Generation of squeezed states using radiation pressure effects

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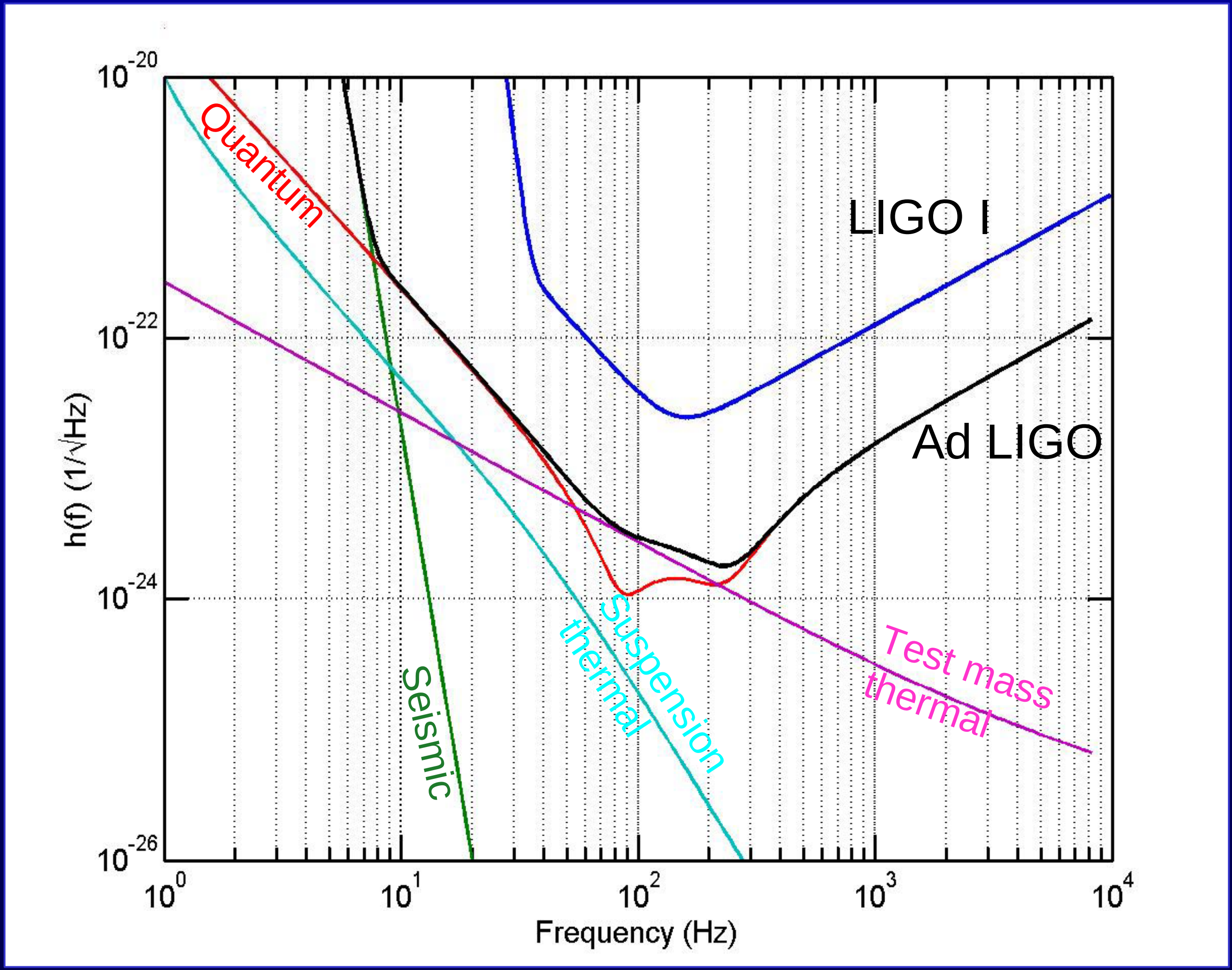
Advanced LIGO

A Quantum Limited Interferometer



Limiting Noise Sources: Optical Noise

- **Shot Noise**
  - Uncertainty in number of photons detected ⇨
  - Higher circulating power P_{bs} ⇨ low optical losses
  - Frequency dependence ⇨ light (GW signal) storage time in the interferometer

