The PHITS Monte Carlo Particle Transport Simulation Code

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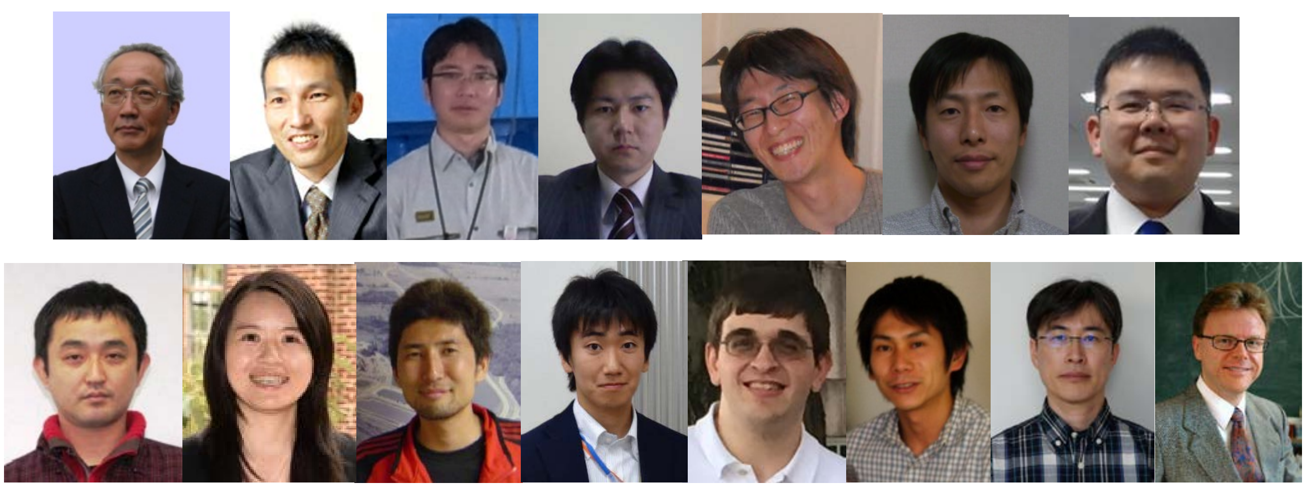

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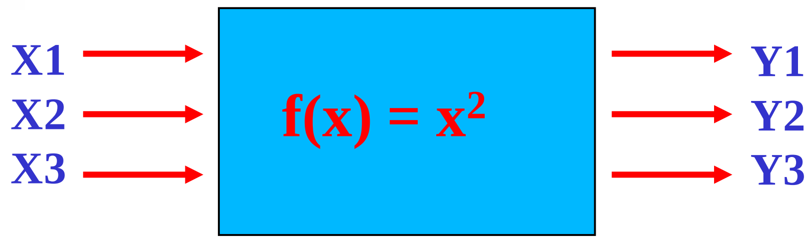
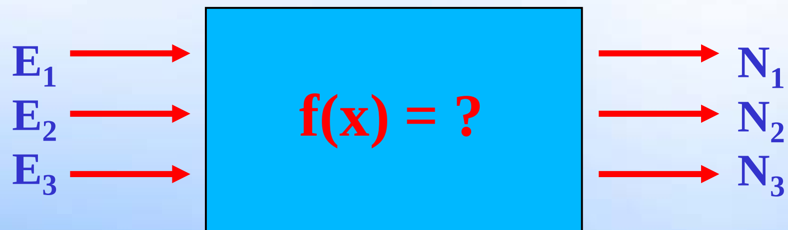
Deterministic vs Monte Carlo (MC)

- In **deterministic models**, the output of the model is fully determined by the parameter values and the initial conditions.



- **Monte Carlo methods** are stochastic techniques to solve problems using ***probabilistic*** (statistical) ***methods*** that utilizes sequences of ***random numbers and probability distributions*** which define the range of outcomes.
- The Monte Carlo method provides approximate solutions to a variety of problems, which may have many variables.

$E_1 = E_2 = E_3 = E$



$N_1 \neq N_2 \neq N_3$

Deterministic Simulation Codes

Advantages

- Exact
- Fast
- Do not require powerful/fast computers.

Disadvantages

- Inaccurate in the case of complicated geometries.
- Do not reconstruct collisions & do not preserve all correlations.
  - It is not possible to model interdependent relationships between input variables.
- Sensitivity Analysis.
  - With just a few cases, deterministic analysis makes it difficult to see which variables impact the outcome the most.
- Scenario Analysis.
  - In deterministic models, it’s very difficult to model different combinations of values for different inputs to see the effects of truly different scenarios.

Monte Carlo Simulation Codes

Advantages

- **Accurate even in the case of complicated geometries.**
- **Reconstruct collisions & preserve all correlations.**
  - **It is possible to model interdependent relationships between input variables.**
- **Probabilistic Results.**
  - **Results show not only what could happen, but how likely each outcome is.**
- **Sensitivity Analysis**.
  - **It is easy to see which inputs had the largest effect on the results.**
- **Scenario Analysis.**
  - **It can can see exactly which inputs had which values when certain outcomes occurred.**

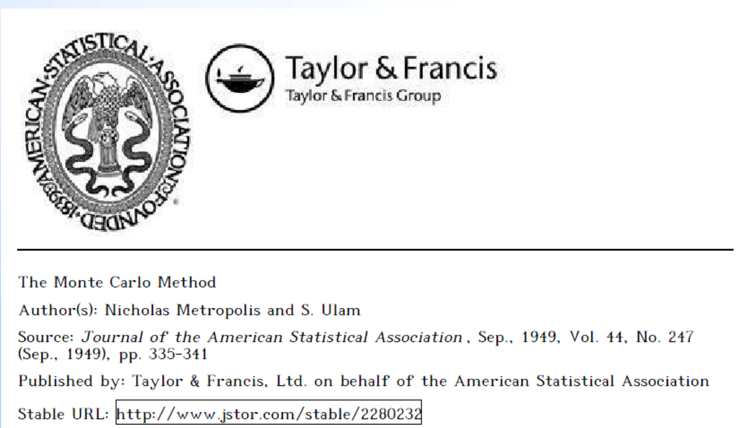
Disadvantages

- **Slow**
- **Require often powerful/fast computers.**

History of Monte Carlo Method

- **Credit for inventing the Monte Carlo method is shared by Stanislaw Ulam, John von Neuman and Nicholas Metropolis, who invented the method to solve neutron diffusion problems for Manhattan Project (1939-46) at Los Alamos.**

- **The 1949 - article “The Monte Carlo Method” in *Journal of the American Statistical Association*, 44 (247), 335-341 by Metropolis and Ulam is often considered as the birth of the Monte Carlo method.**


Taylor & Francis
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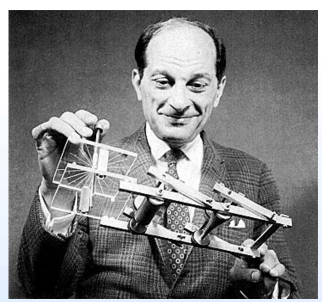
The Monte Carlo Method

Author(s): Nicholas Metropolis and S. Ulam

Source: *Journal of the American Statistical Association*, Sep., 1949, Vol. 44, No. 247 (Sep., 1949), pp. 335-341

Published by: Taylor & Francis, Ltd. on behalf of the American Statistical Association

Stable URL: http://www.jstor.com/stable/2280232


Stanislaw Ulam (13.04.1909-13.05.1984)


John von Neumann (28.12.1903-8.02.1957)

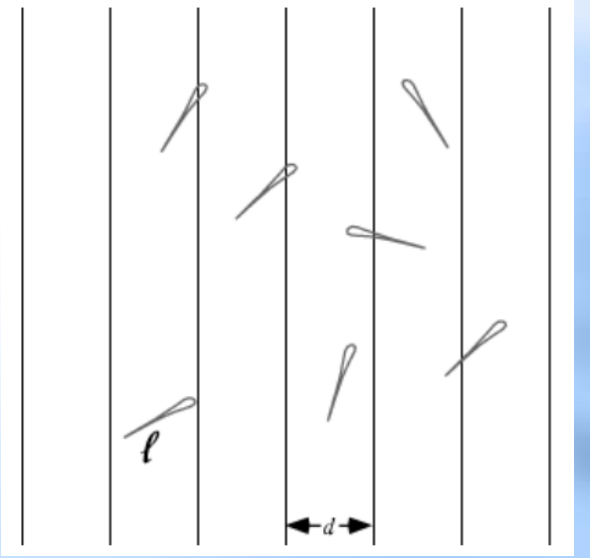

Nicholas Constantine Metropolis (11.06.1915-17.10.1999)

History of Monte Carlo Method

- **Historic example: calculation of π**
  - **Numerically:** **look for an appropriate convergent series and evaluate this approximately.**
  - **By Monte Carlo: look for a stochastic model.**

- **Example: throw a needle on a sheet with equidistant parallel stripes.**

  Distance between stripes: d.
  Length of needle: $l < d$.



