Superconducting-ferromagnetic metamaterials modeling: optimization for a magnetic wormhole device

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http://grupsderecerca.uab.cat/superconductivity/

Bologna, June 2016

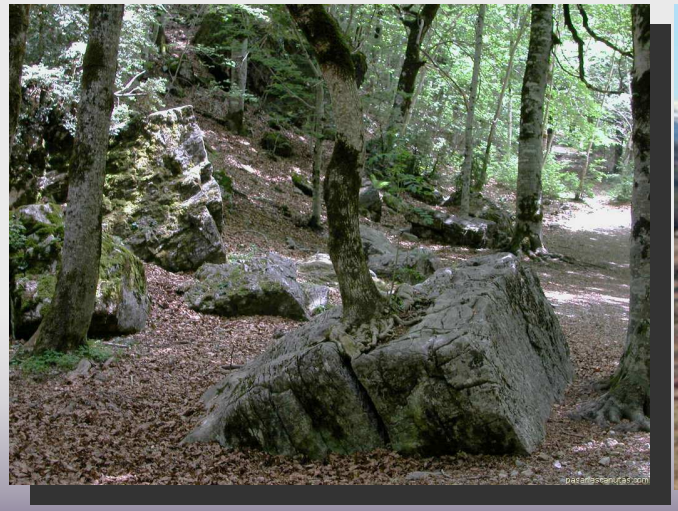
Introduction

System design with materials

Imagine what you want to do…

Look at the Nature to see what materials offers…

Use them to fabricate the imagined system.



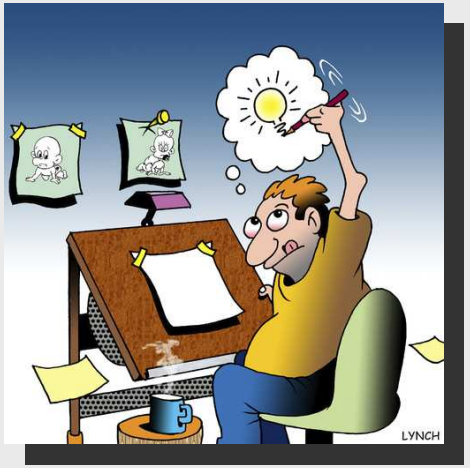
Introduction

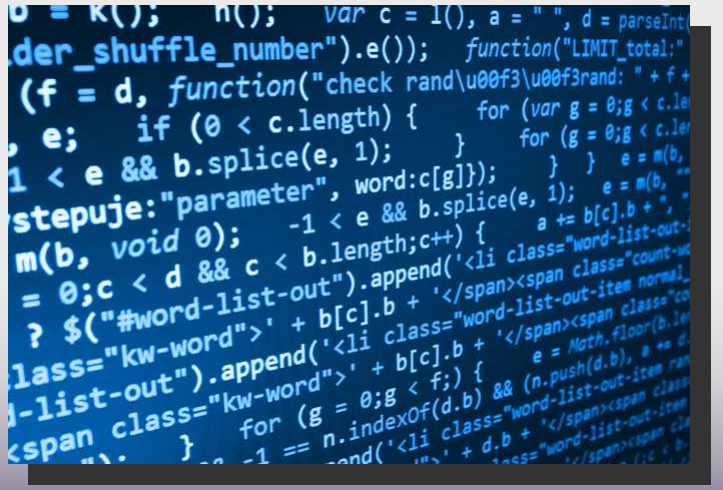
System design with (magnetic) metamaterials

Imagine what you want to do…

Design the **metamaterials** at your will…

Use them to fabricate the imagined system





Introduction. Definition of metamaterials

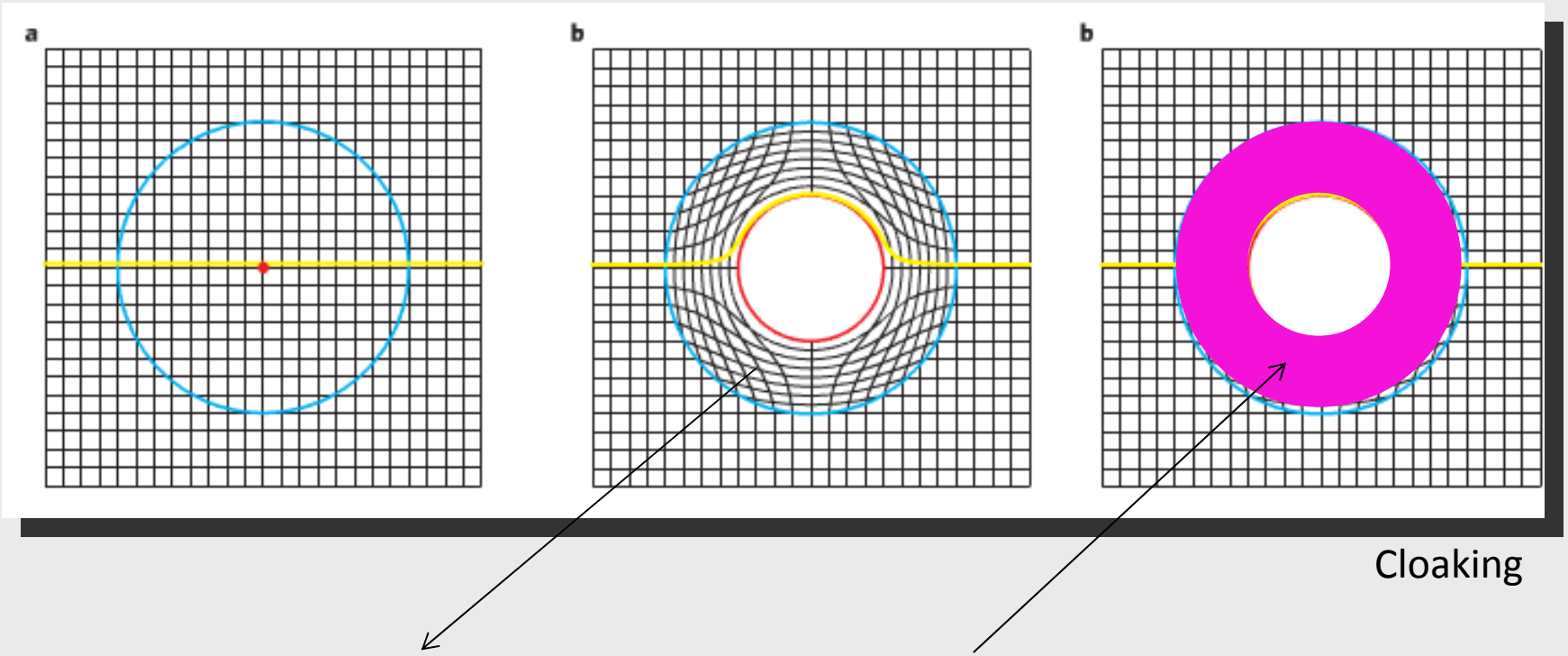
Metamaterials. Materials that have properties that the natural materials do not have.

Metamaterials. Systems~~Materials~~ that have effective properties that the natural materials do not have.

Metamaterials. Systems designed ~~Materials~~ for having ~~that have~~ effective properties that the natural materials do not have.

Introduction: Transformation optics

Maxwell equations are invariant under space transformations…
…transforming the materials in the transformed space.



Cloaking

Transformed space → Equivalent material
(Mathematics) → (Materials science)

Pendry, J.B.; Schurig, D.; Smith, D. R. (2006). Science 312 (5514): 1780

Transformation optics

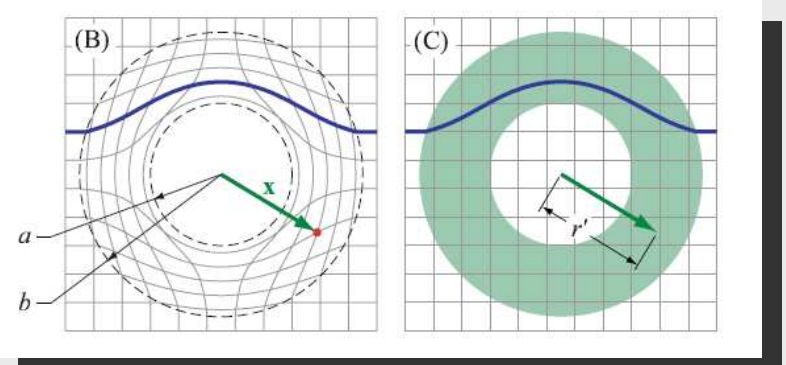
What these materials are made of ?

Do they exist in nature?

Can we design them (metamaterials)?

$$r' = \frac{b-a}{b} r + a$$

Cylindrical cloak



$$\varepsilon = \mu = \frac{\rho}{\rho - a}\mathbf{T} - \frac{2a\rho - a^2}{\rho^3(\rho - a)}\rho \otimes \rho + \left(\frac{b}{b-a}\right)^2 \frac{\rho - a}{\rho}\mathbf{Z}$$

Non-homogeneous and even with components diverging at some points

Anisotropic with different radial functions for different components

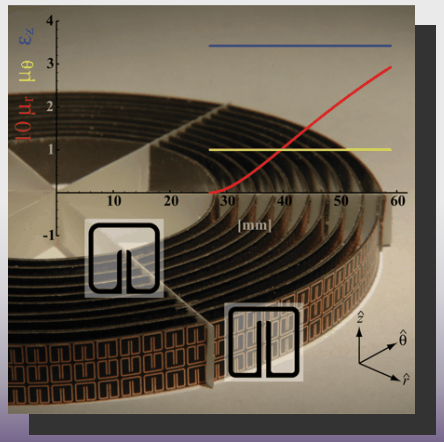
Introduction: Transformation optics

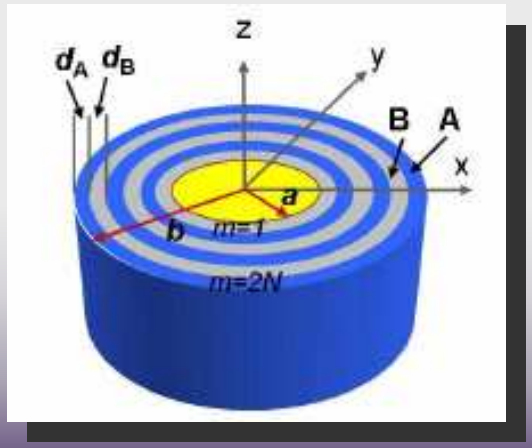
Several strategies can be used

To design materials to satisfy the required permeabilities and permeabilities as effective values (metamaterials)

To simplify requirements renouncing to the exactess of the desired effect: reduced schemes (discretization, rounds-off, averages,…)

To explore different ranges: d. c. range





Summary (of the rest of the talk)

- Transporting static fields
- Cloaking static fields
- Design and test of a ‘magnetic wormhole’

