Quantum Metrology and Gravitational-Wave Detectors

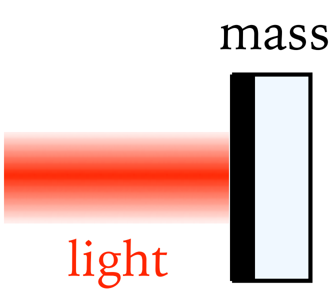
Yanbei Chen

California Institute of Technology

Quantum Limits for GW Detection

Standard Quantum Limit

$$\Delta x \cdot \Delta p \geq \hbar/2$$



probing test-mass position perturbs momentum, causing **back-action** noise

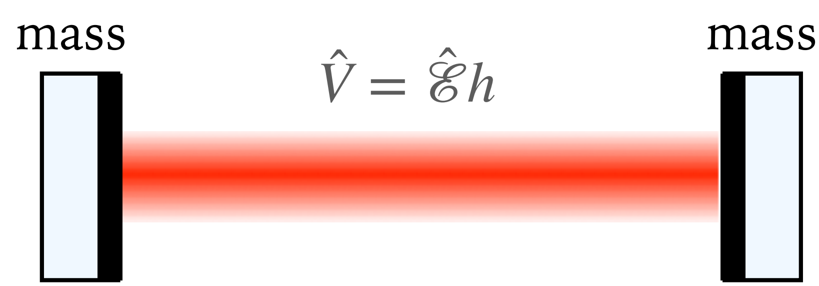
$$S_h^{\mathrm{SQL}} \geq \frac{8\hbar}{M\Omega^2 L^2}$$

can be surpassed by quantum correlations between light and mass.

[Unruh 1979; Caves, 1980s; Kimble et al., 2001]

Energetic Quantum Limit

$$\Delta E \cdot \delta\phi \geq \hbar\omega_0$$



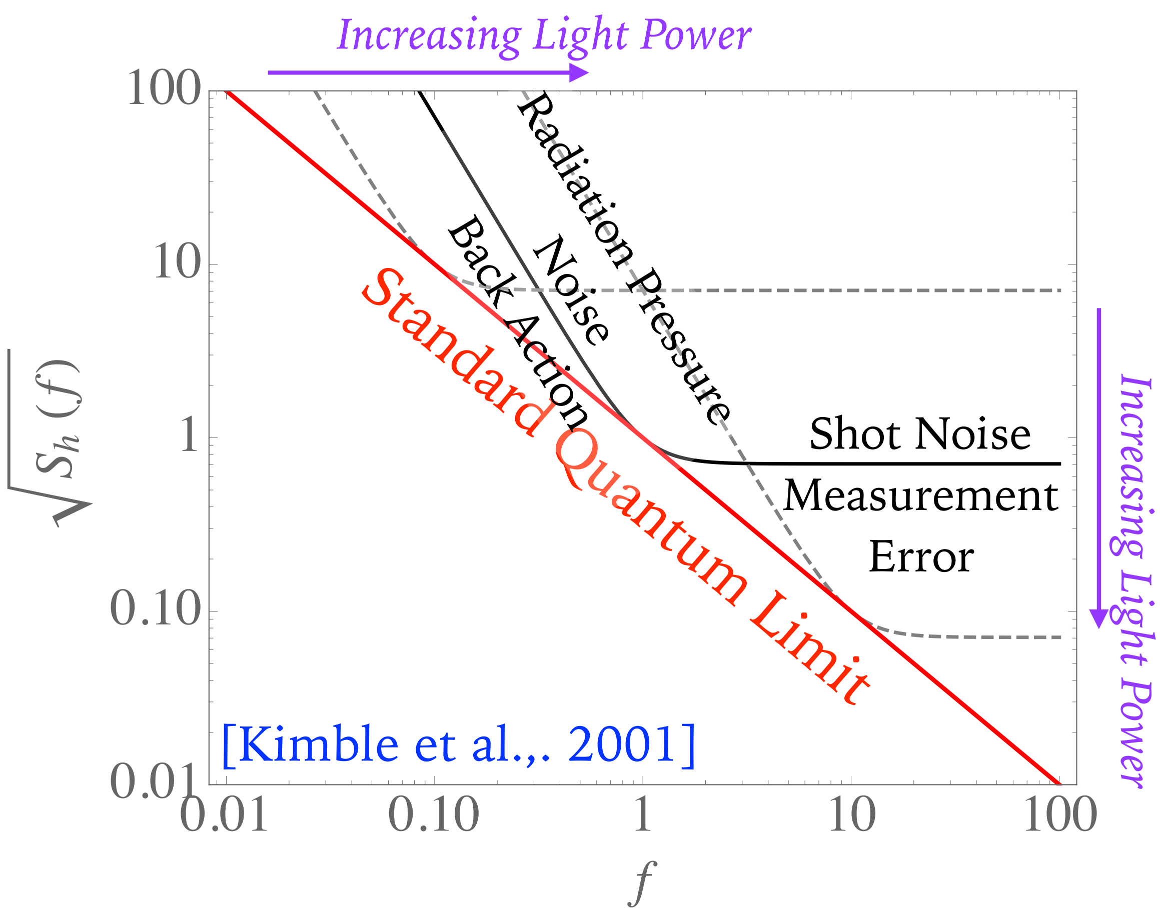
device and GW couple via **intra-cavity energy.** Using Fisher Information,

