AdvancEd aircraft-noise-Alleviation devIceS using meTamaterials

Horizon 2020

Council of European Aerospace Societies

On the integration of acoustic phase-gradient metasurfaces in aeronautics

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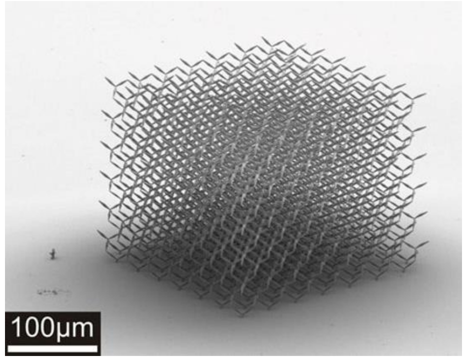
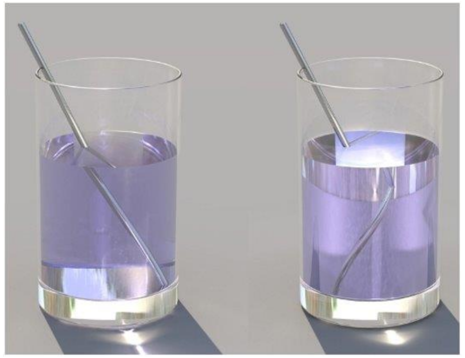
ROMA TRE UNIVERSITÀ DEGLI STUDI

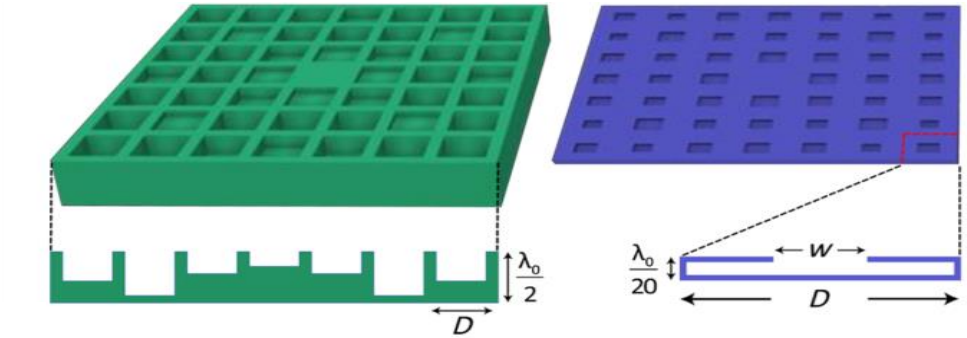
Metamaterials …

Macroscopic composite of periodic or non periodic structures, able to produce responses to a specific excitation not available in nature by conventionally engineered materials, that derive their properties from the designed structures and geometries more than from their chemical composition, and the behavior of properly defined unit cells can be translated into averaged effective parameters.





…and Metasurfaces



A metamaterial device built with a thickness (significantly) below the working wavelength is usually called metasurface. Still its behaviour can be translated into averaged effective parameters

What is a Metabehaviour?

negative bulk modulus

acoustic black hole extraordinary absorption

extraordinary reflection acoustic invisibility

negative mass double negativity negative refractive index

zero index extraordinary refraction

…and other exotic properties still to be imagined…

Generalized Snell's Law

negative bulk modulus

acoustic black hole extraordinary absorption

extraordinary reflection acoustic invisibility

negative mass double negativity negative refractive index

zero index **extraordinary refraction**

$$\sin\theta_r = \frac{\lambda}{2\pi}\frac{\partial}{\partial x}\Delta\phi(x,\lambda) + \sin\theta_i$$

$$n_2\sin\theta_t = \frac{\lambda}{2\pi}\frac{\partial}{\partial x}\Delta\phi(x,\lambda) + n_1\sin\theta_i$$

Generalized Snell's Law

negative bulk modulus

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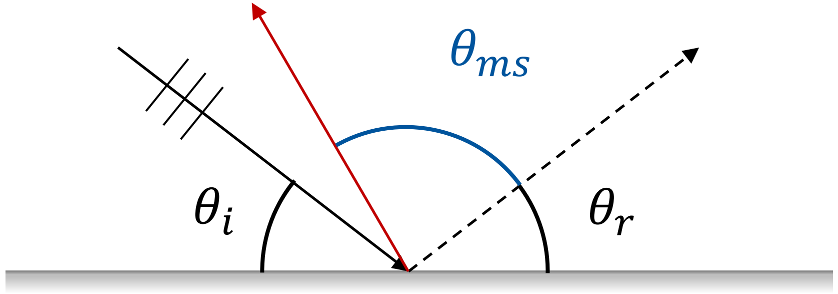


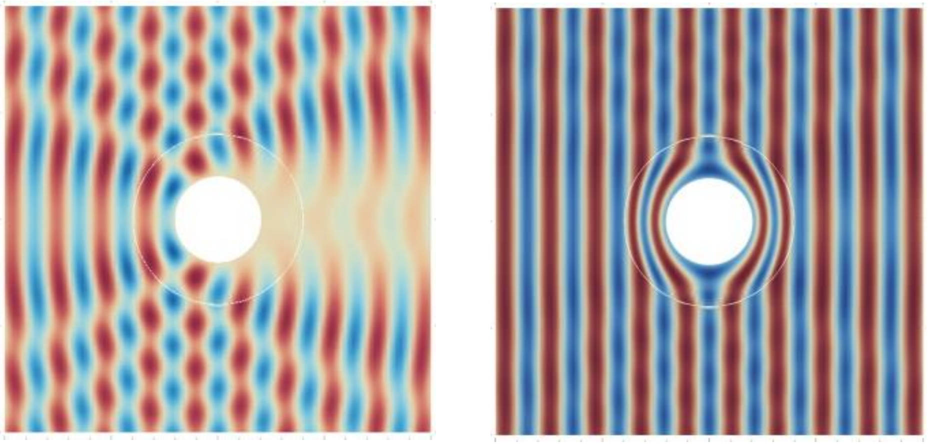
Standard Transformation Acoustics

Mapping: $\Omega \to \omega \qquad \mathbf{x} = \chi(\mathbf{X})$

Deformation gradient: $\mathbf{F} = \bar{\nabla}\mathbf{x} \qquad \Lambda = \det \mathbf{F}$

Polar decomposition: $\mathbf{F} = \mathbf{V}\mathbf{R} \qquad \mathbf{V^2} = \mathbf{F}\mathbf{F^T}$

Laplacian: $\bar{\nabla}^2 f = \Lambda \mathrm{div}\, \Lambda^{-1}\mathbf{V^2}\nabla f$


An application of STA: Acoustic Cloaking [Iemma & Burghignoli, 2012]

$$\frac{\partial^2 p}{\partial t^2} - \frac{\kappa_0}{\rho_0}\bar{\nabla}^2 p = 0, \qquad \mathbf{x} \in \Omega$$

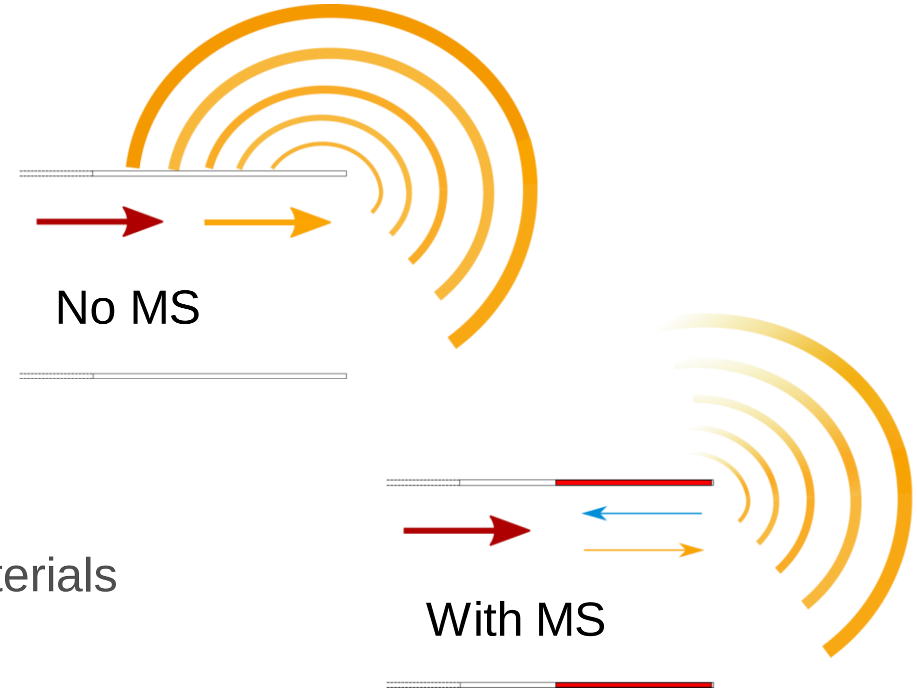
$$\frac{\partial^2 p}{\partial t^2} - \kappa \mathrm{div}\; \boldsymbol{\varrho}^{-1}\nabla p = 0, \qquad \mathbf{x} \in \omega$$

Effective parameters

$$\kappa = \kappa_0 \Lambda, \qquad \boldsymbol{\varrho} = \rho_0 \Lambda \mathbf{V^{-2}}$$

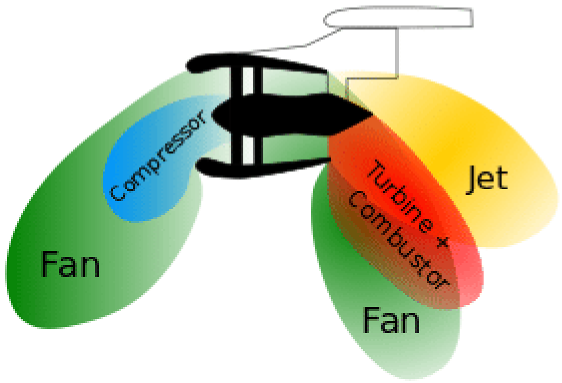
This work

- Enlighten the **link** between STA and GSL
- Effective parameters of a **metafluid** for extraordinary reflection
- Optimized metasurface (with and w/o flow) for **field shaping**
- Towards (possible) **integration** with standard liners and metamaterials

