Thin Film Fabrication of Quantum Upconverting Sensors for Dark Matter Detection

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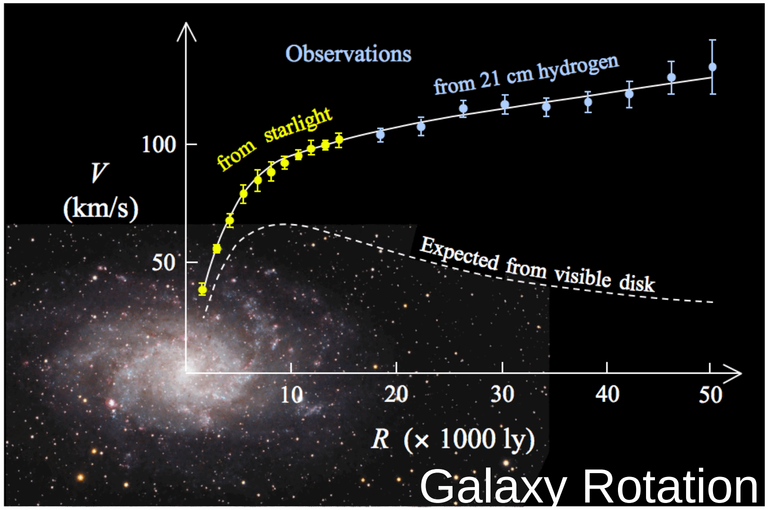
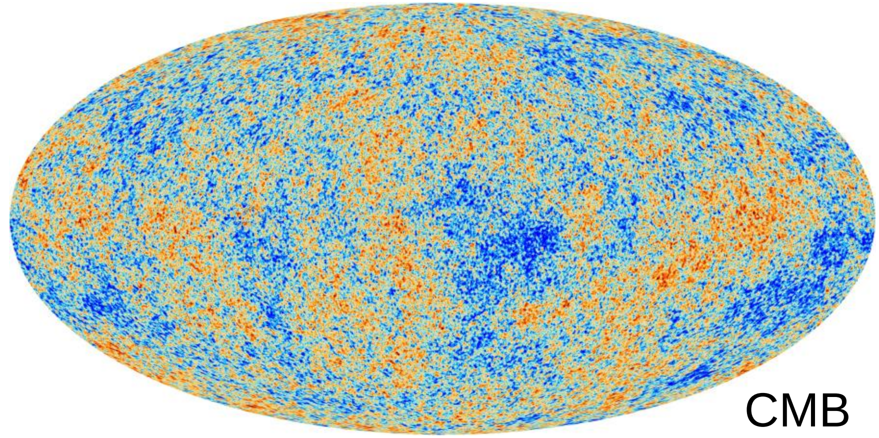
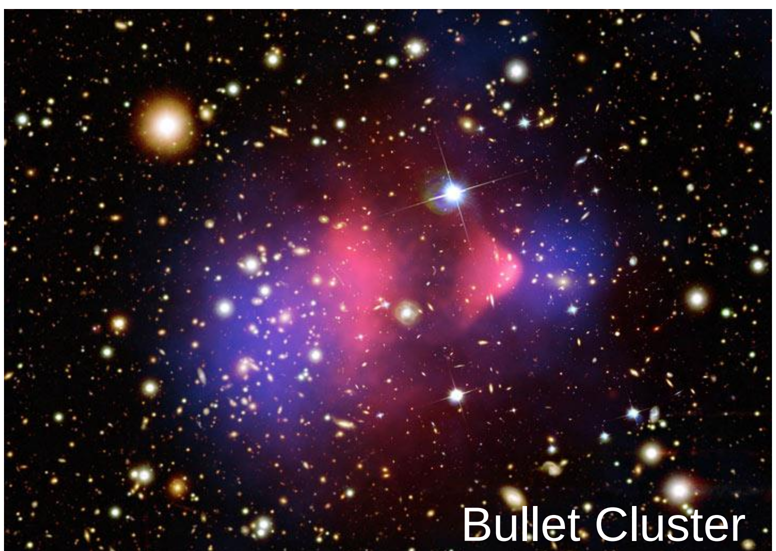
Dark Matter is Out There!



Galaxy Rotation

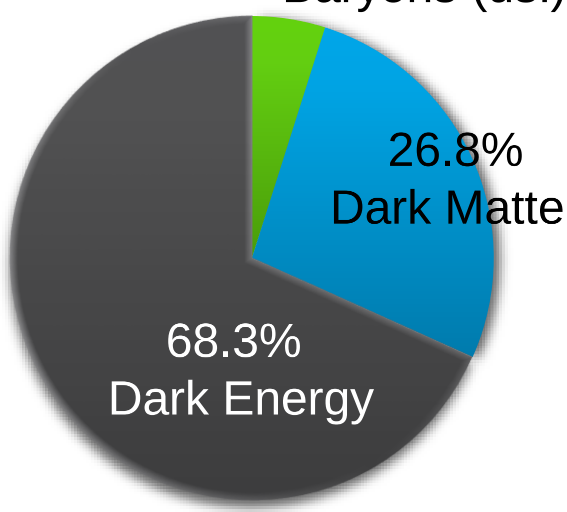


CMB



Bullet Cluster

4.9%
Baryons (us!)



DM Radio tunes into dark matter waves

- DM Radio is optimized to search for wave-like dark matter: Axions and Hidden Photons

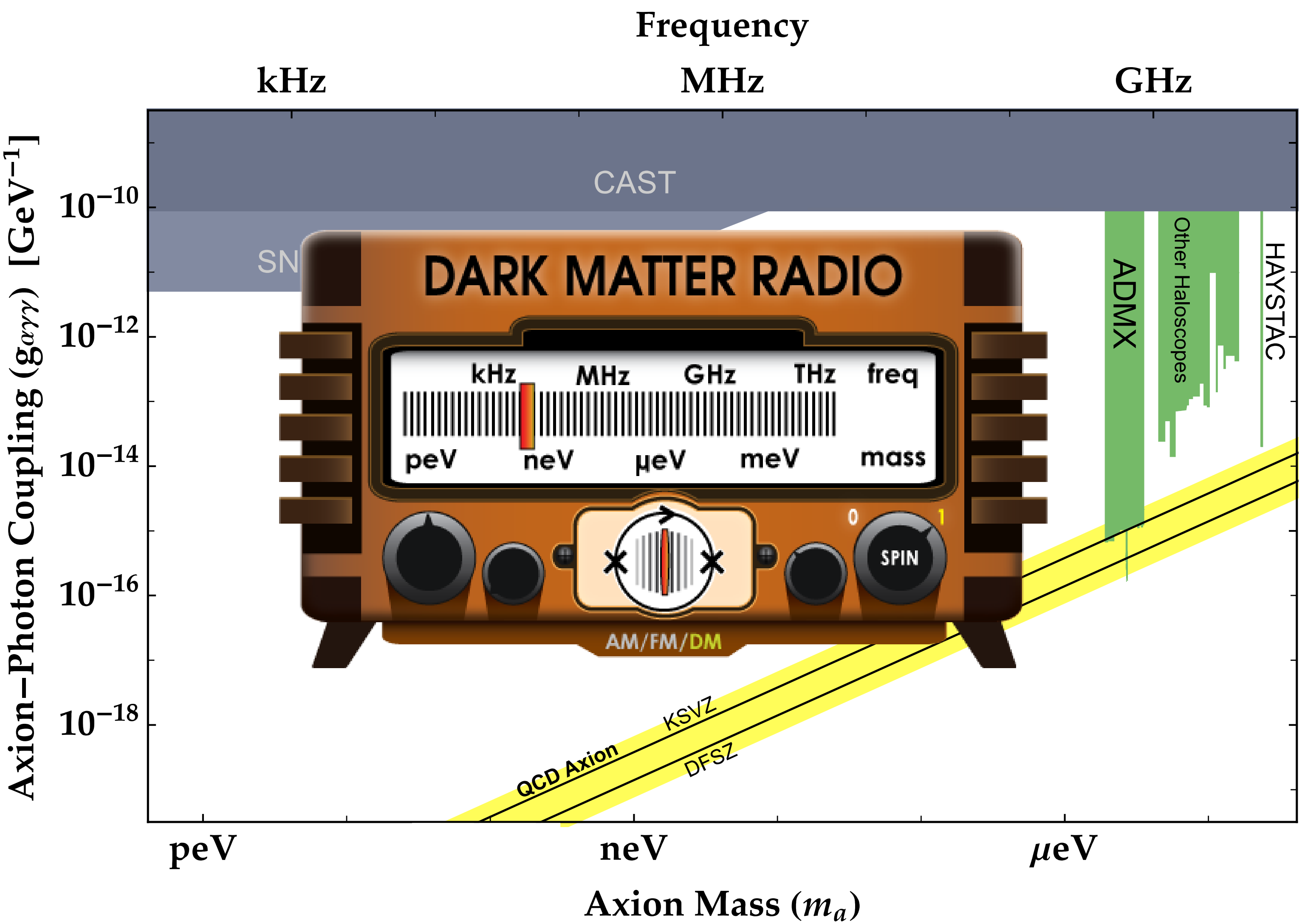
- Below 1 eV wavelengths are very long and the number density is big

