Recent Developments toward Sub-Quantum-Noise-Limited Gravitational-wave Interferometers

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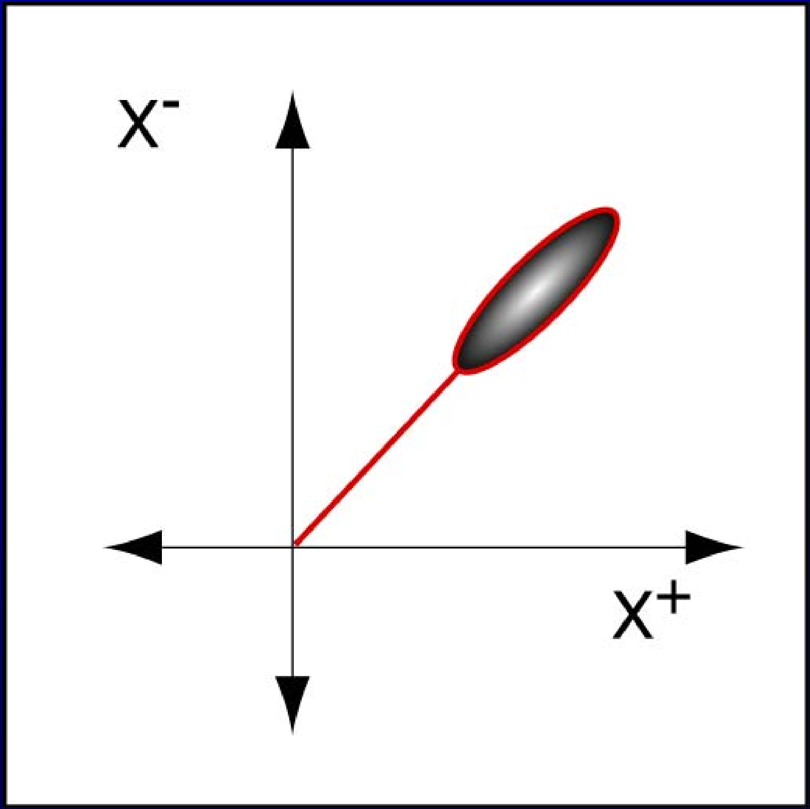
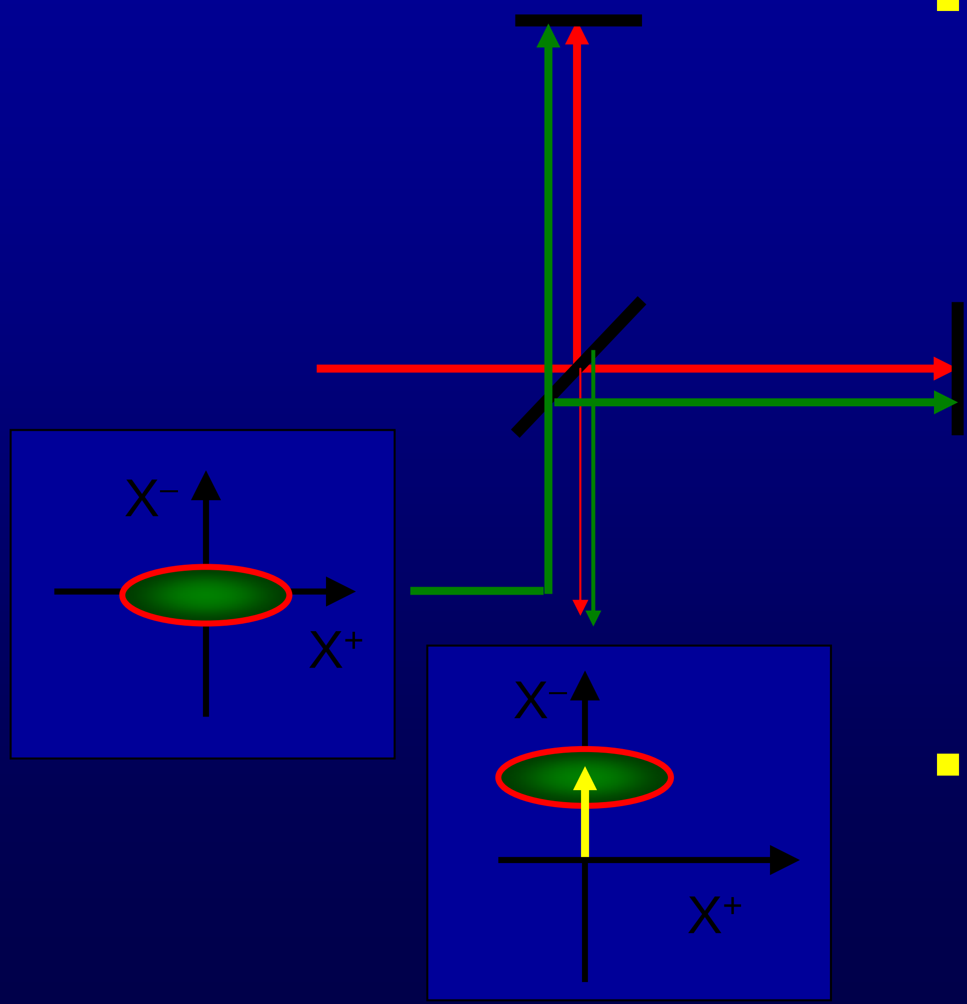
Some quantum states of light

