Title: Macroscopic Quantum Objects

Date: Dec 18, 2014 01:00 PM

URL: http://pirsa.org/14120018

Abstract: <p>With recent advancement of experimental physics, macroscopic objects, which are typically well-described by classical physics, can now be isolated so well from their environment, that their quantum uncertainties can be studied quantitatively. In the research field called â€œoptomechanicsâ€•, mechanical motions of masses from picograms to kilograms are being prepared into nearly pure quantum states, and observed at time scales ranging from nanoseconds to milliseconds. In practice, optomechanics experiments have been constructed to measure extremely weak classical forces, e.g., due to gravitational waves, acting on macroscopic test objects. In this case, experiments must be designed in such a way that quantum uncertainties of the test objects are avoided as much as possible --- often by employing the quantum correlations between the state of light and the motion of the test object, which can build up during the measurement process.</p>

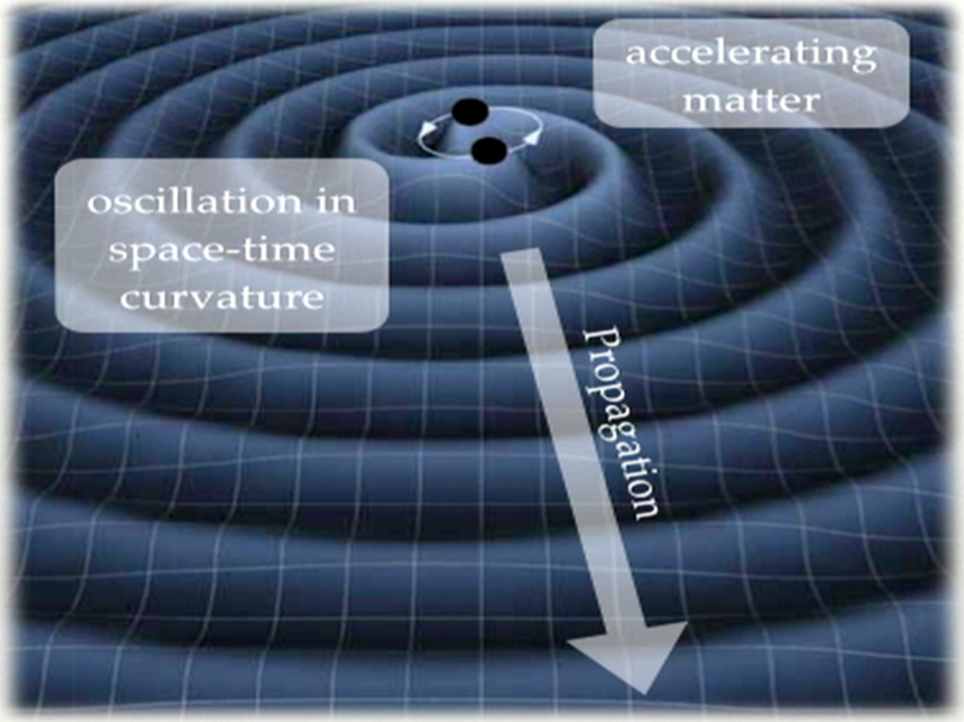
<p>Optomechanics experiments can also be used to search for possible deviations from standard quantum mechanics when macroscopic objects are involved. In this case, experiments are designed to highlight as much as possible the quantum-state evolution of the macroscopic objects. It is hoped that these macroscopic quantum mechanics experiments will either lead our way toward new physics, or at least put experimental constraints on how standard quantum mechanics might be modified.</p>

LIGO Scientific Collaboration

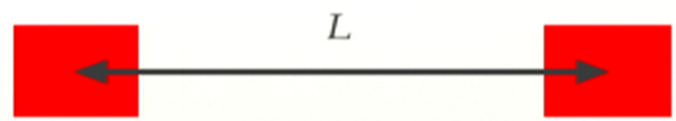
Macroscopic Quantum Objects

Yanbei Chen
California Institute of Technology

Gravitational Waves



Earth

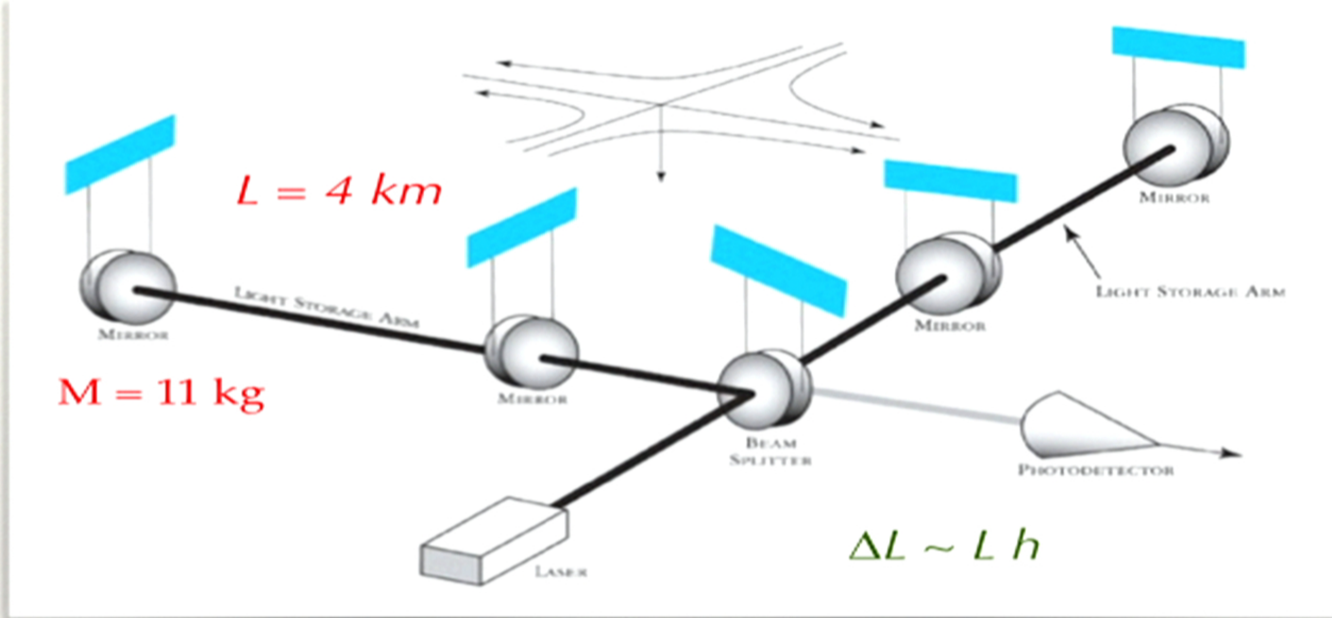


motions of free test masses
separated by $L \ll \lambda$

$\Delta L \sim L\, h$

Laser Interferometer Gravitational Wave Detectors

A detector from the ***Laser Interferometer Gravitational-wave Observatory (LIGO)***



- Michelson Interferometer, with 4 km arms and kg-scale mirrors
- In 2007, $\Delta h \sim 10^{-21}$, $\Delta x \sim 10^{-18}$m at 100 Hz (entire range 10 Hz -- 10 kHz)
  - Each photon resolves $\lambda/F \sim 10^{-8}$m
  - 10^{20} photons injected within 0.01 second
- "Heisenberg Uncertainty": "$\Delta x \cdot \Delta p \sim 100\, \hbar$" $(\Delta p \sim m\Omega \cdot \Delta x)$
- 2nd generation detectors (~2015): "$\Delta x \cdot \Delta p \sim \hbar/2$", 3rd generation, "$\Delta x \cdot \Delta p < \hbar/2$"

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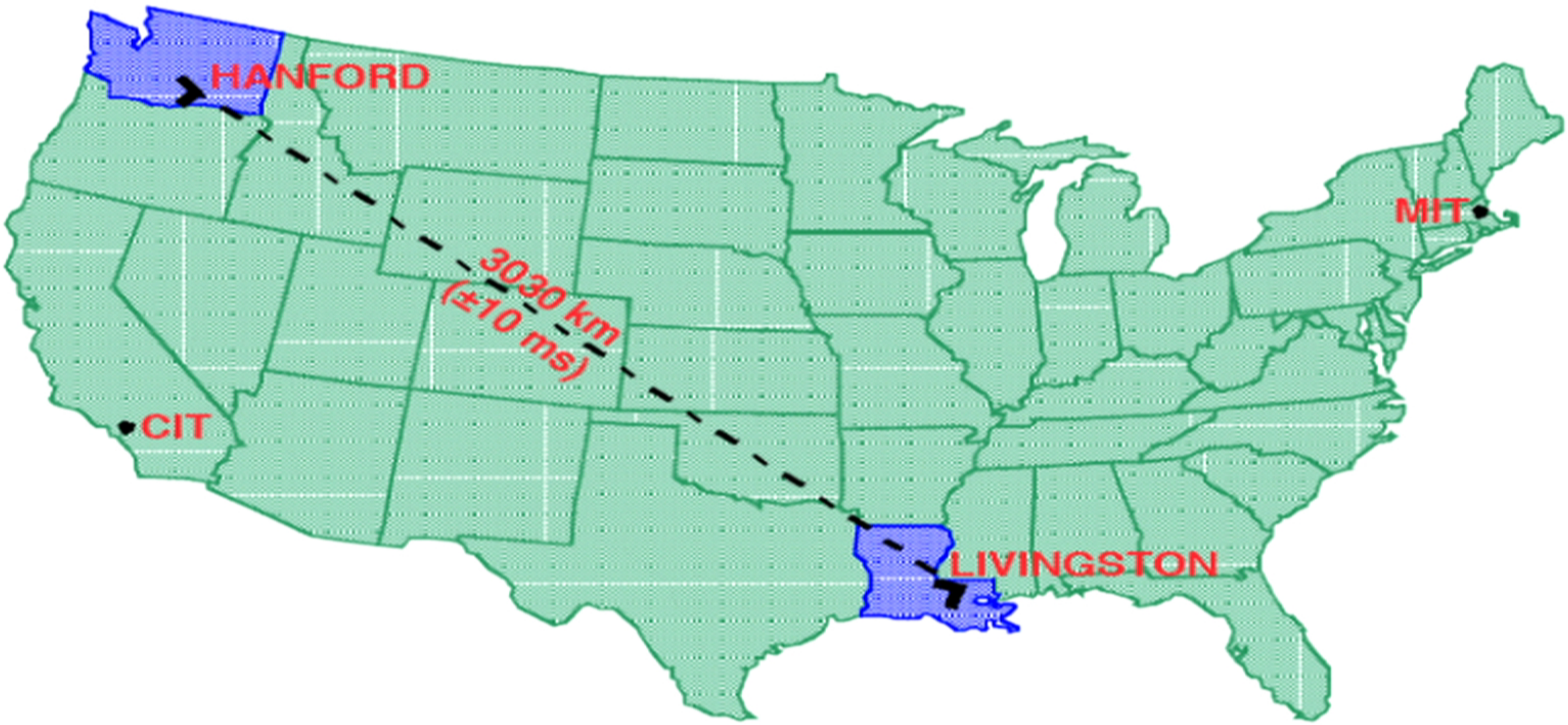
Laser Interferometer Gravitational-wave Observatory (LIGO)



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Laser Interferometer Gravitational-wave Observatory (LIGO)

LIGO Hanford, WA site

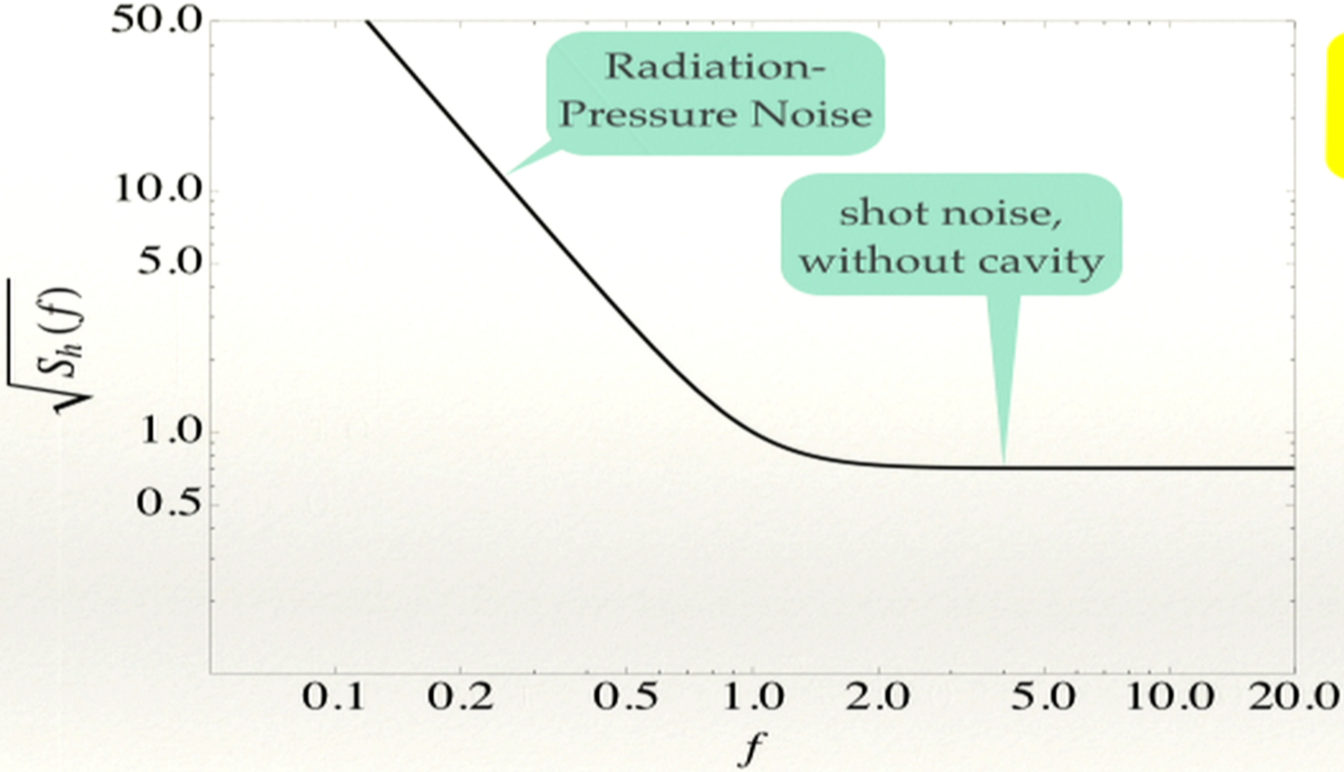
LIGO Livingston, LA site

4

A Global Network

5

Standard Quantum Limit



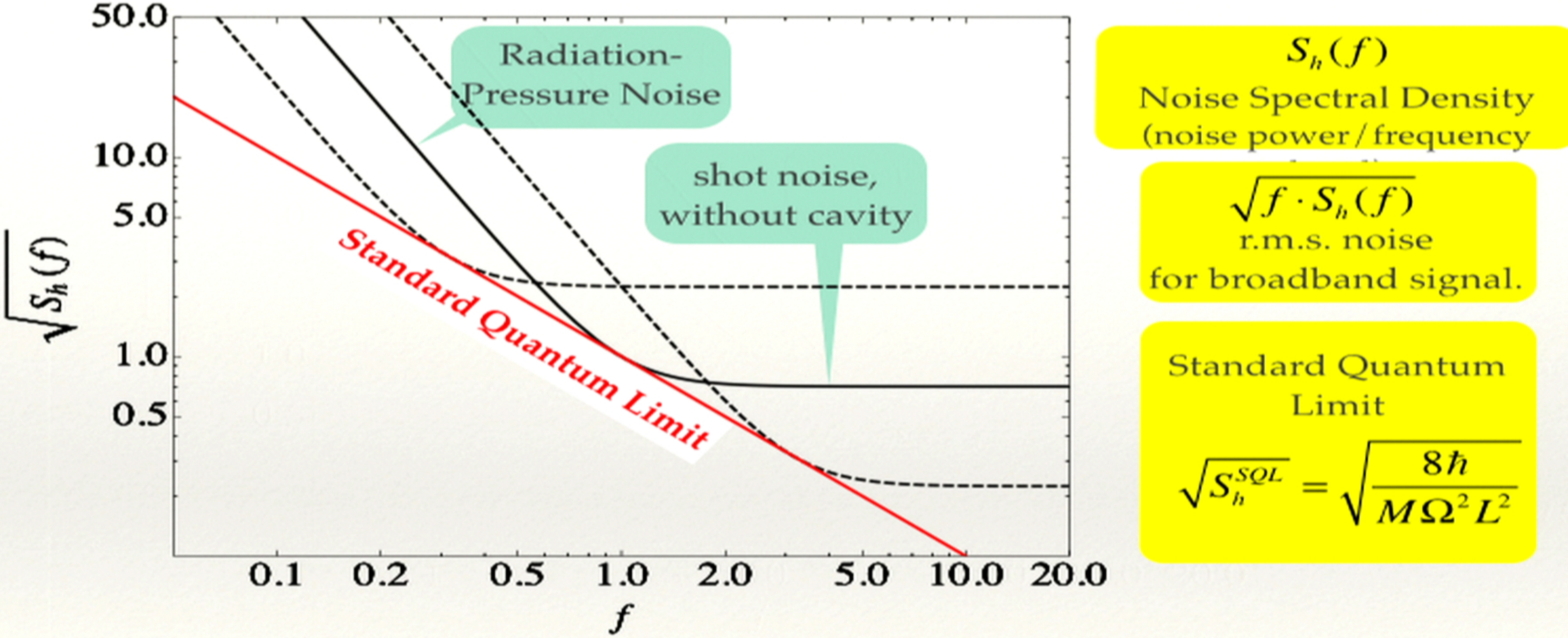
$S_h(f)$
Noise Spectral Density
(noise power / frequency

$\sqrt{f \cdot S_h(f)}$
r.m.s. noise
for broadband signal.

