Quantum-Limited Scan Strategies: Fundamental Limits on Axion and Hidden Photon Detection

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LTD-17
PE-24

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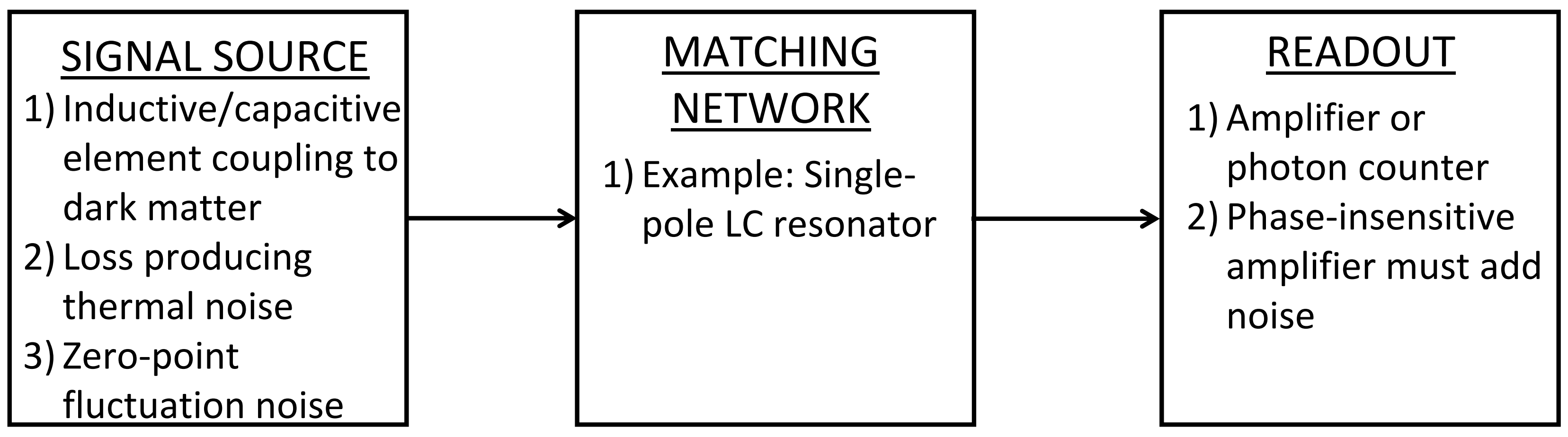
PREPRINT IN PREPARATION! Email schaudh2@stanford.edu for details and requests.

INTRODUCTION

- Axion and hidden photon: two promising candidates for cold dark matter
- Axion and hidden photon manifest as effective current density, produce detectable AC electromagnetic fields
- Frequency: $\nu_{DM} = mc^2/h$, Bandwidth: $\Delta\nu_{DM} \sim 10^{-6}\nu_{DM}$
- Three parts to dark matter detector (Fig. 1), e.g. scanning resonator (Fig. 2, 4a)
- If thermal noise dominates readout noise (Fig. 3), SNR independent of matching network- not considered previously
- ***What is optimal resonator? What is optimal scan strategy?***



SIGNAL SOURCE
1) Inductive/capacitive element coupling to dark matter
2) Loss producing thermal noise
3) Zero-point fluctuation noise

MATCHING NETWORK
1) Example: Single-pole LC resonator

READOUT
1) Amplifier or photon counter
2) Phase-insensitive amplifier must add noise

Fig. 1. Schematic of a light-field dark matter detector.