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

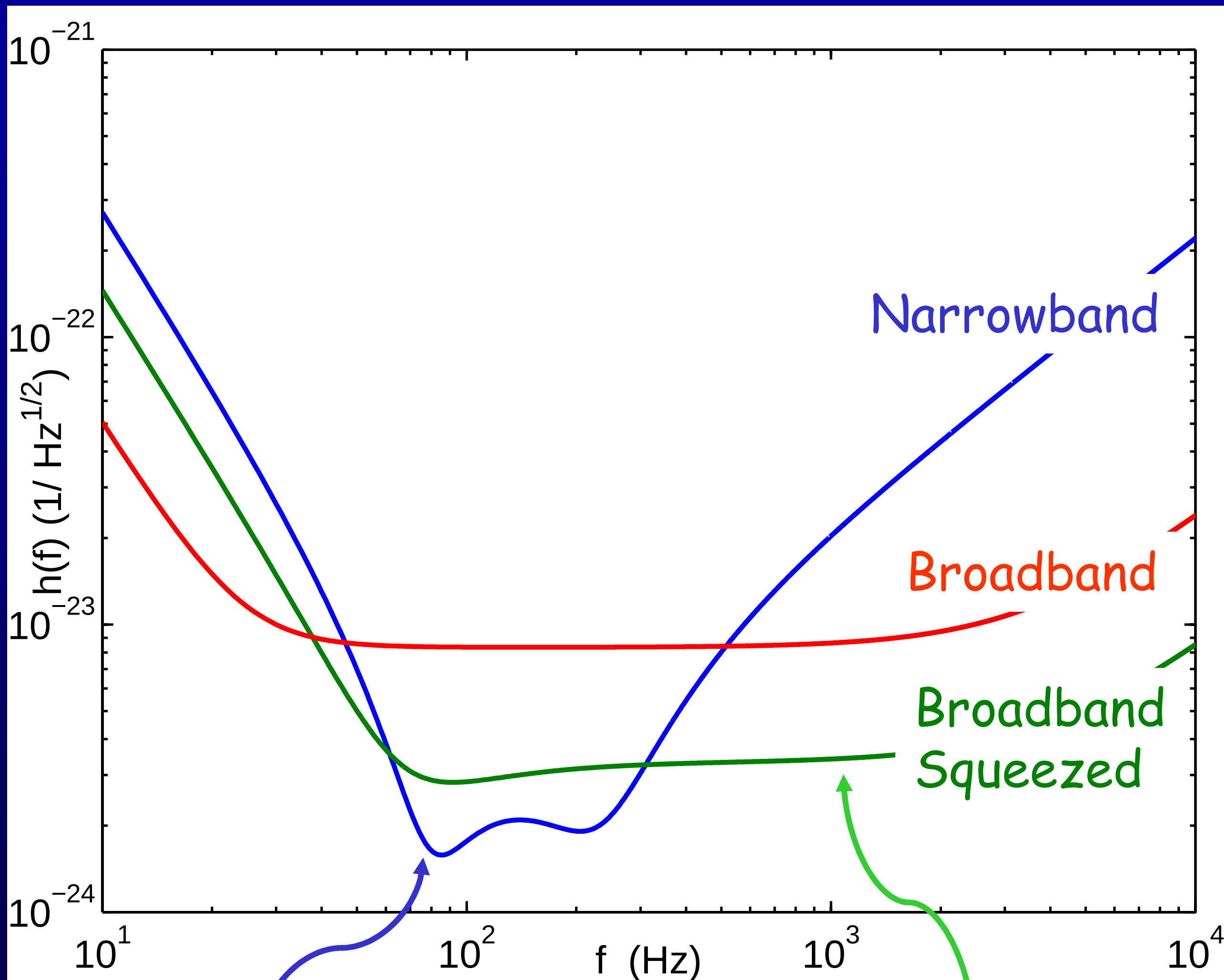


Squeezed input vacuum state in Michelson Interferometer



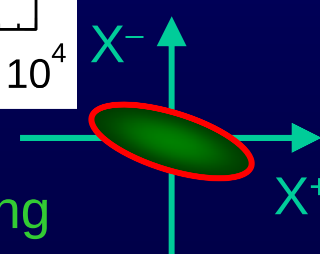
- GW signal in the phase quadrature
  - Not true for all interferometer configurations
  - Detuned signal recycled interferometer → GW signal in both quadratures
- Orient squeezed state to reduce noise in phase quadrature