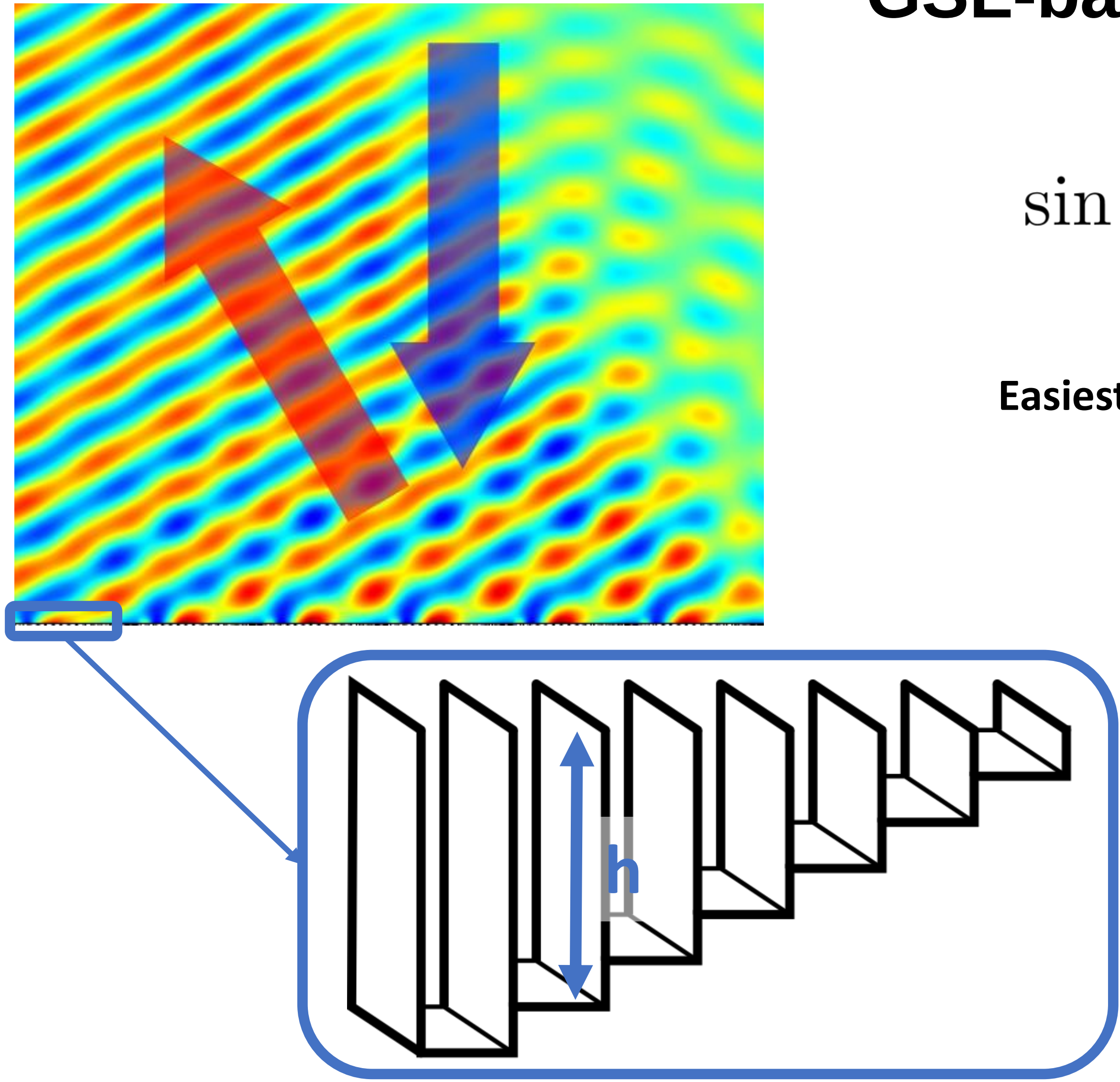


Long term goal

- **Virtual scarfing** for aeronautical nacelles: reducing ground-directed directivity
- **Performance enhancement** of existing acoustic treatments



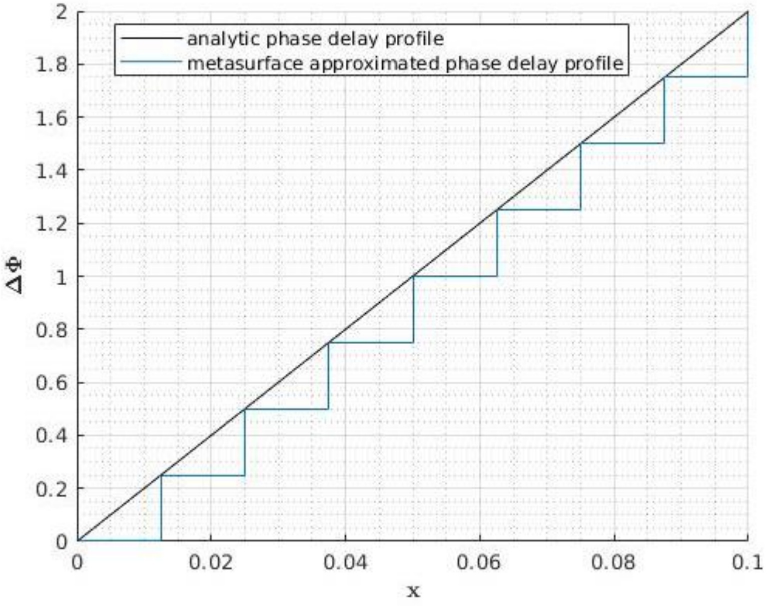
GSL-based Metasurface: basic example



$$\sin \theta_r = \frac{\lambda}{2\pi} \frac{\partial}{\partial x} \Delta\phi(x, \lambda) + \sin \theta_i$$

Easiest implementation → straight wave-guides

$$\Delta\phi = 2\frac{2\pi}{\lambda} h$$



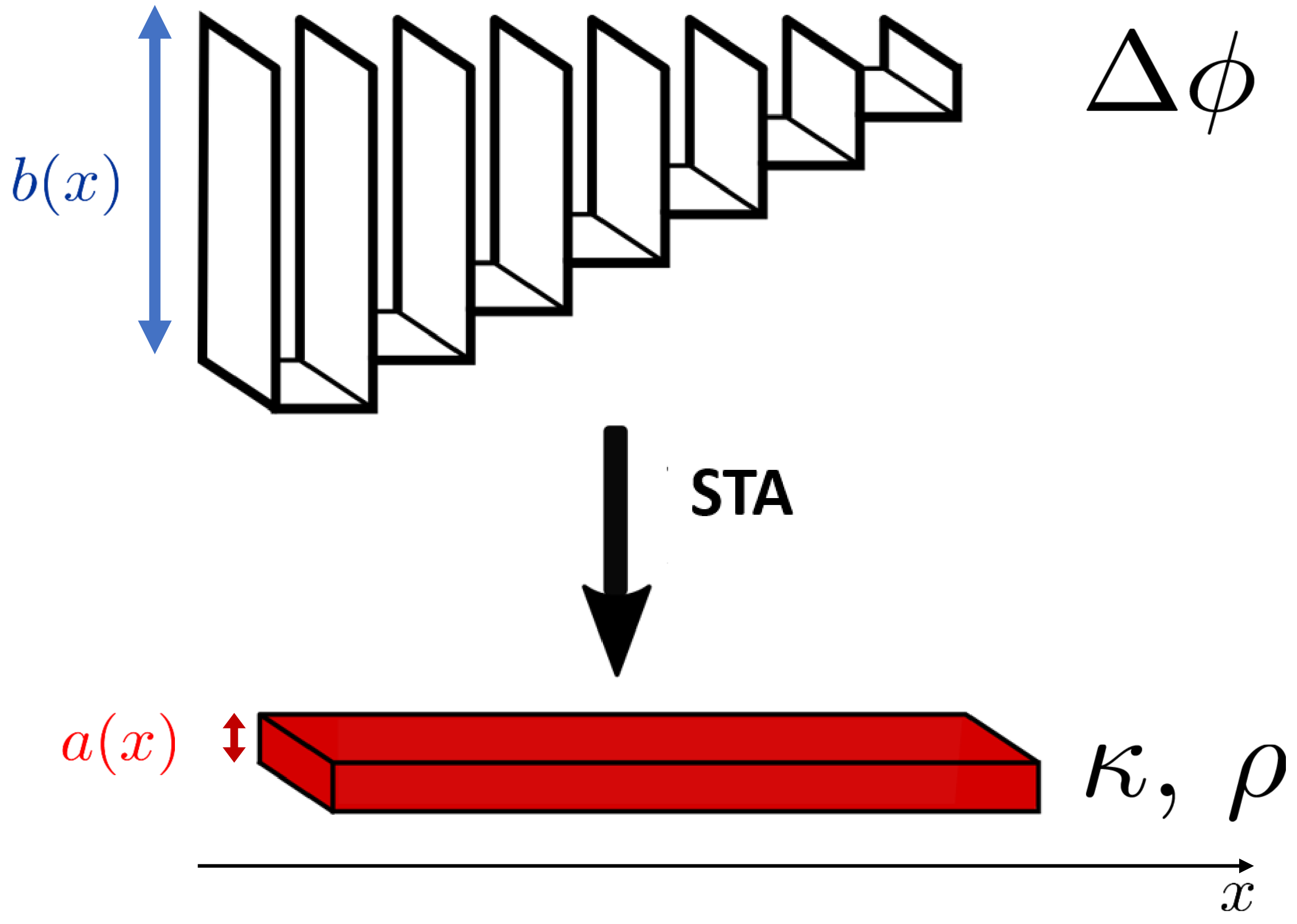
Transformation Acoustics: GSL-based Metasurface (cont'd)

$$\begin{cases} x' = x \\ y' = \dfrac{a(x)}{b(x)} y + q(x) \end{cases}$$

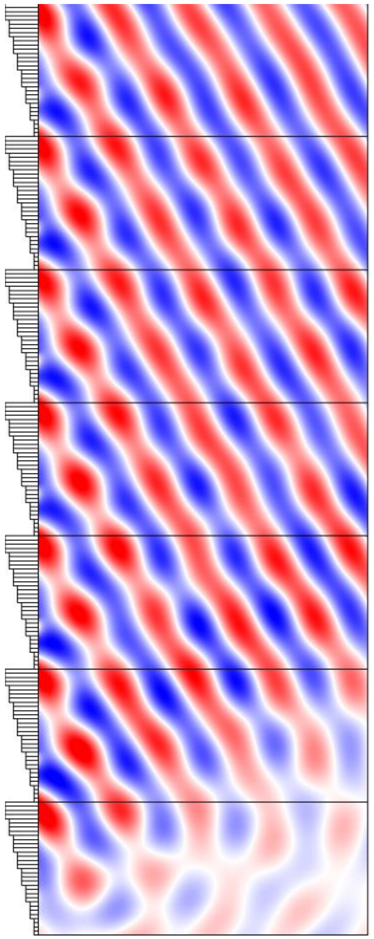
$$\begin{bmatrix} F_{11} = \frac{a(x)}{b(x)} & F_{12} = 0 \\ F_{21} = 0 & F_{22} = 1 \end{bmatrix}$$

