

Geant4-DNA & micro/nanodosimetry: recent developments and perspectives

Sébastien INCERTI

CNRS Nuclei & Particles, LP2i, Bordeaux, France

sebastien.incerti@cnrs.fr

On behalf of the Geant4-DNA Collaboration

Hi-MoCaRT Workshop
Sykia, Greece
March 5-6, 2026



geant4-dna.org

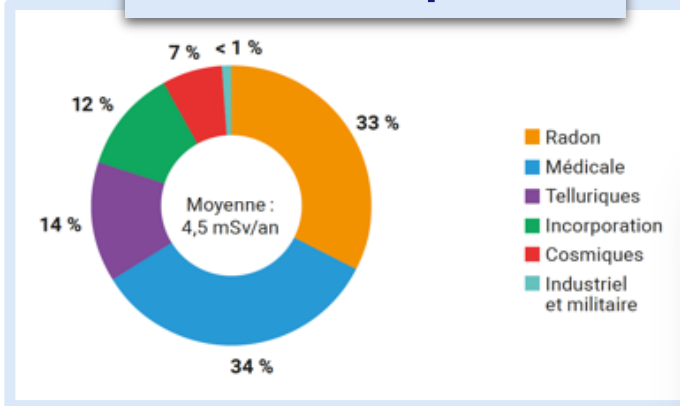
Geant4 version 11.4.0

Context: exposure to ionizing radiation

1 mSv/year
Public

Increasing dose & dose rate *

Chronic exposure



IRSN, France (2014-2019)

Repetitive medical imaging



UCSF & Harvard MS

~10 mSv / scanner abdomen

>100 mSv
Long-term effects

Space missions



ESA

Return trip
6 months: ~ 600 mSv



ESA

Major questions in radiation protection

- What are the **biological effects** of **low doses** of ionizing radiation?
- What are the **risks** associated with **high doses**?

« A major challenge lies in providing a sound **mechanistic** understanding of **low-dose radiation carcinogenesis** »
L. Mullenders et al. (2009)

➔ The Monte Carlo approach...



ESA

6 months = ~ 160 mSv

~2,6 times ISS

Radiotherapy



NCC

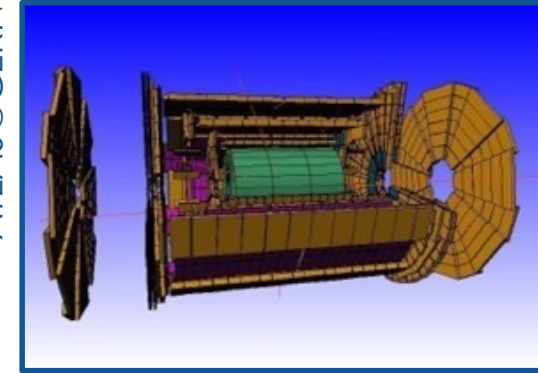
10⁻⁴-10⁻⁵ Gy/s

* Equivalent or effective

The « **Geant4-DNA** » project

- Initiated in **2001**, based on an idea of the **European Space Agency** (P. Nieminen)
 - To develop the **first open source platform** able to **simulate mechanistically the biological effects of ionizing radiation at cellular scale** during manned space missions
- Set of **C++ libraries** able simulate the different stages of the effects of ionizing irradiation
 - Open source, distributable (many OSs), user extensible (OO)
 - Radiation **physics** (particle-matter interactions), radiation **chemistry**, radiation **biology**...
- Fully integrated in the « **Geant4** » Monte Carlo simulation toolkit
 - **Geometry and tracking** – version **4**
 - Developed by an international collaboration, initially for the simulation of the large experiments of the LHC at CERN
- First release of « **Geant4-DNA** » physics models in **2007 (!)**
 - **Step-by-step** simulation of particle transport down to very low energy (~ 10 eV) in the biological medium, under the coordination of INFN Genova, Italy
- **International collaboration established in 2008**
 - 70 collaborators in Oct. 2025
 - Coordinated by CNRS Nuclei & Particles (IN2P3)

ATLAS@CERN



geant4.org



geant4-dna.org



Why Geant4-DNA?

- Main **requirements** for mechanistic radiobiological simulations -

- **Physics: High spatial resolution (down to nm),** through **reliable physics** for **sub-keV** energies

Geant4:

Limited spatial resolution, $E_{\text{limit}} \sim 250\text{eV}$ / Fast

Geant4-DNA:

High spatial resolution, $E_{\text{limit}} \sim 10\text{eV}$ / **Slow**

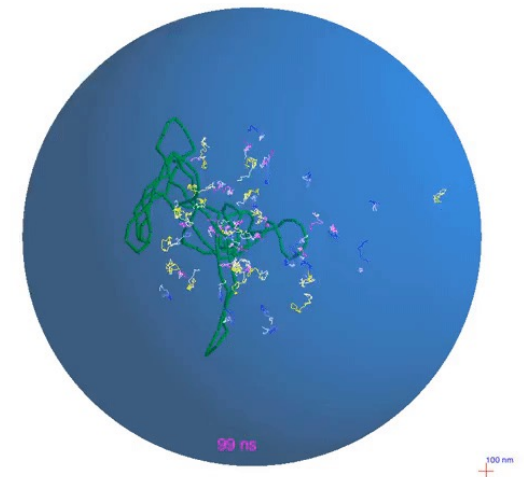
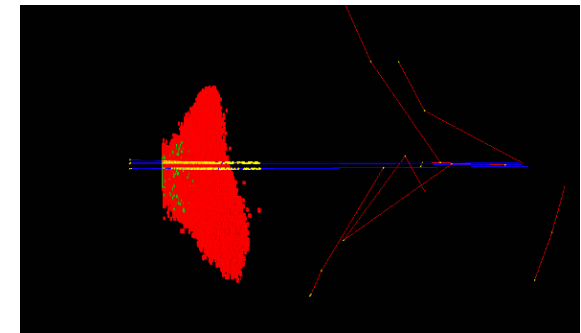
- **Chemistry: Interface for water radiolysis**

Geant4:

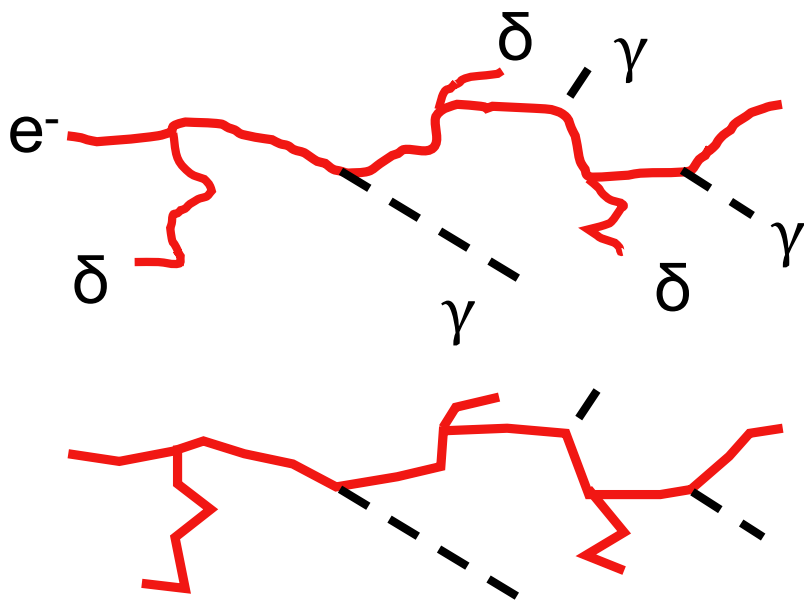
No interface

Geant4-DNA:

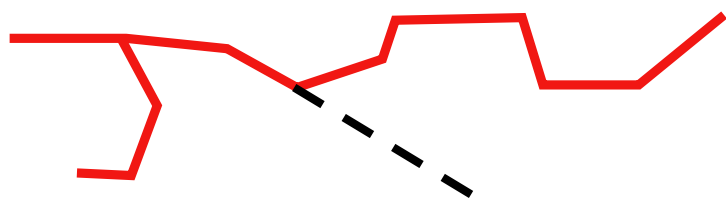
Production/Diffusion of chemical species



Requirement for physics: **High spatial resolution**



High accuracy/Slow computing



Low accuracy / **Fast computing**

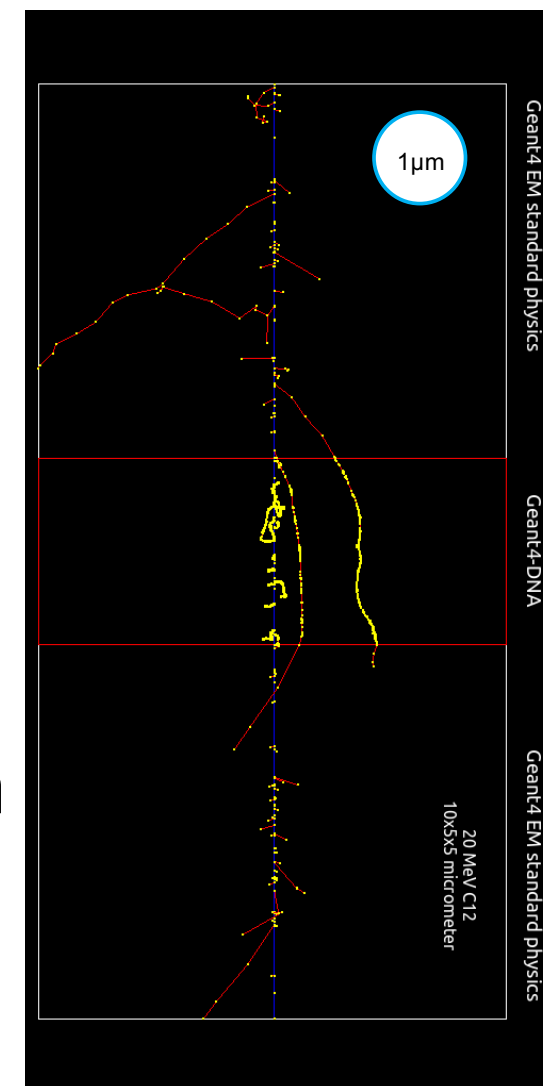
Trajectory in **real world**

Track-Structure approach

- **All physical interactions** are simulated individually in a sequential manner
- Example: **Geant4-DNA**, PARTRAC, RITRACKS, NOREC, KURBUC, PHITS-TS...

Condensed-History approach

- Several discrete physical interactions are “condensed” into a single transport step
- Multiple-scattering approximation
- Example: **Geant4**, PHITS, EGS, FLUKA, PENELOPE, MCNP...