- Shot Noise $\sqrt{S_{shot}} \sim 1/\sqrt{I}$
- Radiation-Pressure Noise $\sqrt{S_{\text{rad press}}} \sim \sqrt{I}/(M\Omega^2)$

6

Standard Quantum Limit



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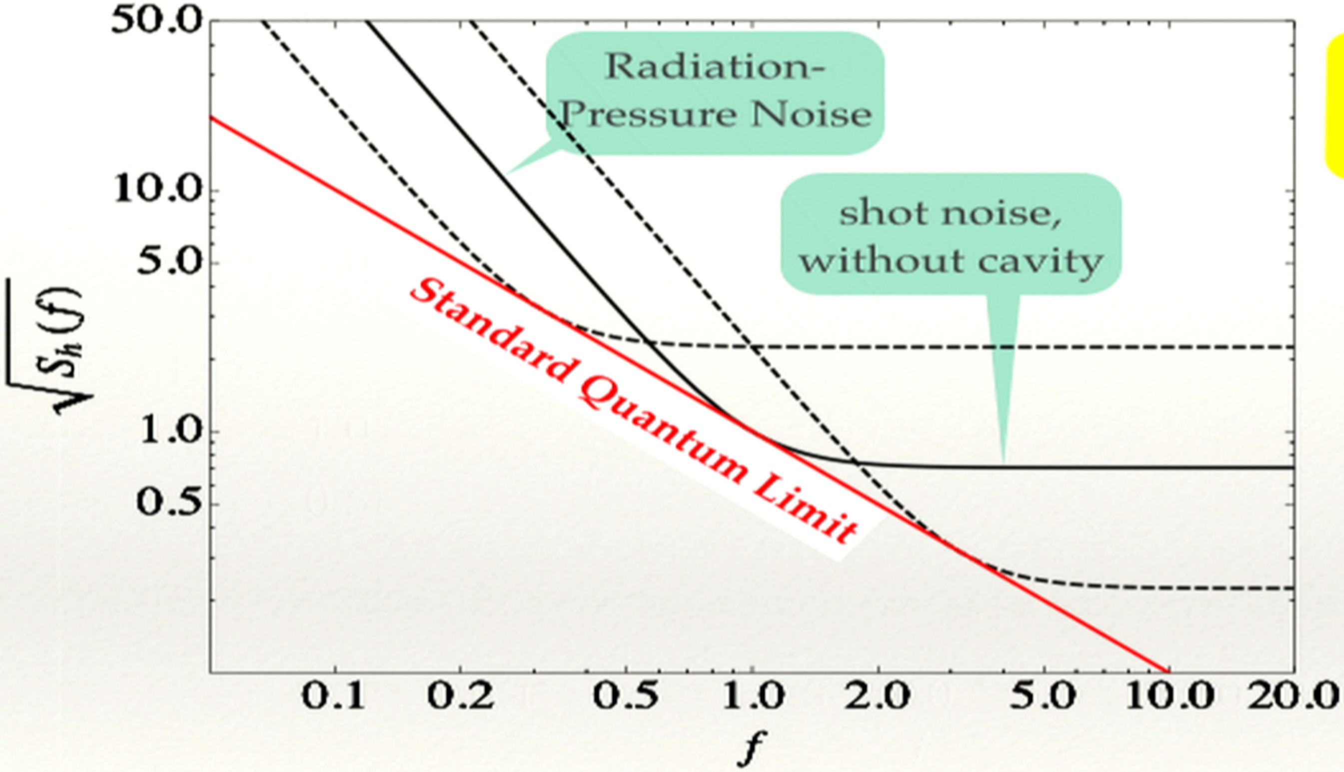
Trade-off Between Shot Noise and Radiation-Pressure Noise: Standard Quantum Limit

Standard Quantum Limit



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Standard Quantum Limit

$$\sqrt{S_h^{SQL}} = \sqrt{\frac{8\hbar}{M\Omega^2 L^2}}$$

at SQL:
"$\Delta x \cdot \Delta p = \hbar/2$"

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Upgrading Advanced LIGO Detectors

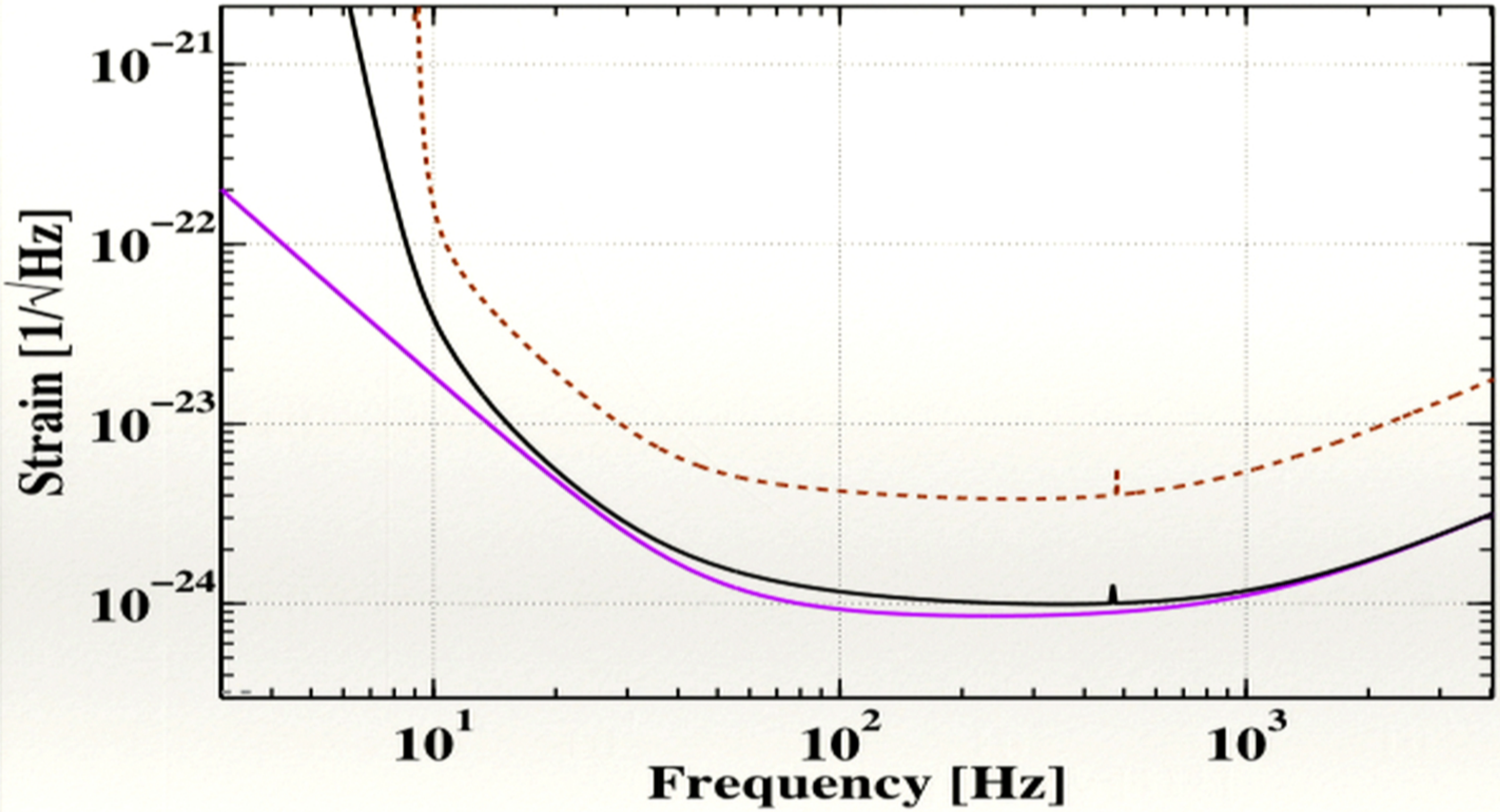

figure from R. Adhikari et al.,
Instrumentation Science White Paper
LIGO-T1300433

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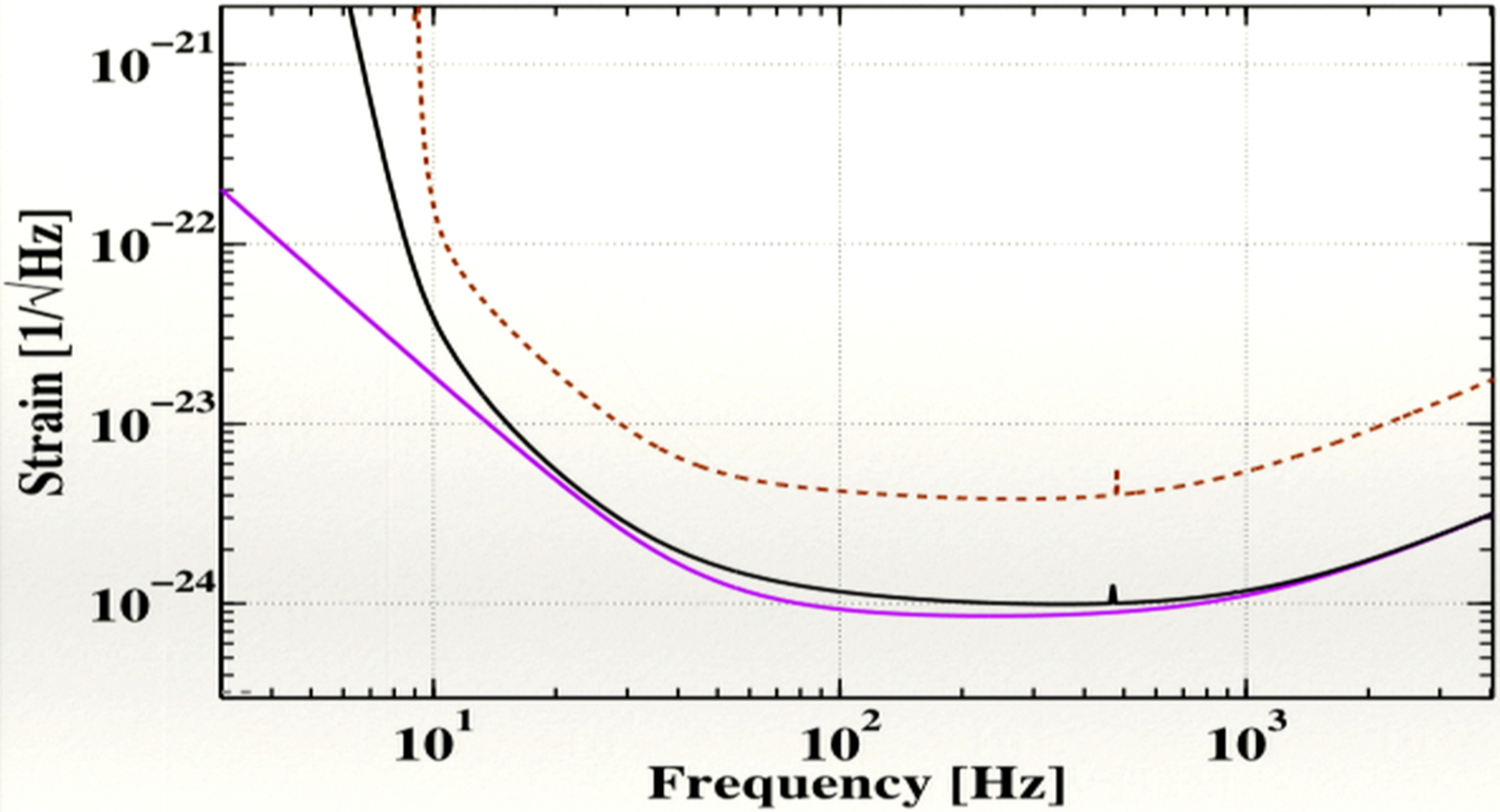

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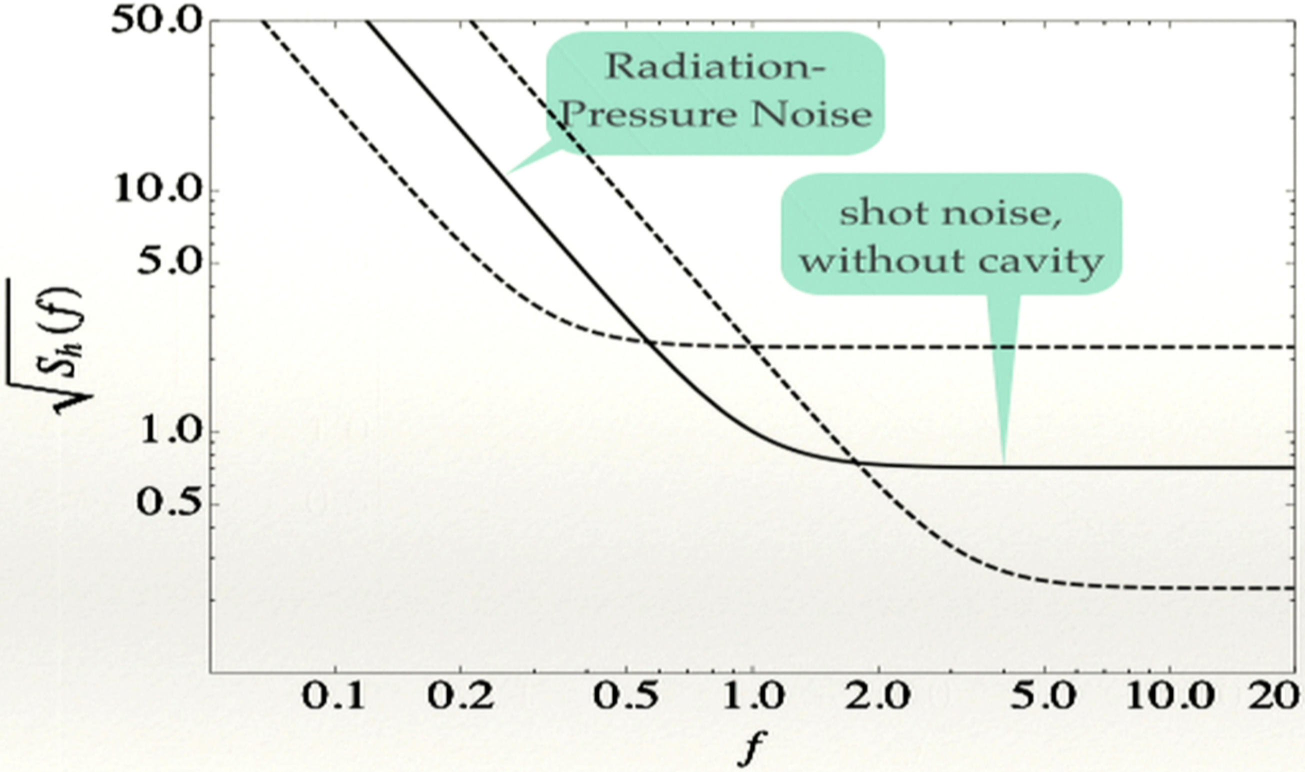

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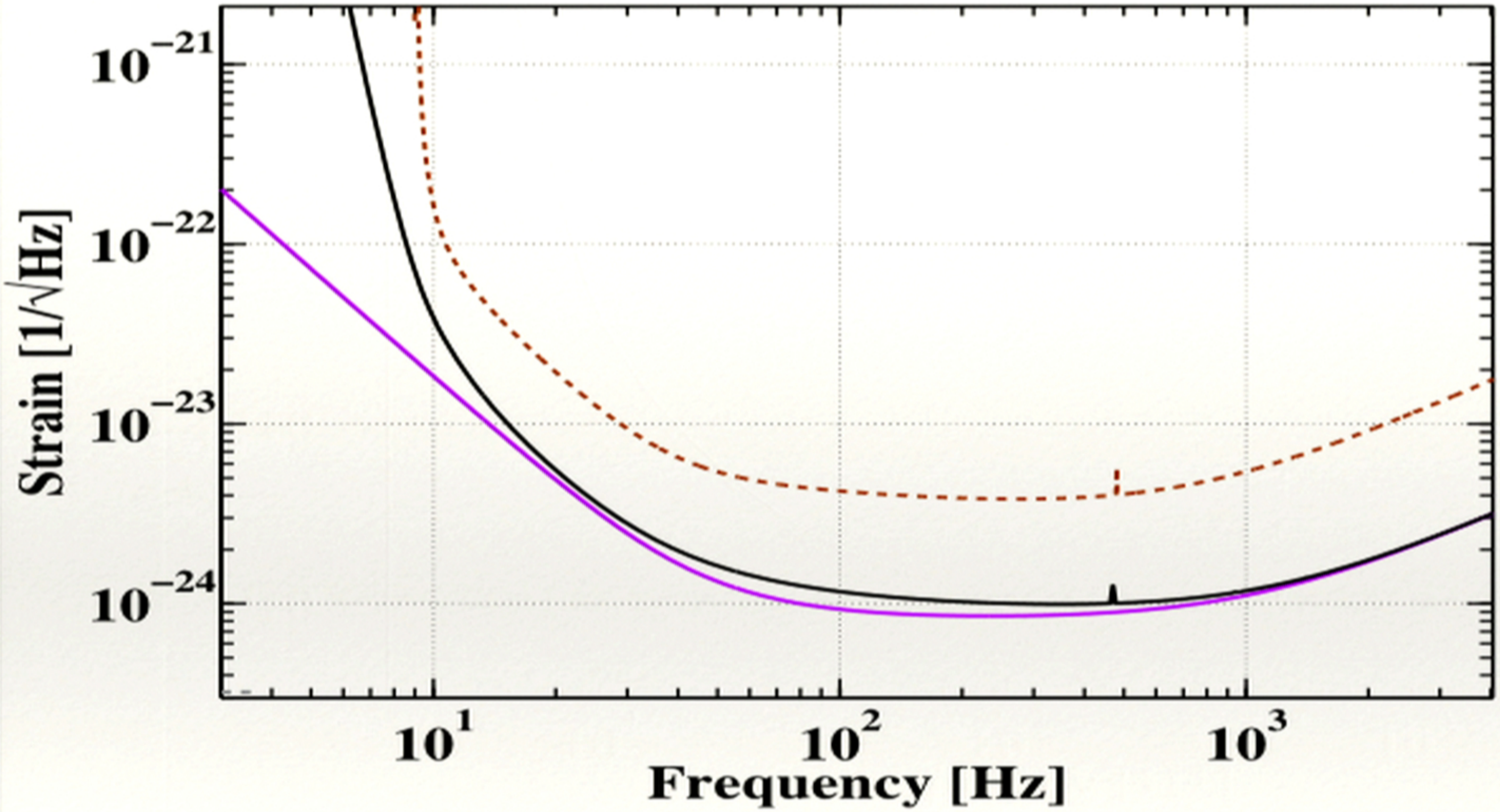