$$\lambda_{\text{coherence}} \approx 100\,\text{km} \times (10^{-8}\text{eV}/m)$$

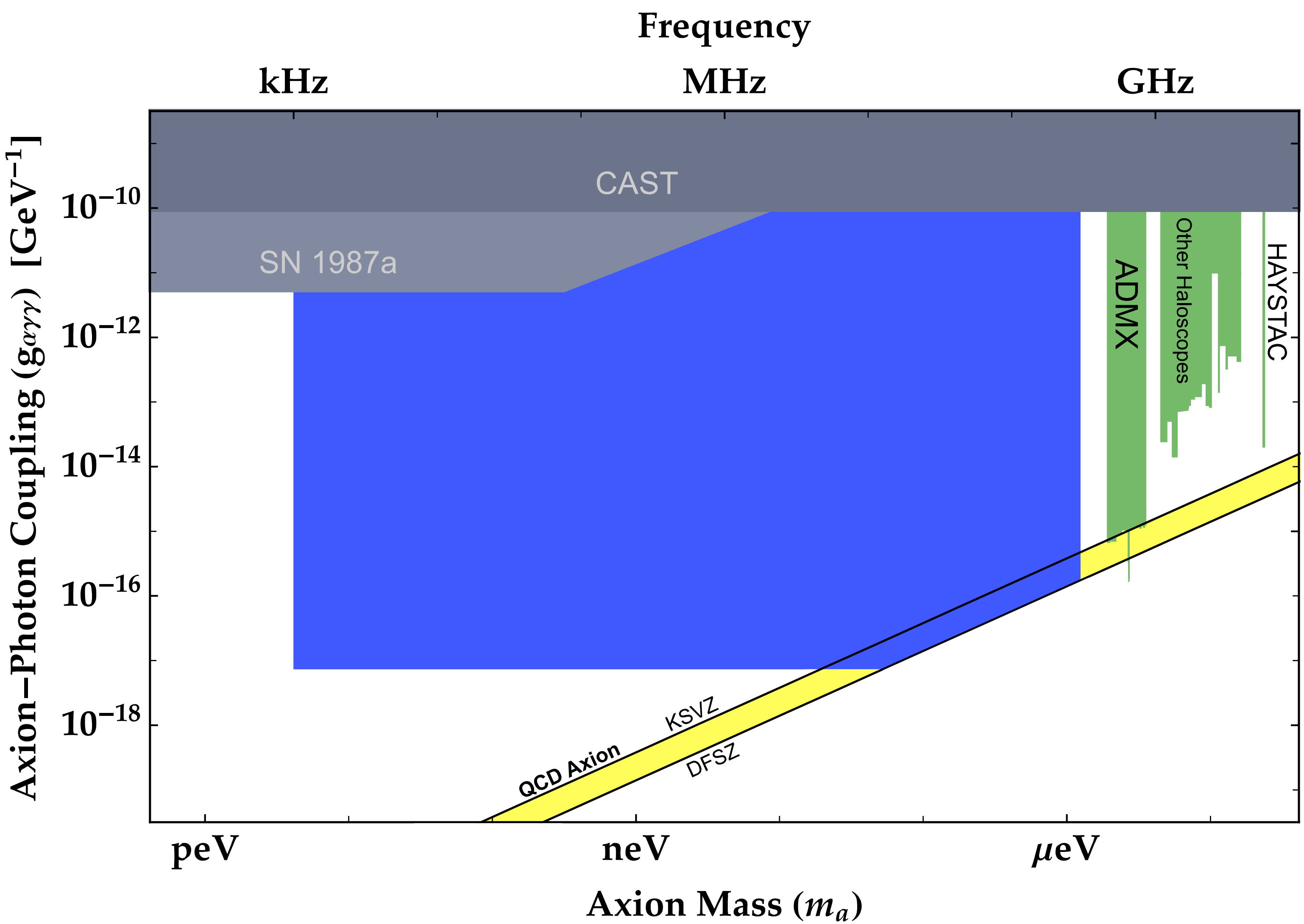
- Lumped-Element resonators give us an advantage of an extremely wide tuning range from 1 kHz to 300MHz!

- Quantum Sensors will allow us to probe a swath of the QCD Axion band

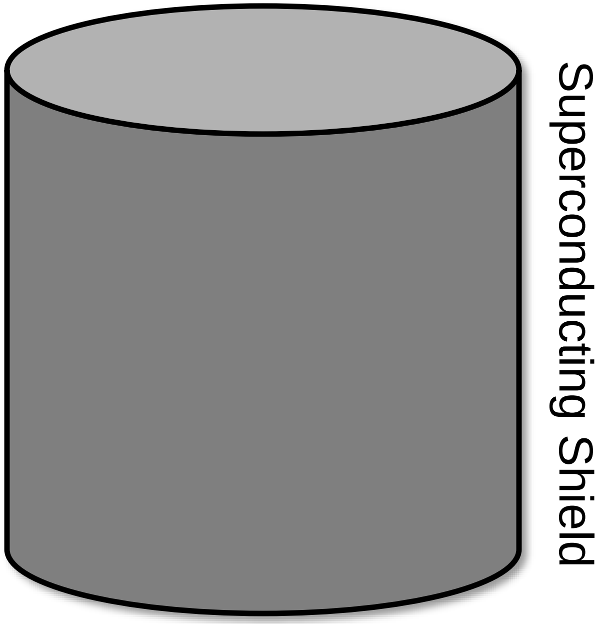
Lumped-element approach can tune a huge range



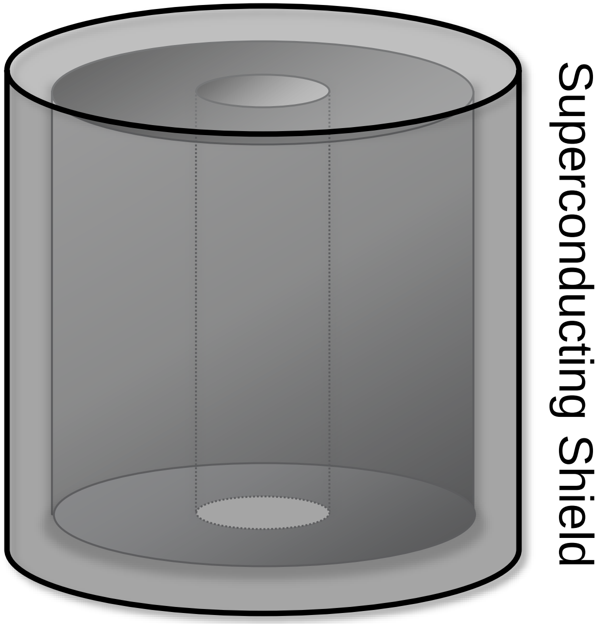
DM Radio will detect or rule-out axions in big area



