Quantum sensing for particle and astrophysics

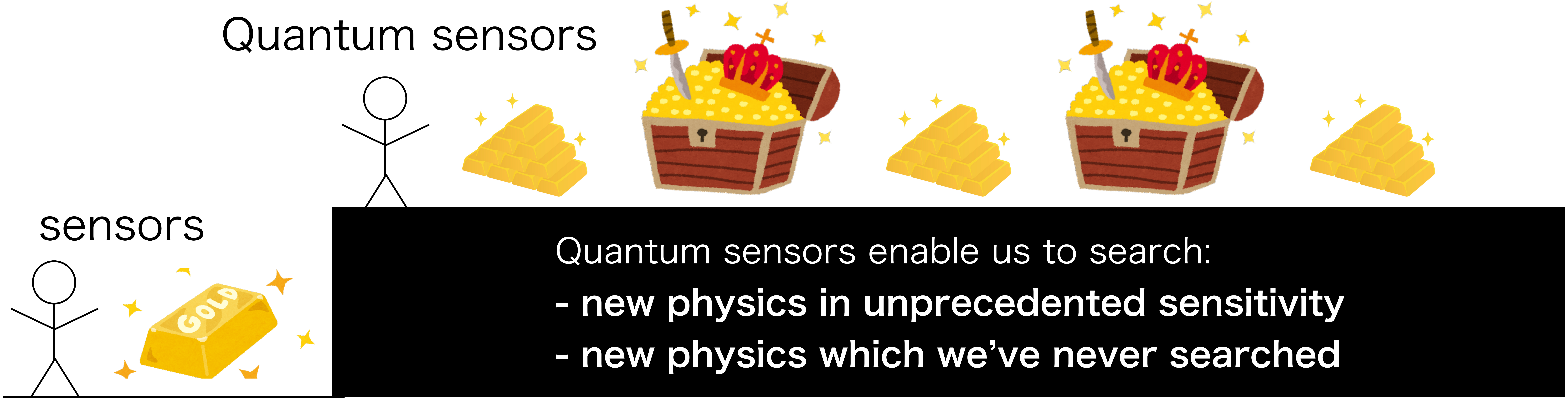
Physics in LHC and Beyond
May 14, 2022
Tatsumi Nitta (University of Tokyo, ICEPP)

Quantum Sensor

“A device, the measurement capabilities of which are enabled by our ability to manipulate and read out its quantum states. ” M. Doser

Quantum states ~ basically low energy

-> ideal for application to the low energy measurement



Quantum sensors enable us to search:

- **new physics in unprecedented sensitivity**
- **new physics which we’ve never searched**

Quantum Sensing for HEP

Superconducting device

Magnetometer: SQUID (ABRACADABRA)

Amplifier: JPA, TWPA (ADMX, HAYSTAC, etc)

Photon counting: Transmon (FNAL/Chicago),
Rydberg Atom (CARRACK, Yale),
SNSPD, TES, MKID, QCDet, etc

Atom Interferometer

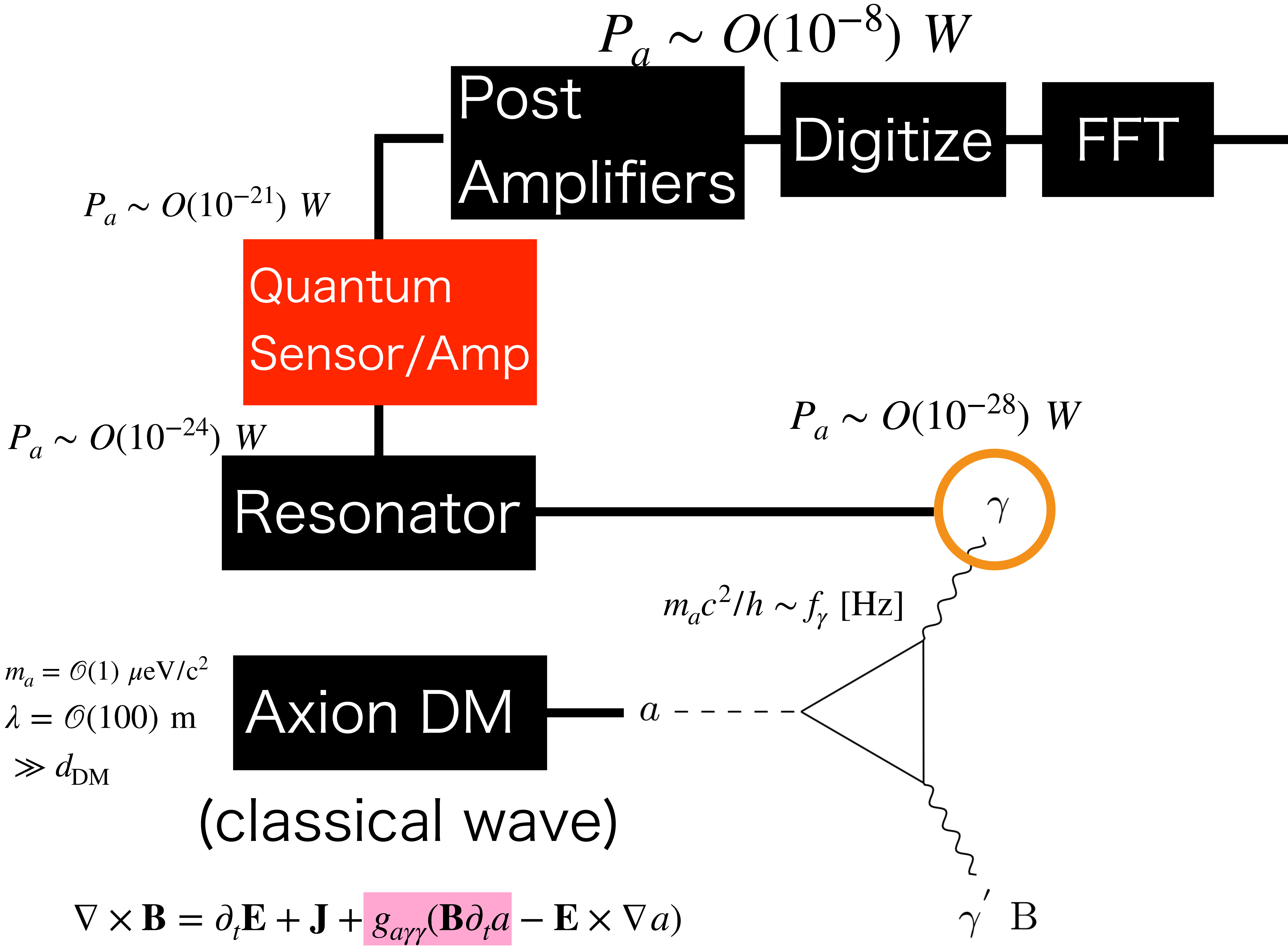
MAGIS-100, AION, MIGA, ZAIGA

Optomechanical sensors

Wind chime

An example: Axion haloscope

P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983)



$P_a \sim O(10^{-8})\ W$

Post Amplifiers

Digitize

FFT

$P_a \sim O(10^{-21})\ W$

Quantum Sensor/Amp

$P_a \sim O(10^{-24})\ W$

Resonator

$P_a \sim O(10^{-28})\ W$

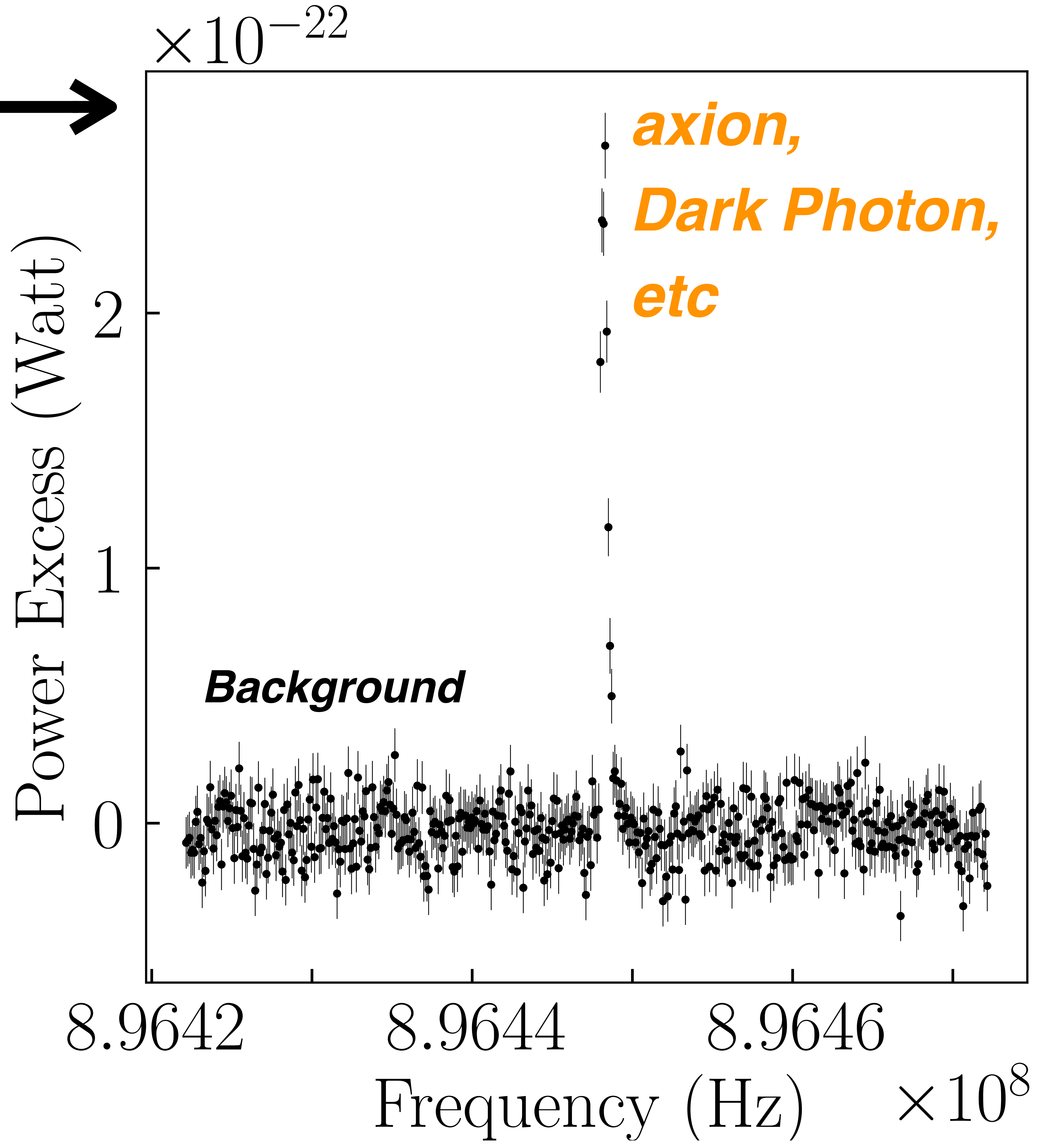
$m_a = \mathcal{O}(1)\ \mu\mathrm{eV/c^2}$

$\lambda = \mathcal{O}(100)\ \mathrm{m}$

$\gg d_{\mathrm{DM}}$

Axion DM

(classical wave)



$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma}(\mathbf{B}\partial_t a - \mathbf{E} \times \nabla a)$$

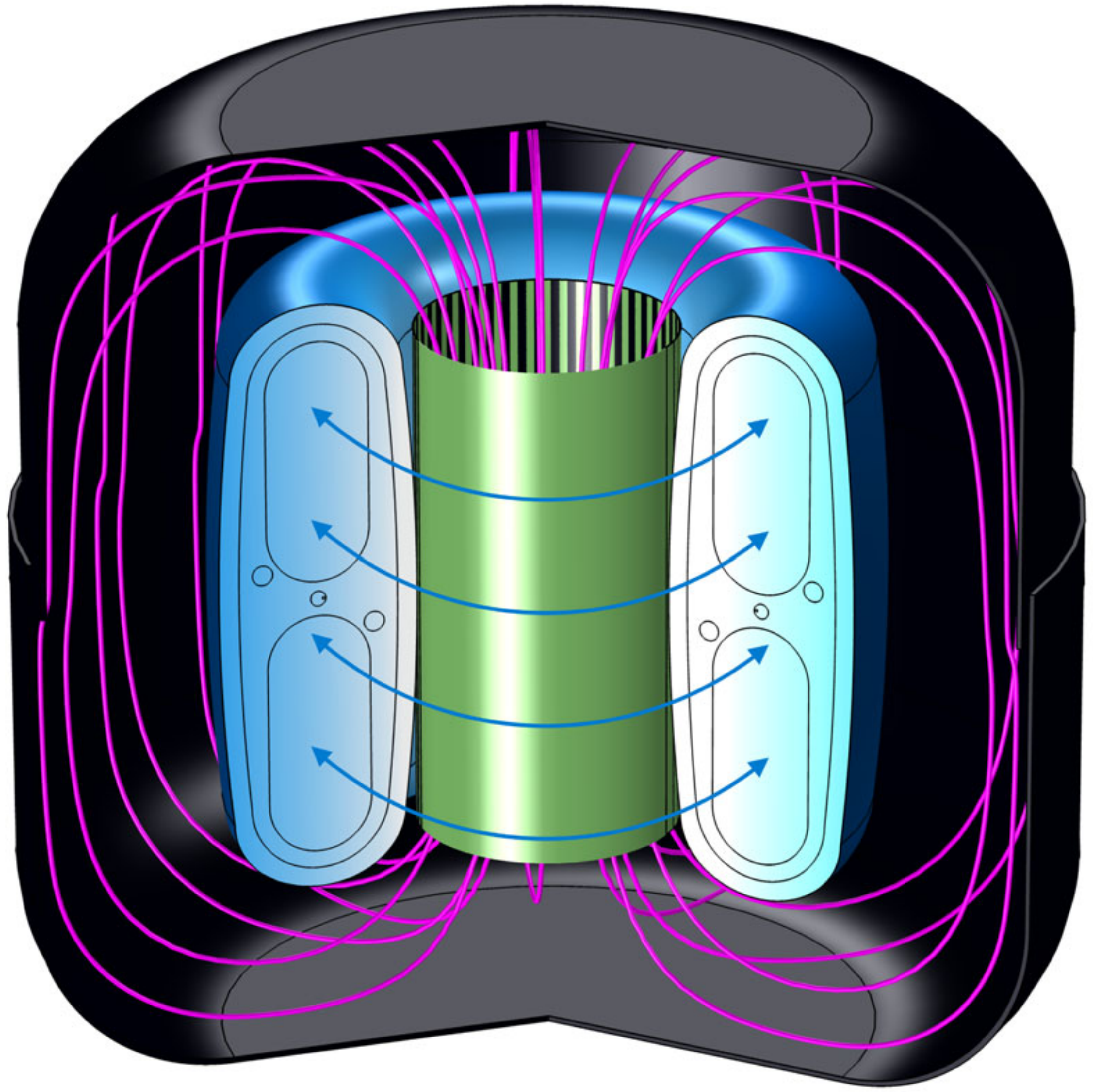
SQUID

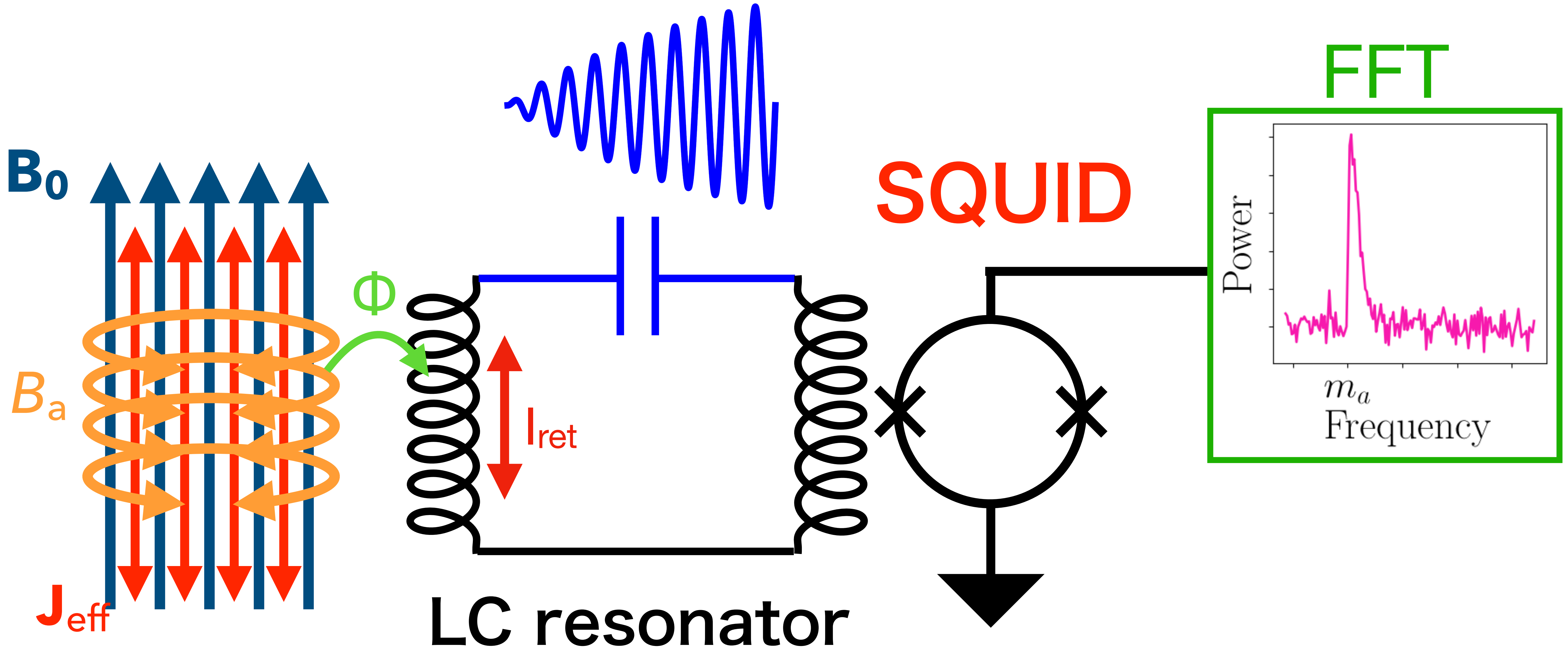
ABRACADABRA
PRL 122, 121802 (2019)
PRD 99, 052012 (2019)
PRL 127, 081801 (2021)

DMRadio
IEEE Trans. on Appl. Superc., 27, 1(2016)