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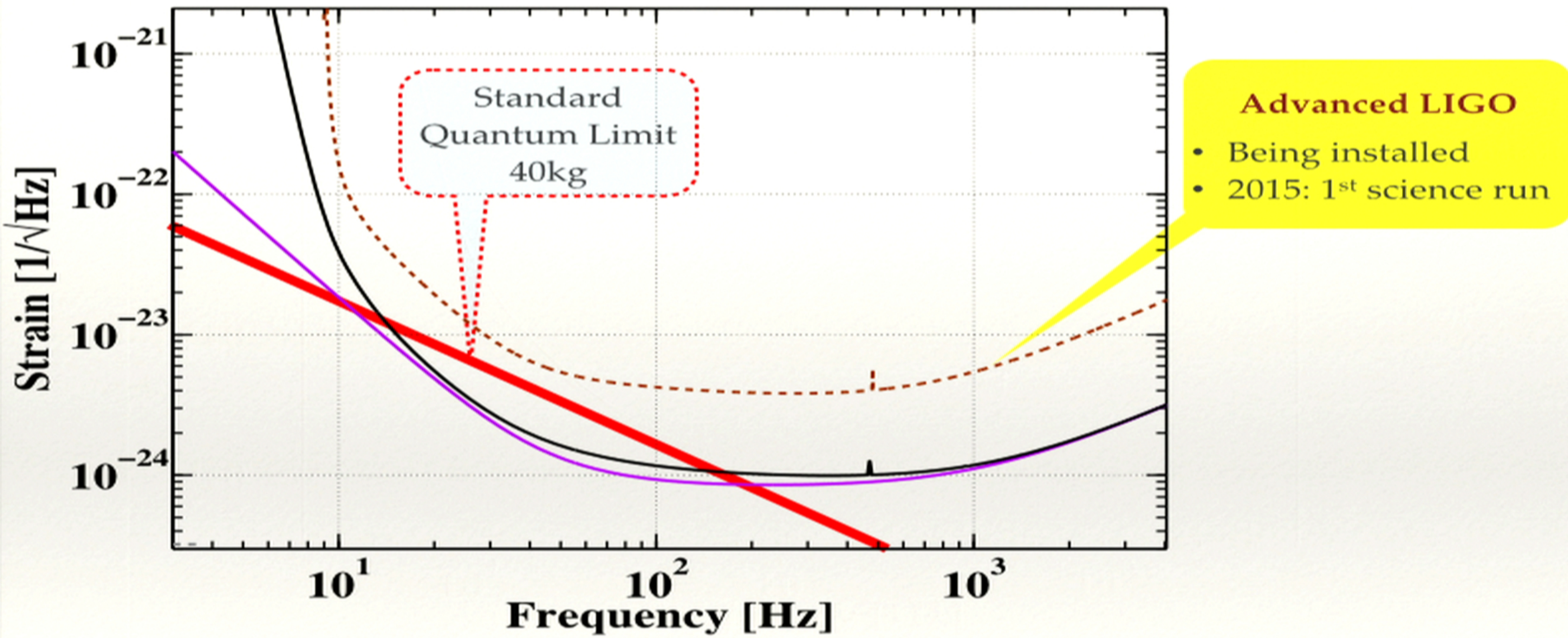

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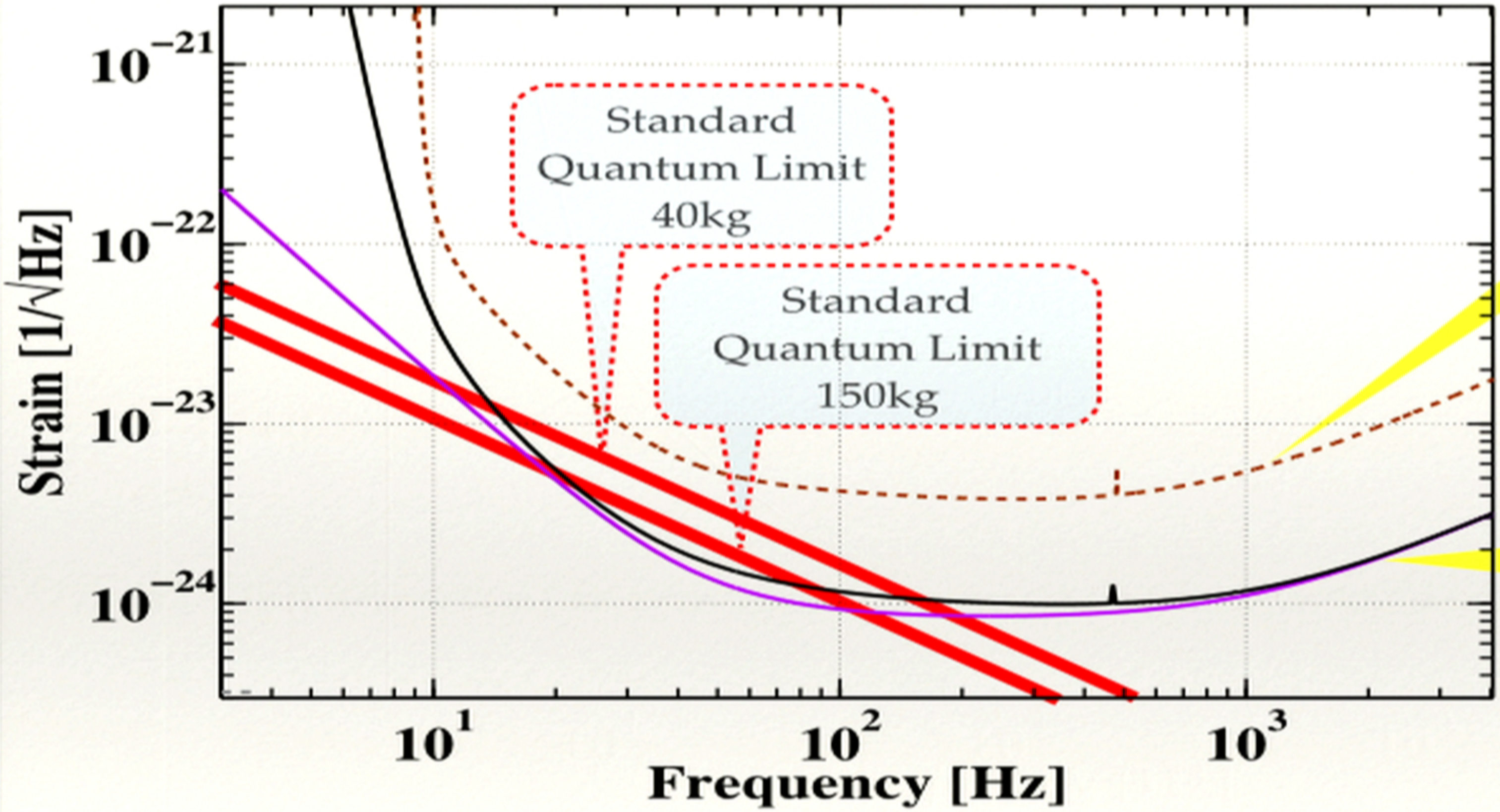


Advanced LIGO

- Being installed
- 2015: 1st science run

LIGO-3

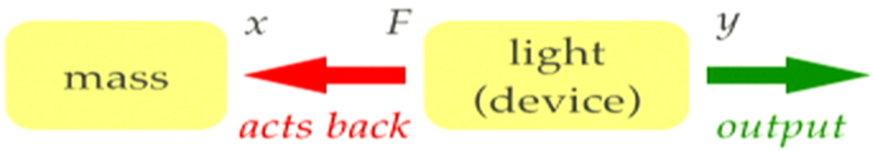
(after some detections)
more detections
more types of sources
more precise
knowledge

figure from R. Adhikari et al.,
Instrumentation Science White Paper
LIGO-T1300433

Origin of the Standard Quantum Limit

test-mass device coupling

$V_I = -\alpha x \cdot F$



- Output field contains: $y = Z + \alpha\left[x_{\text{zero-point}} + x_{\text{signal}} - \alpha\frac{F}{M\Omega^2}\right]$

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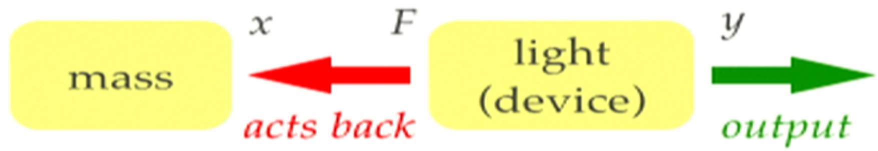

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- Heisenberg Uncertainty Principle: $S_{ZZ} S_{FF} - |S_{ZF}|^2 \geq \hbar^2$

- Total noise spectrum: $$S_{xx}^{\;sig} = \frac{S_{ZZ}}{\alpha^2} + \alpha^2 \frac{S_{FF}}{M^2 \Omega^4} - 2\,\mathrm{Re}\,\frac{S_{ZF}}{M\Omega^2} + S_{xx}^{\;\text{zero-point}}$$

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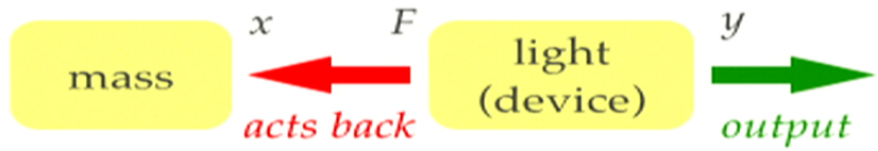

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sensing noise | noise from ZPF | signal | back-action noise

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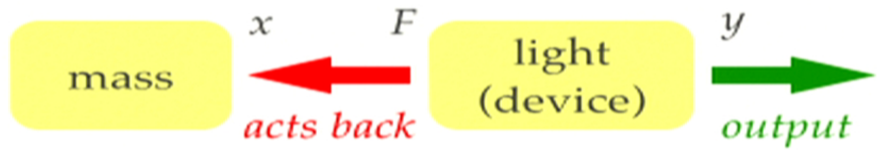
IF $S_{ZF}=0$: $$\frac{S_{ZZ}}{\alpha^2} + \alpha^2\frac{S_{FF}}{M^2\Omega^4} \geq 2\sqrt{\frac{S_{ZZ}S_{FF}}{M^2\Omega^4}} \geq \frac{2\hbar}{M\Omega^2} \equiv S_{xx}^{\text{SQL}}$$

8

Origin of the Standard Quantum Limit

test-mass device coupling

$$V_I = -\alpha x \cdot F$$



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  sensing noise (Z); noise from ZPF ($x_{\text{zero-point}}$); signal (x_{signal}); back-action noise ($\alpha \frac{F}{M\Omega^2}$)

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correlation between sensing and back-action noise

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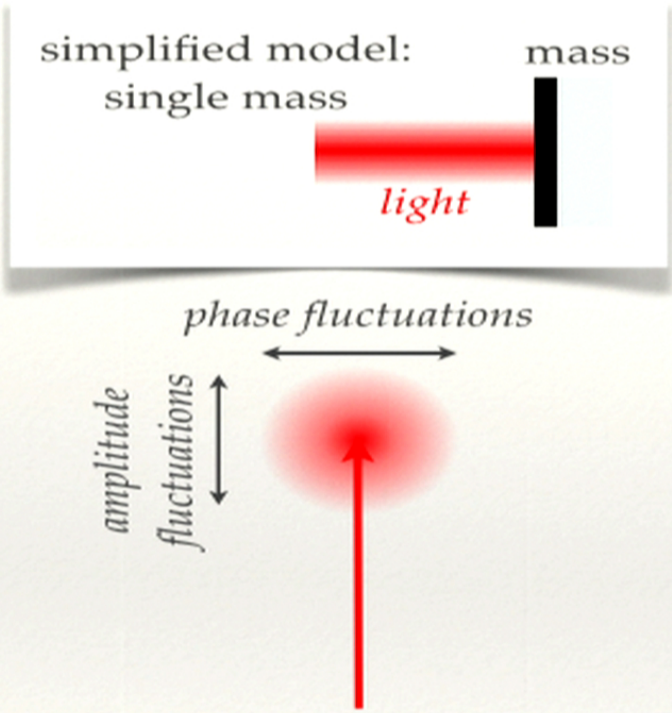
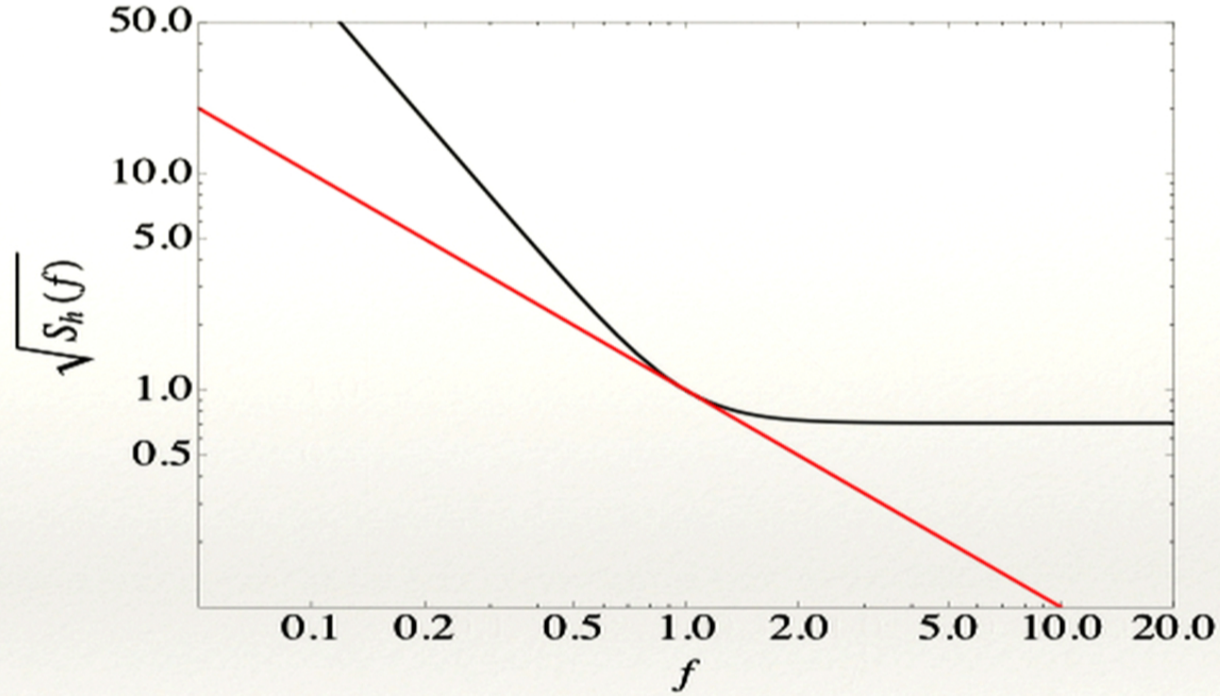
Building the Necessary Correlation

[Caves, Unruh, 1990s; H.J. Kimble et al., 2001]





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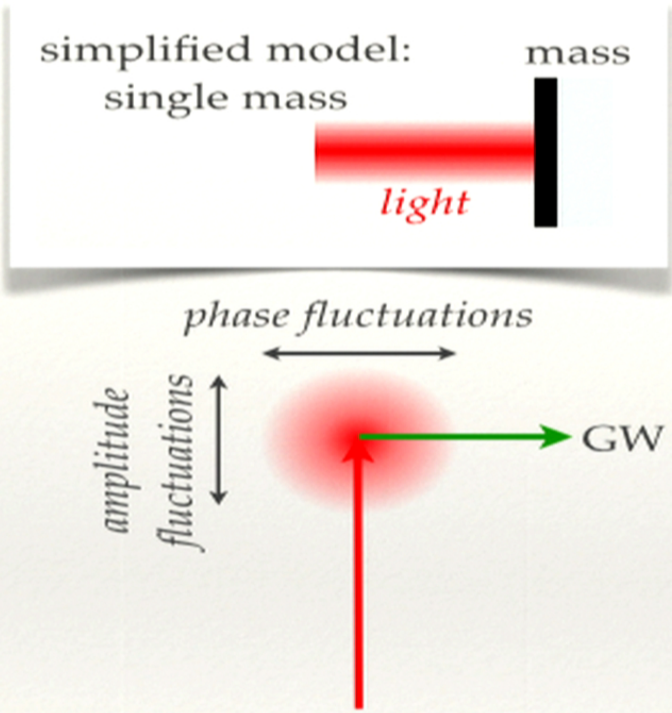

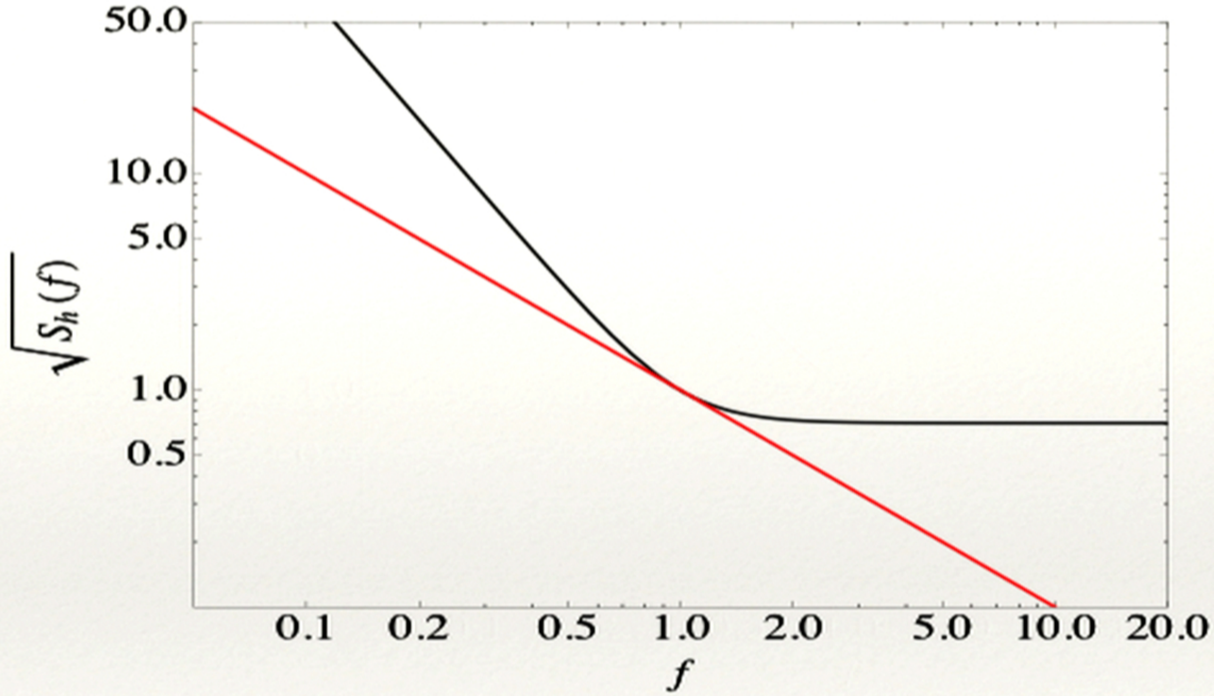

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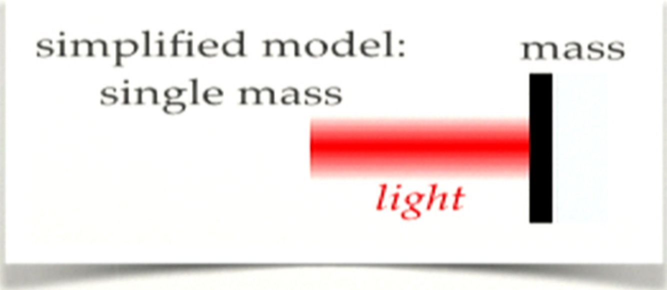