$$S_h \geq \frac{\hbar^2}{S_{\hat{\mathscr{E}}}}$$

higher energy uncertainty leads to better sensitivity

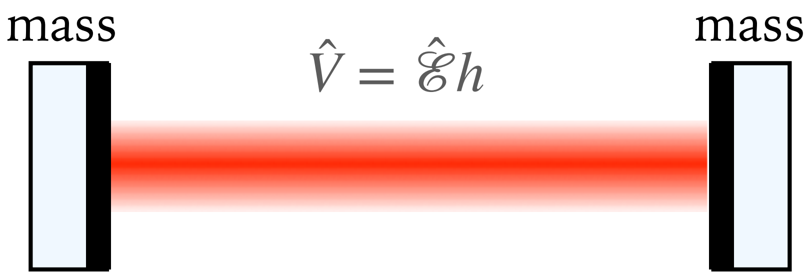
[Braginaky & Khalili, 1990s; Tsang, Wiseman & Caves, 2012; Miao et al., 2017; Pang & Chen, 2019]

Standard Quantum Limit



- SQL can be overcome by building correlations between light and mass.
  - Injection of squeezed vacuum/entangled states
  - Detection of frequency-dependent quadratures
  - Modification of optical transfer functions
  - Modification of test-mass dynamics, optical spring