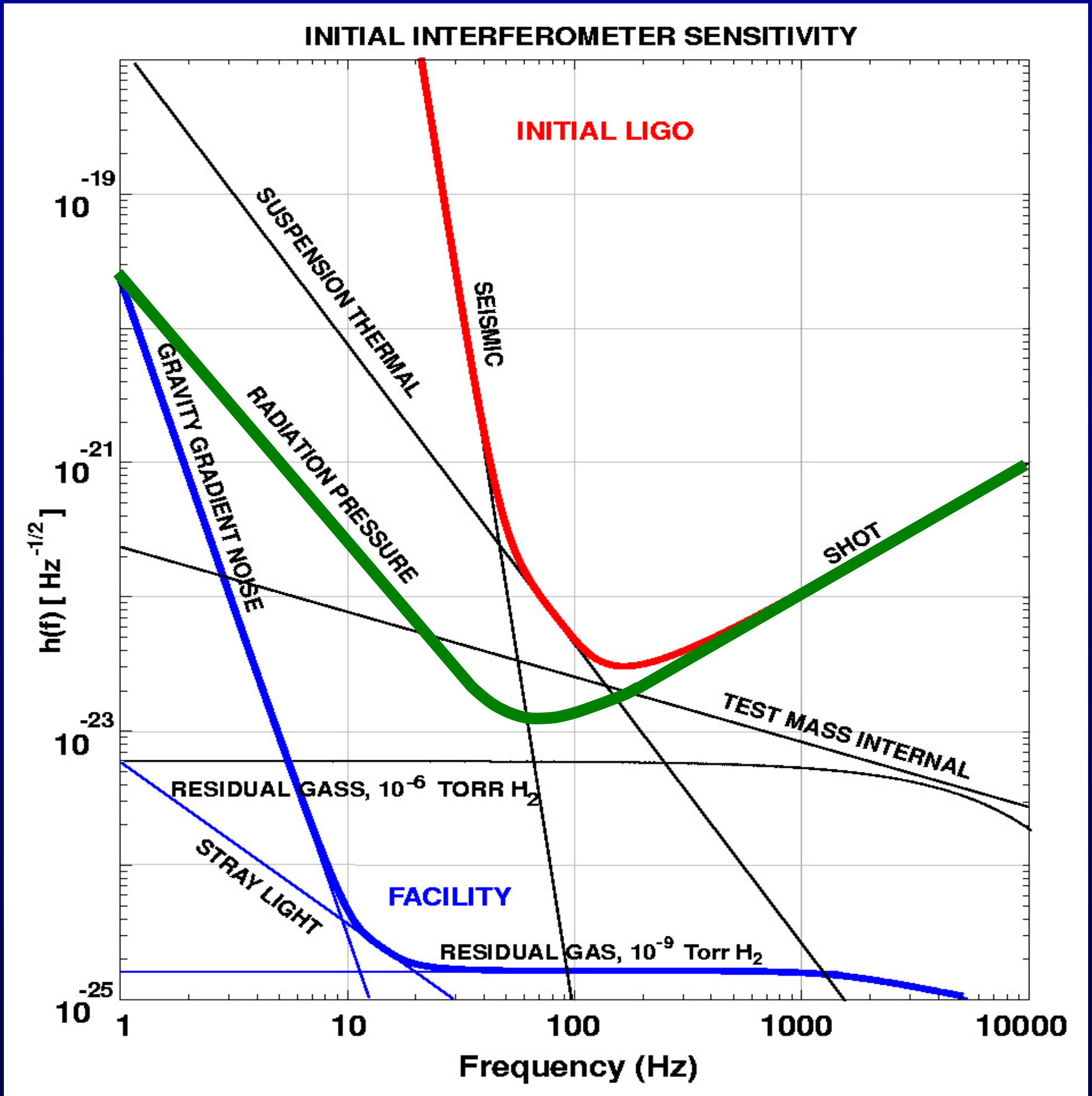
$$h(f) \propto \sqrt{\frac{1}{P_{bs}}}$$

- **Radiation Pressure Noise**
  - Photons impart momentum to cavity mirrors Fluctuations in number of photons ⇨
  - Lower power, P_{bs}
  - Frequency dependence ⇨ response of mass to forces

