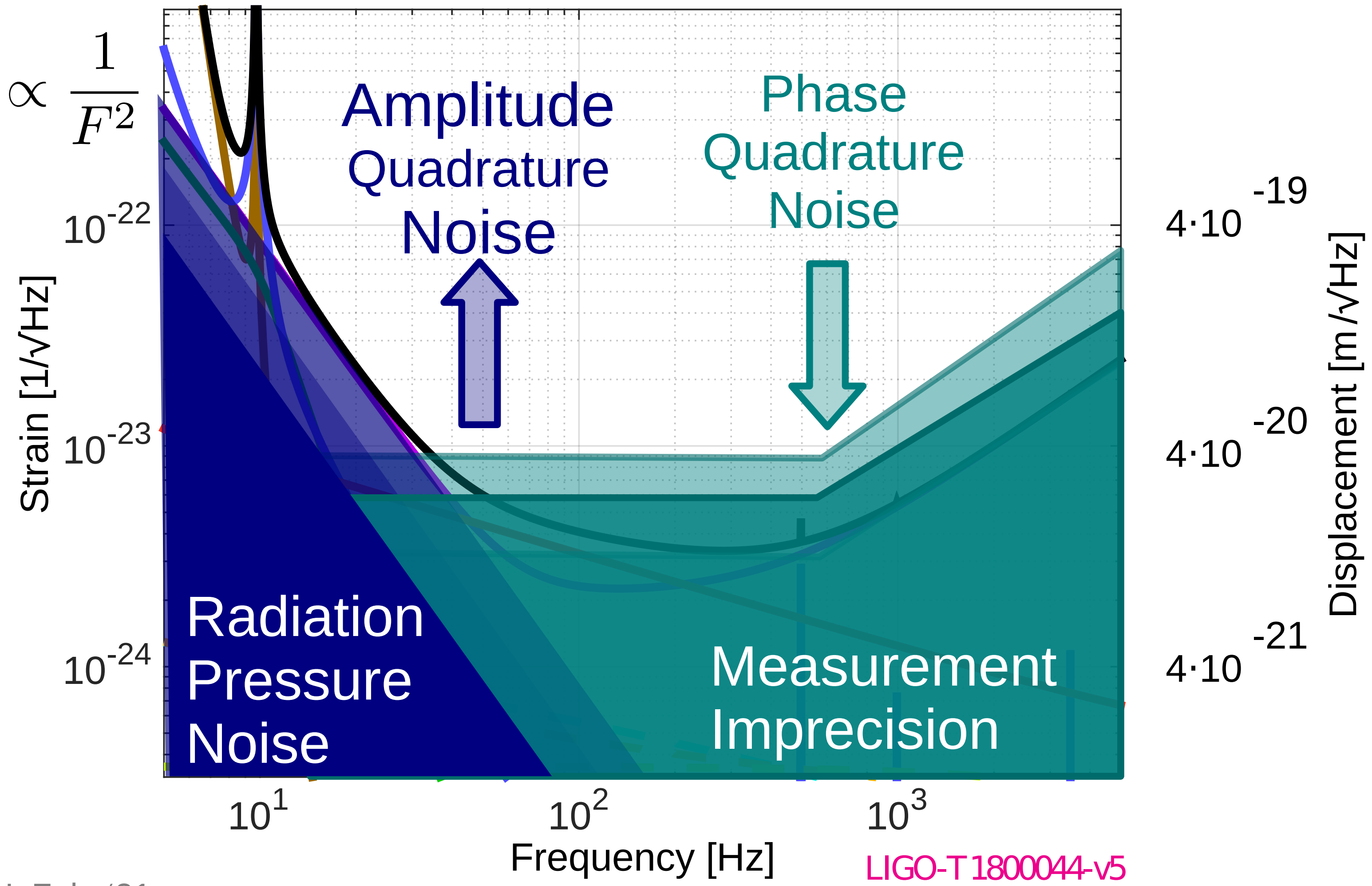


Quantum Noise Contributors



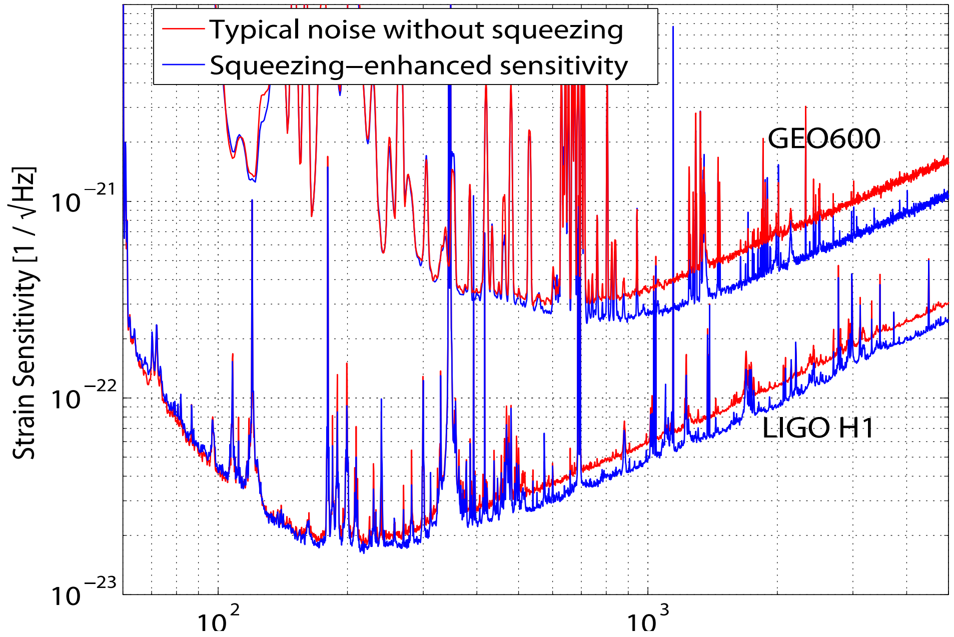
Power Dependence

The cartoon photon picture shows a necessary power dependence
The SQL derivation indicates a *probe-strength* dependence



Measurement and Squeezing in LIGO

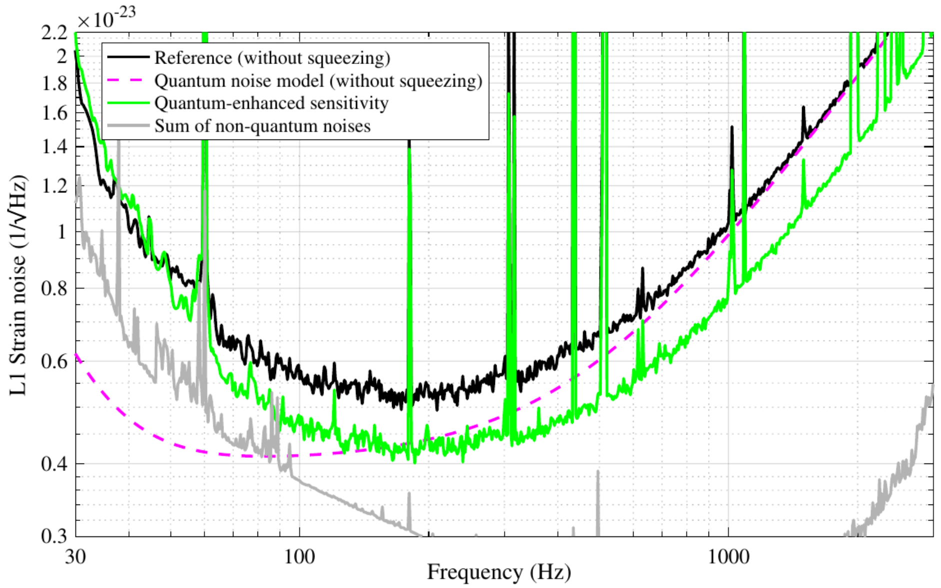
Squeezing's first at-scale demonstrations



Nature Physics 7, 62–965 (2011),
Nature Photonics 7, 613–619 (2013)

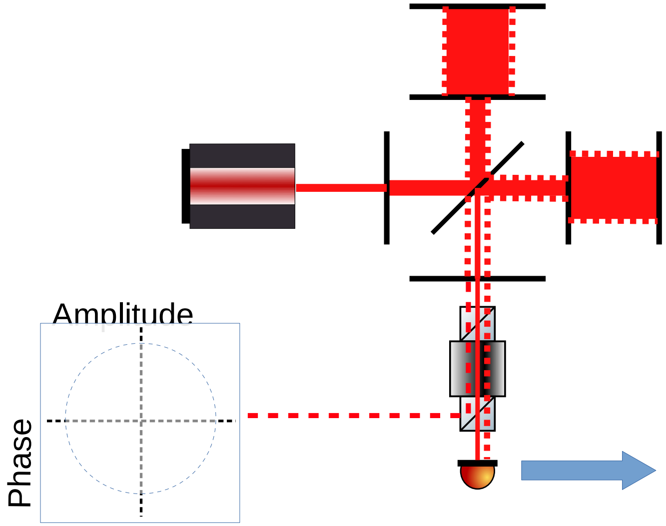
Squeezing in the era of GW discovery

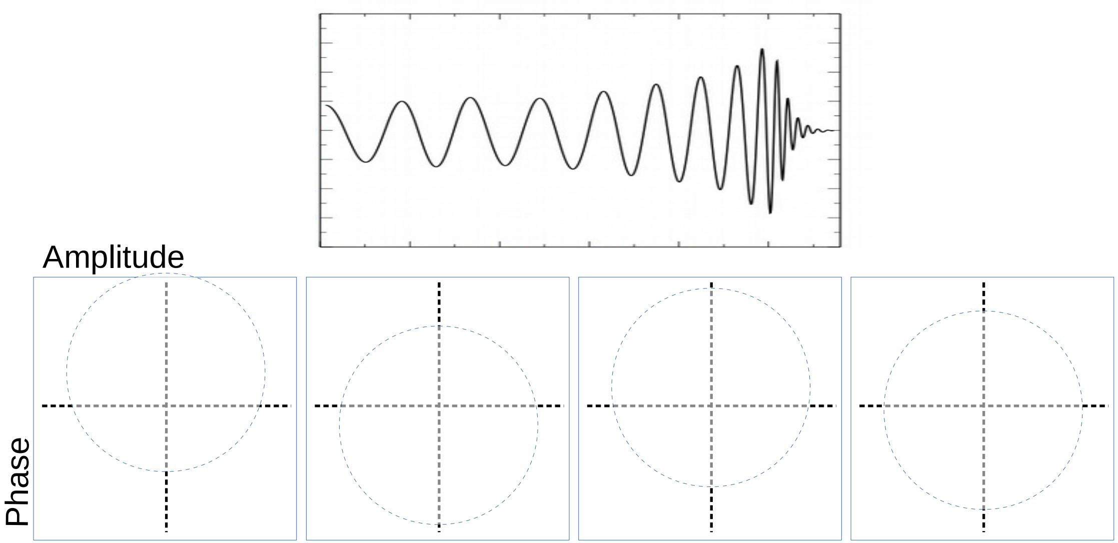
PHYSICAL REVIEW LETTERS **123,** 231107 (2019)



The Measurement Process

- Caves' "Quantum-mechanical Noise in an interferometer," PRD 1981 makes the leap that **the *quantum state* responsible *for noise* is from the *unused port***
- A more modern interpretation is that the interferometer simply applies a displacement operation to its signal state
  - The "default" signal state is vacuum
- What is "a state" here – need sampling definition (will elide, but important)





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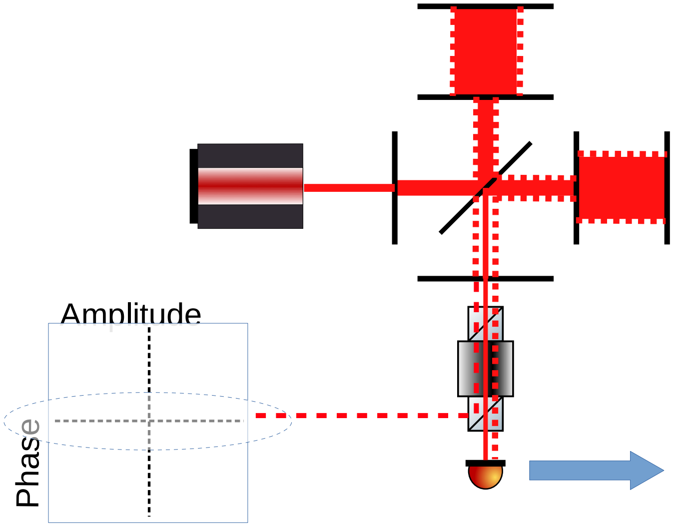
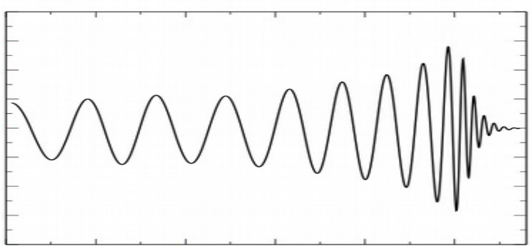
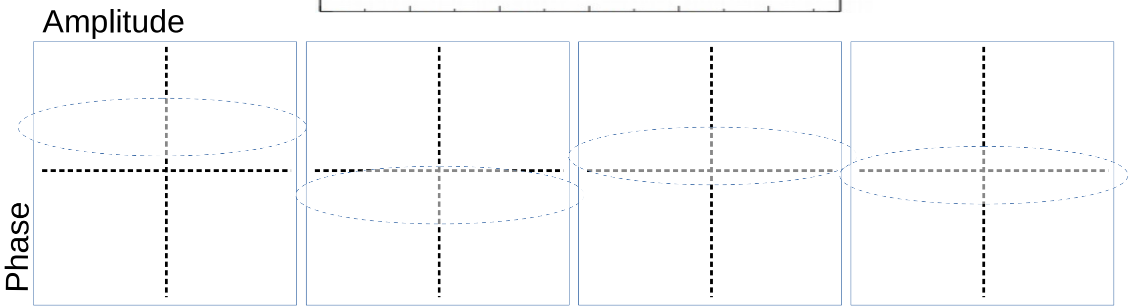


