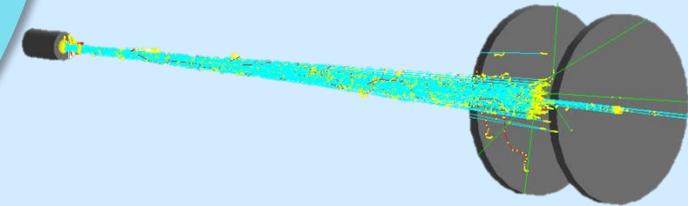
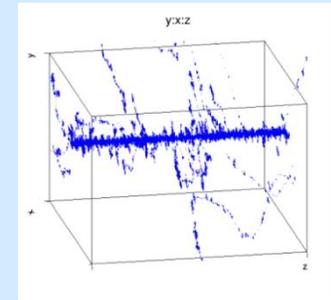
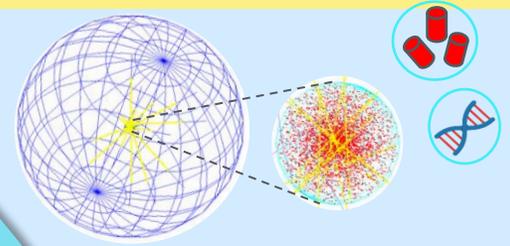
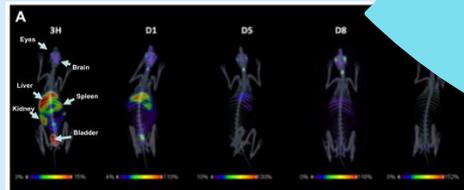
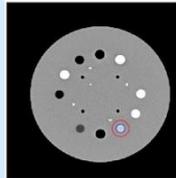
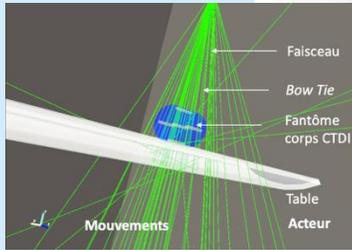
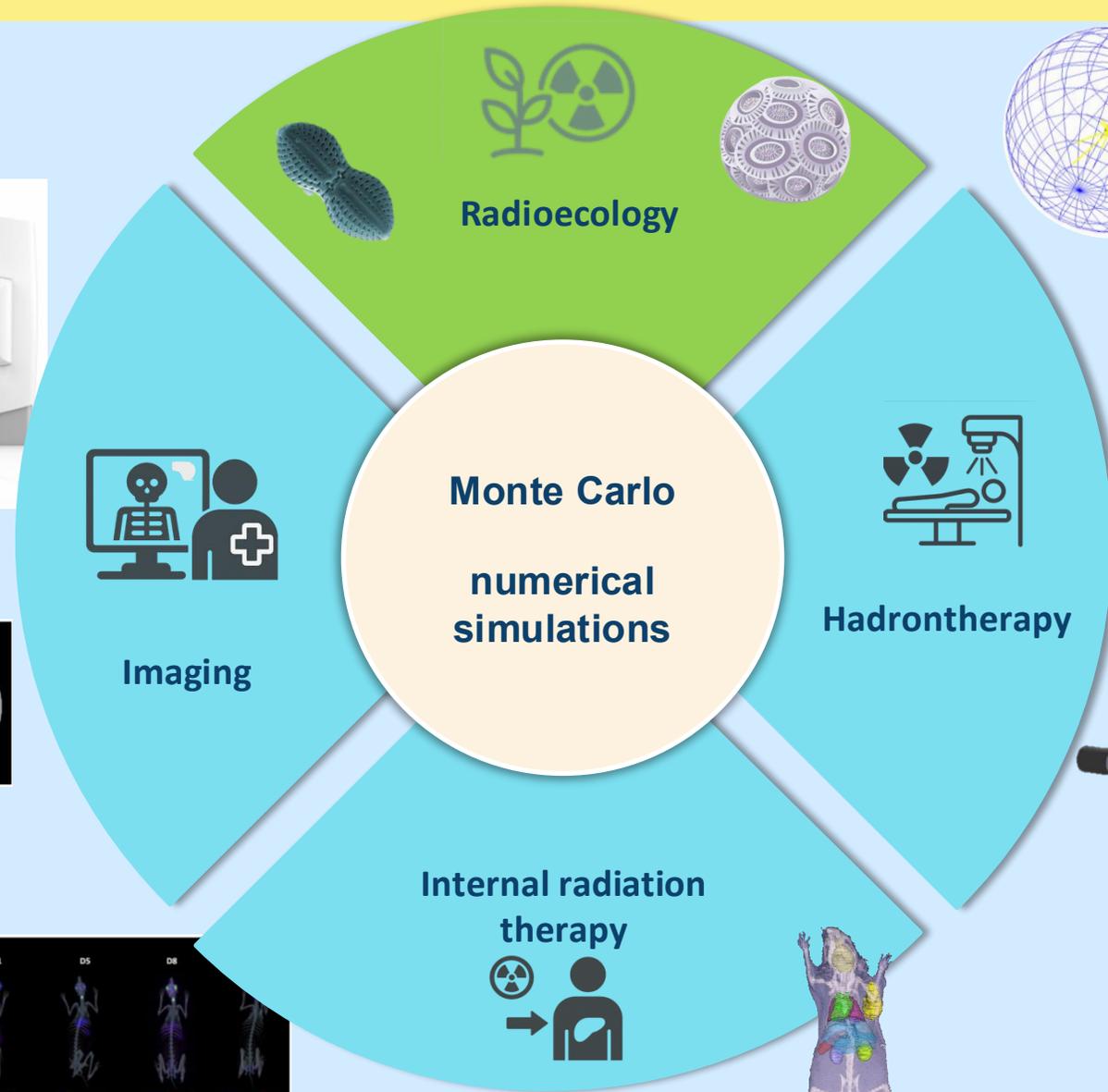




# Developments and studies using the GATE Monte Carlo simulation platform

**Lydia Maigne, Ph D., spokesperson of the OpenGATE collaboration**  
**Laboratoire de Physique de Clermont Auvergne**  
**[lydia.maigne@clermont.in2p3.fr](mailto:lydia.maigne@clermont.in2p3.fr)**





To be recruited  
PostDoc, UCA

microdosimetry  
**ANR IrHydroBrain**



Gaëtan RAYMOND  
PhD student (2021-2025), CIFRE  
Siemens-Unicancer

CT dosimetry and  
image quality



Daeun KWON  
PhD student (2023-2026),  
CNRS-IN2P3

FLASH therapy,  
radiolysis/Radiobiology



David Grimbichler  
IT engineer, CNRS

GATE (C++, Python)...

