Fundamental Physics with the LNF Cold-lab

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Outline

- Stimulating Uncertainty …
- Amplifying the Quantum Vacuum with Superconducting Circuits
- Quantum Mechanics on a Superconducting Circuit
- DCE
- Superconducting Circuits at COLD
- Hawking Radiation

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

Colloquium: Stimulating uncertainty: Amplifying the quantum vacuum with superconducting circuits

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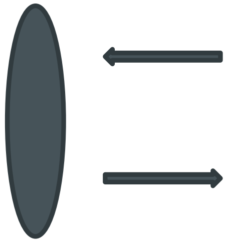
The ability to generate particles from the quantum vacuum is one of the most profound consequences of Heisenberg's uncertainty principle. Although the significance of vacuum fluctuations can be seen throughout physics, the experimental realization of vacuum amplification effects has until now been limited to a few cases. Superconducting circuit devices, driven by the goal to achieve a viable quantum computer, have been used in the experimental demonstration of the dynamical Casimir effect, and may soon be able to realize the elusive verification of analog Hawking radiation. This Colloquium article describes several mechanisms for generating photons from the quantum vacuum and emphasizes their connection to the well-known parametric amplifier from quantum optics. Discussed in detail is the possible realization of each mechanism, or its analog, in superconducting circuit systems. The ability to selectively engineer these circuit devices highlights the relationship between the various amplification mechanisms.

Amplifying the Quantum Vacuum with Superconducting Circuits

"Mirror"



$a_{in}(\omega)$ Ingoing wave

$a_{out}(\omega)$ Outgoing wave

Constant boundary condition

$a_{out}(\omega)=R(\omega)a_{in}(\omega)$

$R(\omega)$ Reflection coefficient

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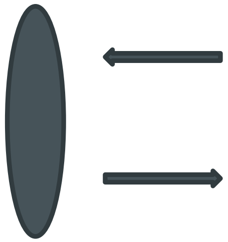

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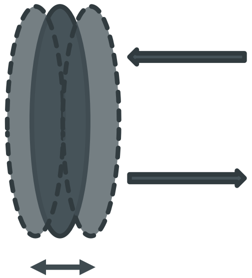
$a_{out}(\omega)$ Outgoing wave

Constant boundary condition

$a_{out}(\omega)=R(\omega)a_{in}(\omega)$

$R(\omega)$ Reflection coefficient

"Mirror driven at 2ω"



$a_{in}(\omega)$ Ingoing wave

$a_{out}(\omega)$ Outgoing wave

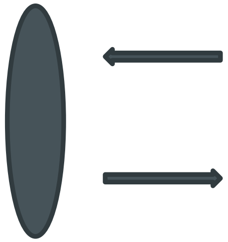
Time dependent boundary condition

$a_{out}(\omega)=R(\omega)a_{in}(\omega)+S(\omega)a^{+}_{in}+\ldots$

$R(\omega)$ Reflection coefficient

Amplifying the Quantum Vacuum with Superconducting Circuits

"Mirror"



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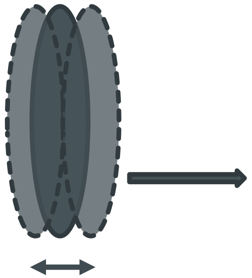


$|in\rangle = |0\rangle$

$a_{out}(\omega)\ |in\rangle = S(\omega)\ |1\rangle$

Time dependent boundary condition

$a_{out}(\omega)=R(\omega)a_{in}(\omega)+S(\omega)a^{+}_{in}+\ldots$

$R(\omega)$ Reflection coefficient

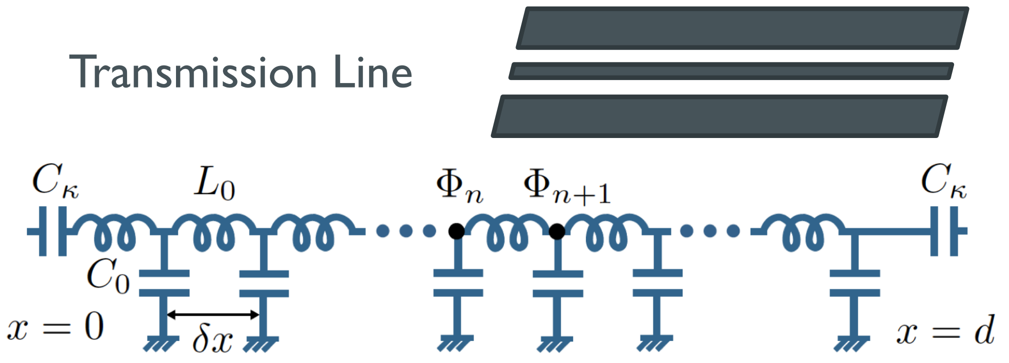
$S(\omega)$ Parametric amplification of quantum vacuum