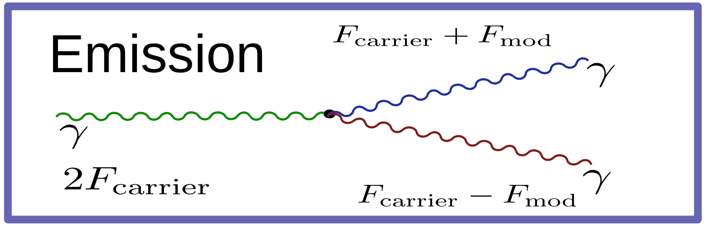


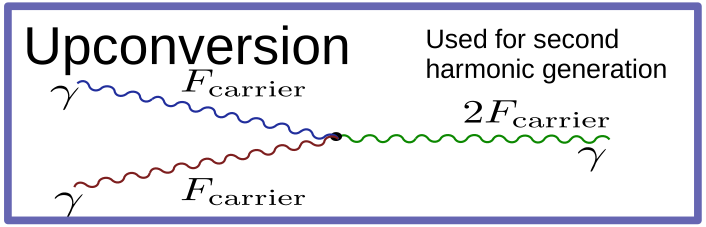


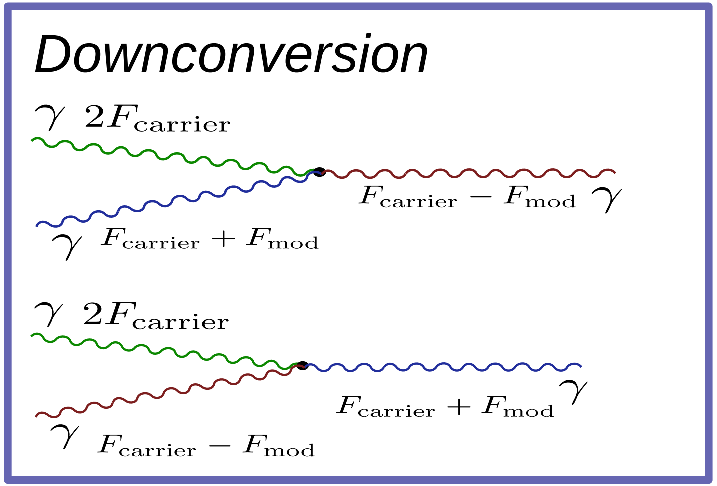
Quantum Process of Squeezing

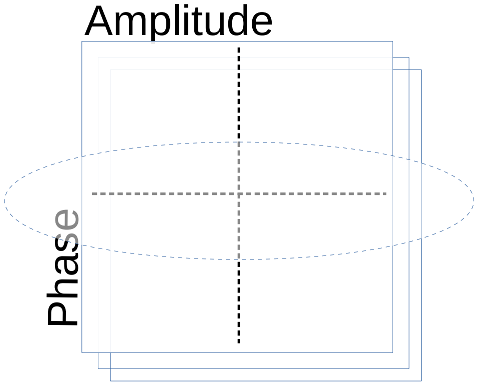
Nonlinear $\chi^{(2)}$ crystal activates a Three-Photon interaction (vertex)

$$\mathcal{H}_{\text{int}} = \kappa b^{\dagger} a a + \text{c.c.}$$









(stacked to represent Phase space at every measurement frequency)

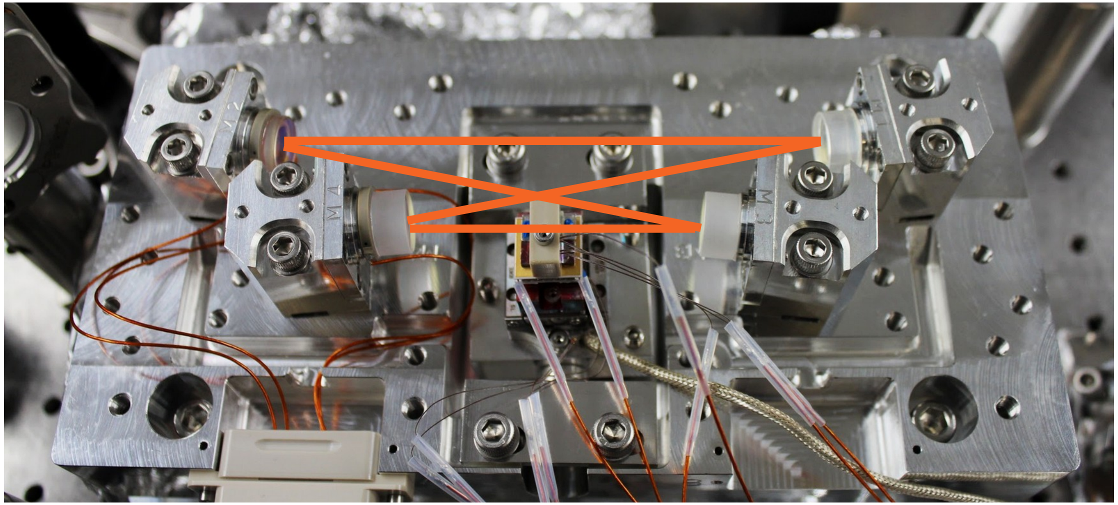
Convert from sideband/ladder operators
To quadrature/Hermitian operators

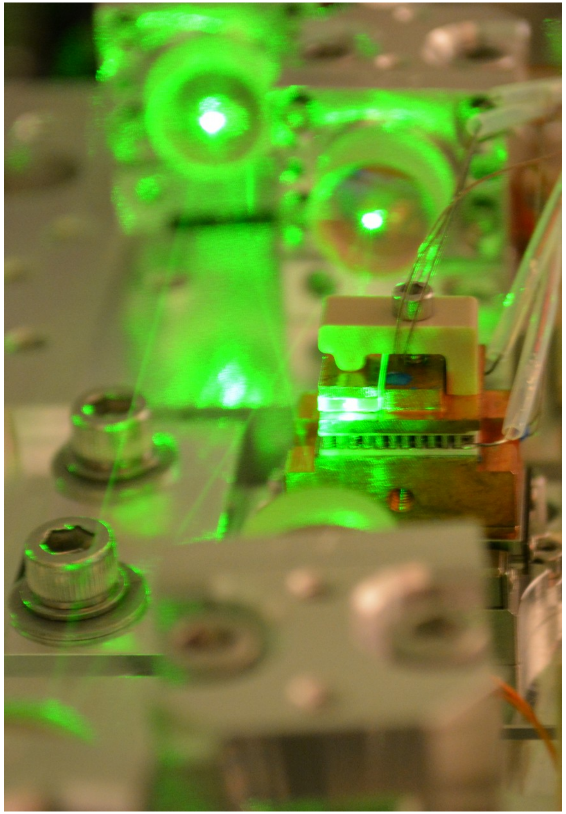
Crystal Optical Parametric Amplifier

nonlinear crystal driven by second harmonic (532nm) + oven + phase control

bowtie cavity

- strengthens interaction
- isolates backscatter





Wade, A. R. et al. Optomechanical design and construction of a vacuum-compatible optical parametric oscillator for generation of squeezed light. *Review of Scientific Instruments 87, 063104 (2016).*

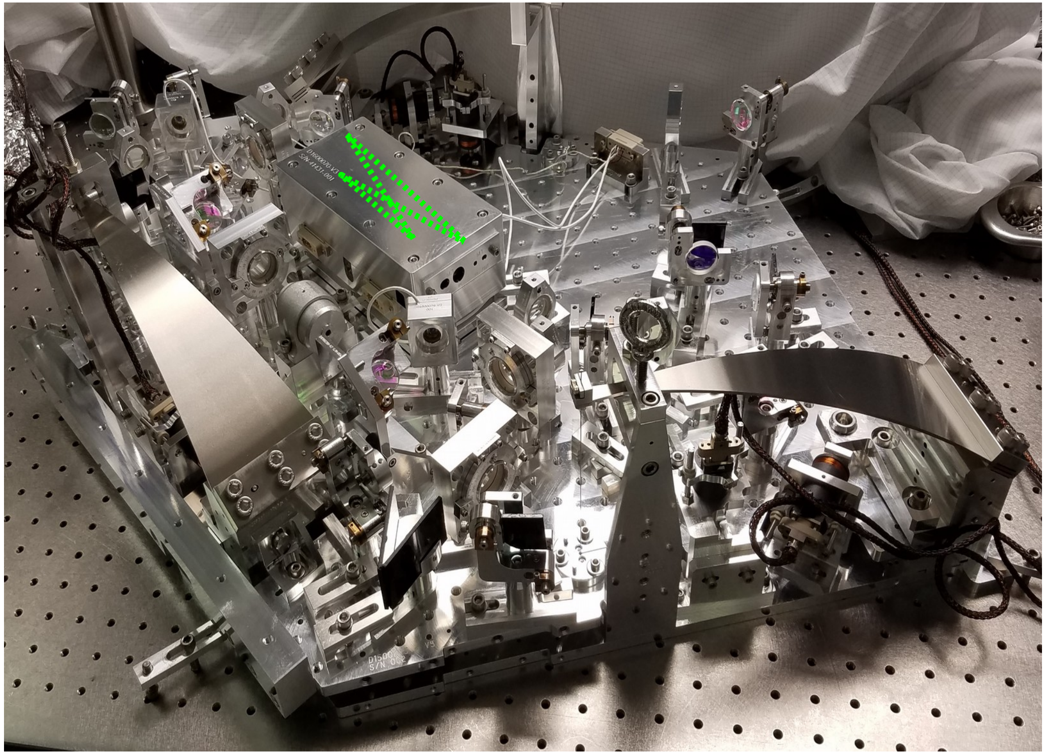
Oelker, E. et al. Ultra-low phase noise squeezed vacuum source for gravitational wave detectors. *Optica, OPTICA 3, 682–685 (2016).*

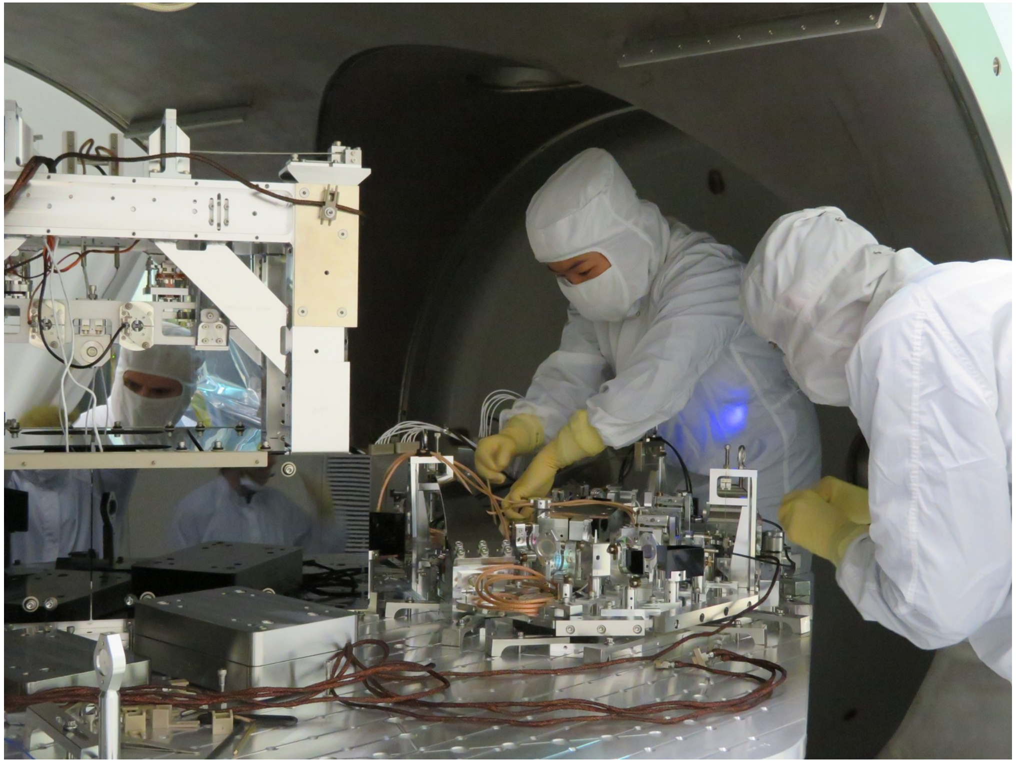
Stefszky, M. et al. An investigation of doubly-resonant optical parametric oscillators and nonlinear crystals for squeezing. *J. Phys. B: At. Mol. Opt. Phys. 44, 015502 (2010).*

The Livingston in-vacuum Platform

Even with a femto-watt of light leaking to the squeezer, you need sub-angstrom noise

The platform is installed on an active inertial In-vacuum optics table, near the readout





above, Maggie Tse operates on the platform

Degradations in Squeezing

Be aware of this distinction:

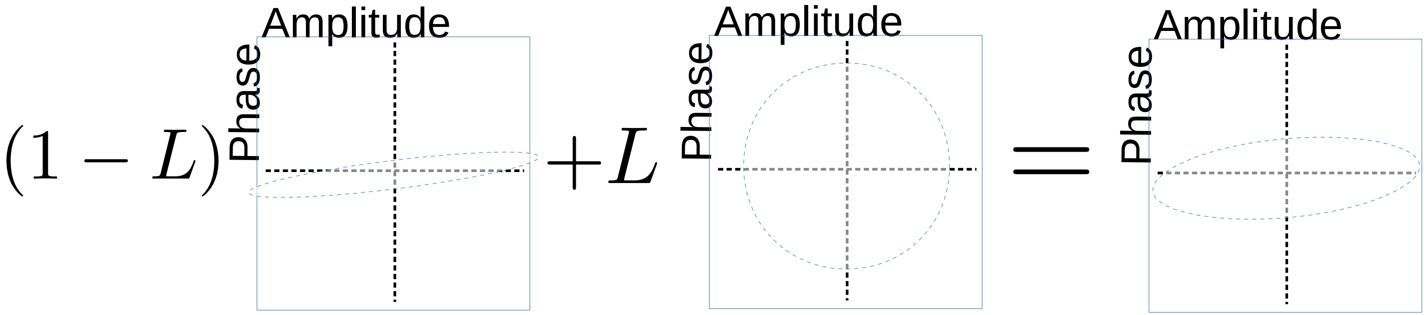
Generated or Injected squeezing

- can be determined from calibration measurements
- Perfect relation between squeezing and antisqueezing (saturates Heisenberg)

Measured squeezing

Measured Antisqueezing

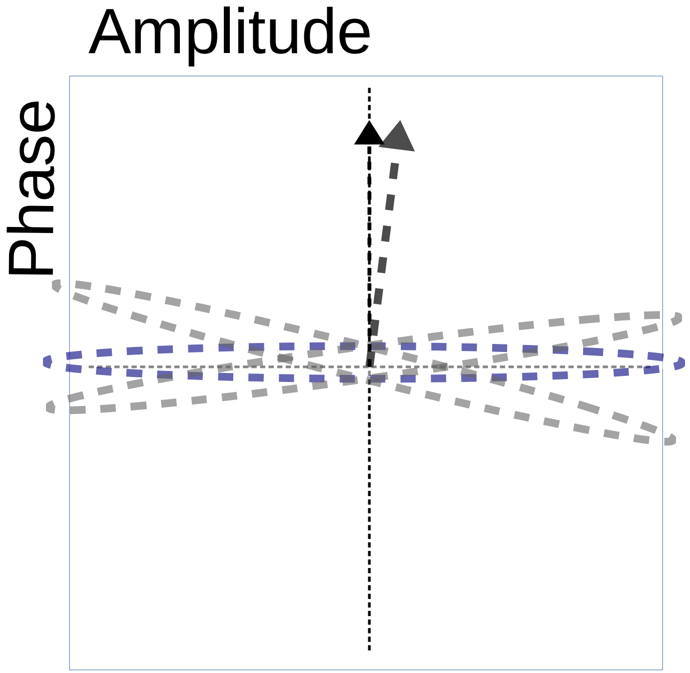
- Degraded by loss and dephasing
- Different effects in each characterizes degradation



$$(1-L)\begin{bmatrix} e^{-2r} & 0 \\ 0 & e^{2r} \end{bmatrix} 2E_\lambda + L \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{\hbar\omega}{2} \xrightarrow{r=\infty} \begin{bmatrix} L & 0 \\ 0 & e^{2r} \end{bmatrix} \frac{\hbar\omega}{2}$$

Phase Noise in Squeezing

- Squeezing Follows independent path
- Fluctuations rotate noise matrix
- Quadratic Effect, but significant at large squeezing



$$\Xi = E\left[\sin^2(\hat{\theta})\right] \qquad 0 \leq \Xi \leq \frac{1}{2}$$

$$(1-\Xi)\begin{bmatrix} e^{-2r} & 0 \\ 0 & e^{2r} \end{bmatrix}\frac{\hbar\omega}{2} + \Xi\begin{bmatrix} e^{2r} & 0 \\ 0 & e^{-2r} \end{bmatrix}\frac{\hbar\omega}{2}$$

Technical Limits of Squeezing

- Phase noise implies point of optimal generated squeezing
- also point of maximum observable squeezing
- In the limit
  - Low phase noise
  - low loss

$$\theta_{\mathrm{rms}} = \sqrt{\Xi} \ll 0.5$$

$$L \ll 1$$

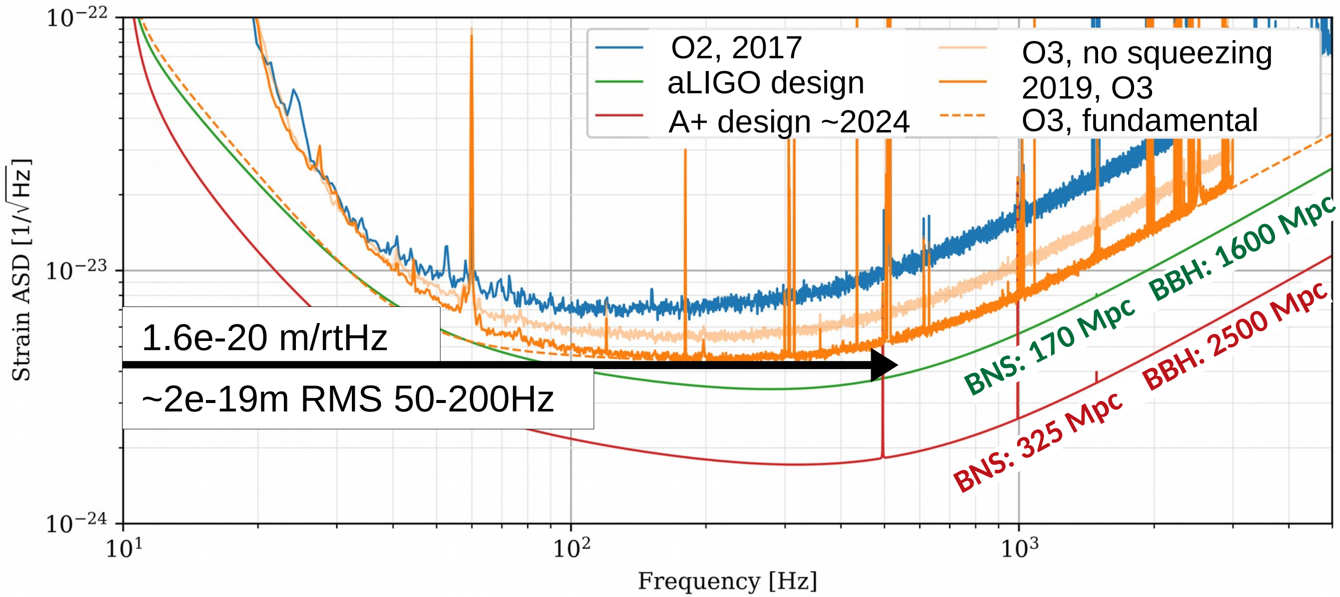
Best Shot noise reduction is: [db]

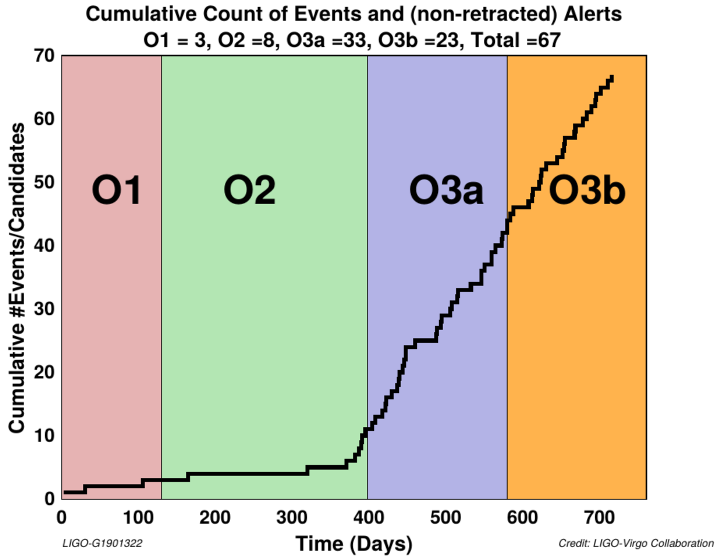
$$10\mathrm{Log}_{10}(2\theta_{\mathrm{rms}} + L)$$

Squeezing in Observing Run 3

- O3 saw *many improvements:*
  Power level, scatter, duty cycle, *grounding*, laser noises, angular and auxiliary control, glitch and data analysis
- The detectors have become *impressively* quantum limited: 120Mpc
- Enter Squeezing, 3db @ ~30% losses 120 → 140MPc
  → 50% rate increase on top of everything else

Buikema, A. et al.
Sensitivity and performance of the Advanced LIGO detectors in the third observing run.
Phys. Rev. D 102, 062003 (2020).

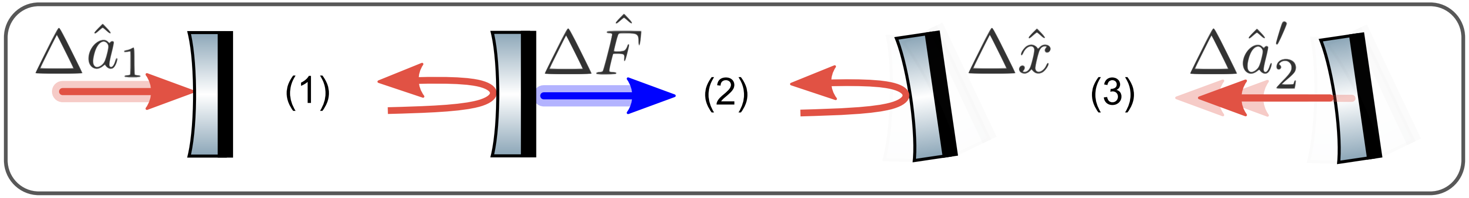




Reference Curves LIGO T1800042-v5 Rates: LIGO-VIRGO Collab. G1901322

Cartoon: “Wave” Picture

Amplitude → Force → Displacement → Phase:

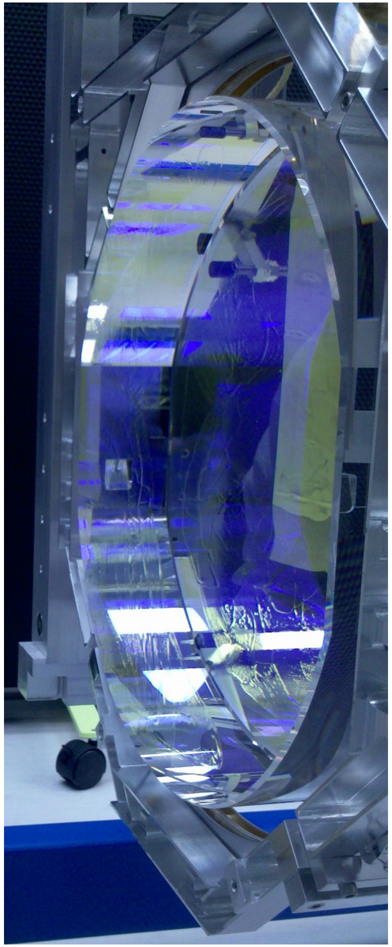


Mechanics cause a shear action on the optical phase-space

Due to radiation pressure & mechanical susceptibility

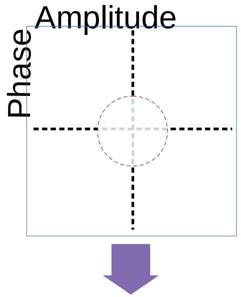
$$\begin{bmatrix}\Delta\hat{a}_1' \\ \Delta\hat{a}_2'\end{bmatrix} = \begin{bmatrix}1 & 0 \\ -\mathcal{K}(F) & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{a}_1 \\ \Delta\hat{a}_2\end{bmatrix}$$

Shear = rotation * squeezing * rotation

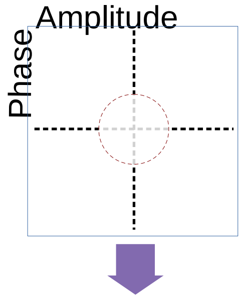


Standard Quantum Limit, optics picture

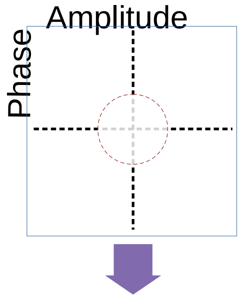
$F \ll 60\text{Hz}^*$



$F = 60\text{Hz}^*$

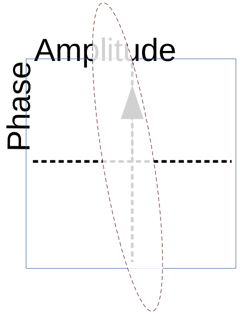


$F \gg 60\text{Hz}^*$

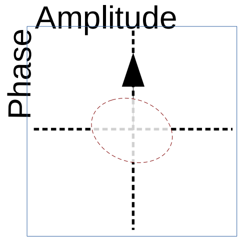


Amplitude → Force → Displacement → Phase:
Phase-space Shear

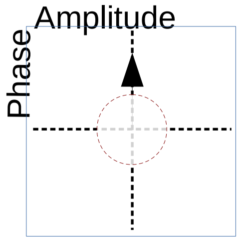
$$\begin{bmatrix}\Delta\hat{a}'_1\\ \Delta\hat{a}'_2\end{bmatrix} = \begin{bmatrix}1 & 0\\ -\mathcal{K}(F) & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{a}_1\\ \Delta\hat{a}_2\end{bmatrix}$$