Effective parameters

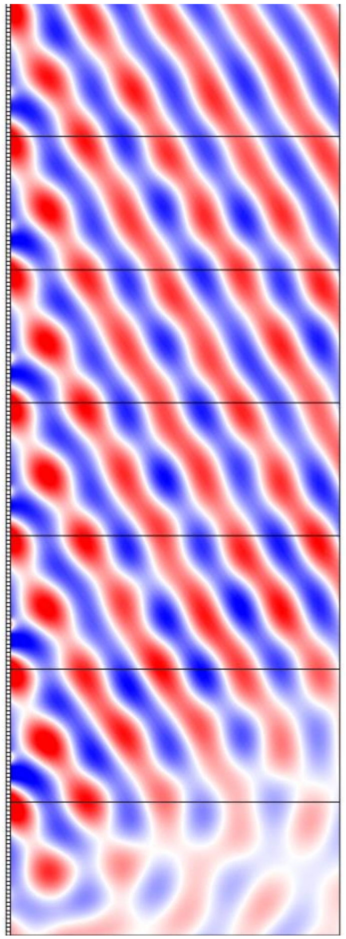
$$\kappa = \frac{a(x)}{b(x)} \kappa_0, \qquad \rho = \frac{b(x)}{a(x)} \rho_0$$



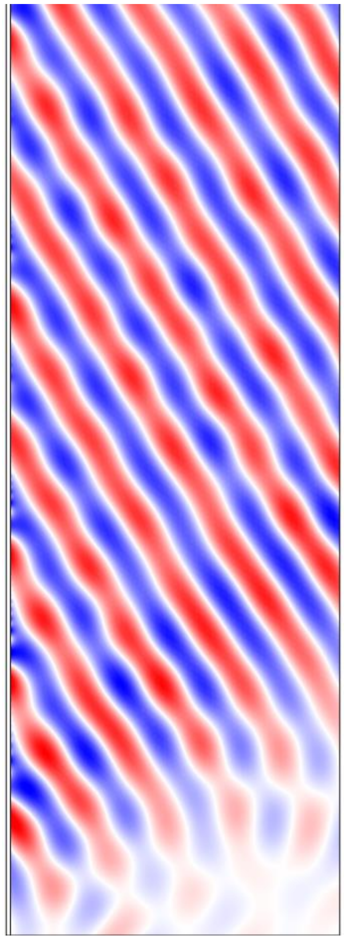
Transformation Acoustics: GSL-based Metasurface (cont'd)



Wave guides



Discrete metafluid



Continuous metafluid

Numerical Setup

Finite **E**lement **M**ethod Analysis

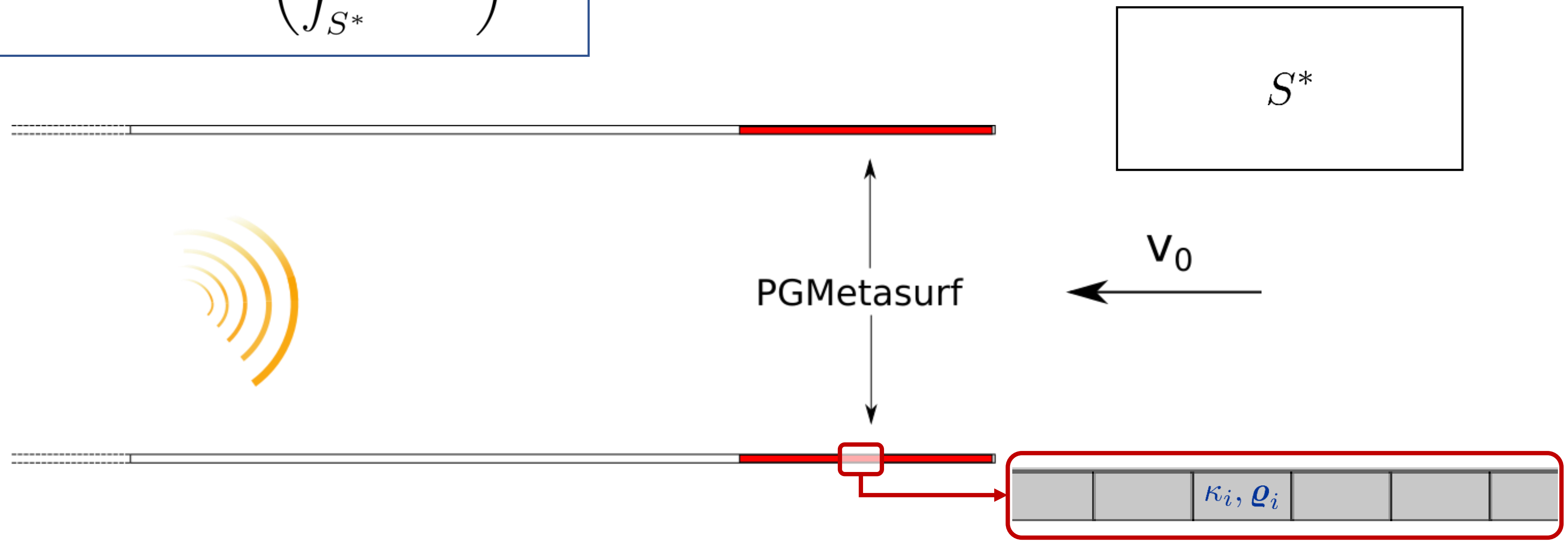
Acoustic propagation in a **uniform** moving medium

$$-\frac{\partial}{\partial t}\left[\frac{\rho_0}{c_0^2}\left(\frac{\partial\varphi}{\partial t}+\mathbf{v}_0\cdot\nabla\varphi\right)\right]+\nabla\cdot\left[\rho_0\nabla\varphi-\frac{\rho_0}{c_0^2}\left(\frac{\partial\varphi}{\partial t}+\mathbf{v}_0\cdot\nabla\varphi\right)\mathbf{v}_0\right]=0$$

Partially **metasurface-lined** duct ($f^* = 3430$ Hz)

Incident field from a **monopolar point source** inside the duct

κ_i, ϱ_i optimized: $\max\left(\int_{S^*}\mathrm{IL}\,dS\right)$



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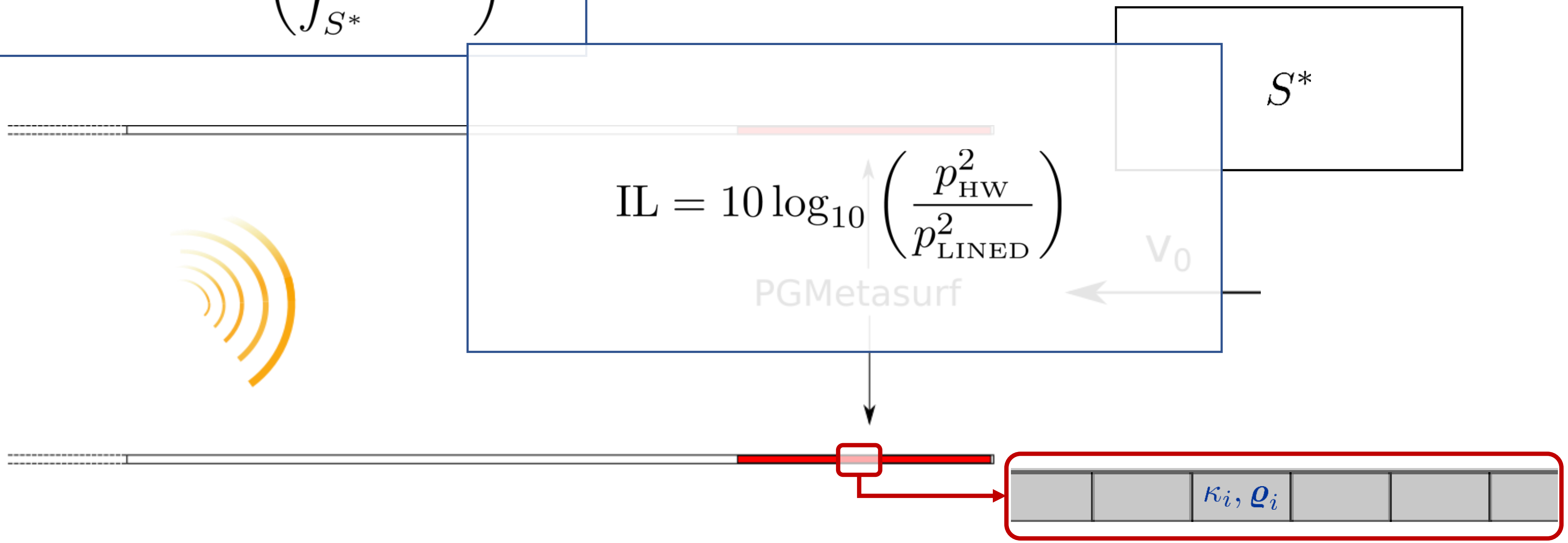
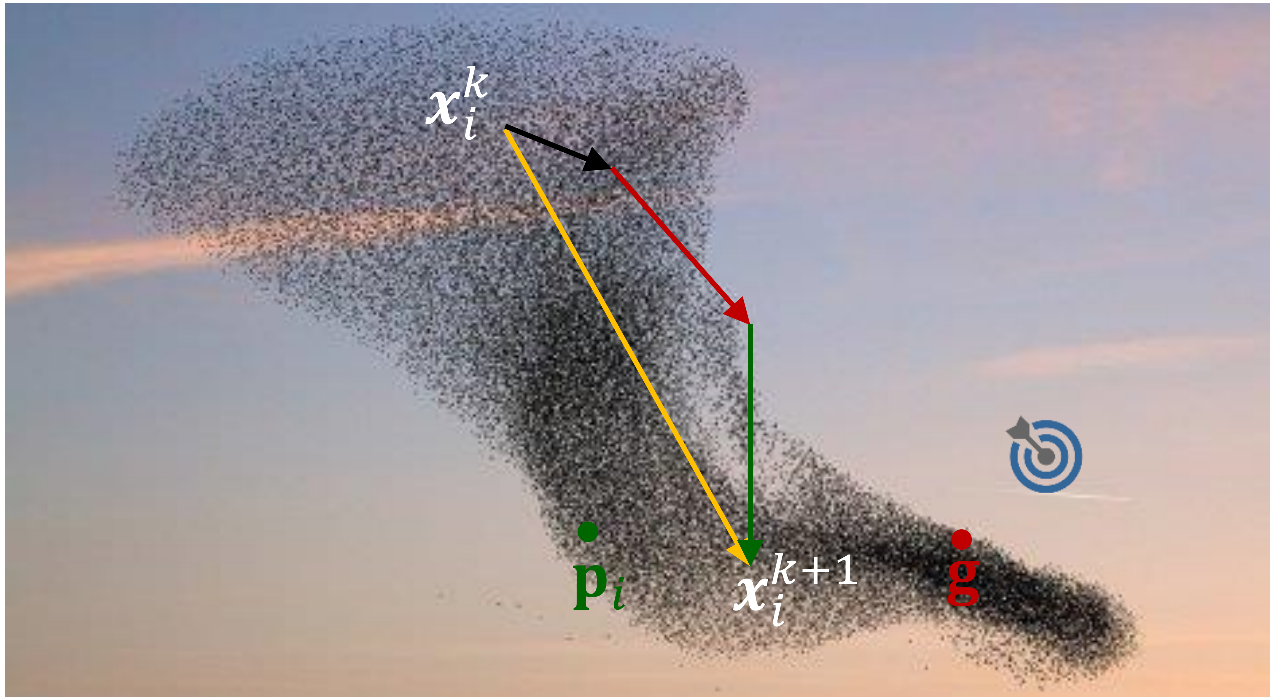
$$\mathrm{IL} = 10\log_{10}\left(\frac{p_{\mathrm{HW}}^2}{p_{\mathrm{LINED}}^2}\right)$$



