

Heterodyne Detection of Axion Dark Matter in SRF Cavities

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JHEP 07 (2020) 088, [hep-ph/1912.11048](#)

A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

Phys.Rev.D 104 (2021) 11, L111701,

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SLAC LDRD Technical Document: PI Sami Tantawi

Gravitational Waves:

221X.XXXXX

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High-level Summary

Oscillating background B -field: Radio-Frequency **up-conversion** approach

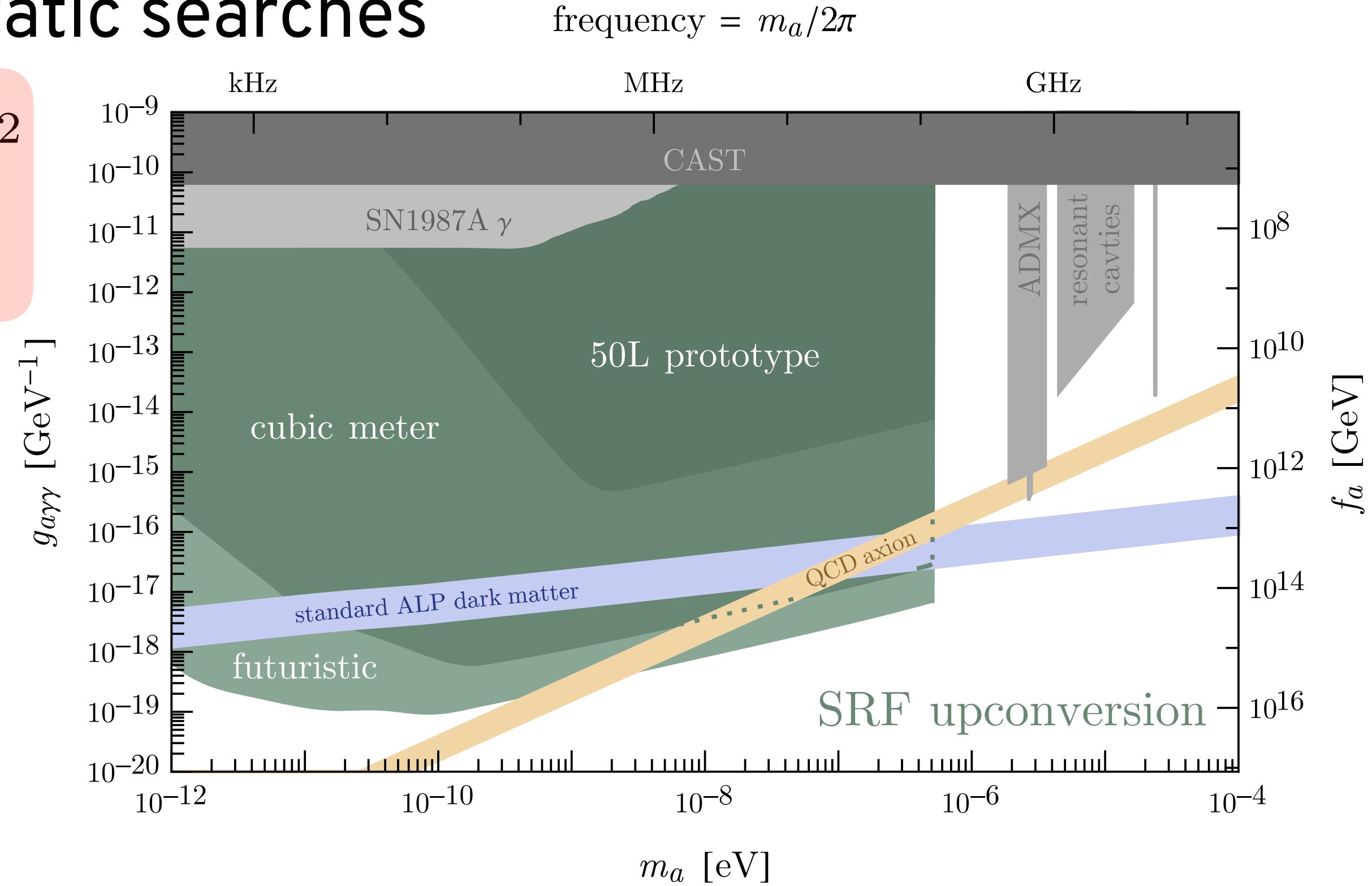
$$\omega_{\text{sig}} = \omega_0 \pm m_a$$

Parametric gain for small axion masses vs. static searches

$$\frac{\text{SNR}}{\text{SNR}^{\text{LC}}} \sim \frac{\omega_0 \pm m_a}{m_a} \left(\frac{Q_{\text{int}}}{Q_{\text{LC}}} \right)^{1/2} \left(\frac{T_{\text{LC}}}{T} \right)^{1/2} \left(\frac{B_0}{B_{\text{LC}}} \right)^2$$

Prototype:

- design underway @ SLAC, PI Sami Tantawi
- commissioned by FNAL SQMS: [hep-ex/2207.11346](#)



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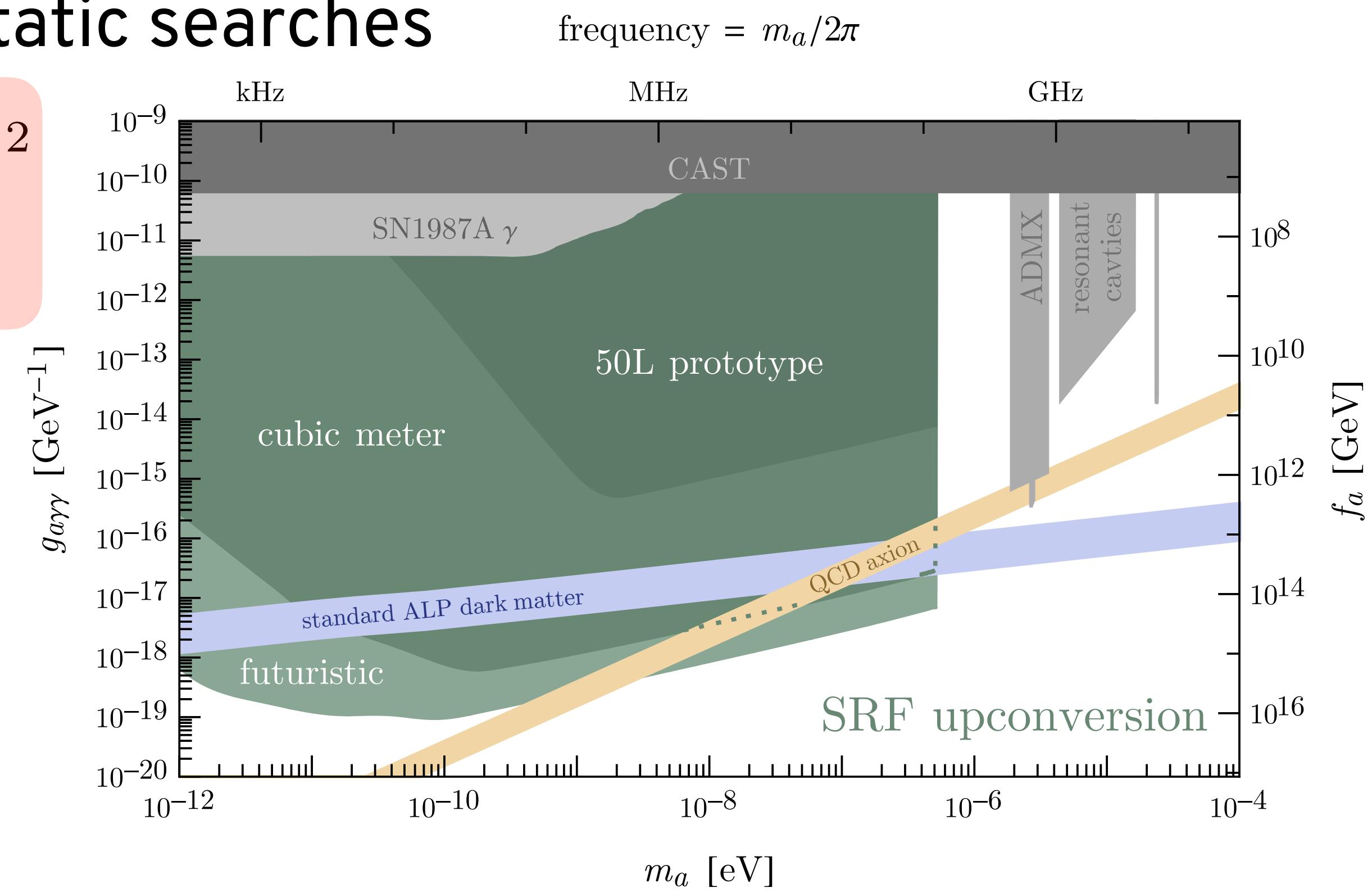
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Same tech. for Gravitational Waves!

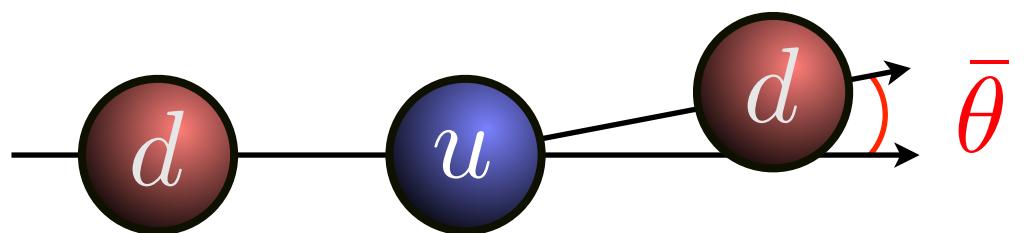


Axion, ALPs and Axion Electrodynamics

Axion introduced to solve strong CP problem

$$d_n \sim 10^{-16} \bar{\theta} \text{ e cm}$$

$$d_n^{\text{exp}} \lesssim 10^{-26} \text{ e cm}$$



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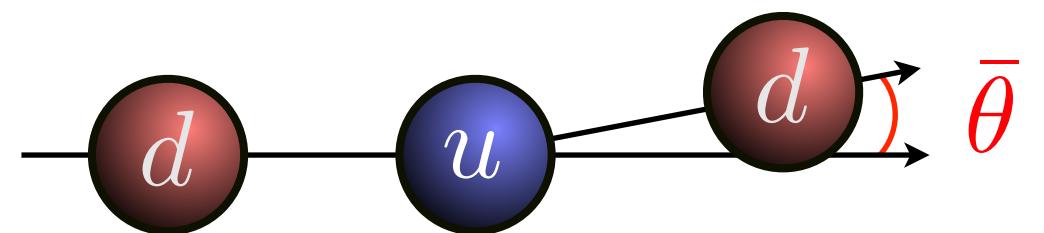
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Weinberg (1978)
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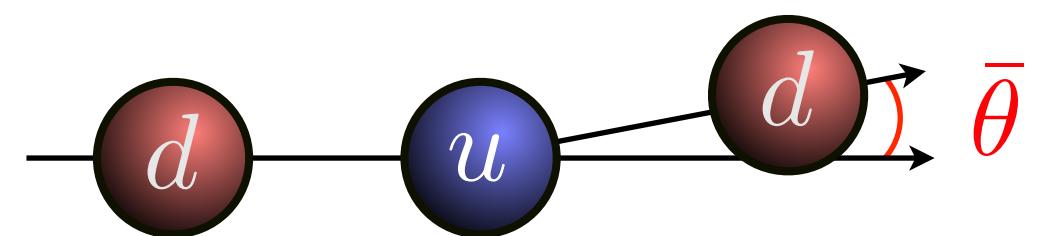
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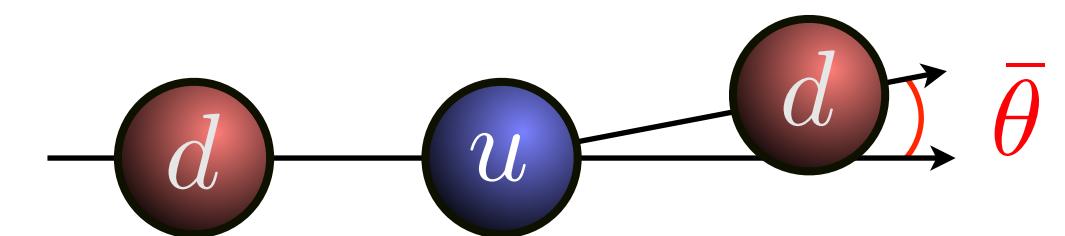
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$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

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

Maxwell's new and improved Equations

Resonant Axion Searches

Presence of axion dark matter \sim effective current

$$J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t \quad \Rightarrow \quad B_a(t) \propto J_{\text{eff}}(t)$$

