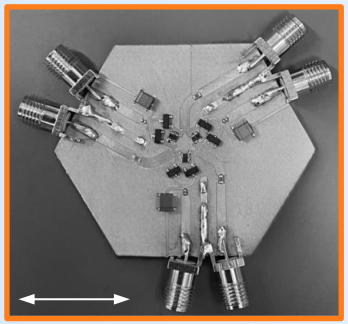

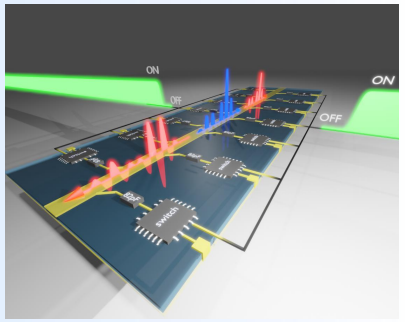


# Synthetic Penrose Super-Radiance and AM-Bandgaps

Andrea Alù

Photonics Initiative, CUNY Advanced Science Research Center
Physics Program, CUNY Graduate Center
Department of Electrical Engineering, City College of New York, CUNY
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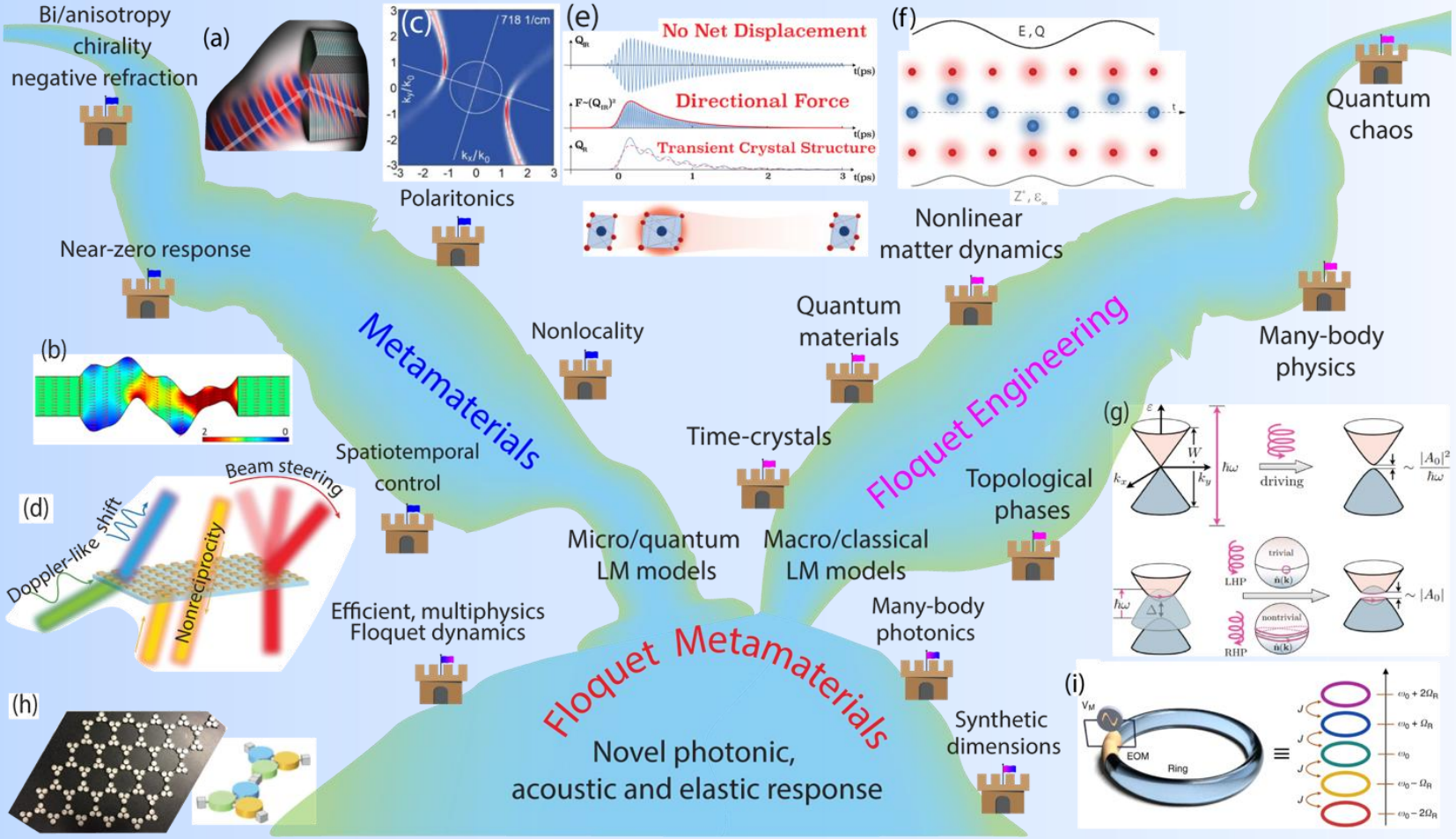
Supported by the ***Air Force Office of Scientific Research*** (***Dr. Arje Nachman***) through an ***SBIR program*** with ***Silicon Audio, Inc.***

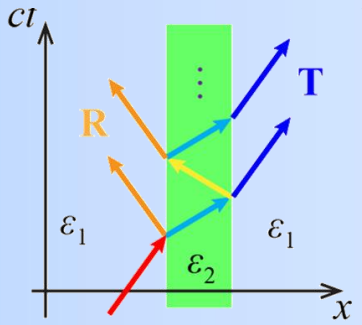
# Time and Floquet Metamaterials




S. Yin, E. Galiffi, A. Alù, *E-Light* **2**, 8 (2022)

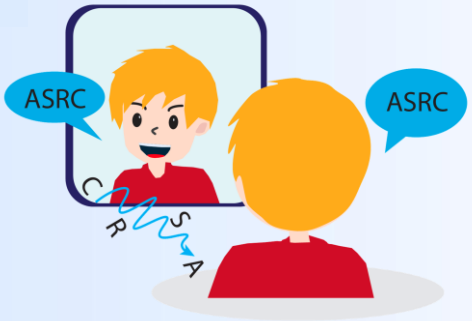
# Time as a New Dimension for Wave Manipulation

## Spatial reflections

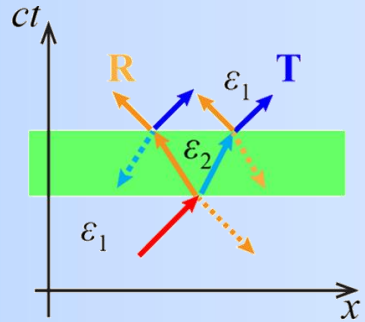



$\omega$ (frequency) and energy are conserved

$k$ (momentum) is reversed

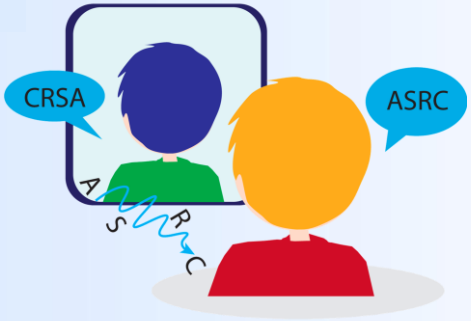



## Temporal reflections



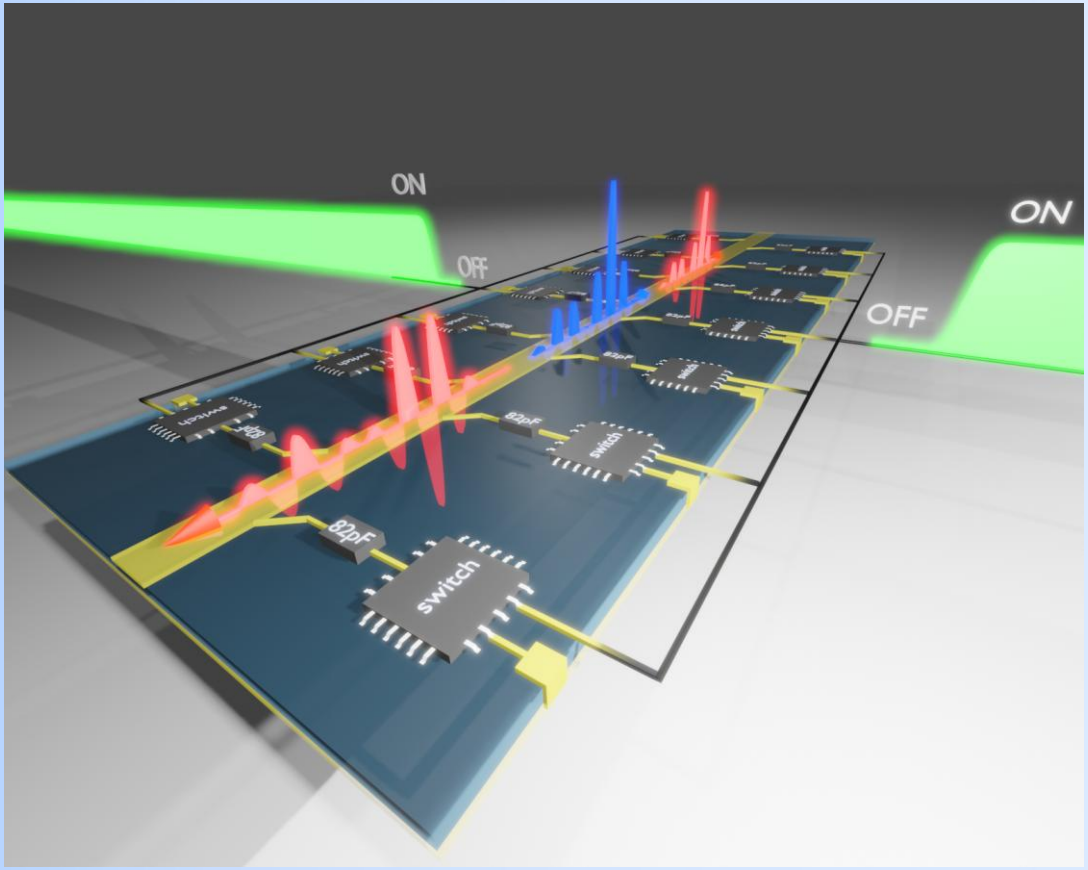

$k$ (momentum) is conserved

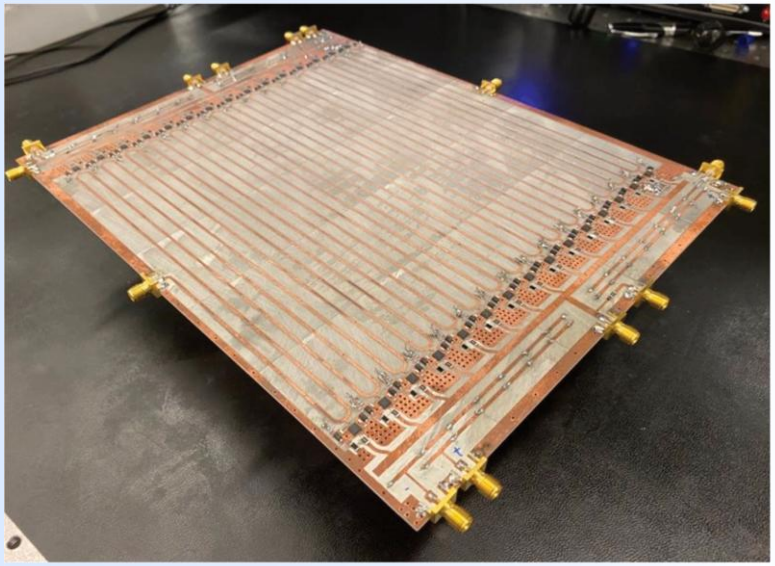
$\omega$ (frequency) and energy change

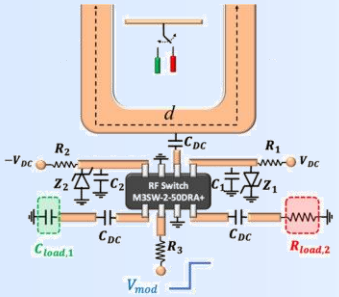


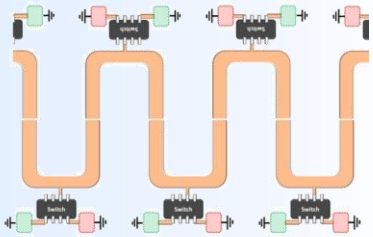

H. Moussa, et al., *Nature Physics* **19**, 863 (2023)

# A Time Metamaterial



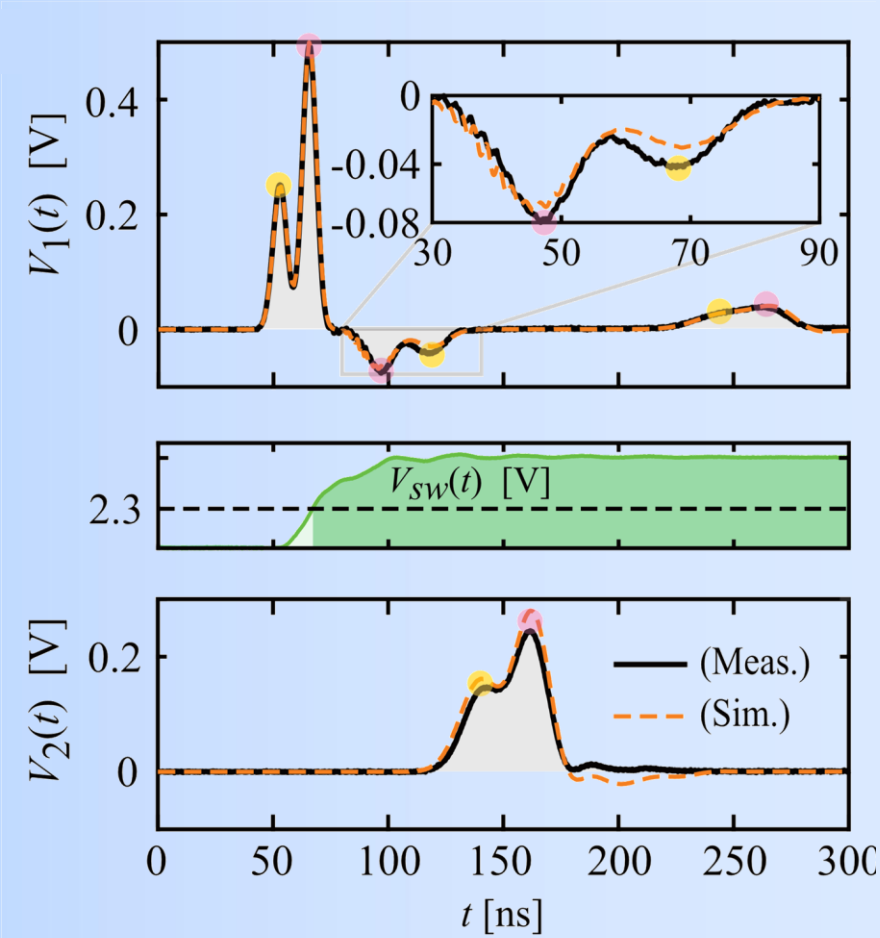



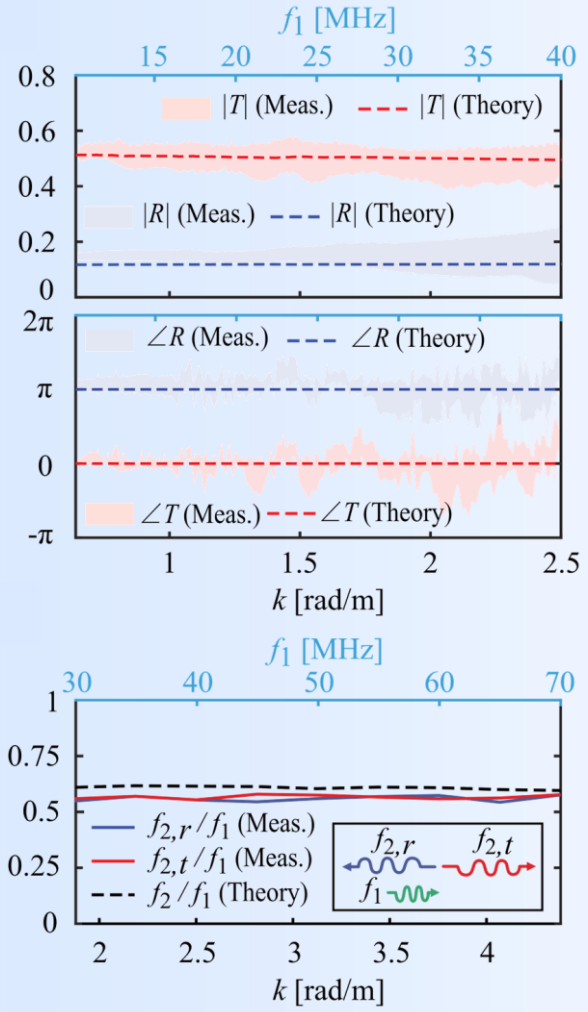


H. Moussa, G. Xu, S. Yin, et al., *Nature Physics* **19**, 863 (2023)
E. Galiffi, G. Xu, S. Yin, et al., *Nature Physics* **19**, 1703 (2023)

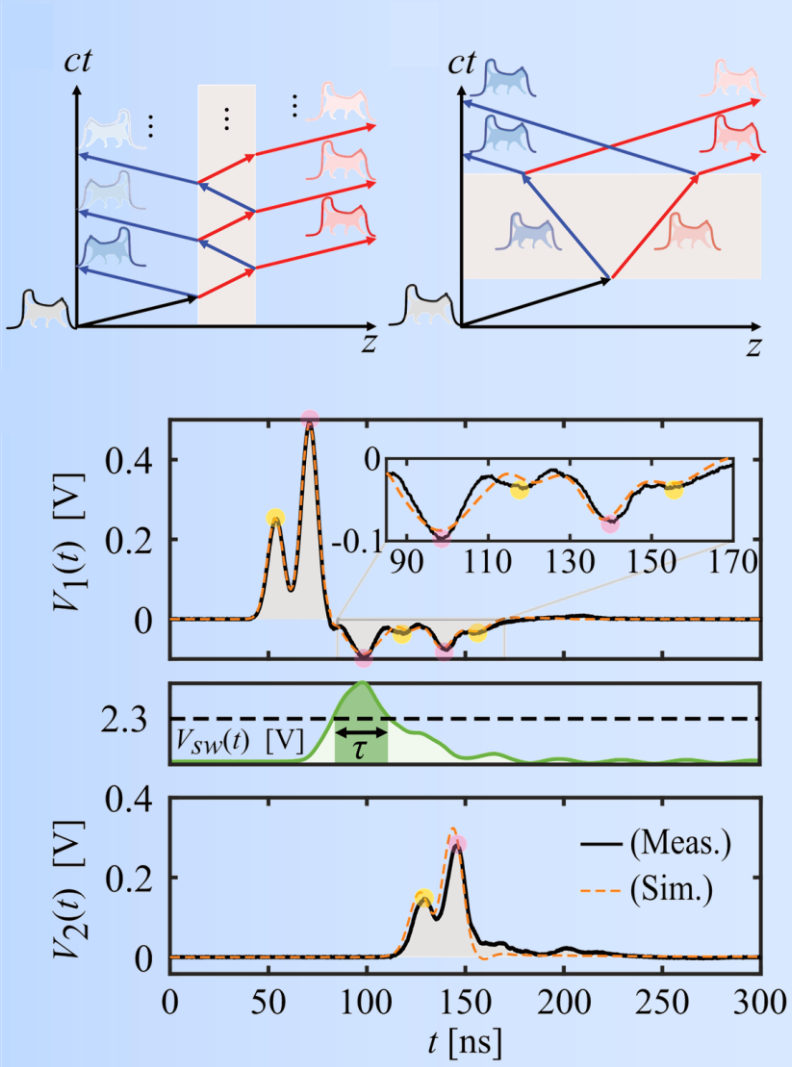
# Observation of Broadband Time Reversal