History of Monte Carlo Method

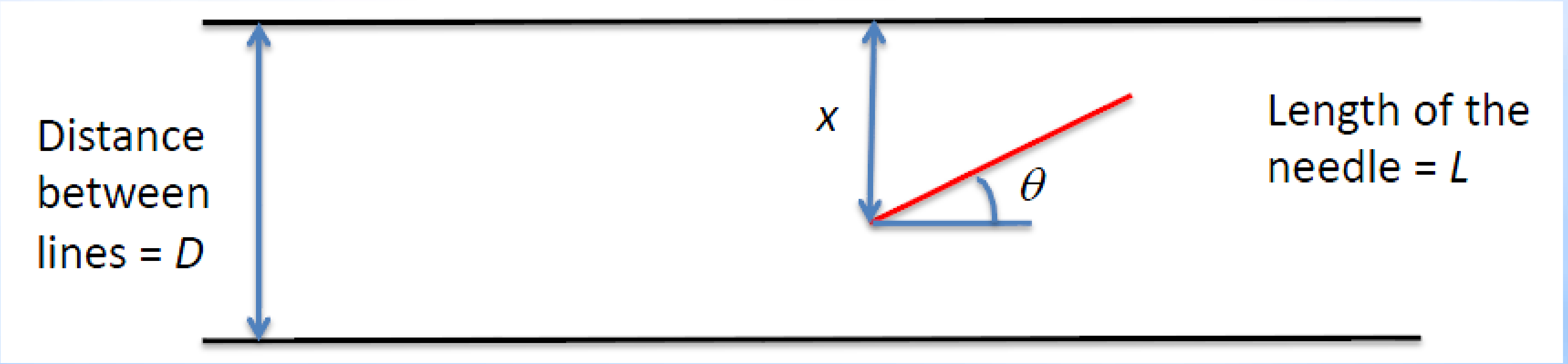
Buffon´s Needle Experiment – First stated in 1777

Georges Louis Leclerc Comte de Buffon
(07.09.1707-16.04.1788)

History of Monte Carlo Method

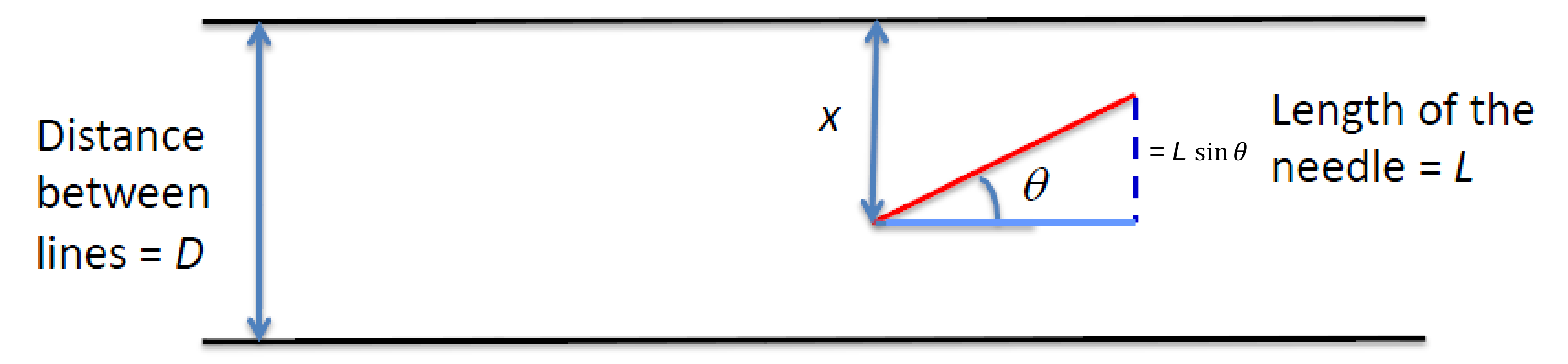
- **Buffon's original "experiment" was to drop a needle of length L on a lined sheet of paper and determine the probability of the needle crossing one of the lines on a paper with parallel lines with spacing D.**

- **Remarkable result: probability is directly related to the value of π.**



History of Monte Carlo Method

- What is the **probability P**, that the needle crosses one of the lines?

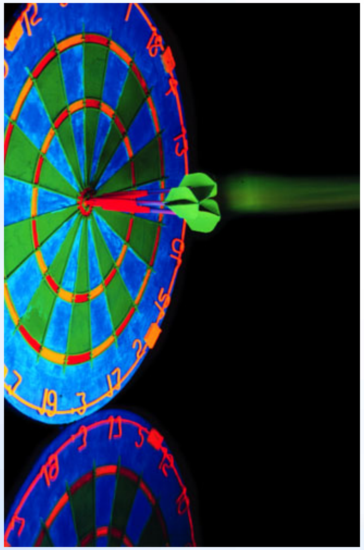


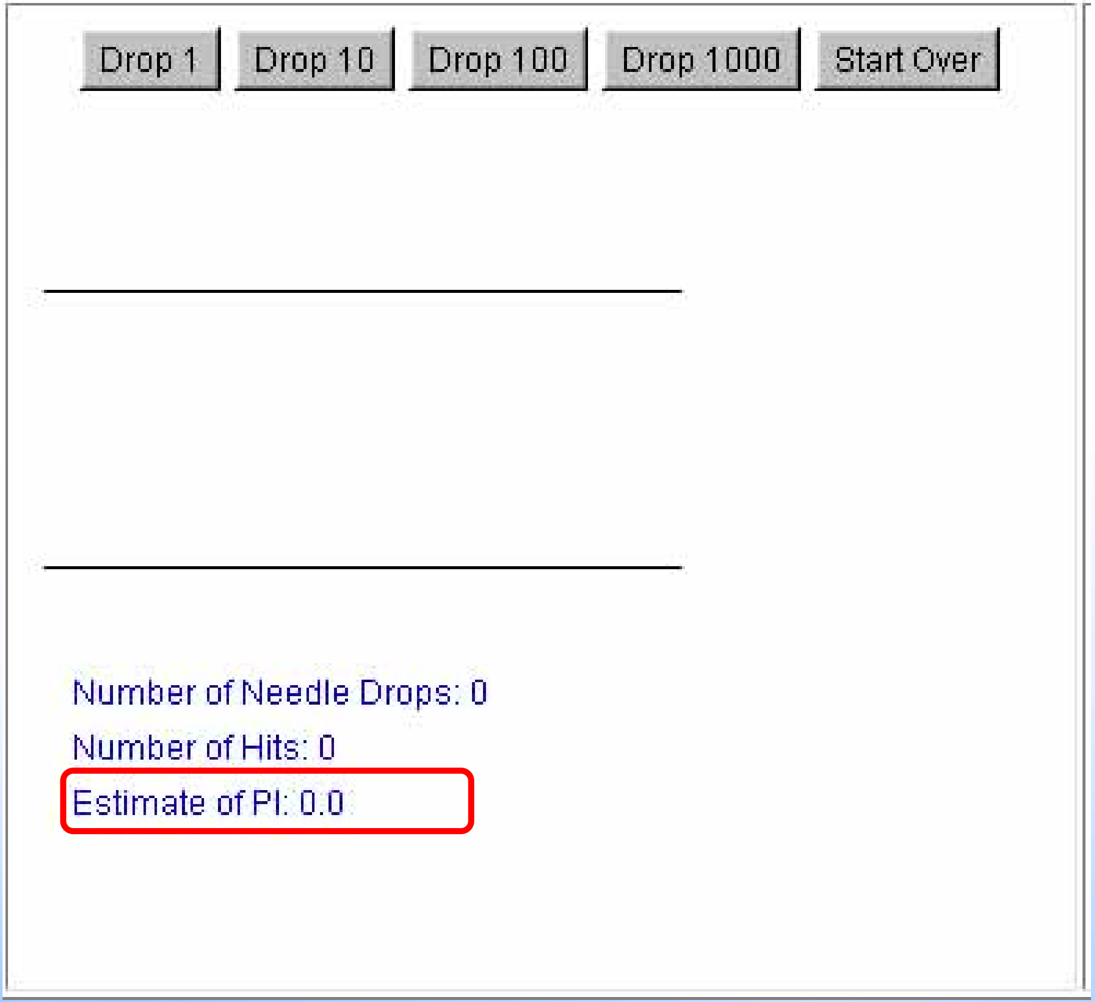
$$P_{cut} = \int_0^{\pi} P_{cut}(\theta)\frac{d\theta}{\pi} = \int_0^{\pi} \frac{L\sin\theta}{D}\frac{d\theta}{\pi} = \frac{L}{\pi D}\int_0^{\pi}\sin\theta\, d\theta = \frac{2L}{\pi D}$$

- **If we drop the needle N times and count R intersections,**

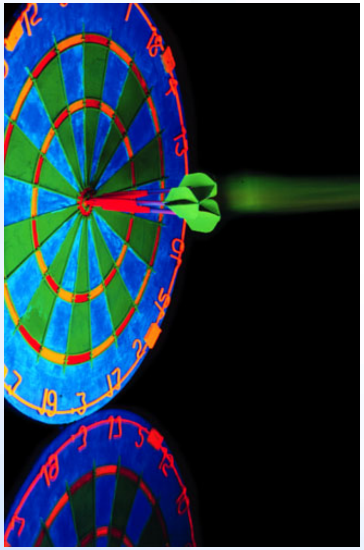
we obtain: $P_{cut} = \frac{R}{N} = \frac{2L}{\pi D} \Rightarrow \boxed{\pi = \frac{2LN}{RD}}$