# The GATE Monte Carlo platform



# The OpenGATE collaboration

25 laboratories, companies, clinics  
developing and validating an **open source**  
platform



Spokesperson  
Lydia Maigne

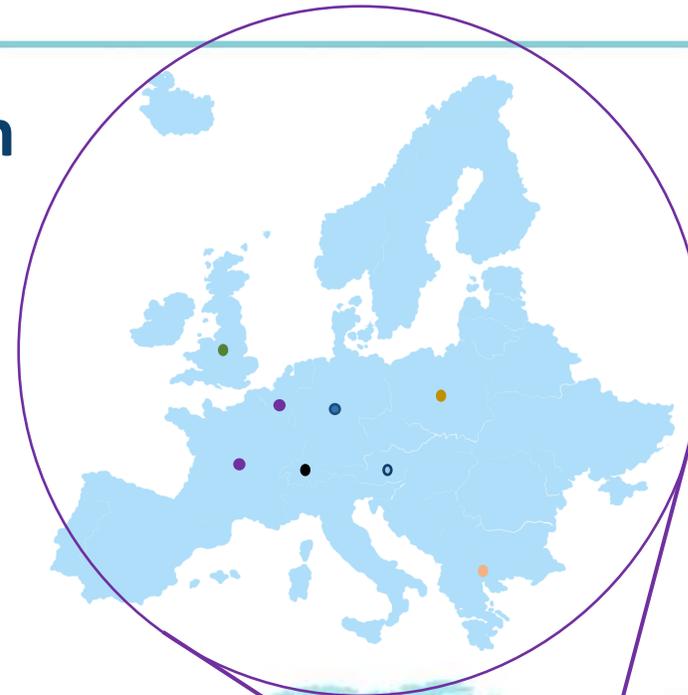


Tech. Coord.  
David Sarrut

## Europe



- FH Aachen, University of Applied Sciences, Julich, Germany
- Medisip, Ghent University, Belgium
- Medical University of Vienna, Wiener Neustadt, Austria
- MedAustron, Wiener Neustadt, Austria
- Christie Medical Physics & Engineering, Manchester, UK
- JPET collaboration, Poland
- Institute of Nuclear Physics Polish Academy of Sciences, Poland
- Univ. of Patras, Dept of Med. Phys., Greece
- BioemTech, Athens, Greece
- Paul Scherrer Institute (PSI), Switzerland



France 

**10 labs**

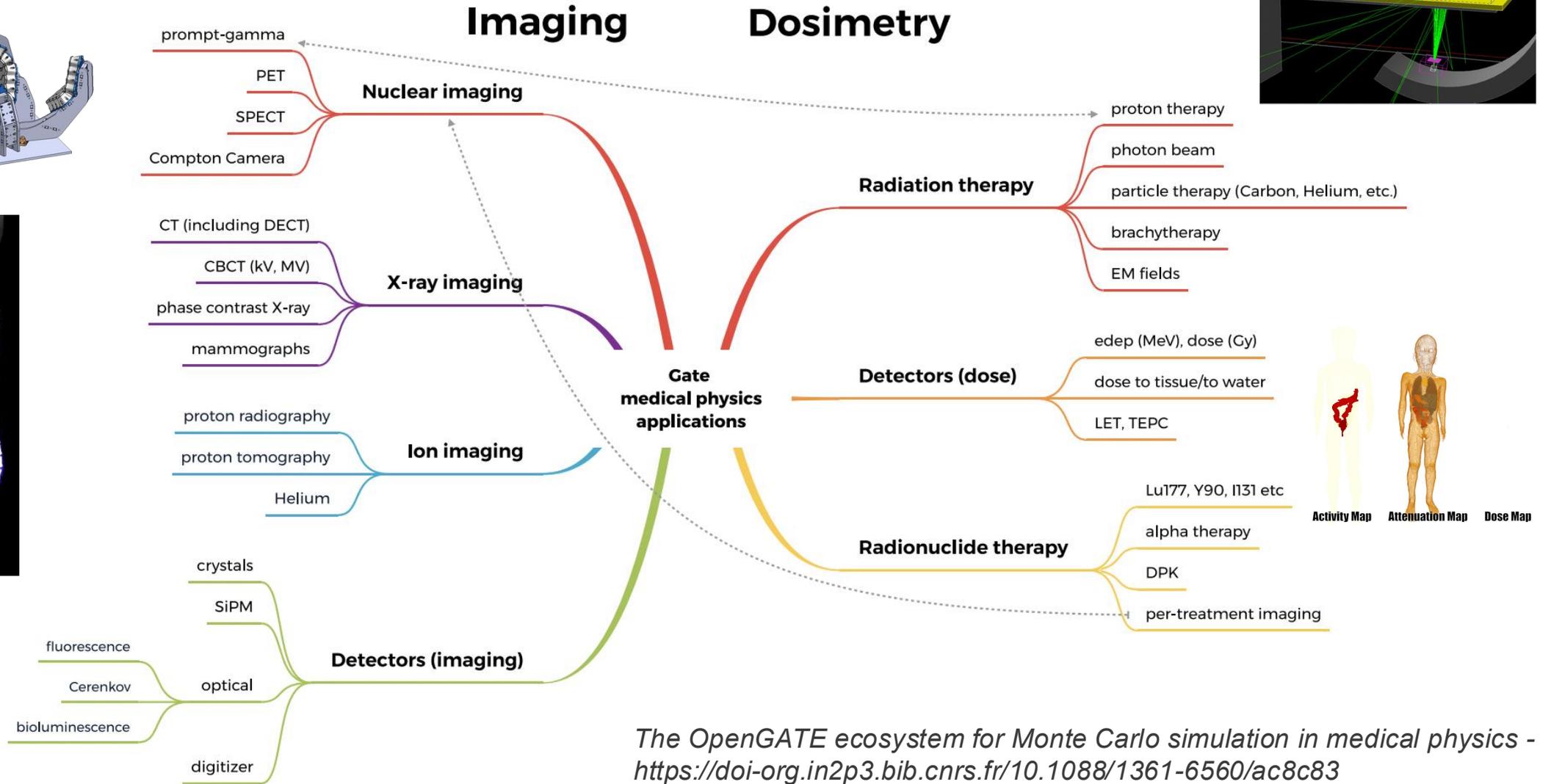
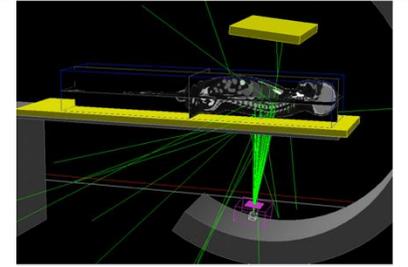
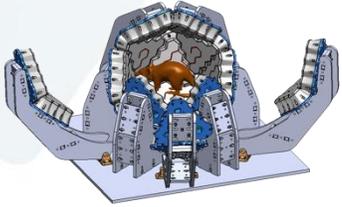
 