Building up the DM Radio for axion detection

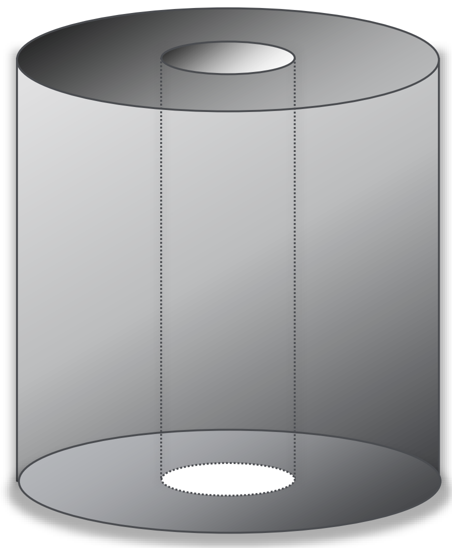


Building up the DM Radio for axion detection



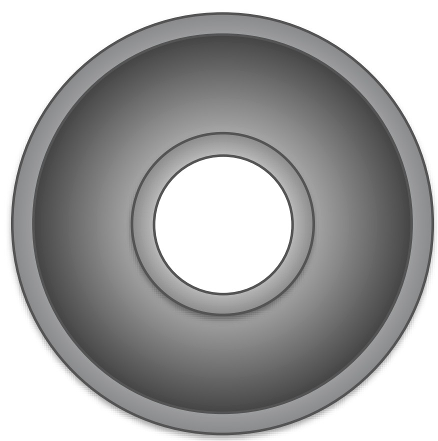
Building up the DM Radio for axion detection

Side View



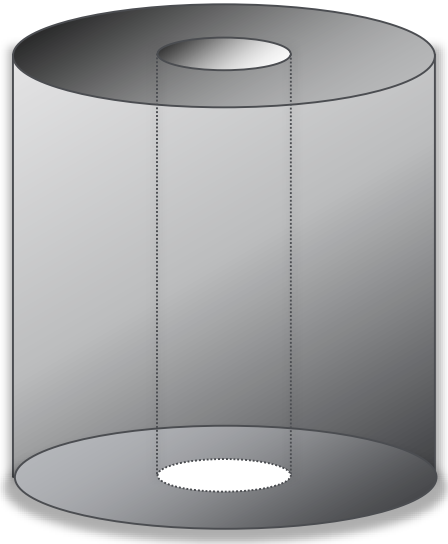
Toroidal Shell

Top Cutaway

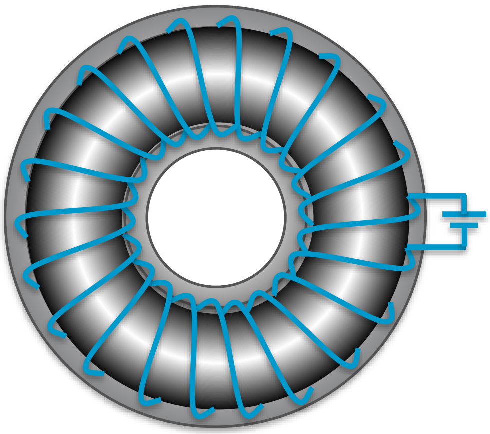


Building up the DM Radio for axion detection

Side View



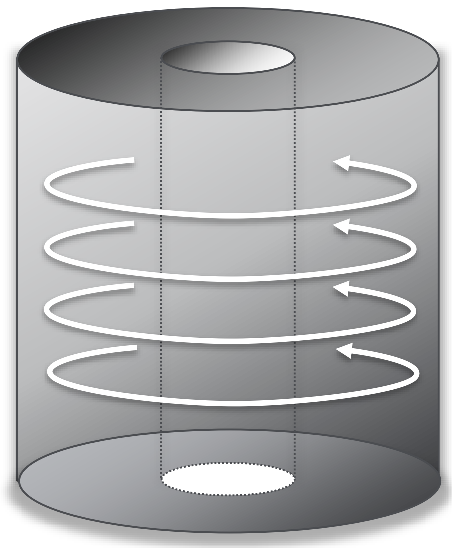
Top Cutaway



Add a toroidal magnet inside for conversion of axions to photon fields

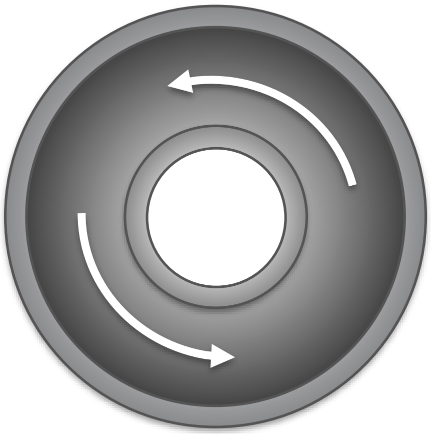
Building up the DM Radio for axion detection