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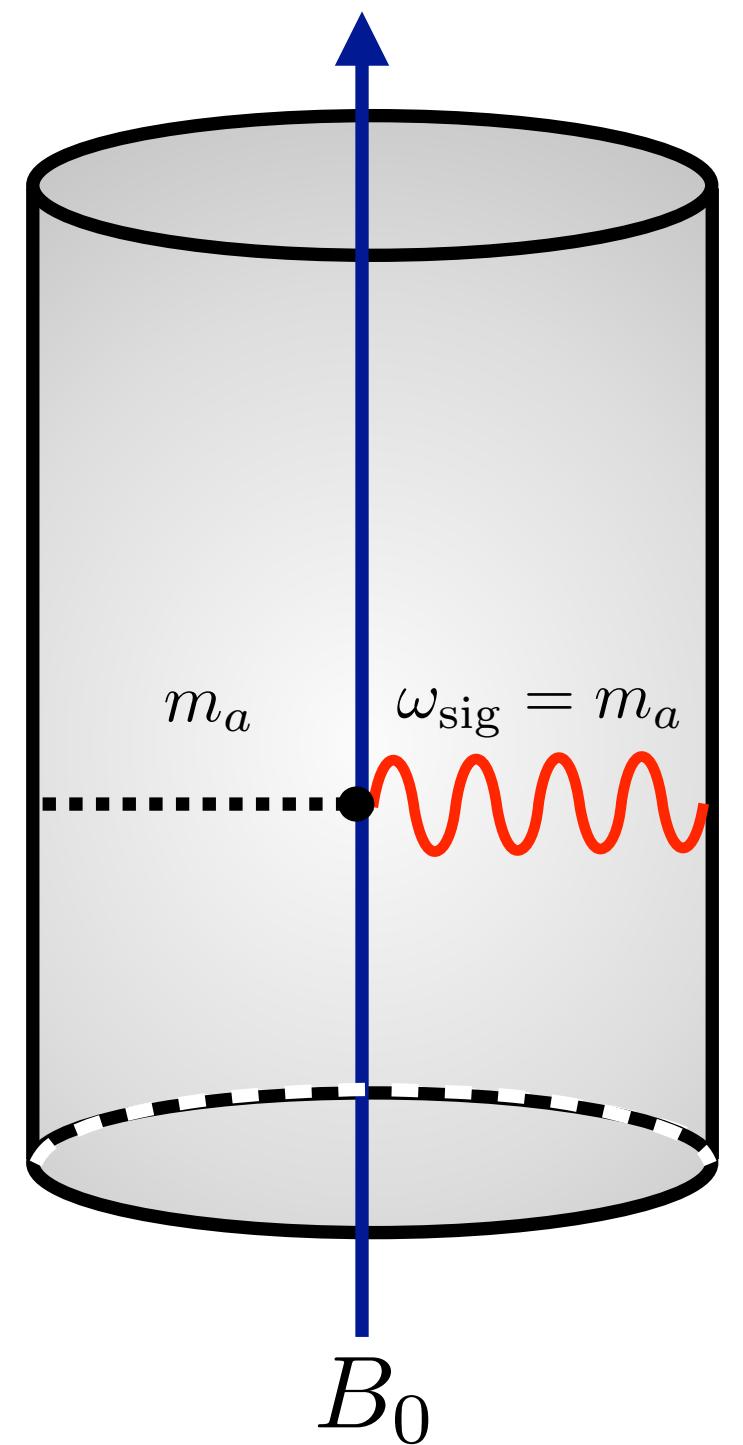
Resonant Approaches

Resonant Approaches

Static-field Haloscope:

e.g. ADMX

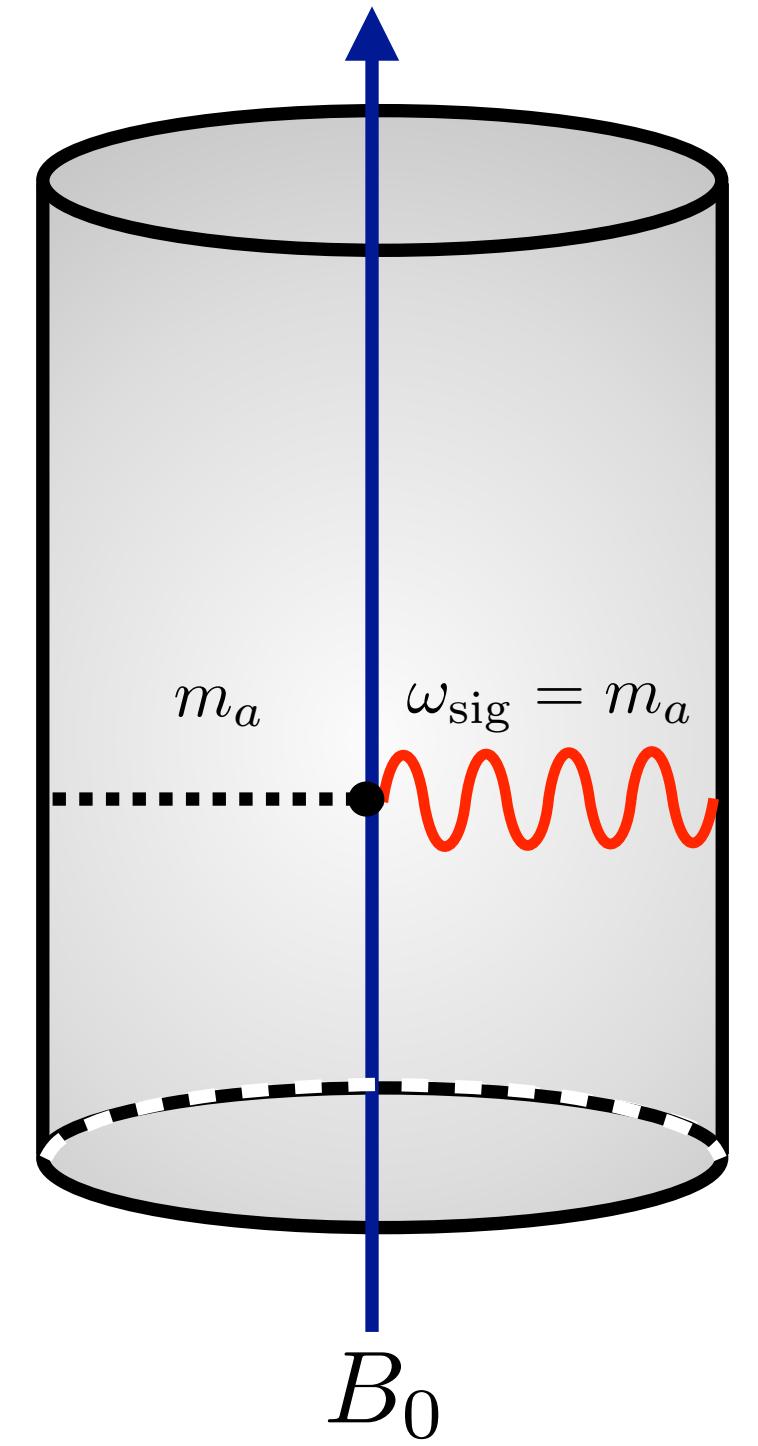
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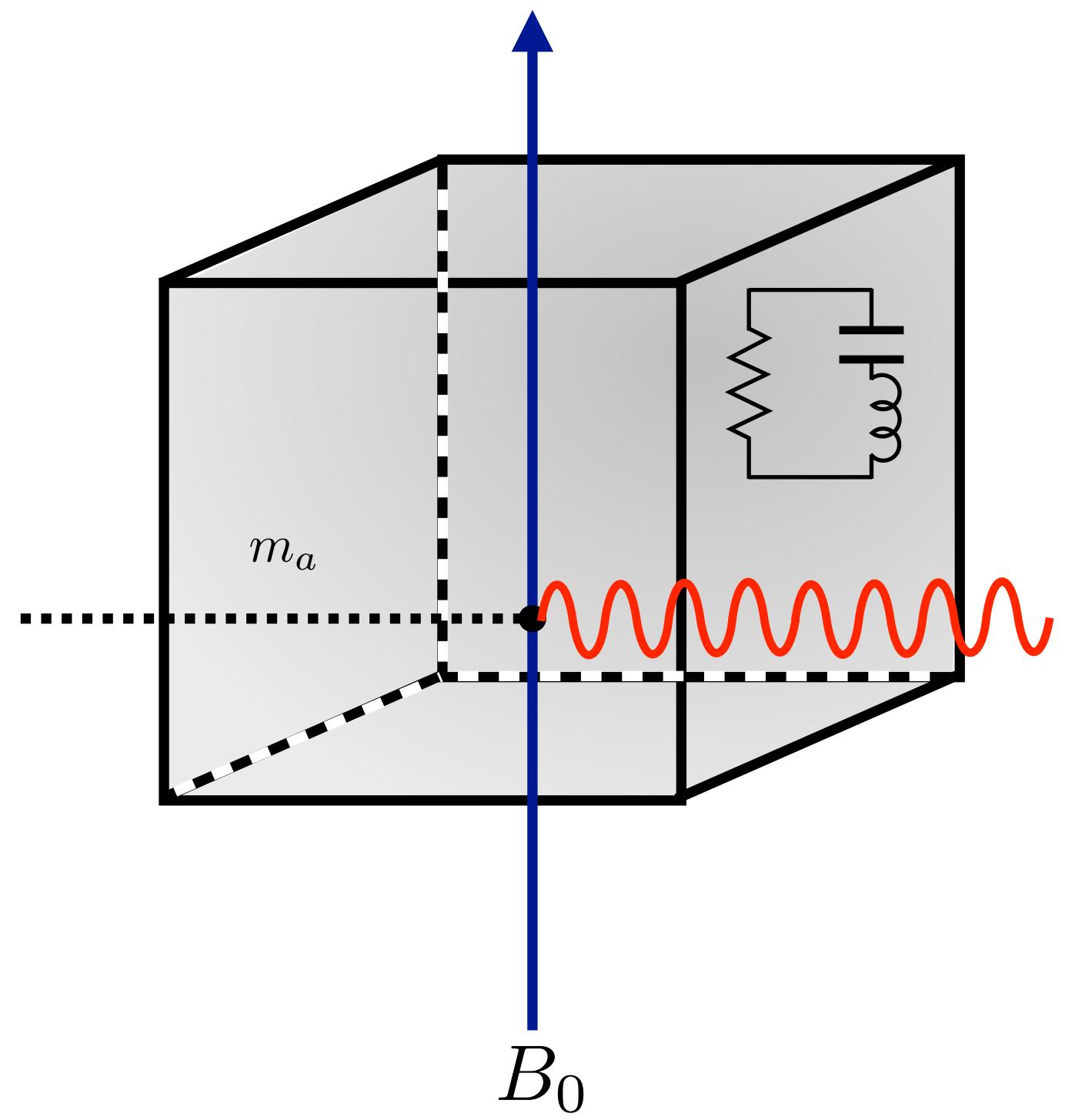
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LC Resonator:
e.g. DM Radio

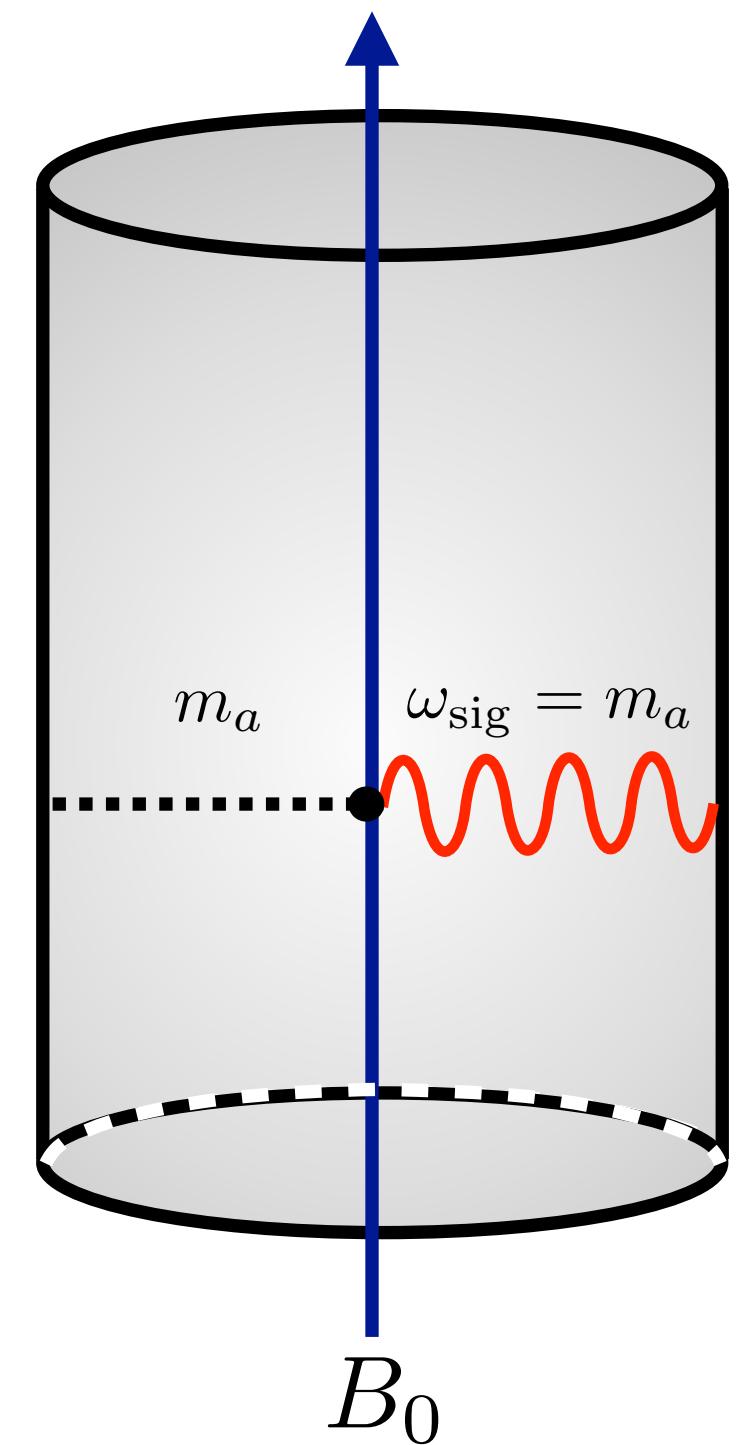
$$\omega_{\text{sig}} = m_a = \omega_{\text{LC}}$$