Sub-quantum-limited interferometer



Quantum correlations

Input squeezing



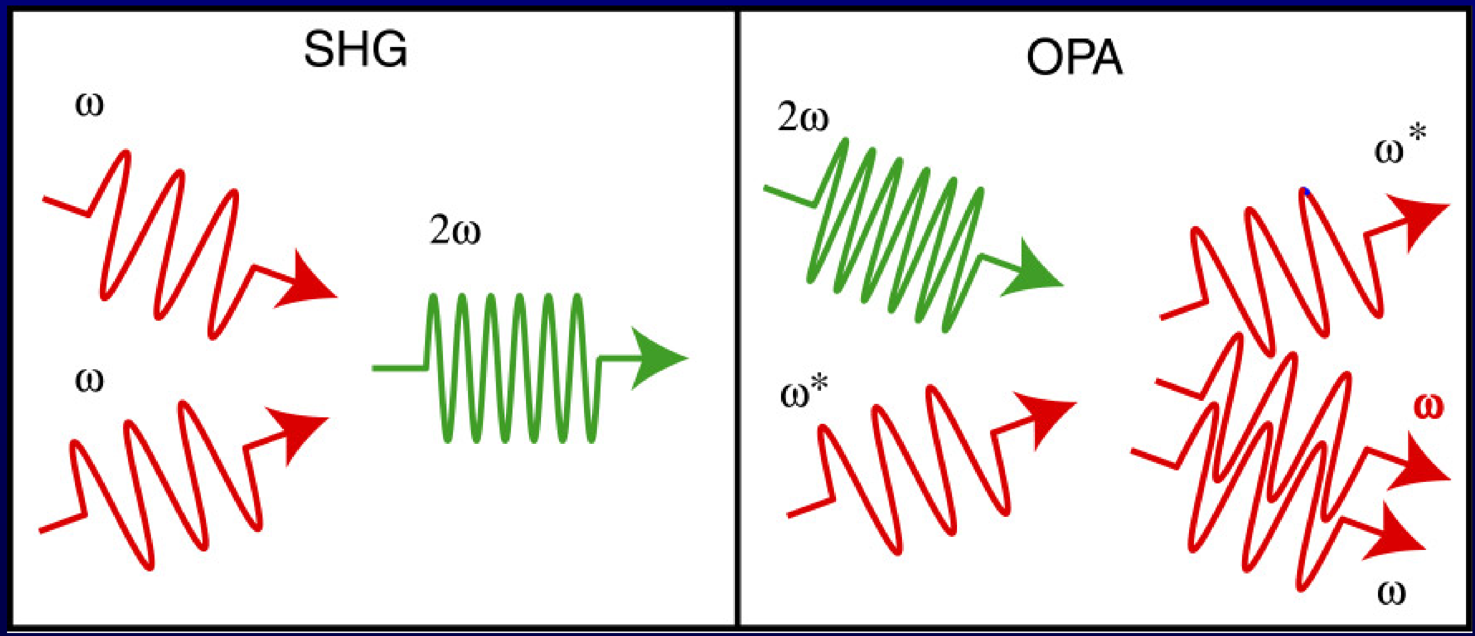
Squeezed vacuum

- 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

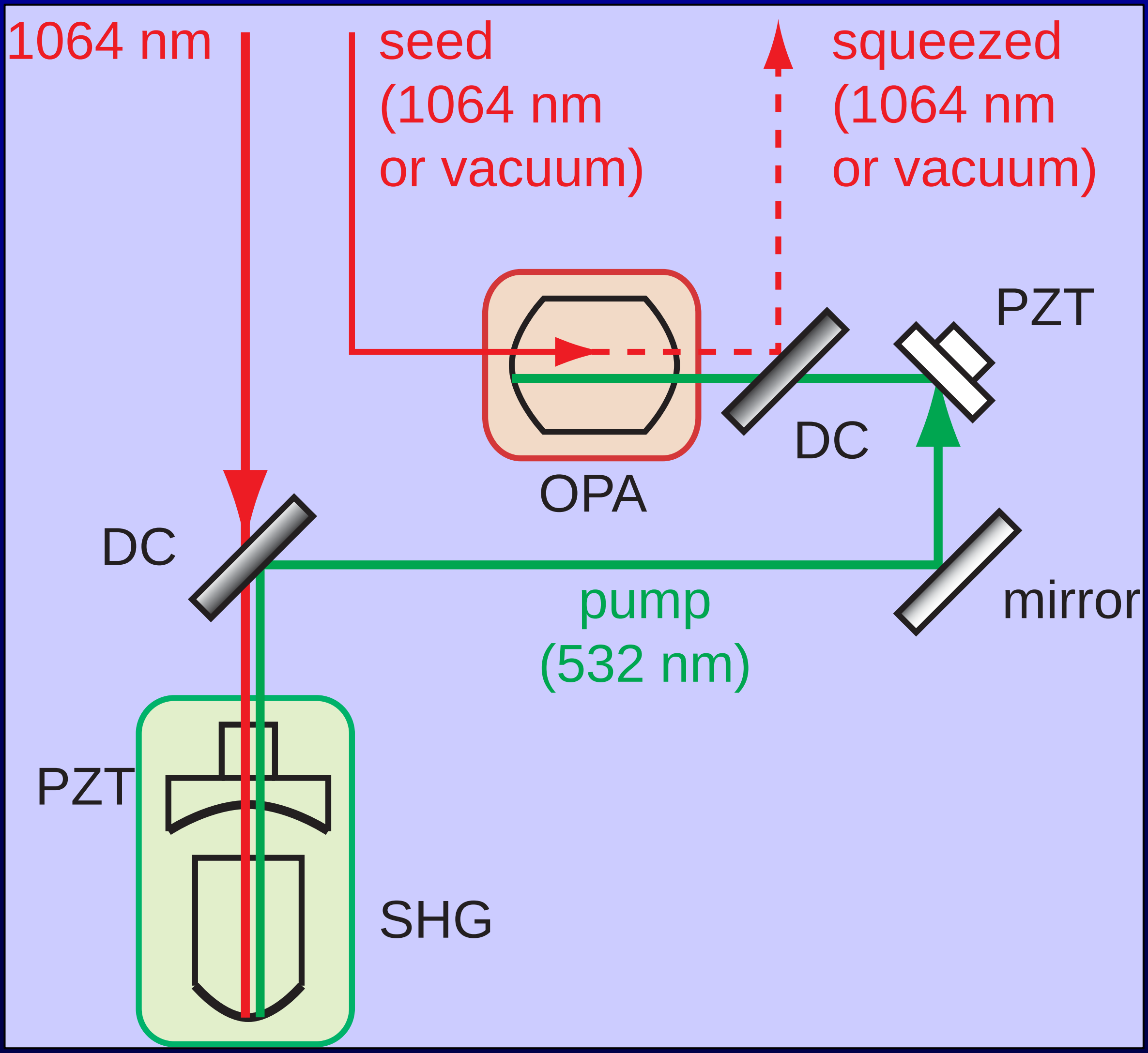
Squeezing using nonlinear optical media

Non-linear crystals

- Optical Parametric Amplification (OPA)
- Three (or four) wave mixing
  - Pump (532nm)
  - Seed (1064nm)



