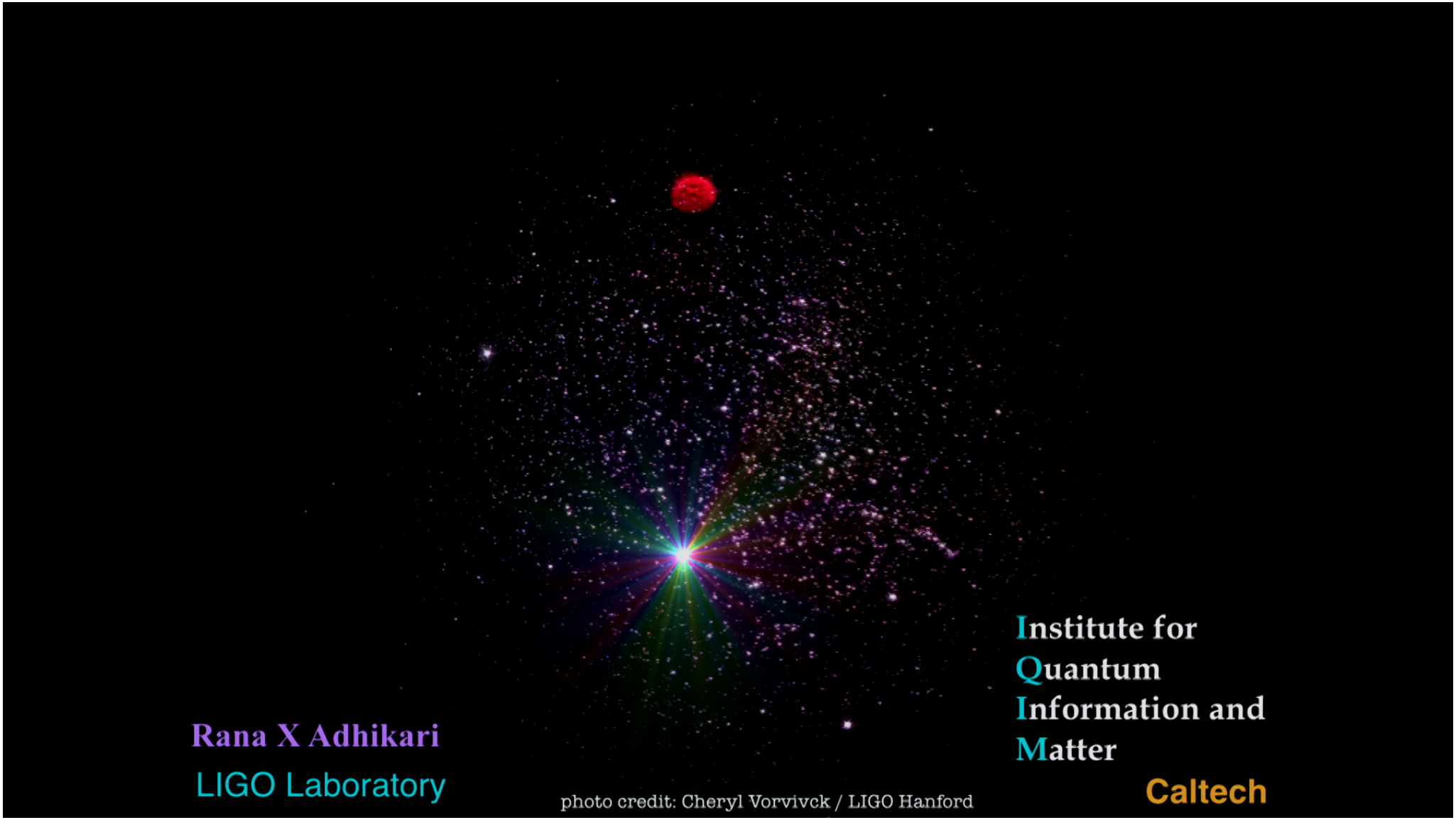
Title: 3G Detectors, Voyager

Date: Jun 11, 2018 03:00 PM

URL: http://pirsa.org/18060048

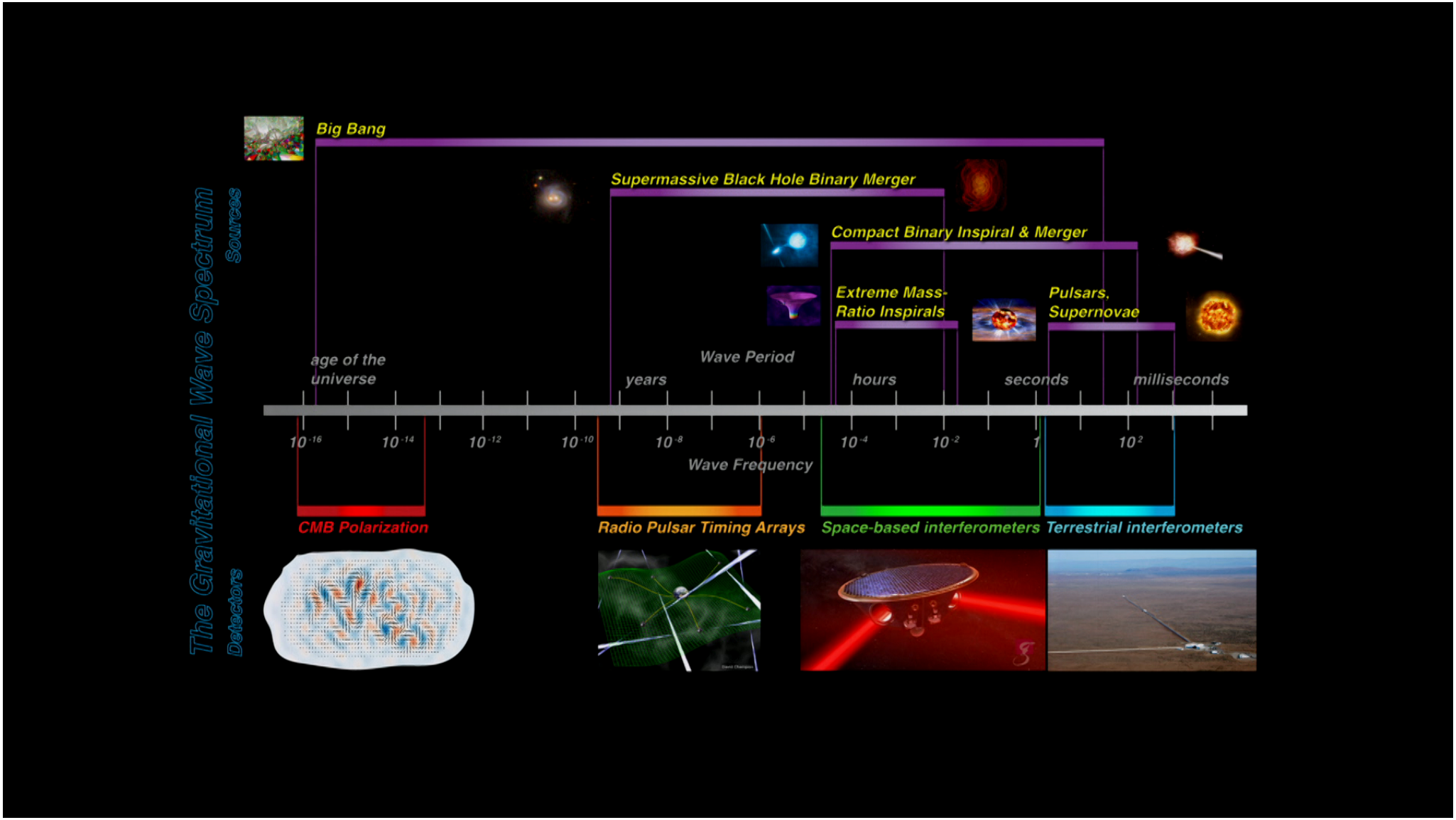
Abstract:

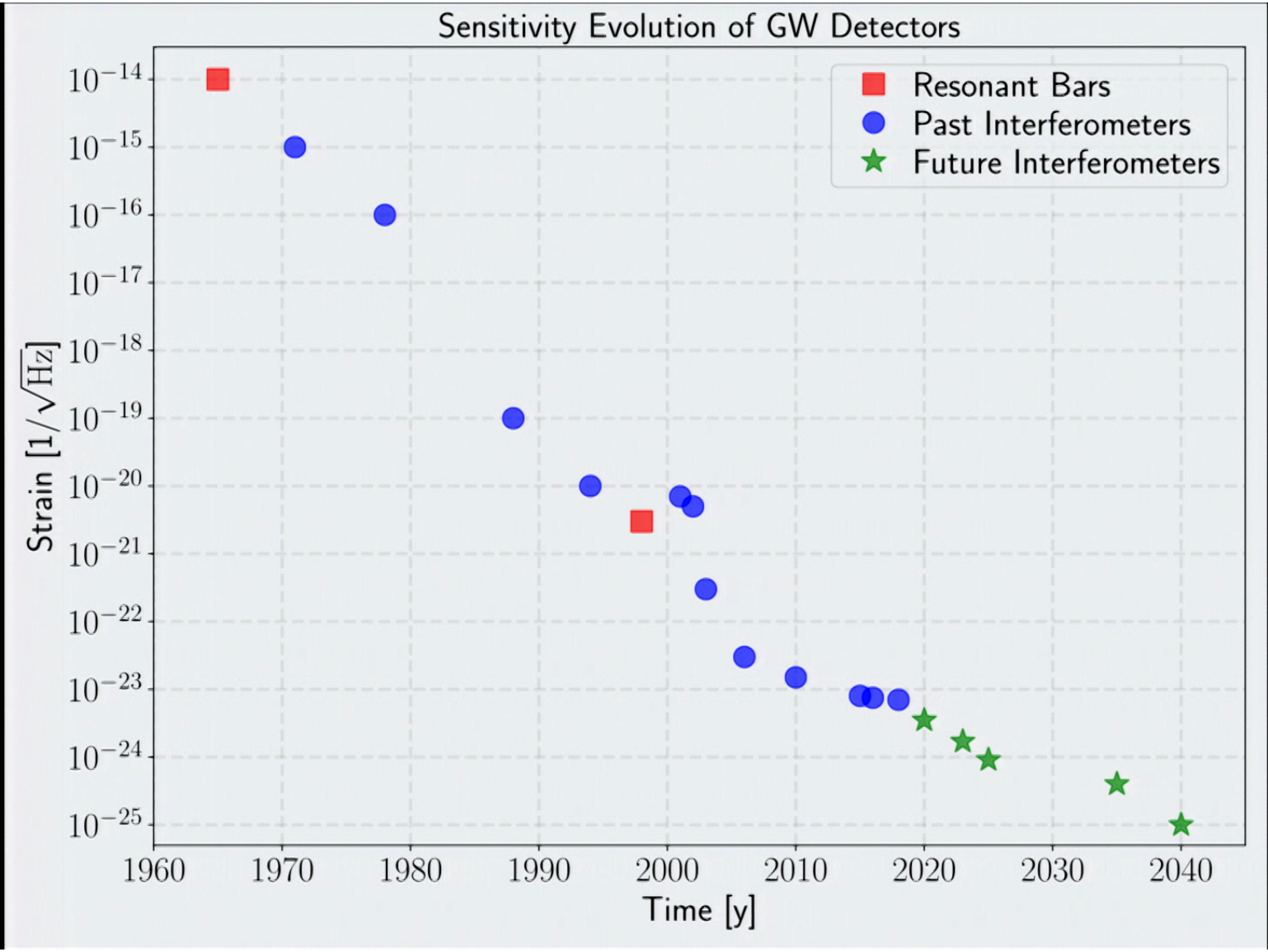

Rana X Adhikari
LIGO Laboratory
photo credit: Cheryl Vorvivck / LIGO Hanford
Institute for
Quantum
Information and
Matter
Caltech