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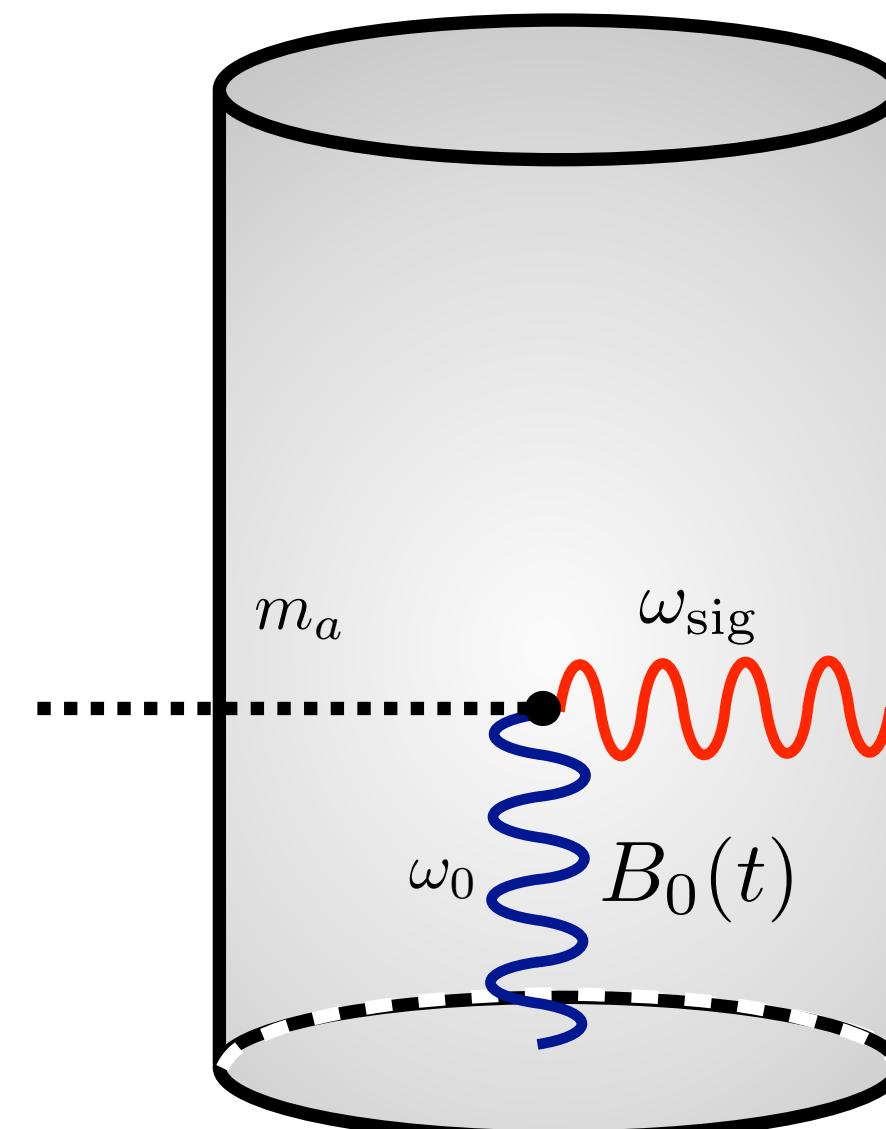
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Heterodyne Resonator:

$$\omega_{\text{sig}} \sim \omega_0 \pm m_a \sim V^{-1/3}$$

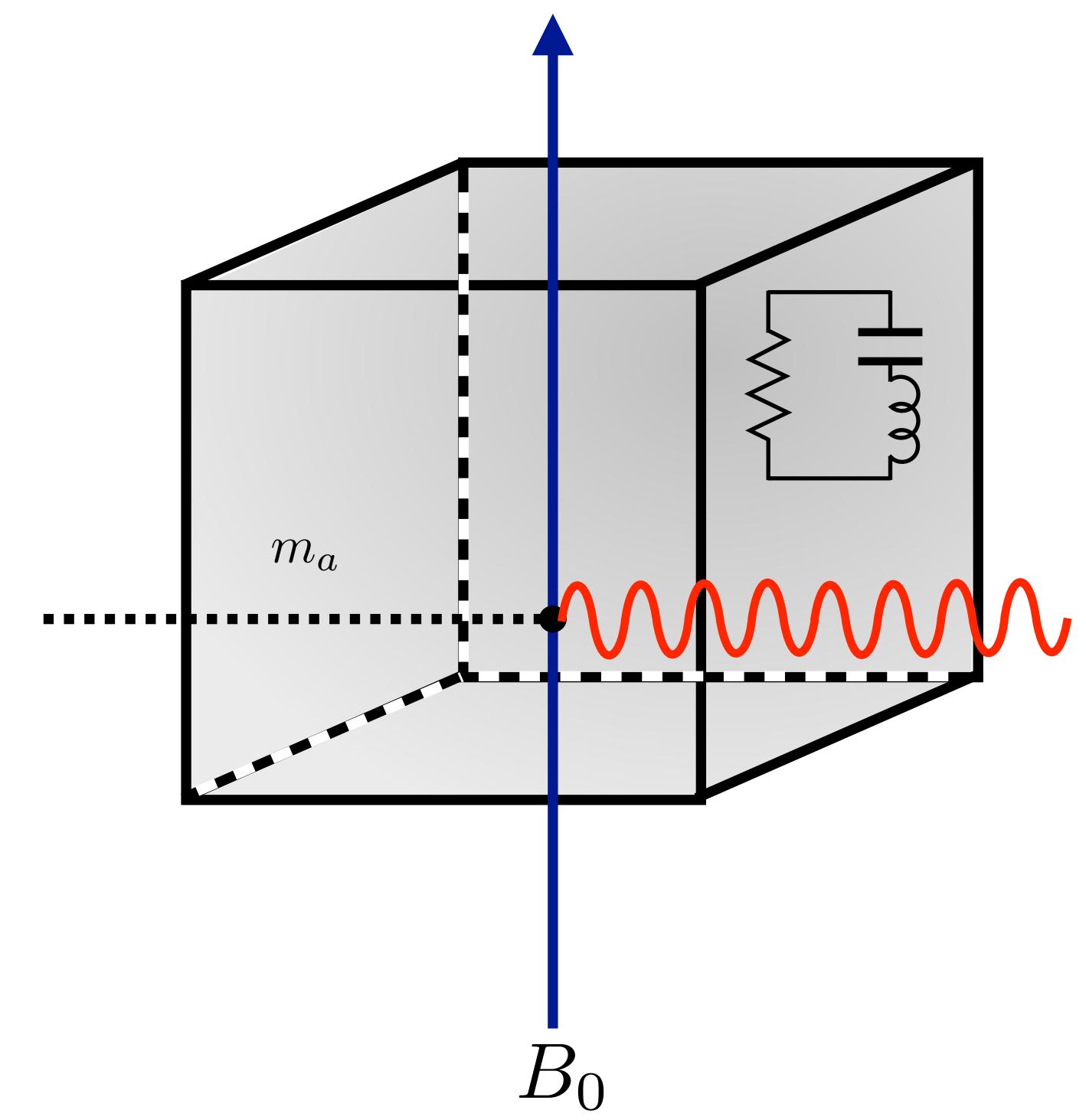


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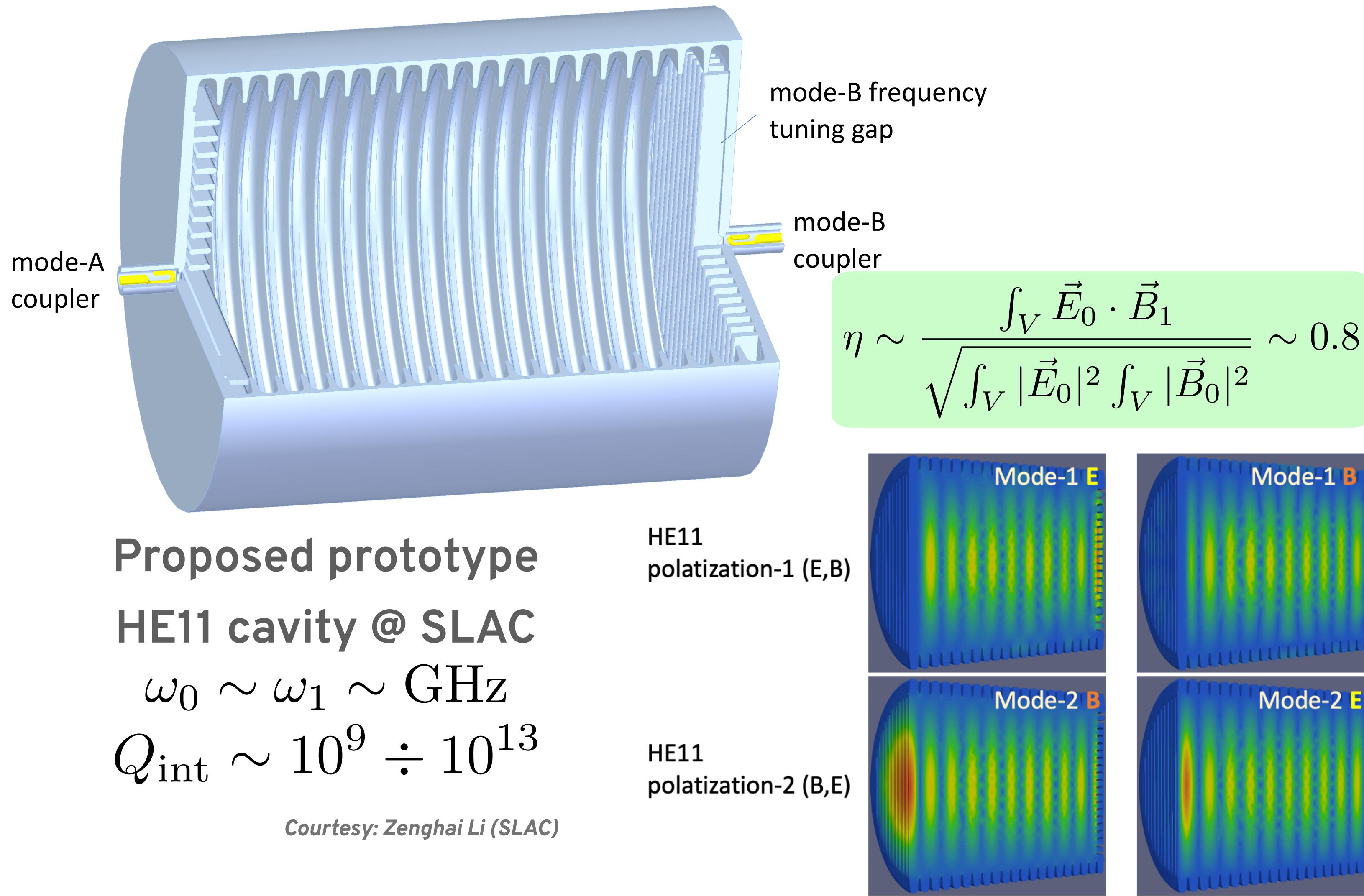
Also: R. Lasenby hep-ph/1912.11467

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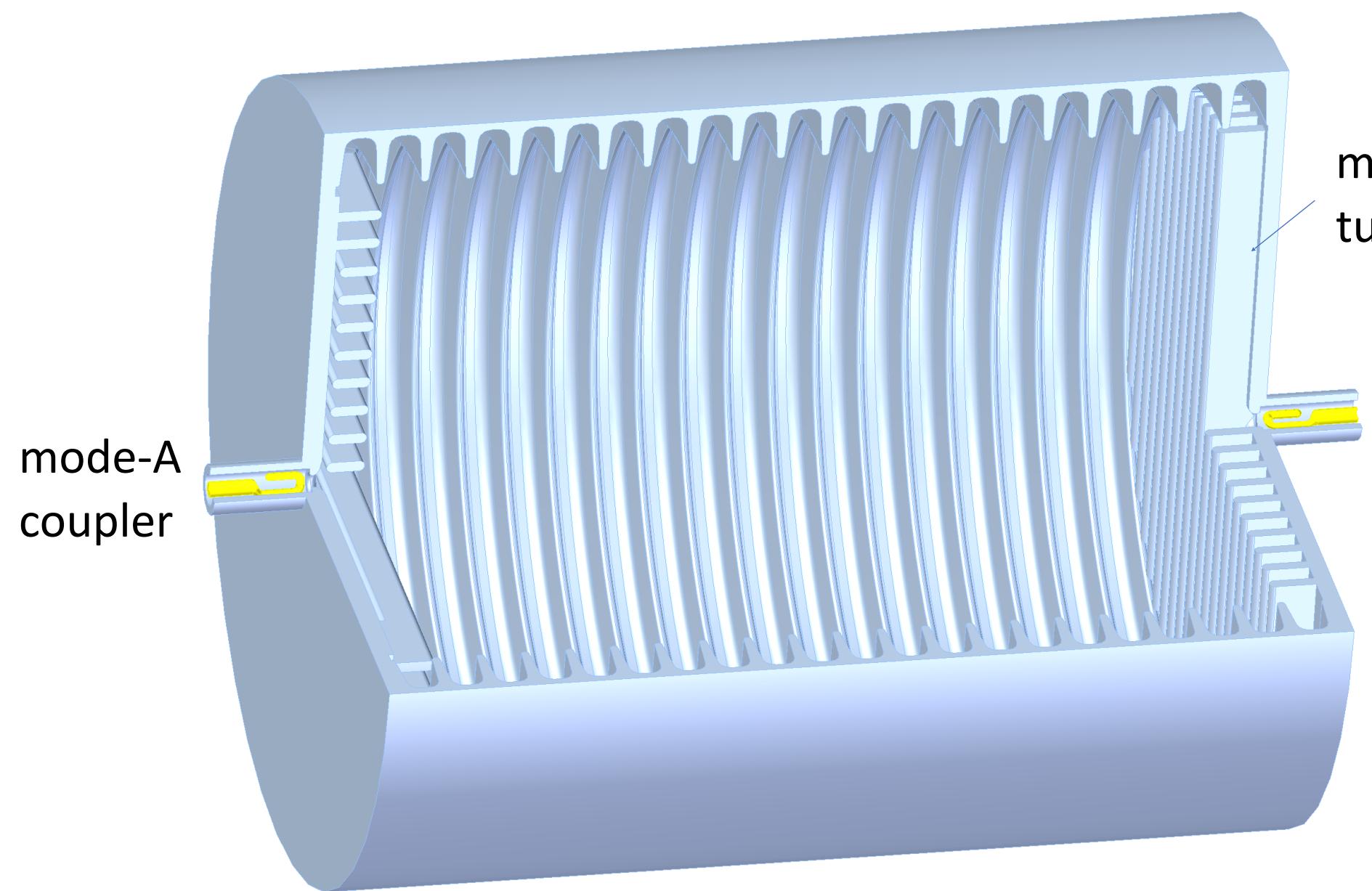
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Axion Resonant Frequency Conversion



Axion Resonant Frequency Conversion



**Proposed prototype
HE11 cavity @ SLAC**

$$\omega_0 \sim \omega_1 \sim \text{GHz}$$
$$Q_{\text{int}} \sim 10^9 \div 10^{13}$$