The Energetic Quantum Limit



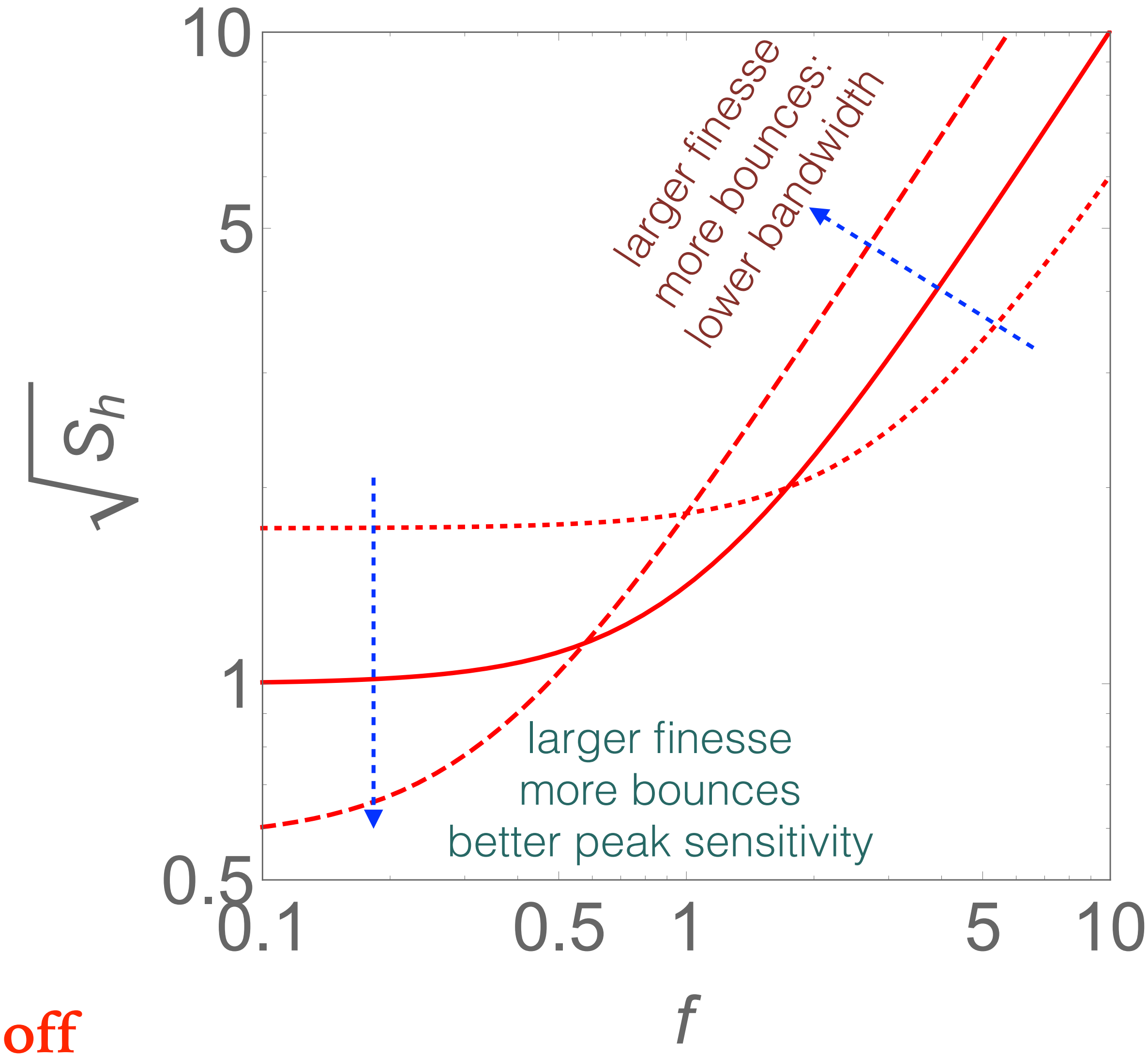
$$S_h \geq \frac{\hbar^2}{S_{\hat{\mathscr{E}}}}$$

$$\int \frac{1}{S_h} \frac{d\Omega}{2\pi} \leq \int \frac{S_{\hat{\mathscr{E}}}}{\hbar^2} \frac{d\Omega}{2\pi} = \frac{\Delta \mathscr{E}^2}{\hbar^2}$$

for coherent state

$$\Delta \mathscr{E}^2 = \mathscr{E}^2 / N$$

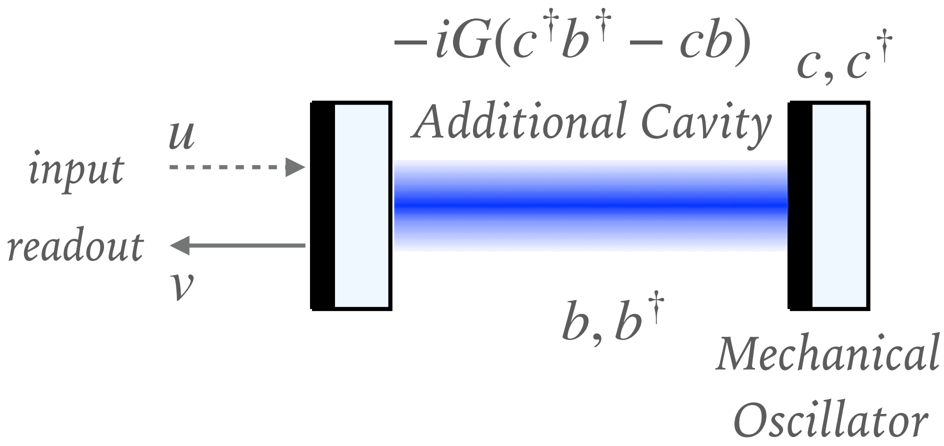
Bandwidth-sensitivity trade-off issue will be more severe for longer interferometers



