QUANTUM SENSING: FROM FUNDAMENTAL UNCERTAINTIES TO EXPERIMENTAL IMPRECISION

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WHAT ARE SENSORS?

Sensors detect and respond to physical changes in a system.

Everyday examples include:

Thermometers

Smoke detectors

Smart watches

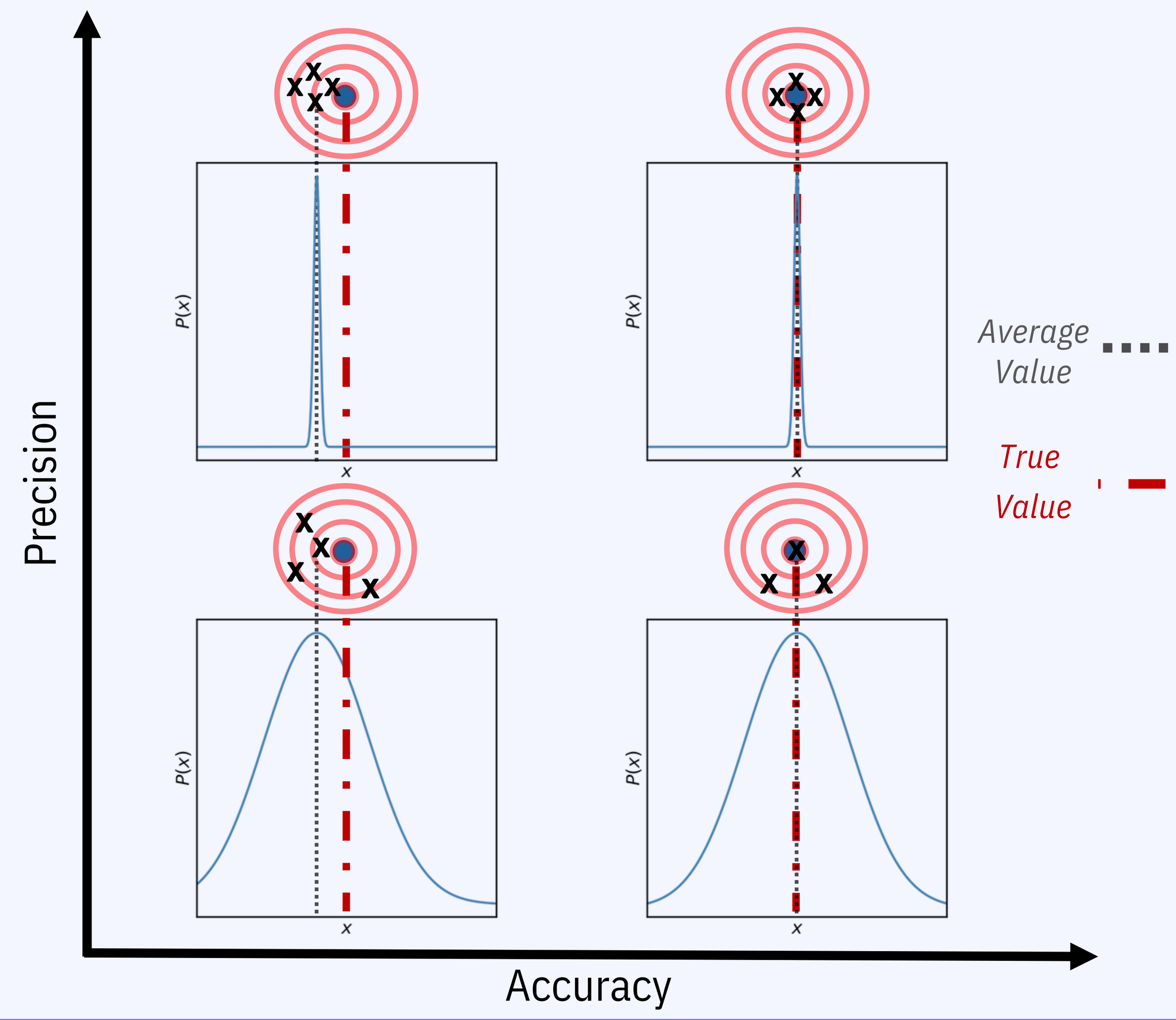
BUT WHAT ARE QUANTUM SENSORS?