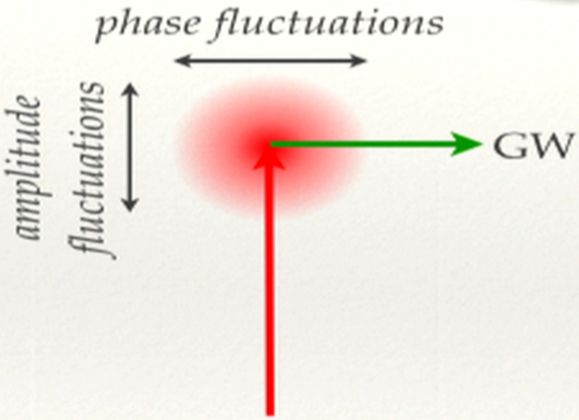

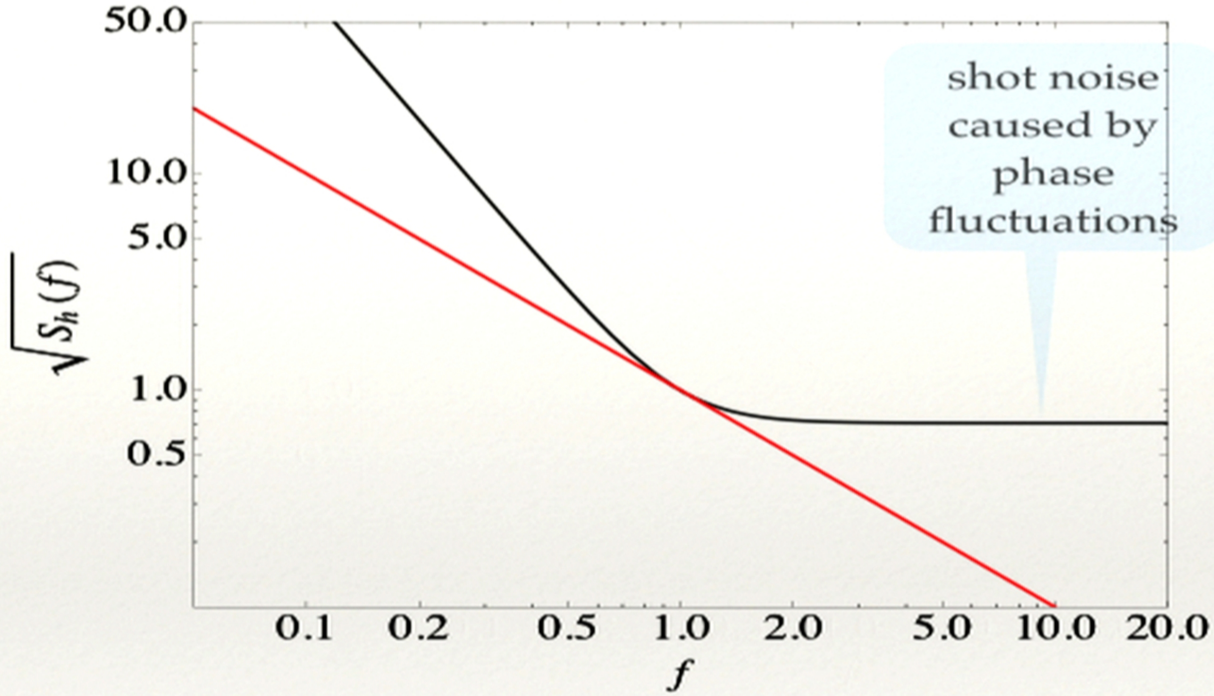

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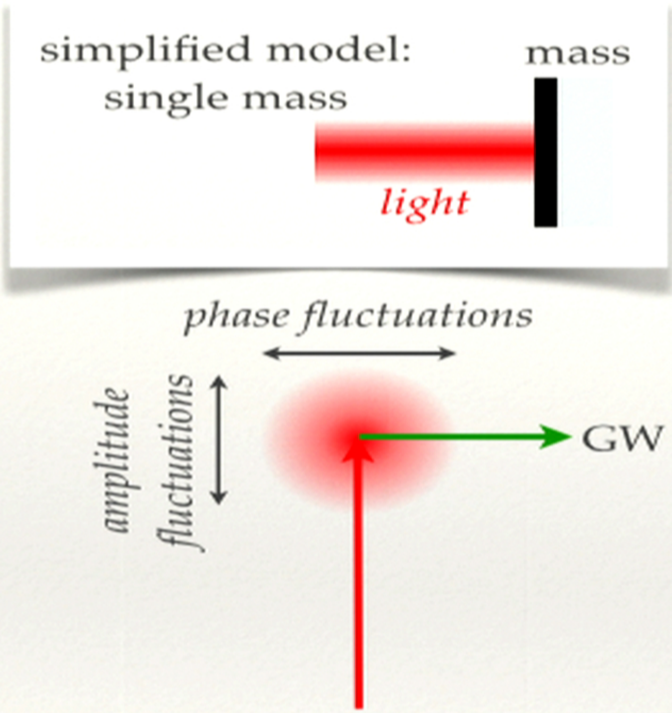

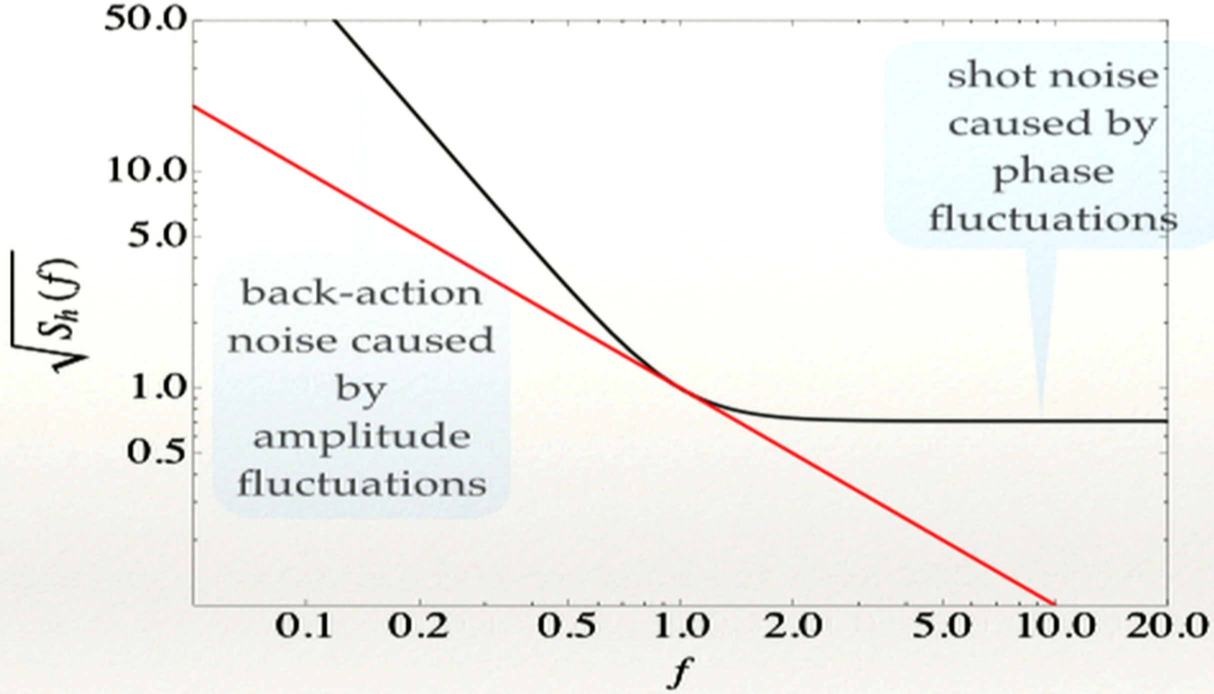

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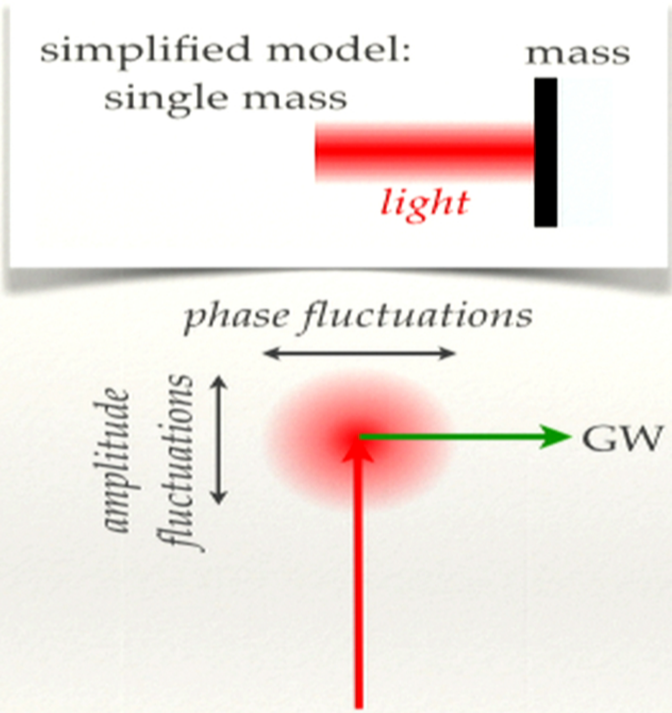

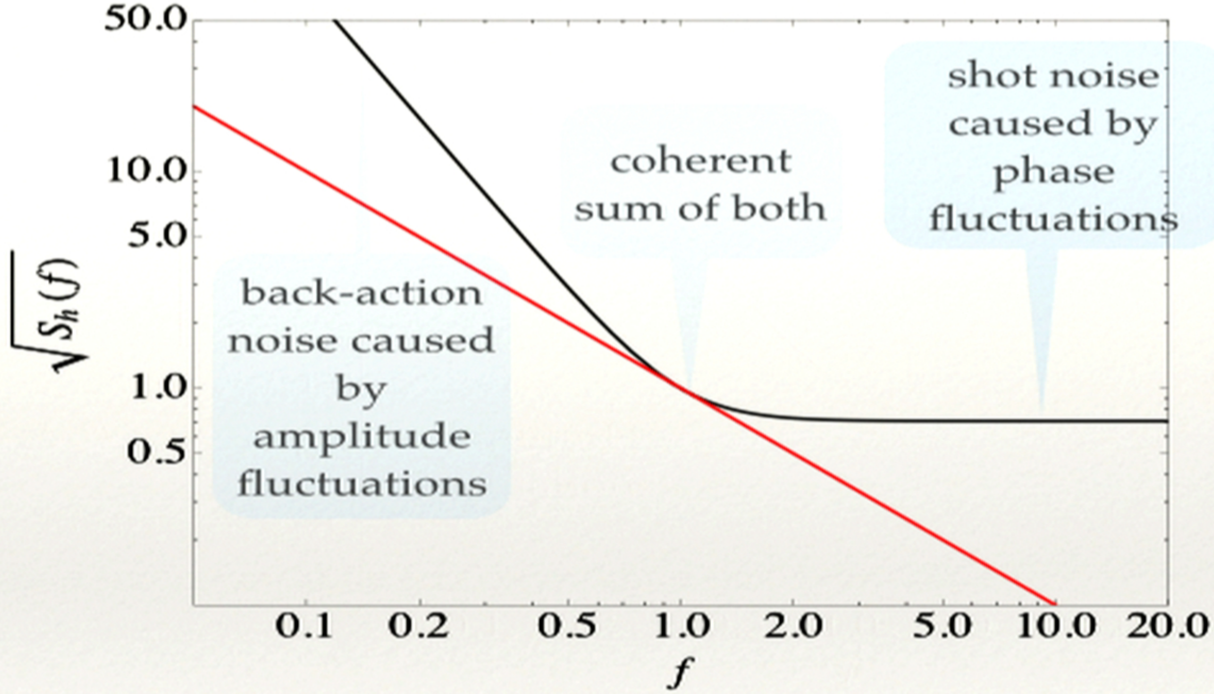

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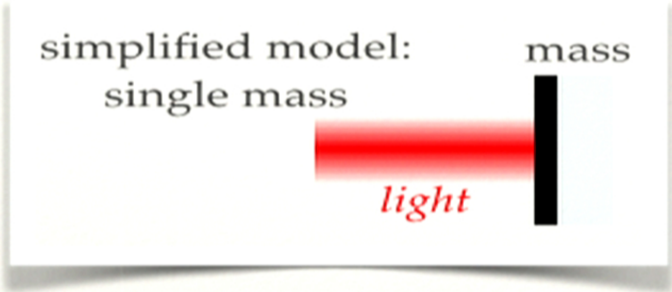

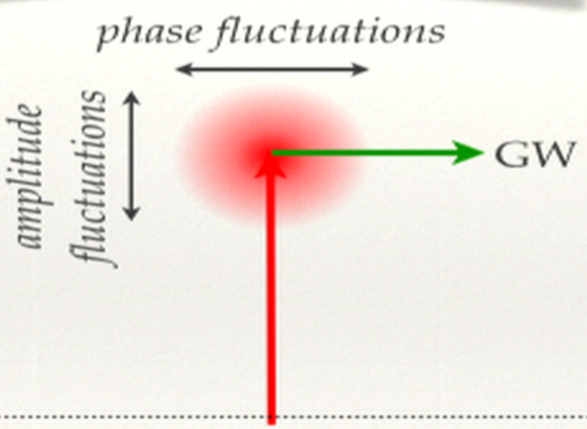

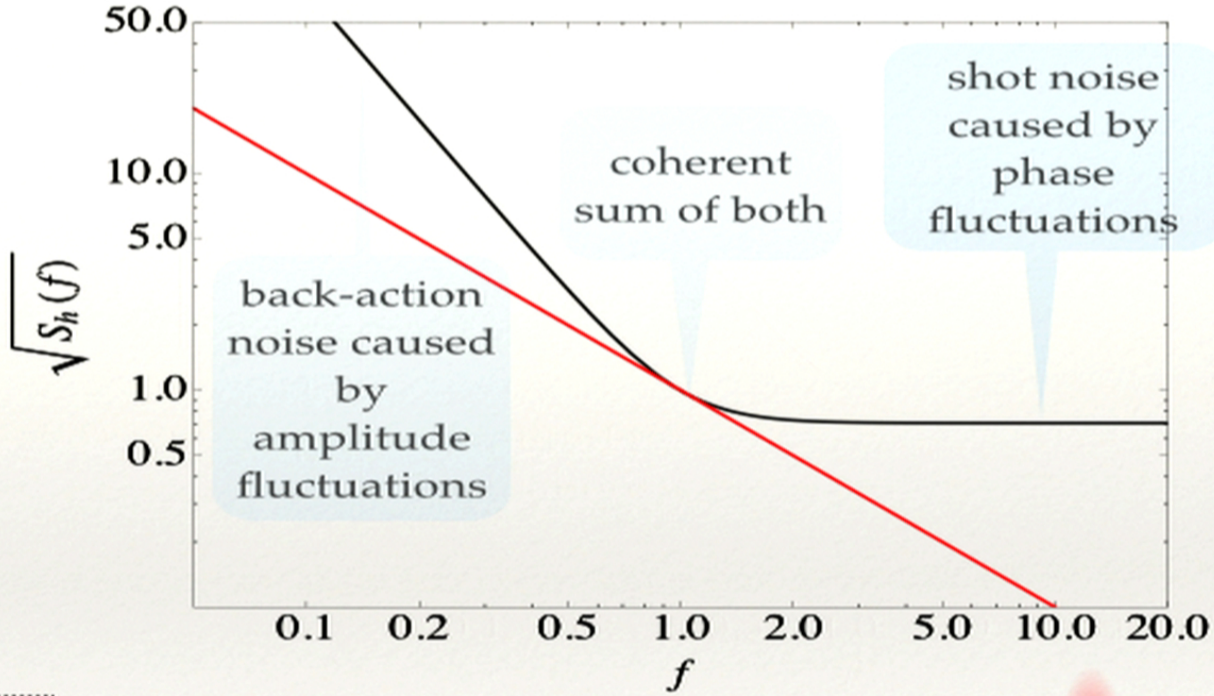

phase squeezed

EM field can be prepared into "squeezed states"

Wu, Xiao & Kimble, 1987
R. Schnabel, N. Mavalvala, D.E. McClelland & P. K. Lam, 2010

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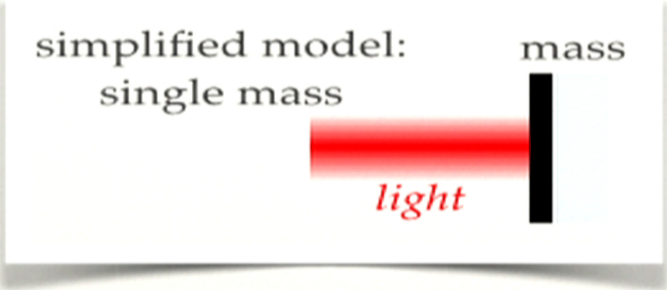