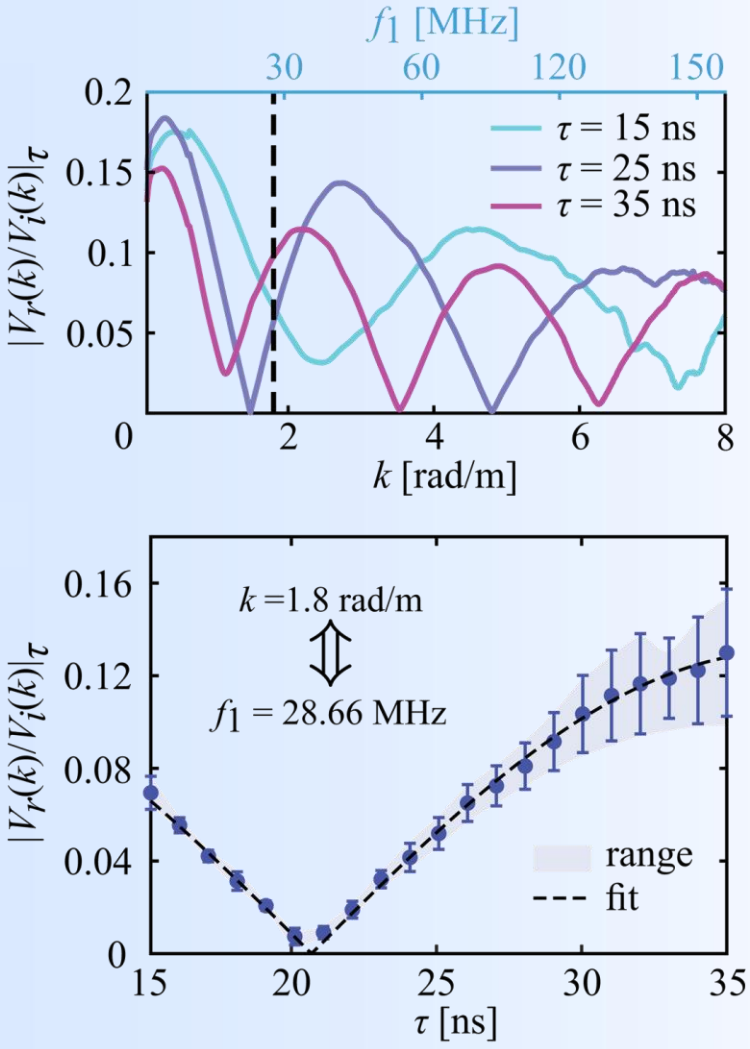



H. Moussa, G. Xu, S. Yin, et al., *Nature Physics* **19**, 863 (2023)

# Scattering and Interference with a Temporal Slab

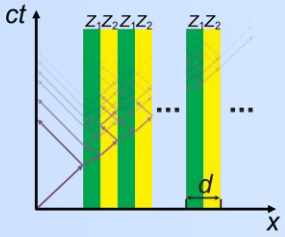



H. Moussa, et al., *Nature Physics* **19**, 863 (2023)

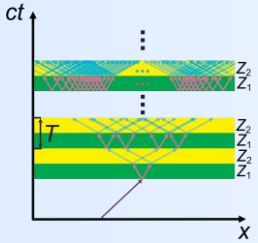
# Time Crystals and K-Gaps

*Photonic crystal*

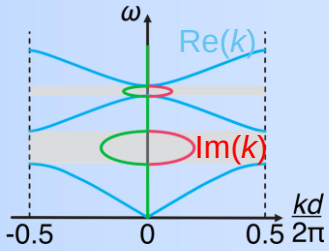


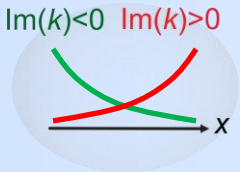

$\psi(x+d) = \psi(x)e^{-jkd}$ $k$: Bloch wavevector

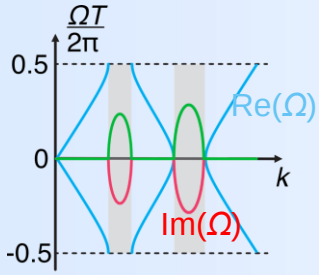
*Photonic time crystal*

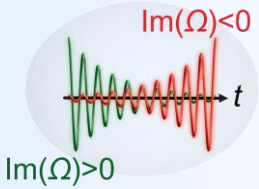



$\psi(t+T) = \psi(t)e^{j\Omega T}$ $\Omega$: Floquet frequency

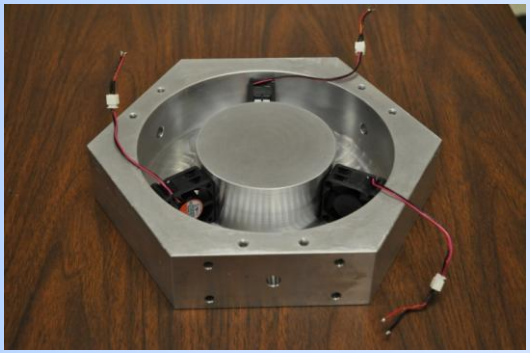


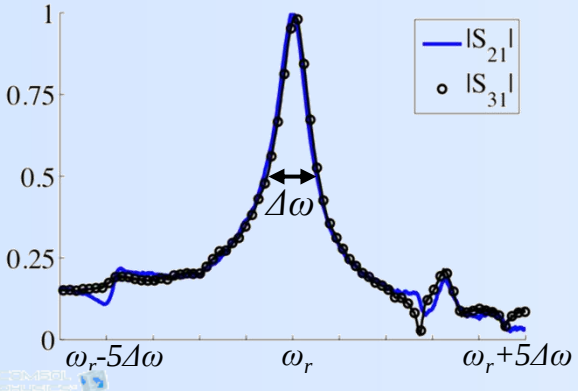



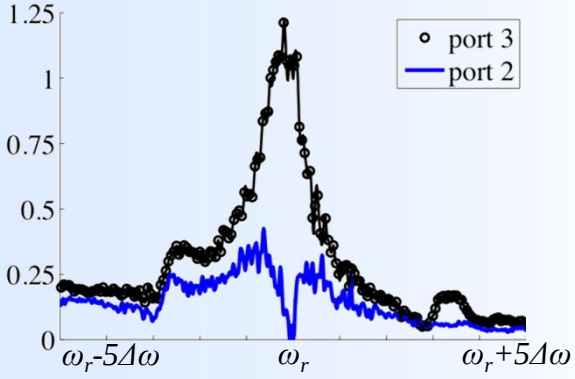



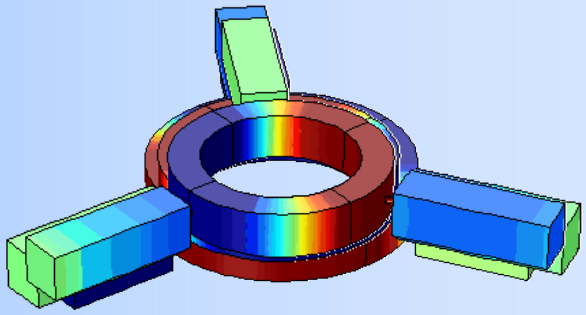
# Angular-Momentum Bias



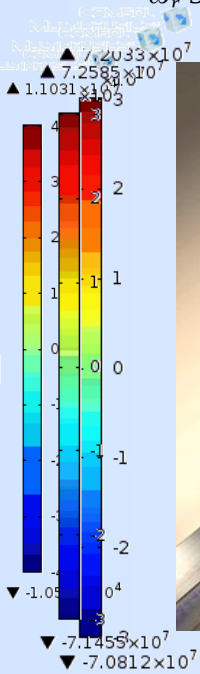


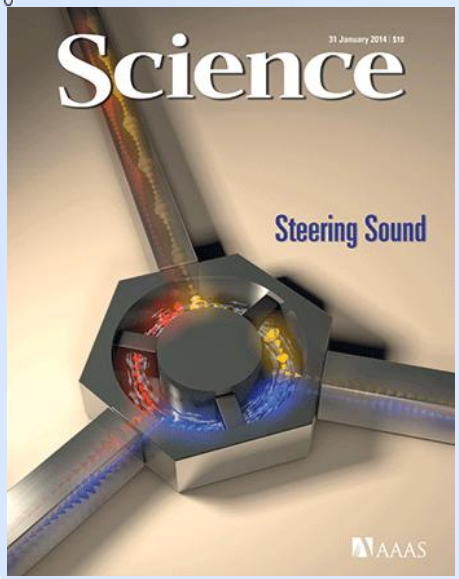



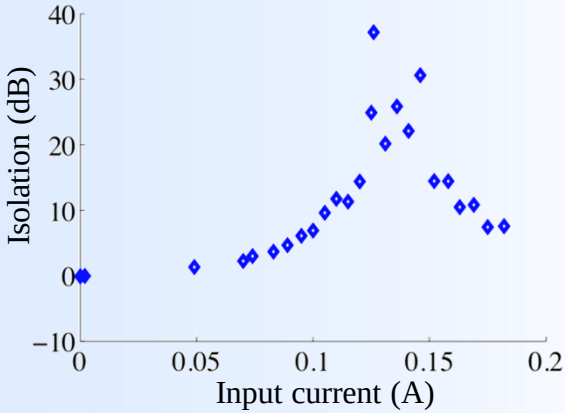

freq(153)=2955.5 Surface: Pressure (Pa)
freq(153)=2955.5 Surface: Pressure (Pa)
freq(58)=944 Surface: Pressure (Pa)



$v = 0.65\,m/s$



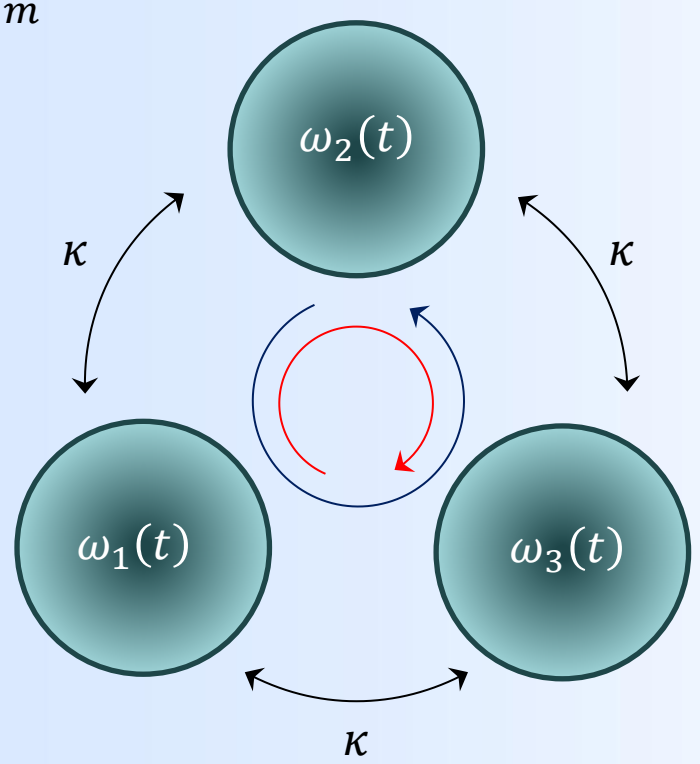




R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

# Synthetic Rotation with Time Modulation

$$\Omega_m = \omega_m / \ell_m$$

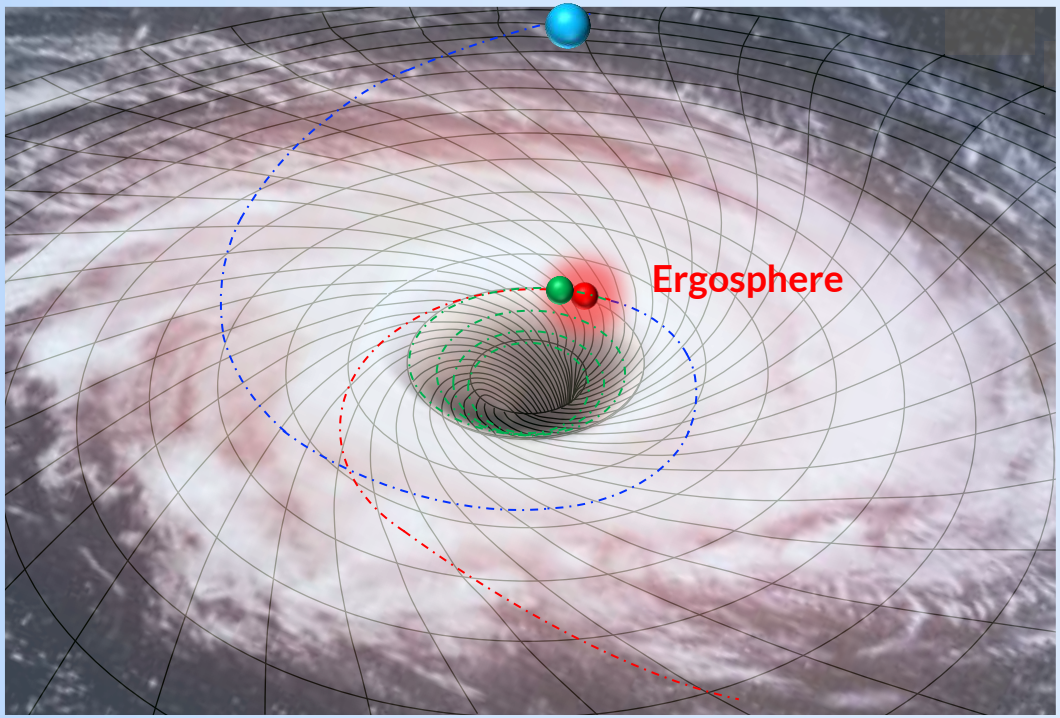



$$\Delta\varepsilon(\varphi, t) = \Delta\varepsilon_m \cos(\omega_m t - \ell_m \varphi)$$

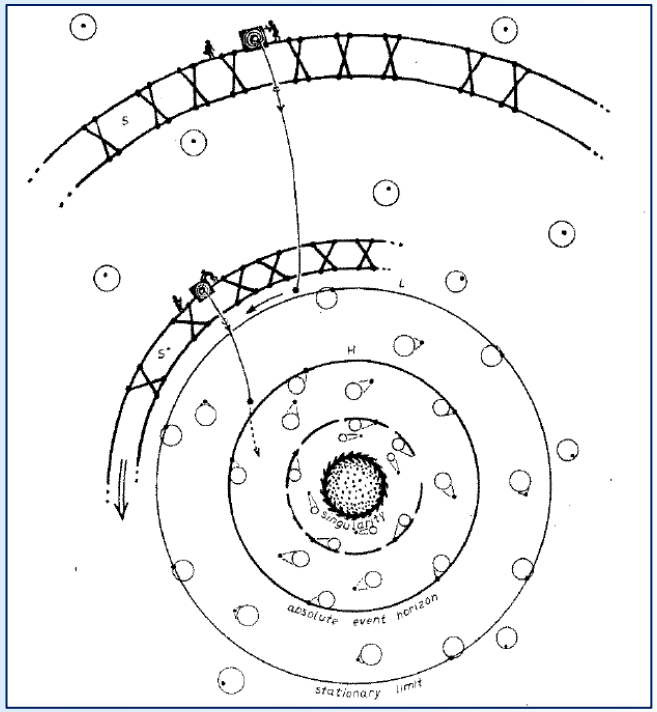
$$\omega_i(t) = \omega_0 + \delta_{\omega_m} \cos(\omega_m t - \ell_m (i-1)\, 2\pi/N)$$

R. Fleury, et. al., *Science* **343**, 516 (2014)
N. A. Estep, et. al., *Nature Phys.* **10**, 923 (2014)

# Extracting Energy From a Rotating Black Hole




Negative energy orbits




## Extraction of Rotational Energy from a Black Hole

R. Penrose

*Department of Mathematics, Birkbeck College, London*

R. M. Floyd

*Willesden College of Technology and Department of Mathematics, Birkbeck College, London*

Received December 16, 1970.

There has been considerable interest recently in the question of the gravitational collapse of a massive body and of the possible astrophysical consequences of the existence of the "black hole" which general relativity predicts should sometimes be the result of such a collapse. In particular, the question has arisen whether the mass–energy content of a black hole could, under suitable circumstances, be a source of available energy. We now consider the extraction of rotational energy from a black hole, not least because the rotational energy (defined appropriately) of a black hole should, in general, be comparable with its total mass–energy[1].

[1] Bardeen, J. M., *Nature*, **226**, 65 (1970).
[2] Israel, W., *General Relativity and Gravitation*, **2**, No. 1 (Plenum, in the press).



R. Penrose,
*Riv. Nuovo Cim. Num. Spec.* 1, 257 (1969)

# Electromagnetic Penrose Super-Radiance

GENERATION OF WAVES BY A ROTATING BODY

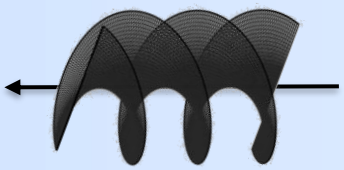
Ya.B. Zel'dovich
Institute of Applied Mathematics, USSR Academy of Sciences
Submitted 9 July 1971
ZhETF Pis. Red. 14, No. 4, 270 - 272 (20 August 1971)

An axially-symmetrical body rotating inside a resonator cavity is capable of amplifying definite oscillation modes inside the resonator, transferring the rotation energy to these oscillations.

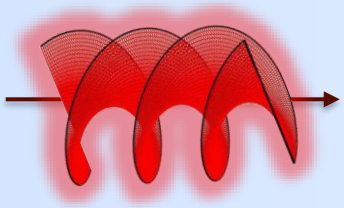
SOVIET PHYSICS JETP VOLUME 35, NUMBER 6 DECEMBER, 1972

**Amplification of Cylindrical Electromagnetic Waves Reflected from a Rotating Body**

**Ya. B. Zel'dovich**
*Institute of Applied Mathematics, USSR Academy of Sciences*
Submitted December 10, 1971
Zh. Eksp. Teor. Fiz. 62, 2076–2081 (June, 1972)

$$E(r,\varphi) = e^{-j\omega t} e^{jn\varphi} e^{-jkr}/\sqrt{r}$$

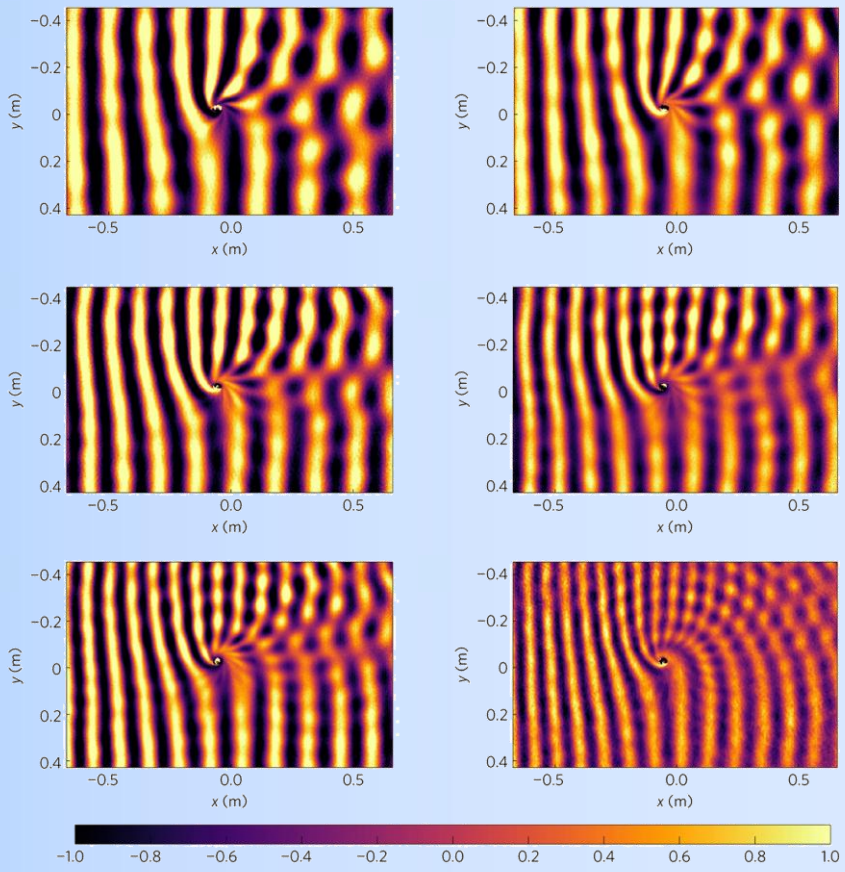


Negative rotational Doppler shift

$$\omega(k) - v.k < 0$$

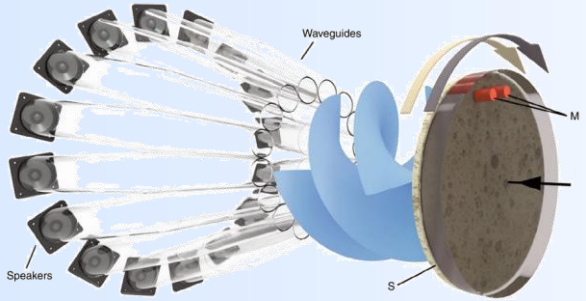
# Wave Amplification From Rotating Bodies