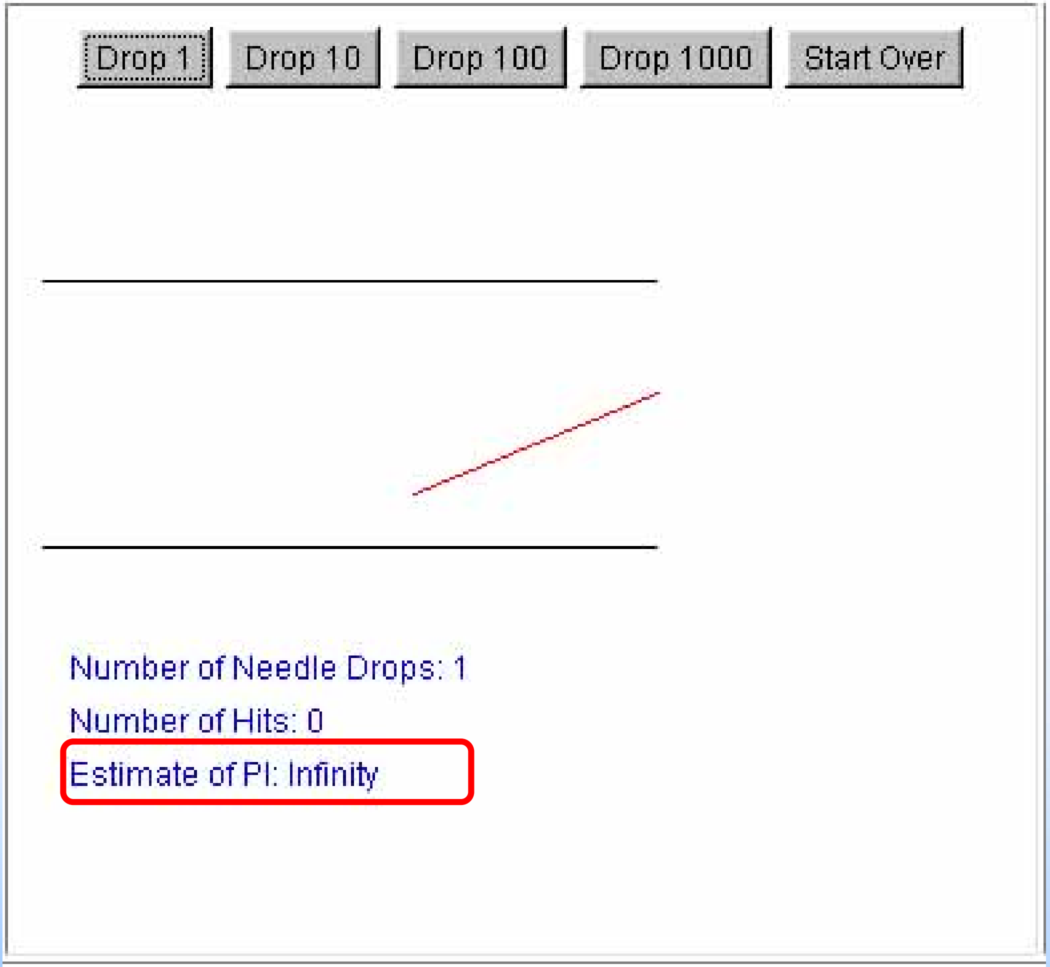
History of Monte Carlo Method



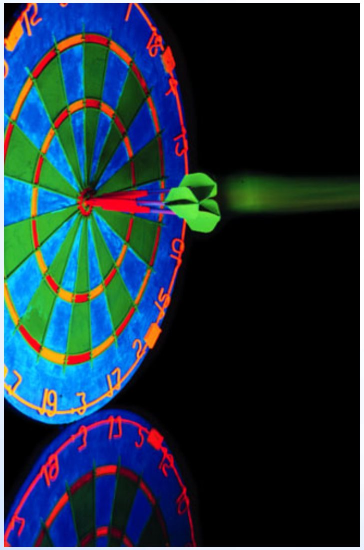


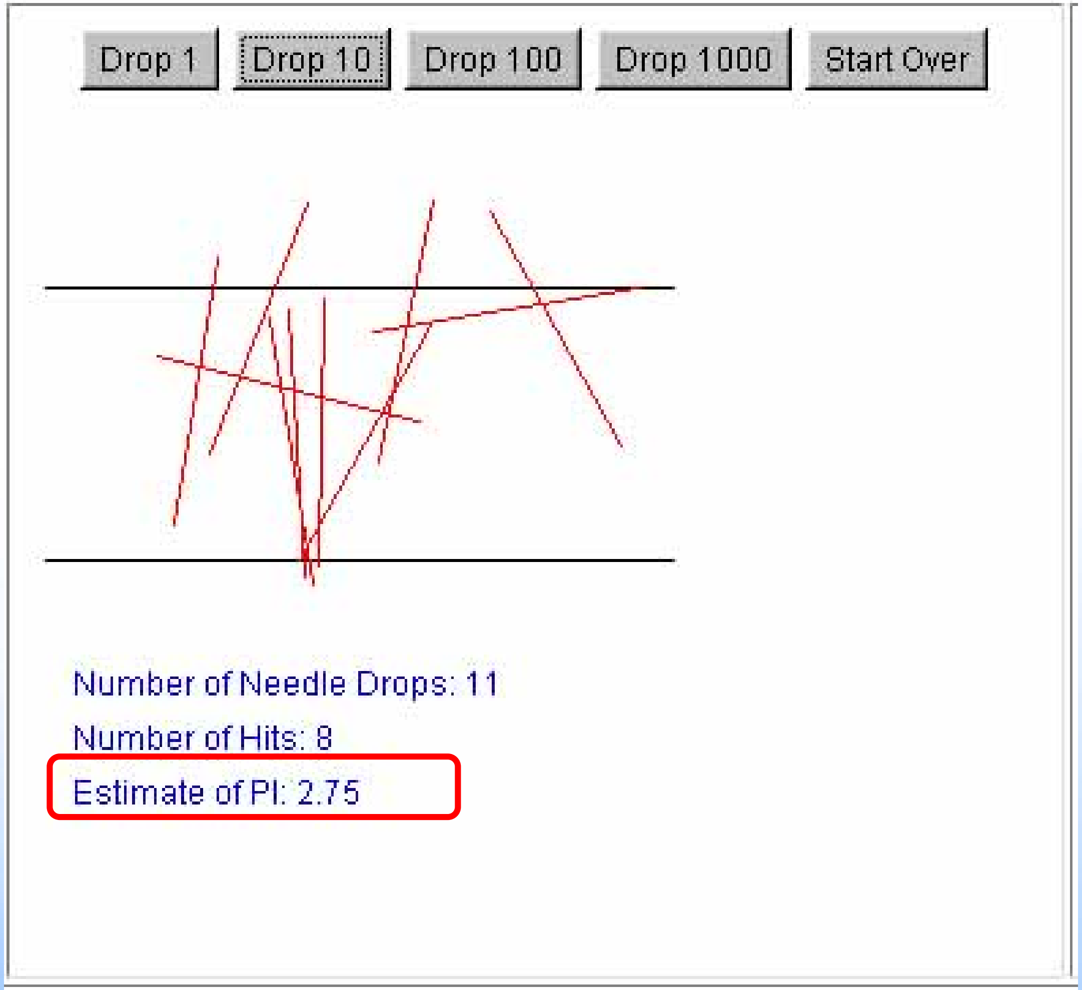
History of Monte Carlo Method





History of Monte Carlo Method





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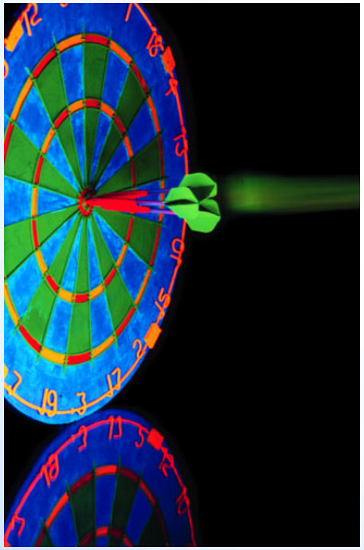
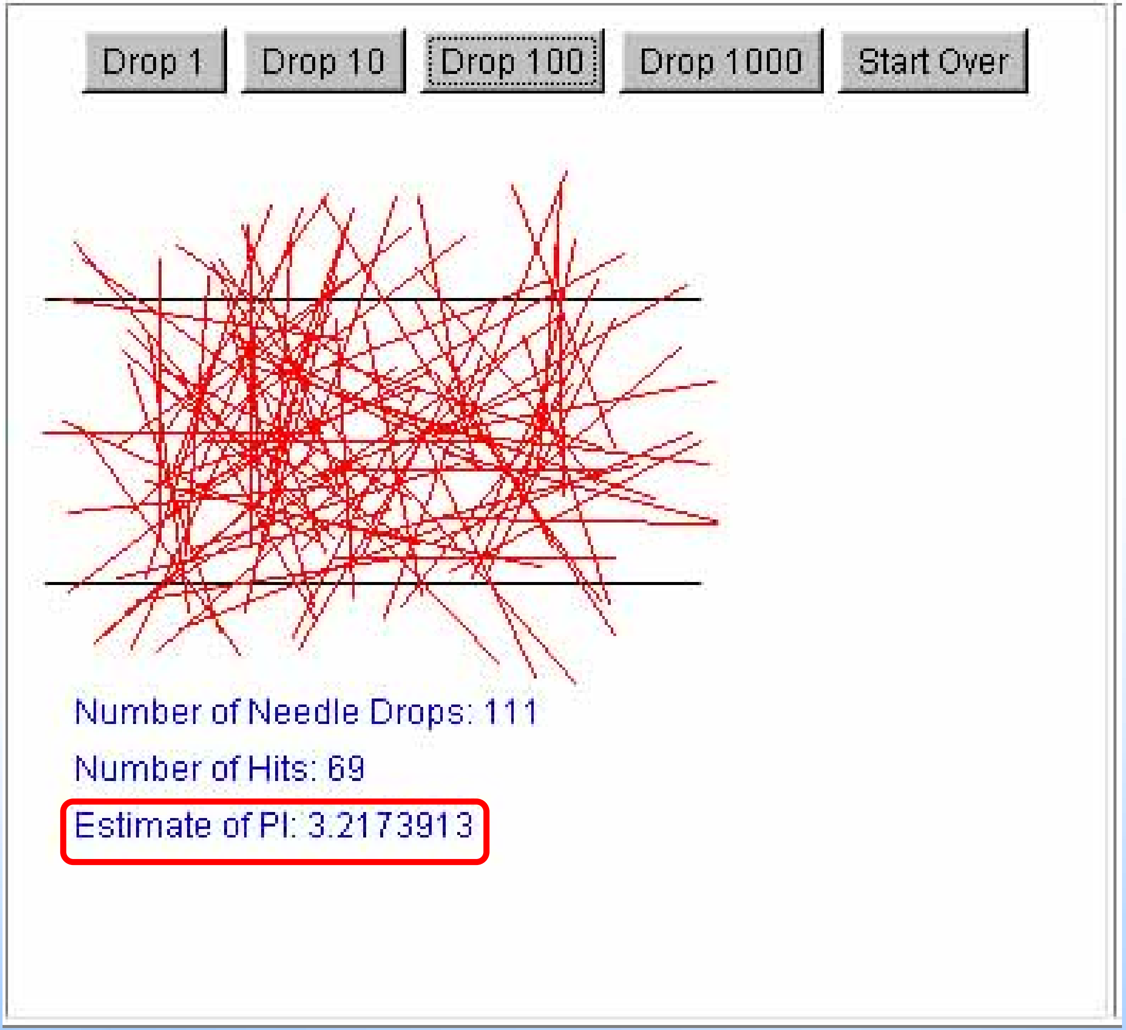
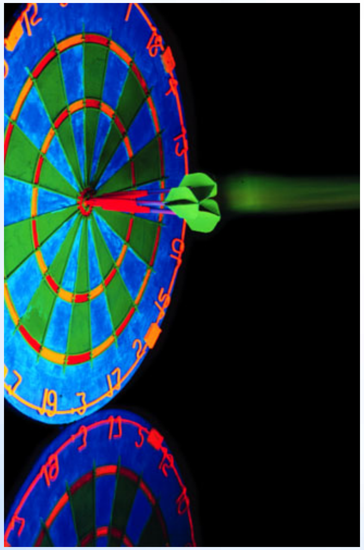
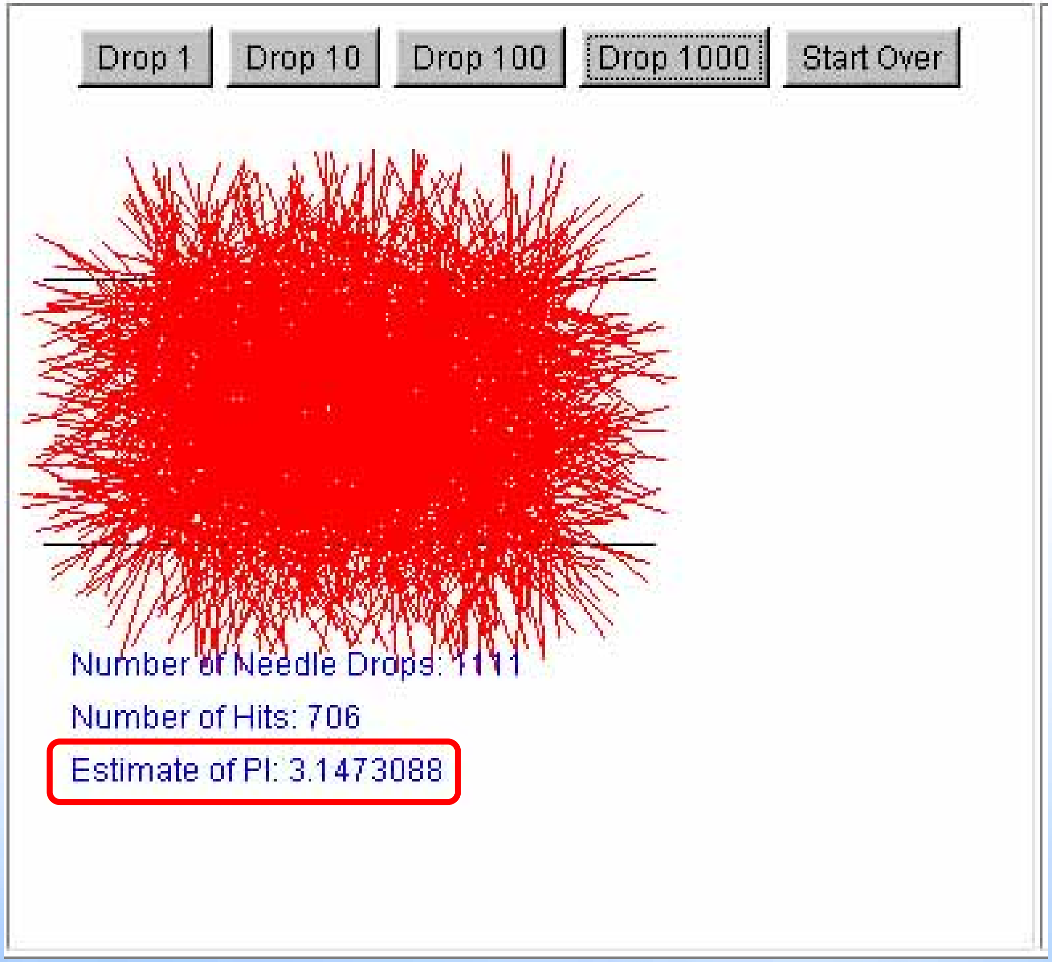




History of Monte Carlo Method





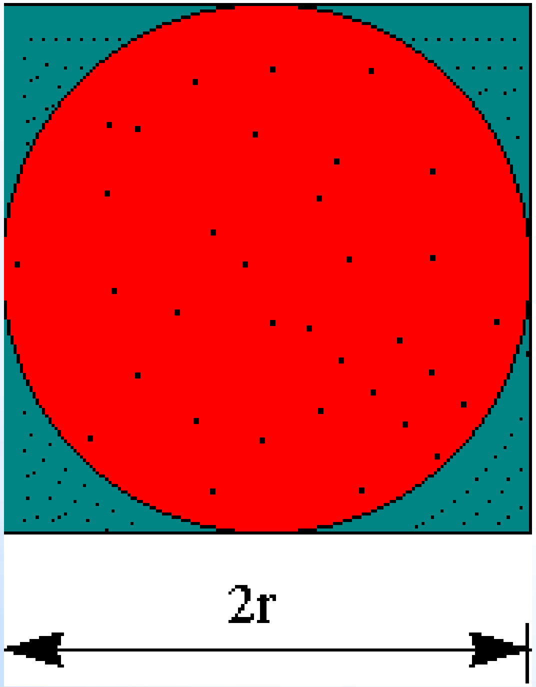
History of Monte Carlo Method

Laplace's method of calculating π (1886)

Pierre-Simon de Laplace
(23.03.1749-05.03.1827)

History of Monte Carlo Method

"Hit or miss" approach



Area of the square = $4r^2$

Area of the circle = πr^2

If we drop a small coin enough many times, N, randomly inside the square and count random hits inside circle N_C, we obtain P_{in}, the probability of random points inside the circle:

$$P_{in} = \frac{N_C}{N}$$

$$P_{in} = \frac{N_C}{N} = \frac{\pi r^2}{4r^2} = \frac{\pi}{4} \Rightarrow \boxed{\pi = \frac{4N_C}{N}}$$

What is PHITS?

