Design of a superconducting magnetic shield closed on both ends for a high-sensitivity particle detector

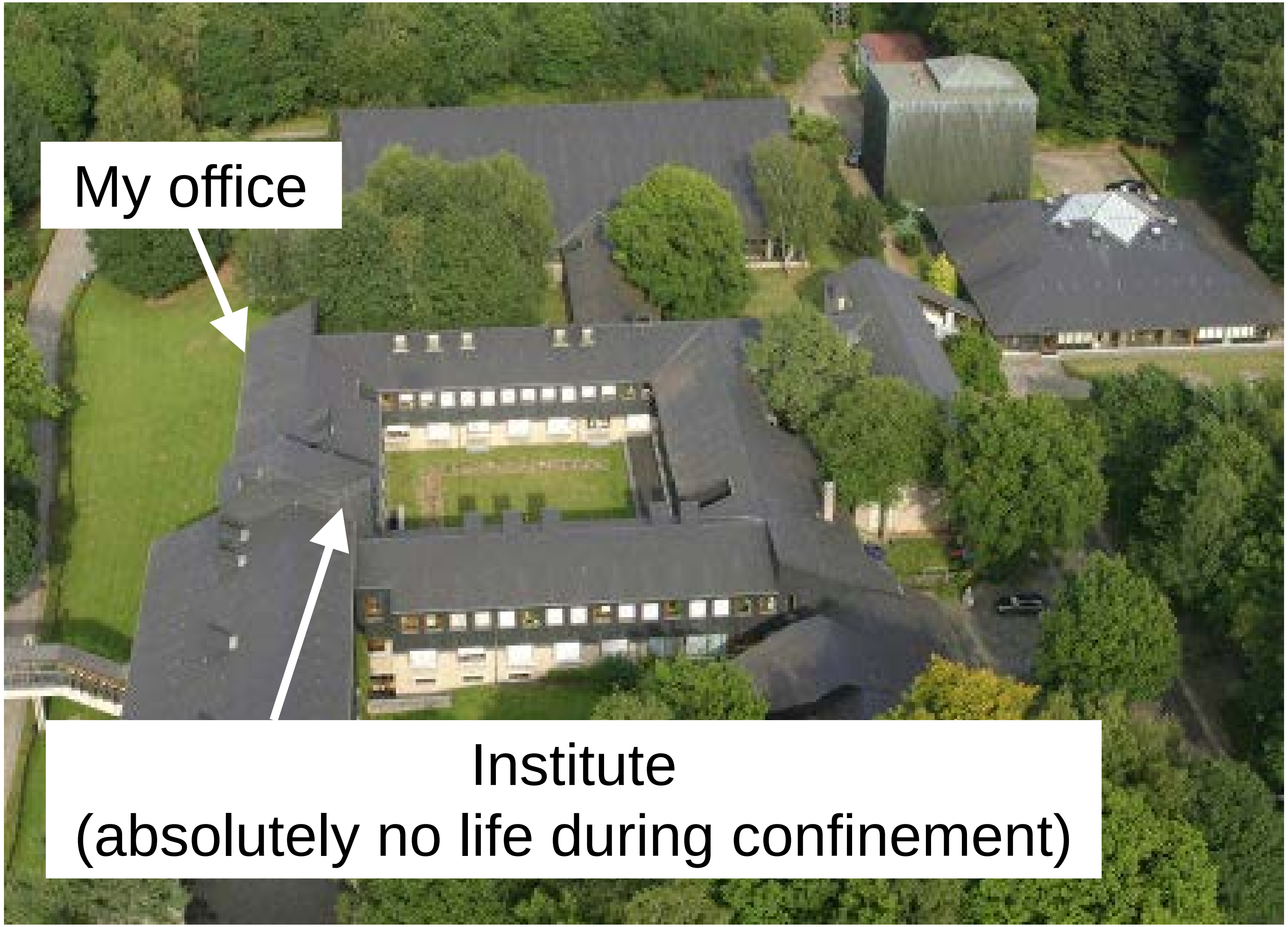
Kevin HOGAN, Philippe VANDERBEMDEN, Benoît VANDERHEYDEN

Montefiore Research Unit, University of Liege, Belgium

Alexey RADOVINSKY, Joe MINERVINI.

Plasma Science and Fusion Center, M.I.T., Cambridge, Massachusets, USA

Montefiore Research Unit, University of Liège, Belgium



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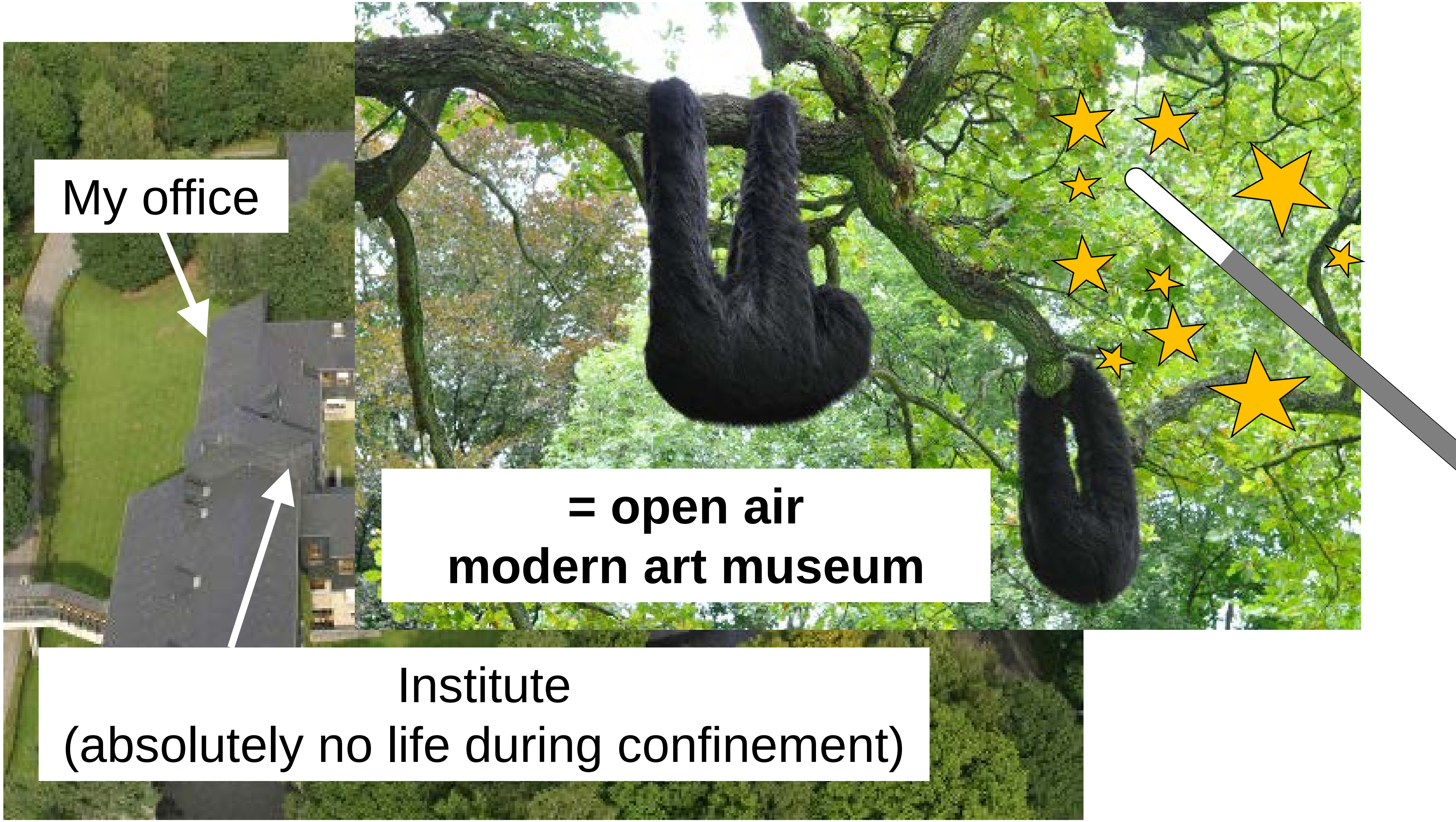
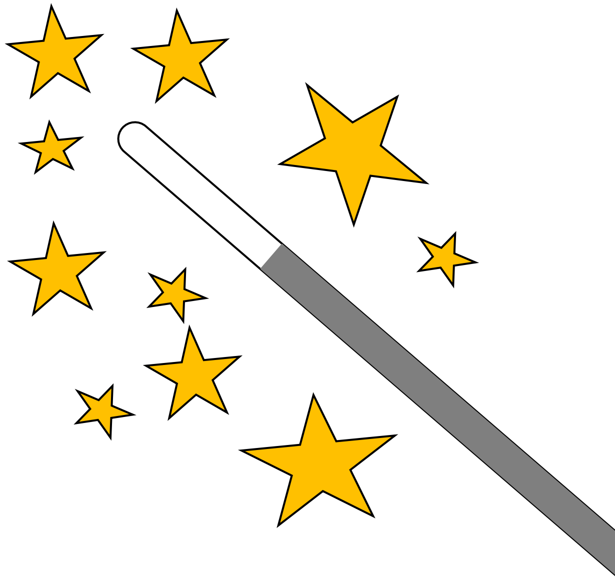


