

# Metamaterials: emergent technology for a new design paradigm

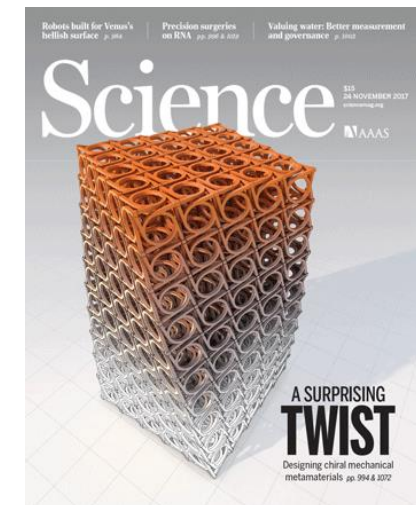
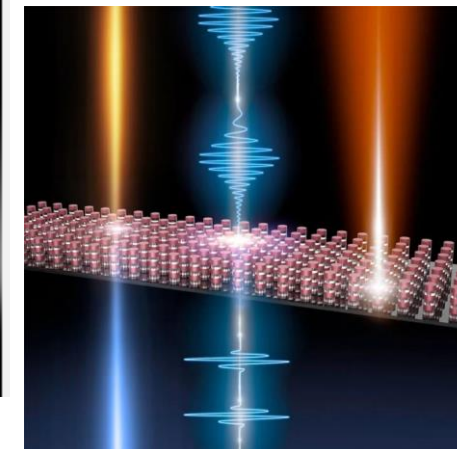
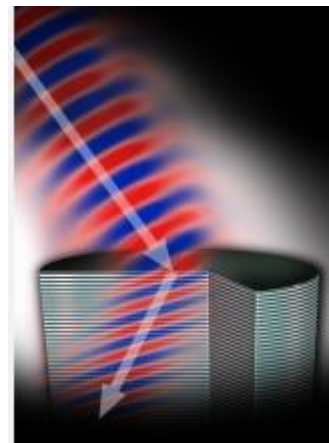
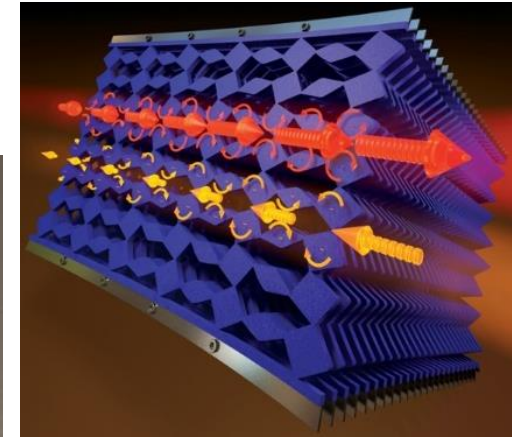
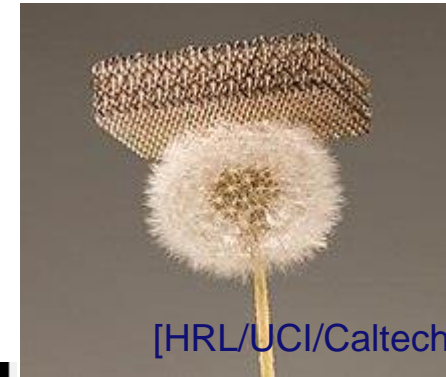
Varvara Kouznetsova

Priscilla B. Silva, Ashwin Sridhar, Lei Liu, Tom Lenders, Xhorxha Kuci,  
Marc Geers



# Metamaterials

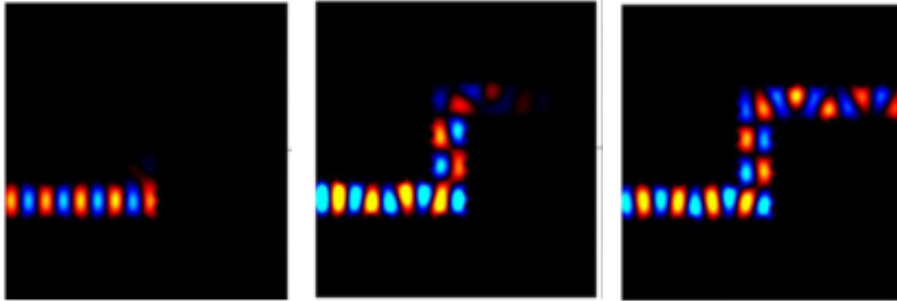
- **Meta** (Greek “beyond”) materials are architected materials with a rationally designed internal structure resulting in unique properties non-existent in natural materials
- **Fundamentally different from other engineered materials:**
  - Alloys, compounds, composites etc: averaged property
  - **Metamaterials: radically new property**
- **Examples of unique metamaterial properties:**
  - Ultra low weight
  - Extreme anisotropy
  - Negative Poisson ratio
  - Linear to rotational motion
  - Zero/controlled thermal expansion
  - Negative effective mass, stiffness
  - Negative refraction/reflection indices
  - Diode-like one-way behaviour
  - ....



# Dynamic Metamaterials

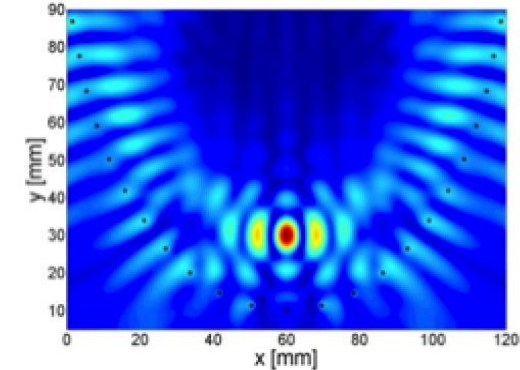
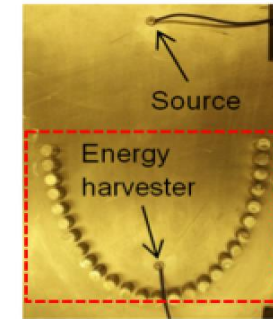
- Metamaterials for control and manipulation of mechanical/acoustic waves