Numerical Optimization

Deterministic Particle Swarm Optimizer



- Based on the social–behavior metaphor of a flock of birds searching for food
- Deterministic
- Derivative Free

$$\mathbf{v}_i^{k+1} = \chi\left[\mathbf{v}_i^k + c_1\left(\mathbf{p}_i - \boldsymbol{x}_i^k\right) + c_2\left(\mathbf{g} - \boldsymbol{x}_i^k\right)\right]$$

$$\boldsymbol{x}_i^{k+1} = \boldsymbol{x}_i^k + \mathbf{v}_i^{k+1} \qquad \boldsymbol{x}_i = \left[x_1, x_2, \dots, x_{N_c}\right]_i^T$$

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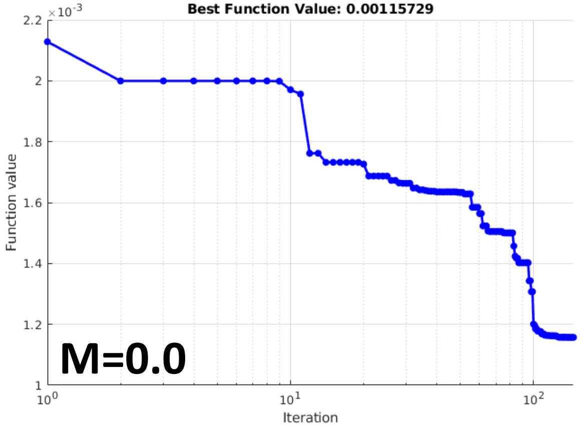
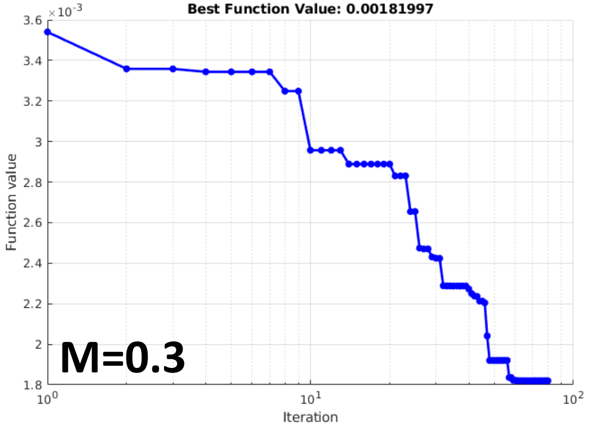
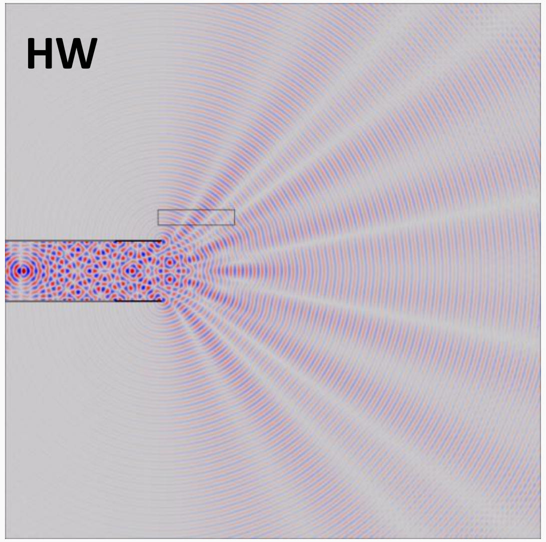
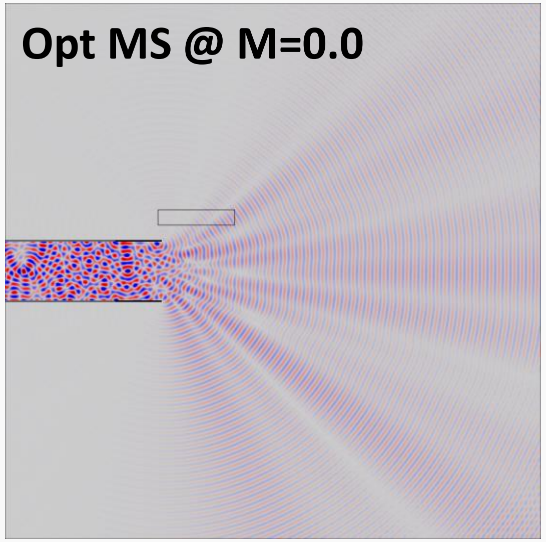
Results: pressure fields