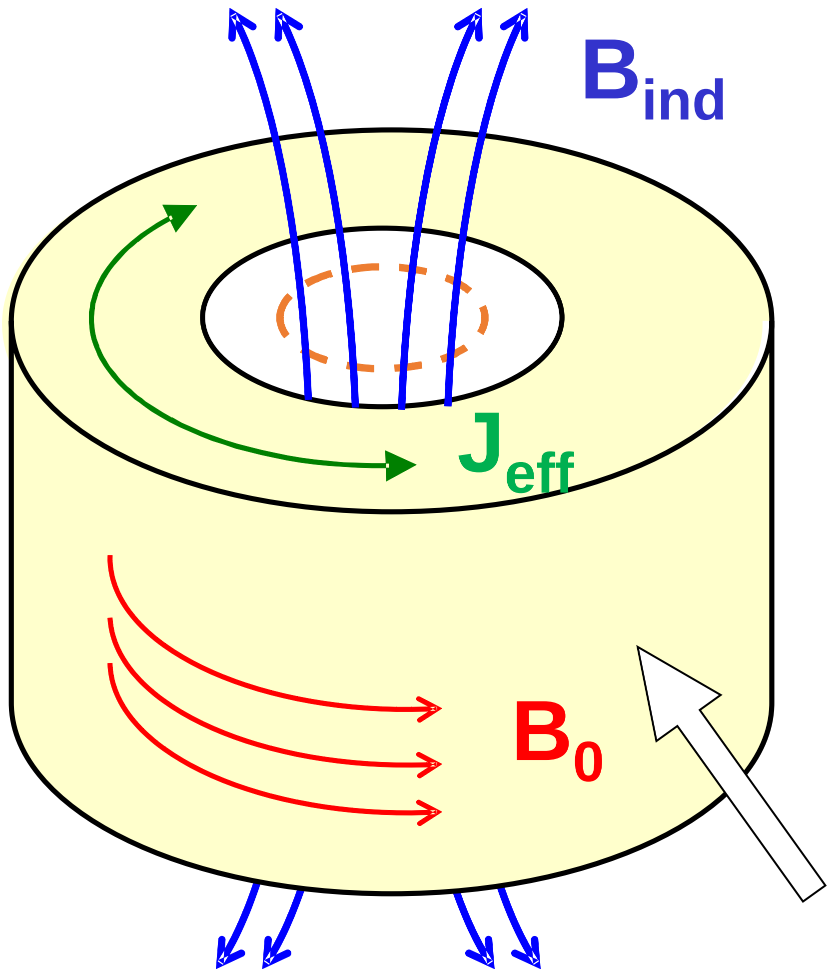
Motivation : The ‘ABRACADABRA’ research project



- In collaboration with the Plasma Science and Fusion Center of the M.I.T.
- The ABRACADABRA project aims at detecting **axions.**
- Axions are **hypothetical elementary particles,** candidates to explain the particle nature of dark matter.
- Experiment based on the principle that axions interact with static magnetic fields (and may change Maxwell’s equations)

__A__ __B__roadband/__R__esonant __A__pproach to __C__osmic __A__xion __D__etection with an __A__mplifying __B__-field __R__ing __A__pparatus

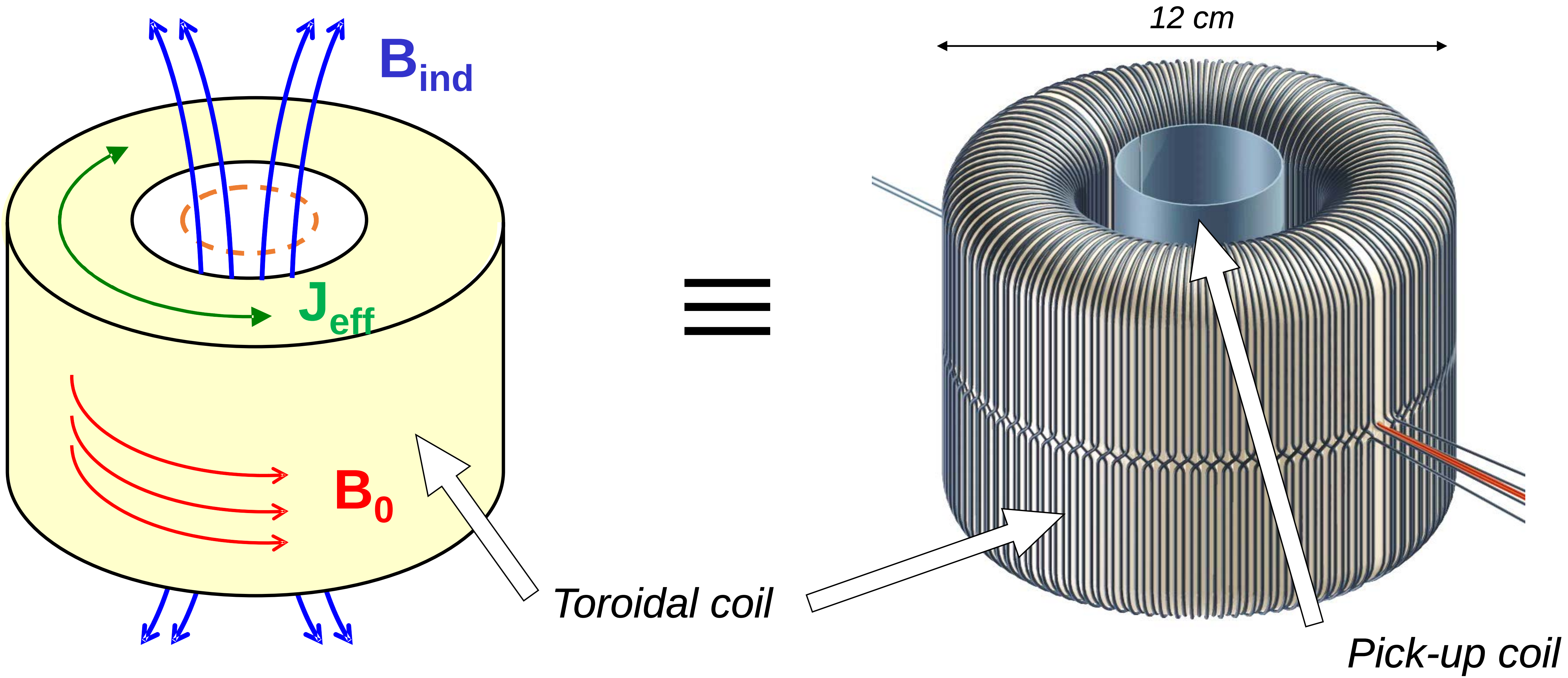
Motivation : The ‘ABRACADABRA’ research project



Toroidal coil

- Generation of a DC azimuthal magnetic field B_0
- The interaction ‘B_0 – axion’ can be treated as an effective **oscillating current** J_{eff} flowing along B_0
- This current generates a **real magnetic field** B_{ind} which can be measured experimentally

