SNOWMASS 2021:

Quantum Sensors for Wavelike Dark Matter Searches

Derek F. Jackson Kimball

California State University – East Bay

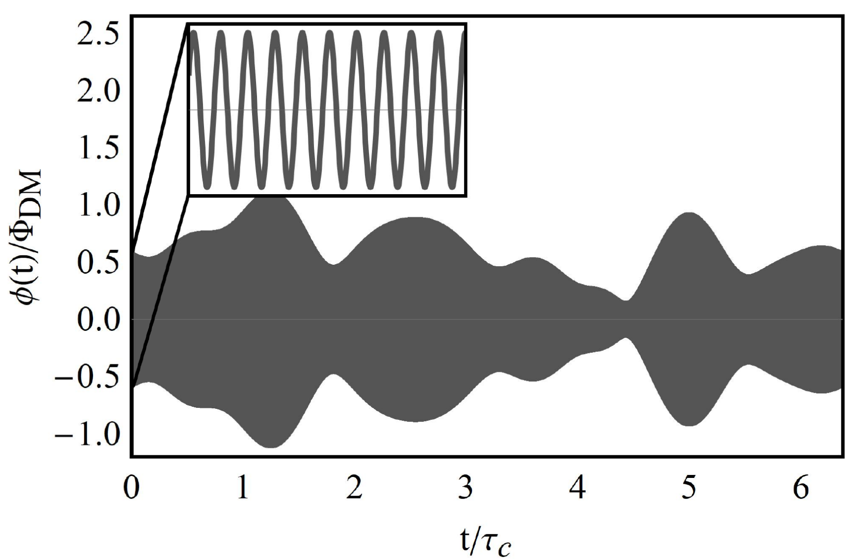
Preliminaries

- Many theories of beyond-the-Standard-Model physics predict the existence of ultralight bosons which could be the dark matter.
- Phenomenology of ultralight bosonic dark matter is well-described locally by oscillating field $\rightarrow$ wavelike dark matter.
- Limited number of "portals" via which wavelike dark matter can interact with Standard Model particles: photons, gluons, fermions, etc.
- Experiments target different portals, mass/frequency ranges.
- Given the broad range of theoretical ideas, it is important to cast a wide experimental net.

Ultralight bosonic dark matter

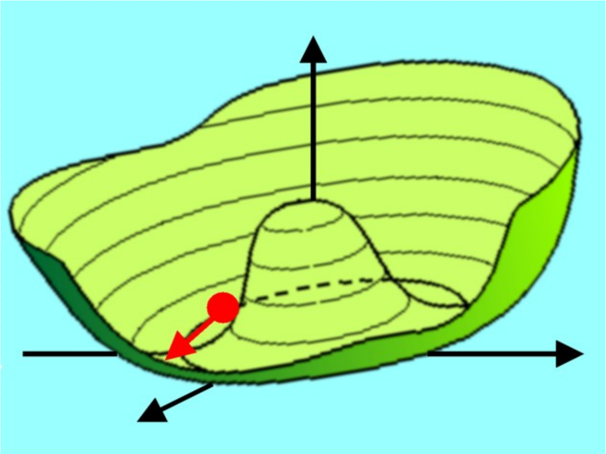
Many bosons occupy a single mode.

Standard Halo Model + negligible self-interactions: manifest as a classical oscillating field with a coherence length given by their deBroglie wavelength.



Axions, ALPs, & Hidden Photons

The QCD axion mass is given by:



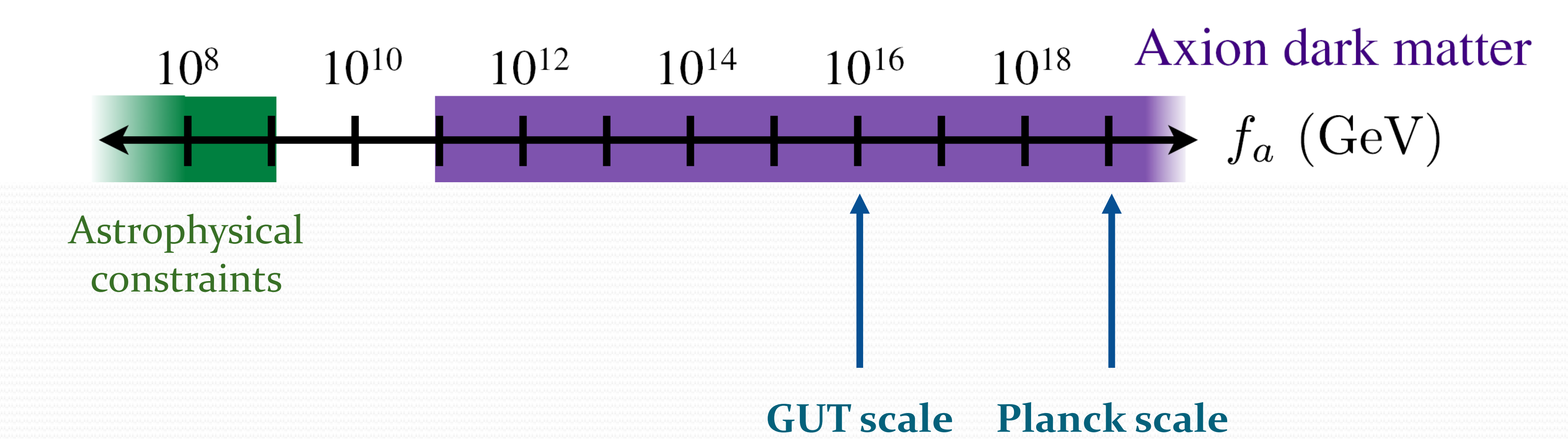
$$m_a \sim \frac{{\Lambda_{\rm QCD}}^2}{f_a}\ .$$

$f_a \rightarrow$ symmetry breaking scale, $\Lambda_{\rm QCD}$ ~ 200 MeV $\rightarrow$ QCD scale.

Axion-like particles (ALPs) may have different Λ and f (e.g., string theories, relaxion scenario).

Hidden photons have a different phenomenology.

Axion/ALP dark matter



QCD axion Compton frequency

Oscillation frequency of the axion field is determined by the axion mass:

$$m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz} \times \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right) .$$

f_a at 10^{13} GeV scale → GHz frequencies,

f_a at GUT scale → MHz frequencies,

f_a at Planck scale → kHz frequencies.

Portals

Different classes of bosons couple differently to Standard Model particles and fields, generating a variety of observables:

Spin	Type	Operator	Interaction	DM effects
0	Scalar	$\varphi h^\dagger h$, $\phi^n \mathcal{O}_{\rm SM}$	Higgs portal or dilaton	Fundamental constant variation
		$aG^{\mu\nu}\tilde{G}_{\mu\nu}$	Axion QCD	Nucleon EDM
	Pseudoscalar	$aF^{\mu\nu}\tilde{F}_{\mu\nu}$	Axion E&M	EMF along B field
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	Axion fermion	Spin torque
1	Vector	$F'_{\mu\nu}F^{\mu\nu}$	Vector-photon mixing	EMF in vacuum
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	Dipole operator	Spin torque
	Axial vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	Minimally coupled	Spin torque

Safronova, Budker, DeMille, Jackson Kimball, Derevianko, and Clark, *Rev. Mod. Phys.* **90**, 025008 (2018).

Axion couplings

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

← Coupling to electromagnetic field

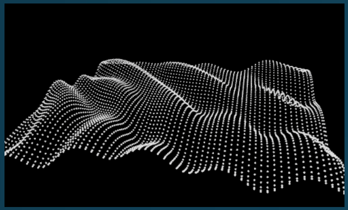
$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

← Coupling to gluon field: nuclear EDMs

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

← Coupling to fermion spins

Ultralight bosonic dark matter

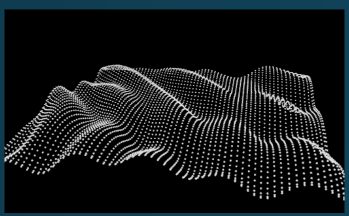


Ultralight bosonic dark matter = oscillating field

Ultralight spin-0 & spin-1 bosons

QCD axion
Axion-like particles (ALPs)
Moduli & other scalar particles
Dark/hidden photons

Portals and observables



Ultralight bosonic dark matter = oscillating field

Ultralight spin-0 & spin-1 bosons

QCD axion
Axion-like particles (ALPs)
Moduli & other scalar particles
Dark/hidden photons

PHOTON COUPLING

TORQUES ON SPINS

FORCES

VARIATION OF “CONSTANTS”

