

Microscale Granular Acoustic Metamaterials

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Assistant Professor

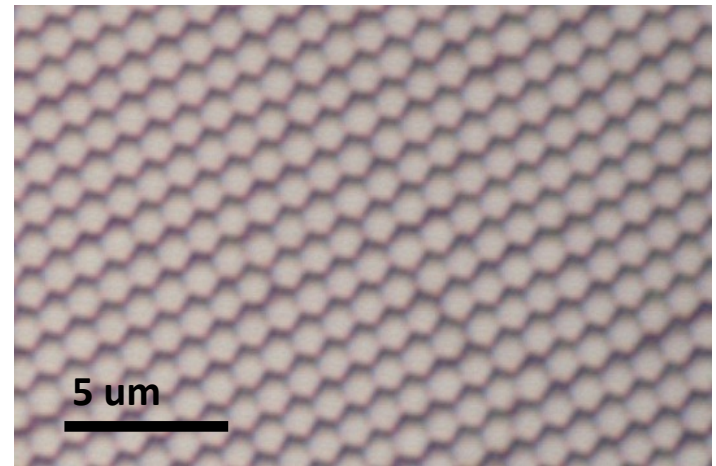
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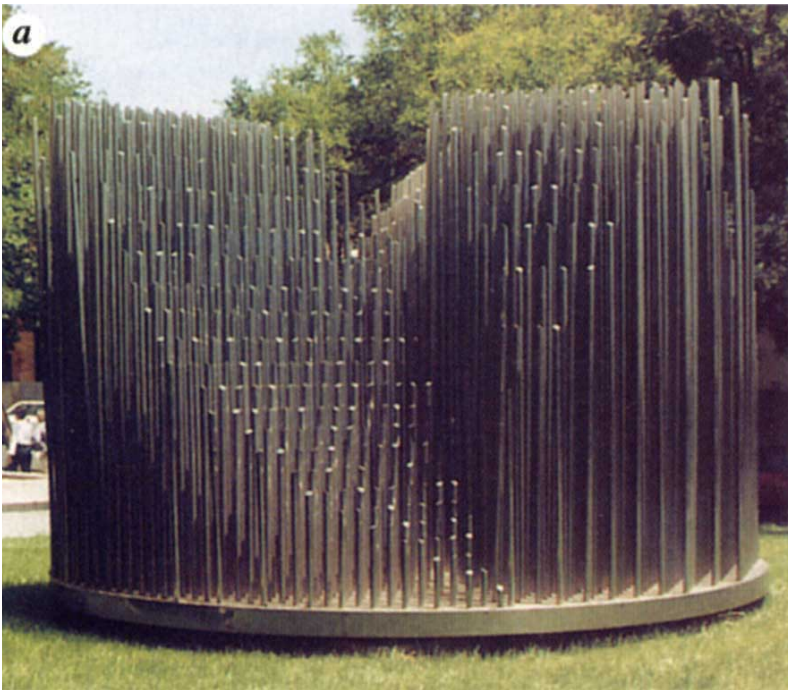
**AmeriMech Symposium: Dynamics of
Periodic Materials and Structures**

April 3-4, 2014



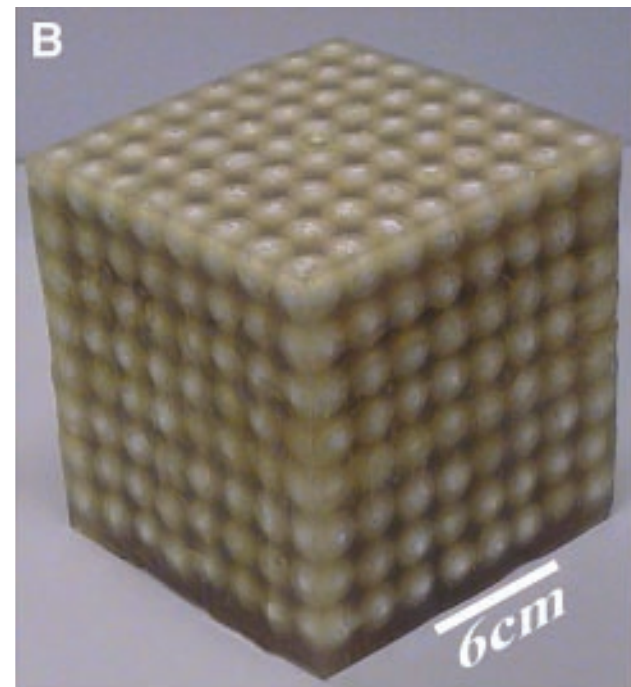
Acoustic Metamaterials: Dispersion

Periodic



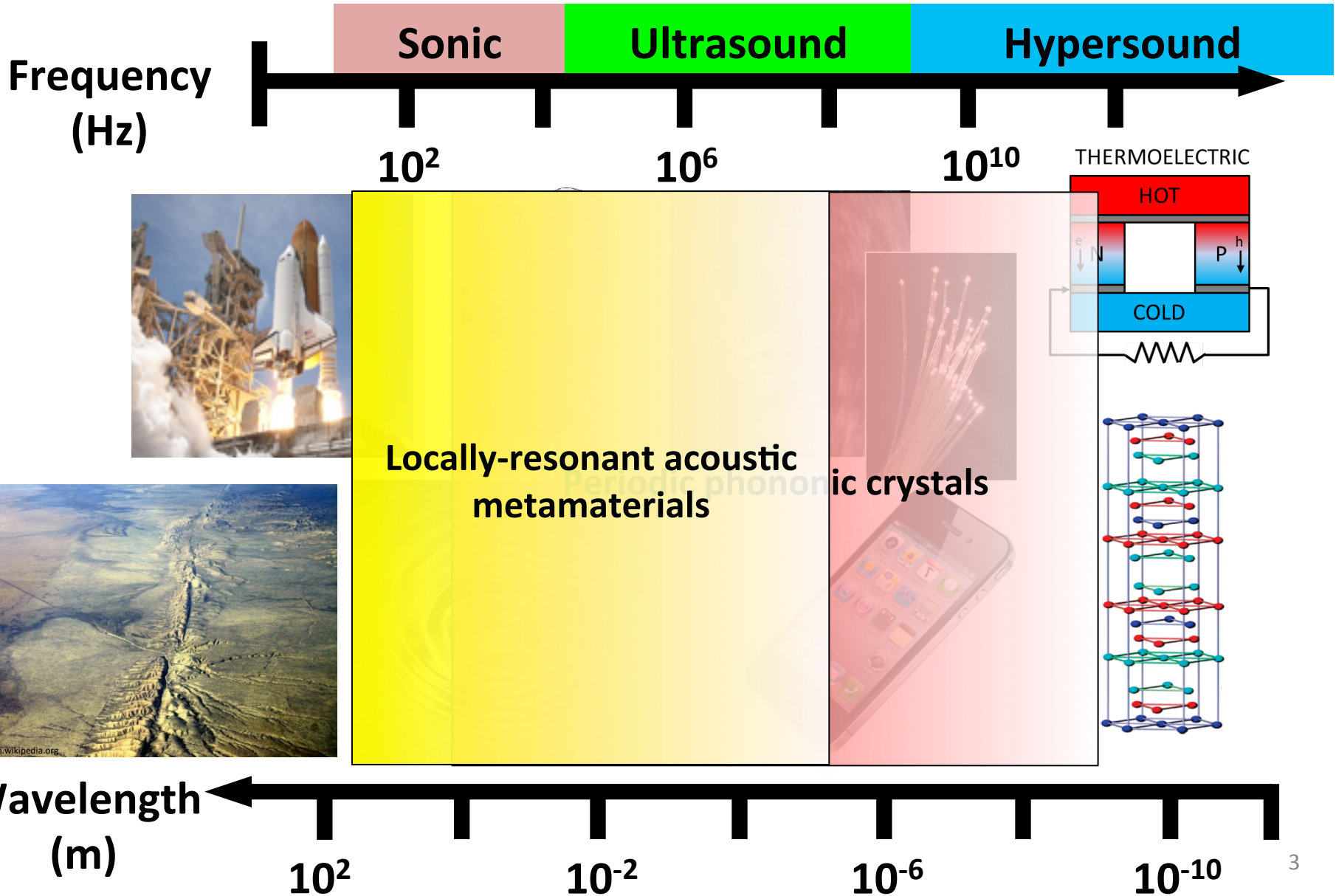
Eusebio Sempere (Madrid)
Martinez Sala, R., et al., Nature (1995)

Locally-resonant



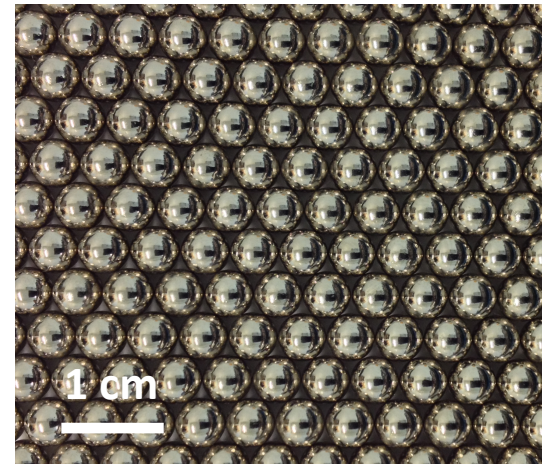
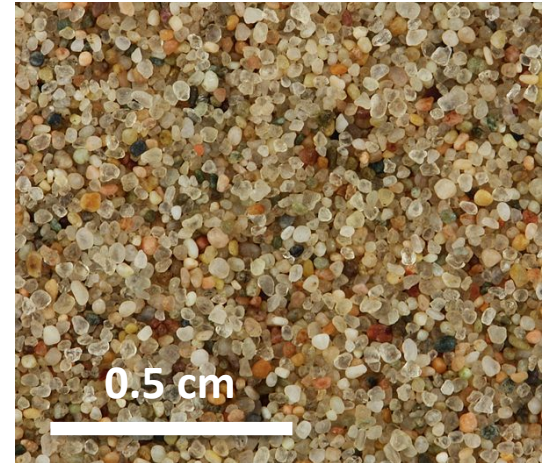
Liu, Z., et al., Science (2000)