## Wave Guiding and filtering



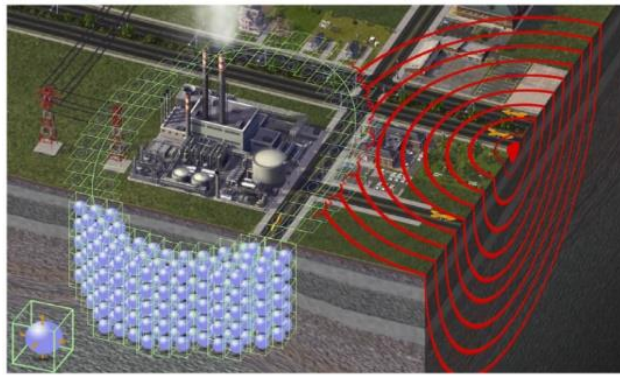
Miyashita et. al., 2005

## Energy Harvesting



M. Carrara et. al., 2013

## Vibration isolation

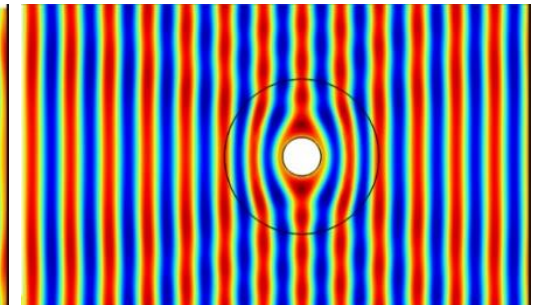
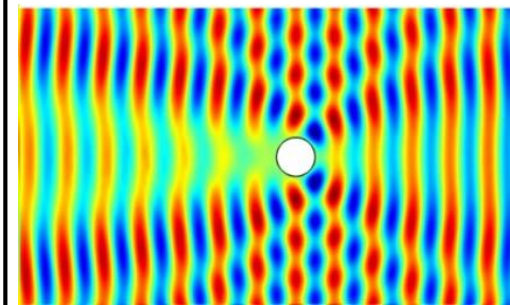


Y. Achaoui et. al. , 2016

## Cloaking of objects from the waves

Regular medium

medium Metamaterial medium

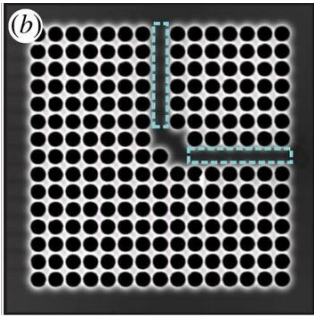


S. A Cummer et.al. , 2007

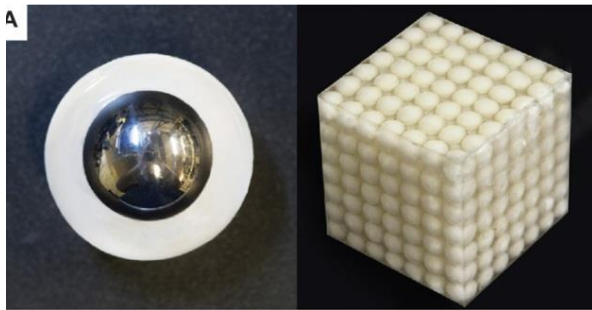


# Dynamic Metamaterials

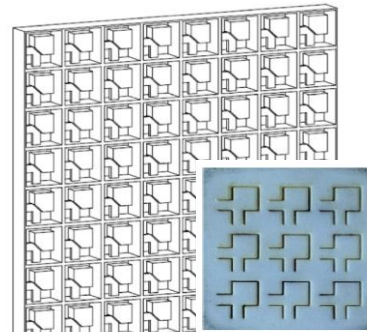
- Substructure designed to interact with (elastic, acoustic) waves of certain frequencies in certain directions



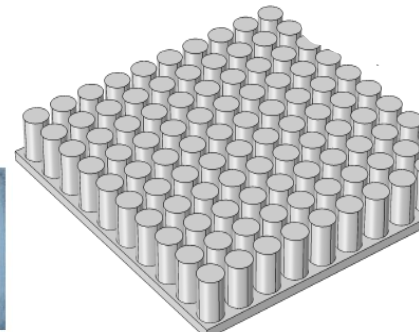
[P. H. Otsuka et.al., 2013]



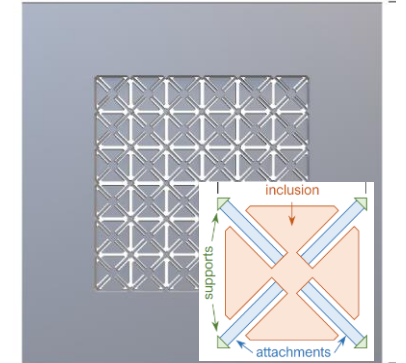
[Z. Liu et.al., *Science*, 2000]



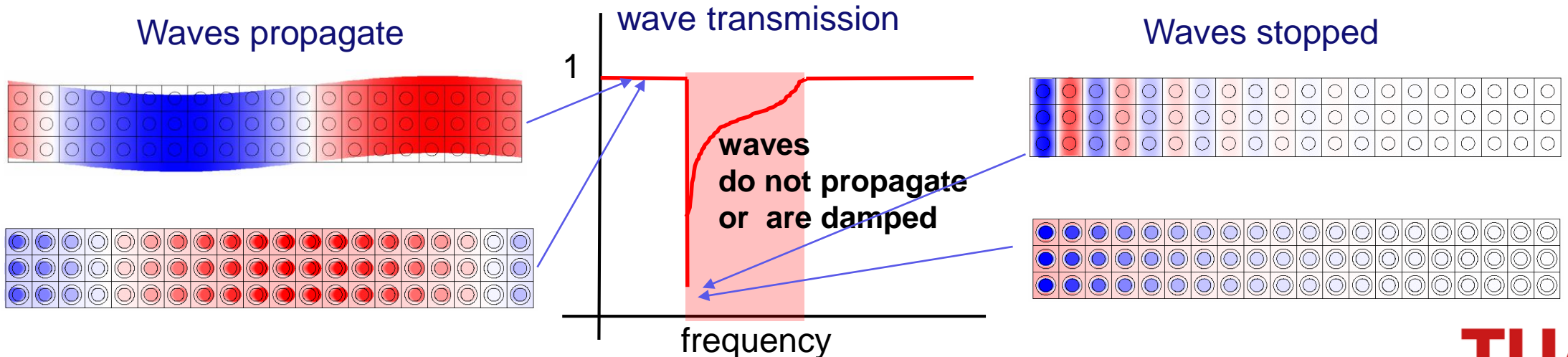
[Ruiz et al. (2016)]