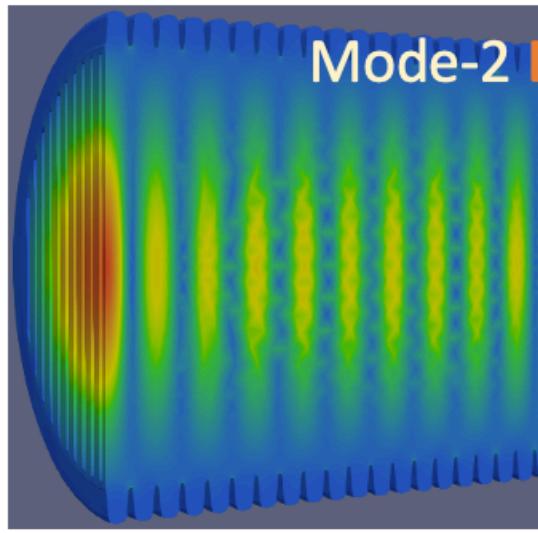
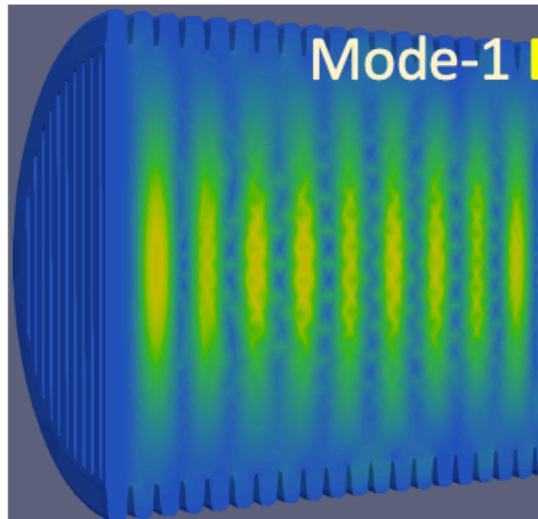
Courtesy: Zenghai Li (SLAC)

mode-B frequency
tuning gap

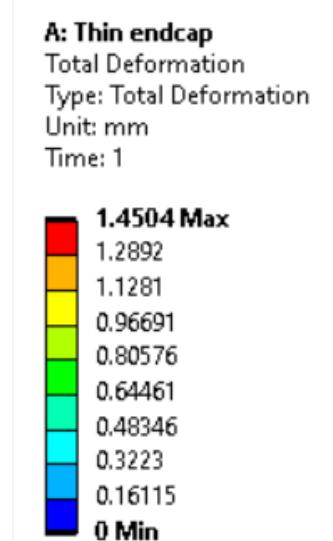
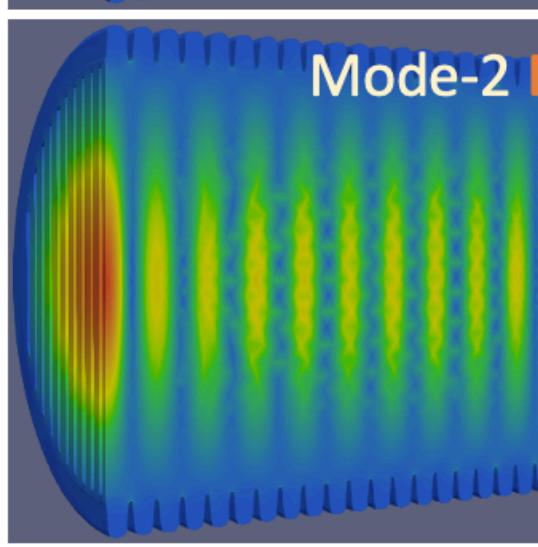
mode-B
coupler

$$\eta \sim \frac{\int_V \vec{E}_0 \cdot \vec{B}_1}{\sqrt{\int_V |\vec{E}_0|^2 \int_V |\vec{B}_0|^2}} \sim 0.8$$

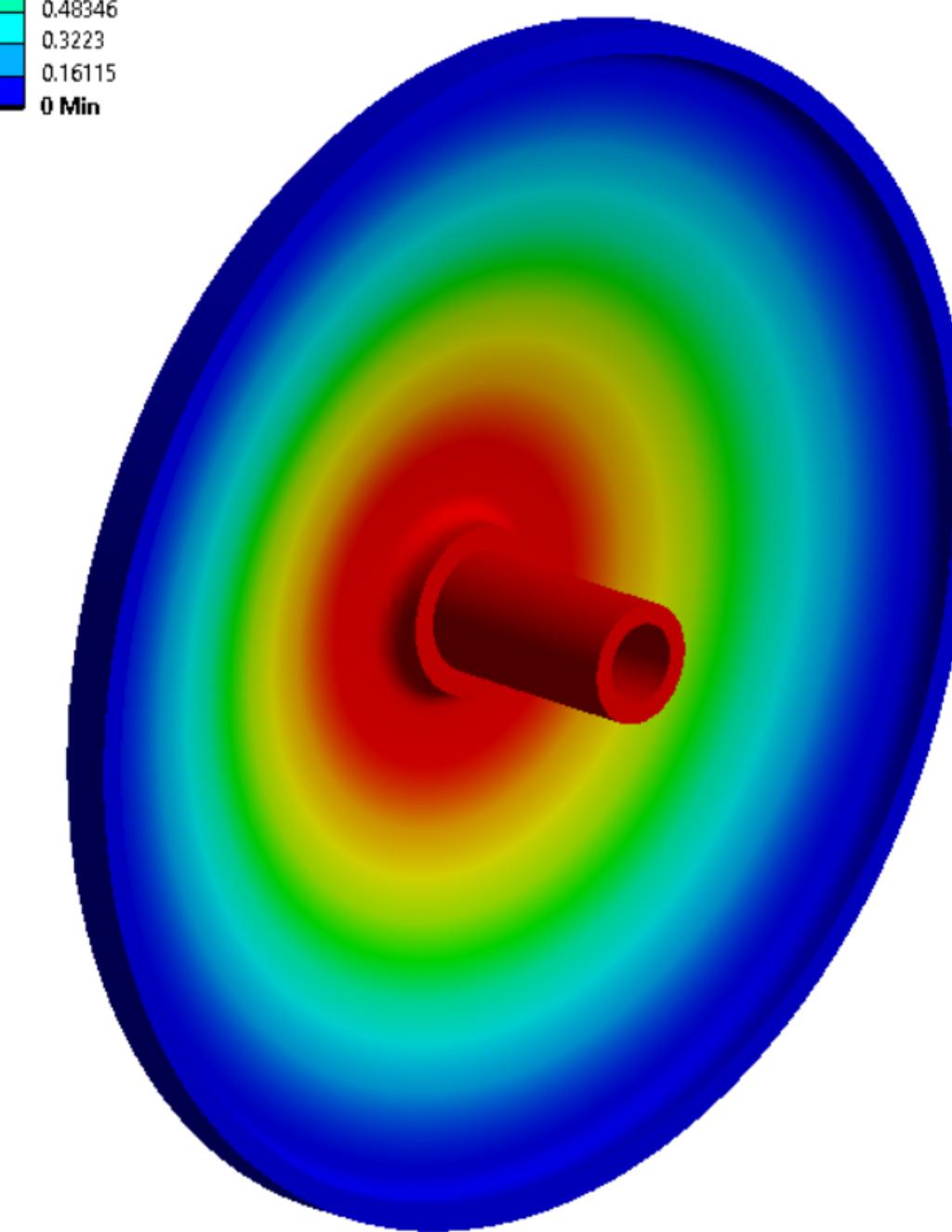
HE11
polatization-1 (E,B)



HE11
polatization-2 (B,E)

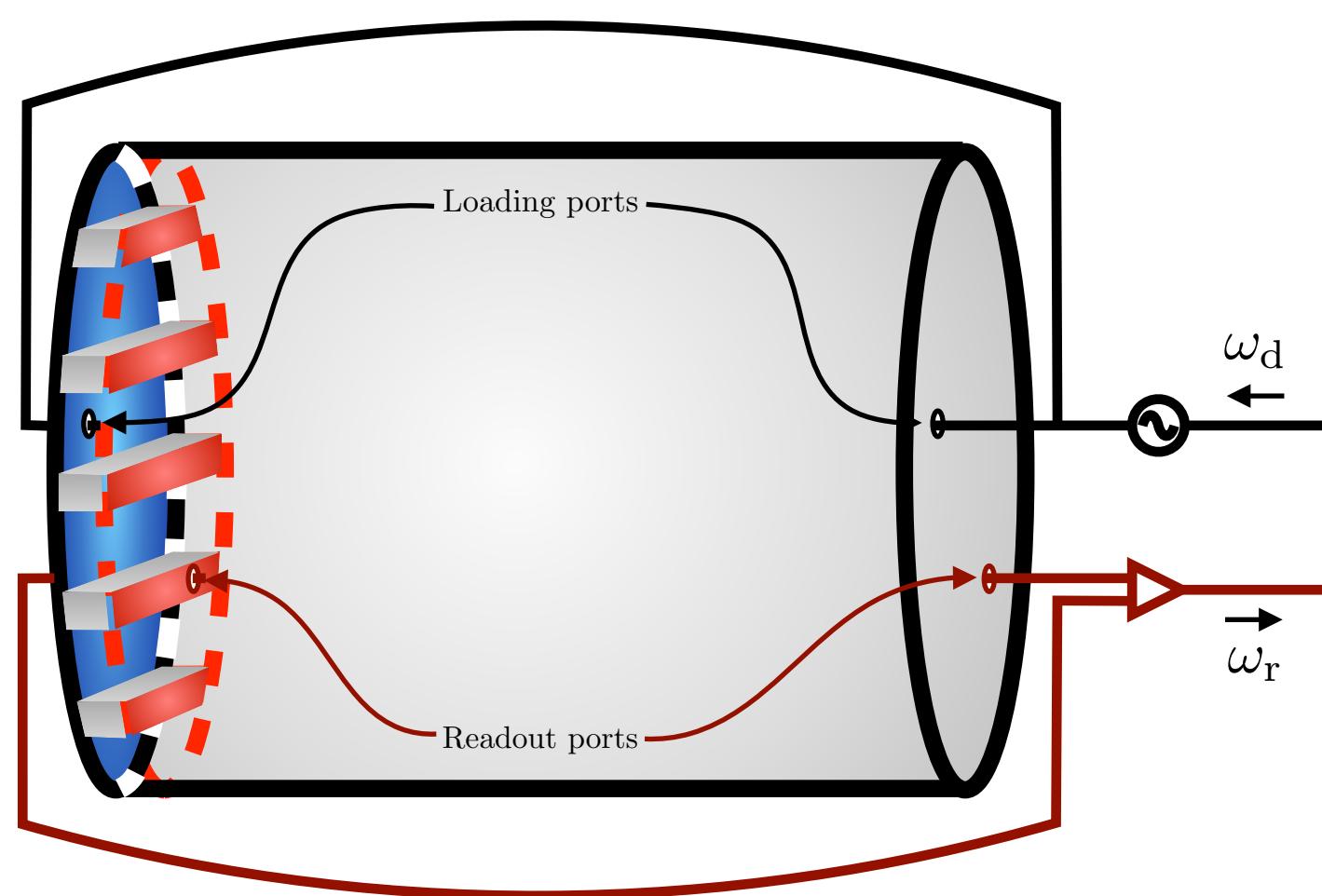


Tunability: $\sim 1\text{mm}$



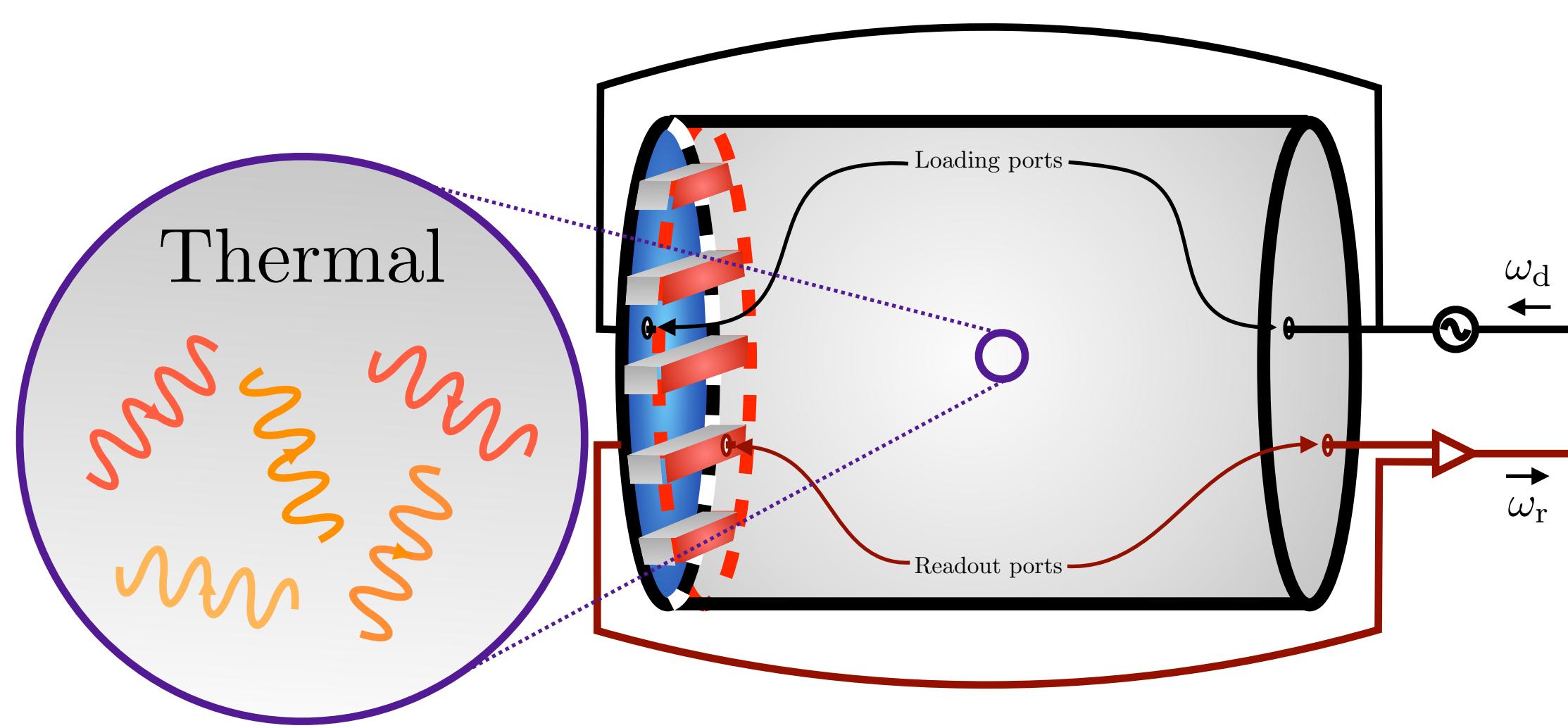
Courtesy: Marco Oriunno (SLAC)