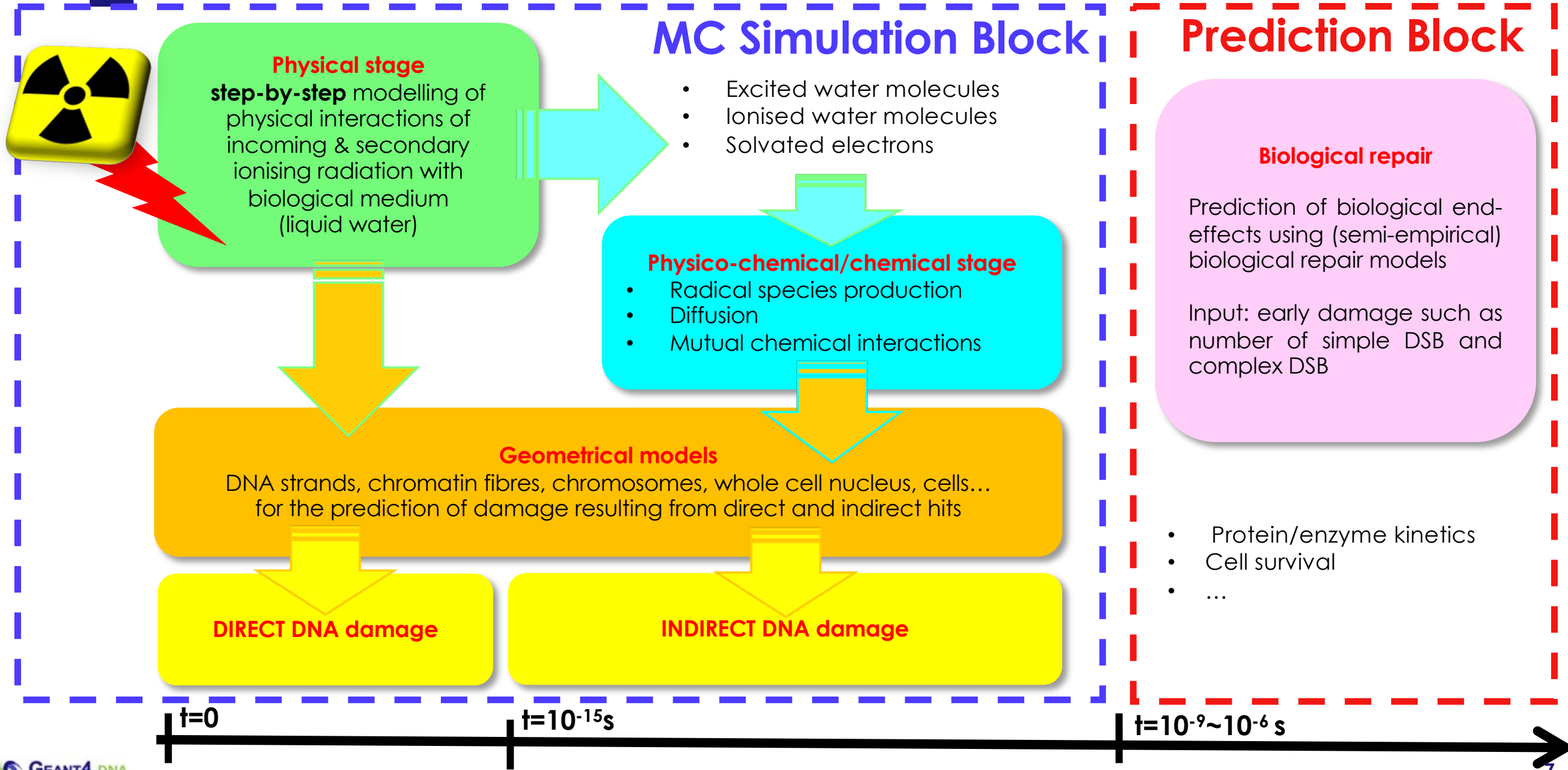


The **unique capabilities** of TS codes

- Simulation of **energy deposition in nm- μ m volumes**
 - **Microdosimetry** (stochastic quantities, e.g. lineal energy)
 - **Nanodosimetry** (ionisation cluster-size distributions) & “**direct**” action / DNA damage
- Simulation of the **chemical stage**
 - **Radiolysis** of water & radical diffusion
 - From **individual ionised and excited water molecules**... (from physics!)
 - “**indirect**” action / DNA damage
- Simulation of the **molecular spectrum of DNA damage**
 - “Complexity” of DNA damage (low- vs. high-LET)
- Provide **radiation “quality”**
 - Calculations of RBE at the DNA level
 - Calculations of the Quality Factor based on the lineal energy (e.g., ICRU 40, TDRA)

 See Alexis' talk

The Geant4-DNA approach



Physics / Geant4-DNA physics stage : 3 physics constructors

■ Geant4-DNA processes and models allows the transport in liquid water

- All processes are **discrete**, no condensed-history approximation
 - **Track-structure** simulations down to very low energy (~ 10 eV) in **liquid water**
 - Better spatial resolution but slower
- **Electrons**: ionisation, excitation, elastic scattering, vibrational excitation, electron attachment
- **Protons, H (0,+)**: ionisation, excitation, elastic, charge increase/decrease processes
- **Alpha, He(0+,2+)**: ionisation, excitation, elastic, charge increase/decrease processes
- **Generic ions**: ionisation

■ The 3 Geant4-DNA « recommended » Physics constructors for simulations in liquid water

- **G4EmDNAPhysics_option2** (since version 9.1): accelerated default constructor, simulating electron interactions (elastic, inelastic, dissociative attachment, vibrational excitation) **up to 1 MeV**, as well as other particle interactions
- **G4EmDNAPhysics_option4** (since version 10.2): contains electron elastic and inelastic models, **up to 10 keV**; now being extended up to 10 MeV (to be released)
- **G4EmDNAPhysics_option6** (since version 10.4): contains CPA100 electron elastic and inelastic models, **up to 256 keV**

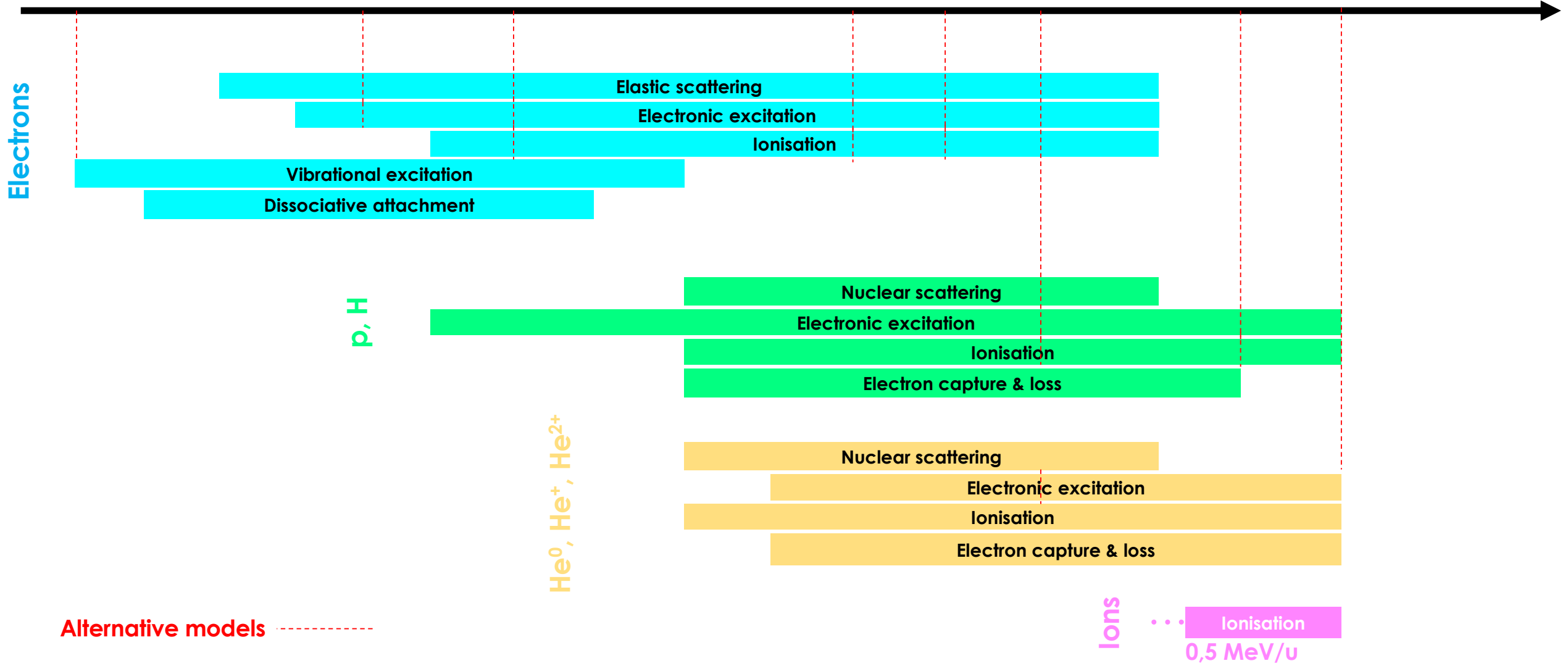
Developed
at Ioannina U.

NOTE

- Protons, alphas, ions can be tracked up to 300 MeV (/u for ions)
- Option4 and option6 can go up to 1 MeV (beyond their default limits, Born models are used)

Physics / Energy coverage of physics processes in liquid water

2 eV 4 eV 7,4 eV 8 eV 9 eV 10 eV 11 eV 13 eV 100 eV 1 keV 10 keV 255 keV 500 keV 1 MeV 100 MeV 300 MeV (/u)



Alternative models

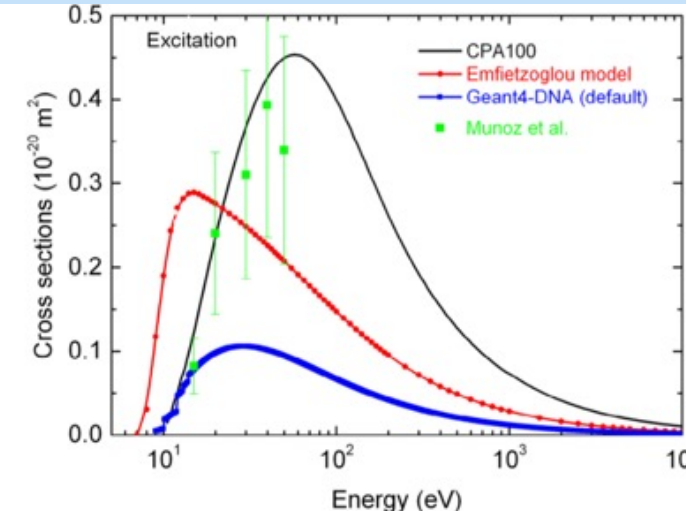
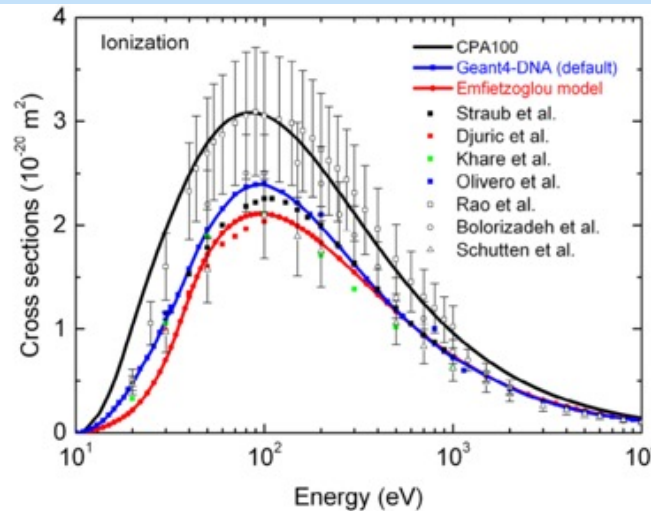
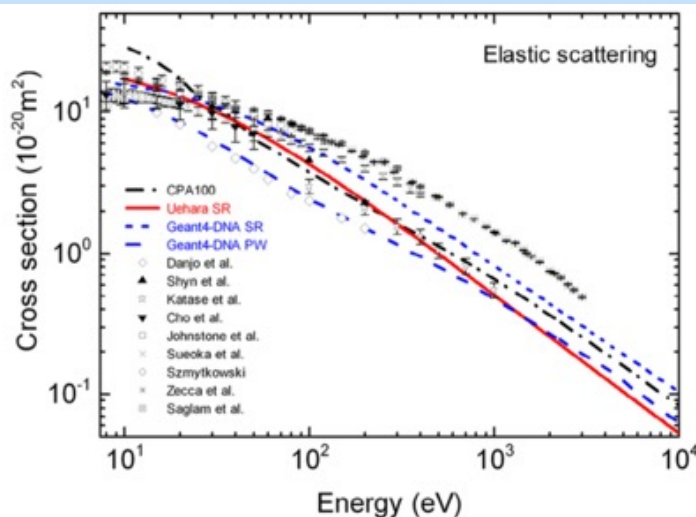
E.g. of validation and verification of Physics : cross sections (CS)

Electron CS:

Elastic

Ionisation

Electronic excitation



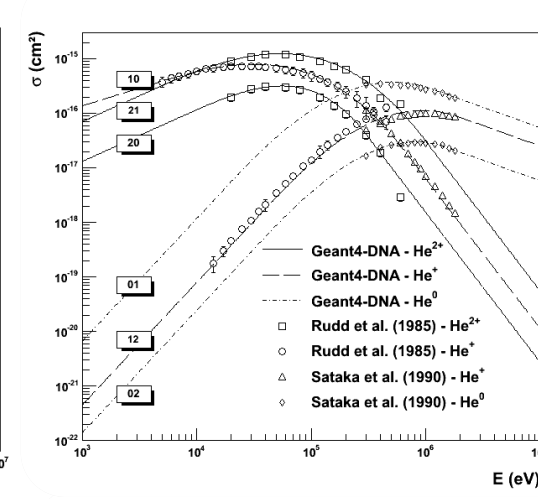
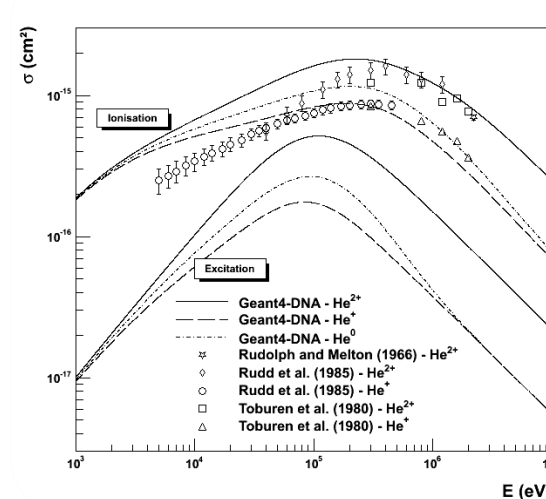
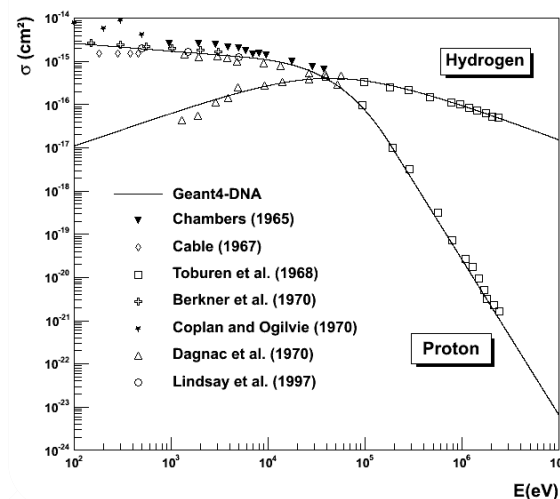
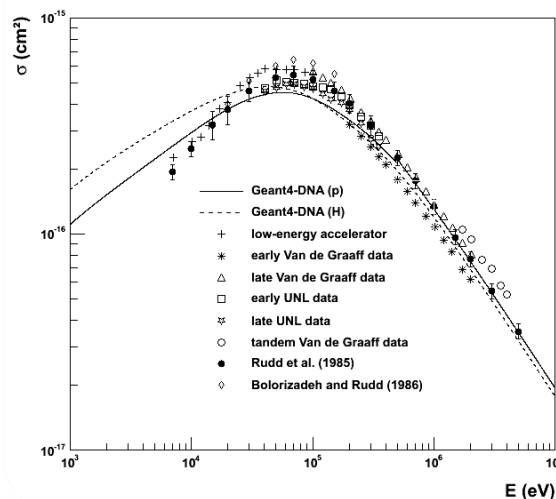
Proton CS:

Ionisation

Charge exchange

Helium CS: Ionisation

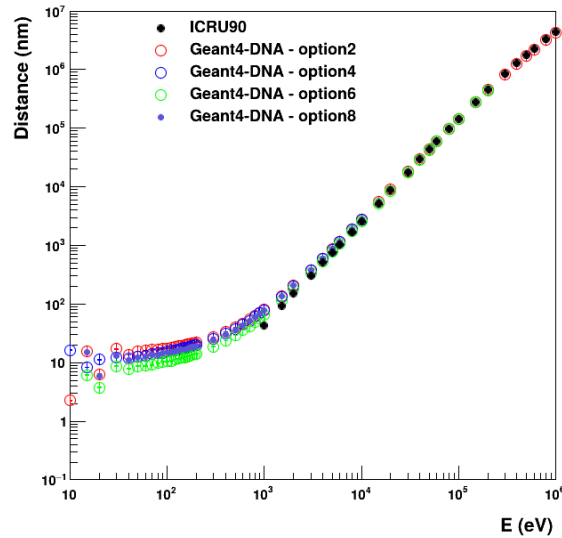
Charge exchange



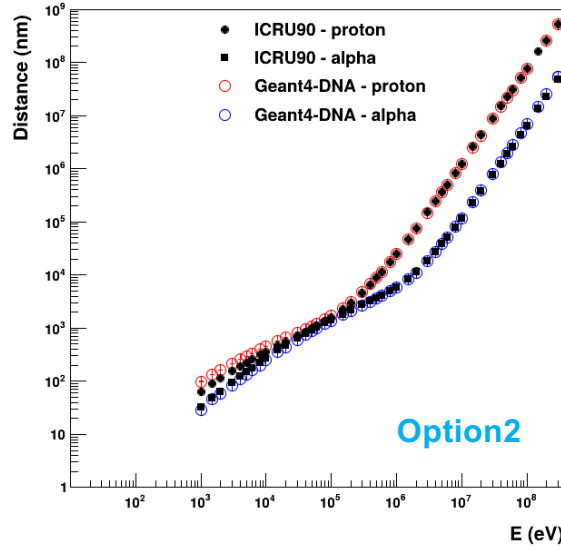
Example of performance : ranges & stopping powers

Range

electrons



protons & alphas

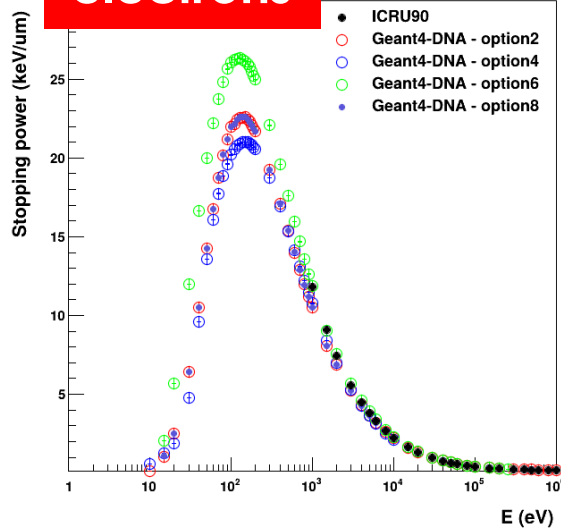


DNA options 2, 4 and 6

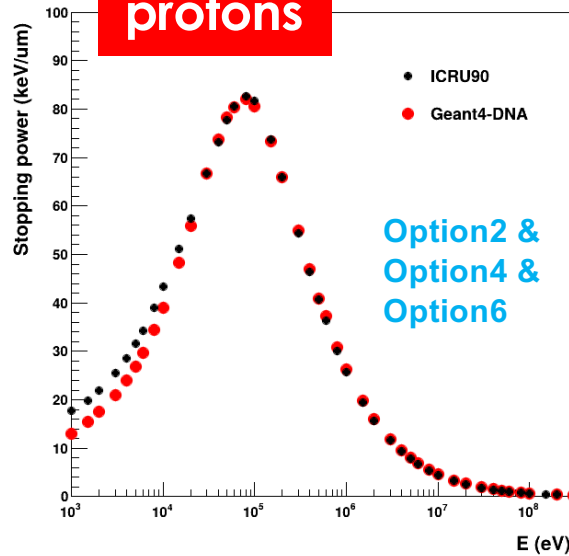
- Differ by their (alternative) electron models
 - no validation possible below 1 keV
- Are identical for light (p, He) and GenericIons
(Option 8 and cosmicDNA are being developed)

Stopping power

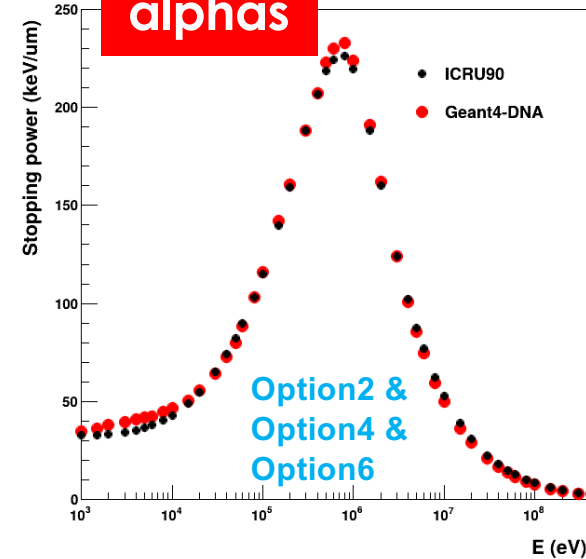
electrons



protons



alphas



Coming soon!

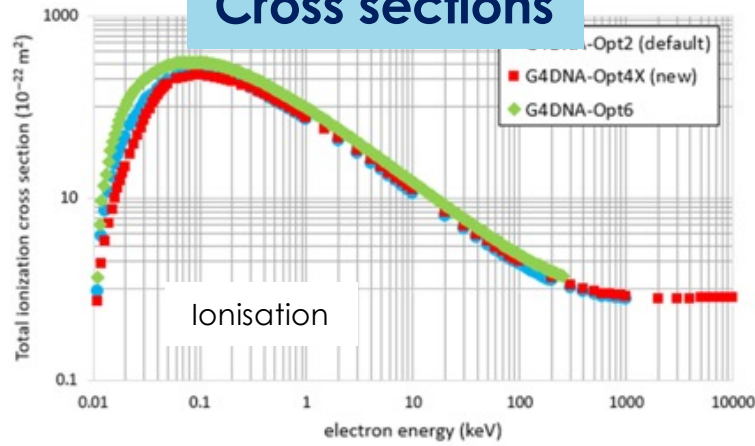
Appl. Sci. 15 (2025) 1183

Ioannina U. et al.

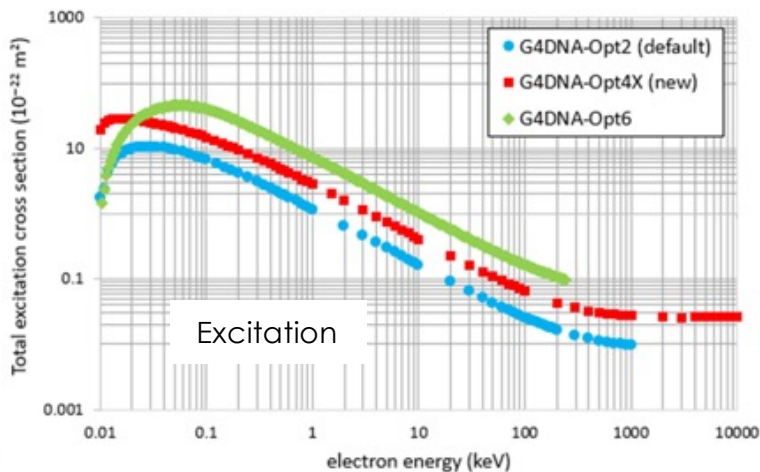
New liquid water model for electrons

- Will fully replace the **option4** model, up to **10 MeV**
 - Updated parameters of the Energy Loss Function
 - New **theoretical corrections** to the PWBA cross sections
 - most accurate theoretical approach among all constructors

Cross sections

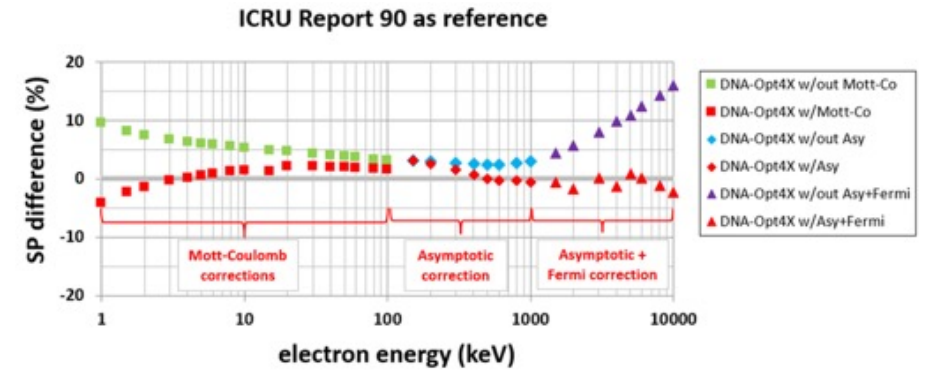
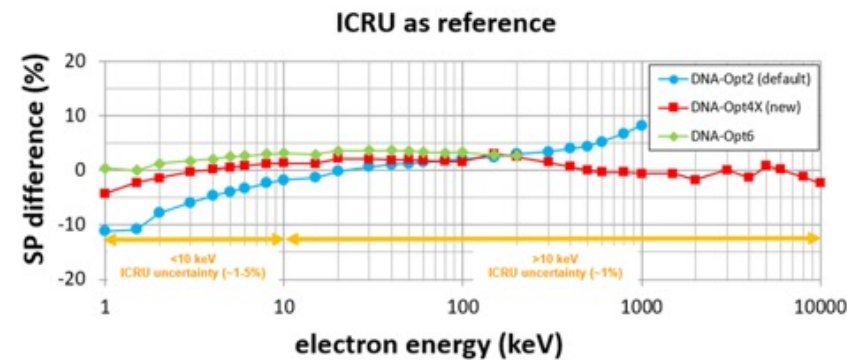
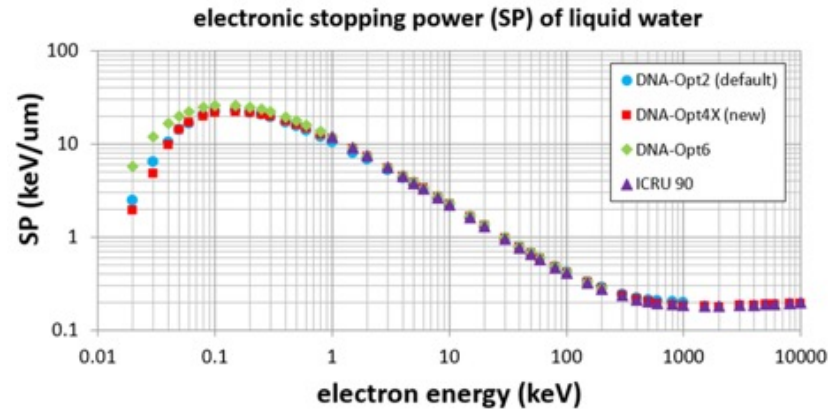