**Elsewhere**

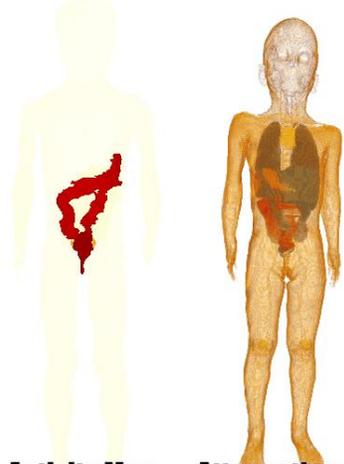
MSKCC, New York, USA  
UC Davis, Davis, USA  
Sogang University, Seoul, South Korea  
QST, Chiba, Japan



The OpenGATE ecosystem for Monte Carlo simulation in medical physics - <https://doi-org.in2p3.bib.cnrs.fr/10.1088/1361-6560/ac8c83>



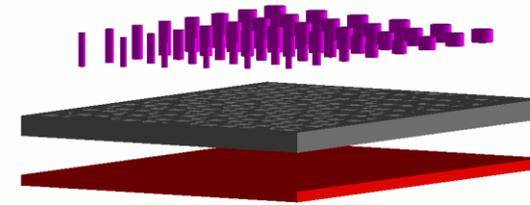
LPC, Clermont-Fd



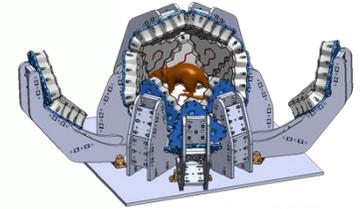
**Activity Map   Attenuation Map   Dose Map**  
BIOEMTECH, Greece



BIOEMTECH, Greece

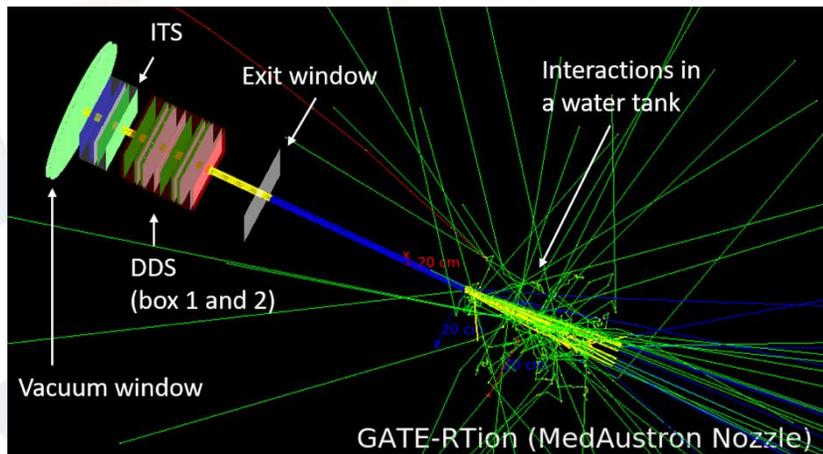


LPC, Clermont-Fd



IcoPET

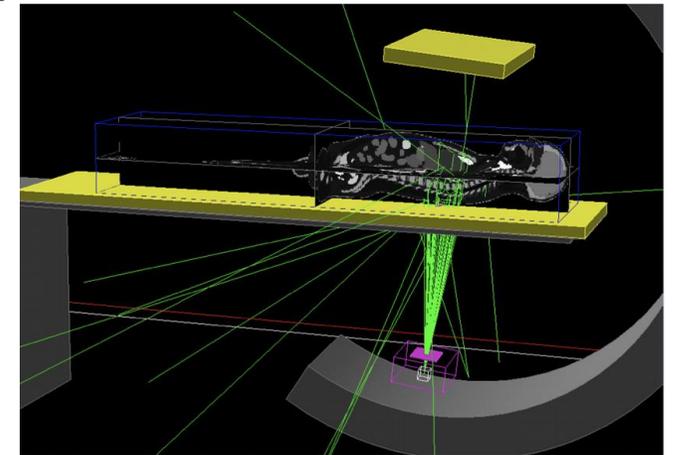
**Open source & open access platform**  
**Developed in C++, 20 years old**  
**More than 2000 users**



GATE-RTion (MedAustron Nozzle)



JPET project



IPHC, Strasbourg

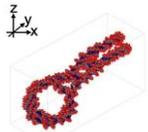
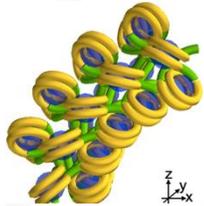
# Multi-scale simulations

Elementary processes:

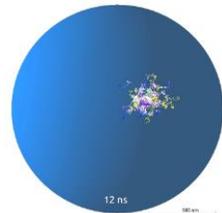
- Ionization
- Excitation
- Fragmentation
- Radical production