Particle and **H**eavy **I**on **T**ransport code **S**ystem

Capability

Transport and collision of nearly all particles over wide energy range using Monte Carlo method

neutron, proton, ions, electron, photon etc

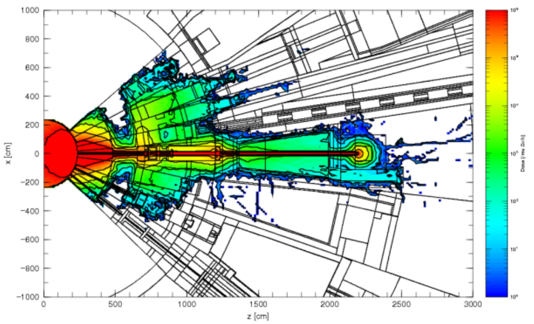
10^{-4} eV to 1 TeV/u

All-in-one-Package

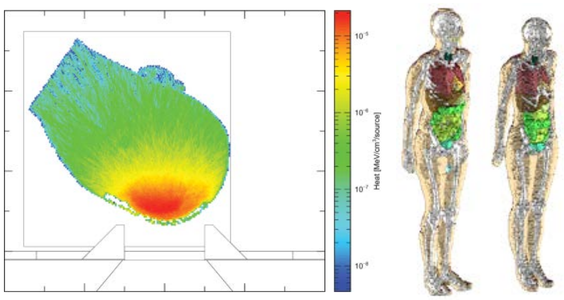
All contents of PHITS (source files, binary, data libraries, graphic utility etc.) are fully integrated in one package

Available in free of charge by submitting application form via PHITS website

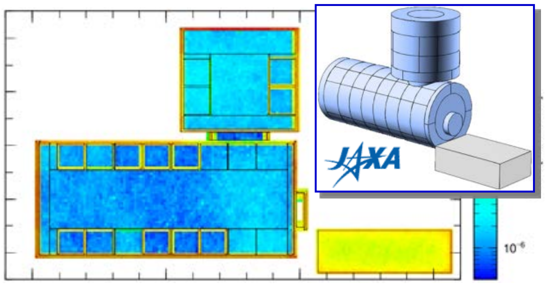
Applications



Accelerator Design

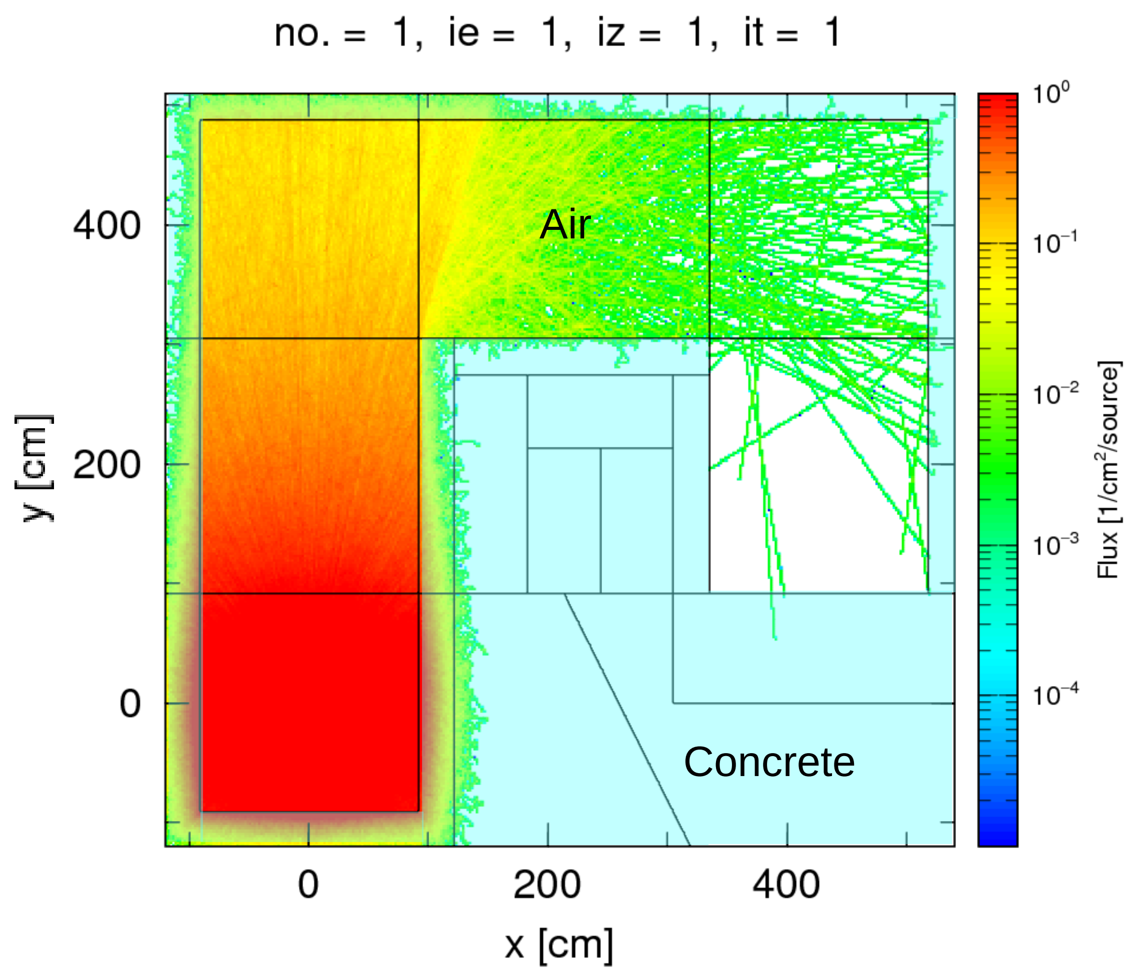


Radiation Therapy & Protection



Space & Geoscience

Example of PHITS Calculation



Motion of 100,000 photons produced from ^{137}Cs simulated by PHITS

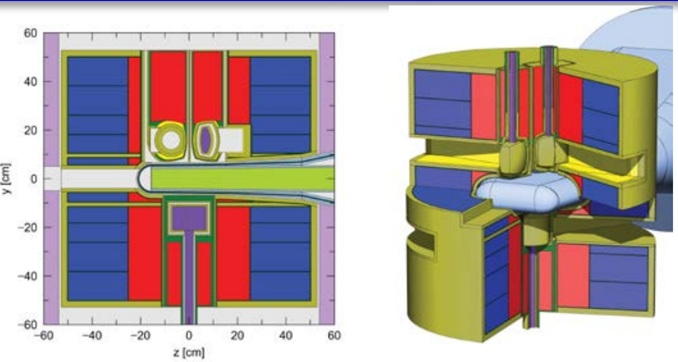
Stochastically simulate the motion of each particle using cross sections
→ Average behavior such as particle flux and mean deposition energy

User Interfaces of PHITS

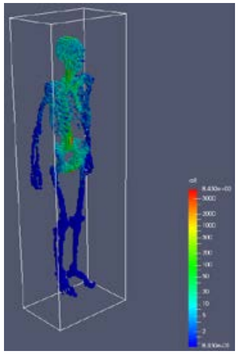
- Source code: Fortran (Intel Fortran 11.1, Gfortran 4.71 or later)
- Input file: Free-format text

You do not have to write Fortran program nor compile PHITS

- Geometry
  - ➢GG format
  - ➢Graphic utility: ANGEL
  - ➢Support software (ParaVIEW*, SuperMC**)



Geometry drawn by ANGEL



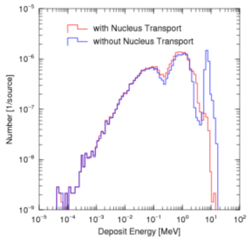
ParaVIEW

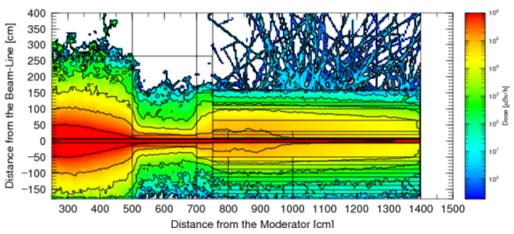
- Tally functions

  Particle fluence, Heat, Particle yield etc.

- Output Data

  Text data, histograms, contour maps





- Platforms

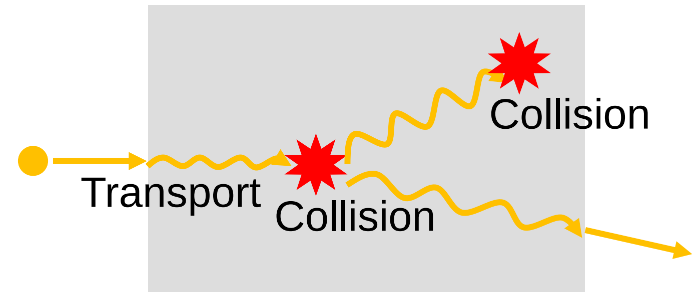
  Windows, Mac and Linux (MPI & OpenMP parallelization available)

*Visualize PHITS geometry & tally results **Convert CAD geometry to PHITS input format

Comparison with other MC codes

Name	Developer	Application	Language	Features
MCNP(X)	LANL	Nuc. Energy Radiology	FORTRAN	World standard of nuclear energy High reliability, Criticality
GEANT4	CERN etc.	High E Phys, Radiology, Astronomy	C++	Object-oriented, Platform to integrate models and tools developed all over the world
FLUKA	CERN, INFN	Accelerator, Radiology, Astronomy	FORTRAN	Applied to accelerator shielding design Particularly popular in EU
EGS	KEK, SLAC	Radiology	FORTRAN	EM cascade code Applied to mainly radiology
SuperMC	FDS	Fusion, Radiology	C++	Developed for ITER High CAD-affinity, Visualization
PHITS	JAEA, RIST, KEK	Accelerator, Radiology, Astronomy	FORTRAN	Easy start-up Applied to accelerator design, radiology, space science