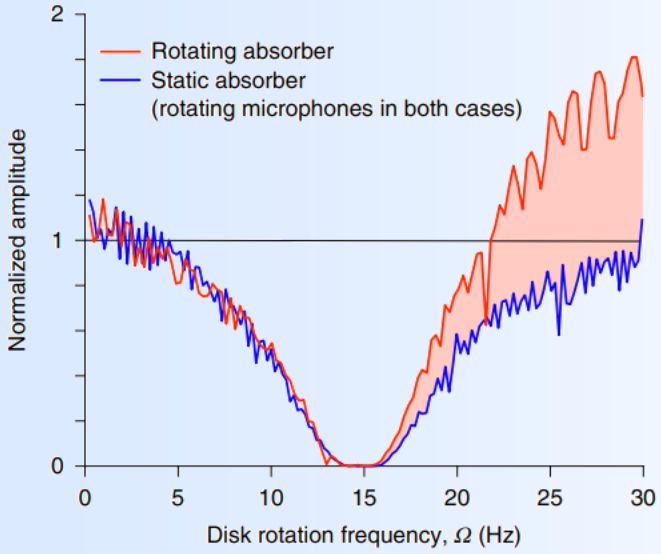
Rotational superradiant scattering in a *water vortex flow*




T. Torres et. al., *Nature Phys.* **13**, 833 (2017)

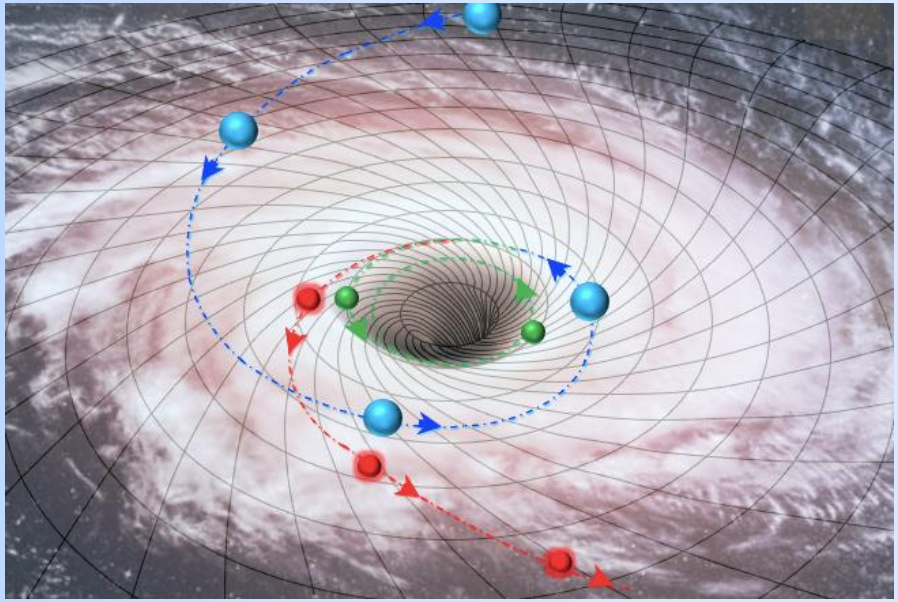
Amplification of acoustic waves from a rotating body

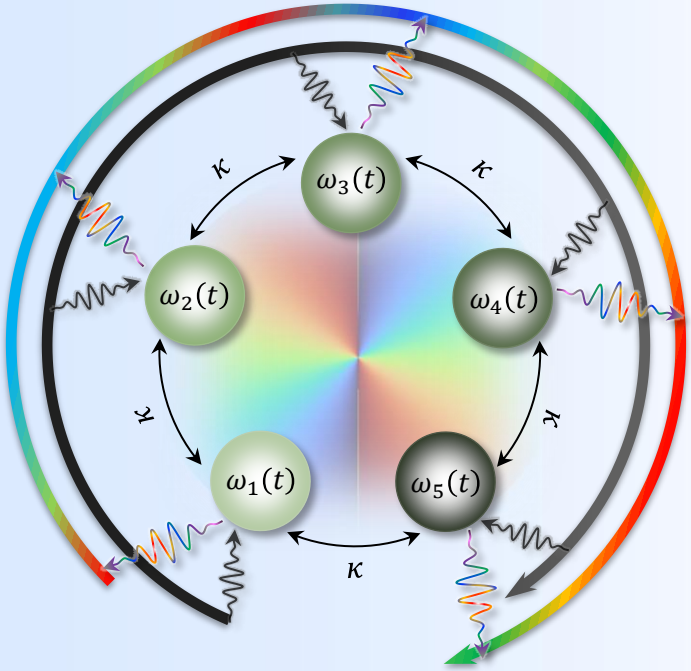



M. Cromb, et al., *Nature Physics* **16**, 1069 (2020)

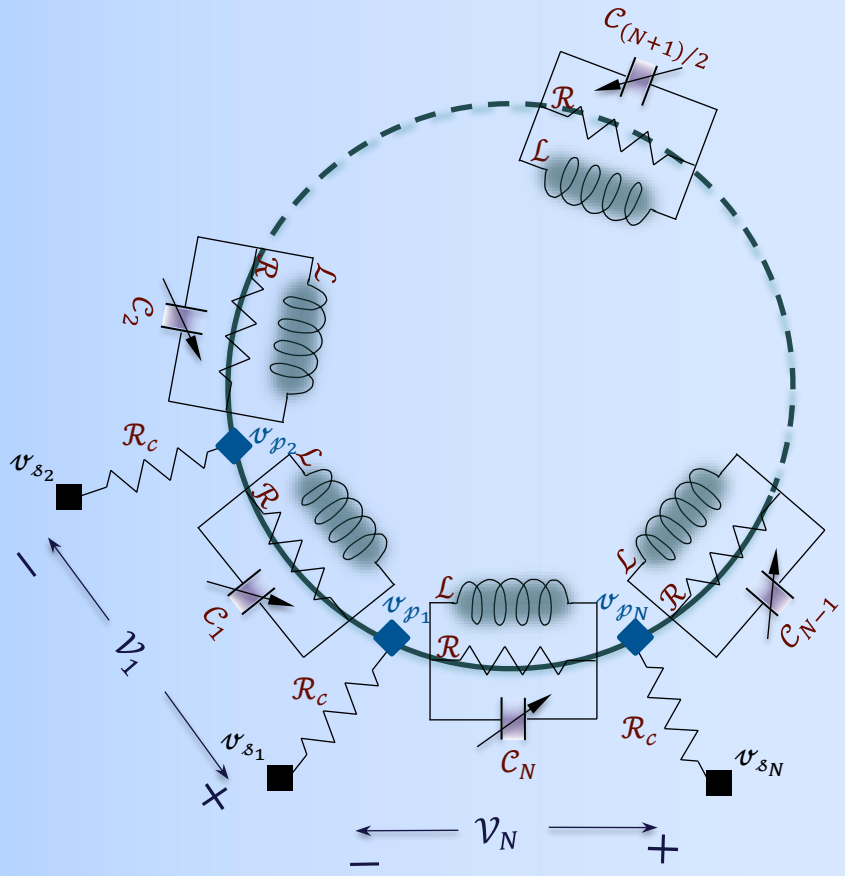
# Synthetic Penrose Super-radiance





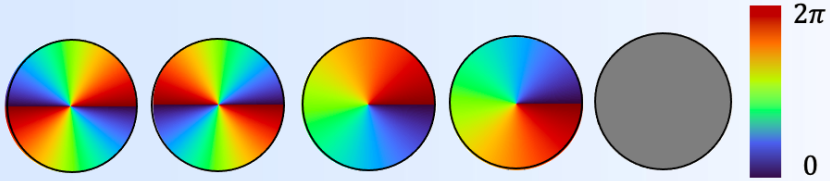

- Excitation with OAM signal
- Synthetic rotation based on Angular Momentum Biasing
- Monitoring the strength of output OAM signals

# Governing Matrix Equation & Harmonic Analysis




$$\left\{\overline{\overline{\boldsymbol{A}}}\ \omega^2+\overline{\overline{\boldsymbol{B}}}\omega+\overline{\overline{\boldsymbol{D}}}\right\}\overline{\boldsymbol{V}}+\frac{\delta}{2}\left\{\omega^2\ \overline{\overline{\boldsymbol{C}}}\overline{\boldsymbol{V}}^{(+)}+\omega^2\ \overline{\overline{\boldsymbol{C}}}^{*}\overline{\boldsymbol{V}}^{(-)}\right\}=\overline{\overline{\boldsymbol{G}}}\ \overline{\boldsymbol{V}_s}$$

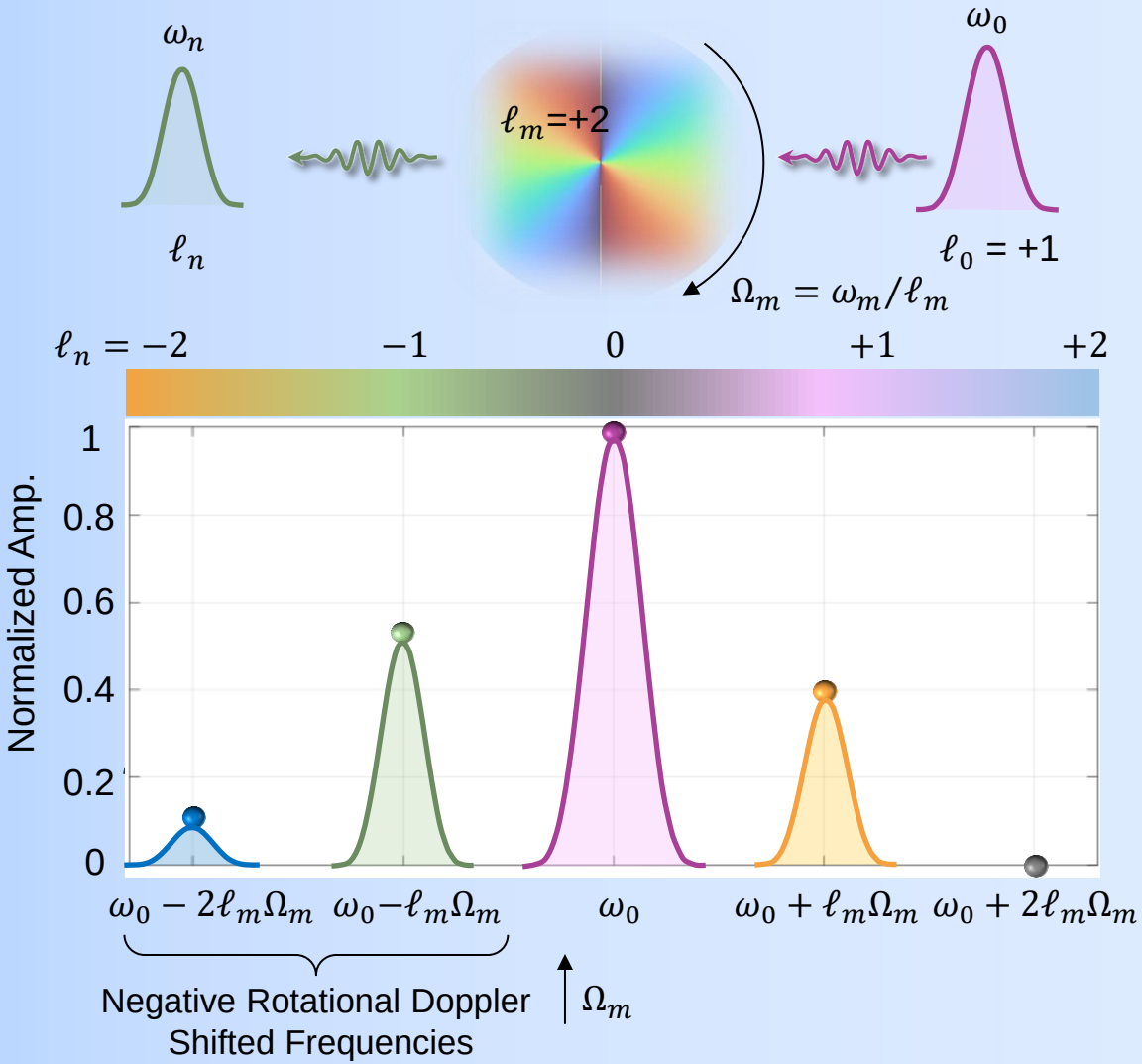
Eigenbasis of the static system

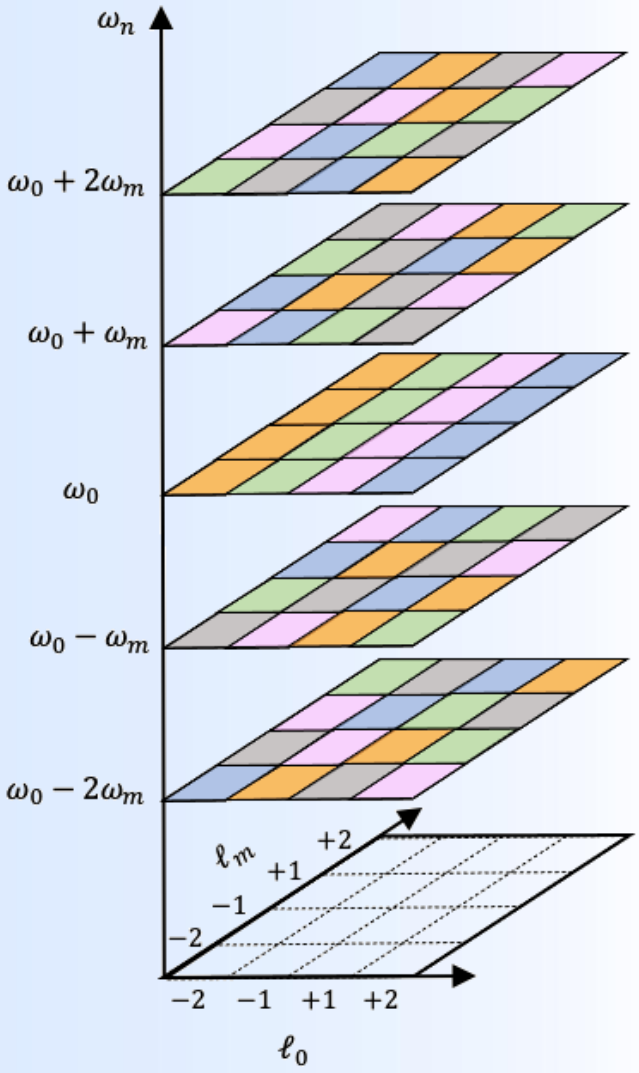



$$\overline{\overline{\boldsymbol{H}}}\ \overline{\boldsymbol{V}}_R+\frac{\delta}{2}\left\{\omega^2\ \overline{\overline{\overline{\boldsymbol{C}}}}_{R(\ell_m)}\overline{\boldsymbol{V}}_R{}^{(+)}+\omega^2\ \overline{\overline{\overline{\boldsymbol{C}}}}^{*}_{R(\ell_m)}\ \overline{\boldsymbol{V}}_R{}^{(-)}\right\}=\overline{\overline{\boldsymbol{G}}}_R\ \overline{\boldsymbol{V}}_{s,R}$$

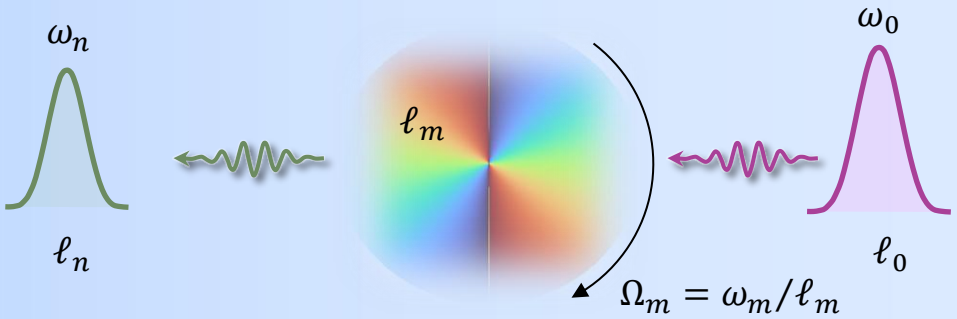
$$\overline{\overline{\boldsymbol{H}}}=\overline{\overline{\boldsymbol{A}}}_R\ \omega^2+\overline{\overline{\boldsymbol{B}}}_R\ \omega+\overline{\overline{\boldsymbol{D}}}_R$$