Ionisation

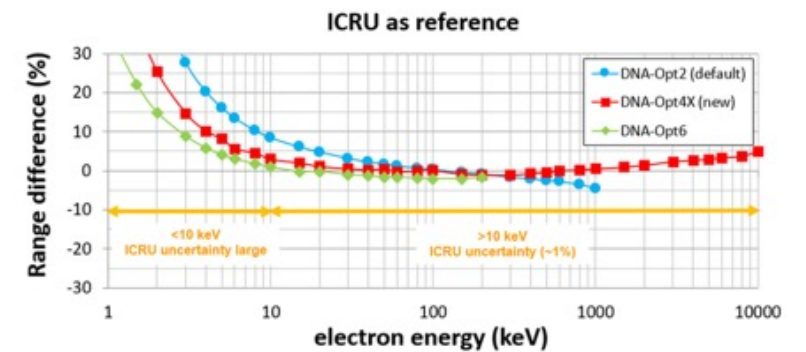
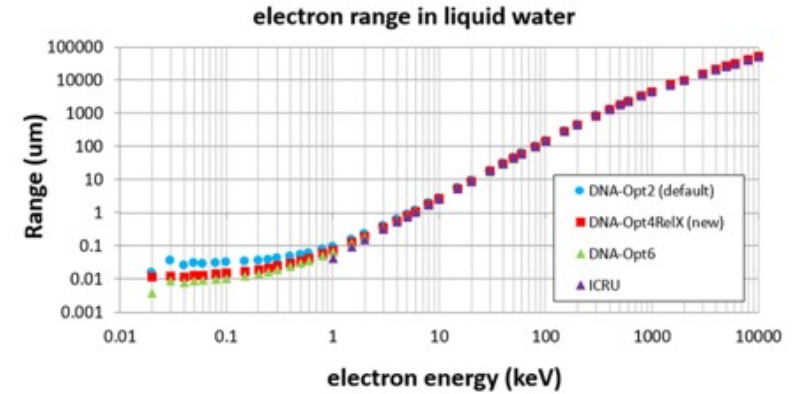


Excitation

(Electronic) stopping power



Range



Coming soon!

Beyond liquid water: new models for atmospheric simulations

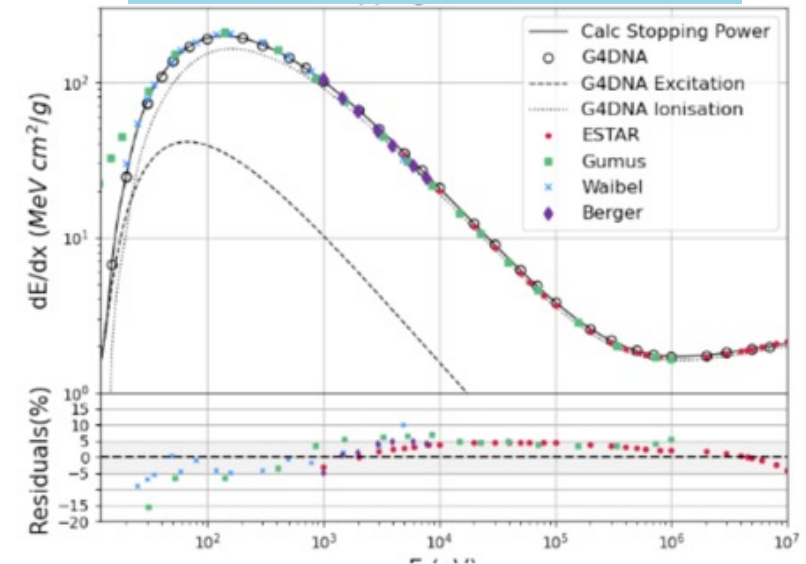
[Phys. Med. 128 \(2024\) 104838](#)

[Phys. Med. 114 \(2023\) 102661](#)

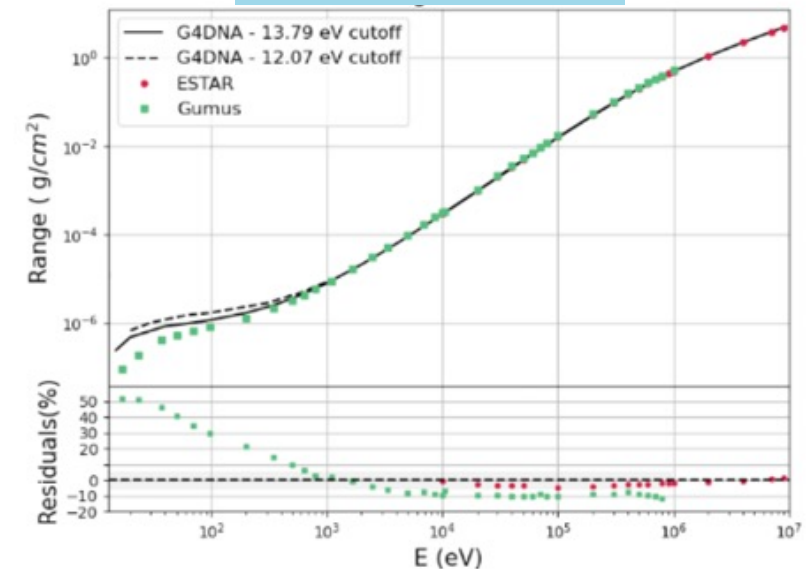
- Cross sections for **electron impact on N_2 , O_2 , CO_2** molecules have been implemented in Geant4-DNA (energy range: 10 eV – 10 MeV) for track-structure simulations in atmospheres
- 3 physics model classes:
 - **Elastic** scattering (Independent Atomic Model with Screening Coefficients)
 - **Ionisation** (Relativistic Binary Encounter Bethe Model)
 - **Excitation** (Porter's formula with fitted parameters)
- Ranges and stopping powers have been verified vs NIST
- Work in progress & future
 - A draft **physico-chemistry dissociation process** has been developed through the dissociation branching ratios for N_2 and O_2
 - Extension of cross sections to positrons (10 eV – 10 MeV)

Roma U. et al.

Stopping power in CO₂

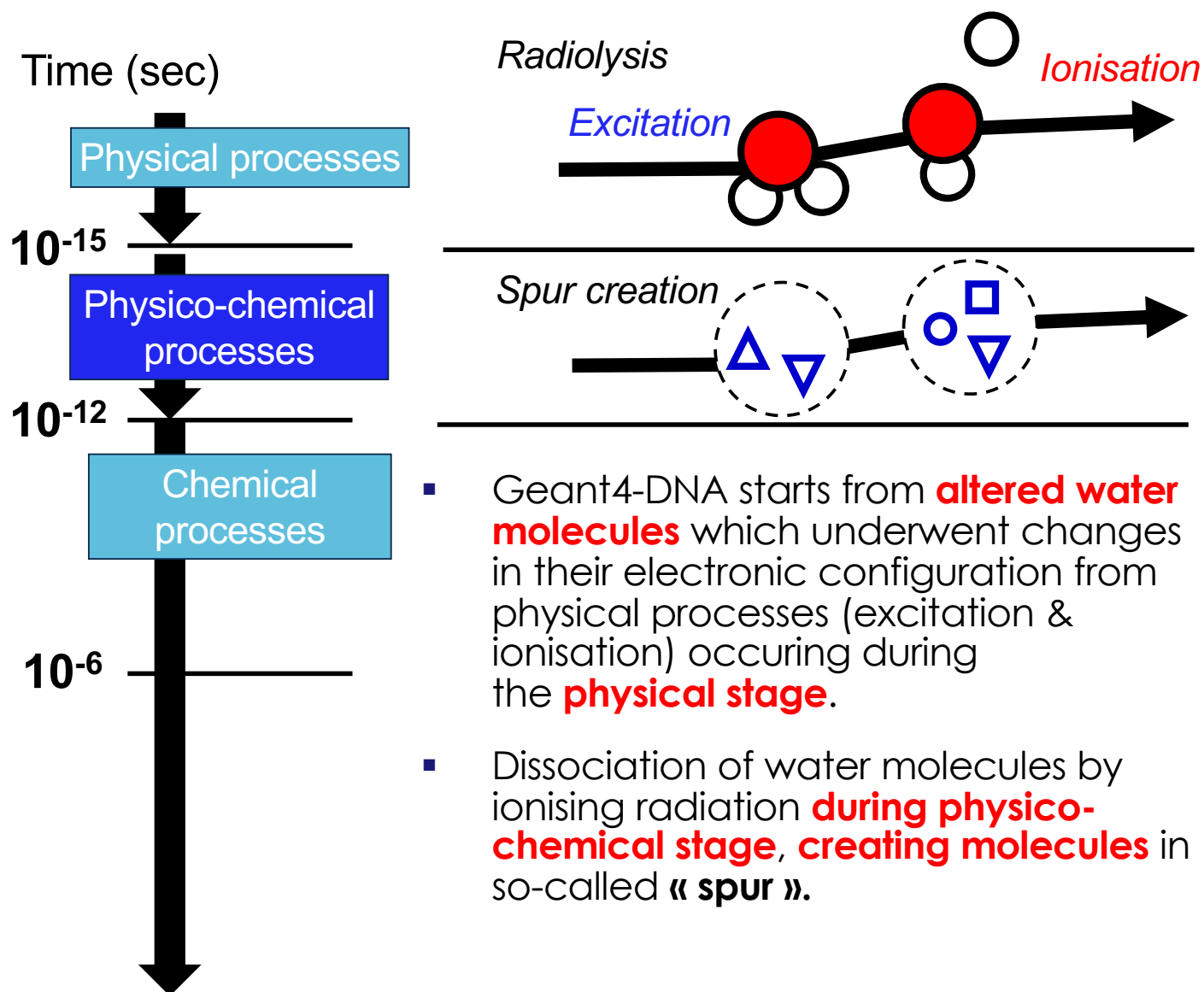


Range in CO₂



Satisfactory agreement on stopping power and ranges for incident energies exceeding 200 eV

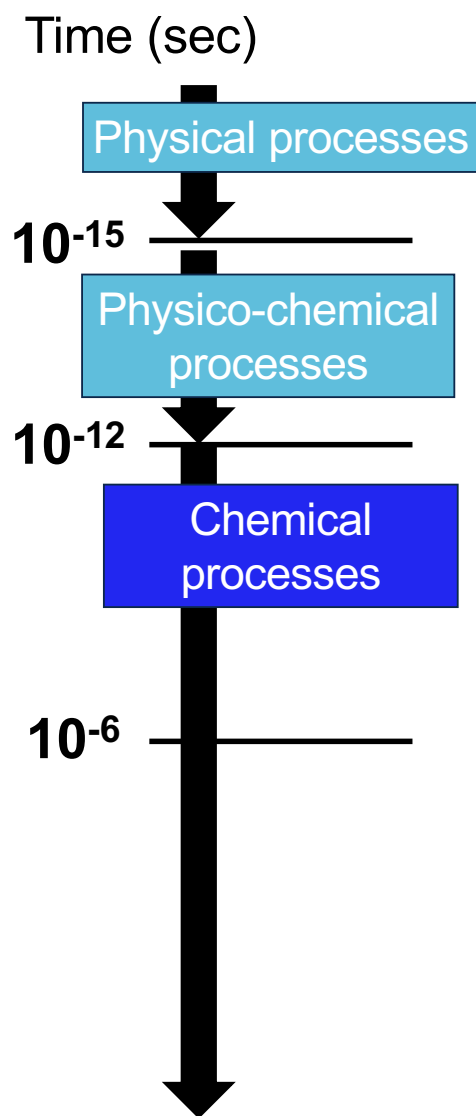
Chemistry / Physico-chemical stage: Molecule production