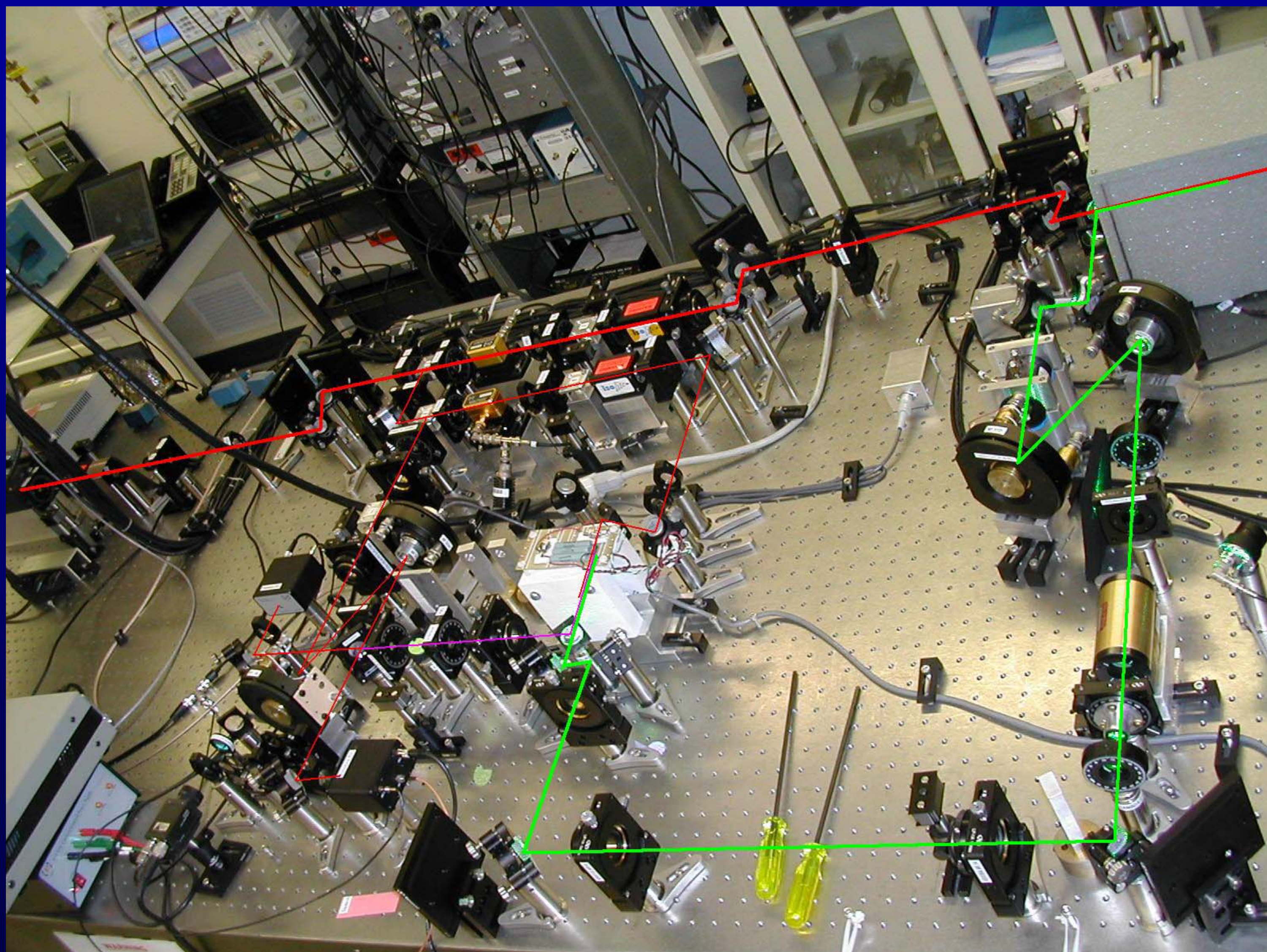
Optical Parametric Oscillator



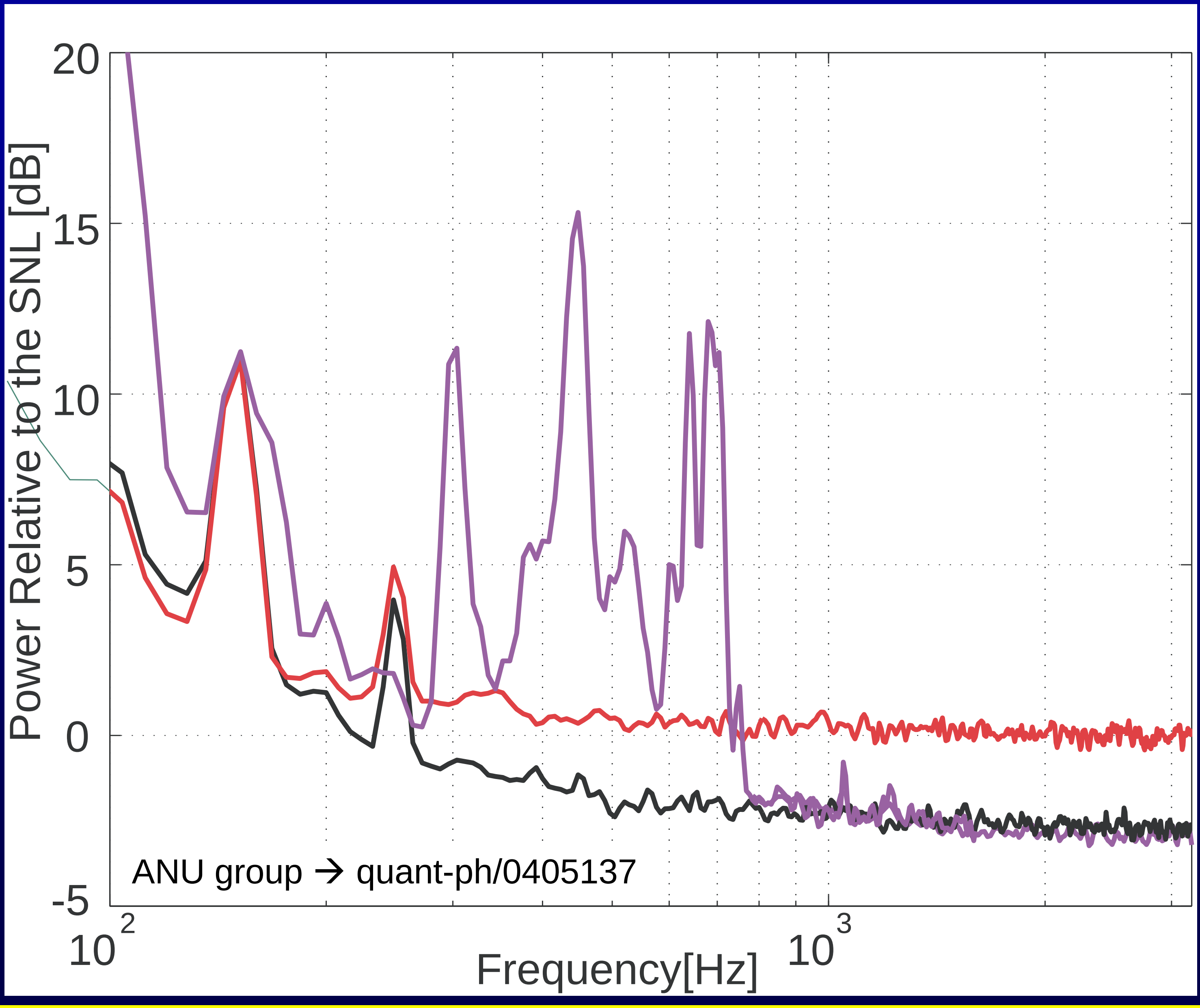
What's new since last year?

- Squeezing at audio frequencies (ANU, Caltech)
- Next-generation crystals in use (Hannover)
- Testing filter cavities (Hannover, MIT)
- Testing noise couplings (ANU, MIT)
- Detailed calculations of noise budget (ANU, MIT)
  - Photo-thermal noise not a problem
  - Pump noise coupling being considered