Quantized Modes of the Transmission Line Resonator

Kinetic term

$$L = \frac{1}{2}\sum_{k=1,N}\left[\Delta z C_0 \dot{\phi}_k^2 - \frac{(\phi_{k+1}-\phi_k)^2}{\Delta z L_0}\right]$$

Potential term



Charge Q and flux ϕ are conjugate variables

$$q_{k\neq 0} = \frac{\partial L}{\partial \dot{\phi}_k} = \Delta z C_0 \dot{\phi}_k$$

Quantization condition

$$[Q(x), \phi(x')] = i\hbar\delta(x - x')$$

[Outgoing wave + Ingoing wave]

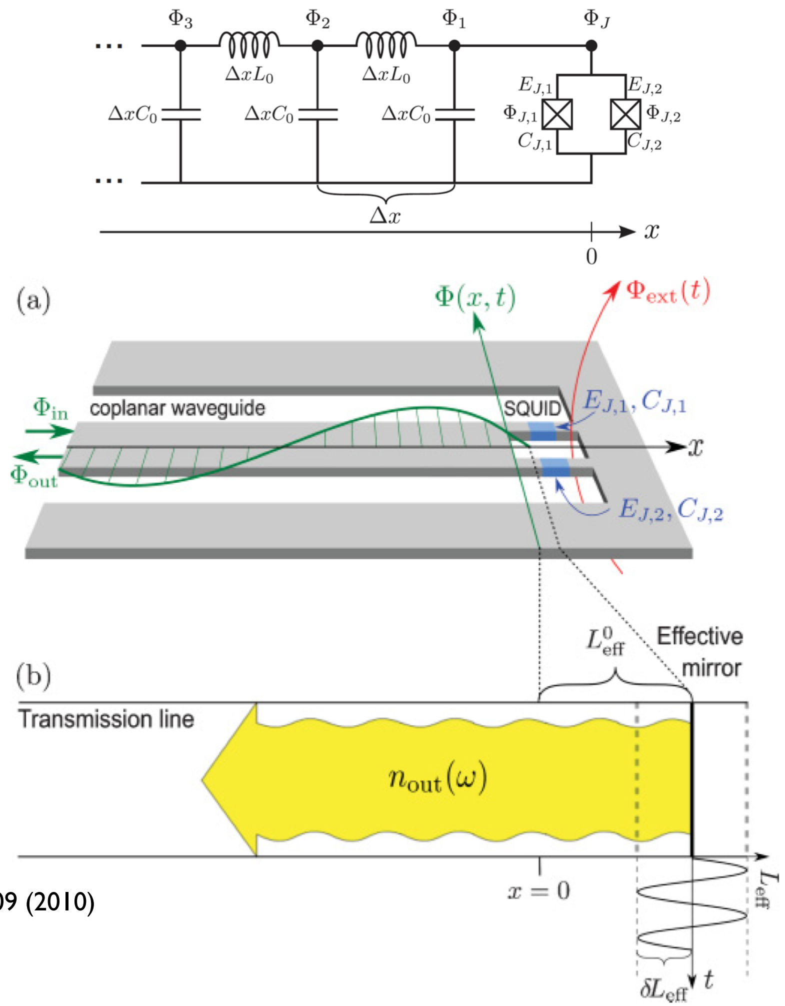
$$\phi(x,t) = \sqrt{\frac{\hbar Z_0}{4\pi}}\int_0^\infty \frac{d\omega}{\sqrt{\omega}}\left[a^{out}(\omega)\exp\left[-i(\omega t - kx)\right] + a^{in}(\omega)\exp\left[-i(\omega t + kx)\right]\right] + h.c.$$

Dynamical Casimir Effect in Superconducting Microwave Circuits

Experiment on a SC circuit: the "Mirror" is a SQUID. It imposes a time dependent boundary condition in the CPW. The SQUID is driven by external flux bias at frequency ω_d.