$\mathcal{K} \gg 1$



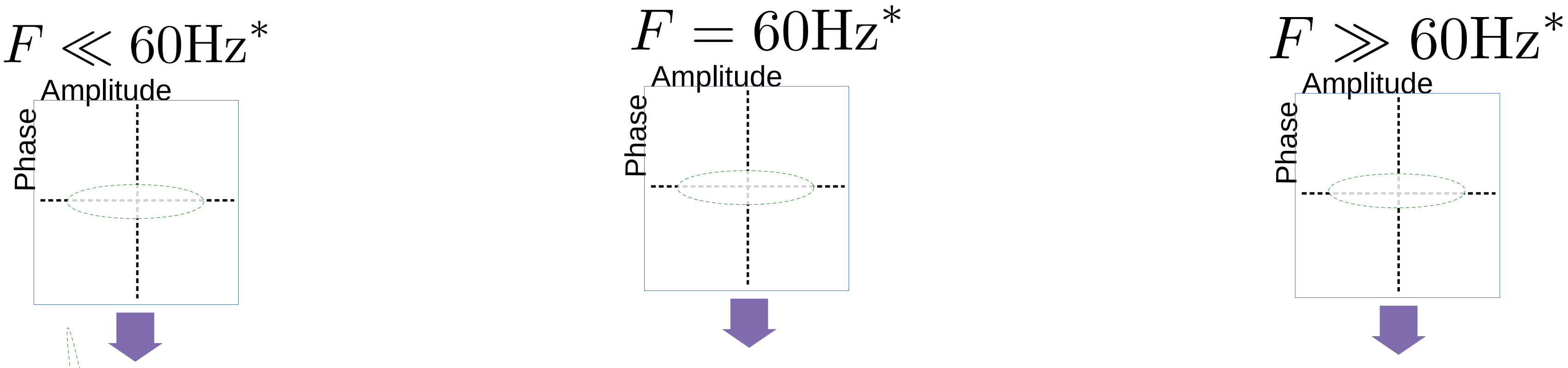
$\mathcal{K} \approx 1$



$\mathcal{K} \ll 1$

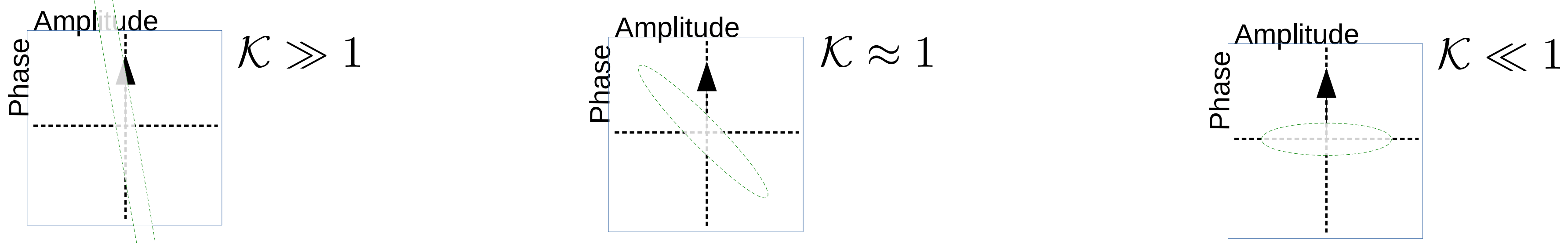
* ~60Hz is approximate crossover only in aLIGO full power design

Squeezing Probes Harder



Amplitude → Force → Displacement → Phase:
Phase-space Shear

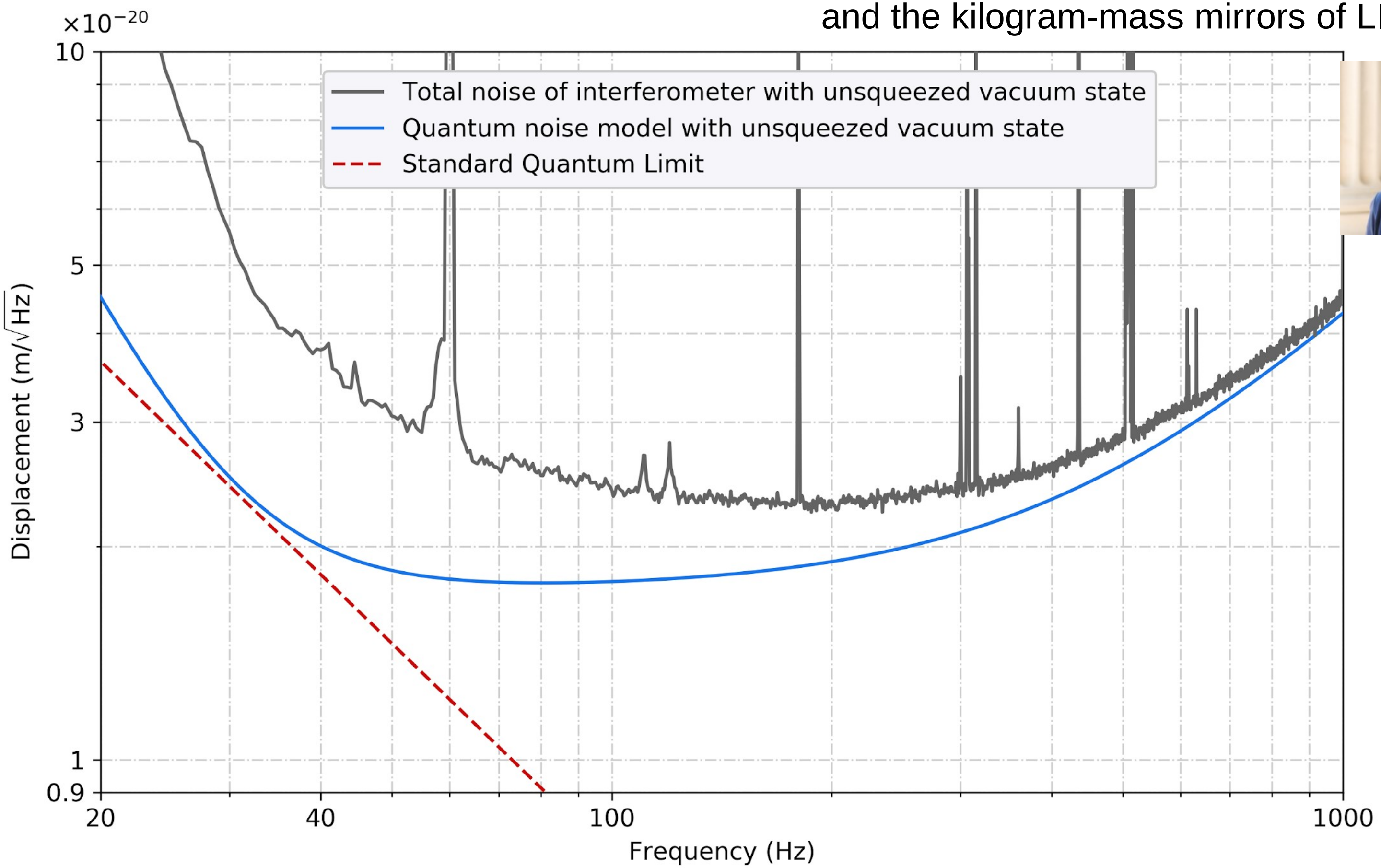
$$\begin{bmatrix}\Delta\hat{a}'_1\\ \Delta\hat{a}'_2\end{bmatrix} = \begin{bmatrix}1 & 0\\ -\mathcal{K}(F) & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{a}_1\\ \Delta\hat{a}_2\end{bmatrix}$$



* ~60Hz is approximate crossover only in aLIGO full power design

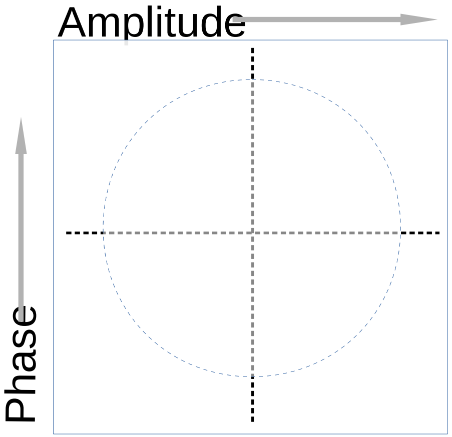
Testing the SQL

Haocun Yu. McCuller, L. et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).



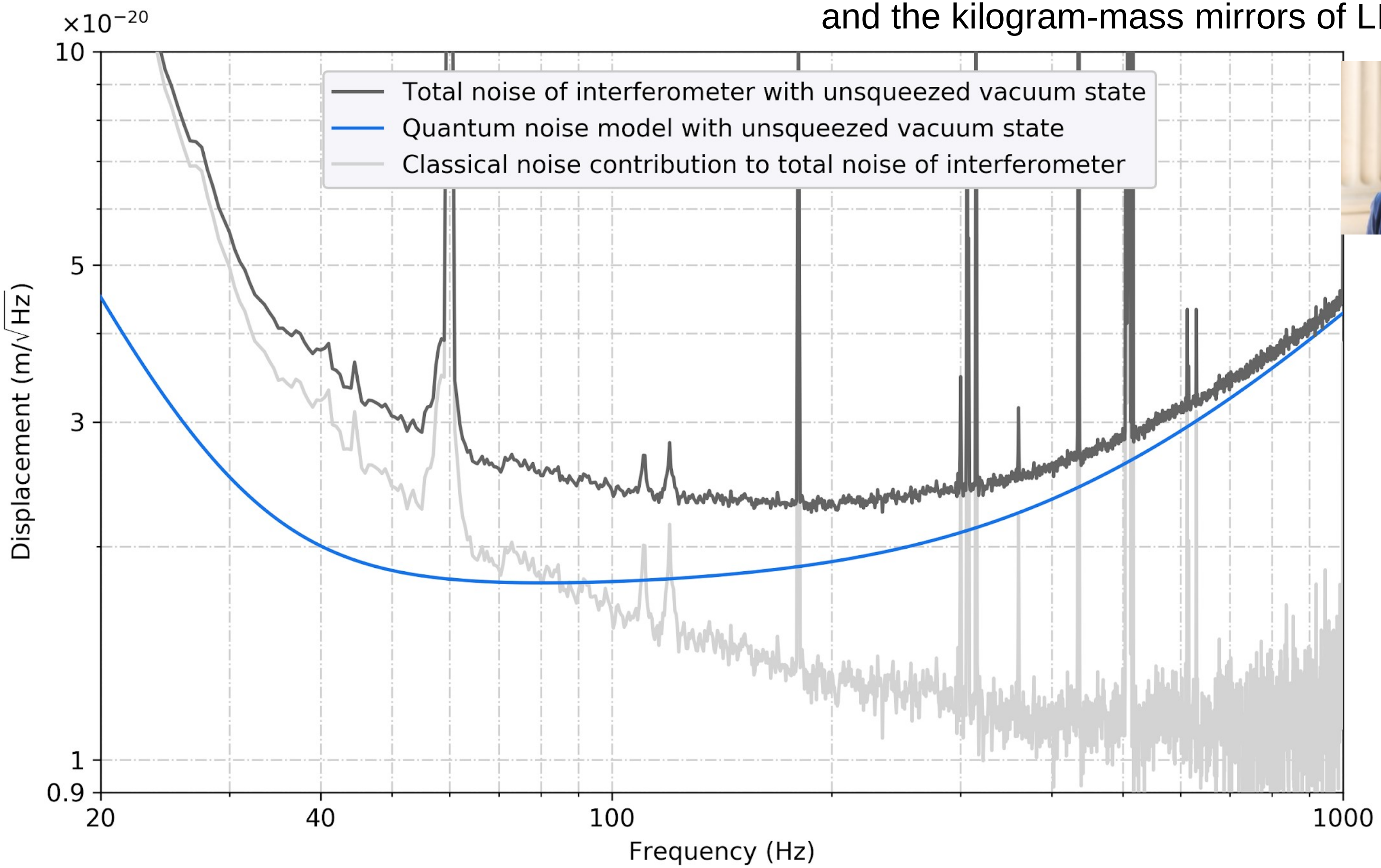
Left: measurements performed by Haocun Yu