$$h(f) \propto \sqrt{\frac{P_{bs}}{M^2 f^4}}$$

➔ Optimal input power depends on frequency

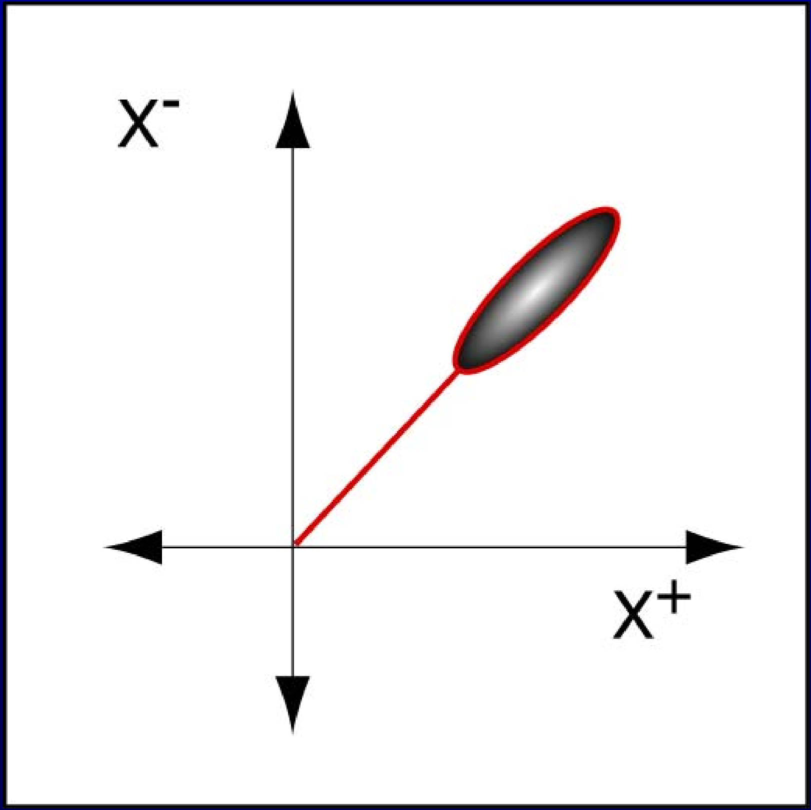
Initial LIGO



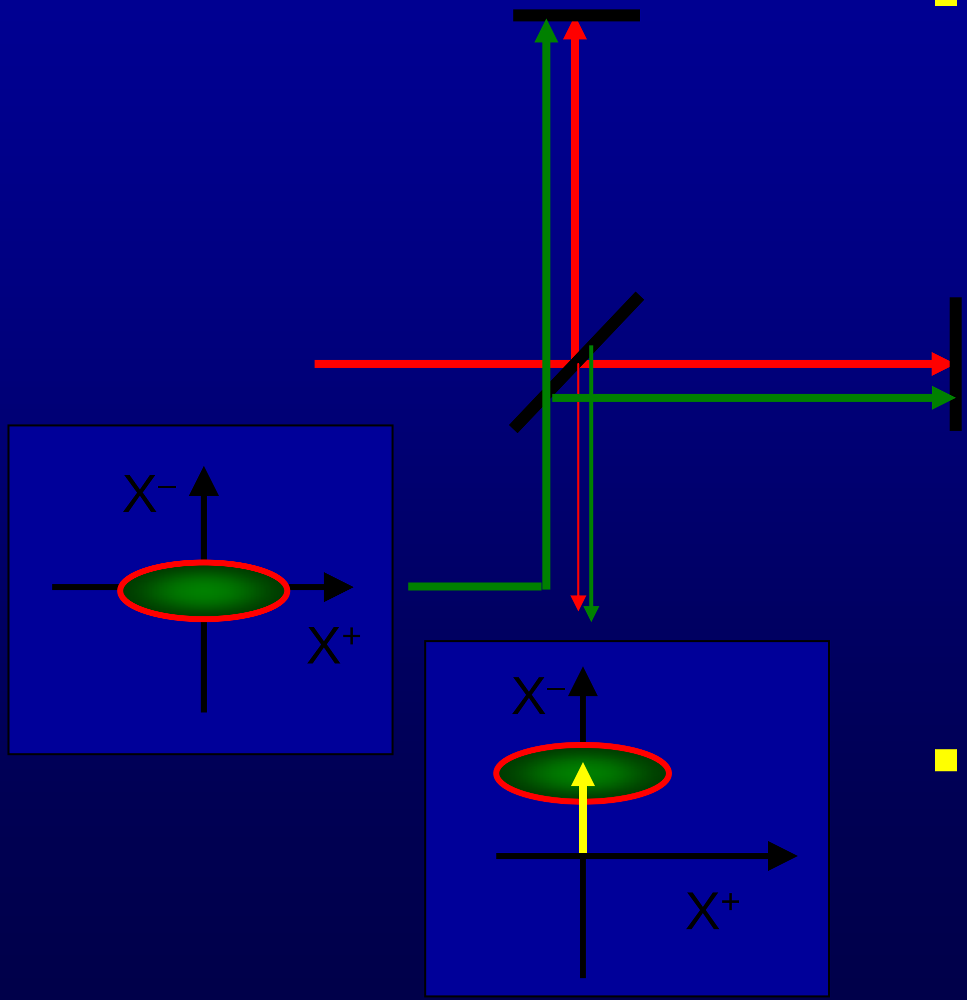
Sub-Quantum Interferometers

Some quantum states of light

- Analogous to the phasor diagram
- Stick → dc term
- Ball → fluctuations
- Common states
  - Coherent state
  - Vacuum state
  - Amplitude squeezed state
  - Phase squeezed state

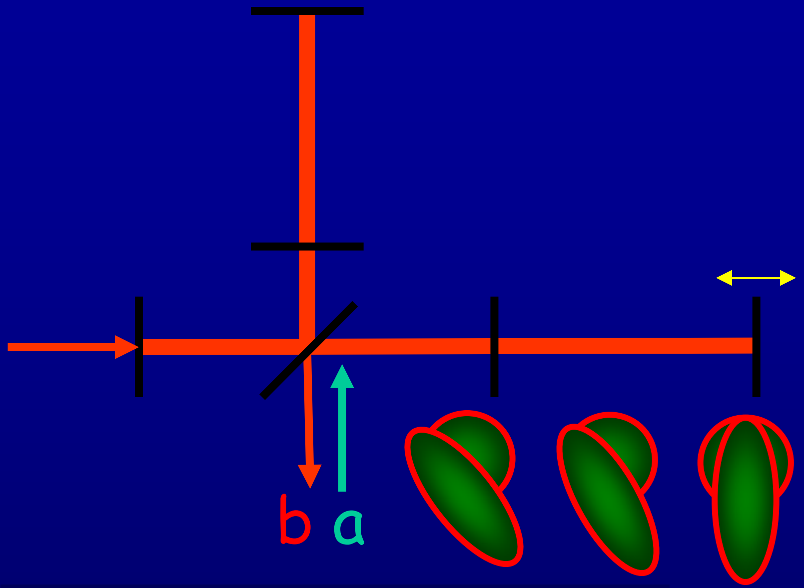


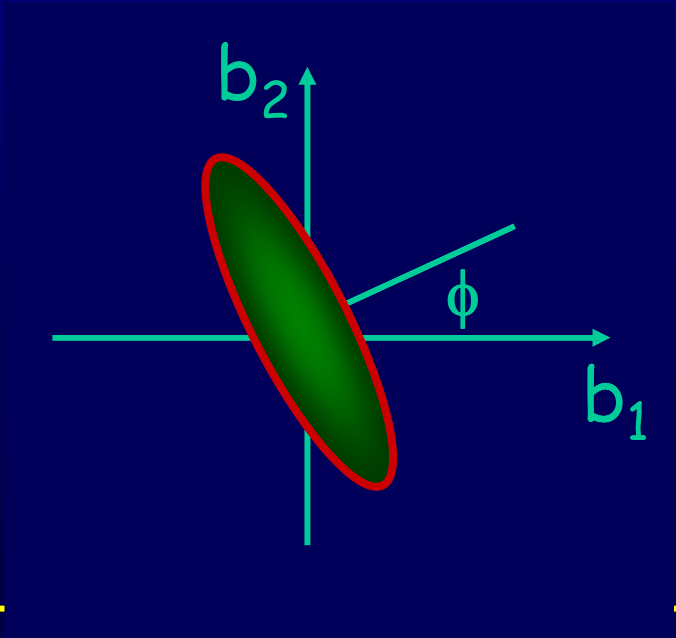
Squeezed input vacuum state in Michelson Interferometer