Utilize Josephson relations

ABRACADABRA-10cm





Sensitive to axion DM having mass below 1 μeV

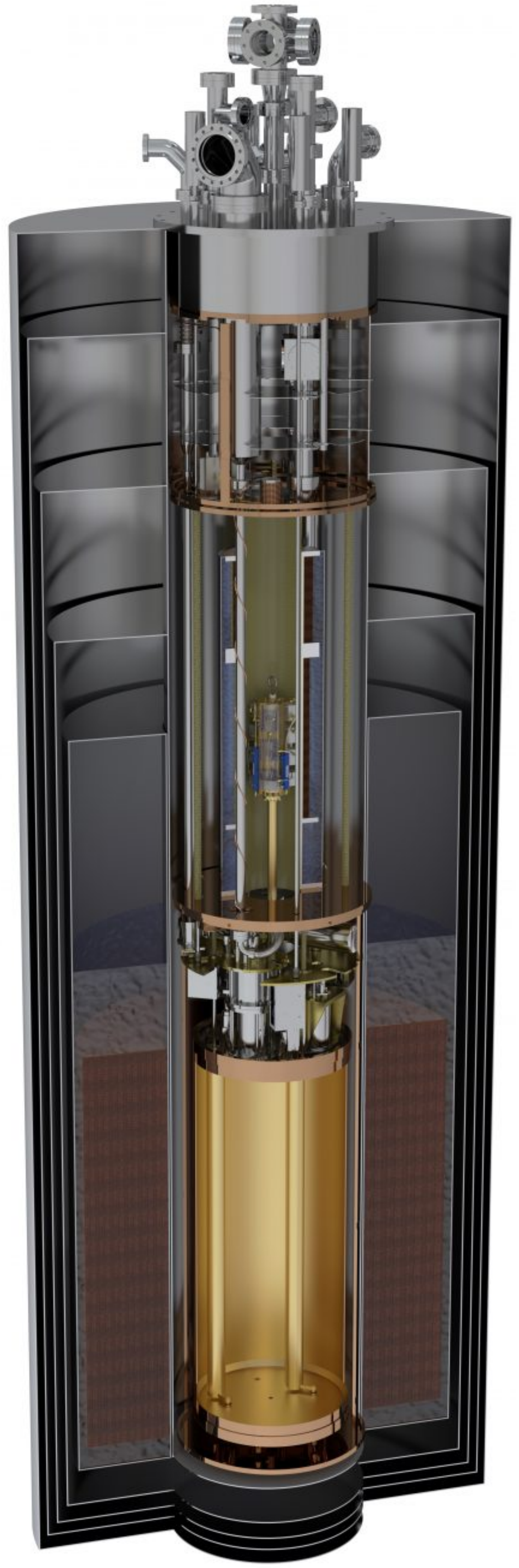
DM-radio collaboration is aiming to reach DFSZ axions with m^3 size detector

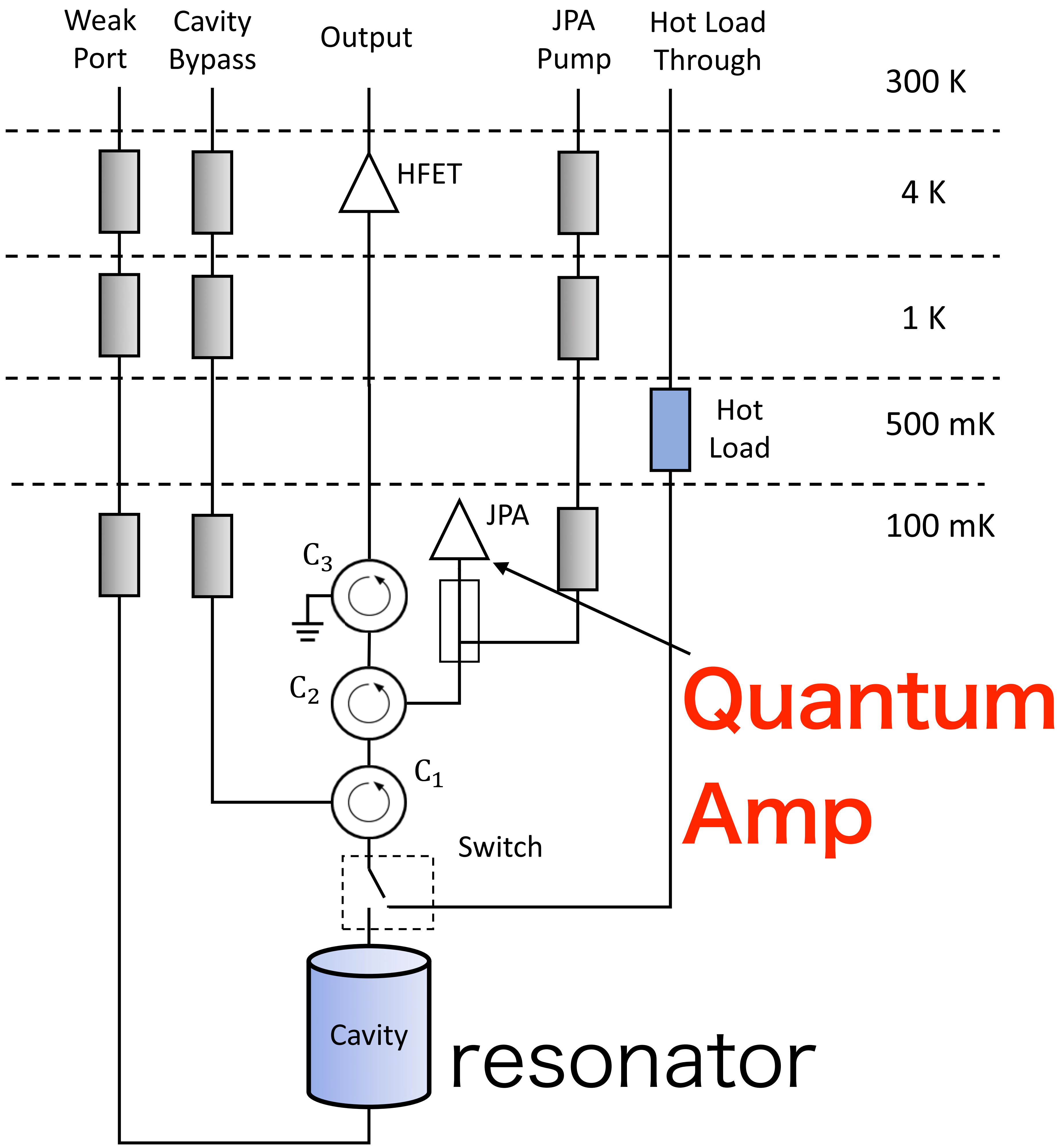
JPA/TWPA

ADMX
PRL 122, 151301 (2018)
PRL 124, 1013013 (2020)
PRL 127, 261803 (2021) etc

HAYSTAC
PRL 118, 061302 (2017)
Nature 590, 238-242 (2021)

ADMX-sidecar
arXiv:2110.10262 (2021)

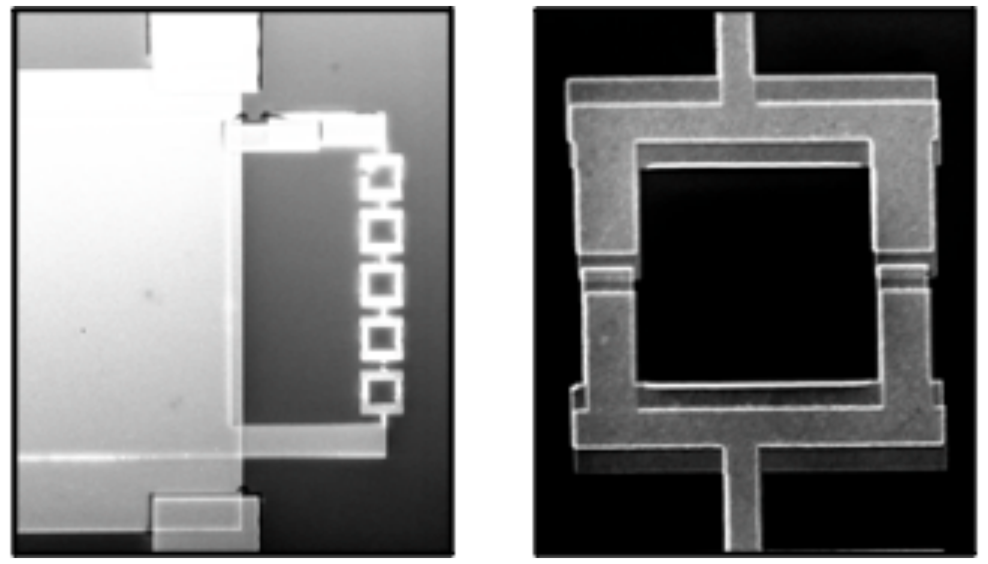




Quantum Amp

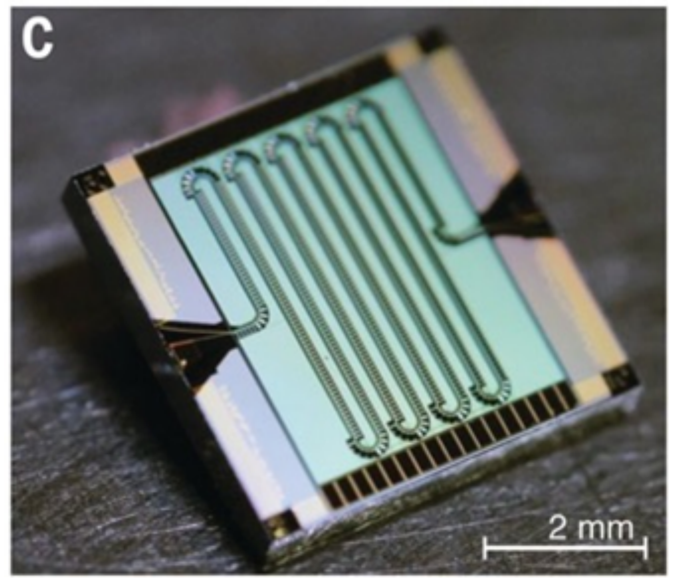
resonator

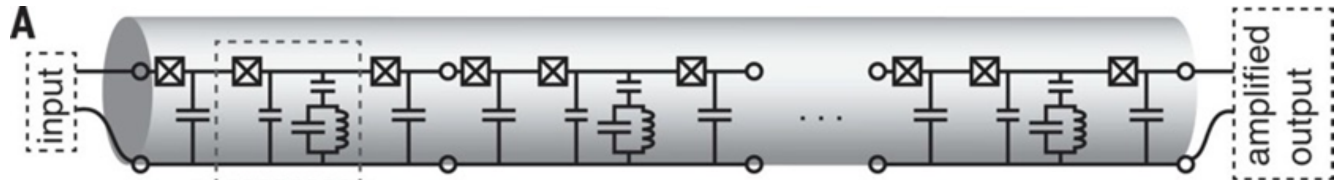
JPA (Josephson Parametric Amplifier)



works at GHz
30 dB gain

TWPA (Traveling Wave Parametric Amplifier)





Broadband amplification
~ O(GHz) (but less gain)

Amplifier only adds idler temperature

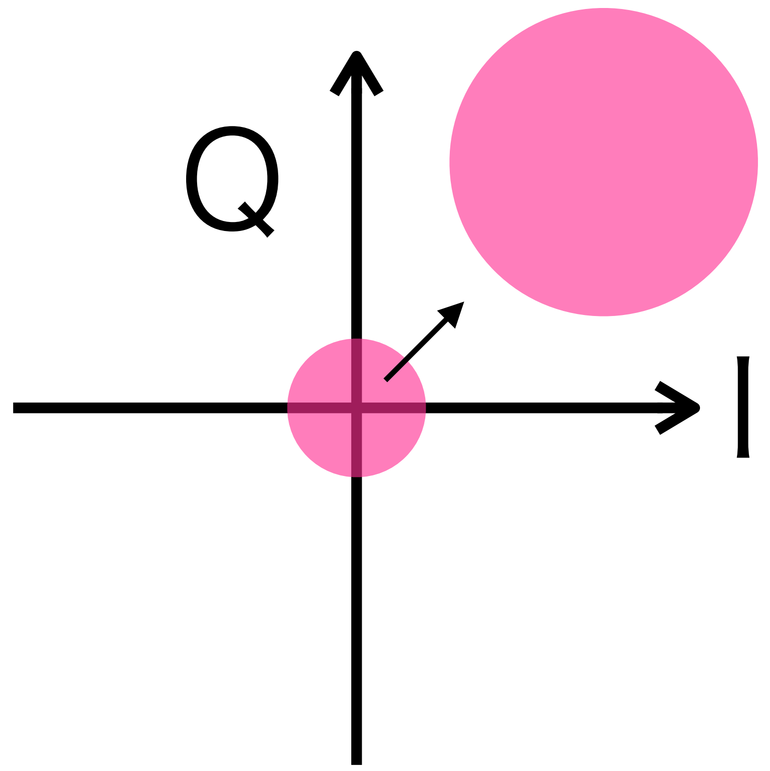
~ 200 mK ~ $10^{-24}\ W/Hz$

SQL (Standard Quantum Limit)

Phys. Rev. D **23**, 1693 (1981)

Standard quantum amplifiers' performance is limited by SQL

Quantum Limited Amps

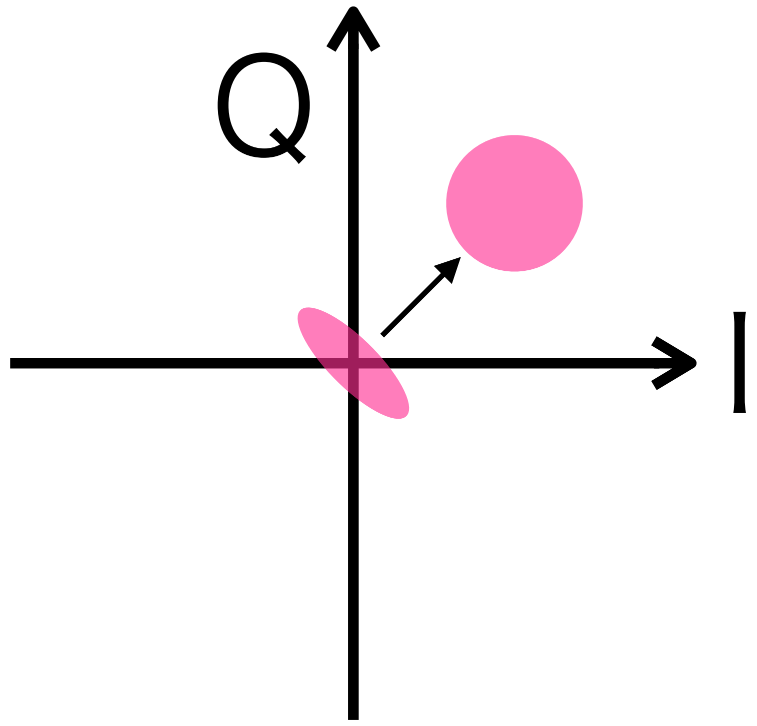


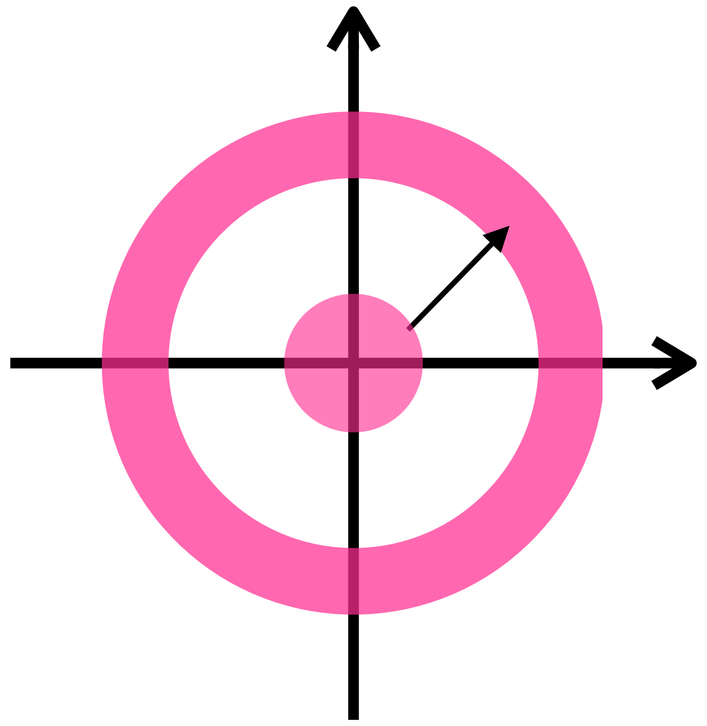
JPA/TWPA itself

$\Delta n \Delta \phi \geq \frac{1}{2}$: ~30 mK@1GHz,

~300 mK@10GHz

Defeating SQL





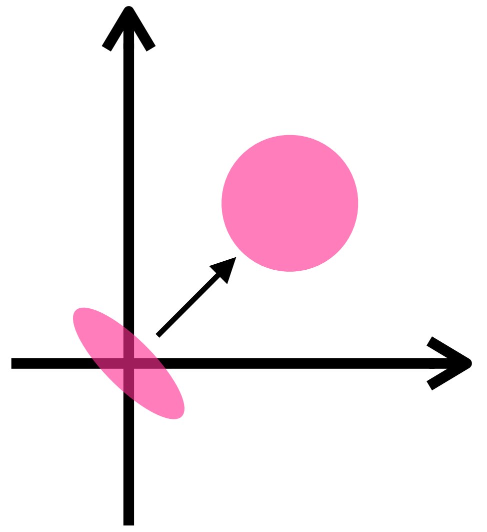
Quantum Squeezing

Single Photon Detection

TAMA/LIGO/
Virgo/KAGRA
HAYSTAC

Rydberg Atom
Superconducting Qubit
etc

Quantum Squeezing



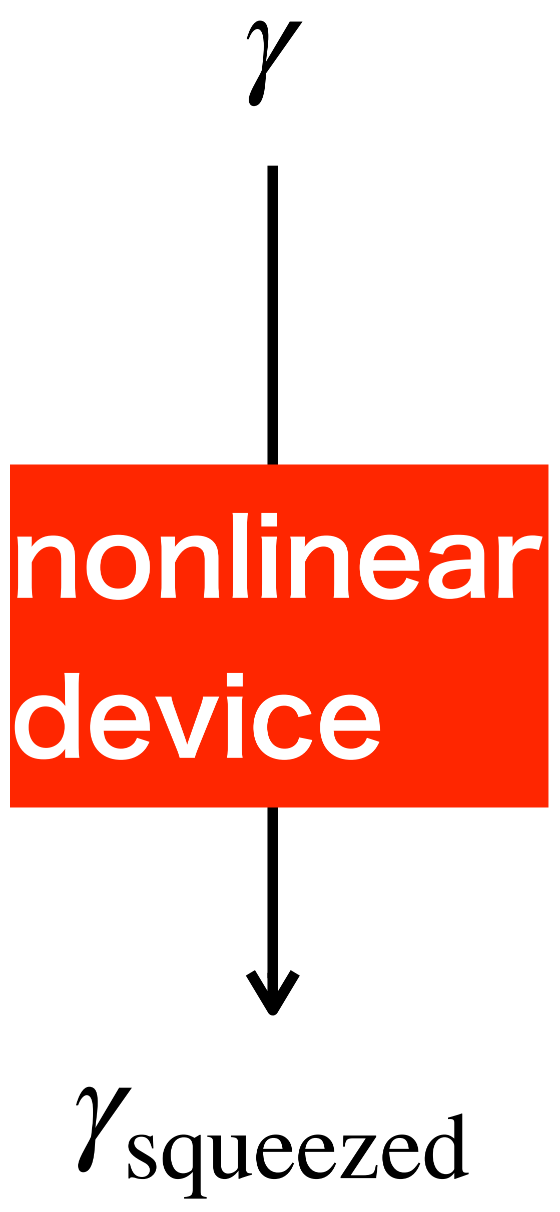
LIGO

Nature 7, 613-619 (2013)

PRL 123, 231107 (2021)

HAYSTAC

Nature 590, 238-242 (2021)