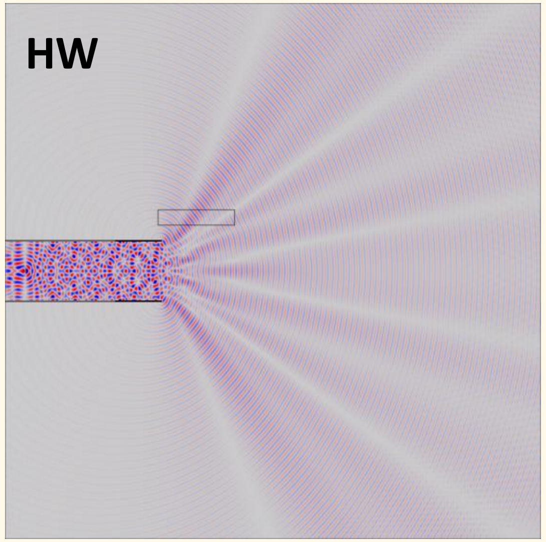


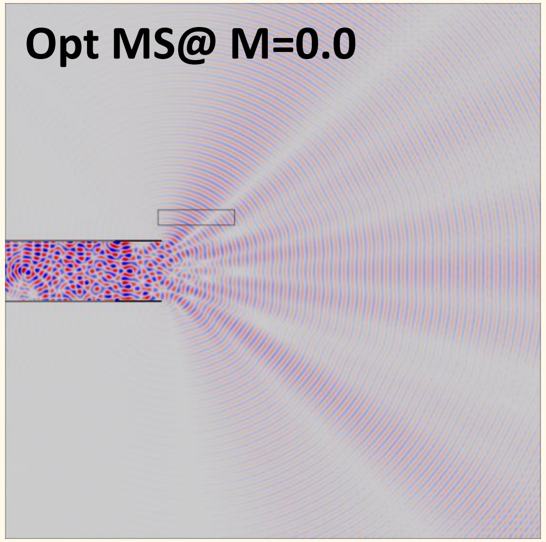
M=0.0

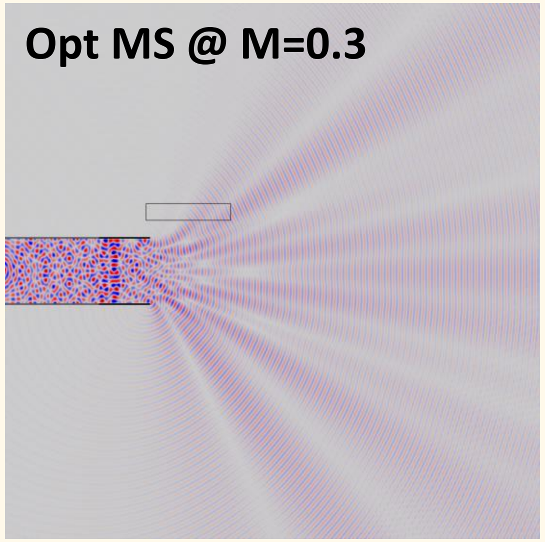




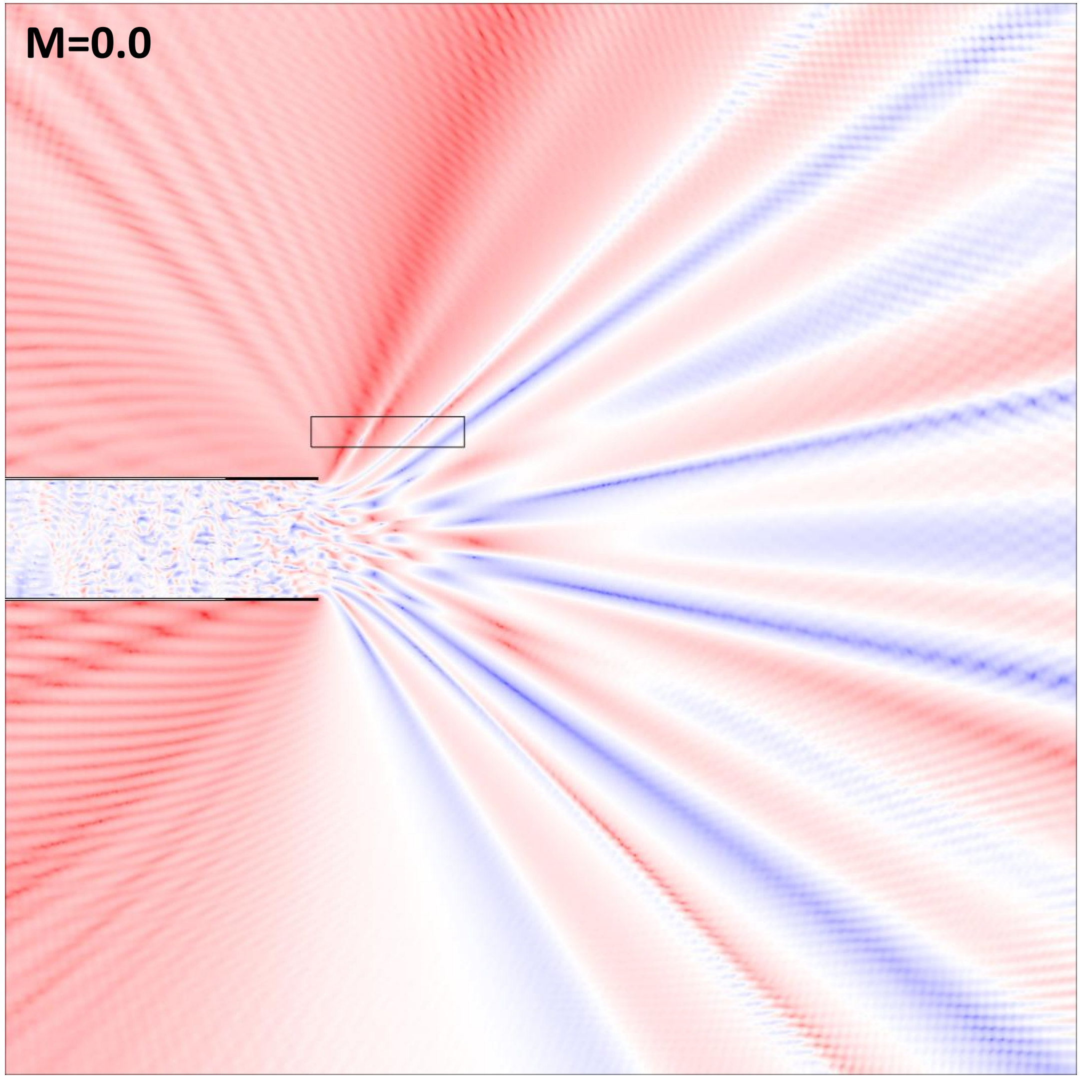
M=0.3

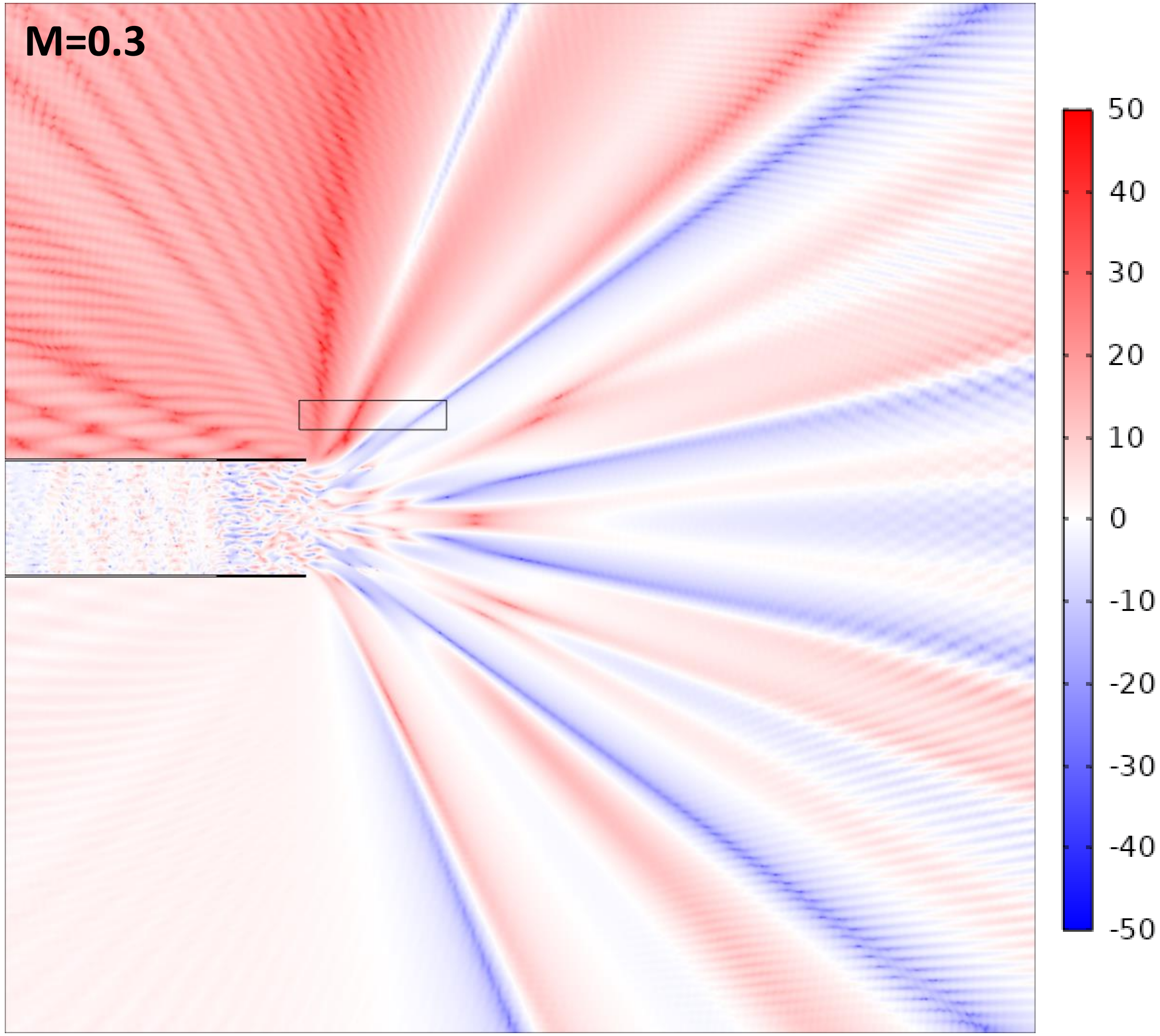






Results: IL HW vs. MS





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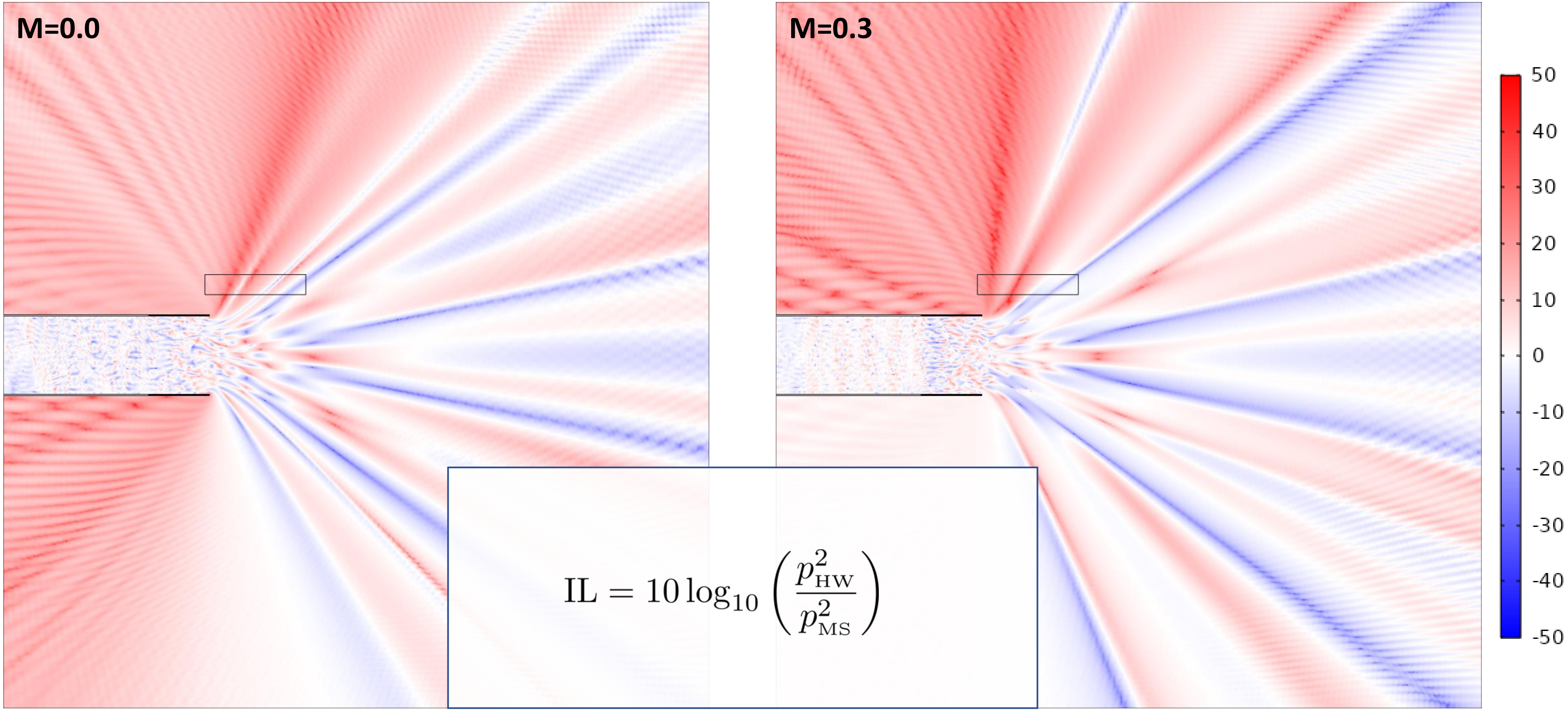
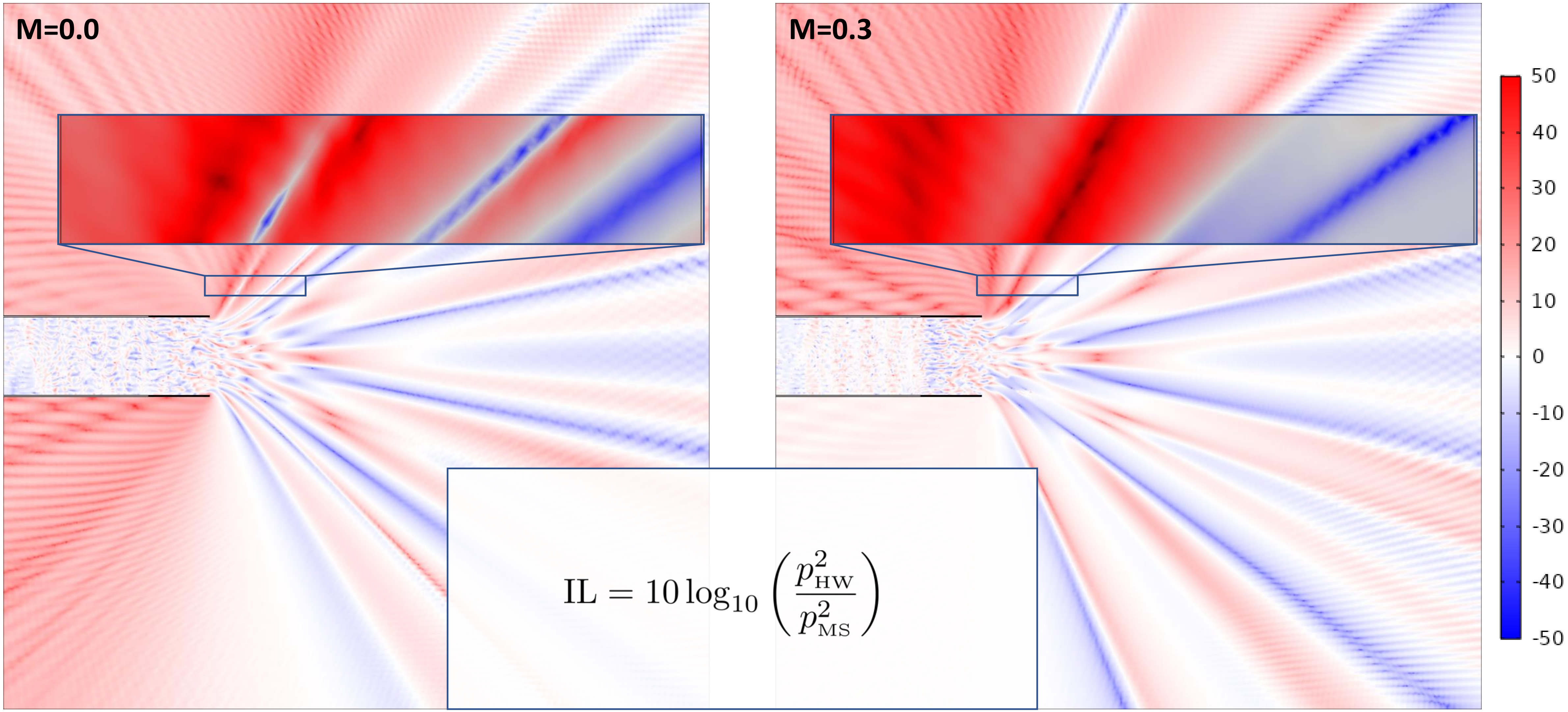