- GW signal in the phase quadrature
  - Not true for all interferometer configurations
  - Detuned signal recycled interferometer → GW signal in both quadratures
- Orient squeezed state to reduce noise in phase quadrature

Back Action Produces Squeezing





- Vacuum state enters anti-symmetric port
- Amplitude fluctuations of input state drive mirror position
- Mirror motion imposes those amplitude fluctuations onto phase of output field

Squeezing produced by back-action force of fluctuating radiation pressure on mirrors

Frequency-dependent coupling constant

Newton's law

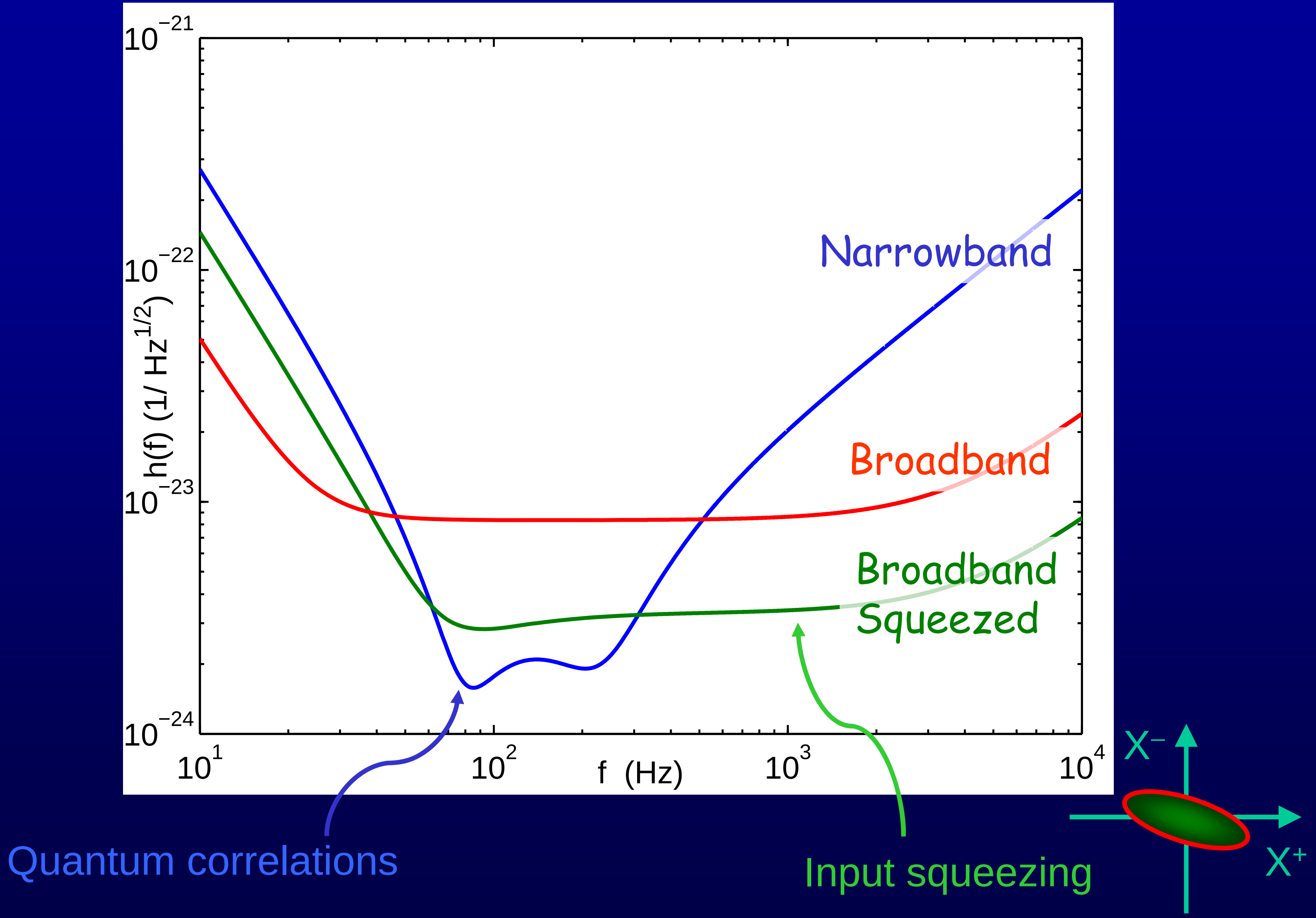
$$\kappa = \frac{2I_0}{I_{SQL}} \frac{1}{\Omega^2}$$ for simple Michelson

$$\kappa = \frac{2I_0}{I_{SQL}} \frac{1}{\Omega^2} \frac{\gamma^4}{\left(\Omega^2 + \gamma^2\right)}$$ for conventional ifo

Cavity pole

Couples radiation pressure to mirror motion

Sub-quantum-limited interferometer



Squeezing – the ubiquitous fix?