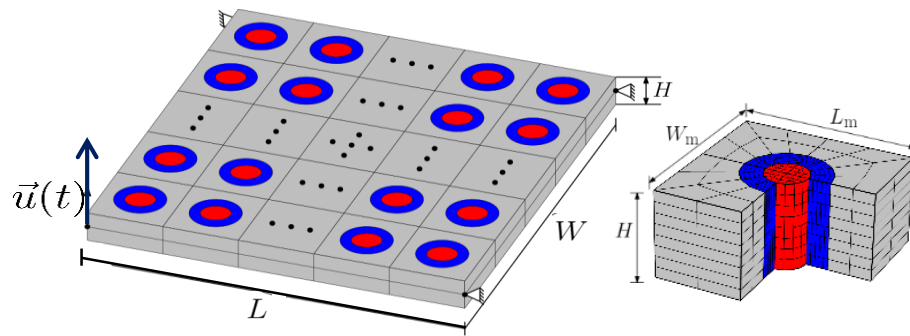
[Faiz et al. (2020)]



[Roca et al. (2020)]

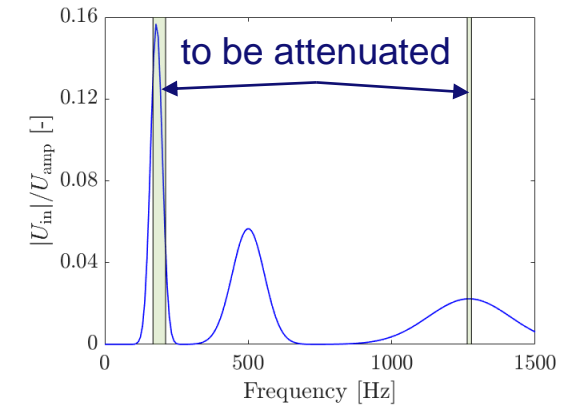
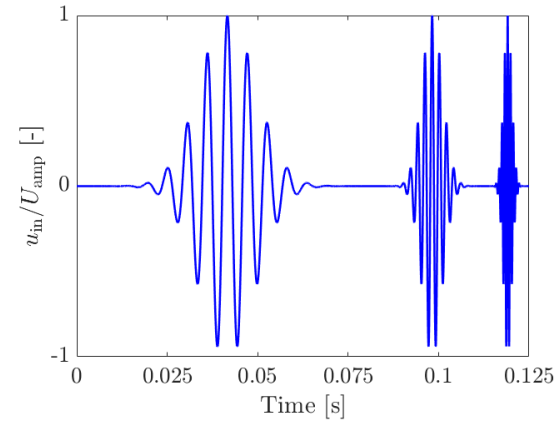


# Example 1: Attenuation of plate vibration

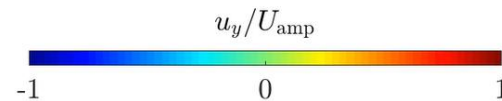
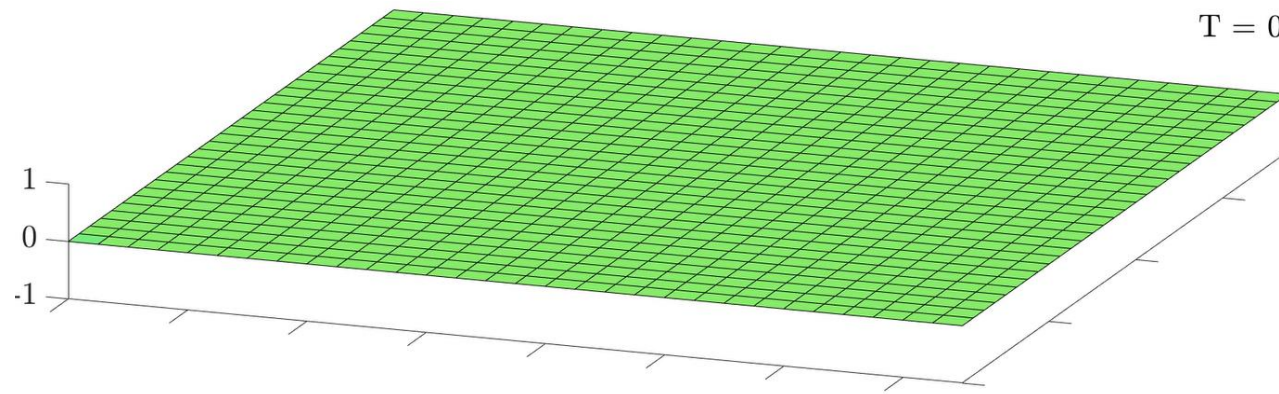
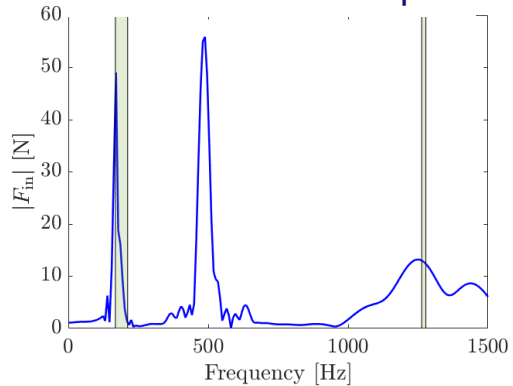


- Panel dimensions  $L \times W = 750 \times 750$  [mm]
- Equivalent to  $75 \times 75$  unit cells