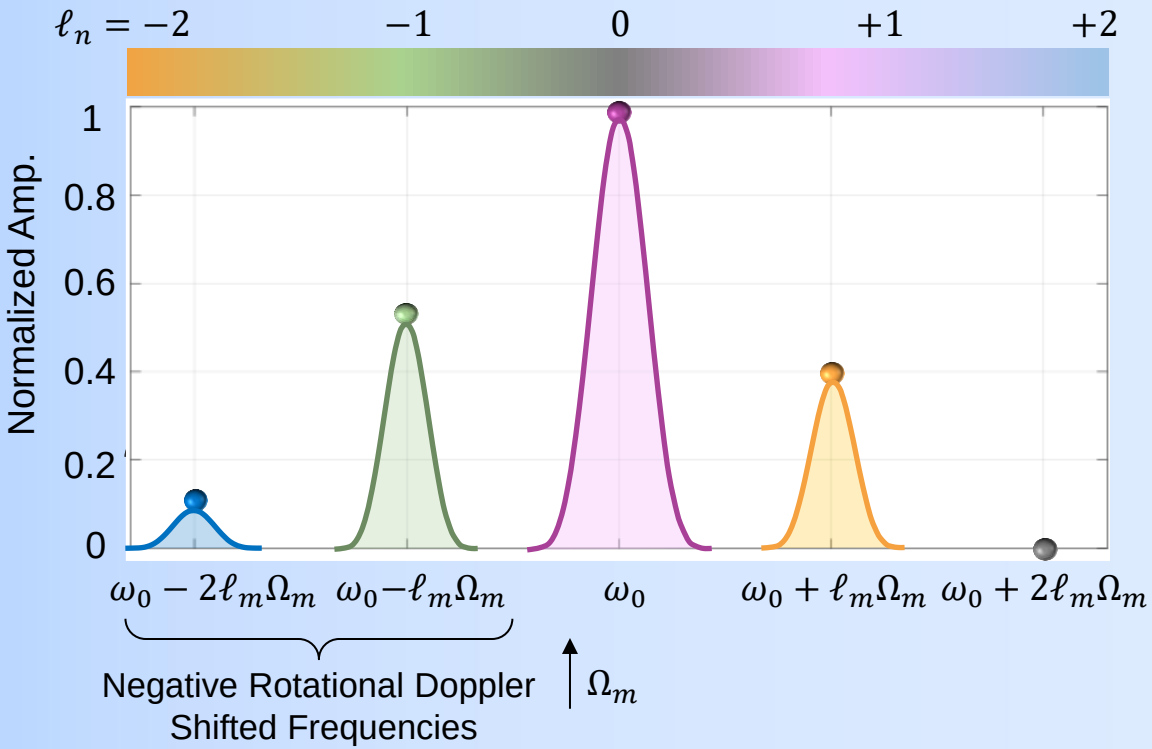
# Synthetic Rotational Doppler Effect

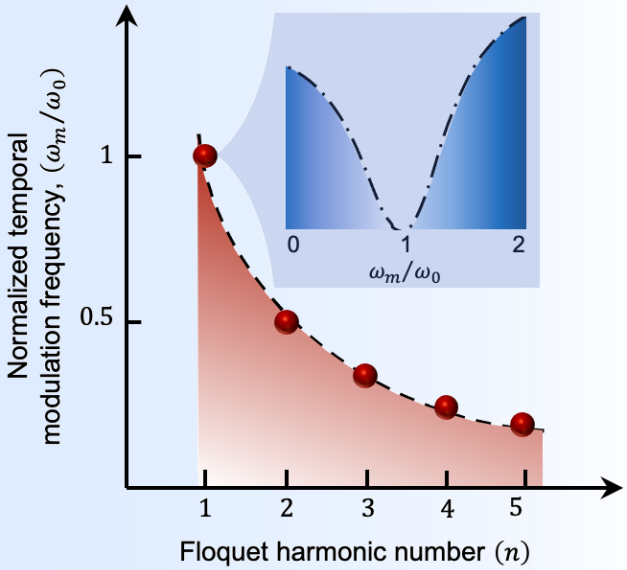


# Synthetic Negative Rotation Doppler Shift

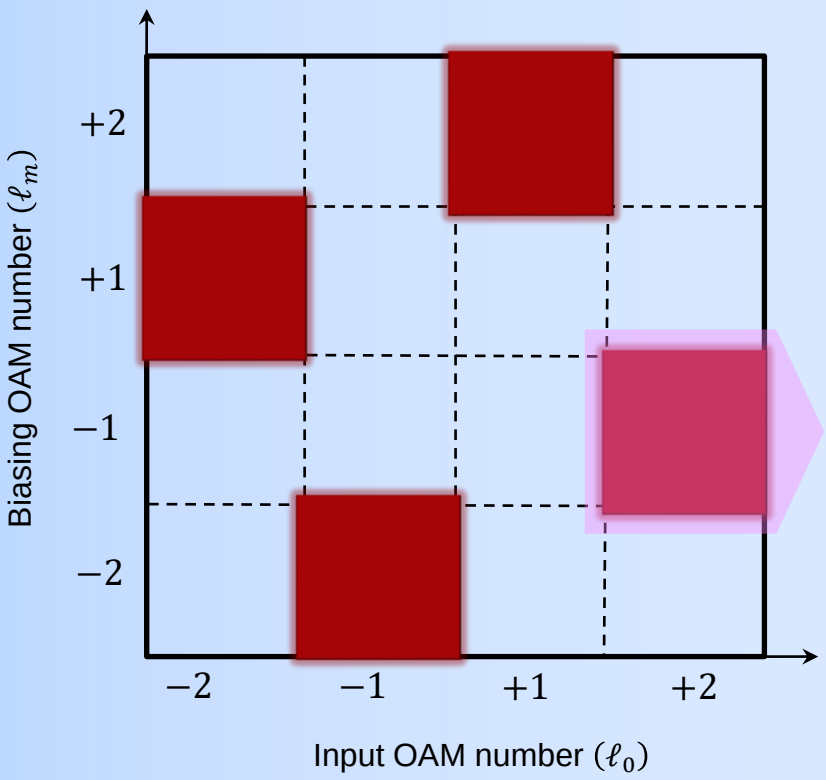


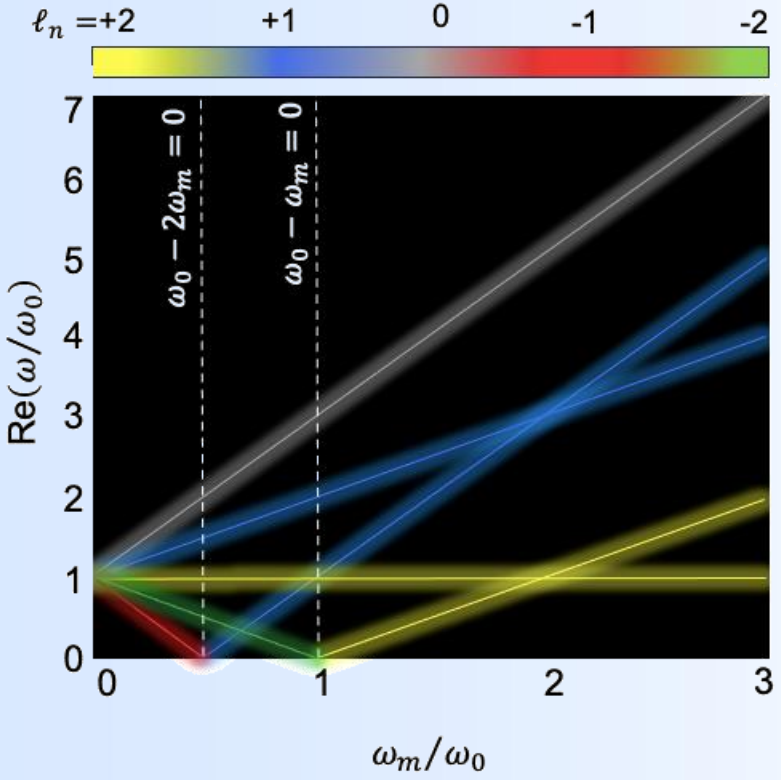




$$\omega_m = \omega_0/n$$

# Synthetic Penrose Super-Radiance

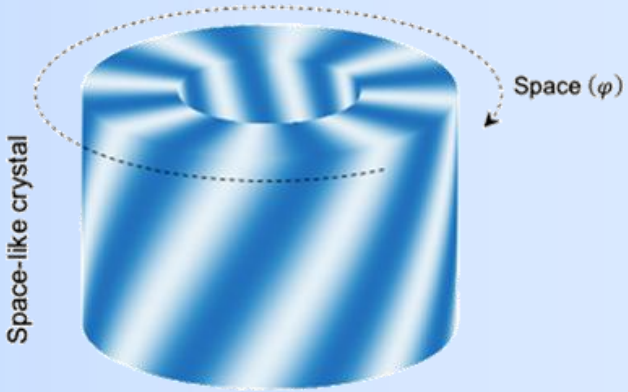


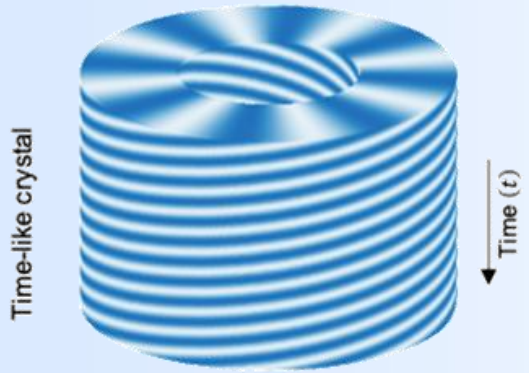



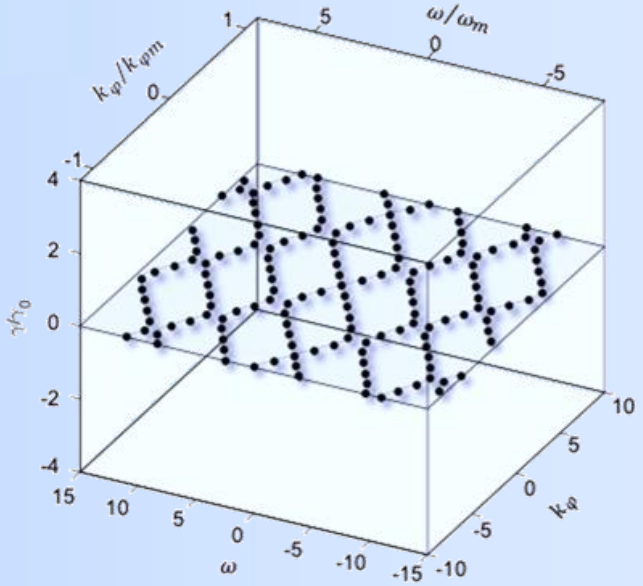

Phase matching between the

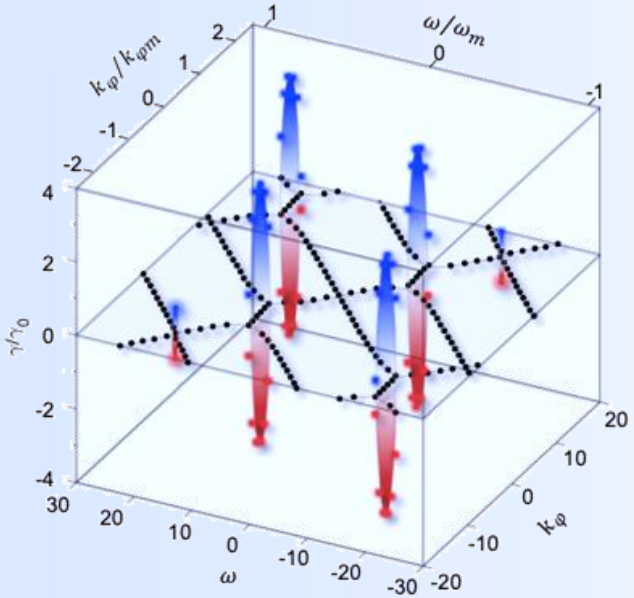
- Modulation and fundamental harmonic
- Interacting harmonics