Motivation : The ‘ABRACADABRA’ research project



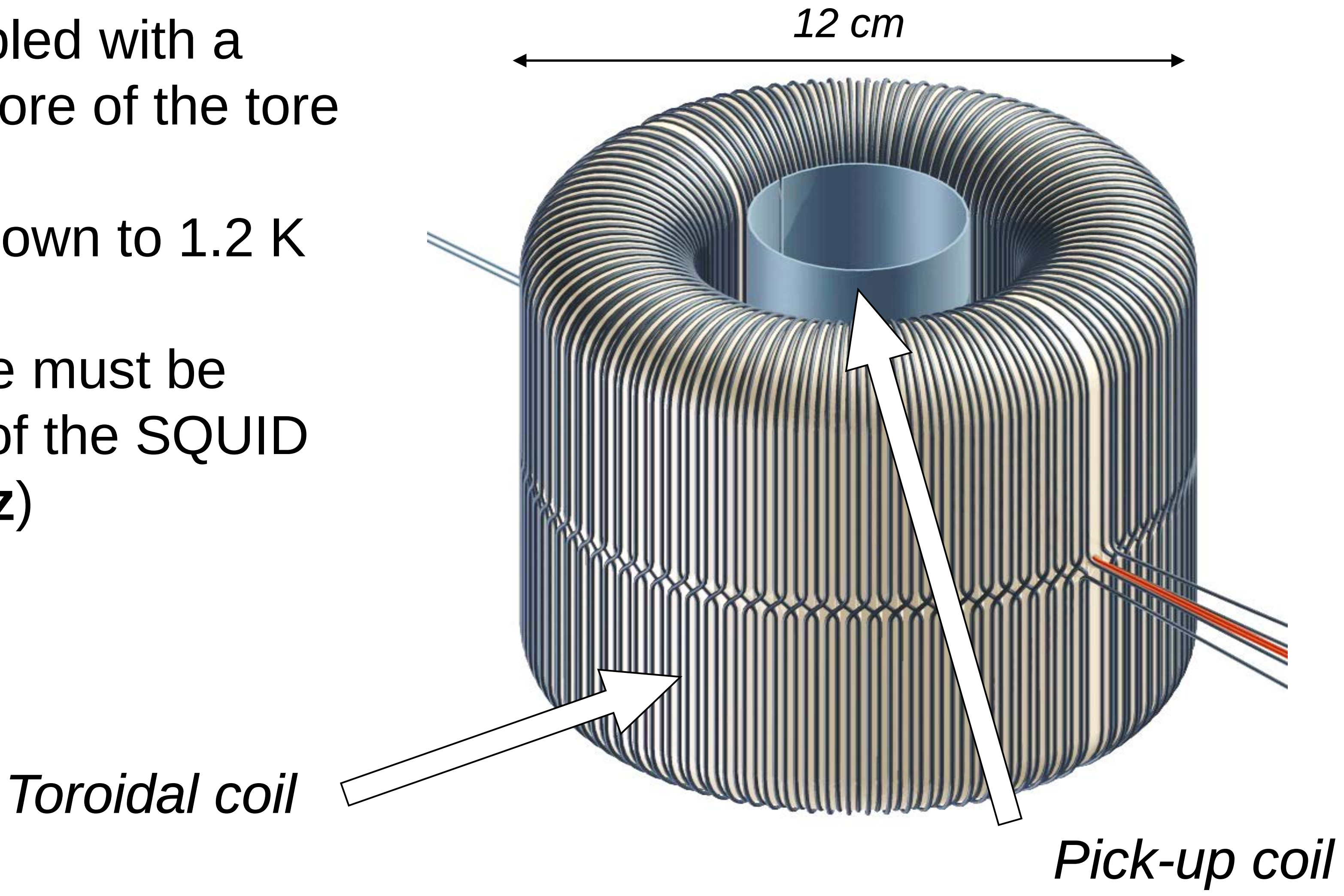
Yo. Kahn *et al.*, *Microwave Cavities and Detectors for Axion Research,* pp 135-142, 2018

Motivation : The ‘ABRACADABRA’ research project

- A pick-up coil inductively coupled with a SQUID is located inside the bore of the tore
- The whole system is cooled down to 1.2 K
- Environmental magnetic noise must be below the current shot noise of the SQUID (i.e. **0.01 fT/ √Hz for *f* > 50 Hz**)

⇩

Efficient magnetic shield to be designed



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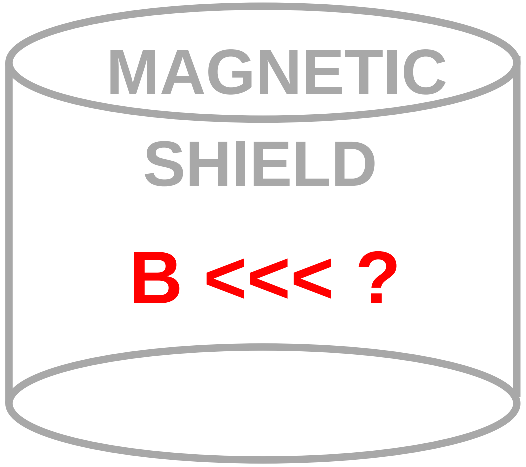
Questions of this work



- Magnetic shield closed on both ends, aspect ratio ~ 1
- Conventional ferromagnetic material should be avoided
- Only **Type-I superconductors** can be considered
- Shielding ensured by **macroscopic current loops**

✓ **What is the most efficient geometry of the shield ?**

- ‘OPERA’ modelling software : Linear *E-J* relationship
- ‘ELEKTRA’ module for analysis of eddy currents
- Type-I superconductor ~ conductor with $\boldsymbol{\sigma = 10^{30}}$ **S/m**

✓ **What are the modelling possibilities of ‘OPERA’ ?**

Methodology

1

- Study magnetic shields of well-known, axisymmetric geometries
- Compare :

Analytical $B(z)$	OPERA Ohm, $\sigma = 10^{30}$ S/m	GetDP [2D] London Equations

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2

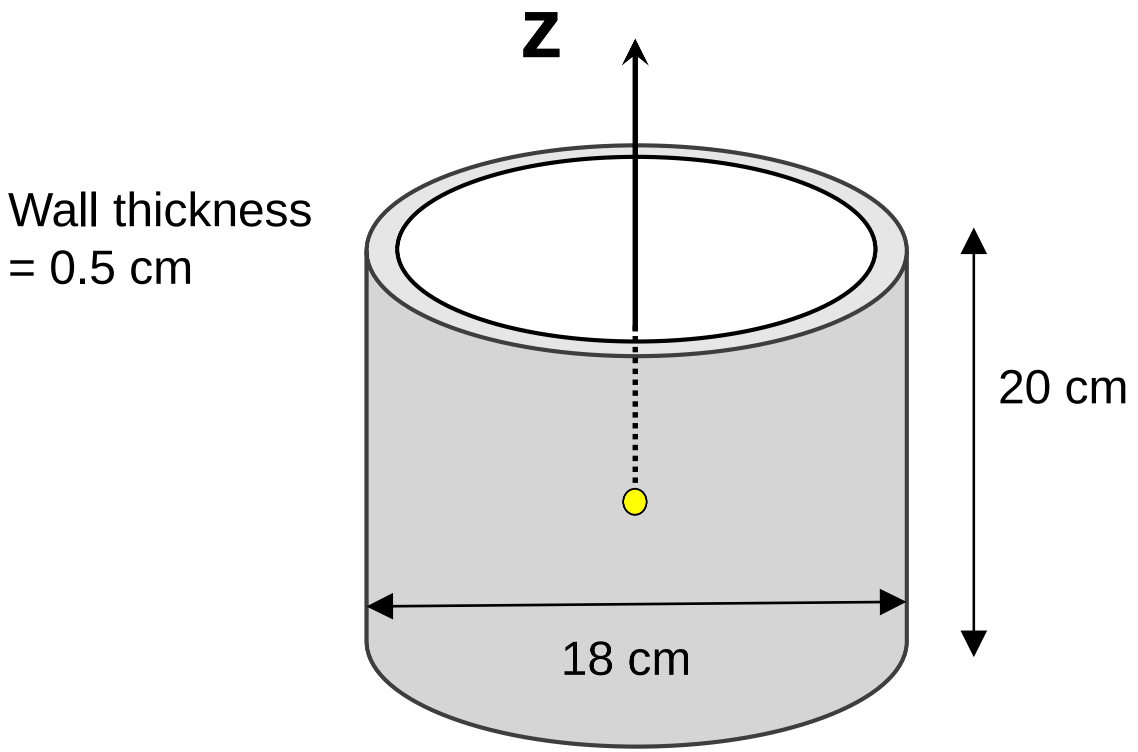
- Investigate magnetic shields of various closed geometries adapted to the experiment

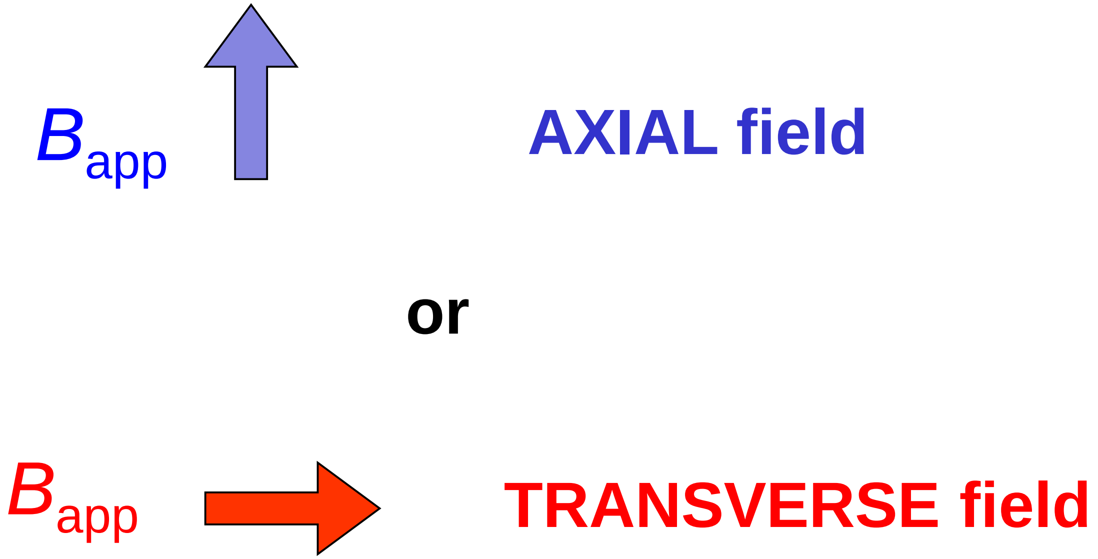
$B_{app} = 1$ mT ⇨ B_{in} ⇨ $SF = \frac{B_{app}}{B_{in}}$