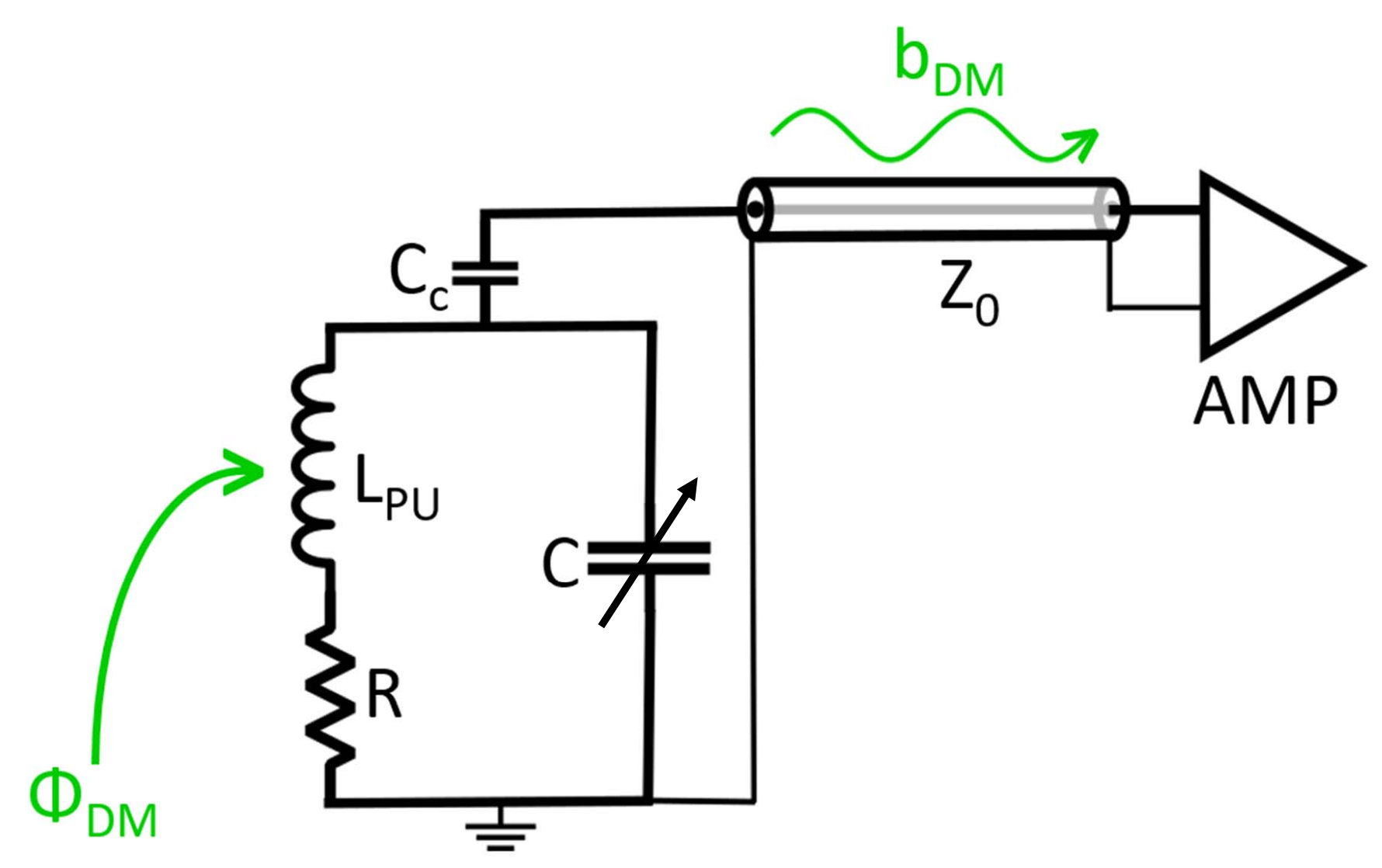


Fig. 2. Equivalent circuit model for resonant detector in scattering mode. Resonator tuned by changing capacitance. Used in ADMX/HAYSTAC.