No injected squeezing



Determine Instrument Noise

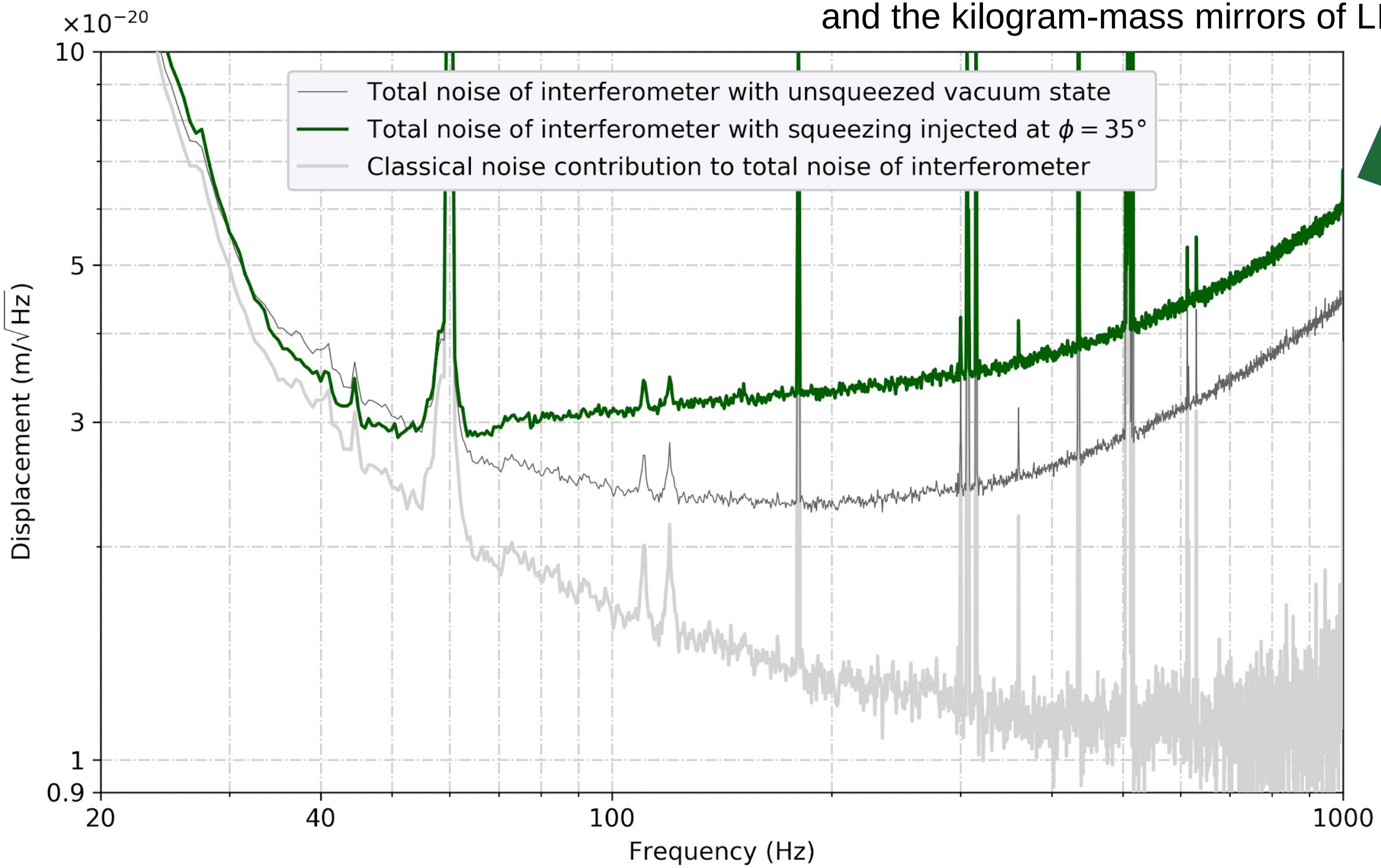
Haocun Yu. McCuller, L. et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).



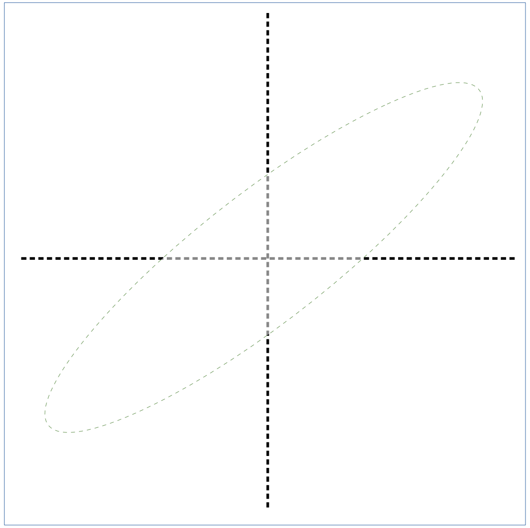
Left: measurements performed by Haocun Yu

Inject Squeezing at an Angle

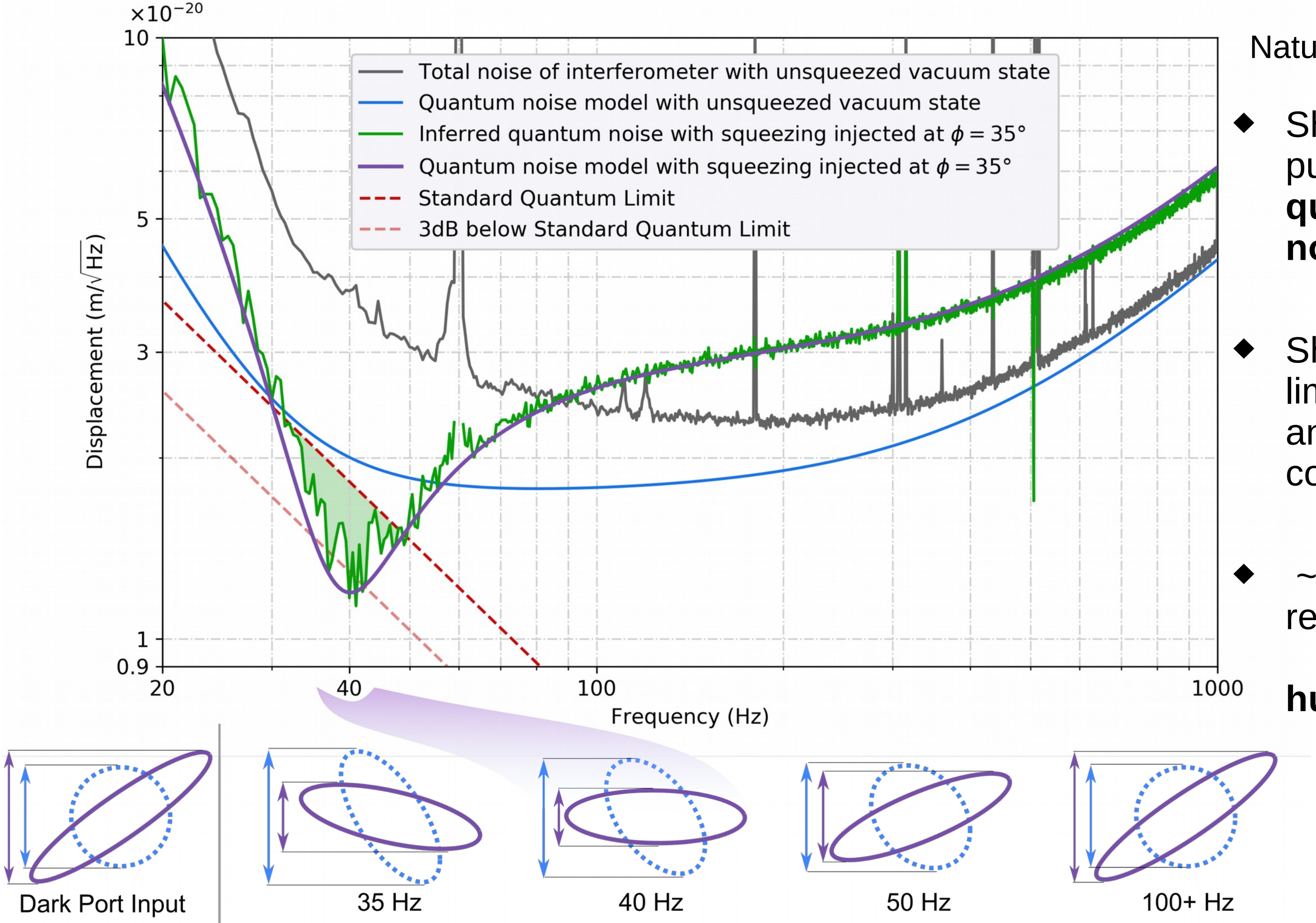
Haocun Yu. McCuller, L. et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).



Squeezing
at 33deg injected



Sub-SQL Quantum Noise in 40kg



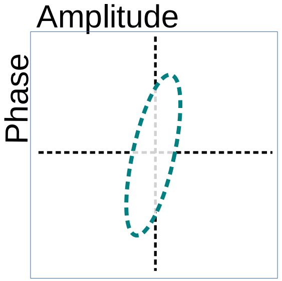
Nature 583, 43–47 (2020).

- Shows that the vacuum indeed pushes the mirrors: **quantum radiation pressure noise**
- Shows that the SQL is not a limit → mirror motion creates and maintains quantum correlations
- ~billion-times heavier than recent sub-SQL measurements,

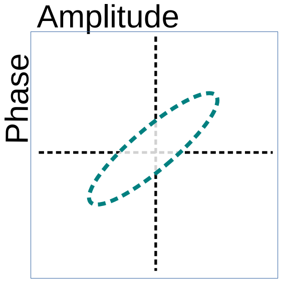
human scale! Room temp.!

But I want more Squeezing *and* more Astrophysics

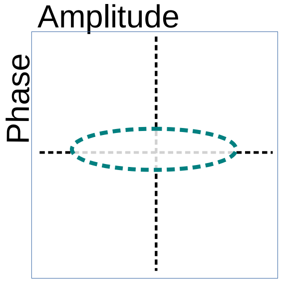
$F \ll 60\text{Hz}^*$



$F = 60\text{Hz}^*$

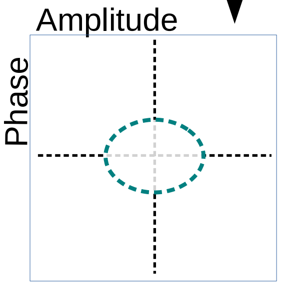


$F \gg 60\text{Hz}^*$

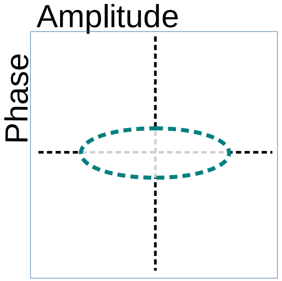


merely unsqueezes

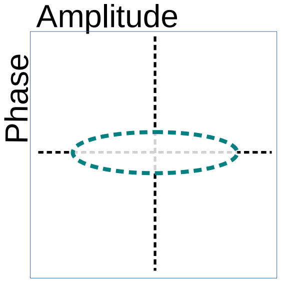
Frequency Dependent Squeezing



$\mathcal{K} \gg 1$



$\mathcal{K} \approx 1$



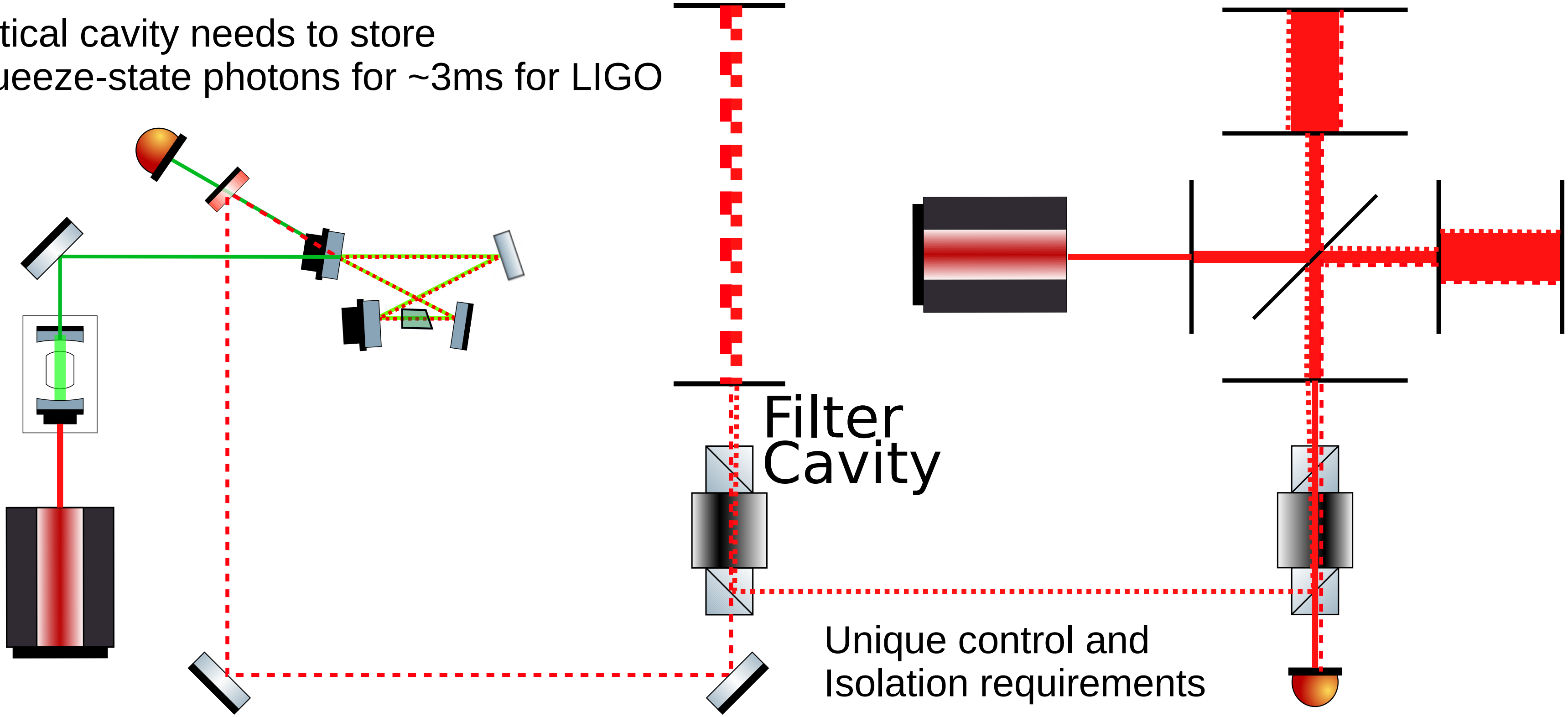
$\mathcal{K} \ll 1$

Quantum Filter Cavity

McCuller, L. et al. Frequency-Dependent Squeezing for Advanced LIGO. Phys. Rev. Lett. 124, 171102 (2020).

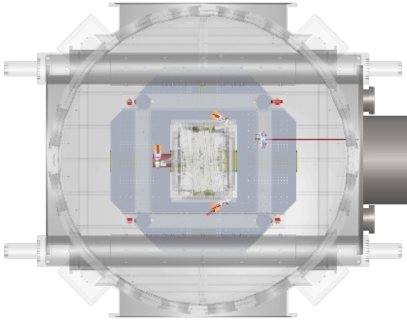
Zhao, Y. et al. Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors. Phys. Rev. Lett. 124, 171101 (2020).