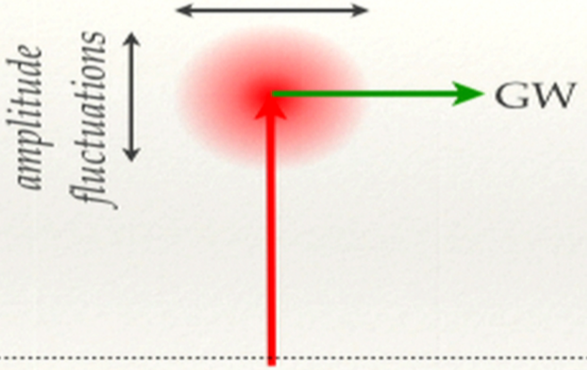

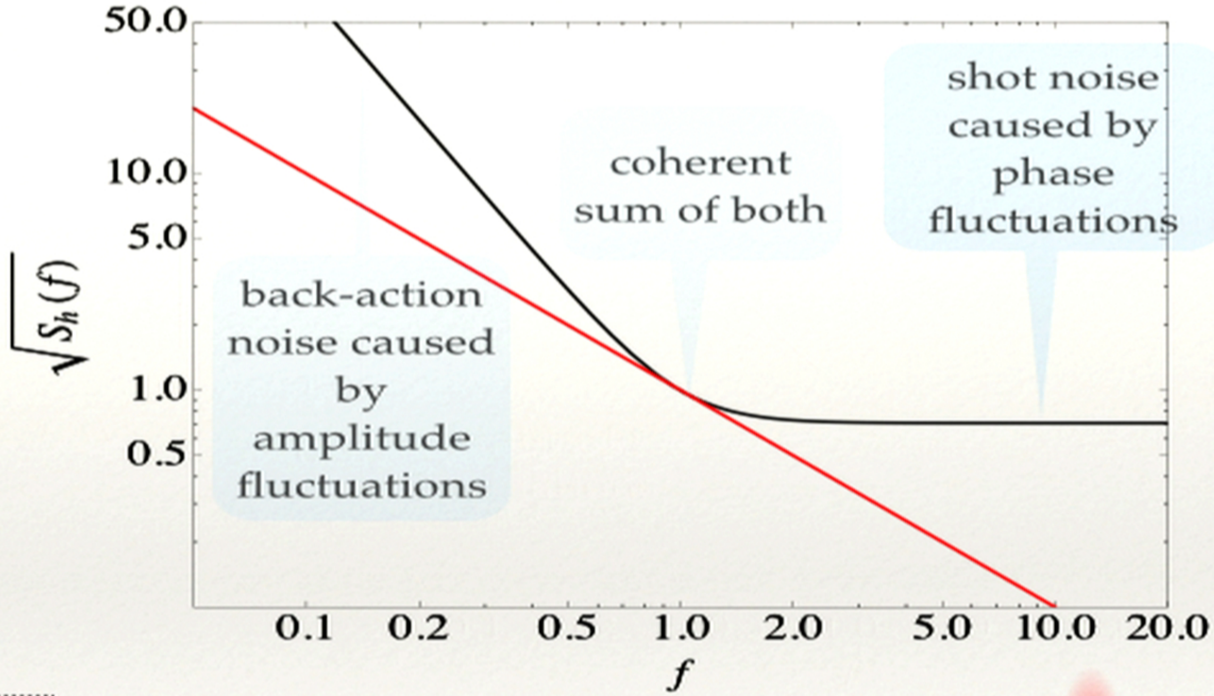

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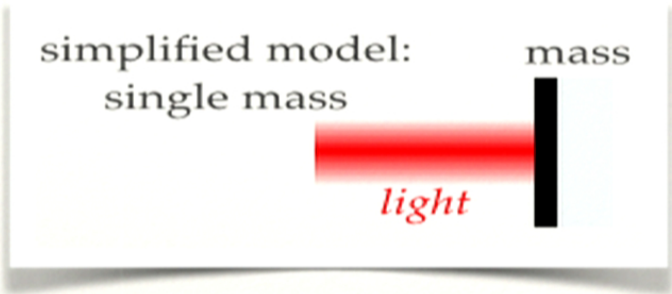

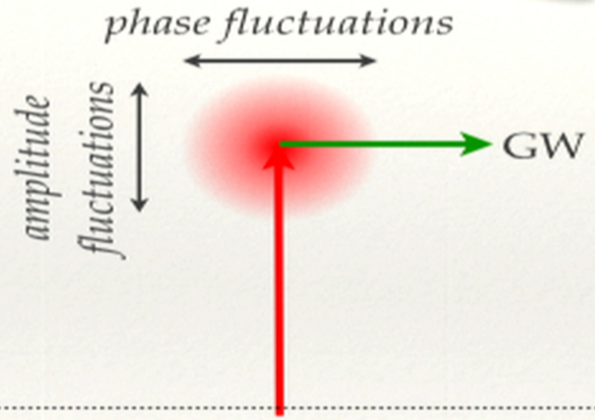

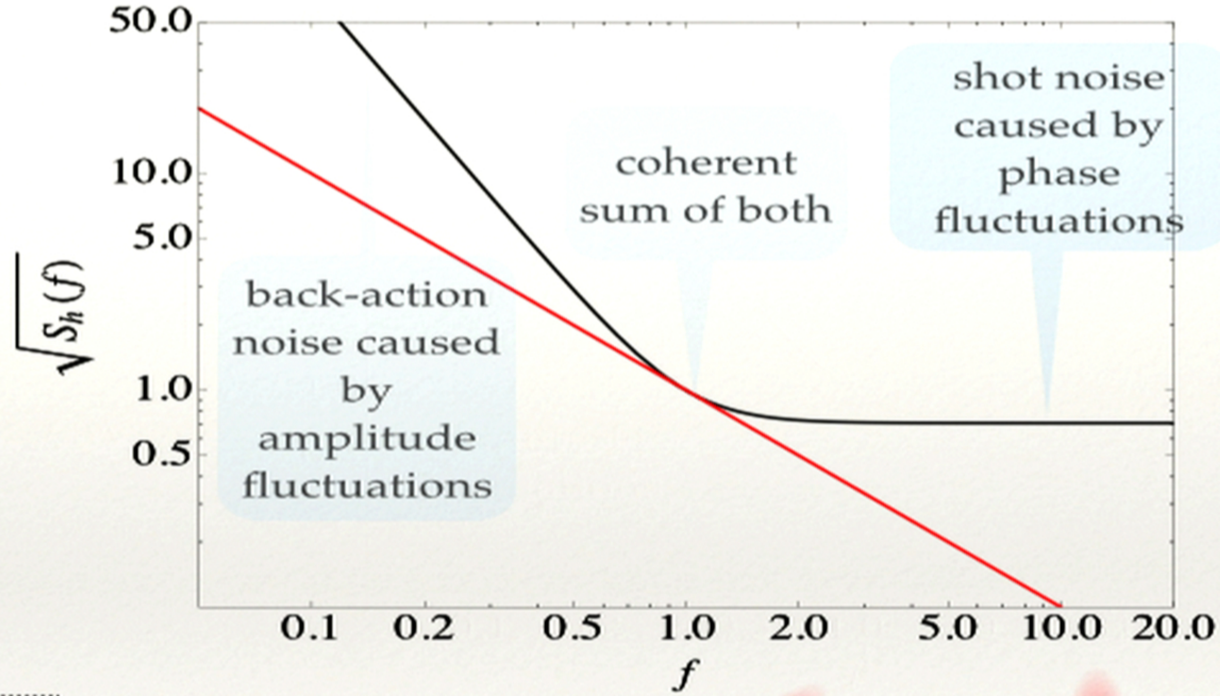

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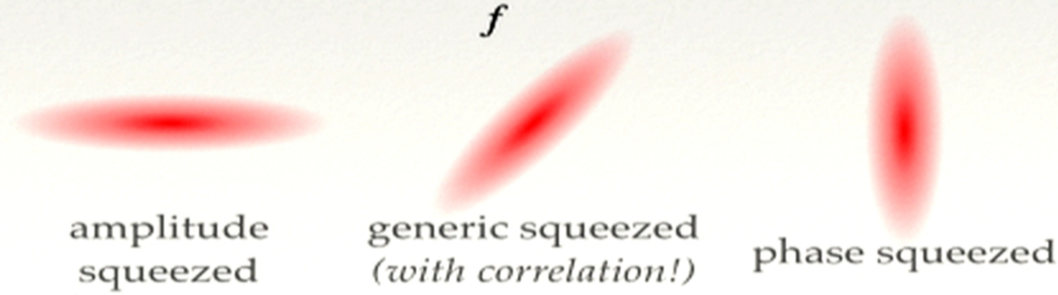

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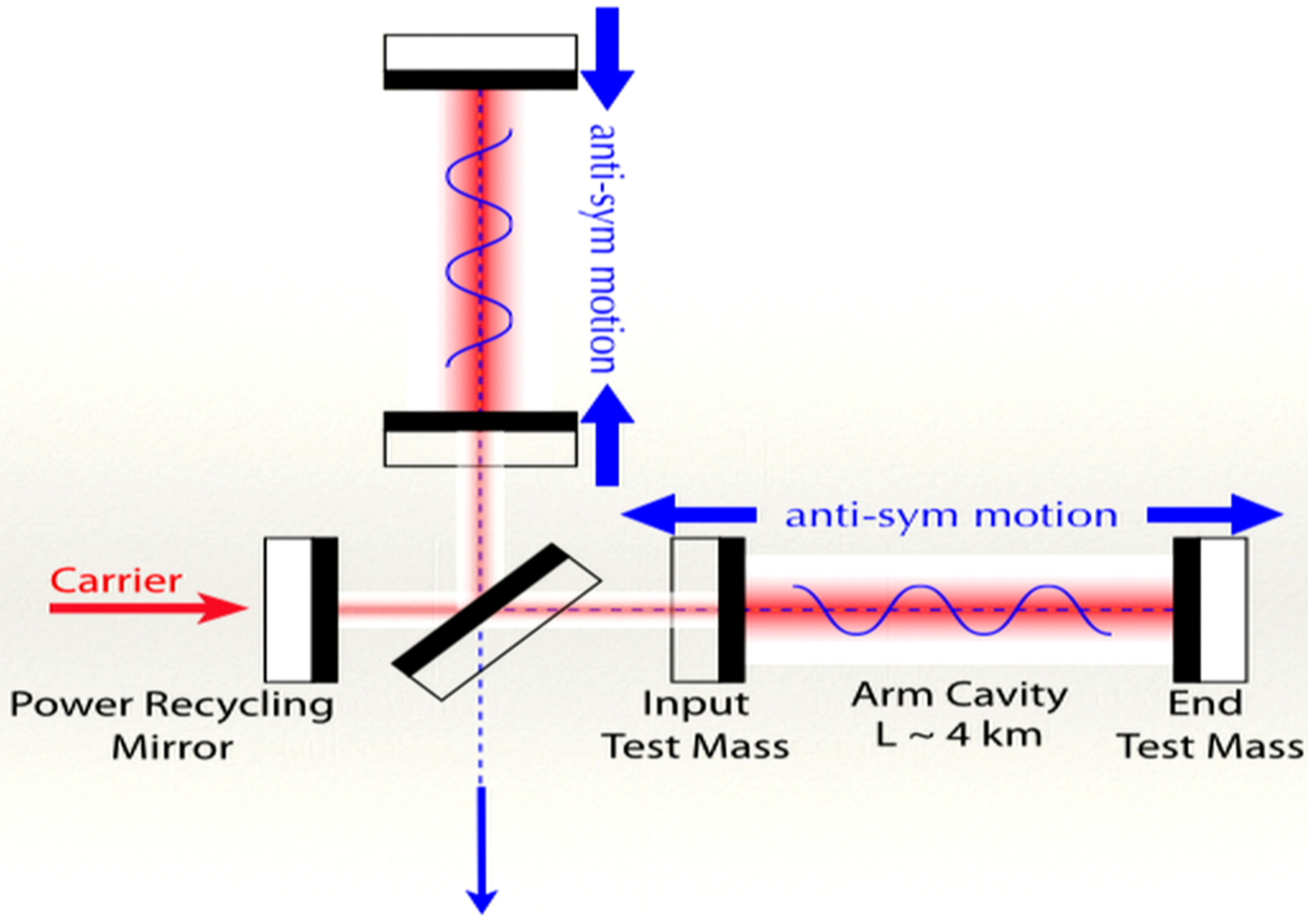
Injection of Squeezed Vacuum



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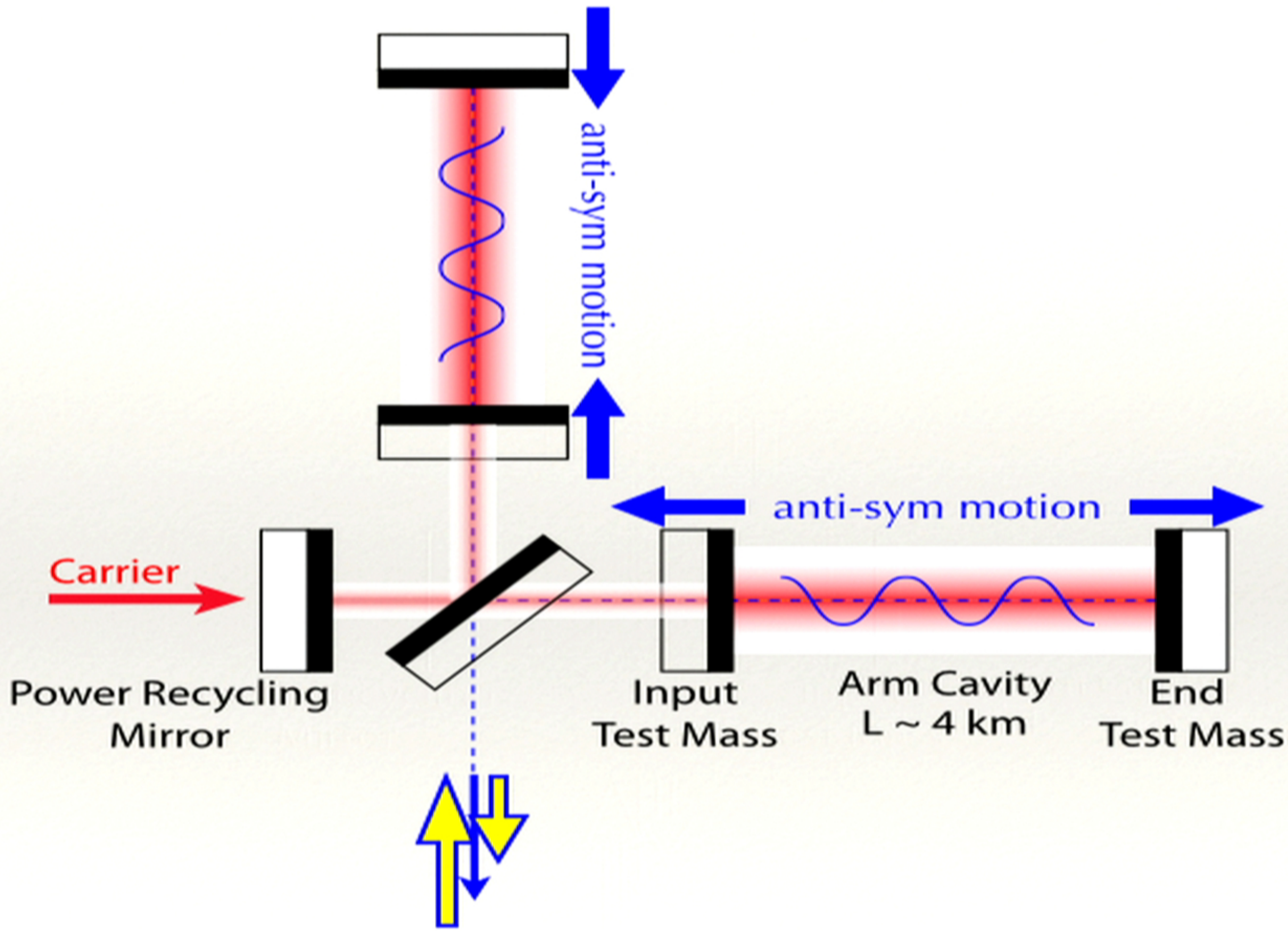

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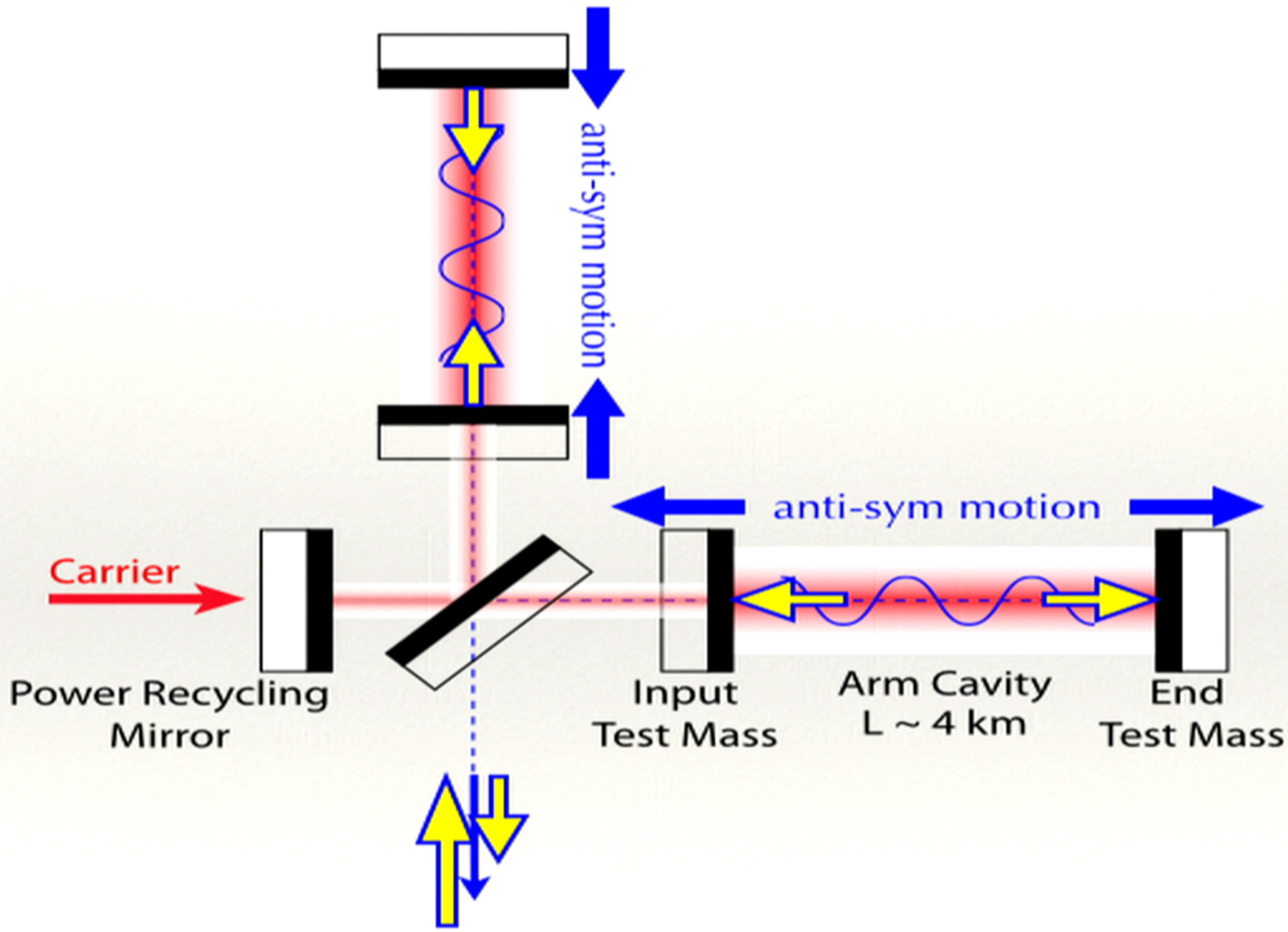
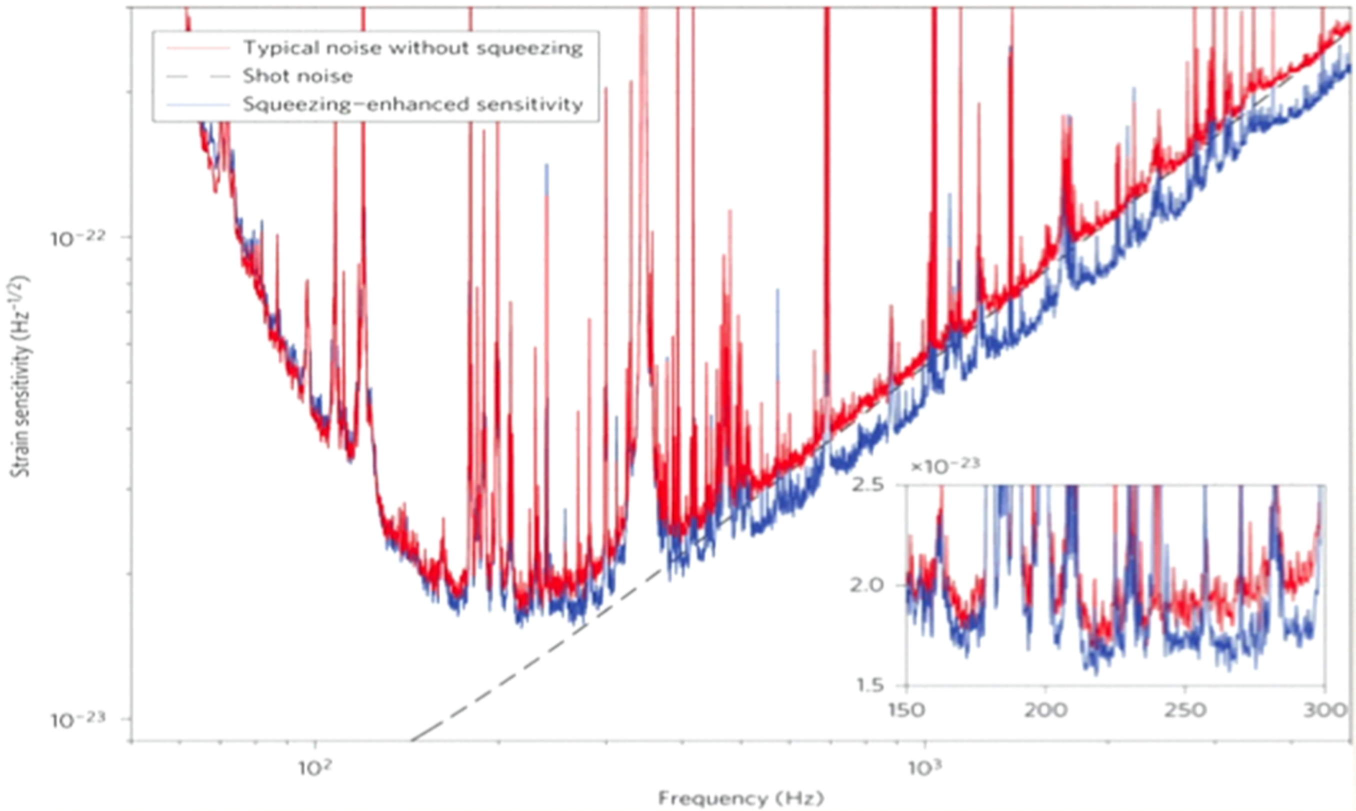