Quantum sensors can be classified under two flavors:

- Using an inherently quantum effect as a resource to sense something.
- Using a system operating at the nanoscale as a sensor.

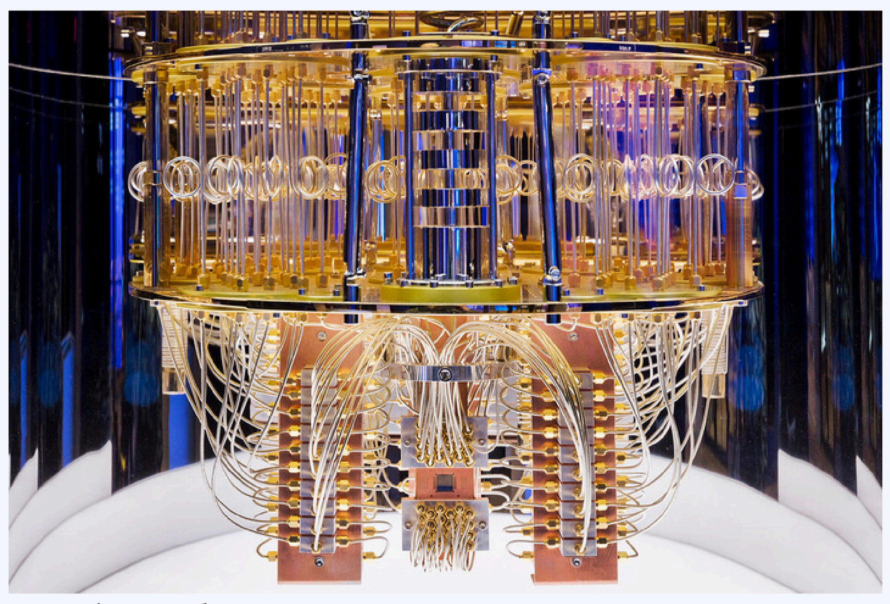
PRECISION

Precise sensors are crucial: we want to obtain reliable and consistent measurement readings.



PRECISION FOR TECH

Quantum computers are encased in cryogenic chambers. Temperatures of almost zero Kelvin are required as *Qubits* are delicate: temperature fluctuations can make them lose coherence, something we wish to exploit.



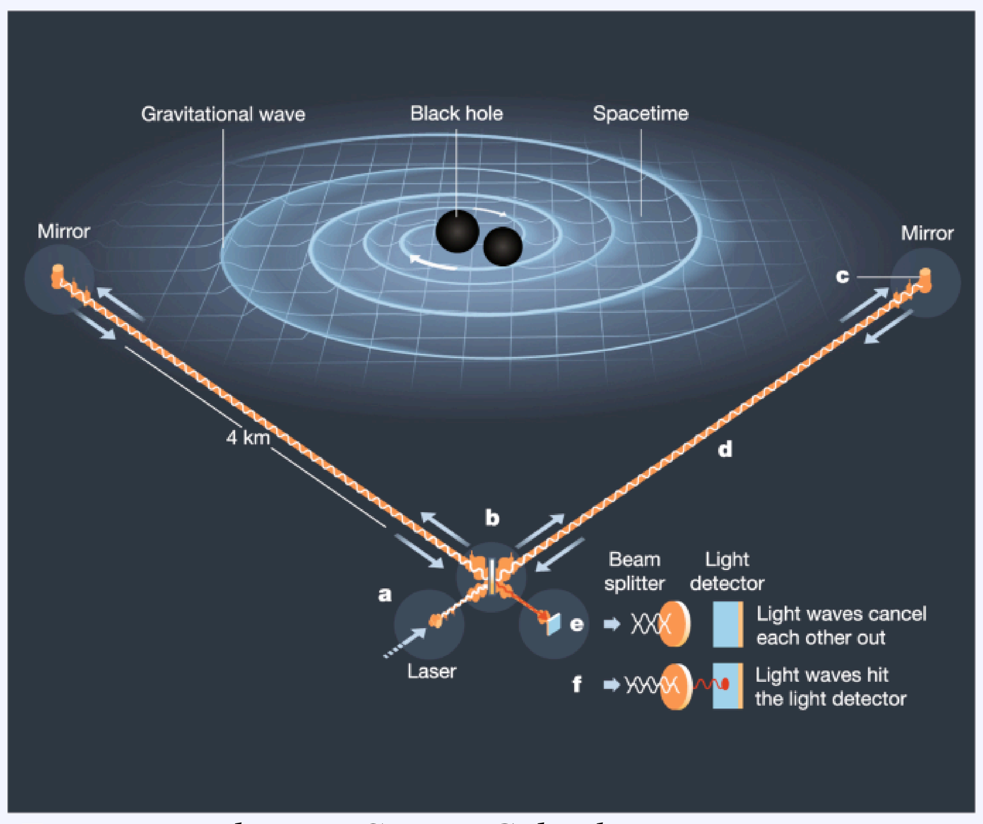
IBM's Eagle quantum computer.