J. R. Claycomb and J. H. Miller Jr., *Rev. Sci. Instrum. vol. 70, pp. 4562-4598* (1999).
GetDP: A General Environment for the Treatment of Discrete Problems, [Online]. *http://getdep.info*

Shields of known geometry

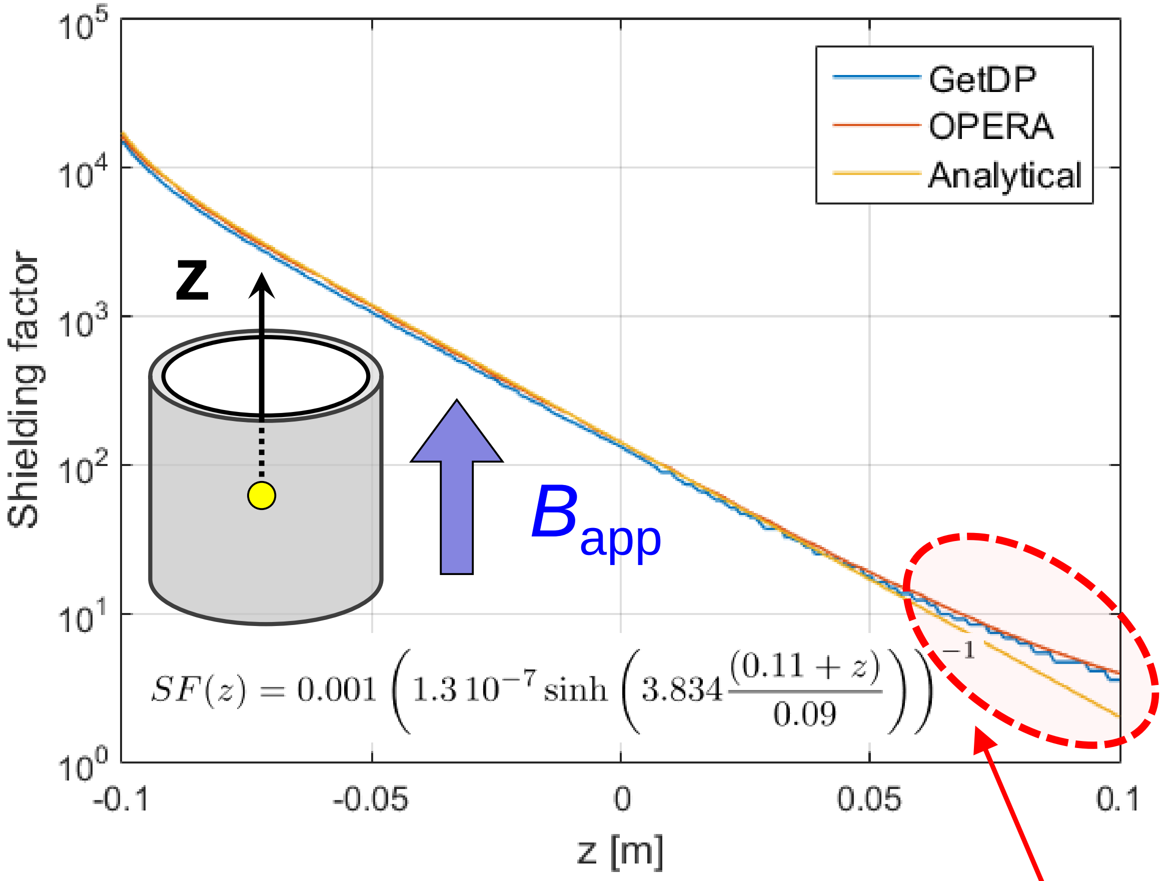
Semi-closed tube with aspect ratio ~ 1

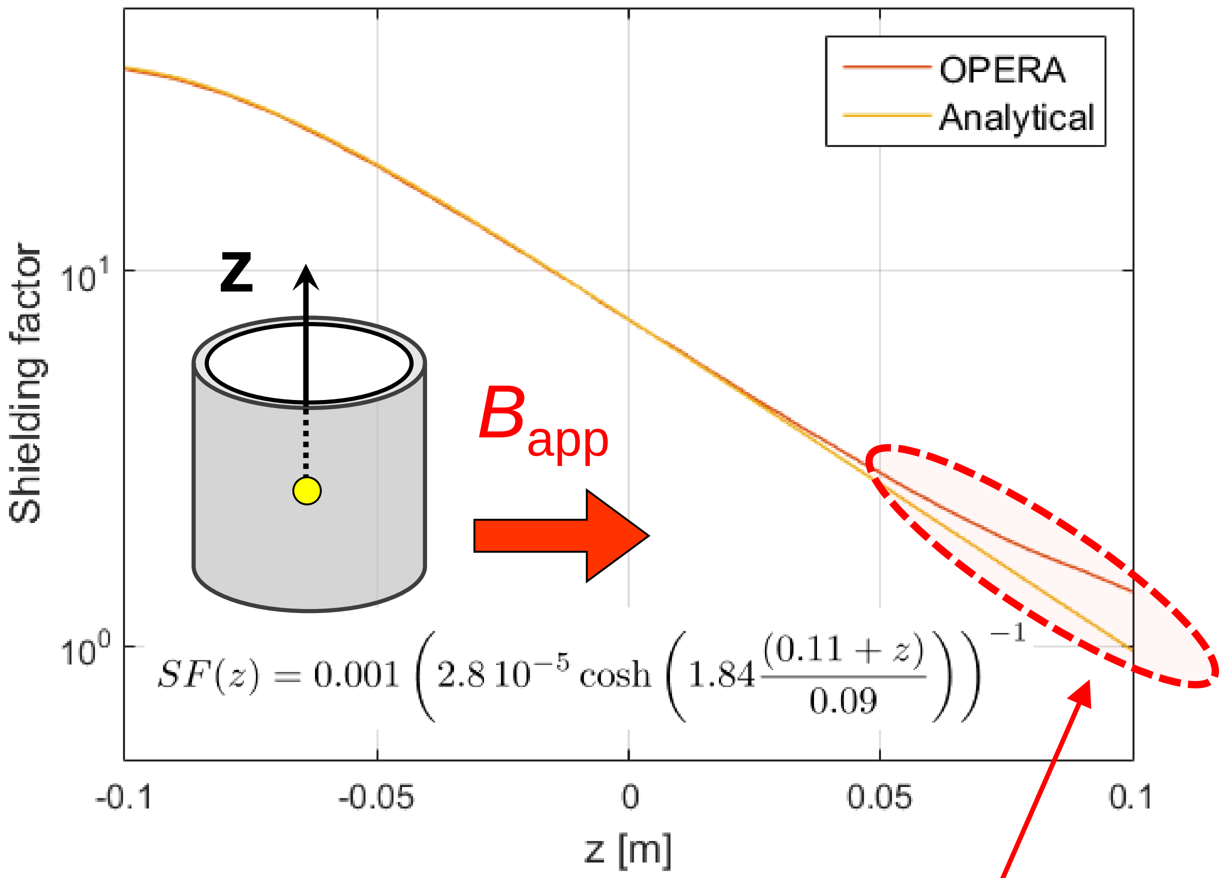




1

Shields of known geometry

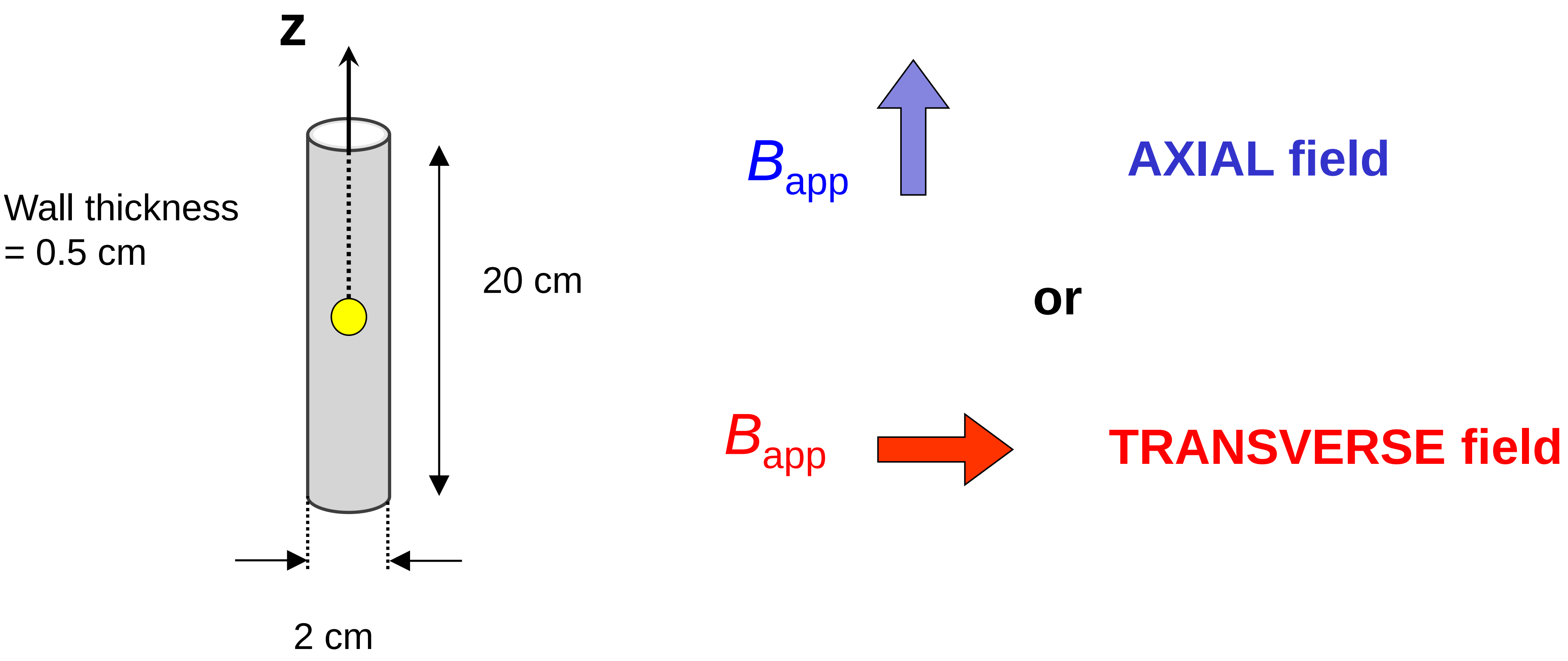




Analytical expressions are valid deep inside the tube (SF >> 1)