Typical Experimental Setup



Low frequency squeezing at ANU



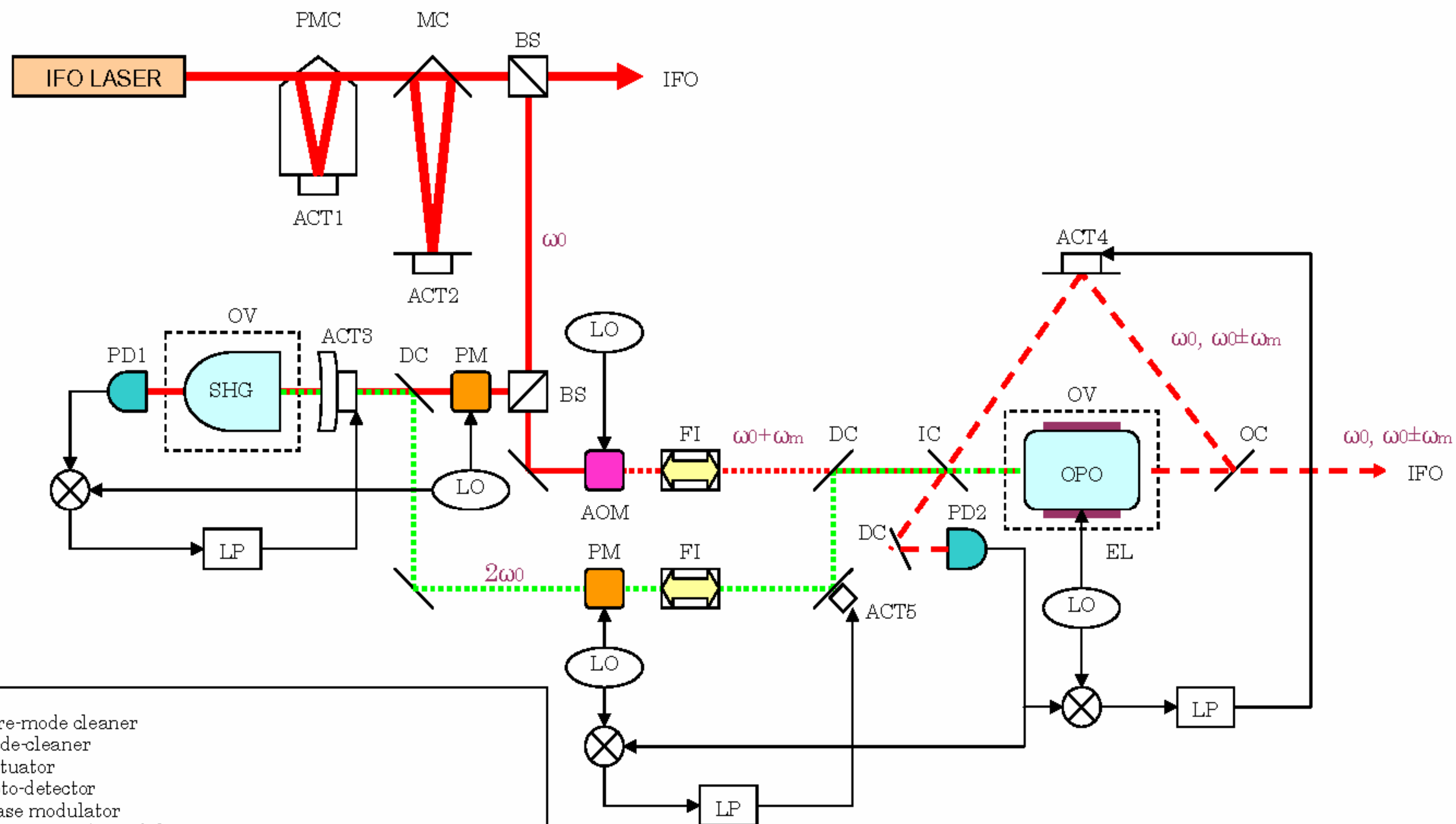
What's next

- Ultimate goal

  PERFORM A SUSPENDED INTERFEROMETER TEST

- Issues to work out
  - Coupling into interferometer dark port through output mode cleaner etc
  - Error signals for optimum quadrature

Injected Squeezing into Interferometer



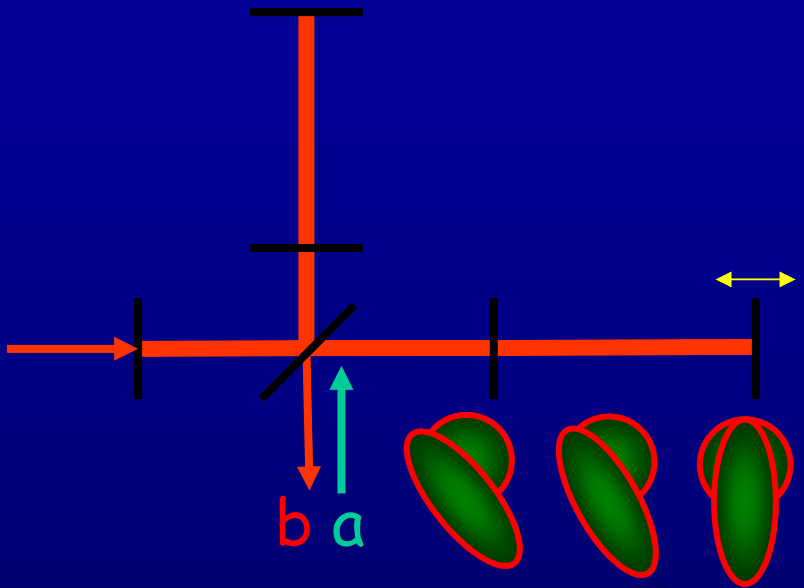
PMC: pre-mode cleaner
MC: mode-cleaner
ACT: actuator
PD: photo-detector
PM: phase modulator
AOM: acousto-optic modulator
LP: low-pass filter
DC: dichroic mirror
BS: beam-splitter
EL: electrode
FI: Faraday isolator
IFO: interferometer
LO: local oscillator
OV: oven
SHG: second-harmonic generator
OPO: optical parametric oscillator
IC: input coupler (HR at fundamental, AR at second-harmonic)
OC: output coupler (HR at both fundamental and second-harmonic)

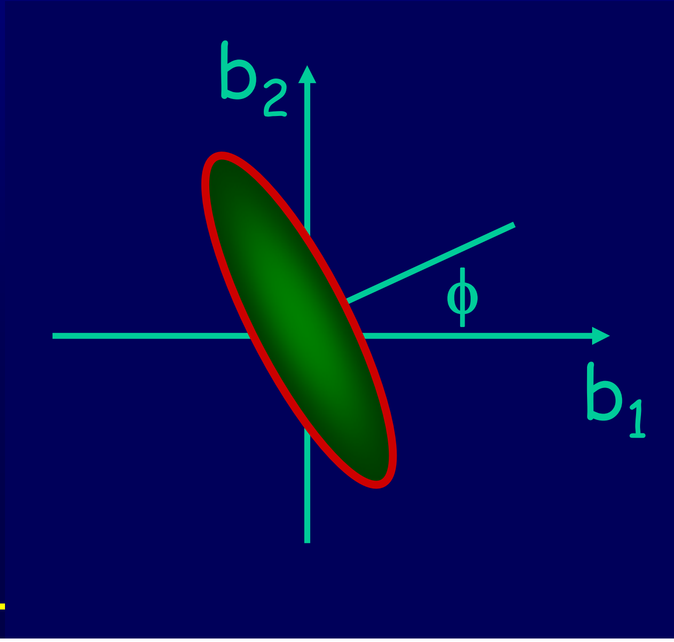
One Example
Cavity Length = 30 cm
FSR = 500 MHz
Cavity Linewidth = 13MHz