10

Squeezing in LIGO



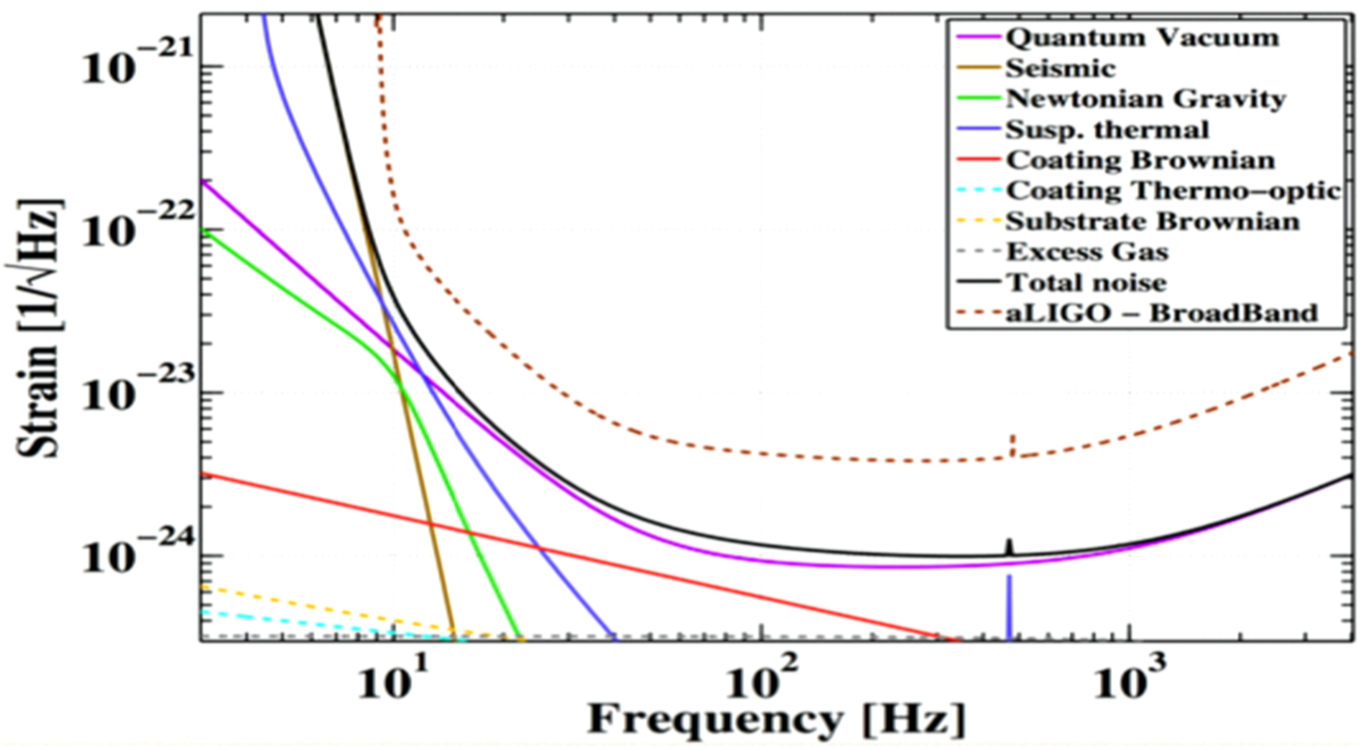
Phase Squeezing in LIGO

[LIGO Scientific Collaboration, 2013]

limited by optical losses

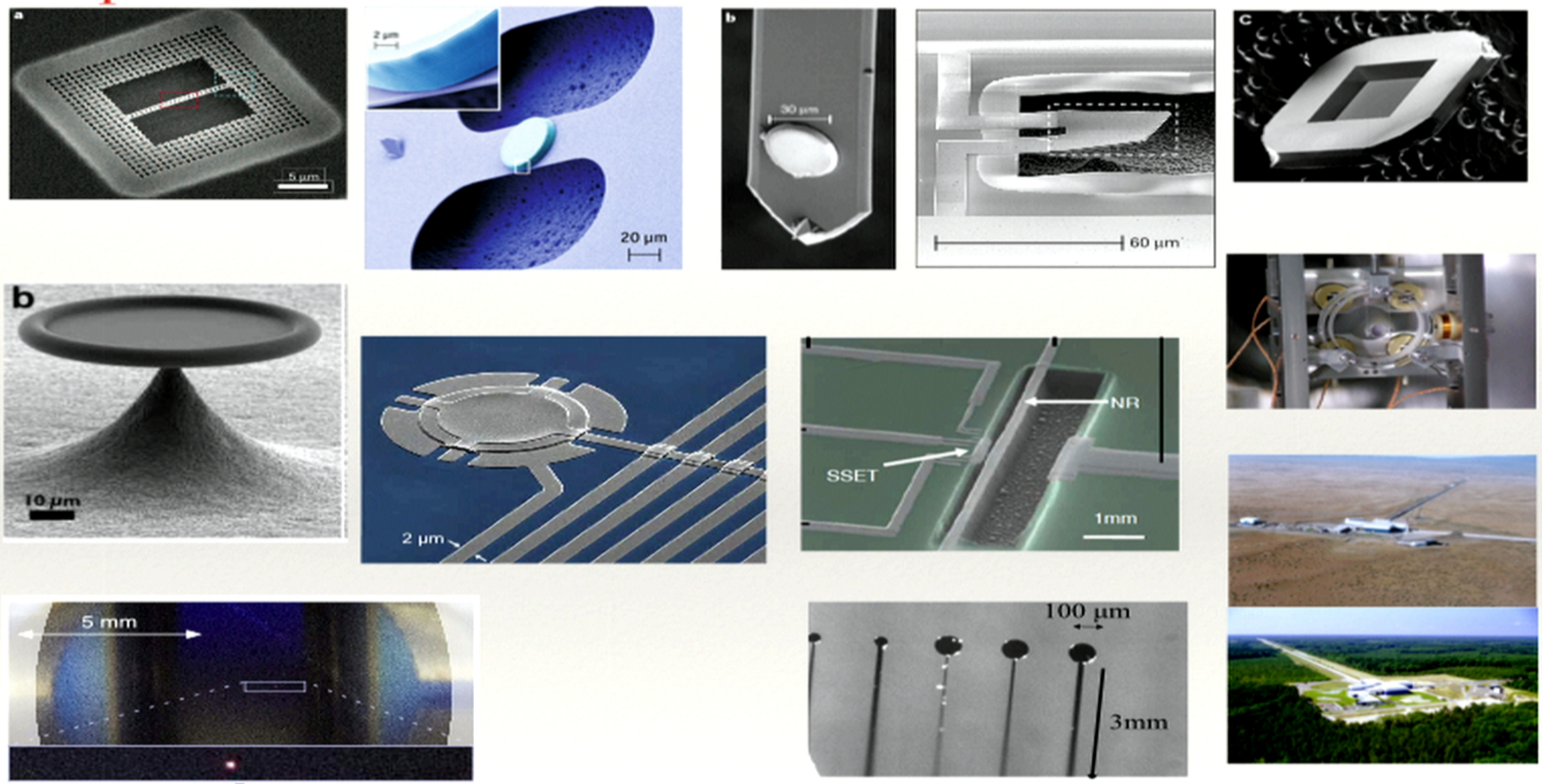
- initial LIGO
  - ~2dB squeezing
- Advanced LIGO
  - permits ~6 dB
- LIGO-3
  - frequency-dependent
  - requires "filter cavities"

Other sources of noise ...



R&D in LIGO makes test masses “more and more quantum“

Optomechanics/Electromechanics at Different Scales



Macroscopic Quantum Mechanics

Demonstration of (Macroscopic) Quantum Mechanics

- Prepare & verify quantum states (e.g., entanglement) of macroscopic objects
- Prepare quantum states without classical counterparts
- Quantum state of macroscopic objects can be reconstructed through tomography.

[review articles by Aspelmeyer, Kippenberg and Marquardt, 2013; Meystre, 2013; Y Chen, 2013]

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"Testing Quantum Mechanics"?

Testing Macroscopic Quantum Mechanics

- Does standard quantum mechanics apply to a macroscopic test mass? *(Why not?)*

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- **Motivation 1:** "Intrinsic Randomness of Quantum Mechanics"
  - Macroscopic world is classical, while microscopic world is quantum.
  - "Quantum Measurement" is necessary to convert from quantum to classical.
  - "Quantum Measurement gives random answers.

- **"Collapse Models"**
  - Conversion from quantum to classical happens spontaneously, but in an unknown manner.
  - A. Bassi et al., Rev. Mod. Phys., 2013; O. Romero-Isart, PRA 2011; O. Romero-Isart et al., PRL 2011.

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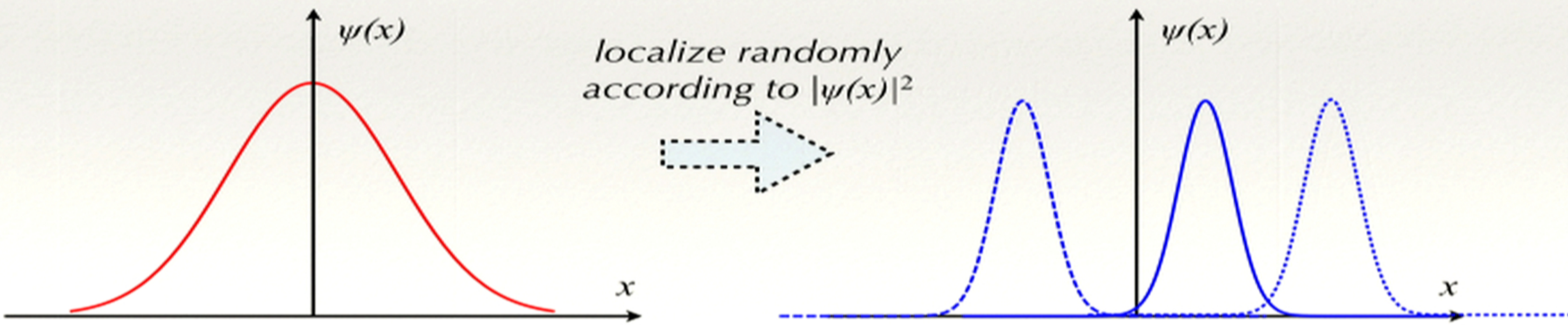


15

Collapse Models

- **Collapse in x will cause disturbance in p.**
- Diffusion in phase space, same as a *stochastic force*.
- Example: **"CSL" models**

each atom feels a random force due to the collapses the total force scales with mass

Nimmrichter, Hornberger and Hammerer (2014)

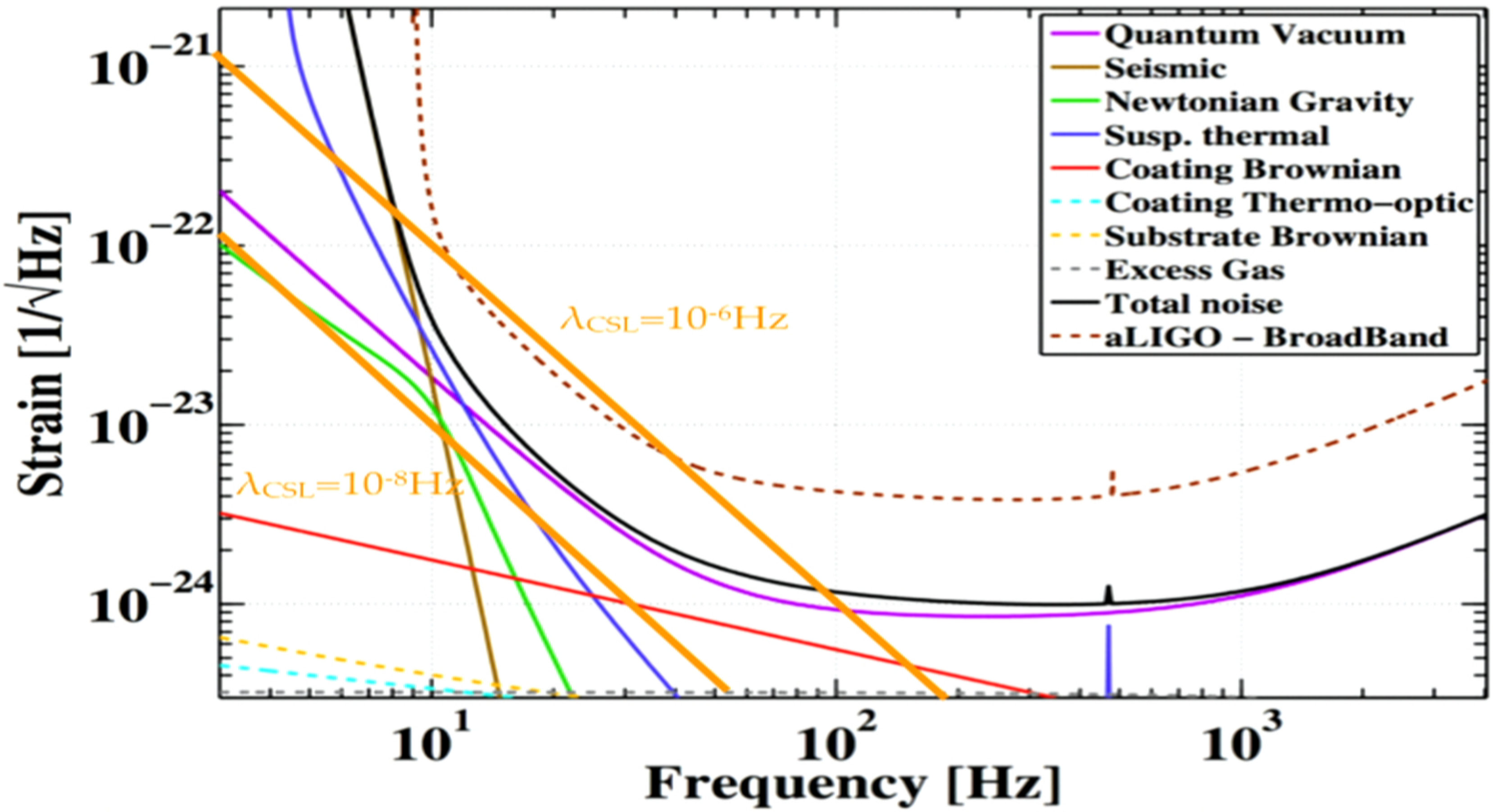
$$S_f^{\rm CSL} \propto m^{2/3}\,, \quad S_f^{\rm Gravity} \propto m$$

$$S_f^{\rm SQL} = 2\hbar m\omega^2$$

$$S_f^{\rm SQL}/S_f^{\rm CSL} \propto m^{1/3}\omega^2\,, \quad S_f^{\rm SQL}/S_f^{\rm Gravity} \propto \omega^2\,.$$

This means low-frequency oscillators are more promising in testing these models.