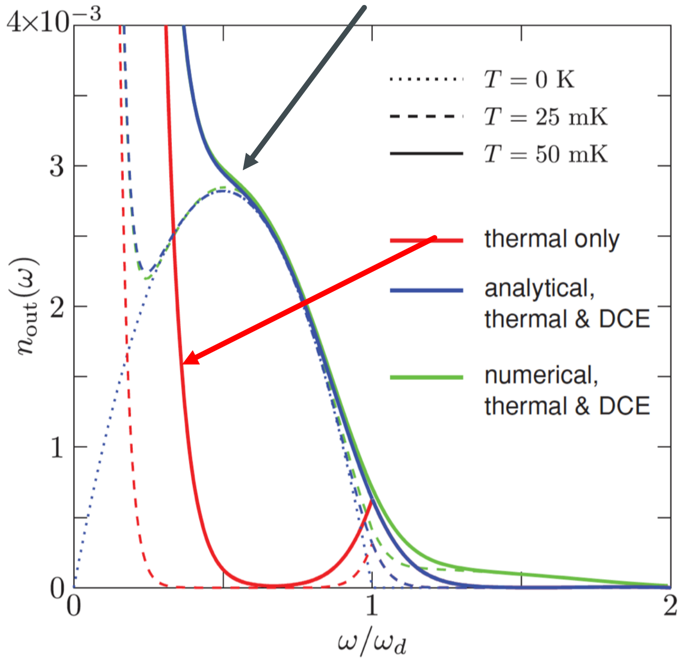
Vacuum →

Radiation ←



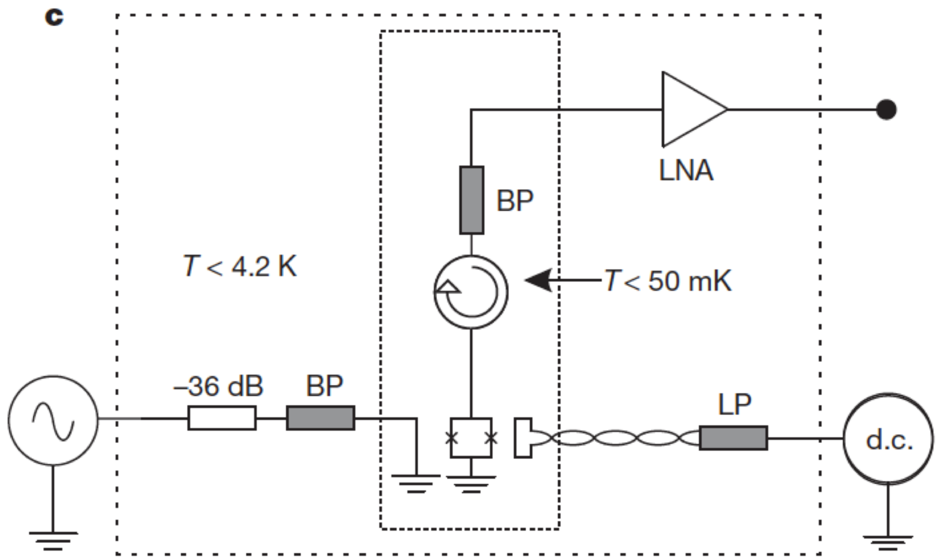
Predicted photon spectrum

DCE photon peaked at $\omega_d/2$

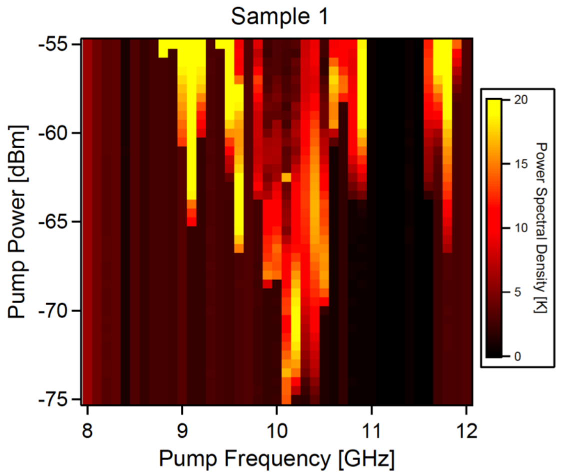


Johansson Johansson Wilson Nori PHYSICAL REVIEW A 82, 052509 (2010)

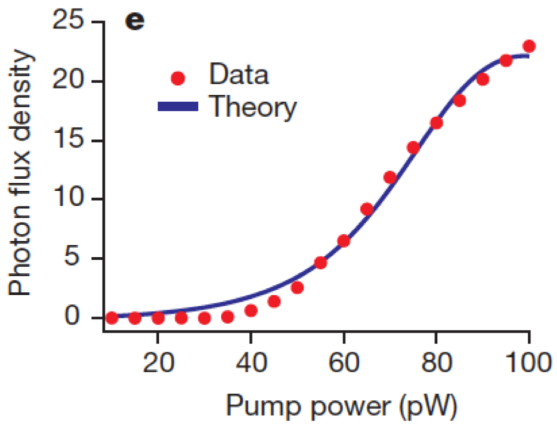
Experimental Measurement of DCE in a SC Circuit