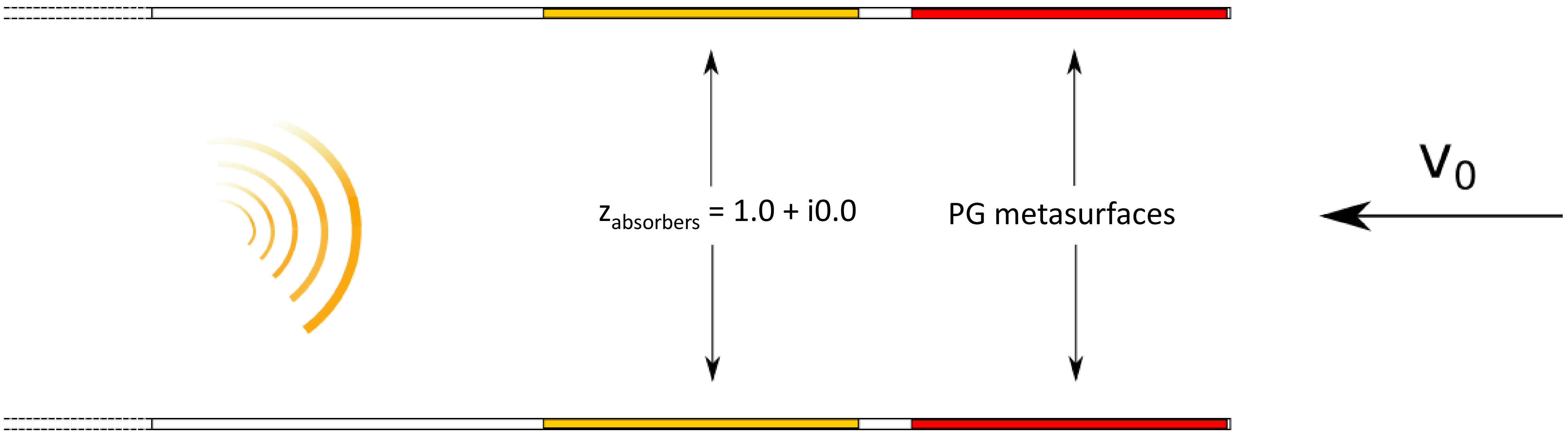
$$\mathrm{IL} = 10\log_{10}\left(\frac{p_{\mathrm{HW}}^2}{p_{\mathrm{MS}}^2}\right)$$

Results: IL HW vs. MS

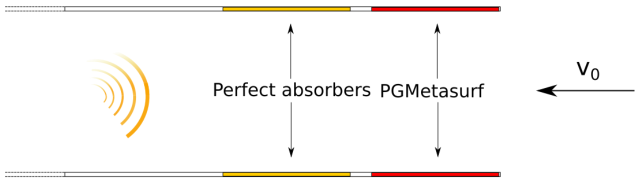


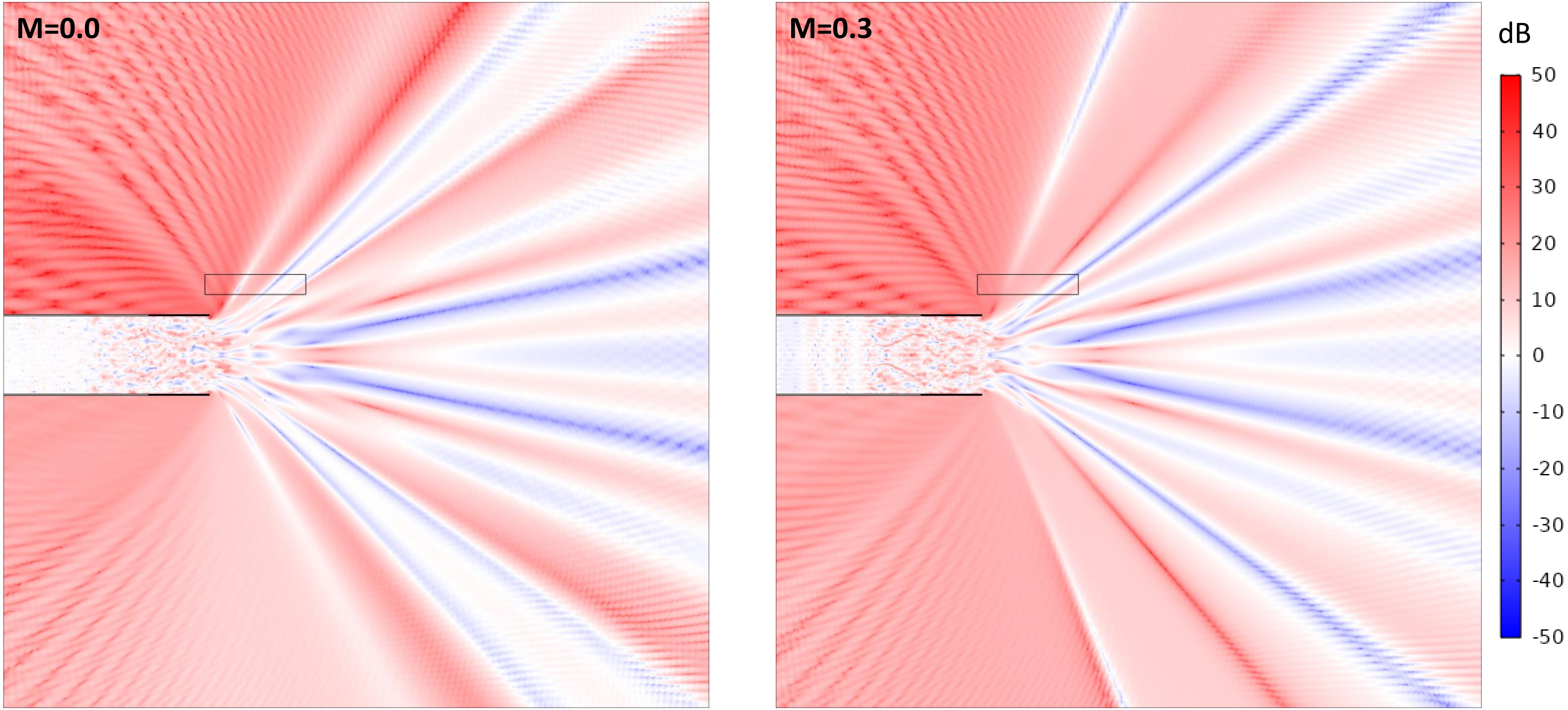
$$\mathrm{IL} = 10\log_{10}\left(\frac{p_{\mathrm{HW}}^2}{p_{\mathrm{MS}}^2}\right)$$

