

DE LA RECHERCHE À L'INDUSTRIE



FuSuMaTech  
Workshop  
December 14th, 2021

[www.cea.fr](http://www.cea.fr)

# Prospective of superconductive magnets for medical applications

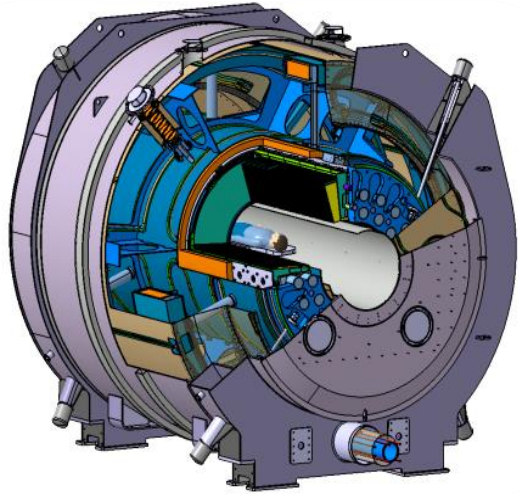
D. Le Bihan

NeuroSpin Founding Director  
Iseult Project former Strategic Pilot



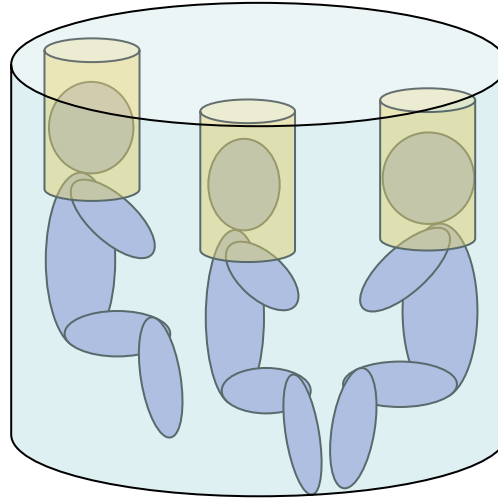
Ad hoc Working Group  
on **F**uture **S**uperconducting  
**M**agnet **T**echnology

# Prospective of superconductive magnets for medical applications



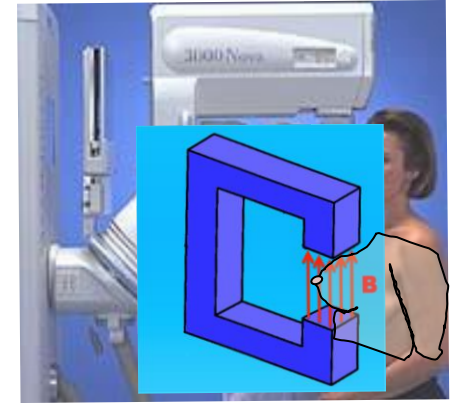
UHF (>14T) brain MRI

*High Bo*



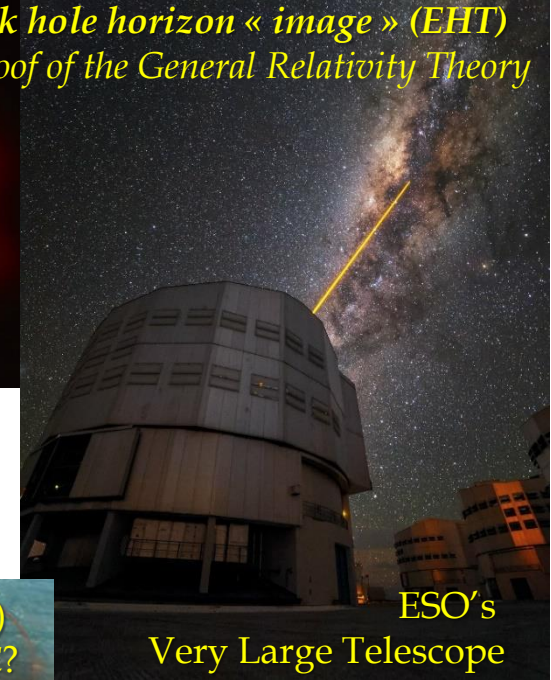
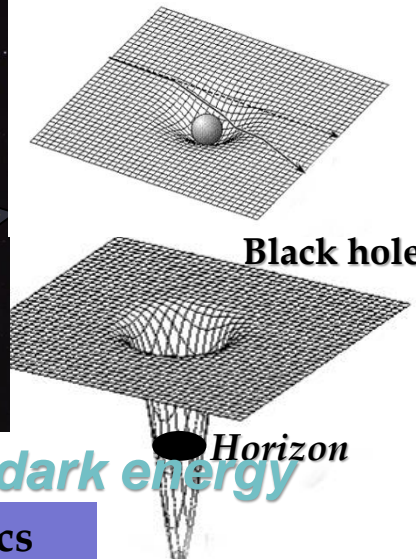
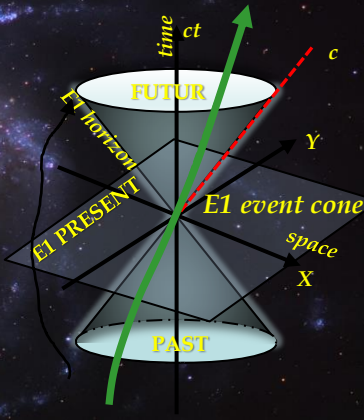
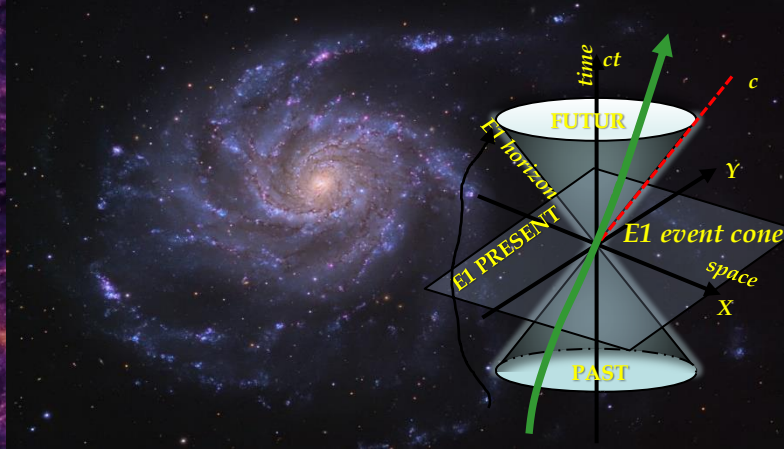
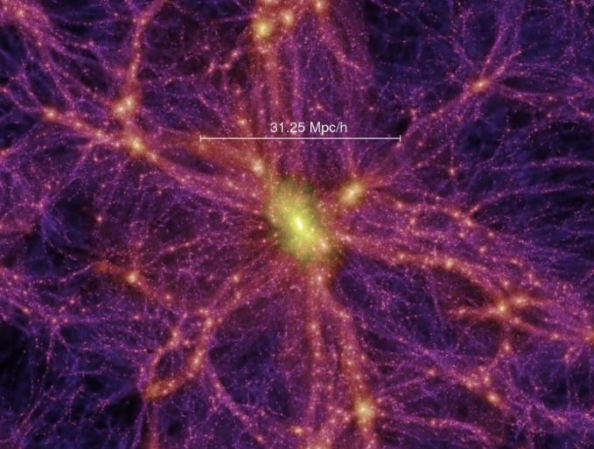
Social fMRI