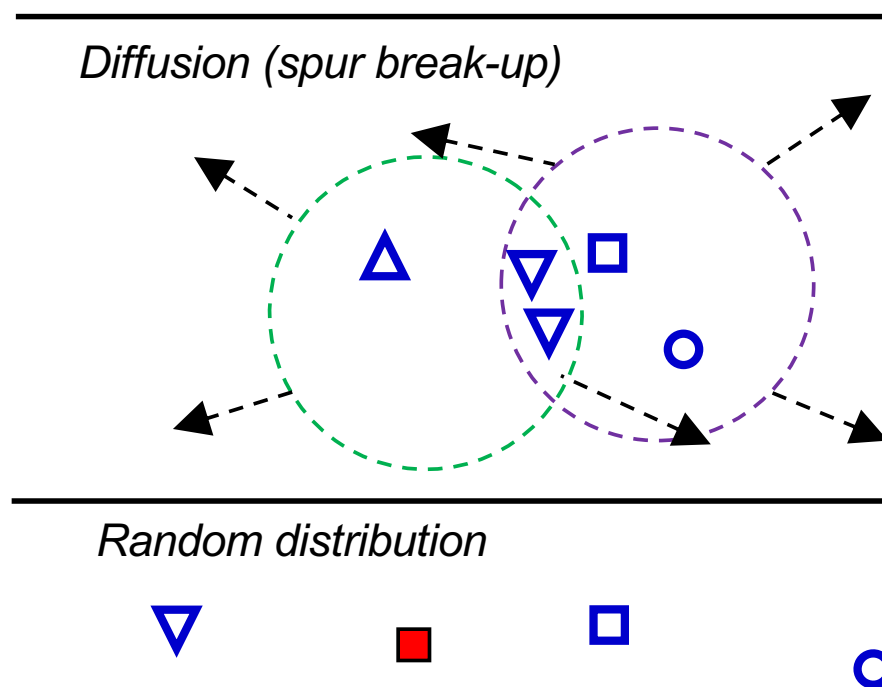
Electronic state	Dissociation channels	Fraction (%)
All single ionisation states	$H_3O^+ + \bullet OH$	100
Excitation state A1B1: (1b1) \rightarrow (4a1/3s)	$\bullet OH + H\bullet$ $H_2O + \Delta E$	65 35
Excitation state B1A1: (3a1) \rightarrow (4a1/3s)	$H_3O^+ + \bullet OH + e^-_{aq}$ $\bullet OH + \bullet OH + H_2$ $H_2O + \Delta E$	55 15 30
Excitation state: Rydberg, diffusion bands	$H_3O^+ + \bullet OH + e^-_{aq}$ $H_2O + \Delta E$	50 50
Dissociative attachment	$\bullet OH + OH^- + H_2$	100

Ref: [J. Comput. Phys. 274, 841-882 \(2014\)](#)

Chemistry / Chemical stage: Diffusion of molecules



- After the physico-chemical stage, molecules **diffuse, breaking-up spurs**.
- The molecules are distributed **homogeneously**, after about 1 μ s from irradiation.
- Most parameters can be easily changed by the user (e.g., diffusion coefficients).



Species	Diffusion coefficient D (10 ⁻⁹ m ² s ⁻¹)
H ₃ O ⁺	9.0
H•	7.0
OH ⁻	5.0
e ⁻ _{aq}	4.9
H ₂	5.0
•OH	2.8
H ₂ O ₂	1.4
H ₂ O	2.0

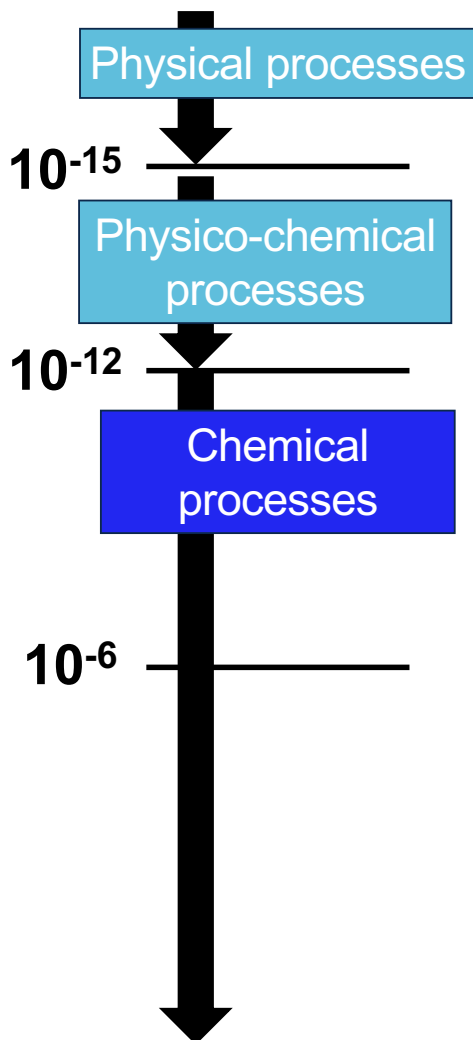
Ref: [J. Comput. Phys. 274, 841-882 \(2014\)](#)

Chemistry / Chemical stage: 4 alternative diffusion models

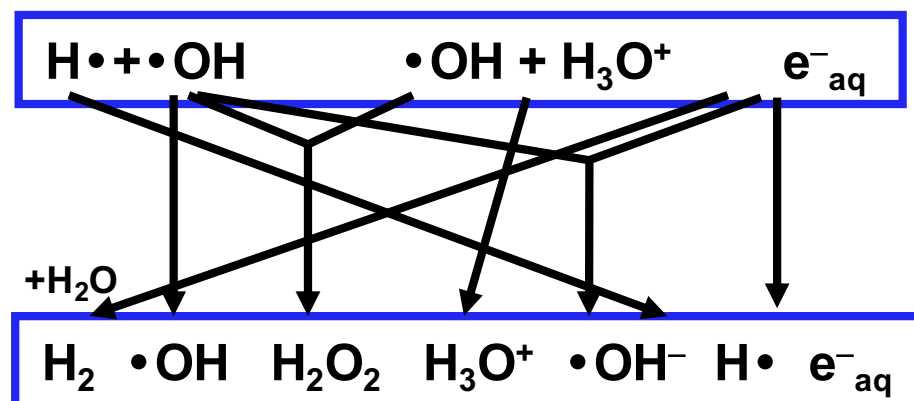
- **Step-by-Step approach (SBS)**
 - Transport of chemical species in **discrete steps** (or time steps Δt) through Brownian motion until a chemical encounter defines a reaction.
 - Allows full **spatio-temporal tracking** of species
- **Independent Reaction Time (IRT)**
 - Calculates chemical reaction probability
 - Reaction times are sampled for every potential pair of reactants
 - Reactions are then modelled sequentially, starting with those with the shortest reaction time
 - Products of chemical reactions may undergo further reactions
 - **Very fast**, but **NO** spatiotemporal information on species
- **Synchronized Independent Reaction Time (IRT-sync)**
 - It uses as the time step the randomly sampled time given by the IRT model until the next expected reaction
 - After each time step, synchronization of the time and position of all diffusing species
 - Allows **access to spatiotemporal information at specific times for all chemical species**, which can then be coupled with information on **geometry** and boundaries.
- **Mesoscopic (new)**
 - **A compartment-based representation that describes the evolution of species through their concentrations in different compartments (voxels)**
 - **Can be used beyond the microsecond, at higher LET ...**

Chemistry / Chemical stage: Reactions

Time (sec)



- During the chemical stage, a molecule can encounter and react with another molecule, creating a new molecule.
- Geant4-DNA tables to manage the reaction probabilities, e.g. as listed.



Reaction	Reaction rate ($10^7 \text{ m}^3 \text{ mol}^{-1} \text{ s}^{-1}$)
$H_3O^+ + OH^- \rightarrow 2 H_2O$	14.3
$\bullet OH + e^-_{aq} \rightarrow OH^-$	2.95
$H\bullet + e^-_{aq} + H_2O \rightarrow OH^- + H_2$	2.65
$H_3O^+ + e^-_{aq} \rightarrow H\bullet + H_2O$	2.11
$H\bullet + \bullet OH \rightarrow H_2O$	1.44
$H_2O_2 + e^-_{aq} \rightarrow OH^- + \bullet OH$	1.41
$H\bullet + H\bullet \rightarrow H_2$	1.20
$e^-_{aq} + e^-_{aq} + 2 H_2O \rightarrow 2 OH^- + H_2$	0.50
$\bullet OH + \bullet OH \rightarrow H_2O_2$	0.44

Ref: [J. Comput. Phys. 274, 841-882 \(2014\)](#)

Chemistry / Chemical stage: 4 chemistry constructors

- The chemistry constructors gather

- **chemical species** definition
- description of the **physico-chemical** stage
- **chemical reactions**

- List of Geant4-DNA chemistry constructors

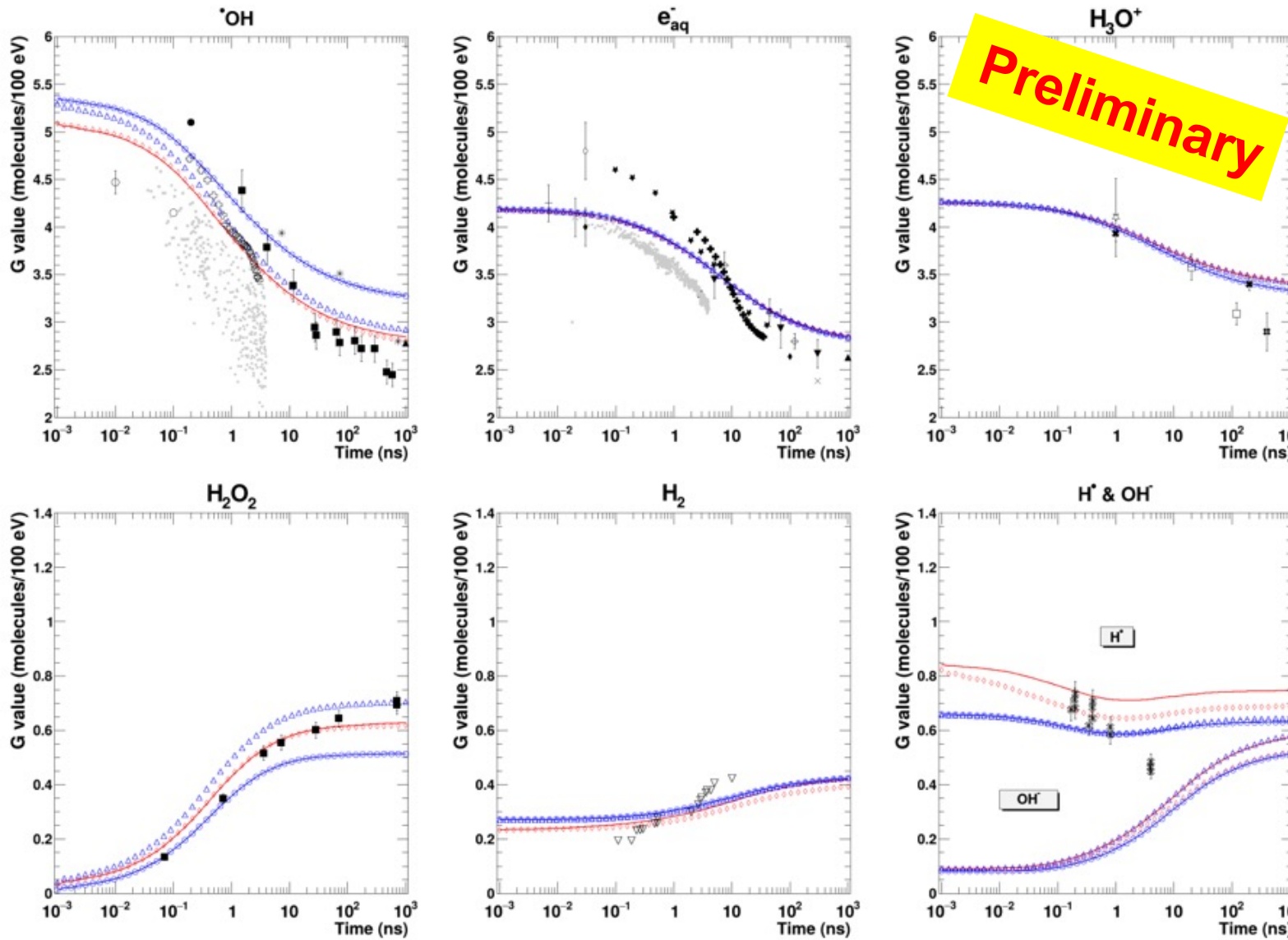
- **G4EmDNAChemistry**: First constructor implemented with parameter values from Karamitros et al.
– from PARTRAC
- **G4EmDNAChemistry_option1**: Implements a revisited set of chemistry parameters from Shin et al.
– from TRACs + Burns et al. (1981) + Rowe et al. (1988)
- **G4EmDNAChemistry_option2**: Includes chemistry parameters for reactions with DNA components
– from Buxton et al. (1988)
- **G4EmDNAChemistry_option3**: Implements the IRT approach from Ramos-Mendez et al. (2020)
– from RITRACKS & Elliot et al. (1994)