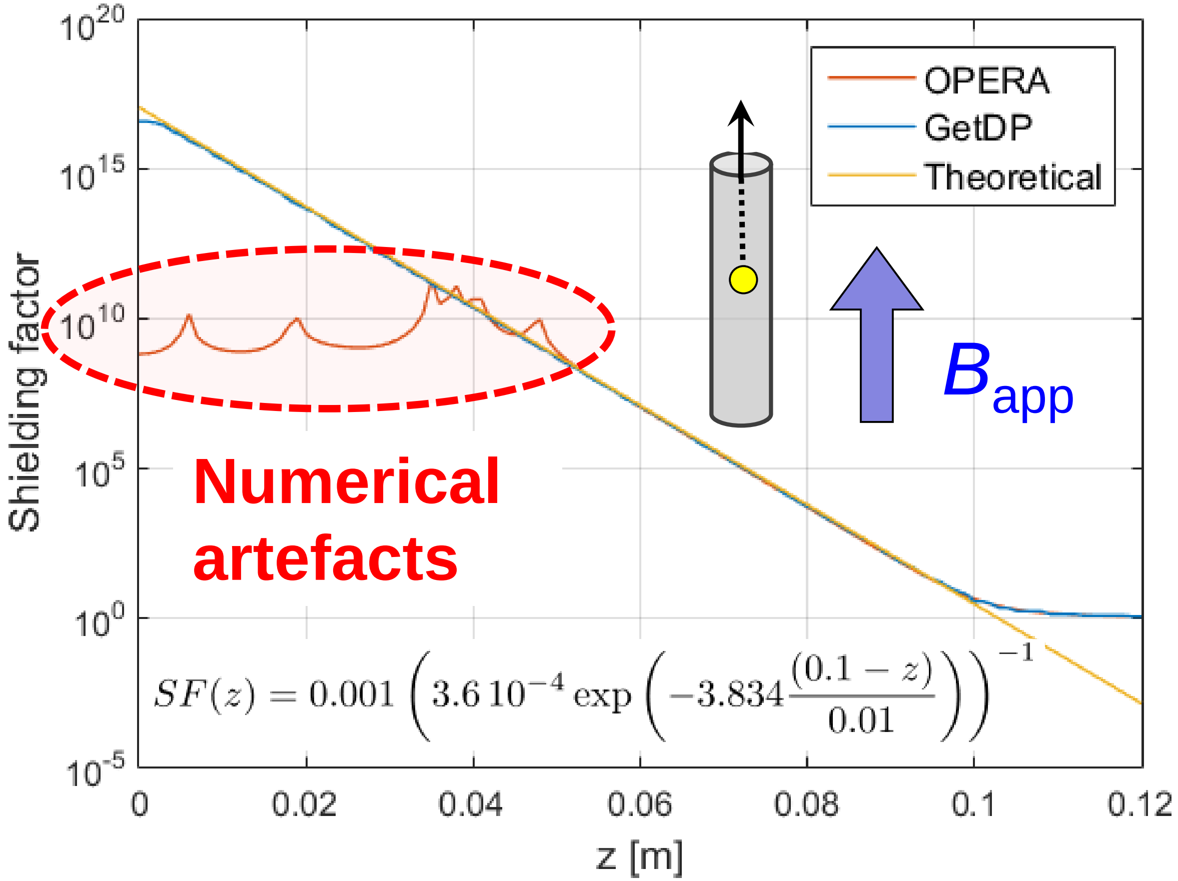
Shields of known geometry

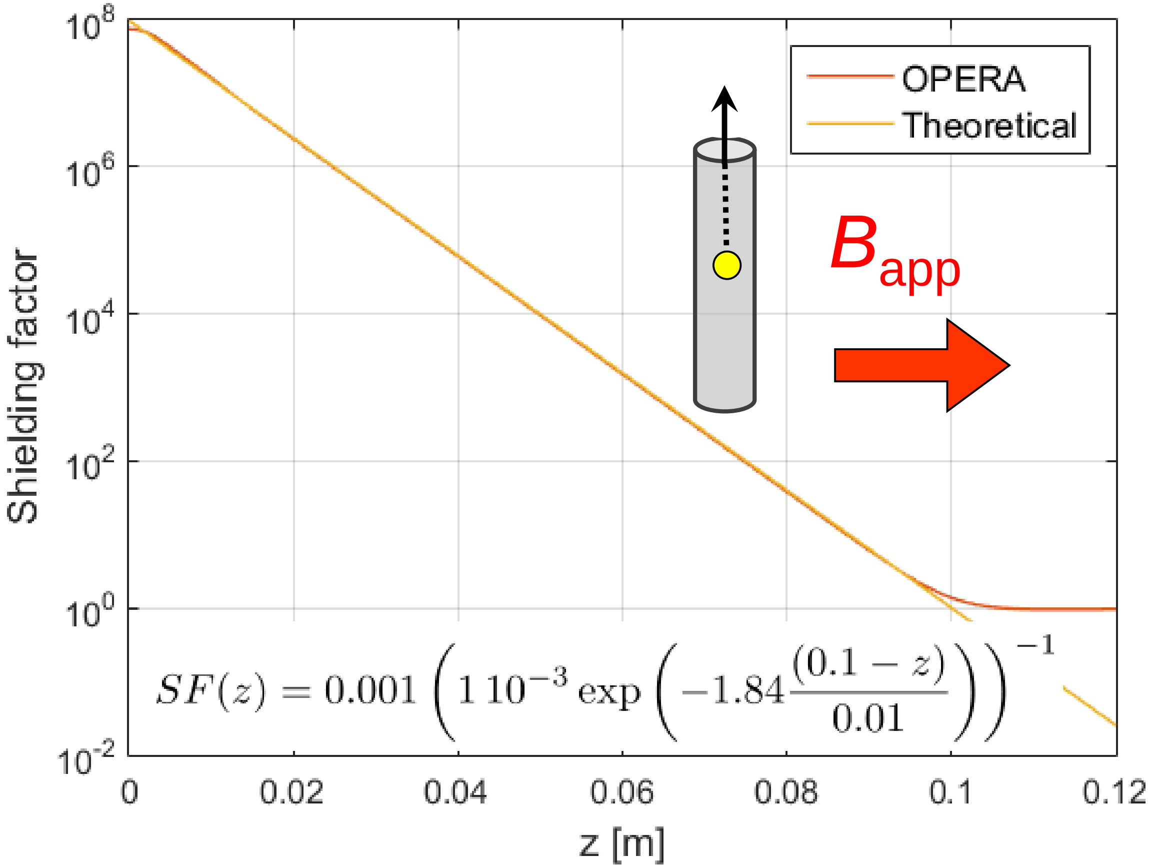
Open tube with aspect ratio ~ 10



Shields of known geometry

1

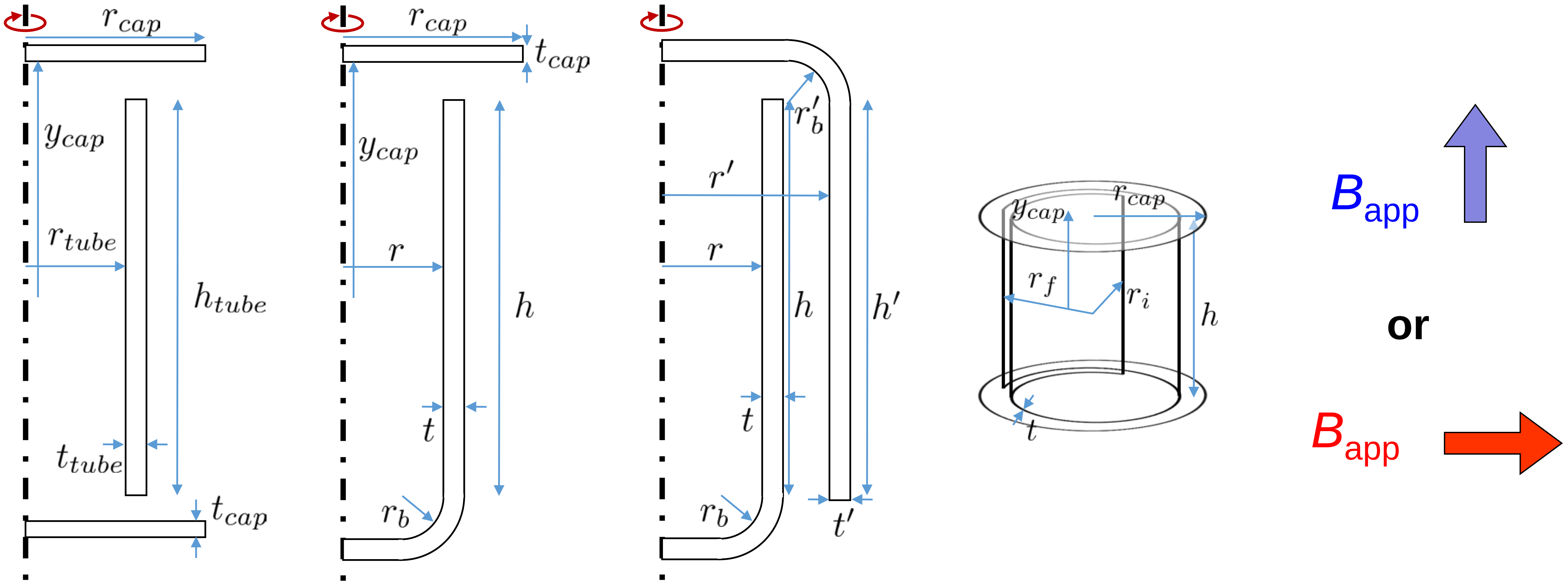




- OPERA and GetDP results are coherent with analytical results.
- OPERA should not be used for handling SF > 10^8 in this analysis