Scalability and Acoustic Waves



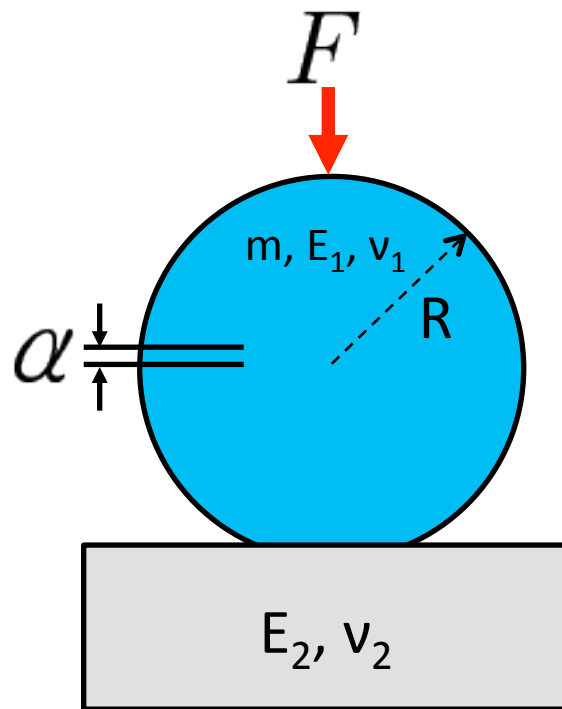
Granular Media

- Common
- Highly complex (pencils and bullets)
- **Highly nonlinear**
- **Metamaterial (dispersive)**
- Self-assembly

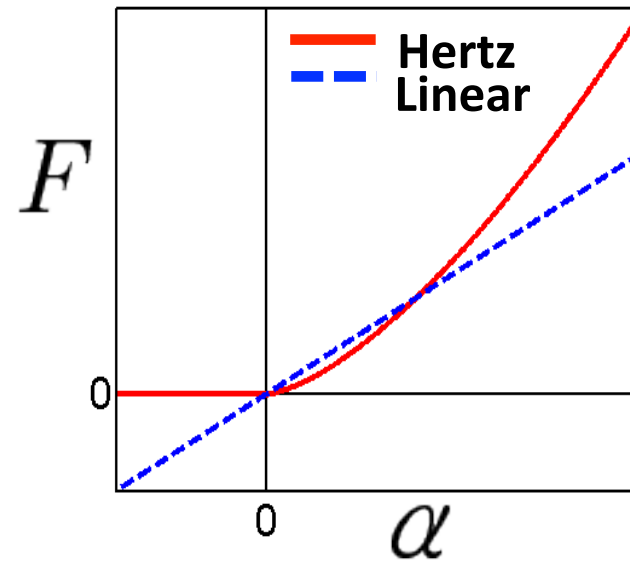


Granular Contact Mechanics

Hertz Normal Contact

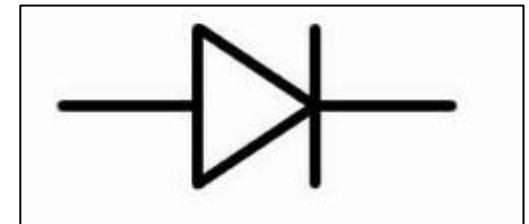
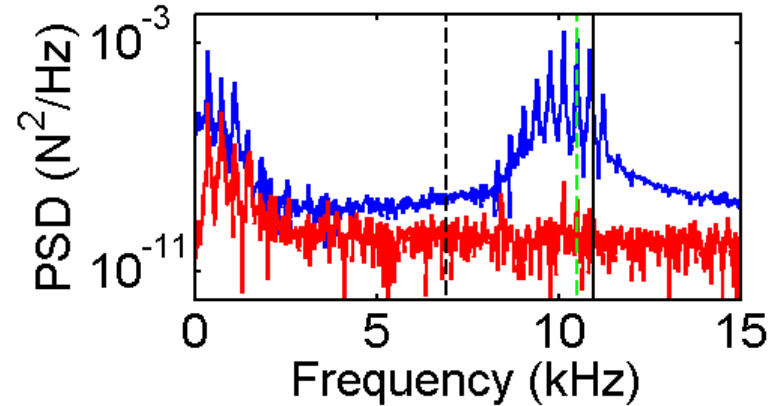


$$F = A[\alpha]_+^{3/2}$$



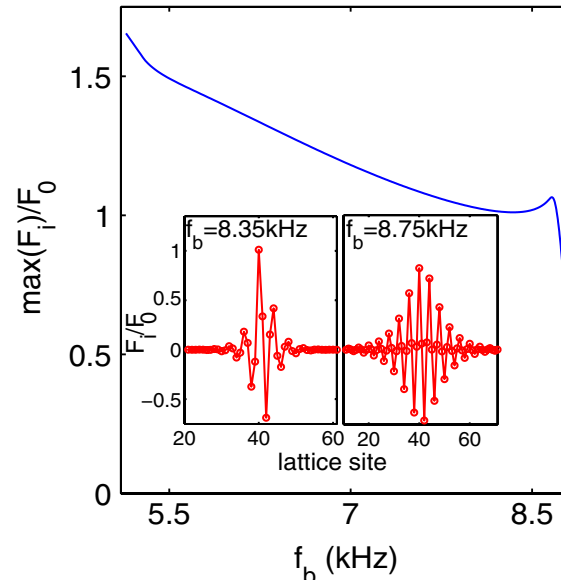
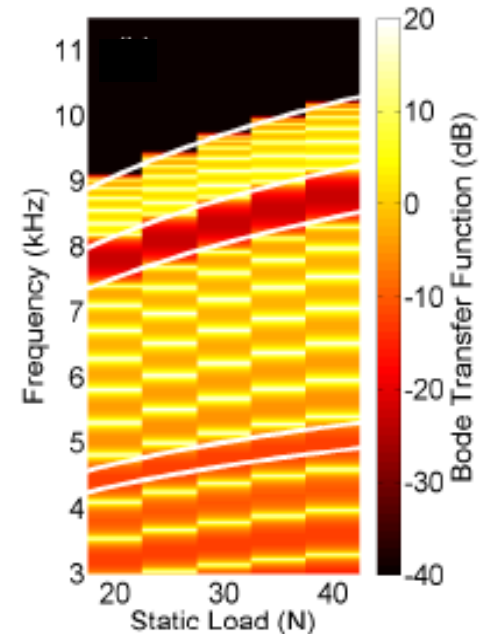
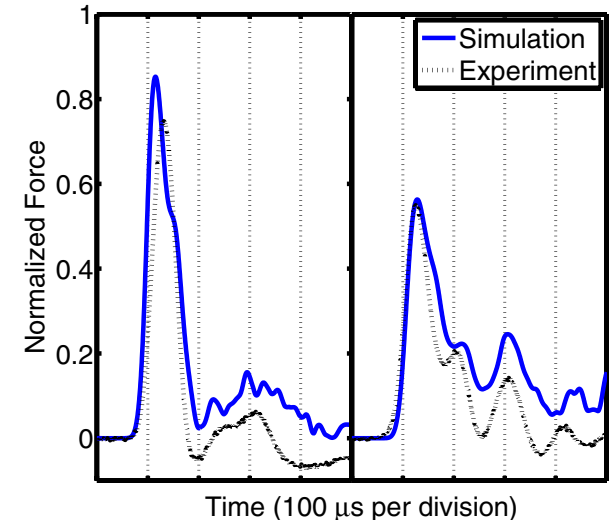
Nonlinearity and Dispersion

- Nonlinearity is useful
- Many problems are nonlinear
- Dispersion and nonlinearity are linked
- Granular media lends both