γ

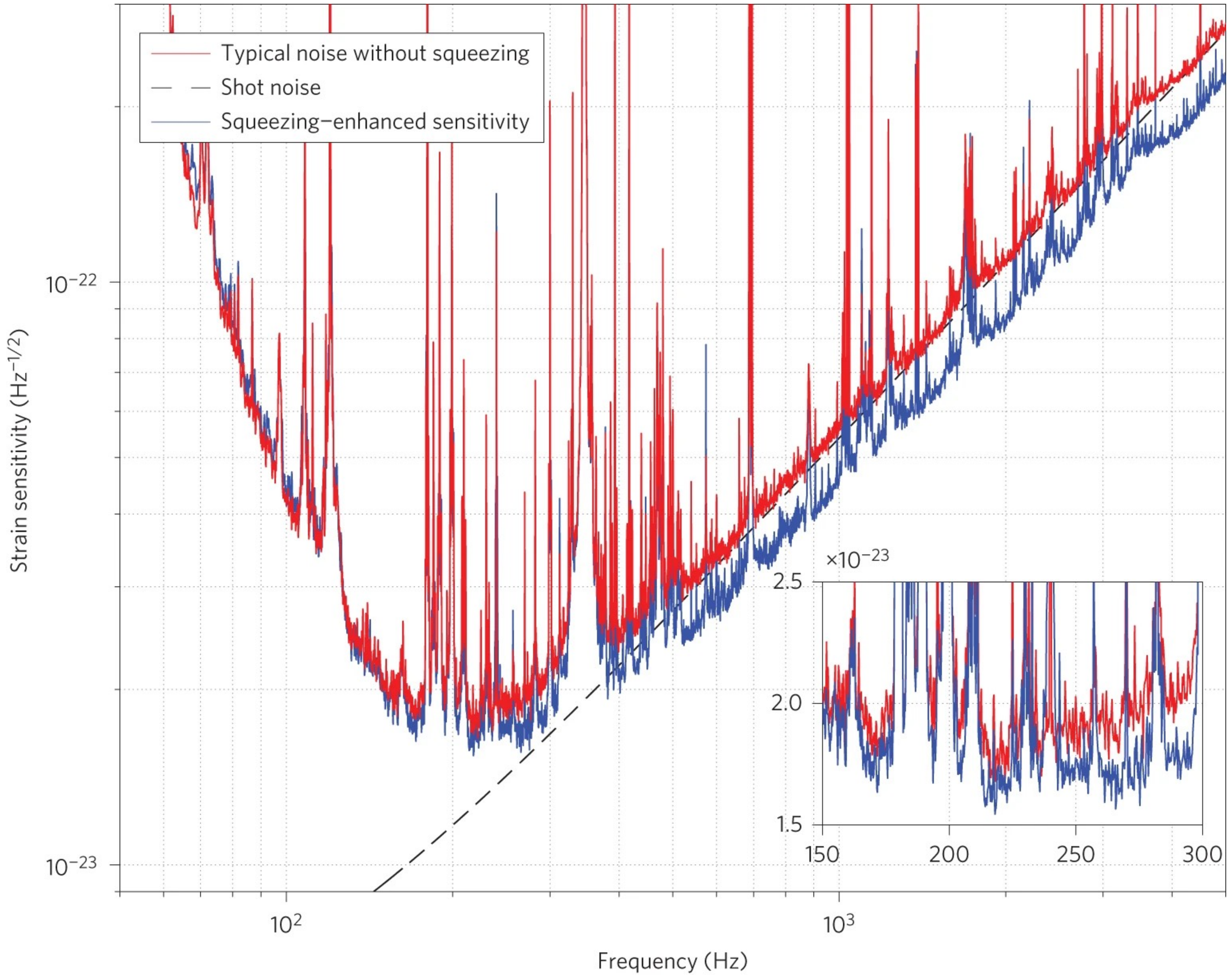
nonlinear device

γ_{squeezed}

LIGO

nonlinearity: PPKTP crystal (OPO)

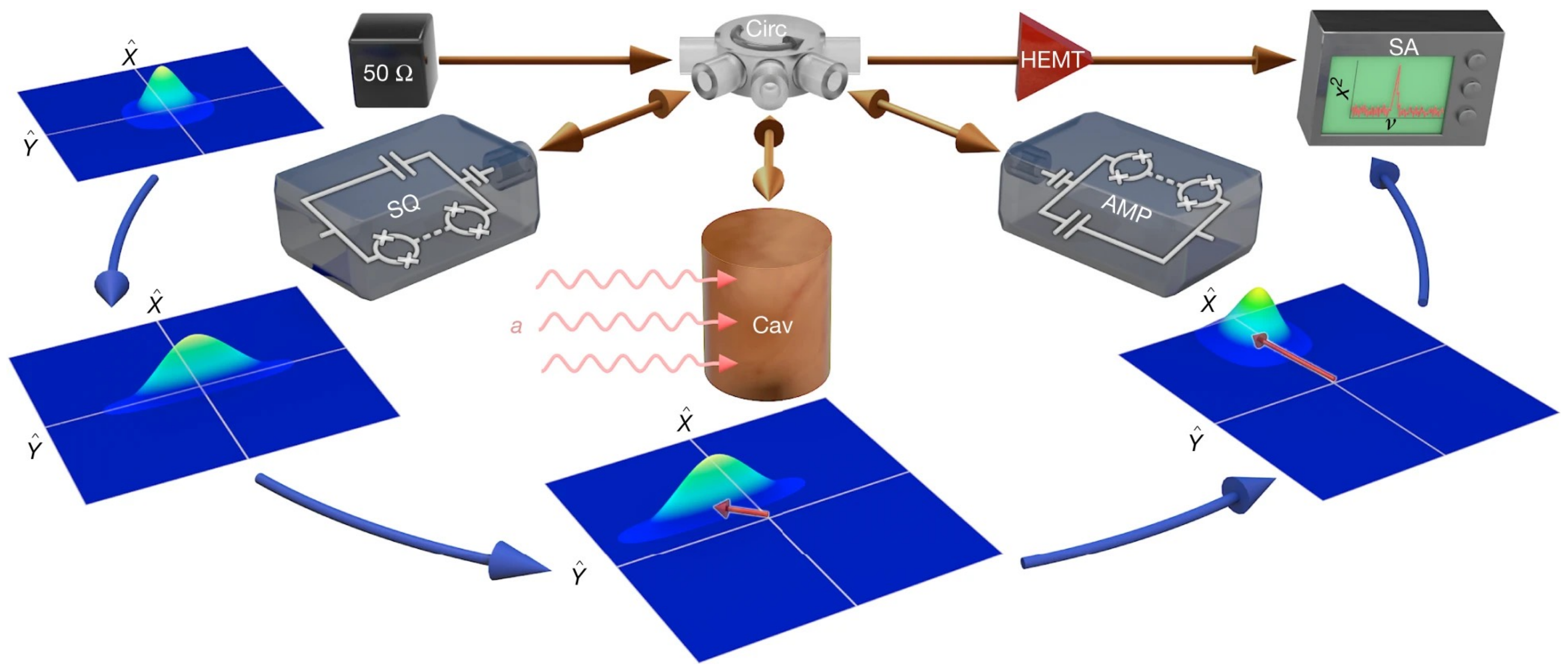
2 dB improvement against SQL



HAYSTAC

nonlinearity: Josephson Junction (JPA)

4 dB improvement against SQL



Loss of intermediate device limits their squeezing quality

$\epsilon\gamma_{\text{squeezed}} + (1-\epsilon)\gamma_{\text{circulator}}$

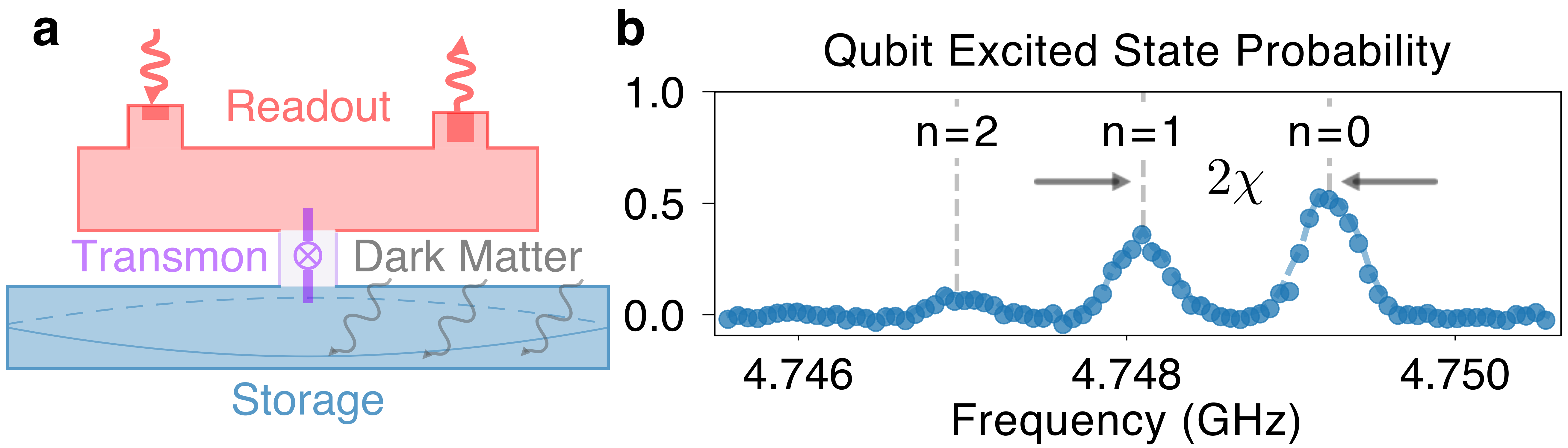
Single Photon Detection (Superconducting qubit)

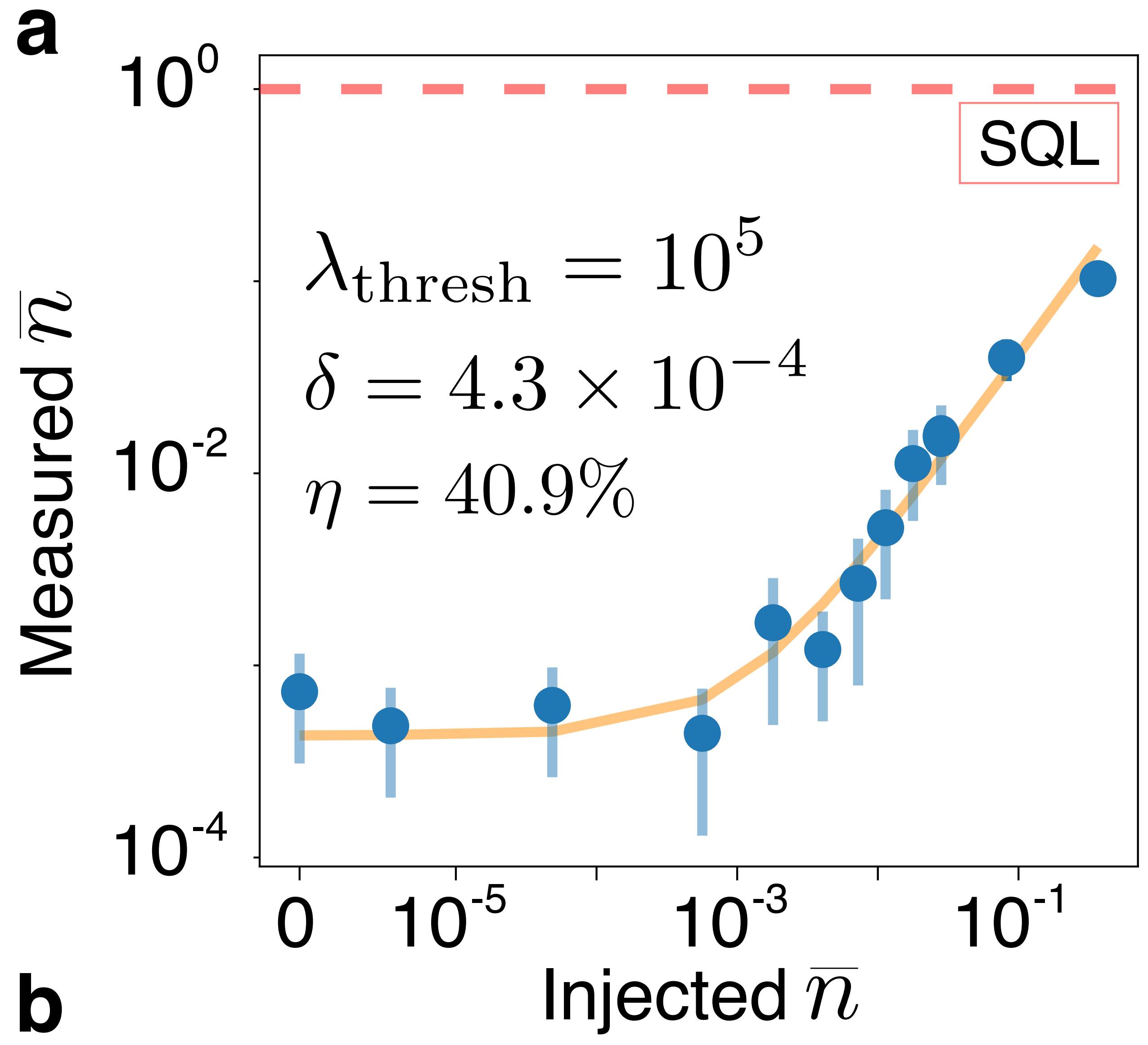
FNAL/Chicago

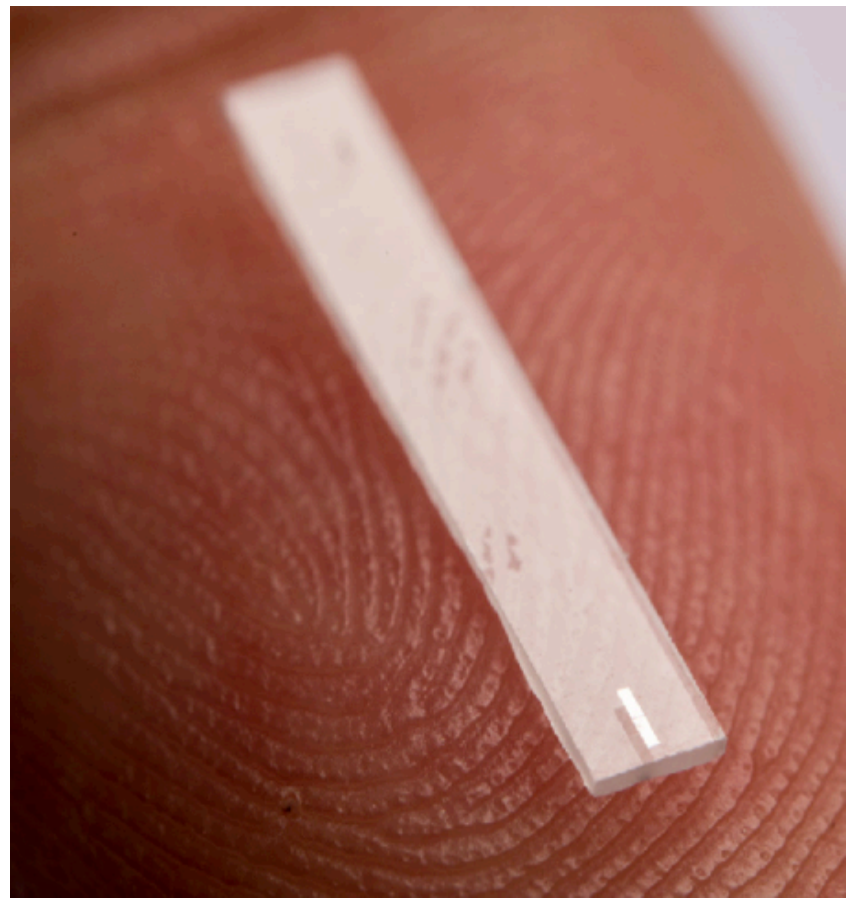
PRL 126 141302 (2021)

$$\mathcal{H}/\hbar = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

Achieved ~15 dB improvement against the SQL







Detecting one photon

→ phase uncertainty goes ∞

Evading the SQL

Advanced qubit can tune those frequency

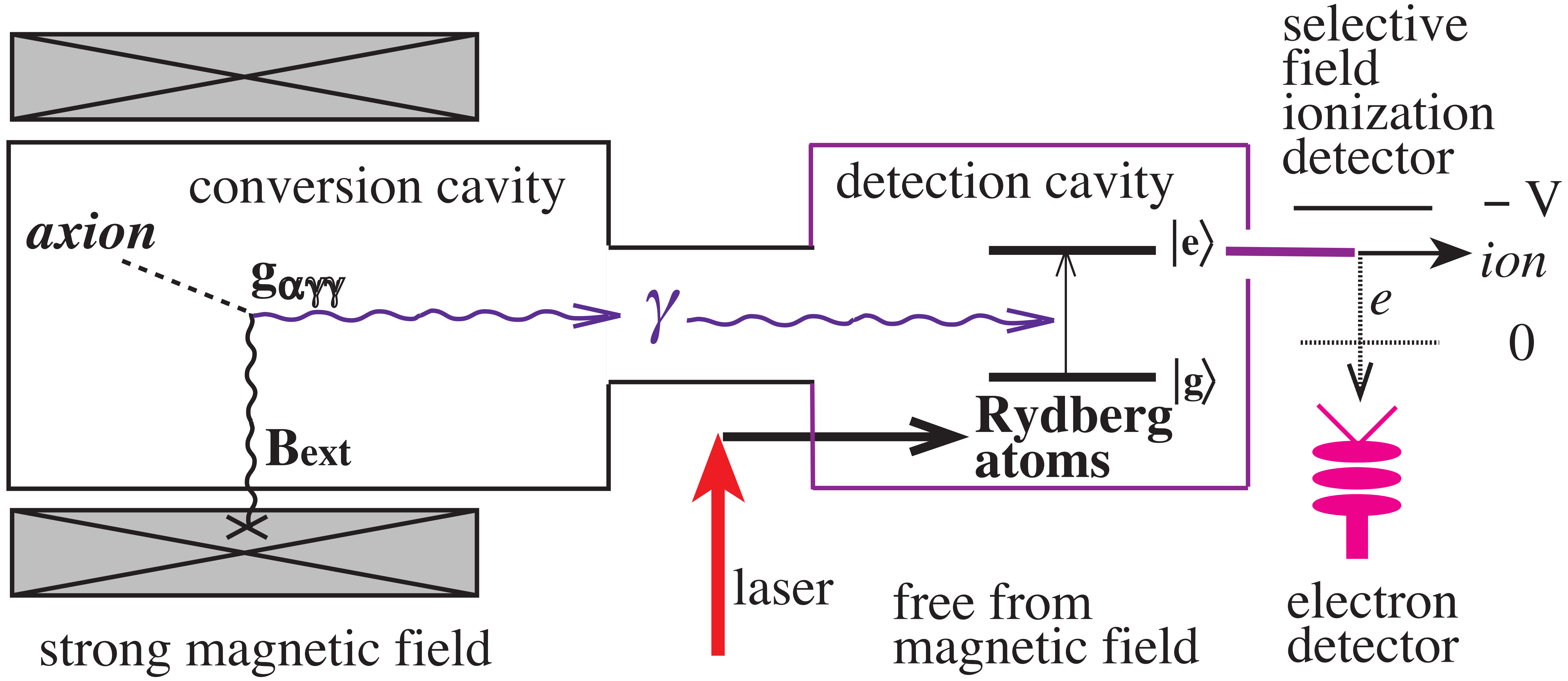
Single Photon Detection (Rydberg Atom)