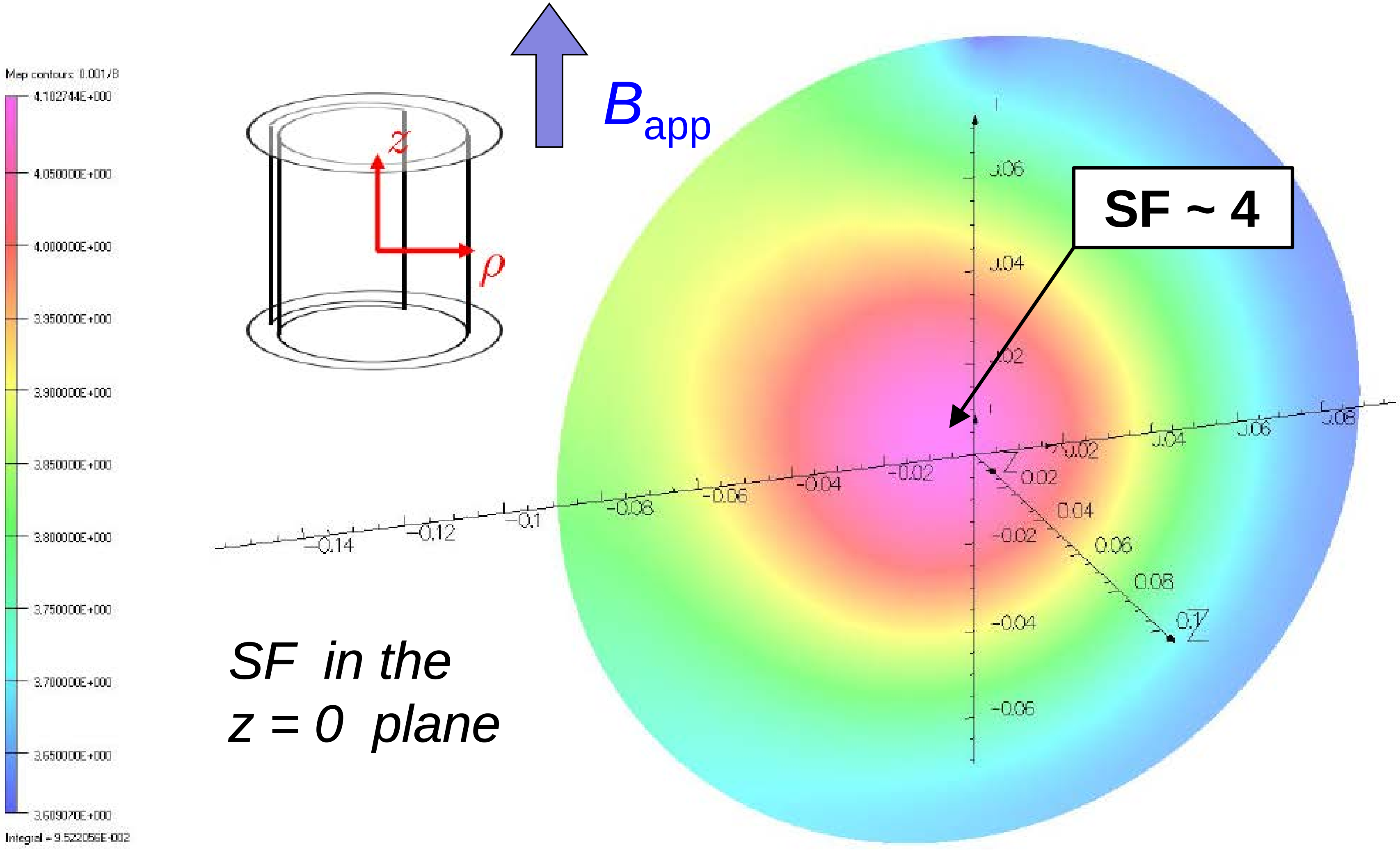
2 Shields closed on both ends for the application

OPEN TUBE WITH 2 CAPS	CLOSED TUBE WITH 1 CAP	2 CLOSED TUBES HEAD-TO-FOOT	SWISS-ROLL + 2 CAPS



(1) (2) (3) (4)

2 Superconducting swiss-roll with 2 caps



SF in the z = 0 plane

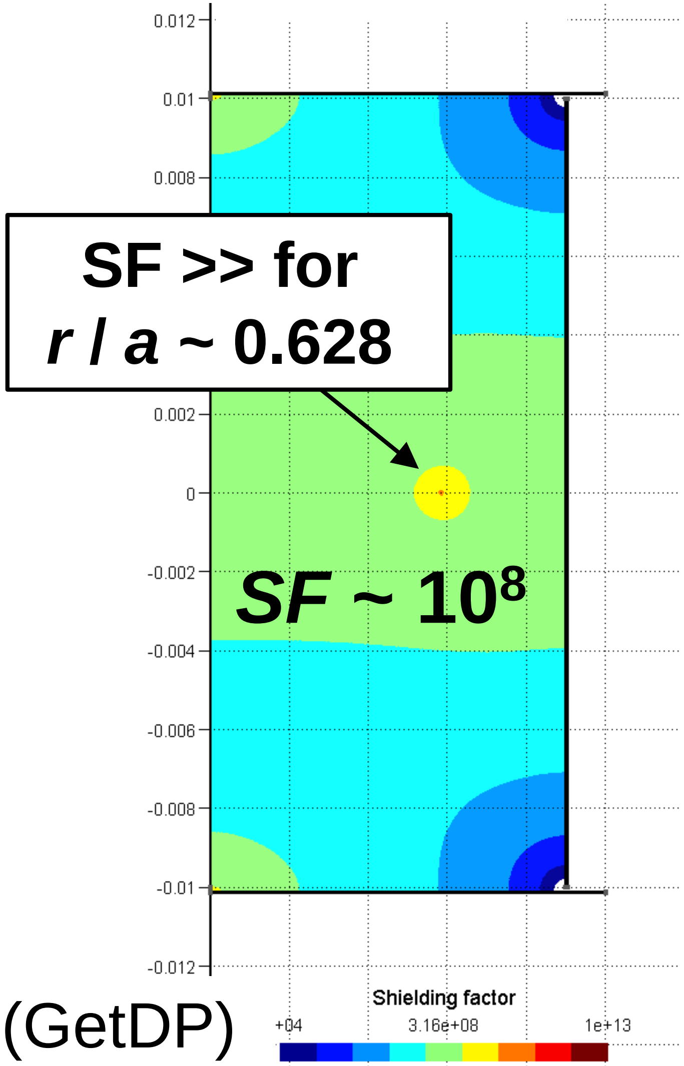
(OPERA)