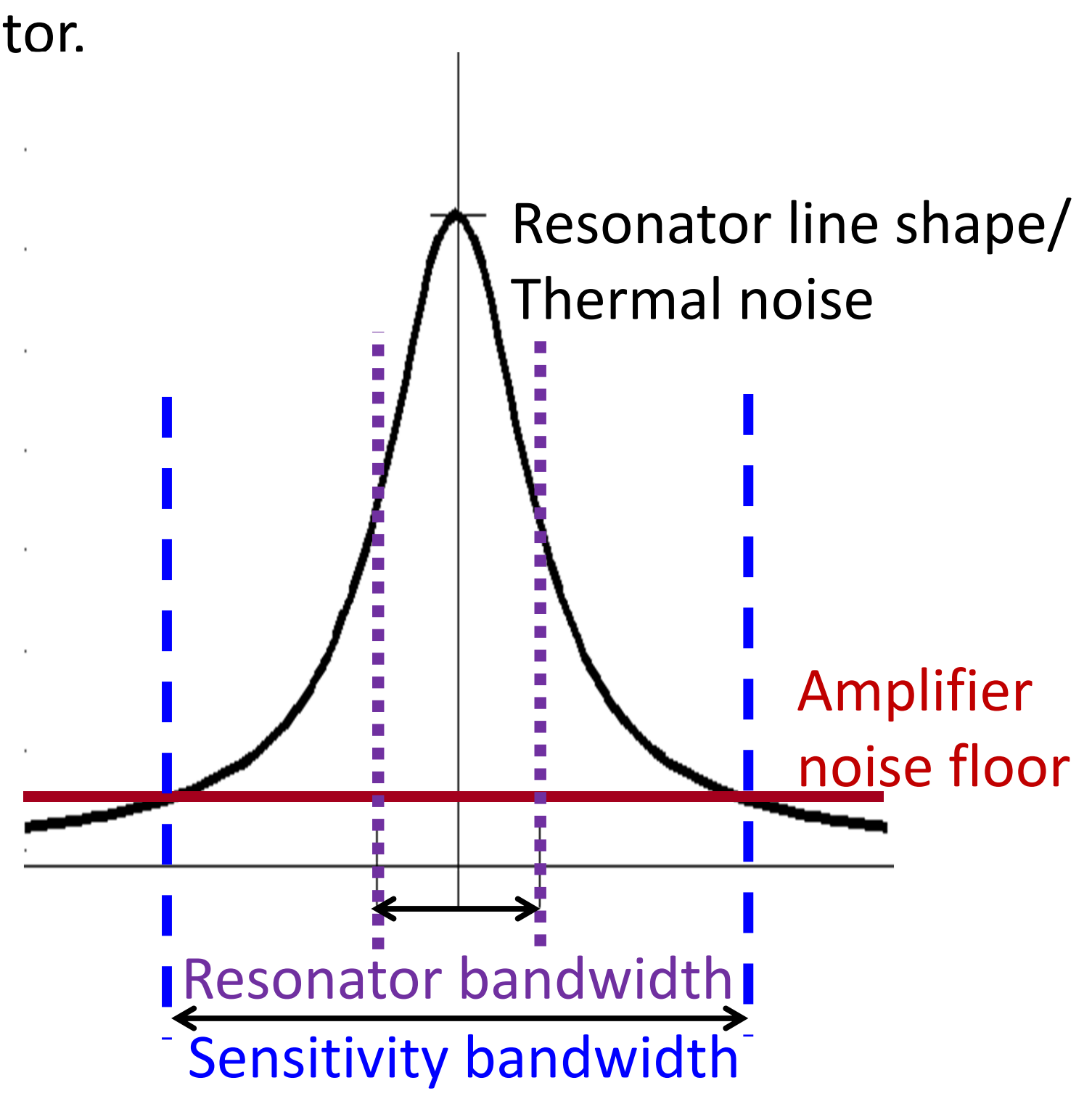


Fig. 3. Resonator output noise spectrum. Use all info over sensitivity bandwidth, rather than smaller resonator bandwidth.