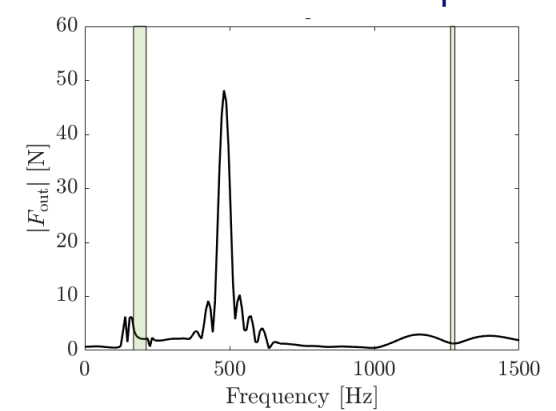
Excitation signal:



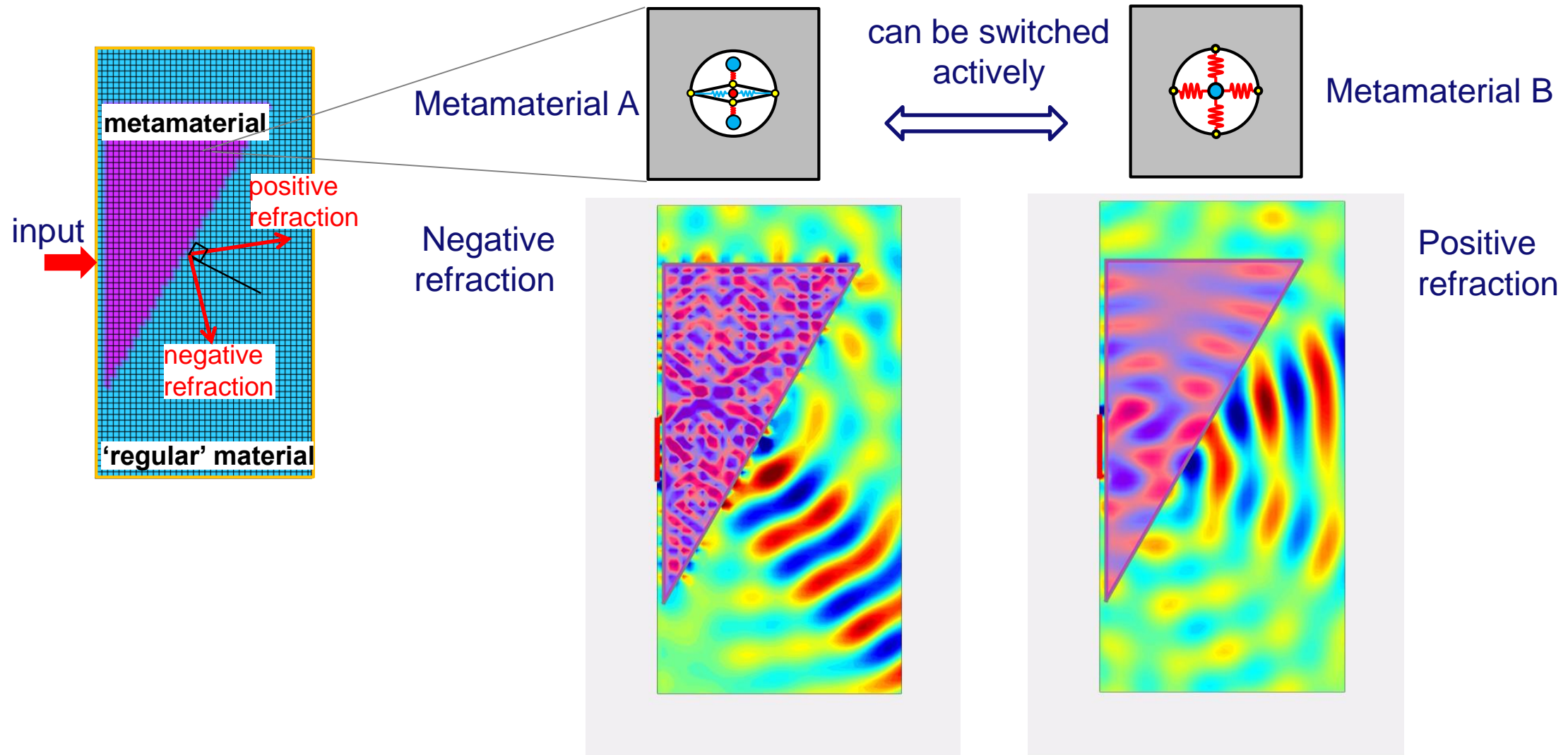
Reaction force at input



Reaction force at output



## Example 2: Wave filtering/redirection



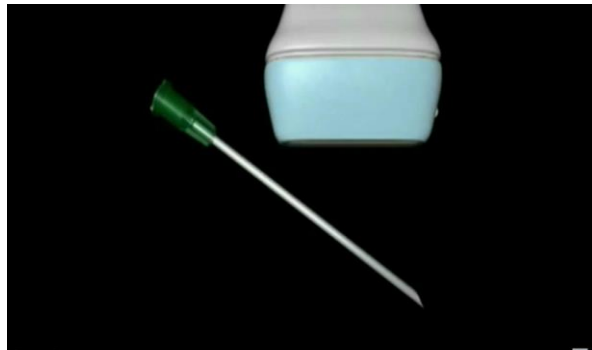


# Example 3: Negative reflection from graded metasurface

Ultrasound guided medical procedures



[C. Eder, (2017)]

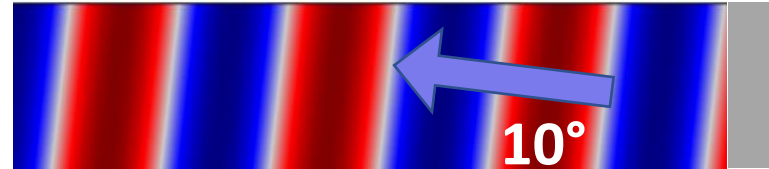


[[https://www.youtube.com/watch?v=m1QMmQjD4BM&list=LL&ab\\_channel=VascularOnlineTrainingVOT](https://www.youtube.com/watch?v=m1QMmQjD4BM&list=LL&ab_channel=VascularOnlineTrainingVOT)]