Physical Processes included in PHITS



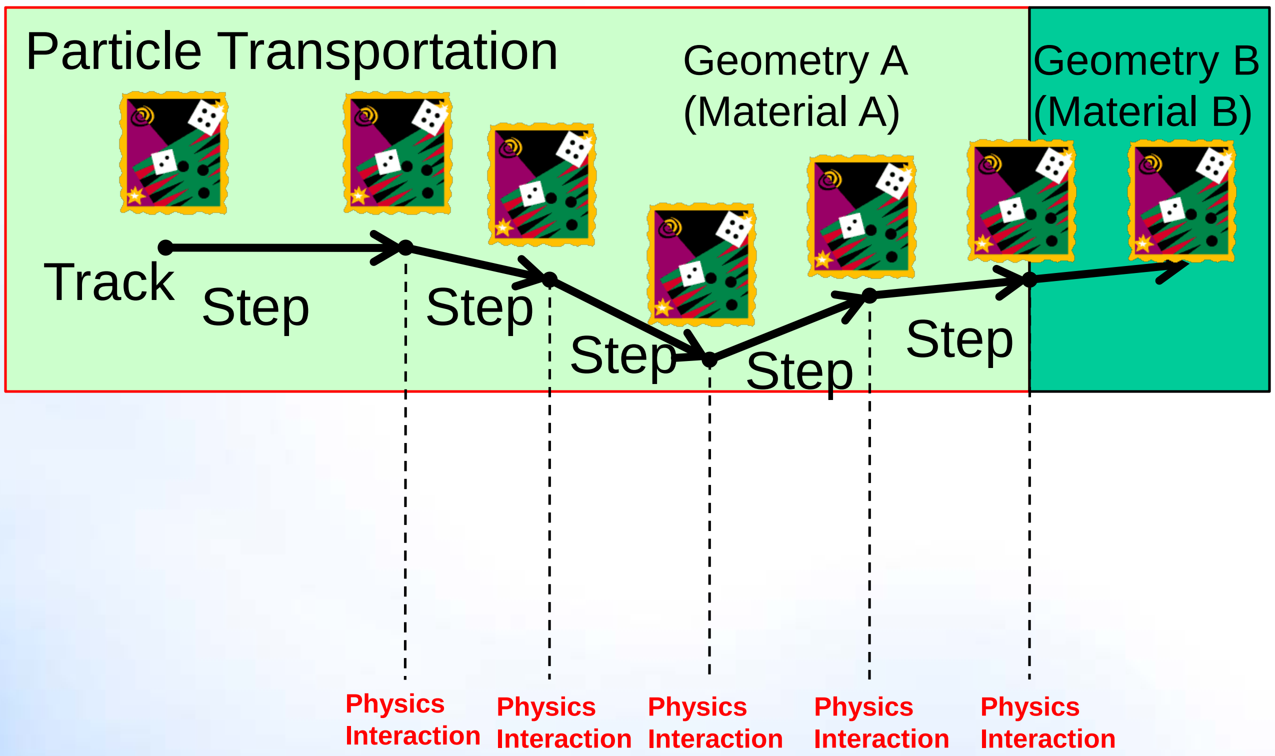
Transport between collisions

- **External Field** and Optical devices
  - Magnetic Field
  - Gravity
  - Super mirror (reflection)
- **Ionization process** for charge particle
  - dE/dx : ATIMA code
    Continuous-slowing-down Approximation (CSDA)
  - δ-ray generation
  - Microdosimetric function
  - Track-structure simulation

Collision with nucleus

- **Low-energy Neutrons Photons, Electrons** — Nuclear Data (JENDL-4.0 etc.) + Event Generator Mode
- **High-energy nucleons** — Intra-Nuclear Cascade → Evaporation
- **Heavy Ions** — Quantum Molecular Dynamics → Evaporation

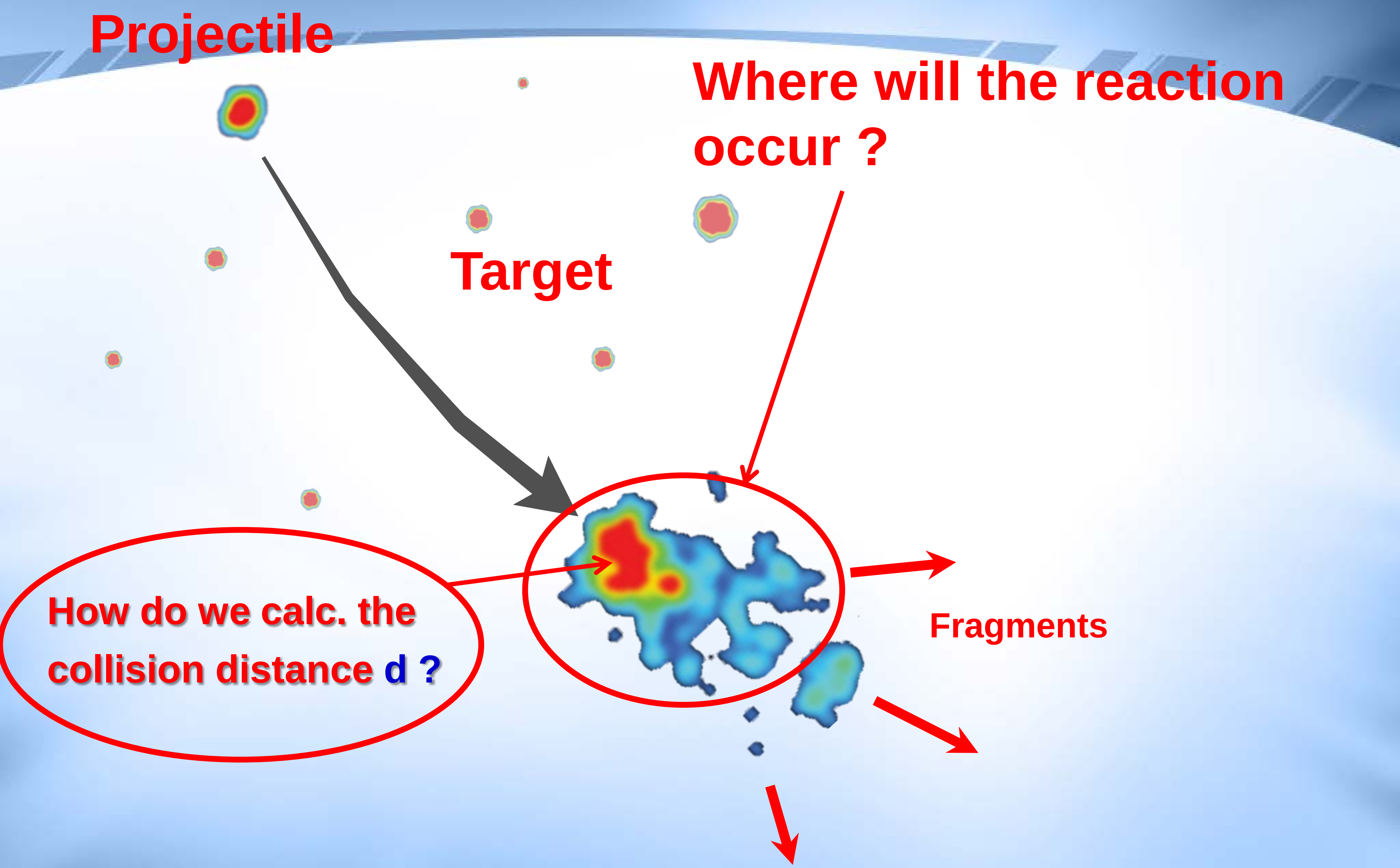
Basic idea of MC simulation



Transport: step length is controlled by 1) Interaction length of physics process
2) Geometrical boundary

Physics Interaction: sampling interaction probability

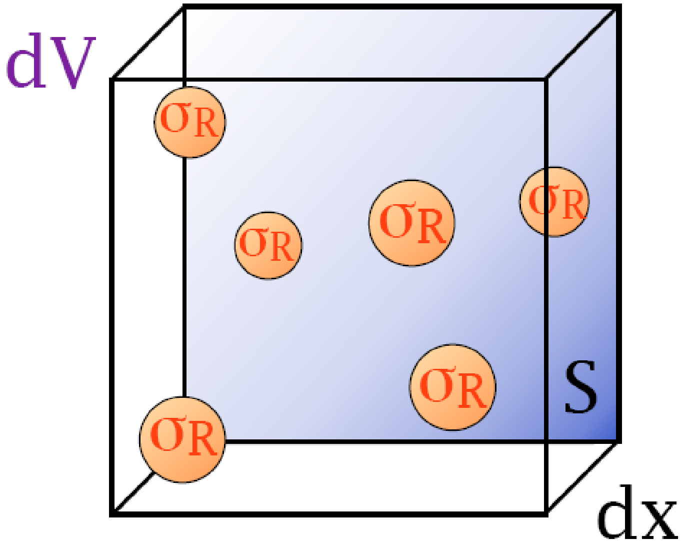
Transport of Nucleus in Matter



Calculation of Collision Distance d

No. of nucleus per unit volume:

$n = \rho \cdot N_A / m_a$ [#/cm^3]



Where

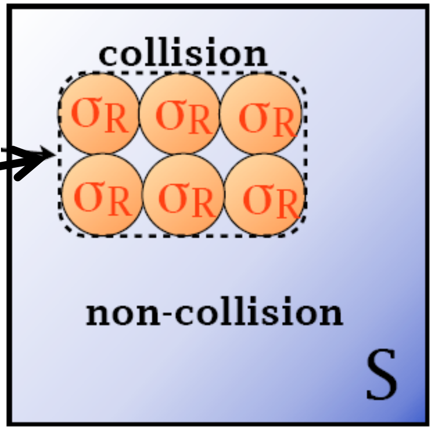
ρ: density [g/cm^3]

N_A: the Avogadro no. [#/mol]

m_a: atomic mass [g/mol]