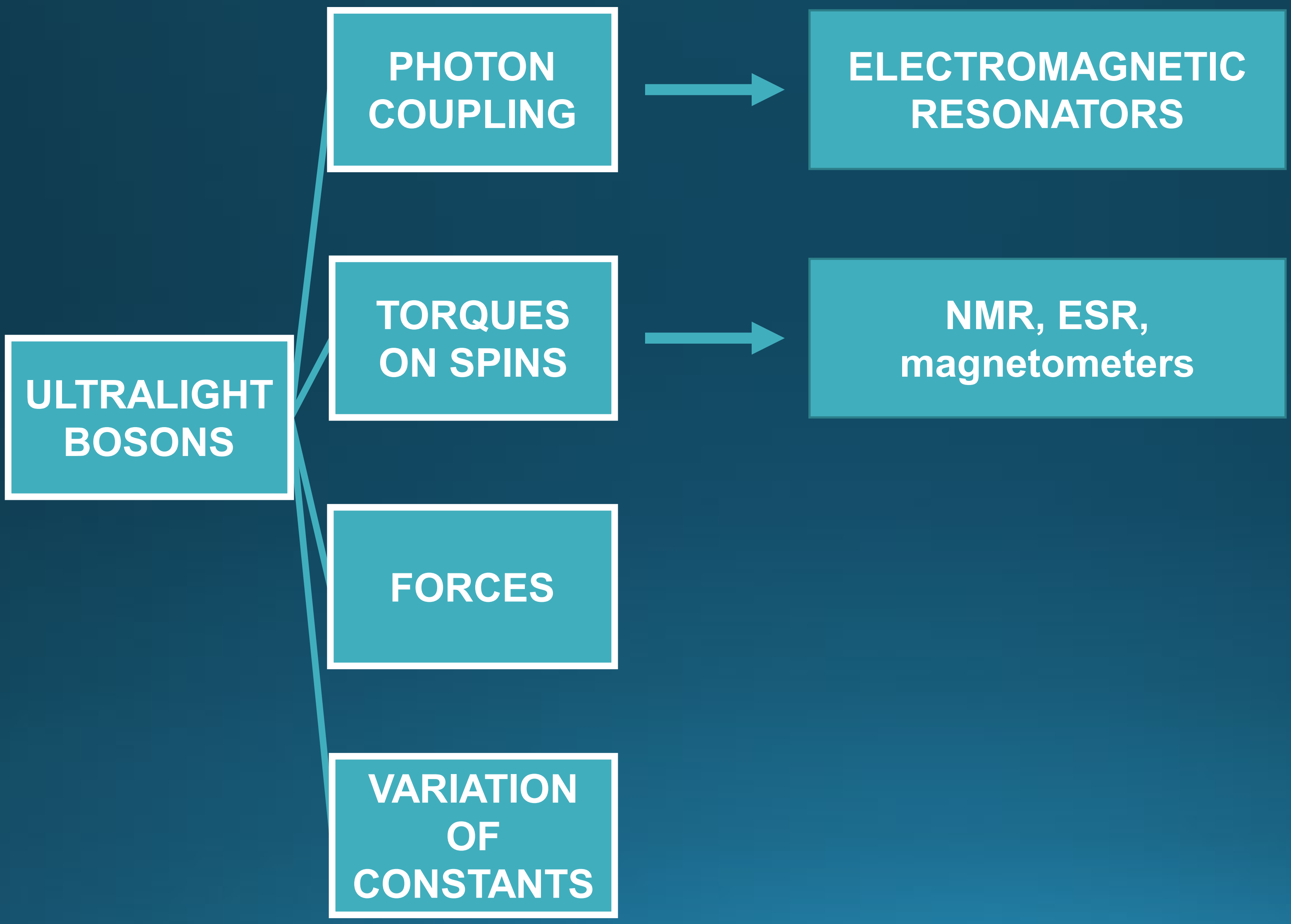
Experimental techniques

ULTRALIGHT BOSONS

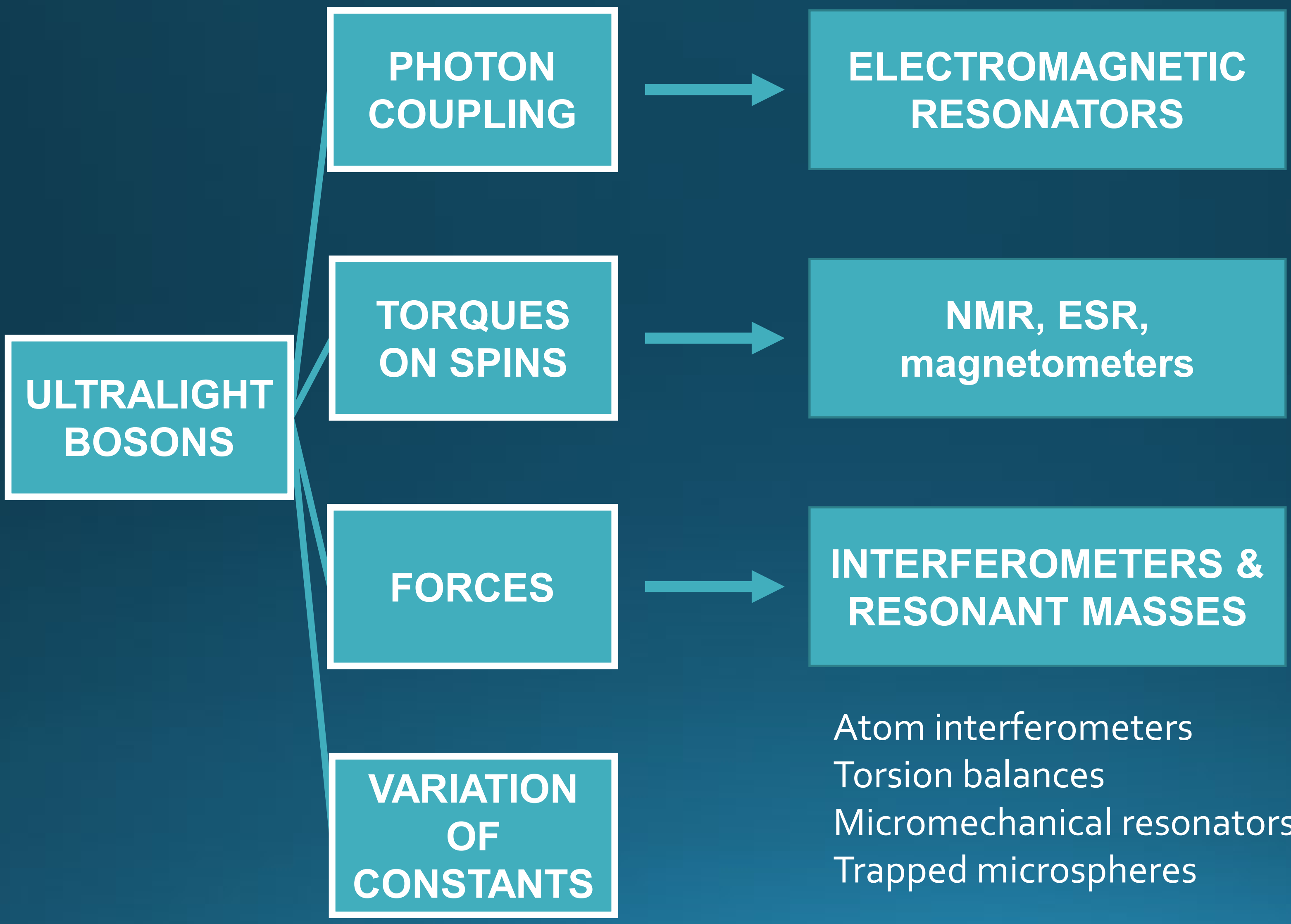
- PHOTON COUPLING → ELECTROMAGNETIC RESONATORS
- TORQUES ON SPINS
- FORCES
- VARIATION OF CONSTANTS

Microwave/RF/audio cavities
LC circuits
Fabry-Perot resonators

Experimental techniques

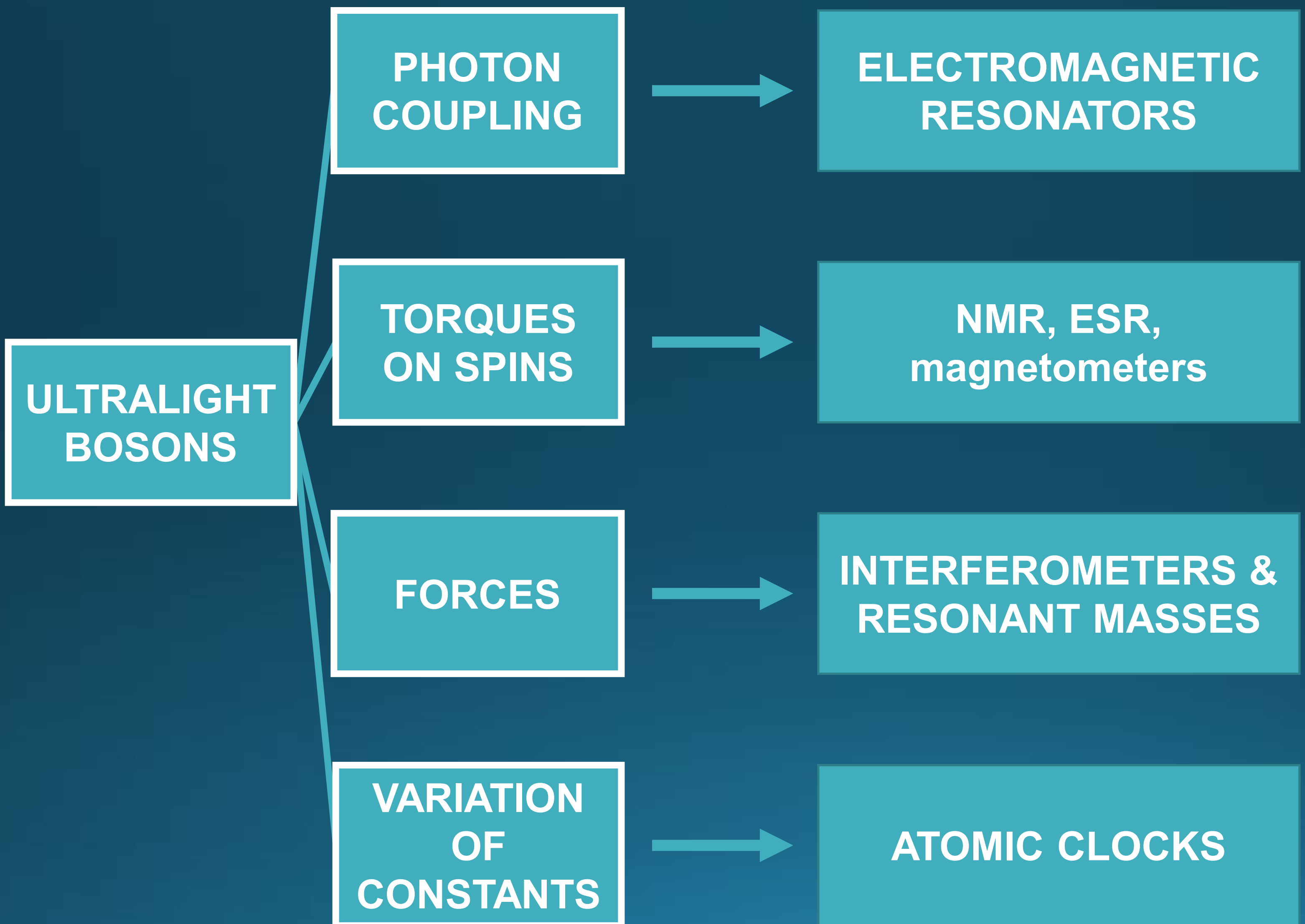


Experimental techniques

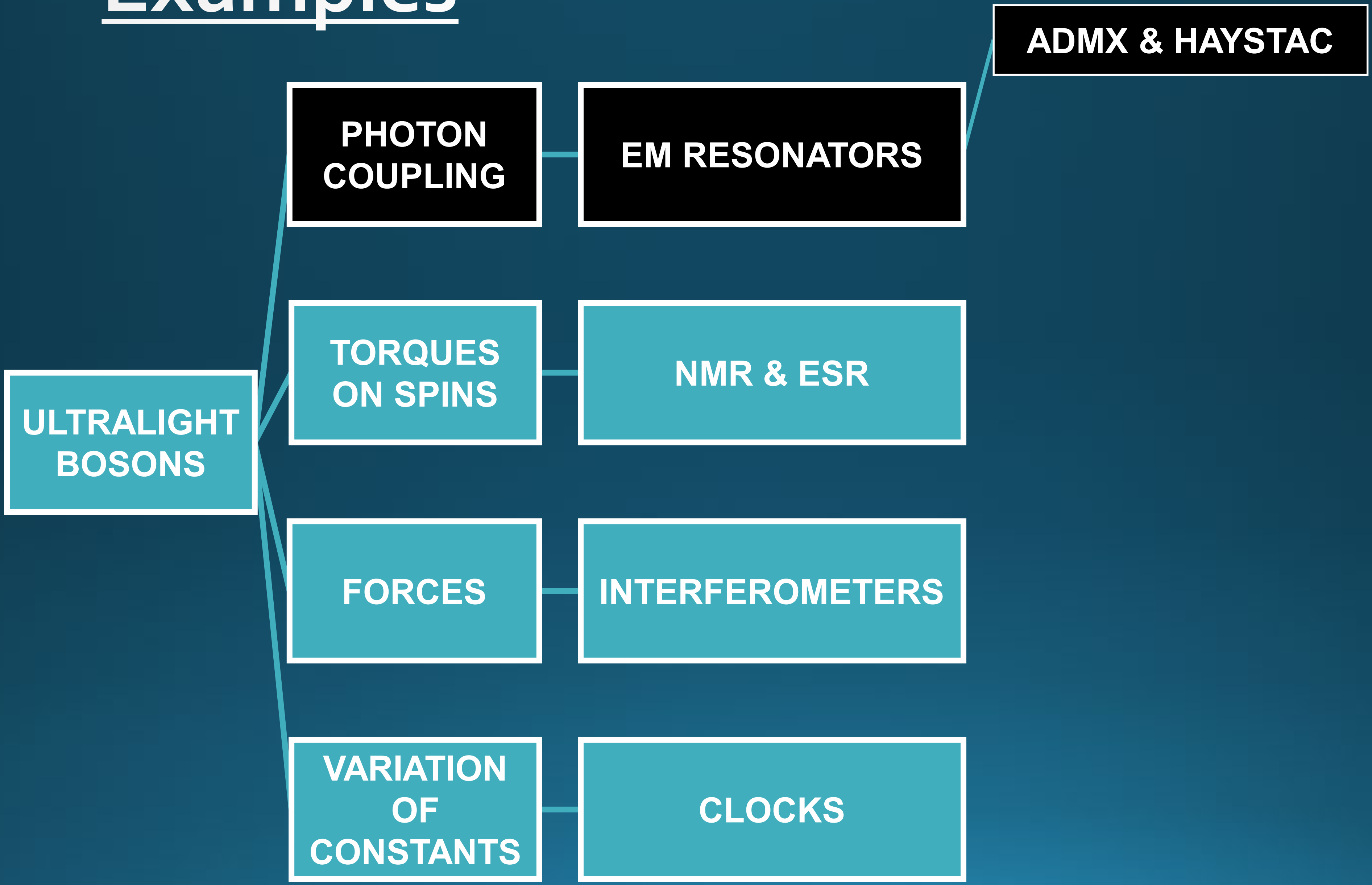


Atom interferometers
Torsion balances
Micromechanical resonators
Trapped microspheres