Main Laser:
Second-Harmonic Laser:
Frequency-Shifted Sub-Carrier:
Squeezed Vacuum + FSSC (Signal) + Idler:

Squeezing using back-action effects

Back Action Produces Squeezing





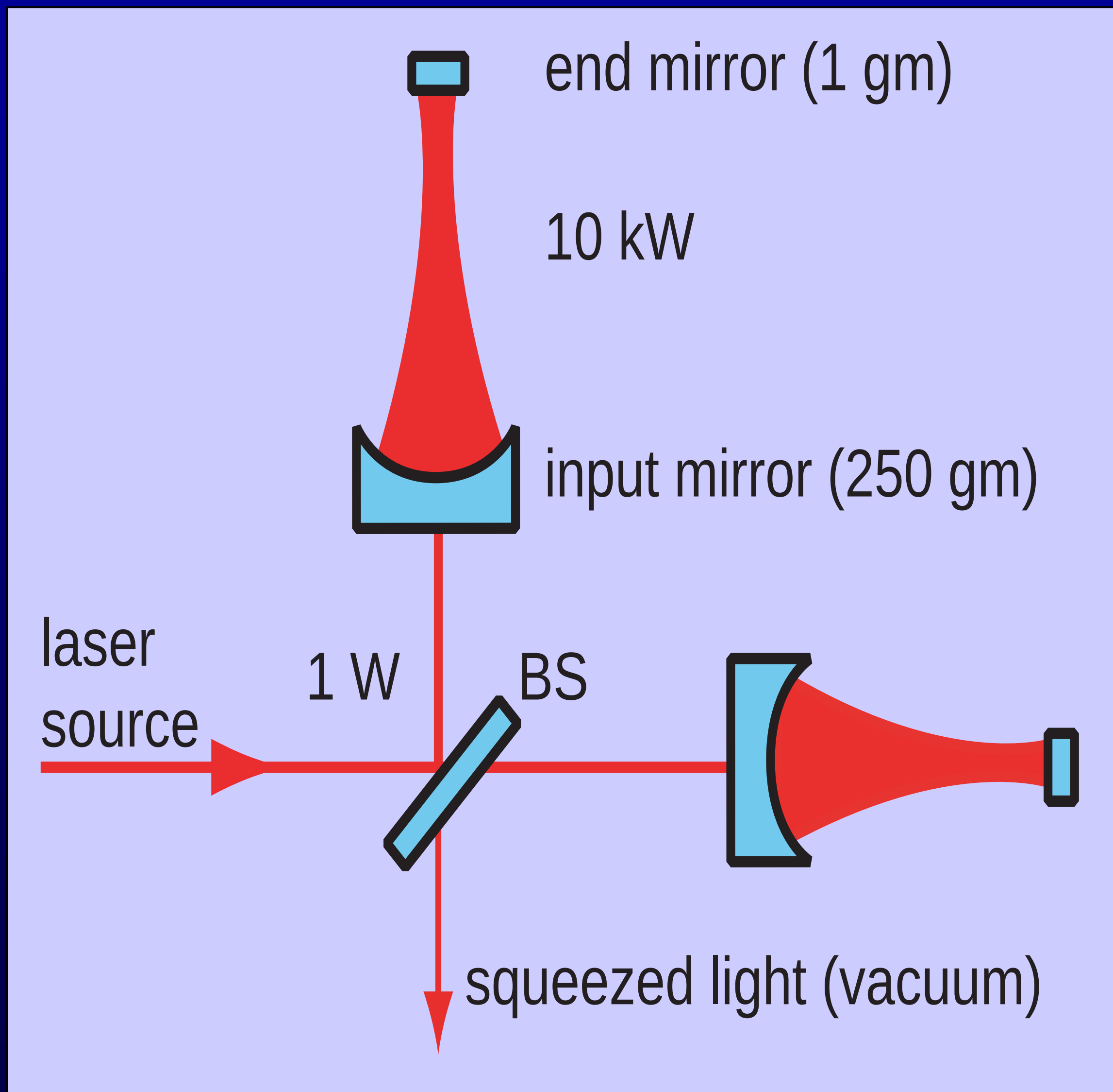
- Vacuum state enters anti-symmetric port
- Amplitude fluctuations of input state drive mirror position
- Mirror motion imposes those amplitude fluctuations onto phase of output field