Sub cellular structures

Nano dosimetry



Delage et al. 2015



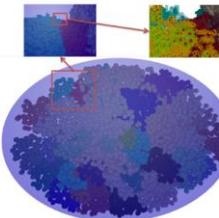
J. Comput. Phys. 274 (2014) 841-882

Death, cycle arrest  
Migration /metastases  
Mechanical properties  
Morphology

Micro dosimetry

Molecules

Cell



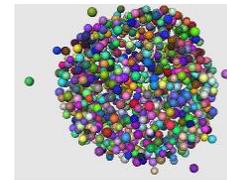
Sc. Rep. 7 (2017) 11923

LPCHEM code

Evolution of tumour  
- Growing  
- Control  
- Vascularisation

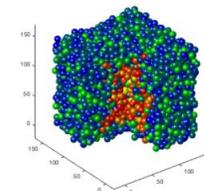
Bystander

Clusters of cells / Organ



cpop.in2p3.fr

MSB

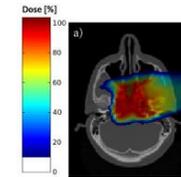


Dubour A et al. (2018), Modeling the dynamics of oligodendrocyte precursor cells and the genesis of gliomas, PLoS Comput Biol., 14, e1005977.

Organ motion  
Patient morphology  
Cancer induction

Biological dose

Patient



NanOx

PMRT

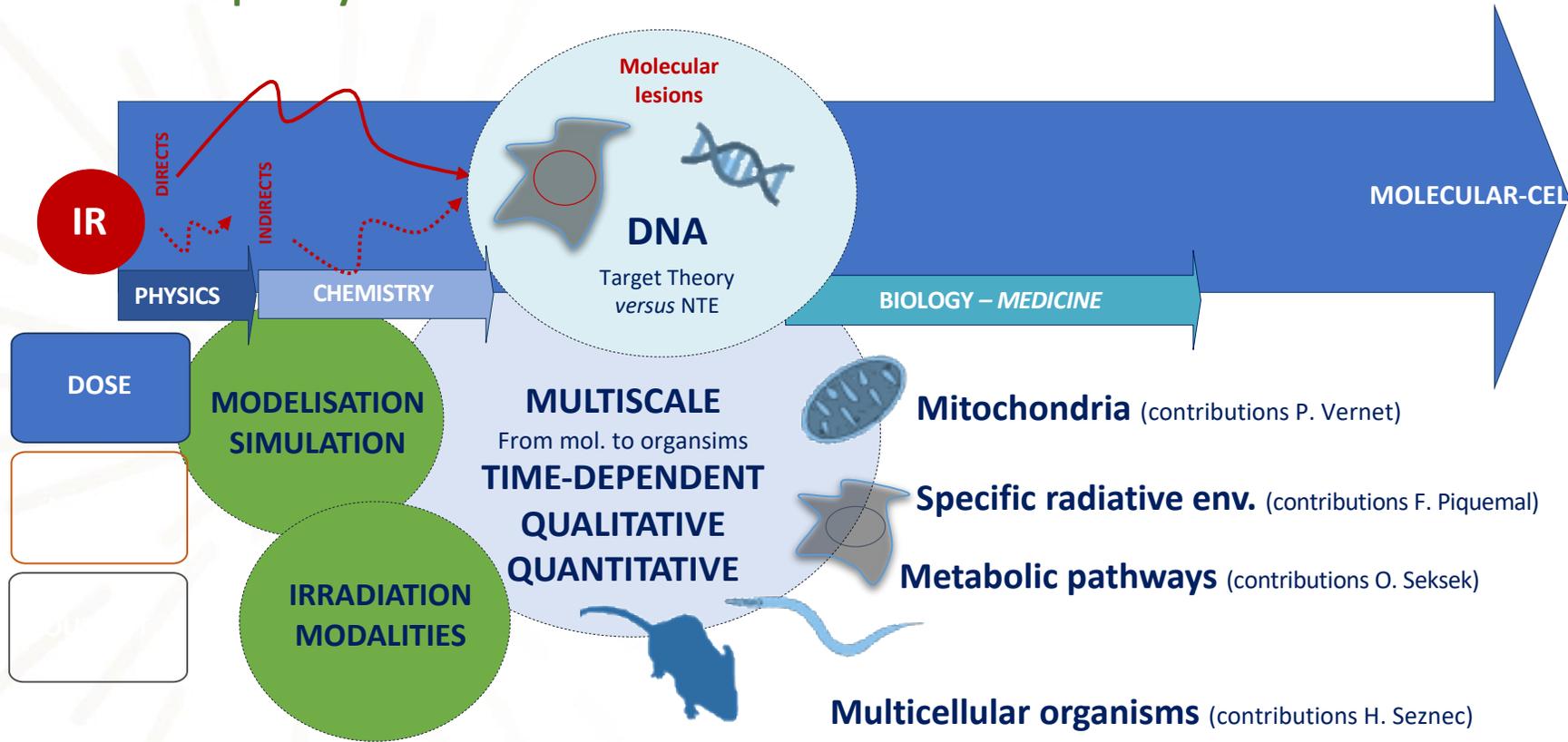


Open source and open access toolkits



# To radiation biology applications

## ► Interdisciplinary research



- From **PHYSICS, CHEMISTRY** to **BIOLOGY** and **MEDICINE**
- From **IN-SILICO MODELING** to **IN-VITRO** and **IN-VIVO VALIDATION**
- From **MOLECULES** to **ORGANISM**



```
pip install opengate  
opengate_tests
```