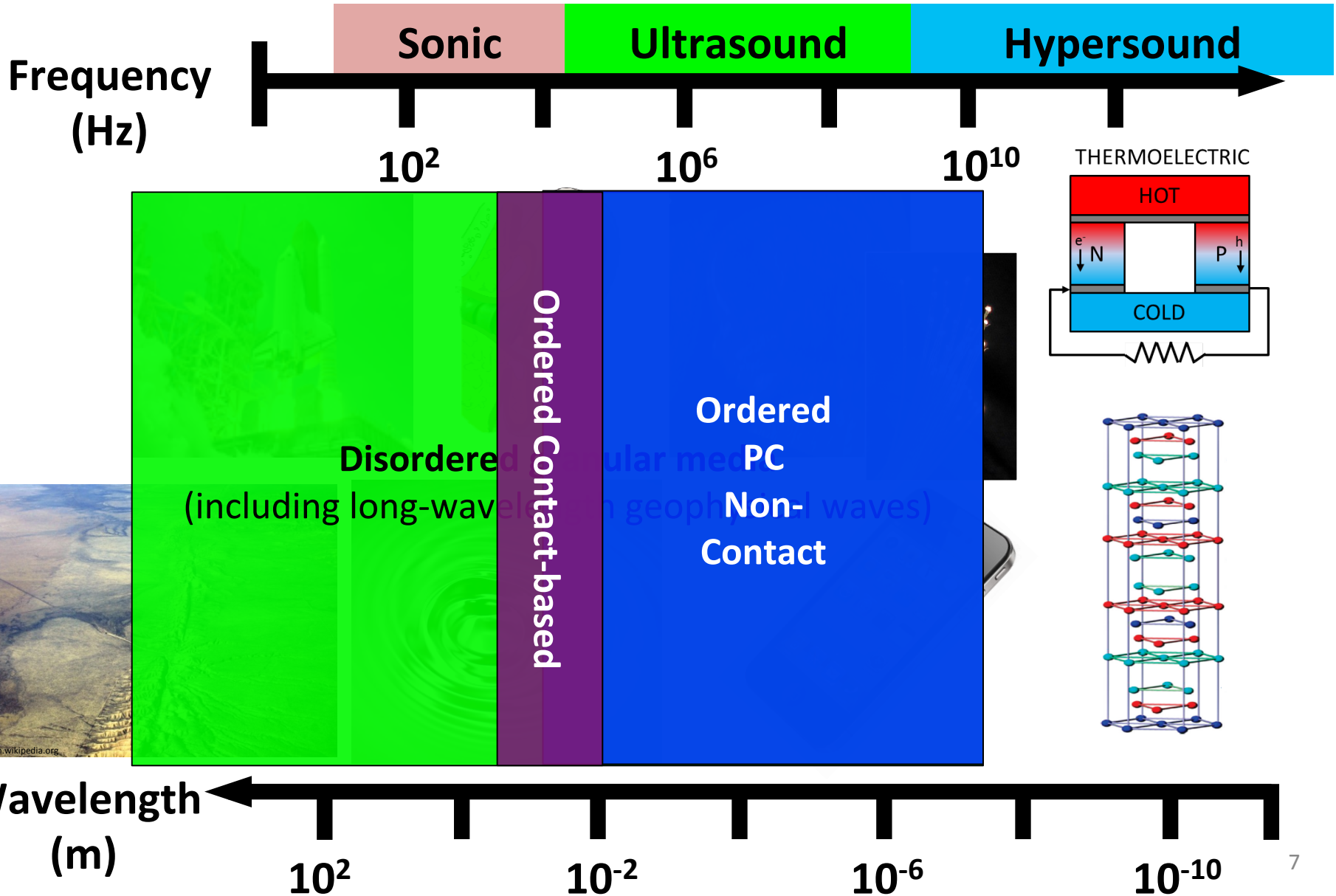


$D=0.1$

$D=0.7$

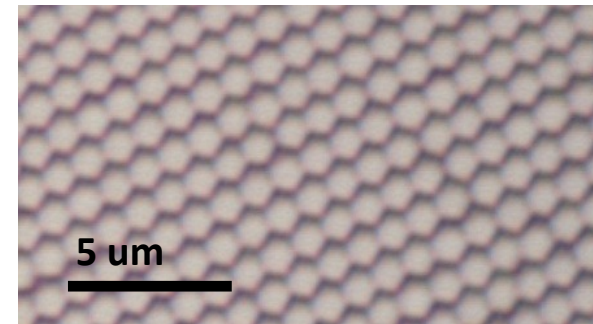
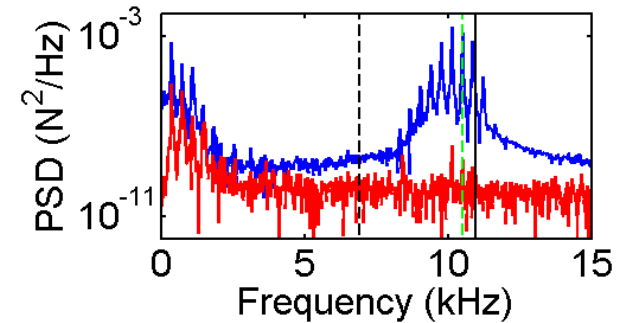


Scalability and Acoustic Waves



Granular Acoustic Metamaterials: Opportunities

- Fundamental interplay between nonlinearity and tailored dispersion
- Granular media and metamaterial scalability
- Understand complex bulk granular phenomena via ordered structures



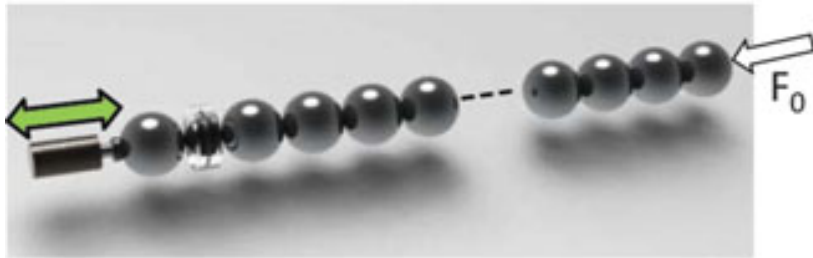
Two Examples

Acoustic Diode:

Periodic

Nonlinearity + Dispersion

Macroscale



Boechler, N., Theocharis, G., and Daraio, C., Nature Mater. (2011)

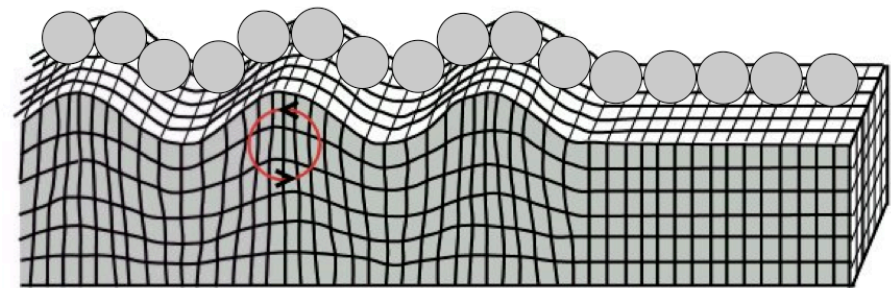
SAW Metamaterial:

Locally-resonant

Scalability

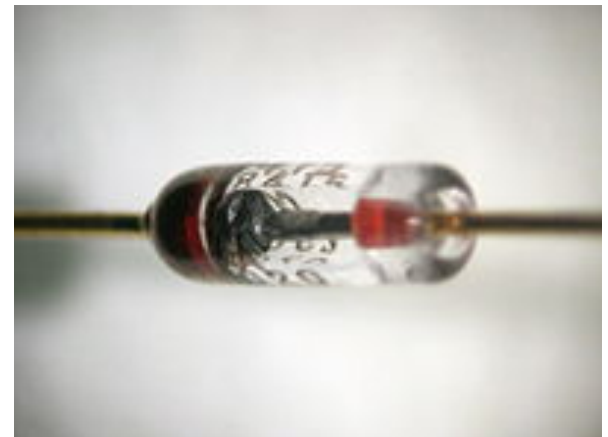
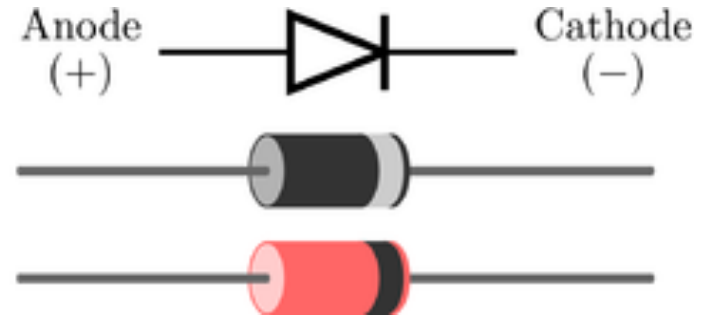
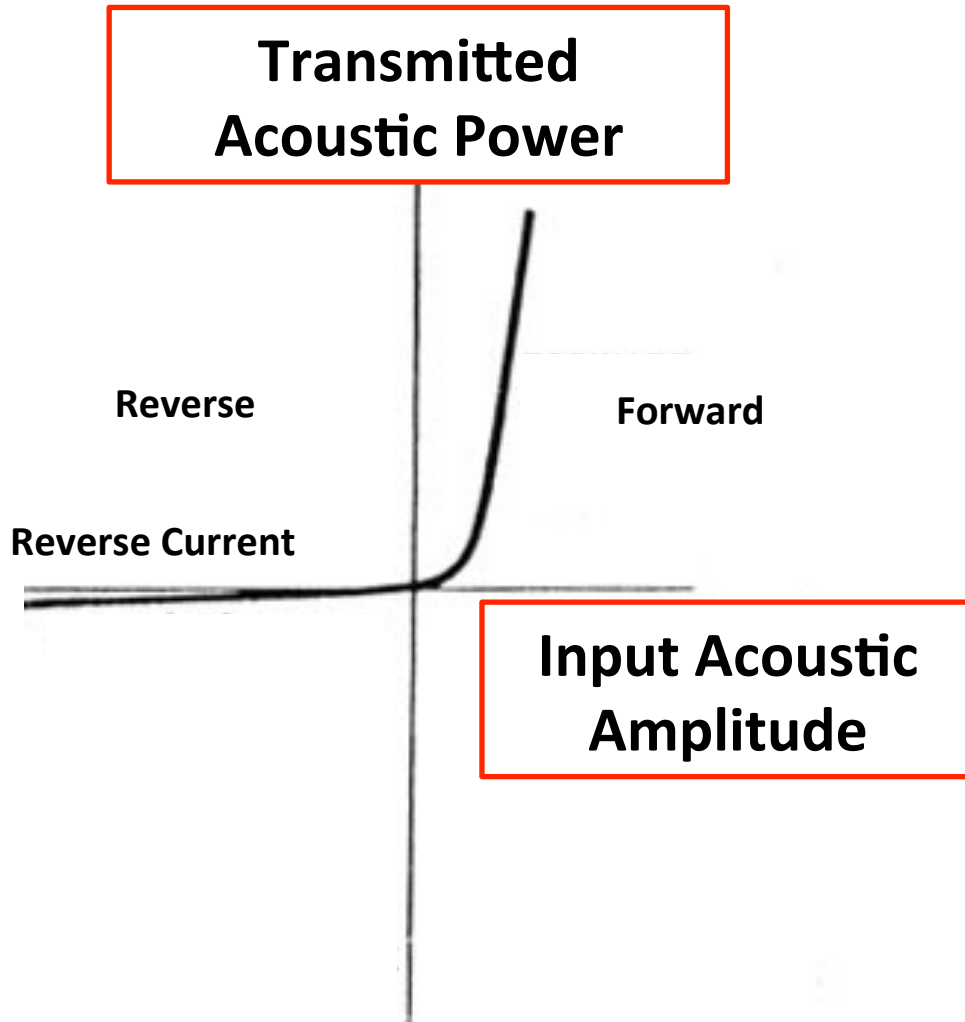
Microscale