Experimental techniques

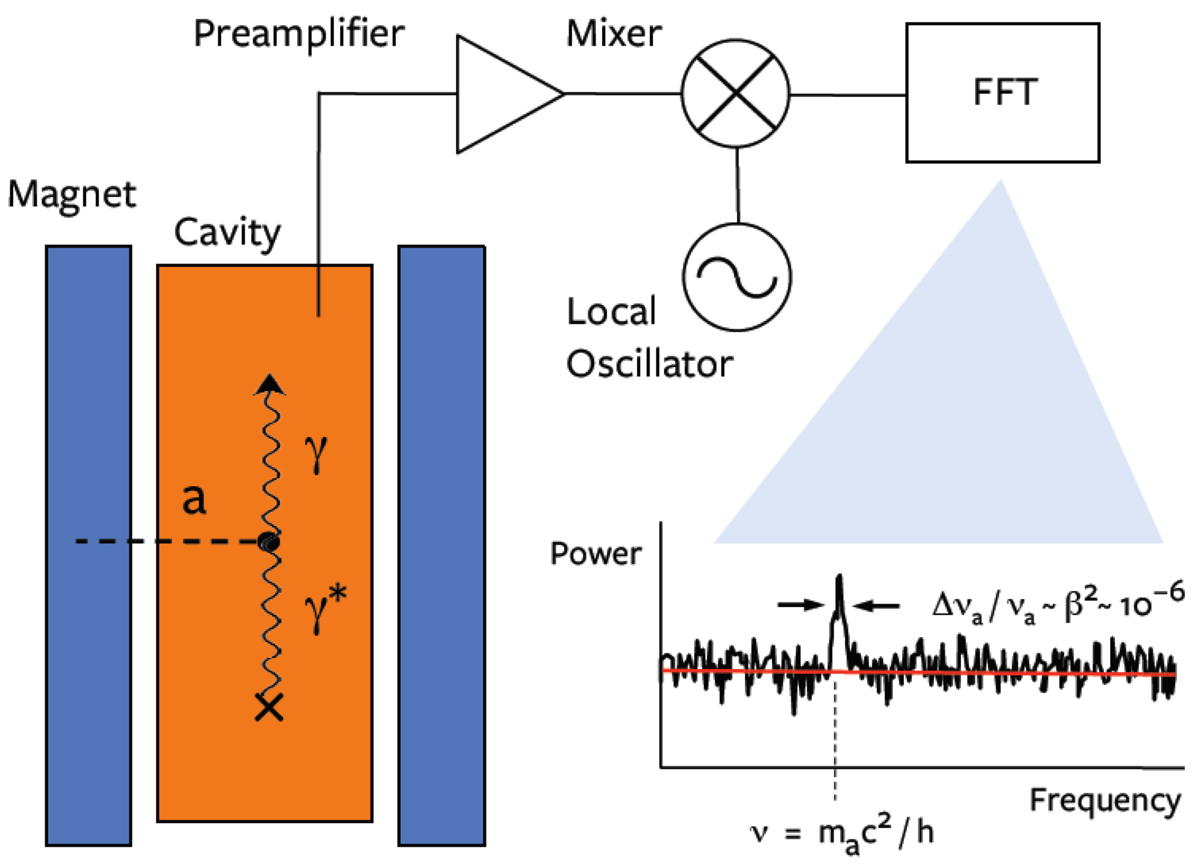


Examples

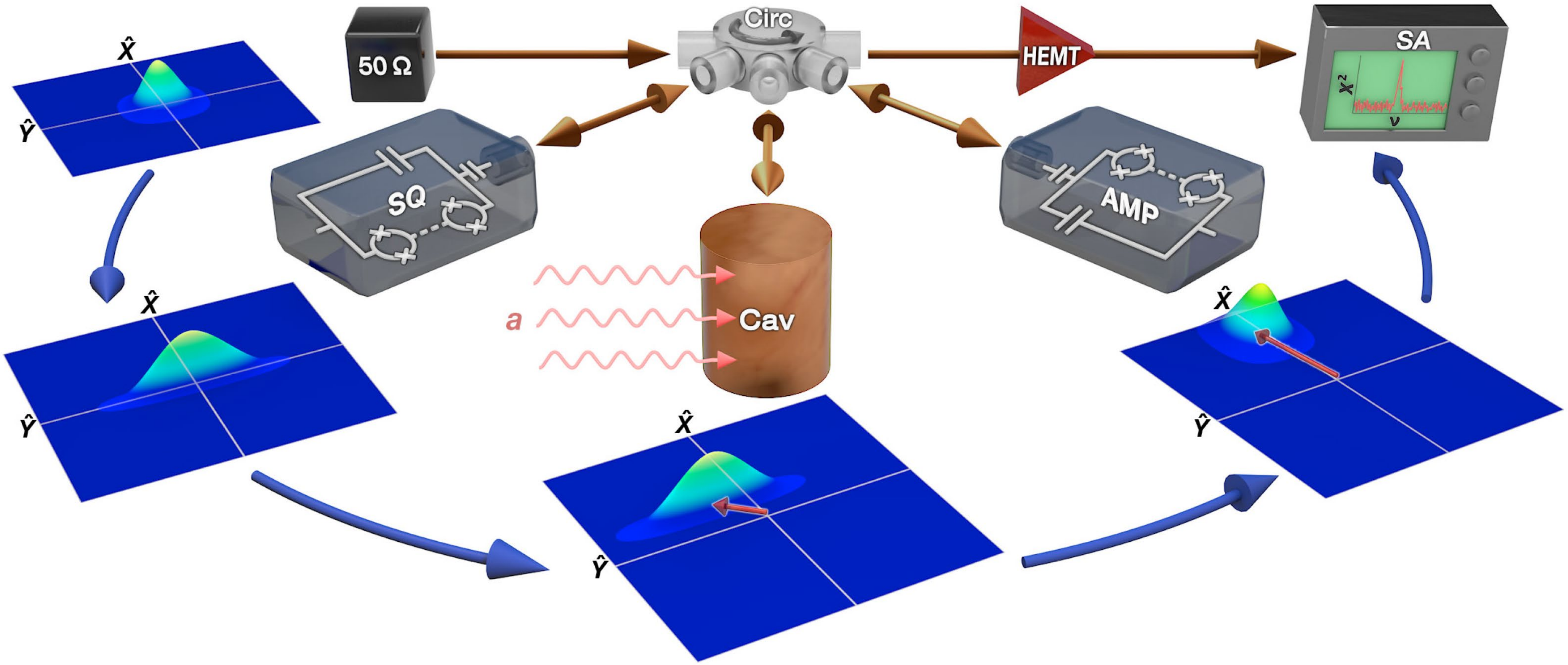


ADMX & HAYSTAC
PHOTON COUPLING
EM RESONATORS
TORQUES ON SPINS
NMR & ESR
ULTRALIGHT BOSONS
FORCES
INTERFEROMETERS
VARIATION OF CONSTANTS
CLOCKS

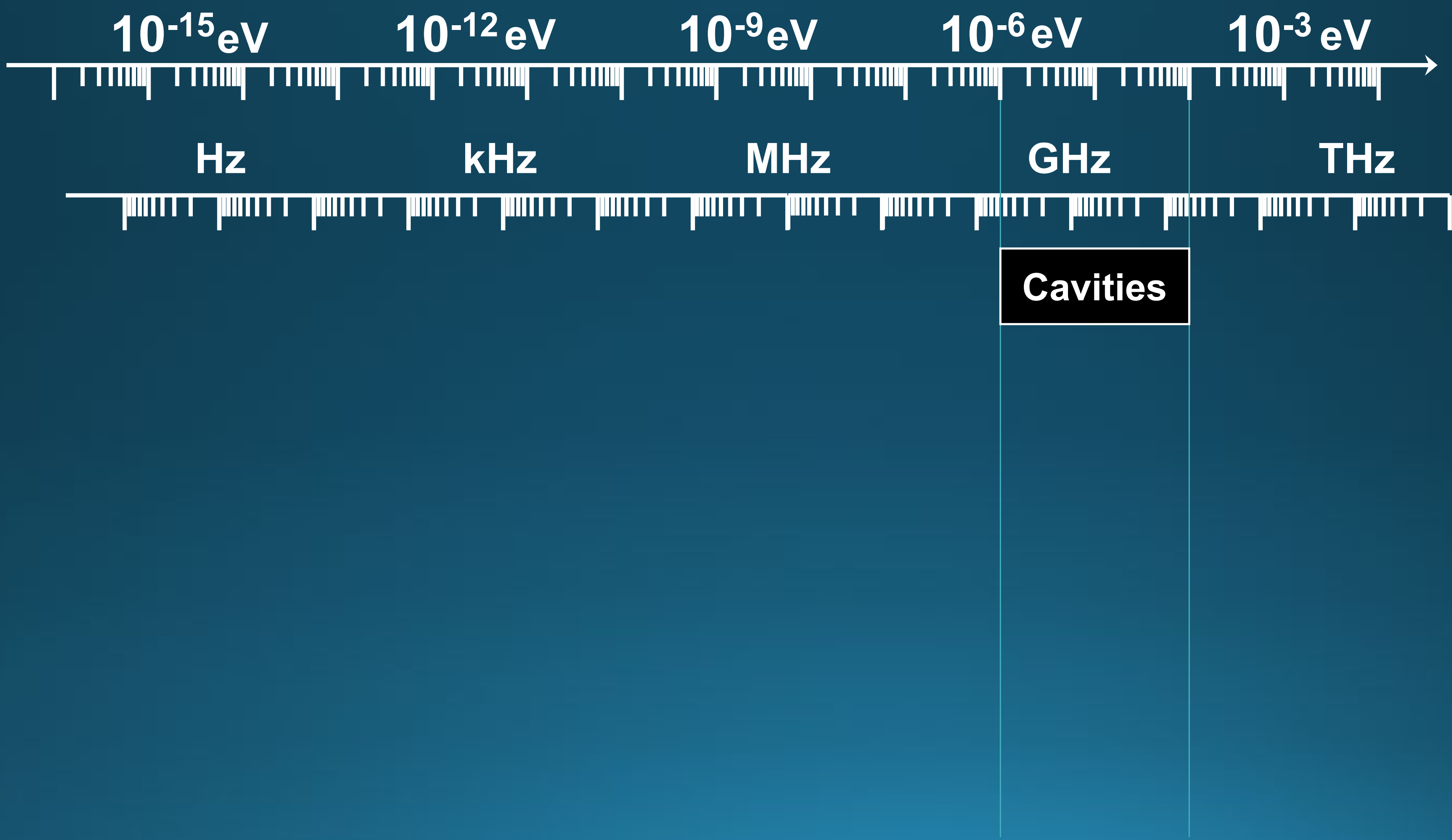
ADMX: Axion Dark Matter eXperiment



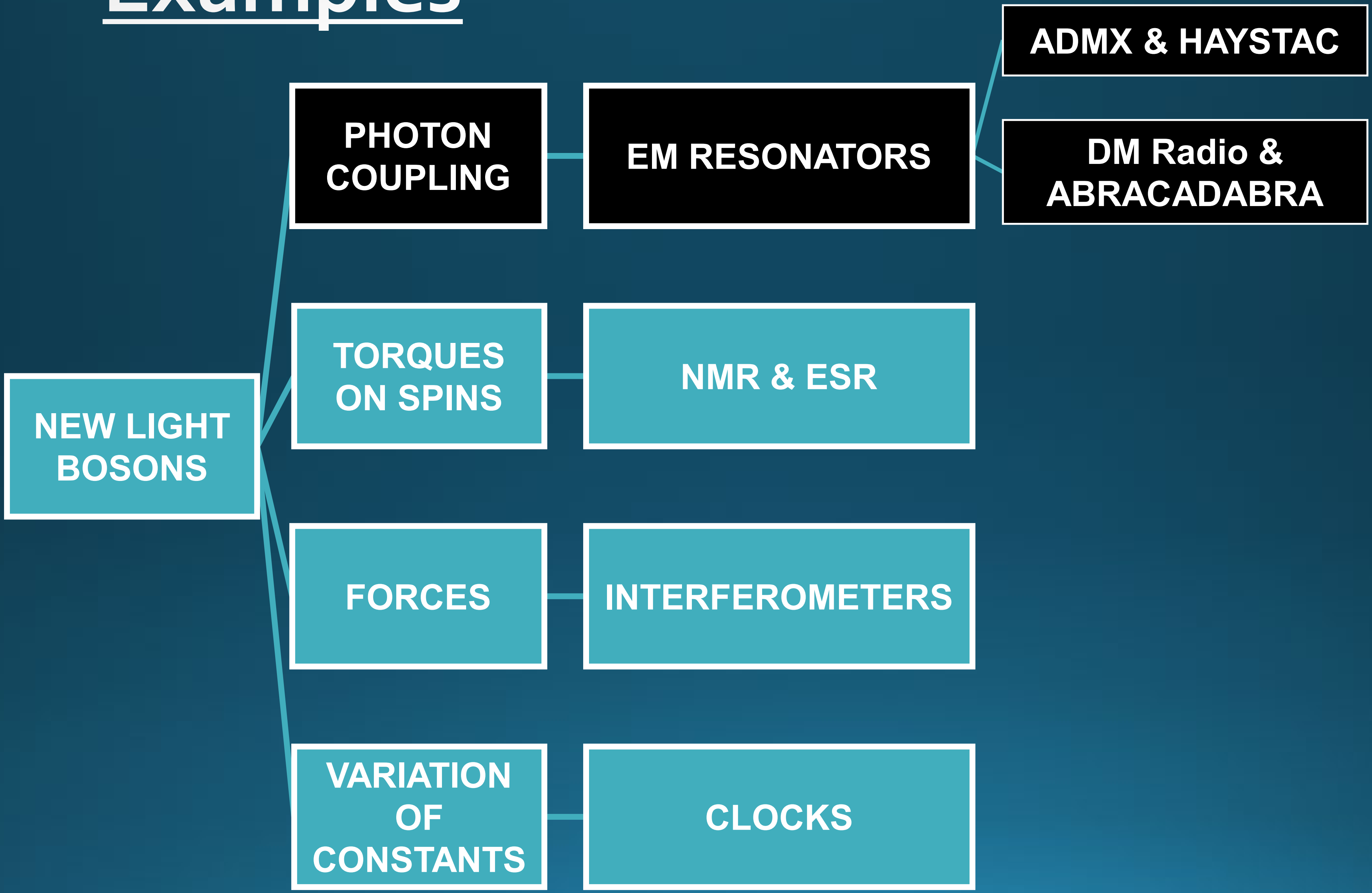
HAYSTAC:
Haloscope at Yale Sensitive to Axion CDM



Mass/frequency range



Examples

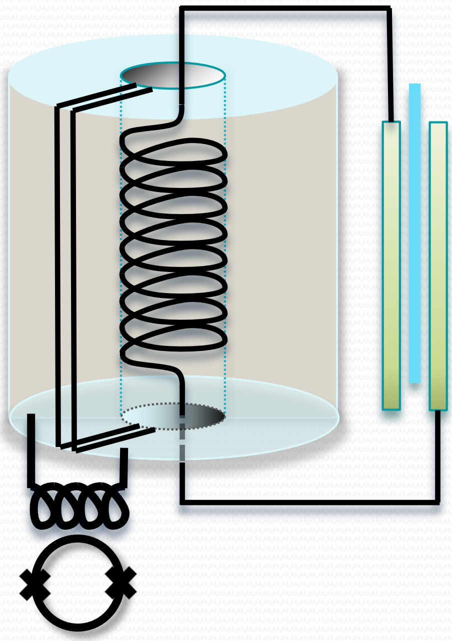

ADMX & HAYSTAC
PHOTON COUPLING
EM RESONATORS
DM Radio & ABRACADABRA
TORQUES ON SPINS
NMR & ESR
NEW LIGHT BOSONS
FORCES
INTERFEROMETERS
VARIATION OF CONSTANTS
CLOCKS

DM Radio/ABRACADABRA

Superconducting lumped-element detector

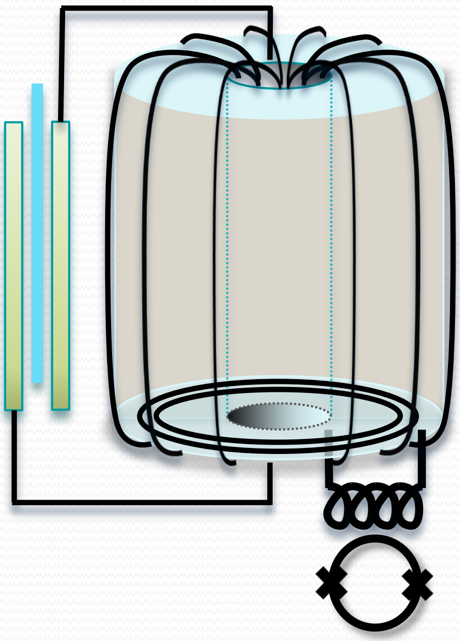
<u>Axions</u>

(with applied B-field)