- SF **too low** (≤ 4.1)
- The swiss roll **shields itself**
- Shielding mainly provided **by the caps**

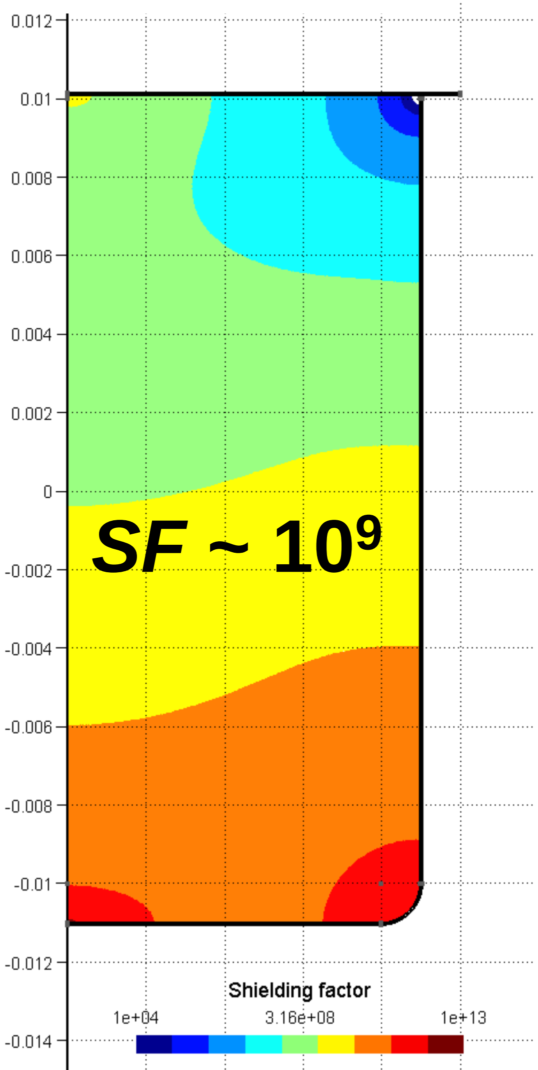
2

Shields closed on both ends : axial field

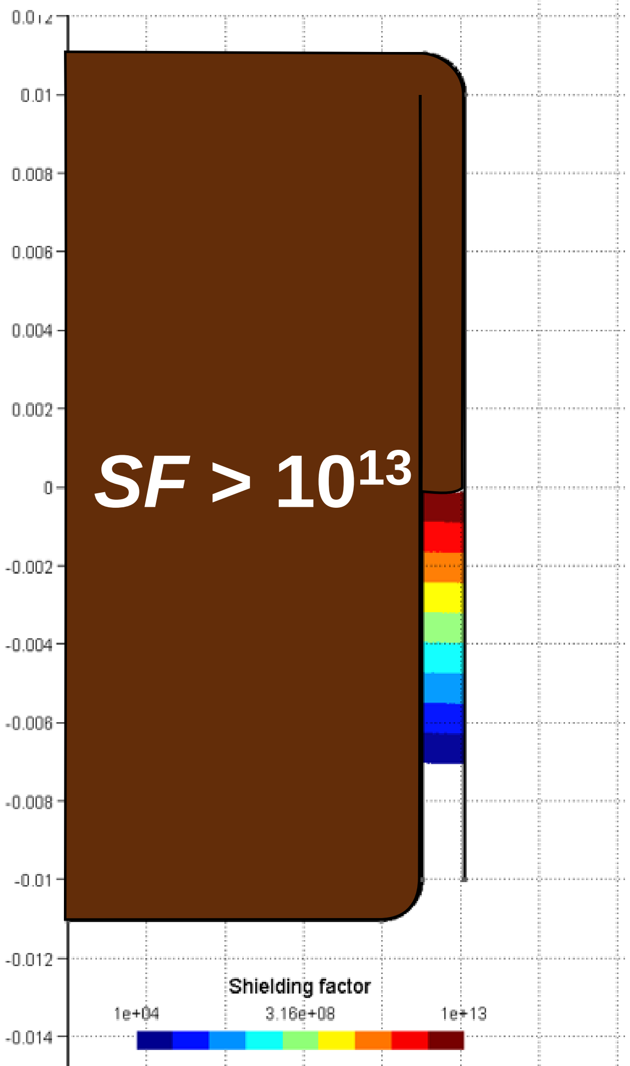
OPEN TUBE WITH 2 CAPS



CLOSED TUBE WITH 1 CAP



2 CLOSED TUBES HEAD-TO-FOOT



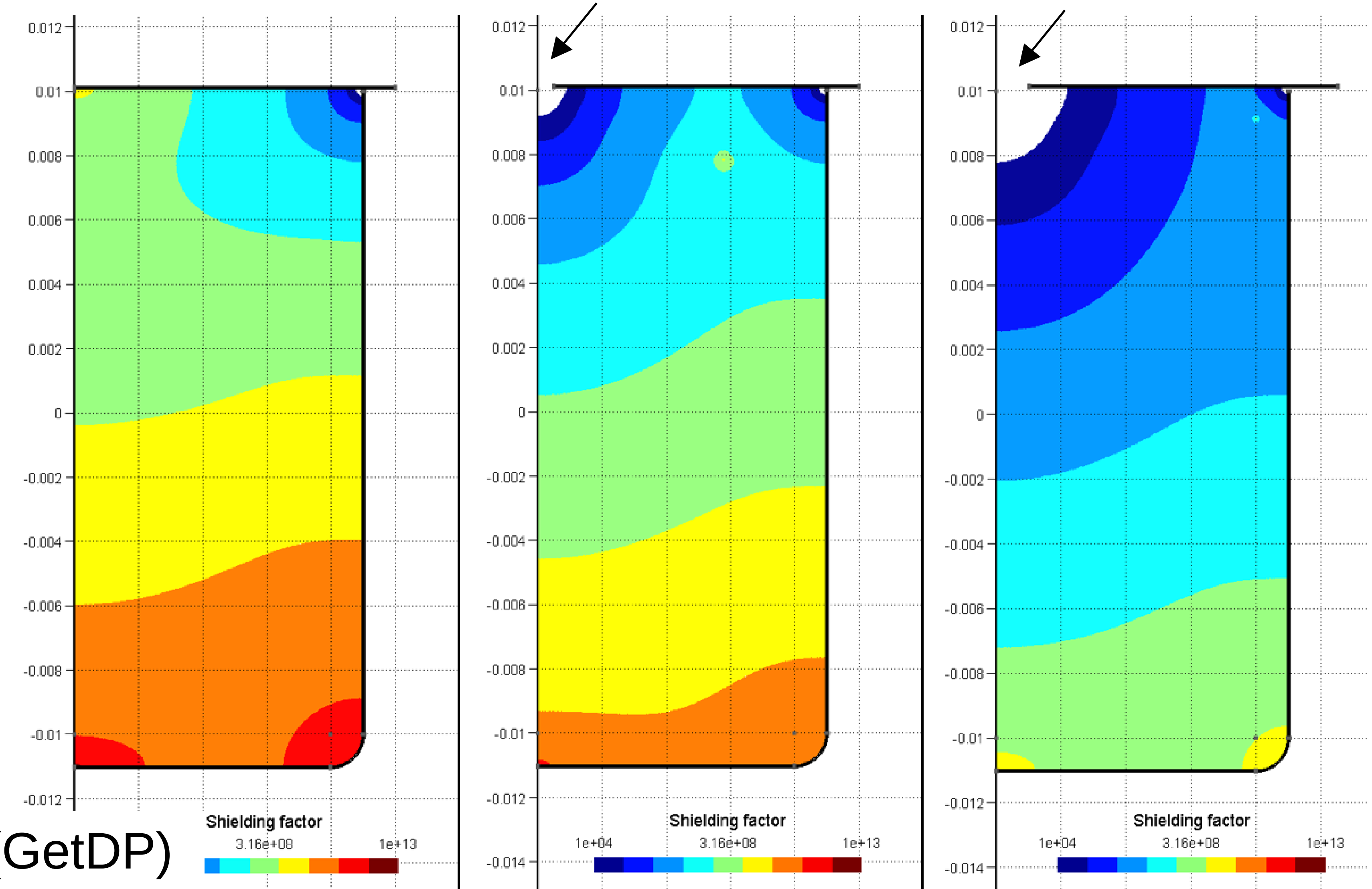
B_{app}

- All OK but the first two have **no feedthrough for wires**

(GetDP)