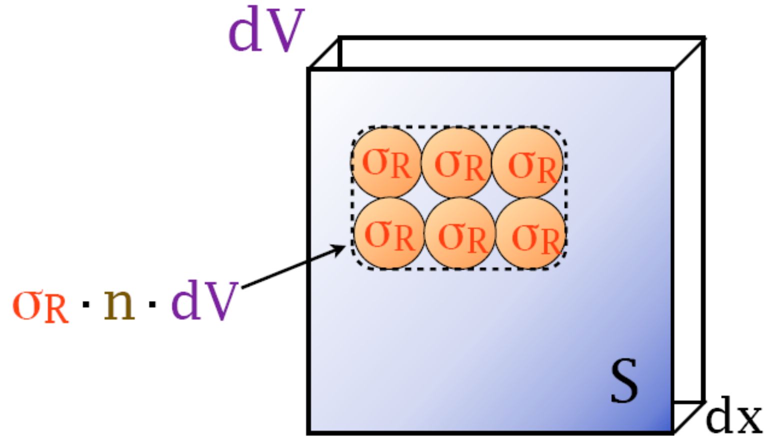
Mean collision area:

$\sigma_R \cdot n \cdot dV$ [cm^2]



***Where* σ_R : total reaction cross section**

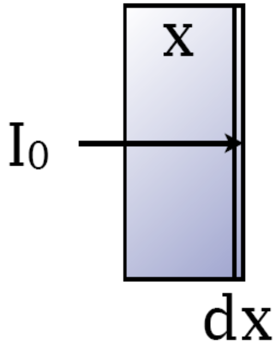
Calculation of collision distance d



Collision probability:

$$C = \sigma_R \cdot n \cdot dV / S = \sigma_R \cdot n \cdot dx$$

The probability of a collision at a distance "x":

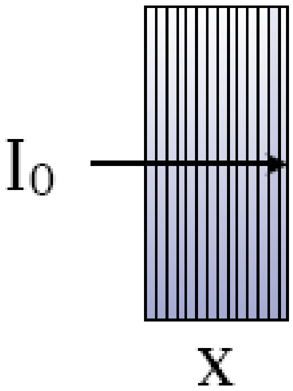


$$p(x) = e^{-\Sigma x} \cdot \Sigma\, dx$$

Where Σ is the macroscopic cross section

$$\Sigma = \sigma_R \cdot n \; [1/cm]$$

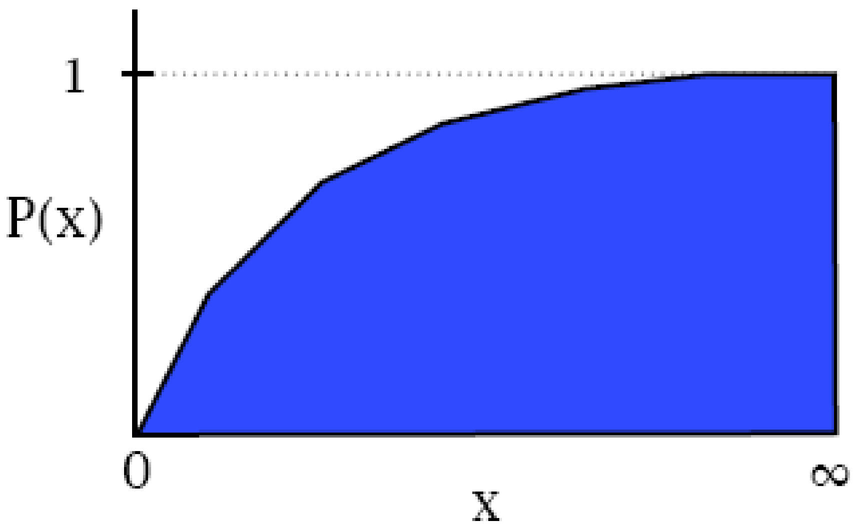
Calculation of d in Monte Carlo codes



Probability function that the projectile will collide within x:

$$P(x) = \int_0^x p(x) = \int_0^x e^{\Sigma \cdot x} \cdot \Sigma \cdot dx = 1 - e^{-\Sigma \cdot x}$$

$$P(x)_{r\,[0\to 1]} = 1 - e^{-\Sigma x} \Rightarrow \ln P(x)_{r\,[0\to 1]} = -\Sigma x$$

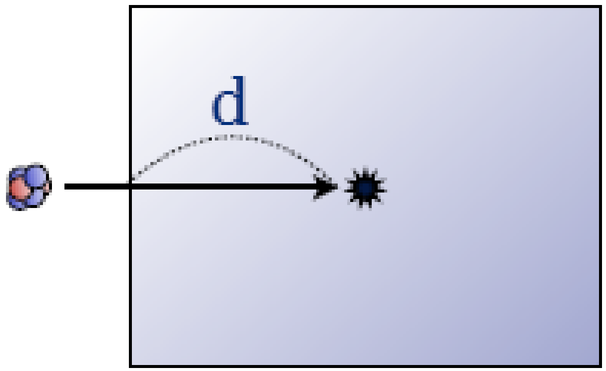


$$\Rightarrow x = \frac{\ln P(x)_{r\,[0\to 1]}}{\Sigma}$$

Where "r" is a random no. between 0 and 1

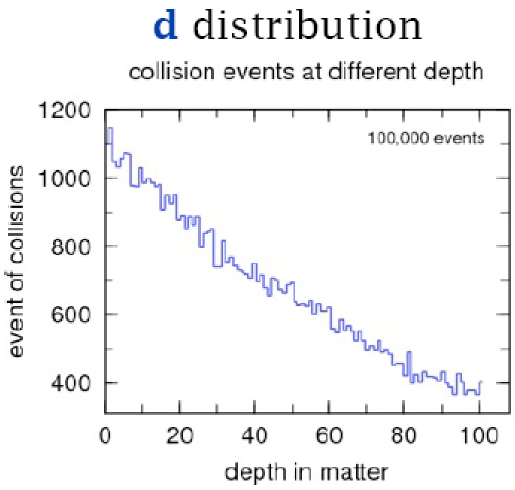
Calculation of d in Monte Carlo Codes

Probability of collision at x=d:



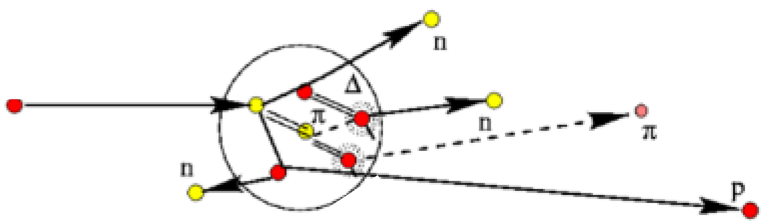
$$d = \frac{\ln P(x=d)_{r\,[0\rightarrow 1]}}{\Sigma} = \frac{\ln P(x=d)_{r\,[0\rightarrow 1]}}{\sigma_R n}$$

Where "r" is a random no. between 0 and 1

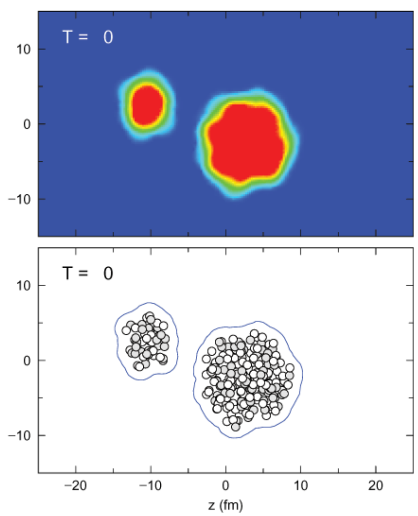


Two-Step Model for high energy p+N and N+N Reactions*

1. Dynamical/Pre-equilibrium Stage

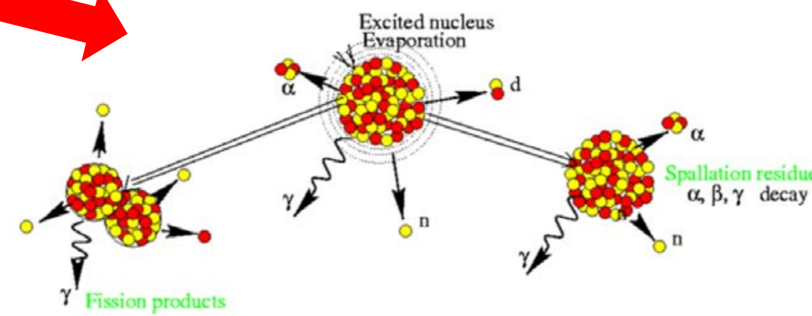


Intra-Nuclear Cascade (INC) Models



Quantum Molecular Dynamics (QMD) Models

2. De-excitation Stage



Evaporation/Fission/
Multifragmentation Models

* 2 stage process proposed by Serber. Phys. Rev. **72**, 1114 – Publshed 1 December 1947

Two-Step Model for high energy p+N and N+N Reactions*

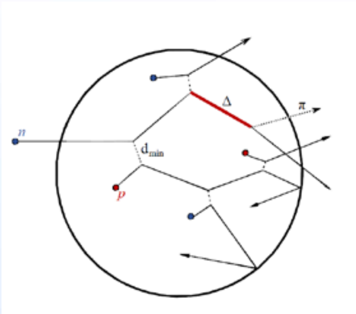
- **Dynamical/Pre-equilibrium stage**
  - Intra-nuclear cascade or QMD models
  - Fast process: interaction time (≈ 10^{-22} s)
  - Pre-equilibrium nucleon emission