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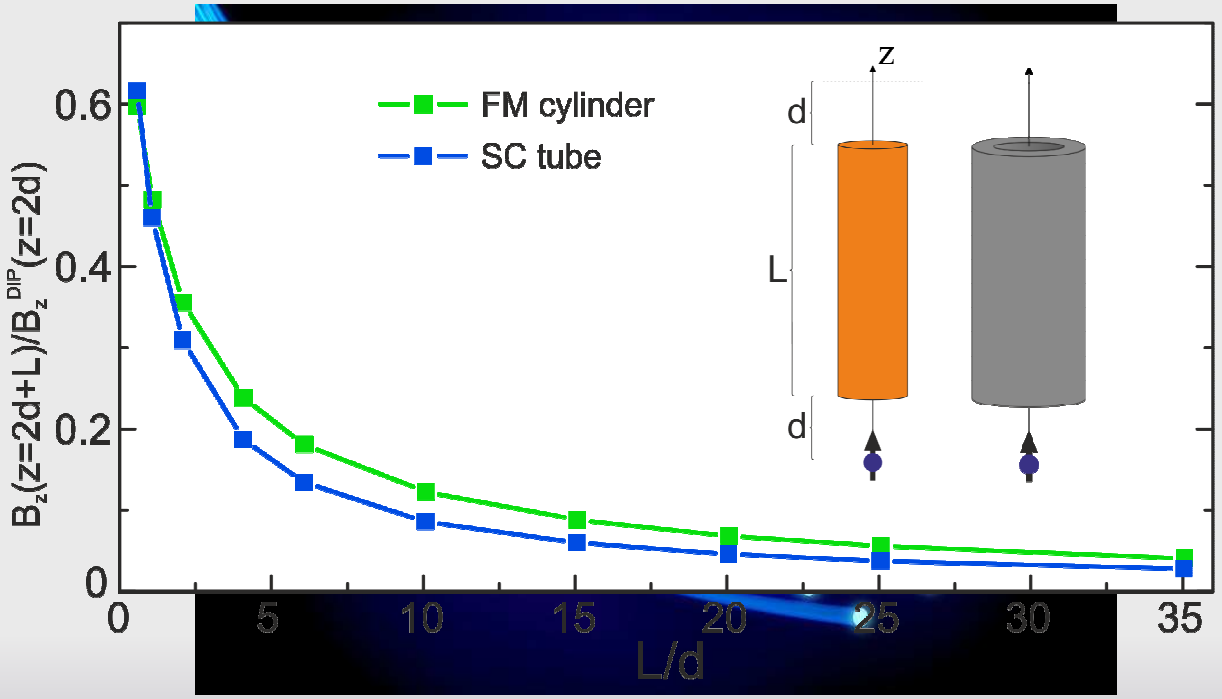
Designing a magnetic wormhole

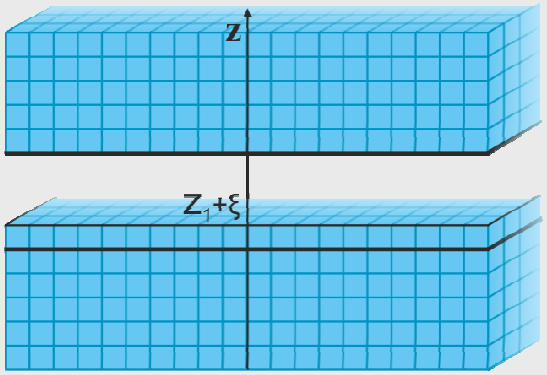
- Light is easily guided with optical fibers and waveguides
- Static magnetic fields rapidly decay with the distance

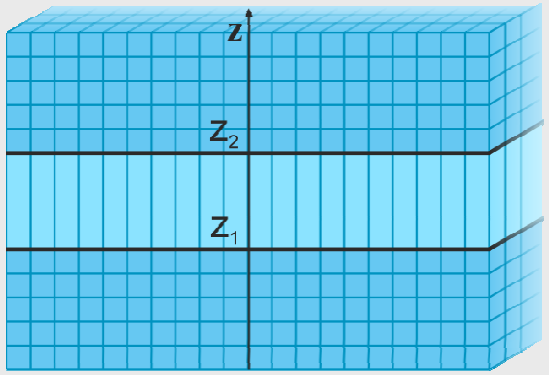


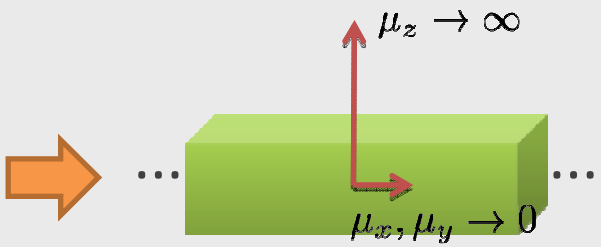
Designing a magnetic wormhole

- We apply the following space transformation

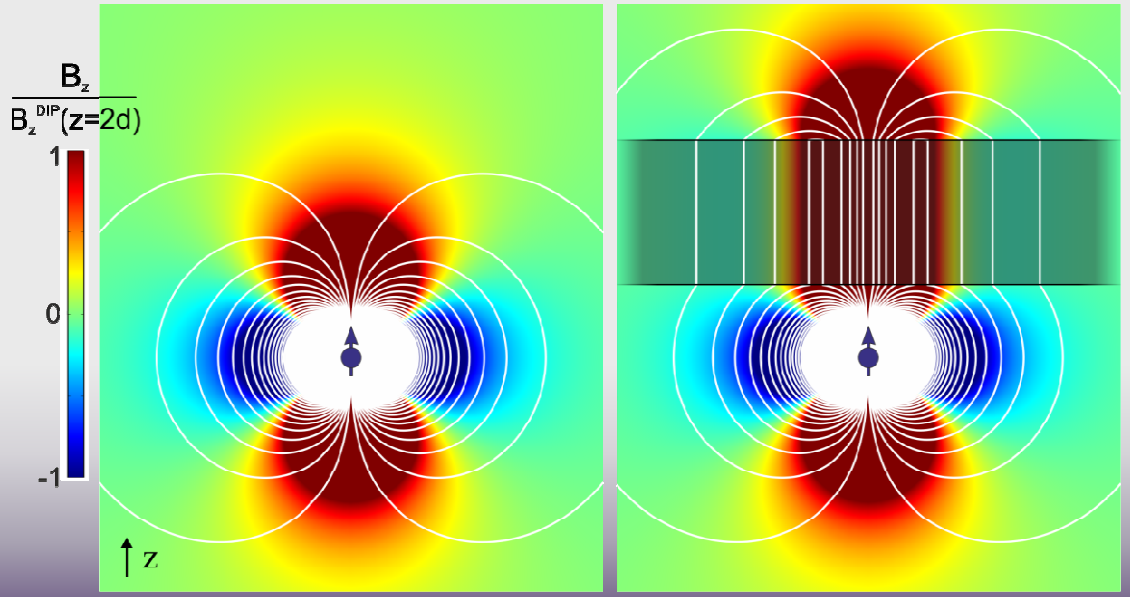
in collaboration with J. I. Cirac (MPQ Munich) and O. Romero-Isart (IQOQI Innsbruck)





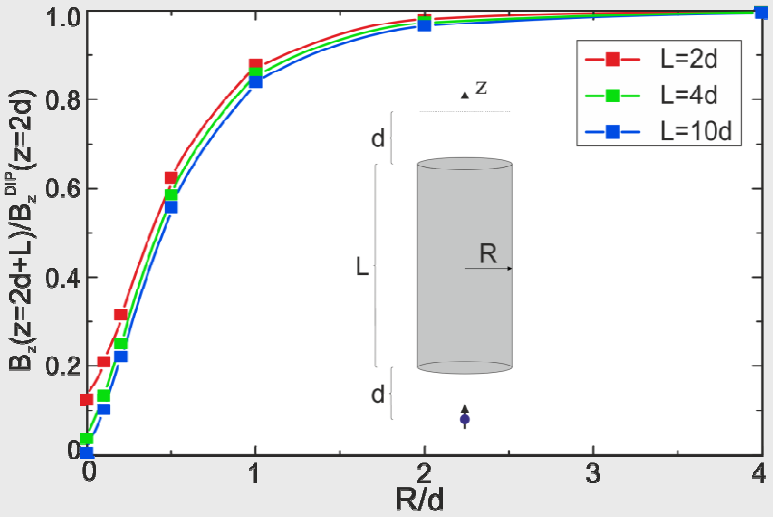


requires **infinite material** with
large μ_z and small μ_x, μ_y

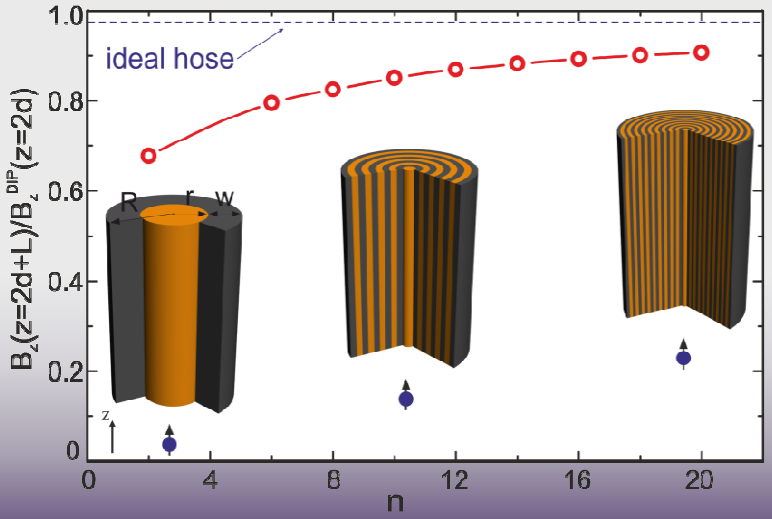


Transporting static fields

- We address the two limitations separately



good transfer results also for finite cylinders

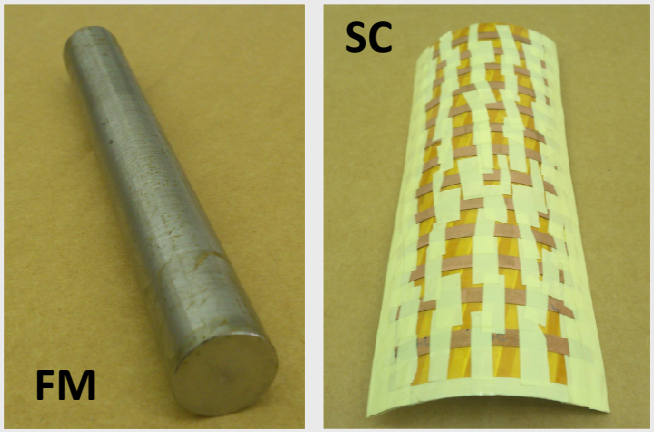


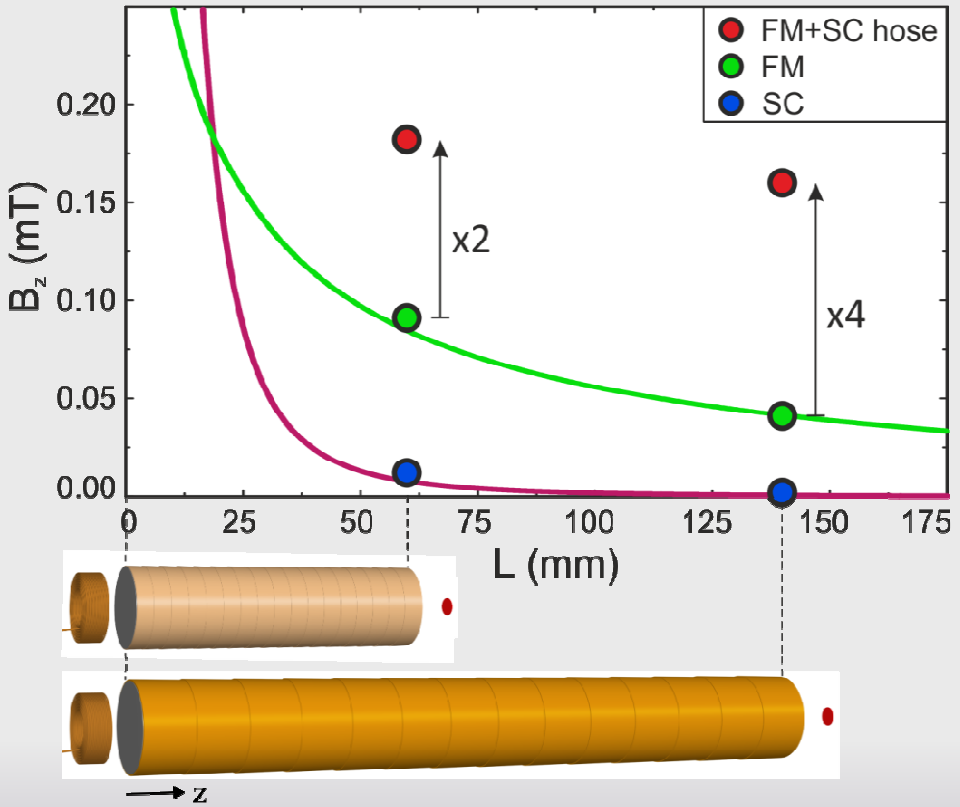
ideal material discretized into SC and FM alternating shells