The Questions

- Are there BSM effects visible in NS tidal disruption?
- Phase transitions in early universe?
- **Ringdown of Kinks in Cosmic Strings**
- **Dispersion of GW in Spacetime** (1605.01103)
- **Our Wildest Imaginings: 2030 - 2040**

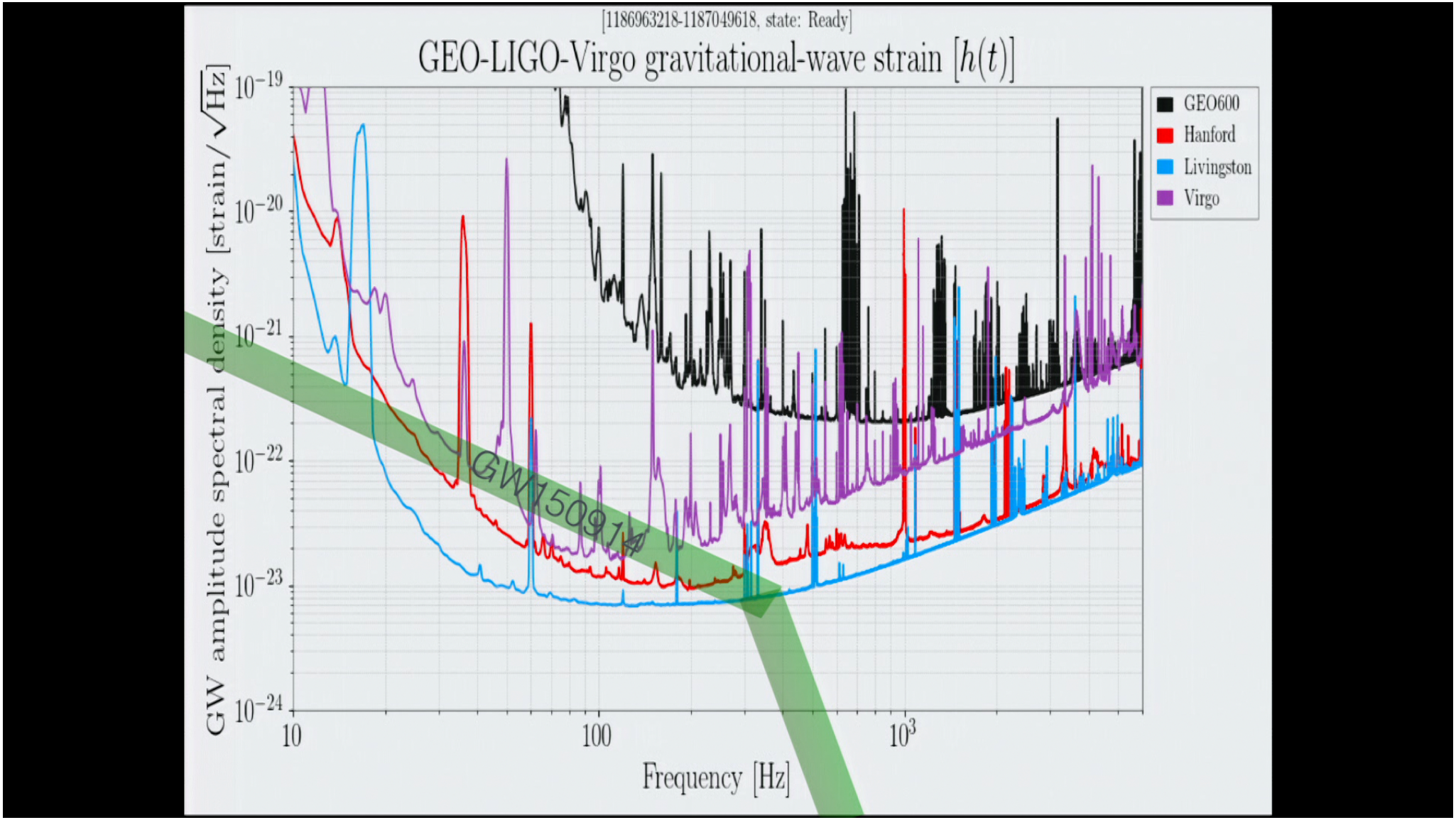

CAUTION


The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers


Sensitivity Evolution of GW Detectors
Resonant Bars
Past Interferometers
Future Interferometers
Strain [1/√Hz]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1960
1970
1980
1990
2000
2010
2020
2030
2040
Time [y]

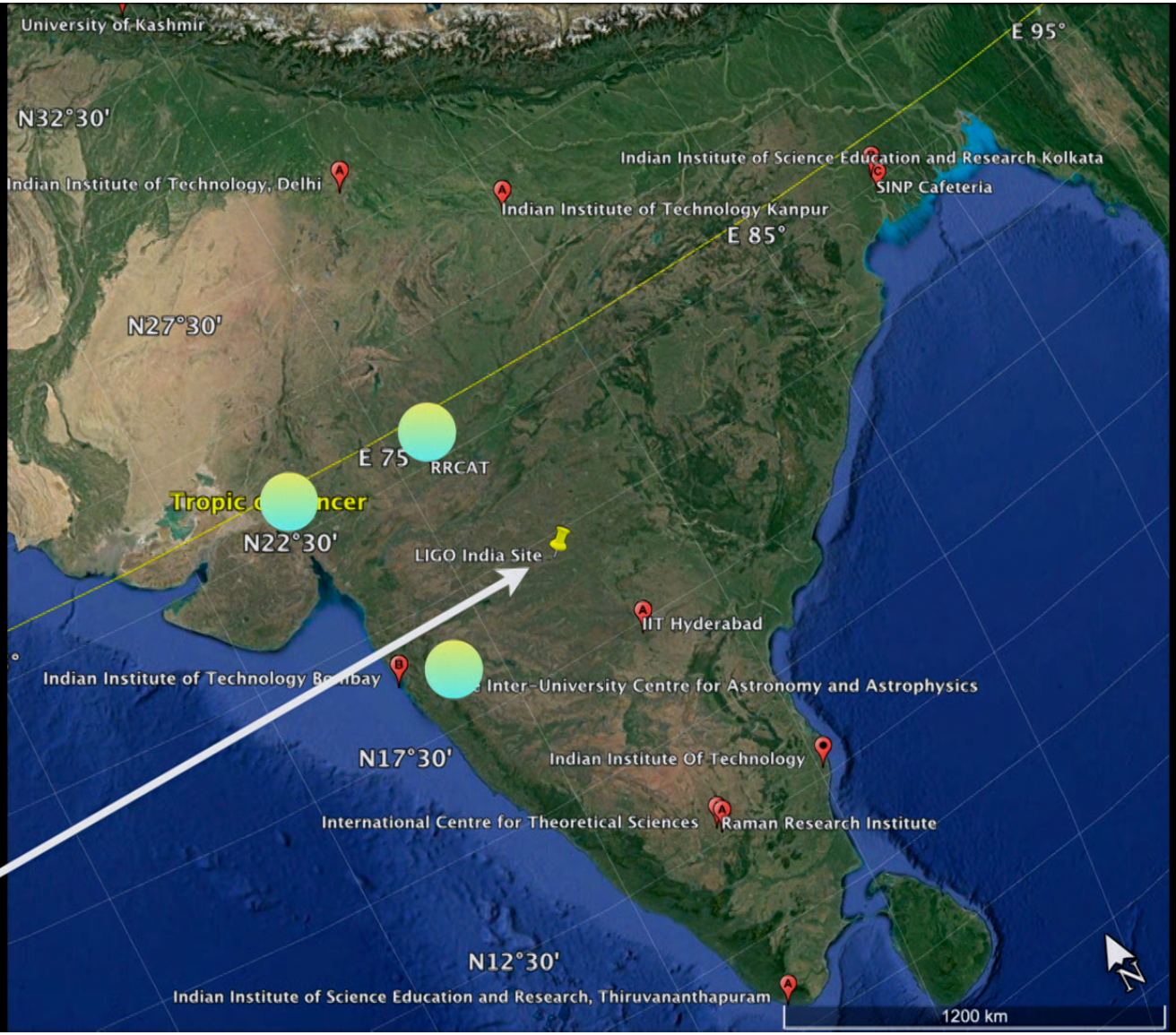

Livingston
Hanford

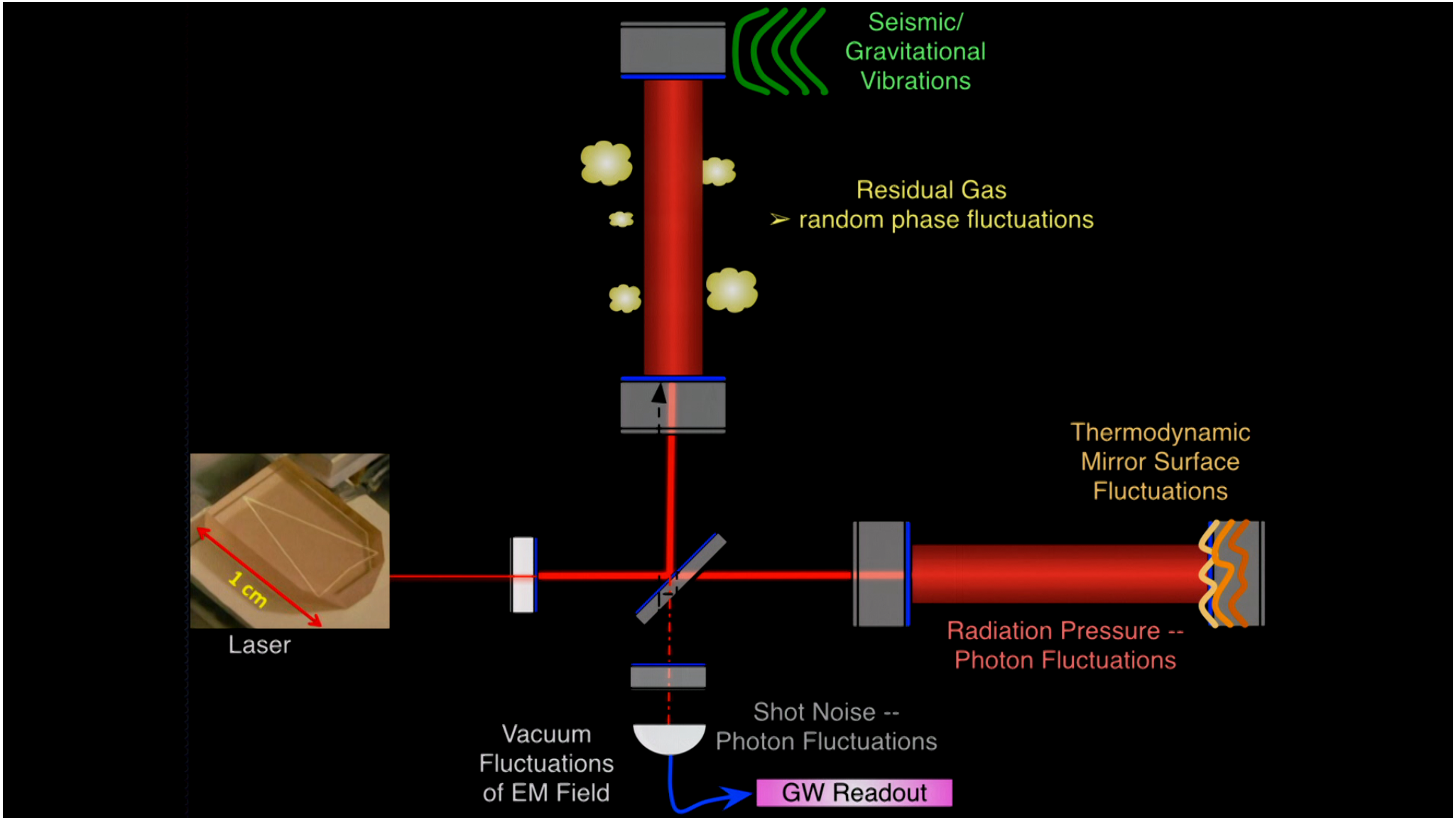
KAGRA
(3000)
Kamioka,
Japan


[1186963218-1187049618, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain [h(t)]
GW amplitude spectral density [strain/√Hz]
Frequency [Hz]
GEO600
Hanford
Livingston
Virgo
GW150914