Rayleigh Wave

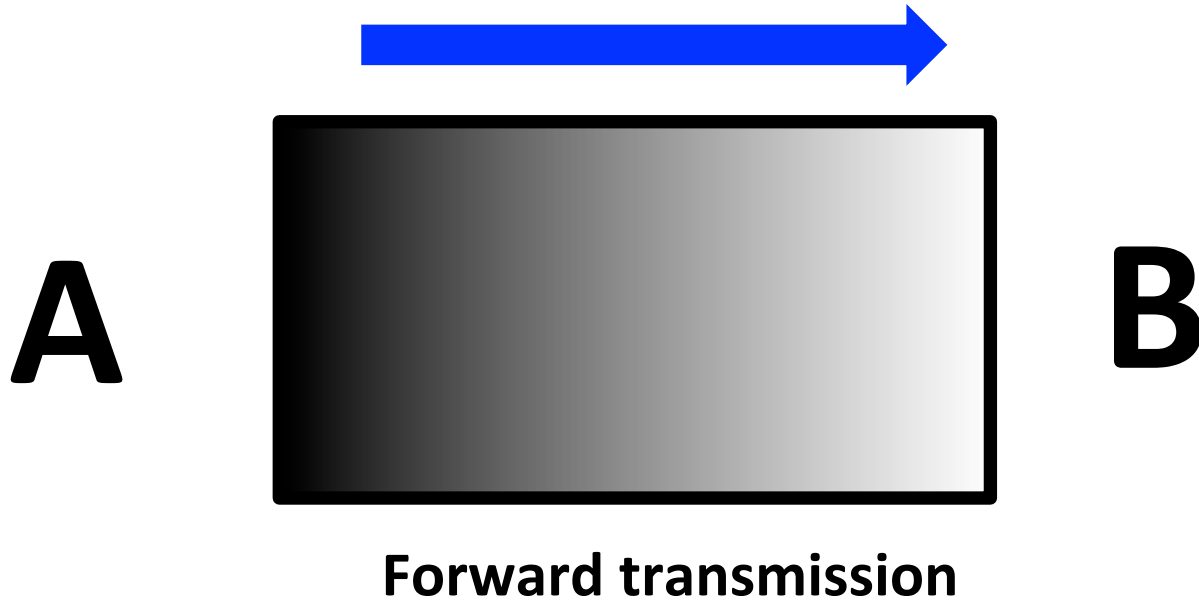


Boechler, N., Eliason, J., Kumar, A., Maznev, A., Nelson, K., and Fang, N., Phys. Rev. Lett. (2013)

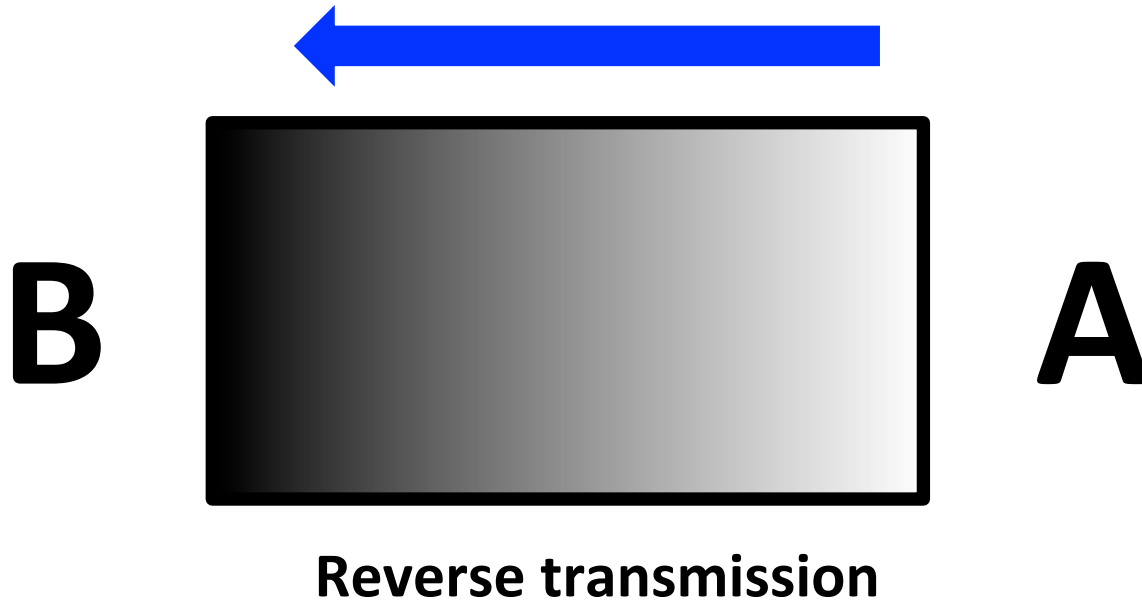
Acoustic Diode



Acoustic Reciprocity



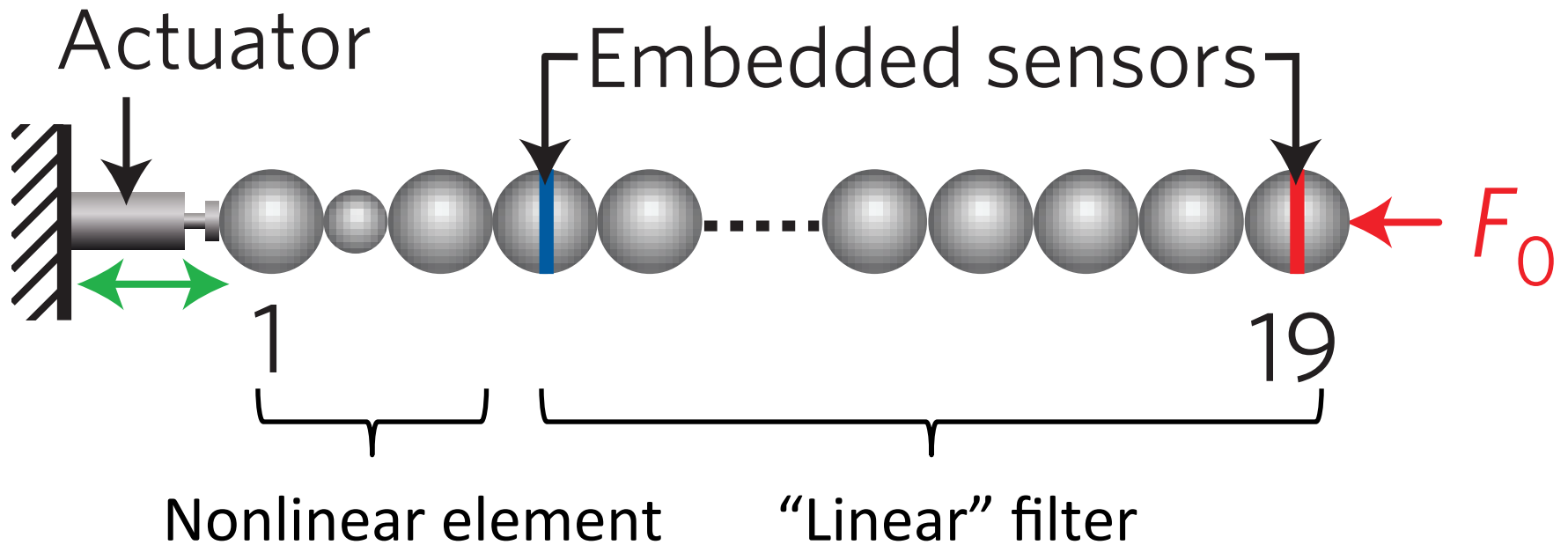
Acoustic Reciprocity



Linear: B (forward) = B (reverse), given same A (input)