even for only two shells (n=2) good transfer results

Transporting static fields

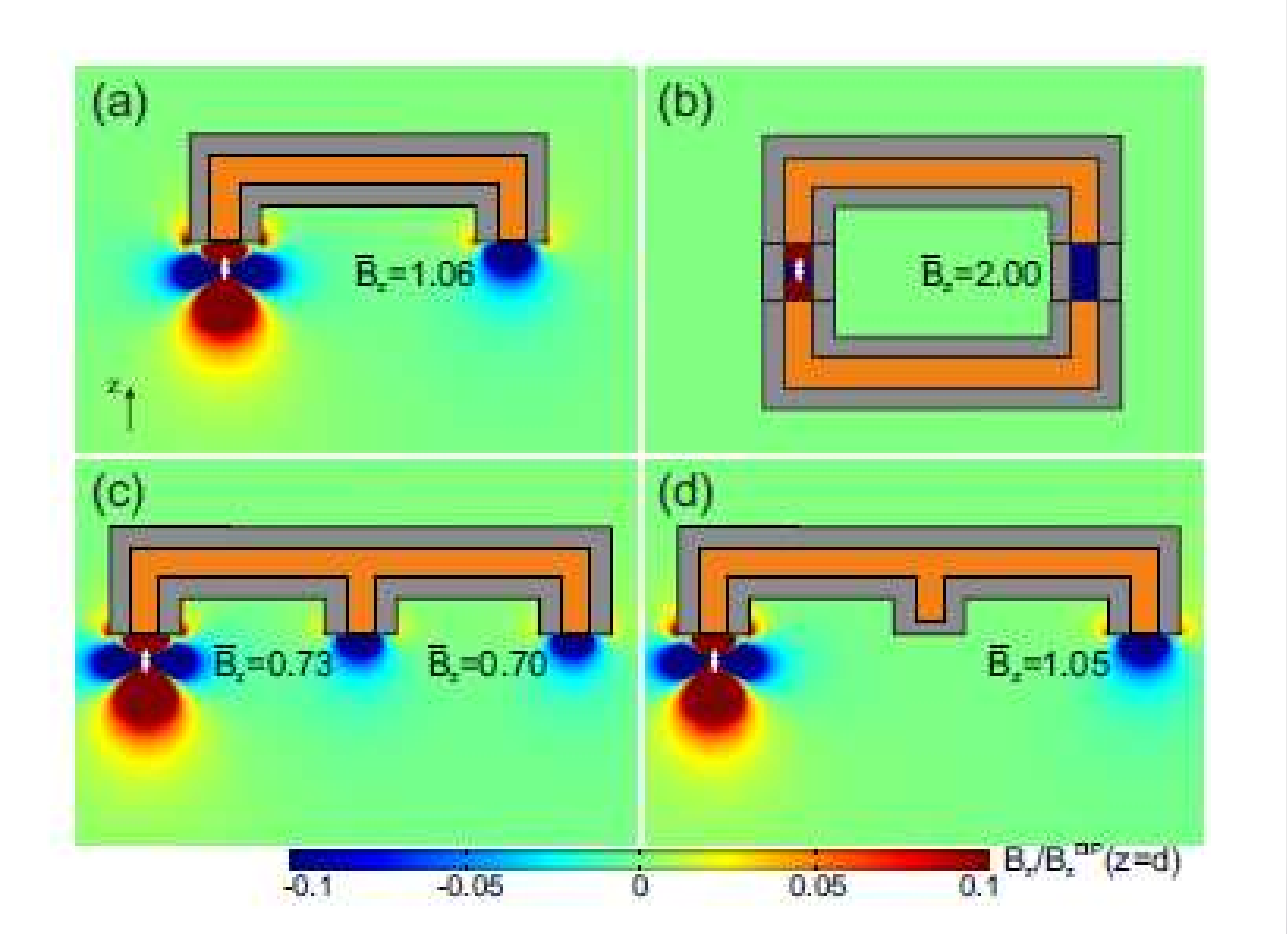
- Two houses experimentally realized using **coated conductors** and **ferromagnets**





Transporting static fields

- Complex hoses with several ends were studied numerically and analytically



Navau, Prat-Camps, Romero-Isart, Cirac, Sanchez
Phys. Rev. Lett., **112, 253901** (2014).

Transporting static fields

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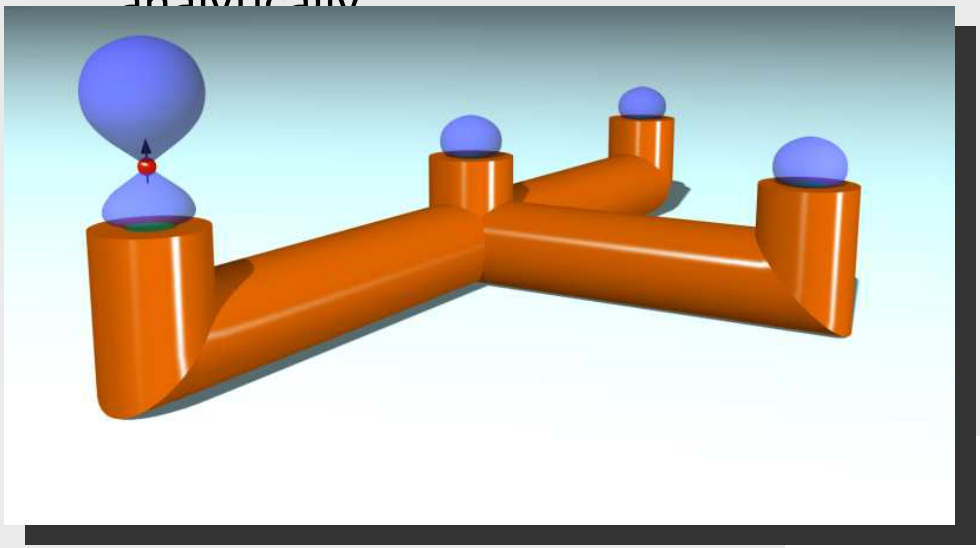

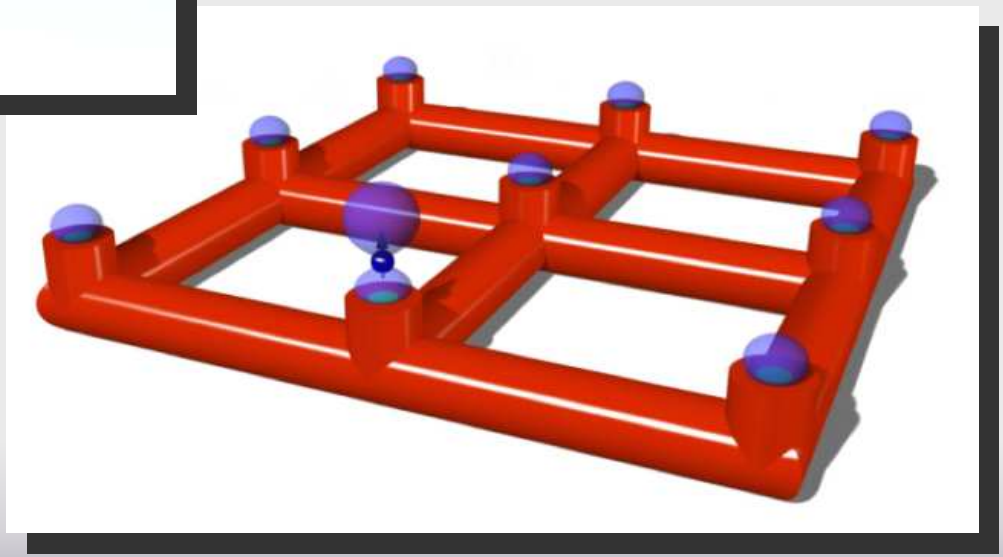

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Summary (of the rest of the talk)

- Transporting static fields
- Cloaking static fields
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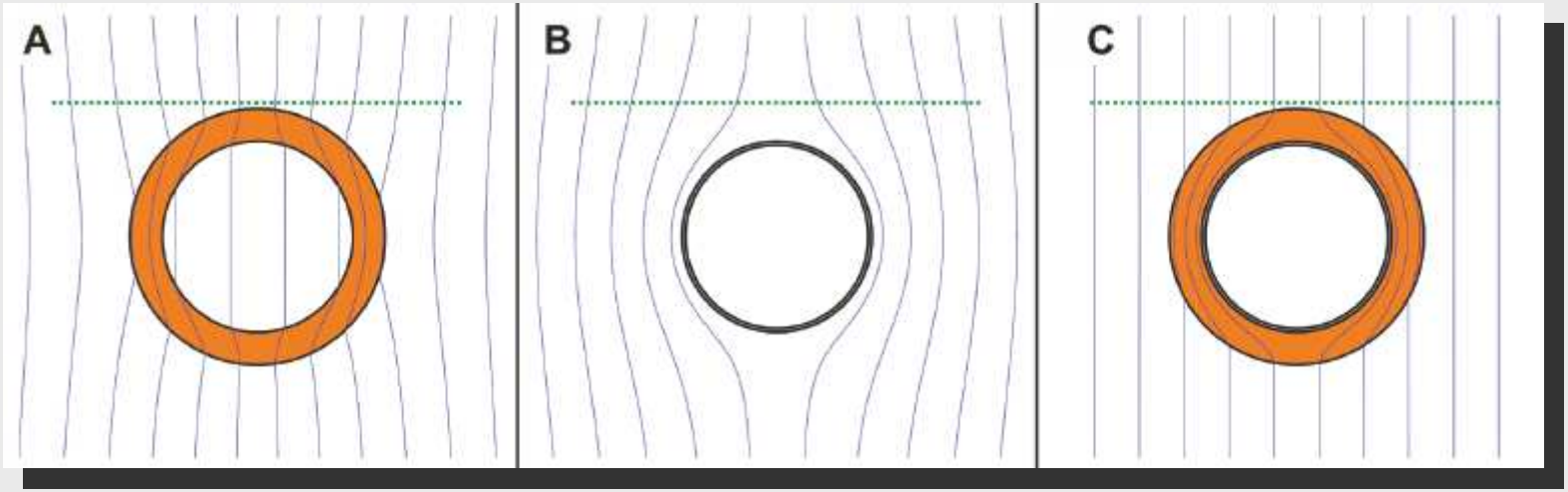
Cloaking static fields

Is there a simple (i. e. bilayer) system that exactly cloaks a ***uniform*** applied field?

$\mu > 1$ $\mu = 0$ μ_1 , μ_2 ?