*Large size*



MammoMRI

*Small & Cheap*



Our **universe**: Stars, galaxies – Matter, dark matter, dark energy

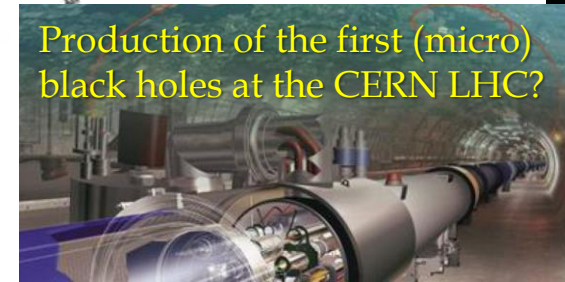
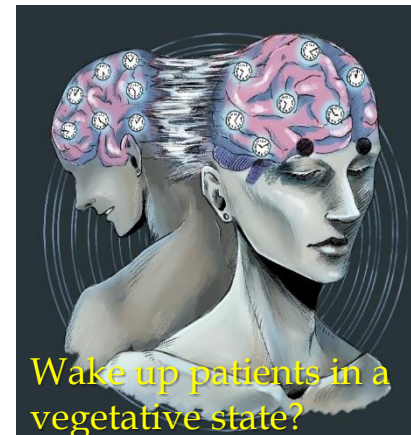
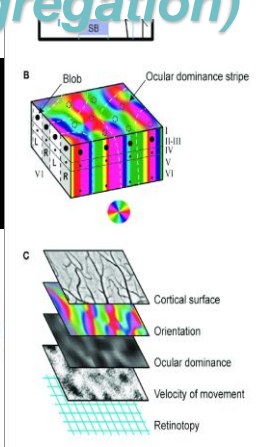
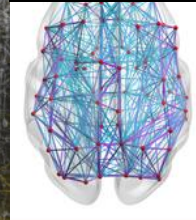
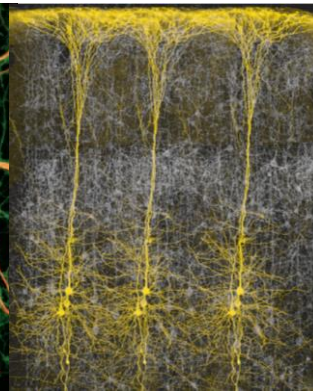
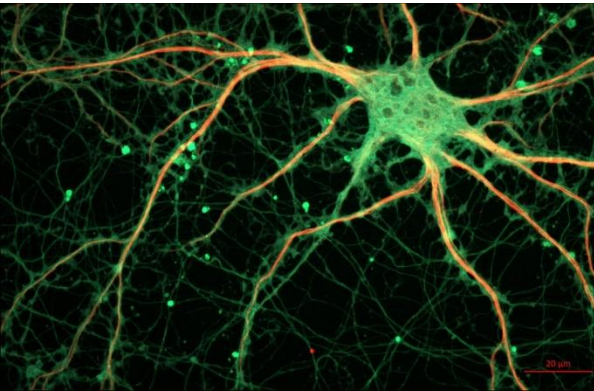
Electromagnetism, General relativity *space-time*, quantum mechanics  
 Universe expansion, black holes, big bang, gravitational waves

***ΛCDM model***

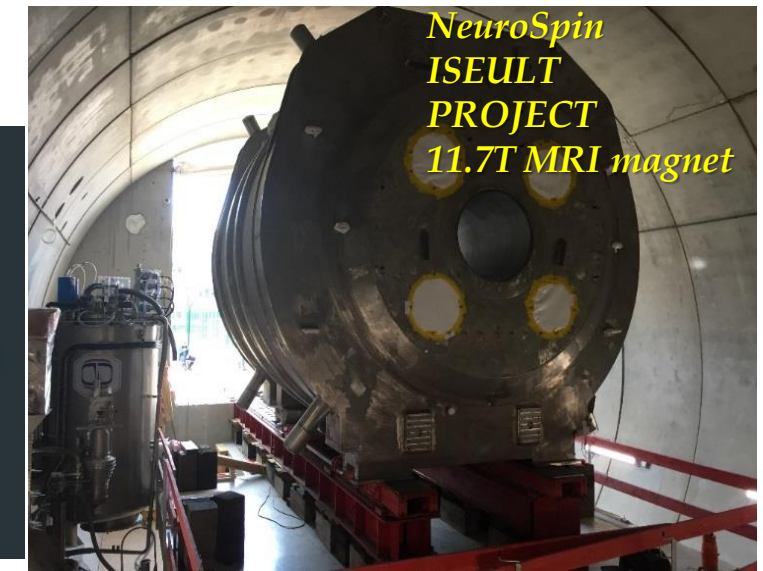
Brain functional microstructure & dynamics, **connectome** *space-time*  
 Consciousness, social interactions, mind disorders