- They are compatible with several **diffusion models**

- **SBS** is available to all chemistry constructors
- option3 is also compatible with the **IRT and IRT-syn** diffusion models (fastest) – currently **recommended**

Example of performance: radiochemical yields vs time

By Adrien Paillet et al., CNRS/Bordeaux



Geant4-DNA - SBS - G4EmDNAPhysics_option2

- UI
- G4EmDNAChemistry_option3
- G4EmDNAChemistry
- ▲ G4EmDNAChemistry_option1
- G4EmDNAChemistry_option2

Experimental values for incident electrons

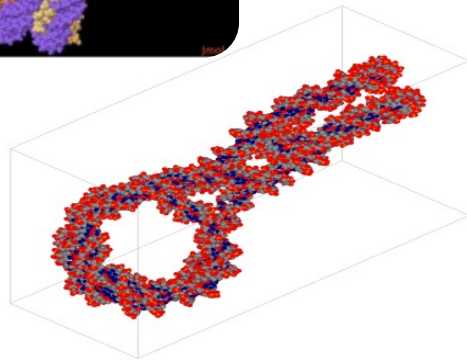
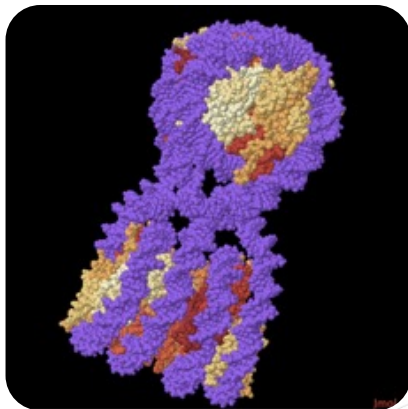
- Wang et al. (2018) - 7.5 MeV
- Pachnerova et al. (2015) - PROTONS 30 MeV
- Ma LTD et al. (2015) - 7 MeV
- Ma STD et al. (2015) - 7 MeV
- El Omar et al. (2011) - 7 MeV
- × Muroya et al. (2005) - 20 MeV
- Bartels et al. (2000) - 20 MeV
- LaVerne (2000) - source ^{60}Co
- ▲ Elliot et al. (1993) - 2.25 MeV
- ▼ Shiraishi et al. (1988) - 35 MeV
- Anderson et al. (1985) - 3.5 MeV
- △ Belloni et al. (1983) - 0.6 MeV
- ◇ Sumiyoshi and Katayama (1982) - 45 MeV
- (× 0.8) Jonah et al. (1977) - 20-22 MeV
- ★ Jonah et al. (1976) - 20-22 MeV
- ✱ Pikaev et al. (1976) - 5 MeV
- ▽ Draganic and Draganic (1975) - source ^{60}Co
- ◆ Wolff et al. (1973) - 41 MeV
- ◆ Jonah et al. (1973) - 19 MeV
- ◇ Buxton (1972) - 2.9 MeV
- ✱ Draganic and Draganic (1972) - source ^{60}Co
- ◆ Cercek and Kongshaug (1969) - source ^{60}Co & 8 MeV
- ◆ Schmidt and Ander (1969) - 15 MeV

Geometries / Geant4-DNA models (available in examples)



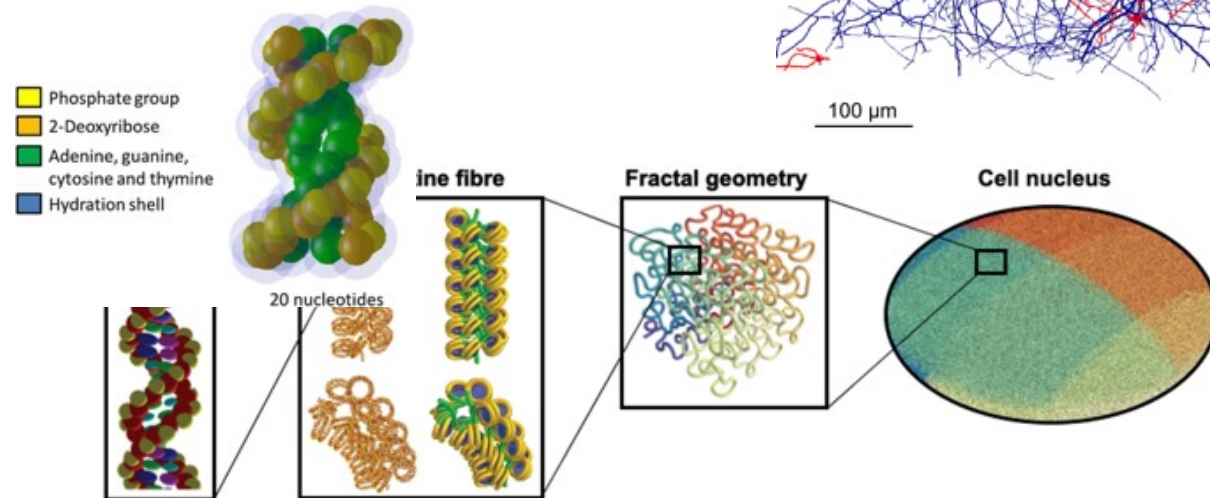
Atomic scale

- `pdb4dna`



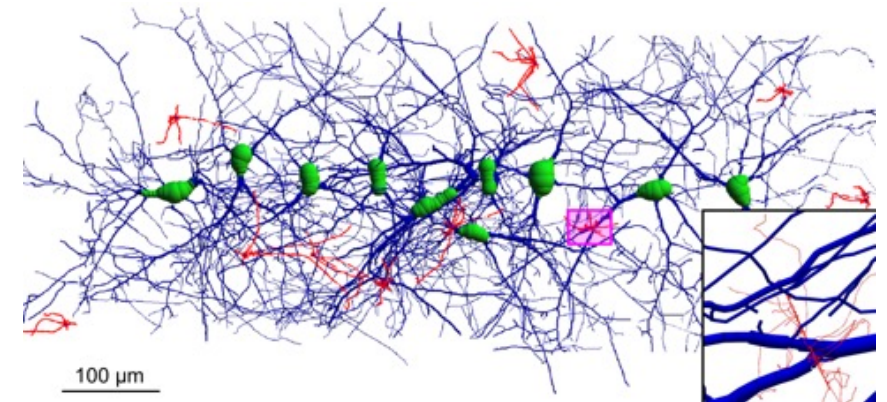
Molecular scale

- `wholeNuclearDNA`
- `dnadamage1,2`
- `dsbandrepair`
- `molecularDNA`

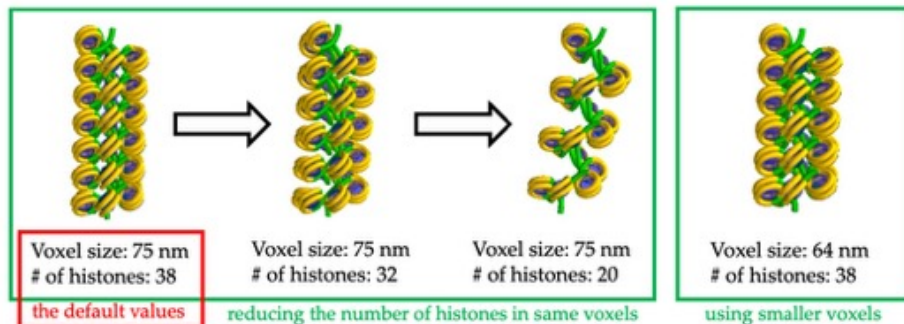


Cellular scale or larger

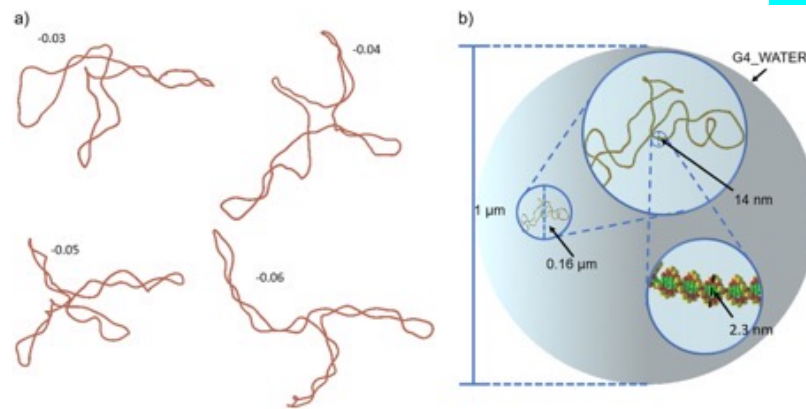
- `microbeam`
- `neuron`



Geometries: library

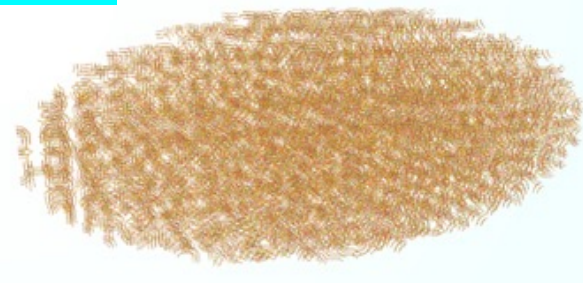


Phage DNA & plasmids



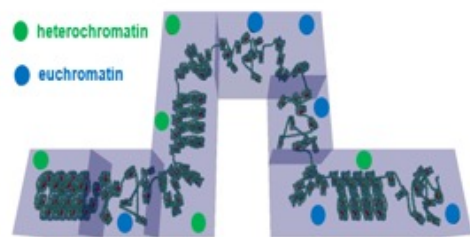
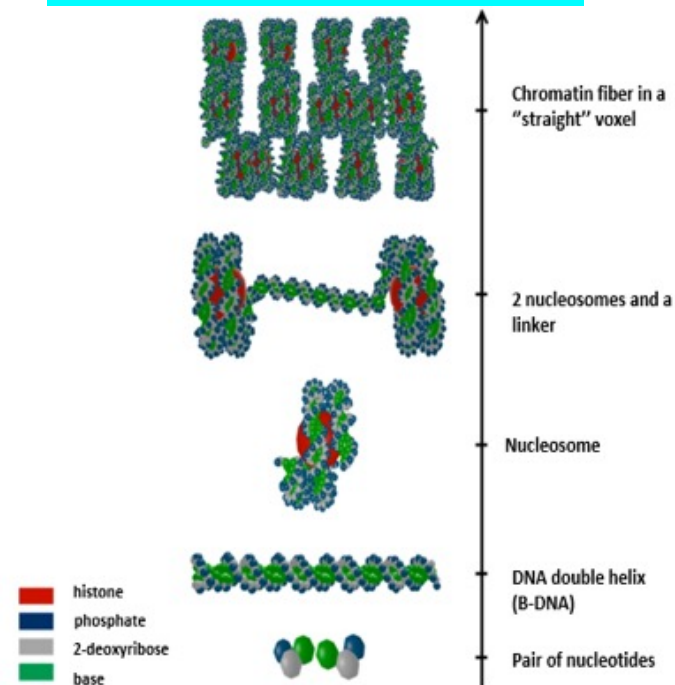
Yeast