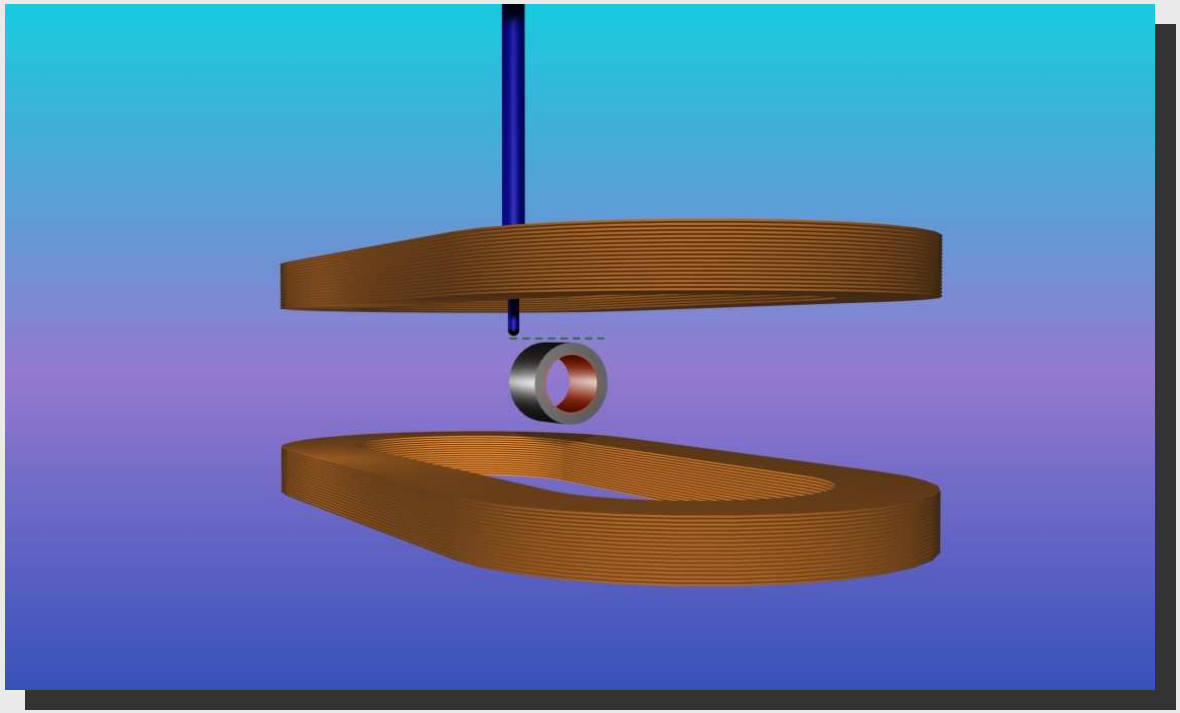
FM- Impelling field lines

SC- Expelling field lines

No distortion outside
Zero inside

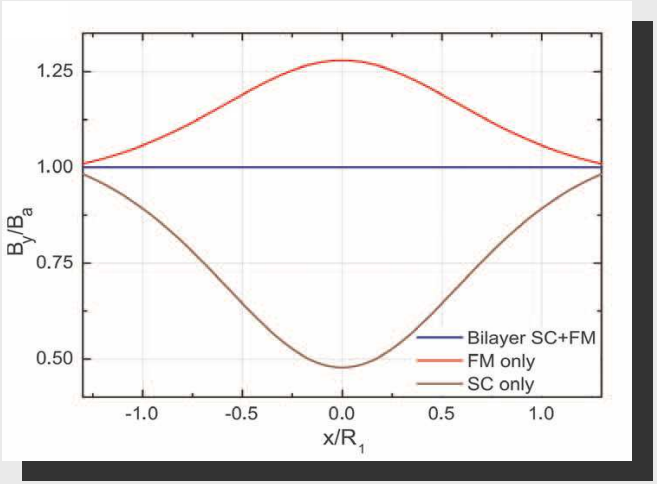
$$\mu_2 = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}.$$

Cloaking static fields

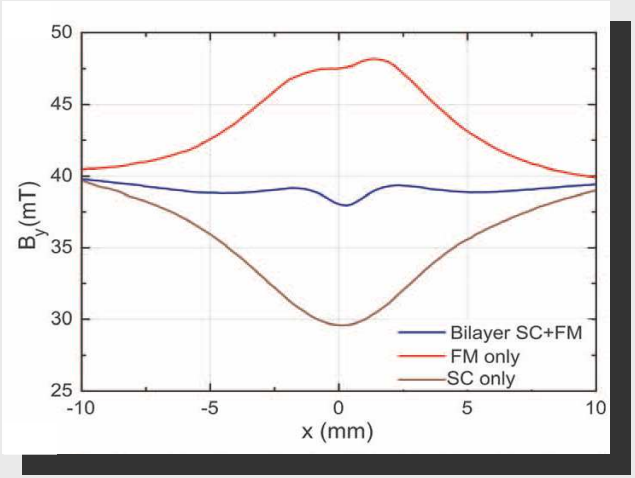


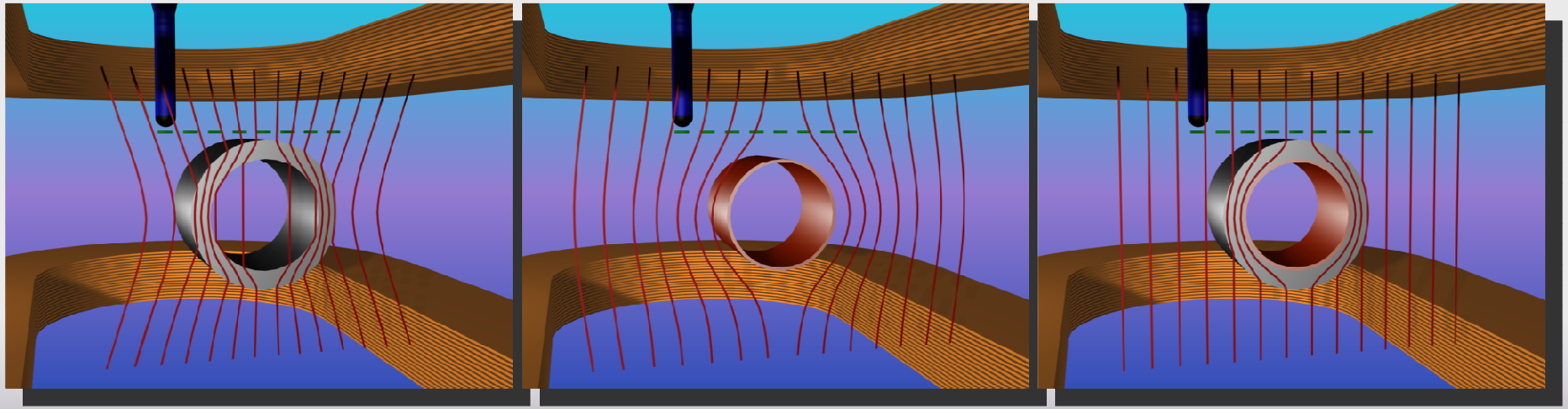
Cloaking static fields

Analytic (Ideal situation)



Experiment





Gömöry, Solovyov, Souc, Navau, Prat-Camps, Sanchez
Science 335, 1466 (2012)

Summary (of the rest of the talk)

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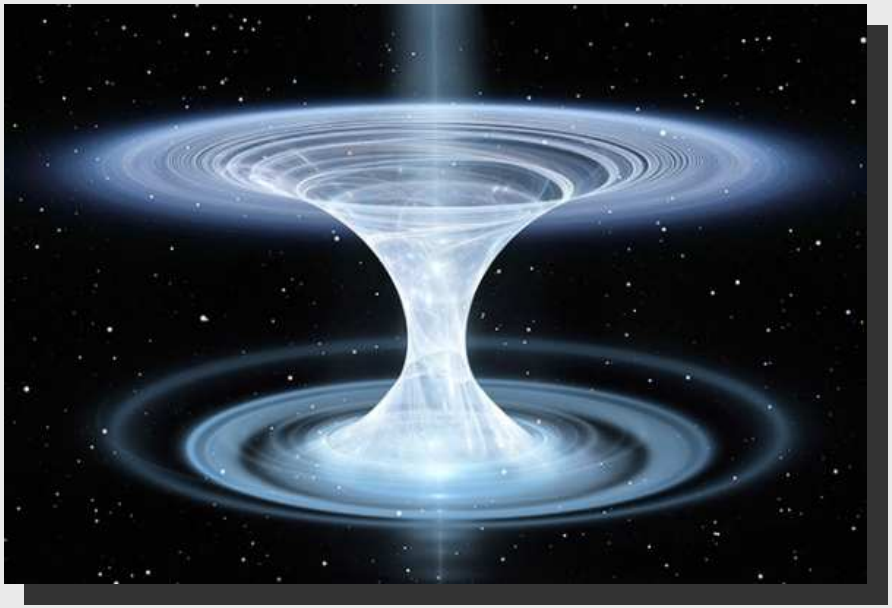
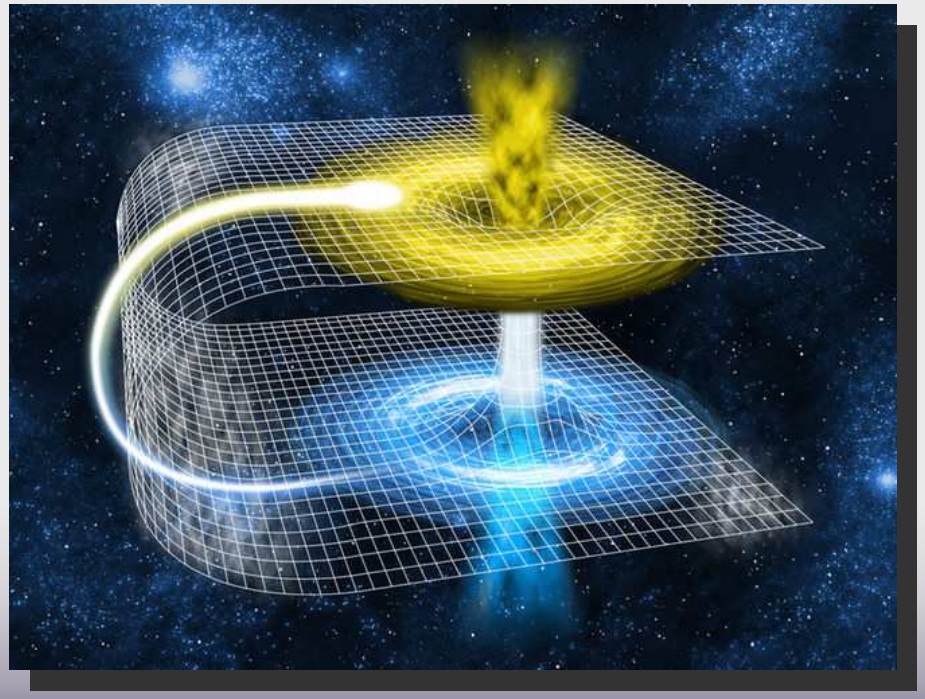
Defining a magnetic wormhole