***Neural code?***

Our **brain**: Neurons, layers & columns – **Gray matter** (*spatial segregation*), **white matter** (*temporal segregation*)



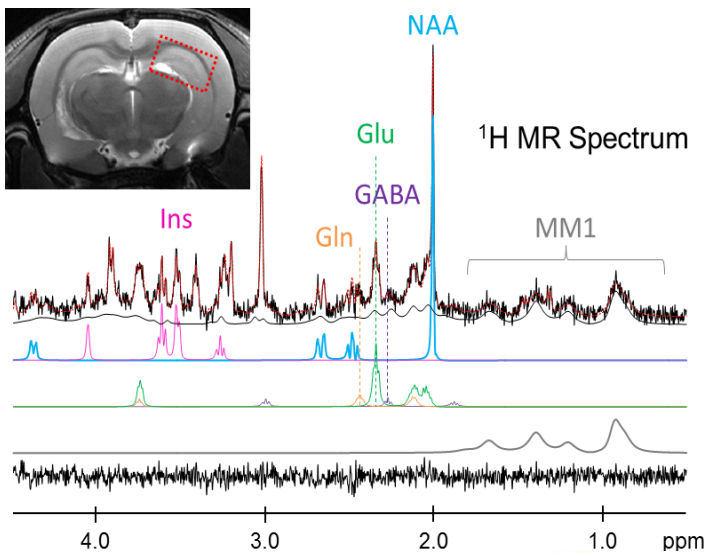
Production of the first (micro) black holes at the CERN LHC?



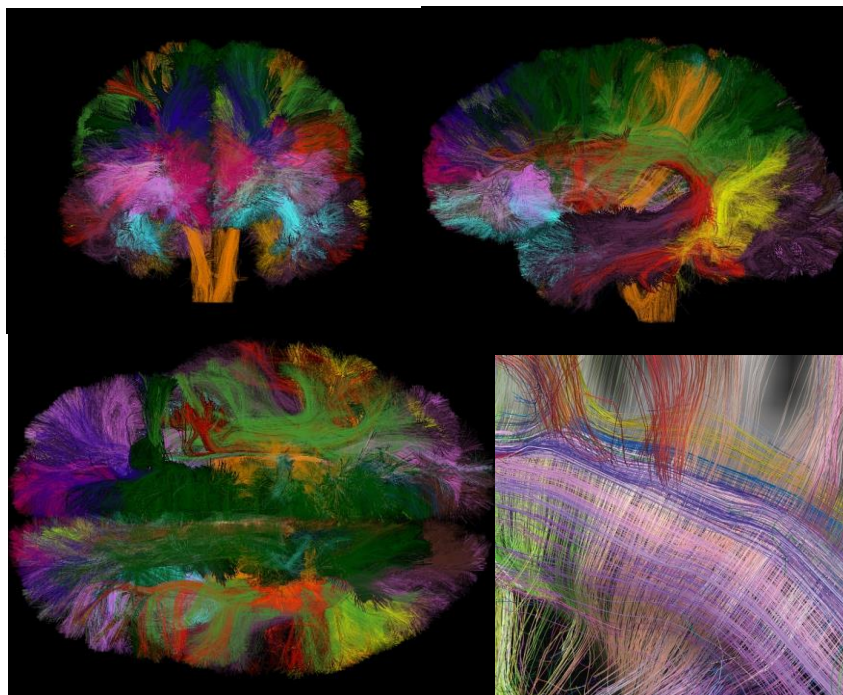
# WHAT CAN WE SEE WITH (human) NEUROIMAGING?