Observed power at $\omega_d/2$

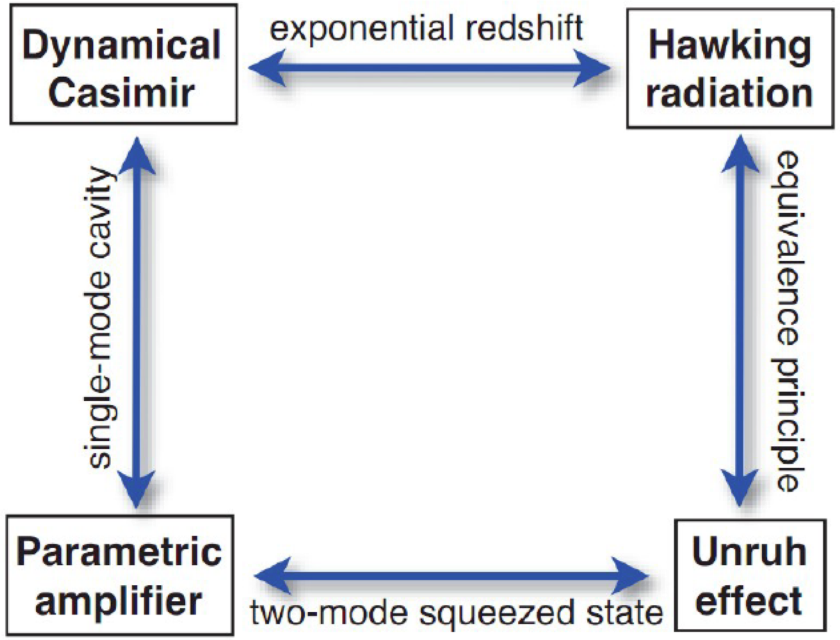


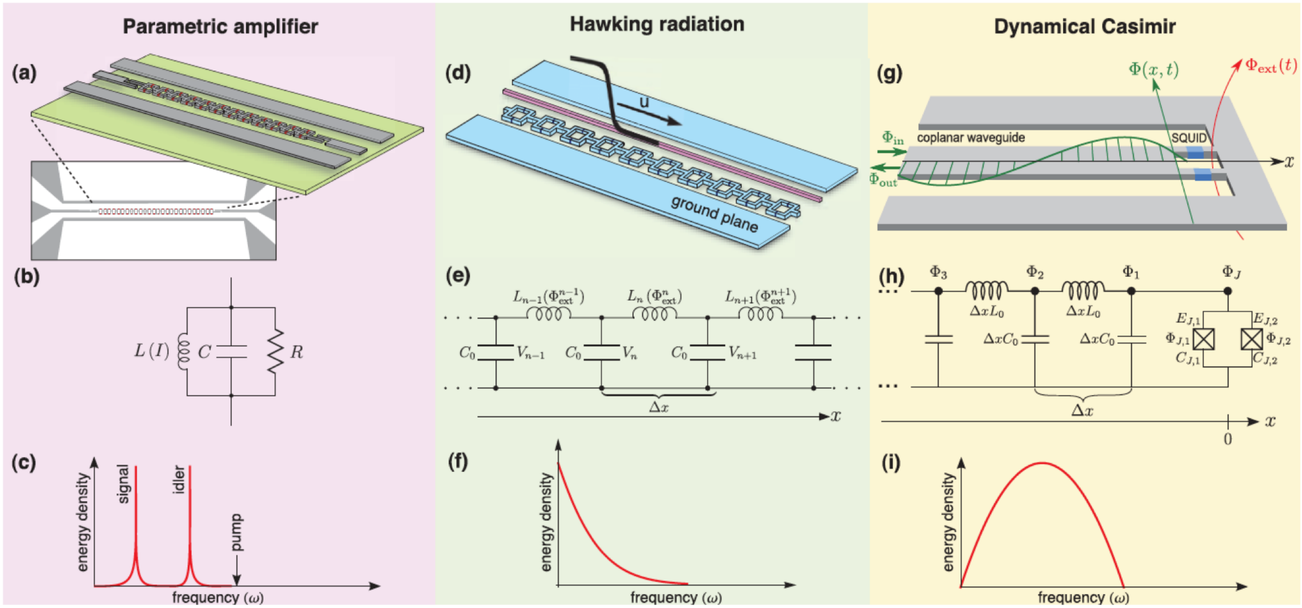
Data/Theory comparison of photon flux



Wilson, C., Johansson, G., Pourkabirian, A. *et al.* Observation of the dynamical Casimir effect in a superconducting circuit. *Nature* **479,** 376–379 (2011). https://doi.org/10.1038/nature10561