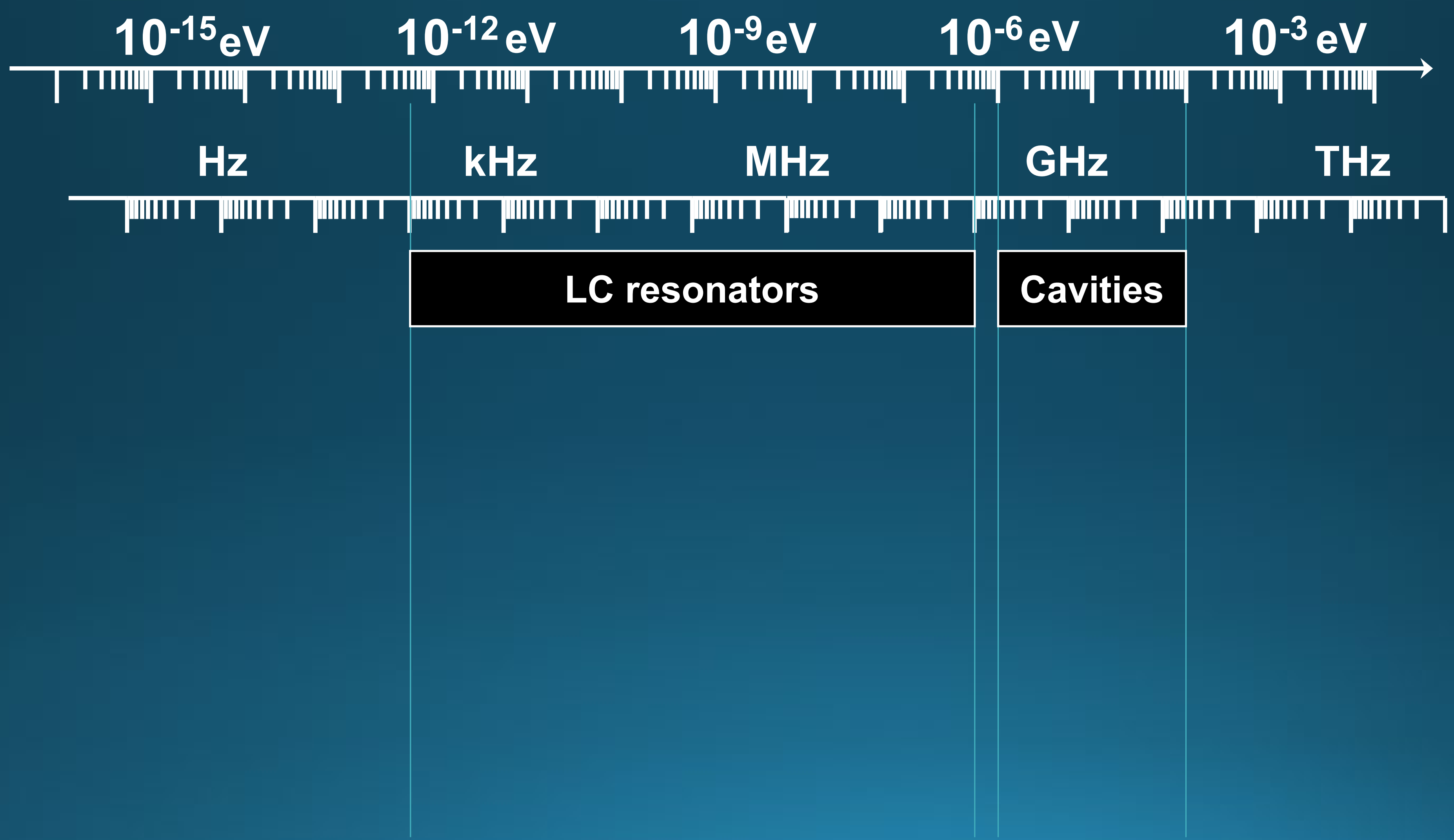


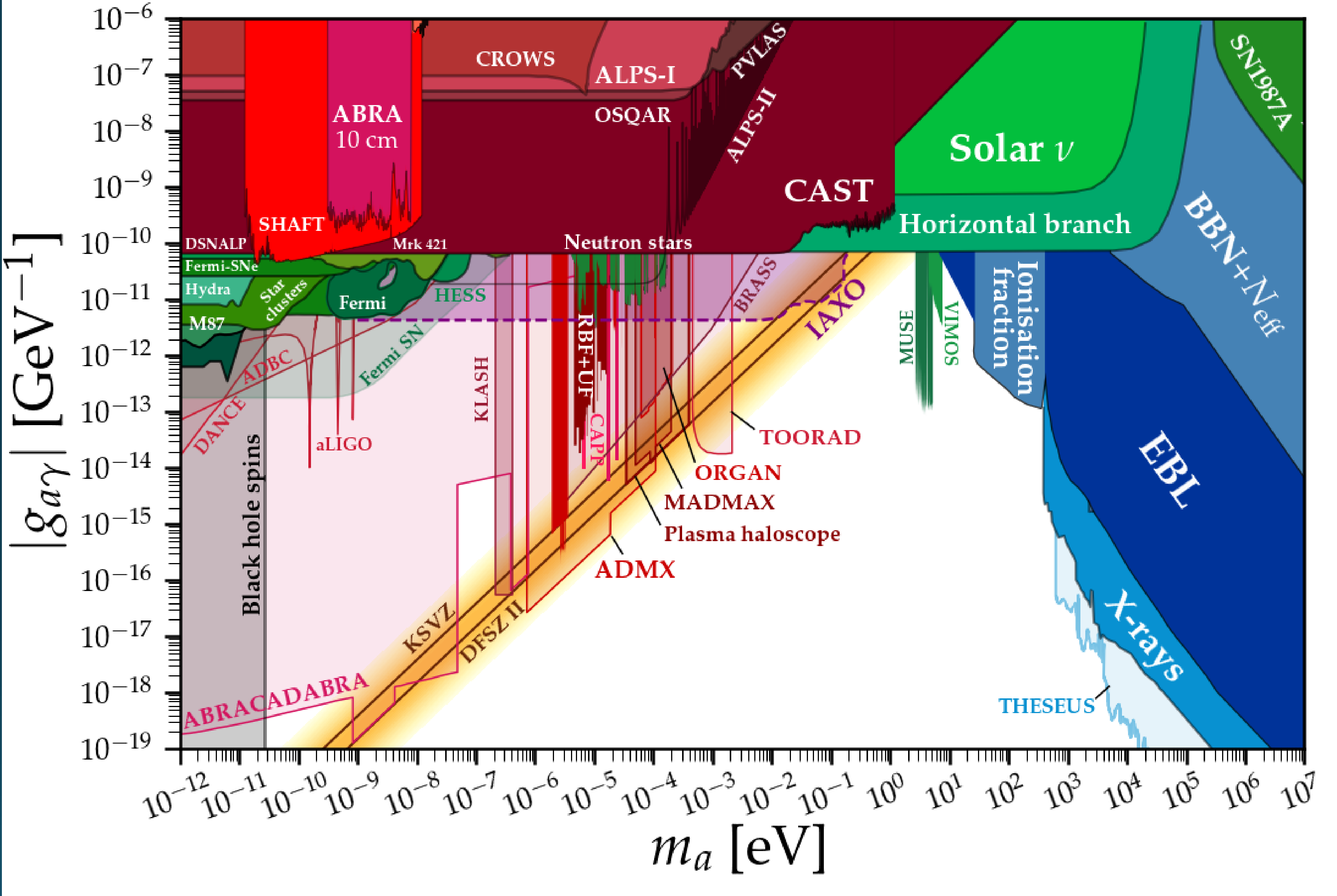
<u>Hidden Photons</u>

(no B-field required)



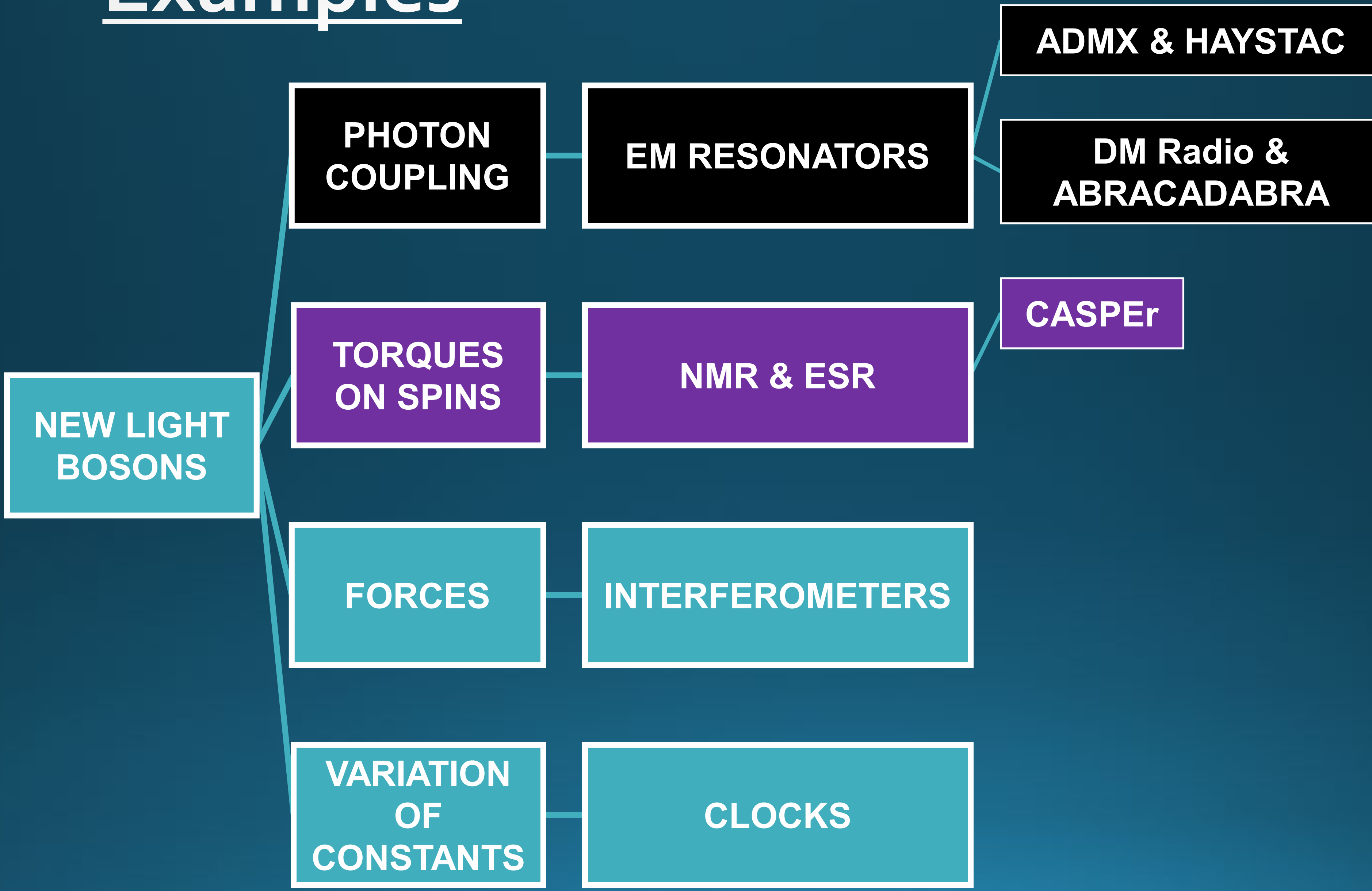
Mass/frequency range





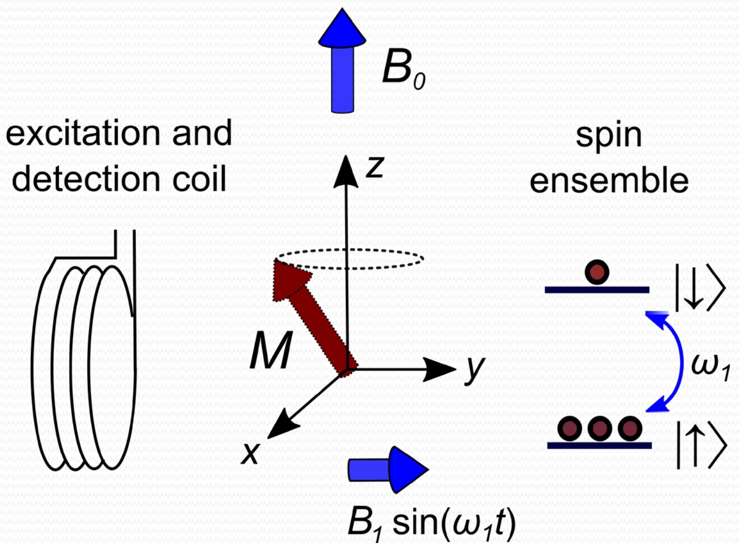
https://cajohare.github.io/AxionLimits/

Examples

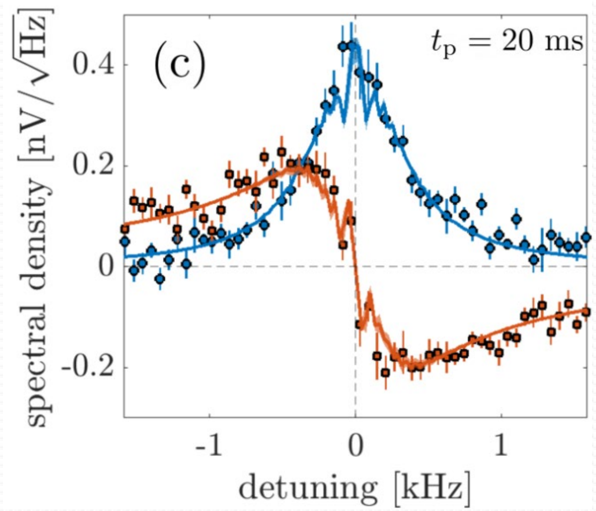

NEW LIGHT BOSONS
PHOTON COUPLING
EM RESONATORS
ADMX & HAYSTAC
DM Radio & ABRACADABRA
TORQUES ON SPINS
NMR & ESR
CASPEr
FORCES
INTERFEROMETERS
VARIATION OF CONSTANTS
CLOCKS