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

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



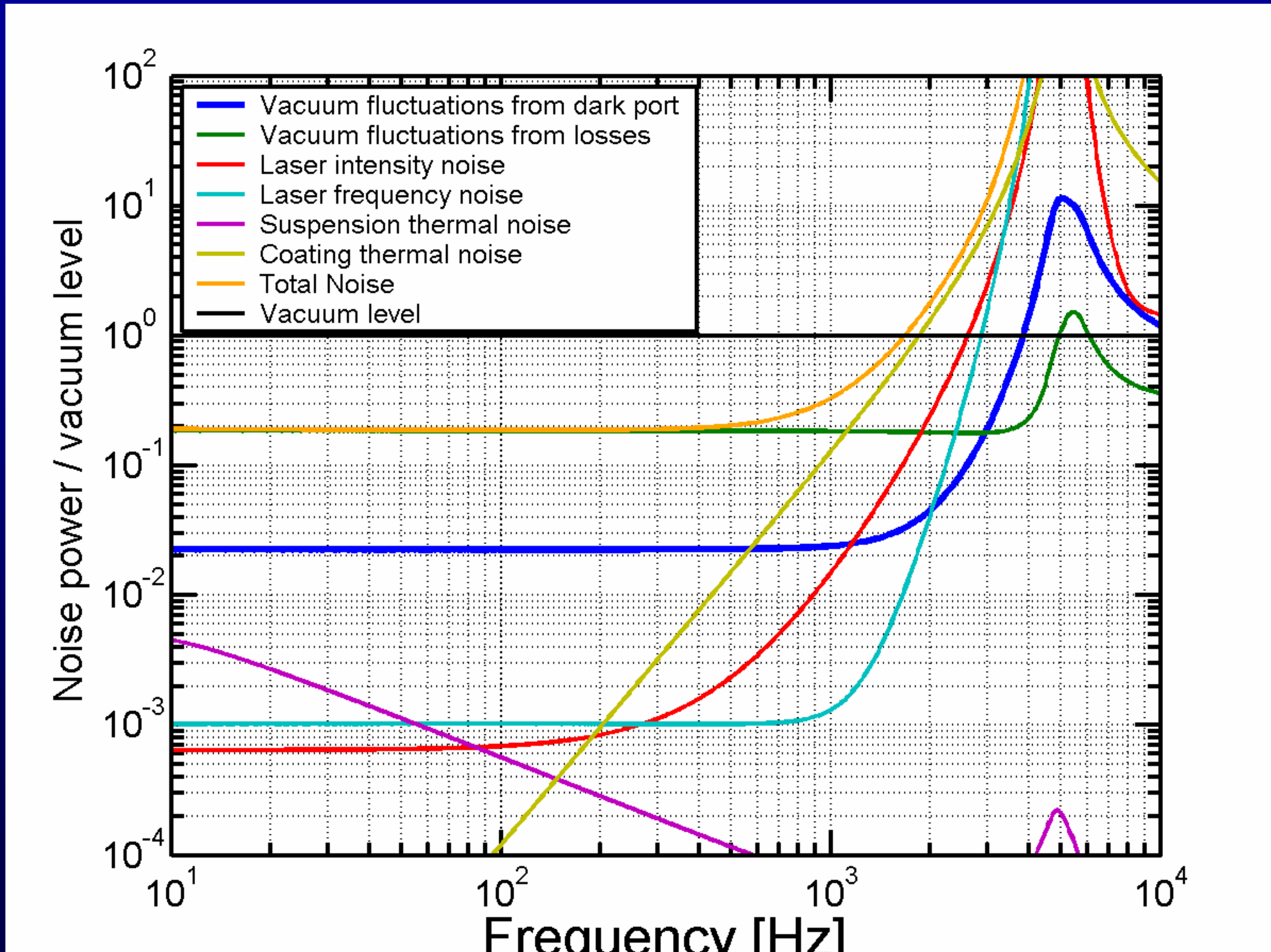
Key ingredients

- 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

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	$\Delta_{\rm BS}$	0.01	–	Mich. phase imbalance	$\Delta\alpha_{\rm M}$		
Mich. loss imbalance	$\Delta\epsilon_{\rm M}$			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}	$\mathrm{Hz}^{-1/2}$	Laser frequency noise	–	10^{-4}	$\mathrm{Hz}/\sqrt{\mathrm{Hz}}$

Noise budget



Work so far

- Detailed simulation of noise couplings
  - Uses first fully quantum mechanical simulation code for a GW interferometer
- Location and infrastructure
  - LASTI laser, vacuum envelop and seismic isolation
- Cavity geometrical parameters
- Monolithic fused silica suspensions for mini-mirror

What's next

- Design completion
  - Suspension
  - Control system
- High finesse cavity tests
  - Fixed mini-mirror – optical tests
  - Suspended mini-mirror – includes mirror dynamics and radiation-pressure coupling
- Complete interferometer

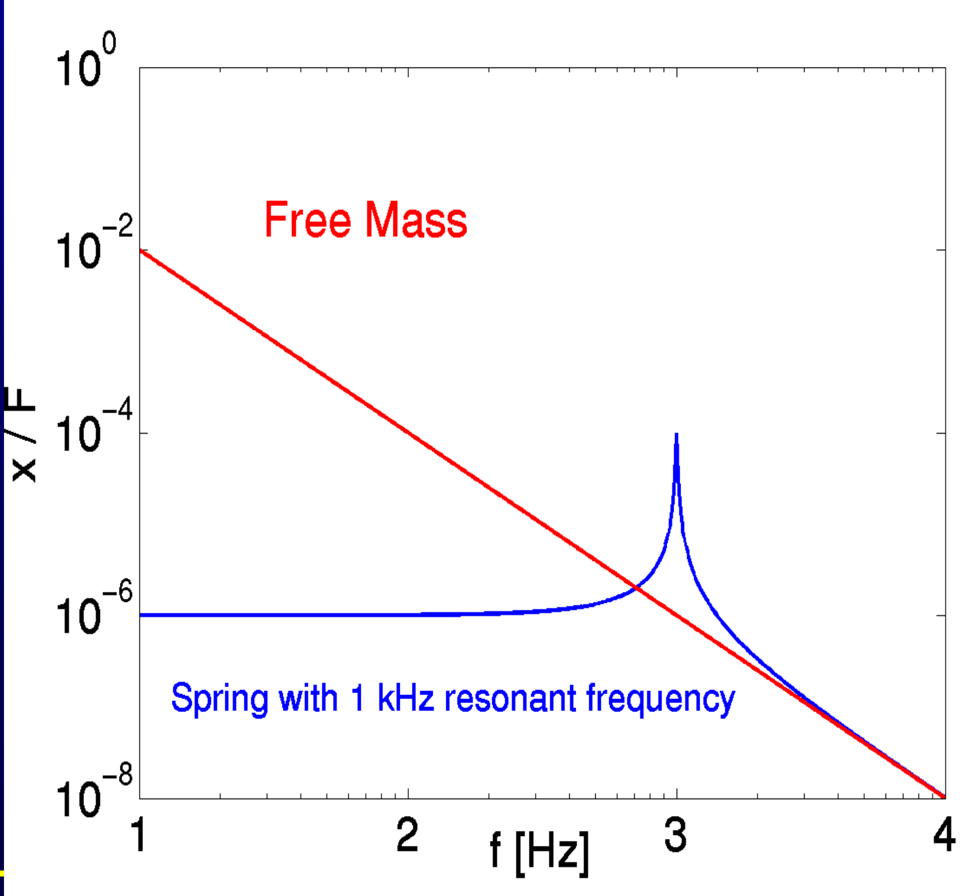
Why is this interesting/important?