"Mizuno Theorem", 1990s

White-Light Cavity

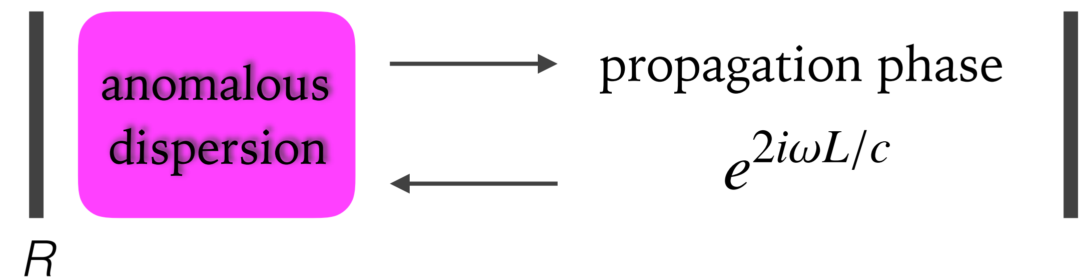
[Wicht, 1990s, Wise et al, 2000s, Shahriar, 2010s]



$$b_{1,2}(\Omega) \approx \frac{\Omega + i\gamma_{\rm OM}}{\Omega - i\gamma_{\rm OM}} a_{1,2}(\Omega)$$

This has an "anomalous dispersion"!

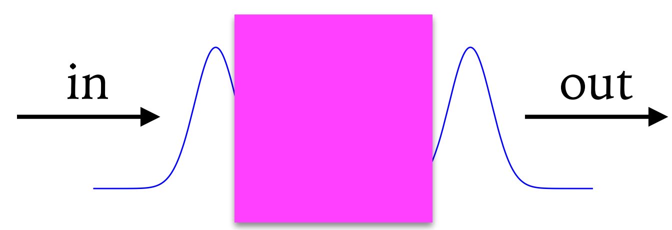
[Miao et al., 2015]