# Water (proton) MRI

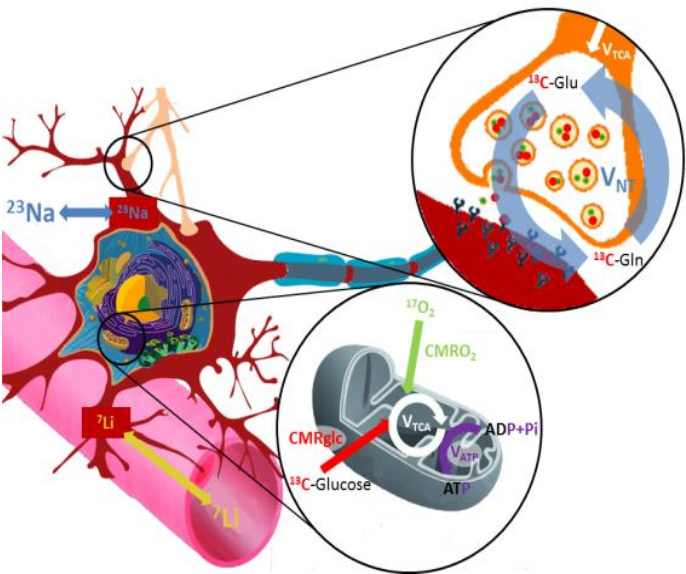
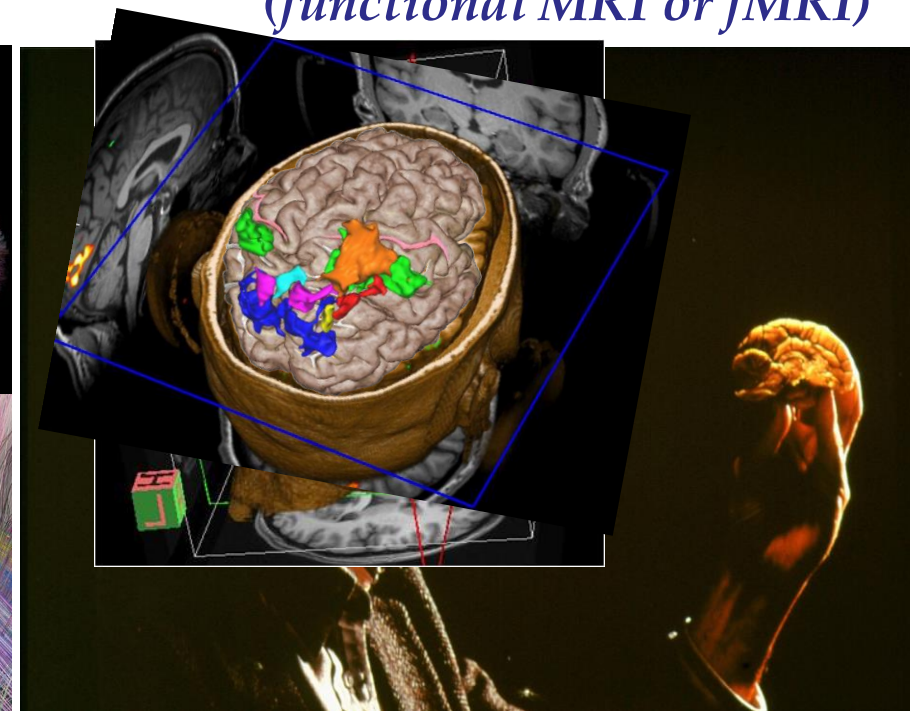
## Brain chemistry metabolism & neurotransmission



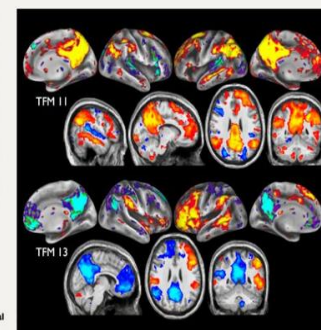
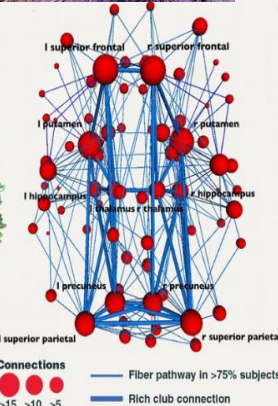
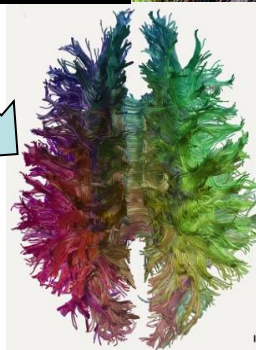
## Brain *connexions* (Diffusion MRI & DTI)



## Brain at work (functional MRI or fMRI)

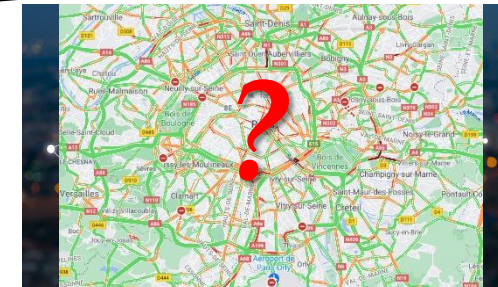


## Wired connectivity



Park HJ, Friston K. Science 2013

## Functional connectivity



**Brain connectome = multiple scale connectivity**

# CONCEIVE: The Iseult Project (genesis phase 2001-2004)

2001

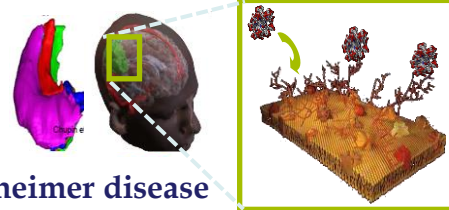
- 3T :  $\approx$  100 installed systems
- 1x 7T (USA) + 2 orders (USA, J)
- $\rightarrow$  11.7T at CEA?**



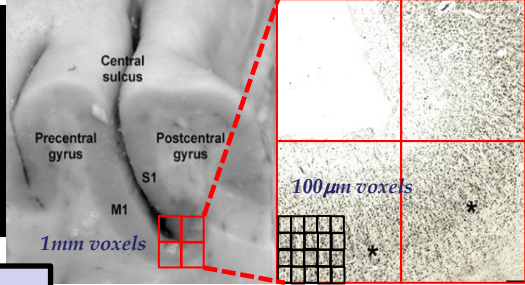
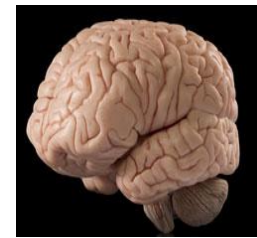
D. Le Bihan

Roy Gordon (Vice president, Bruker):

« You are mad » (RSNA, Chicago, Nov 27, 2001)



Alzheimer disease  
Molecular imaging



Mesoscale cortex architecture

Better see...