CASPEr:
Cosmic Axion Spin Precession Experiment

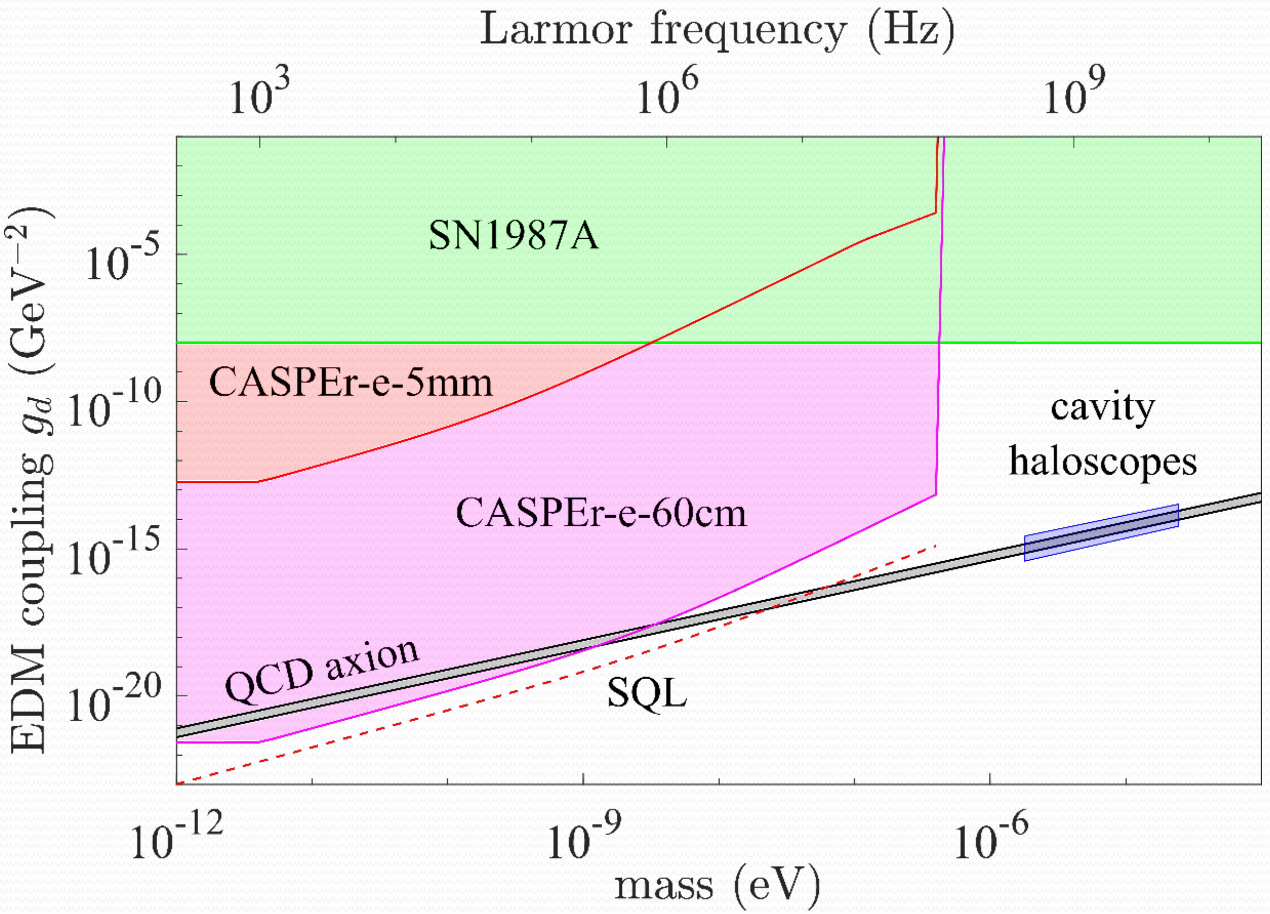
NMR-based search for axion-induced EDM and axion-spin couplings.



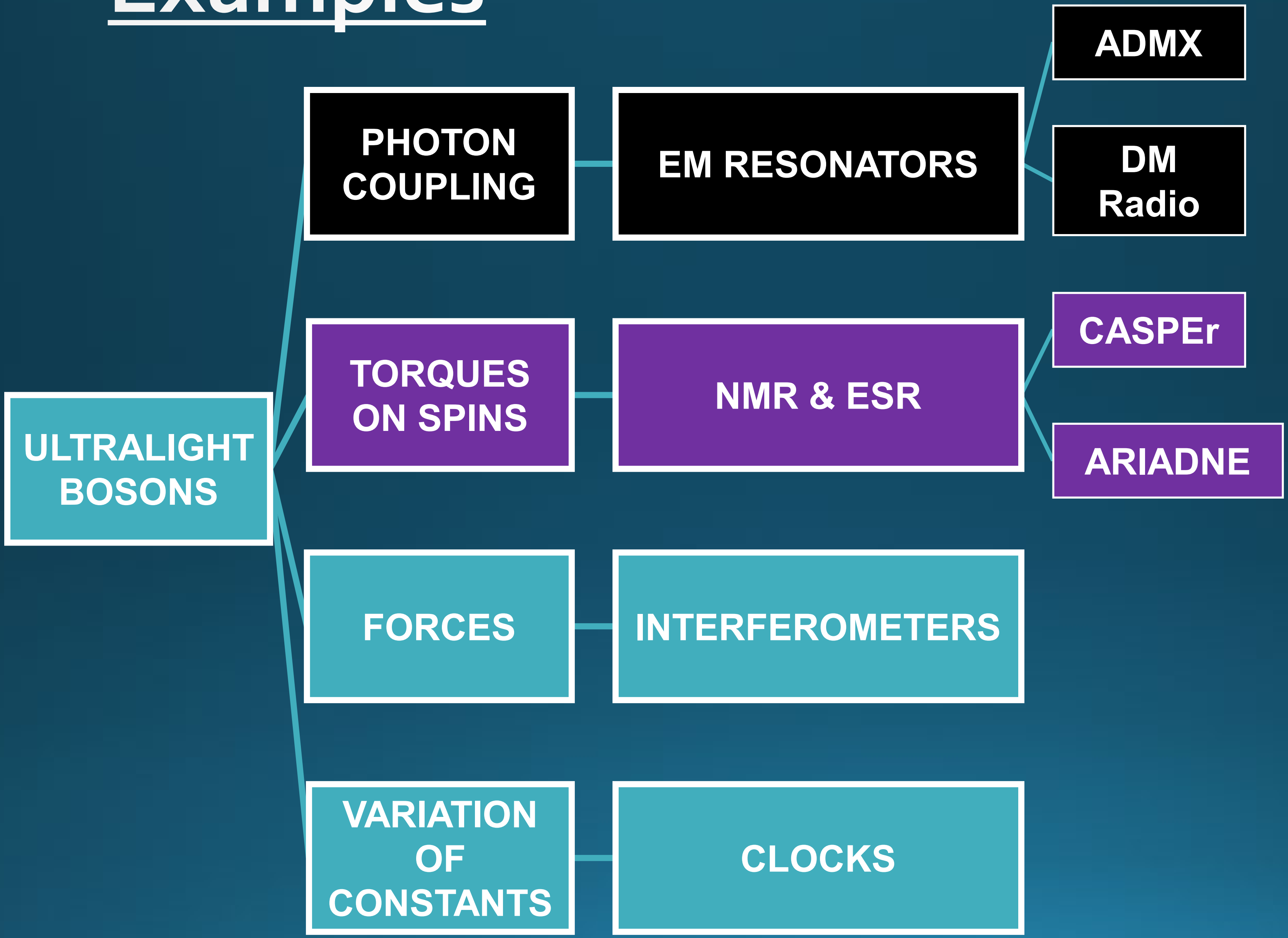
^{207}Pb NMR at 4 K



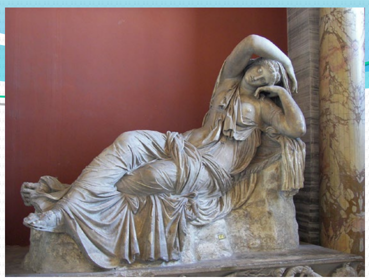
CASPEr:
Cosmic Axion Spin Precession Experiment

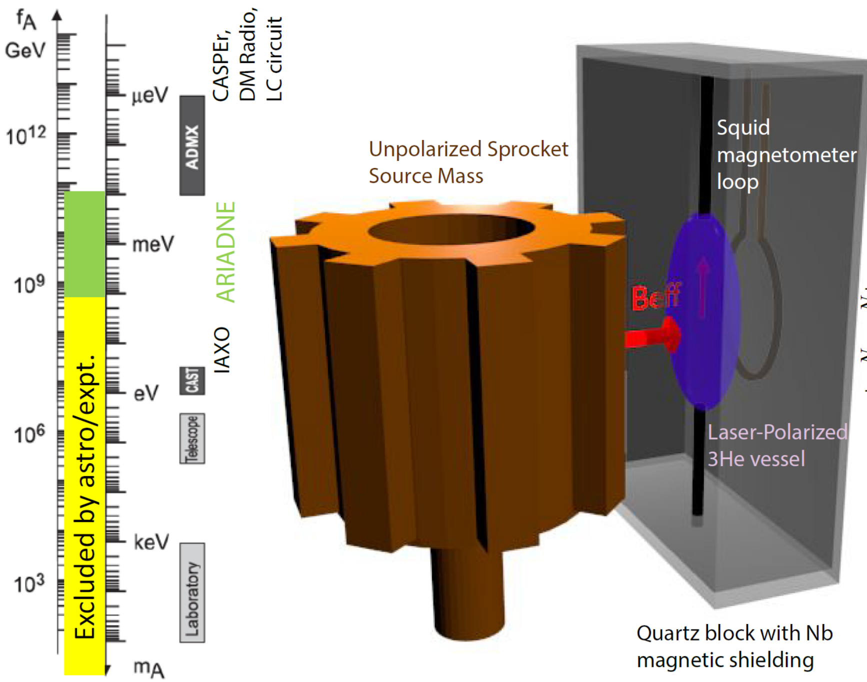


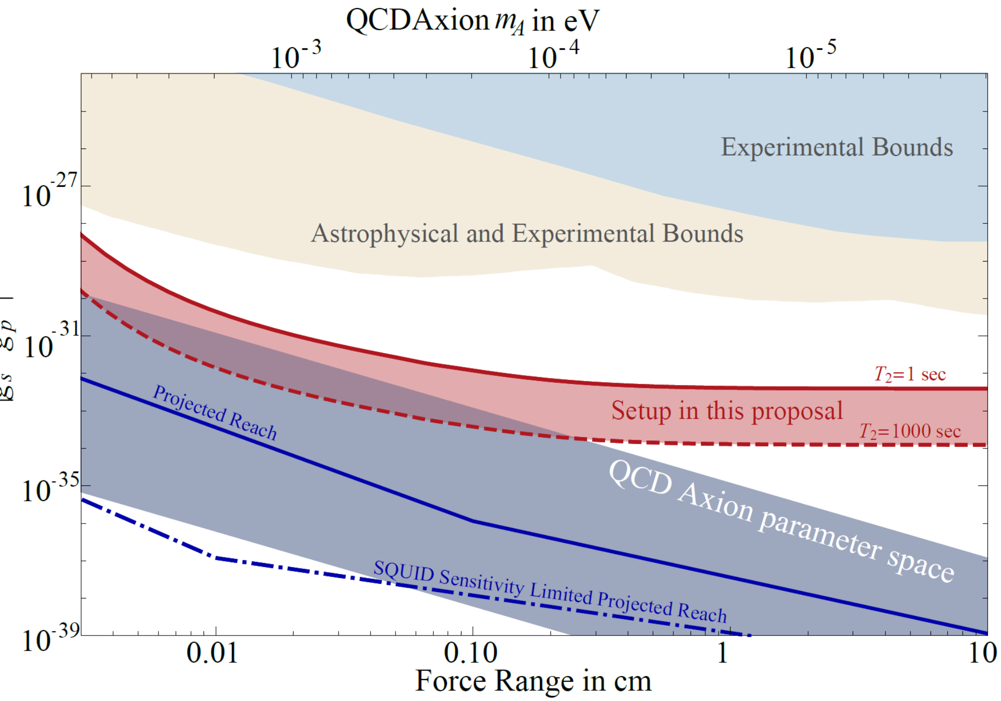
Examples


ULTRALIGHT BOSONS
PHOTON COUPLING
EM RESONATORS
ADMX
DM Radio
TORQUES ON SPINS
NMR & ESR
CASPEr
ARIADNE
FORCES
INTERFEROMETERS
VARIATION OF CONSTANTS
CLOCKS

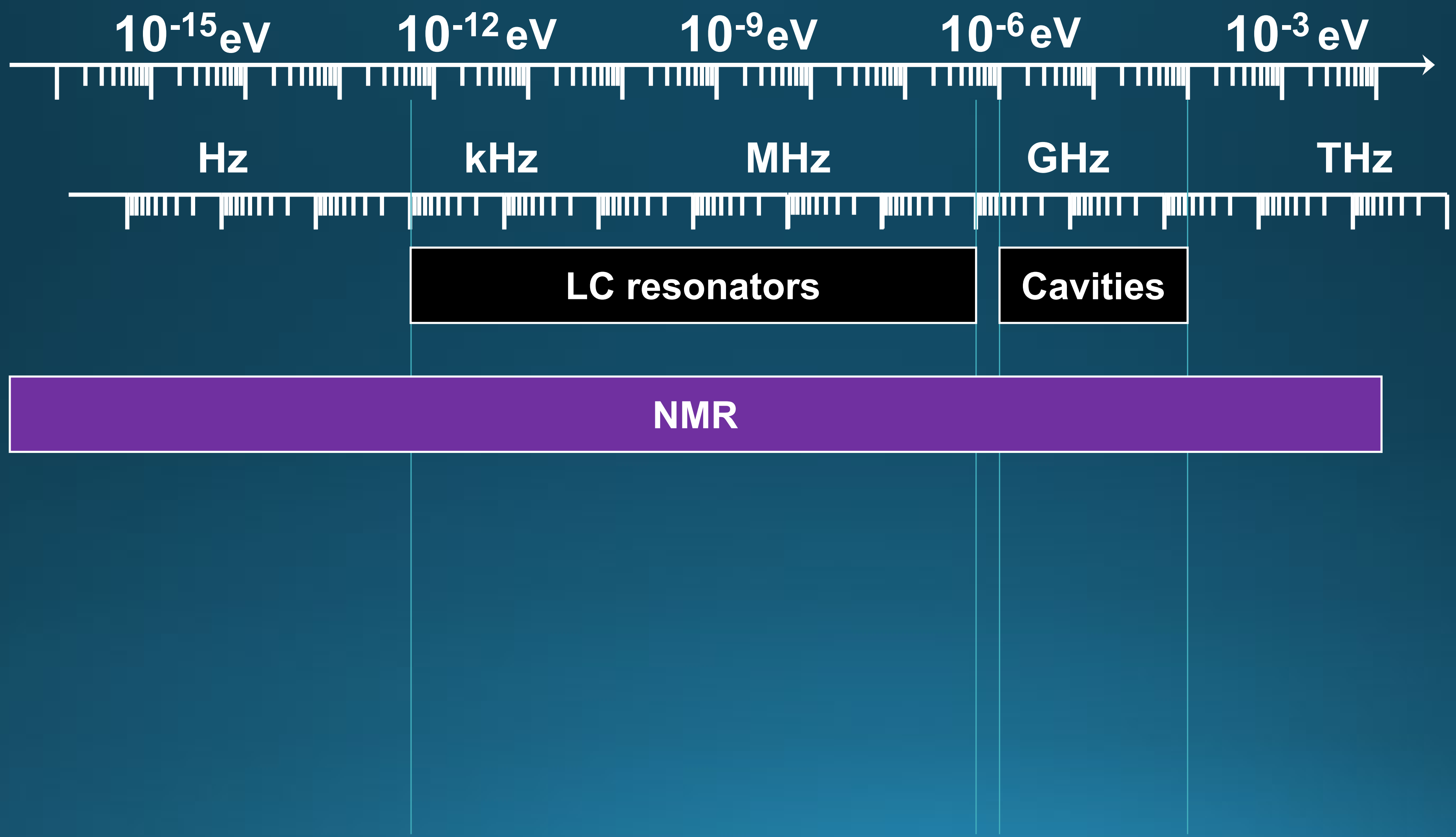
ARIADNE:
(Axion Resonant InterAction Detection Experiment)