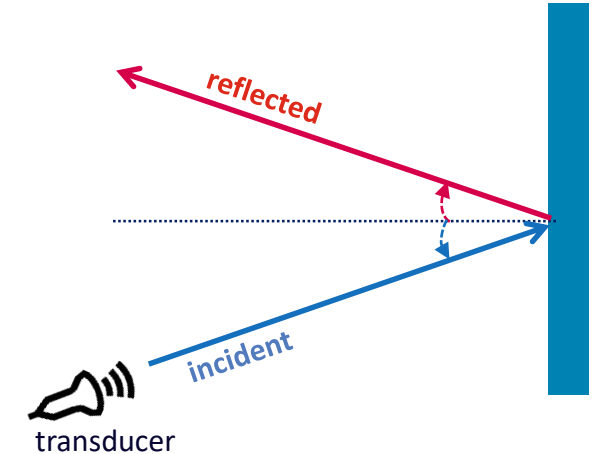
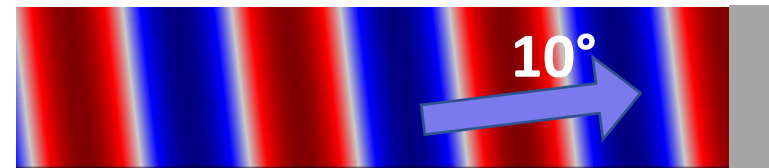
How to redirect the reflected wave back to the probe?

## Classical law of reflection

Reflected pressure wave

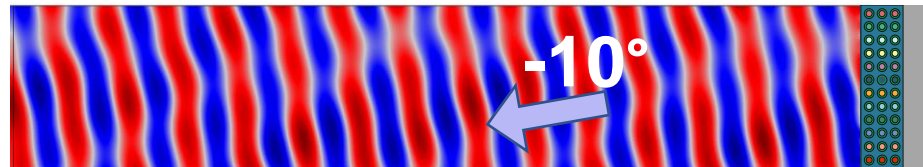


Incident pressure wave

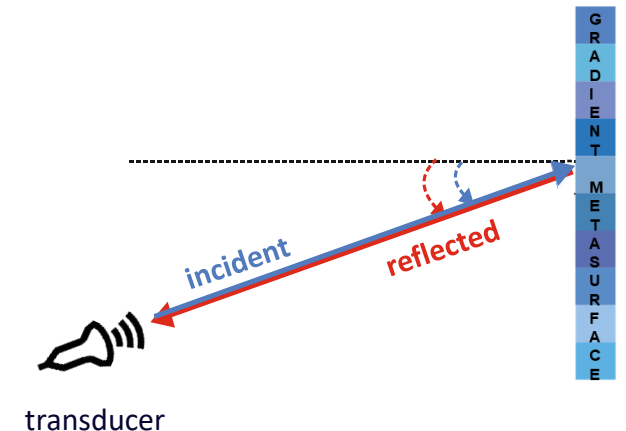
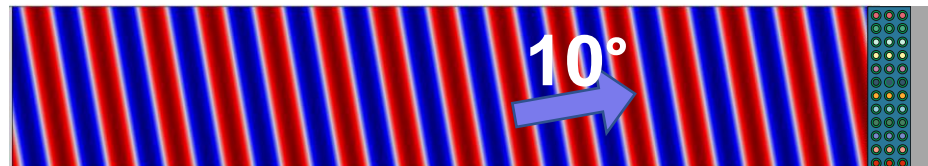