2 Closed tube with one cap : influence of a hole

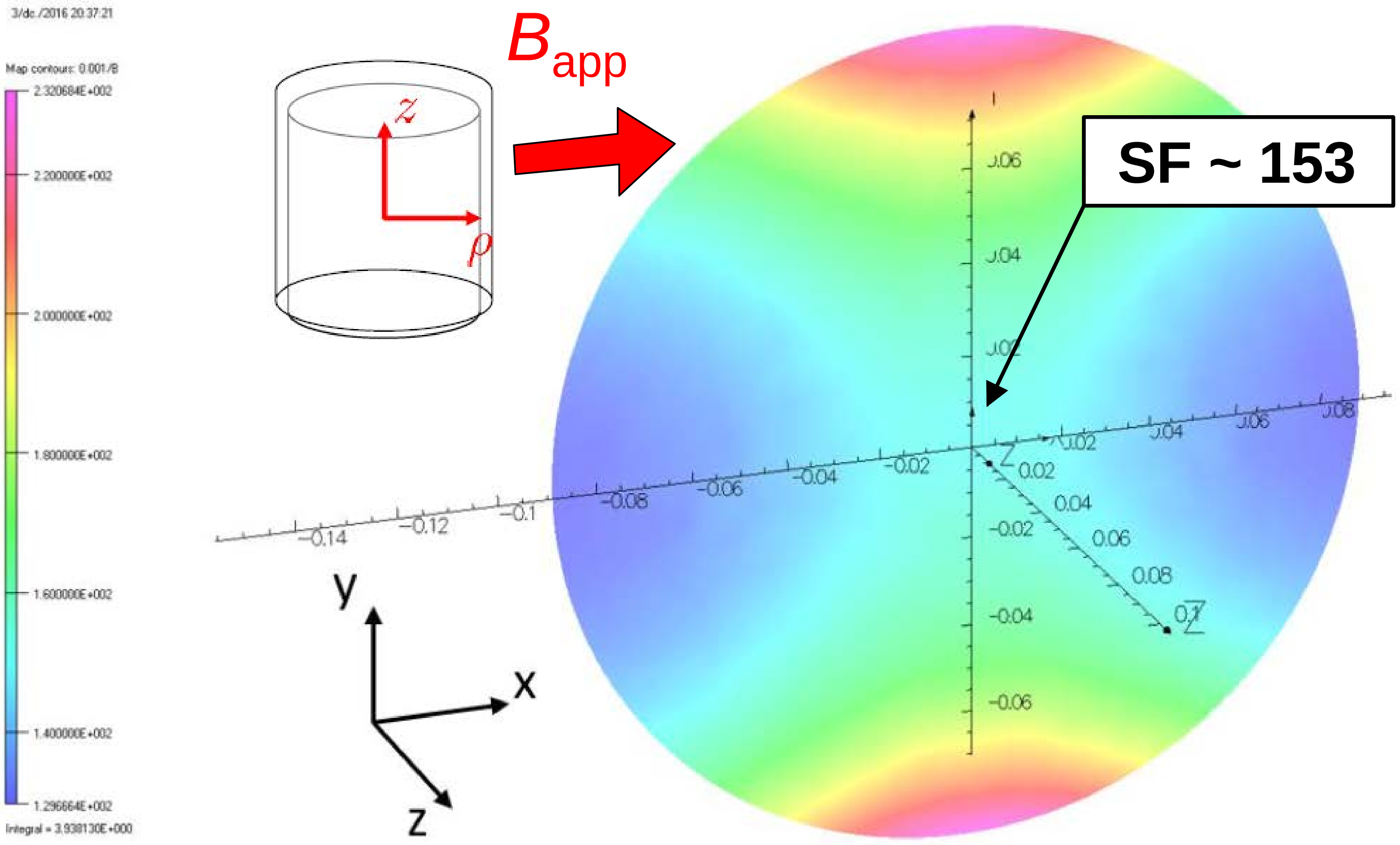
NO HOLE | 10 mm HOLE | 20 mm HOLE



- Hole → decrease of the shielding factor by **1 or 2 orders of magnitude**

(GetDP)

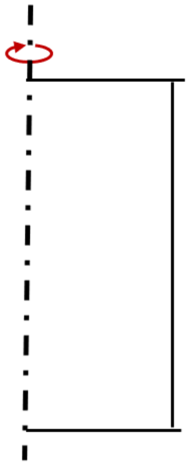
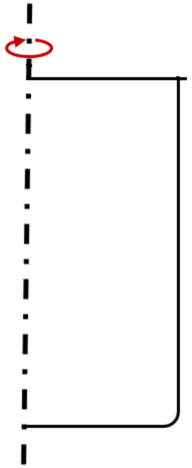
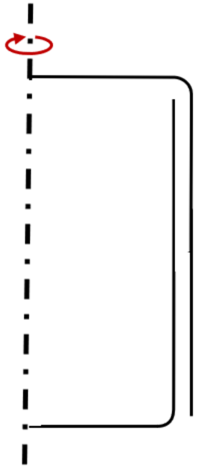
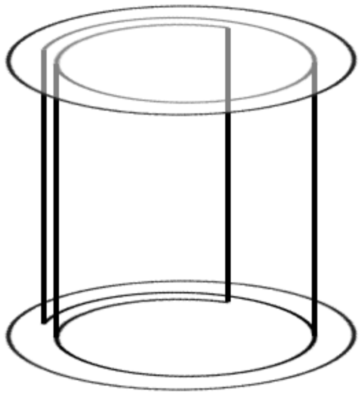
2 closed tubes head-to-foot : Transverse field



- Much smaller SF than in the axial field,
- Configuration with the **highest SF anyway**

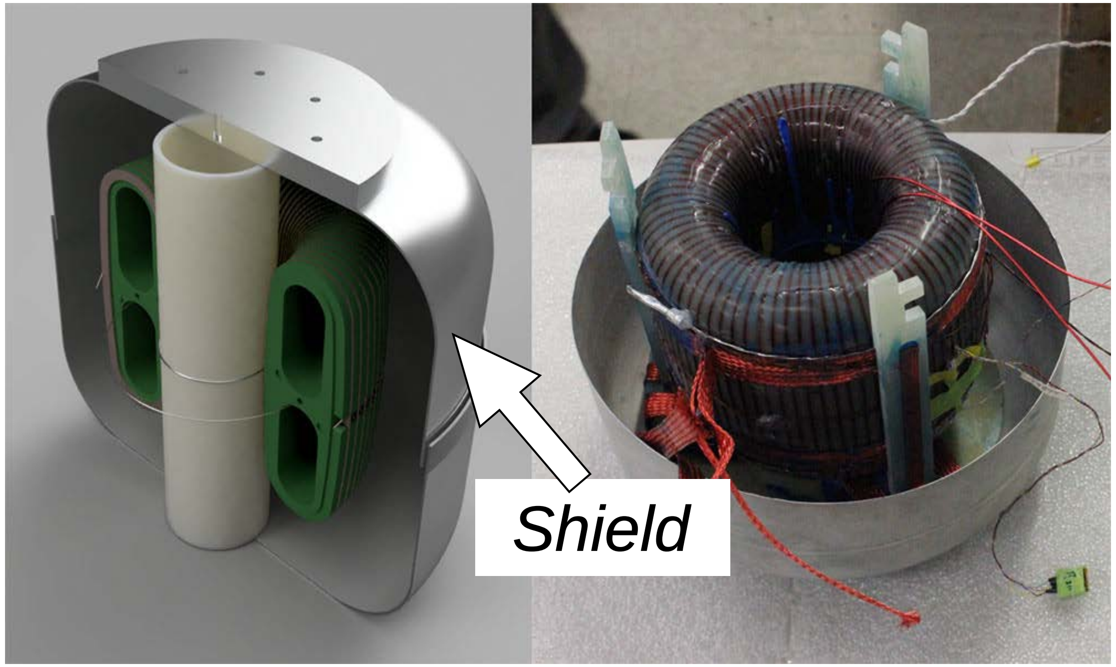
(OPERA) *SF in the z = 0 plane*

Summary and conclusions

	OPEN TUBE WITH 2 CAPS	CLOSED TUBE WITH 1 CAP	2 CLOSED TUBES HEAD-TO-FOOT	SWISS-ROLL + 2 CAPS
				
B_{app} ↑	$> 10^8$	$> 10^8$	$> 10^{13}$	~ 4
B_{app} →	~ 13	~ 18	~ 153	~ 8
	✗	✗	✓	✗

‘ABRACADABRA’ : final prototype

- Shield made of 2 closed tubes, spin-coated with tin (T_c = 3.72 K), welded shut
- The experiments demonstrated the capabilities of thebroadband axion search ABRACADABRA-10 cm
- No evidence of an axion signal in the mass range $3.1 \times 10^{-10} – 8.3 \times 10^{-9}$ eV



$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

J. L. Ouellet et al. *Phys. Rev. Lett*. 122, 121802 (2019)

Acknowledgements

Fonds de la recherche scientifique (FRS-FNRS)
Fonds pour la formation à la recherche dans l'industrie et l'agriculture (FRIA), Belgium

University of Liege
Belgium

Kevin HOGAN
Benoît VANDERHEYDEN

Plasma Science and Fusion Center
Massachusetts Institute of Technology

Alexey RADOVINSKY
Joe MINERVINI
Makoto TAKAYASU