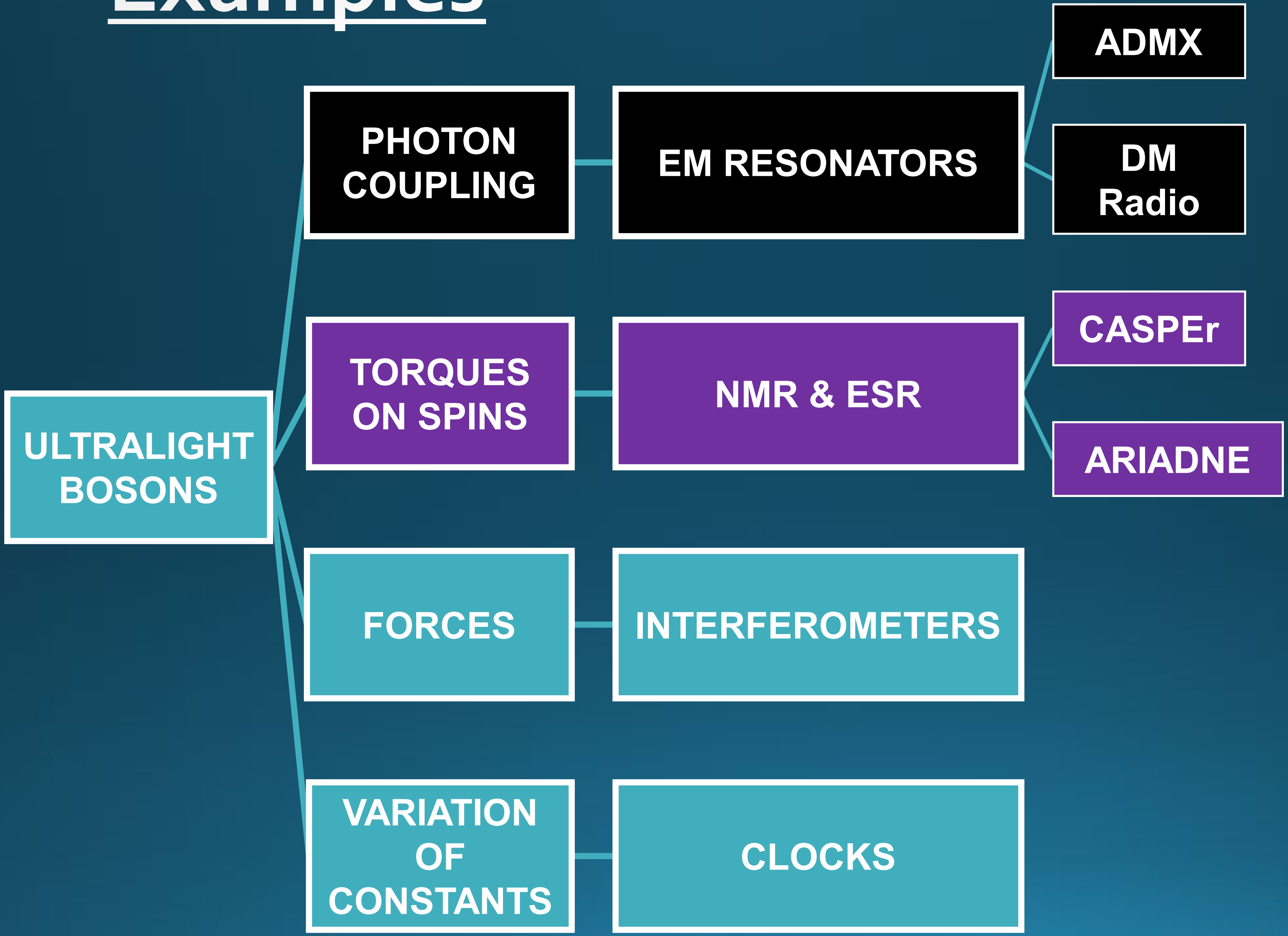




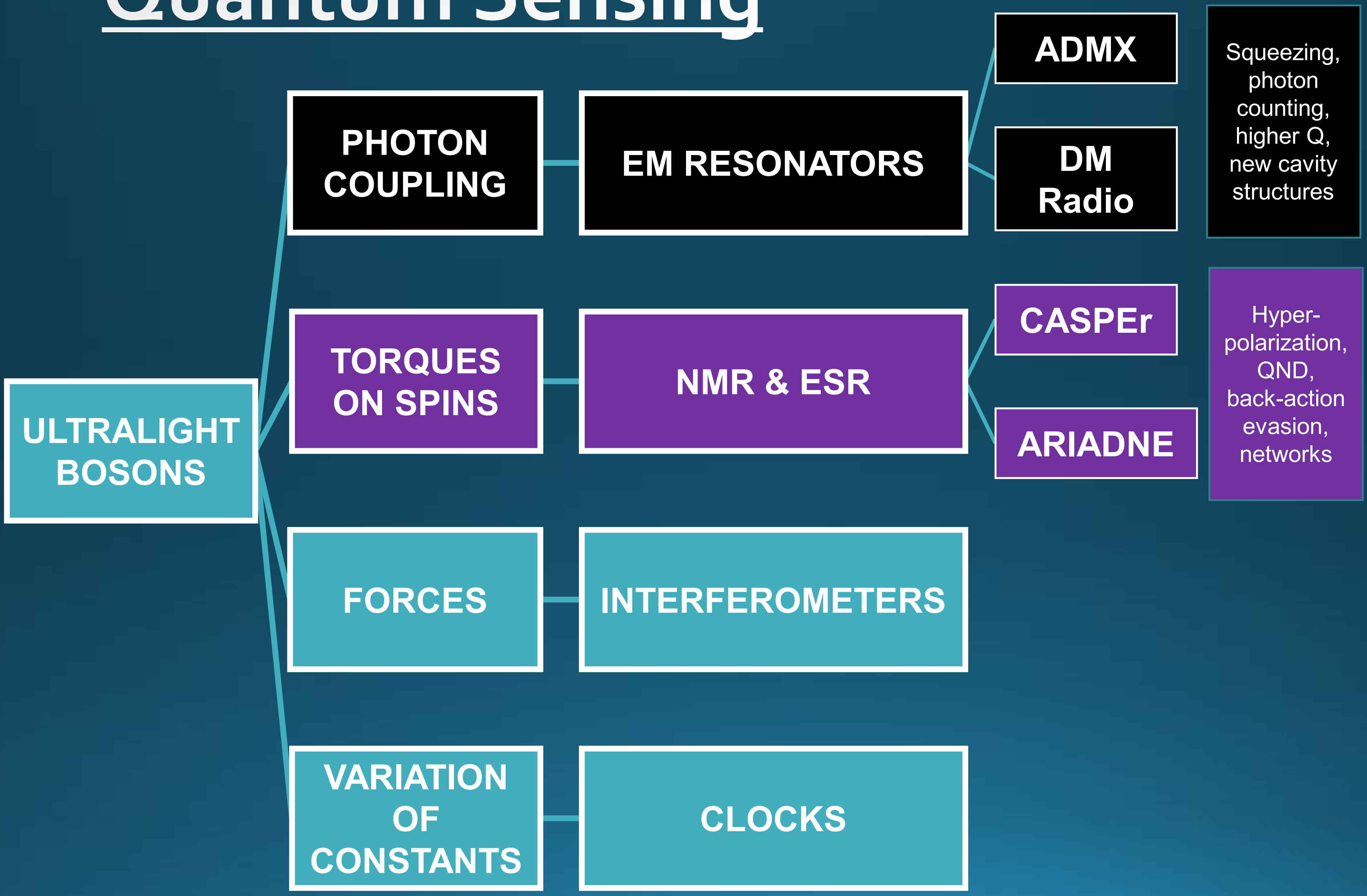
Mass/frequency range



Examples


ULTRALIGHT BOSONS
PHOTON COUPLING
EM RESONATORS
ADMX
DM Radio
TORQUES ON SPINS
NMR & ESR
CASPEr
ARIADNE
FORCES
INTERFEROMETERS
VARIATION OF CONSTANTS
CLOCKS

Quantum Sensing

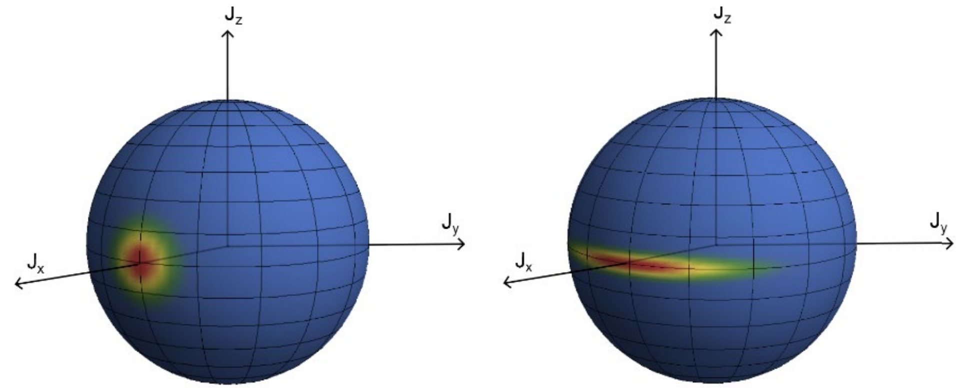


Quantum Sensing

Detector figures of merit can sometimes be improved by making use of quantum correlations: entanglement & squeezing

- Measurements beyond SQL

  [LIGO collab., *Nature Photon*. **7**, 613 (2013)]
  [O. Hosten, et al., *Nature* **529**, 505 (2016)]

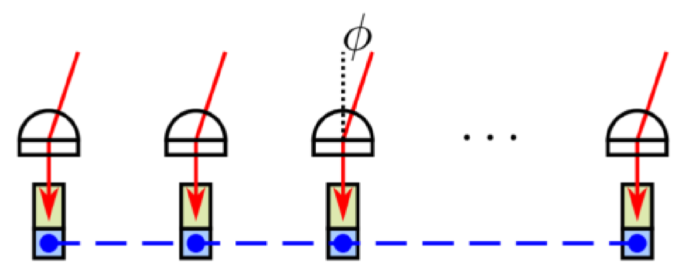


- QND measurements, back-action evasion

  [D. B. Hume, et al., *Phys. Rev. Lett*. **99**, 120502 (2007)]
  [I. Lovchinsky, et al., *Science* **351**, 836 (2016)]

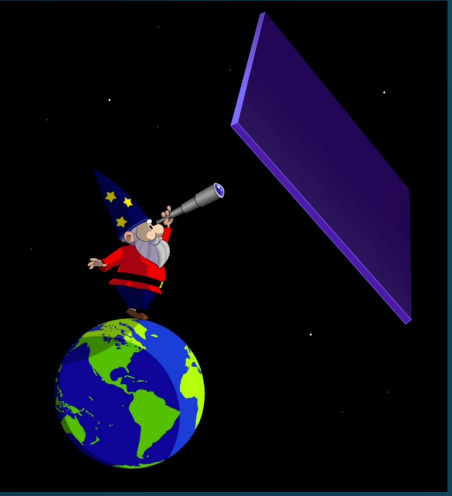
- Dynamic Hamiltonian engineering of many-body spin systems

  [J. Choi, et al., *Phys. Rev. X* **10**, 031002 (2020)]