Side View



B_0 toroid inside

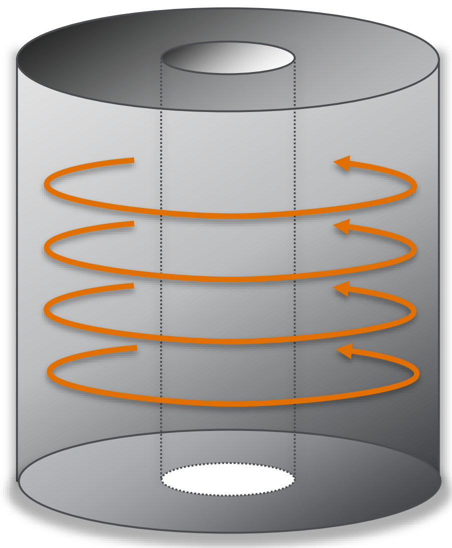
Top Cutaway



B_0
dc circulating field

Building up the DM Radio for axion detection

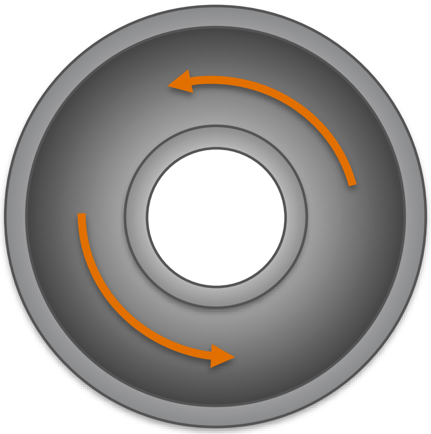
Side View



A coupled axion will create an oscillating current parallel to B_0

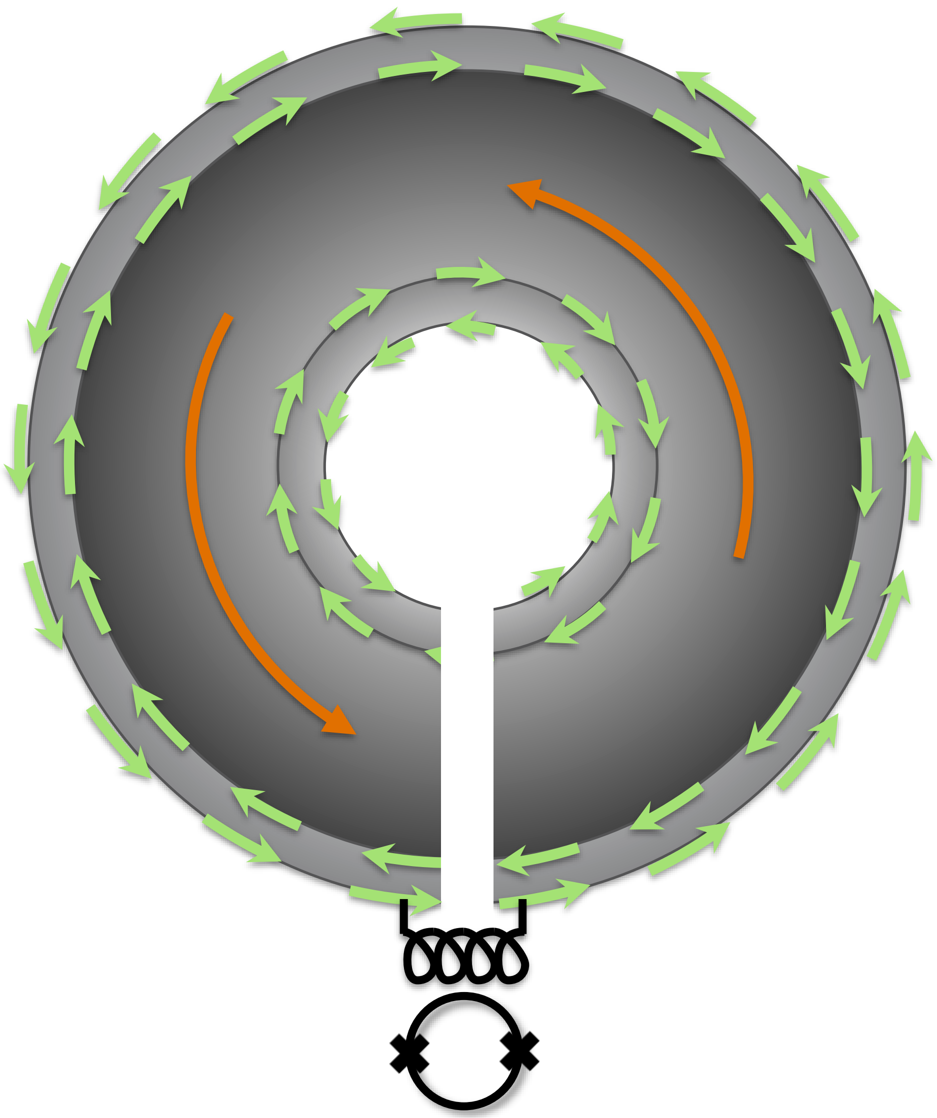
$$\vec{J}_a(t)$$

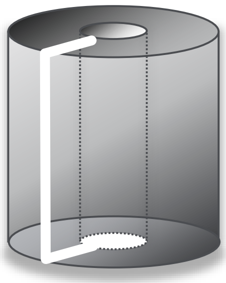
Top Cutaway



Building up the DM Radio for axion detection

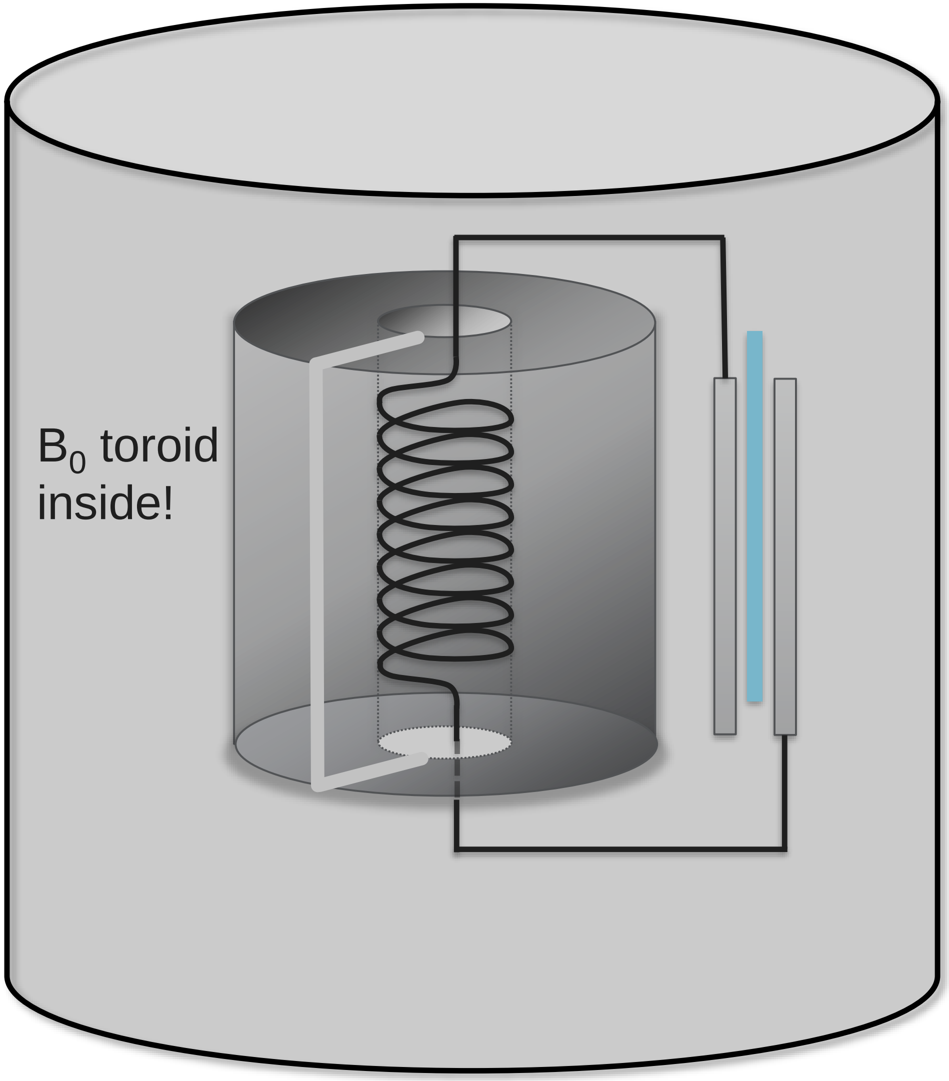
Top Cutaway

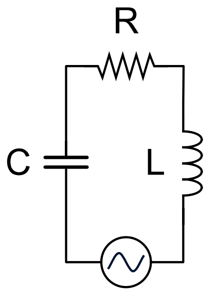




Side View

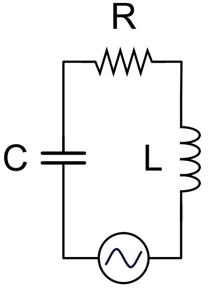
DM Radio is a lumped-element dark matter detector





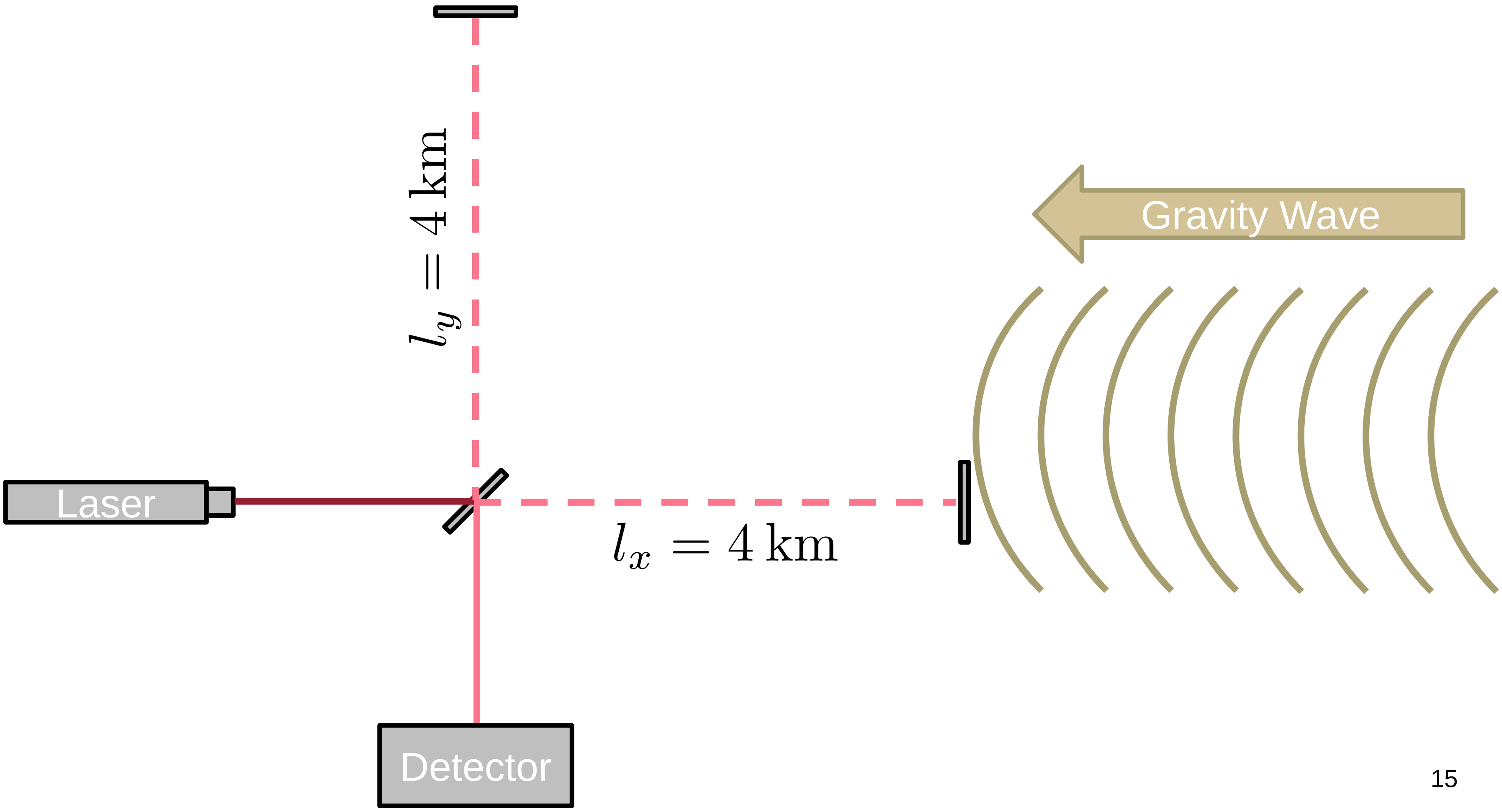
Quantum Readout of the DM Radio Oscillator