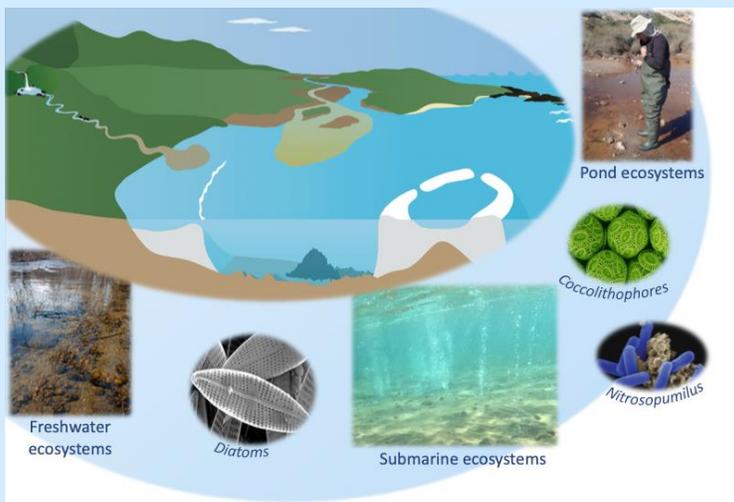
See: <https://github.com/OpenGATE/opengate>

Docs: <https://opengate-python.readthedocs.io>

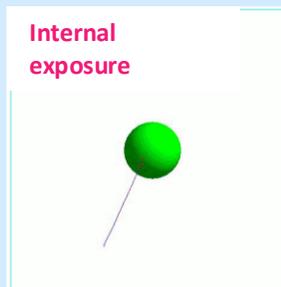
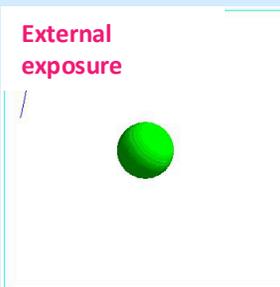
Examples: <https://github.com/OpenGATE/GateContrib>

**More than 100 tests & examples available**

# μdosimetry for radioecology



Evaluate the dose received by microorganisms living in naturally radioactive ecosystems



## GATE MARIM DB

**42** microorganisms diameters  
**0.5** to **1200 μm**

**α-emitters**  
<sup>238</sup>U, <sup>232</sup>Th decay chains

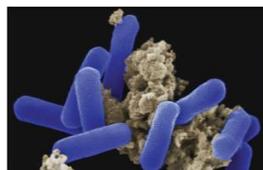
### EXPOSURES

**INTERNAL**  
Medium water

**EXTERNAL**  
Porosity:  
0, 50 and 100 %

**Edep** (MeV Bq<sup>-1</sup> s<sup>-1</sup>)  
&  
**DCC values** (μGy h<sup>-1</sup> per Bq kg<sup>-1</sup>)

### NITROSOPUMILUS MARITIMUS



Diameter 0.5 μm  
50% water and sediments

External	Internal	activity 1000 Bq L <sup>-1</sup>
2.04 μGy h <sup>-1</sup>	9.63·10 <sup>-3</sup> μGy h <sup>-1</sup>	

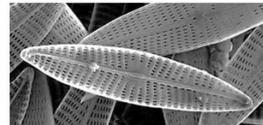
### COCCOLITHOPHORE EMILIANIA HUXLEYI



Diameter 10 μm  
50% water and sediments

External	Internal	activity 1000 Bq L <sup>-1</sup>
1.77 μGy h <sup>-1</sup>	2.05·10 <sup>-1</sup> μGy h <sup>-1</sup>	

### DIATOM



Diameter 20 μm  
100% water

External	Internal	activity 1000 Bq L <sup>-1</sup>
2.79 μGy h <sup>-1</sup>	3.82·10 <sup>-1</sup> μGy h <sup>-1</sup>	

Exposure:

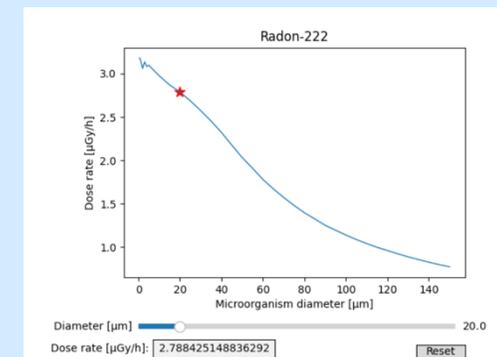
Select environment density only for external exposure  
Environment density (g/cm<sup>3</sup>):

Pure water      Pure sediment

Radionucl...

Activity concentration:  Units:  
 Bq/kg  
 Bq/m<sup>3</sup>  
 Bq/L

Microorganism Diameter (μm):



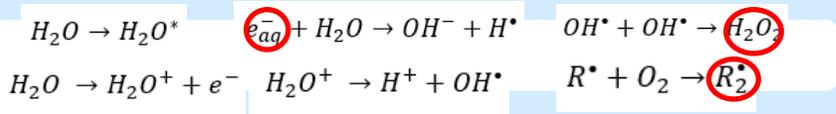
## Scientific production (1 DB, 2 papers)

GATE MARIM DB - <https://github.com/lpc-umr6533/marim>

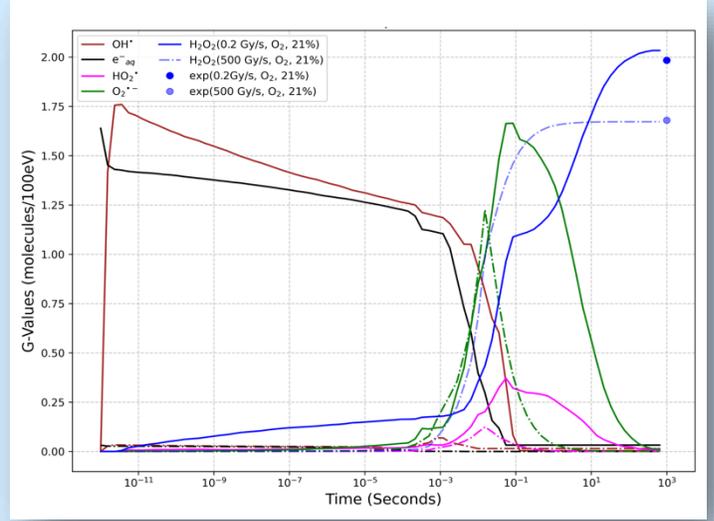
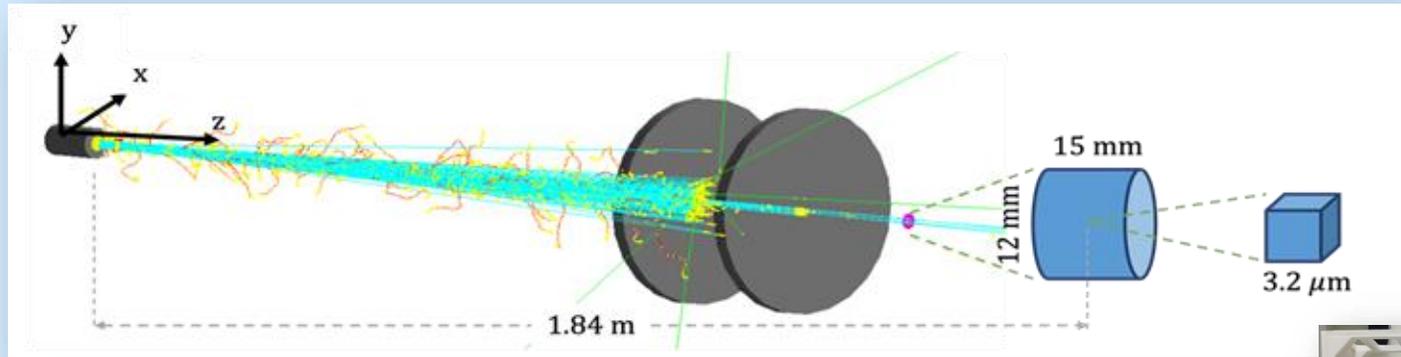
G R. Fois et al, **Journal of Environmental Radioactivity**, <https://doi.org/10.1016/j.jenvrad.2025.107639>