In astrophysics: tunnel that connects two distant points of the universe

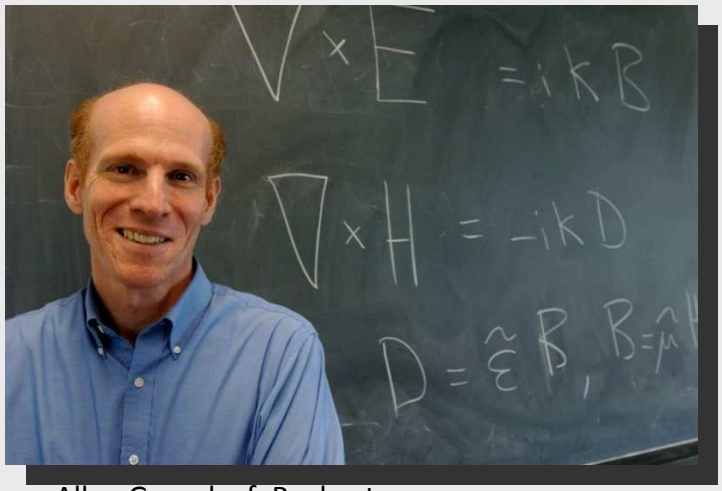




Defining a magnetic wormhole

Reformulation for **electromagnetic waves**: tunnel that connects two distant points through an invisible path

Greenleaf, Kurylev, Lassas, Uhlmann
Phys. Rev. Lett. **99**, 183901 (2007)



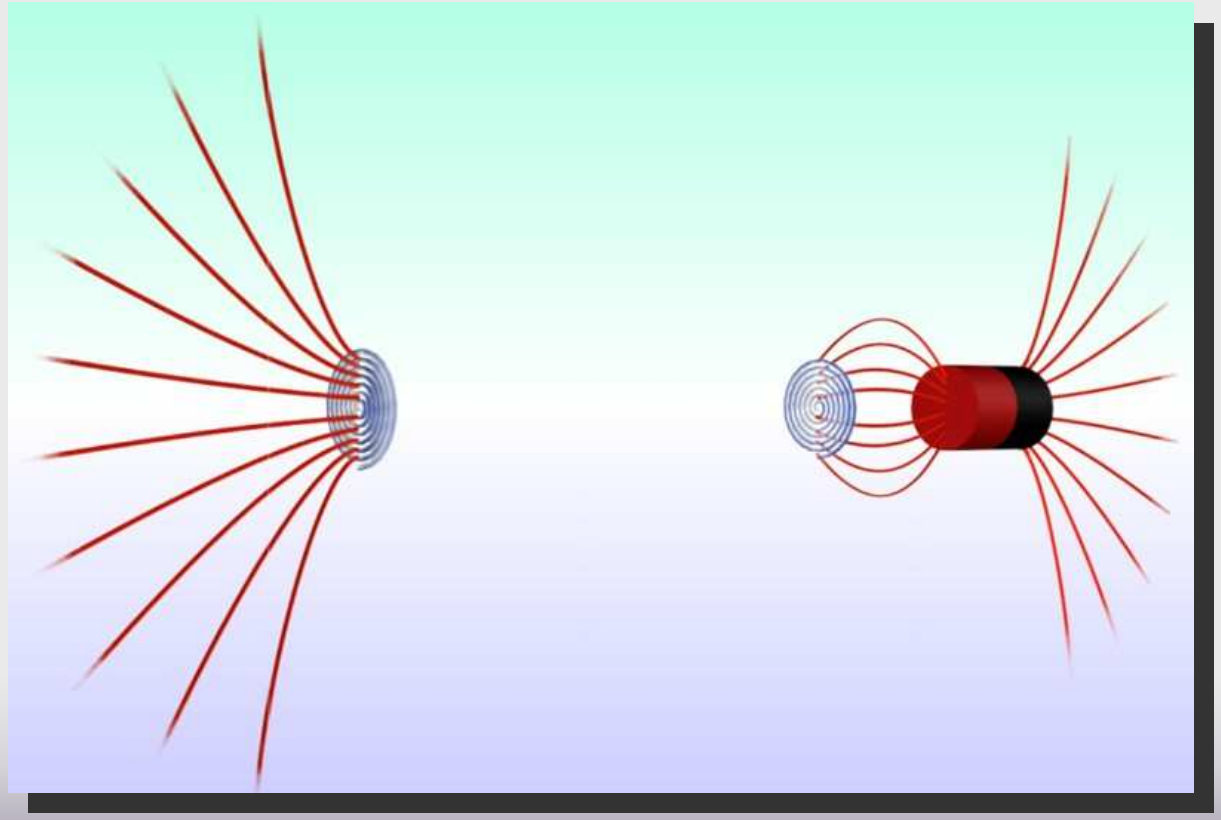
Allan Greenleaf, Rochester

Formulas were given for light,

but the materials needed do not exist!

Defining a magnetic wormhole

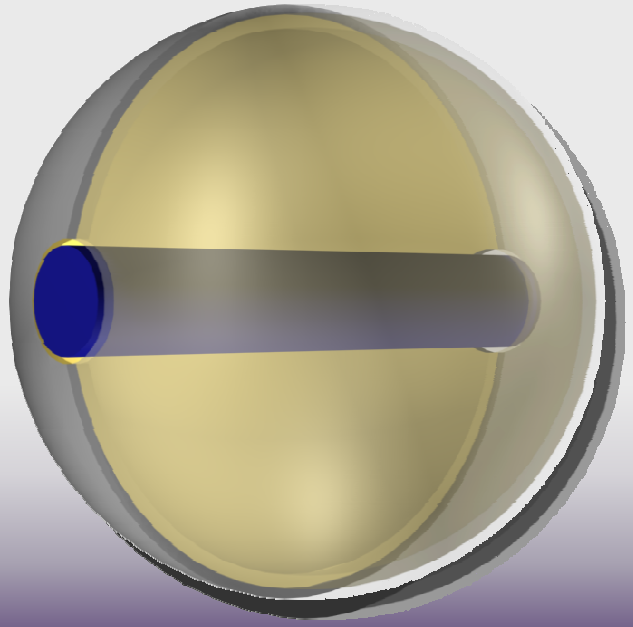
Reformulation for **magnetostatic fields**: tunnel that (magnetically) connects two distant points through a (magnetically) invisible path



Designing a magnetic wormhole

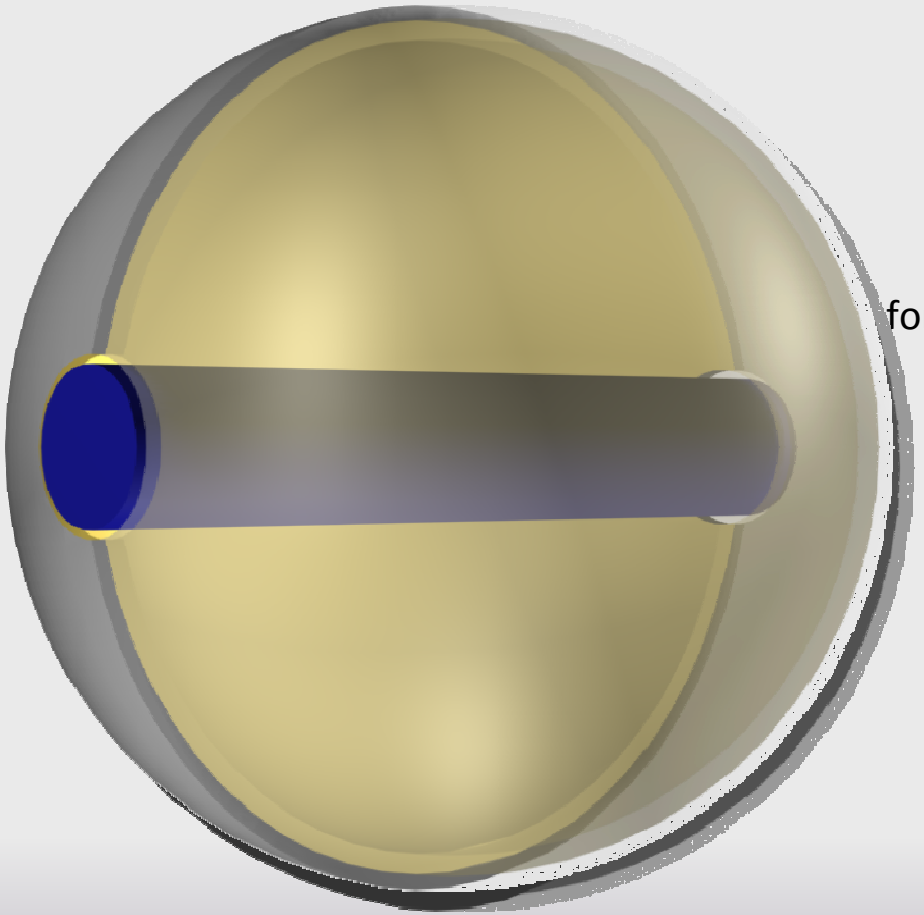
Transfer of magnetic fields → magnetic hose

Full 3D spherical magnetic cloak



Designing a magnetic wormhole

We need to design a full 3D spherical magnetic cloak

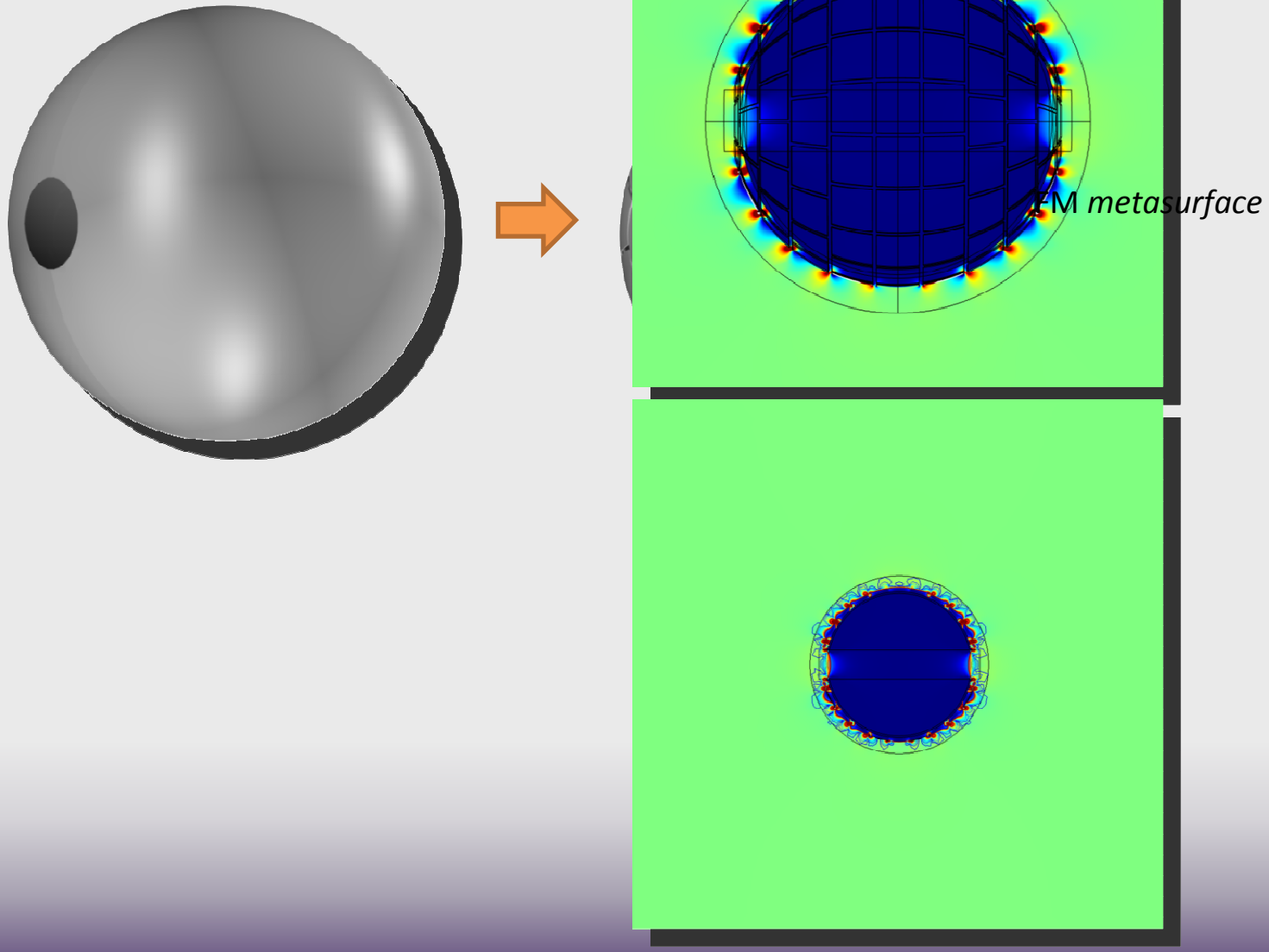


$$\mu_2 = \frac{2R_2^3 + R_1^3}{2(R_2^3 - R_1^3)}$$

for $R_2 \to R_1$ and $\mu_2 \to$ the bilayer effectively cloaks any magnetic field