- All interferometer configurations can benefit from squeezing
  - Radiation pressure noise can be removed from readout in certain cases
  - Shot noise limit only improved by more power (yikes!) or squeezing (eek!)
  - Reduction in shot noise by squeezing can allow for reduction in circulating power (for the same sensitivity) – important for power-handling

Squeezed vacuum

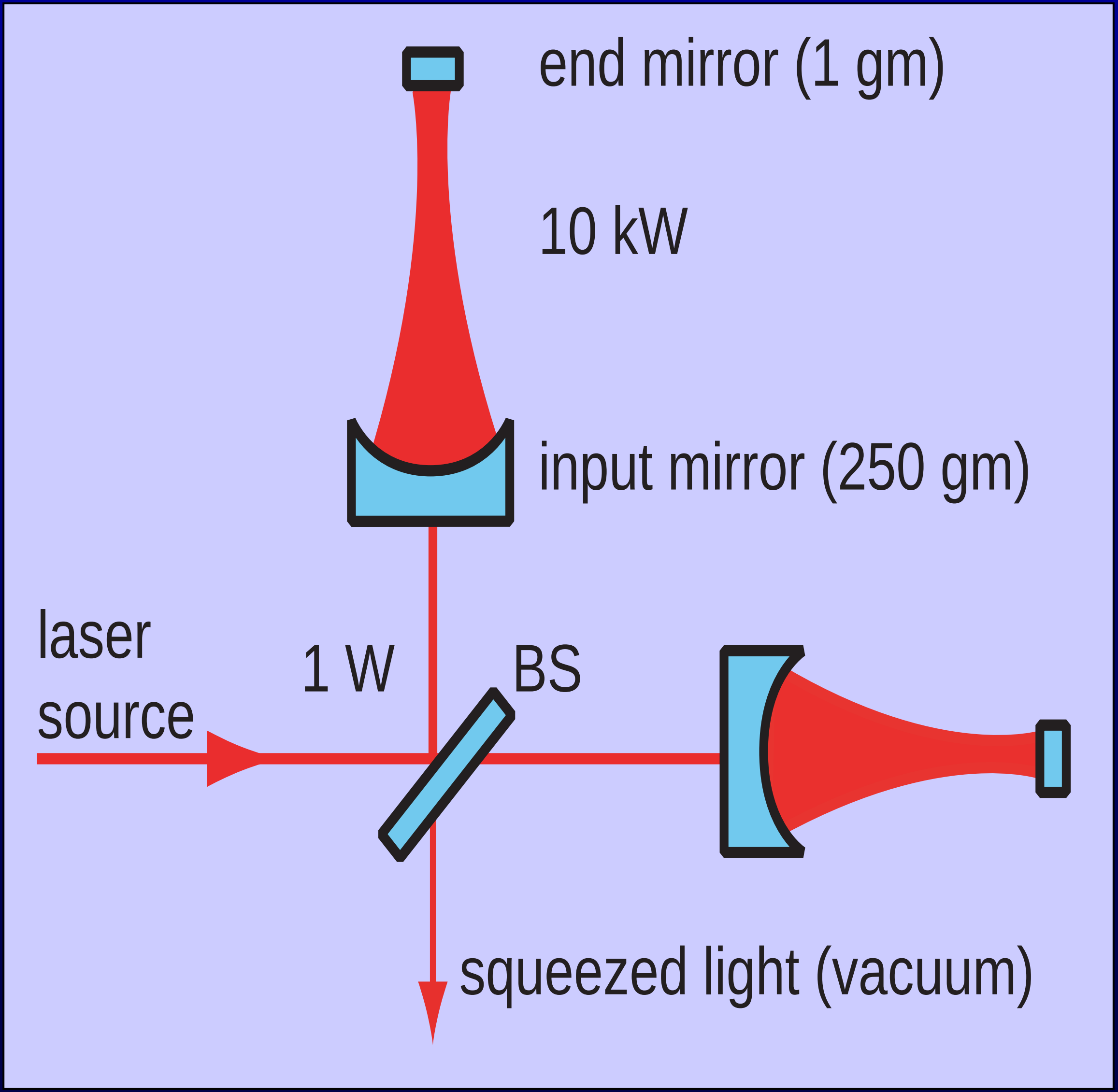
- Requirements
  - Squeezing at low frequencies (within GW band)
  - Frequency-dependent squeeze angle
  - Increased levels of squeezing
- Generation methods
  - Non-linear optical media ($\chi^{(2)}$ and $\chi^{(3)}$ non-linearites) ← crystal-based squeezing
  - Radiation pressure effects in interferometers ← ponderomotive squeezing
- Challenges
  - Frequency-dependence → filter cavities
    - Amplitude filters
    - Squeeze angle rotation filters
  - Low-loss optical systems

Squeezing using back-action effects

The principle

- A “tabletop” interferometer to generate squeezed light as an alternative to nonlinear optical media
- Use radiation pressure as the squeezing mechanism
- Relies on intrinsic quantum physics of optical field–mechanical oscillator correlations
- Squeezing produced even when the sensitivity is far worse than the SQL
  - Due to noise suppression a la optical springs