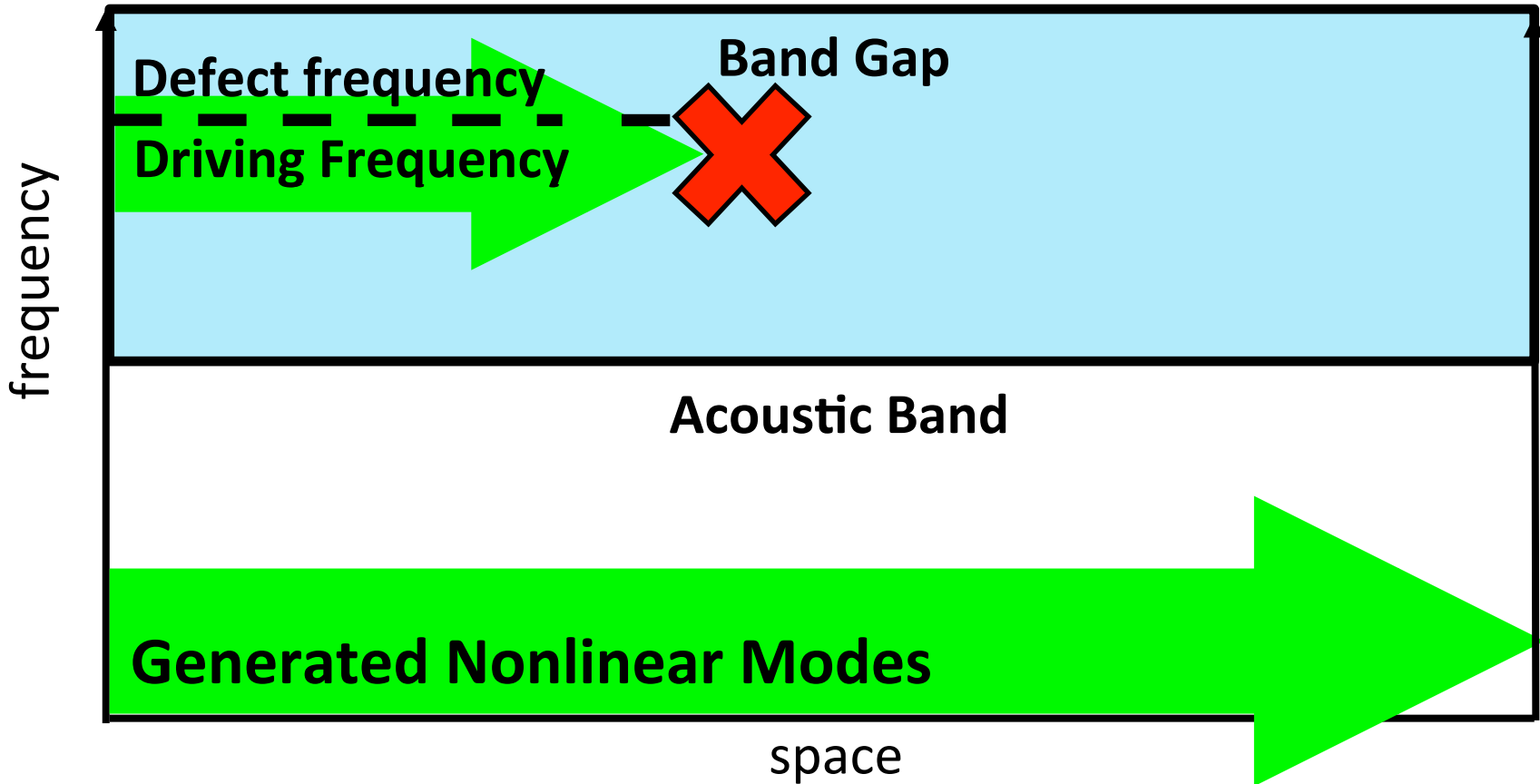
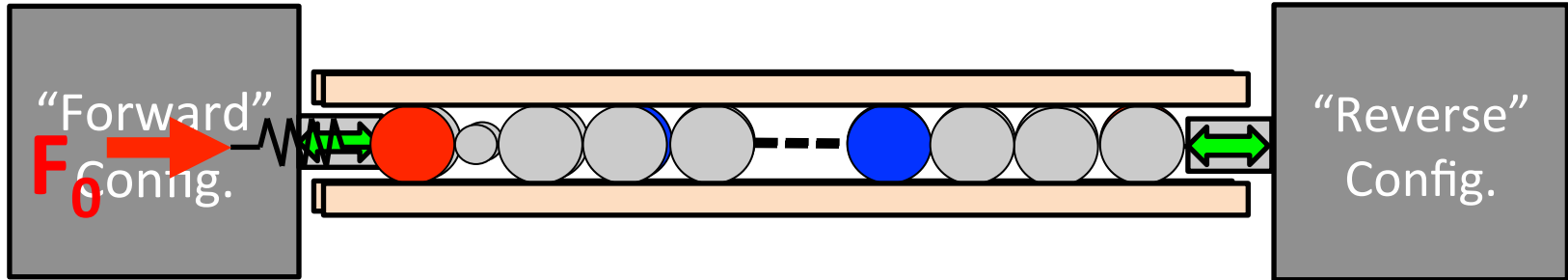
Nonlinear: B (forward) \neq B (reverse), given same A (input)

Granular Acoustic Diode Concept

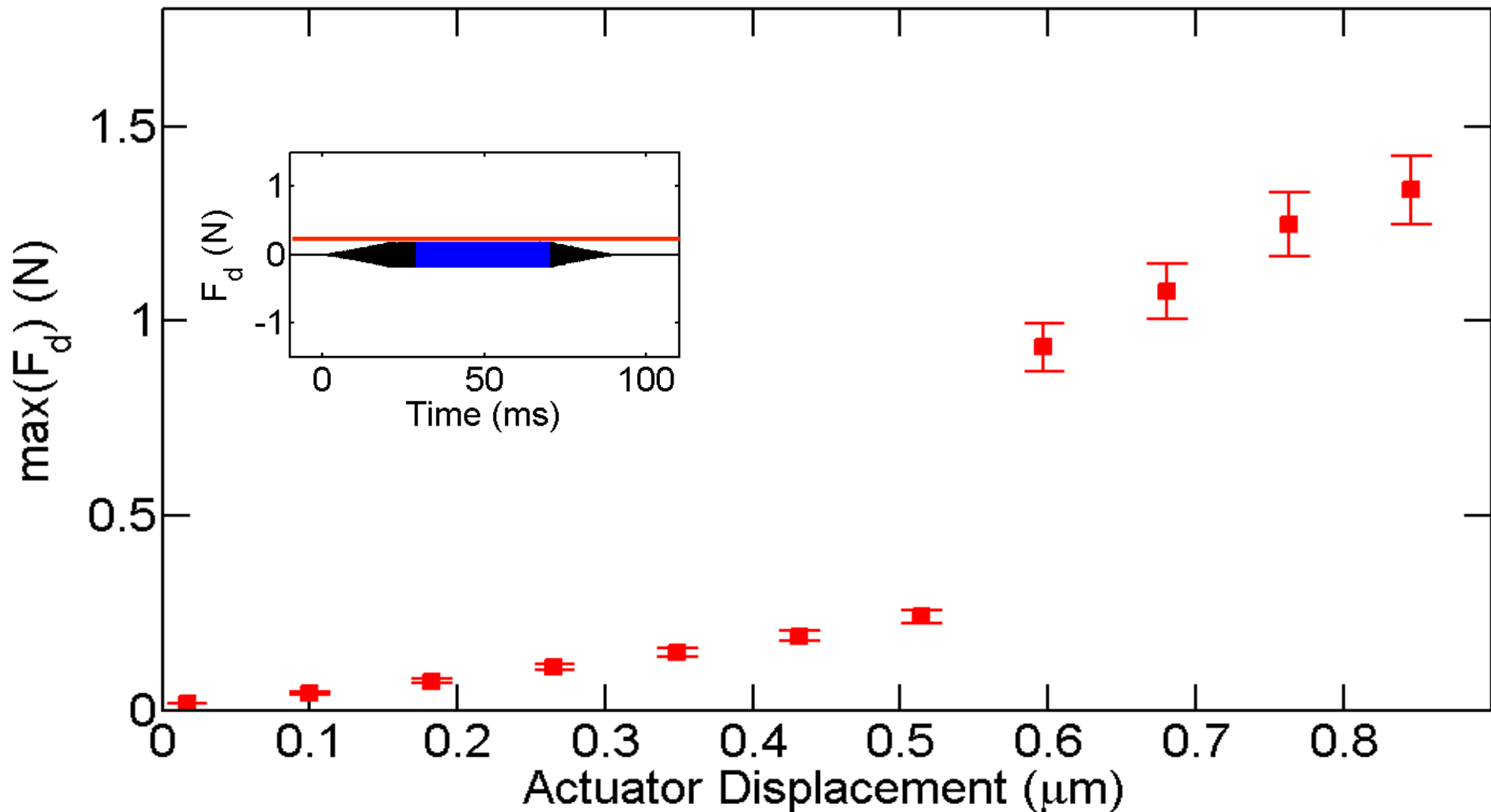


2 cm diameter steel particles

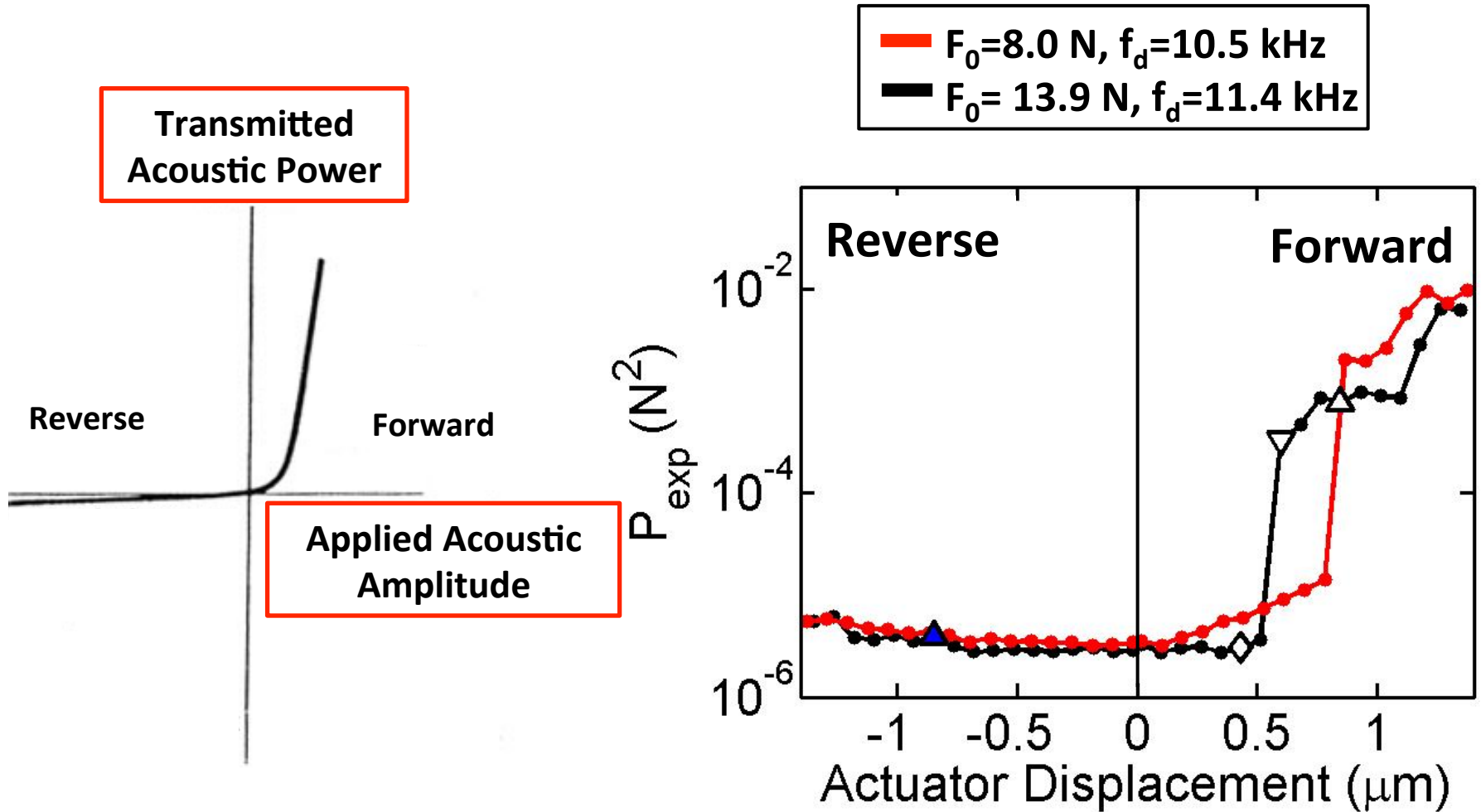
Tunable Acoustic Diode



Tunable Diode: Forward Configuration (w/ dissipation)