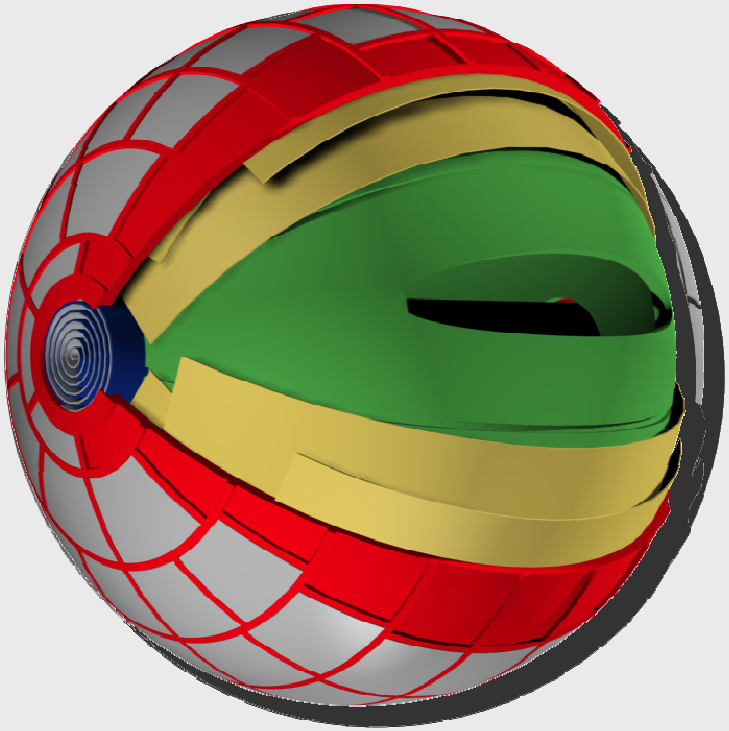
Interior superconductor (μ_1=0)
Exterior with μ_2

Designing a magnetic wormhole



Designing a magnetic wormhole

- Experimental realization



- **Hose** made of FM foil
- spherical **SC shell** made of 32 coated conductor pieces
- spherical **FM metasurface** made of 155 thin pieces

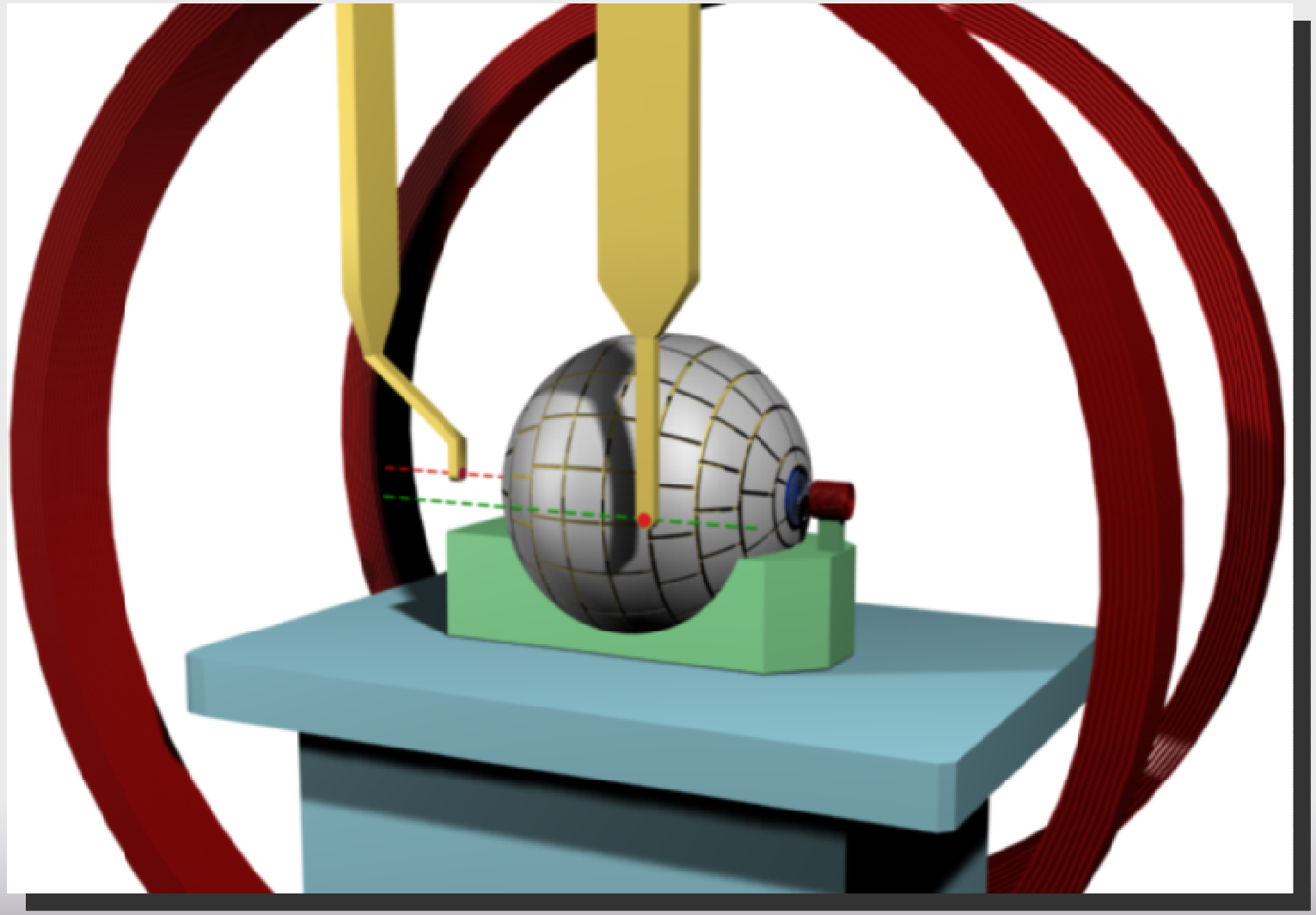
Prat-Camps, Navau, Sanchez
***Scientific Reports* 5, 12488 (2015)**

Designing a magnetic wormhole

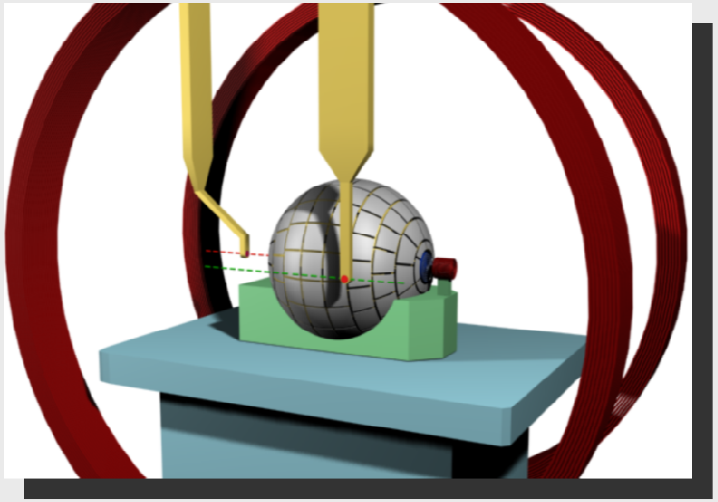
- Experimental realization

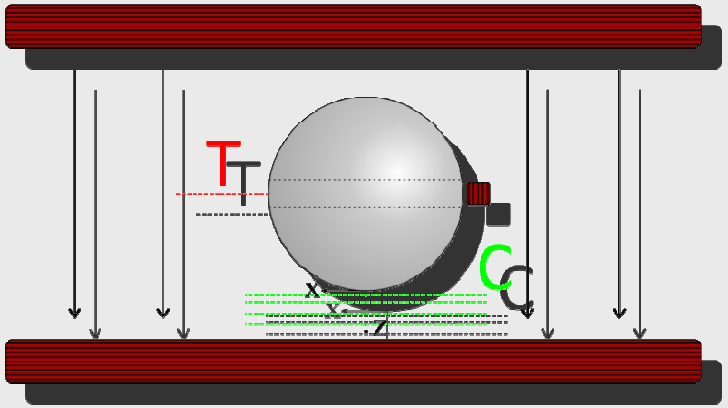
Prat-Camps, Navau, Sanchez
***Scientific Reports* 5, 12488 (2015)**