EXAMPLE: RESONANT BETTER THAN BROADBAND LR

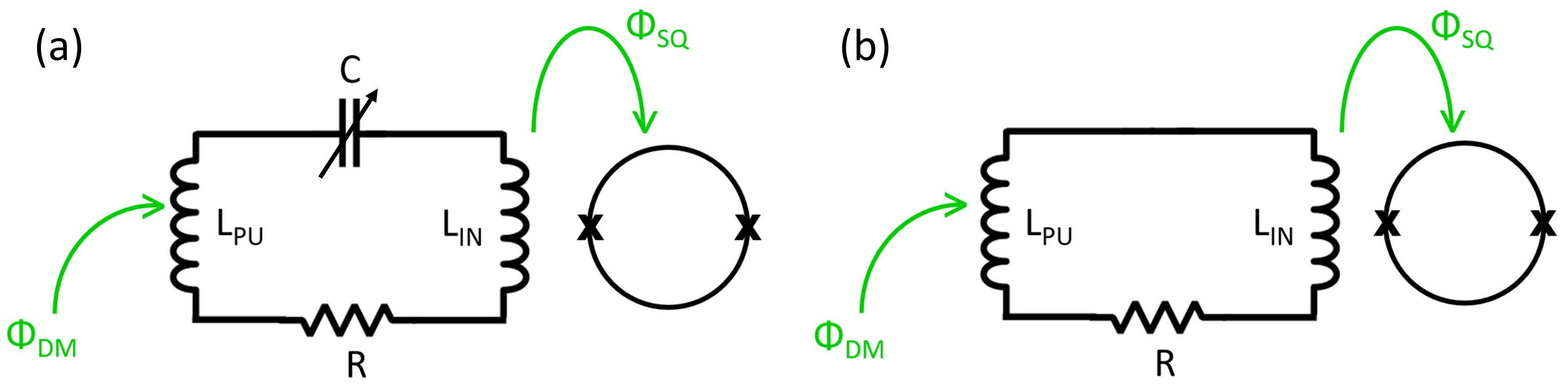


Fig. 4. **(a)** Resonant RLC input circuit read out by SQUID. **(b)** Broadband LR circuit.

- Kahn et al, PRL **117**, 141801 (2016) claim broadband better than Q= 10^6 for frequencies below ~100 kHz in presence of only imprecision noise
- Considered only info within resonator bandwidth
- ***Considering sensitivity bandwidth, resonant is much better than broadband at all frequencies at which a resonator can practically be made***