Precise temperature readings are needed to ensure the system operates as intended!

MODERN QUANTUM SENSORS

LIGO: GRAVITY WAVE DETECTOR

Detection of gravitational waves whose origin came from the merging of two black holes (2015/2016).



Experimental setup. Source Caltech.

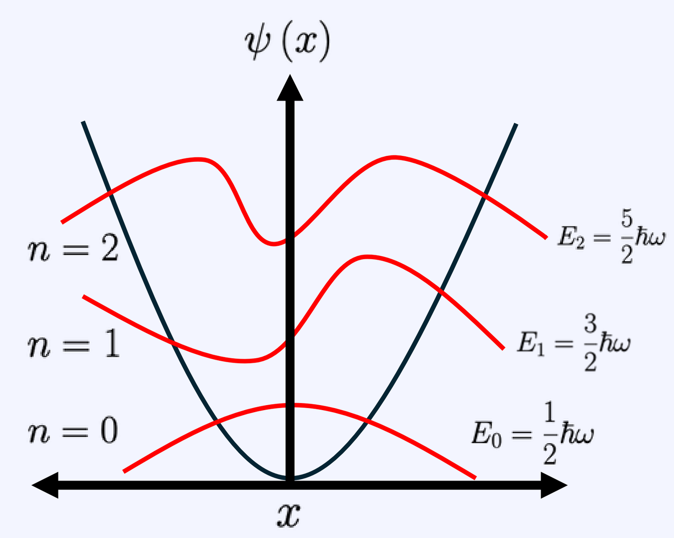
This was achieved using interferometry. But, device not sensitive enough to detect gravity waves from different sources, such as supernovae.

NEW EXPERIMENT WILL HARNESS QUANTUM PROPERTIES OF LIGHT

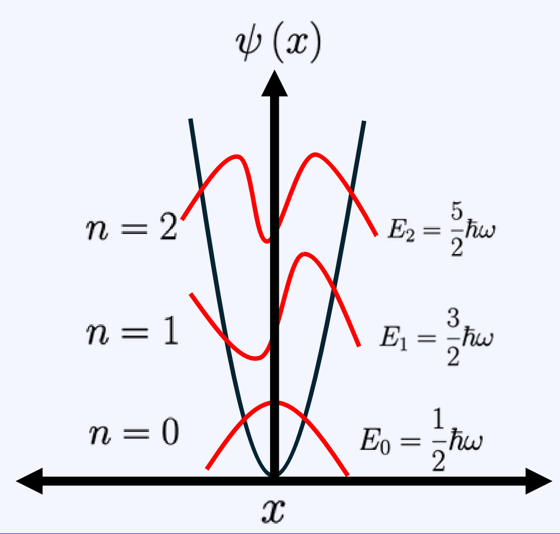
SQUEEZED LIGHT: INCREASING THE SENSITIVITY