S. Kolovi et al, **PlosOne**, <https://doi.org/10.1371/journal.pone.0292608>

# Water radiolysis in FLASH therapy



H<sup>+</sup> (68 MeV) et He<sup>2+</sup> (70 MeV) [0,1 Gy/s – 300 kGy/s]

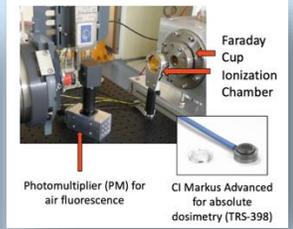


LET (keV/μm) vs Depth (mm)

pH scale (0-14)

O<sub>2</sub> molecule

Pulse diagram: Macro-pulse (period 32.84 ns), Micro-pulse (period 32.84 ns), Dose (10 – 80 Gy), Time (6.3 10<sup>-5</sup> s – 1.9 s)



ARRONAX

**Scientific production (1 code, 1 paper)**  
 G R. Fois et al, *Medical Physics*, <https://doi.org/10.1002/mp.17281>

# Innovative internal radiation therapies

**$^{131}\text{I}$ -ICF01012**

**Melanoma**

**$^{177}\text{Lu}$ -Tz**

**$^{177}\text{Lu}$ -PSMA**

**Peritoneal carcinosis**

**Breast cancer**

**$^{99\text{m}}\text{Tc}$ -NTP-15-5**

**$^{68}\text{Ga}/^{64}\text{Cu}/^{67}\text{C}$  u-chelator**

**Cartilage**

**(arthrosis)**

**$^{90}\text{Y}$  chitosan hydrogel**

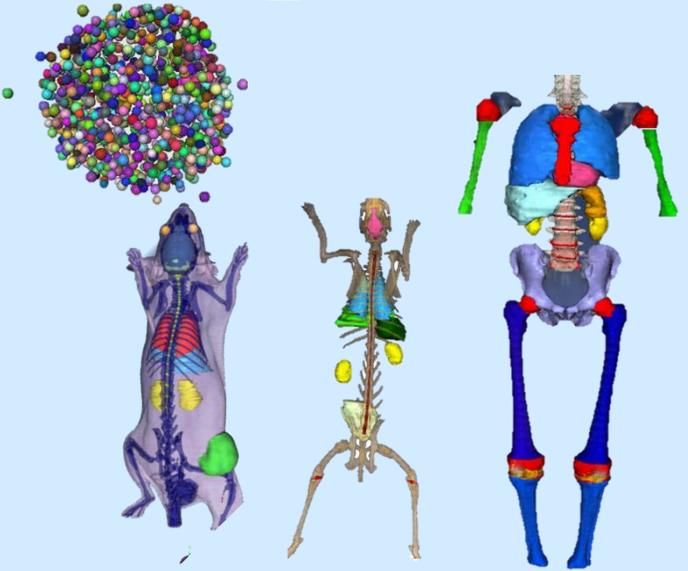
**Glioblastoma**

More than 15 years of partnership

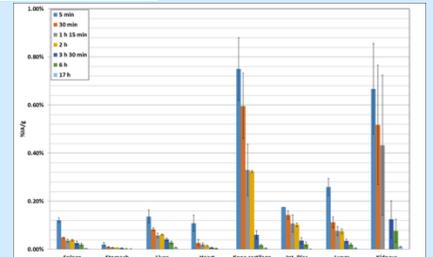
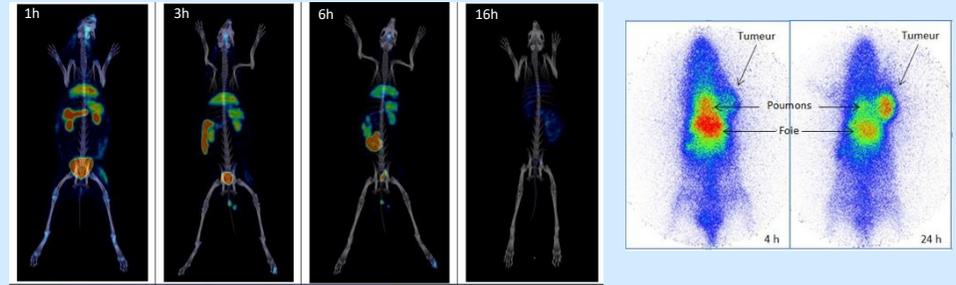
IMOST-Centre Jean Perrin

**Clinical trials**

**MELRIV - CARSPECT**



3D CT image (spheroid, rodents, human)