E. coli bacterium



Available in the “**moleculardna**” and “**dsbandrepair**” simulation chains

Voxels of chromatin

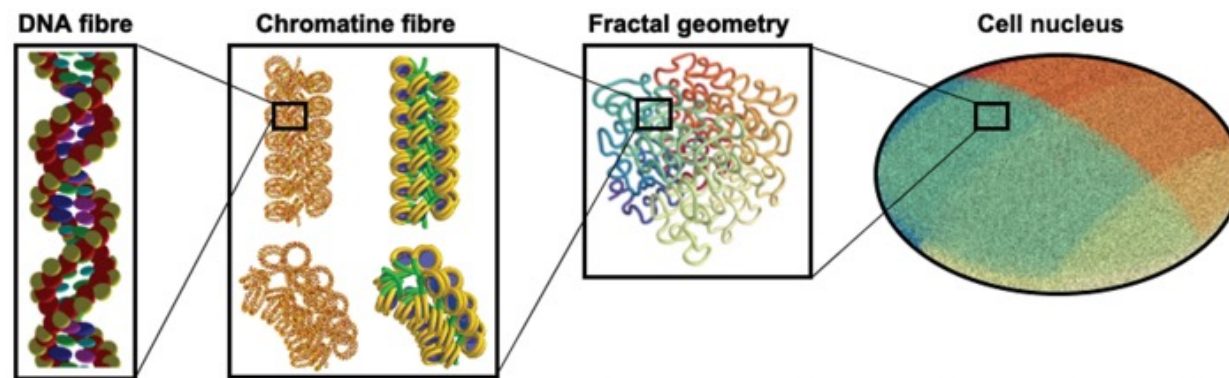
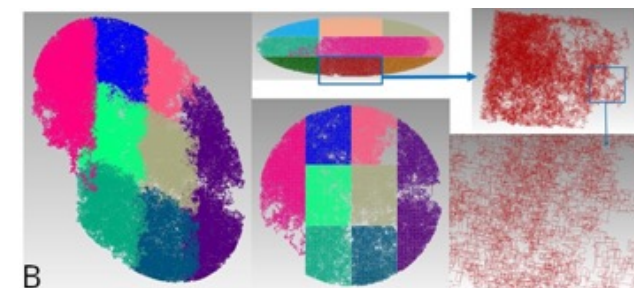


Human fibroblast (6 Gbp)



Human endothelium (6 Gbp)

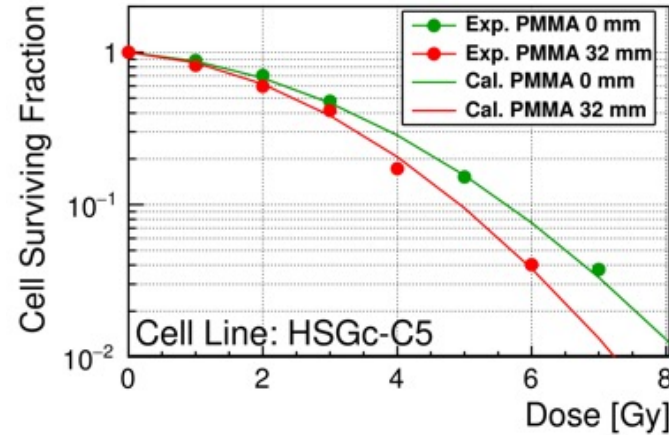
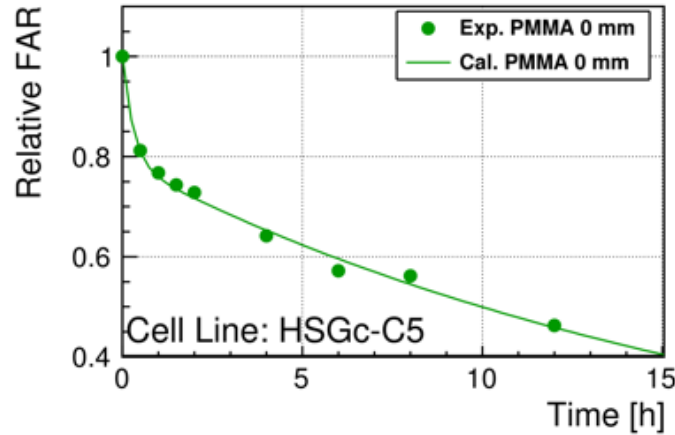
Various cell nuclei



DNA damage simulation: Ex. of validation and verification of the 2 simulation chains

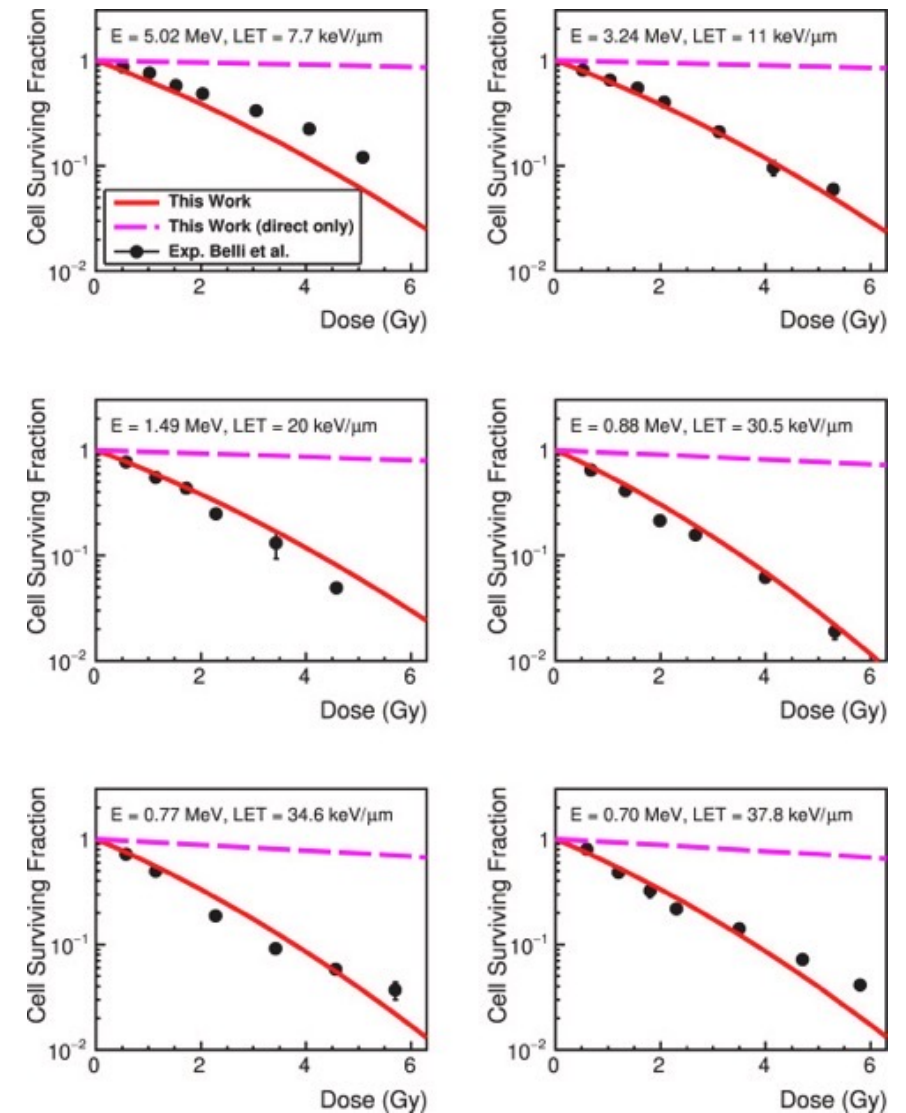
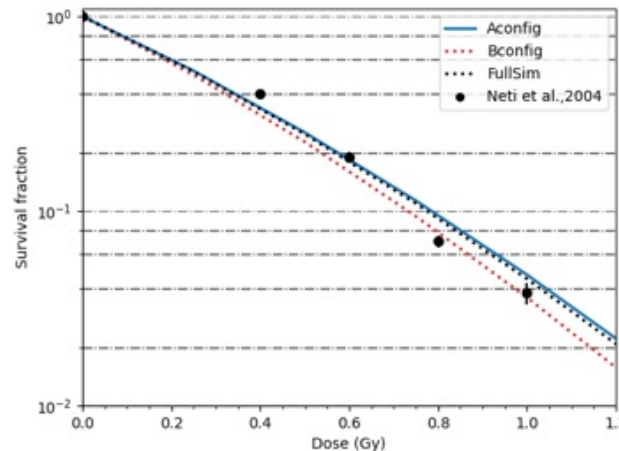
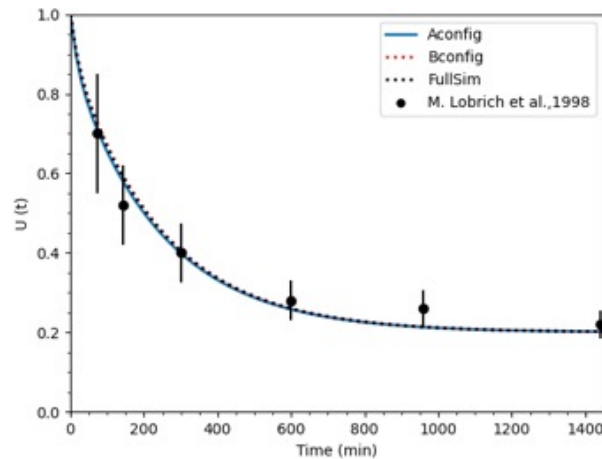
moleculardna: proton, TLK model, HSGc-G5 cell

moleculardna: proton, TLK model, V79 cell



dsbandrepair:
alpha, LEM-IV model

dsbandrepair:
alpha, TLK model



Computing time: drawback

Physics

- Physical interactions are simulated step-by-step (individual molecular interactions required like ionisations & excitations)
 - Impacts **ions heavier than alpha particles**, especially **at high LET**: C, N, O... produce **so many electrons**...
 - Computing optimization **to investigate** : biasing? Other?

Chemistry

- Time step model is the main source:
 - SBS approach is the reference & slowest one : now rarely used
 - IRT-sync preferred** when tracking of species in geometry is needed

Combination Physics + Chemistry + (huge) Geometry

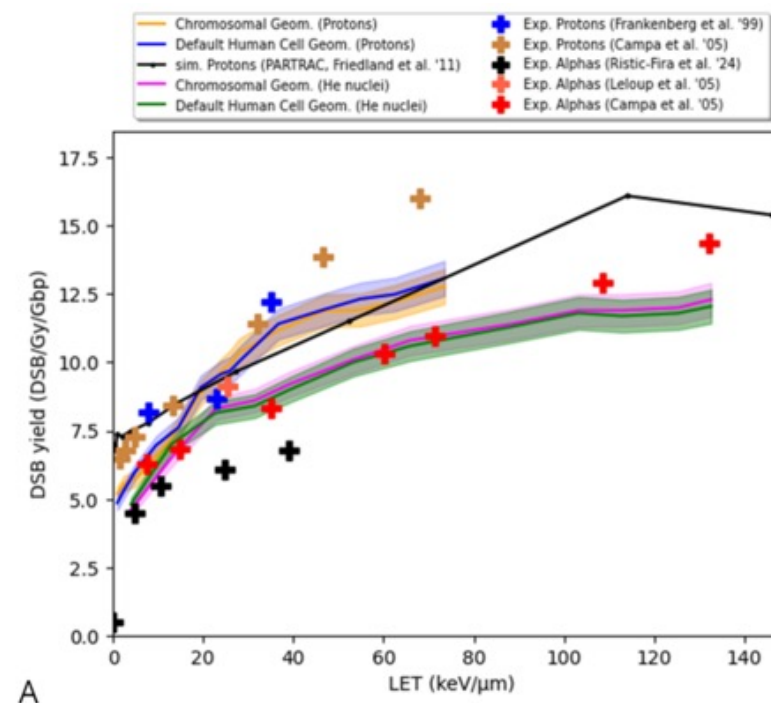
- Use case: prediction of early damage in a cell nucleus (6.4 Gbp) at high LET
 - Alphas of 30 MeV** (LET is about 23 keV/ μm) : 1876 alphas take about 21 hours on 1000 CPUs (2 alphas/CPU)
 - At 5 MeV** (LET is around 80 keV/ μm), **more than 6 days for 1000 particles (1 alpha/CPU)**...

CPU time for G-values

TABLE VIII. Simulation times (rounded) needed to produce Figures 8 and 9. Simulations were distributed on 90 threads (see computer specifications in Section II C 3). For G versus time simulations, 10^4 electrons are shot. For G versus MZ^2/E simulations, 10^4 electrons, 270 protons and 10 alpha particles are shot per incident energy value.