SQUEEZED LIGHT

Consider the quantum harmonic oscillator:



The harmonic oscillator can be squeezed,



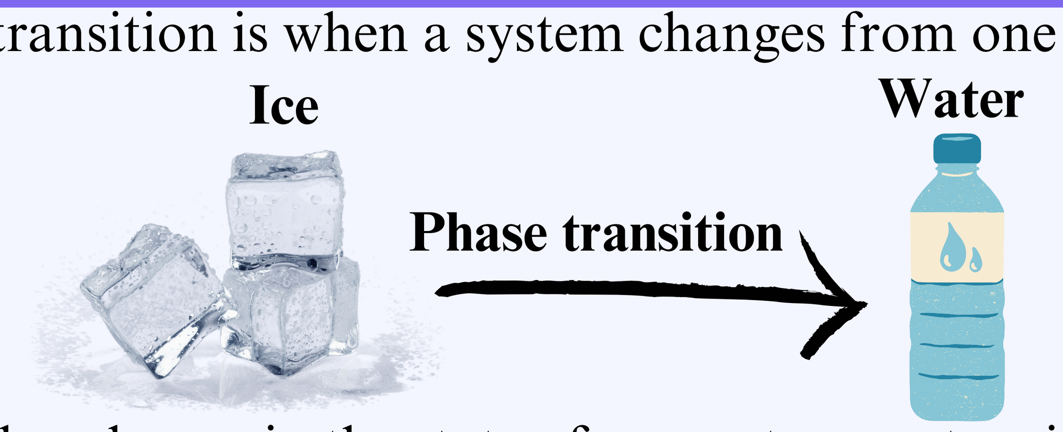
PROBLEM!?

In theoretically assessing a probes sensing capabilities, we assume that we have **perfect knowledge/control** over all system parameters - except for the one we wish to sense!

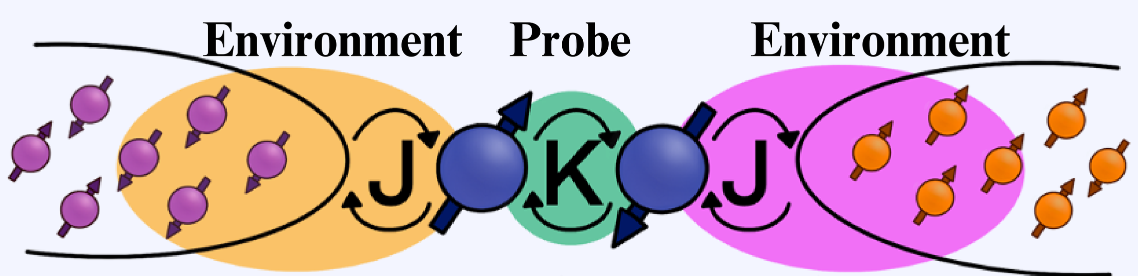
- **WHAT HAPPENS IF WE DO NOT KNOW SOME OF THE SYSTEM PARAMETERS?**
- **WHAT HAPPENS IF WE HAVE IMPRECISE MEASUREMENT?**
- **IN ACCOUNTING FOR THESE: DO WE MAINTAIN A QUANTUM IMPROVEMENT?**

SCENARIO: LACK OF KNOWLEDGE

A phase transition is when a system changes from one state to another.