# Angular-Momentum Bandgaps

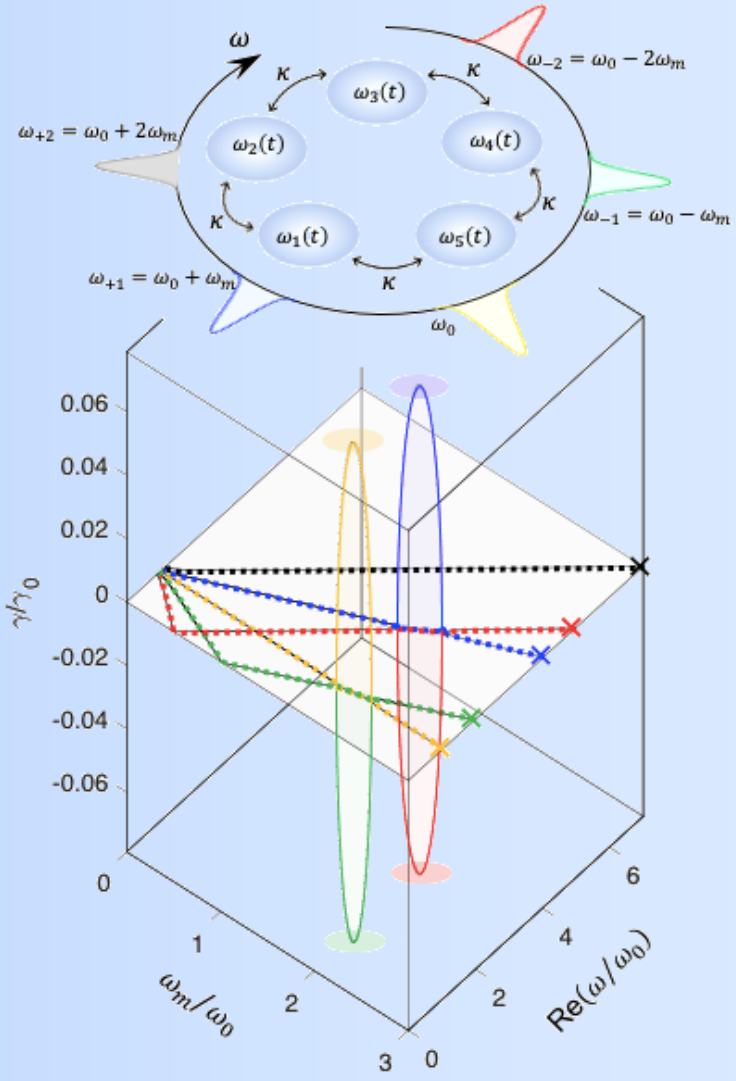


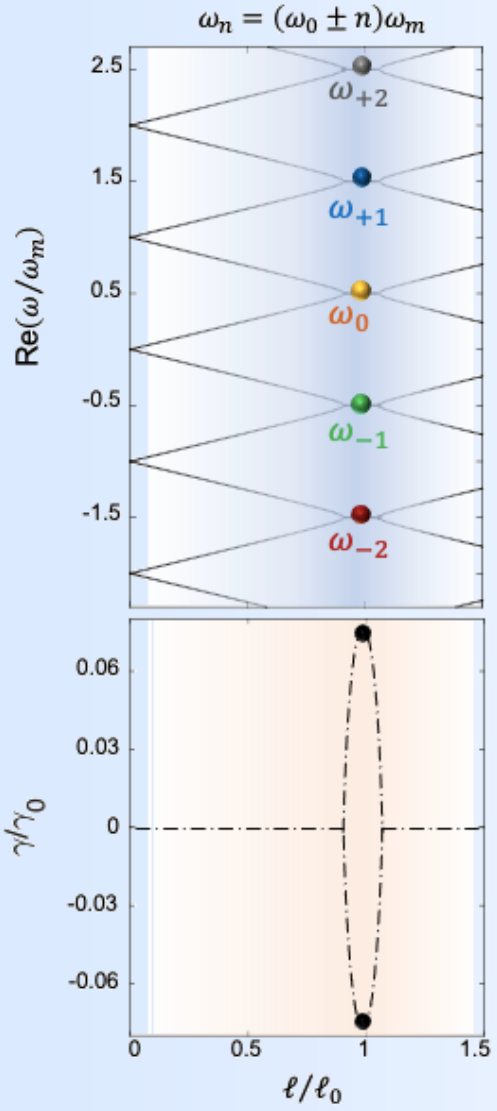



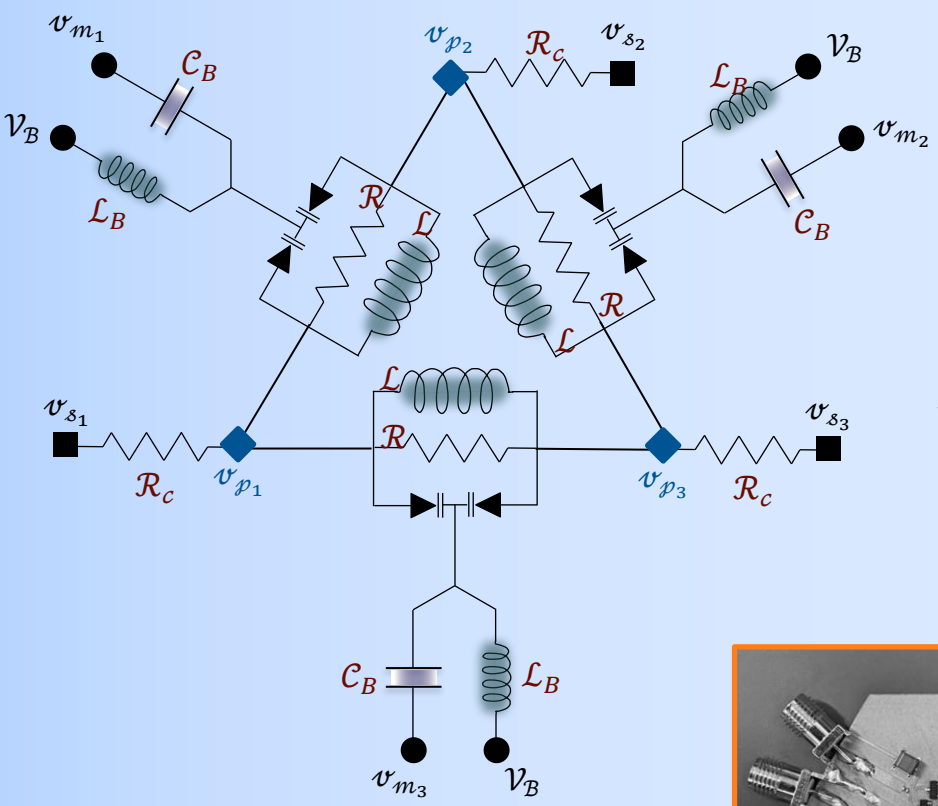



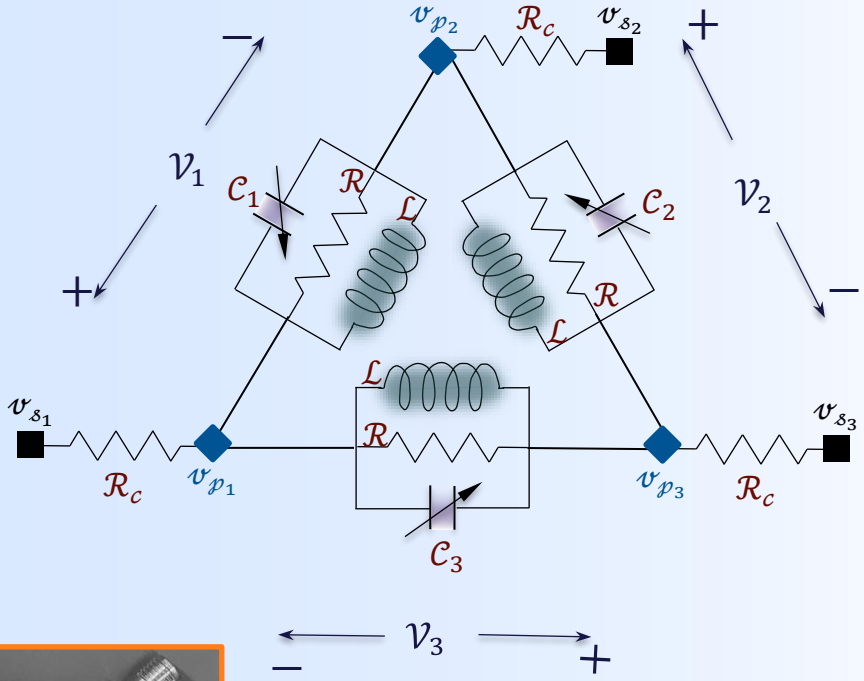
# Angular-Momentum Bandgaps

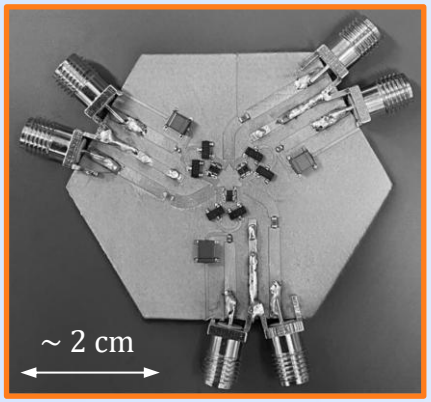


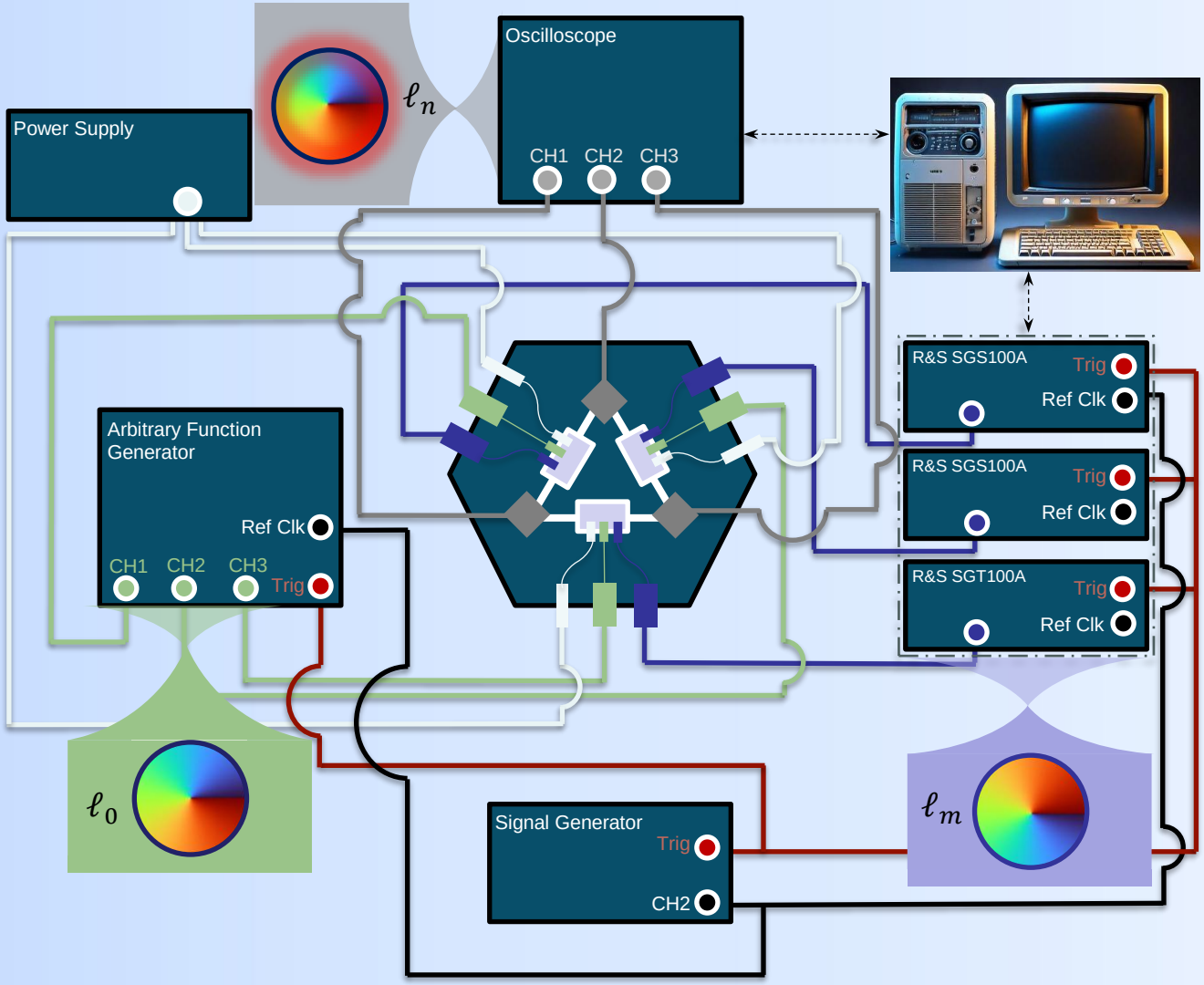
# Synthetically Rotating Circuit



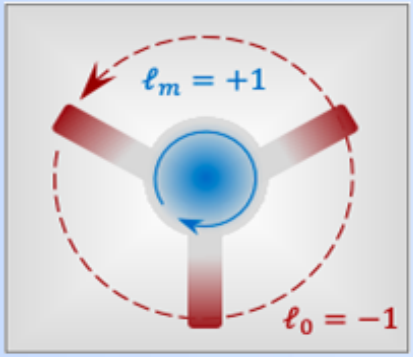



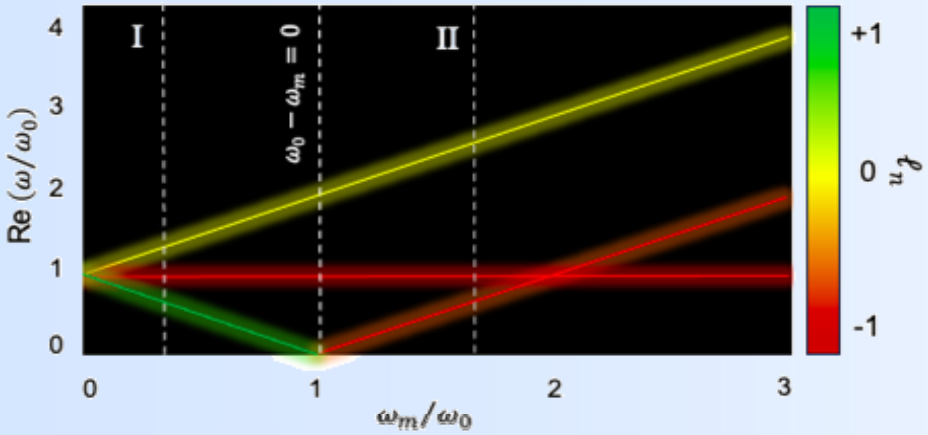



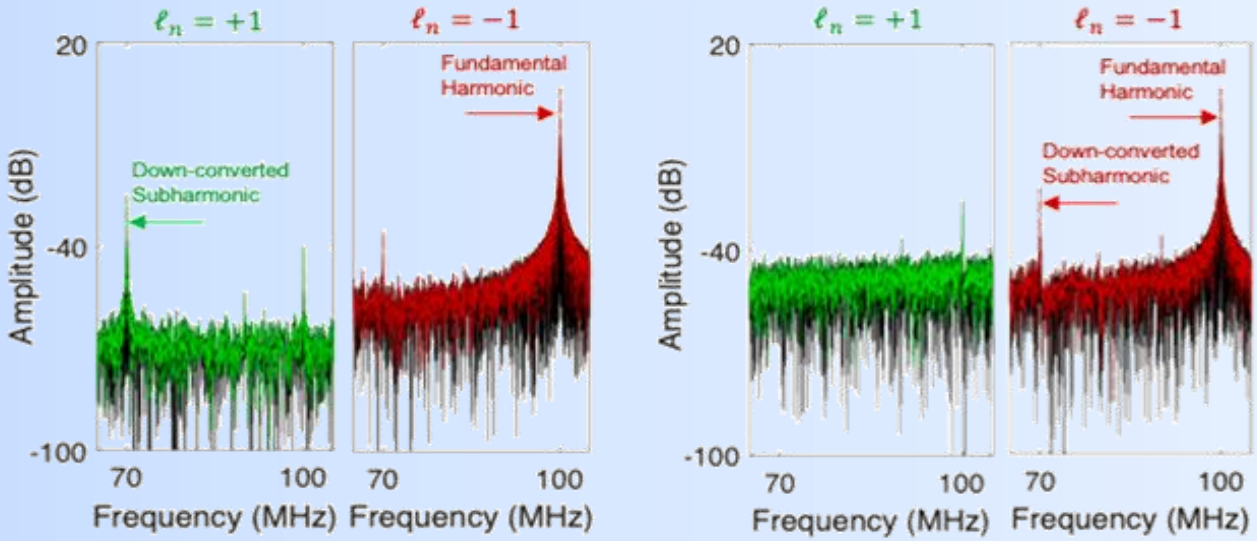
# Experimental Setup



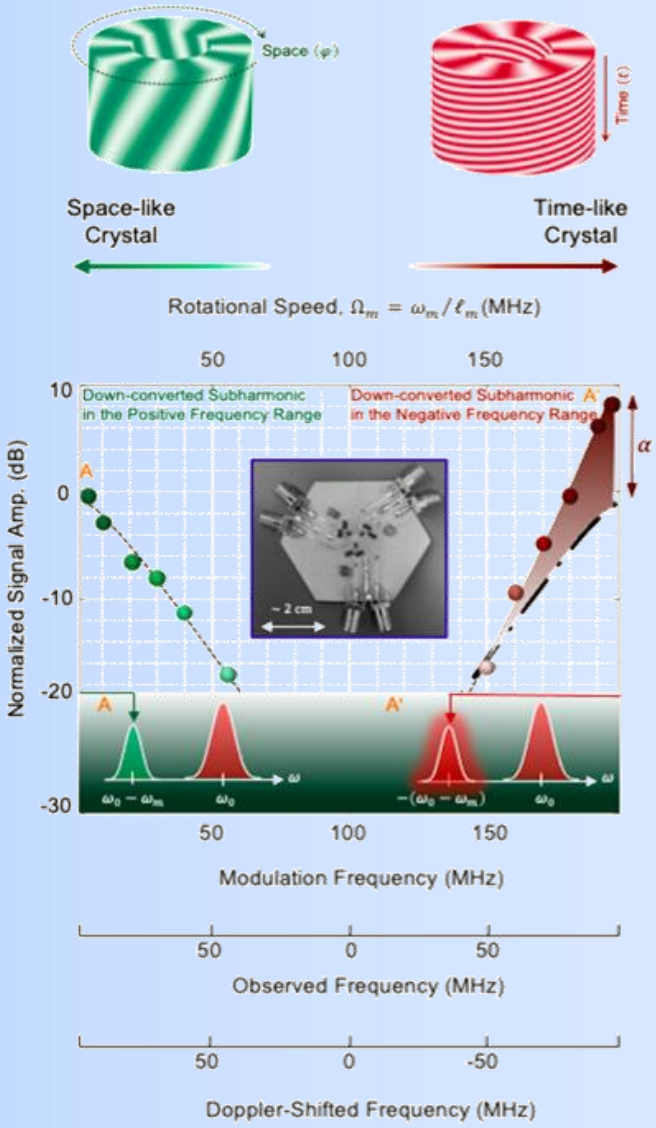
# Observation of Synthetic Penrose Super-Radiance

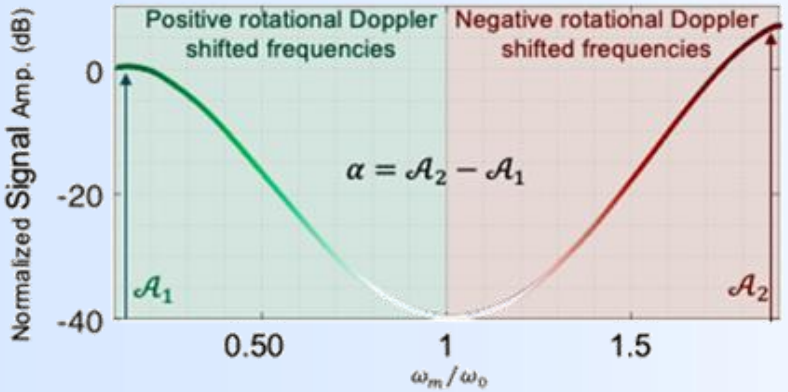


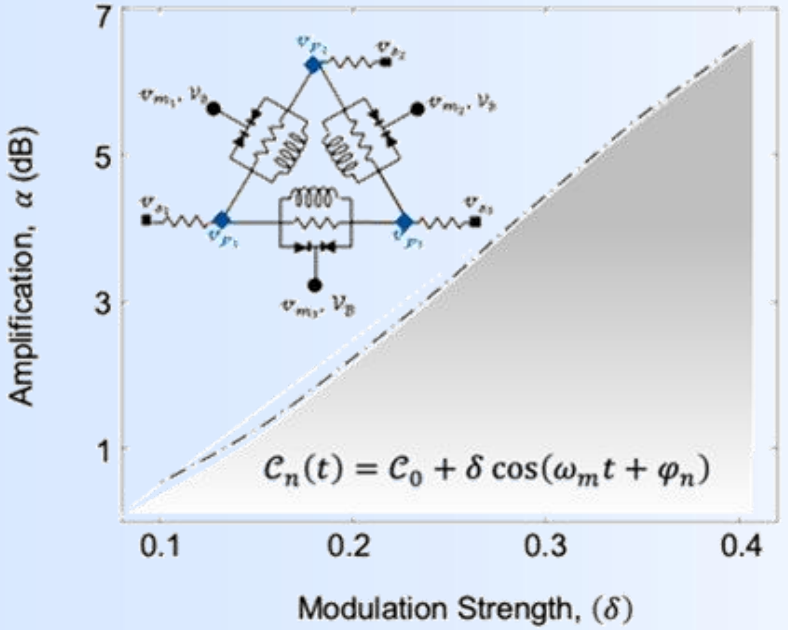



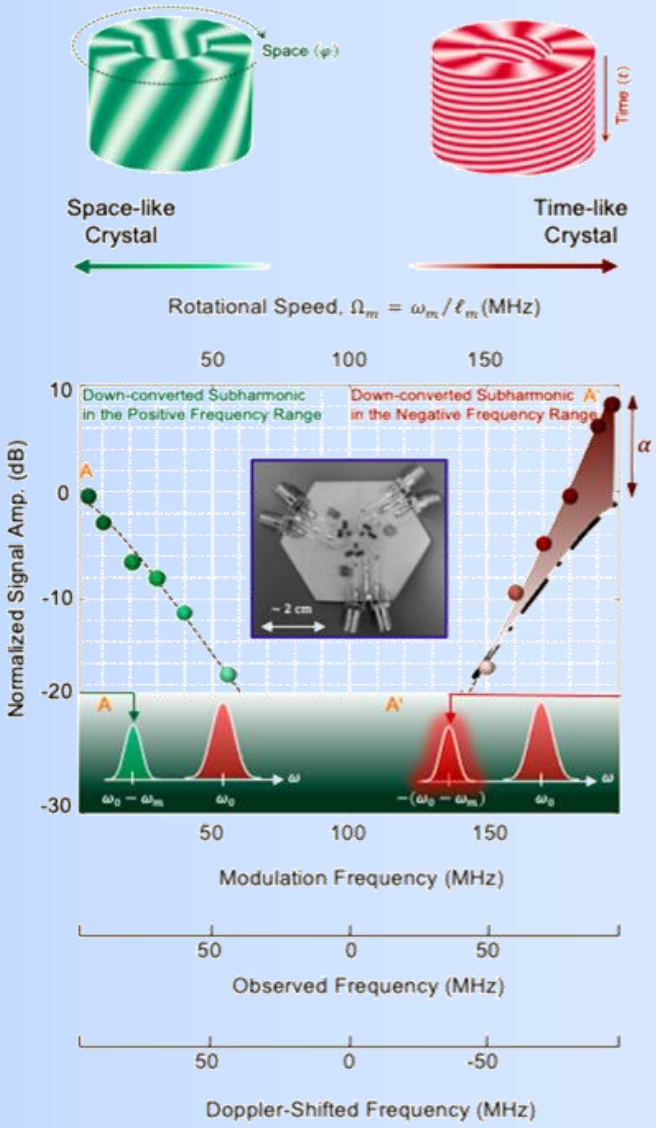
# Observation of Synthetic Penrose Super-Radiance

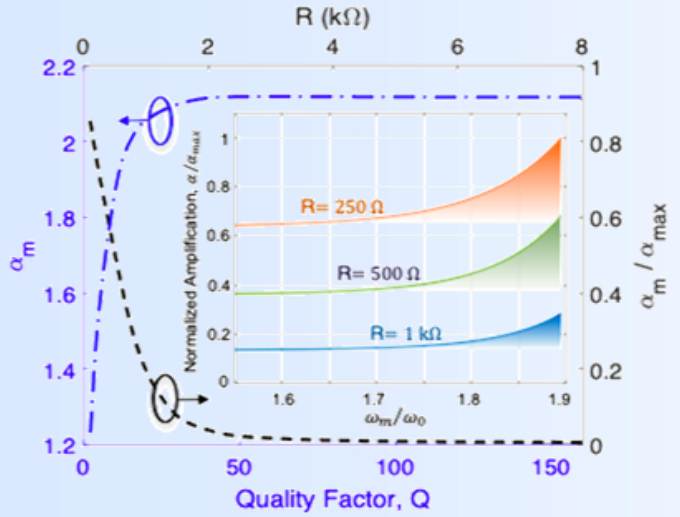


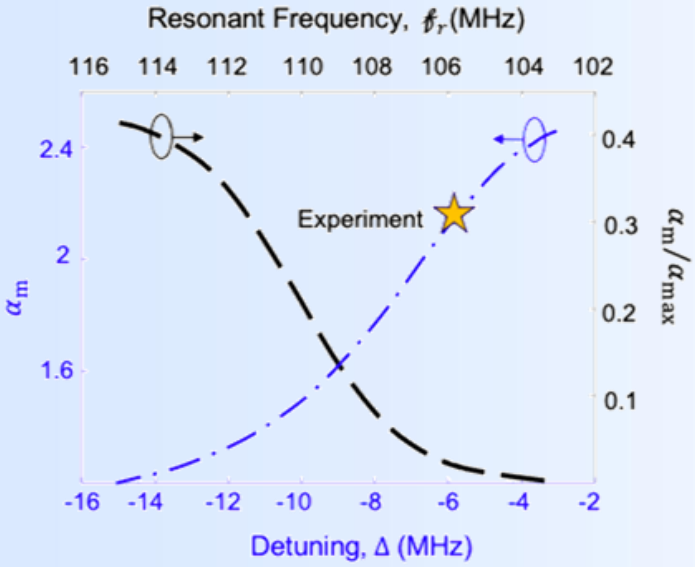



# Observation of Synthetic Penrose Super-Radiance



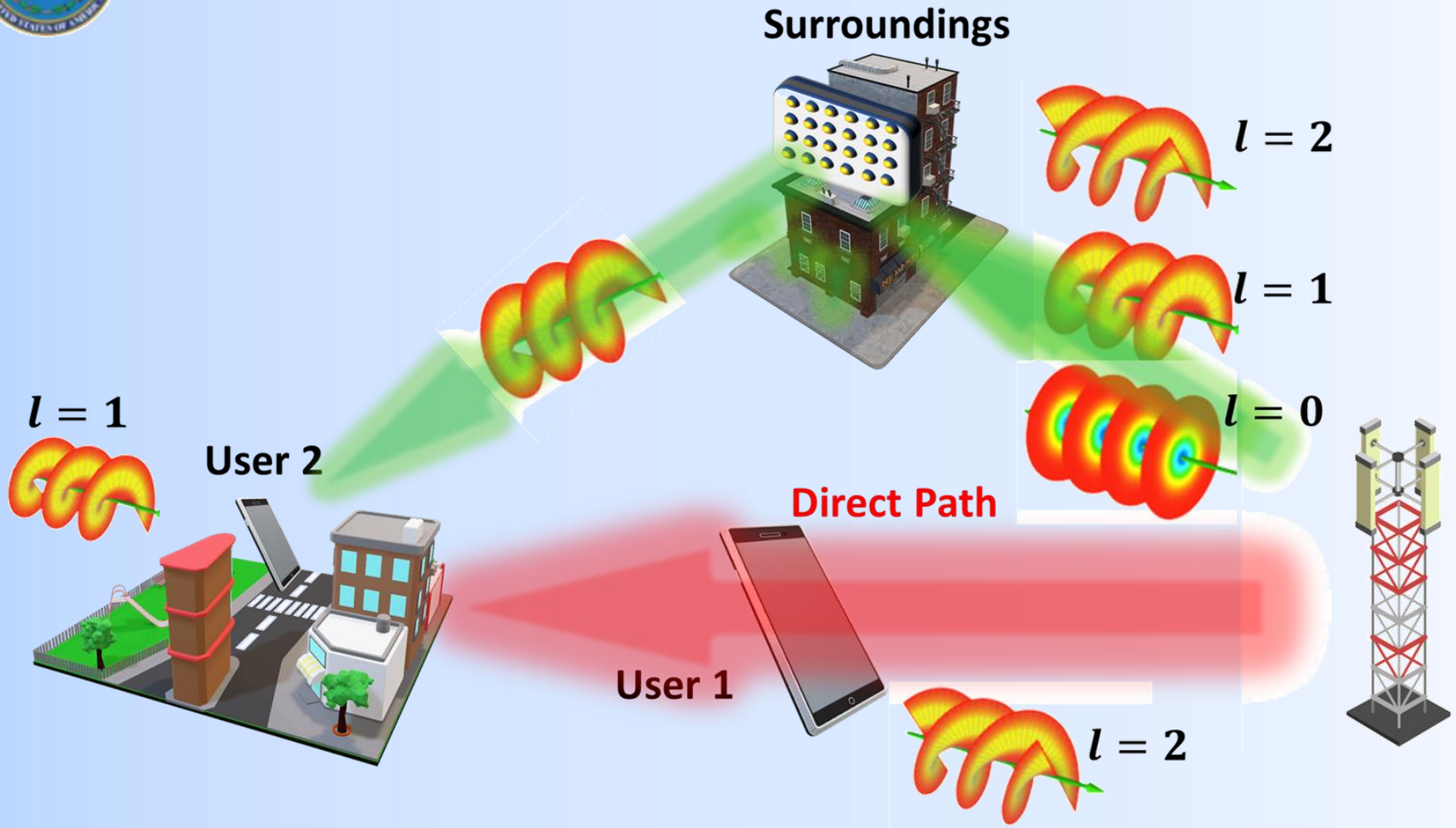



# Penrose Super-Radiance for 6G Communications

**BARI: Bilateral Academic Research Initiative**

*International partnerships for high-impact science*



# Spontaneous Emission and Quantum Friction

The metric near such a body is described by the well-known Kerr solution. The gravitational capture of the particles and the waves by the so-called trapping surface replaces absorption; the trapping surface ("the horizon of events") is located inside the surface $g_{00} = 0$. Finally, in a quantum analysis of the wave field one should expect spontaneous radiation of energy and momentum by the rotating body. The effect, however, is negligibly small, less than $\hbar\omega^4/c^3$ for power and $\hbar\omega^3/c^3$ for the decelerating moment of the force (for a rest mass $m = 0$, in addition, we have omitted the dimensionless function $\beta$).

Y. B. Zeldovich, *ZhETP Pis. Red.* **14**, 270 (1971)

PRL 105, 113601 (2010) PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2010

**Vacuum Friction in Rotating Particles**

A. Manjavacas and F. J. García de Abajo*
*Instituto de Óptica—CSIC, Serrano 121, 28006 Madrid, Spain*
(Received 8 March 2010; published 8 September 2010)

We study the frictional torque acting on particles rotating in empty space. At zero temperature, vacuum friction transforms mechanical energy into light emission and produces particle heating. However, particle cooling relative to the environment occurs at finite temperatures and low rotation velocities. Radiation emission is boosted and its spectrum significantly departed from a hot-body emission profile as the velocity increases. Stopping times ranging from hours to billions of years are predicted for materials, particle sizes, and temperatures accessible to experiment. Implications for the behavior of cosmic dust are discussed.