- First ever demonstration of ponderomotive 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

The End

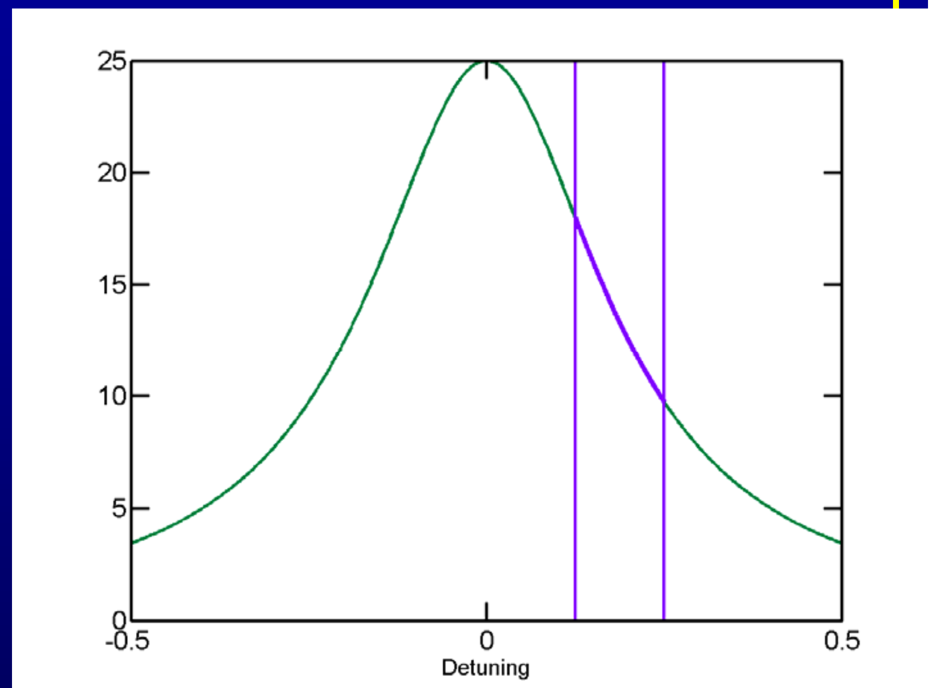
Optical Springs

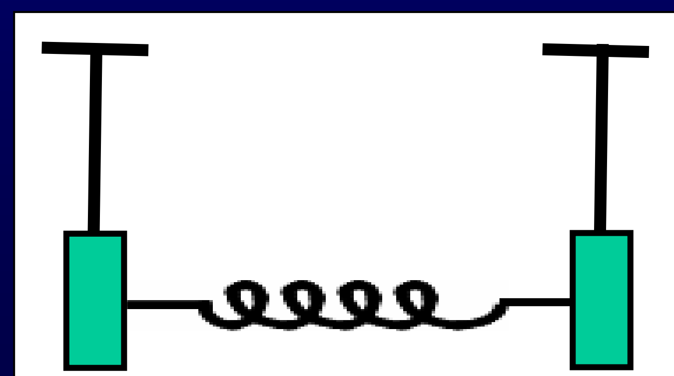
- Modify test mass dynamics
- Suppress displacement noise (compared to free mass case)
- Why not use a mechanical spring?
  - Displacements due to thermal noise introduced by the high frequency (mechanical) spring will wash out the effects of squeezing
- Connect low-frequency mechanical oscillator to (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



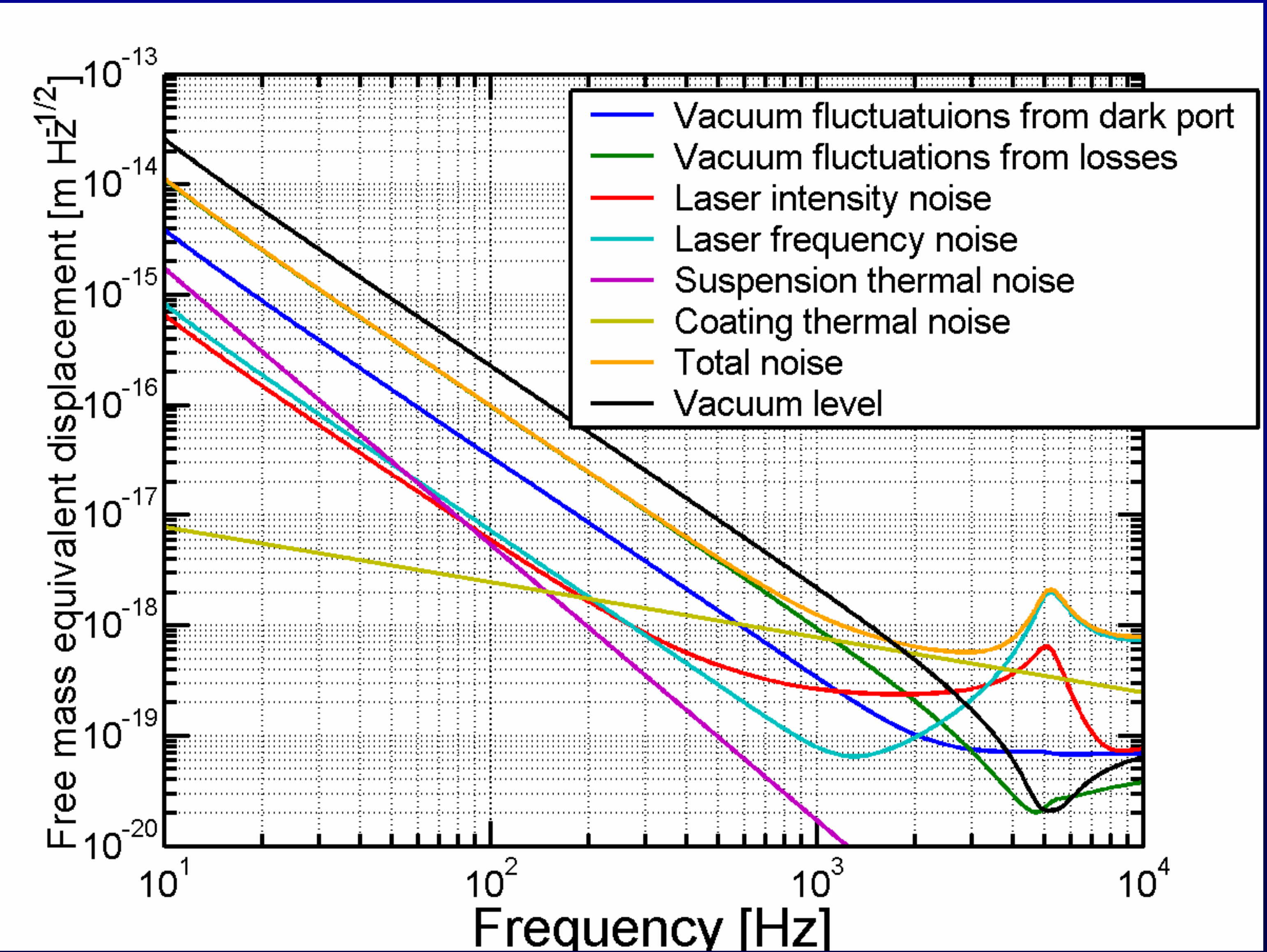
Detuned cavity for optical spring

- 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





Noise budget – Equivalent displacement



Squeezed Vacuum