Superconducting Circuits Implementation of Vacuum Amplification

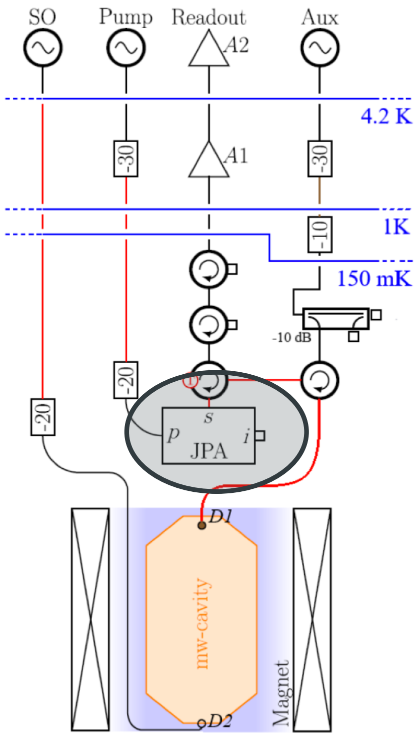


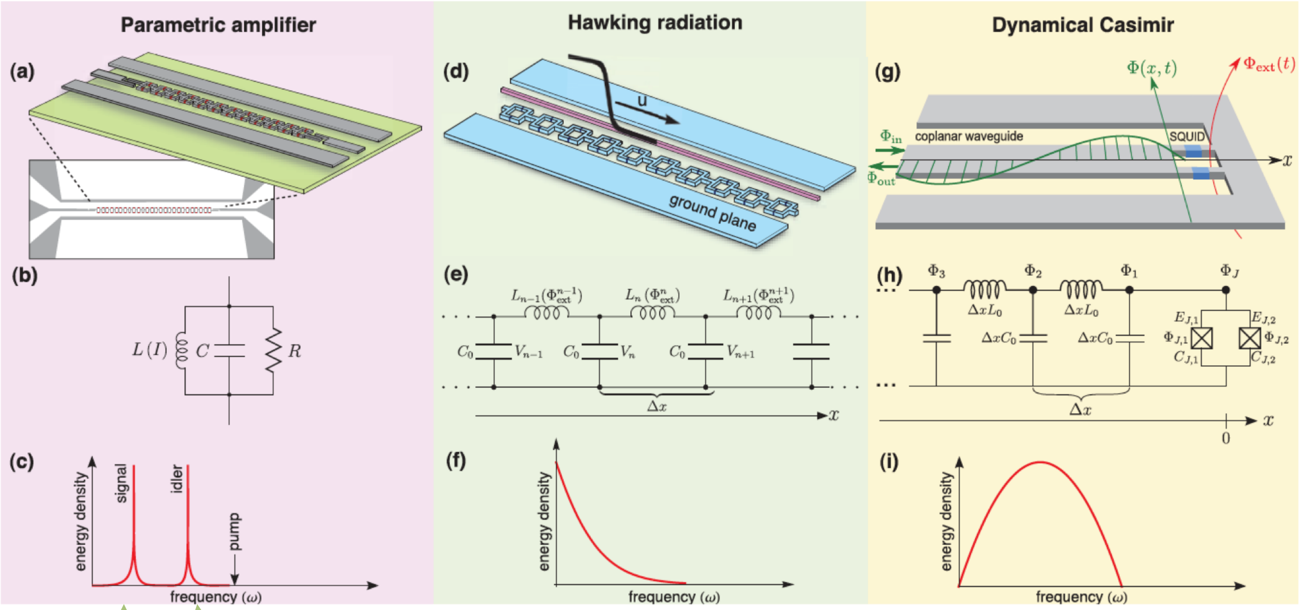


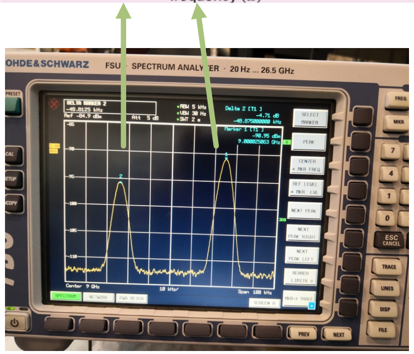
Nation et al. REVIEWS OF MODERN PHYSICS, VOLUME 84, 2012

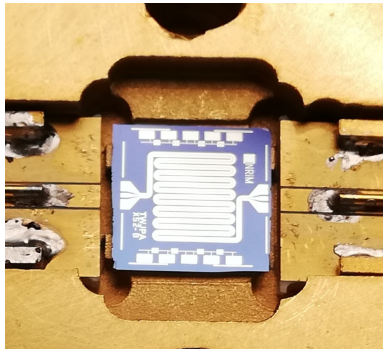
Superconducting Circuits at COLD Laboratory