DOI: 10.1103/PhysRevLett.105.113601 PACS numbers: 42.50.Wk, 41.60.−m, 45.20.dc, 78.70.−g

PRL 108, 230403 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

**Spontaneous Emission by Rotating Objects: A Scattering Approach**

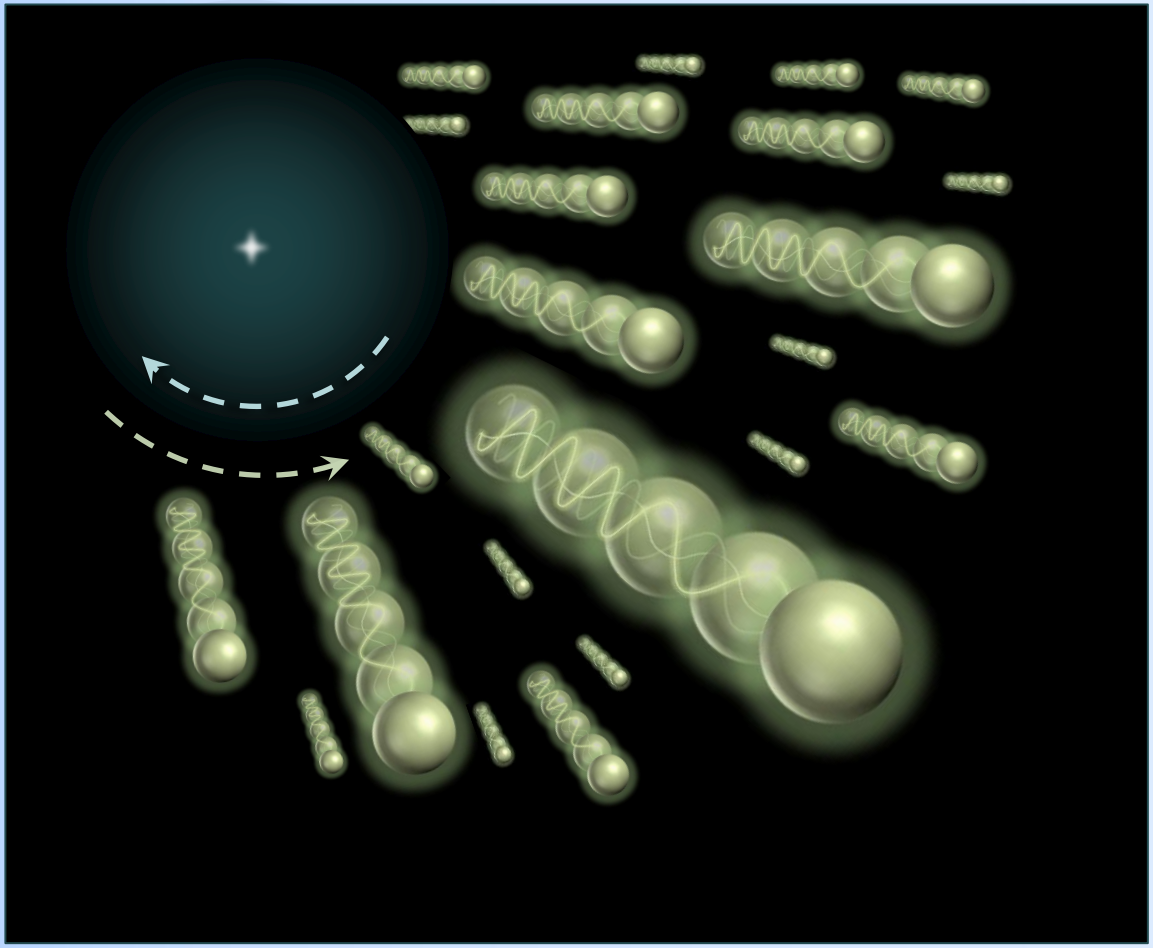
Mohammad F. Maghrebi,[1,2] Robert L. Jaffe,[1,2] and Mehran Kardar[2]
[1]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 9 February 2012; published 7 June 2012)

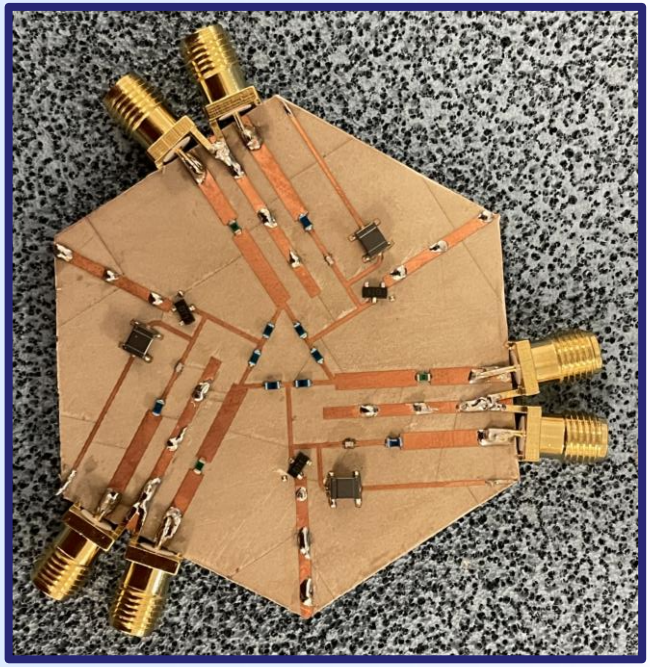
We study the quantum electrodynamics vacuum in the presence of a body rotating along its axis of symmetry and show that the object spontaneously emits energy if it is lossy. The radiated power is expressed as a general trace formula solely in terms of the scattering matrix, making an explicit connection to the conjecture of Zel'dovich [JETP Lett. 14, **180** (1971)] on rotating objects. We further show that a rotating body drags along nearby objects while making them spin parallel to its own rotation axis.

DOI: 10.1103/PhysRevLett.108.230403 PACS numbers: 03.70.+k, 12.20.−m, 42.50.Lc

Also related to the dynamical Casimir effect and quantum friction

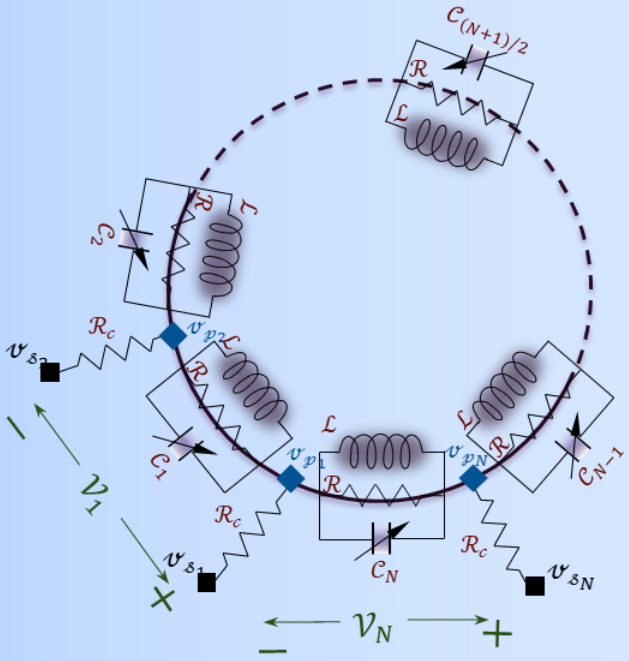
# Emission and Friction from Synthetic Rotation





# Spontaneous Emission from Synthetic Rotation

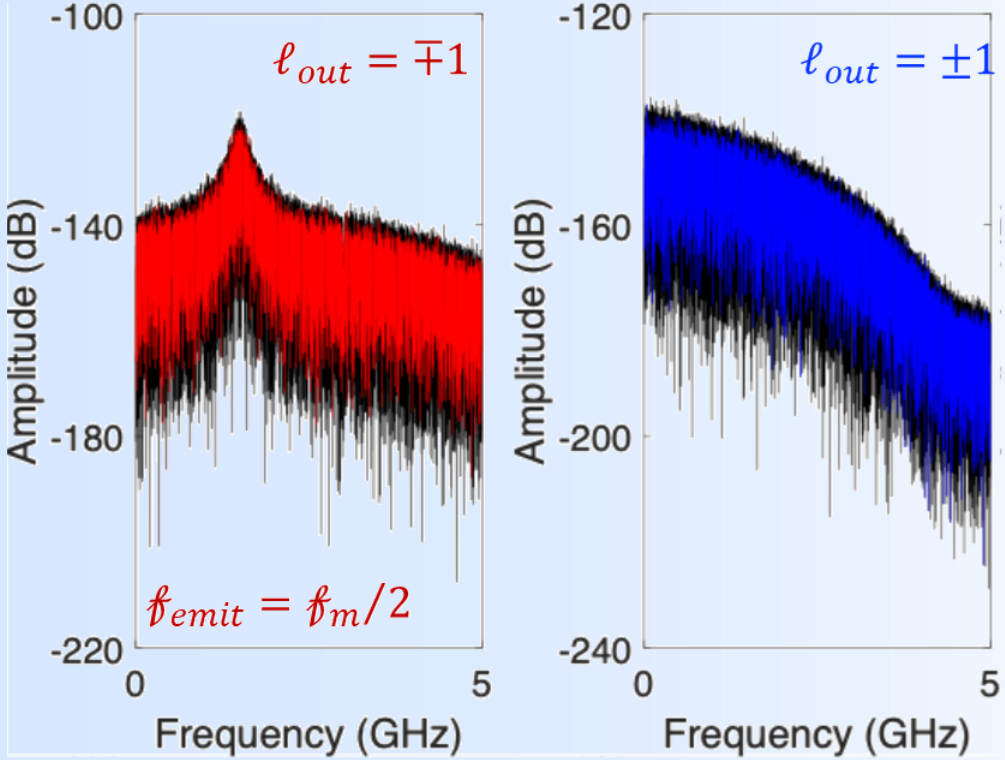
Low-Q scenario




$\mathcal{f}_m = 3$ GHz

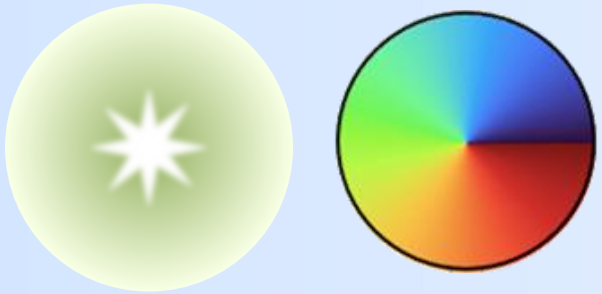
$\mathcal{f}_{res} = 10$ MHz

$\ell_m = \pm 1$



# Spontaneous Emission from Synthetic Rotation

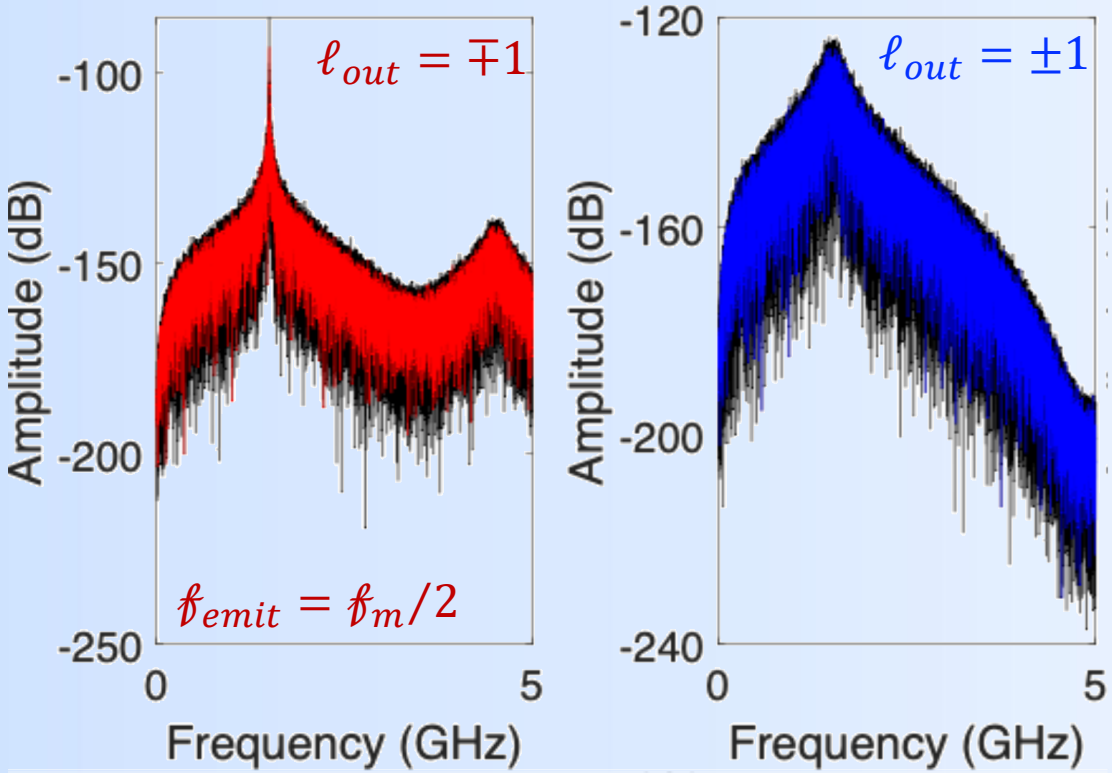
High-Q scenario



$\not{f}_m = 3$ GHz

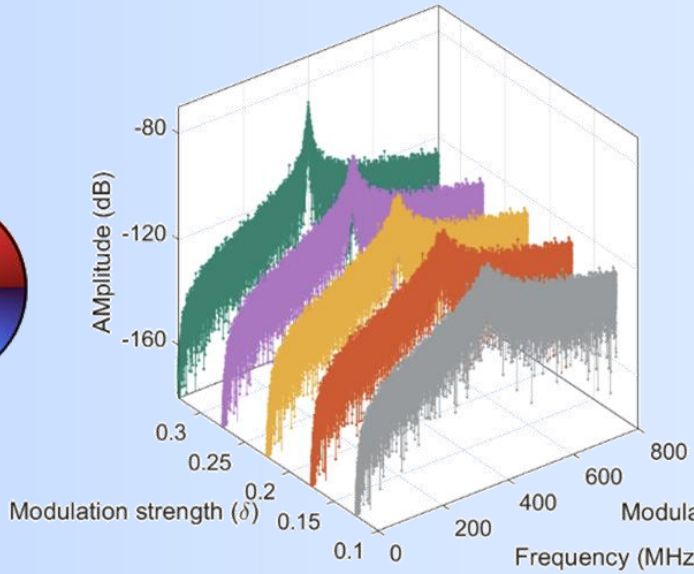
$\not{f}_{res} = 1.5$ GHz

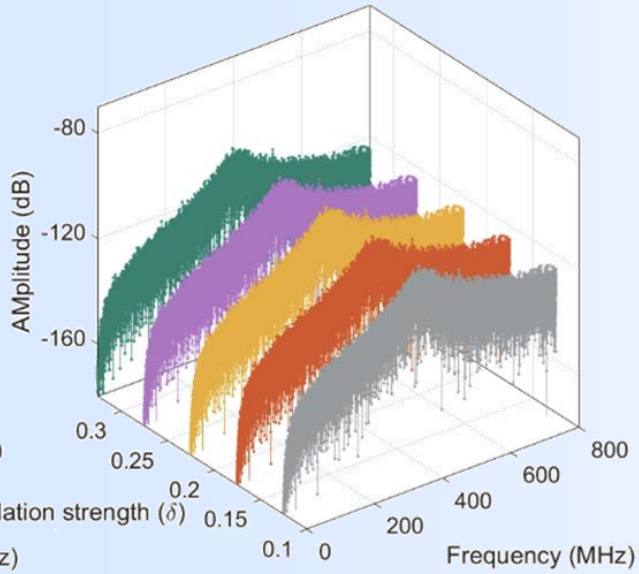
$\ell_m = \pm 1$



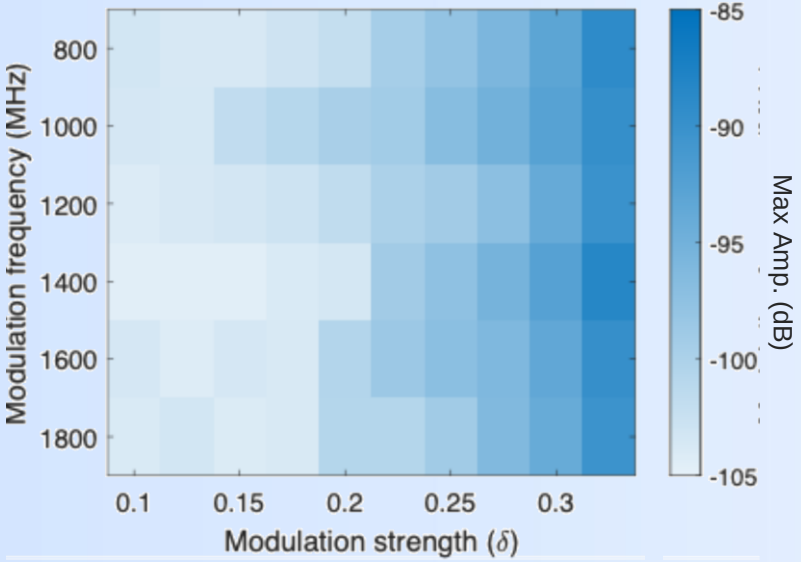
# Spontaneous Emission from Synthetic Rotation