Optical cavity needs to store squeeze-state photons for ~3ms for LIGO

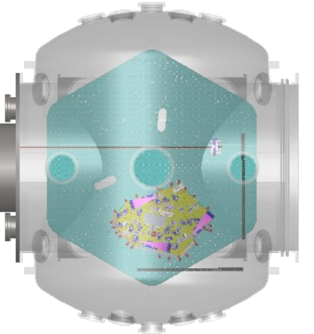


Unique control and Isolation requirements

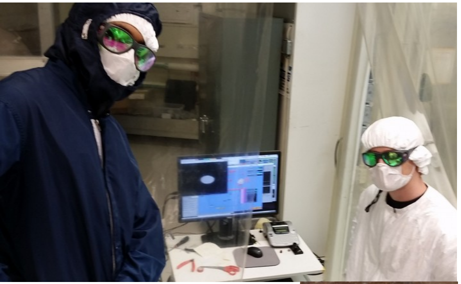
MIT 16m Filter Cavity



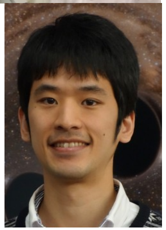
Finesse 80,000 → ~100Hz linewidth → photons travel ~1000km

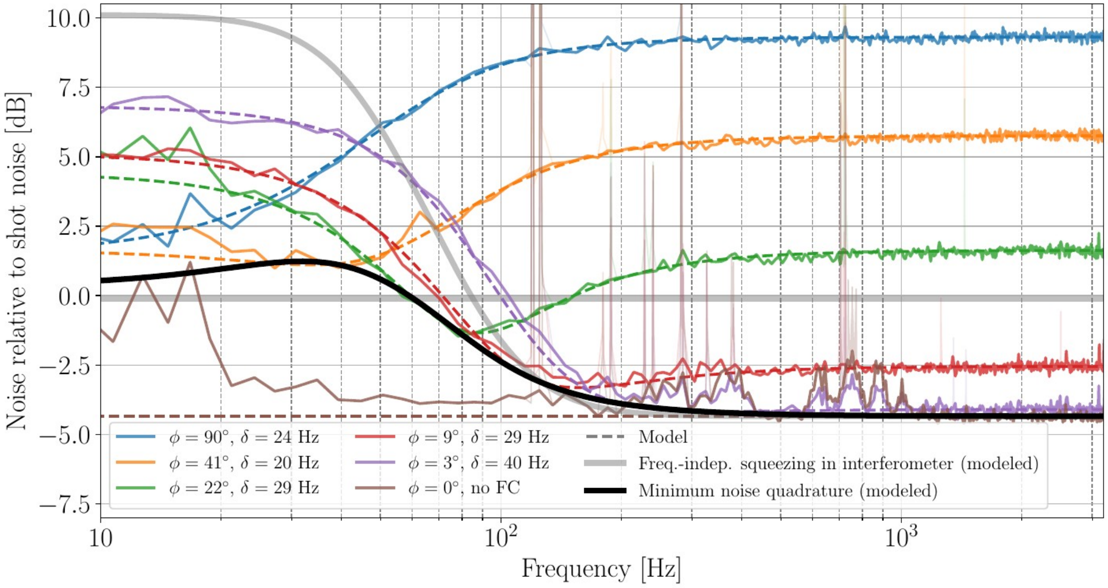


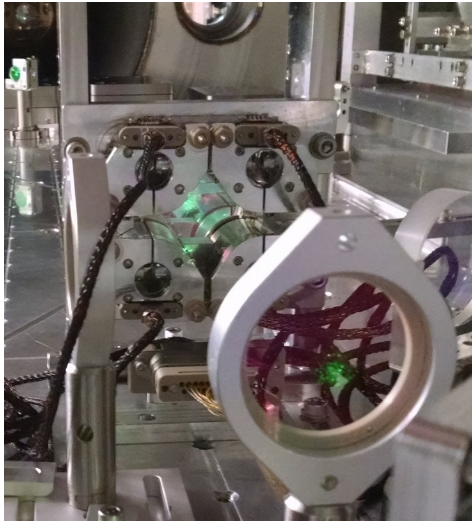
McCuller, L. et al. Frequency-Dependent Squeezing for Advanced LIGO.
Phys. Rev. Lett. 124, 171102 (2020).



Chris Whittle,
Dhruva Ganapathy
and
Kentaro Komori

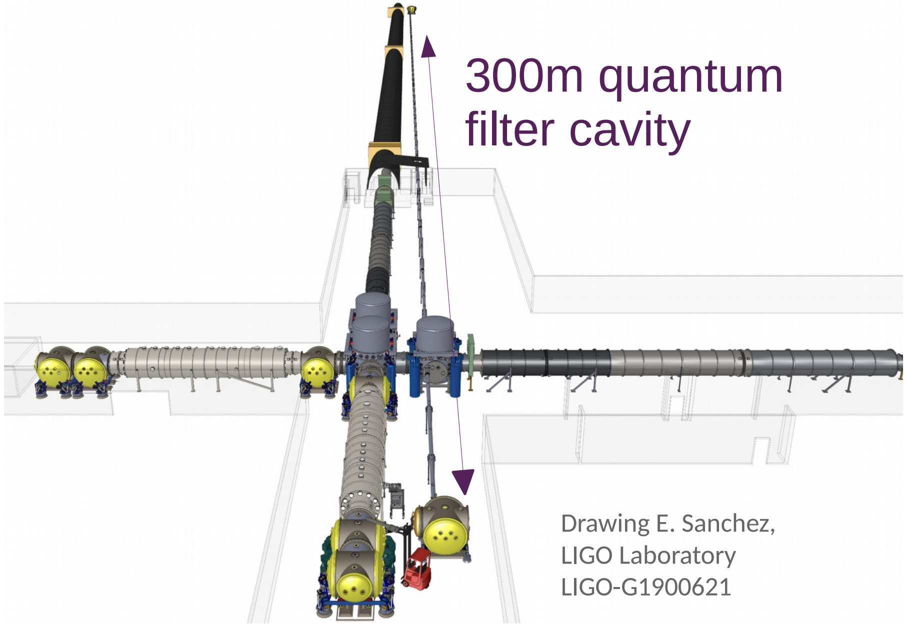


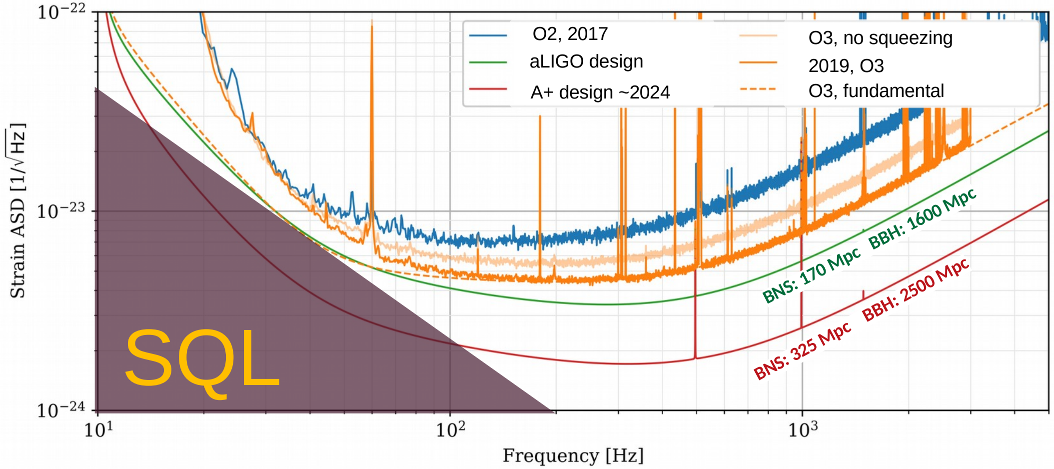




The A+ Upgrade

- 6db of frequency-dependent squeezing
  - Early install, aiming at 4.5db in Run 4
  - Sub-SQL during observations!
- 2x improved coating thermal noise
  - Still researching, but good leads
- Active wavefront control
  - Lowers squeezing loss
- Balanced homodyne readout
  - Multiple benefits
- Bigger Beamsplitter



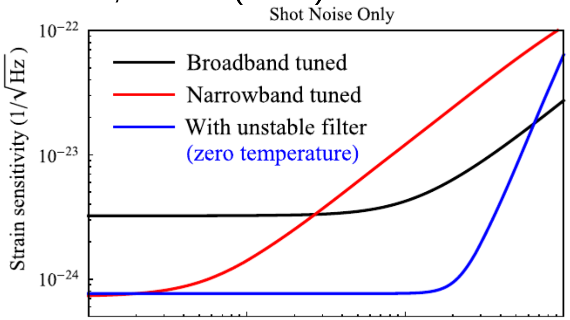


Reference Curves LIGO T1800042-v5

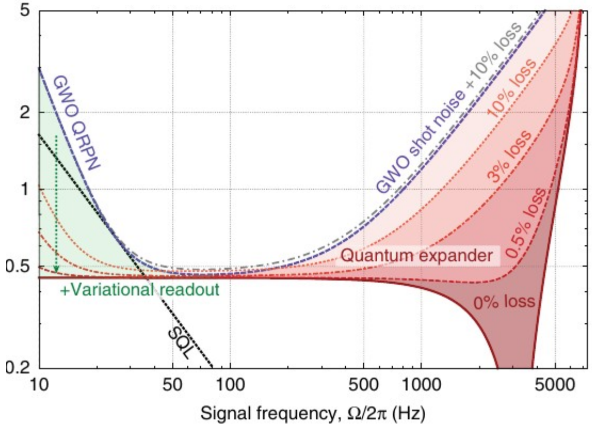
Quantum Physics for Fundamental Physics

- Now solidly in the NISQ-era of quantum metrology
  - Squeezed states are Gaussian states
  - Limited by loss: $10\mathrm{Log}_{10}(2\theta_{\mathrm{rms}} + L)$
- Can we do better?

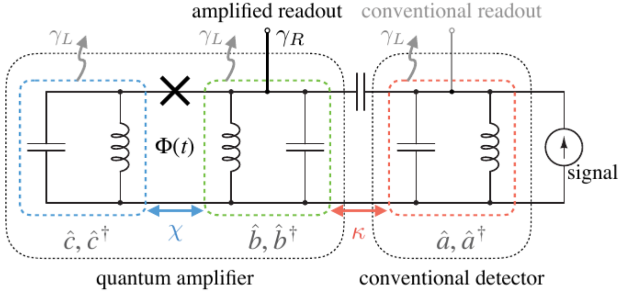
Unstable Cavities
PRL 115, 211104(2015)



Intracavity Squeezing
(quantum expanders)
Korobko et al.
Light: Science & Applications (2019)



GW and axion
PT-symmetric
unstable cavity
realizations:
arXiv:2012.00836



nonGaussian states...?!

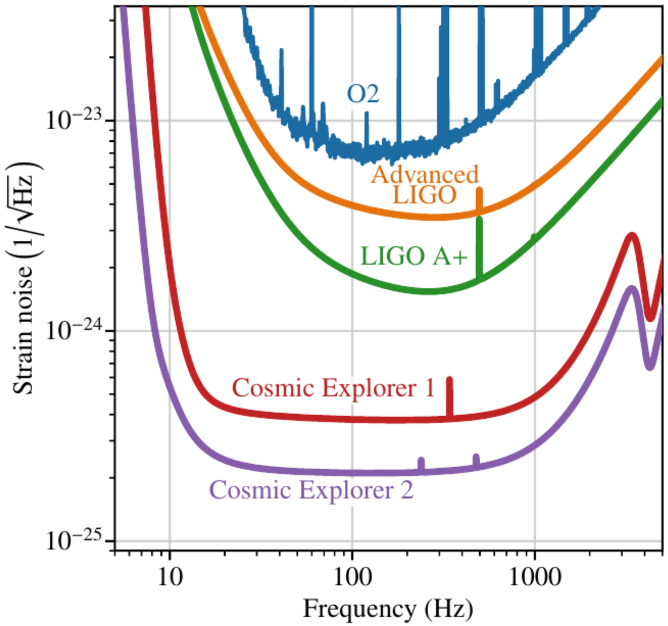
the Third Generation of Detectors

- Cosmic Explorer (US) and Einstein Telescope (EU)
  - 10-40km observatories
    (conceptual designs)
  - 10x more optical power
  - <u>10db squeezing</u>
  - Larger suspensions
  - Lower frequencies

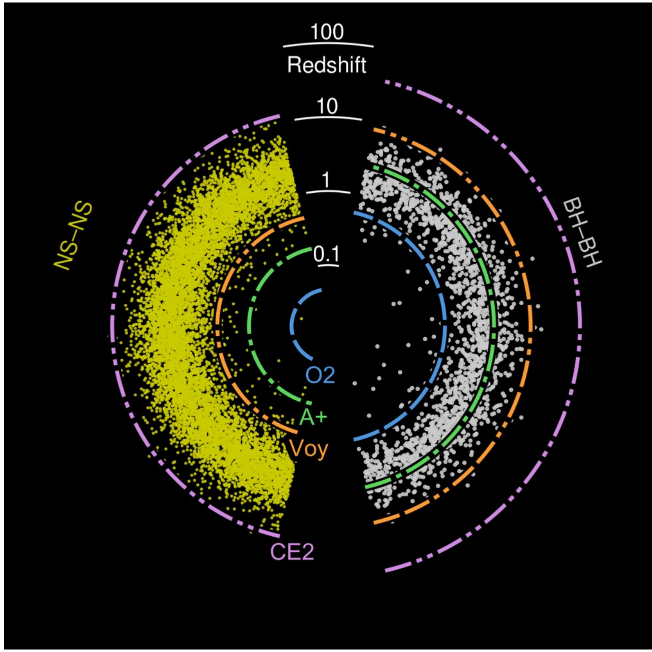
Join the consortium

https://cosmicexplorer.org/

1903.04615



See nearly all binary neutron star events (left) and see black hole events to before BH's exist



E. Hall/S. Vitale

- Probe cosmological history of gravitational-wave astronomy
  - High event rates – far detections
  - Extreme signal-to-noise – near detections

- What will the landscape be for multi-messenger observatories and complementarities?