...to better understand

... and discover

IOP Publishing  
Supercond. Sci. Technol. 36 (2017) 023003 (20pp)  
doi:10.1088/1361-6682/36/2/023003

Topical Review

Human brain MRI at 500MHz, scientific perspectives and technological challenges

Denis Le Bihan and Thierry Schild

Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), Division de Fondamentaux

10.55T @ July 4th, 2019  
11.7T @ July 19, 2019



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, JUNE 2020

Commissioning Completion of the Iseult Whole Body 11.7 T MRI System

Lionel Quettier, Guy Aubert, Jean Belorgey, Christophe Berriand, Philippe Bredy, Guillaume Dilasser, Olivier Dubois, Graham Gilgrass, Quentin Guibard, Vincent Jannou, François-Paul Juster, Hervé Lannou, Frédéric Molinari, François Nouris, Armand Roger, Thierry Schild, Loris Scala, Armand Sinnou, Vadim Stepanov, and Pierre Vekriac

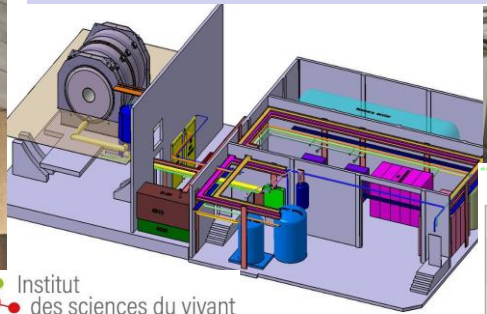
(Invited Paper)

Tomorrow: **Mesoscale** brain functional architecture ( $\sim 100\mu\text{m}$ )

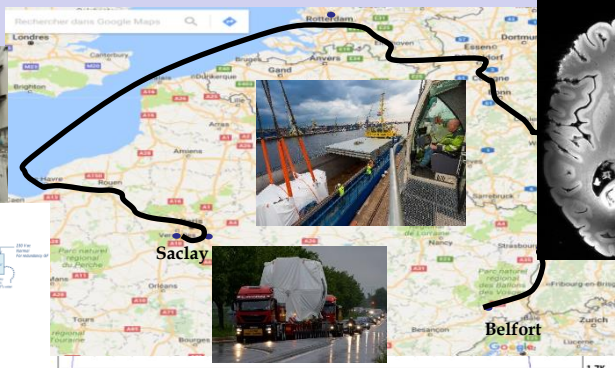
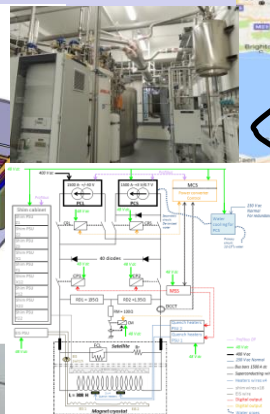
- $\triangleright$  *In vivo*, non invasively
- $\triangleright$  In the **Human Brain**
- $\triangleright$  Over the **whole** brain

## Neural Code ?

## ULTRA-HIGH FIELD MRI



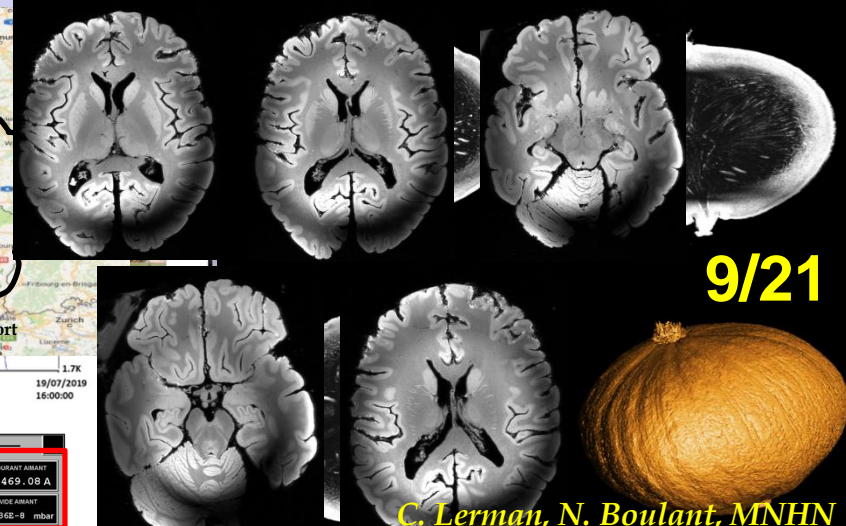
Institut des sciences du vivant  
**Frédéric Joliot**



17/07/2019 10:00

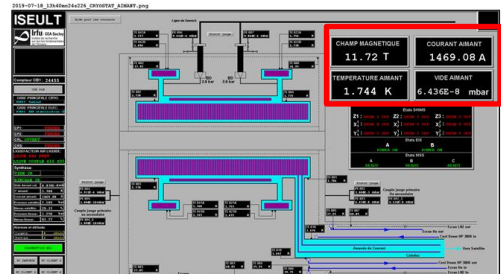
17K

19/07/2019 16:00:00



9/21

C. Lerman, N. Boulant, MNHN



CEA acclaimed Know-How in magnet design, cryogenics and cybernetics

# FuSuMaTech: >14T human MRI magnet?

## The liquid helium crisis (MRI)

**2001**  
 - 3T : ≈ 100 installed systems  
 - 1x 7T (USA) + 2 orders (USA, J)  
**→ 11.7T at CEA?**



Roy Gordon (Vice president, Bruker):  
 « You are mad » (RSNA, Chicago, Nov 27, 2001)

**2021: Madness has been contagious (no vaccine so far)**  
 - 11.7T reached @ NeuroSpin  
 - 3T : ≈ 7000 installed systems  
 - 7T : ≈ 100 installed systems  
 - 1x 8T & 3x 9.4T (USA, Germany)  
 - 1 x 10,5T Minneapolis  
 - 2 head-only 11.7T systems: USA (NIH), KOREA  
 - 2 projects for 14T: Heidelberg/Germany, Shangai  
 - USA projet (14T or 20T)