QUAX

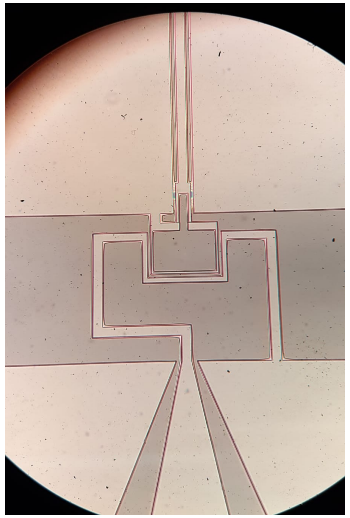


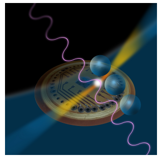






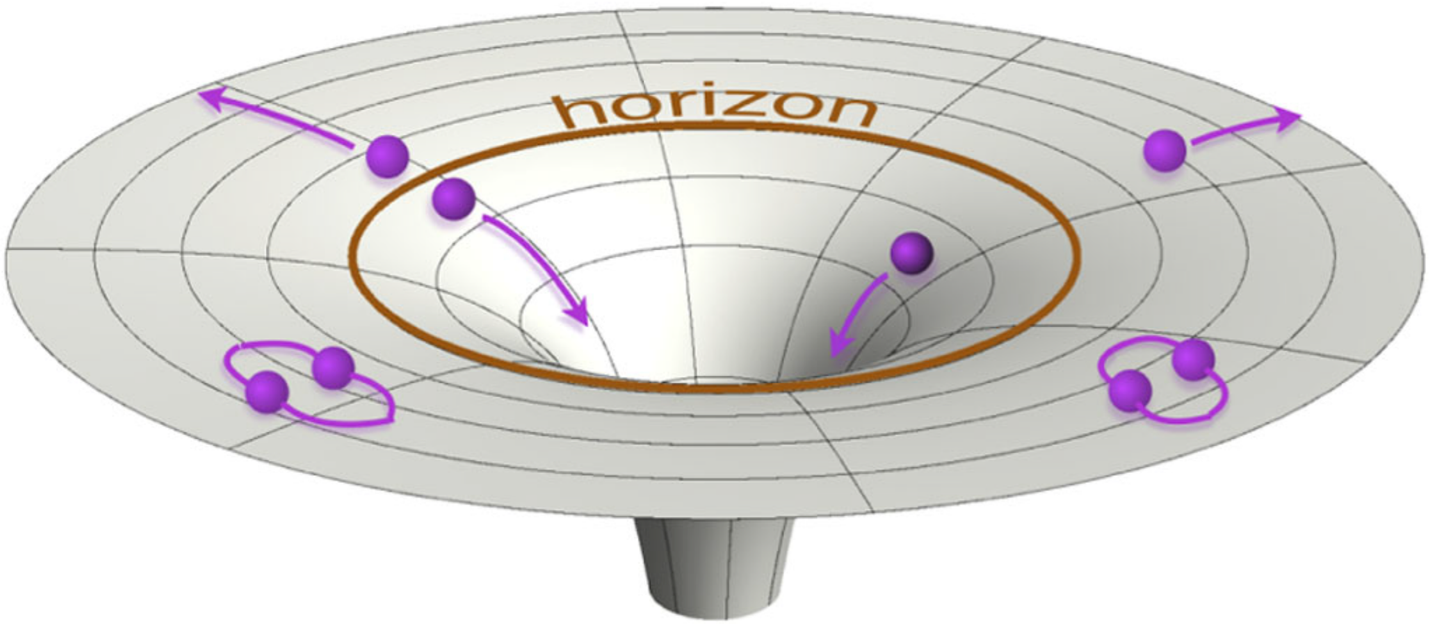
DART WARS





SIMP

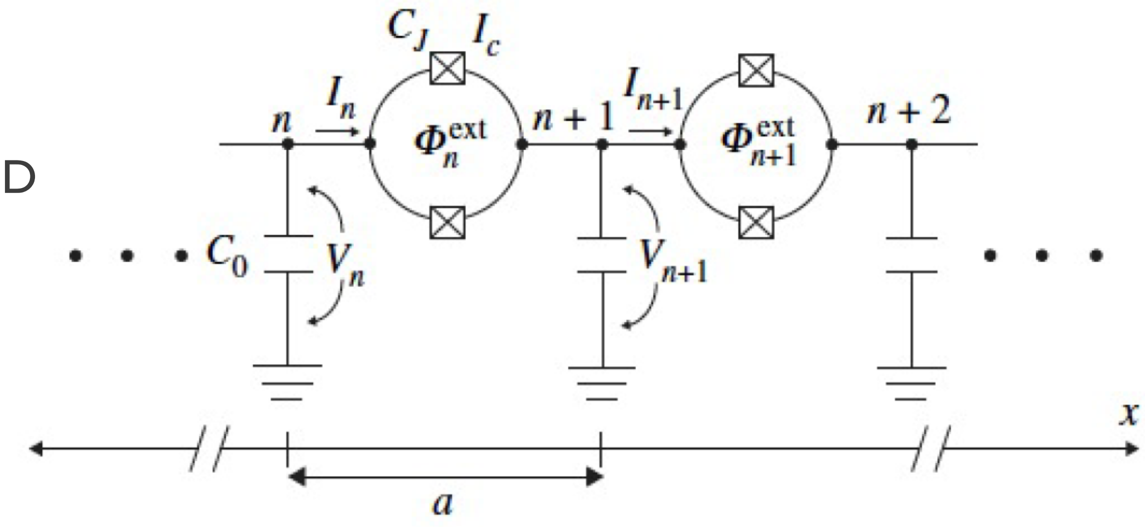
HAWKING Radiation



M. P. Blencowe, H. Wang - Phil Trans. R. Soc. A**378** 201900224 (2020) - (2003.00382)

A schematic view of a dc-SQUID array transmission line (circuitry providing the space-time dependent flux bias not shown)

Transmission line with DC SQUID as inductances



NB - JJ elements (crossed boxes) have the same I_c and C_J.