Collapse Models with LIGO



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Testing Macroscopic Quantum Mechanics

- Does standard quantum mechanics apply to a macroscopic test mass? *(Why not?)*
- **Motivation 2: how to confirm that gravity is quantum.**

If you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

R.P. Feynman, 1957

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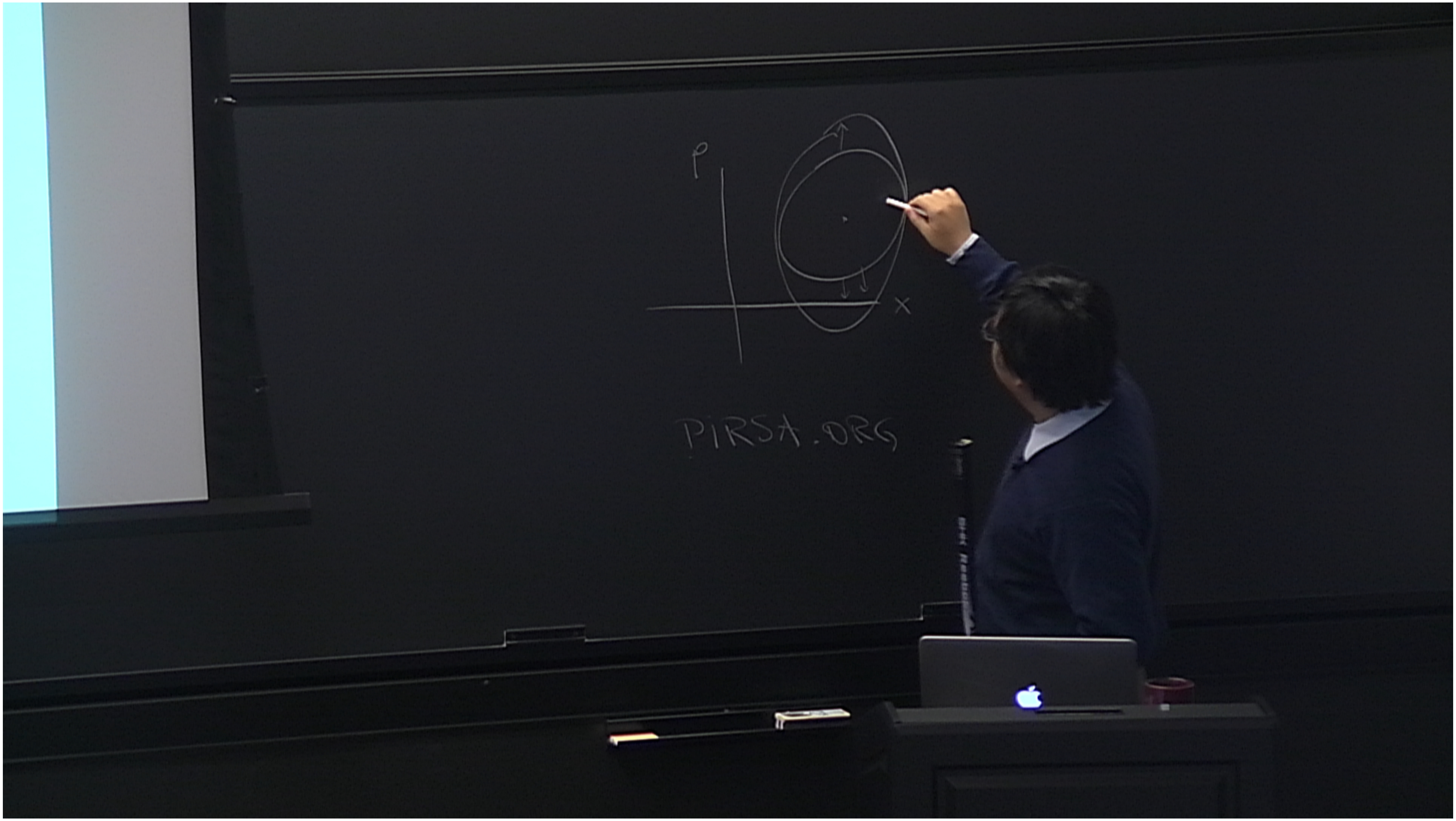
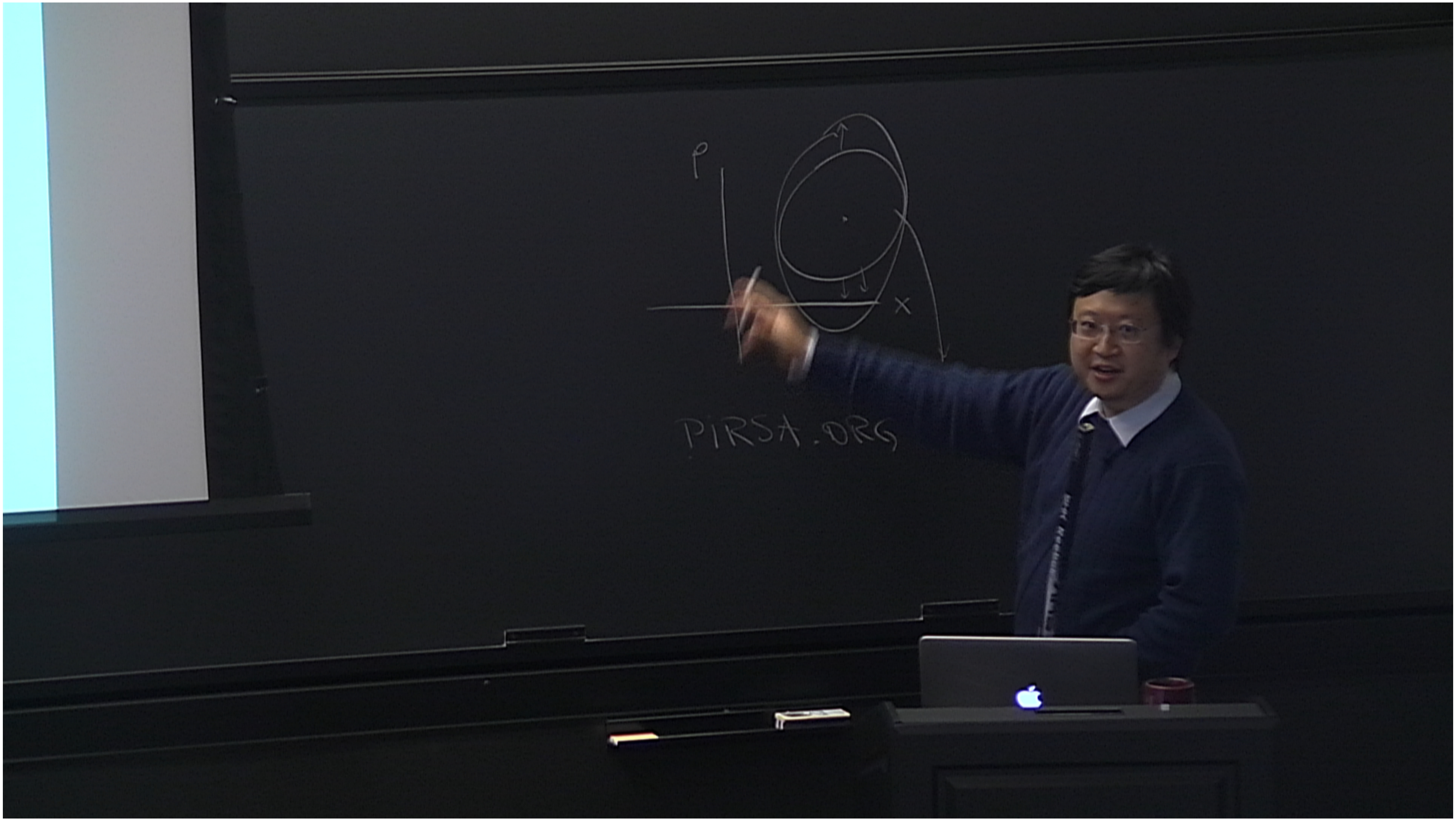

p
x
PIRSA.ORG


p
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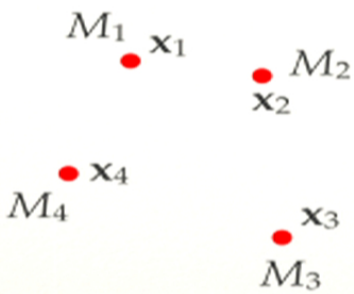
Physics of "Self-Gravitating" Quantum Systems



$$\hat{\phi}(\mathbf{x}) = -\sum G \frac{M_j}{|\mathbf{x} - \hat{\mathbf{x}}_j|}$$

$$\hat{V} = \sum_i -\frac{1}{2} M_j \hat{\phi}(\hat{\mathbf{x}}_j) = -\sum_{i<k} \frac{G M_j M_k}{|\hat{\mathbf{x}}_j - \hat{\mathbf{x}}_k|} + (\text{Self Energy})$$

This potential term appears in the Schrödinger Equation

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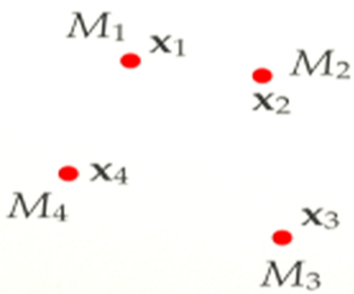

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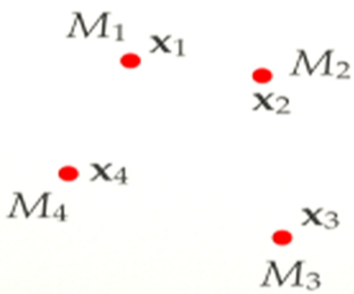
If quantum information can pass from A to B through $\hat{\phi}$, then gravity must be quantum.

Physics of "Self-Gravitating" Quantum Systems



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This potential term appears in the Schrödinger Equation

If quantum information can pass from A to B through $\hat{\phi}$, then gravity must be quantum.

By contrast, what are the alternatives?

1. Gravity is just classical, ϕ takes expectation value. *[Møller 1962, Rosenfeld 1963, Kibble 1976, Diosi 1981; H. Yang et al., 2013]*
2. Gravity is "classical" through continuous measurement, causing error in quantum-information transfer and decoherence. *[Kafri & Taylor, 2013; Kafri, Taylor & Milburn, 2014; Diosi, 1987]*

Classical Gravity: Schrödinger-Newton Equation

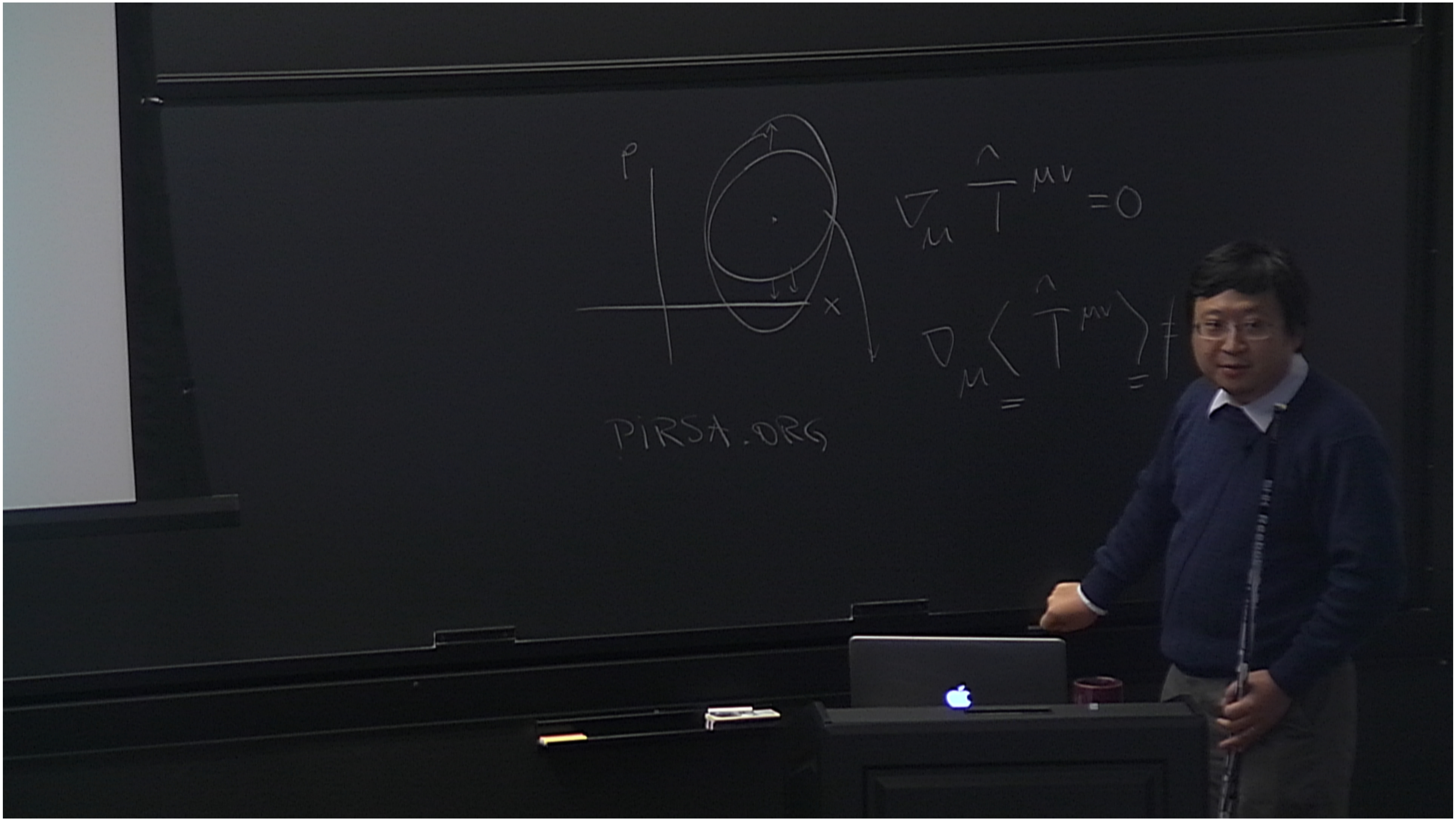
$$\nabla^2\phi = 4\pi G\langle\hat{\rho}\rangle \Rightarrow \phi(\mathbf{x}) = -\int d^3\mathbf{y}\,\frac{G\langle\hat{\rho}(\mathbf{y})\rangle}{|\mathbf{x}-\mathbf{y}|}$$

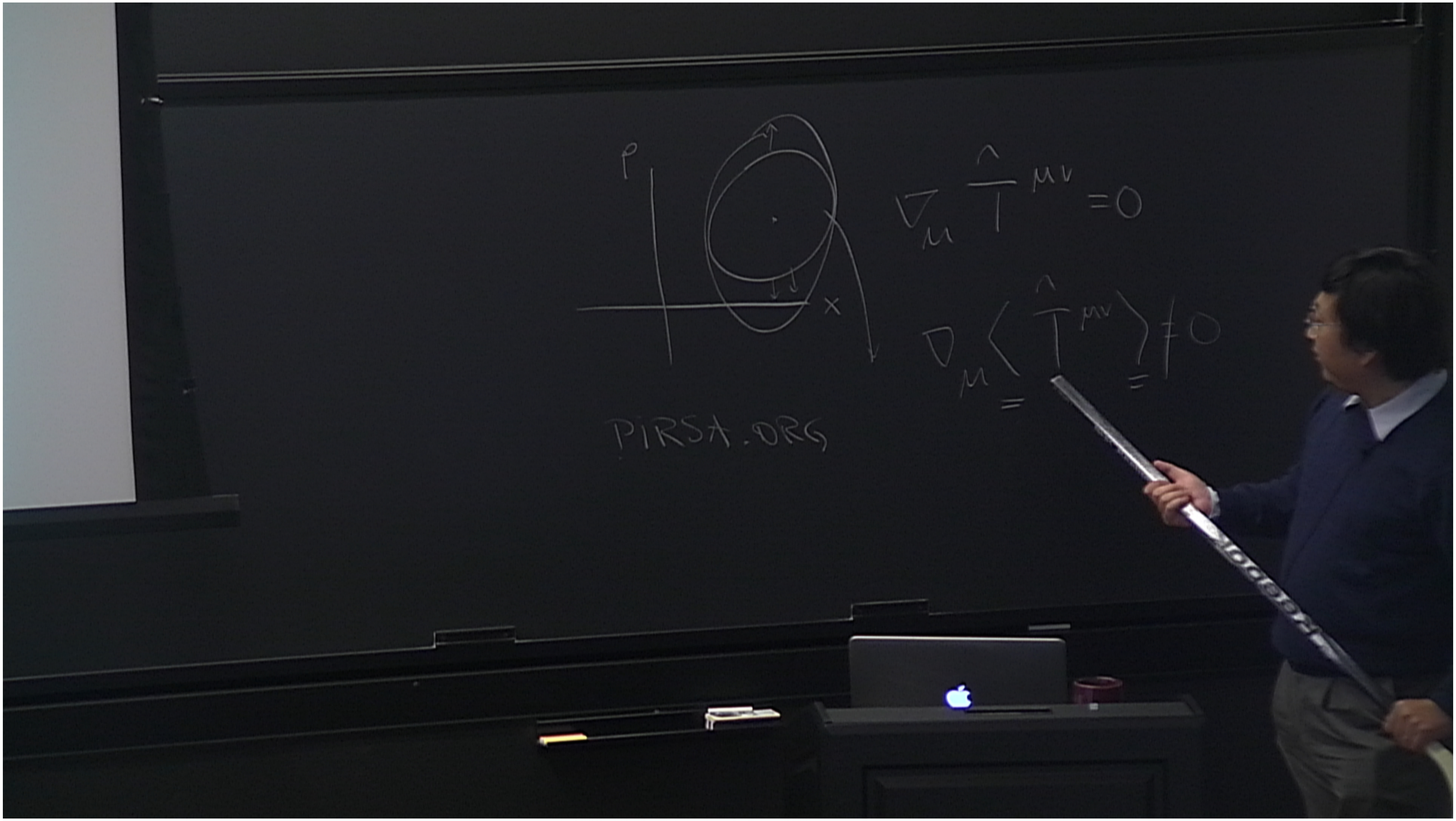
$$i\hbar\partial_t\psi(\mathbf{x}_1,\ldots,\mathbf{x}_n) = \hat{H}_0\psi(\mathbf{x}_1,\ldots,\mathbf{x}_n) - \frac{1}{2}\sum_j M_j\phi(\mathbf{x}_j)\psi(\mathbf{x}_1,\ldots,\mathbf{x}_n)$$

[Møller 1962, Rosenfeld 1963; Kibble 1976; Diosi 1981; Carlip 2008; Guilini 2012; H. Yang et al., 2013]

Features of the Schrödinger-Newton Equation

1. Nonlinear Quantum Mechanics
2. Recovers classical dynamics.
3. Absolutely No Quantum Information Transfer Between Objects.
4. Center of Mass separates out, satisfies a separate equation.