$\ell = -1$



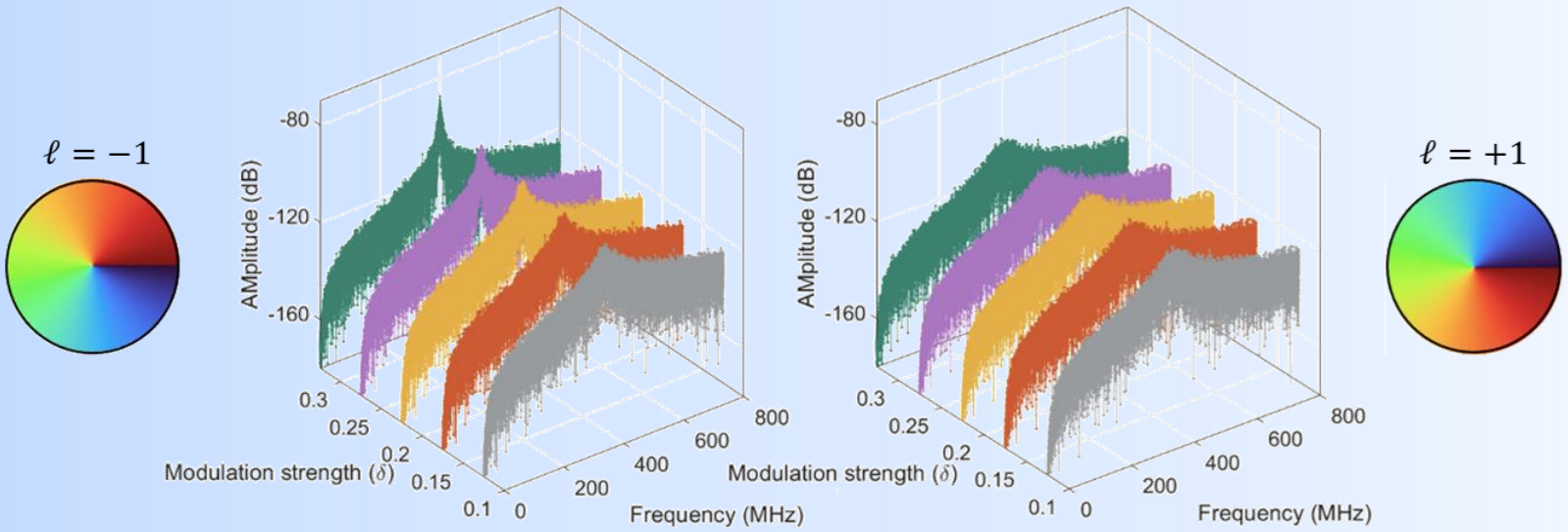



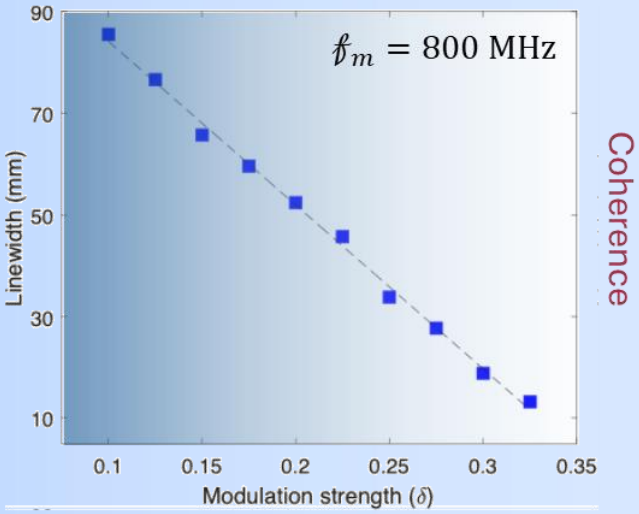

$\ell = +1$



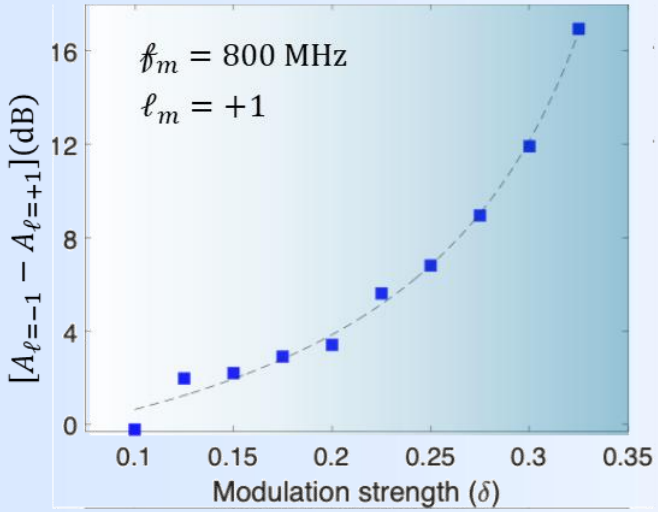

Strength of emission

# Spontaneous Emission from Synthetic Rotation



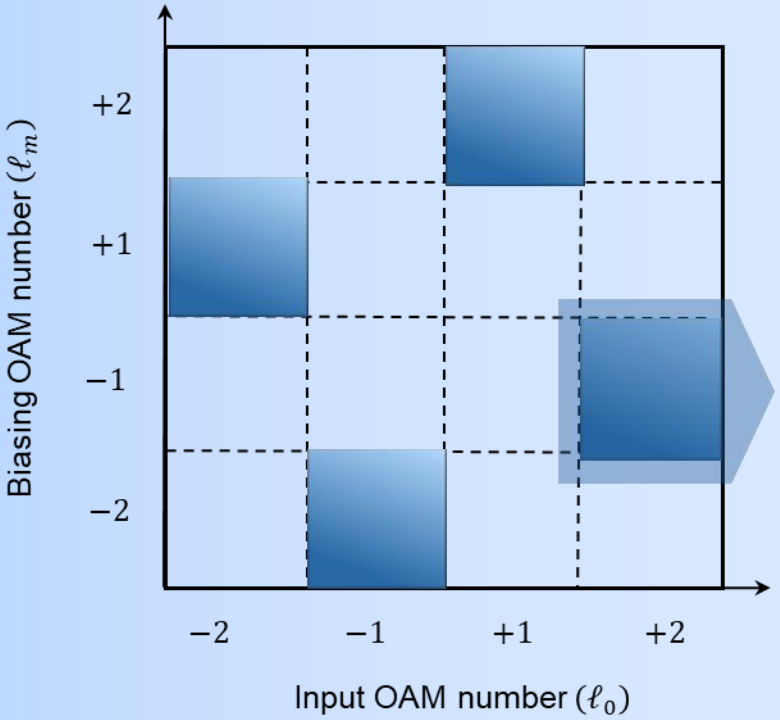



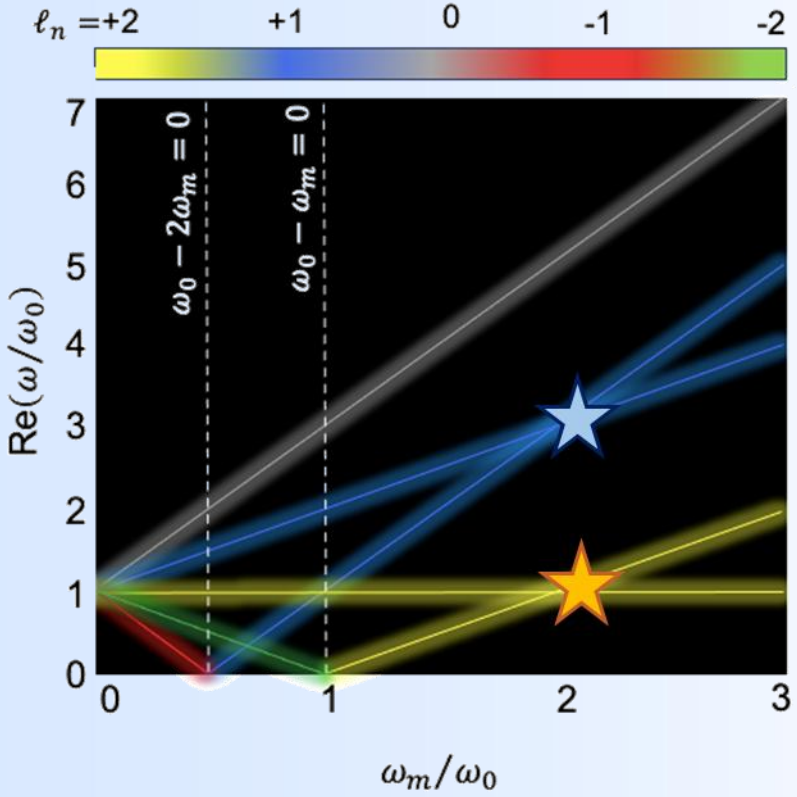

Coherence




Emission in specific OAM channel

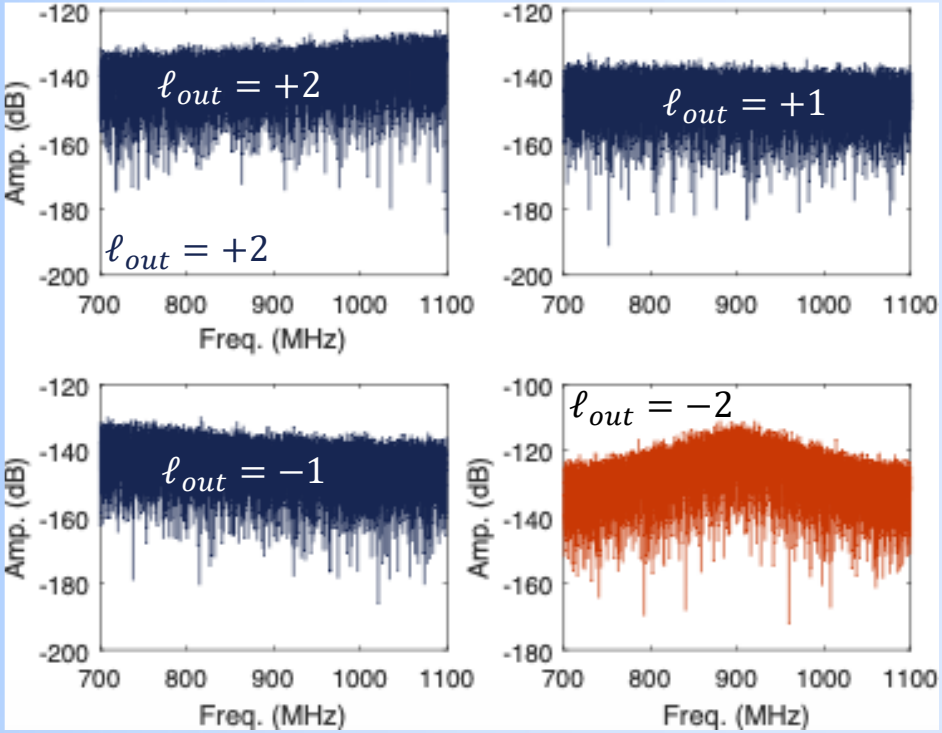
# Spontaneous Emission from Synthetic Rotation

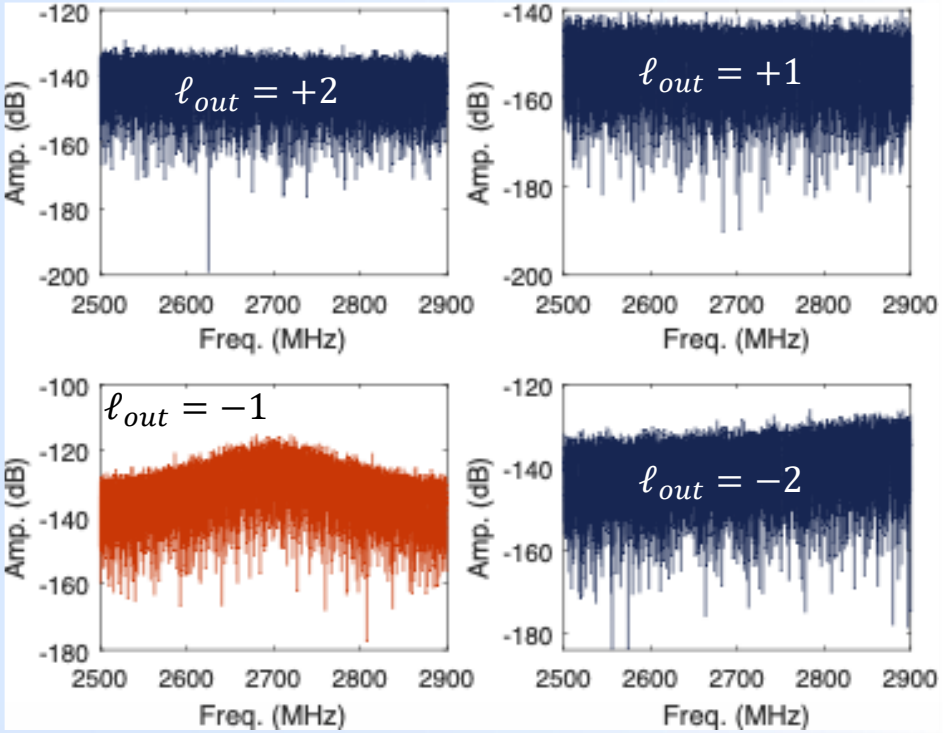


# Spontaneous Emission from Synthetic Rotation

$$f_m = 1.8\ \text{GHz} \quad , \quad \ell_m = +1 \quad , \quad f_{res} = 10\ \text{MHz}$$



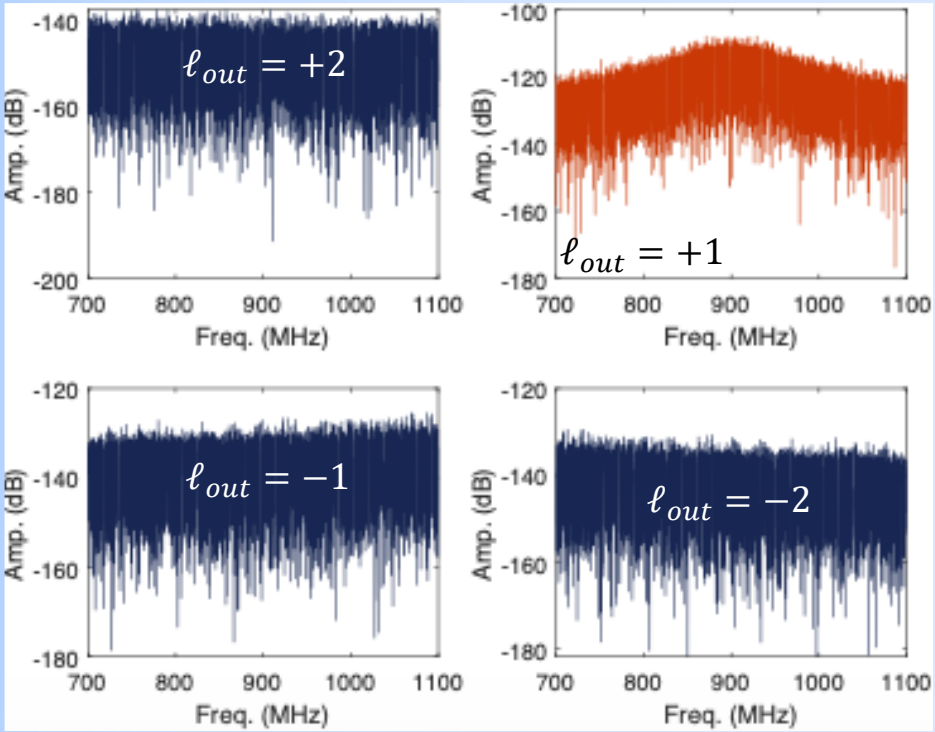



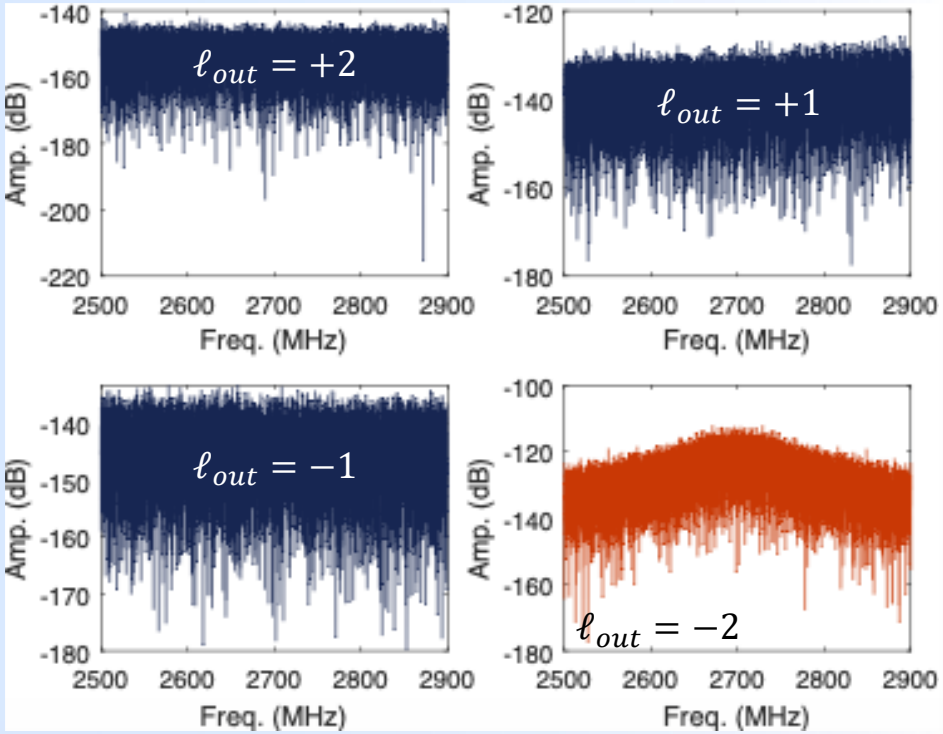

$$f_{emit} = f_0 = f_m/2$$

$$f_{emit} = f_0 + f_m = 3f_m/2$$

# Spontaneous Emission from Synthetic Rotation

$$f_m = 1.8\ \text{GHz} \quad , \quad \ell_m = +2 \quad , \quad f_{res} = 10\ \text{MHz}$$



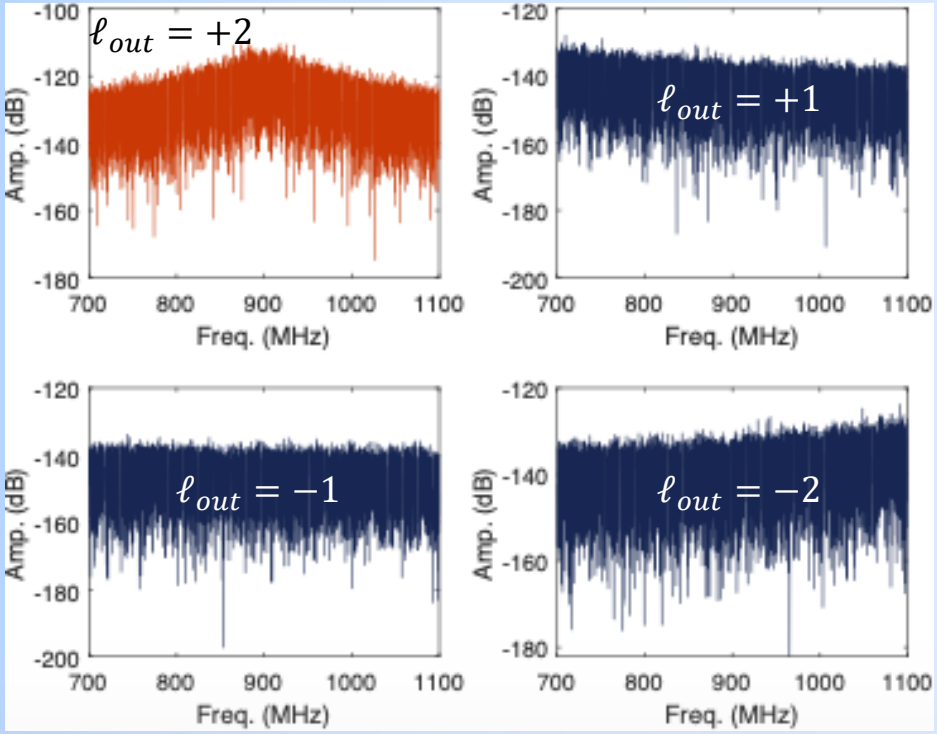




$$f_{emit} = f_0 = f_m/2$$

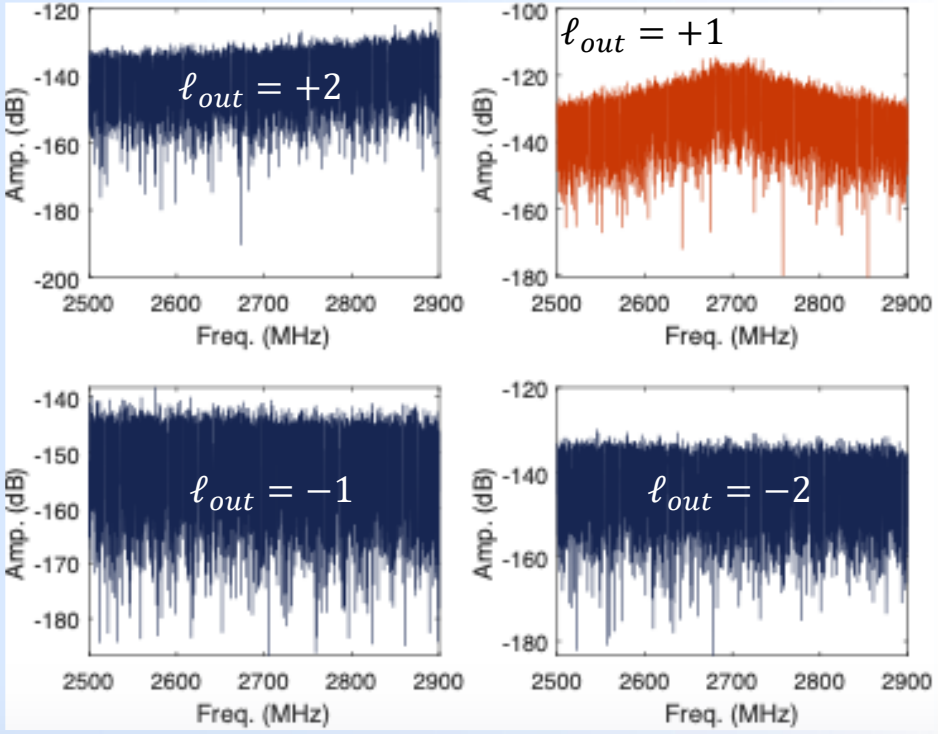
$$f_{emit} = f_0 + f_m = 3f_m/2$$

# Spontaneous Emission from Synthetic Rotation

$$f_m = 1.8\ \text{GHz} \quad , \quad \ell_m = -1 \quad , \quad f_{res} = 10\ \text{MHz}$$