The Ponderomotive Interferometer

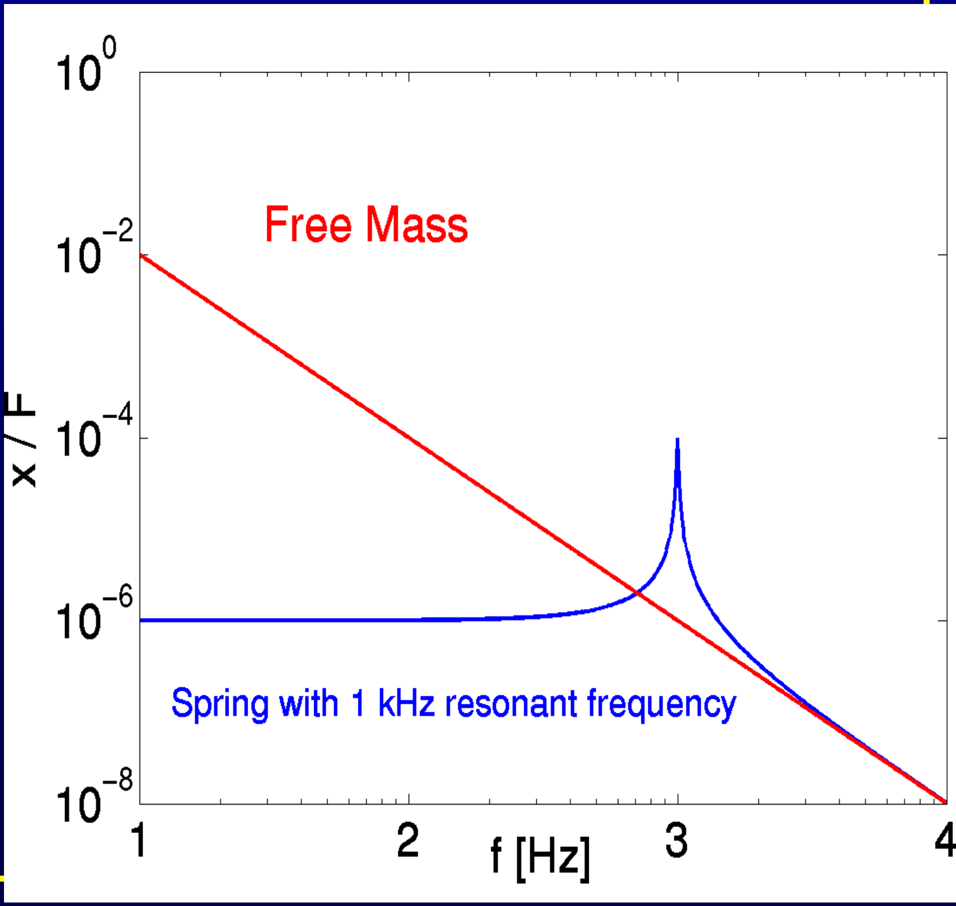


Key ingredients

- High circulating laser power
  - 10 kW
- High-finesse cavities
  - 15000
- Light, low-noise mechanical oscillator mirror
  - 1 gm with 1 Hz resonant frequency
- Optical spring
  - Detuned arm cavities

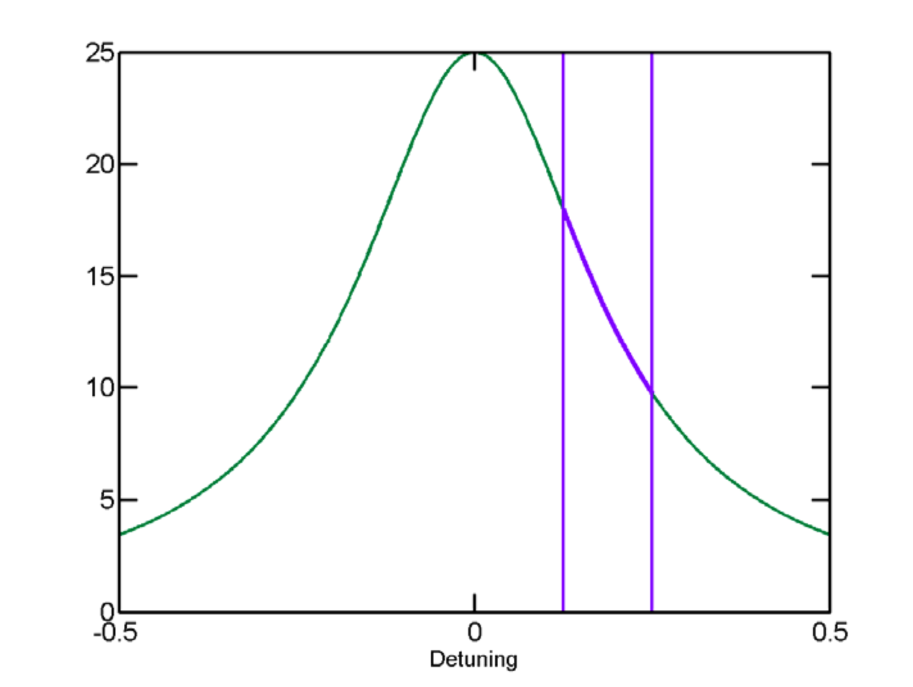
Optical Springs

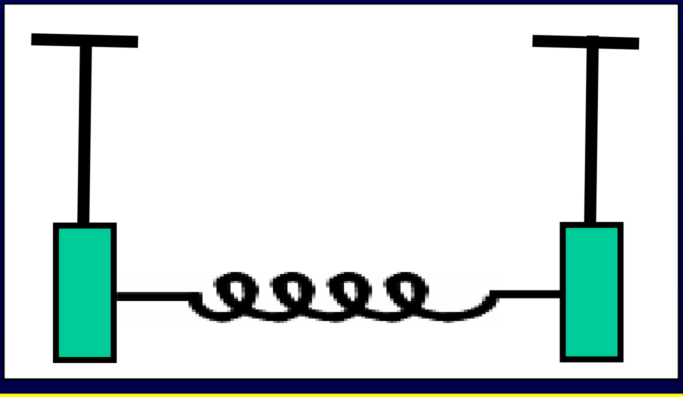
- Modify test mass dynamics
- Suppress displacement noise (compared to free mass case)
- Why not use a mechanical spring?
  - Displacements due to thermal noise introduced by the high frequency (mechanical) spring will wash out the effects of squeezing
- Connect low-frequency mechanical oscillator to (nearly) noiseless optical spring
- An optical spring with a high resonant frequency will not change the thermal force spectrum of the mechanical pendulum
  - Use a low resonant frequency mechanical pendulum to minimize thermal noise
  - Use an optical spring to produce a flat response out to higher frequencies