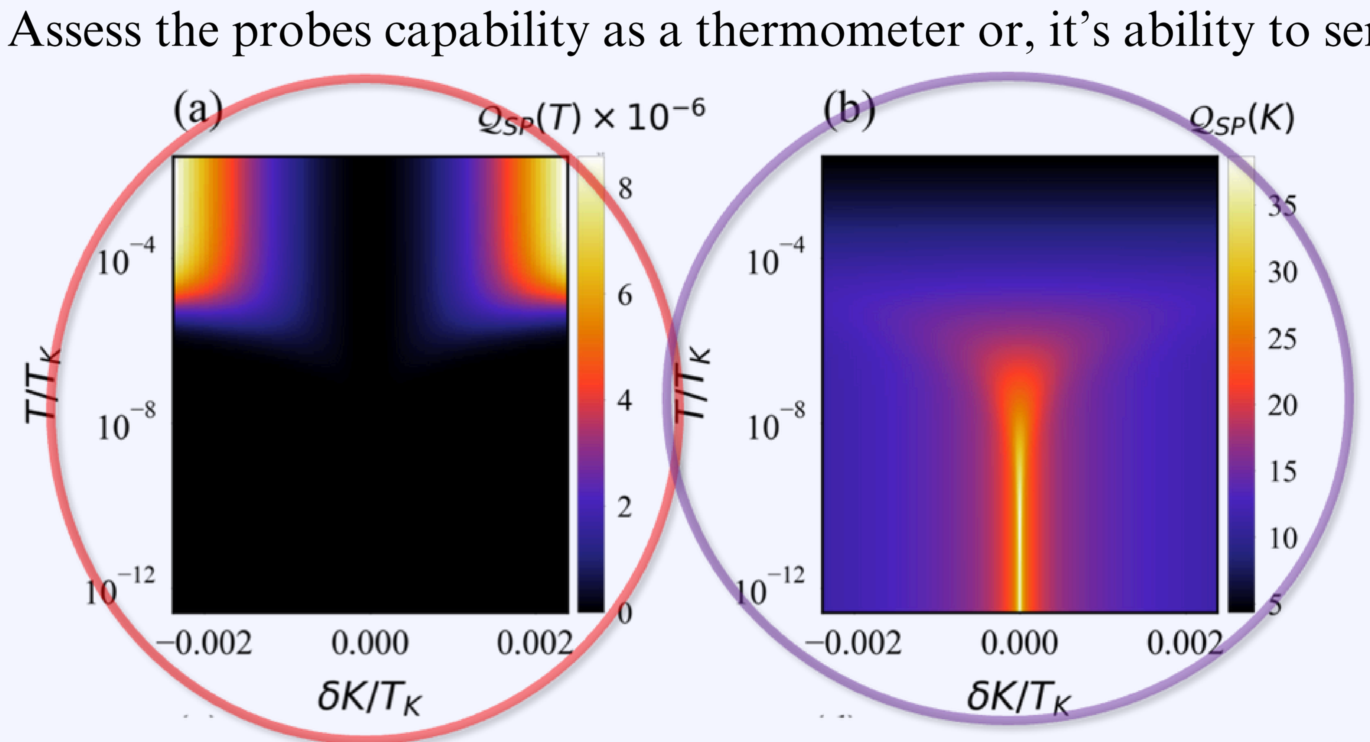
This sudden change in the state of a quantum system is known to provide massive enhancement in sensing capabilities.



$$\hat{H} = \hat{H}_E + \hat{H}_{\text{probe}} + J\left(\hat{\vec{S}}_{IL}\cdot\hat{\vec{s}}_{EL} + \hat{\vec{S}}_{IR}\cdot\hat{\vec{s}}_{ER}\right)$$

One phase is when the spins are entangled. Another phase is when the spins are entangled with their environment.

Assess the probes capability as a thermometer or, it's ability to sense the spin-coupling.



The probe is a poor thermometer but, it's excellent at sensing the spin-coupling.

The probe is excellent at sensing the spin-coupling when we perfectly know the temperature. What happens if we do not know the temperature?

$$\mathcal{Q}_{MP}(\lambda_A,\lambda_A) = \lambda_A^2\frac{\det(\mathcal{H})}{\mathcal{H}_{\lambda_B,\lambda_B}} = \mathcal{Q}_{SP}(\lambda_A) - \frac{(\lambda_A\lambda_B\mathcal{H}_{\lambda_A,\lambda_B})^2}{\mathcal{Q}_{SP}(\lambda_B)}$$

SCENARIO: MEASUREMENT IMPRECISION

Let's say we wish to estimate some frequency ω , but I have some imprecision in the magnetic field I apply g. How good is my sensor compared with the optimal case when I have some Gaussian uncertainty?