Radiopharmaceuticals biodistribution from SPECT and PET imaging

ORGANS	Dose ( $\mu\text{Gy}/\text{MBq}$ )	Imaging
Liver	3.12 ± 0.52	
Kidney right	4.61 ± 1.62	
Kidney left	3.99 ± 1.59	
Spleen	1.82 ± 0.42	
Stomach	1.04 ± 0.29	
Lung right	1.84 ± 0.37	
Lung left	1.62 ± 0.37	
Heart	1.48 ± 0.34	
Brain	0.019 ± 0.004	
Bladder	0.09 ± 0.02	
Spinal cord	0.74 ± 0.19	
<b>CARTILAGES</b>		
Knee cartilage (av)	3.96 ± 0.45	
Hip cartilage (av)	1.05 ± 0.12	
Humerus cartilage (av)	1.16 ± 0.15	
Sternum cartilage	1.04 ± 0.19	
Lumbar disc (av)	0.20 ± 0.06	
Thoracic disc (av)	0.14 ± 0.03	
<b>RED BONE MARROW</b>		
Lumbar vertebrae (av)	0.84 ± 0.25	
Thoracic vertebrae (av)	1.15 ± 0.27	
Femur (top)	0.80 ± 0.09	
Femur (bottom)	0.62 ± 0.12	
Tibia	0.58 ± 0.06	
Pelvis	0.51 ± 0.12	
Humerus	0.57 ± 0.08	
Sternum	0.64 ± 0.13	

Dose calculation in human for  $^{99\text{m}}\text{Tc}$ -NTP15-5 SPECT imaging

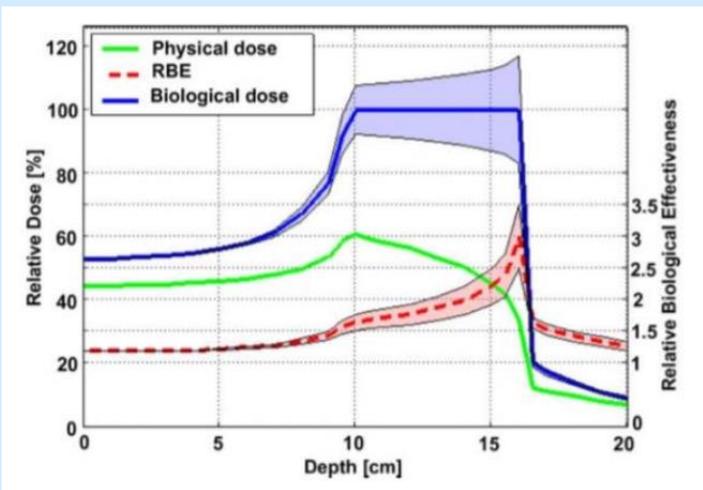
**Scientific production**

Chanchou et al, EJNMMI research, <https://doi.org/10.1186/s13550-025-01318-3>

Thivat et al, Frontiers in Medicine, <https://doi.org/10.1186/s12885-022-09495-3>

Fois et al, Medical Physics, <https://doi.org/10.1002/mp.14603>

Maigne et al, EJMP, <https://doi.org/10.1016/j.ejmp.2021.07.016>



**RBE x Physical dose = Biological dose**

$$RBE = \frac{D_X}{D_R}$$

$D_X$  : Reference absorbed dose for RX

$D_R$ : Absorbed dose for R-type beam causing the same biological damage

Different biological models tested:  
mMKM, NanOx...



Biological data

Géométries cellulaires sensibles  
 $\alpha$  and  $\beta$  cell survival parameters



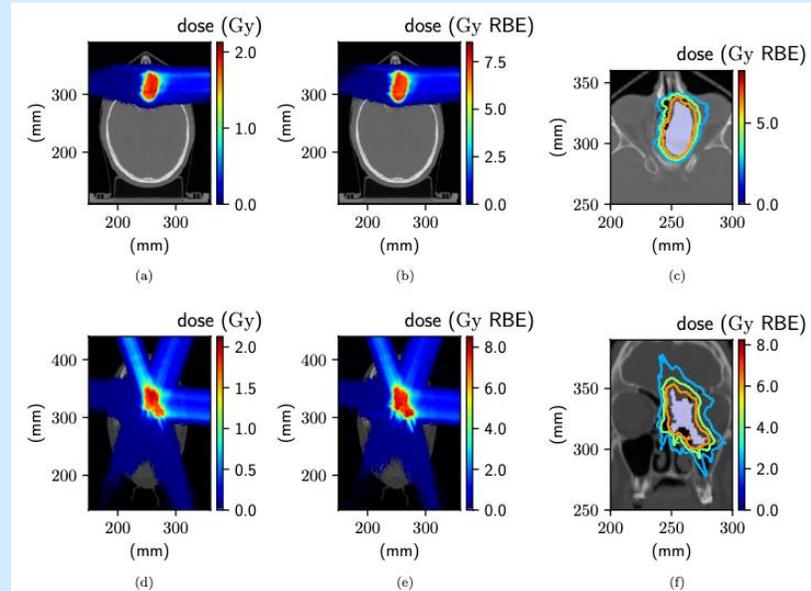
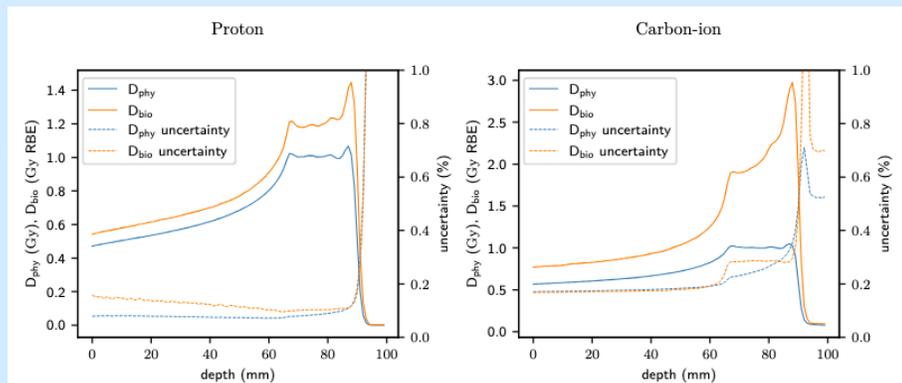
Physical data