Tunable Diode: Transmitted Power (Experimental)



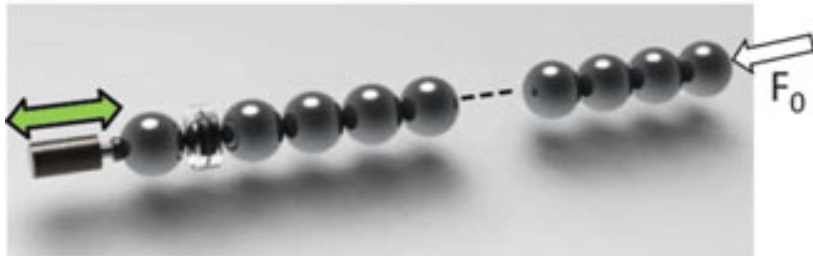
Two Examples

Acoustic Diode:

Periodic

Nonlinearity + Dispersion

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Boechler, N., Theocharis, G., and Daraio, C., *Nature Mater.* (2011)

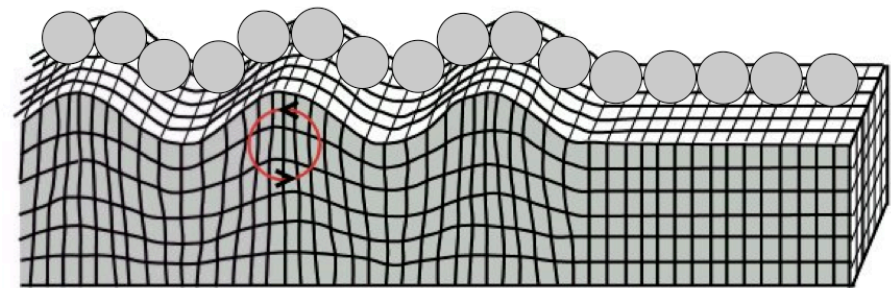
SAW Metamaterial:

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Scalability

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Rayleigh Wave

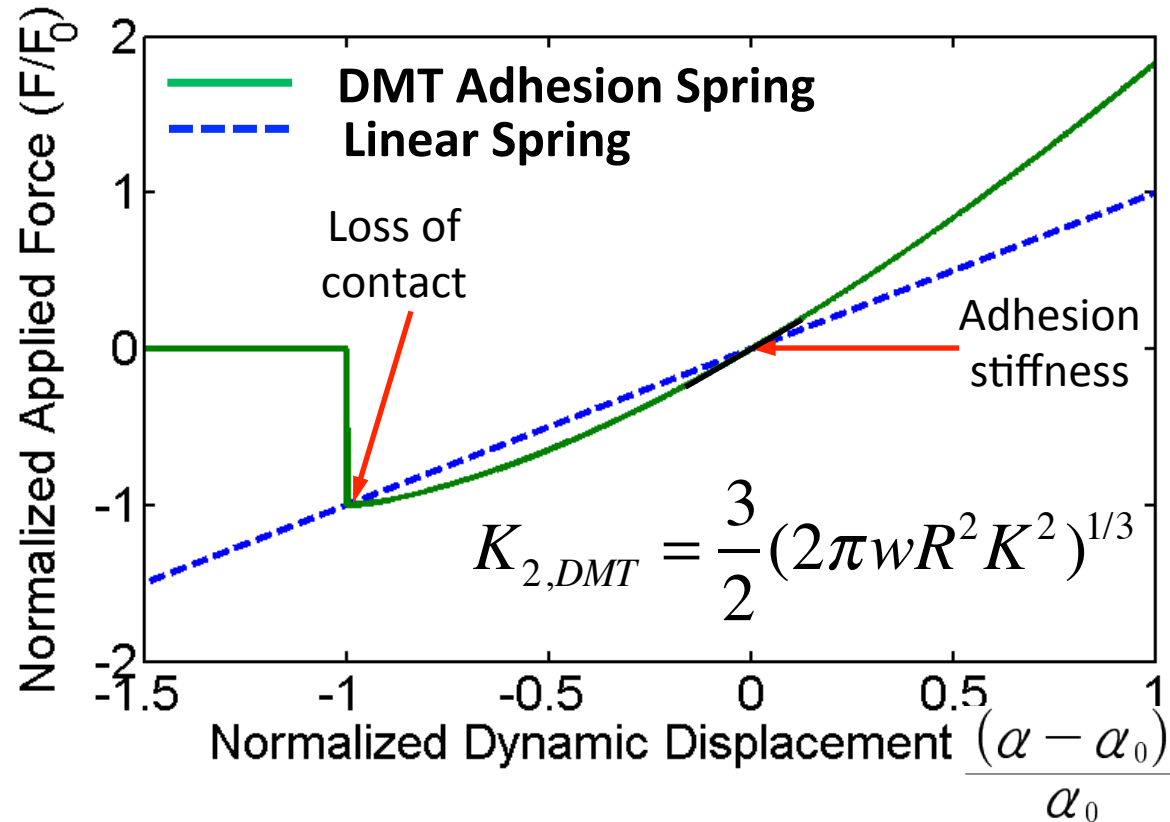
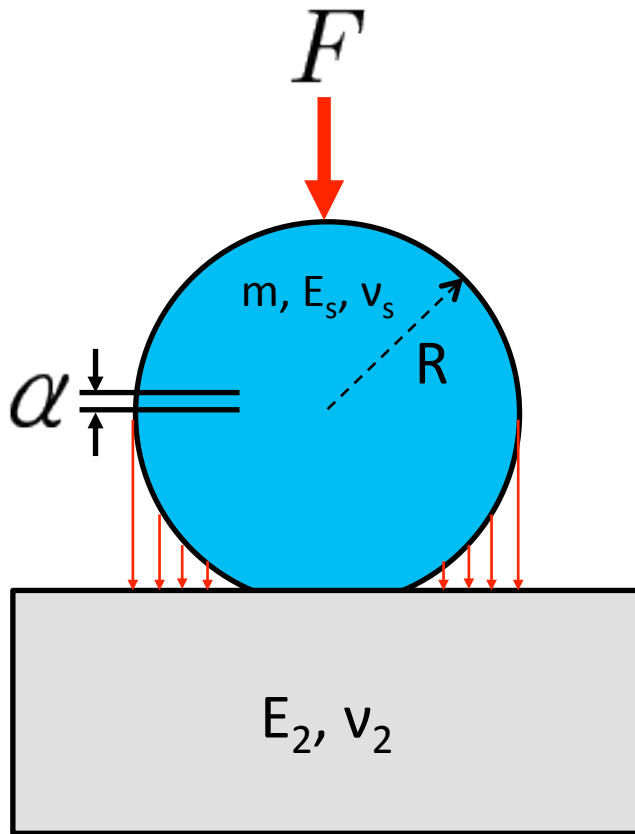


Boechler, N., Eliason, J., Kumar, A., Maznev, A., Nelson, K., and Fang, N., *Phys. Rev. Lett.* (2013)

Microscale Contact Mechanics

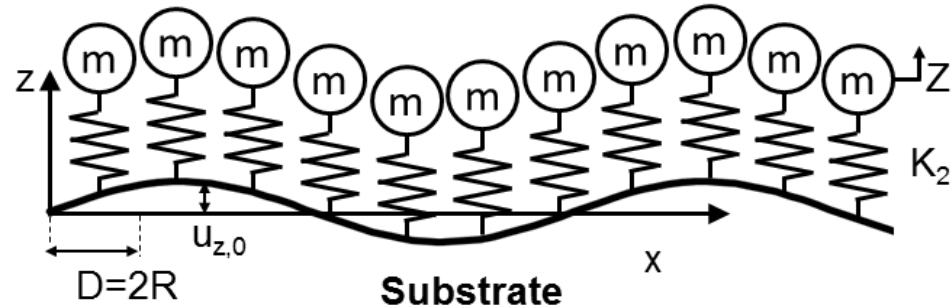
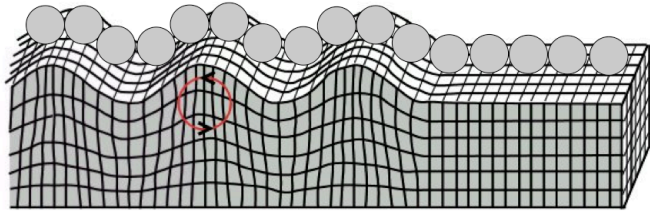
DMT model (incorporating adhesive Van der Waals forces):