### Superconducting Materials for Magnets

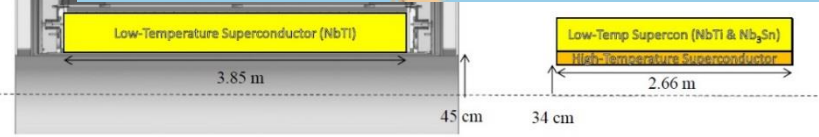
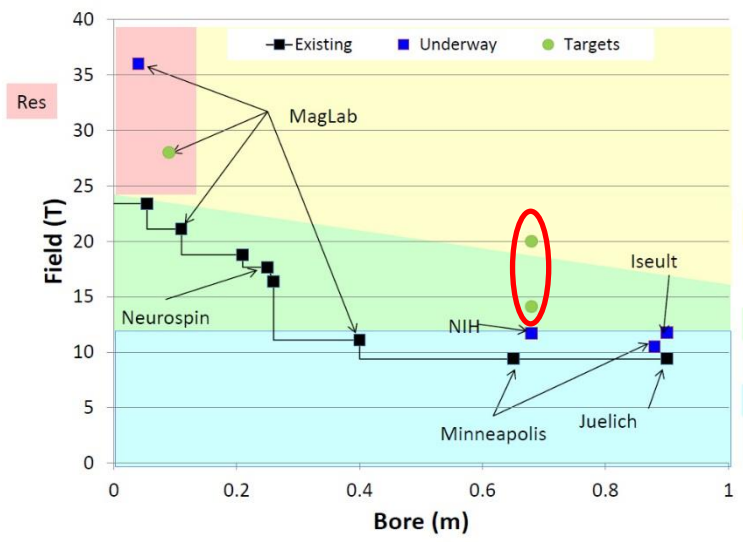
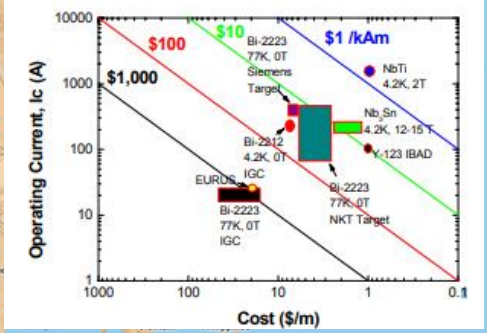


Country	Billion Cubic Metres
United States	20.6
Qatar	10.1
Algeria	8.2
Russia	6.8
Canada	2.0
China	1.1

The values above are estimated helium resources from the USGS Mineral Commodity Summary



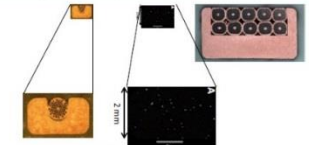
**Nuclear magnetization**  
 $Mo \approx \gamma B_0 / kT$   
 = f(\$\$\$)!



Parameter	Iseult	MagLab 20 T Concept
Conductor Mass (Ton)	65	~35
Stored Energy (MJ)	338	~350
Current Density (A/mm <sup>2</sup> )	26.4	~40
Magnet Design	CEA	MagLab

HTS + high-strength materials at 4 K operate at high field and current-density resulting in compact magnets.

	110	200	110	200
Stabilizer	Cu	Cu	He	He
C <sub>p</sub> (mJ/cc/K)	1	1	552	552
Protection	Cu	Cu	Cu	Cu
J <sub>cu</sub> (A/mm <sup>2</sup> )	~280	~230	~70	~250

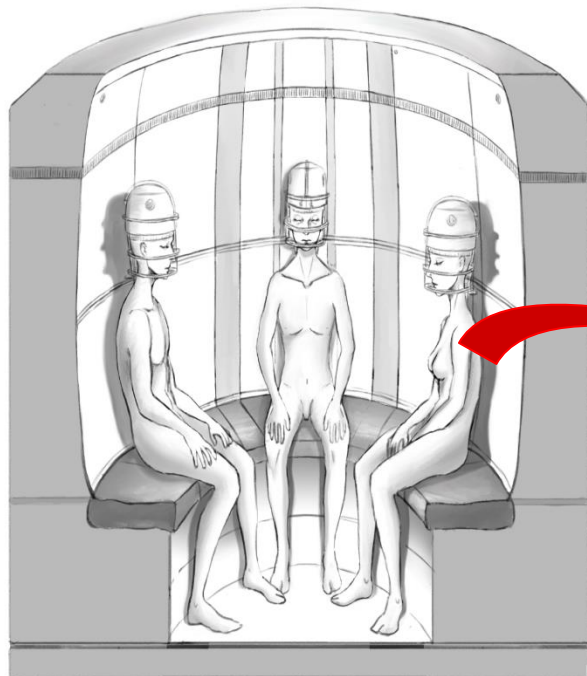


1,400 / 250 = 5.6 > 3.14

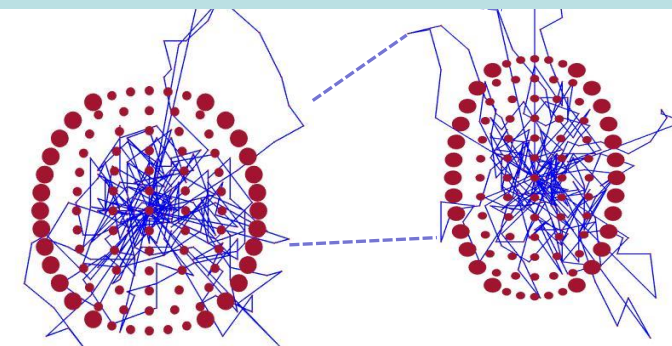
# Brain space-time model « dark » energy: *Social interactions*