All Noise Sources

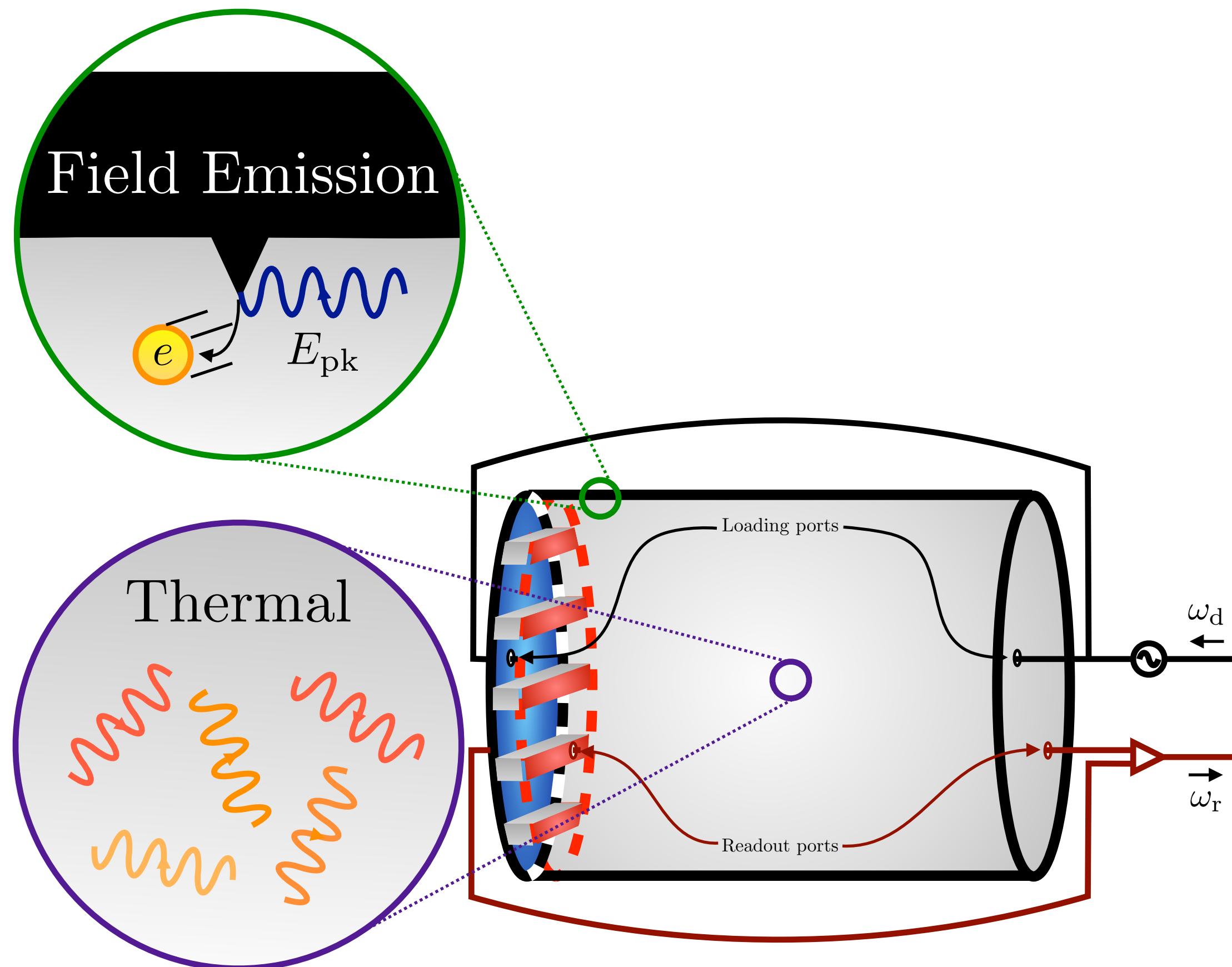


All Noise Sources

- *Thermal noise*: requires cryo

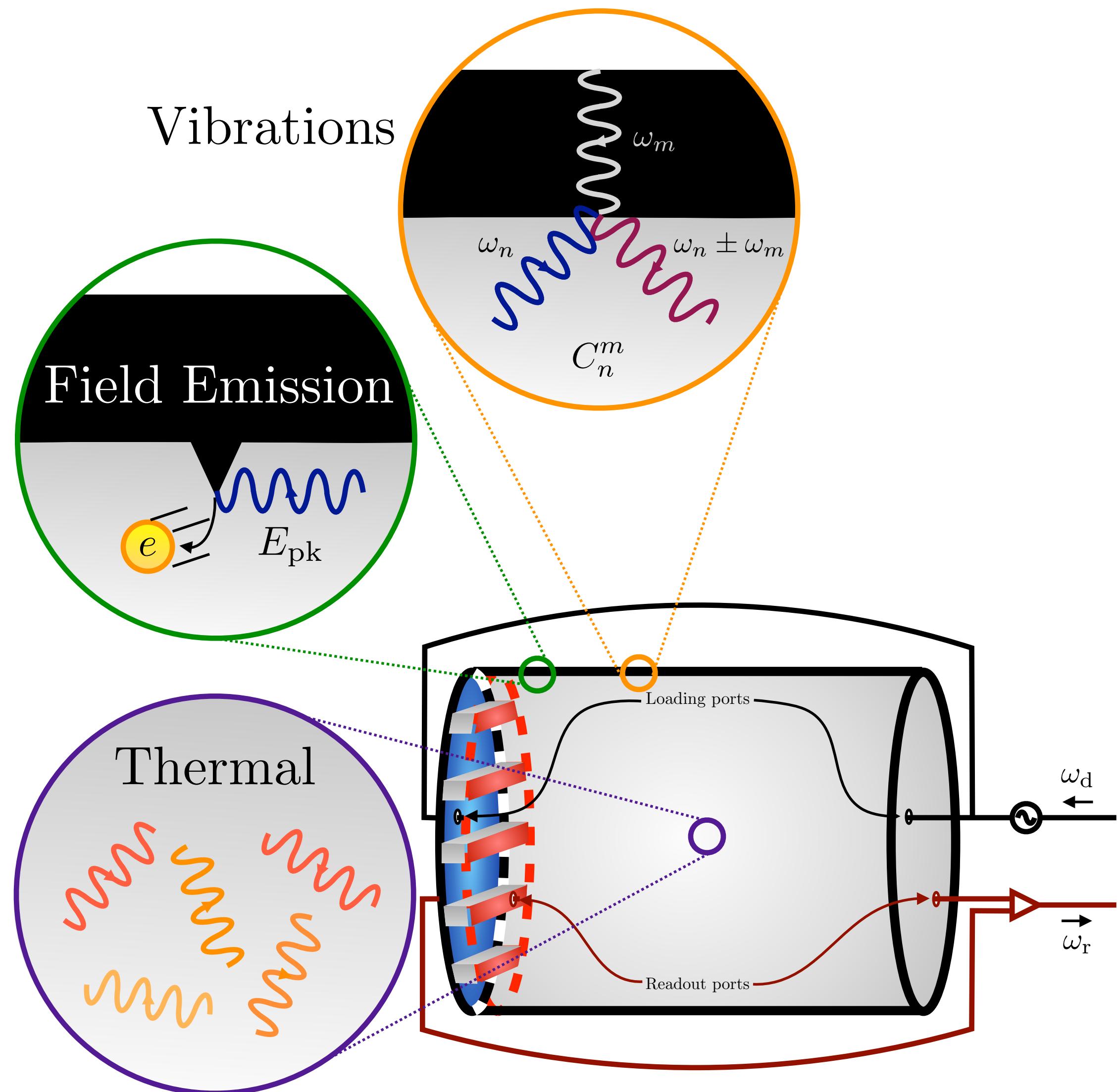


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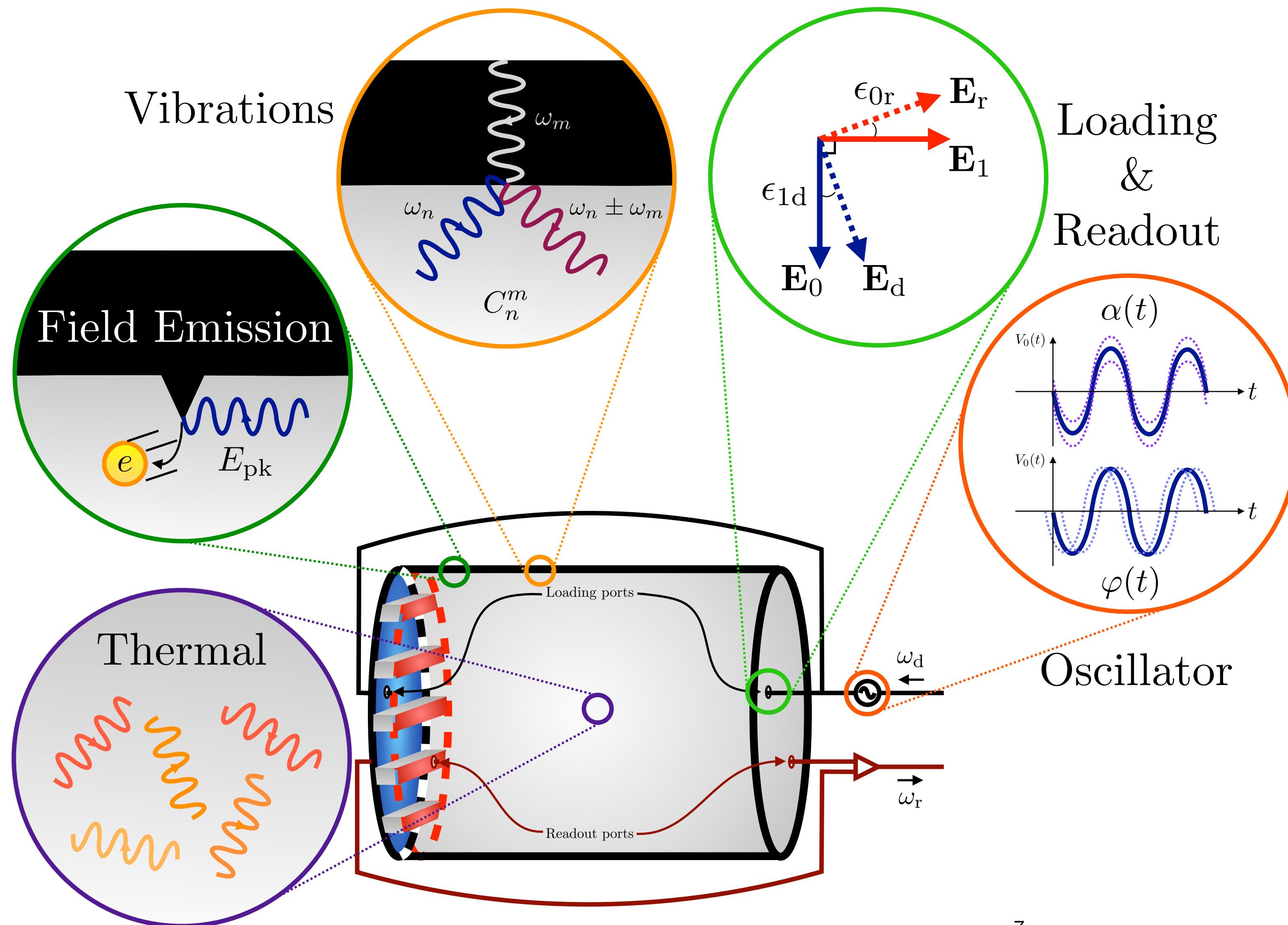
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- **Field Emission:** careful design & limits peak B-field

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- **Vibrations:** design to reduce microphonics, seismic isolation, cryo