Detuned cavity for optical spring

- Positive detuning
  - Detuning increases
  - Cavity becomes longer
  - Power in cavity decreases
  - Radiation-pressure force decreases
  - Mirror 'restored' to original position
  - Cavity becomes shorter
  - Power in cavity increases
  - Mirror still 'restored' to original position

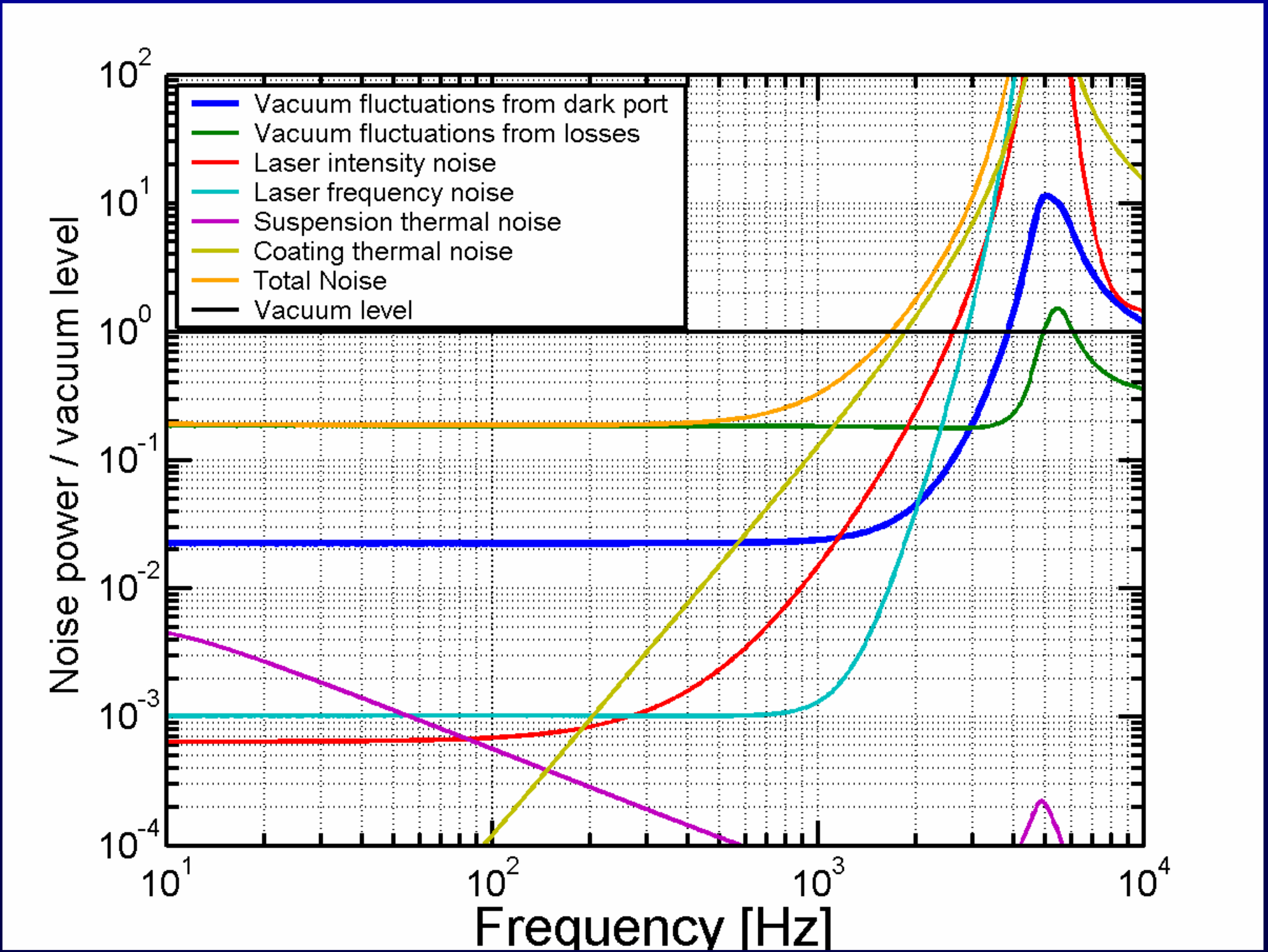




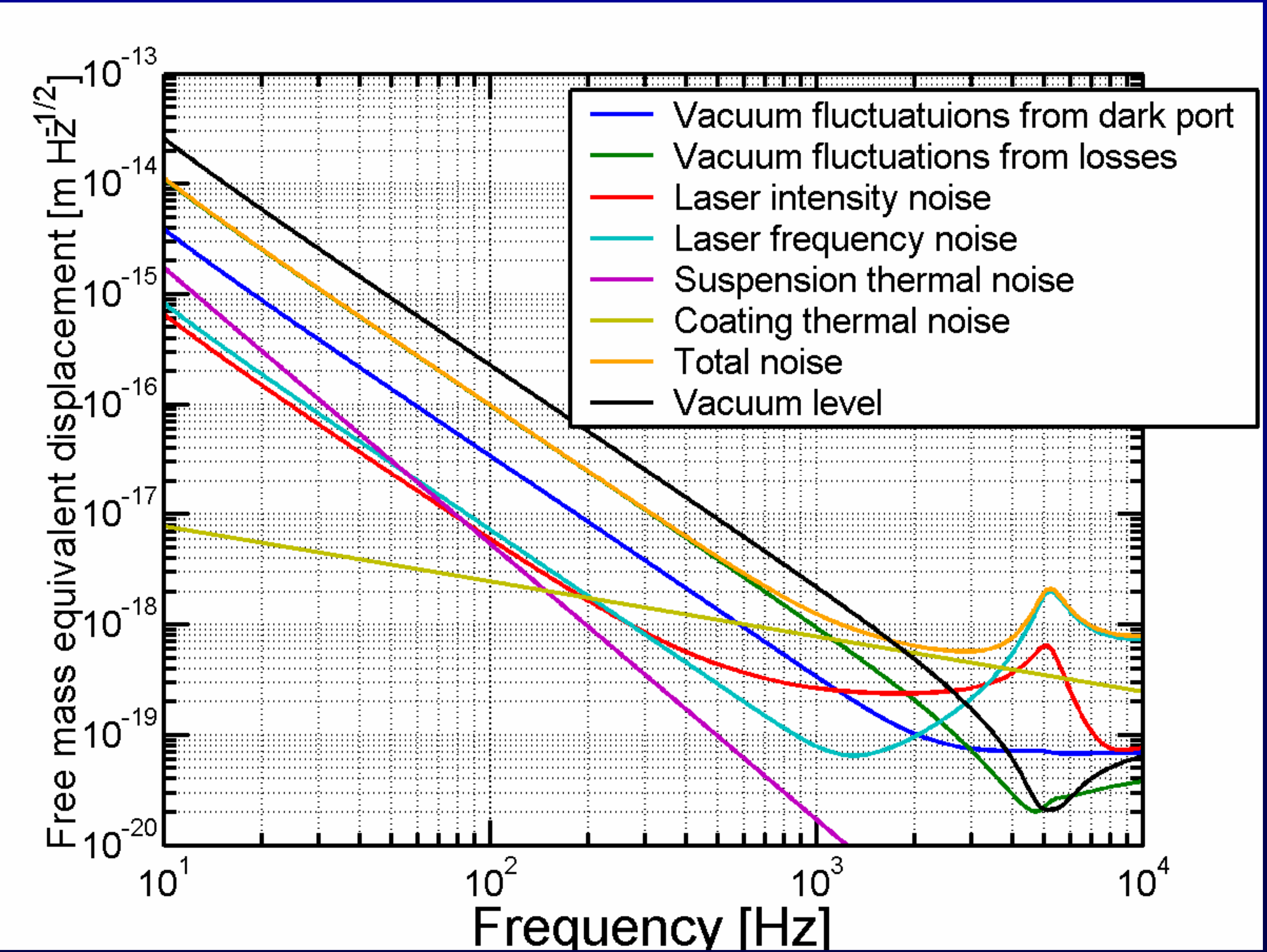
Assumed experimental parameters

Parameter	Symbol	Value	Units	Parameter	Symbol	Value	Units
Light wavelength	λ_0	1064	nm	Input mirror trans.	T_{ITM}	4×10^{-4}	–
Input mirror mass	M_{ITM}	0.25	kg	End mirror mass	M_{ETM}	1	g
Arm cavity finesse	$\mathcal{F}$	1.6×10^4	–	Loss per bounce	–	5×10^{-6}	–
Input power	I_0	1	W	Arm cavity detuning	δ	10^{-5}	λ_0
BS refl. imbalance	Δ_{BS}	0.01	–	Mich. phase imbalance	$\Delta\alpha_M$		
Mich. loss imbalance	$\Delta\epsilon_M$			Input mirror mismatch	Δ_T	5×10^{-6}	–
Detuning mismatch	Δ_δ	10^{-7}	λ_0	Arm cavity loss mismatch	Δ_ε	2×10^{-6}	–
Susp. resonant freq.	Ω_0	1.5	Hz	Susp. mech. loss angle	ϕ	10^{-6}	–
Laser intensity noise	–	10^{-8}	$Hz^{-1/2}$	Laser frequency noise	–	10^{-4}	$Hz/\sqrt{Hz}$

Noise budget



Noise budget – Equivalent displacement

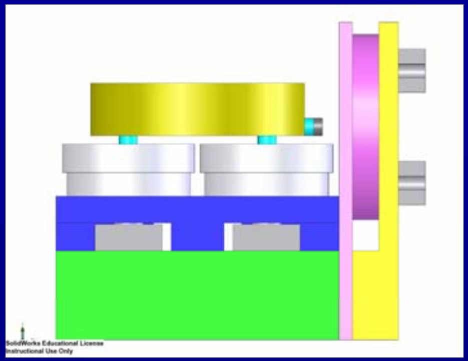


What do we already know?

- Detailed simulation of noise couplings
  - Uses first fully quantum mechanical simulation code for a GW interferometer (Corbitt)