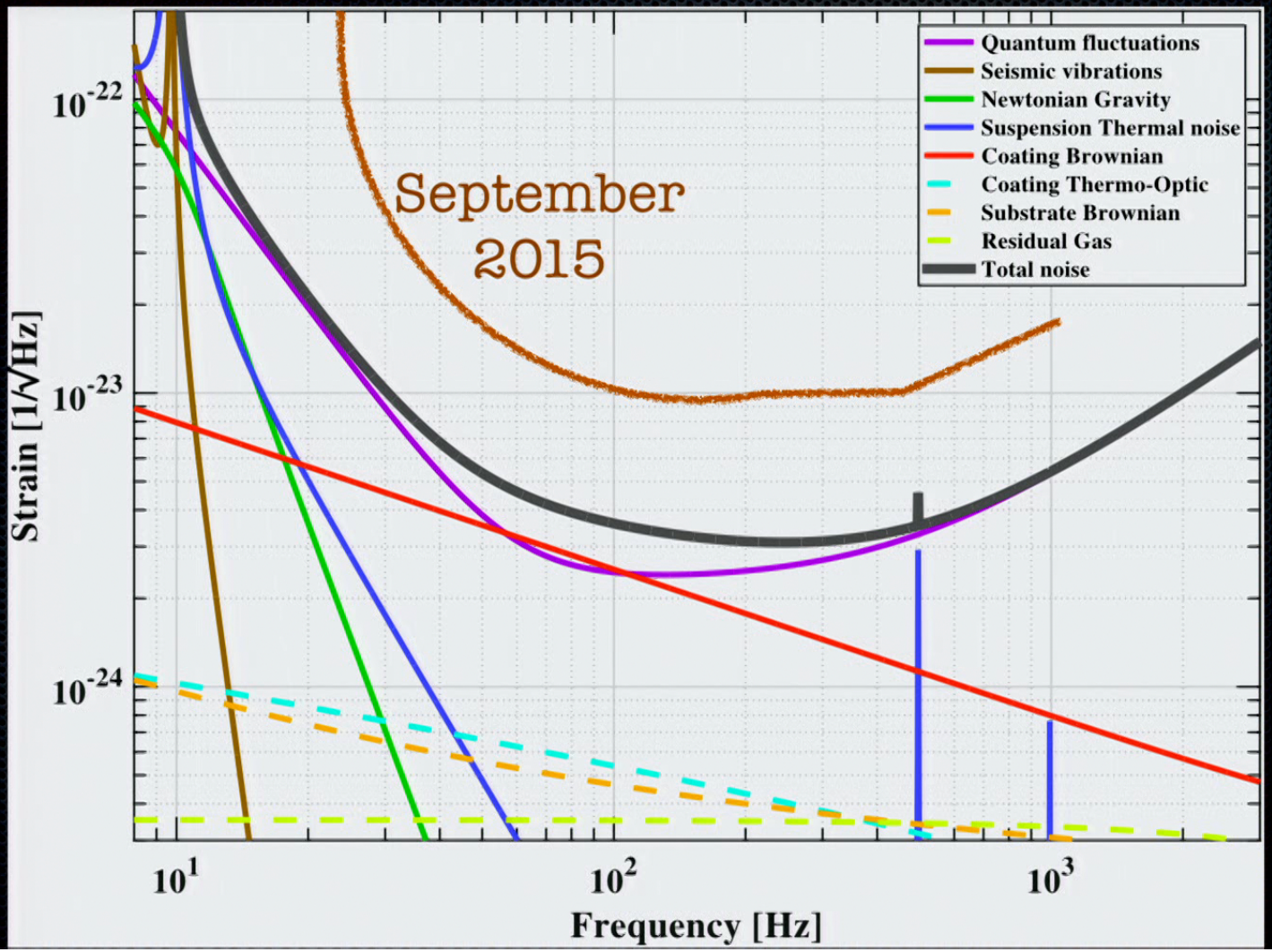
Longer Baselines => Better Angular Resolution

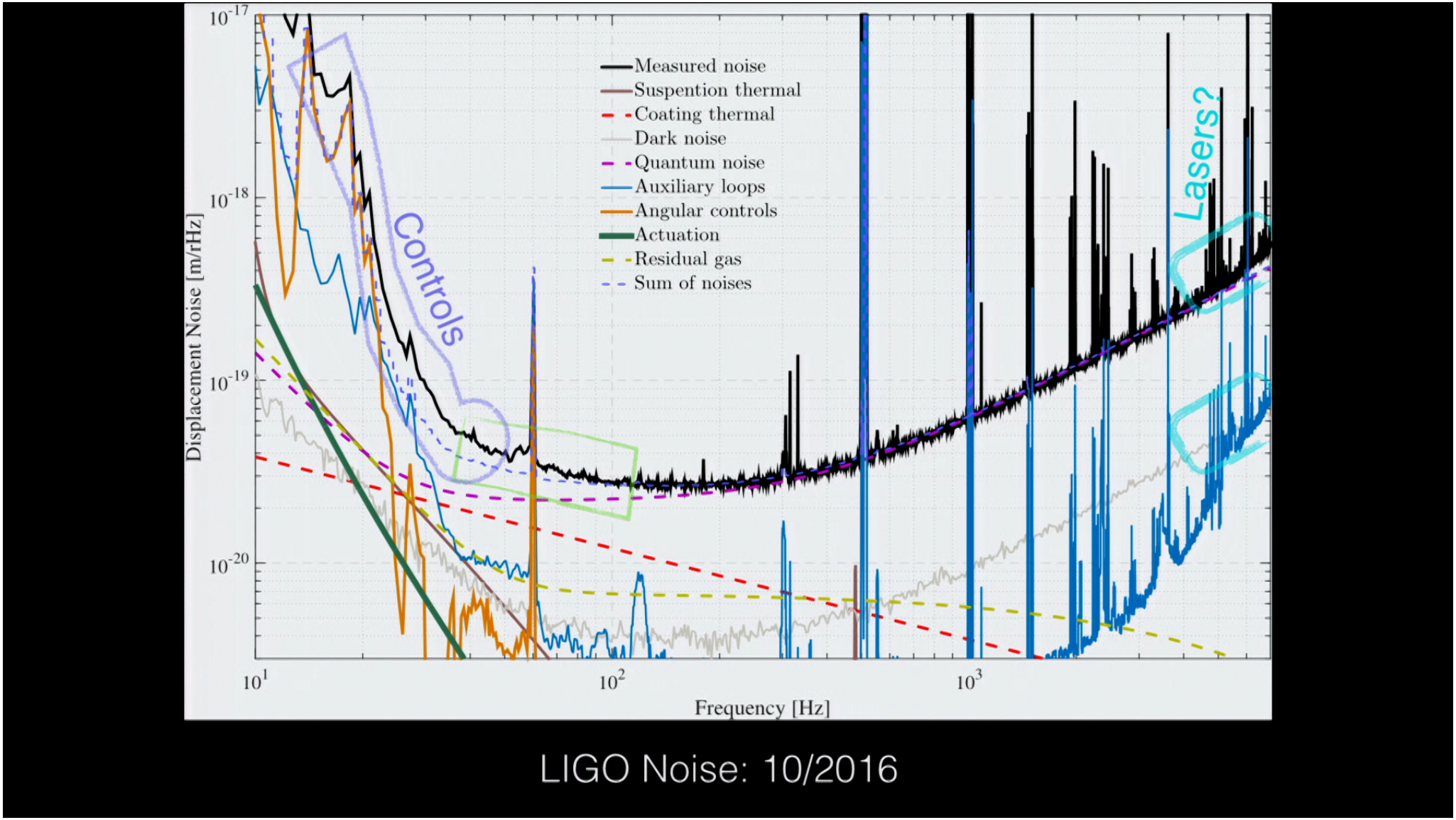
LIGO-India: Aundh Site



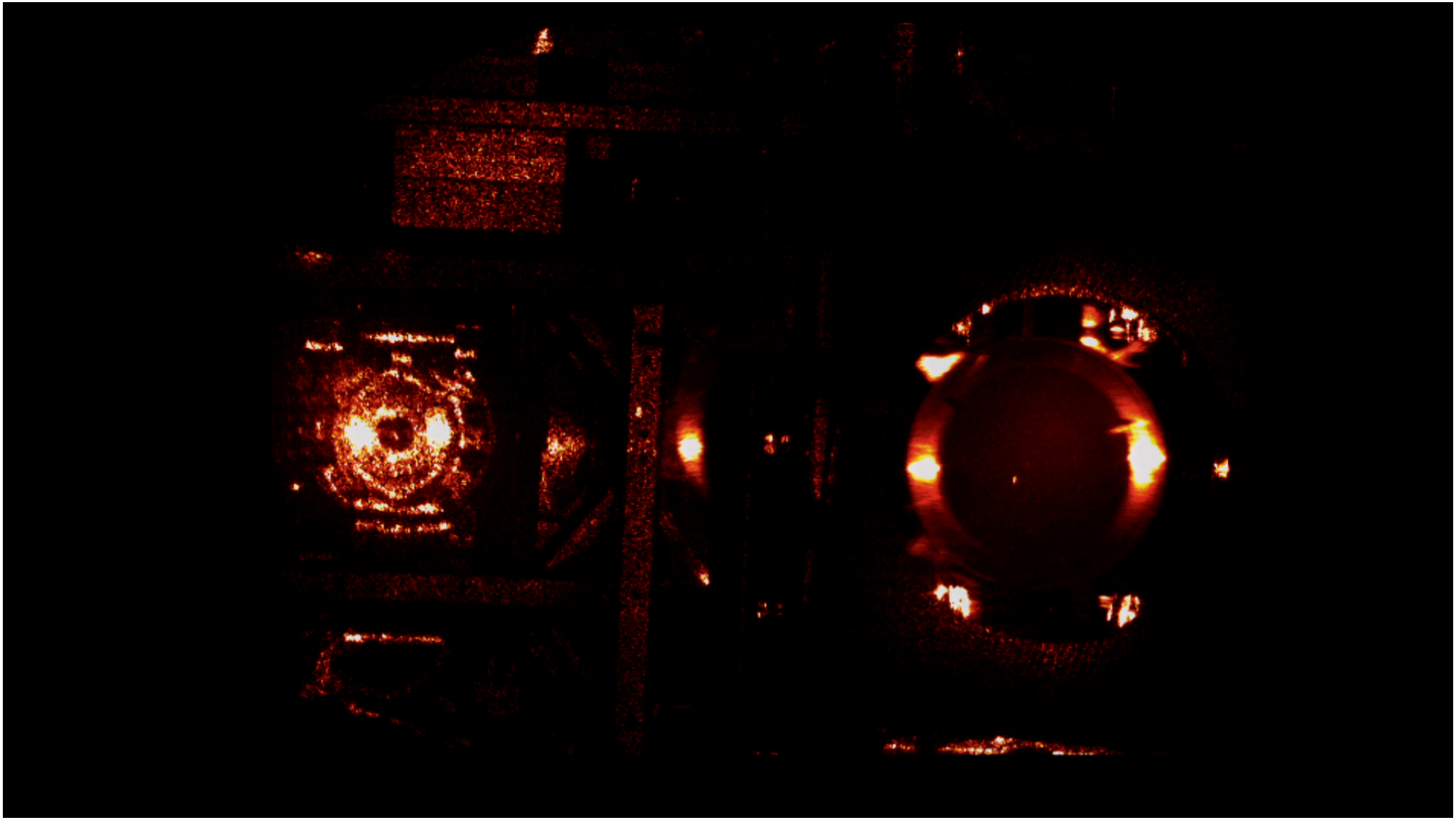

Seismic/
Gravitational
Vibrations
Residual Gas
➢ random phase fluctuations
Thermodynamic
Mirror Surface
Fluctuations
1 cm
Laser
Radiation Pressure --
Photon Fluctuations
Shot Noise --
Photon Fluctuations
Vacuum
Fluctuations
of EM Field
GW Readout