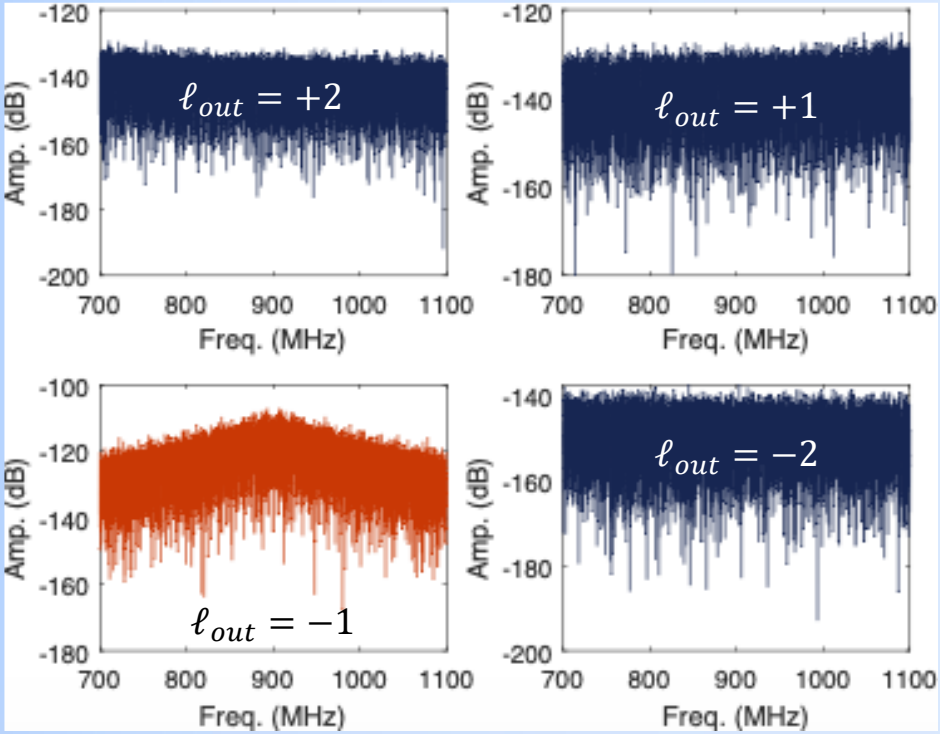

$$f_{emit} = f_0 = f_m/2$$

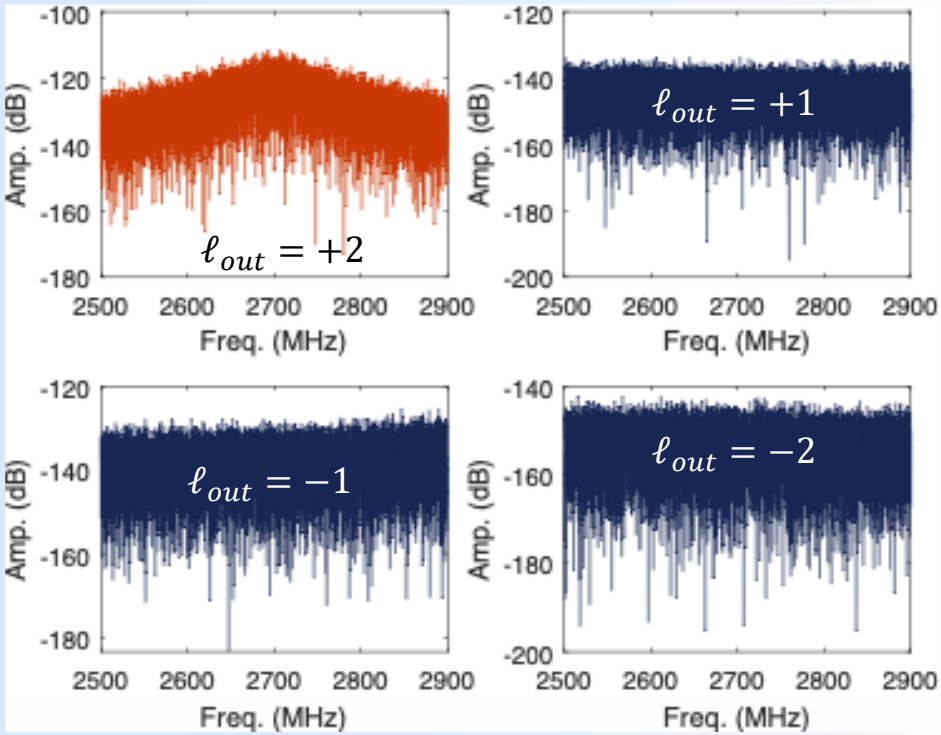



$$f_{emit} = f_0 + f_m = 3f_m/2$$

# Spontaneous Emission from Synthetic Rotation

$$\mathcal{f}_m = 1.8\ \text{GHz} \quad , \quad \ell_m = -2 \quad , \quad \mathcal{f}_{res} = 10\ \text{MHz}$$



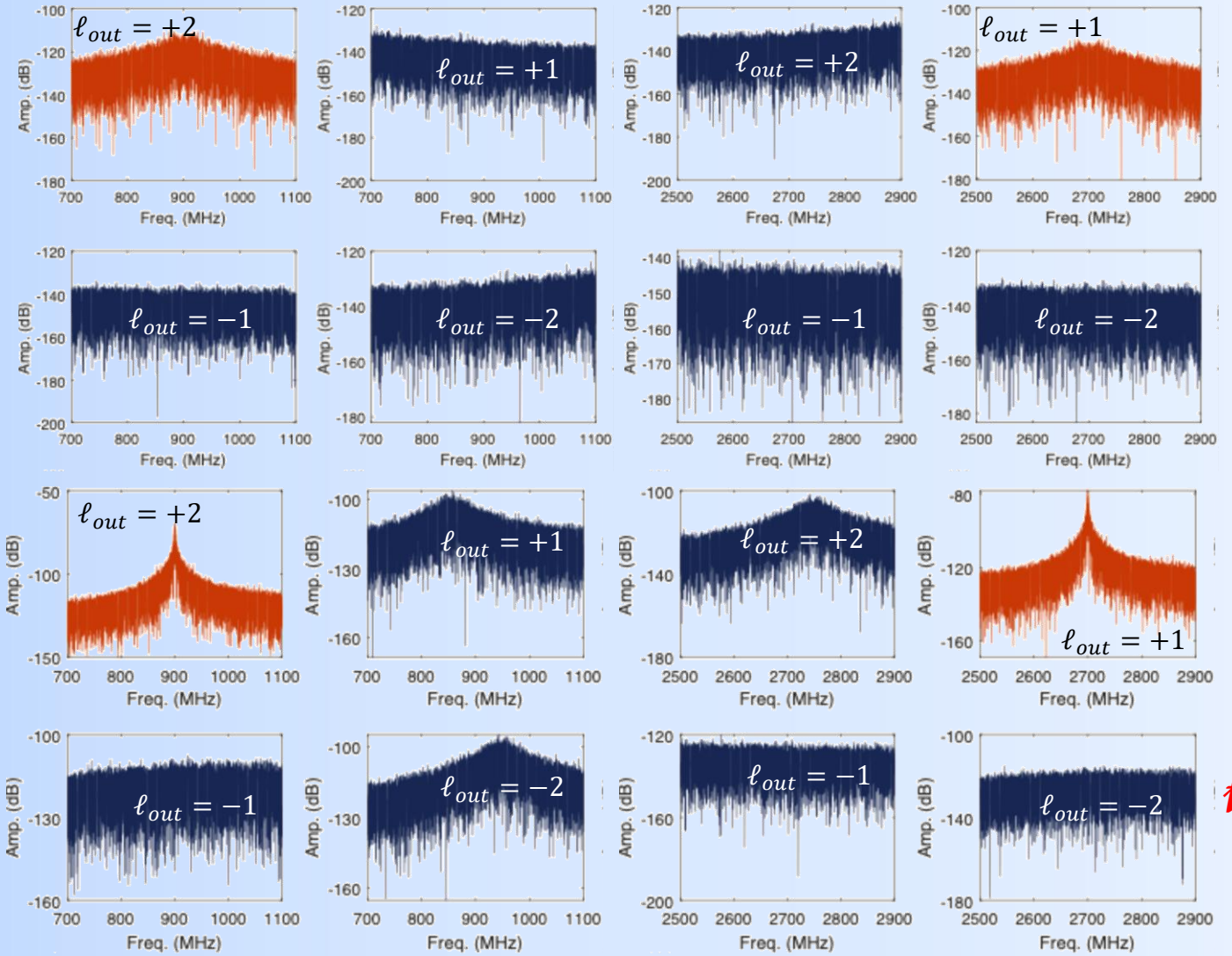




$$\mathcal{f}_{emit} = \mathcal{f}_0 = \mathcal{f}_m/2$$

$$\mathcal{f}_{emit} = \mathcal{f}_0 + \mathcal{f}_m = 3\mathcal{f}_m/2$$

# Spontaneous Emission from Synthetic Rotation

$\mathbf{\mathcal{f}_m = 1.8\ GHz}$ , $\mathbf{\ell_m = -1}$




$\mathcal{f}_{emit} = \mathcal{f}_0 = \mathcal{f}_m/2$

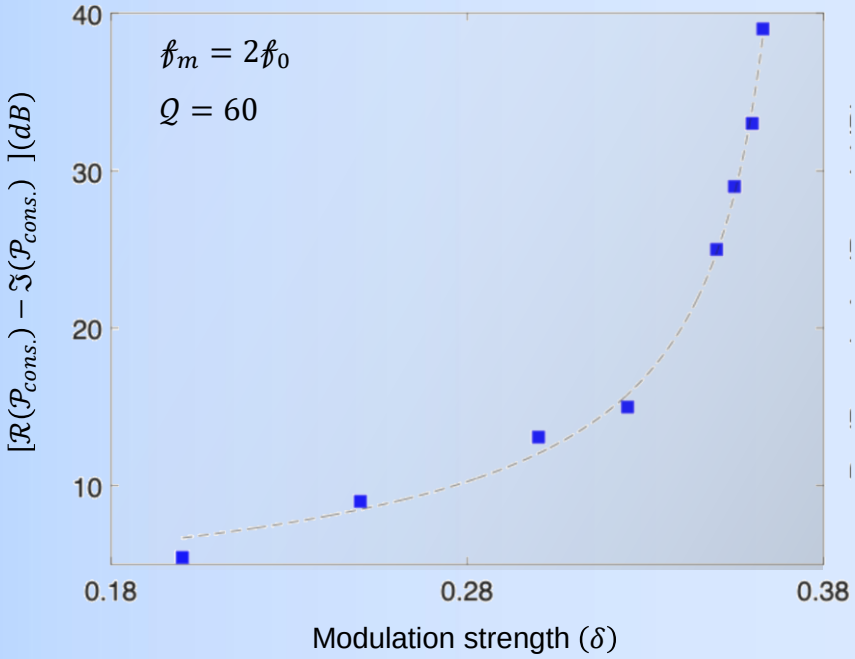
$\mathcal{f}_{emit} = \mathcal{f}_0 + \mathcal{f}_m = 3\mathcal{f}_m/2$

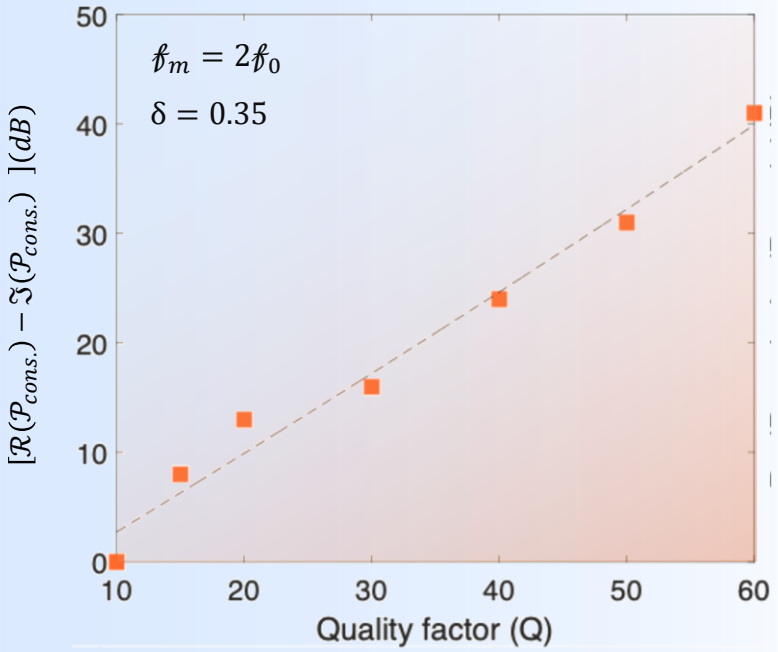
$\mathcal{f}_{res}$= 10 MHz

$\mathcal{f}_{res}$= 900 MHz

# Radiation Dissipative Reaction Force

Classical analogue of quantum friction



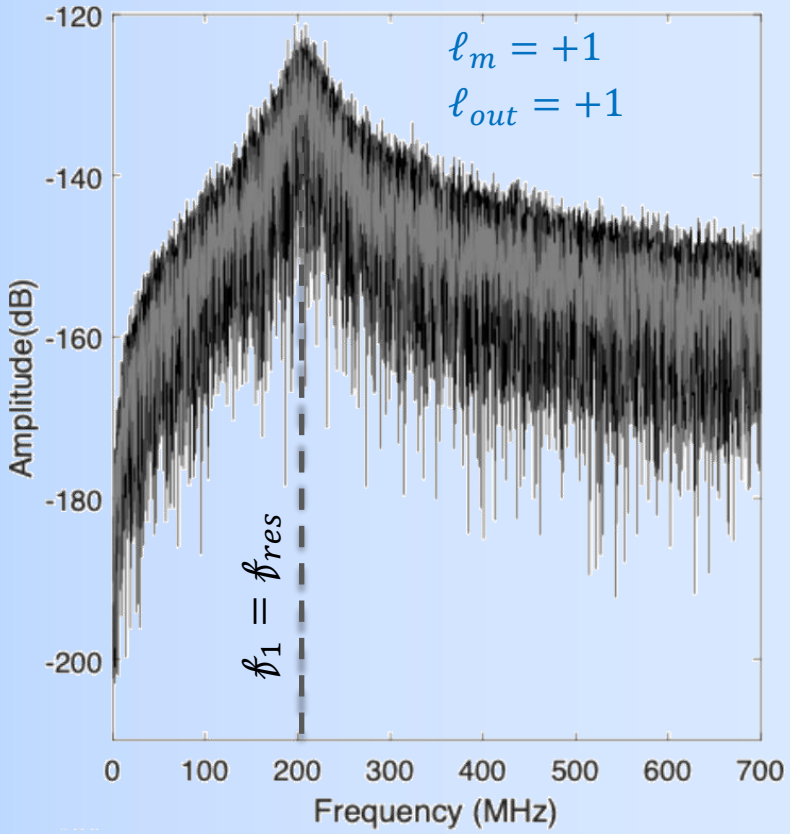



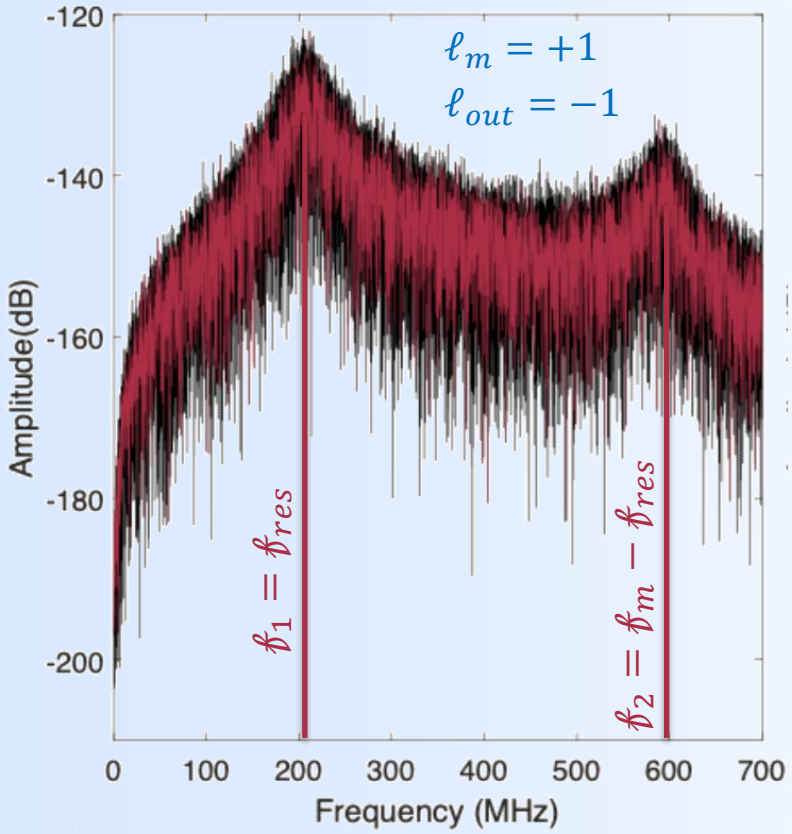
# Classical Analogue of Two-Mode Squeezing

$$\omega_1 + \omega_2 = \omega_m$$

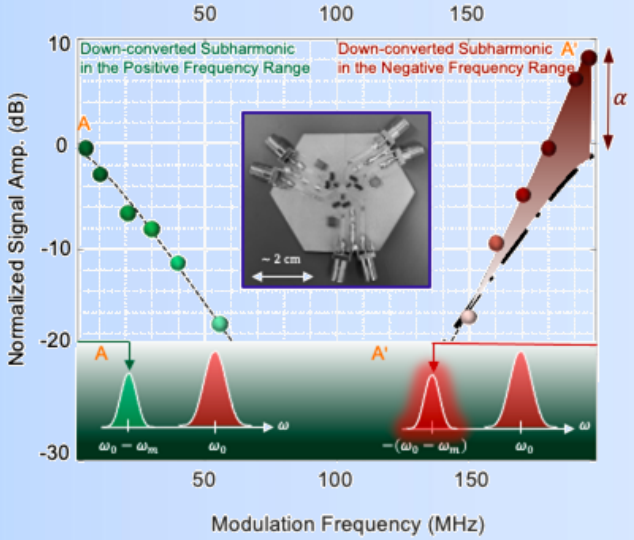
*Frequency correlation* between the generated modes

**Quantum Squeezed States**: Unequal distribution of uncertainty between the two quadrature (i.e., position & momentum).

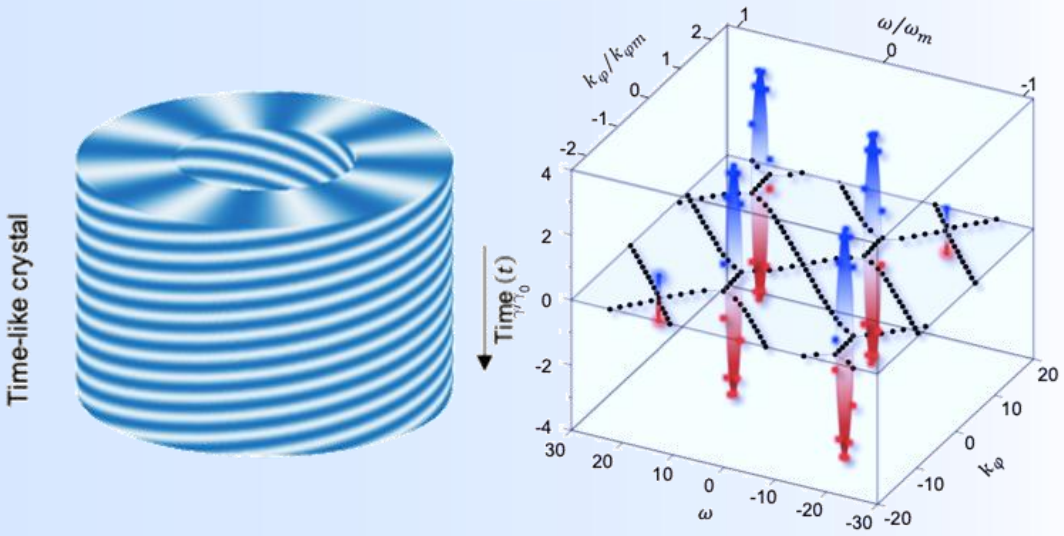


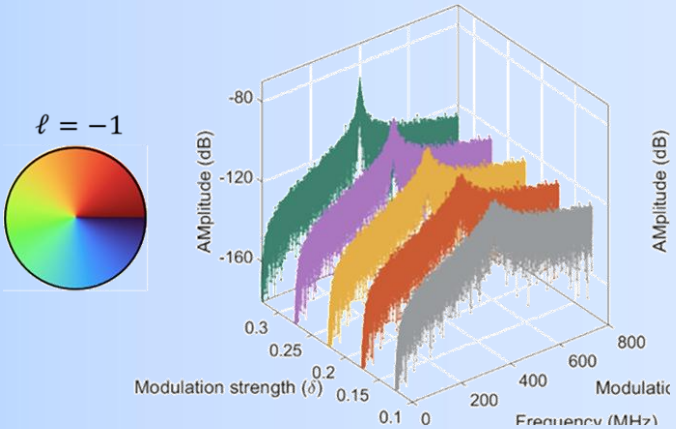
# Synthetic Rotation and Penrose Effect



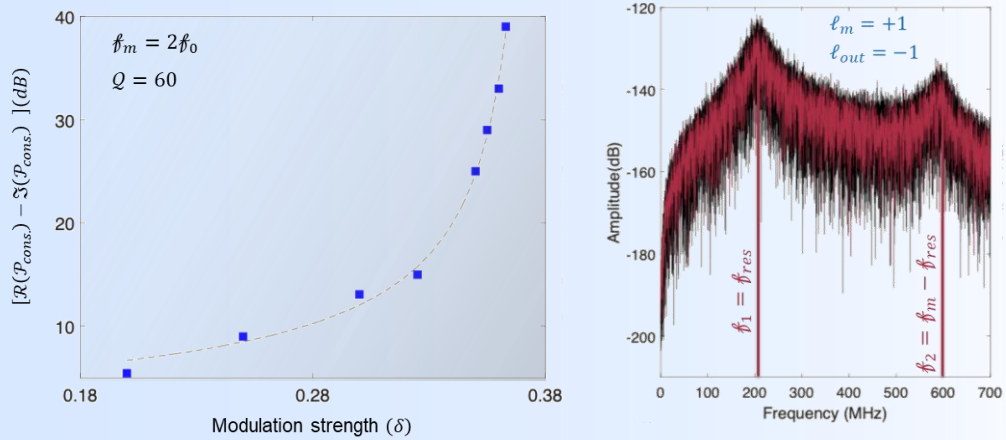

Synthetic Penrose super-radiance




Angular-momentum (AM) bandgaps




AM-selective spontaneous emission




AM-selective squeezing and friction