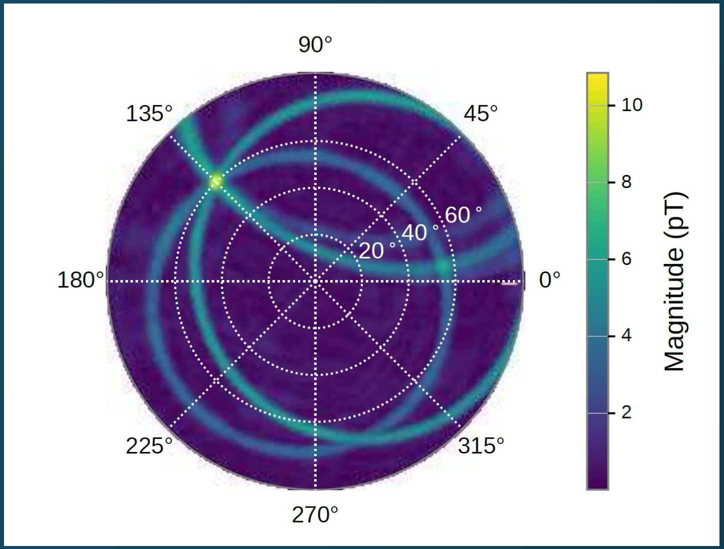


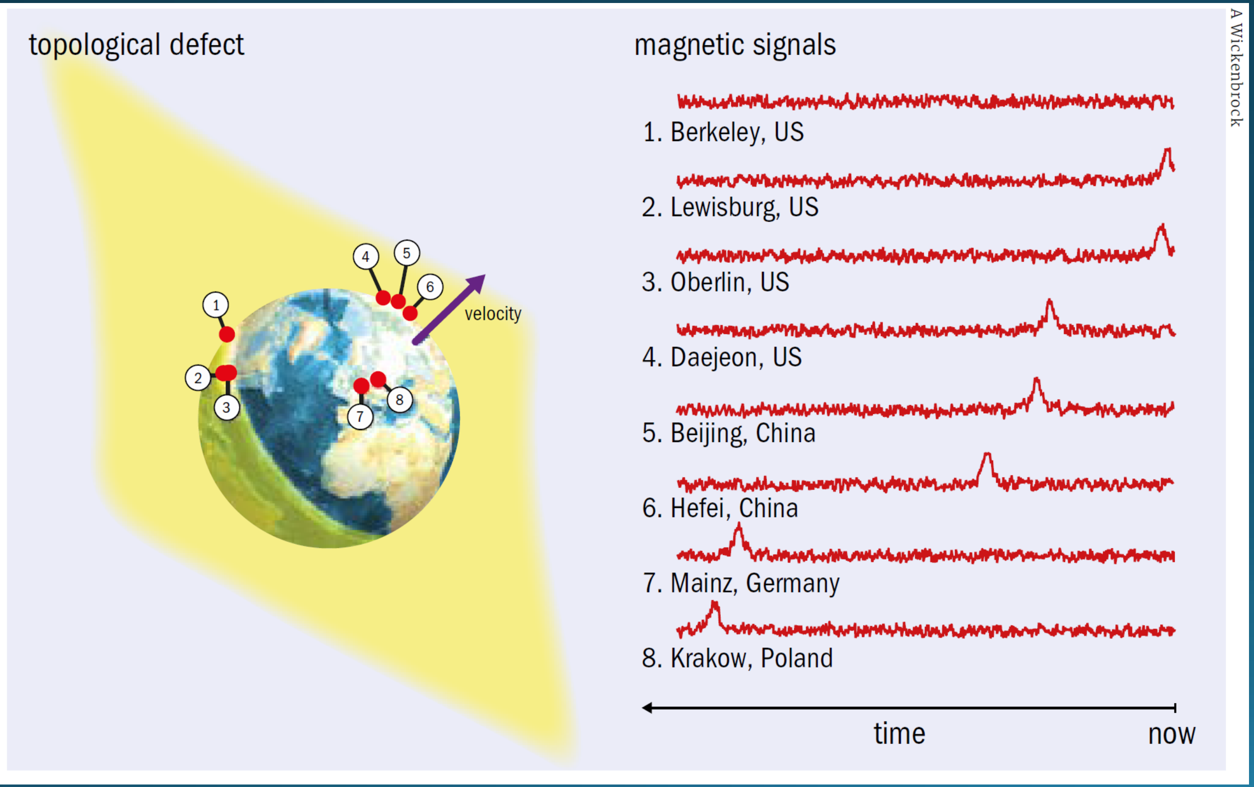
- Quantum sensor networks

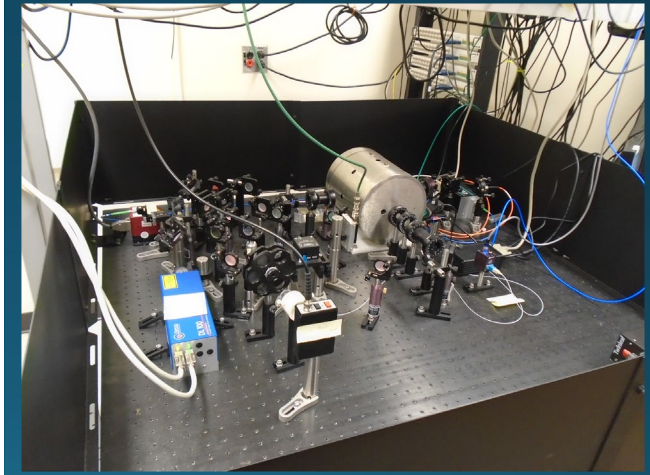
  [D. Gottesman, et al., *Phys. Rev. Lett*. **109**, 070503 (2012)]
  [E. Khabiboulline, et al., *Phys. Rev. Lett*. **123**, 070504 (2019)]



Global Network of Optical Magnetometers to search for Exotic Physics (GNOME)



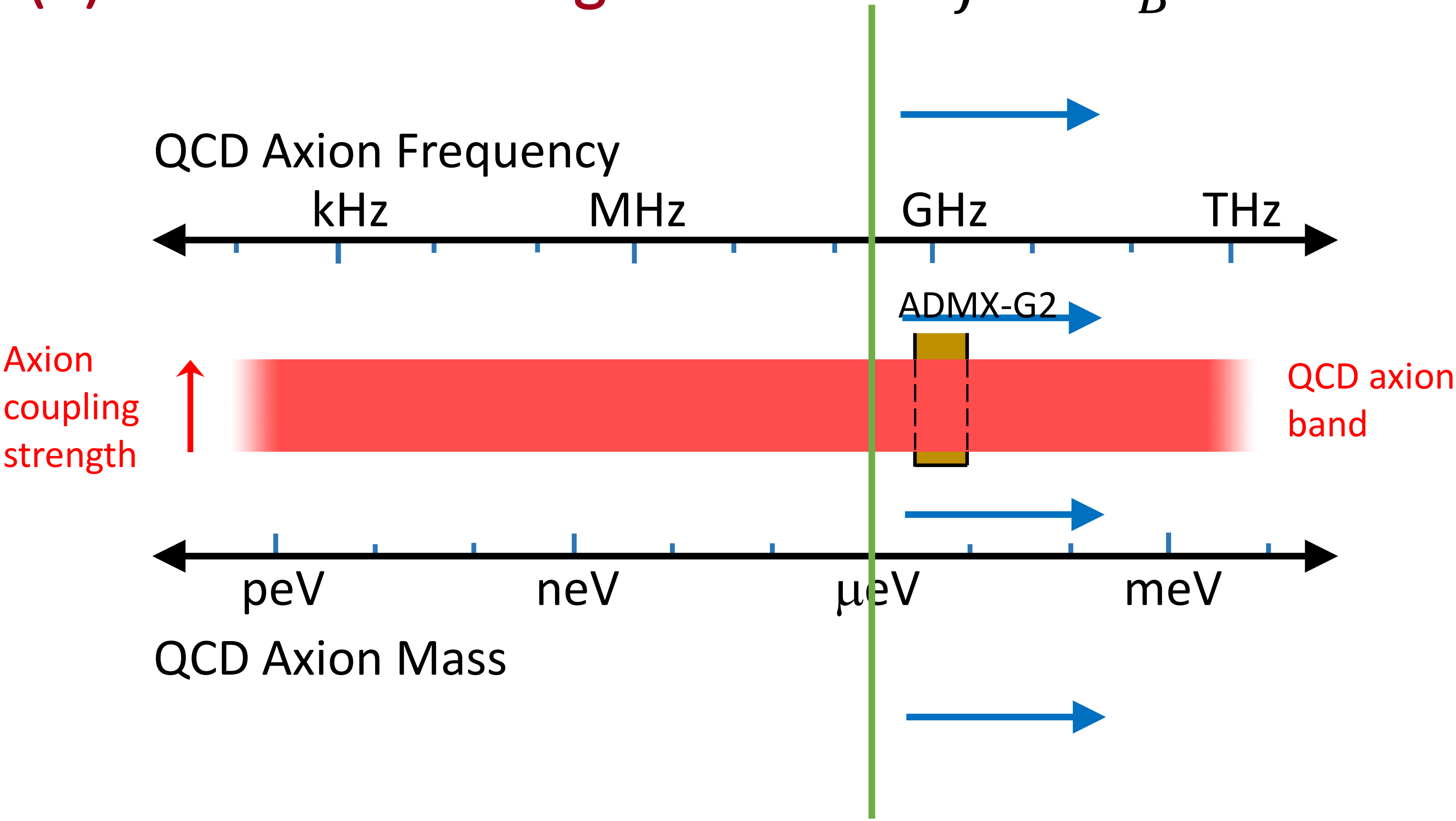




Quantum Sensing

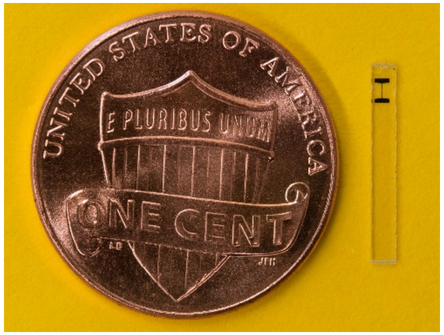
(1) Ground State Regime

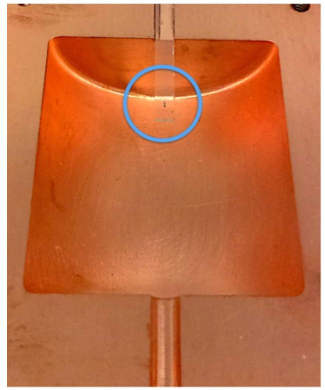
$$hf \gg k_B T$$



Ground state measurement: QND photon counting

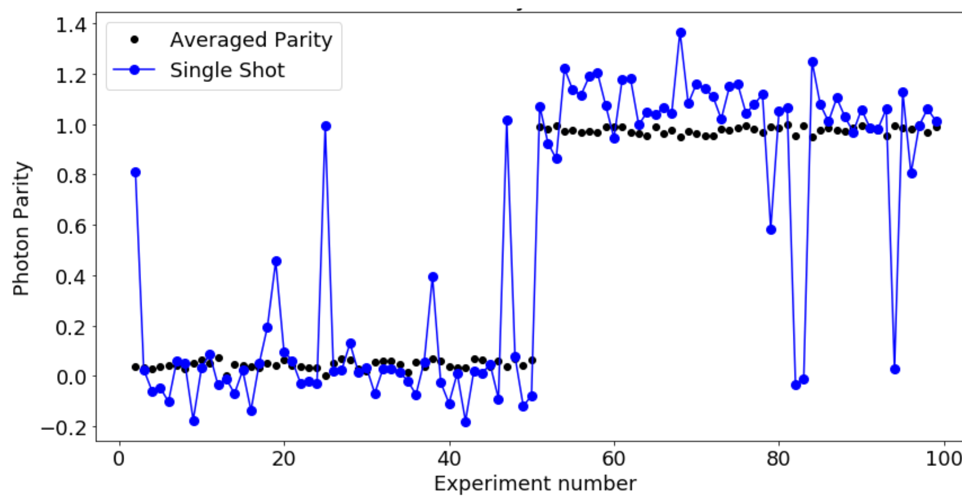
Akash Dixit, Aaron Chou, David Schuster





Use qubit as an atomic clock whose frequency depends on the number of photons in the cavity. The electric field of even a **single photon** will exercise the non-linearity of the qubit oscillator and shift its frequency.

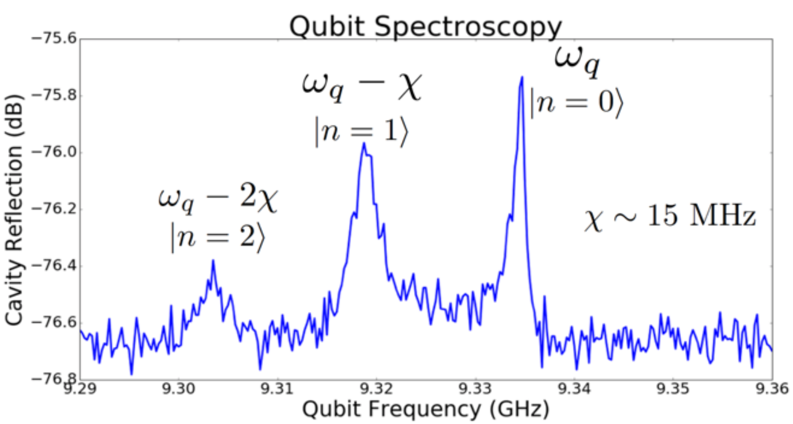
Repeatedly measure the clock frequency to determine whether the cavity contains 0 or 1 photon:



Many QND measurements agree that the cold cavity contains 0 photons

Inject 1 photon

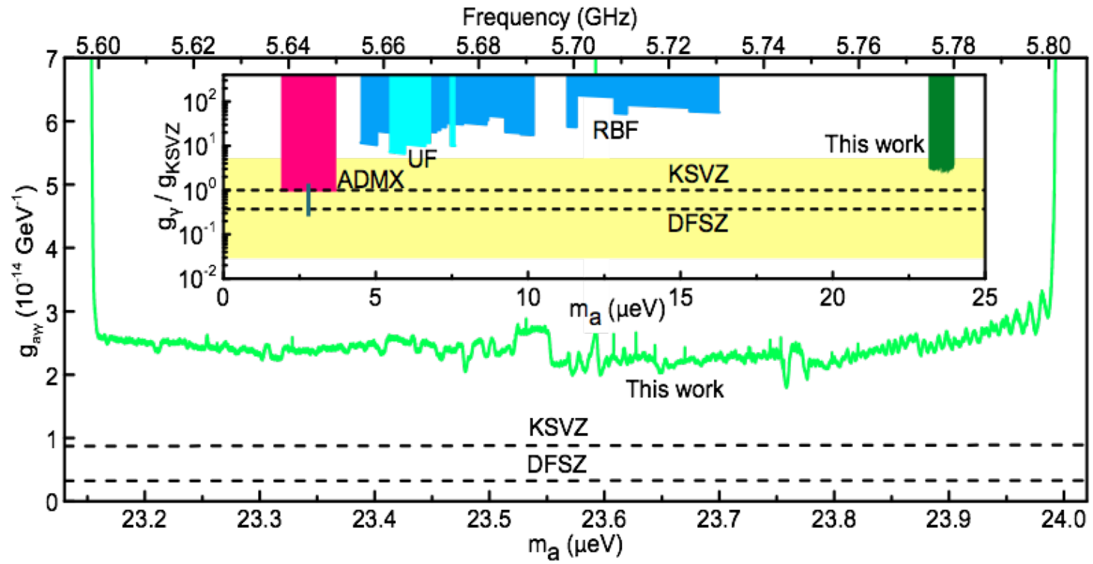
Many QND measurements of the single photon **without absorbing it.**



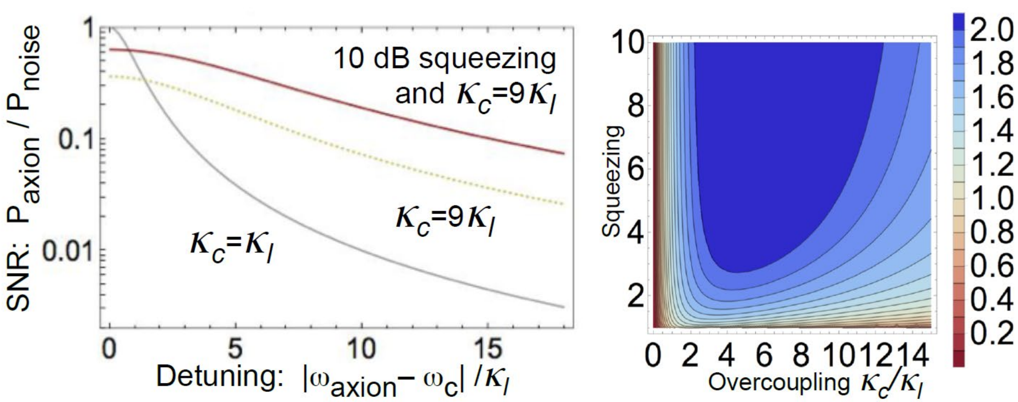
Count # of photons by measuring the quantized frequency shift of the qubit.