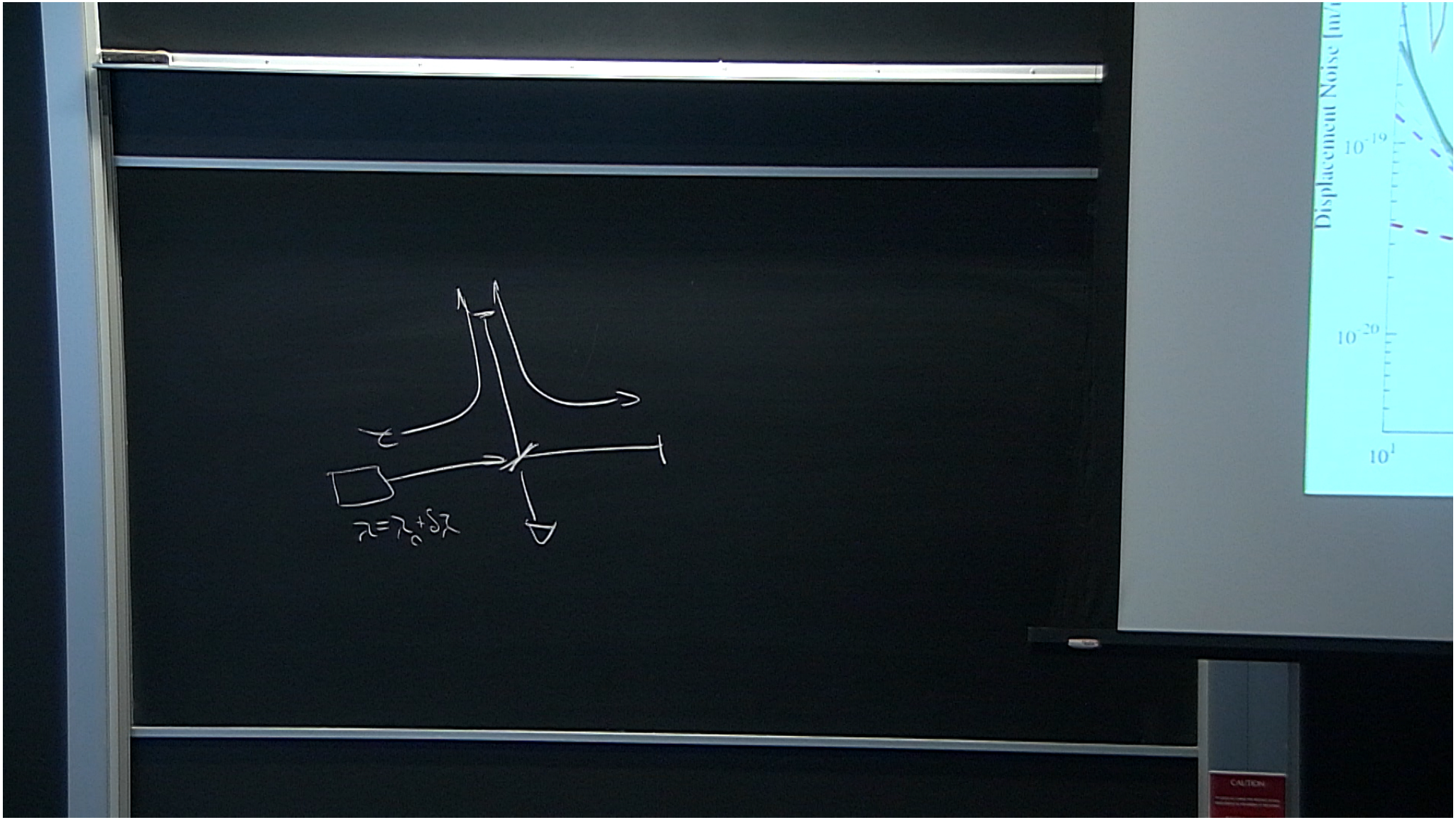
Calculated limits of Advanced LIGO (~2019)

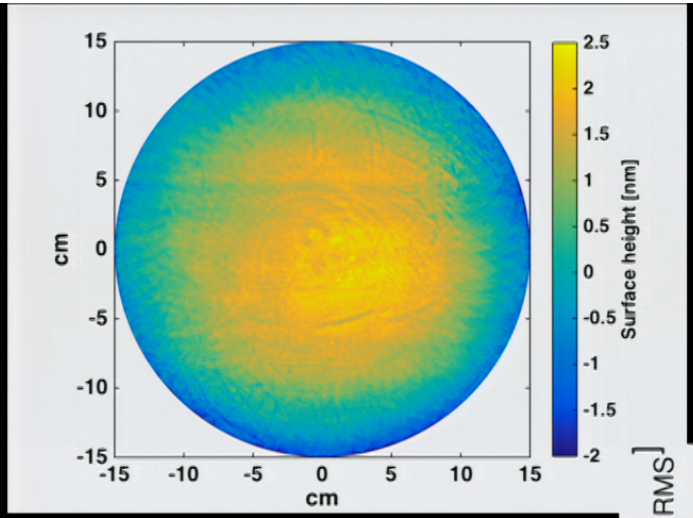


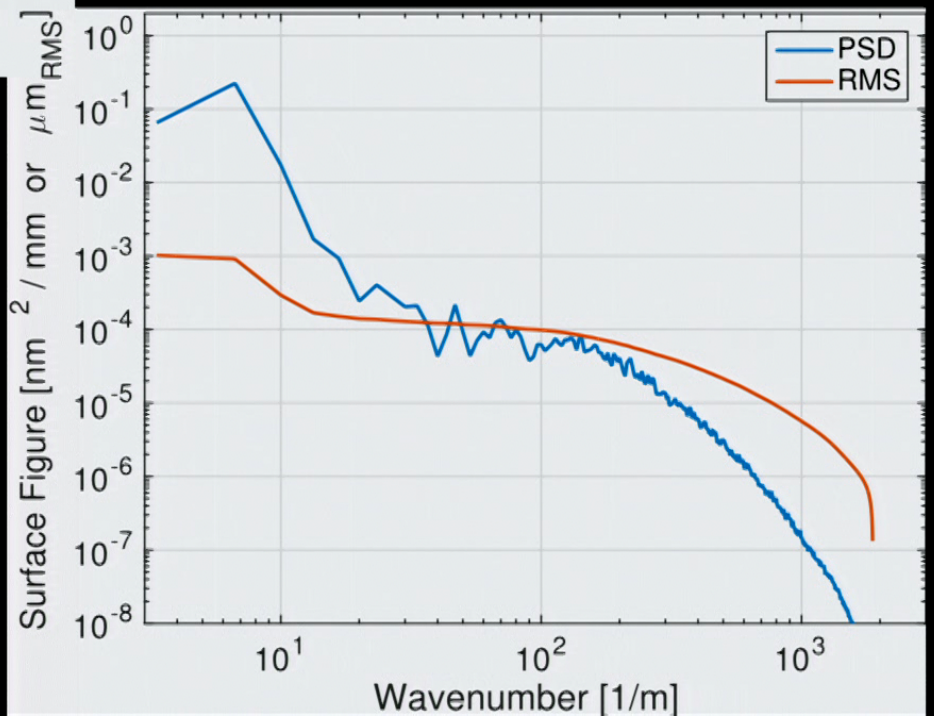


LIGO Noise: 10/2016




Displacement Noise
10^{-19}
10^{-20}
10^{-1}
$L = L_0 + \delta x$


15
10
5
0
-5
-10
-15
cm
-15 -10 -5 0 5 10 15
cm
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Surface height [nm]

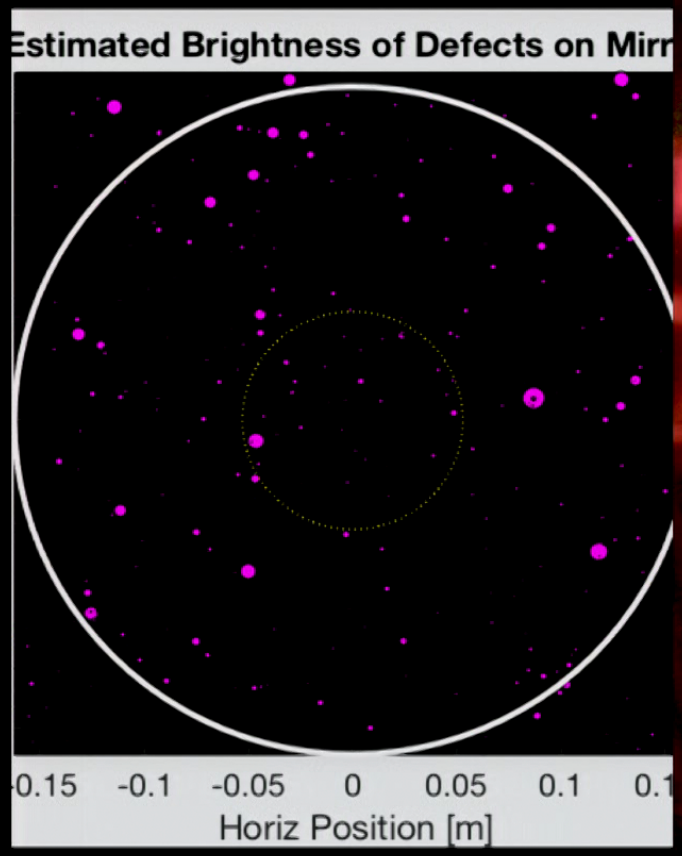

PSD
RMS
Surface Figure [nm 2 / mm or μm RMS]
Wavenumber [1/m]