An exercise: integration with perfect absorbers

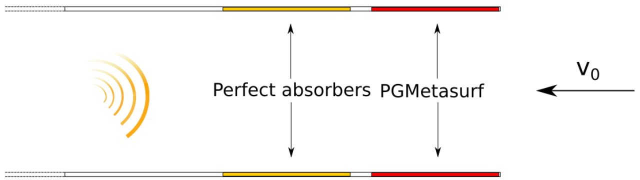


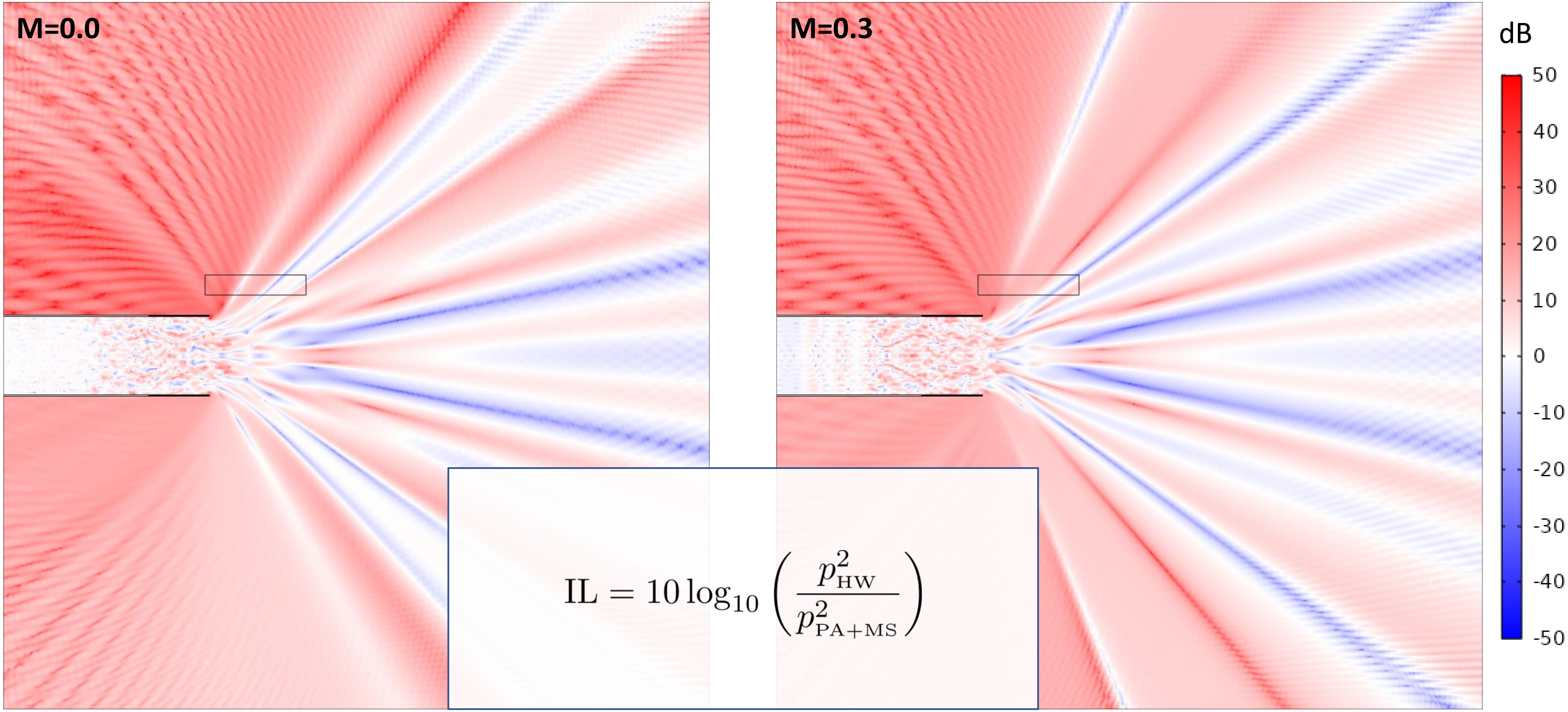
Results: IL HW vs. PA+MS





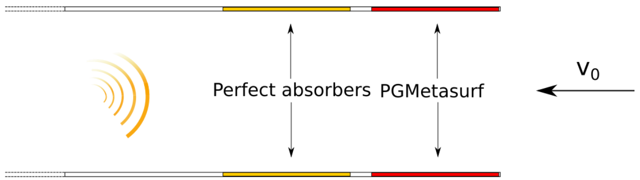
Results: IL HW vs. PA+MS

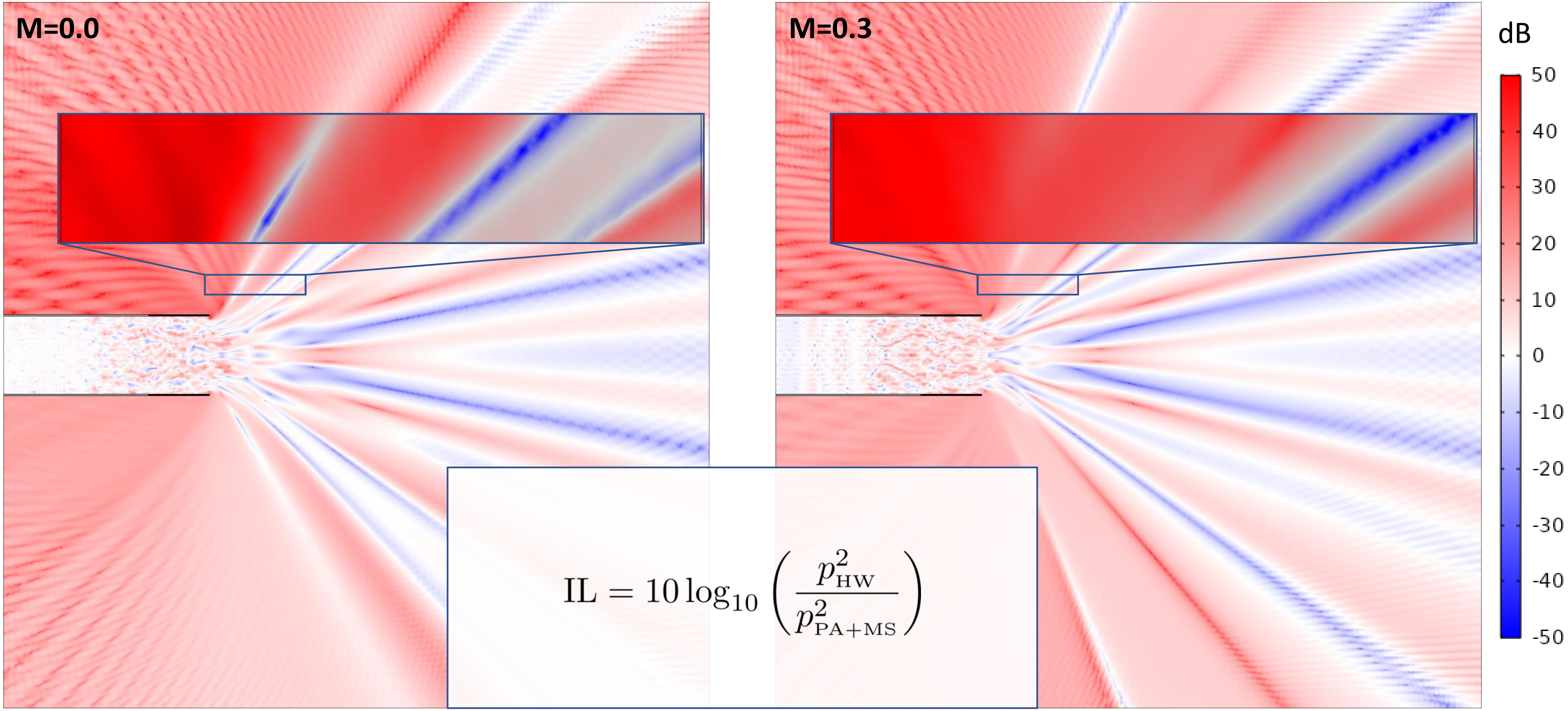




$$\mathrm{IL} = 10\log_{10}\left(\frac{p^2_{\mathrm{HW}}}{p^2_{\mathrm{PA+MS}}}\right)$$

Results: IL HW vs. PA+MS



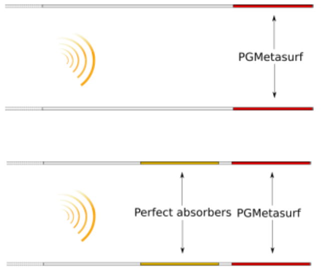


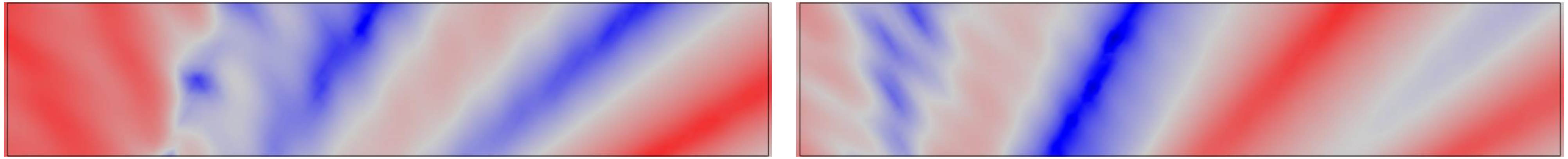
$$IL = 10\log_{10}\left(\frac{p^2_{HW}}{p^2_{PA+MS}}\right)$$

Results: IL on S*

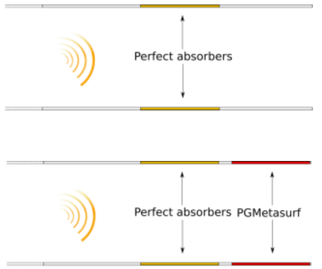
	M=0.0	M=0.3

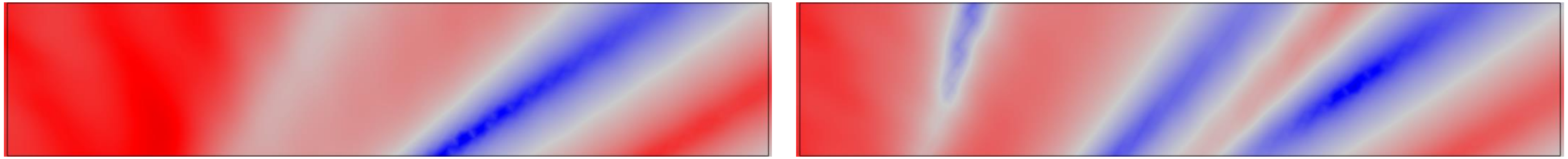
MS vs. PA+MS



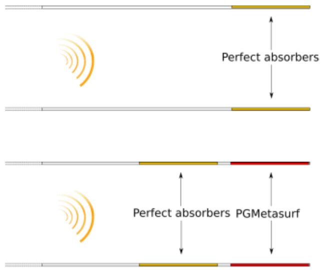


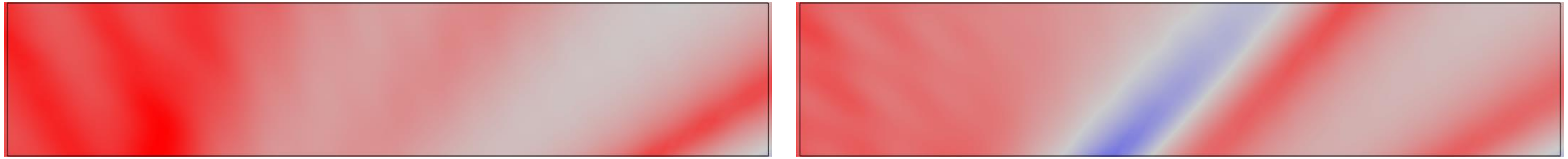
PA vs. PA+MS





PA v2 vs. PA+MS



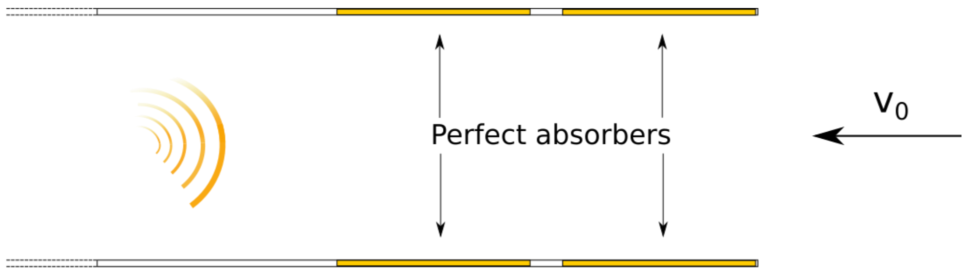


$$\frac{\int_{S^*} p_{\mathrm{LINED}} dS}{\int_{S^*} p_{\mathrm{HW}} dS}$$

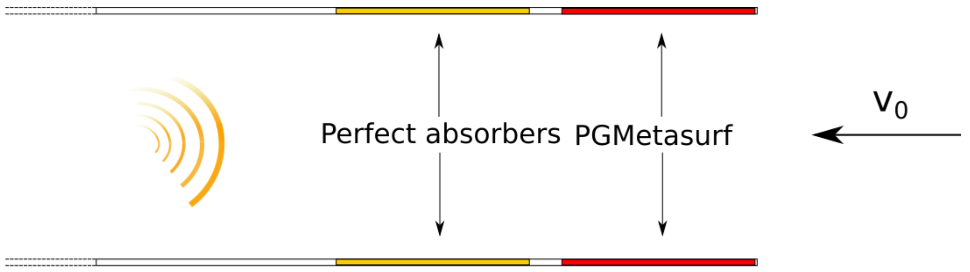
	MS	PA	PA v2	PA+MS
M=0.0	61%	33%	43%	68%
M=0.3	57%	49%	64%	72%

An exercise: integration with perfect absorbers

Same lining length: a fair comparison!