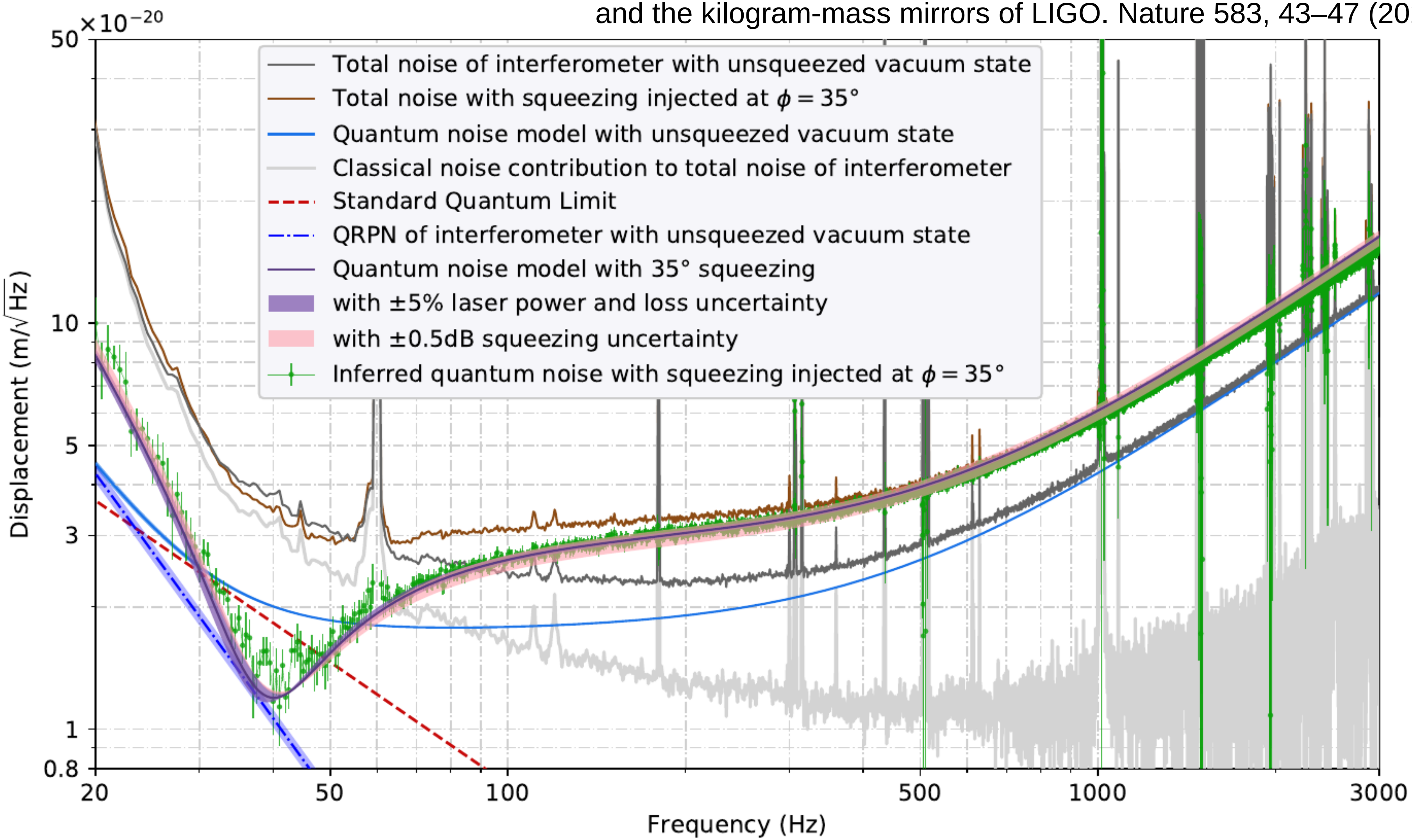
Thank You

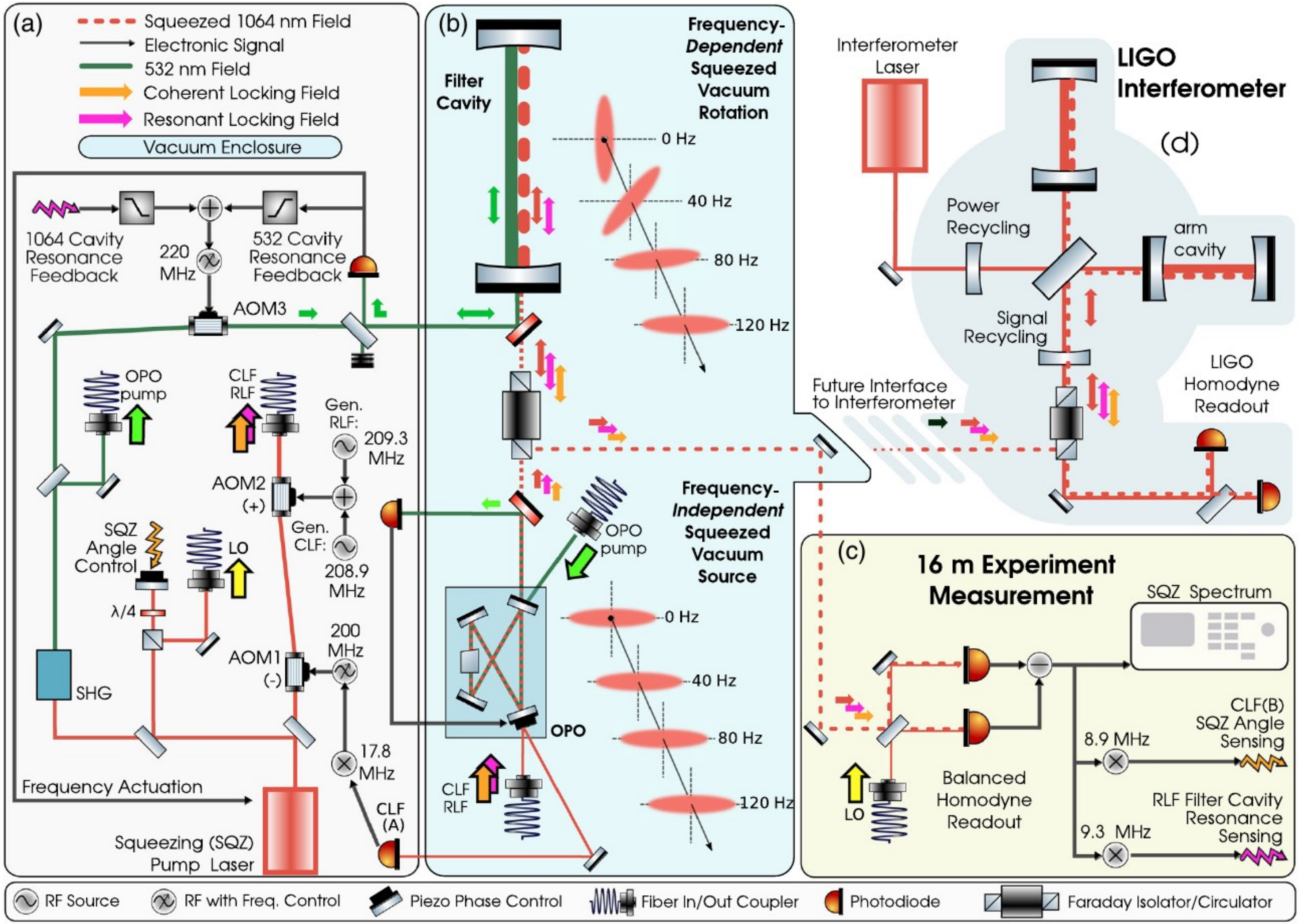
- LIGO, VIRGO, and GEO600 are now all *quantum-enhanced* in the *GW detection era*
- 40kg testmasses are quantum objects at 300K
  - The vacuum pushes mirrors → radiation pressure noise
  - this causes the *Standard Quantum Limit*
  - Not a limit when squeezing due to *quantum correlations*
- The A+ upgrades will improve the LIGO detectors ~8x in rate
  - Sub-SQL observations using frequency-dependent squeezing
  - separately demonstrated both of the necessary experimental components
  - Actively installing *now* for O4

(a personal proud moment)

solving SQZ laser amplitude and phase noise excess at 600kHz.
400ns of cable
RF skills I developed at FNALE990

Haocun Yu. McCuller, L. et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).





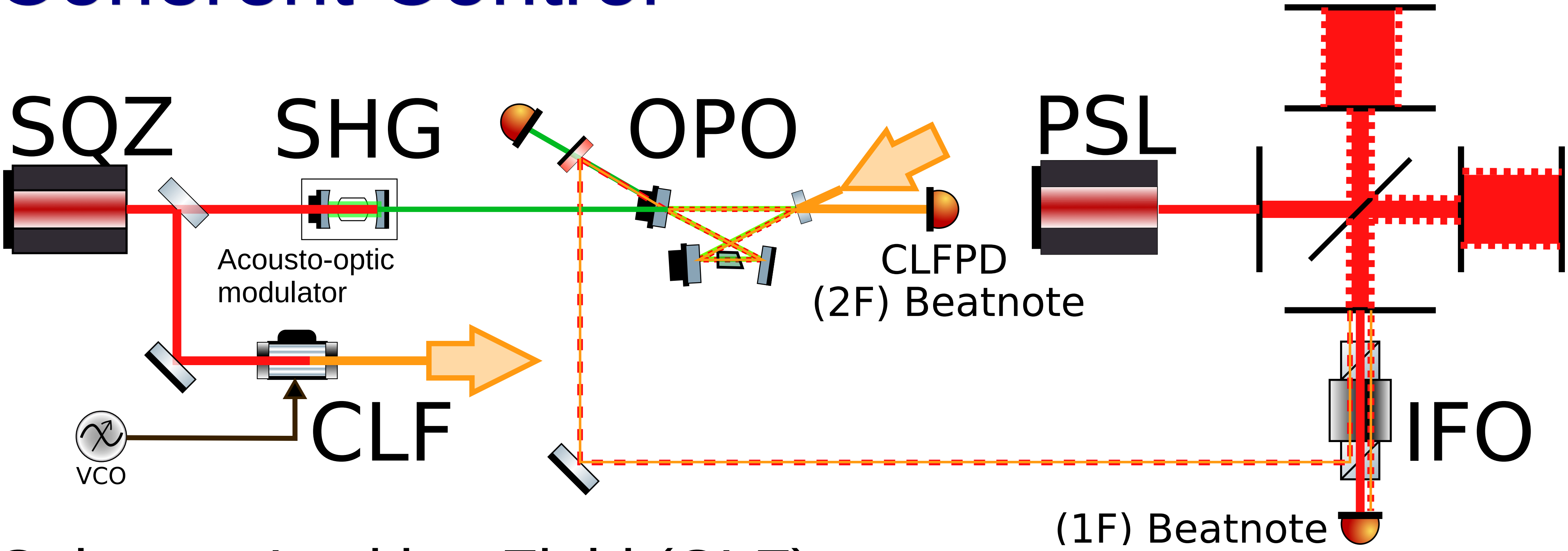
McCuller, L. et al. Frequency-Dependent Squeezing for Advanced LIGO. Phys. Rev. Lett. 124, 171102 (2020).