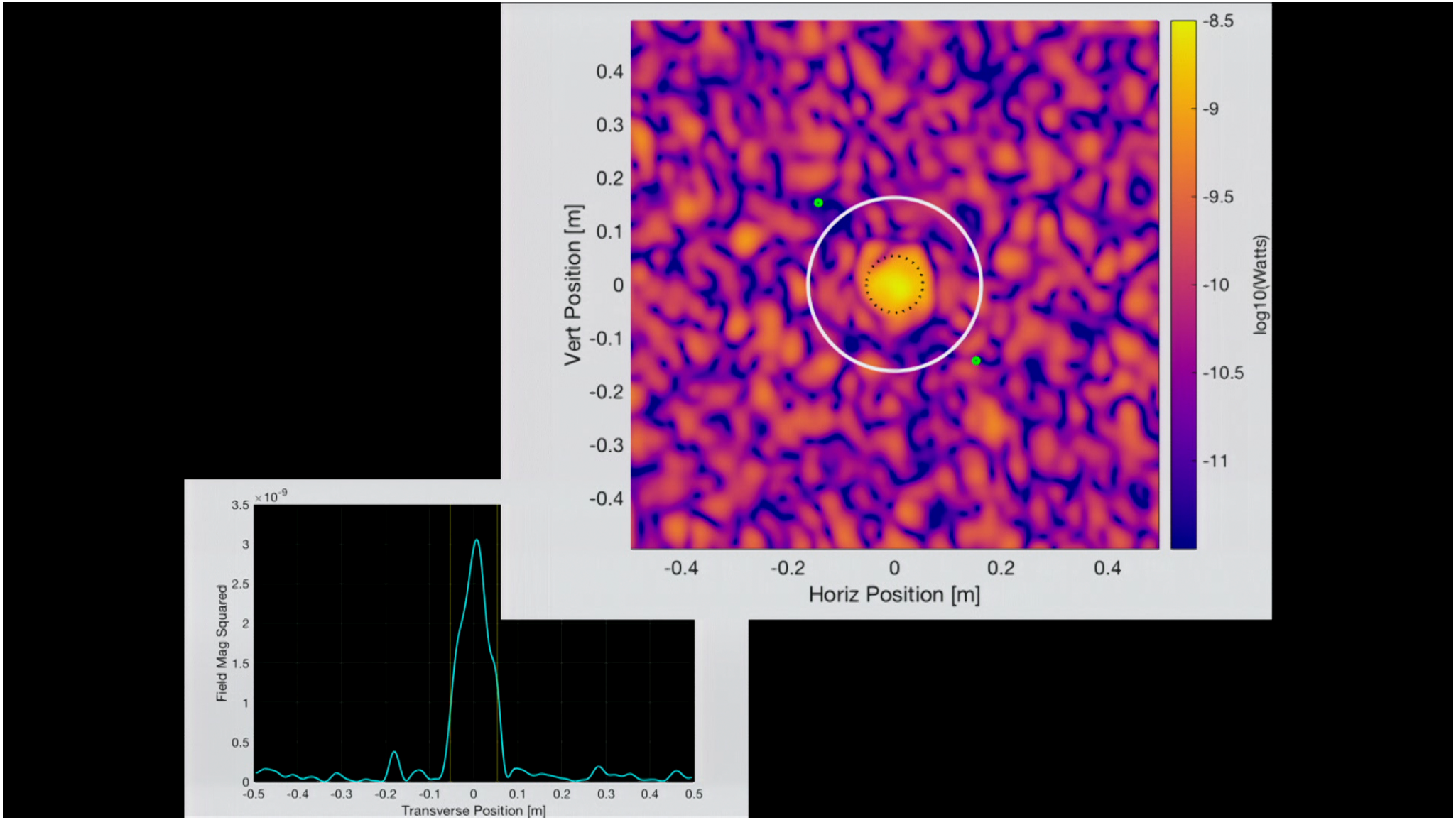
‘Golden Rule’ for optical scattering

$$\frac{dP}{P} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

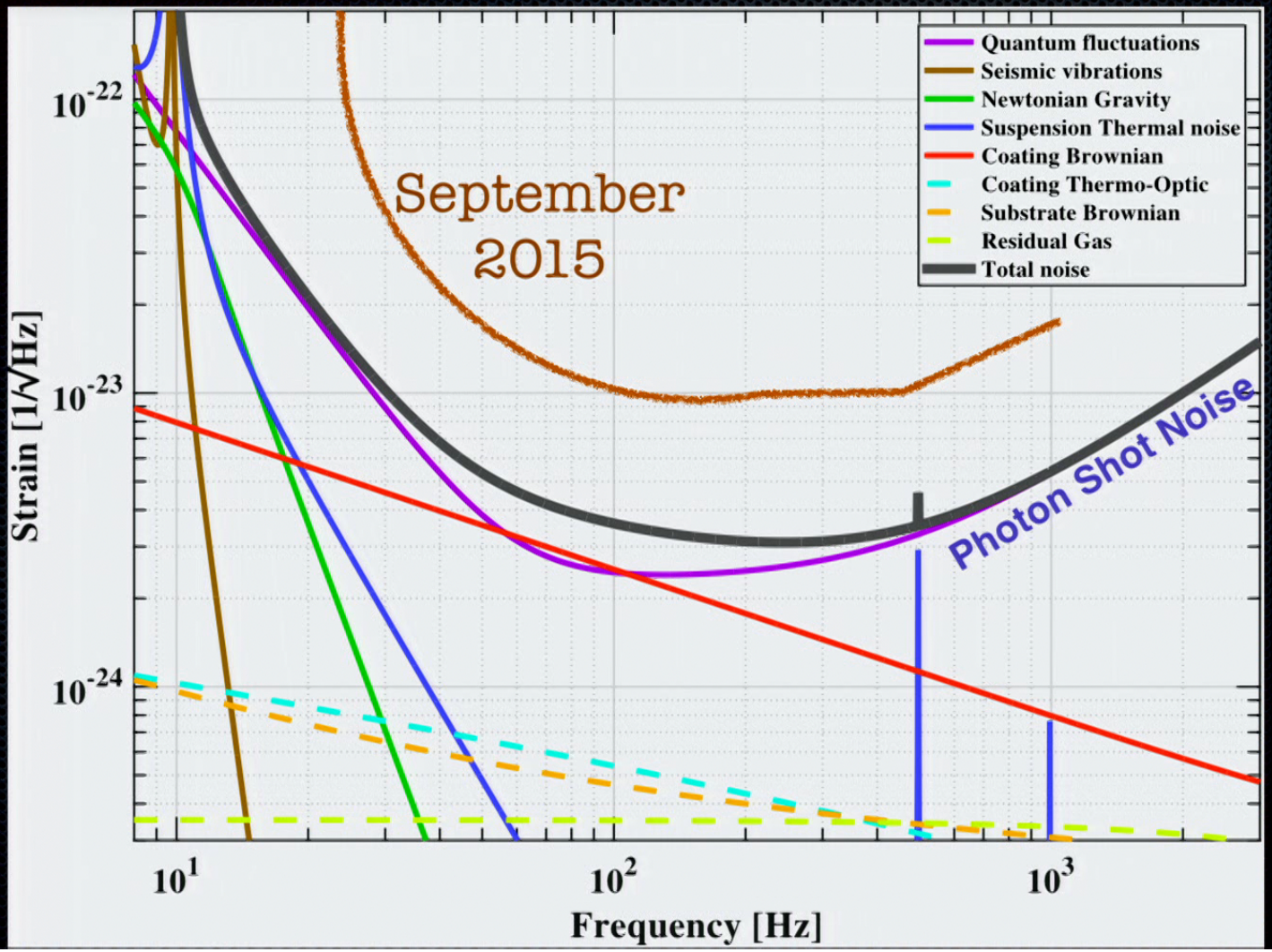
- point defects in amorphous thin films
- caused by crystallization during annealing
- Babinet’s Principle
- phased array problem

photo credit: Travis Sedecki / Rick Savage

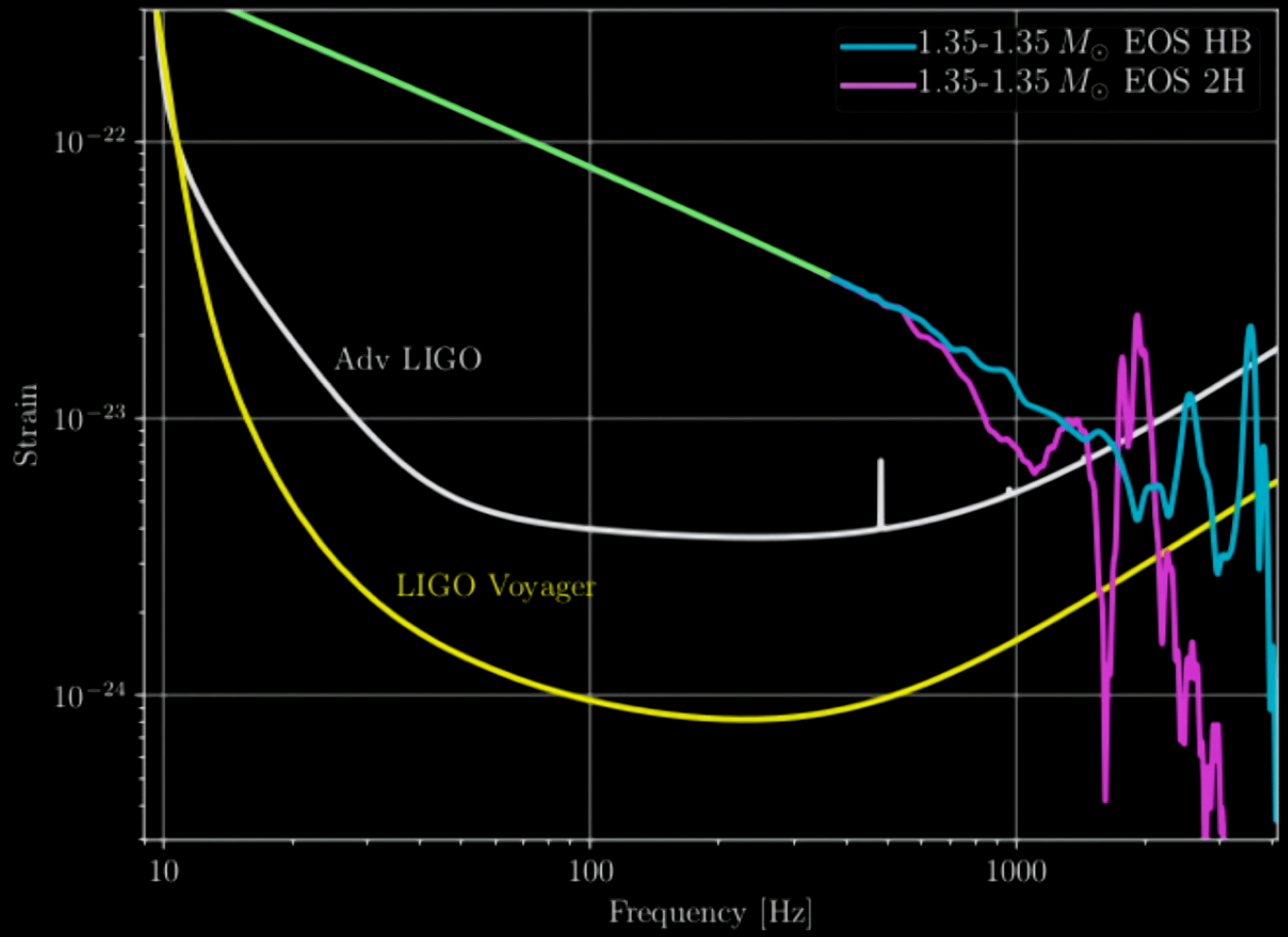

Estimated Brightness of Defects on Mirr
-0.15
-0.1
-0.05
0
0.05
0.1
0.1
Horiz Position [m]


Vert Position [m]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.4
-0.2
0
0.2
0.4
Horiz Position [m]
-8.5
-9
-9.5
-10
-10.5
-11
log10(Watts)
×10^-9
3.5
3
2.5
2
1.5
1
0.5
0
Field Mag Squared
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Transverse Position [m]

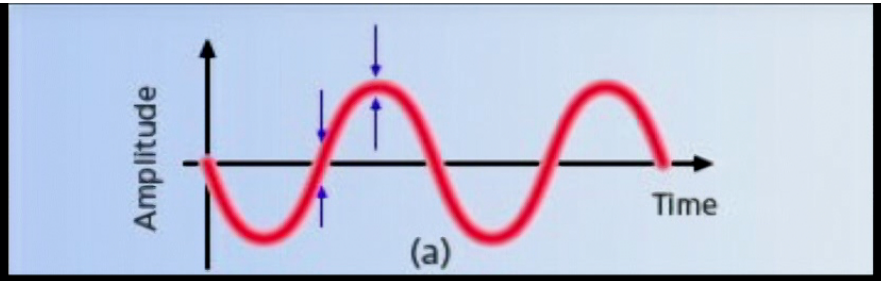
Binary NS: how to measure better?



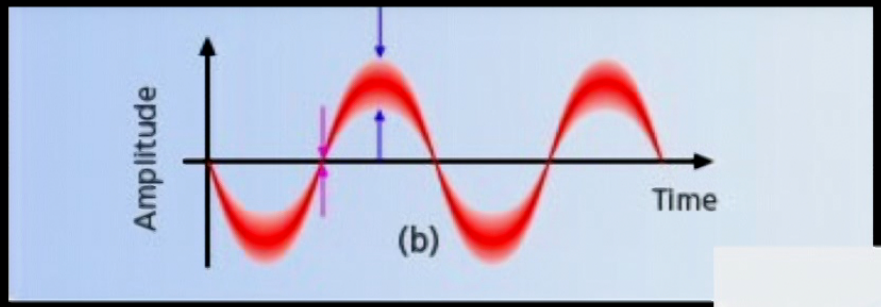
Binary NS: how to measure better?