1 (?) Universe

7,913,129,362 living brains on earth (as of December 13<sup>th</sup>, 2021 @ 4:06pm UTC)



Connecting *brain spacetimes*  
(across miles/centuries)



Relativistic pseudo-diffusion model

Le Bihan D. Brainmultiphysics 2020

<https://doi.org/10.1016/j.brain.2020.100016>

NEW BOOK TO COME ! (2022)

**FuSuMaTech «Social Magnet»**  
Ad hoc Working Group  
on *Future Superconducting Magnet Technology*

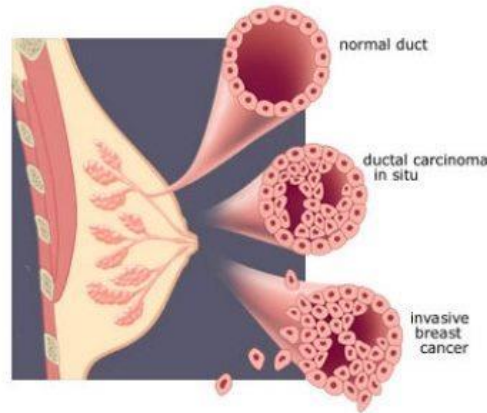


# BREAST CANCER SCREENING

- Breast cancer: good prognosis with early diagnosis (still localized)
  - 61% of early diagnosed cancers have a 5-year survival rate of 99% after treatment,
  - 31% have a 5-year survival rate of 85% after treatment,
- **Which ones??** Often cannot predict on mammograms whether lesions are malignant, requiring active treatment, or not.

**Issues with Mammography (MMG) screening**

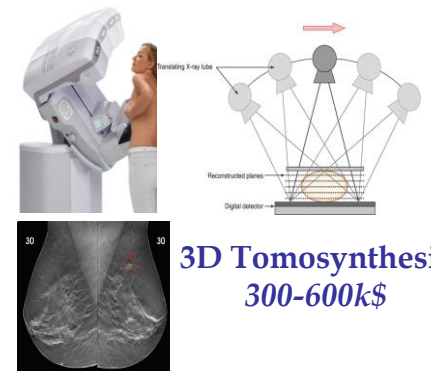
- X-ray exposure
- Overdiagnosis (10-52%):
  - prognostically irrelevant (non-lethal) cancers
  - **Biopsy: Invasive, sparse, scars**
- Underdiagnosis: 50% for early detection
- MMG biased to detect slowly growing cancers
- **40% of women with DCIS have mastectomies (10,000/year USA)**



**Standard Mammography**  
150-450k\$



**Microcalcifications**



**3D Tomosynthesis**  
300-600k\$

Conventional X-ray mammography

- ☺ Cheap (mass screening)
- ☹ False positive/negative

**Current indications of breast MRI (cost: 1000\$, 40min; availability)**

- Second intention (*added cost!*):
  - « Diagnosed » or suspicious lesions (Staging, Scar vs recurrence, implants, problem solving)
  - Screening only of high-risk patients (>6% risk: annual MRI + MMG)
  - Contralateral breast after breast K diagnosis
  - Follow up after breast conserving surgery
  - Genetics, family history
- Standard DCE (vascularity): Sensitivity → 97%, Specificity → 73%
- Ultrafast DCE: Sensitivity → 90%, Specificity → 85%
- **Diffusion MRI (cellularity): Sensitivity → 88%, Specificity → 95%**





# BREAST CANCER SCREENING

## Mammography: Huge MARKET (US)

- 63M >40yo women
- MMG: 65.3% → 41M MMG/year
- MRI: 1.15% → 945000 MRI/year
  - But **MRI is the most sensitive and accurate breast maging tool**
  - Challenges: **cost, availability, technical issues**

## Potentially huge world market for MRI +++++

- ✓ High prevalence of breast cancer, increasing awareness, systematic mass screening, Computer Aided Detection
- ✓ Market: 1.92B\$ in 2021 (6.1% CAGR, Asia: 7.2%)
- ✓ Top Players: Hologic, GE, Siemens, FujiFilm, ....

## Other benefits

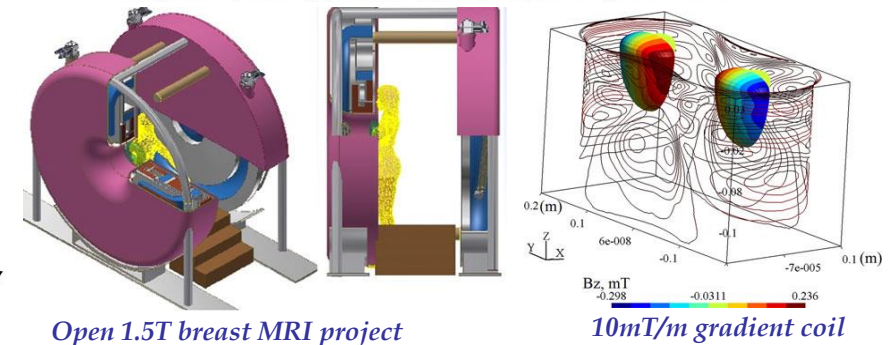
- Outside radiology departments and hospitals?
- Reduced cost
- Availability (mobile systems going to the patients)
- Decrease radiologists burden (AI)