Propagation Phase shift: $\Phi_{\rm propagation}(\omega) = \dfrac{2\omega L}{c}$

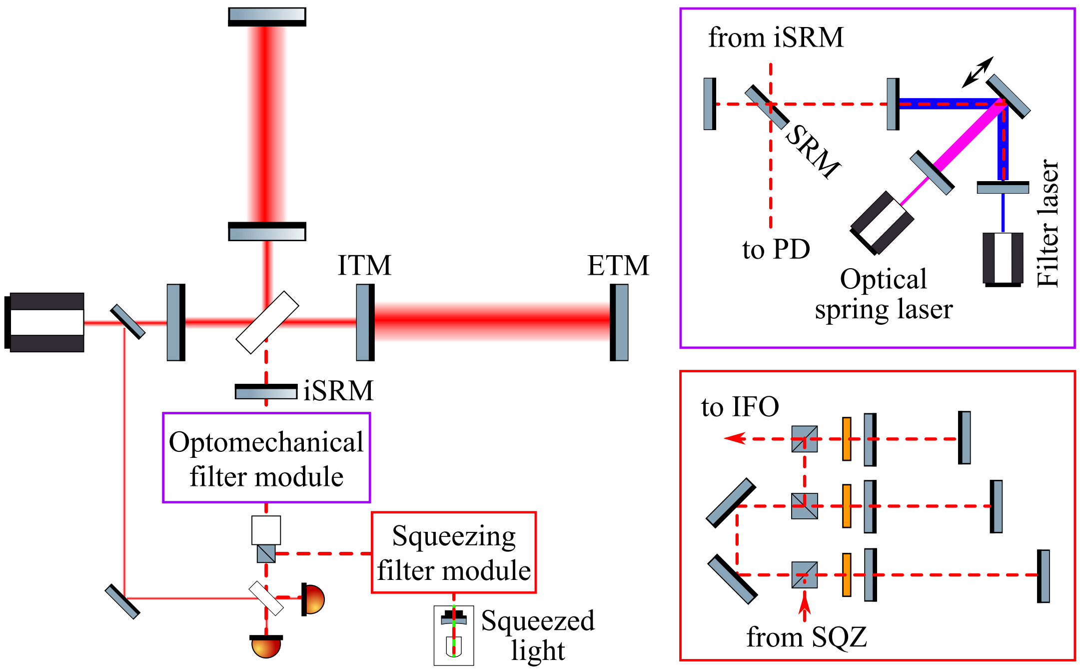
Anomalous Phase shift: $\Phi_{\rm anomalous}(\omega) = -\dfrac{2\omega L}{c}$

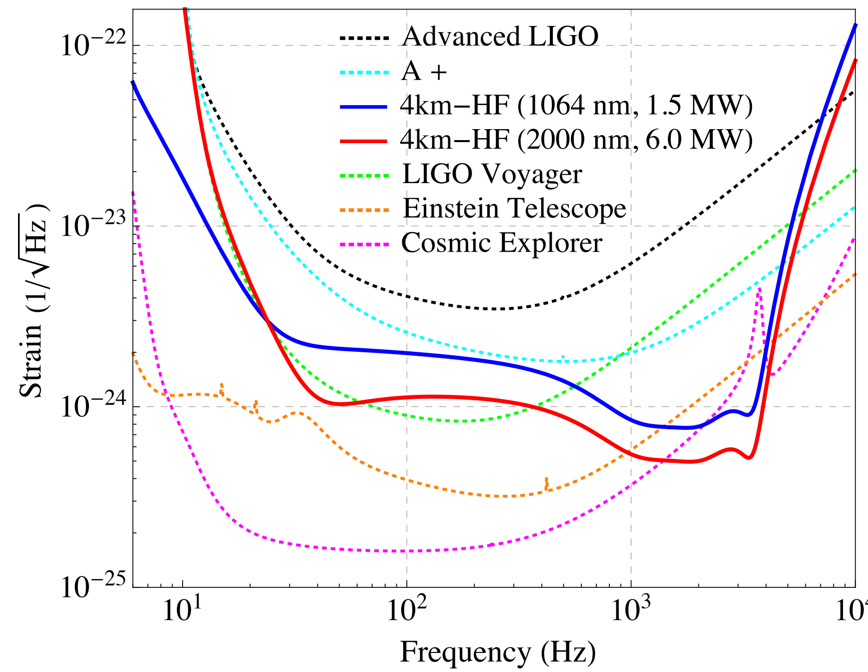
anomalous dispersion: wave packet comes out **before** it goes in!!