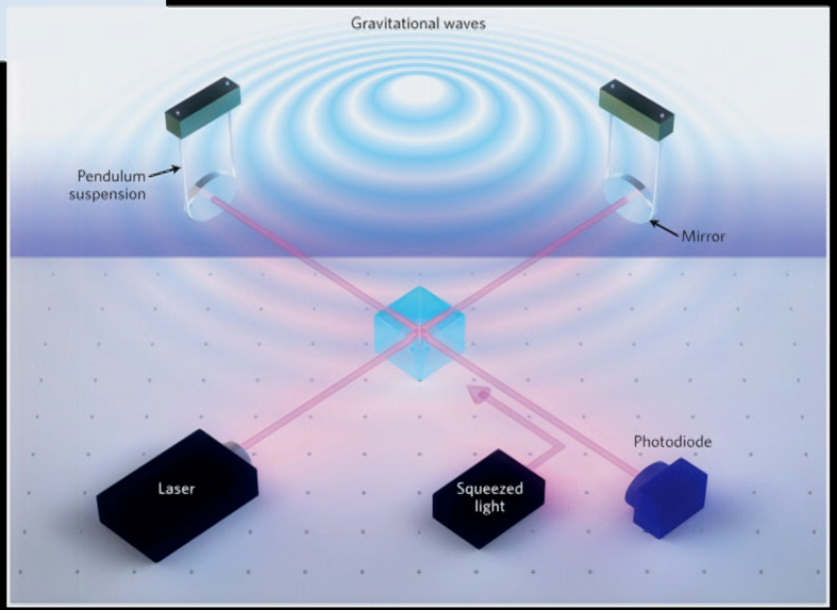
from Jocelyn Read, Katerina Chatziioannou



Vacuum Fluctuations:
equal amounts of
phase and amplitude
noise



Squeezed
Vacuum Fluctuations:
less phase noise,
more amplitude noise



Why a Quantum limit?

- The GW is nearly **noiseless**; spacetime strain should be compared with Planck-scale fluctuations. **SNR > 10^{13}**
- In the audio band, technical noise (gravity, thermodynamics, gas scattering, laser noise) can be mitigated*.
- Photon shot noise is not fundamental.
- The Heisenberg uncertainty on a 40 kg test mass is near the Planck scale.

* using sufficiently advanced technology

Towards the Fundamental Limit for Classical Force Sensing:

the Quantum Cramer-Rao bound

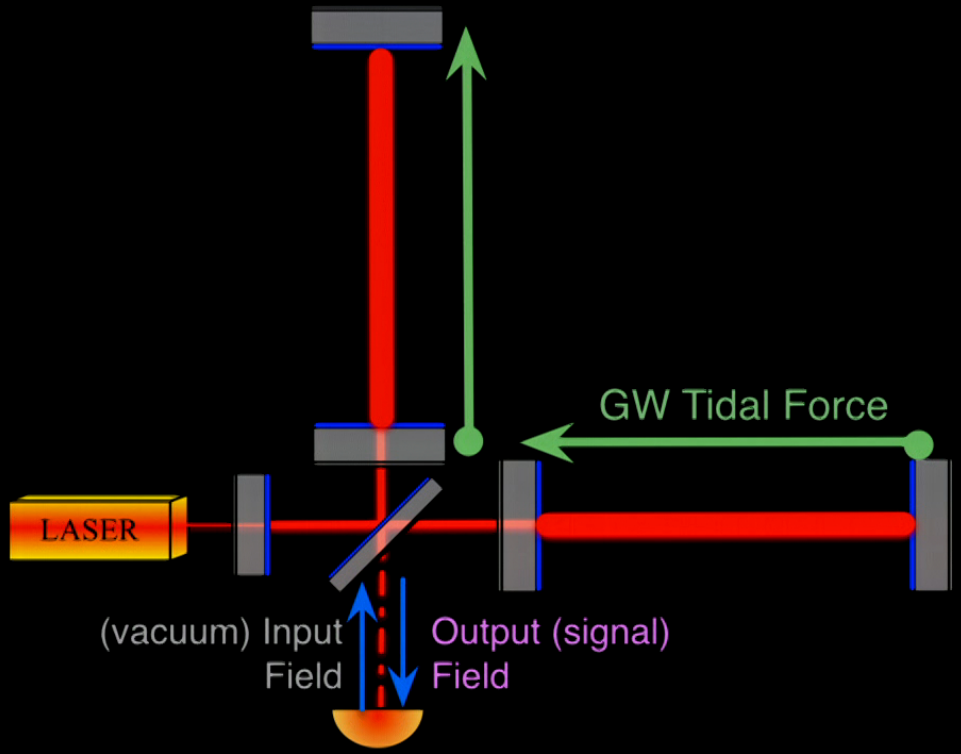
Phys Rev Lett 119, (2017)

- **Gravitational wave: a Classical tidal force**
- the mirror is a quantum harmonic oscillator
- **Optical Field: Coherent state**
  ==> ***quantum fluctuations***



H. Miao, RXA, Belinda **Pang**, Yiqui Ma, Yanbei Chen

Quantum model of a GW Detector



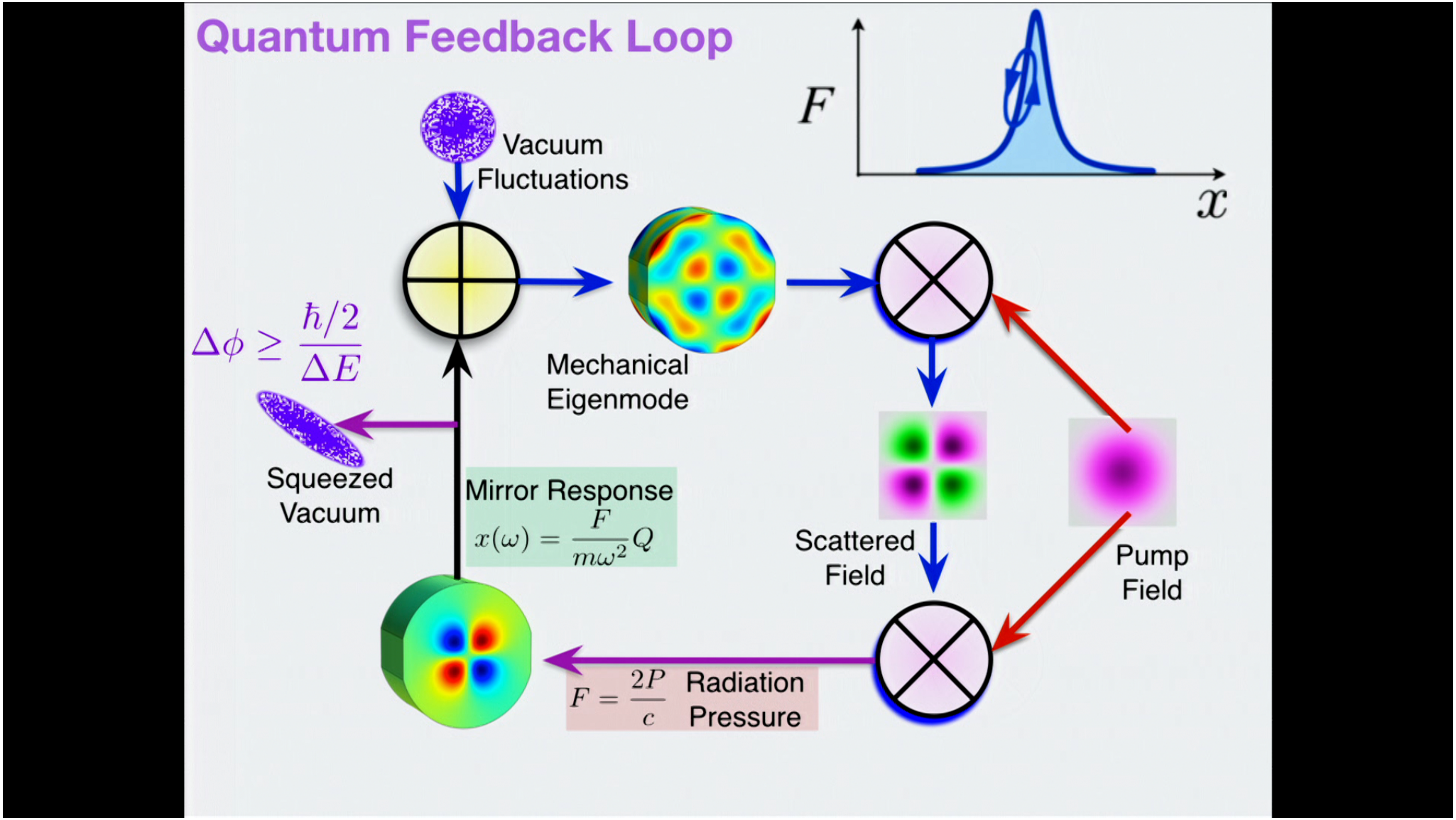
Model: continuous Quantum measurement

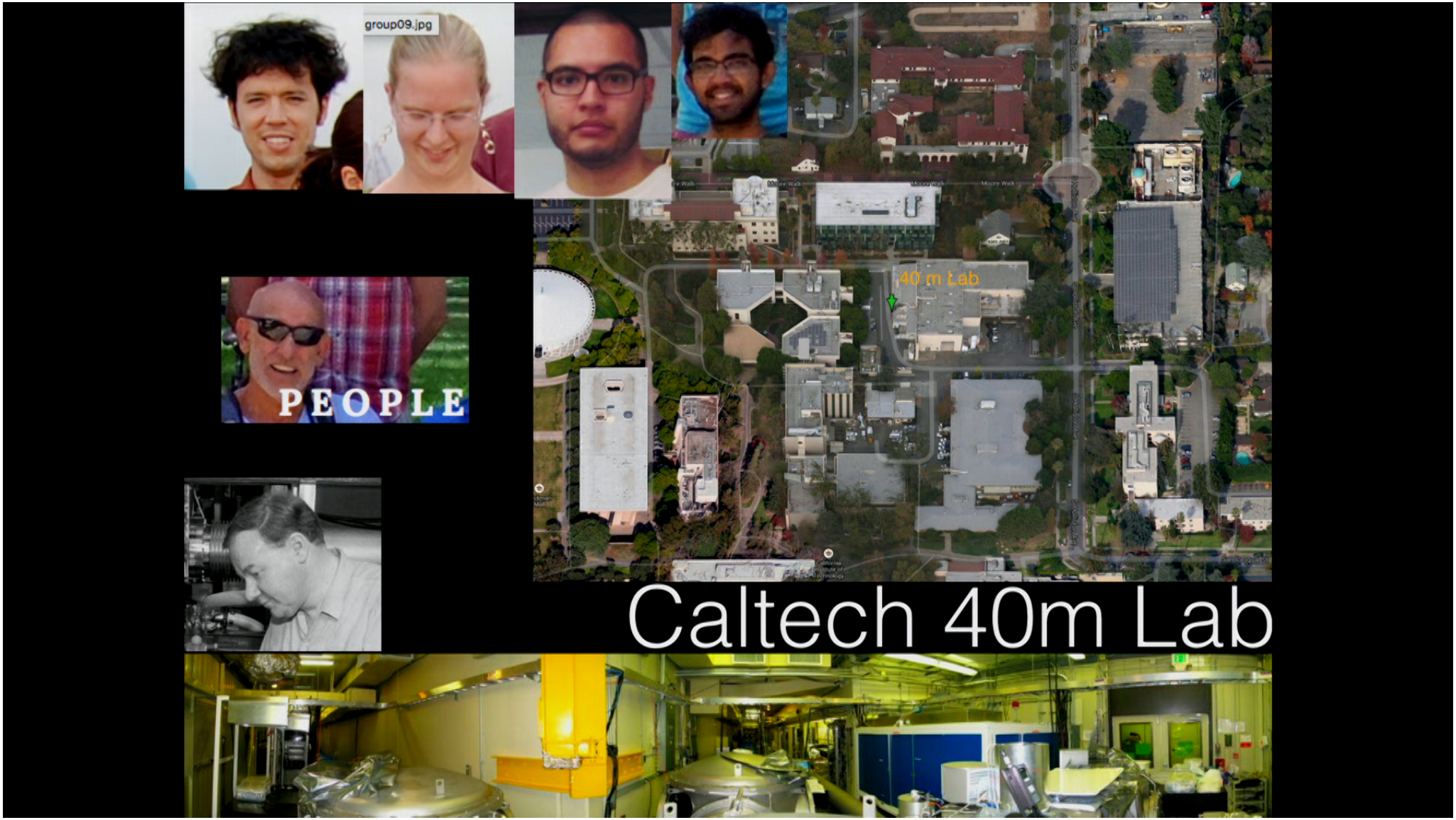
Mirror: a quantum harmonic oscillator (QHO)