$$F = KR^{1/2} \alpha^{3/2} - 2\pi wR$$

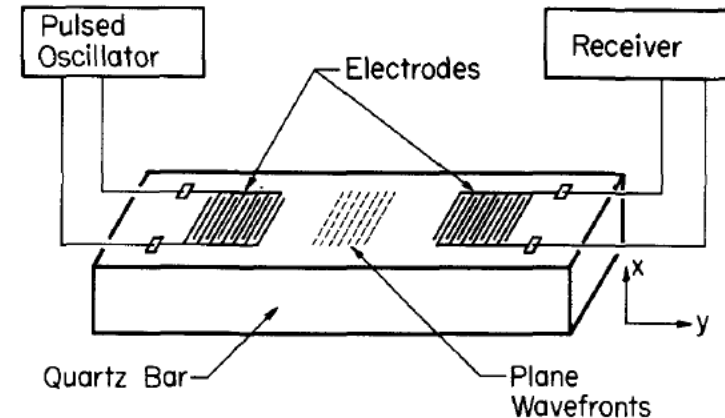


Microspheres Interacting with SAWs

Rayleigh Wave



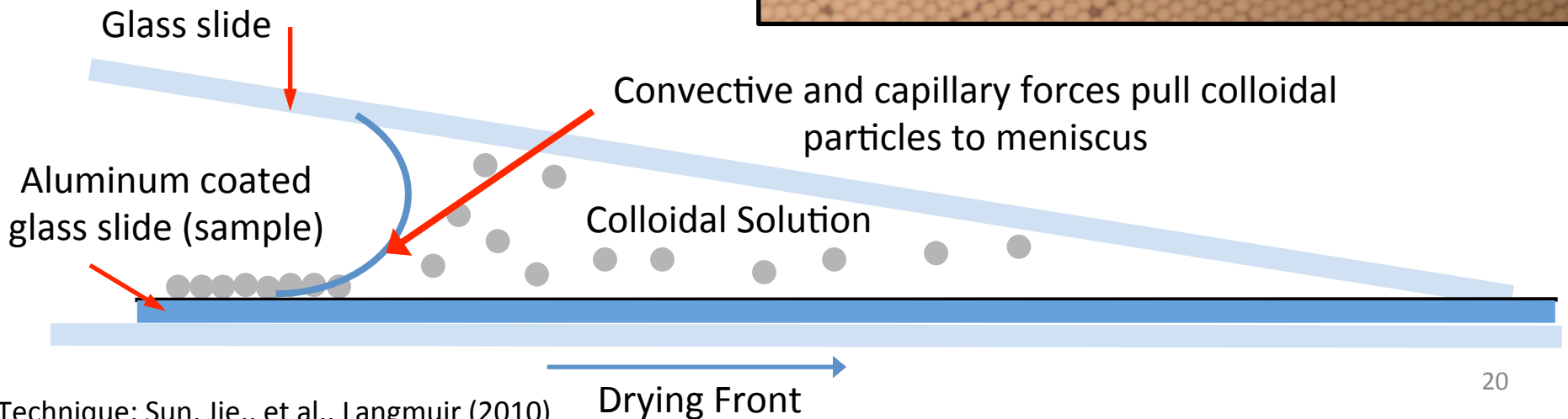
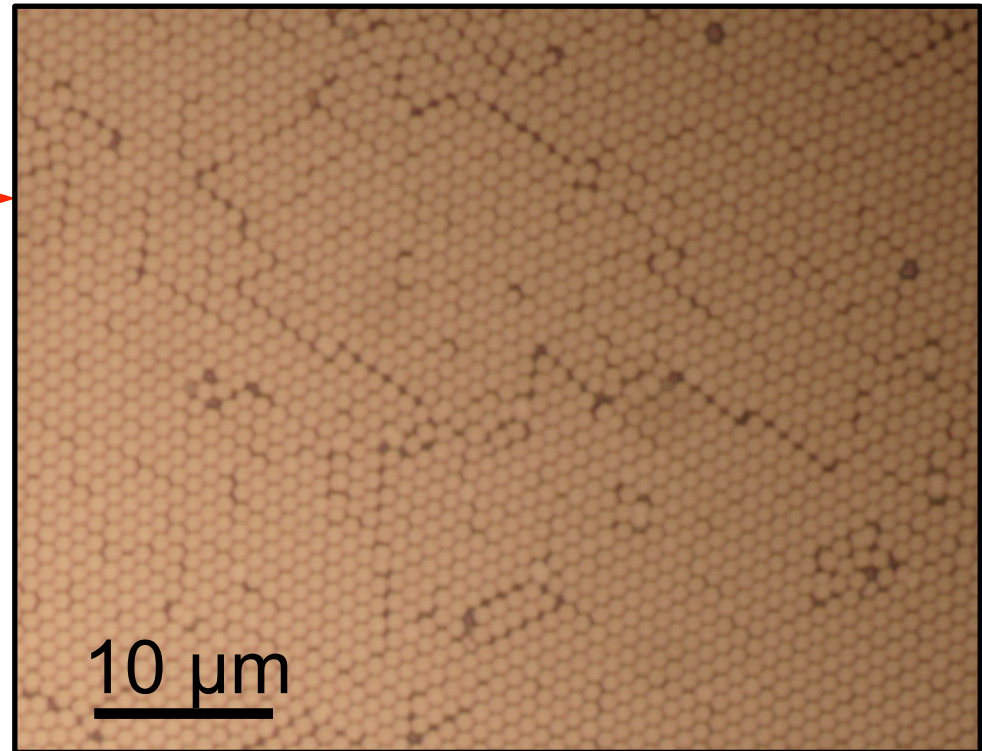
- **Locally-resonant metamaterial for SAWs**
- **Probe contact-resonance of microspheres (scalability)**
- Some SAW application areas:
 - SAW signal processing devices (e.g. filters)
 - SAW sensing (including biosensors), NDT
 - Microfluidic sorting / Acoustic tweezers
 - Earthquakes



White, R. M, and Voltmer, F. W., Appl. Phys. Lett. (1965)

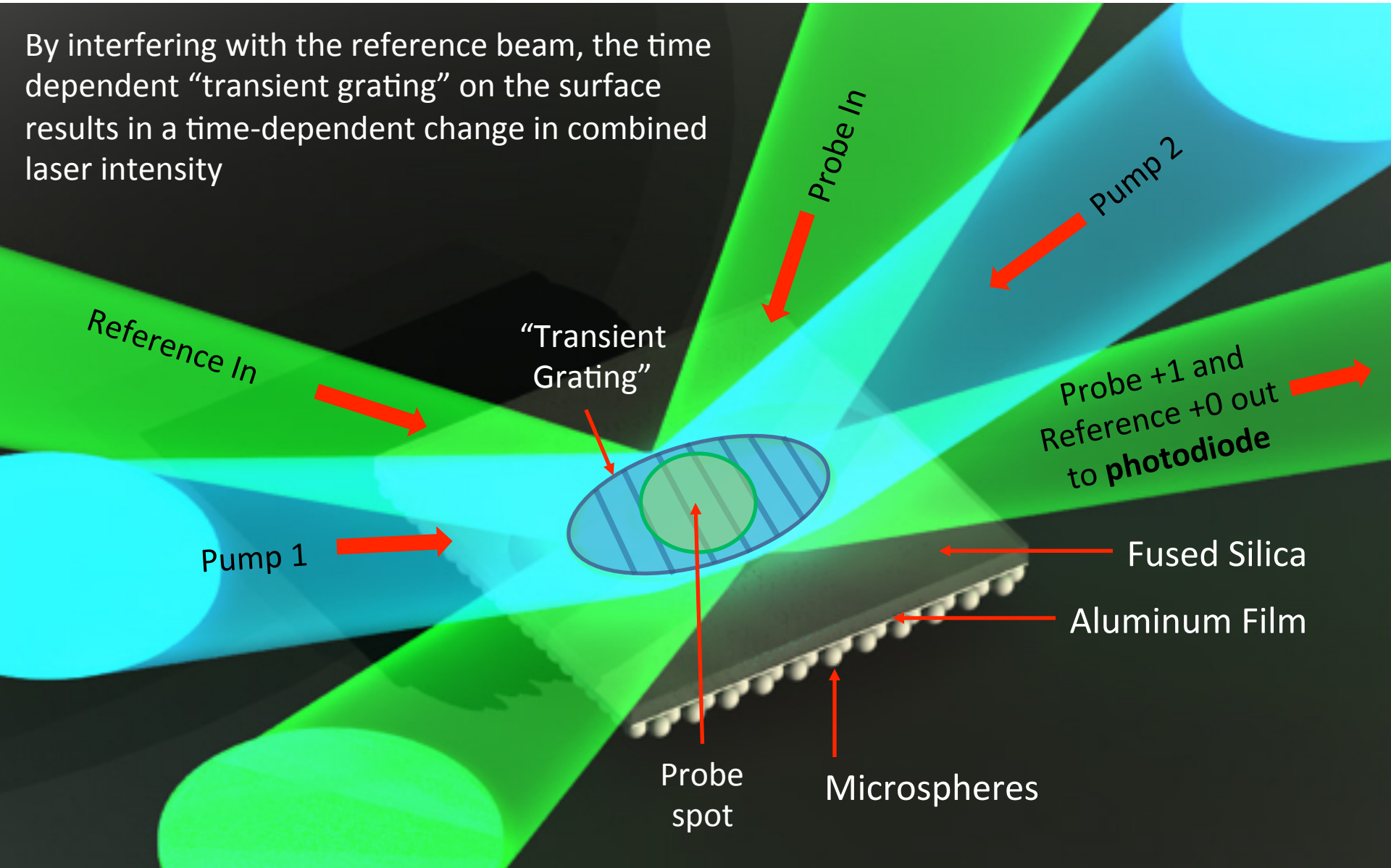
Microsphere Array Fabrication

- Convective self assembly
- Utilizes “coffee ring effect”
- 1 μm silica microspheres on aluminum coated fused silica substrate