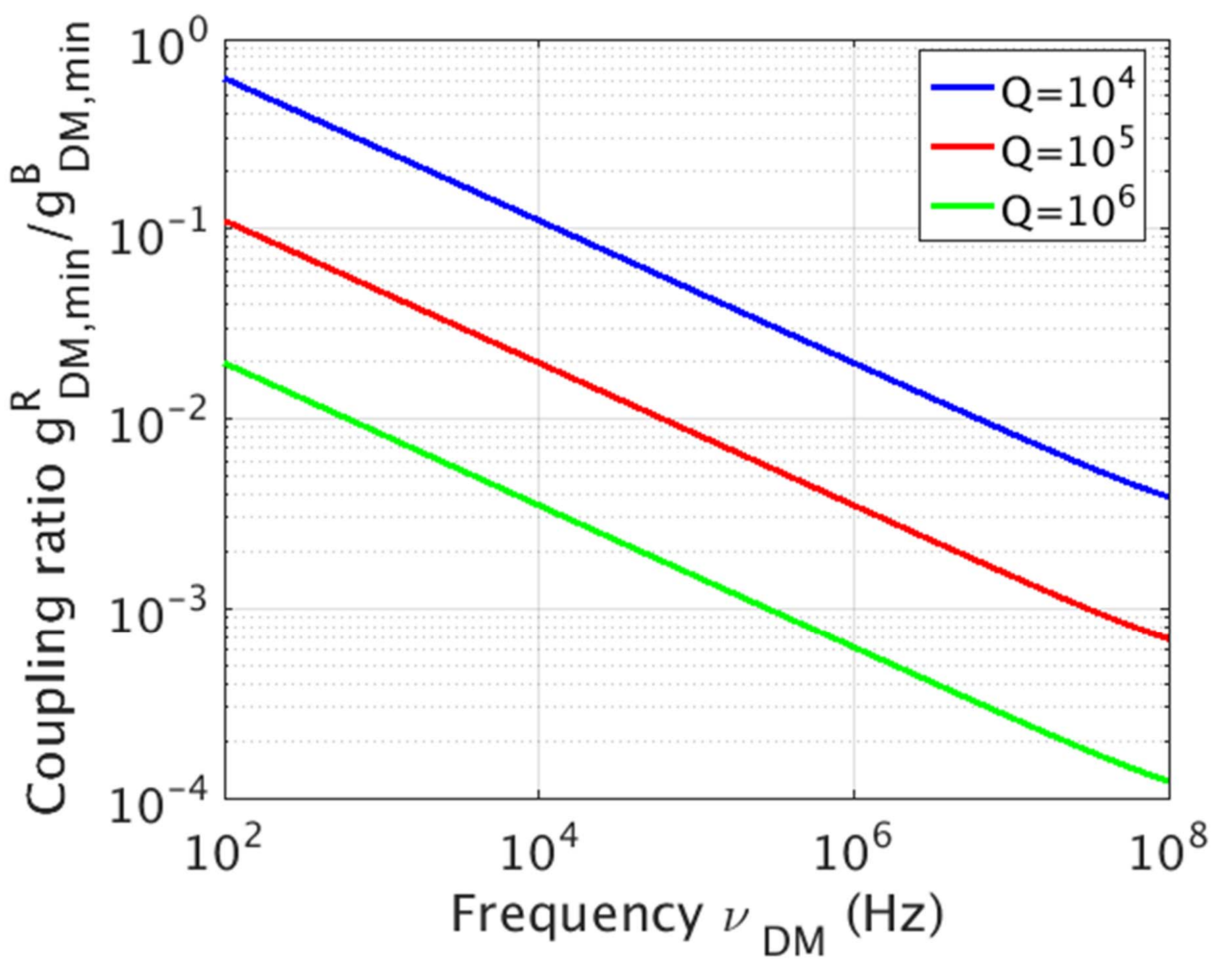


Fig. 5. Ratio of minimum detectable coupling for resonant (R) and broadband (B) plotted vs rest mass frequency.

WHY A RESONATOR? CLOSE TO BODE-FANO LIMIT

- Maximize integrated sensitivity across search band, between ν_l and ν_h
- Figure of merit for scattering system with quantum-limited amplifier:

$$U = \int_{\nu_l}^{\nu_h} d\nu \left(\frac{|S_{21}(\nu)|^2}{|S_{21}(\nu)|^2 n(\nu) + 1}\right)^2$$

$n(\nu)$= cavity thermal occupation number, “1” is standard quantum limit

- Constraint provided by Bode-Fano criterion for matching LR to real impedance:

$$\int_{\nu_l}^{\nu_h} d\nu \, ln\left(\frac{1}{|S_{22}(\nu)|}\right) \le \frac{R}{2L_{PU}} \quad \Rightarrow \quad U \le \begin{cases} \frac{1}{4n(\nu_h)}\frac{R}{L_{PU}}, & n(\nu_h) \gg 1 \\ 0.41\frac{R}{L_{PU}}, & n(\nu_h) \ll 1 \end{cases}$$

- ***Optimal resonator is within ~75% of fundamental limit!***

OPTIMIZING RESONATOR SENSITIVITY: QUANTUM-LIMITED AND BACKACTION-DOMINATED

- Optimize resonator at frequency ν_r with respect to coupling factor

$$\gamma \equiv \frac{Q_{int}}{Q_{cpl}} = \frac{Amplifier\ Noise\ Impedance}{Resonator\ Impedance}$$

- Optimal ratio for maximizing U

$$\gamma_{opt}[n(\nu_r)] = \frac{1}{2}\left(2n(\nu_r) + 1 + \sqrt{(2n(\nu_r)+1)^2 + 8}\right) \approx \begin{cases} 2n(\nu_r) + 1, & n(\nu_r) \gg 1 \\ 2, & n(\nu_r) \ll 1 \end{cases}$$