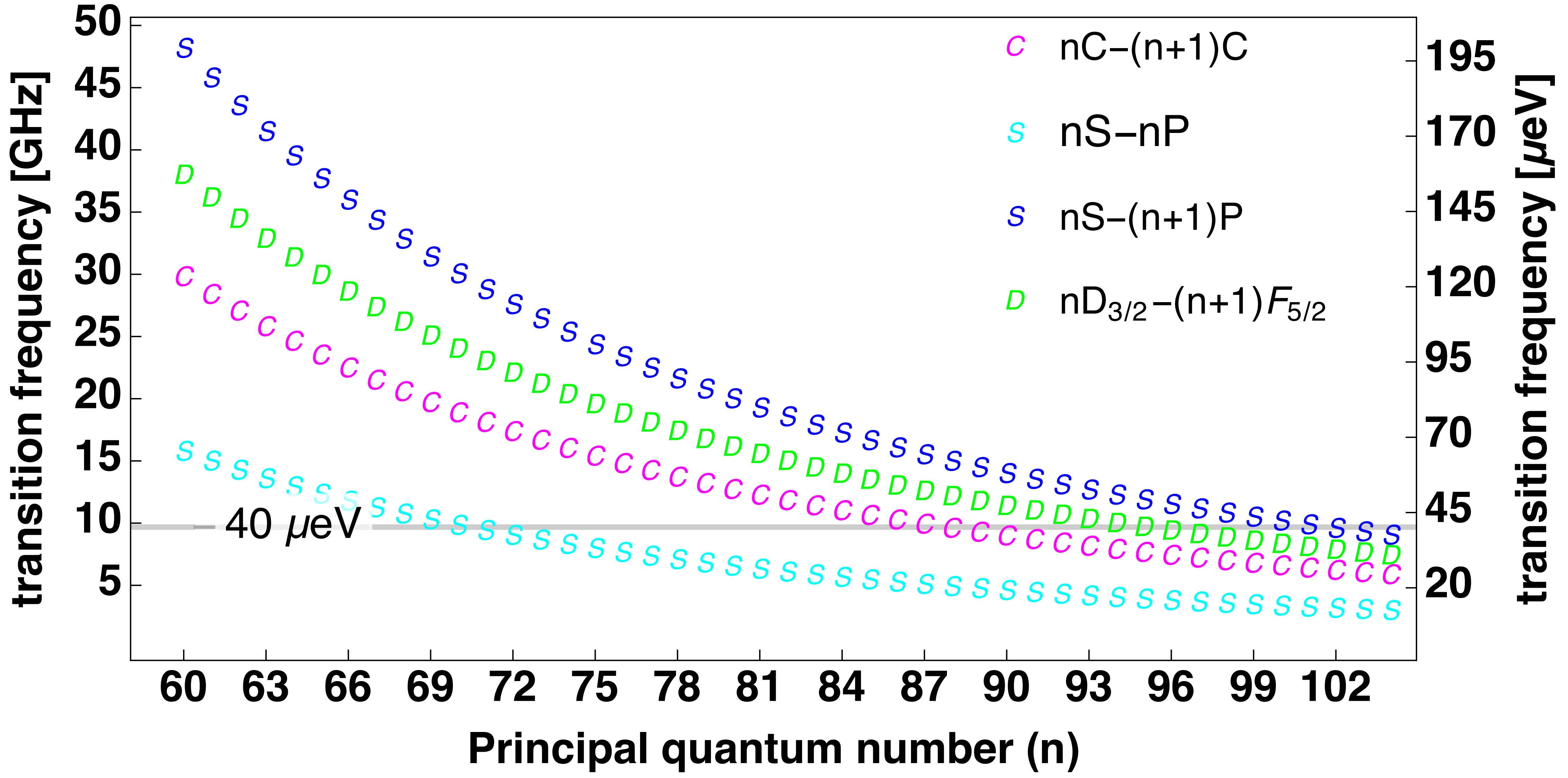
CARRACK
PLA 349 488 (2006)

Yale (Maruyama lab)
arXiv: 2112.04614 (2021)

Rydberg Atom (n~100):

- can detect single photon
- long life time ($\propto n^3$)
- Tunable 10-1000 GHz (n & Zeeman shift)



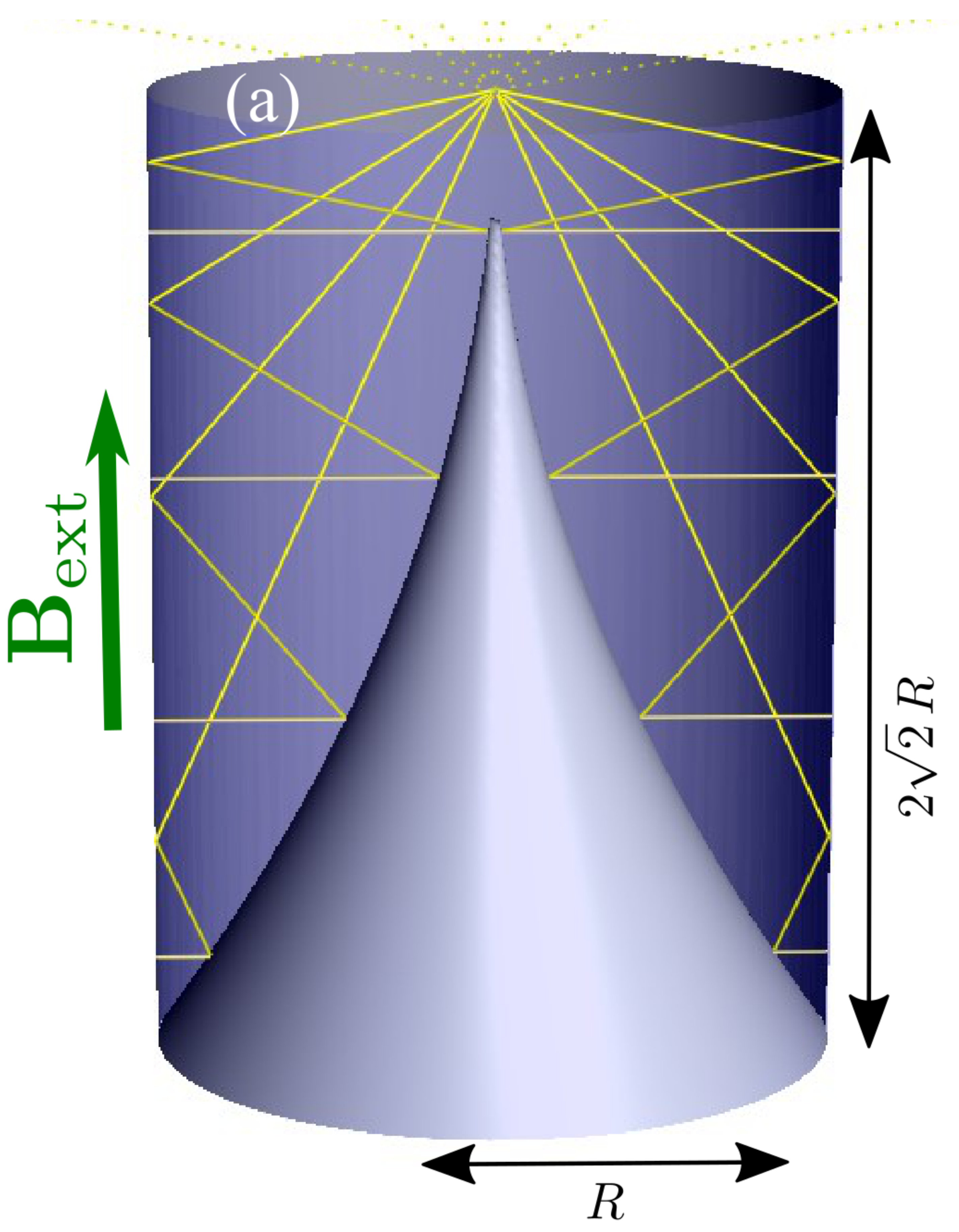


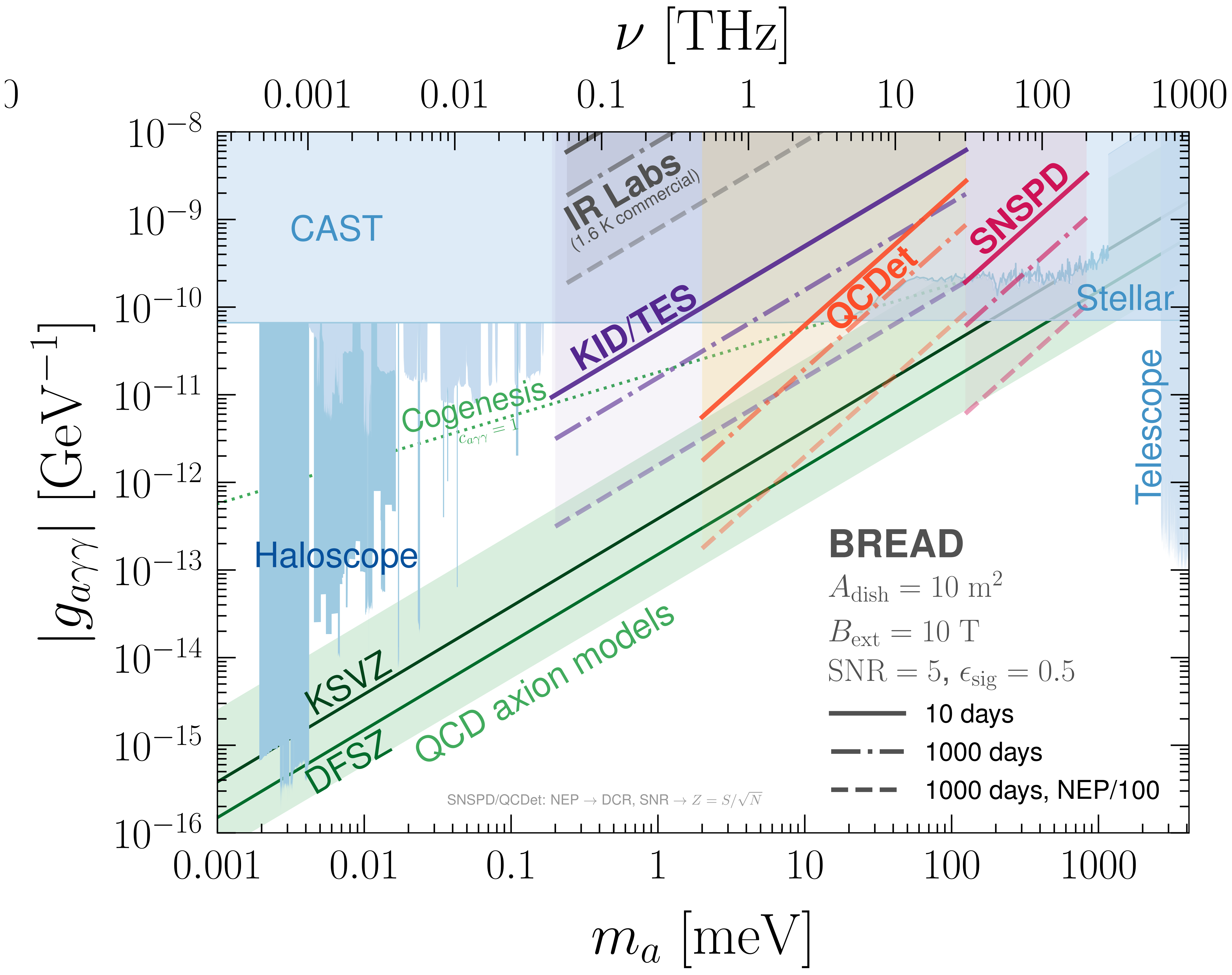
Yale people recently studied transition frequency and n

Single Photon Detection (KID, QCDet, SNSPD)

BREAD

PRL **128**, 131801

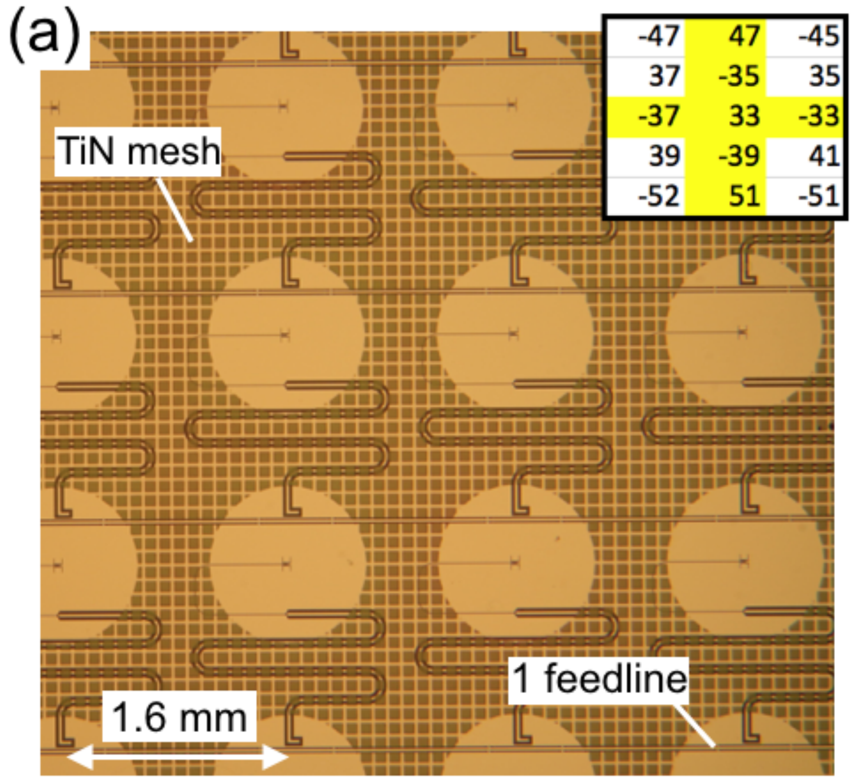


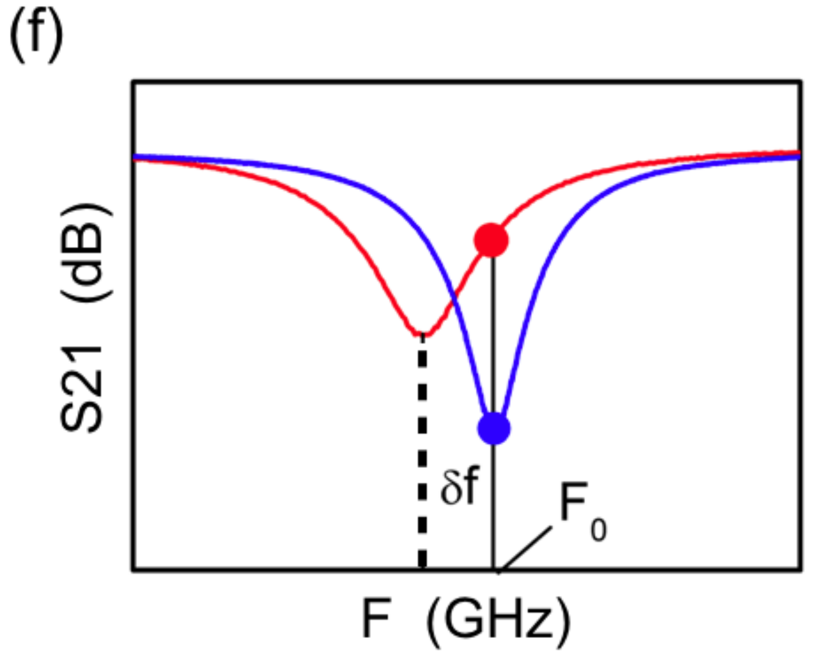


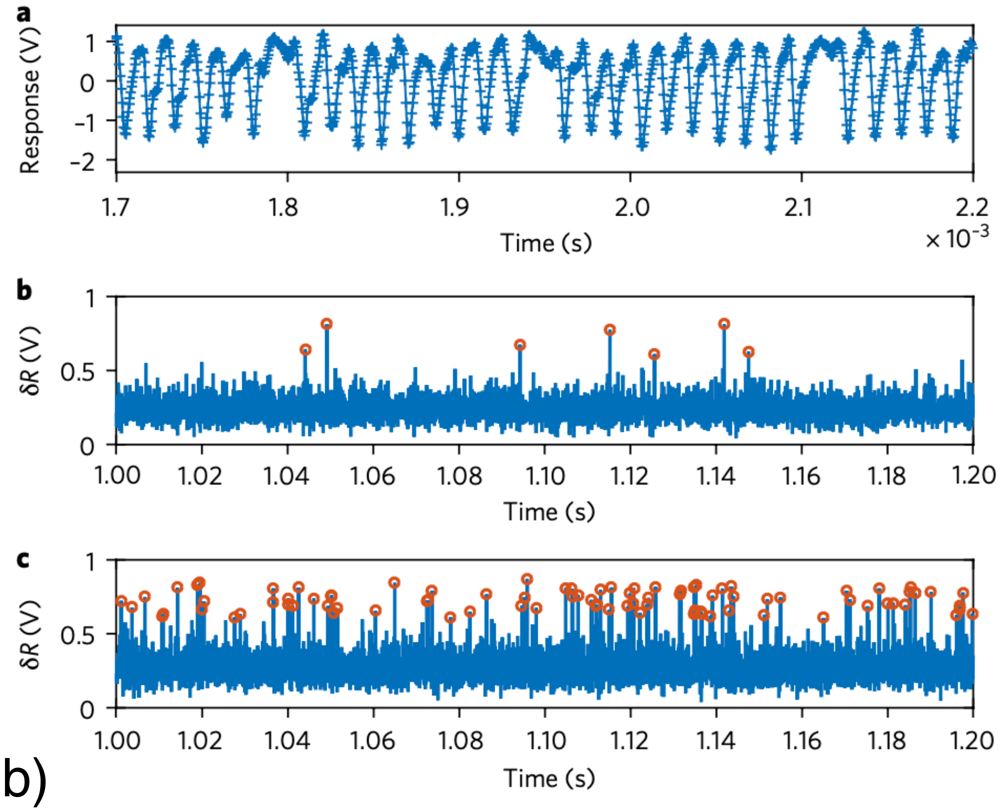
Single Photon Detection (KID, QCDet, SNSPD)

A&A 601, A89 (2017)
Nature 2, 90-97 (2018)
PRL 123, 151802 (2019)