- Now we have a harmonic oscillator driven by a dark matter signal.
- Since this signal is small, we need to apply quantum techniques to sense it.
- Let's take a moment to look at LIGO for inspiration.



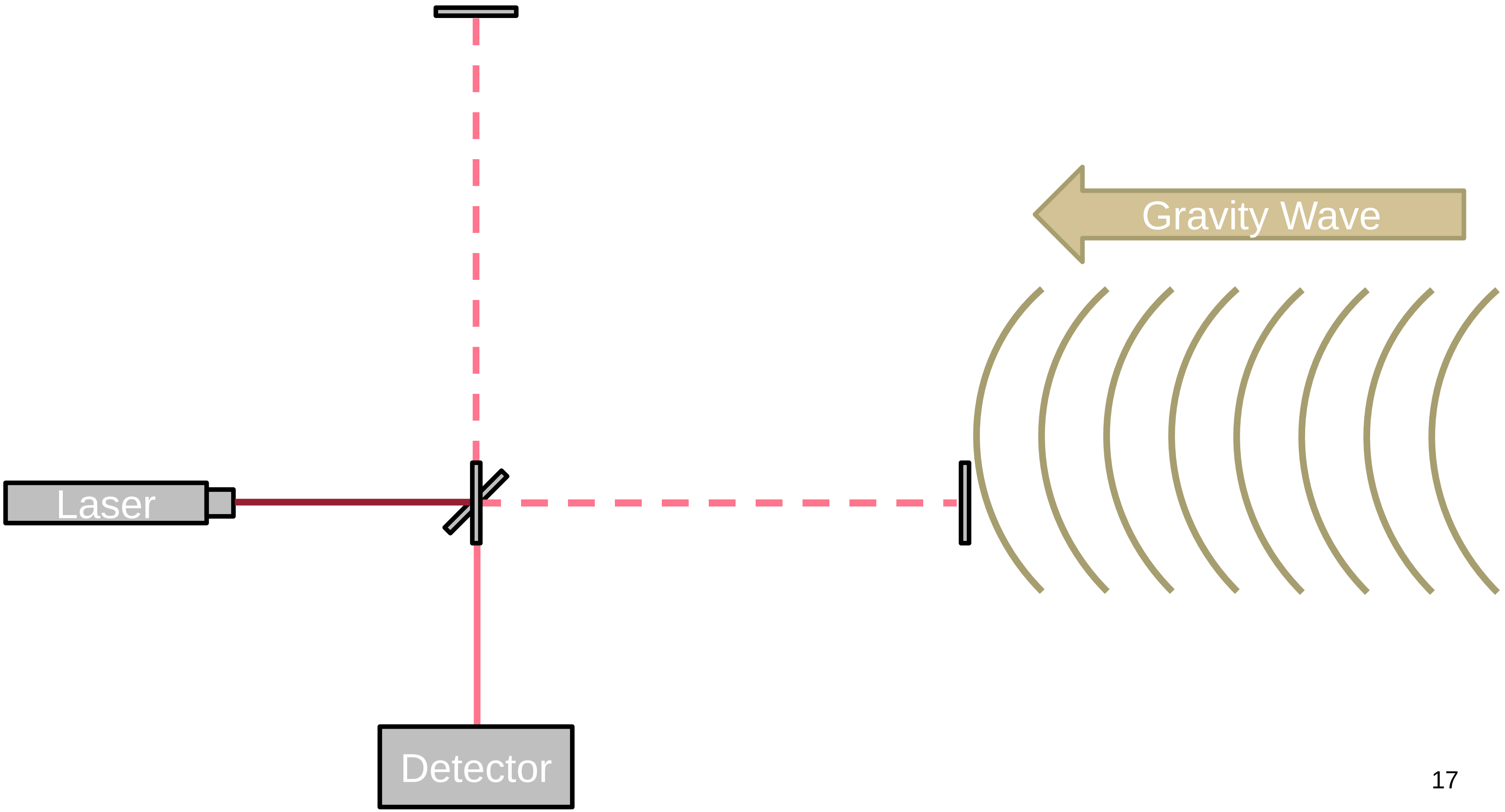
LIGO Basics

Laser **I**nterferometer **G**ravitational-Wave **O**bservatory

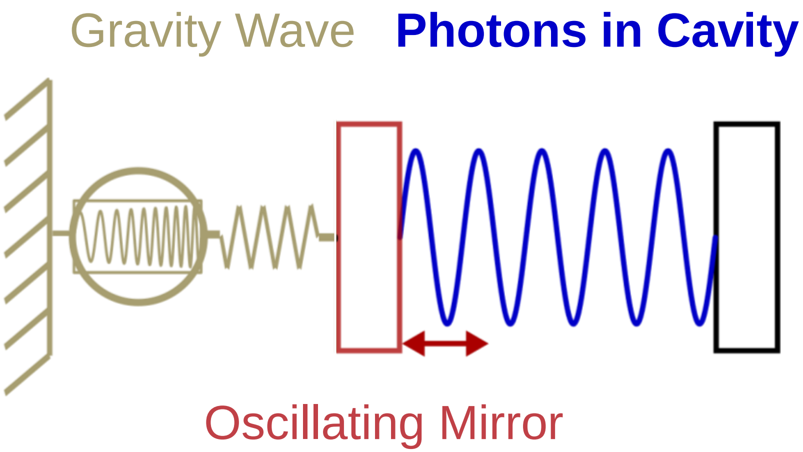


Two Sites for LIGO

Simplify LIGO to Get the Basic Physics



LIGO Exploits the Interplay Between Two Oscillators

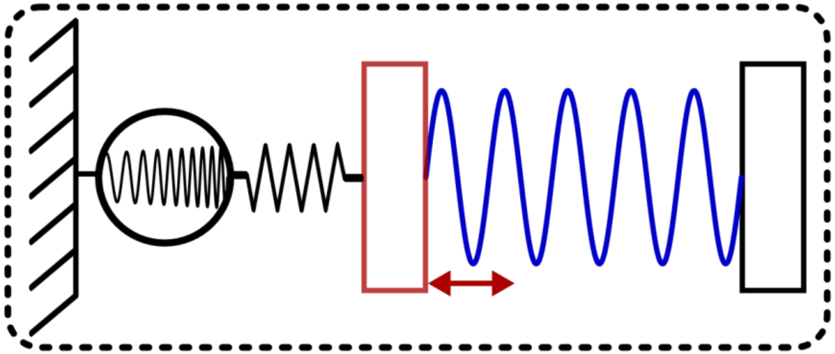


$$\hat{H} = \hbar\omega_a(\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \hbar\omega_b(\hat{b}^\dagger\hat{b} + \frac{1}{2}) + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})$$