We wish to prepare some known quantum state,

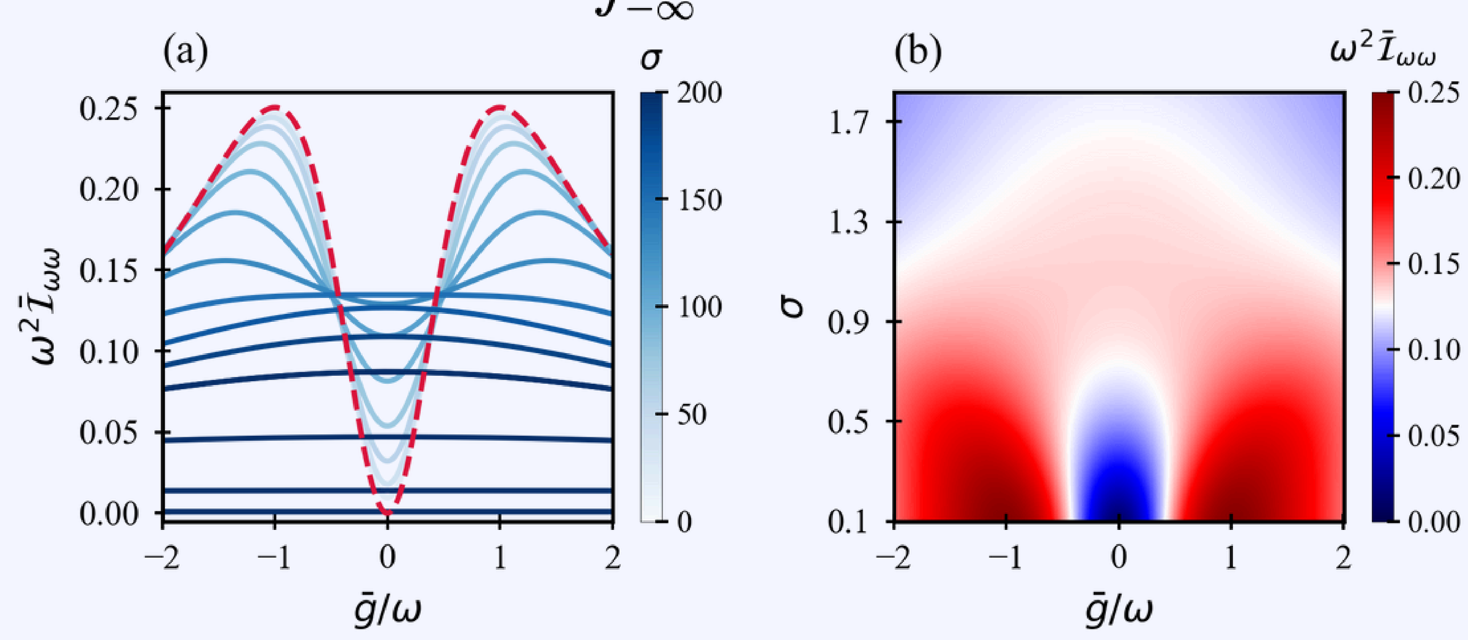
$$\hat{\varrho}(\omega, g) = \sum_i p_i |\psi_i\rangle\langle\psi_i|$$

However, we have some experimental imprecision, and only know the control field with some certainty x,

$$G(g,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{g-\bar{g}}{\sigma}\right)^2}$$

Therefore, our state is thus,

$$\bar{\varrho}(\omega) = \int_{-\infty}^{+\infty} G(g,\sigma)\,\hat{\varrho}(\omega,g)\,dg$$



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[2] C. Hu, In photos: Journey to the center of a quantum computer (2022)
[3] LIGO press release, Caltech (2018)