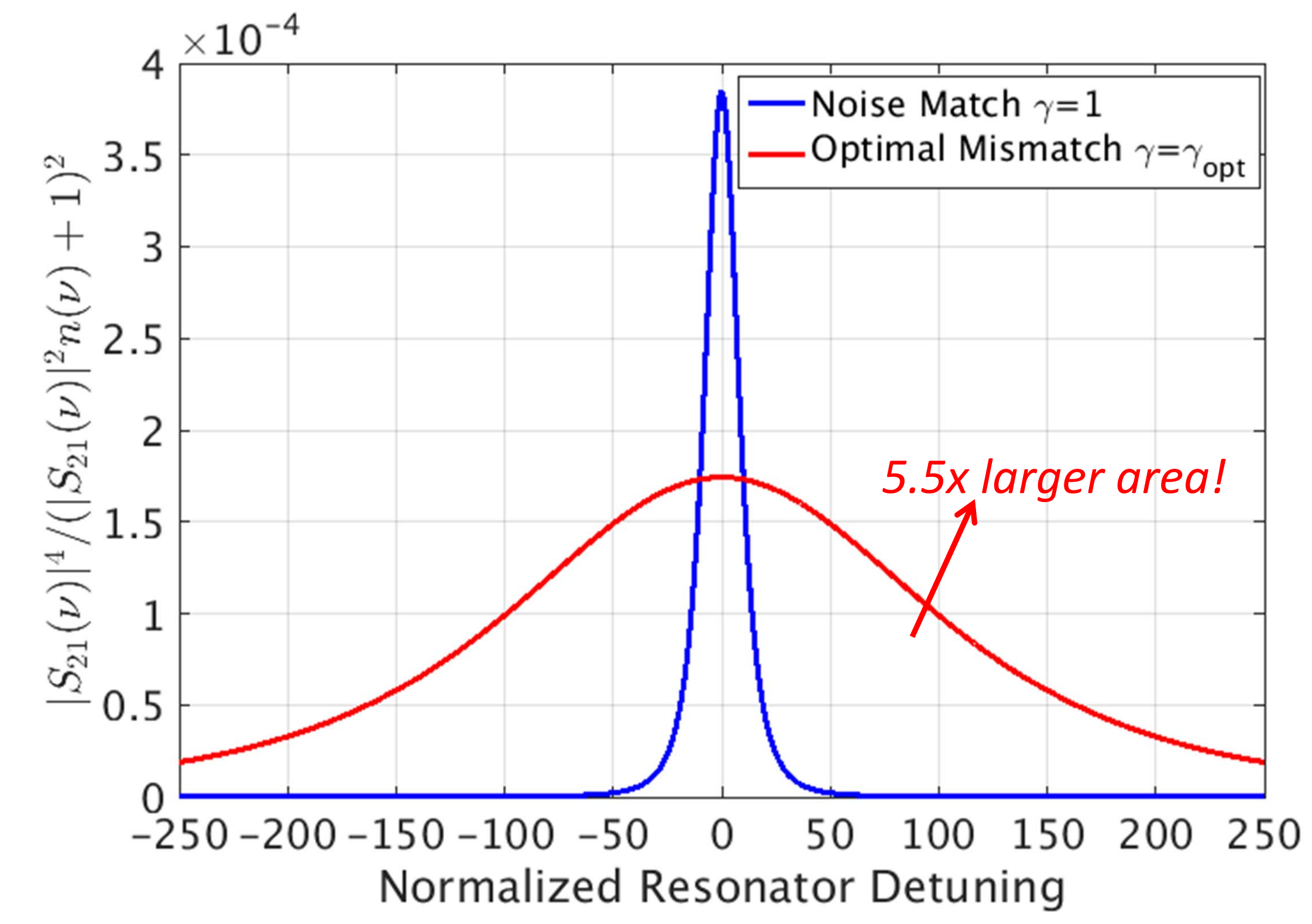


Fig. 6. Integrand of U plotted for noise matching and optimal mismatching for $n(\nu_r)$= 50.

- Same optimization result for quantum-limited SQUID amplifier
- Imprecision and backaction noise inversely proportional on-resonance

$$S^{ref}_{II,imp} = \frac{h\nu_r}{R}\gamma \qquad S^{ref}_{II,back} = \frac{h\nu_r}{R}\frac{1}{\gamma}$$

- Gives tradeoff between on-resonance SNR and sensitivity bandwidth
- ***In optimal resonator readout, amplifier noise is dominated by backaction.***