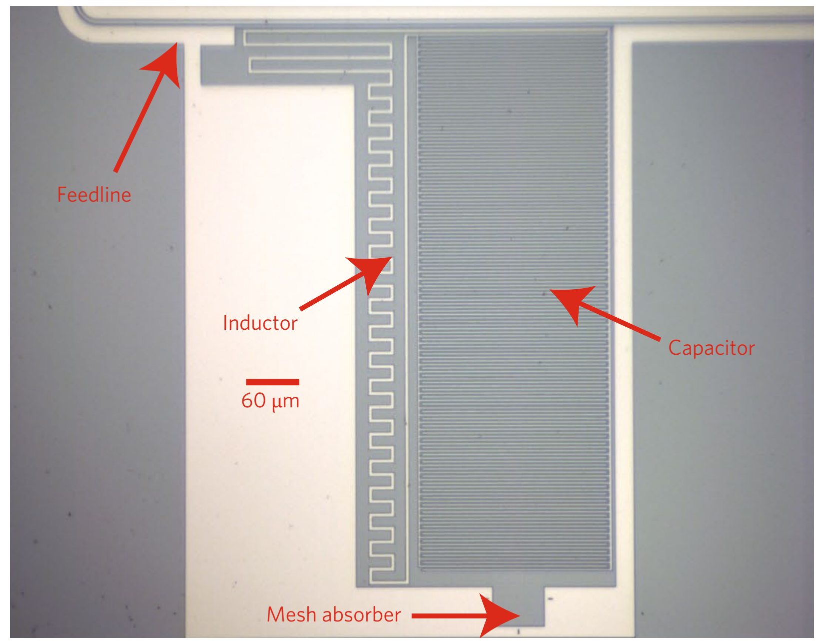
KID



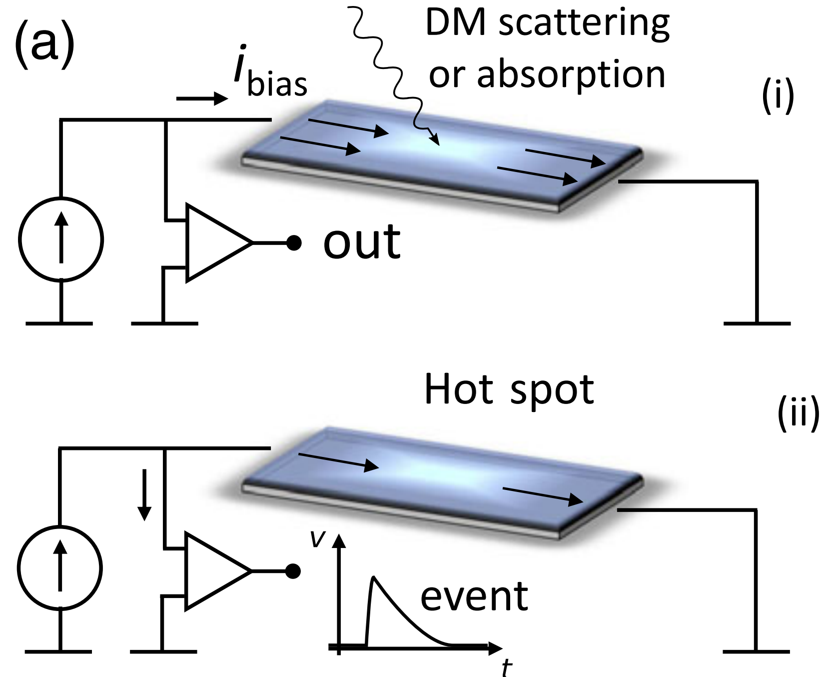


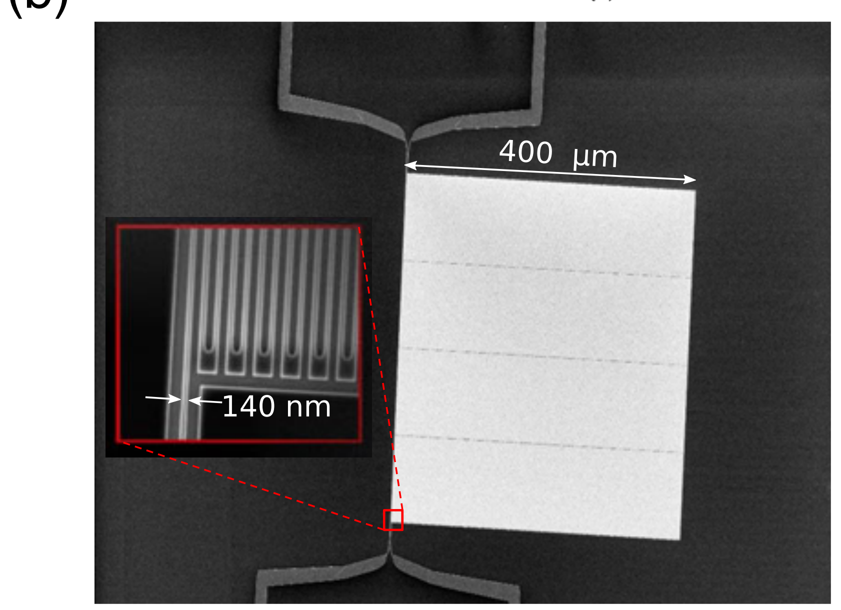


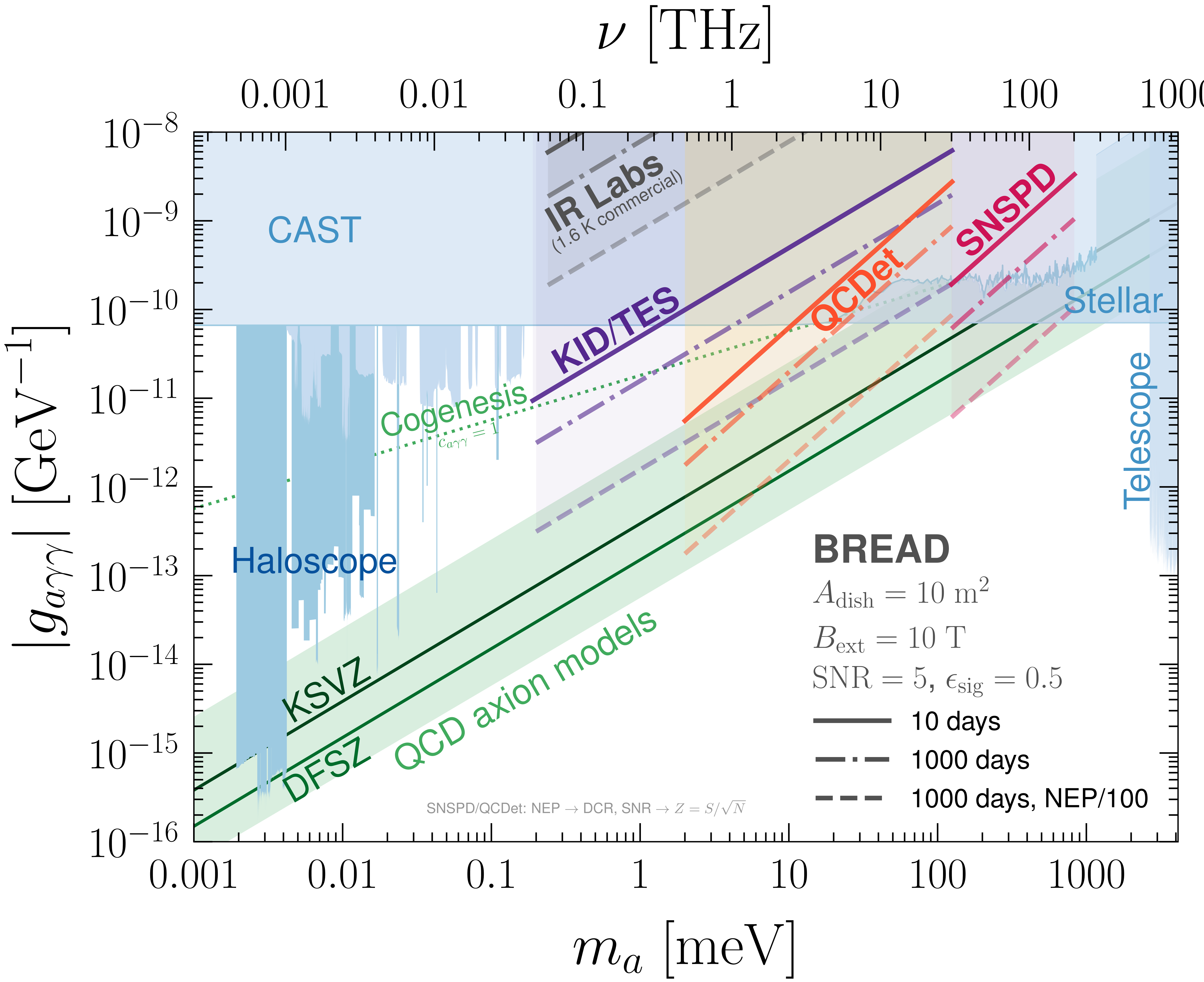
QCDet



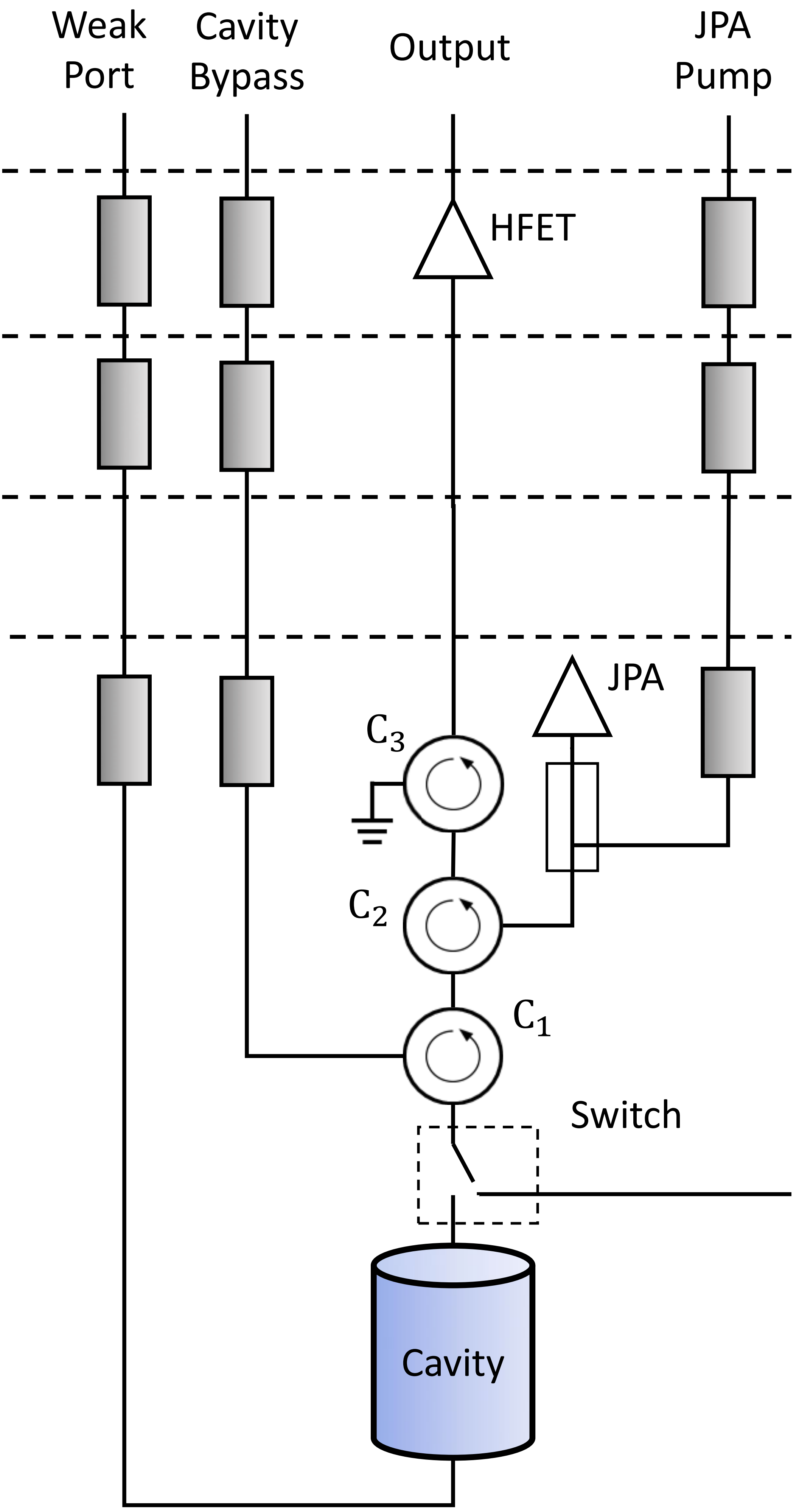
SNSPD

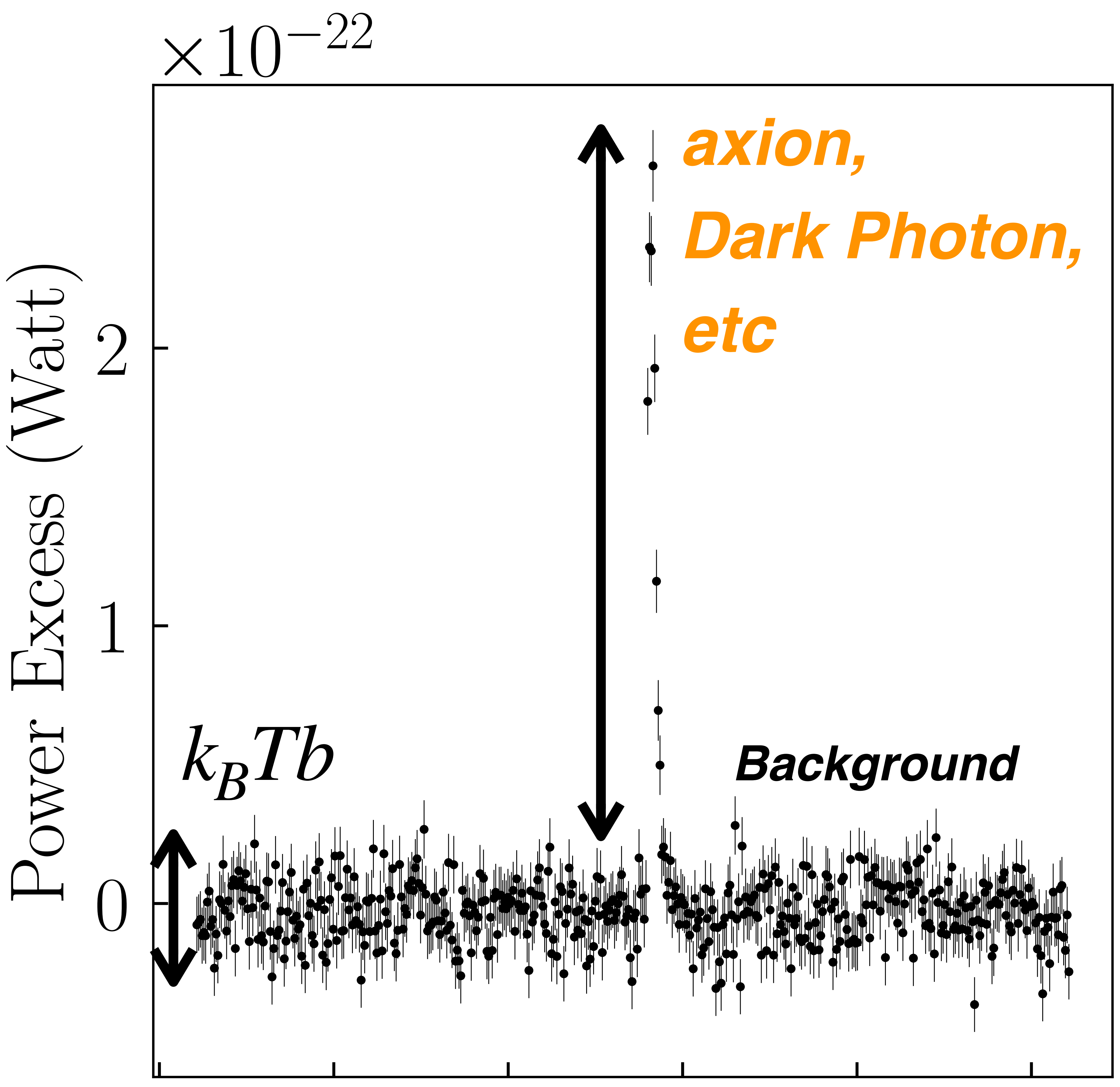






Important advantage about Single Photon Counting





ADMX etc ~ Relative power detector
→ Can't detect any broadband signals
(Basically)

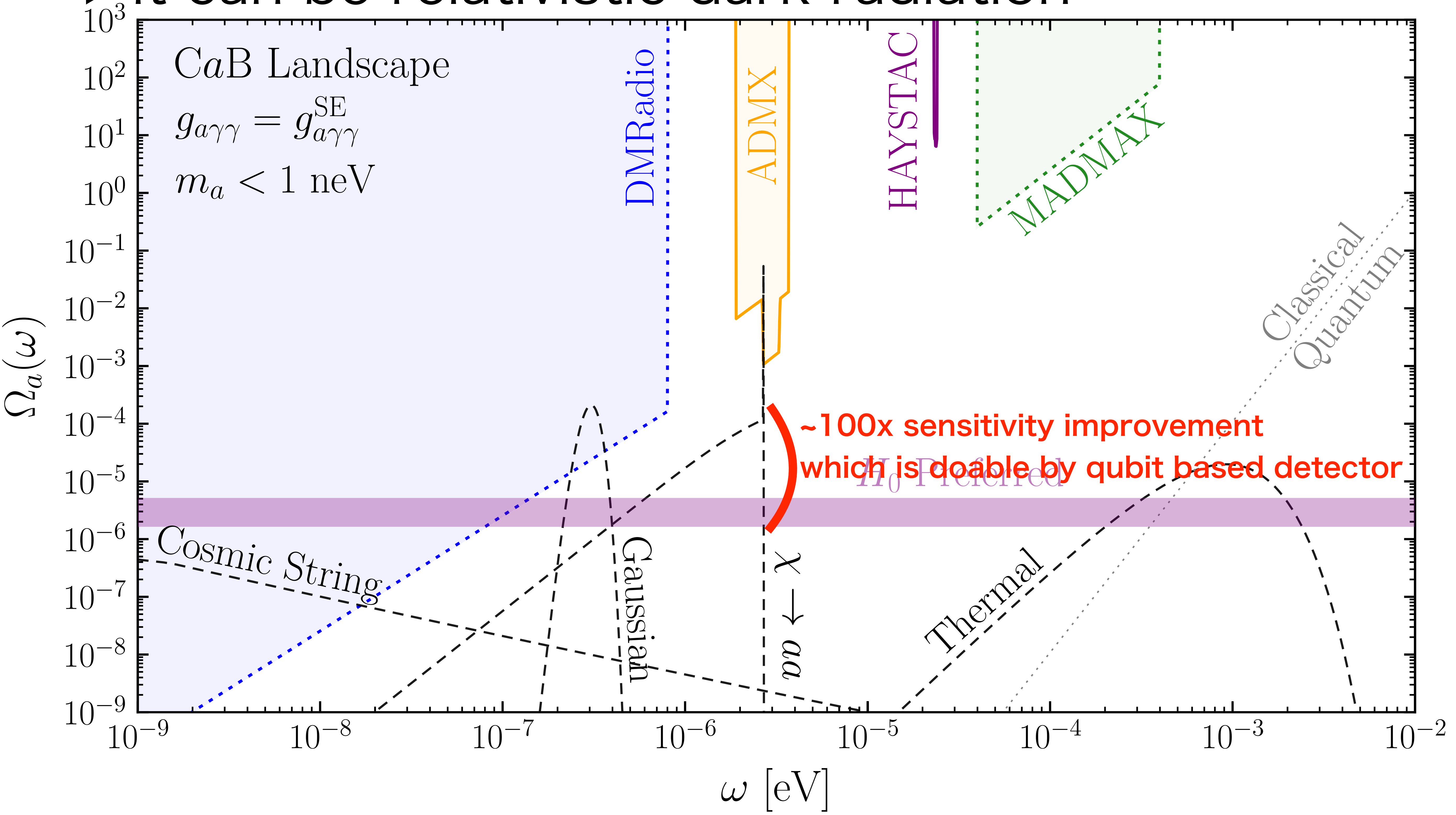
Single Photon Detector
~ Absolute Power Detector
→ Sensitive to broadband signals

Then what physics makes broadband signals?