dc-SQUIDs are threaded with an external magnetic flux varying from cell to cell and in time

Dynamics is more conveniently expressed in terms of the 'phase' coordinate φ_n associated with the voltages across C_0

Use usual flux variable

$$V_n = \frac{\Phi_0}{2\pi}\frac{\mathrm{d}\varphi_n}{\mathrm{d}t} \qquad \left(\Phi_0 = \frac{h}{2e}\right)$$

Long wavelength ($\lambda \gg a$) dynamics $\rightarrow$ continuum limit $\rightarrow$ phase 'field' $\varphi(x,t)$ $\rightarrow$ wave equation (see Blencowe & Wang):

Determine the wave equation

$$-\frac{\partial^2\varphi}{\partial t^2} + \frac{\partial}{\partial x}\left[c^2(x,t)\frac{\partial\varphi}{\partial x}\right] = 0 \qquad (1)$$

where the space-time dependent e.m. wave phase speed is:

Space time dependent speed
Depends on applied flux bias Φ^{ext}

$$c(x,t) = c_0 \sqrt{\cos\left(\pi \frac{\Phi^{\,\text{ext}}}{\Phi_0}\right)}$$

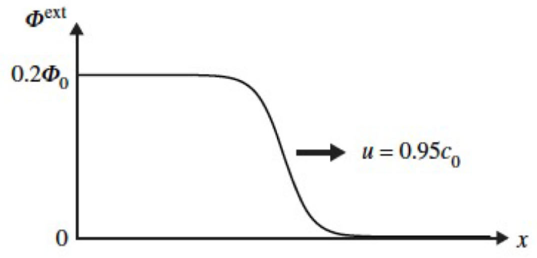
with

$$c_0 = c(x,t)\,|_{\Phi^{\,\text{ext}}=0} = a\sqrt{4\pi \frac{I_c}{\Phi_0\, C_0}}$$

Apply "travelling" flux bias at speed u

Propagating flux front moves with speed u $\rightarrow$ going into comoving frame

$$(x,t) \rightarrow (x - u\,t, t)$$



Wave equation in the comoving frame

the wave equation becomes

$$\left\{-\frac{\partial^2}{\partial t^2}+2\,u\,\frac{\partial^2}{\partial x\,\partial t}+\frac{\partial}{\partial x}\left[c^2(x)-u^2\right]\frac{\partial}{\partial x}\right\}\varphi=0 \qquad (2)$$

that can expressed in the general covariant form ($g=\det g_{\mu\nu}$)

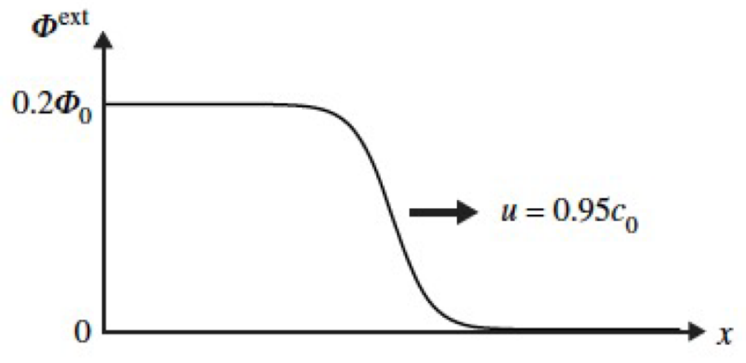
$$\frac{1}{\sqrt{-g}}\,\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\,\partial_\nu\,\varphi\right)=0$$

with effective metric

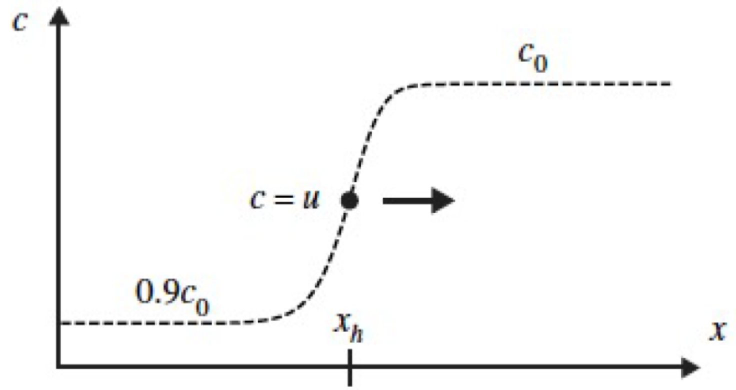
$$g^{\mu\nu}=\frac{1}{c(x)}\begin{pmatrix}-1 & u\\ u & c^2(x)-u^2\end{pmatrix}$$

i.e., event horizon ($g_{00}=0$) where $c(x)=u$

Example - a flux step of magnitude $\Phi^{\text{ext}} = 0.2\,\Phi_0$ moving with speed $u = 0.95\,c_0$



$\rightarrow$ function $c(x, t)$



Quantization: $\varphi \to \hat{\varphi} \to$ photon pair production from e.m. vacuum near to $x_h \to$ analogue Hawking radiation with temperature

$$T_{\mathrm{H}} = \frac{\hbar}{2\pi k_{\mathrm{B}}} \mid \frac{\partial c(x)}{\partial x} |_{x=x_h} \quad (3)$$

Radiated power in the comoving frame (Nation et al., Phys. Rev. Lett **103**, 087004 (2009) - 0904.2589)

$$P = \frac{\pi}{12\,\hbar} \left(k_{\mathrm{B}}\, T_{\mathrm{H}}\right)^2$$

NB - For a detector at the end of the line, the radiation will be doppler shifted yielding higher power. However, the rate of emitted photons remains approximately unchanged.