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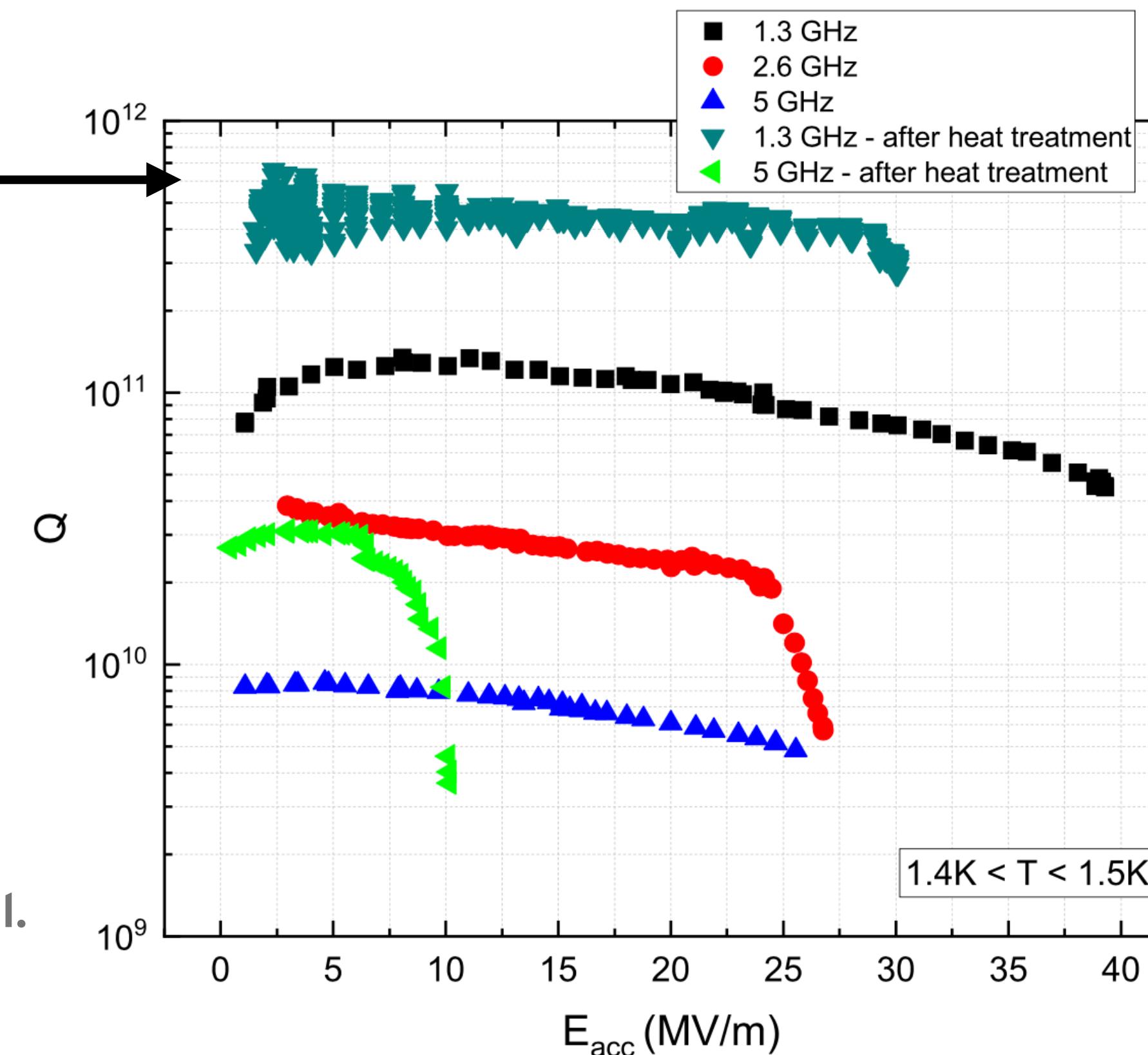
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- **Vibrations**: design to reduce microphonics, seismic isolation, cryo
- **Loading/Readout & Phase**: design to improve coupling to pump & signal modes. Low phase-noise pump & readout electronics

Technology Requirements

Q-factor & B-field:

$Q \sim 4 \times 10^{11} @ B \sim 0.1T$

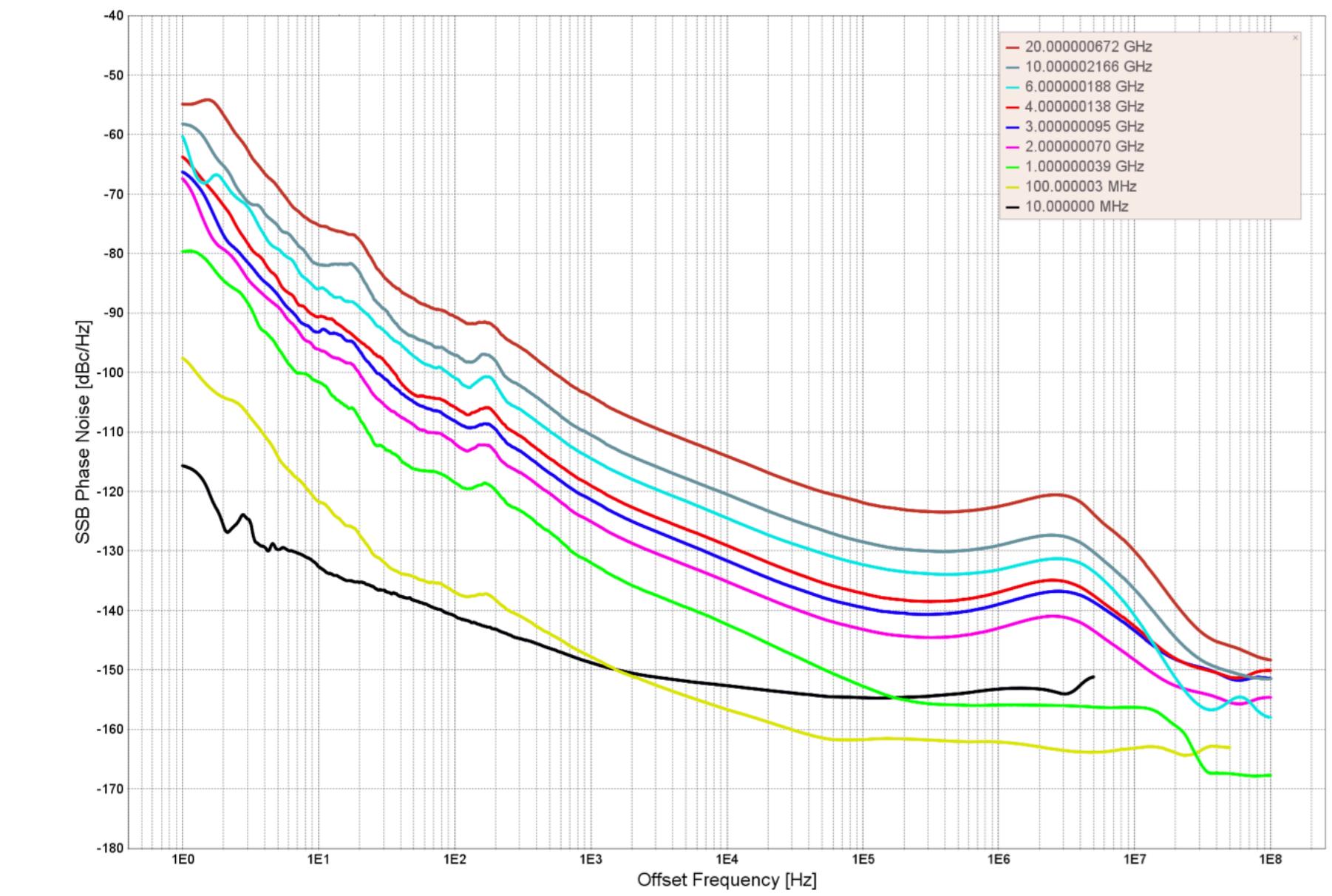
arXiv: 1810.03703 Romanenko et al.



Phase noise: BN865-M

TYPICAL PERFORMANCE CURVES

Phase Noise Performance with option LN



Technology Requirements

Mode rejection:

$\epsilon = 10^{-7}$ achieved



[gr-qc/0502054](https://arxiv.org/abs/gr-qc/0502054) Ballantini, ..., Calatroni et al
[physics/0004031](https://arxiv.org/abs/physics/0004031) Bernard, Gemme, Parodi, Picasso

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More on this...

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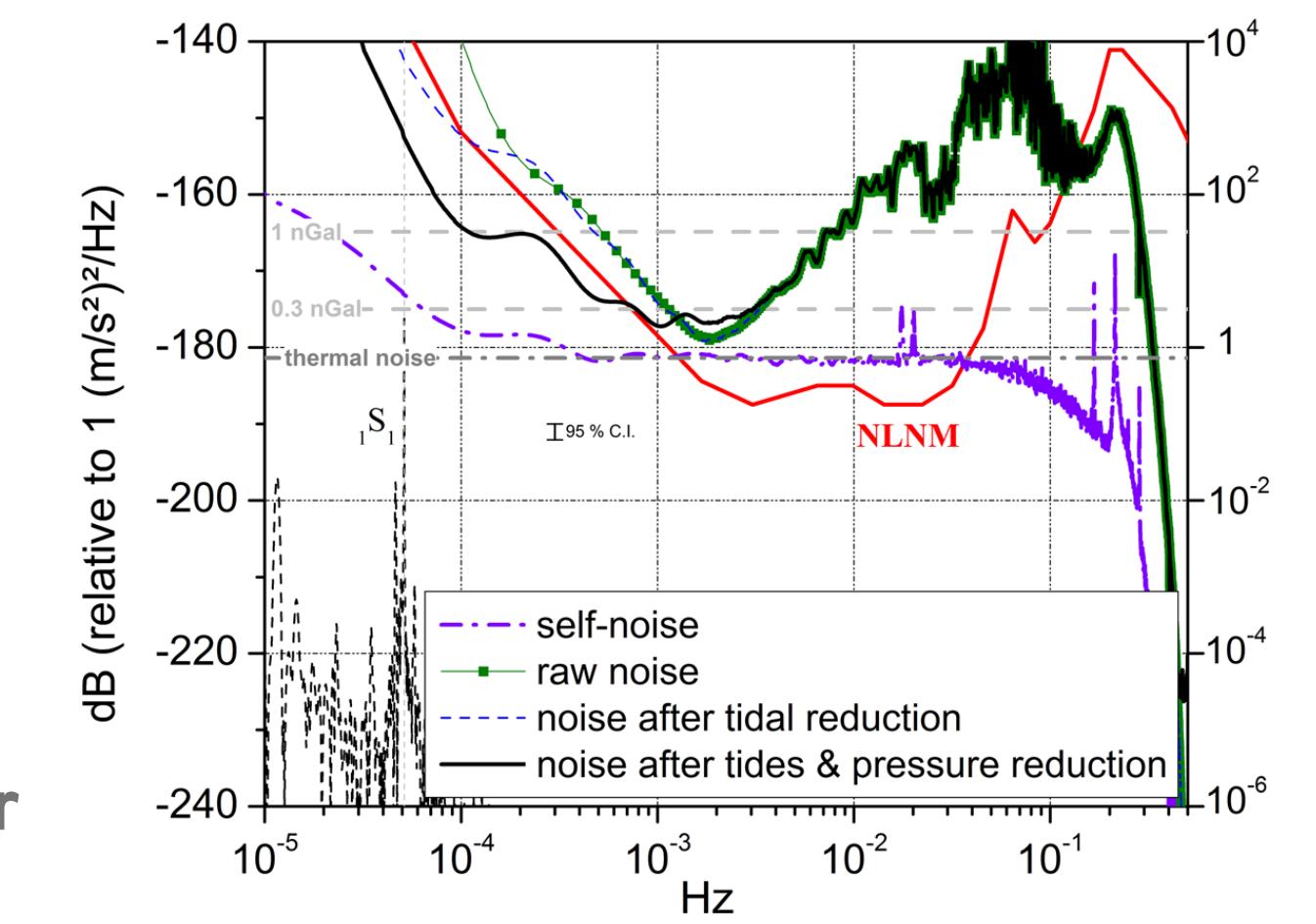
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Low-frequency seismic noise:

$\Delta\omega/\omega \sim \delta \sim 10^{-10}$
DarkSRF (2020)

Scientific Reports 8, 15324 (2018) Rosat & Hinderer



Signal to Noise

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Thermal noise dominated:

$$\text{SNR} \sim \frac{\rho_{\text{DM}} V}{m_a \omega_1} (g_{a\gamma\gamma} \eta_{10} B_0)^2 \left(\frac{Q_a Q_{\text{int}} t_e}{T} \right)^{1/2}$$

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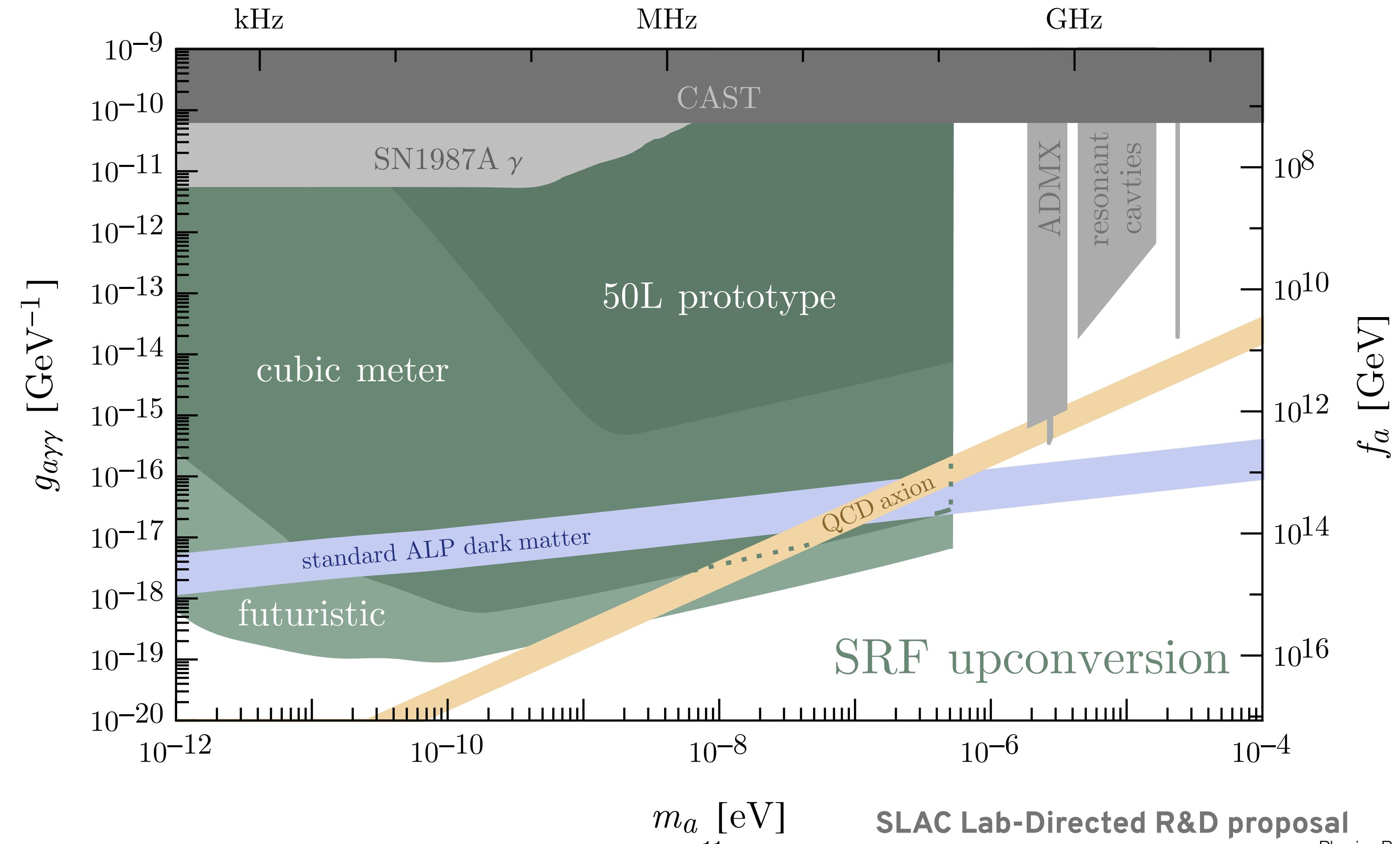
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Prototype R&D FUNDED at SLAC



