Quantum sensing limits from energy, space and time

Morgan W. Mitchell[1, 2]

[1] ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain.

[2]ICREA -- Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain.

We describe a class of quantum sensing limits that – unlike the standard quantum limit and Heisenberg limit – make no reference to particle number [1]. Rather, these "energy resolution limits" constrain E_R, the *energy resolution per bandwidth*, a figure of merit that combines the measurement noise, duration or bandwidth, and size of the sensed region. Technology-specific energy resolution limits have been derived for a number of important sensing modalities [2] and seem to converge near a limiting value of $E_R = \hbar$. We review the state of knowledge about such limits, and consider the possibility that a more general, technology-spanning limit constrains energy resolution. Possible sources include the Margolus-Levitin bound on the speed of quantum evolution and the Bremermann-Beckenstein bound on the entropy of a space-time region of given energy and volume.

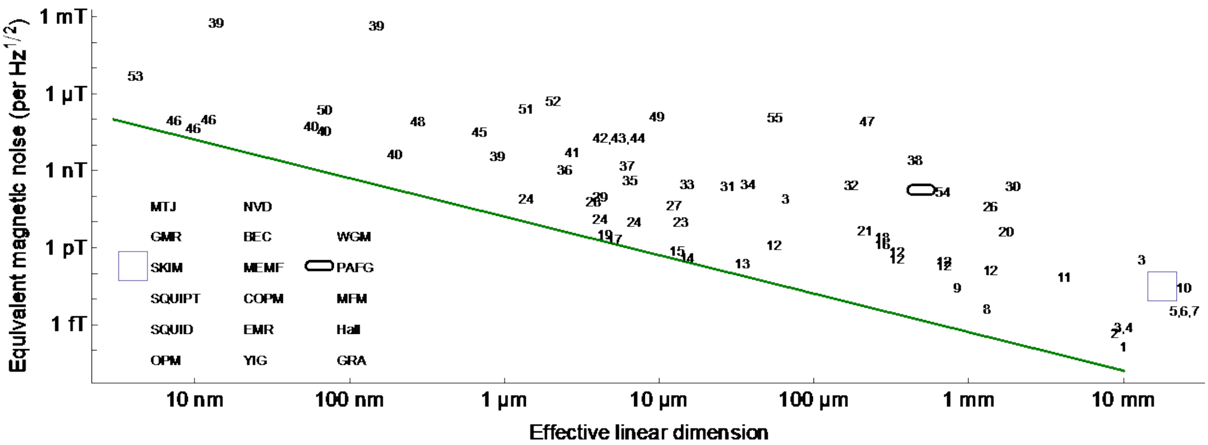

Figure 1. Reported low-frequency magnetic sensitivity versus size of the sensed region for several high-performance magnetic sensor types. MTJ - magnetic tunnel junction; GMR - giant magneto-resistance; SKIM - superconducting kinetic impedance magnetometer; SQUIPT - superconducting quantum interference proximity transistor; SQUID superconducting quantum interference device; OPM optically-pumped magnetometer; NVD - nitrogen-vacancy center in diamond (including RF sensors below 10 um); BEC Bose-Einstein condensate; MEMF - magnetoelectric multiferroic; COPM - cold-atom OPM; EMR extraordinary magneto-resistance; YIG yttrium-aluminum-garnet; GRA - graphene, MFM - magnetic force microscope, PAFG - parallel gating fluxgate, WGM - whispering-gallery mode magnetostrictive. Green line shows an energy resolution per bandwidth of $\hbar$.

[1] M. W. Mitchell, "Number-Unconstrained Quantum Sensing" Quantum Science and Technology 2, 044005 (2017).

[2] M. W. Mitchell, "Sensor self-interaction, scale-invariant spin dynamics, and the $\hbar$ limit of magnetic field sensing" arXiv:1904.01528 (2019).