Broadband signals

Cosmic axion background (CaB) Phys. Rev. D 103, 115004

Axion does not necessary to be DM (nonrelativistic)
-> it can be relativistic dark radiation

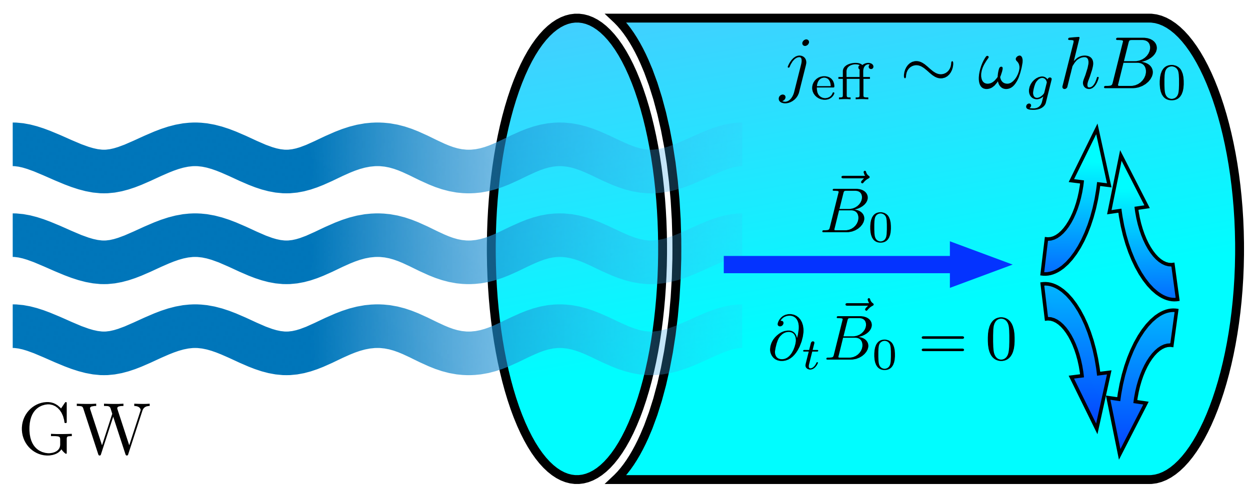


~100x sensitivity improvement
which is doable by qubit based detector

arXiv:2112.11465v1

High Frequency Gravitational Wave (~GHz)

PBH merger or
PBH superradiance
may makes GHz GW

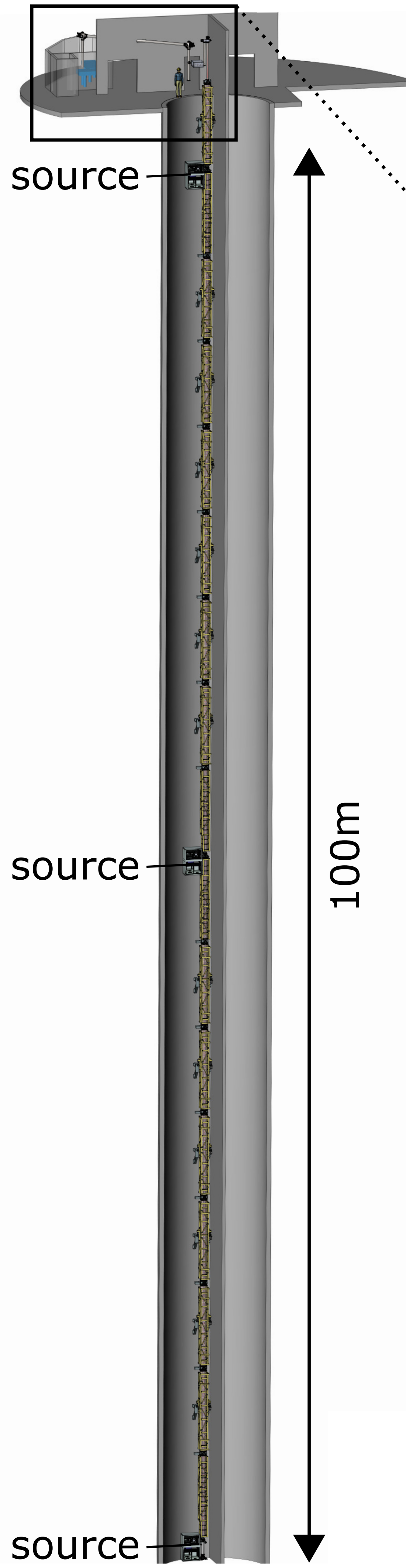


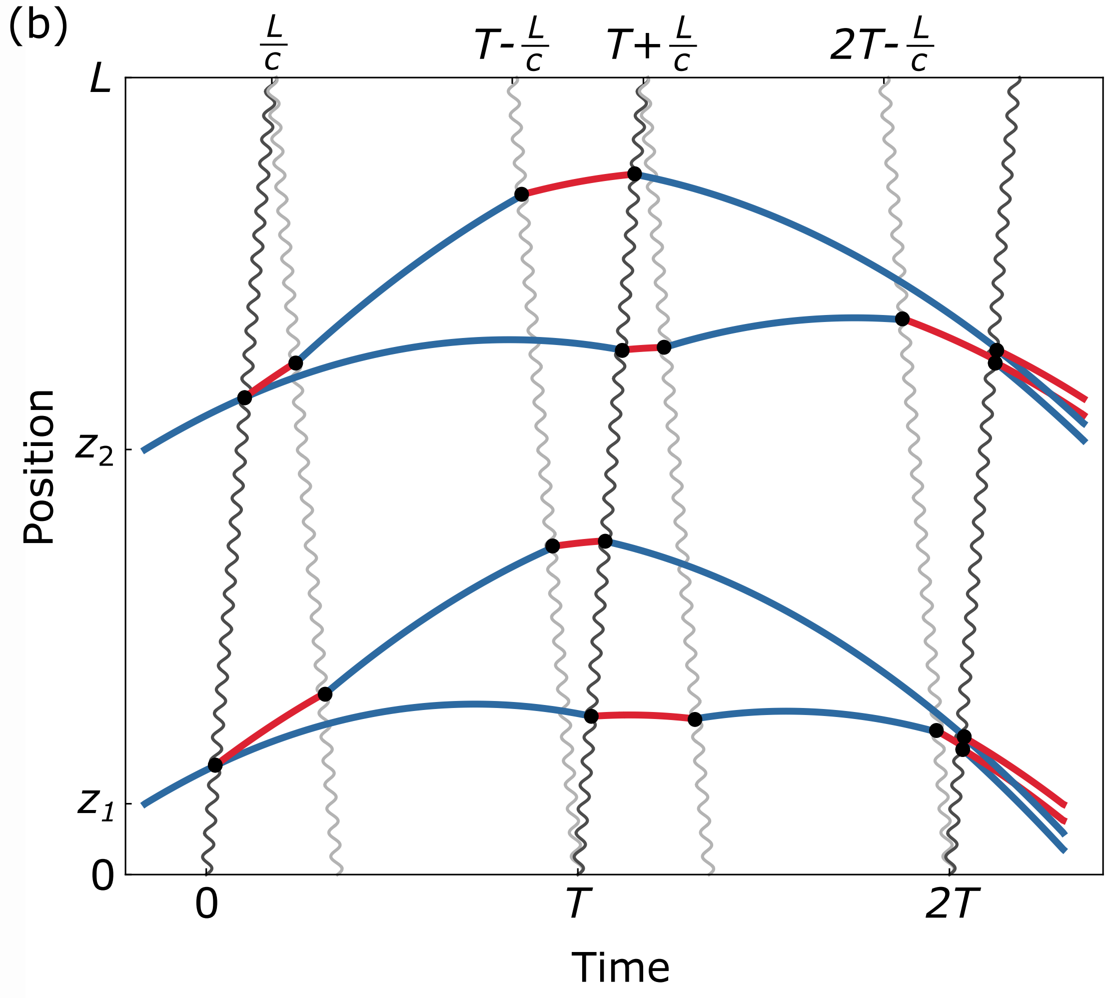
It can reach $h \sim 10^{-22}$

Quantum sensing enable us to search new physics we’ve never searched

Atomic Interferometer

MAGIS-100 (USA)
AION (UK)
MIGA (France)
ZAIGA (China)

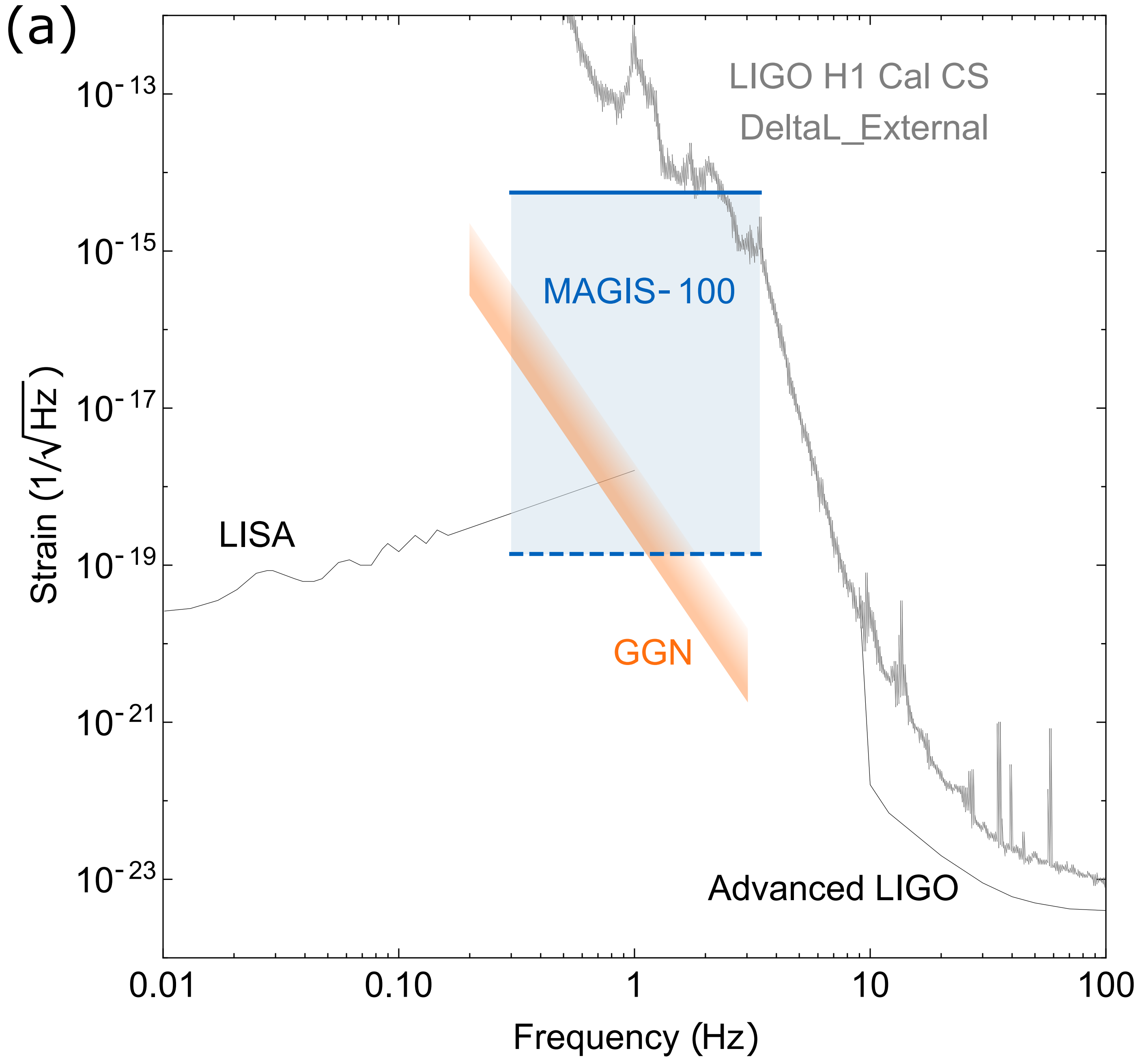




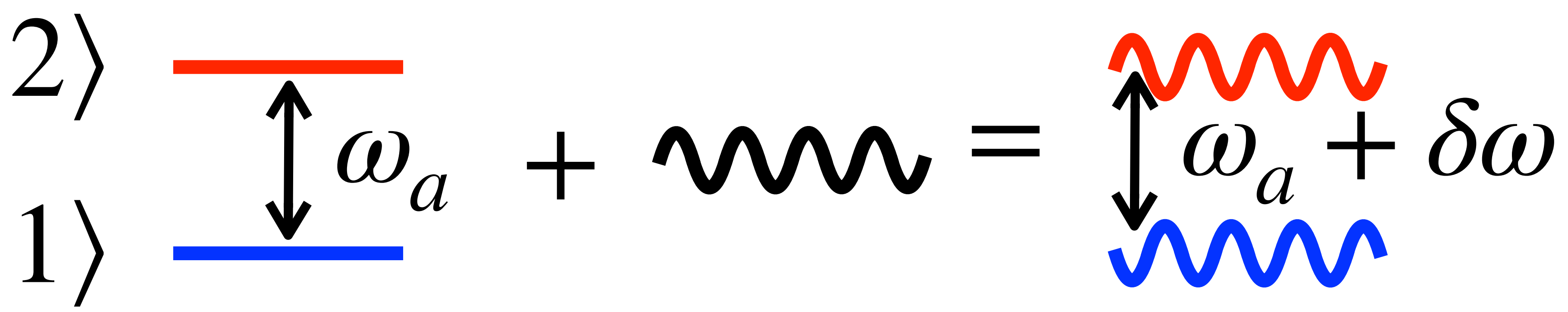
GW search

phase difference of two clocks sensitive to path

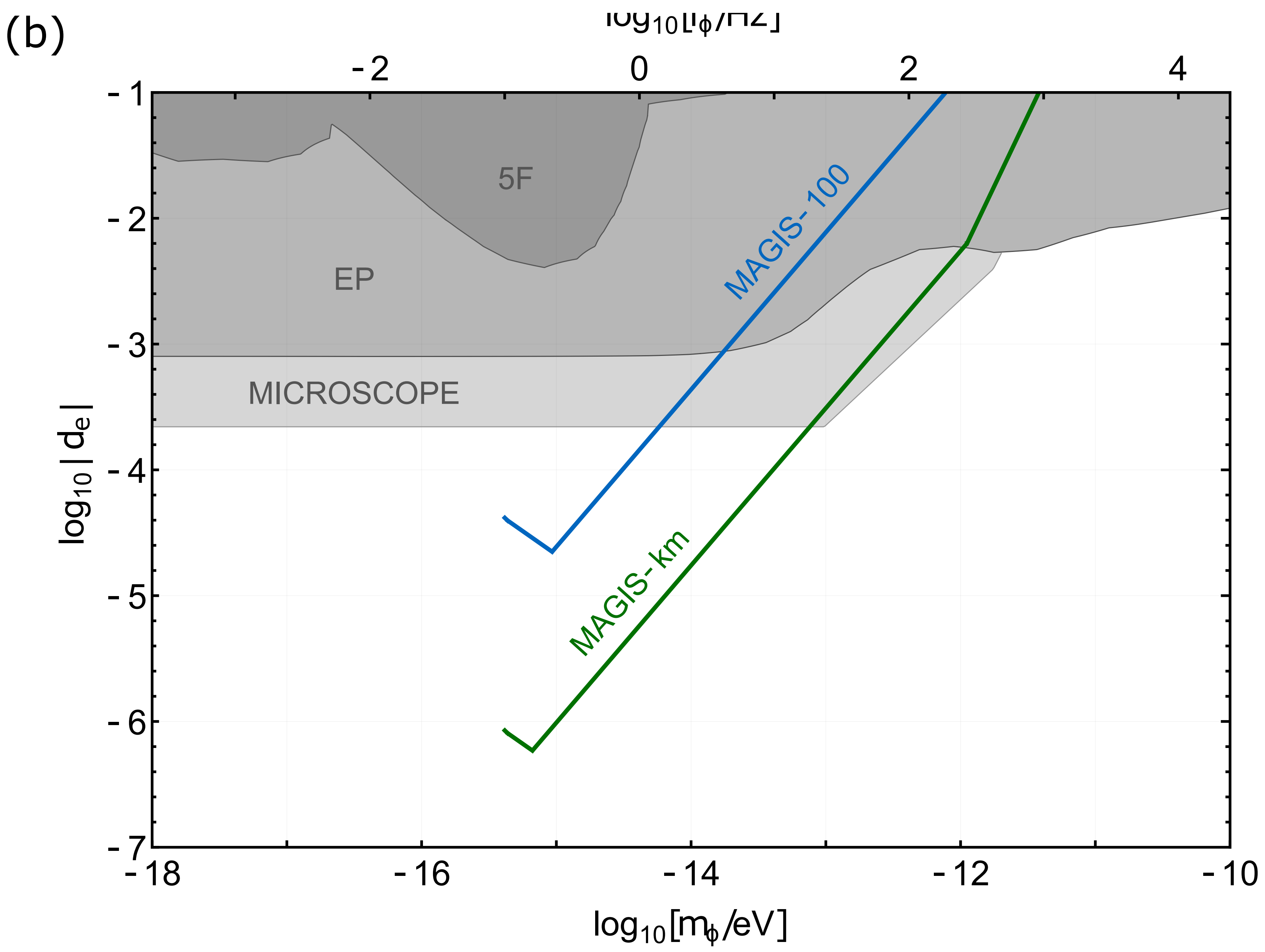
$$\phi \propto \omega_a L/c$$



wavelike DM search



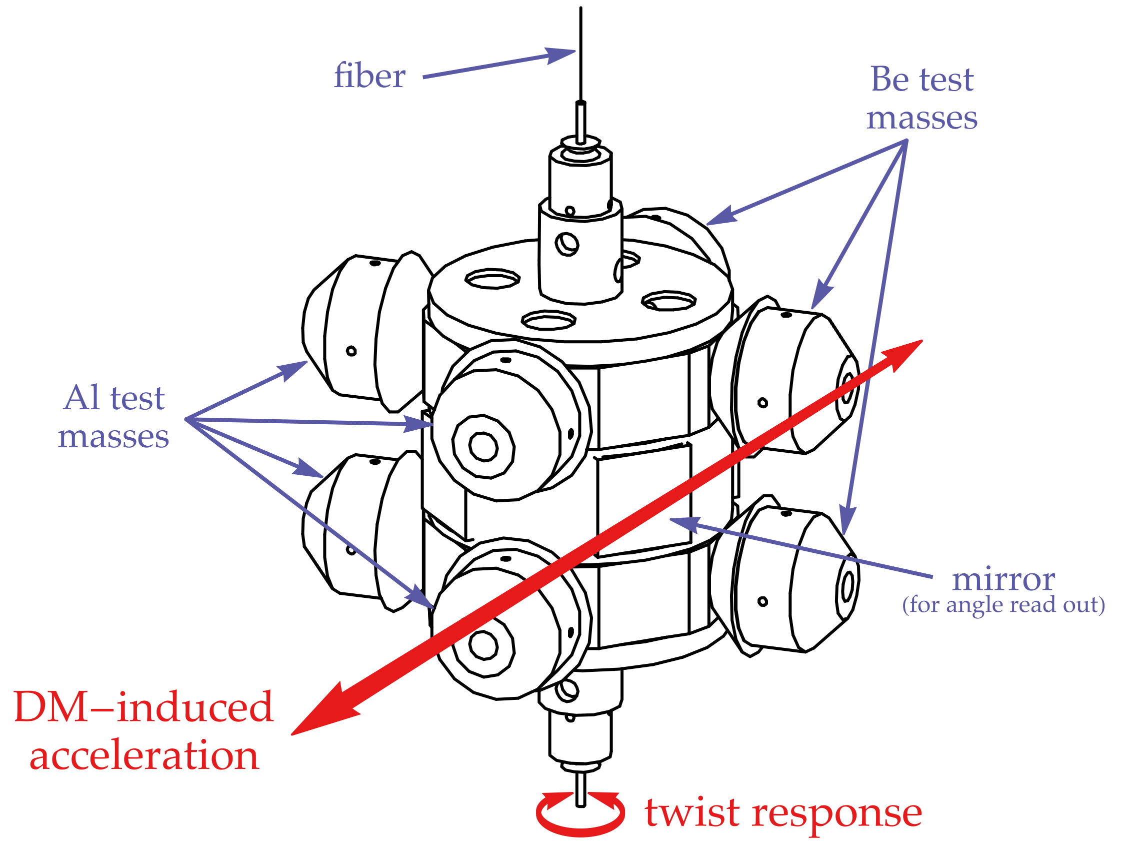
$$|2\rangle,\ |1\rangle \quad \omega_a \; + \; \sim\sim \; = \; \omega_a + \delta\omega$$