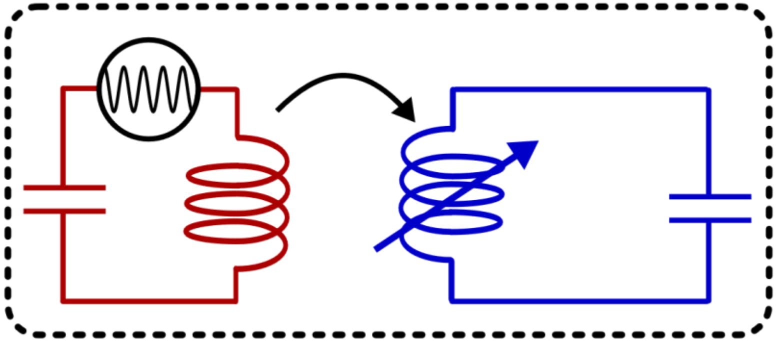
Microwave Circuits Built with the Same Physics

We can borrow the lessons learned from LIGO and apply it to fabricated microwave circuits because the physics is the same!

Optical-Mechanical Resonator



Microwave Circuit Resonator

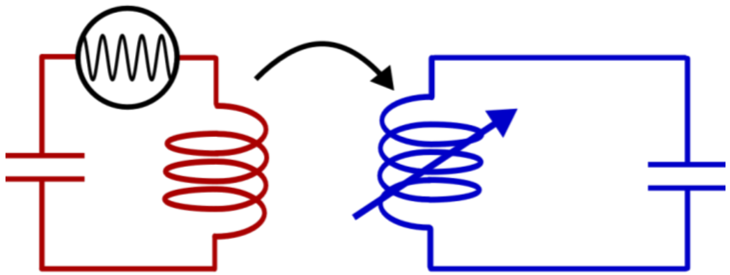


$$\hat{H} = \hbar\omega_a(\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \hbar\omega_b(\hat{b}^\dagger\hat{b} + \frac{1}{2}) + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})$$

Microwave Circuits Built with the Same Physics

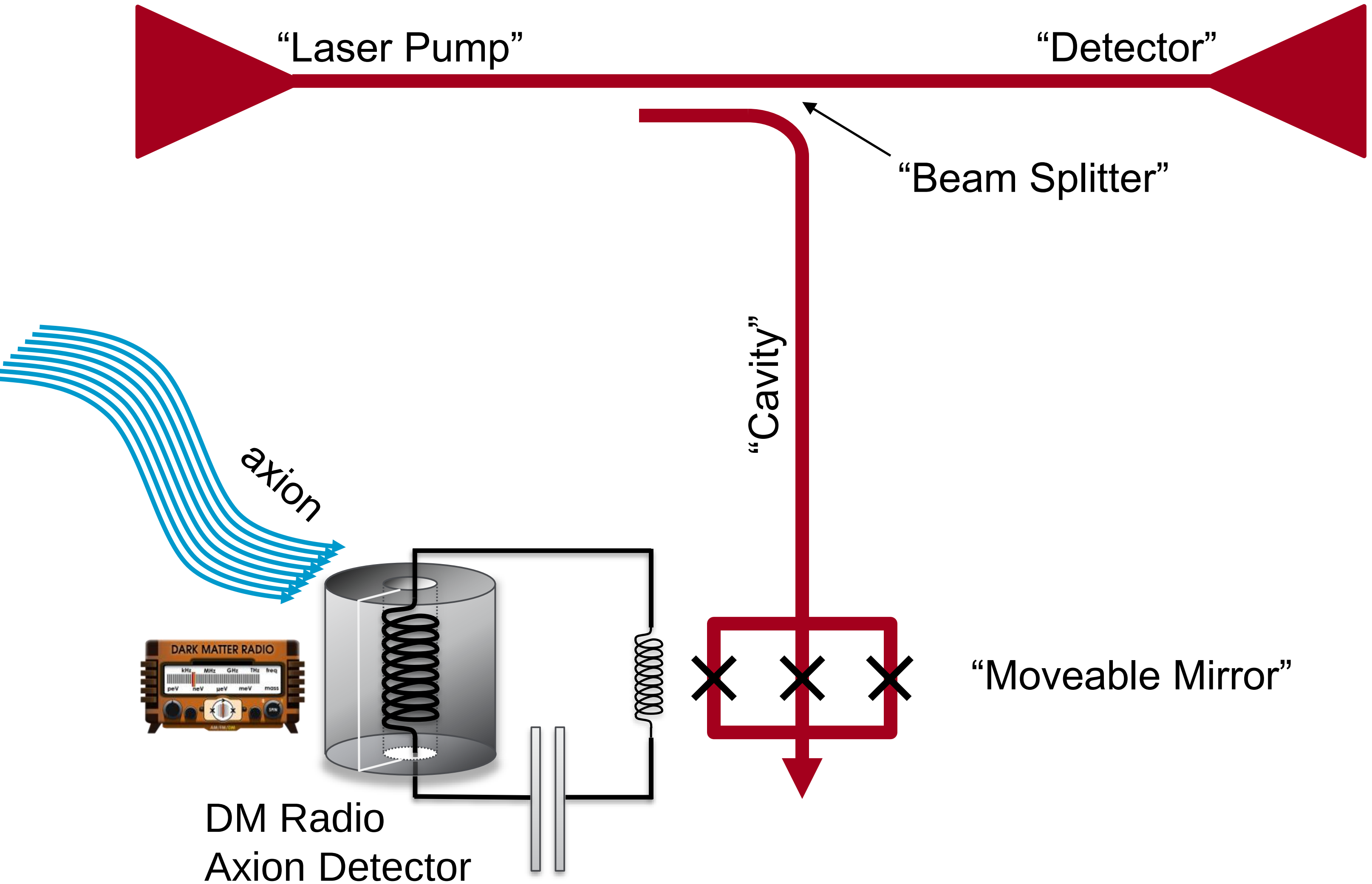
- Dark matter excites a resonance (kHz – MHz) [red circuit]
- Couples to microwave resonator (GHz) [blue circuit]
- Up-conversion happens due to changes in flux through variable inductor (“moveable mirror”)