Example

- phase speed step length $\sim 10\, a$
- step height $\approx 0.1\, c_0$

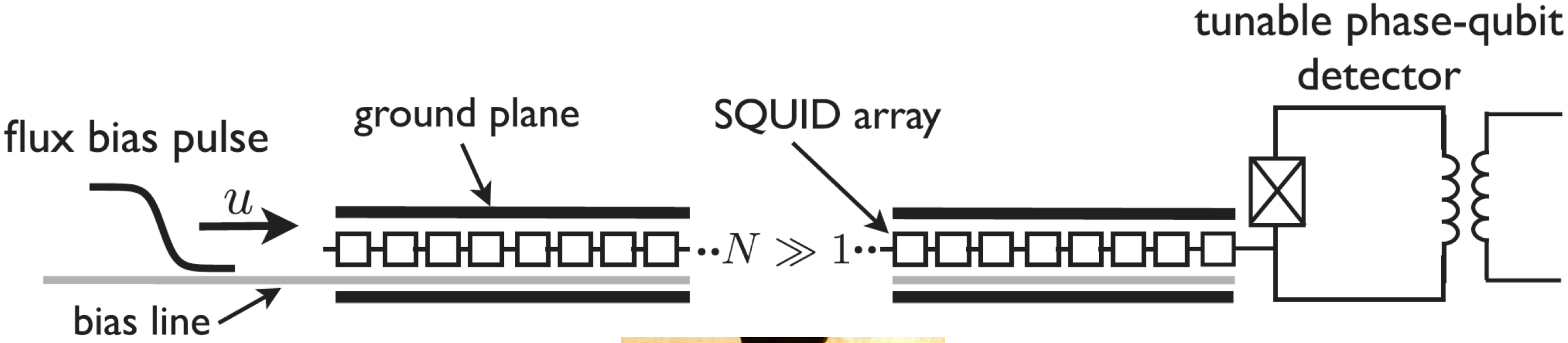
$$\left| \frac{\partial c(x)}{\partial x} \right| \approx 0.01\, c_0 \qquad \rightarrow \qquad T_{\mathrm{H}} = \frac{0.01}{\pi k_{\mathrm{B}}} \sqrt{\frac{\hbar\, e\, I_c}{C_0}} \qquad (4)$$

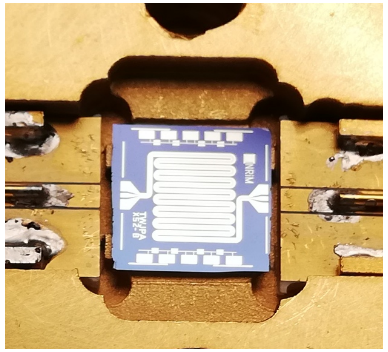
$$I_c = 5\, \mu\mathrm{A}\, ;\, C_0 = 1\, \mathrm{f}F \qquad \rightarrow \qquad T_{\mathrm{H}} \approx 70\, \mathrm{m}K$$

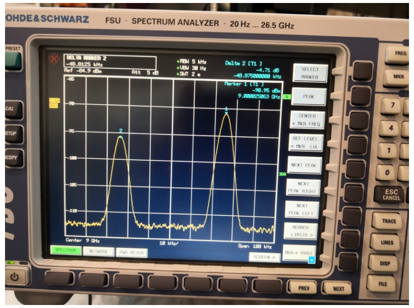
With the bias pulse considered and $T_H = 120$ mK, Nation et al. have estimated an average emission rate of one photon per pulse for ~ 4800 SQUID's. (Increase the pulse repetitions in order to accumulate sufficient photon counts to verify the HR)

Unlike a real BH, both photons may be detected in this device.

LAB frame: a detector at the far end of the array will see two incoming photons. One photon in front of the horizon, and one behind, with the former having a slightly higher propagation velocity.







PRL 103, 087004 (2009)

Conclusion

- Superconducting circuits and Josephson metamaterials offer a unique opportunity to investigate the properties of quantum vacuum
- DCE was experimentally observed in 2011 setting a stimulating precedent; Hawking Radiation may be the next!
- Several of these technology are already available at COLD Lab and the discussion is ongoing with interested collegues of other institutes for future collaborations and projects.