here it just means system is unstable

WLC Interferometer

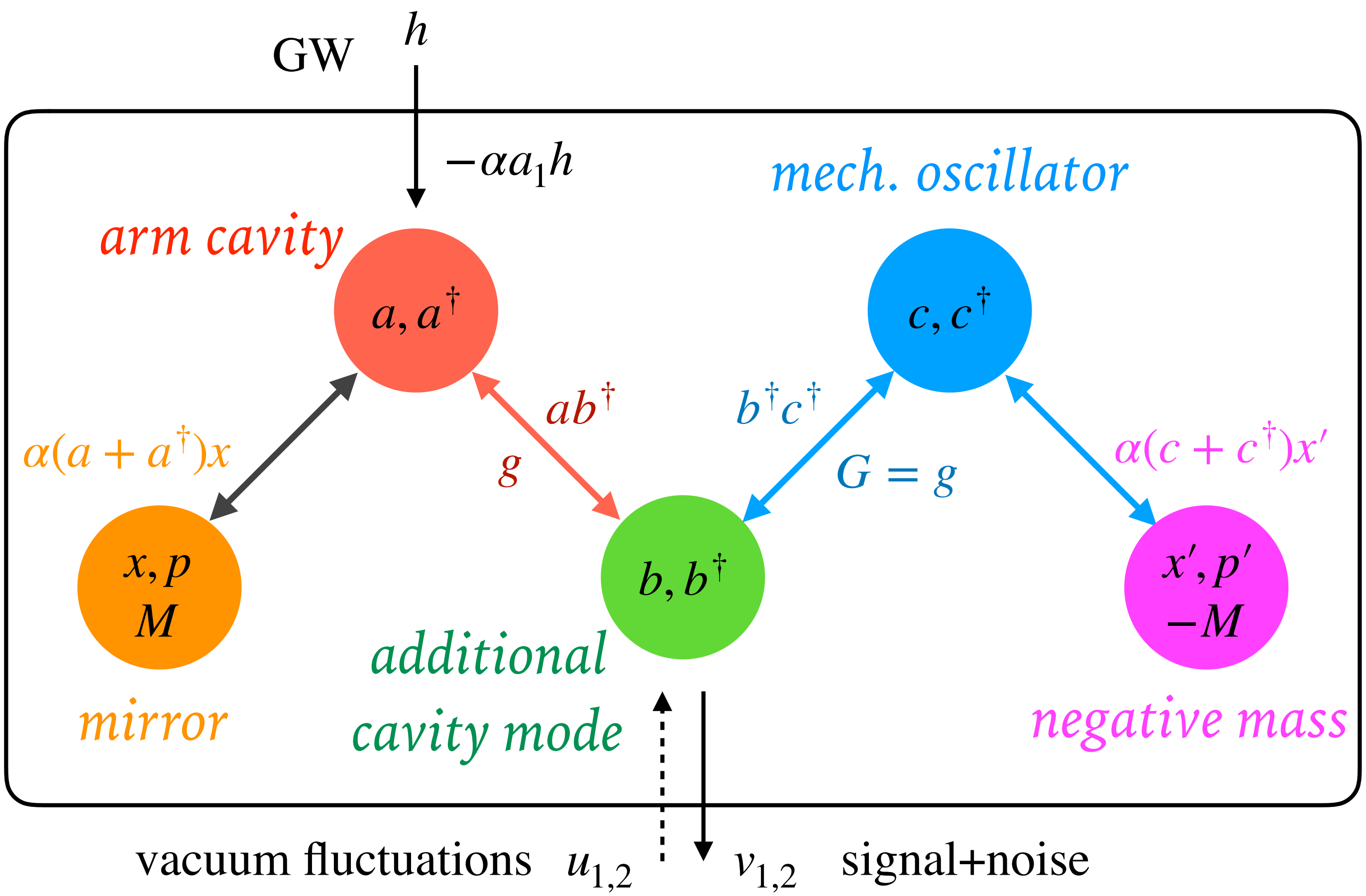




[Miao, Yang and Matynov, 2018]