Microwave Circuit Resonator

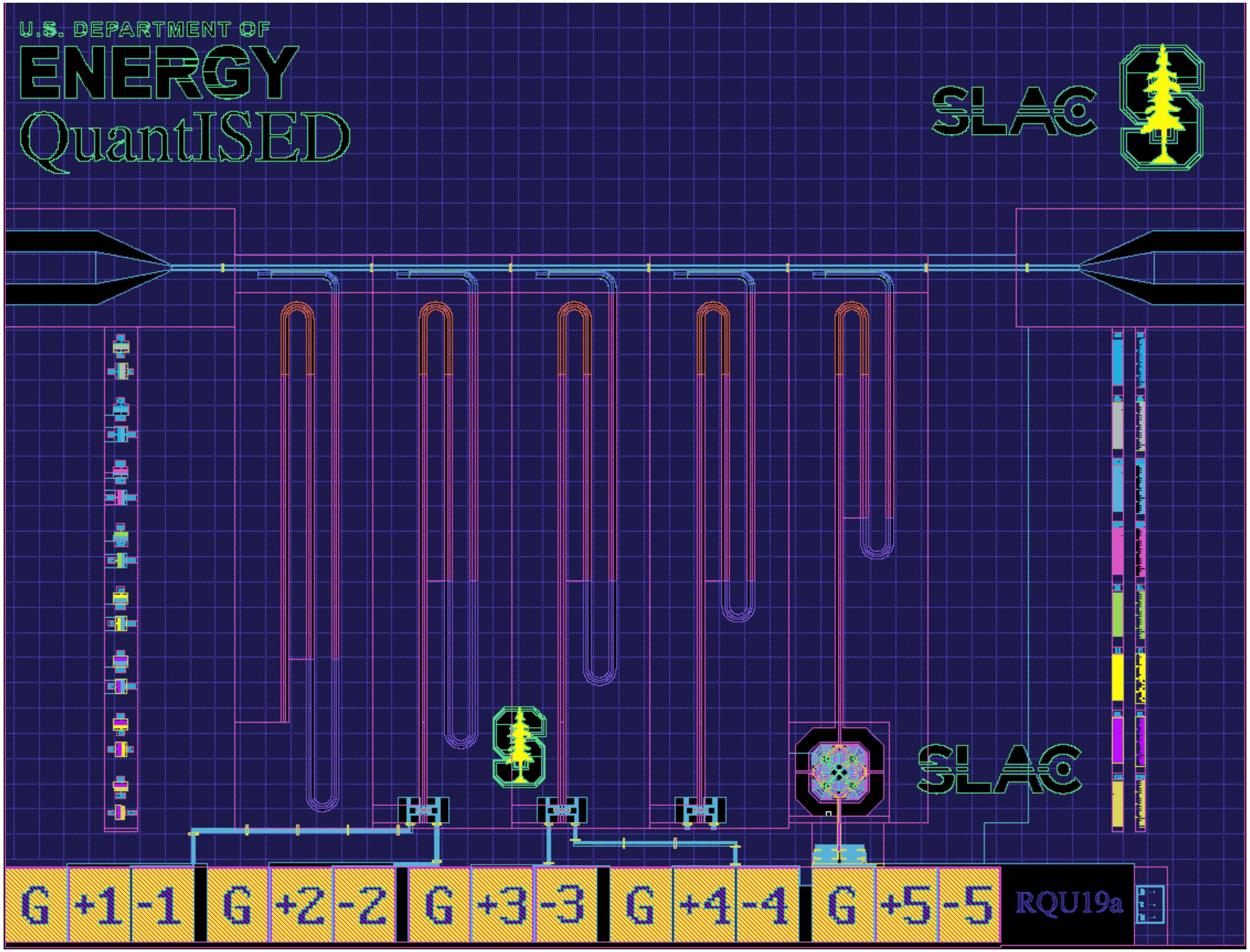


$$\hat{H} = \hbar\omega_a(\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \hbar\omega_b(\hat{b}^\dagger\hat{b} + \frac{1}{2}) + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})$$

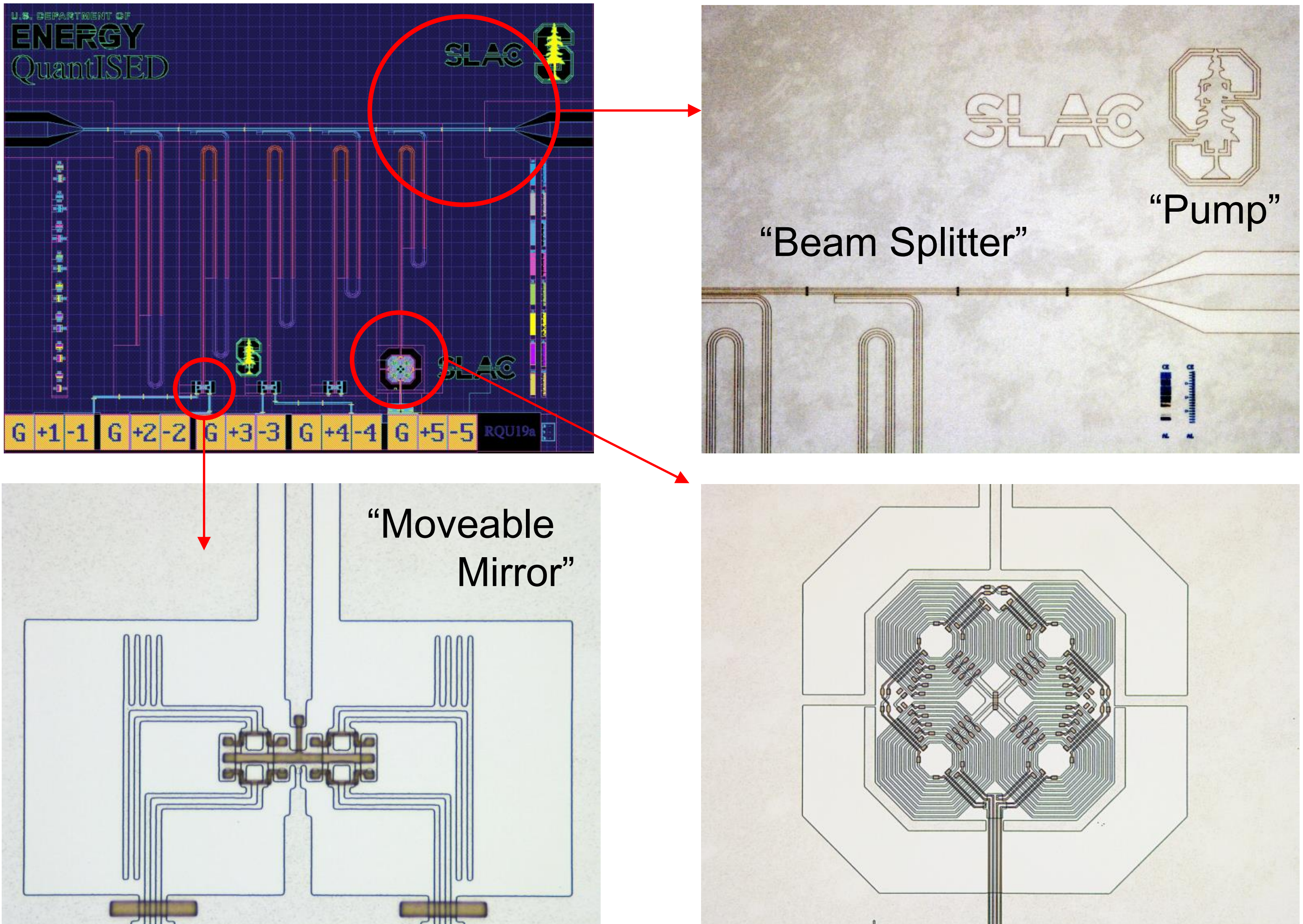
LIGO as a Microwave Circuit Model for Dark Matter



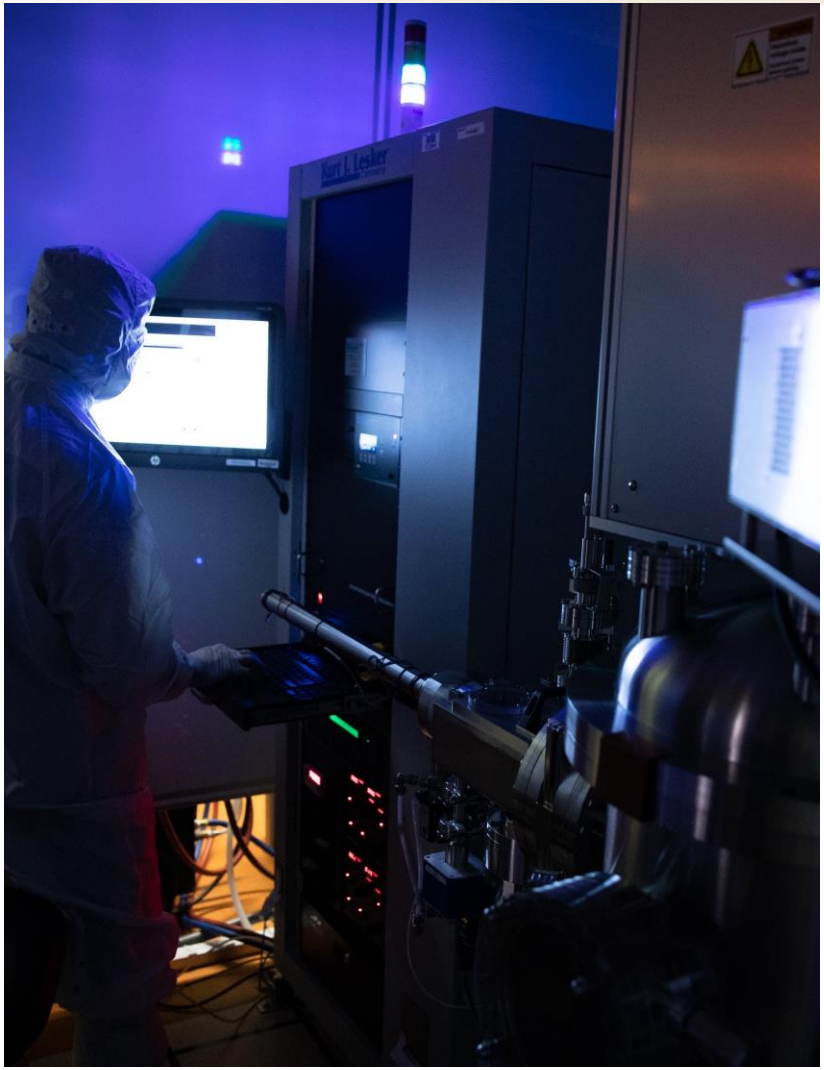
Initial Designs for RF Quantum Upconverter