## Negative reflection from graded metasurface

Reflected pressure wave

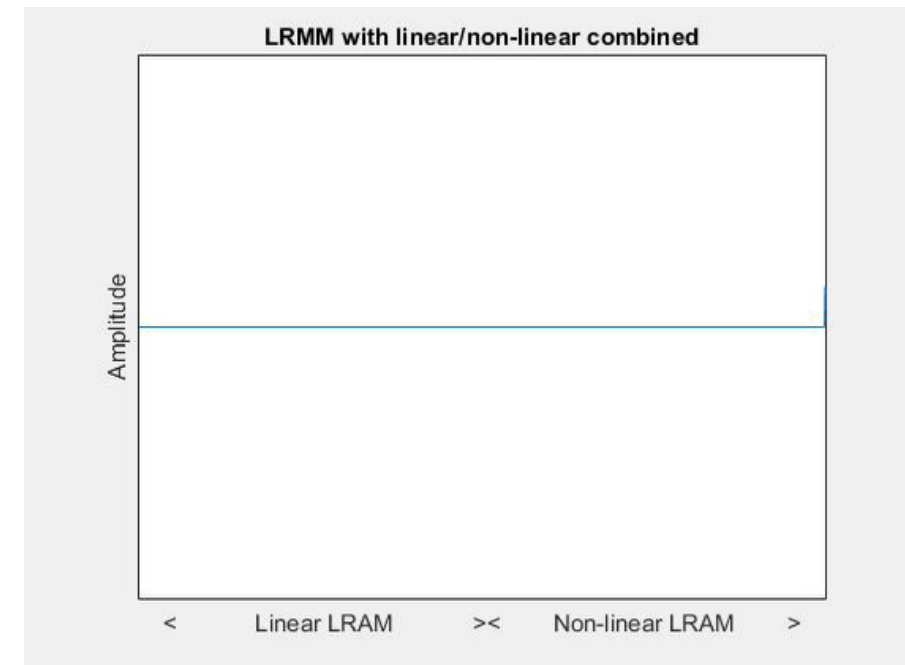
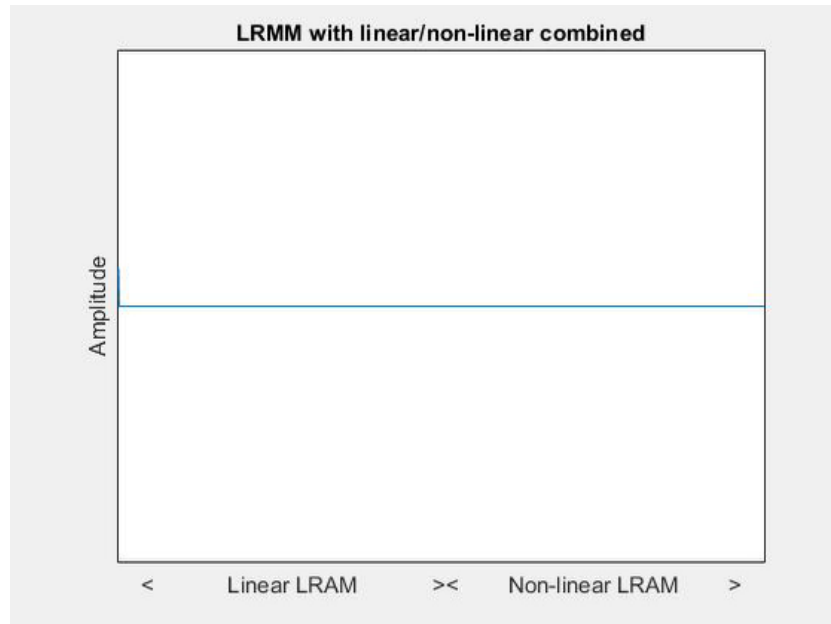
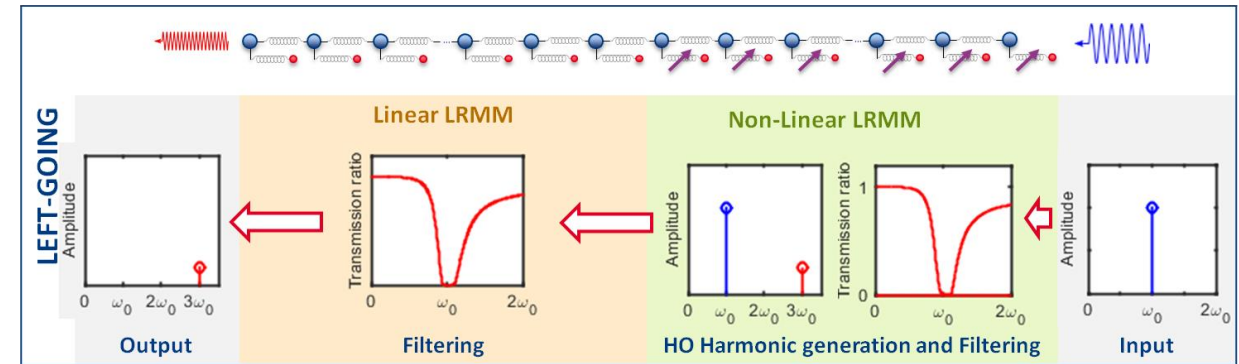
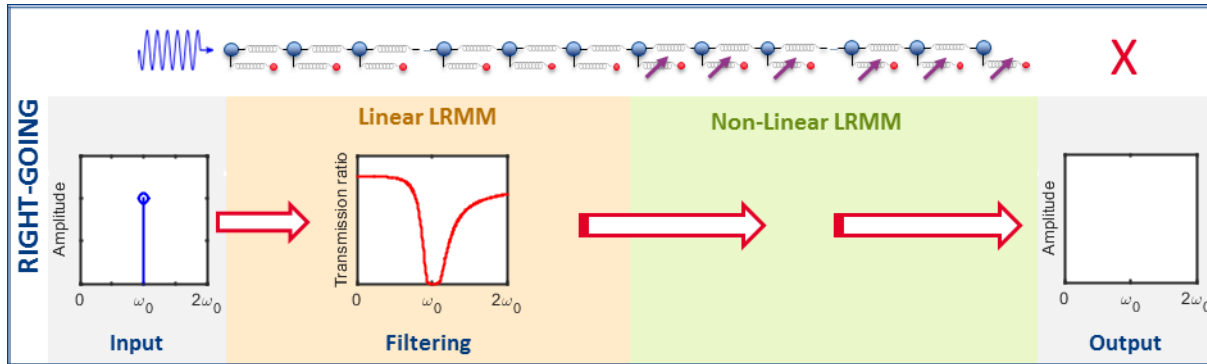


Incident pressure wave



[Kuci, Geers, Kouznetsova, in preparation]

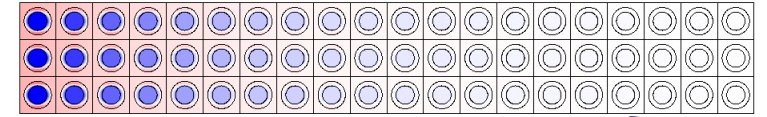
# Example 4: wave diode





# State of the art in dynamical metamaterials applications and challenges

- **State of the art of dynamical metamaterials:**
  - currently at low Technology Readiness Level (TRL 1 -> TRL2)
  - (virtually) no practical designs / applications
  - literature:
    - fundamental developments assuming ideal conditions (e.g. infinite structures)
    - lab demonstrators replicating the ideal conditions
- **Challenges from fundamentals to applications:**
  - integration of metamaterials into existing systems
  - finite size domains with boundaries and interfaces
  - non-trivial dynamic loadings, excitations and constraints, non-linearities
  - economically viable manufacturing techniques
  - new, unconventional, design principles



# Towards practical metamaterial design and applications

Design for  
metamaterial integration in  
complex systems?