LIGO Scientific Collaboration

Caltech
Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut
American University Washington, DC
Andrews University
Bar-Ilan University
Bard College
Bellevue College
California State University Fullerton
Cal State LA
Carleton College
MIT
Christopher Newport University
Colorado State University
Columbia University in the City of New York
Concordia University Wisconsin
Cornell University
Embry-Riddle Aeronautical University
Georgia Tech
NASA Goddard Space Flight Center
INPE
Haverford College
Hillsdale College
Hobart & William Smith Colleges
International Institute of Physics
LSU Louisiana State University
Maastricht University
Marquette University Be The Difference.
NASA Marshall Space Flight Center
Missouri S&T
Montana State University
Montclair State University
Lomonosov Moscow State University
Northwestern
PennState
RIT
Sonoma State University
Flatiron Institute Center for Computational Astrophysics
Syracuse University
Science & Technology Facilities Council Rutherford Appleton Laboratory
King's College London
Southern University and Agricultural & Mechanical College
Stanford University
Stony Brook University
University of the West of Scotland UWS
University of Birmingham
Cardiff University Prifysgol Caerdydd
Australian National University
Charles Sturt University
Monash University
Texas Tech University
Texas A&M
Polytechnique Montréal
The University of Arizona
University of Arkansas
University of Portsmouth
University of Glasgow
University of Southampton
OzGrav
Swinburne University of Technology
UBC
Berkeley University of California
The University of Chicago
Universität Hamburg
The University Of Sheffield.
GEO 600
The University of Adelaide
The University of Melbourne
The University of Western Australia
Universität Bonn
The University of Rhode Island
USC Universidade de Santiago de Compostela
UF University of Florida
University of Cambridge
Leibniz Universität Hannover
University of Maryland
University of Michigan
University of Minnesota
The University of Mississippi
University of Oregon
Texas The University of Texas at Austin
UTRGV
Universitat de les Illes Balears
東京大学 The University of Tokyo
The University of Utah
University of Washington
W Bothell
UWM University of Wisconsin Milwaukee
Lancaster University
University of Zurich
University of Strathclyde Glasgow
IISER Kolkata
tifr
ICTS International Centre for Theoretical Sciences
IISER Pune
Vanderbilt University
Villanova University
VU Vrije Universiteit Amsterdam
West Virginia University
CMI Chennai Mathematical Institute
DCSEM
RRCAT
NIMS National Institute for Mathematical Sciences | South Korea
KISTI 한국과학기술정보연구원
한양대학교 Hanyang University
서울대학교
UNIST
인제대학교 Inje University
LIGO-India Scientific Collaboration
IIT Hyderabad
IUCAA
KASI Korea Astronomy and Space Science Institute
Pusan National University
Sungkyunkwan University
Ewha
Korean Gravitational-Wave Group

LIGO
G1300394
v22

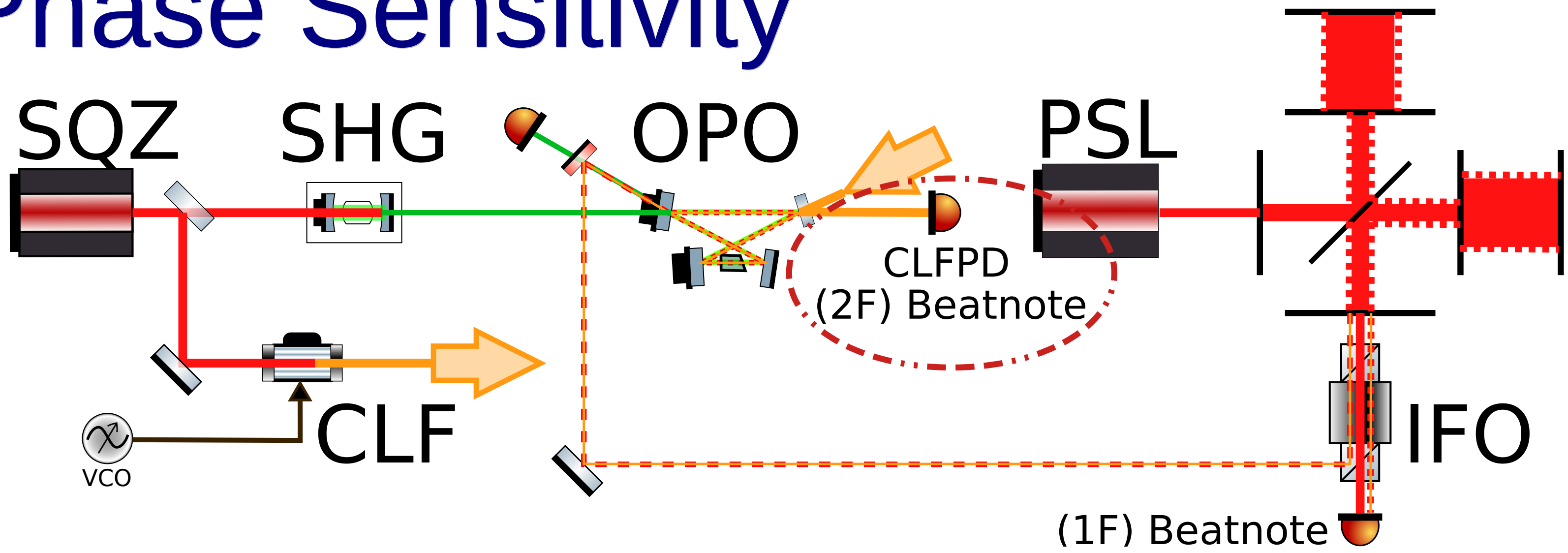
Coherent Control



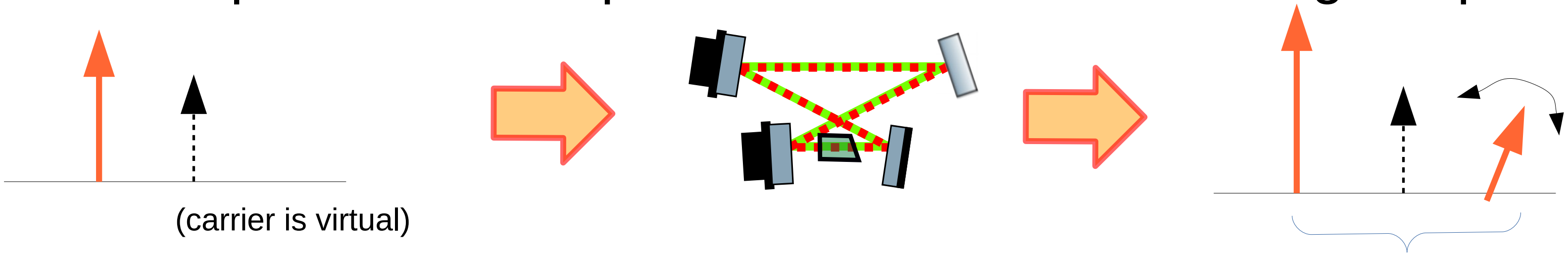
Coherent Locking Field (CLF)

RF single sideband created with acousto-optic modulator, added to squeezed light
Sees the nonlinear gain, co-propagates with the squeezing.
Also called the coherent control field.

CLF Phase Sensitivity

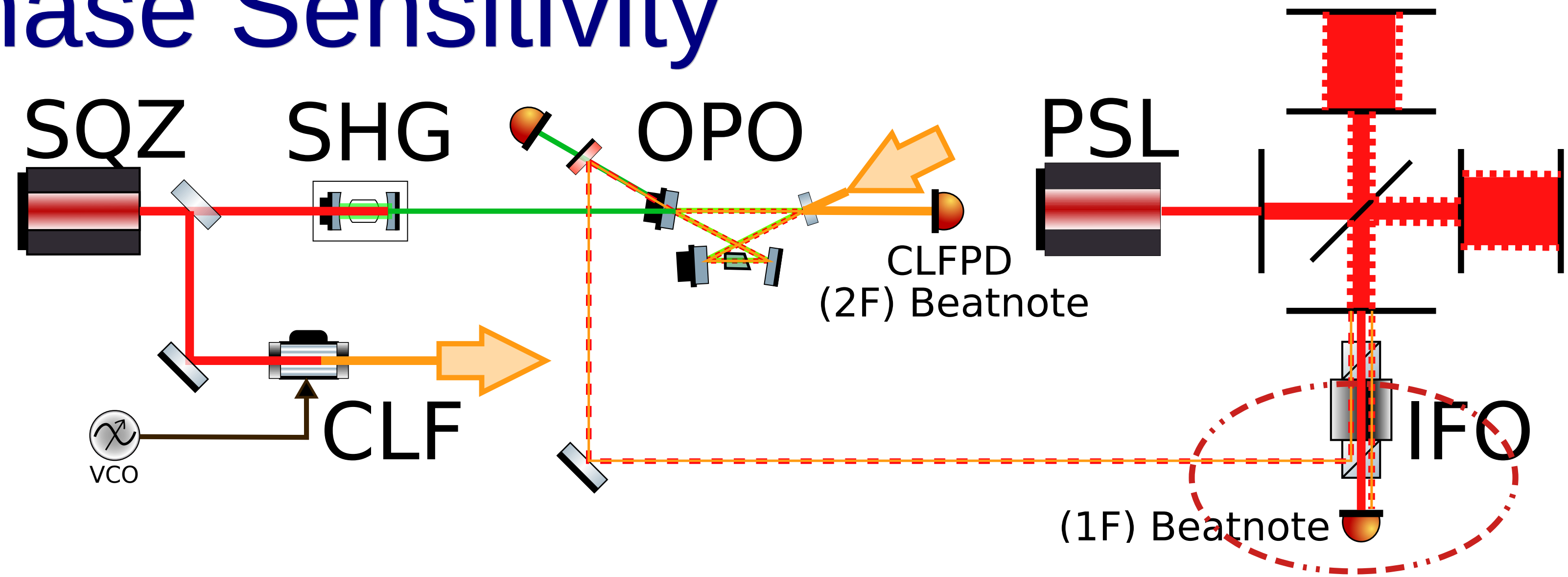


Phase-sensitive parametric amplification is used for sensing the pump phase

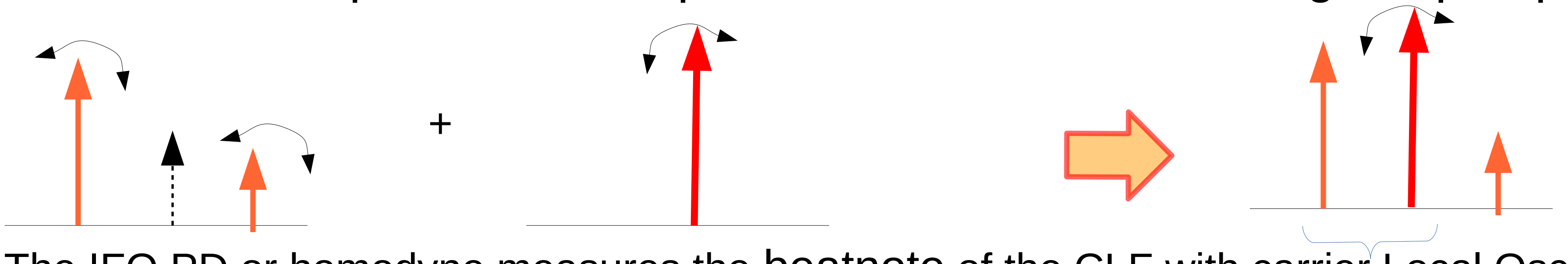


The CLF PD measures the beatnote of these two beams, senses the difference between the pump phase and the CLF optical phase

CLF Phase Sensitivity



Phase-sensitive parametric amplification is used for sensing the pump phase

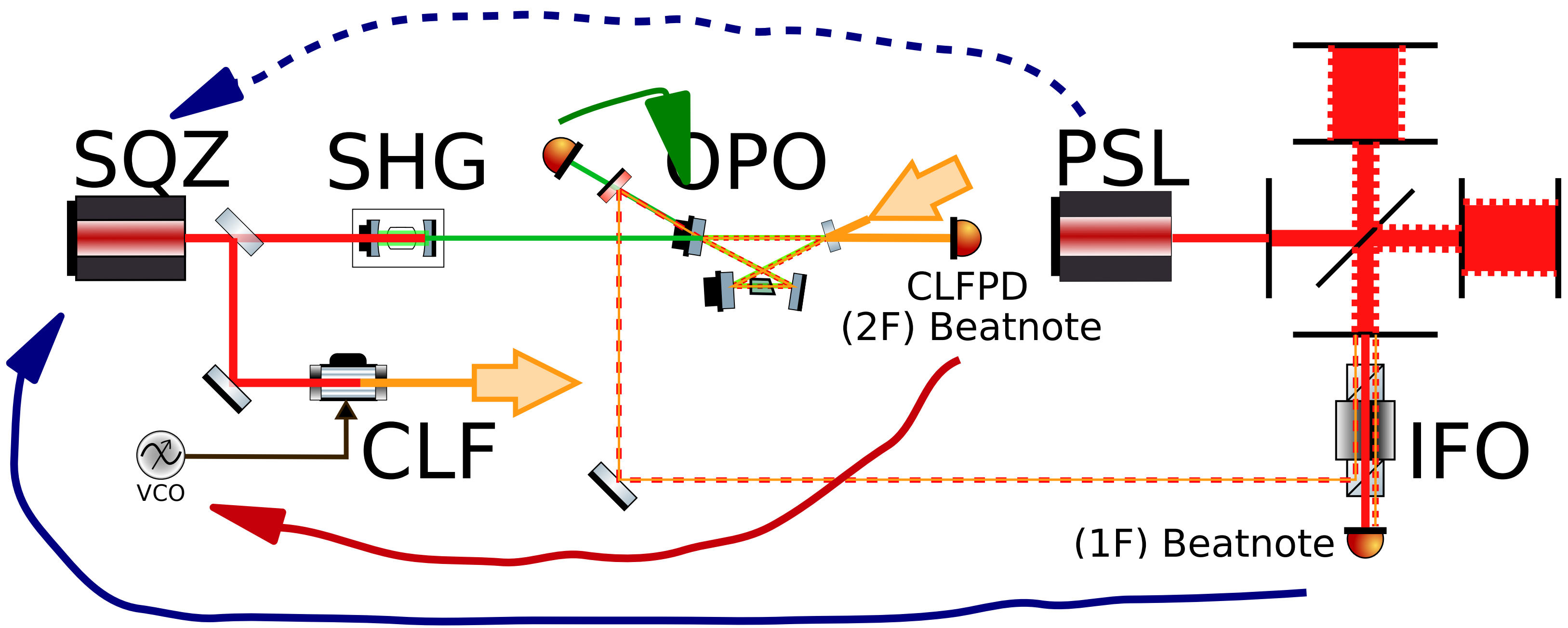


The IFO PD or homodyne measures the beatnote of the CLF with carrier Local Oscillator, senses the difference between the LO phase and the CLF optical phase

Squeeze Control Logic

- If the pump phase is “locked” to the CLF phase
- And the LO phase is “locked” to the CLF phase
- Then the pump phase follows the LO phase
- Implied: the squeezing phase follows the LO phase
- There is freedom to choose which phases actually move to implement “locking” control loops

Control Flow



>100kHz PSL Freq. Servo to SQZ Freq. (has residual noise)

~2-10kHz IFO (CLF 1F beatnote) to SQZ Phase (SQZANGLE)

~2-5kHz CLFPD 2F beatnote to RF Voltage controlled oscillator

~1kHz OPO PDH to OPO PZT (SHG is similar)