Figure Credit: Aaron Chou, FNAL

HAYSTAC: Acceleration through squeezing



HAYSTAC run 1 & 2 combined exclusion plot

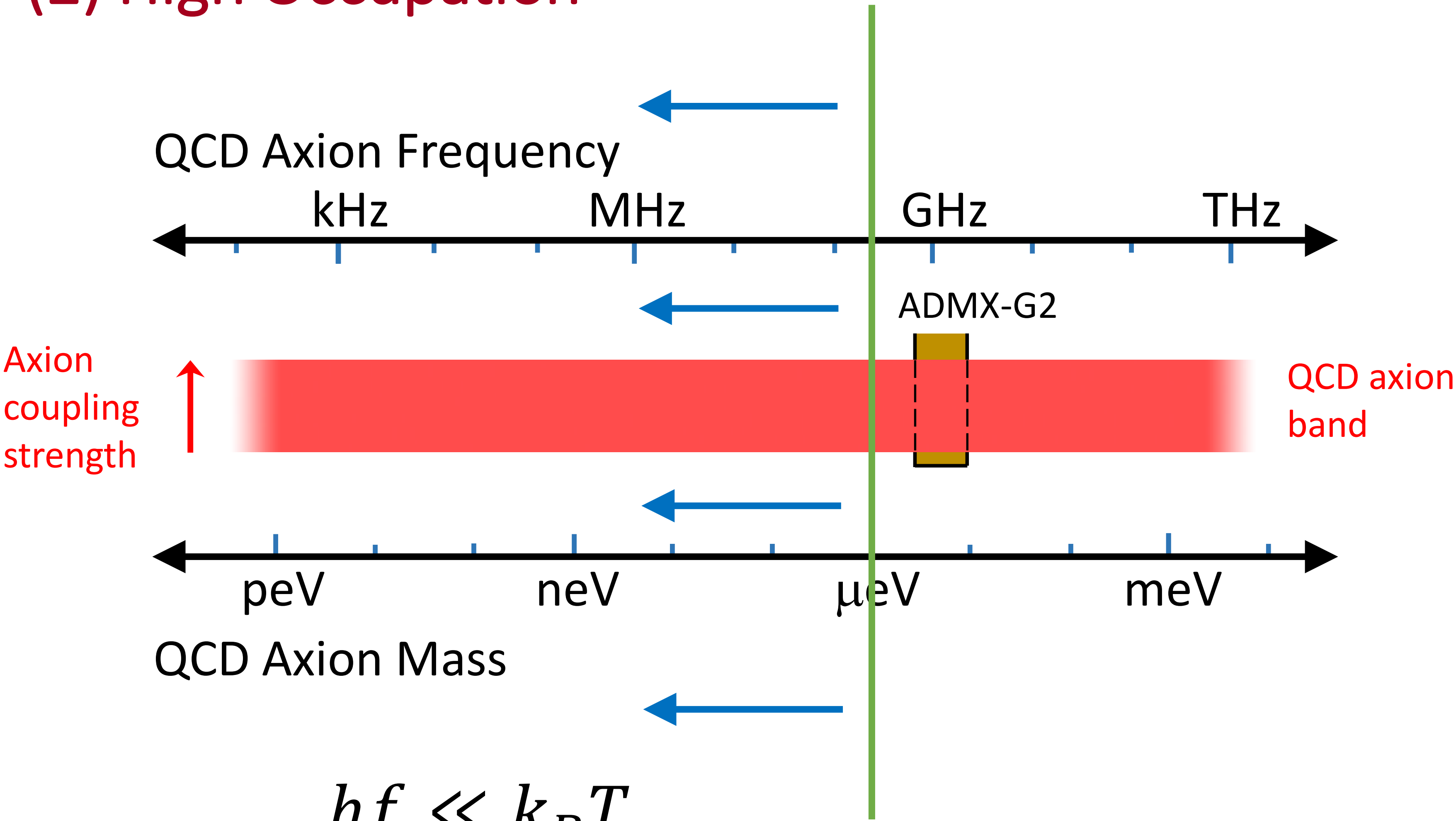


HAYSTAC Phase II squeezed state receiver projected acceleration

Droster, Alex G., and Karl van Bibber. "HAYSTAC Status, Results, and Plans." *arXiv:1901.01668* (2019).

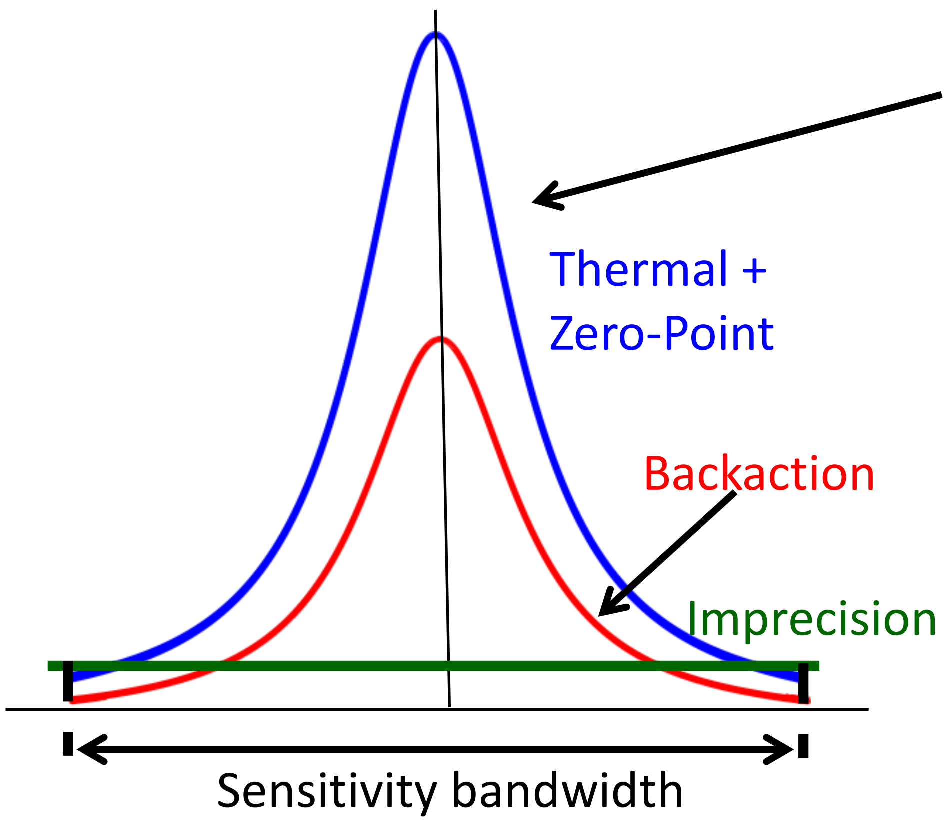
Quantum Sensing

(2) High Occupation



$$hf \ll k_B T$$

Photon counting is useless when $hf \ll k_B T$



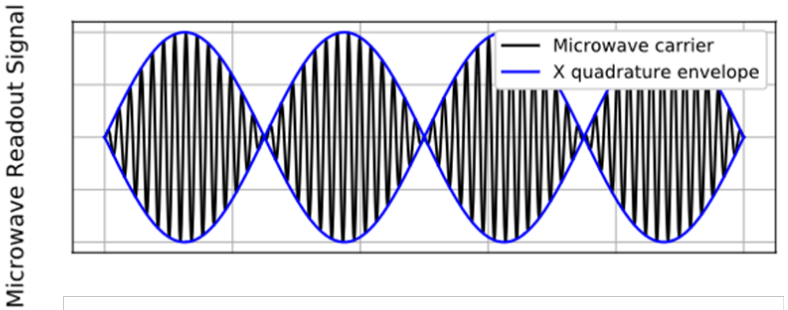
- $\sqrt{N}$ thermal fluctuations in the number of resonator photons
- Sensitivity not improved by photon counting
- Goal: reduce backaction & imprecision noise to widen sensitivity bandwidth.

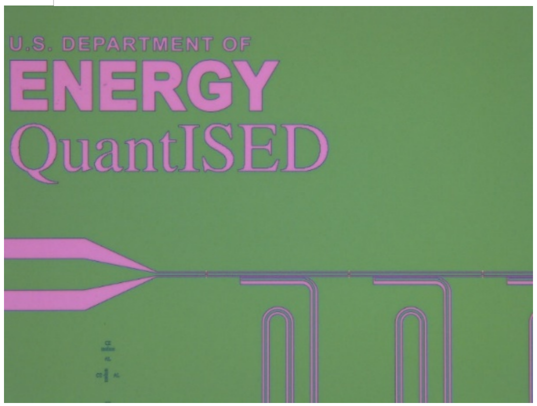
$\rightarrow$ **Backaction evasion**

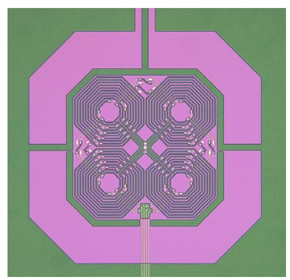
Implement ***backaction evasion*** protocol to reduce both imprecision and backaction noise below the standard quantum limit, increasing the sensitivity bandwidth

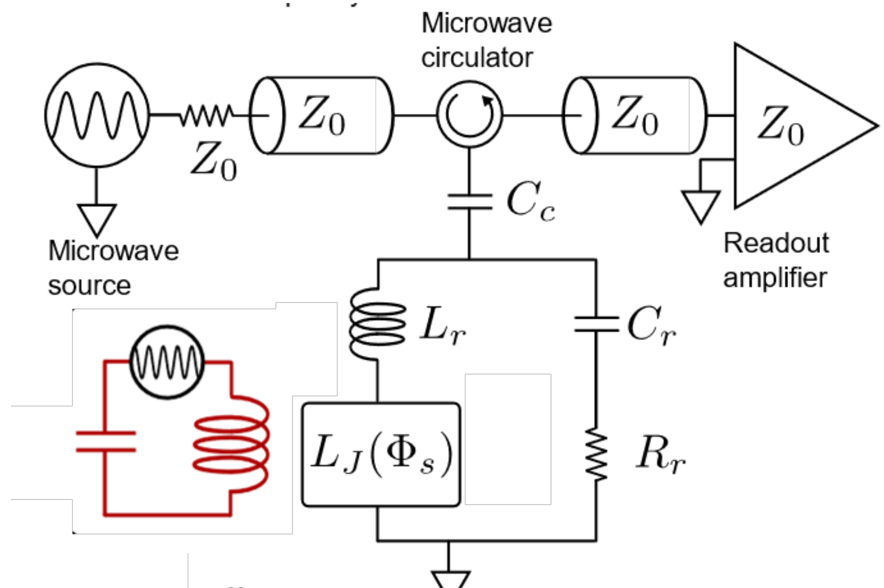
High Occupation: RF Quantum Upconverters

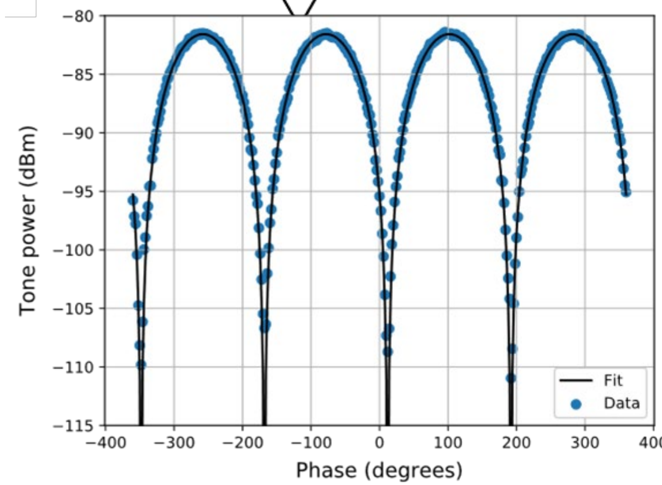
Quantum Backaction Evasion











30 dB of phase-sensitive gain achieved

Figure Credit: Kent Irwin, Stanford/SLAC