	SBS	IRT	IRT-syn
G versus time	9 h 40 min	< 1 min	10 min
G versus MZ^2/E			
Electrons	-	< 1min	7 min
Protons	-	5 h 40 min	32 h 30 min
Alpha particles	-	17 h 20 min	26 h 00 min

DNA-DSB versus LET



1) Geant4-DNA on GPU: MPEXS-DNA

- Geant4 KEK team, Japan (S. Okada et al.)
- Reimplemented Geant4-DNA processes of the **physics** stage and the **chemical (SBS)** stage by using the **CUDA language**
- MPEXS-DNA achieves similar accuracy Geant4-DNA and PARTRAC
- Allows calculations that are, at maximum, **2029 times** faster than conventional simulations using a CPU (Phys + Chem)
- No handling of geometries
- Accessible under contract only...
- **An approach to follow?**

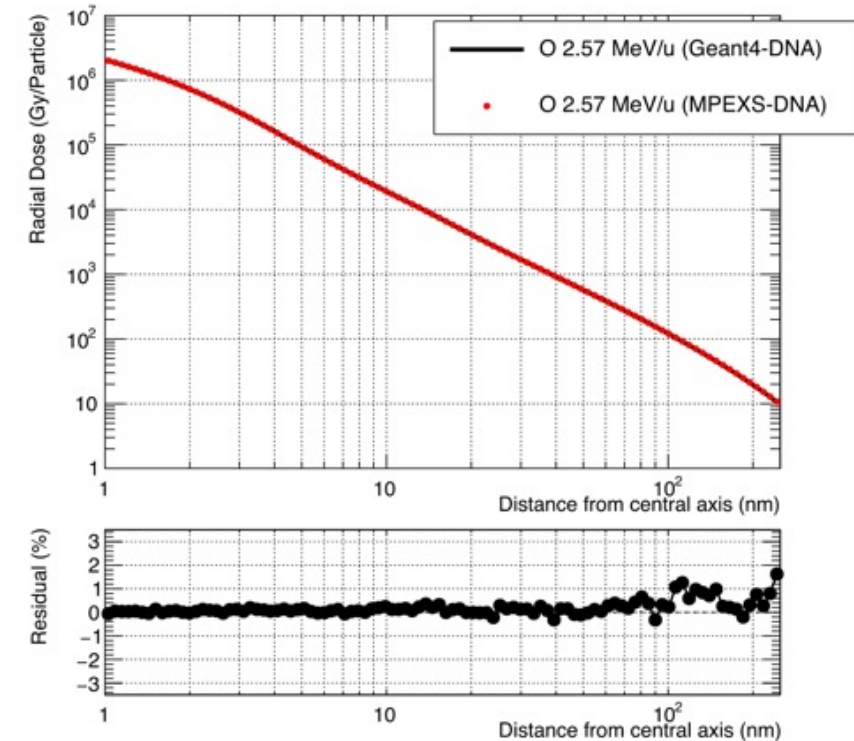


TABLE XVIII. Benchmark results for 5 MeV proton irradiation between Geant4-DNA 10.02 p03 (CPU) and MPEXS-DNA (GPU)

	Geant4-DNA	MPEXS-DNA
Initial particle	Protons with kinetic energy of 5 MeV	
Target size	$1 \times 1 \times 1 \mu\text{m}^3$	
Number of voxels in the target	A single voxel	
Throughput (the physics stage)	1155.8	615 902.2
Speedup factor	–	532.9
Throughput (the chemical stage)	0.265	536.04
Speedup factor	–	2023
Throughput (the physics and the chemical stages)	0.264	535.58
Speedup factor	–	2029

2) Geant4-DNA & AI: GANDALF

- INFN-LNS team, Italy (A. Sciuto et al.)
- Python-based ML tool called **GANDALF**
 - A training module fed with Geant4-DNA (early DNA damages) and Geant4 (LET) data
 - A ML solver that uses LET as input to predict damage yields
- Tested on **E. coli bacterium**
 - About 4.63 Mbp of DNA
- Can reproduce damages
 - E.g. SSB/DSB vs LET
- Another approach to follow for TS Physics, Chemistry ... ?
 - Even if models continue to be improved

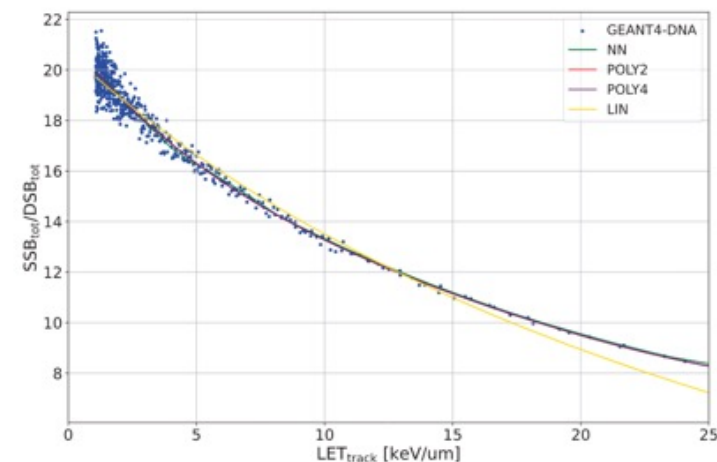
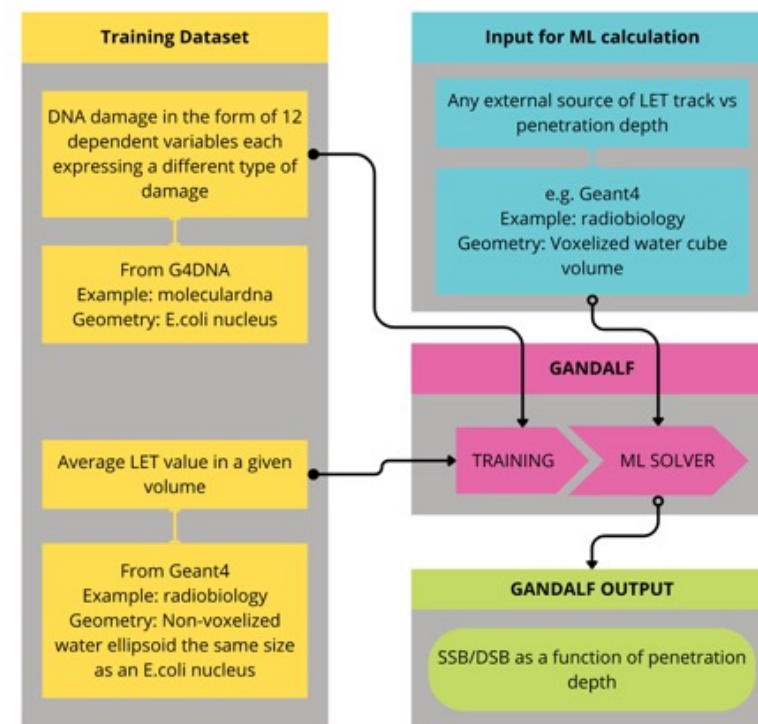


Fig. 4. Comparison between SSB_{tot}/DSB_{tot} versus LET_{track} obtained in the training range with NN (in green), POLY2 (in red), POLY4 (in purple) and LIN (in yellow) against data generated directly with Geant4-DNA (in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Geant4-DNA: What to expect in the coming years

■ Physics

- Delivery of recently published physics models:
 - **e-** models in **liquid water up to 10 MeV** in **option4** constructor (coll. with Ioannina U. et al.)
 - **e-** in **gold** - version 2 in **option4** constructor (coll. with Ioannina U. et al.)
 - **e-** in **O2 & N2 & CO2** (coll. with Roma U. et al.)
 - **Li** in liquid water (coll. with UCSF, ASNR, CNRS/LP2i et al.)
- New « **option 7 / cosmicDNA** » constructor (e-, p, ions) (coll. with Wollongong U. et al.)
- New discrete cross section models for **C in liquid water** ions are under development (coll. UCSF + ASNR + CNRS/LP2i)
- New discrete e- cross section models for **ice water** under development (coll. with Weizman I. et al.)
- New set of **physics models from LPCHEM software** (coll. CNRS/IP2i + LP2i + B. Gervais)
- Removal of older physics constructors

■ Chemistry

- Prototype testing and experimental validation of **multi-pulse radiolysis** (UHDR example) from CONV to UHDR irradiation (coll. CNRS/LP2i & LPCA, VINATOM, INFN, Subatech/Arronax, CHUV)

■ Damage prediction

- Convergence of « dsbandrepair » and « molecularDNA » **simulation chains**: common geometries, compatibility with UHDR radiolysis (coll. CNRS/LP2i & ASNR & VINATOM)
- Additional **geometries of biological models** compatible with the simulation chains (e.g., new cell lines) (coll. with Swinburne U. et al.)
- Extension of the two chains to **use cases in medical physics** (e.g. new radionuclides, BNCT, hadrons, VHEE, Flash...) (open)
- Additional **biological repair models** (coll. with D. Sakata et al.)

■ Computing

- **We will probably follow Geant4's strategy (GPU, AI)**

Some comments

- **Physics models / electrons** are at the heart of everything: TS, chemistry, biological damage, ... « starting point »
 - Beyond energy deposition (dose)
 - **Greece** has been a **major actor since 2007** for electron Physics models
- Strong potential for **multi-scale MC simulations** benefiting from Geant4-DNA functionalities for **space applications**
 - Multi-scale: space, time, energy, **dose rate**...
 - **Track structures** in various materials on the **eV to hundreds MeV** scale
 - **Radiation chemistry** in water (liquid, gas, ice...) **from a few ps to minutes–hours, from CONV to UHDR**
 - Plenty of **Geant4-DNA examples (physics, chemistry, geometries)**
- **GPU doable**, see MPEXS-DNA (discrete physics, SBS chemistry) but avoid proprietary code...
 - Why not a new « **G4DNAEm** » component à la « G4HepEm » from / with Mihaly et al. ?
- **AI worth investigation**, although Physics & Chemistry models are still being refined... (started 20 years ago!)
- **Not limited to radiation biology, new application domains**
 - Environmental exposure (e.g., organisms in harsh living conditions)
 - Planetary science (gas phase)
 - Exobiology (solid phase)
- All is **fully included in Geant4**

Hopefully all these features could become available through GRAS !

Where to find more information ?

<https://geant4-dna.org/>



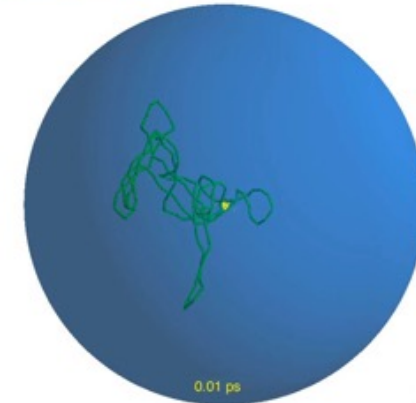
Thank you for your attention!

GEANT4-DNA : EXTENDING THE GEANT4 MONTE CARLO SIMULATION TOOLKIT FOR RADIATION BIOPHYSICS & RADIOBIOLOGY

Welcome to the web page of the Geant4-DNA project !

The *Geant4* general purpose particle-matter Monte Carlo simulation toolkit is being extended with processes for the **modeling of biological damage induced by ionising radiation at the DNA scale**. Such developments are on-going in the framework of the Geant4-DNA project. This project was originally initiated by the *European Space Agency (ESA)*. Developments are undertaken by an international collaboration, coordinated since 2008 by the *National Institute of Nuclear and Particle Physics (IN2P3)* of the *National Centre for Scientific Research (CNRS)* in France, in collaboration with the *Geant4@IN2P3* activities.

Once published, all developments are freely accessible in **full open access** through the *Geant4* toolkit or through our *Geant4 Virtual Machine*.



Irradiation of a pBR322 plasmid, including radiolysis
- movie courtesy of V. Stepan -

On-going **developments** include

- *Physics* processes in liquid water and other materials
- *Physico-chemistry* and *chemistry* processes for water radiolysis
- Molecular *geometries*
- Quantification of *biological damage* (such as single-strand, double-strand breaks, base oxidation, ...)

News

Mar. 18-20, 2026: *Geant4-DNA tutorial* at the Princess Srisavangavadhana Faculty of Medicine of the Chulabhorn Royal Academy of Thailand, Bangkok

Dec. 19, 2025: The *Geant4 11.4.0* LP2i Virtual Machine with AlmaLinux 9 has been released, see [link](#).

Dec. 13, 2025: update of *macOS installation instructions* for Tahoe 26.2