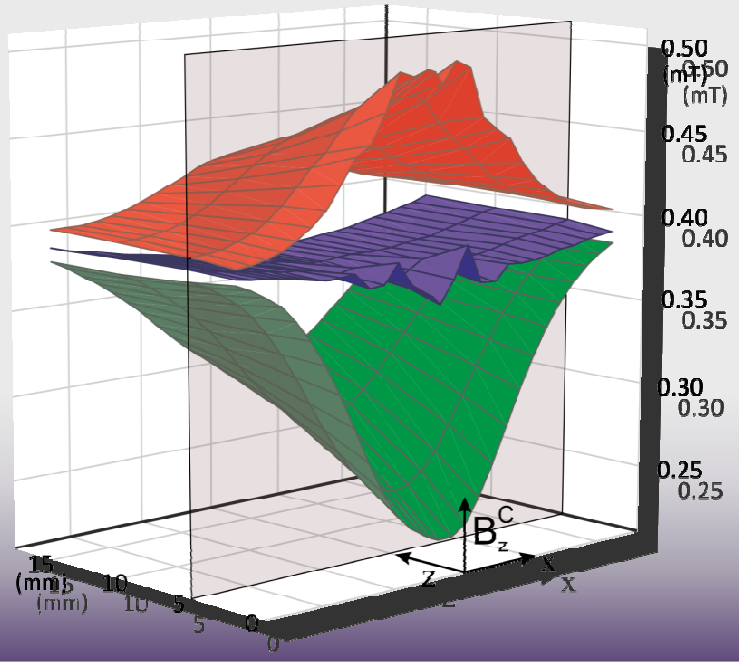
Testing the magnetic wormhole

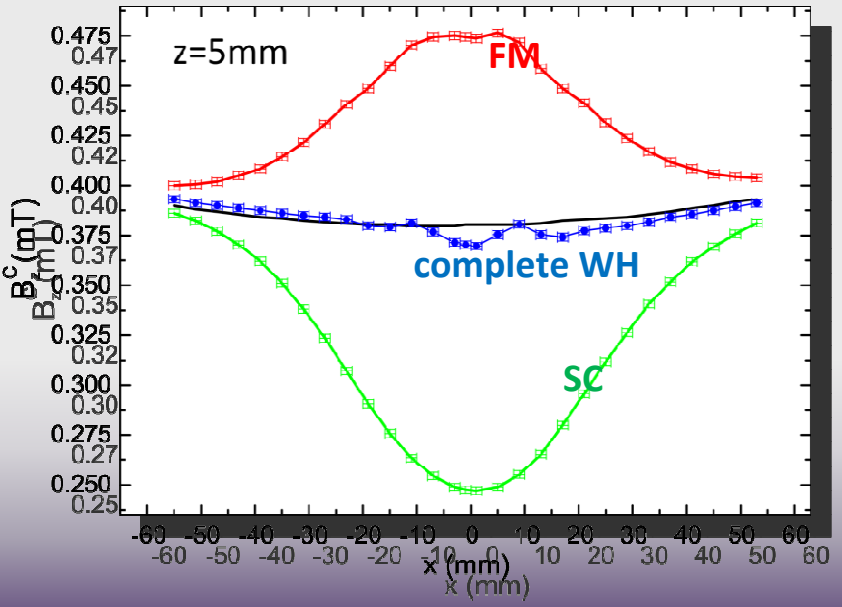


Testing the magnetic wormhole



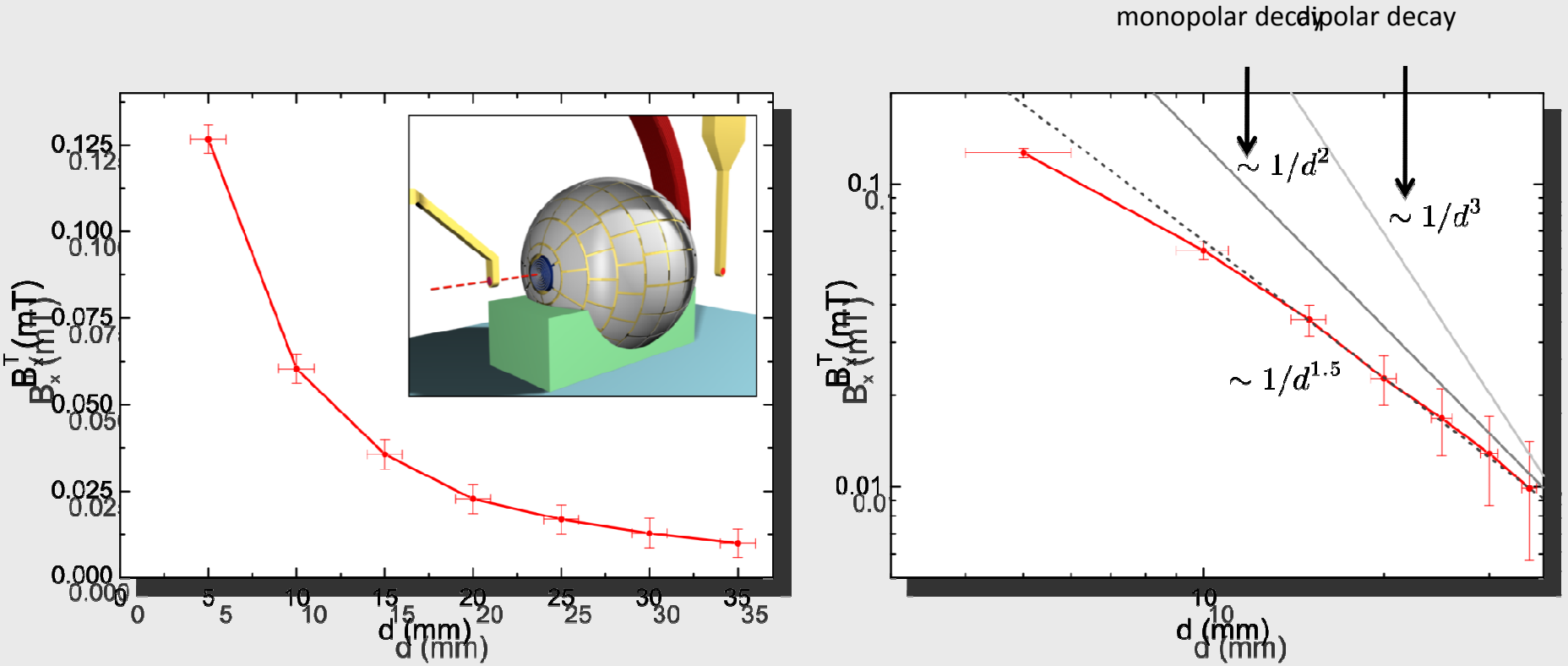




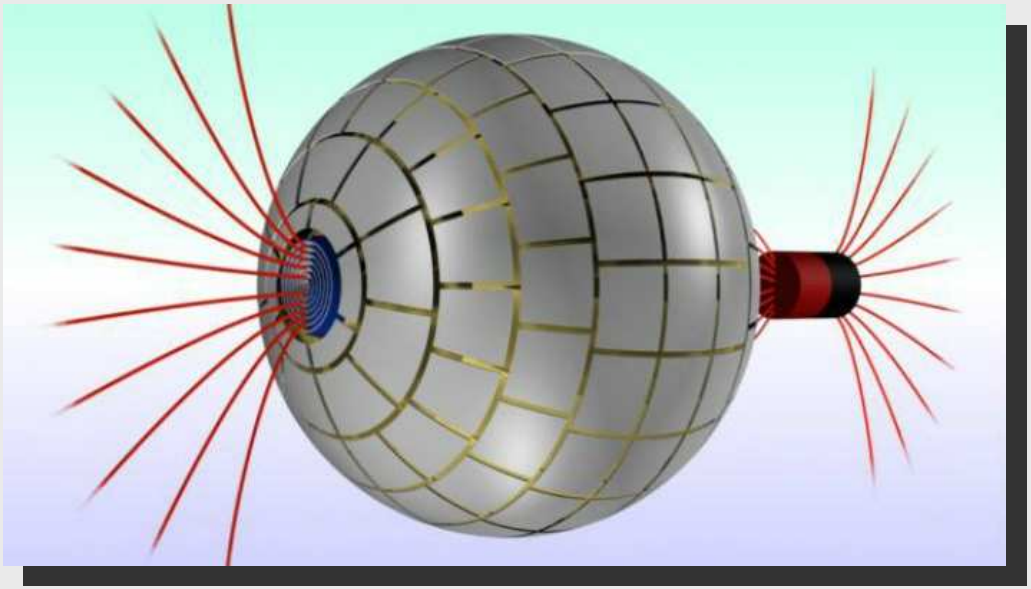


Testing the magnetic wormhole

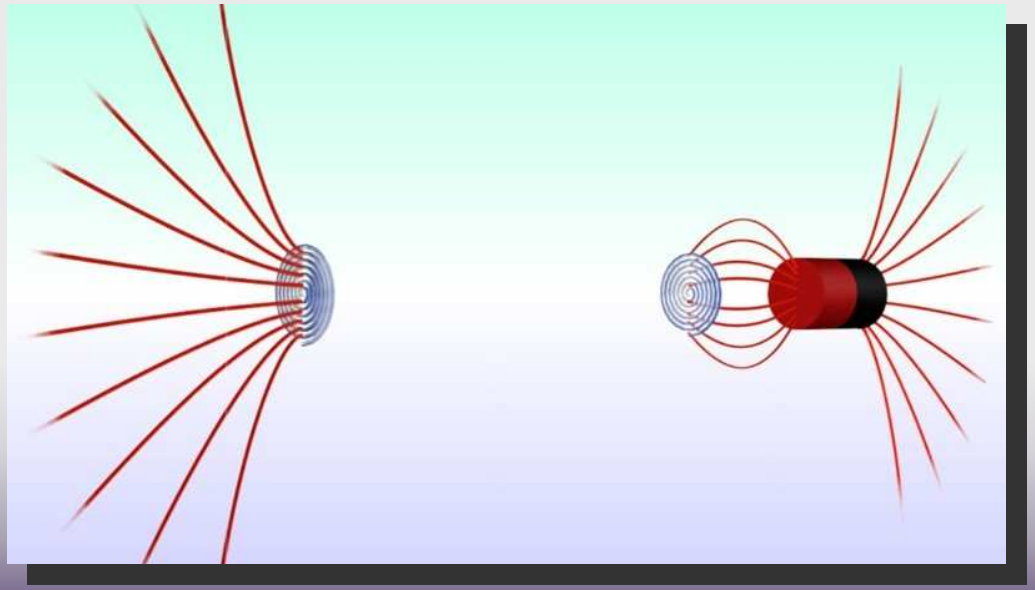
- Field transmission measurements



Testing the magnetic wormhole



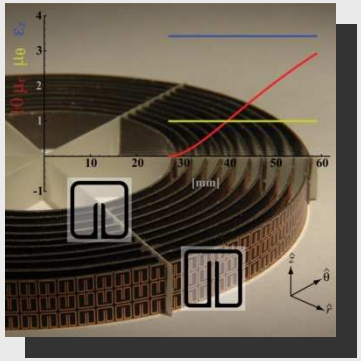
Normal view

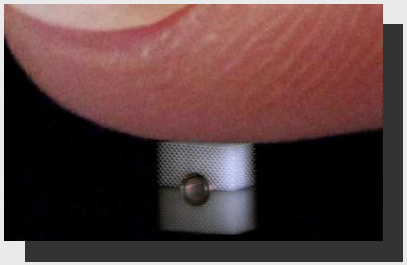
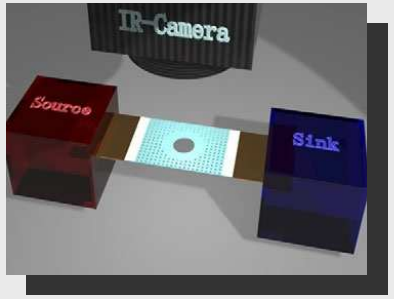


Magnetic view

Conclusions

Metamaterials for new applications



Superconducting-ferromagnetic hybrids for dc magnetic metamaterials (extreme values of permeability)

Modeling for design and optimization of the systems.

Thank you

Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

icrea
Institució Catalana de Recerca i Estudis Avançats

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Thanks for your attention

http://grupsderecerca.uab.cat/superconductivity/

Bolonia, June 2016

Introduction: Transformation optics

Maxwell equations are invariant under space transformations

$$\nabla \times \mathbf{E} + i\omega\mu\mathbf{H} = 0,$$

$$\nabla \times \mathbf{H} - i\omega\varepsilon\mathbf{E} = 0$$

Coordinate transformation
$x'=x'(x)$

$$\nabla \times \mathbf{E}' + i\omega\mu'\mathbf{H}' = 0,$$

$$\nabla \times \mathbf{H}' - i\omega\varepsilon'\mathbf{E}' = 0$$

$$\varepsilon^{i'j'} = \left|\det\left(\Lambda_i^{i'}\right)\right|^{-1} \Lambda_i^{i'}\Lambda_j^{j'}\varepsilon^{ij}$$

$$\mu^{i'j'} = \left|\det\left(\Lambda_i^{i'}\right)\right|^{-1} \Lambda_i^{i'}\Lambda_j^{j'}\mu^{ij}$$

Pendry, J.B.; Schurig, D.; Smith, D. R. (2006). Science 312 (5514): 1780

The Jacobian transformation matrix between the virtual space and the original space

$$\Lambda_{\alpha}^{\alpha'} = \partial x'^{\alpha'}/\partial x^{\alpha}$$

Superconducting-ferromagnetic metamaterials modeling: optimization for a magnetic wormhole device