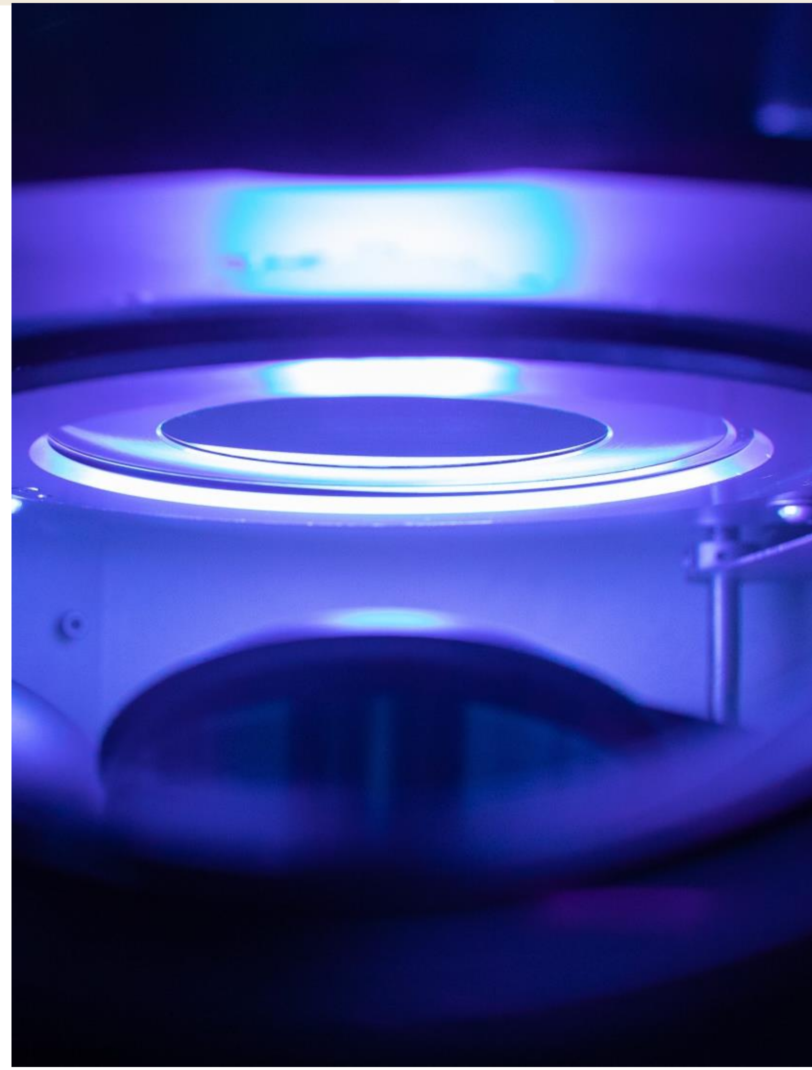


Prototype Fabrication of RQUs

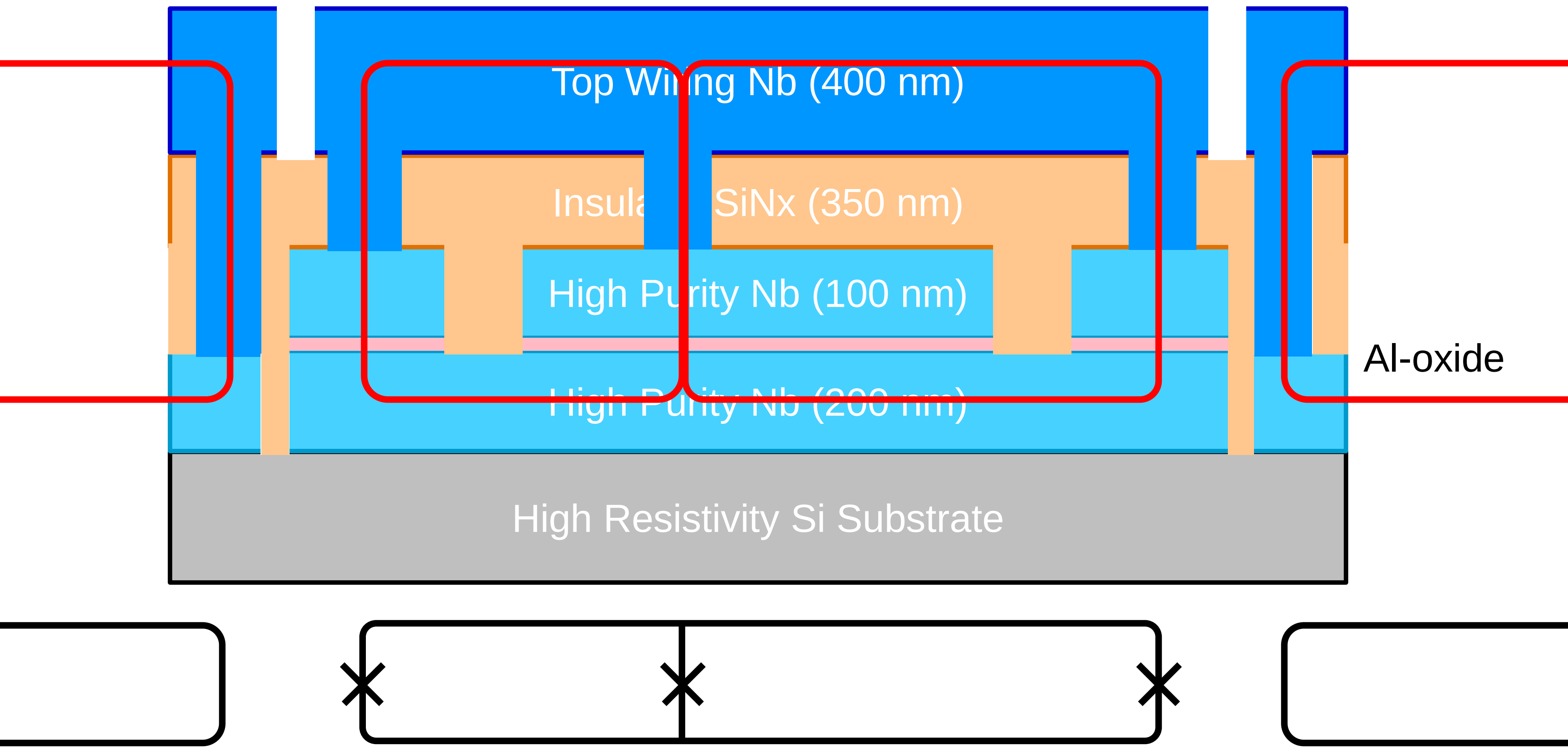


Thin Film Fabrication for RQUs





Fabrication Layers for RQUs with Trilayer Oxidation



Conclusions

- RF Quantum Upconverters are based on the same physics from experiments like LIGO
- Low frequency oscillator (large occupation number state) coupled to a high frequency oscillator (small occupation number state)
- Thin film fabrication requires very clean environments, pure materials, and tight controls on the chemistry and energy of the deposition and etches.
- Stephen's Talk will demonstrate the power of RQUs