More recent work at Caltech/ANU/UWA: broadband amplification can also be stable

More Theoretical Directions



(a,x)
FP Micheislon

(a,b,x)
speed meter

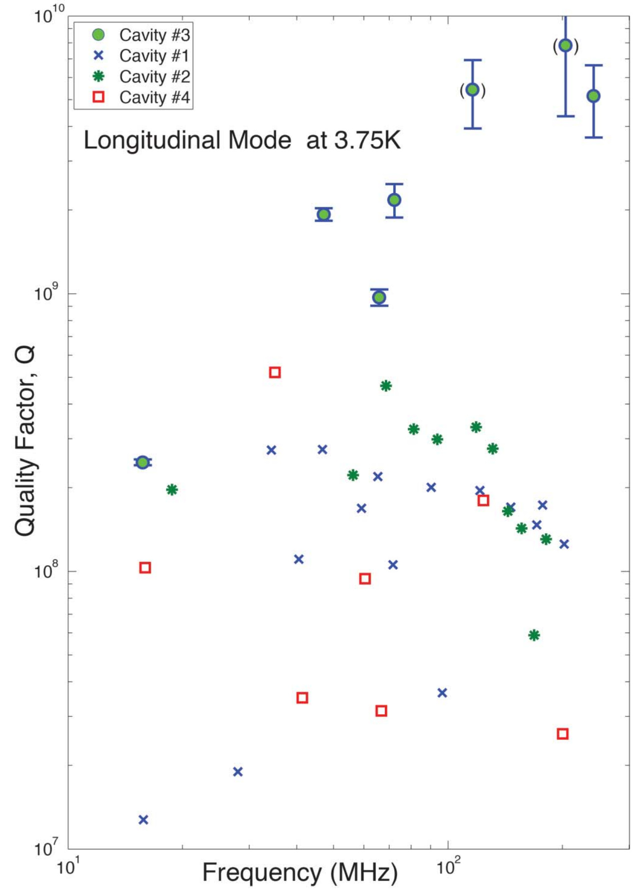
(a,b,x,c)
white-light interferometer

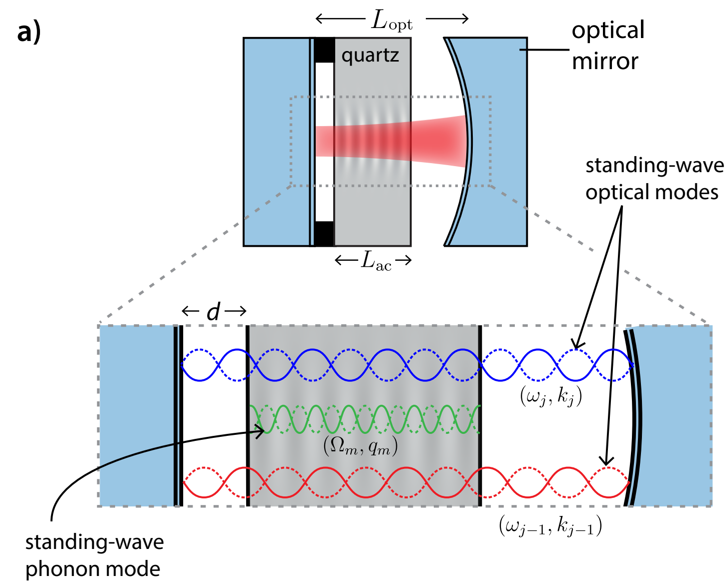
(a,b,x,c,x')
back-action-evading
(quantum-mechanics free)
white-light interferometer

- Coherent Quantum feedback system (stable/unstable) [Nurdin, James, Petersen, 2009]
- Quantum Error Correction [Zhou, Zhang, Preskill & Jiang, 2018]
- Non-reciprocity, PT symmetry and Exceptional Points [Miri & Alu, 2019]
- "Quantum Mechanics Free" measuring devices [Tsang & Caves, 2012]
- Optimization of quantum networks.