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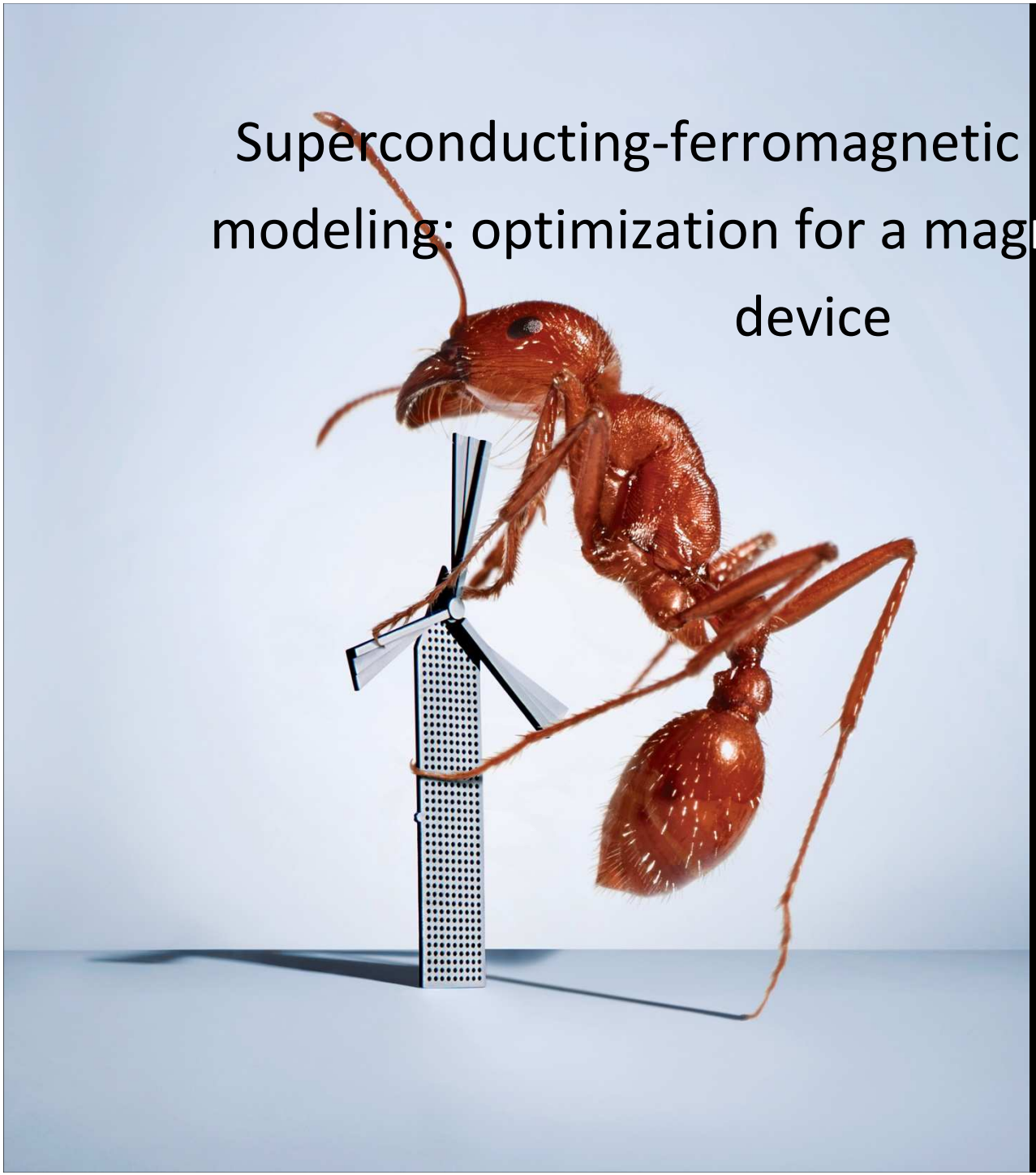
Universitat Autònoma de Barcelona

http://grupsderecerca.uab.cat/superconductivity/



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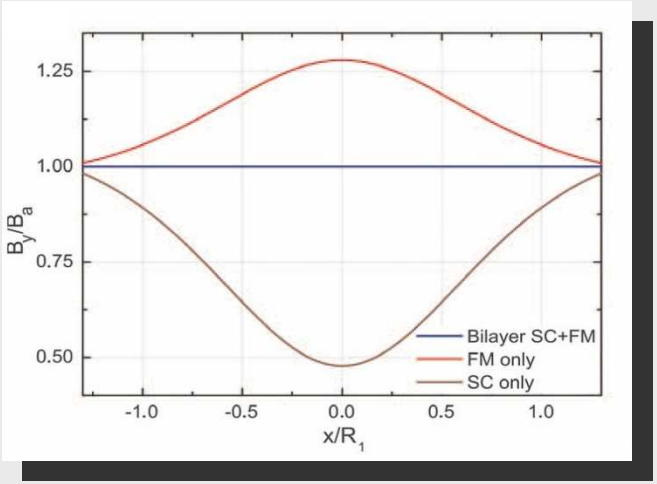
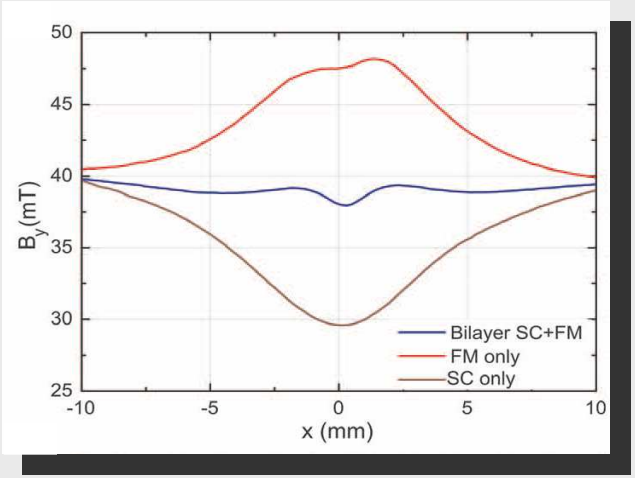
Bologna, June 2016

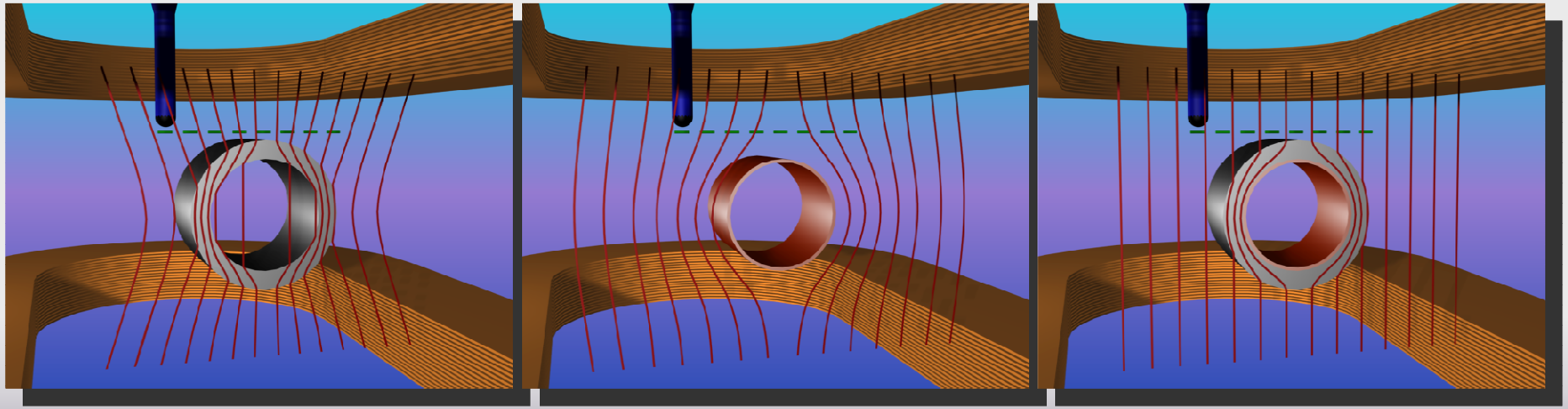
Designing a magnetic wormhole

Analytic (Ideal situation)



Experiment





Gömöry, Solovyov, Souc, Navau, Prat-Camps, Sanchez
Science 335, 1466 (2012)

Introduction

Can we look at the Nature and find some materials and/or tools for helping us?

Introduction

System design (20th century)

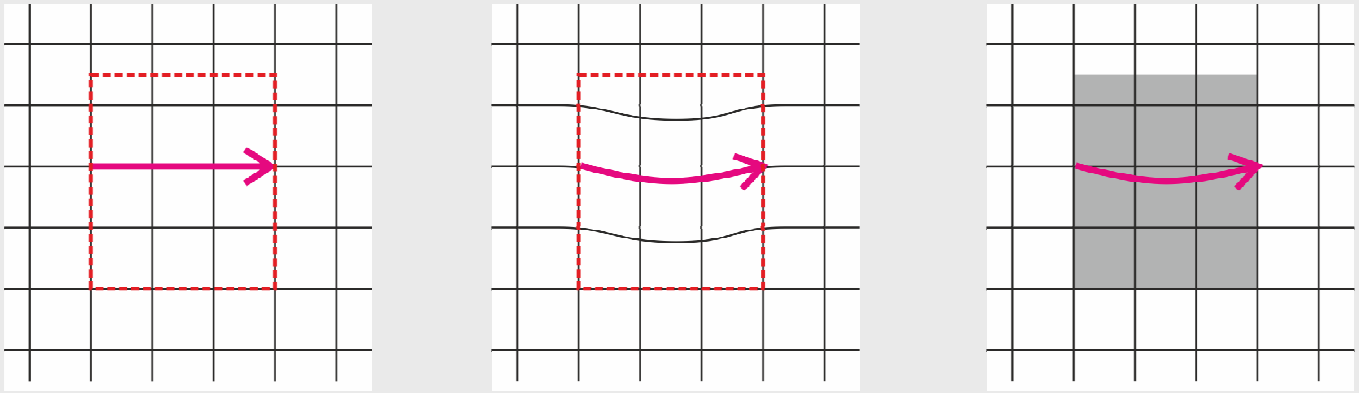
Imagine what you want to do…

Look at the Nature to see what it offers…

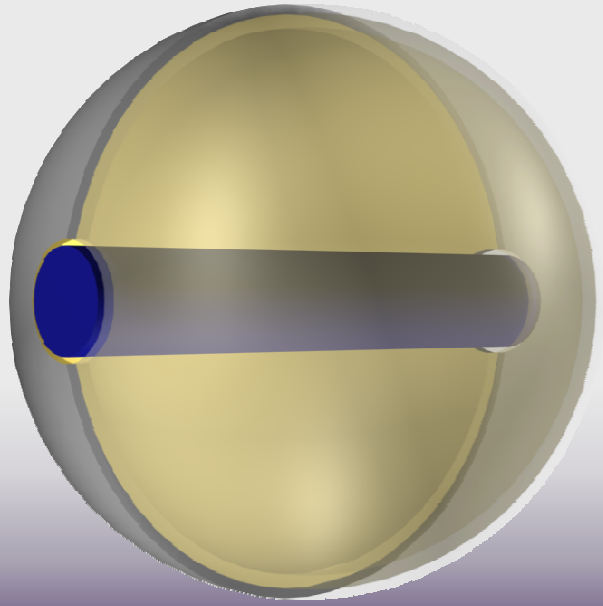
Fabricate the materials you need to our benefit

Introduction. Transformation optics

- Tool to design electromagnetic devices to shape electromagnetic fields in the desired way



Pendry, J.B.; Schurig, D.; Smith, D. R. (2006). Science 312 (5514): 1780
U. Leonhardt, Science 312 (5781): 1777

Designing a magnetic wormhole

Full 3D spherical magnetic cloak (bilayer)