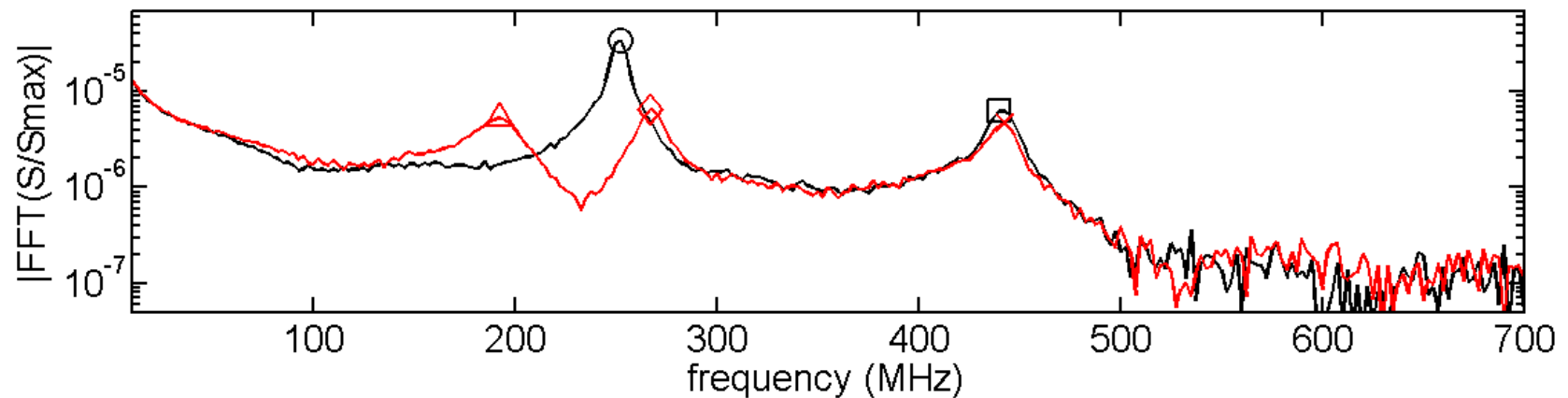
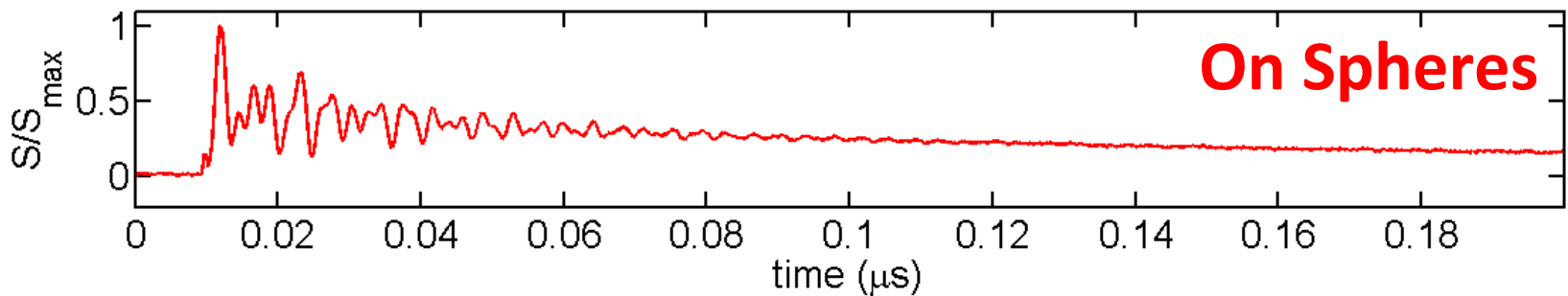
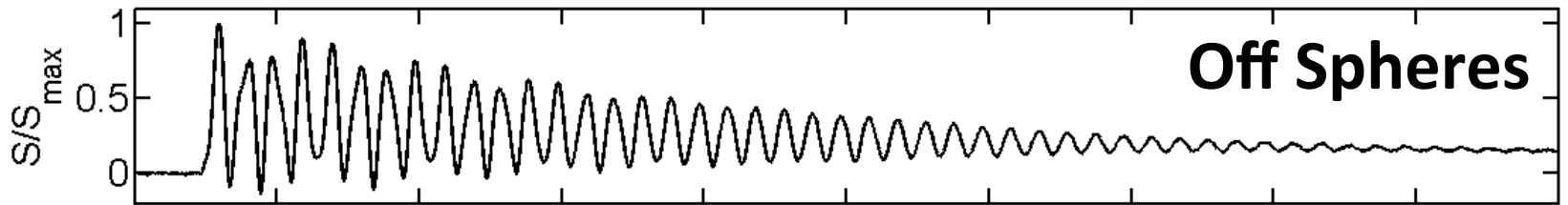
Experiments: Transient Grating

By interfering with the reference beam, the time dependent “transient grating” on the surface results in a time-dependent change in combined laser intensity



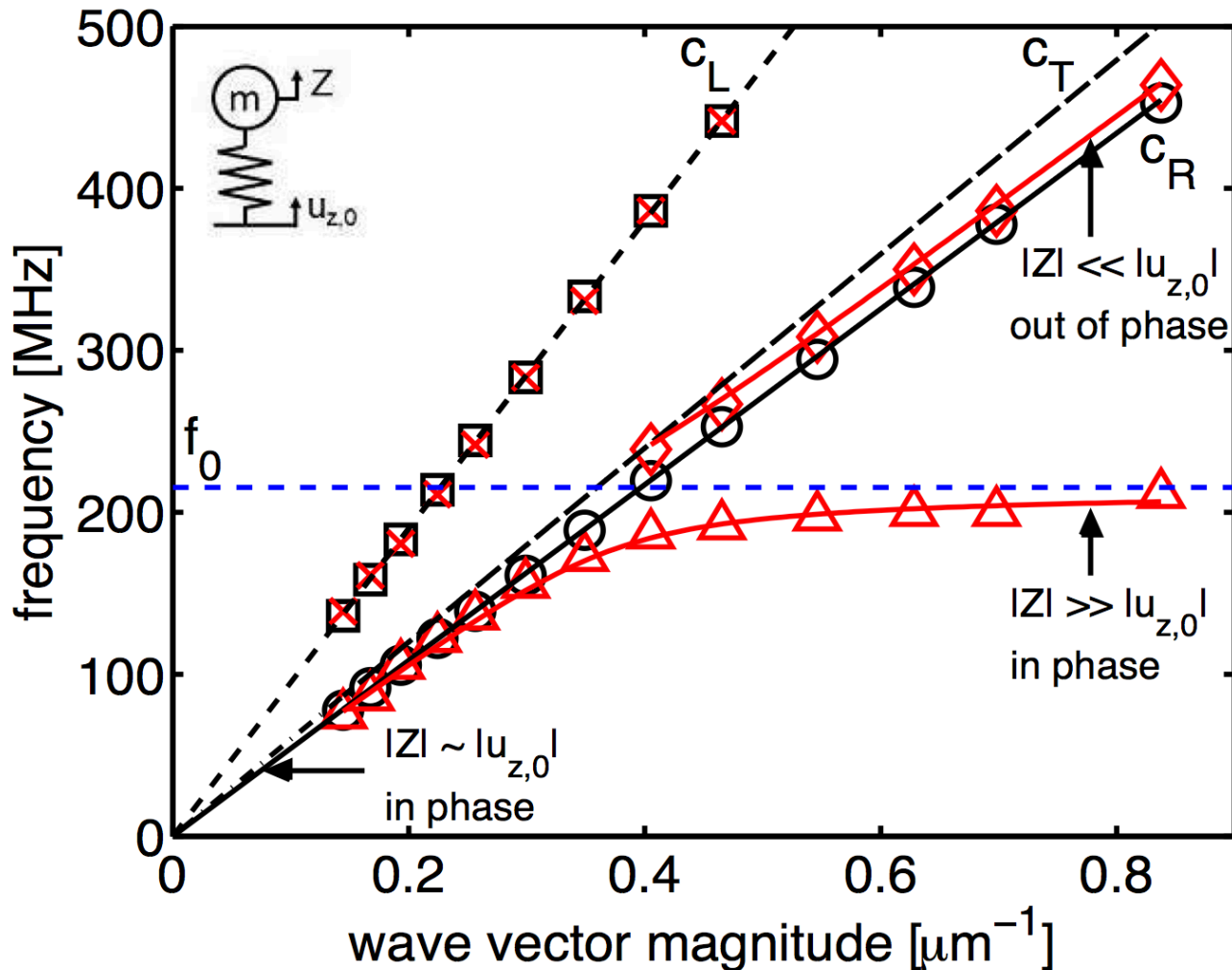
Experiments

$$\lambda_s = 13.5 \mu\text{m}$$



Experiments

$$\left(\frac{\omega^2}{\omega_0^2} - 1\right) \left[\left(2 - \frac{\omega^2}{k^2 c_T^2}\right)^2 - 4 \left(1 - \frac{\omega^2}{k^2 c_L^2}\right)^{1/2} \left(1 - \frac{\omega^2}{k^2 c_T^2}\right)^{1/2} \right] = \frac{m}{A \rho_2} \frac{\omega^4 \left(1 - \frac{\omega^2}{k^2 c_L^2}\right)^{1/2}}{k^3 c_T^4}$$



Summary and Opportunities

- **Two examples**

- Acoustic diode: nonlinearity + dispersion
- SAW metamaterial: granular scalability

- **Opportunities**

- Fundamental interplay between nonlinearity and tailored dispersion
- Granular media and metamaterial scalability
- Understand complex bulk granular phenomena via ordered structures

Acknowledgements



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- Dr. Alex Maznev (MIT)
- Jeff Eliason (MIT)
- Prof. Chiara Daraio (ETH Zurich)
- Dr. Georgios Thoecharis (U. Le Mans)



- AmeriMech Symposium Sponsors



- Papers for today's presentation:

- Boechler, N., et al., "Interaction of a Contact Resonance of Microspheres with Surface Acoustic Waves", *Phys. Rev. Lett.*, 111, 036103 (2013)
- Boechler, N., Theocharis, G., Daraio, C., "Bifurcation-based acoustic switching and rectification", *Nature Mater.*, 10, 665 (2011)