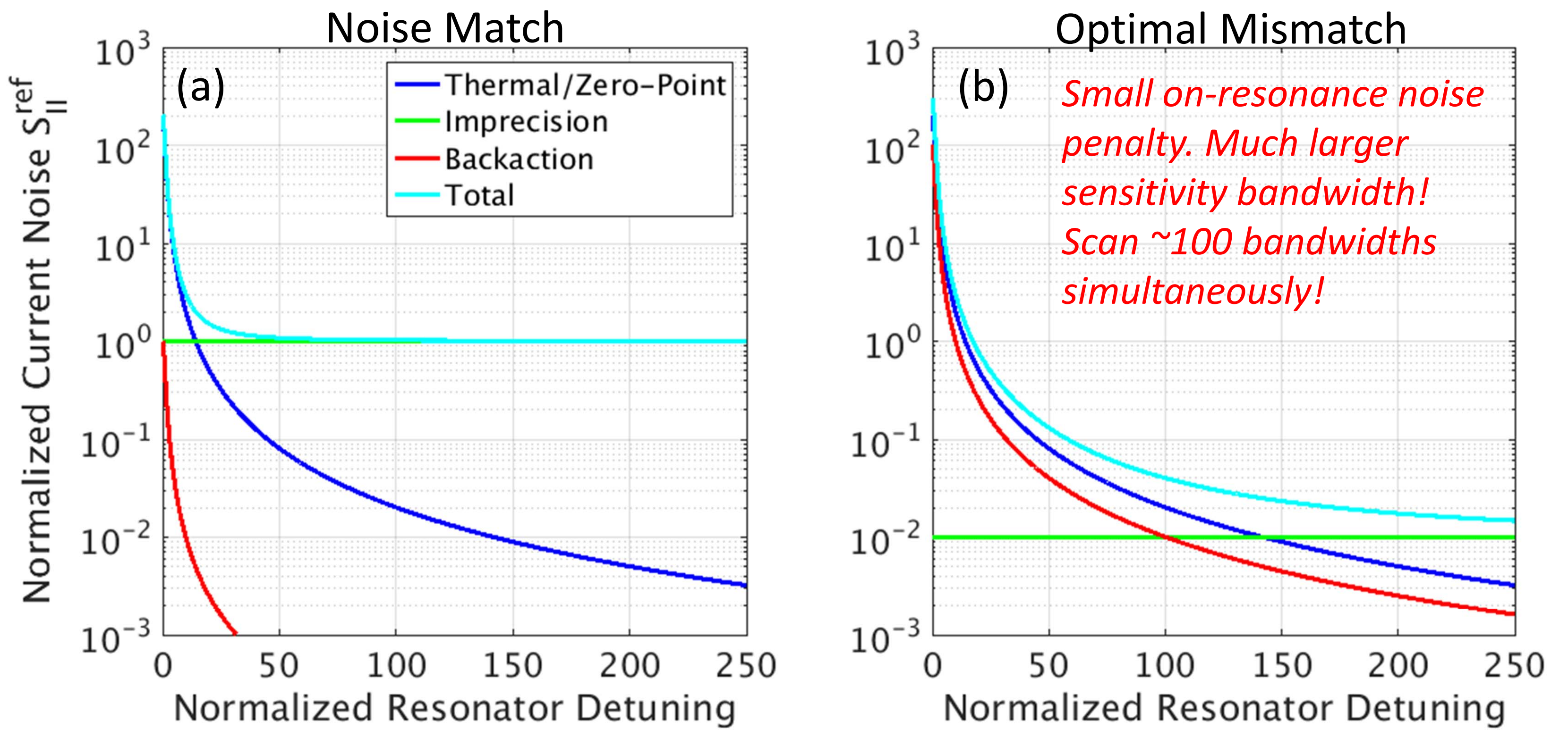


Fig. 7. Current noise normalized to $h\nu_r/R$ vs resonator detuning normalized to resonator half width . Thermal occupation $n(\nu_r)$= 50. **(a)** Noise match. **(b)** Optimal mismatch.