Accelerometers

Phys. Rev. D **93**, 075029 (2016)

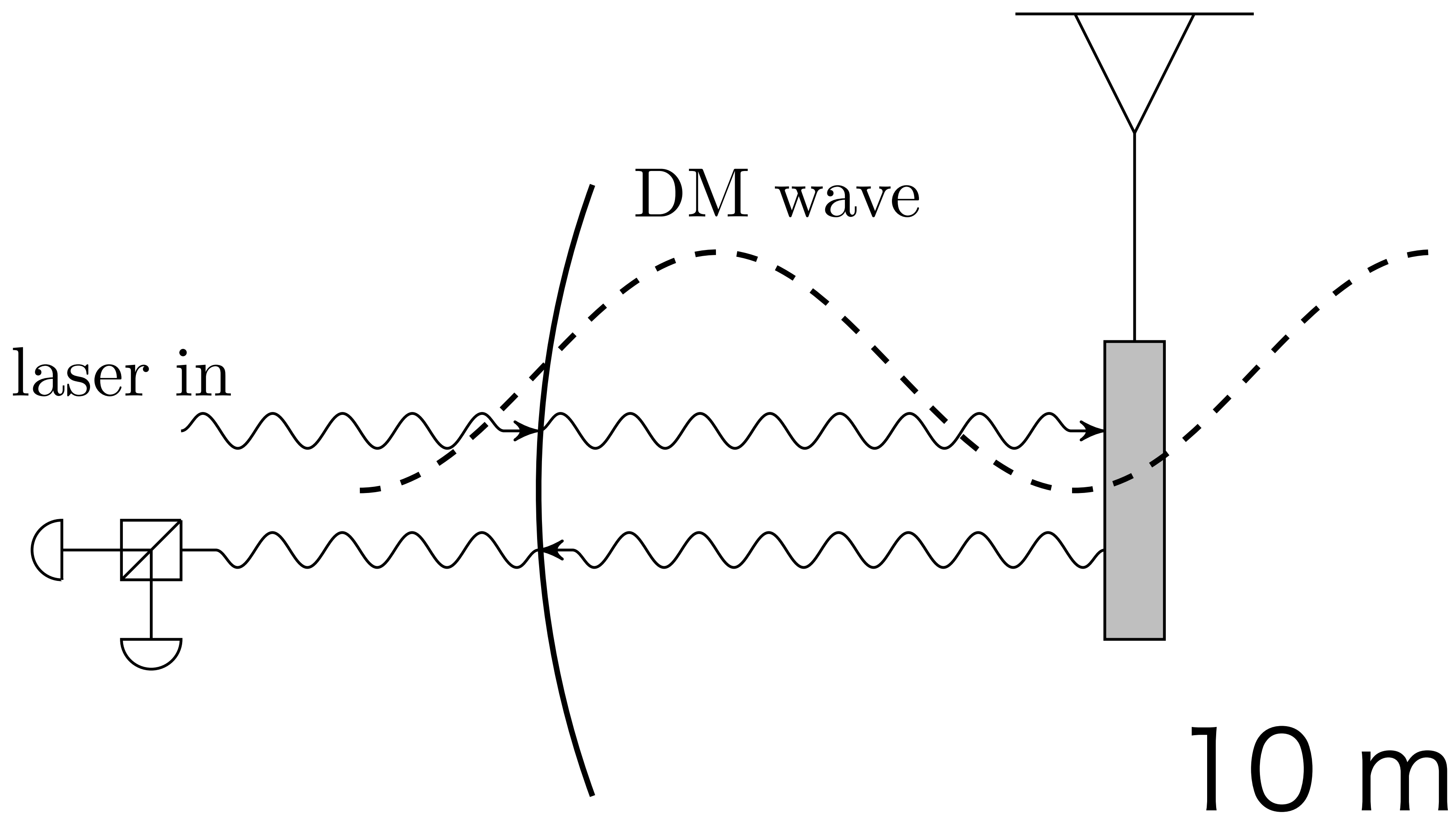
arXiv:1908.04797v2



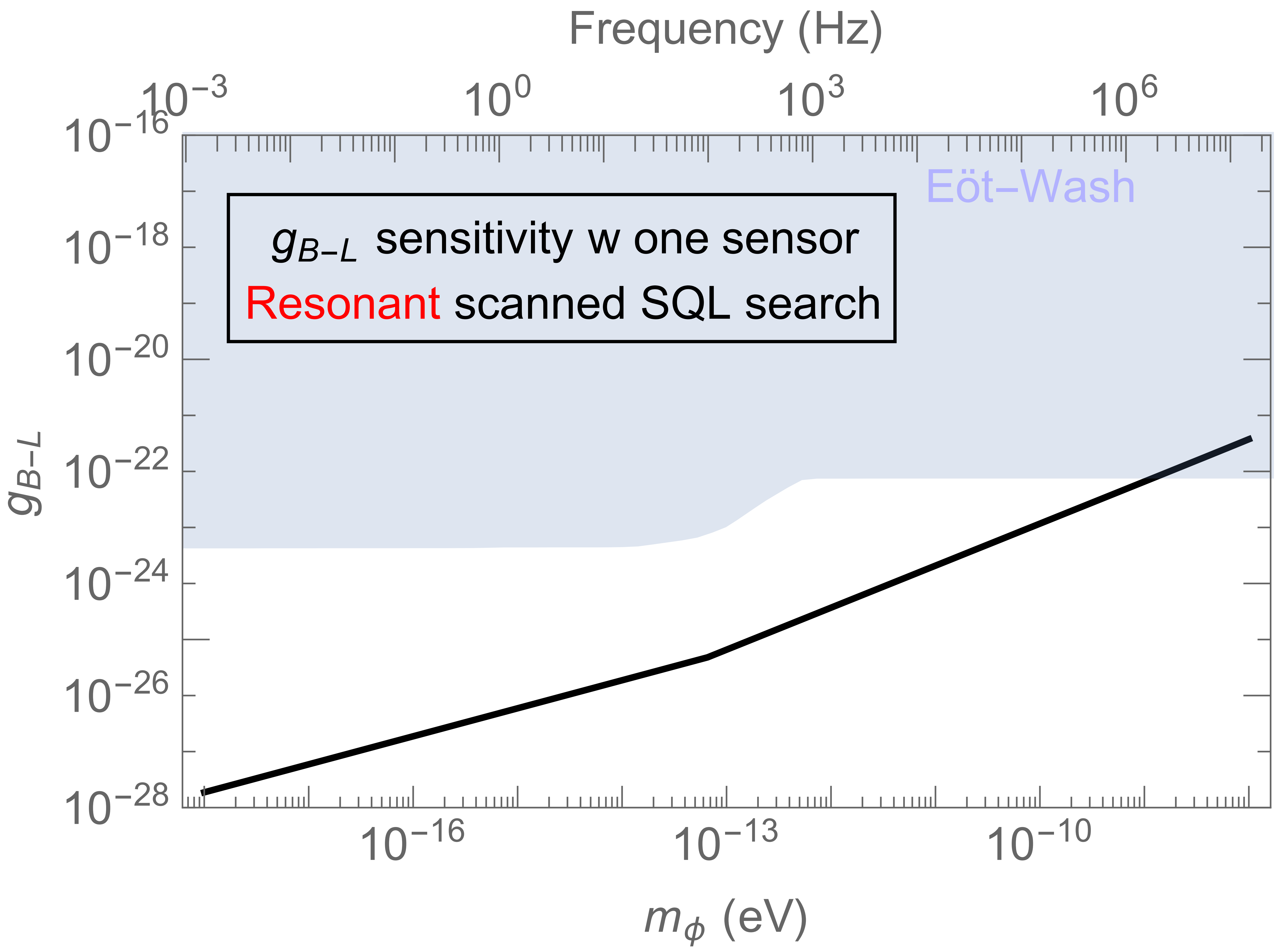
torsion balance
(Eöt-Wash)

Can detect force produced by wavelike DM

10^{-38} N/neutron



10 mK

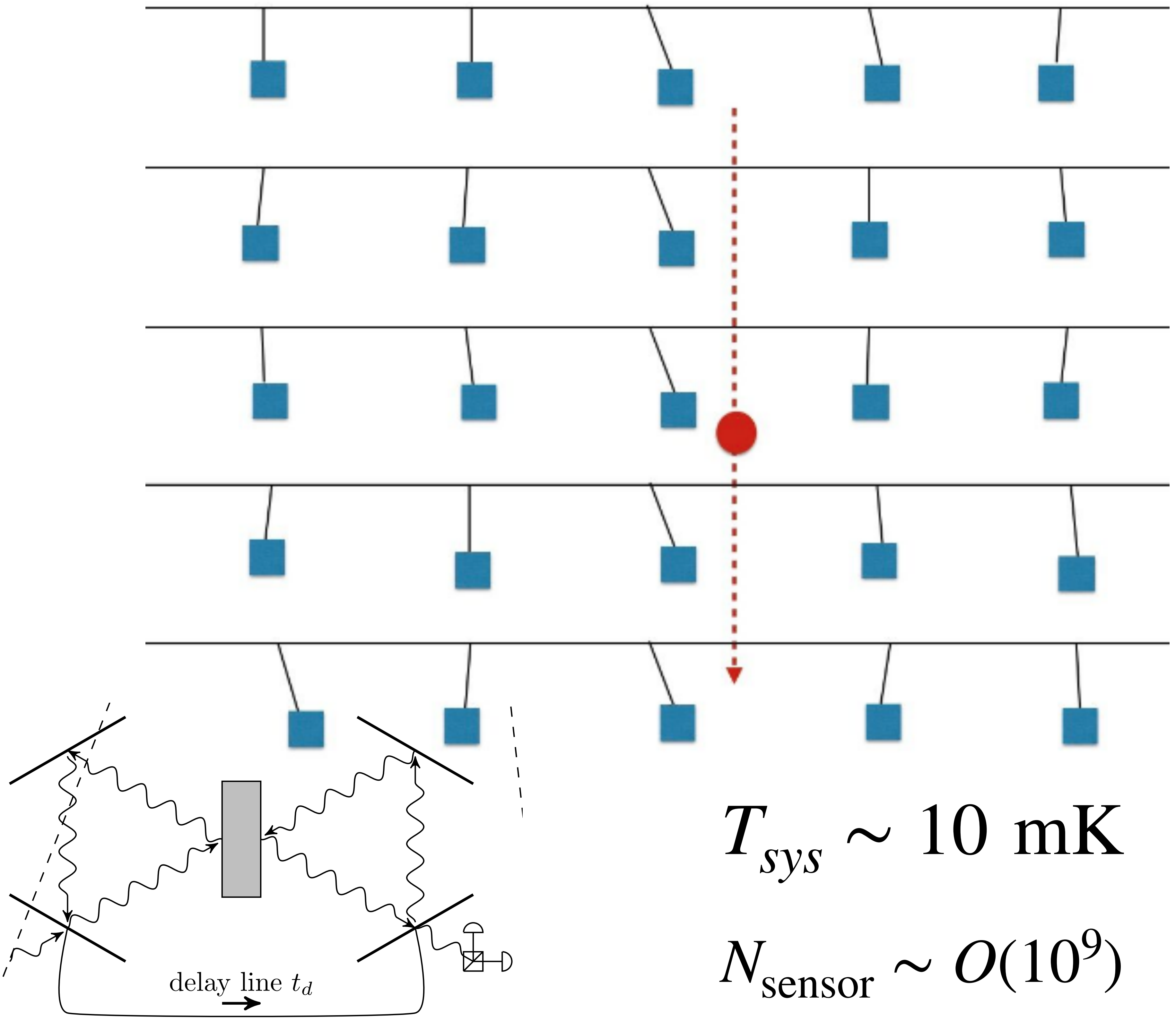


better sensitivity to dark matter having B-L interaction

Wind chime

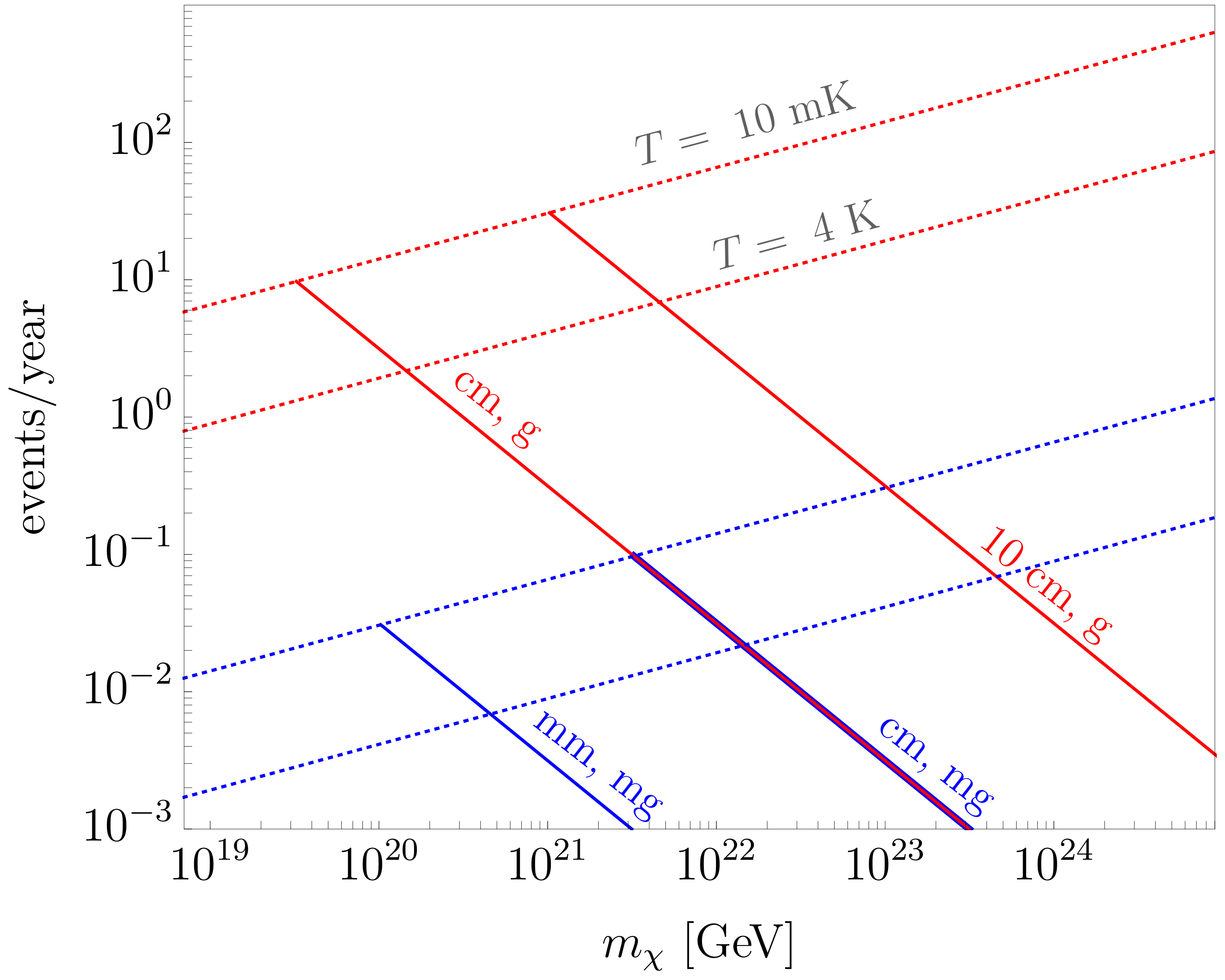
Phys. Rev. D **102**, 072003

Search for Planck scale DM with gravitational interaction → The most robust detection technique