Specific energy deposited to  
cell and micro and nano  
scales

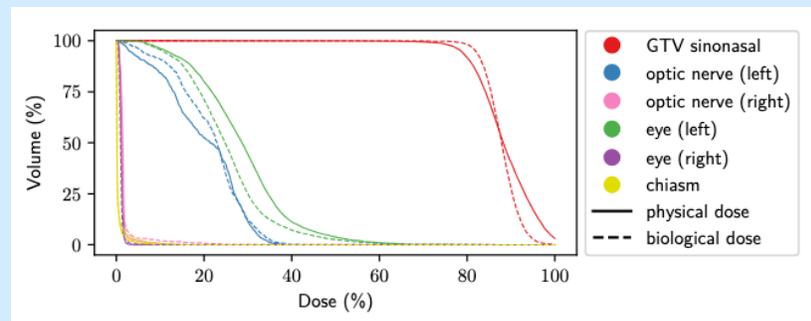


Chemical data

Radiolytic yields in sensitive  
volumes



Physical and biological PBS carbon-ion doses simulated with GATE/NanOx for a patient with a tumor (the GTV is highlighted in light purple) in the sinonasal region.



Cumulative physical and biological DVH for the GTV and OARs (optic nerve (left and right), eye (left and right) and chiasm) of the carbon-ion treatment plan simulated with GATE

## Scientific production

Pereda et al, Phys. Med. Biol., submitted

Ali et al, Cancers, <https://doi.org/10.3390/cancers14071667>

Ali et al, Medical Physics, <https://doi.org/10.1002/mp.15609>



# Réseau de collaboration



Encadrement  
Equipe  
Simulation  
**LPCA**

1 PostDoc  
2 doctorants  
1 IR

**COPIL  
LabEx  
PRIMES**  
Coordinatrice  
WP5

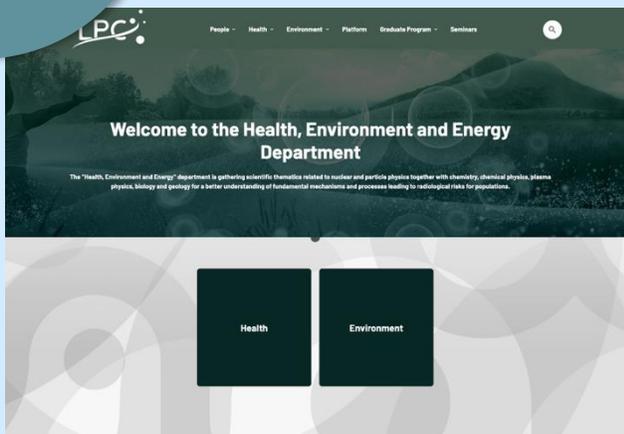
**COPIL**  
Resp. Axe  
transverse  
Calcul



Resp.  
**Master  
Projet  
FLASH**

**Collaboration  
Scientifique  
internationale**  
**OpenGATE**  
Porte-parole

Plateforme de simulation  
open source  
20 ans d'expérience  
25 partenaires (public, privé)  
+ 30 développeurs  
+ de 2000 utilisateurs



## cnrs Formation entreprises

- Depuis 2019
- Formation à distance
- 3 jours, 7h/j, 1 à 3 /an, intra
- 10 à 15 apprenants
  - Privé: THALES, ORANO...
  - Public: CNRS, CEA, ASNR...
- Séquences de 2h avec cours et travaux pratiques

Contenu  
pédagogique

Ressources  
de calcul



Evaluation

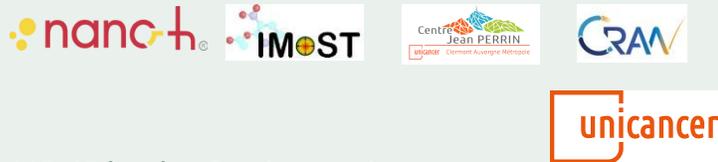


## 

- À partir de 2025
- Formation hybride
- 3 jours, 7h/j, 1/an
- 10 à 15 apprenants
  - médecins médicaux,  
radiothérapeutes,  
médecins nucléaires,  
radiologues,  
dosimétristes...
- Séquences de 2h avec cours et travaux pratiques

Coordination of Master project FLASH  
(Lydia Maigne)  
2026-2029 (WP4 – Digital twins & WP5 –  
Open database)

NEMESIS project



ANR IRhydroBrain project



## What are the fundamental mechanisms involved in the FLASH effect in hadron therapy?

- Impact of different temporal beam structures
- High-fidelity digital twins validated against experimental data
- Simulation of water radiolysis in biological environments

## Are we able to provide personalized digital twins for targeted alpha therapy?

- Model the Relative Biological Efficiency (RBE)
- Differentiate the biological response (cell types, cellular cycles and tumour environment)
- Precisely characterize cell and sub-cellular damage
- Consolidate collaborations with industrials and clinical partners

## Does GATE10 will become THE gold-standard opensource multi-scale simulation platform?

- Establish a sustainable framework with IN2P3 and INSERM/ASNR partners
- Consolidate our collaboration with the Geant4-DNA collaboration
- Promote the usage of the platform (trainings, schools...)
- Propose high-quality research service provision

Extension of the GATE MARIM DB to artificial radioisotopes



Apply to European or PEPR calls in radioprotection



## Can we develop cross-species biophysical models that predict risk from microdosimetric parameters?

- Integrate radiobiological weighting factors (RBE, radiation quality, LET) for environmental dose–effect extrapolation.

## How do microdosimetric energy distributions correlate with biological endpoints across species?

- DNA double-strand break yields, oxidative stress, bystander effects, reproductive toxicity, etc.
- Are there conserved biomarkers of radiation effect applicable to both humans and wildlife?

## How can microdosimetry models be integrated into One Health risk-assessment systems?

- Combine environmental dosimetry, ecotoxicology, and human radioprotection databases.
- Develop interoperable data standards linking microdosimetric metrics to exposure and health outcomes.



**Merci pour votre attention**

**[lydia.maigne@clermont.in2p3.fr](mailto:lydia.maigne@clermont.in2p3.fr)**