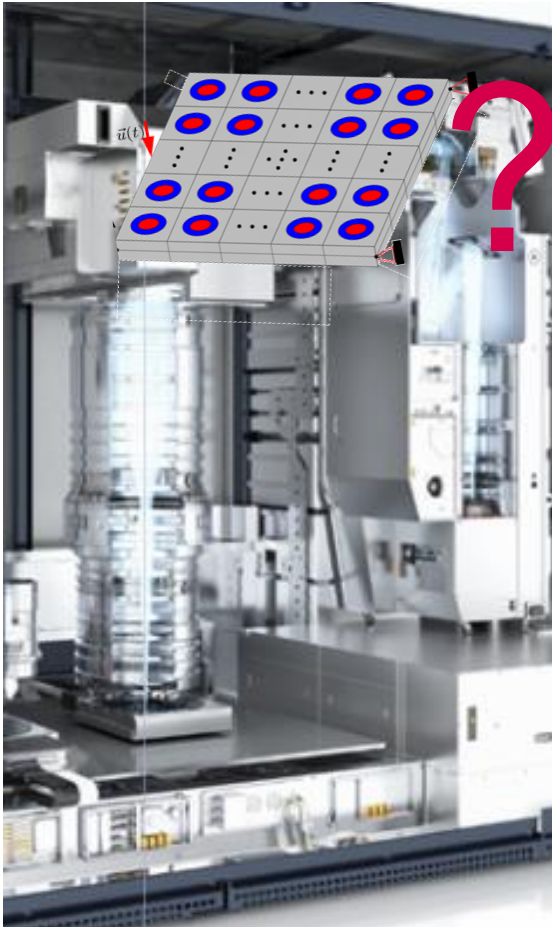
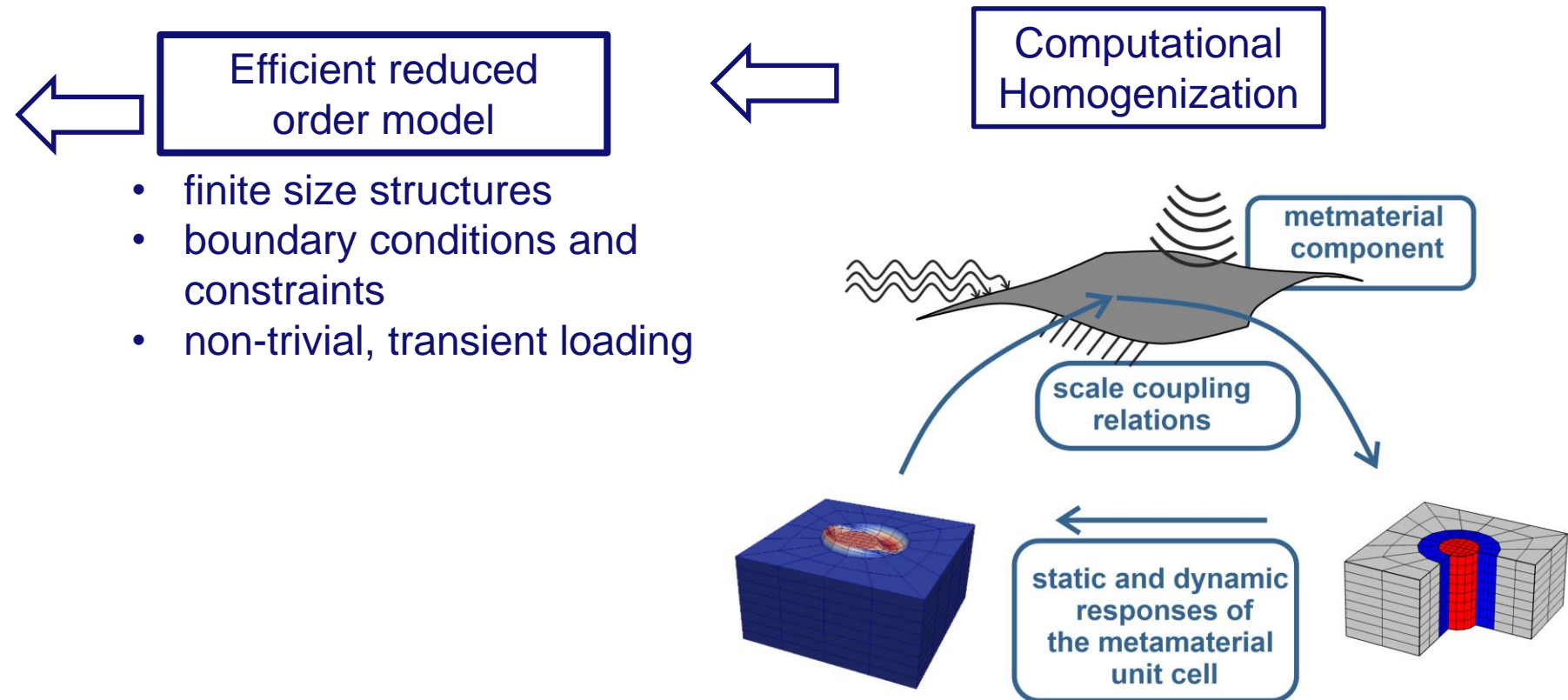
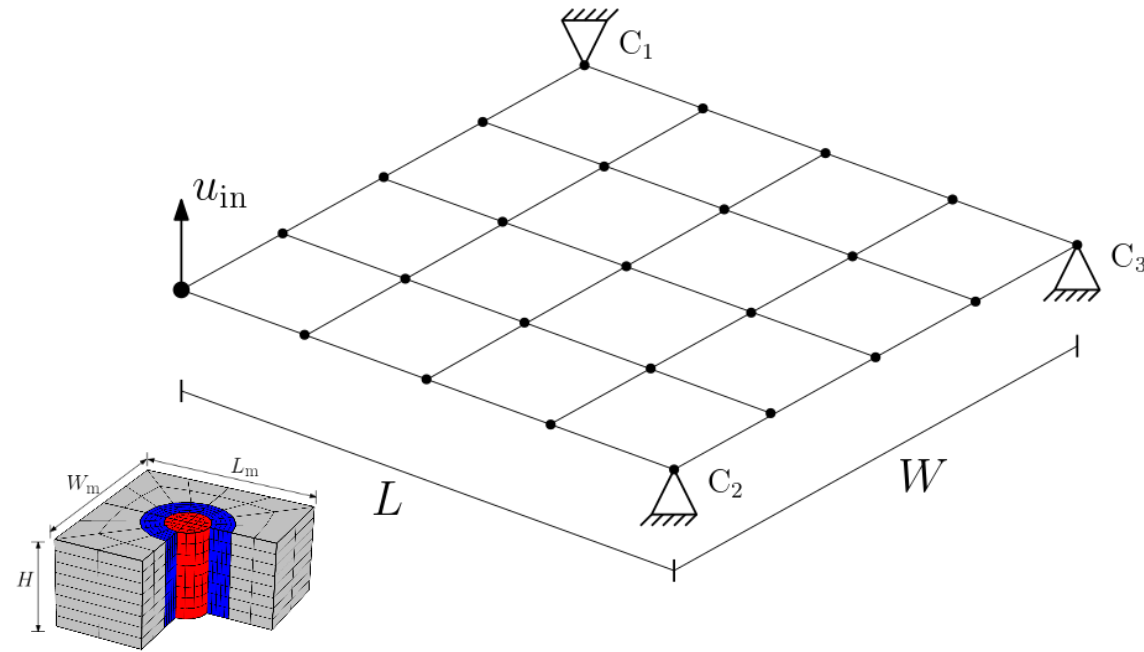