ρ
x
$\nabla_\mu \hat{T}^{\mu\nu} = 0$
$\nabla_\mu \langle \hat{T}^{\mu\nu} \rangle \neq$
PIRSA.ORG



ρ
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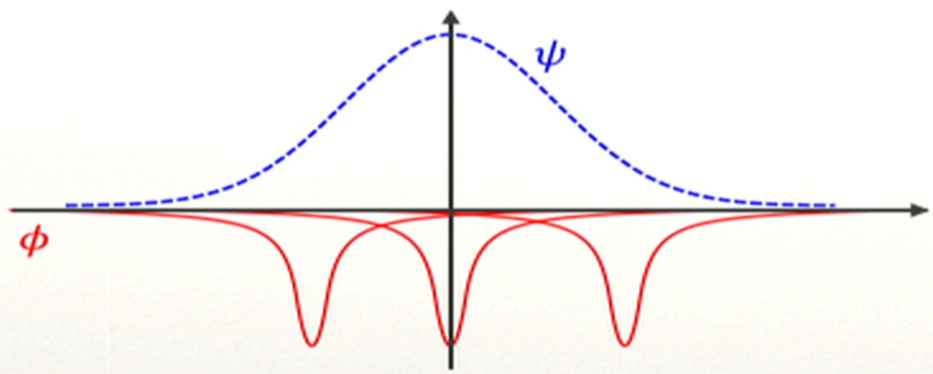
PIRSA.ORG

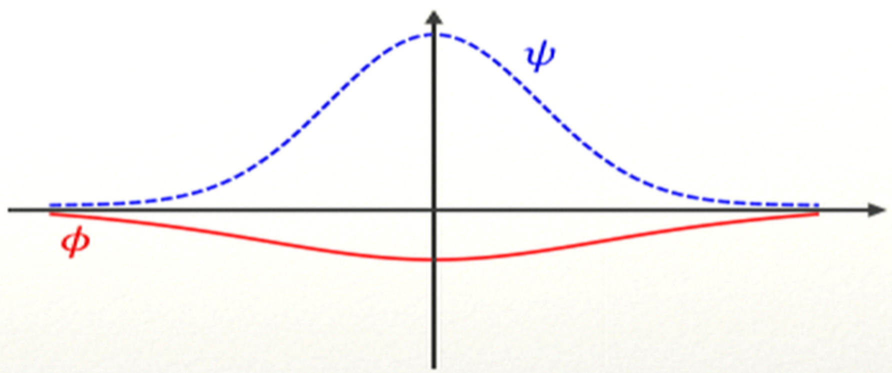
Self Interaction in Classical Gravity

Quantum "Self Gravity"



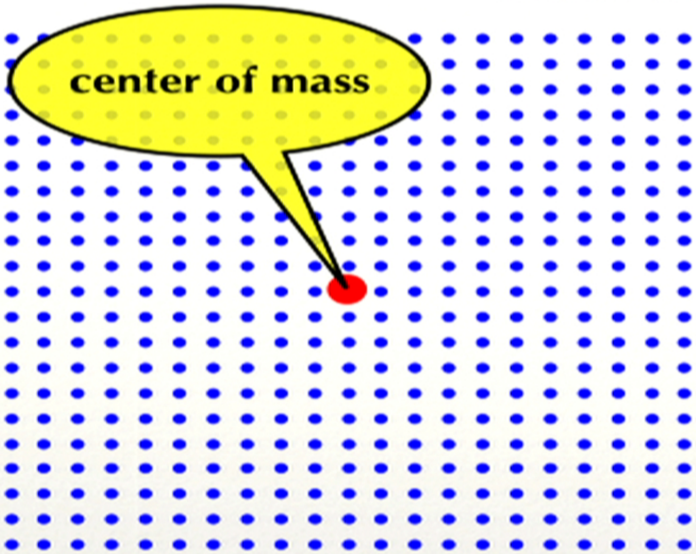
particle carries own gravity field
gravity field entangled with particle
back action negligible

Classical "Self Gravity"

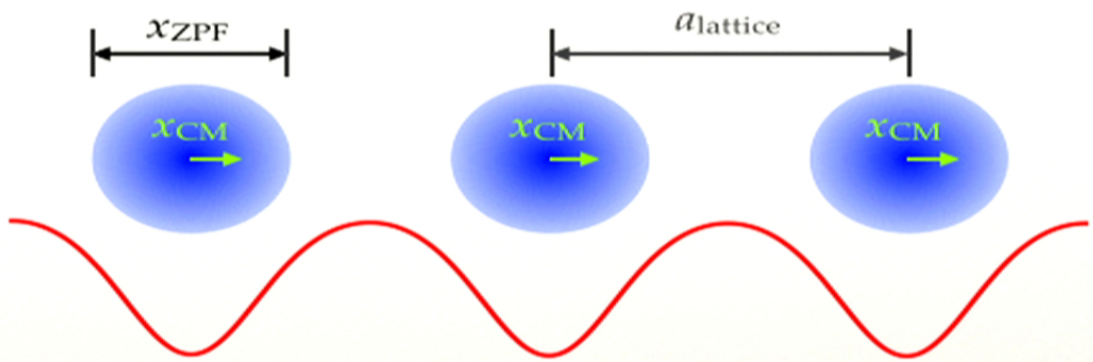


unique classical field
wave packet attracted by its own potential

Self Interaction for Crystals



a **macroscopic crystal** made up from atoms



$$x_{\rm ZPF} \sim \sqrt{\frac{\hbar}{m\omega_{\rm Debye}}} \sim 10^{-12}\,{\rm m} \ll a_{\rm lattice} \sim 10^{-10}\,{\rm m}$$

$$x_{\rm CM} \ll x_{\rm ZPF}$$

$$i\hbar\frac{\partial\Psi_{\rm CM}}{\partial t} = \left[-\frac{\hbar^2\nabla^2}{2M} + \frac{1}{2}M\omega_{\rm CM}^2 x^2 + \frac{1}{2}M\omega_{\rm SN}^2(x - \langle x\rangle)^2\right]\Psi_{\rm CM}$$

$$\omega_{\rm SN}^2 = \frac{Gm}{12\sqrt{\pi}x_{\rm ZPF}^3} \gg \omega_g^2 \qquad \omega_{\rm SN}^{\rm Si} = 4\times 10^{-2}\,{\rm s}^{-1} \approx 100\,\omega_g^{\rm Si}$$

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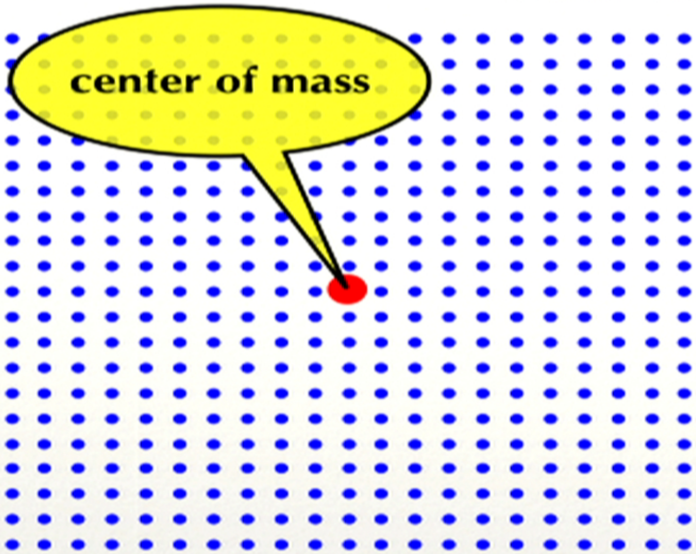

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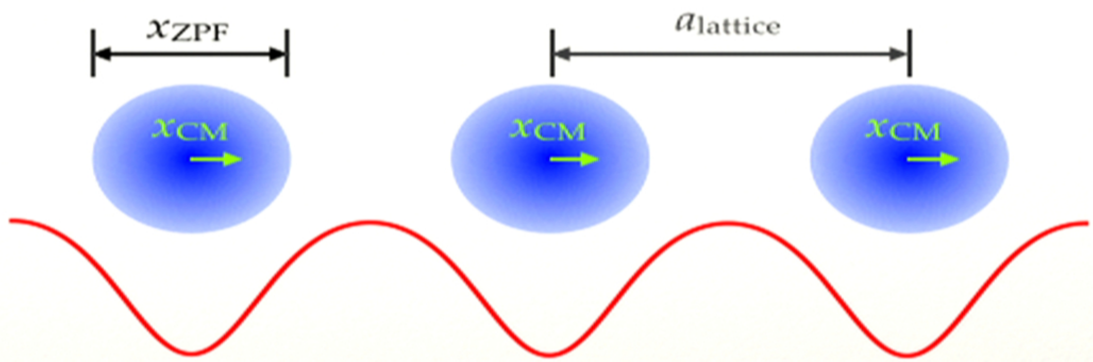

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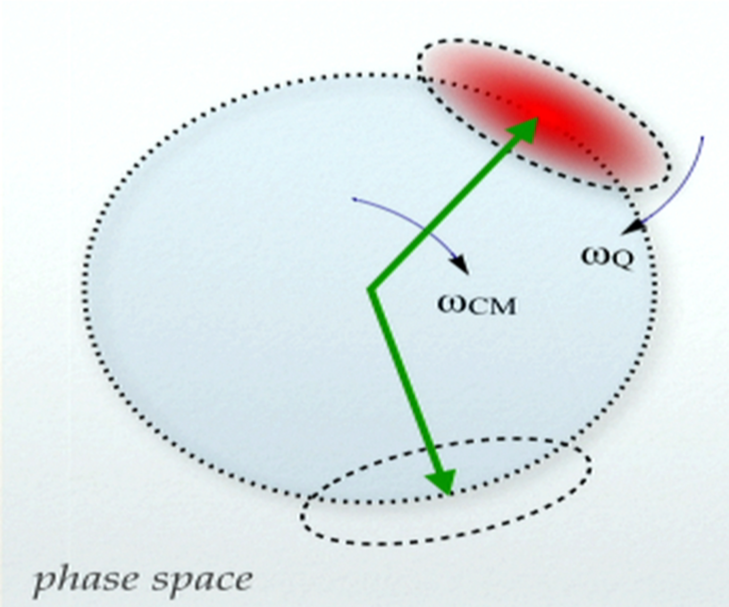
$$\omega^{\mathrm{Nb}} = 0.1\,\mathrm{s}^{-1}, \quad \omega_{\mathrm{SN}}^{\mathrm{W}} = 0.25\,\mathrm{s}^{-1}$$

Classical Gravity: Macroscopic Test Mass



$$\dot{\hat{x}} = \hat{p}/M$$
$$\dot{\hat{p}} = -M\omega_{\rm CM}^2\hat{x} - M\omega_{\rm SN}^2(\hat{x} - \langle\hat{x}\rangle)$$

$\omega_c/(2\pi)$ (Hz)	100	10	1	0.1
Q^{Si}	3×10^8	3×10^6	3×10^4	300
Q^{Nb}	4×10^7	4×10^5	4×10^3	40
Q^{W}	6×10^6	6×10^4	6×10^2	6

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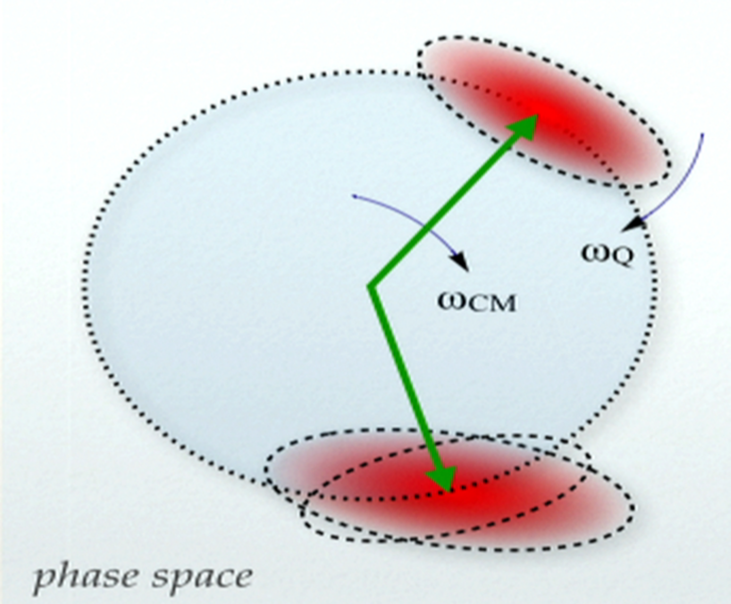

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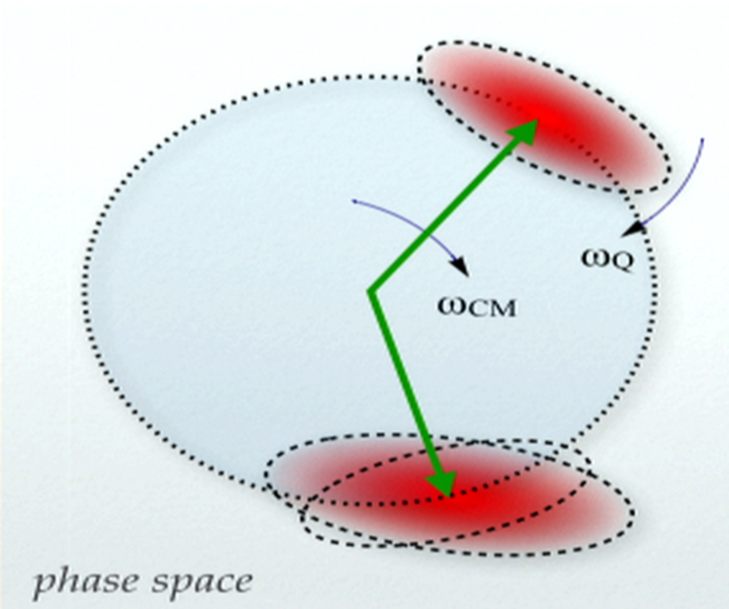

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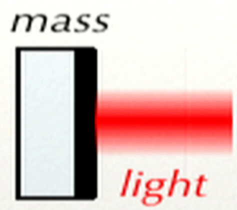
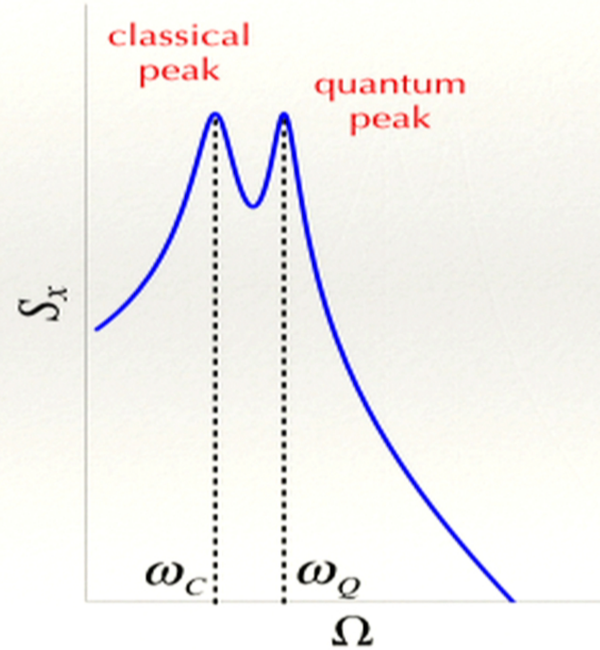
Quantum noise ellipse rotate at a different frequency:

$$\omega_{\rm Q}^2 = \omega_{\rm CM}^2 + \omega_{\rm SN}^2$$





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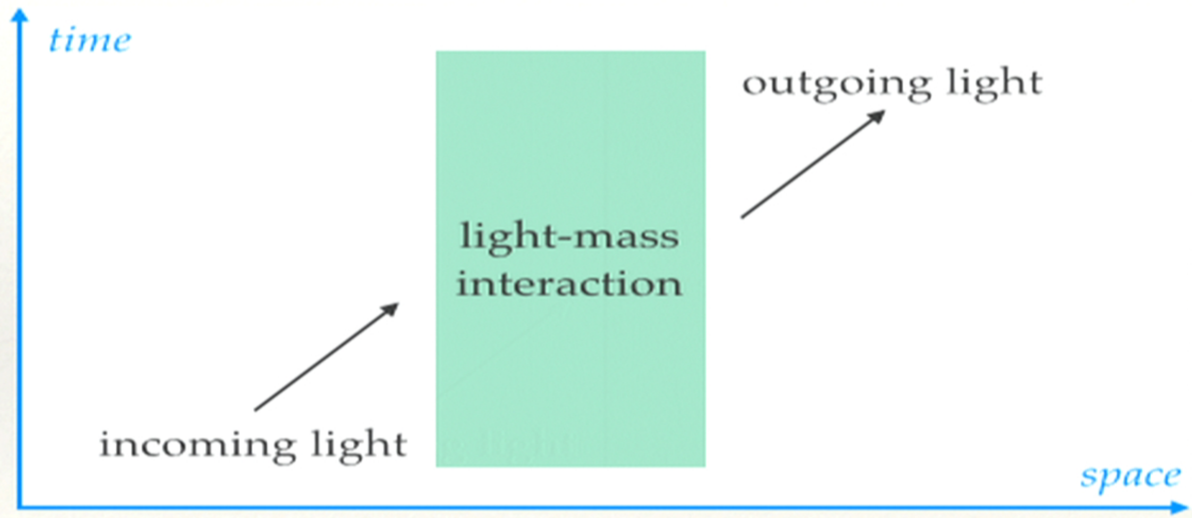
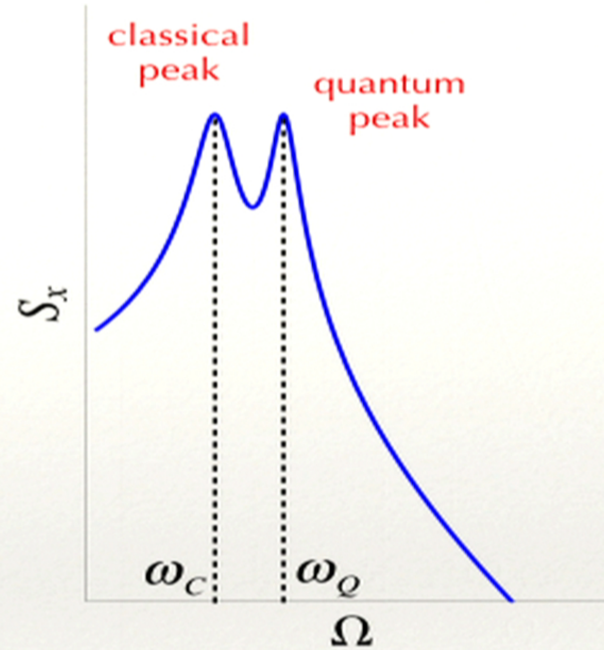
"Fundamental Flaw" of Classical Gravity

1. Interpretation of quantum-state reduction is a long-standing issue.

2. According to standard (linear quantum mechanics), wavefunction collapse can take place at any "moment".





3. Unlike other situations, nonlinear quantum mechanics actually *depends on interpretation of quantum mechanics:* Different features at ω_Q will be predicted using other interpretations.

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Summary

1. An important ingredient of LIGO noise is due to **Heisenberg Uncertainty** of **kg-scale test masses**
   - Standard Quantum Limit represents the trade-off between **sensing** and **back-action noise**
   - techniques have been developed to circumvent SQL by altering optical configurations, often requiring **correlations between sensing and back-action noise**.

2. Various proposals for modifying quantum mechanics for macroscopic objects can be tested
   - none of the individual theories look correct/fully-motivated on its own
   - the effects they induce (excess noise, separation in frequencies) can be tested
   - even some ***gravity*** effects seems within reach *[as well as "nonlinear QM", Bialynicki-Birula and Mycielski 1970s , Weinberg 1980s, Gähler, Klein & Zeilinger, 1981]*