frequency = $m_a/2\pi$

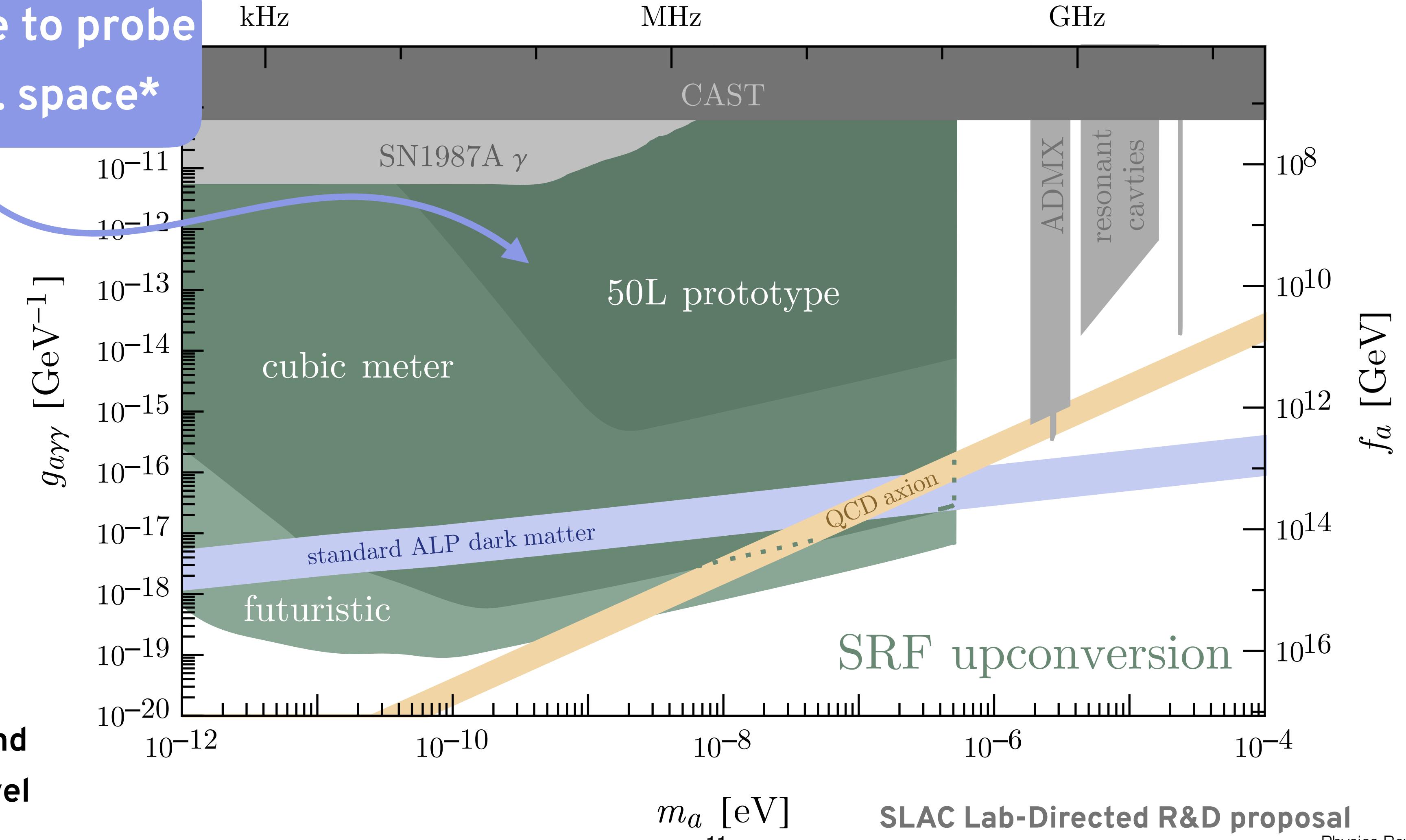


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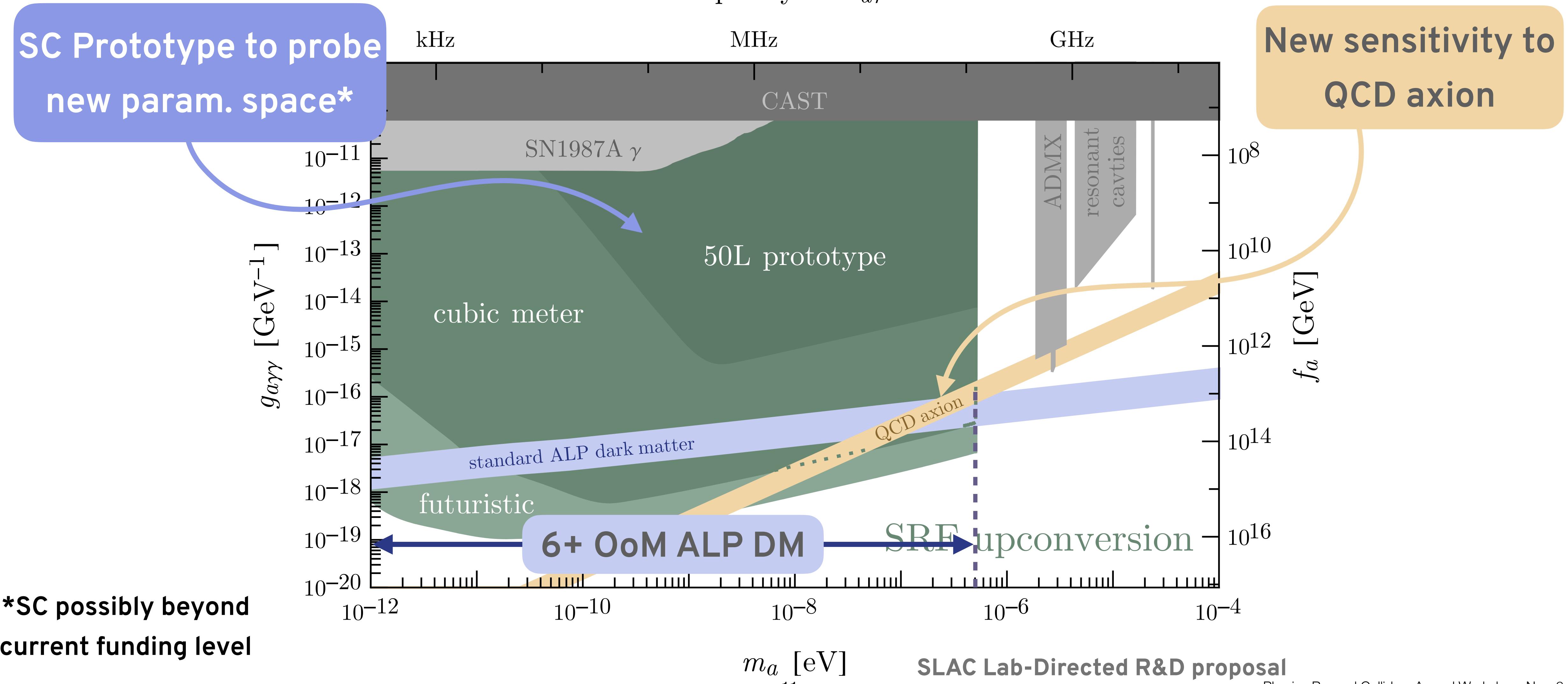


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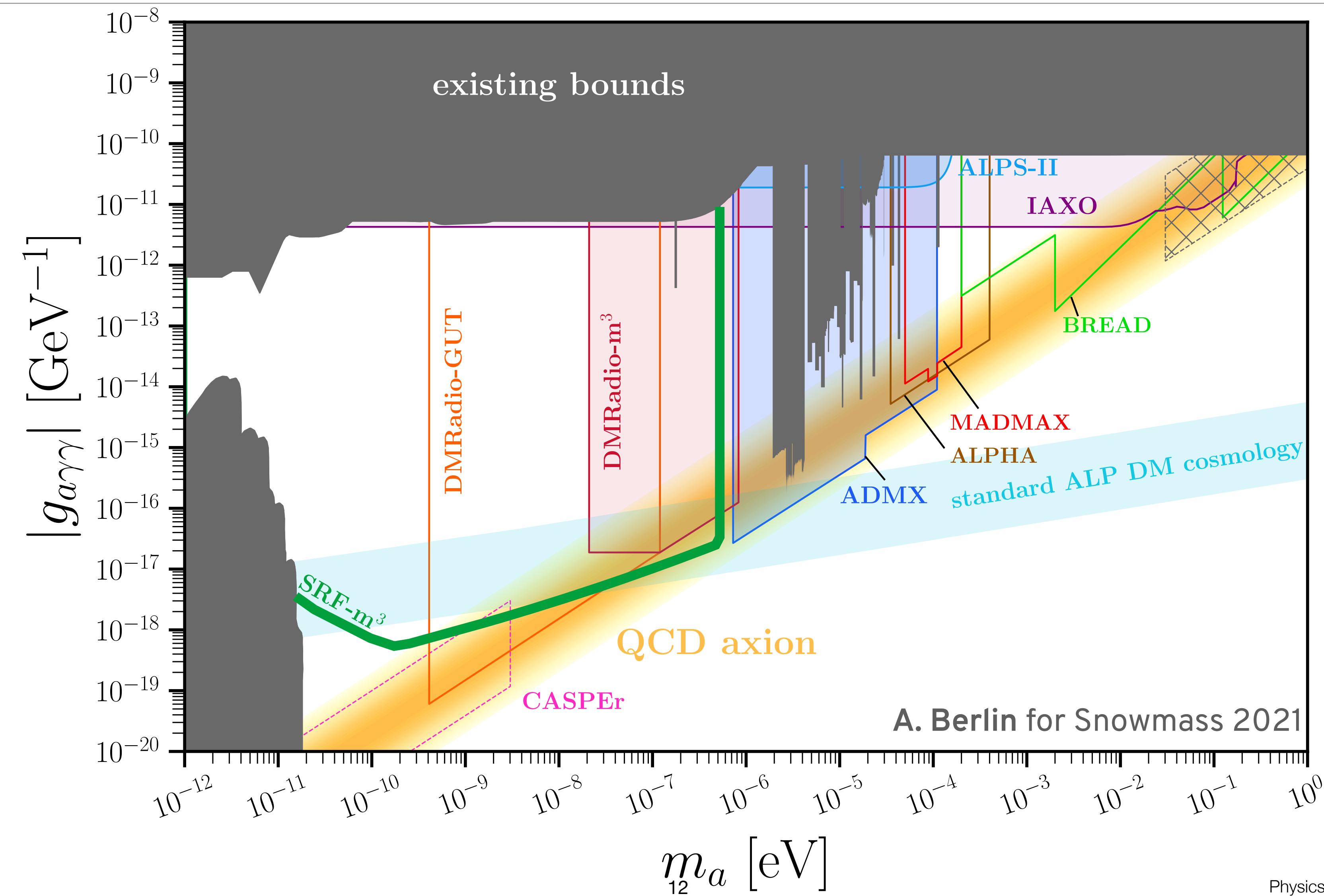
SC Prototype to probe
new param. space*



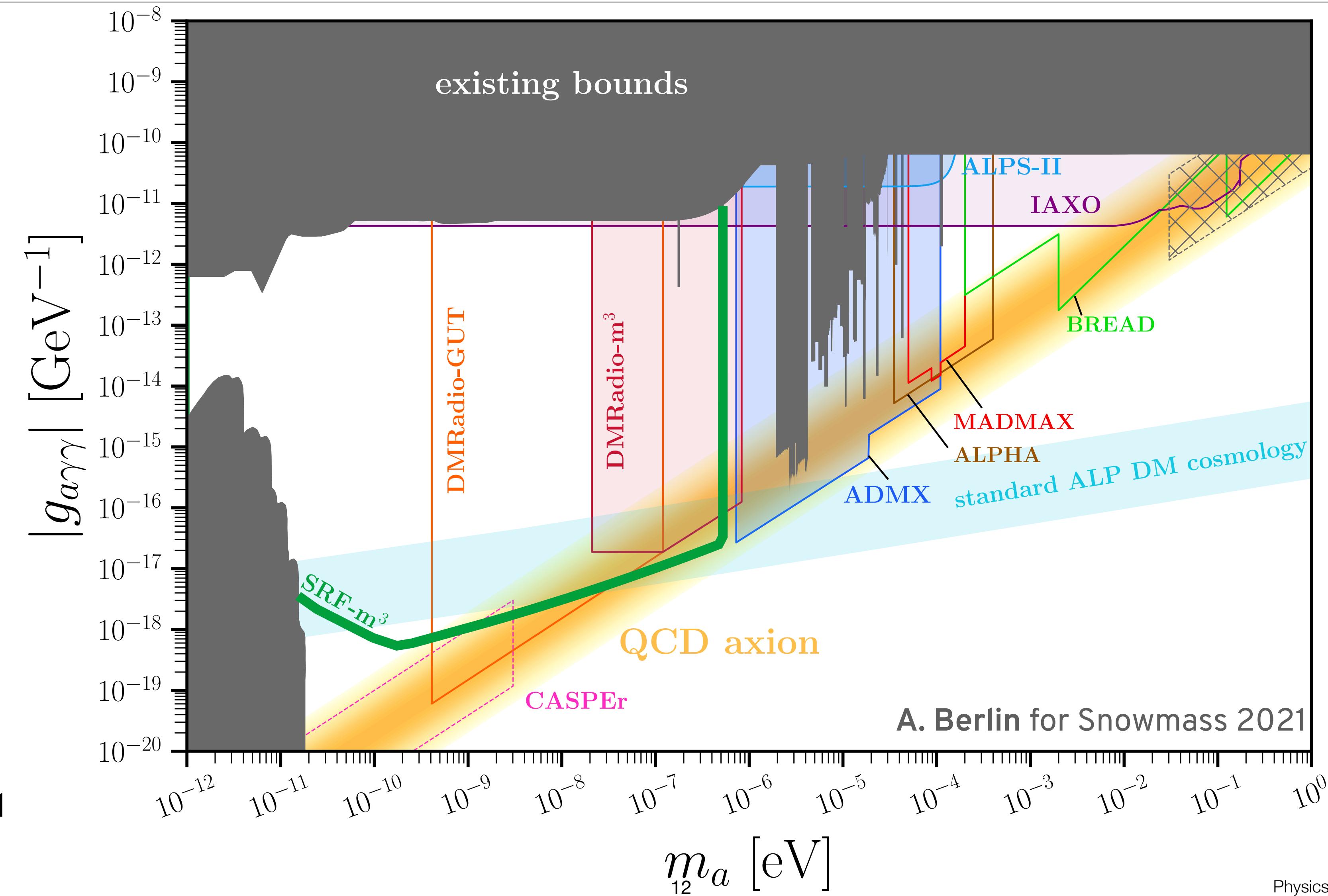
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Experimental Context*:



Experimental Context*:



*Bear in mind social
context of figure

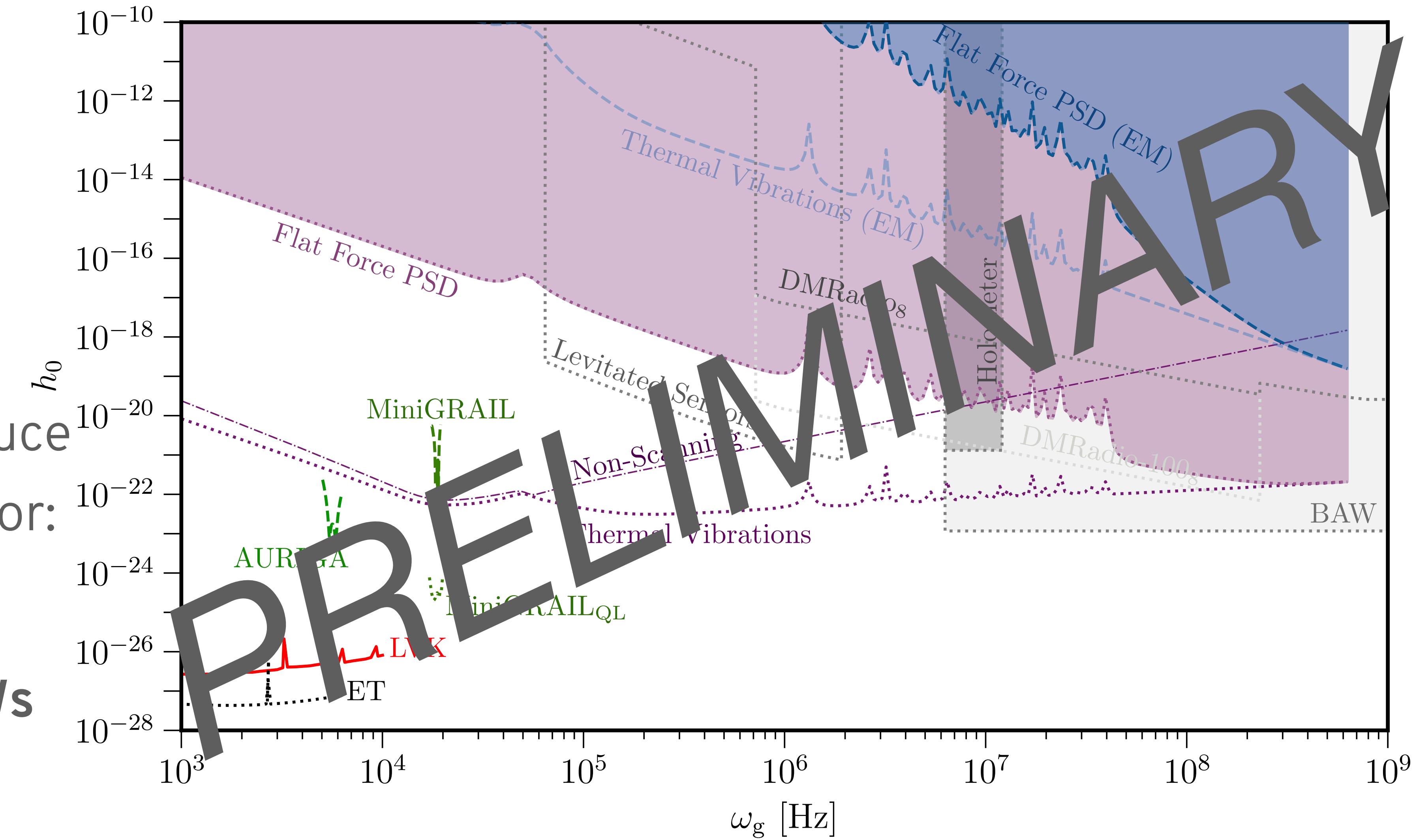
Develop Technology for GW searches

MAGO collaboration @
CERN in early 2000's

With current tech. –
shaded regions

Synergistic R&D to reduce
to thermal vibration floor:

**IMPROVE AXION
SEARCH & BONUS GWs**



Outlook

Oscillating background B -field: Radio-Frequency **up-conversion** approach

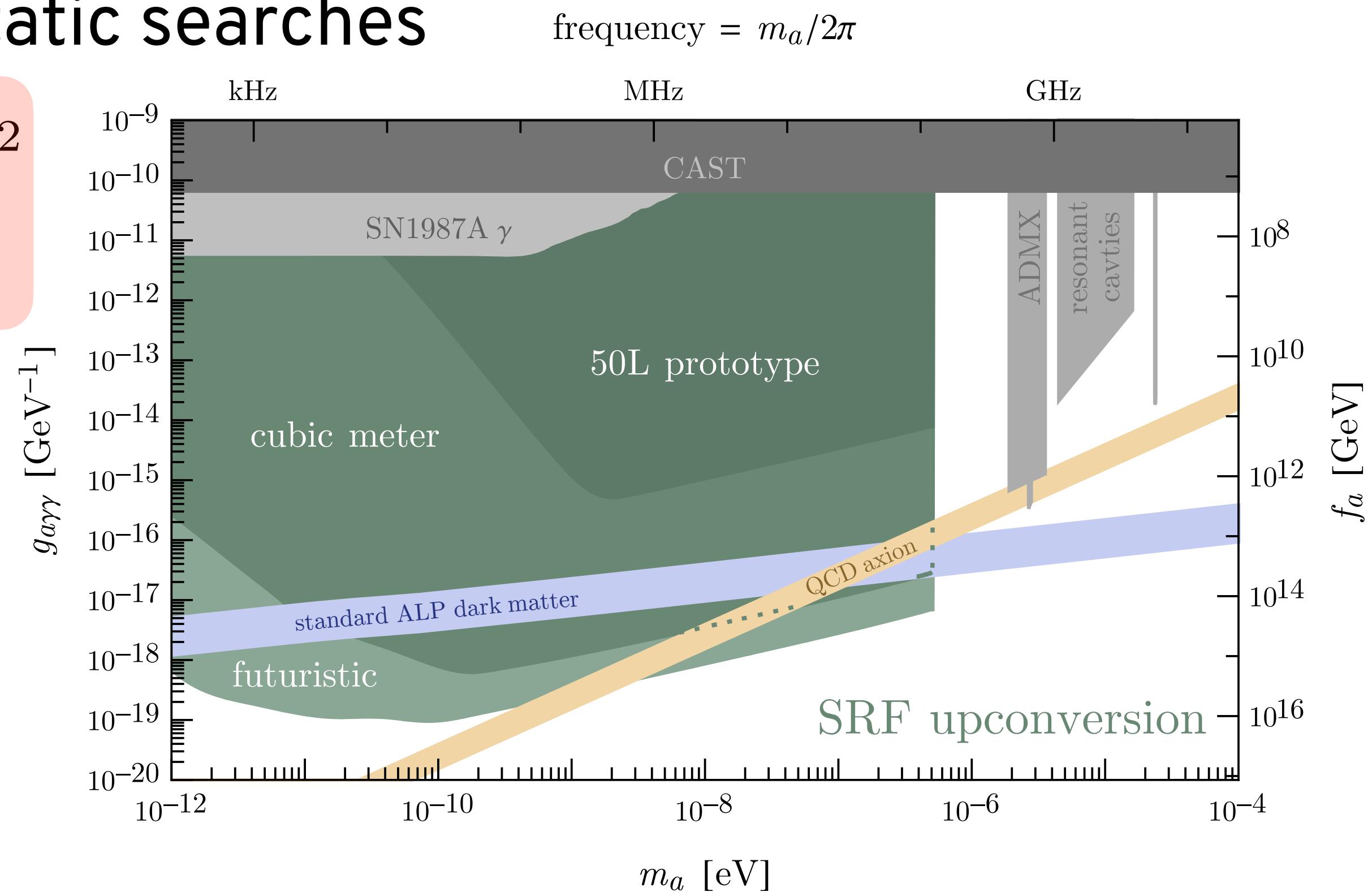
$$\omega_{\text{sig}} = \omega_0 \pm m_a$$

Parametric gain for small axion masses vs. static searches

$$\frac{\text{SNR}}{\text{SNR}^{\text{LC}}} \sim \frac{\omega_0 \pm m_a}{m_a} \left(\frac{Q_{\text{int}}}{Q_{\text{LC}}} \right)^{1/2} \left(\frac{T_{\text{LC}}}{T} \right)^{1/2} \left(\frac{B_0}{B_{\text{LC}}} \right)^2$$

Prototype:

- design underway @ SLAC, PI Sami Tantawi
 - commissioned by FNAL SQMS: [hep-ex/2207.11346](https://arxiv.org/abs/hep-ex/2207.11346)
 - input from PBC received and much appreciated!



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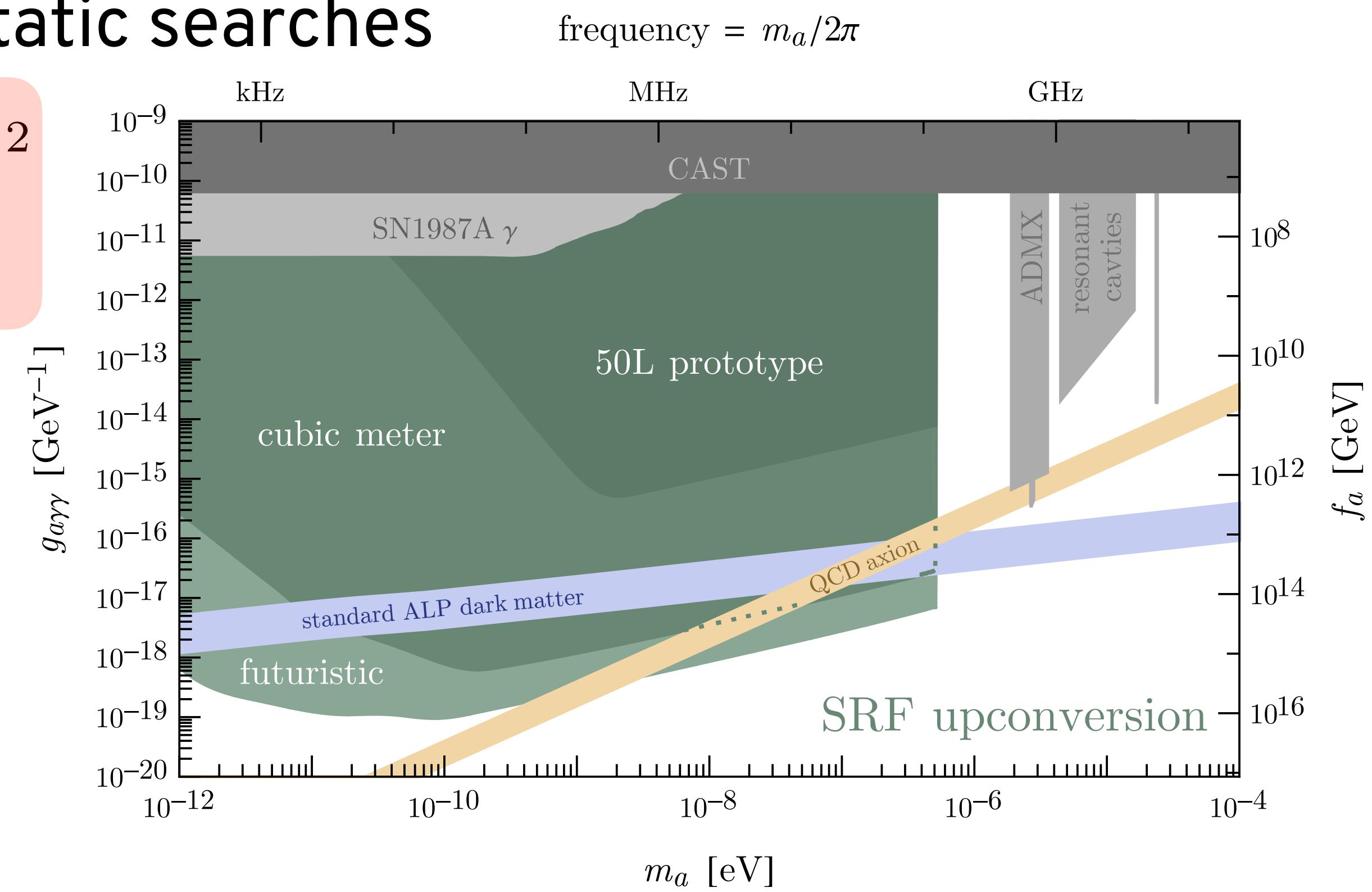
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Same tech. for Gravitational Waves!



Backup: prototype @ SLAC