Image source:  
<https://www.asml.com/en/products/duv-lithography-systems>

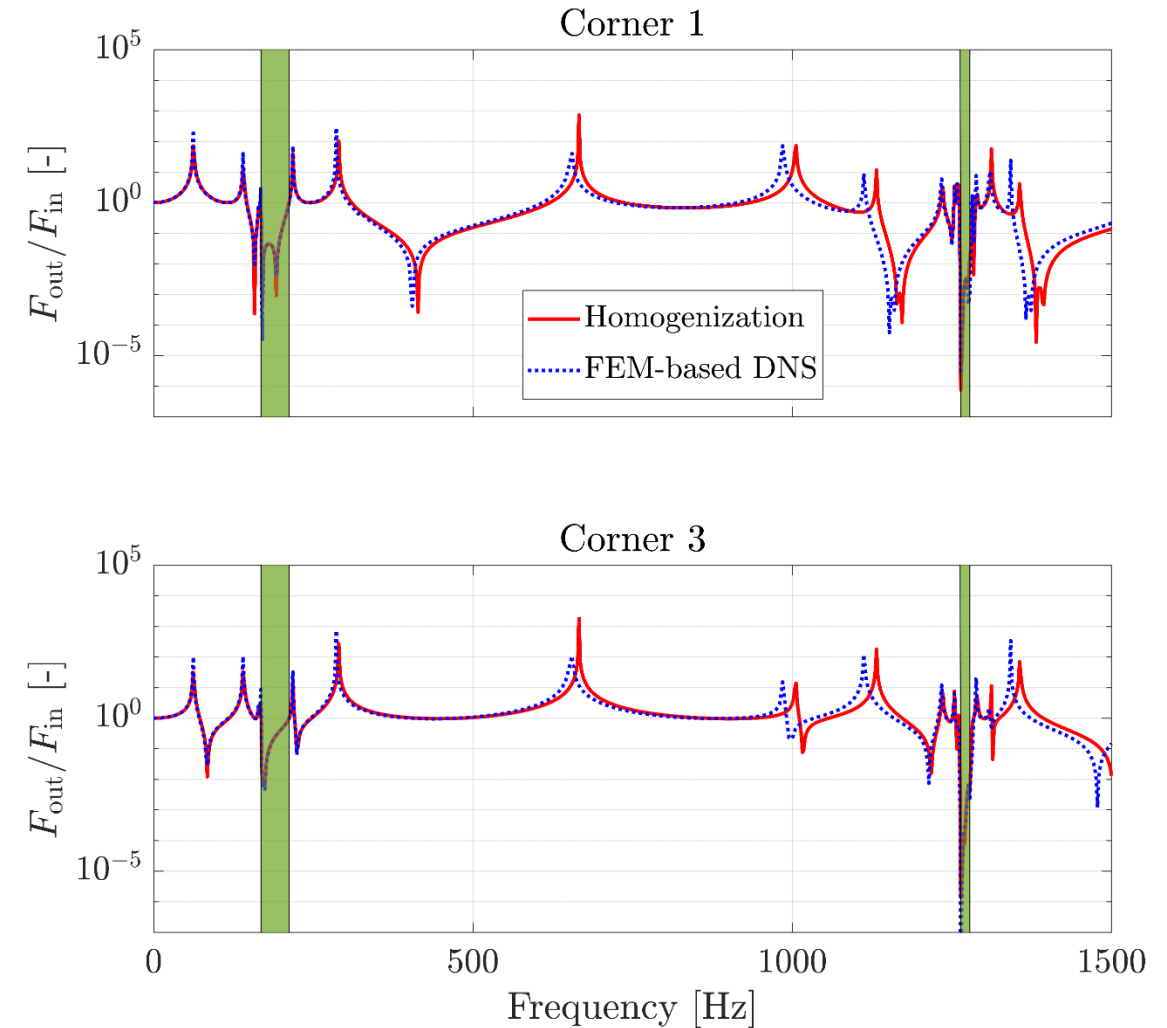


[Pham, Kouznetsova, Geers, JMPS (2013),  
Sridhar, Kouznetsova, Geers, Comp.Mech. (2016), Int.J.Mech.Sci. (2017), JMPS (2018)  
Sridhar, Liu, Kouznetsova, Geers, JMPS (2018),  
van Nuland, Silva, Sridhar, Kouznetsova, Geers, Math.Mech.Solids. (2019)  
Liu, Sridhar, Geers, Kouznetsova, CMAME (2021).]

# Homogenization model validation



- Frequency response is well described by the homogenization based reduced model
- Factor 33 faster compared to the fully resolved Direct Numerical Simulation (DNS, reference)





# Conclusions

- **Dynamic metamaterials**
  - can be designed to manipulate mechanical/acoustic waves
  - can provide unprecedented solutions not possible with 'regular' materials and current design strategies
  - have potential for applications across many domains of technological and societal relevance
- **What is currently missing?**
  - methods and tools for design with metamaterials at system level
  - economically viable manufacturing techniques
  - lack of metamaterial knowledge at engineering floor

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