  - Used in AdLIGO simulations (Fritschel and Popescu)
  - “Exported” to Hannover and Glasgow (Schnabel and Strain)
- Location and infrastructure
  - LASTI laser, vacuum envelop and seismic isolation
- Cavity geometrical parameters
- Mini-mirror suspensions

What's next

- Design completion
  - Suspension
  - Control system



- High finesse cavity tests
  - Suspended-mirror high-finesse cavity – optical tests, laser characterization
  - Suspended mini-mirror – includes mirror dynamics and radiation-pressure coupling
- Complete interferometer

Why is this interesting/important?

- First ever (?) demonstration of radiation-pressure induced squeezing
- Probes quantum mechanics of optical field-mechanical oscillator coupling at 1 g mass scales
- Test of low noise optical spring
  - Suppression of thermal noise
- Simulations and techniques useful for AdLIGO and other GW interferometers
  - Quantum optical simulation package
  - Michelson detuning
- Role of feedback control in these quantum systems

Conclusions

- Advanced LIGO is expected to reach the quantum noise limit in most of the band
- QND techniques needed to do better
- Squeezed states of the EM field appears to be a promising approach
- Factors of 2 to 5 improvements foreseeable in the next decade
  - Not fundamental but technical
- Need to push on this to be ready for third generation instruments