More Experimental Directions

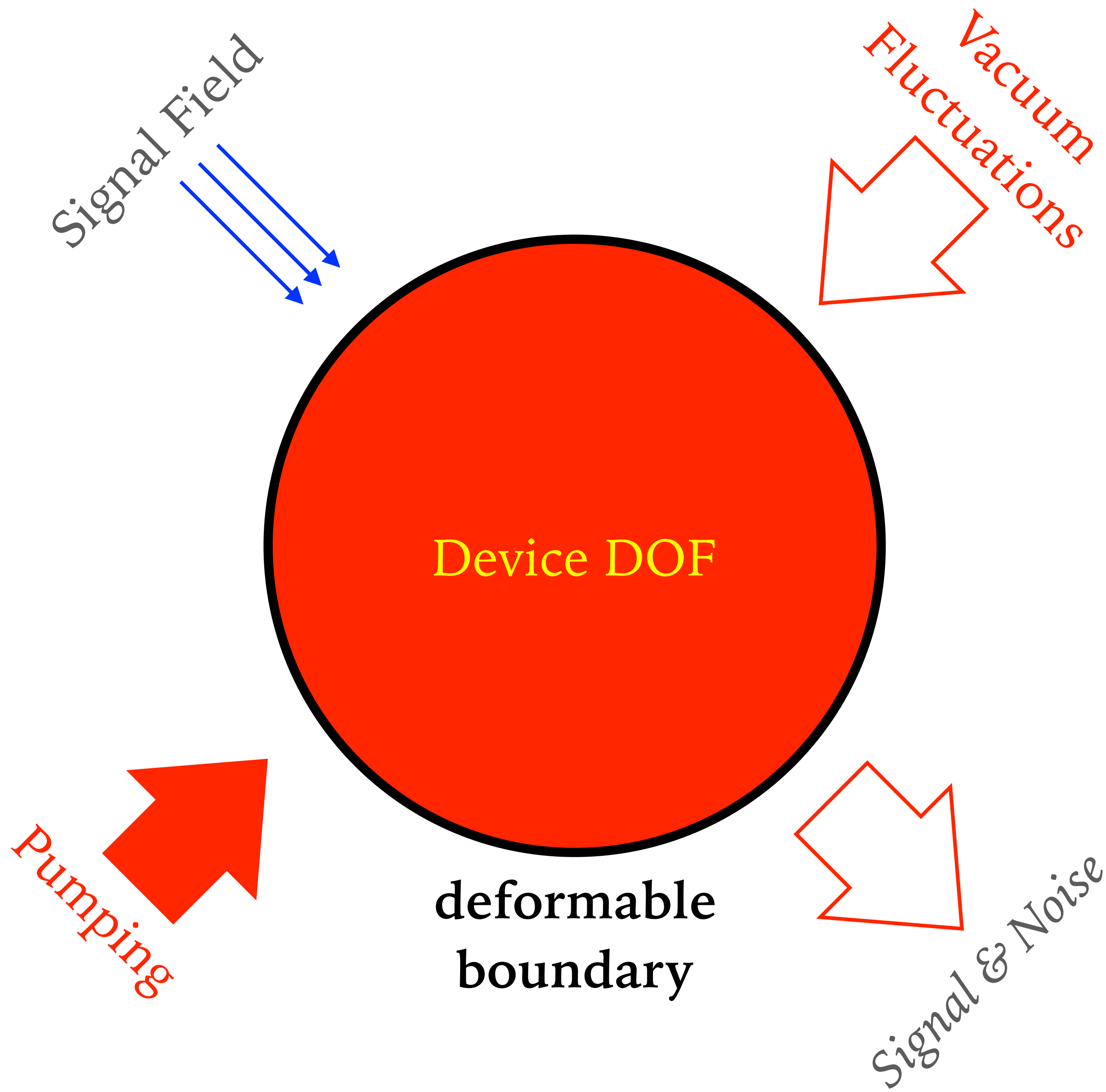
- Bulk acoustic oscillators
- Microwave circuits
- Superfluid helium oscillators
- Superfluid helium droplets
- Diamond NV centers





[Galliou *et al.*, 2013; Kharel *et al.*, 2018]

GW Detector ⇒ X Detector



GW

$$\int d^3\mathbf{x} h_{ij}\hat{T}^{ij} \propto \hat{\mathscr{E}}(h_{xx} - h_{yy})$$

Axion

$$g_{a\gamma\gamma}\int d^3\mathbf{x}\, \Phi\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}$$

X

$$\int d^3\mathbf{x} \left(\begin{matrix} novel \\ field \end{matrix}\right)\left(\begin{matrix} novel \\ excitations \end{matrix}\right)$$