$T_{sys} \sim 10$ mK

$N_{\text{sensor}} \sim O(10^9)$

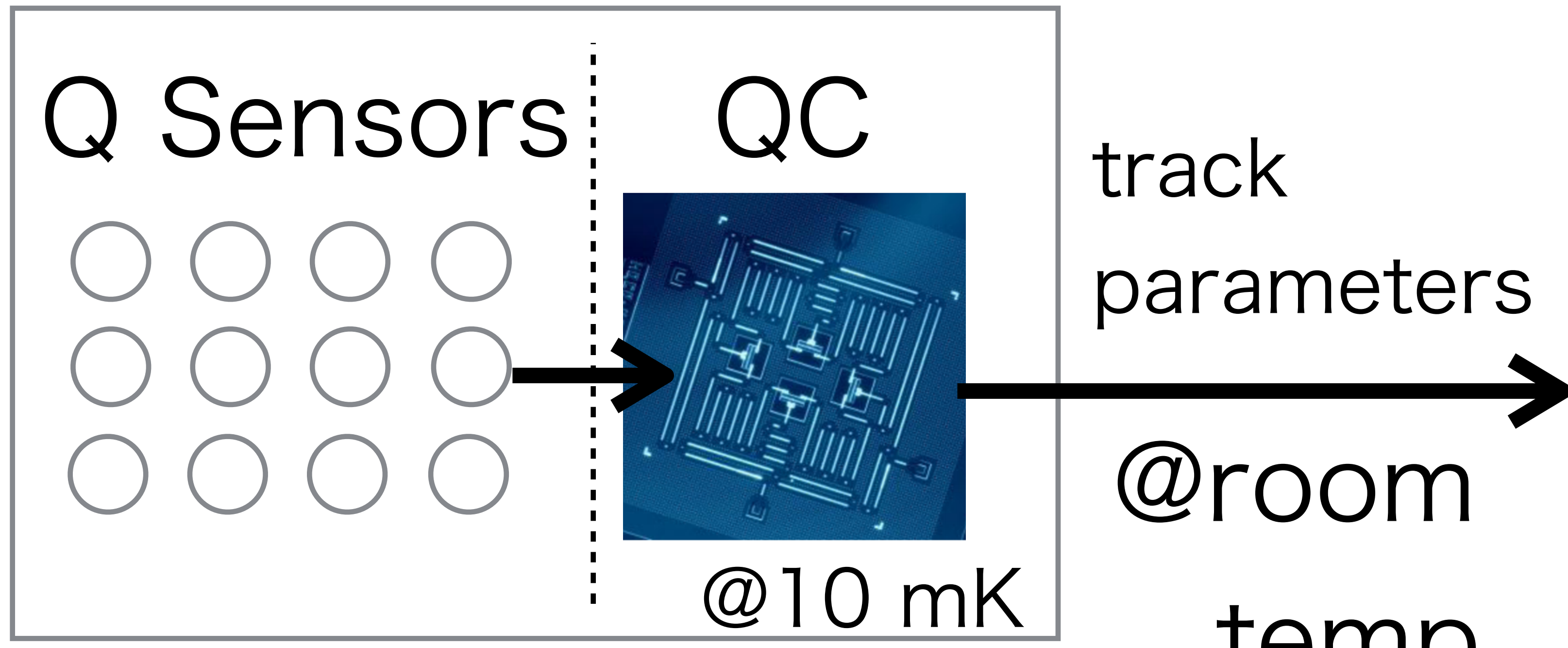


event rate ∝ $1/m_\chi$ due to number flux

Have to read out signals from dill fridge

#Channels ~ ATLAS pixel

maybe setup like



Q Sensors

QC

@10 mK

track parameters

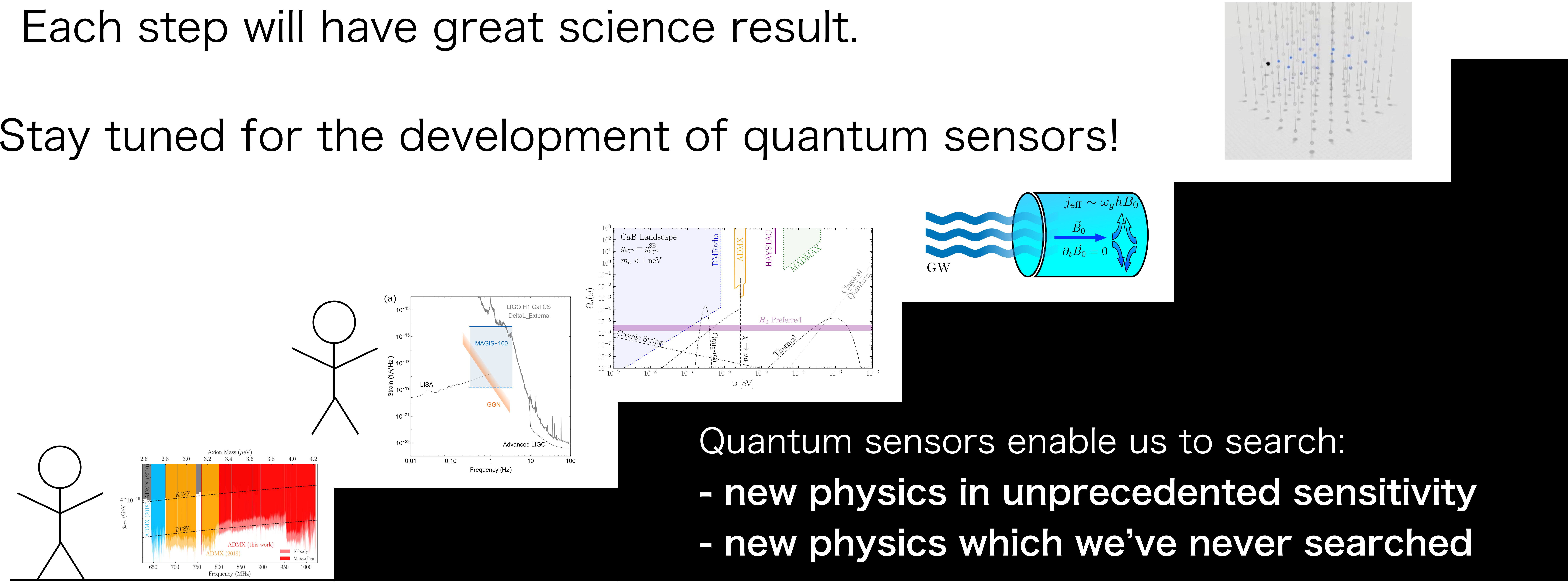
@room temp

Ultimate quantum detector!

Summary

Introduced some use-cases of quantum sensors:
- Classical to quantum sensing isn't jump but step-by-step.
- Each step will have great science result.

Stay tuned for the development of quantum sensors!



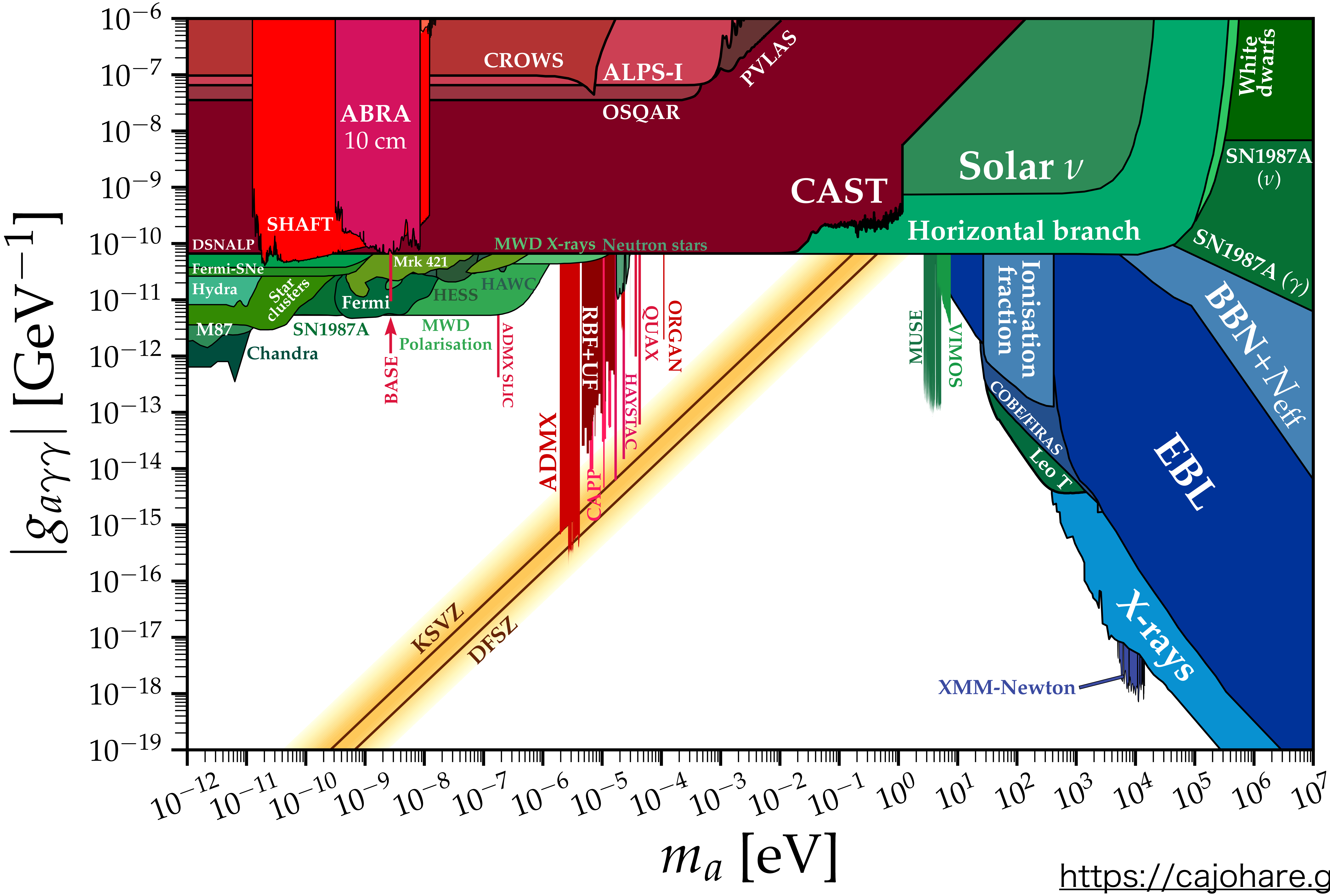
Quantum sensors enable us to search:

- new physics in unprecedented sensitivity

- new physics which we've never searched

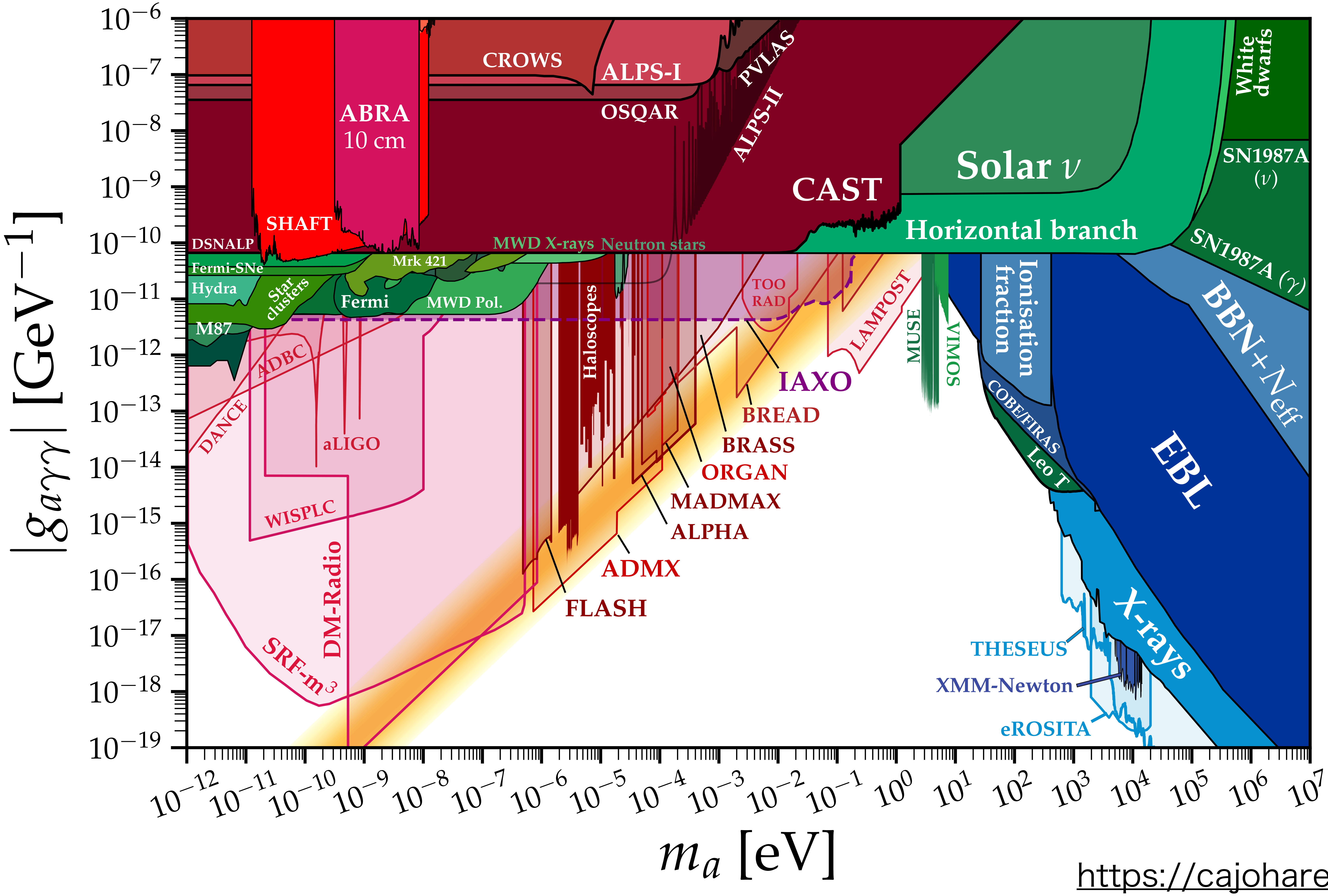
Backup

An example: Axion haloscope



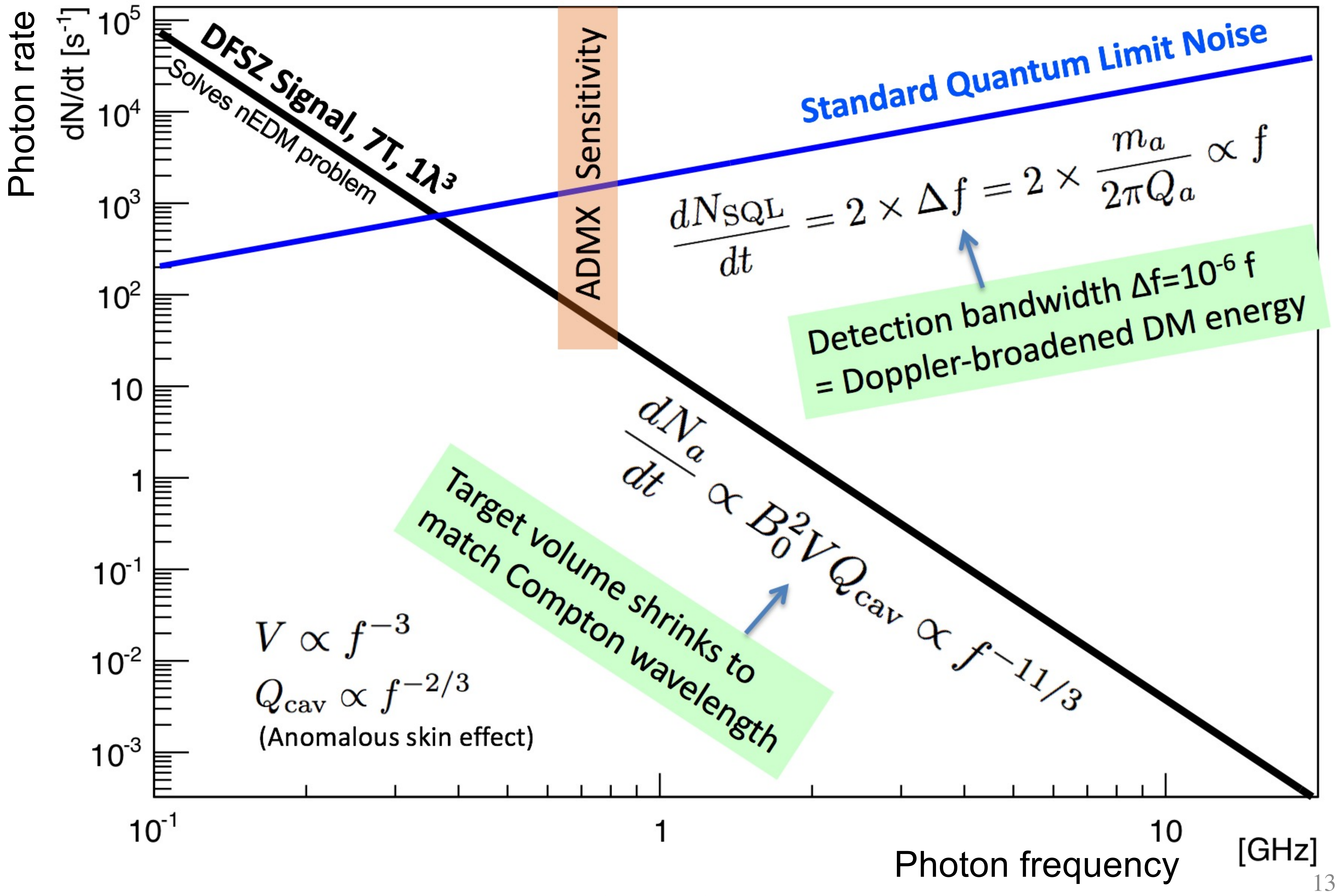
https://cajohare.github.io/AxionLimits/

An example: Axion haloscope



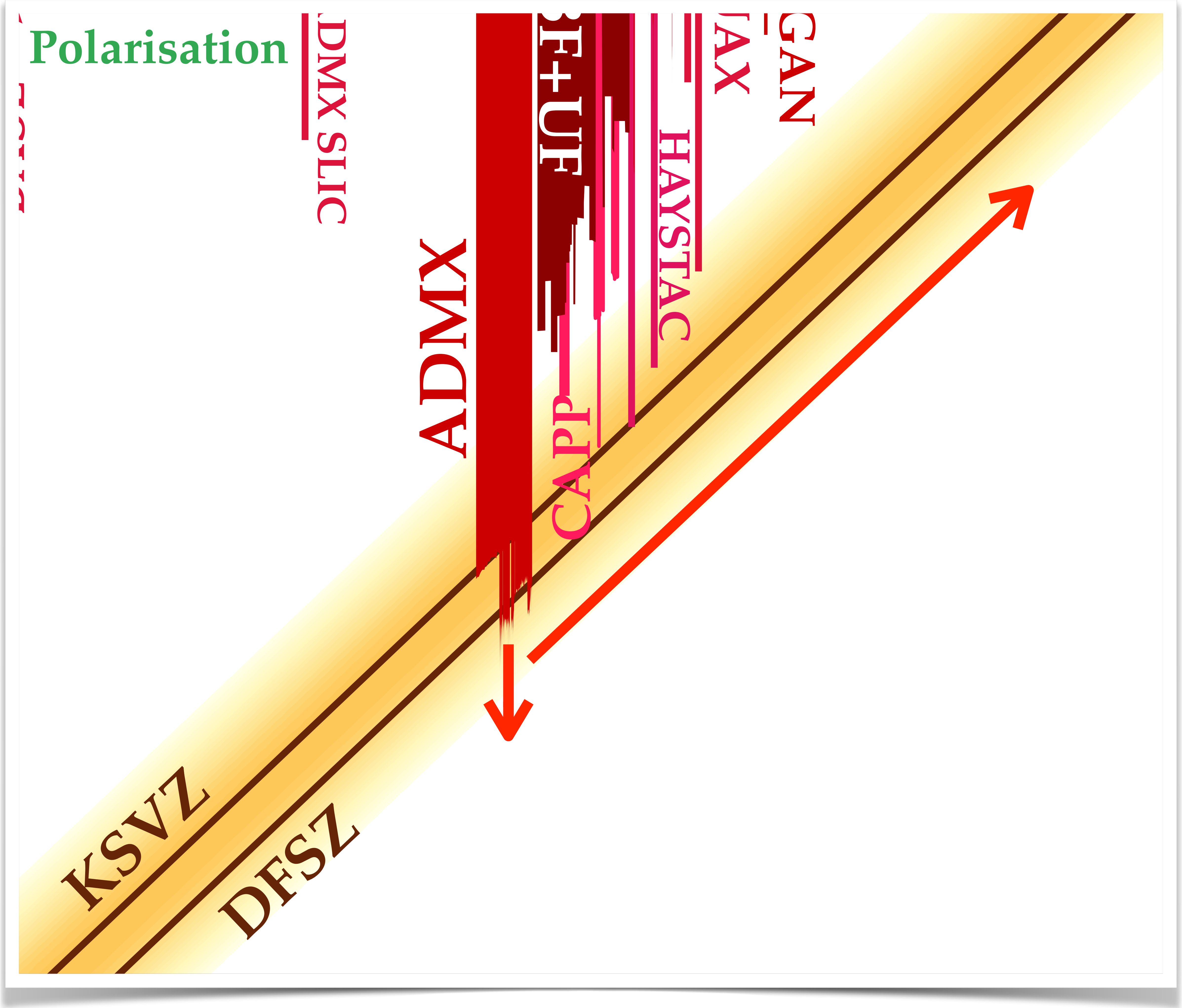
https://cajohare.github.io/AxionLimits/

Limitation



Aaron S. Chou, U.Tokyo workshop, March 9, 2022

Expected sensitivity



Already reported ~15 dB better than SQL for Dark Photon search (Phys. Rev. Lett. **126**, 141302)

This eventually enable to search

- axion dark matter even if it composes 3% of total dark matter
- or 5x smaller coupling than DFSZ
- or 1000x faster scan speed