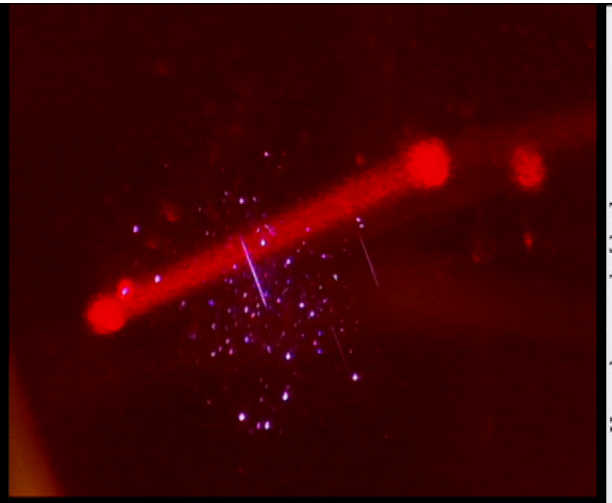
G Wave: a *Classical* force

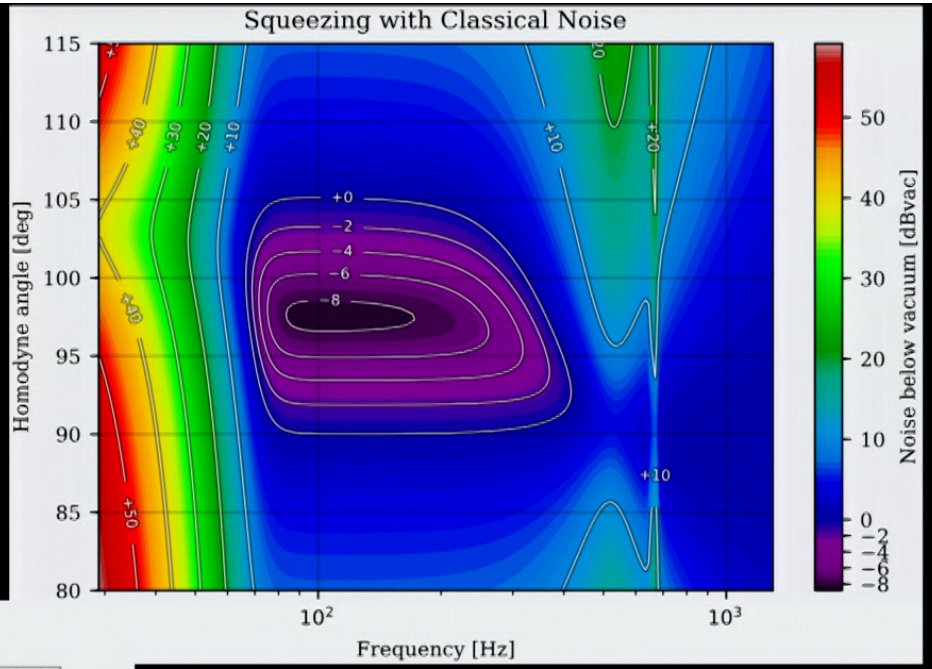
Laser Field: a quantum field

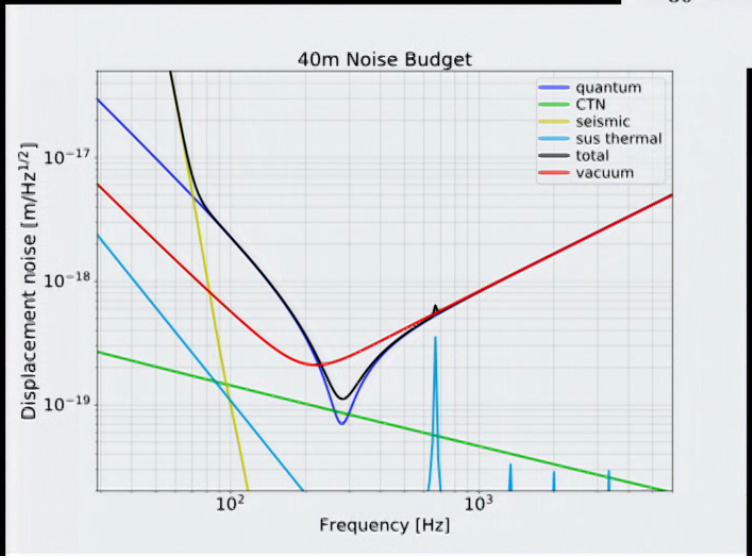
Photo Diode: Projective Measurement


Quantum Feedback Loop
F
x
Vacuum
Fluctuations
$\Delta\phi \geq \frac{\hbar/2}{\Delta E}$
Mechanical
Eigenmode
Squeezed
Vacuum
Mirror Response
$x(\omega) = \frac{F}{m\omega^2}Q$
Scattered
Field
Pump
Field
$F = \frac{2P}{c}$ Radiation
Pressure