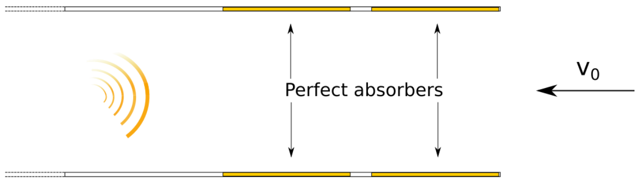


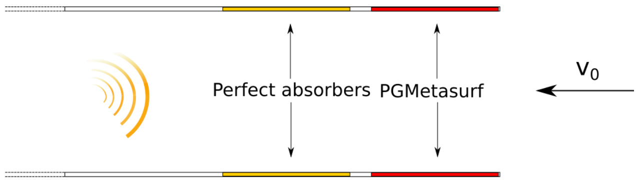
PA* (**PA***: same length of PA+MS)

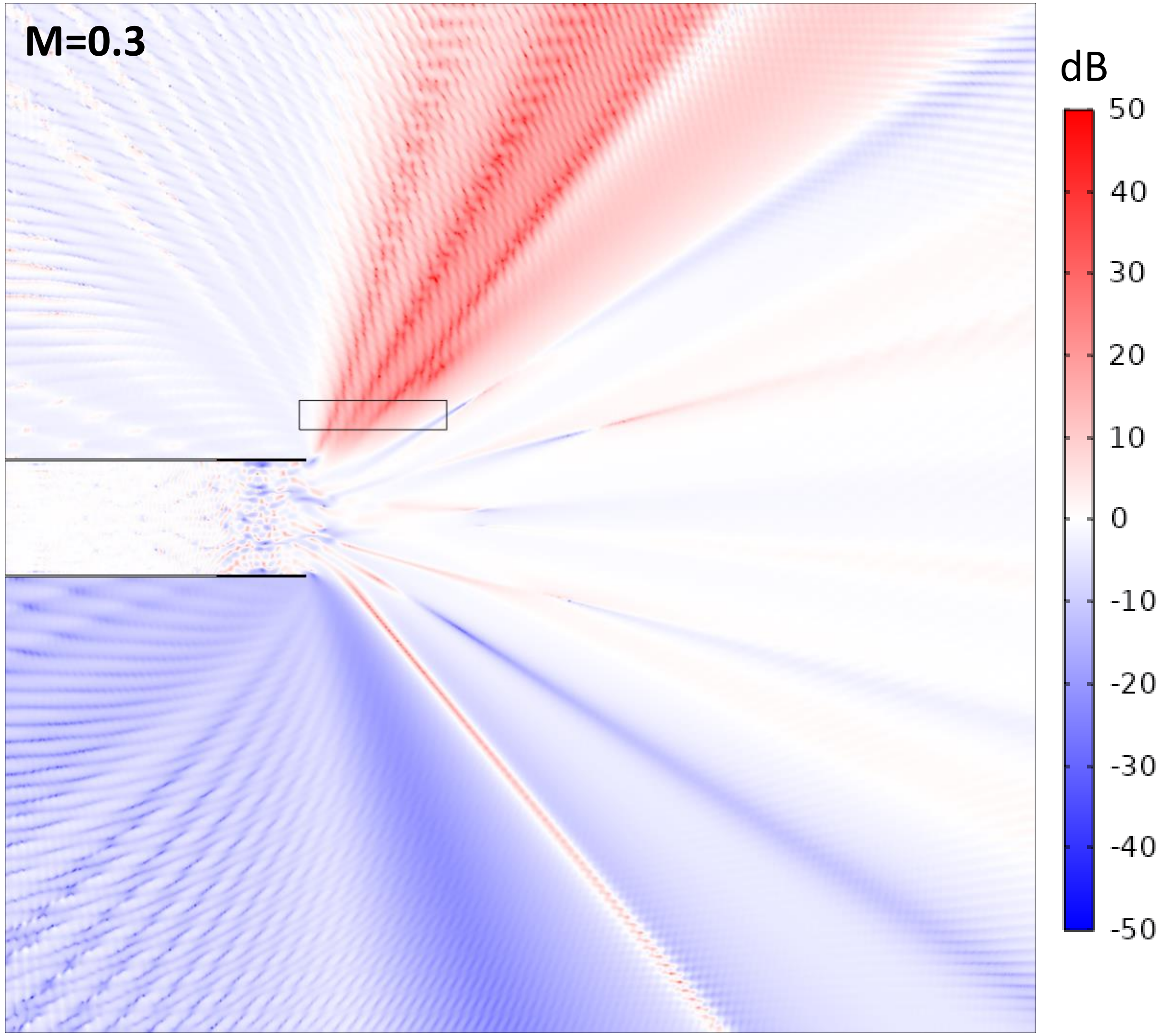


PA+MS** (**MS****: optimized MS in the presence of PA)

Results: IL PA* vs. PA+MS**

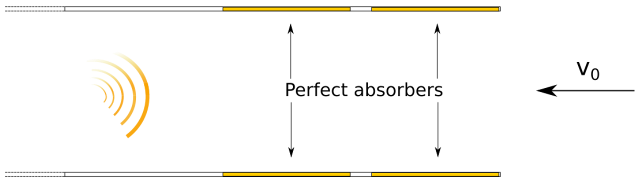


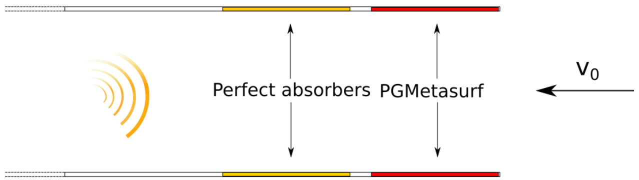


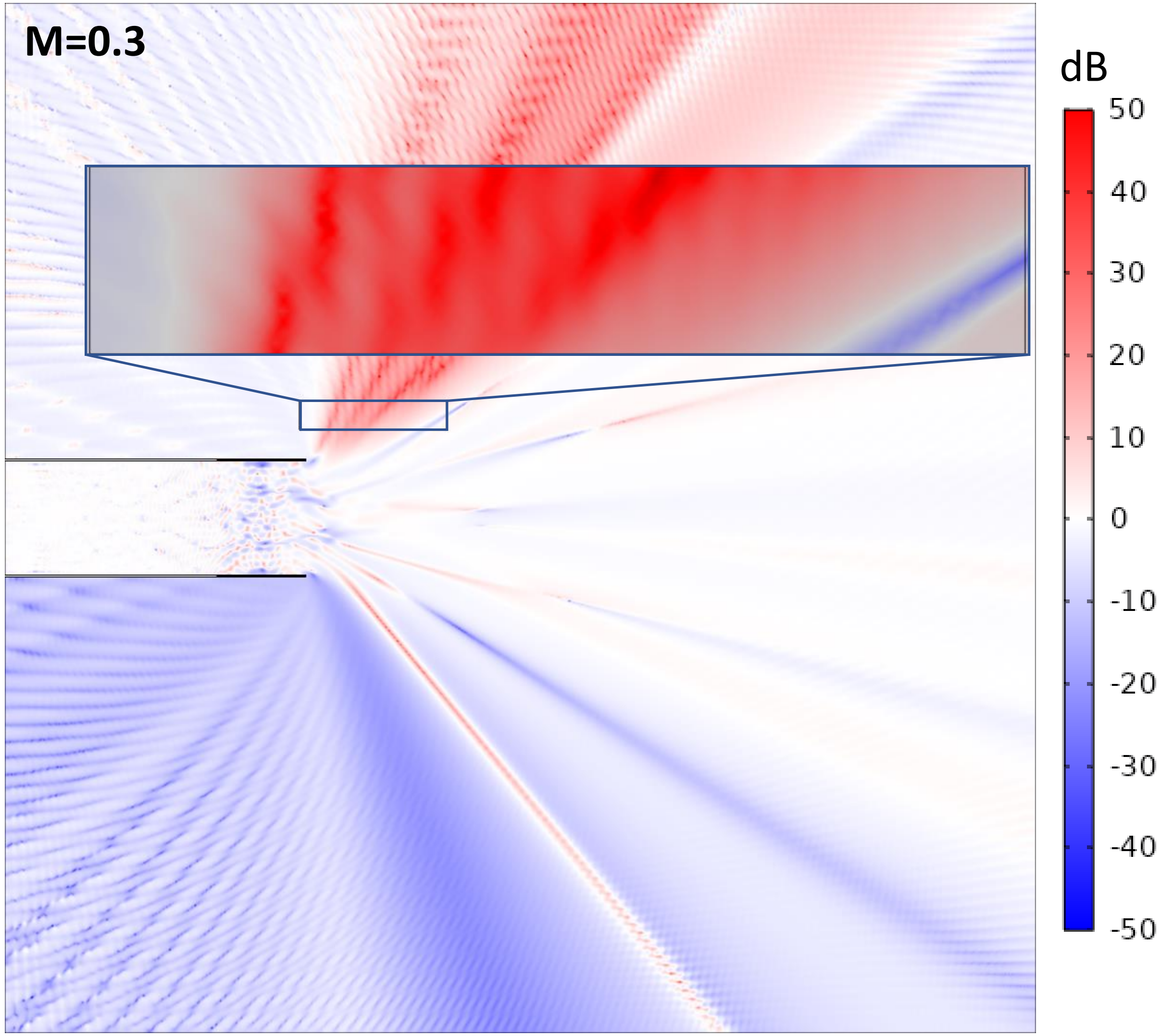


$$\mathrm{IL} = 10 \log_{10} \left(\frac{p^2_{\mathrm{PA*}}}{p^2_{\mathrm{PA+MS**}}} \right)$$

Results: IL PA* vs. PA+MS**

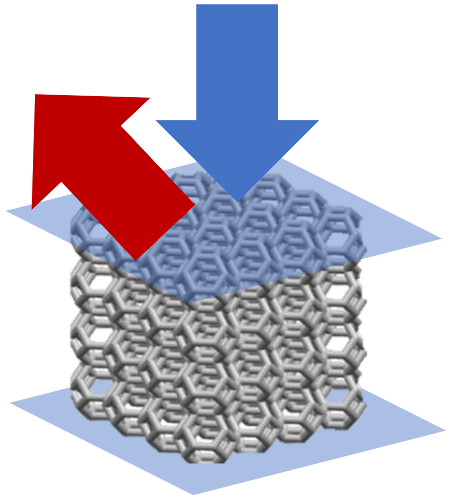






$$\mathrm{IL} = 10\log_{10}\left(\frac{p^2_{\mathrm{PA*}}}{p^2_{\mathrm{PA+MS**}}}\right)$$

Remarks and future development

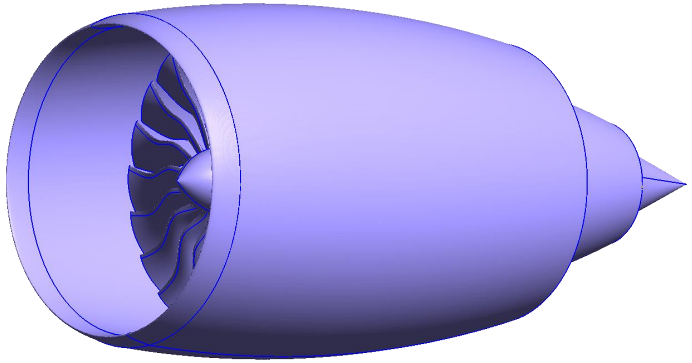


Achievement

- Equivalent metafluids for GSL-based metasurfaces
- Framework for efficient phase profile optimization (with flow)
- Preliminary integration of optimized MS in a 2D duct

On going activities

- More realistic geometry
- More realistic sources
- More realistic flow
- Validation against experiments in presence of flow



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