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017

4

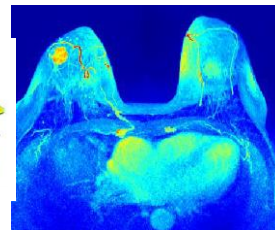
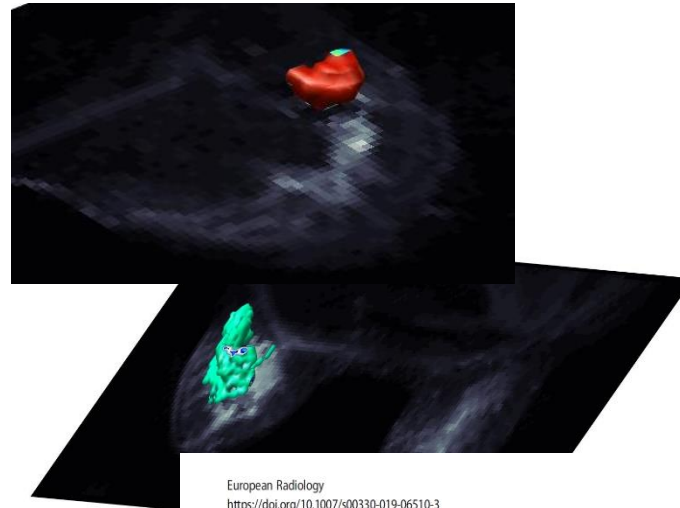
## New Magnet Technology for a 1.5 T Open-MRI Breast Imager

Akhdiyor Sattarov, Peter McIntyre, Jeff Breitschopf, Daniel Chavez, James Gerity, and Joshua Kellams



Open 1.5T breast MRI project

10mT/m gradient coil



Case#114avg/Lesion  
 Global Raw S-Index: 56 PROLIFERATING/Malignant  
 Heterogeneity index:20 / Conspicuity index:13.3  
 Malignant charge: 1326mm<sup>3</sup>  
 sADC:1.02E-3mm<sup>2</sup>/s BR=4 (35%)  
 Biomarkers /HER+ (74%) /PgR- (64%)

Collab Pr. Goto, Kyoto Prefectural Faculty of Medicine

European Radiology  
<https://doi.org/10.1007/s00330-019-06510-3>

BREAST

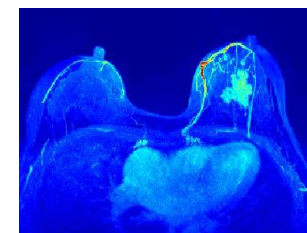
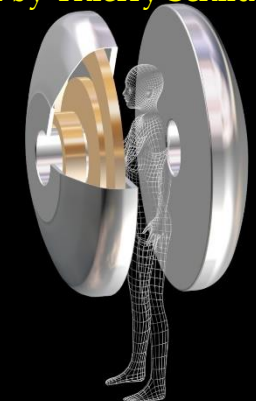
Diffusion-weighted imaging of the breast—a consensus and mission statement from the **EUSOBI** International Breast Diffusion-Weighted Imaging working group

Pascal Baltzer<sup>1</sup> · Ritse M. Mann<sup>2,3</sup> · Mami Iima<sup>4</sup> · Eric E. Sigmund<sup>5</sup> · Paola Clauser<sup>1</sup> · Fiona J. Gilbert<sup>6</sup> · Laura Martincich<sup>7</sup> · Savannah C. Partridge<sup>8</sup> · Andrew Patterson<sup>6</sup> · Katja Pinker<sup>1,9</sup> · Fabienne Thibault<sup>10</sup> · Julia Camps-Herrero<sup>11</sup> · Denis Le Bihan<sup>12</sup> · On behalf of the EUSOBI international Breast Diffusion-Weighted Imaging working group

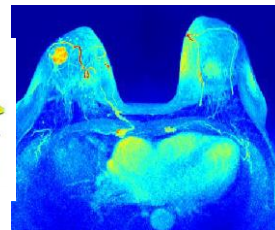
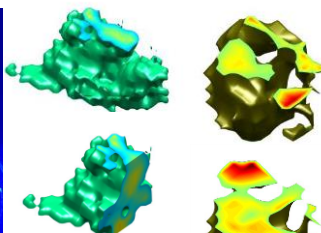
**NEW BOOK TO COME ! (2022)**

Received: 13 March 2019 / Revised: 3 September 2019 / Accepted: 10 October 2019  
 © The Author(s) 2019

## Proposal by Thierry Schild



Case#95avg/Lesion  
 Global Raw S-Index: 30 QUIET TISSUE (Benign)  
 Heterogeneity index:20 / Conspicuity index:16.3  
 Malignant charge: 1243mm<sup>3</sup>  
 sADC:1.39E-3mm<sup>2</sup>/s BR<2/BR=3 (76%)

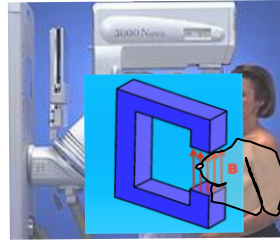


Collab Pr. Goto, Kyoto Prefectural Faculty of Medicine

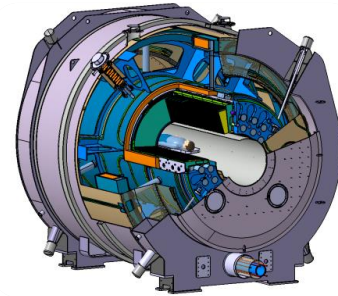
**Non-Gaussian Diffusion MRI based  
 Breast cancer virtual biopsy  
 Automatic detection/analysis  
 (CEA patent, D. Le Bihan, 2015)**

# Prospective of superconductive magnets for medical applications

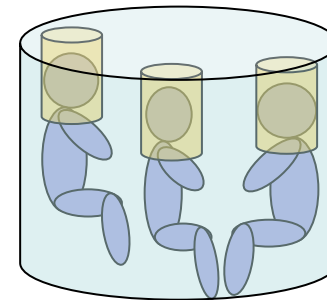
Clinical need  
Market



**#1 MammoMRI +++**  
*Small & Cheap*



**#3 >14T brain MRI**  
*High Bo*



**#4 Social fMRI**  
*Large size*

Science