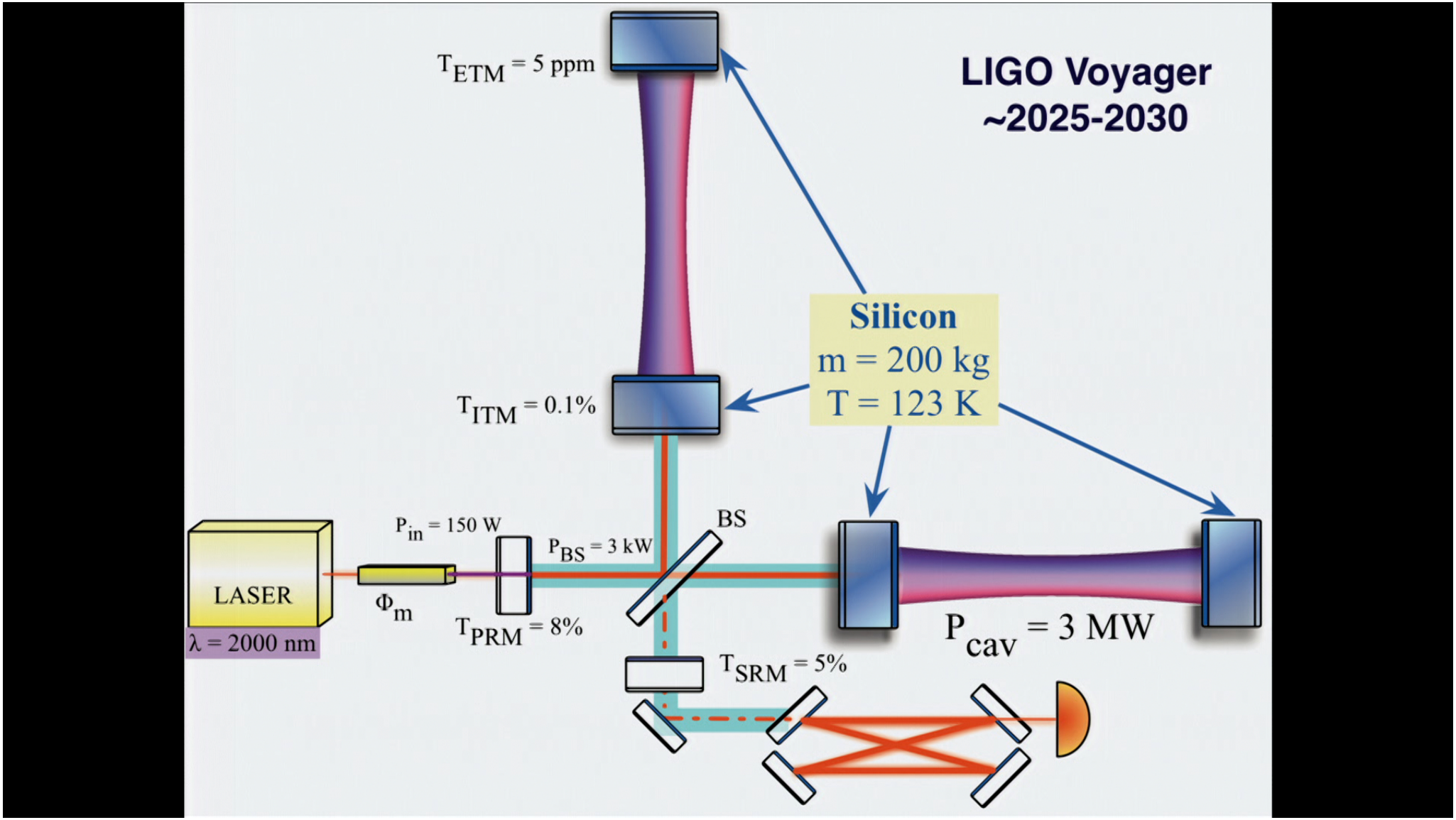

group09.jpg
PEOPLE
40 m Lab
Caltech 40m Lab

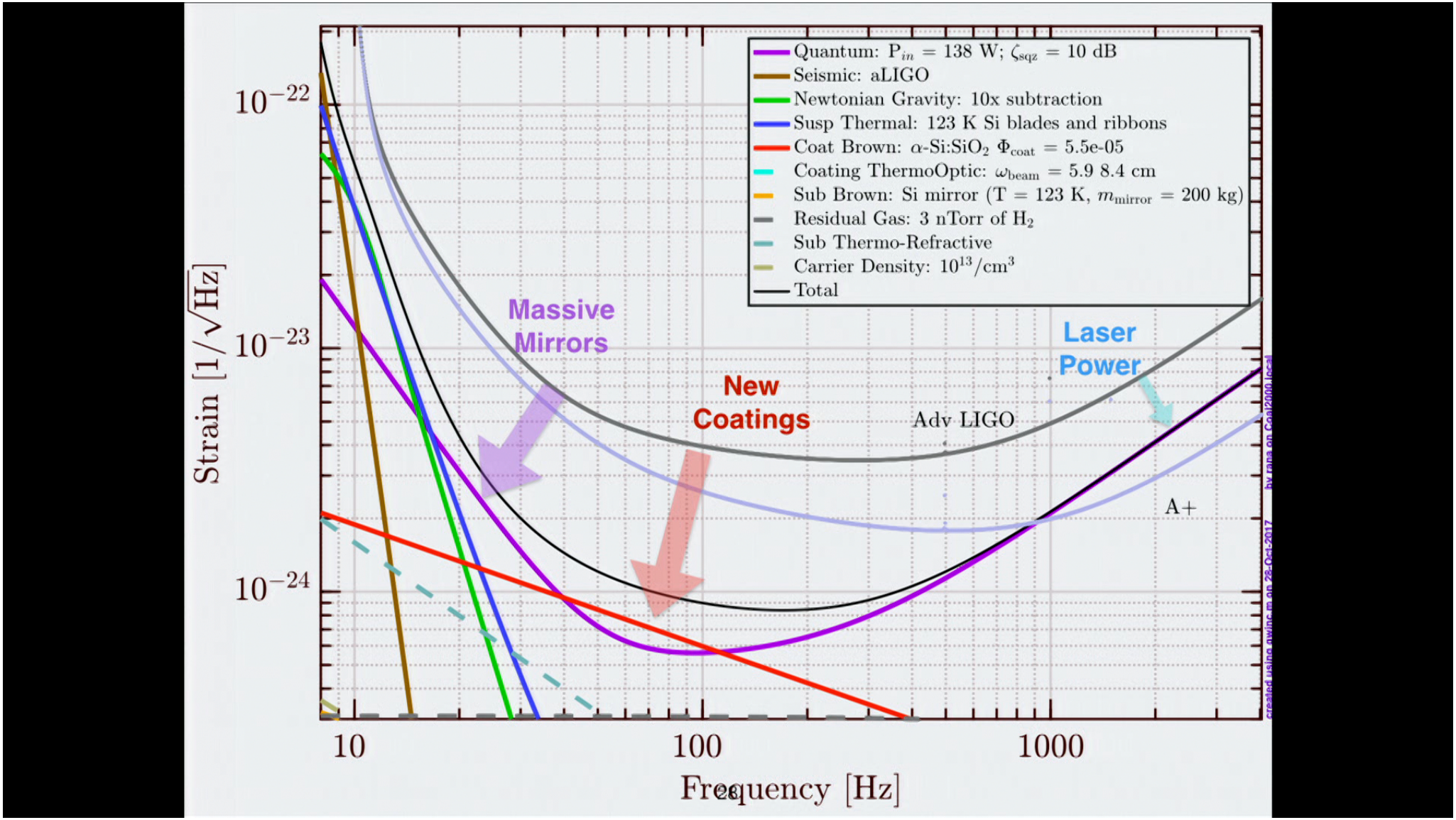


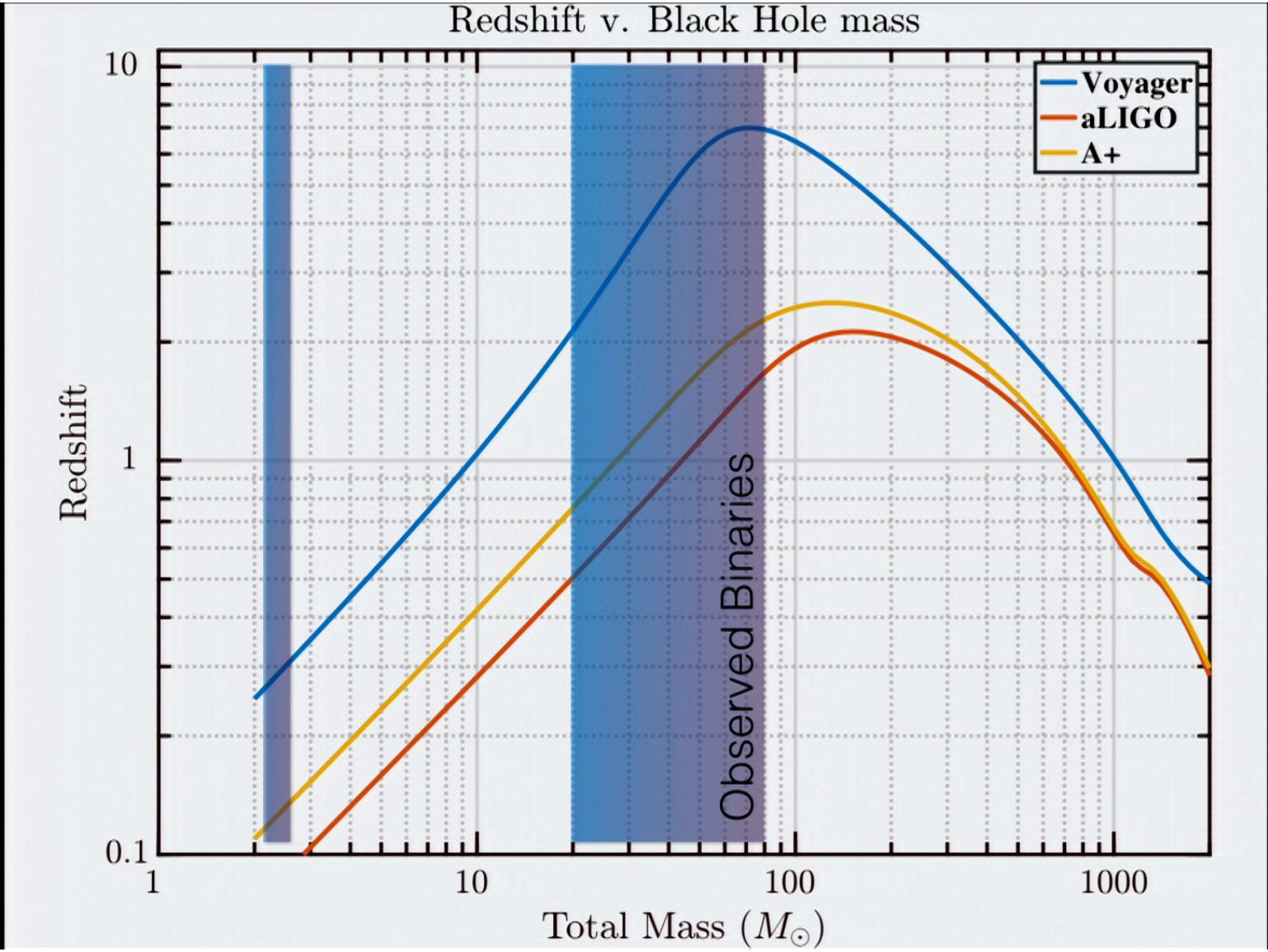


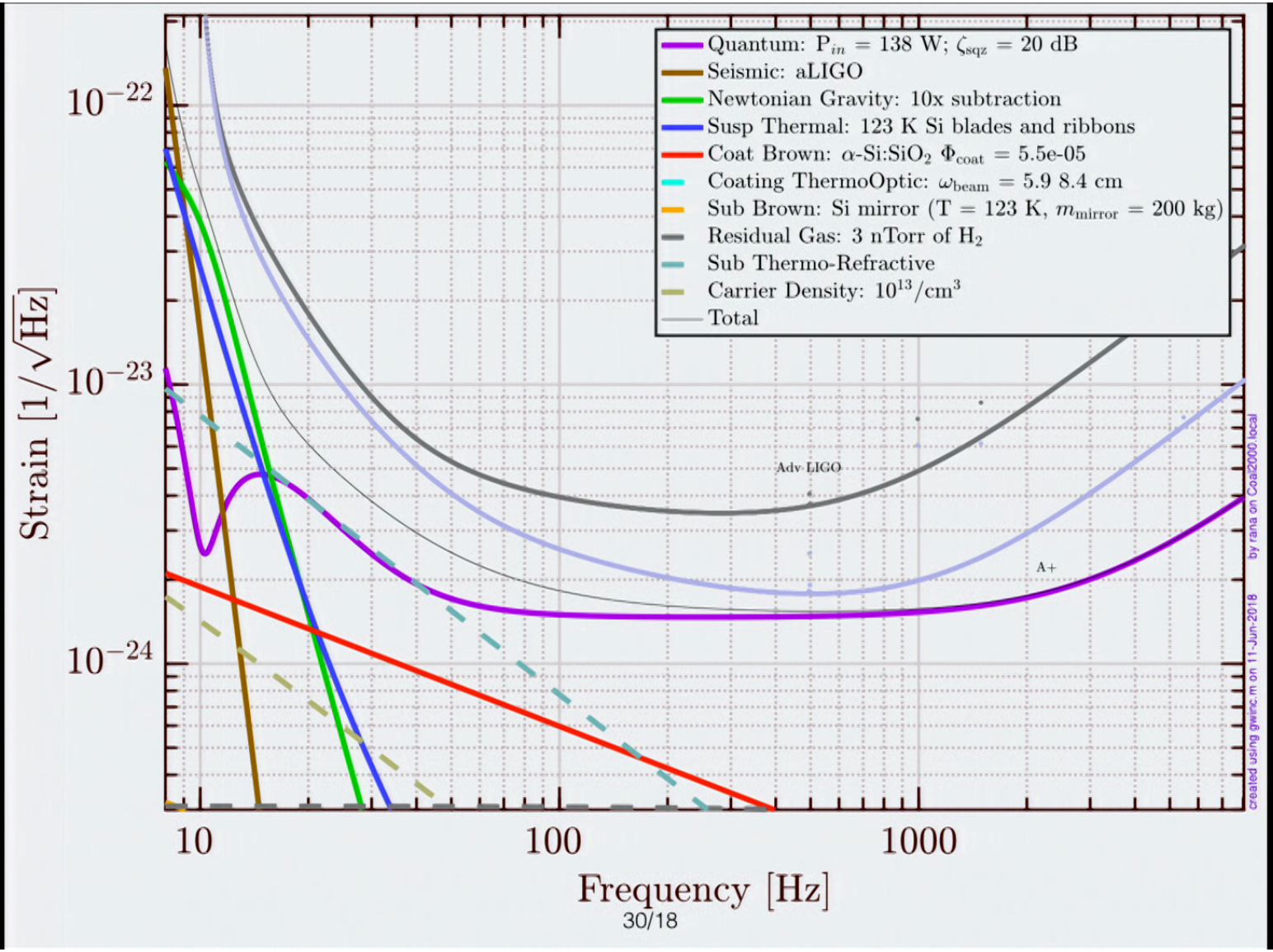


Evan Hall, Kevin Kuns, Gautam V


LIGO Voyager
~2025-2030
T_{ETM} = 5 ppm
T_{ITM} = 0.1%
Silicon
m = 200 kg
T = 123 K
LASER
λ = 2000 nm
P_{in} = 150 W
Φ_m
T_{PRM} = 8%
P_{BS} = 3 kW
BS
T_{SRM} = 5%
P_{cav} = 3 MW


Quantum: P_{in} = 138 W; ζ_{sqz} = 10 dB
Seismic: aLIGO
Newtonian Gravity: 10x subtraction
Susp Thermal: 123 K Si blades and ribbons
Coat Brown: α-Si:SiO_2 Φ_{coat} = 5.5e-05
Coating ThermoOptic: ω_{beam} = 5.9 8.4 cm
Sub Brown: Si mirror (T = 123 K, m_{mirror} = 200 kg)
Residual Gas: 3 nTorr of H_2
Sub Thermo-Refractive
Carrier Density: $10^{13}/cm^3$
Total
Massive Mirrors
New Coatings
Laser Power
Adv LIGO
A+
Strain [$1/\sqrt{Hz}$]
10^{-22}
10^{-23}
10^{-24}
10
100
1000
Frequency [Hz]
28


Redshift v. Black Hole mass
Redshift
10
1
0.1
1
10
100
1000
Total Mass ($M_\odot$)
Voyager
aLIGO
A+
Observed Binaries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Coating ThermoOptic: ω_{beam} = 5.9 8.4 cm
Sub Brown: Si mirror (T = 123 K, m_{mirror} = 200 kg)
Residual Gas: 3 nTorr of H$_2$
Sub Thermo-Refractive
Carrier Density: 10^{13}/cm^3
Total
Adv LIGO
A+
Strain [1/$\sqrt{\text{Hz}}$]
10^{-22}
10^{-23}
10^{-24}
10
100
1000
Frequency [Hz]
30/18
created using gwinc.m on 11-Jun-2018
by rana on Coal2000.local

‘Golden Rule’ for optical scattering

$$\frac{dP}{P} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

- point defects in amorphous thin films
- caused by crystallization during annealing
- Babinet’s Principle
- phased array problem

photo credit: Travis Sedecki / Rick Savage

The Future

- 2019:: 2 LIGOs x2, + 1 Virgo
- 2020:: 2 LIGOs x2, 1 Virgo, 1 iKAGRA
- 2024: LIGO+, Virgo+, KAGRA ?
- 2026: (Cryogenic) LIGO Voyager (5x LIGO)
- 2035+: Einstein Telescope, Cosmic Explorer, *LISA*, **TIANGO**