IMPROVED SCIENCE REACH WITH OPTIMAL SCAN

- Optimal time distribution is equal time per decade, maximizes exclusion area
- ***Should aim for as high Q as possible, even above “dark matter Q”=10^6***

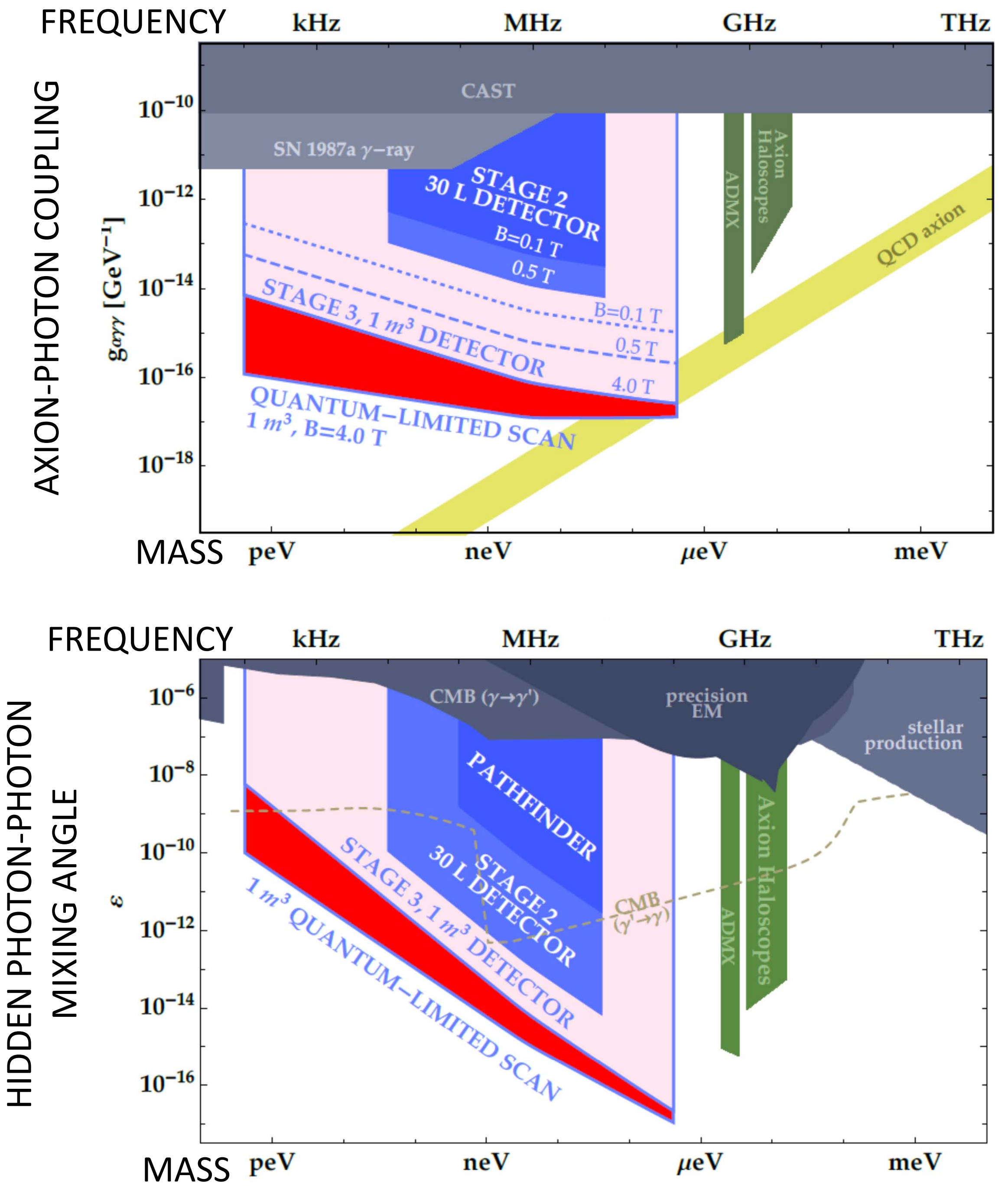


Fig. 8. **Top**: Axion exclusion plot. **Bottom**: Hidden photon exclusion plot.

DM Radio Quantum-Limited Scan: Four order of magnitude improvement in scan speed at 100 kHz!

- COMING SOON-Extension to nonclassical methods: squeezing/photon counting
- Implementation in DM Radio experiment

- S. Chaudhuri thanks Jonas Zmuidzinas, Harvey Moseley, Karl van Bibber, and Michel Devoret for useful conversations