- **De-excitation stage**
  (mostly nucleon, cluster and γ evaporation and fission)
  - Statistical equilibrium
    1. Excited remnants have forgotten the entrance channel
    2. De-excitation mechanisms:

       - Evaporation, Fission or Multifragmentation followed by Evaporation
  - Slow process: de-excitation time (10^{-20} – 10^{-16} s)
  - Energy and angular momentum release
  - Final residue (A_{res}, Z_{res})

Nuclear Reaction Models - Dynamical Step

Intra-Nuclear Cascade (INC) Models

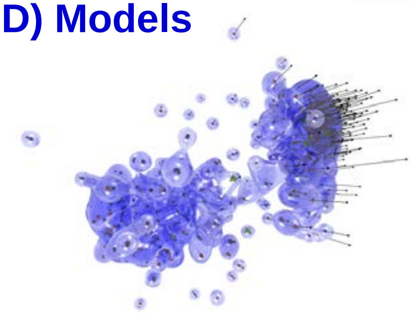


- Straight-line trajectories
- Mean-field potential
- Binary collisions with Pauli blocking
- Limitations
  - Mean free path > de Broglie wavelength

$$\Lambda = \frac{1}{\rho_0\, \sigma_{NN}\, f_{\mathrm{Pauli}}} \qquad \lambda = \frac{h}{p_{\mathrm{lab}}}$$

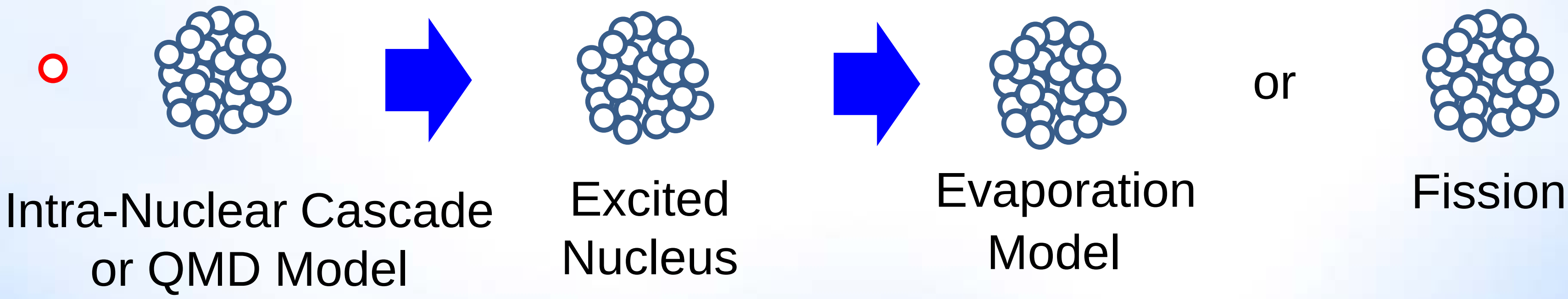
  - $E_{proj,lab}$ ≈ 20 MeV/nucleon – 3 GeV/nucleon
  - A_{proj}: p, n, $\pi^{+/-}$, A < 4

Quantum Molecular Dynamics (QMD) Models

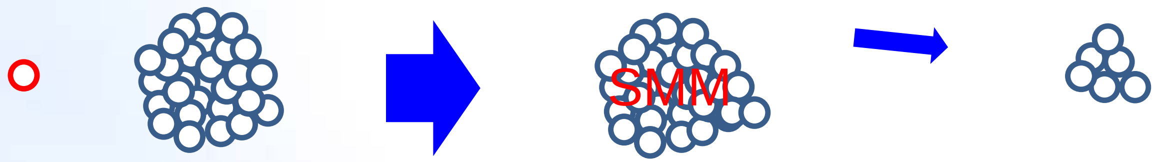


- Nucleons as wave packets
- Curved trajectories
- Potential built from nucleon-nucleon interactions
- Two- or three-body forces
- Binary collisions with Pauli blocking
- Limitations
  - $E_{proj,lab}$ ≈ 10 MeV/nucleon – 3 GeV/nucleon
  - A_{proj}: any nucleus

De-excitation by Evaporation or Fission



De-excitation by SMM and Evaporation

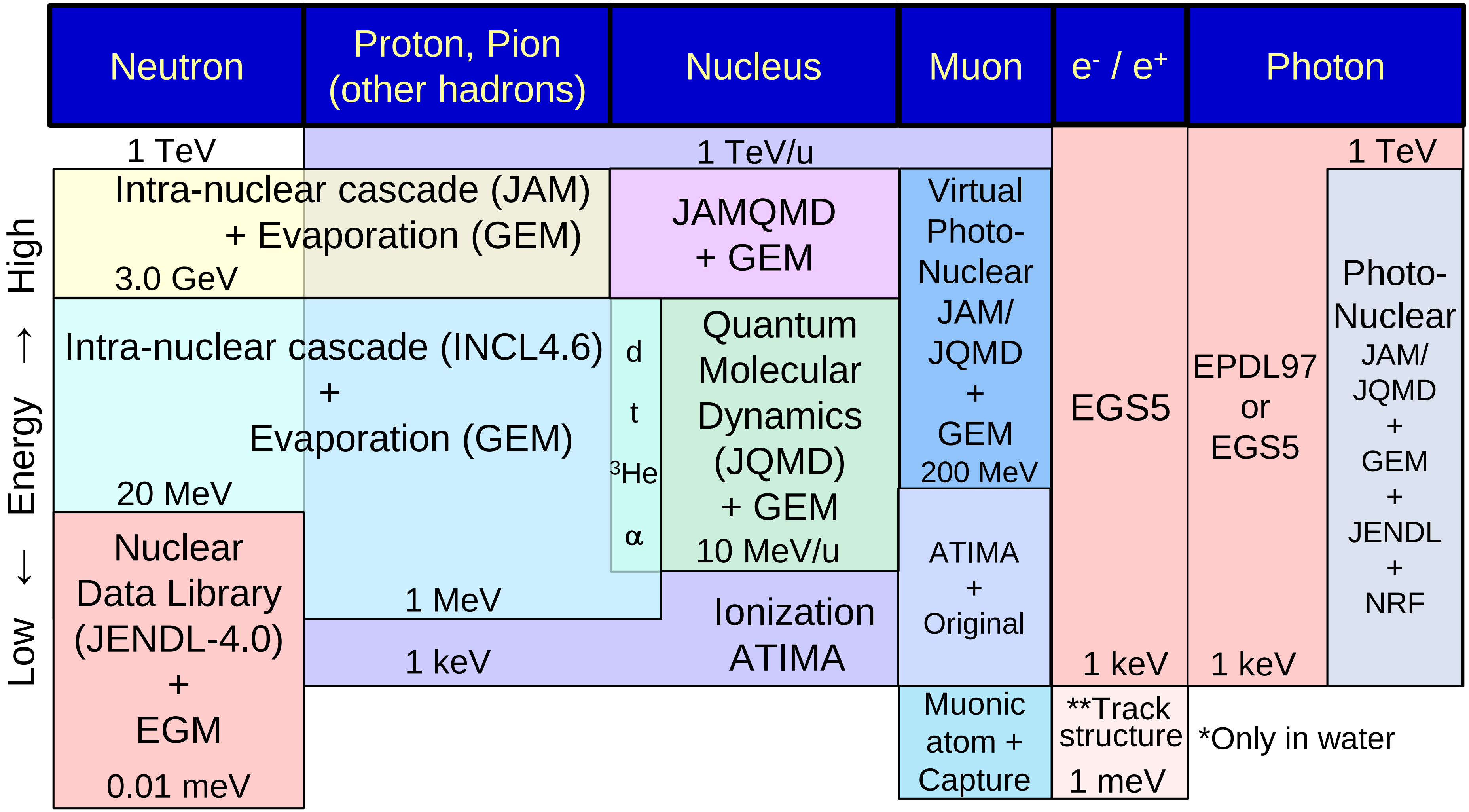


Intra-Nuclear Cascade
or QMD Model

Excited
Nucleus

Evaporation
Model

Map of Models Recommended to Use in PHITS

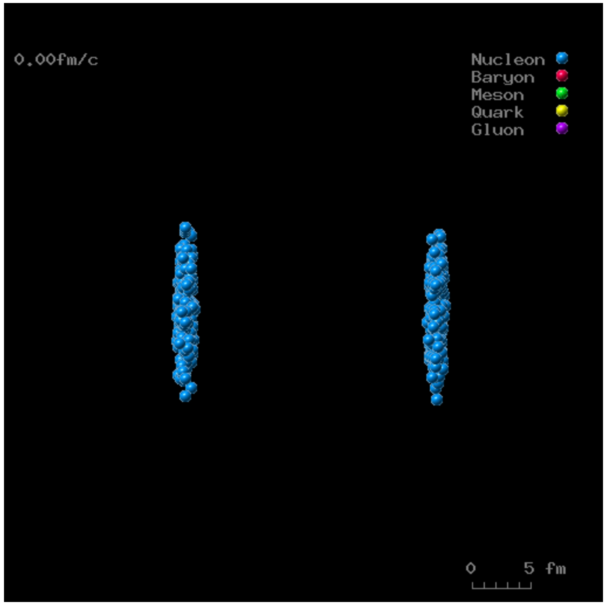


Physics models of PHITS and their switching energies

Switching energies can be changed in input file of PHITS

JAM (Jet AA Microscopic Transport) Model

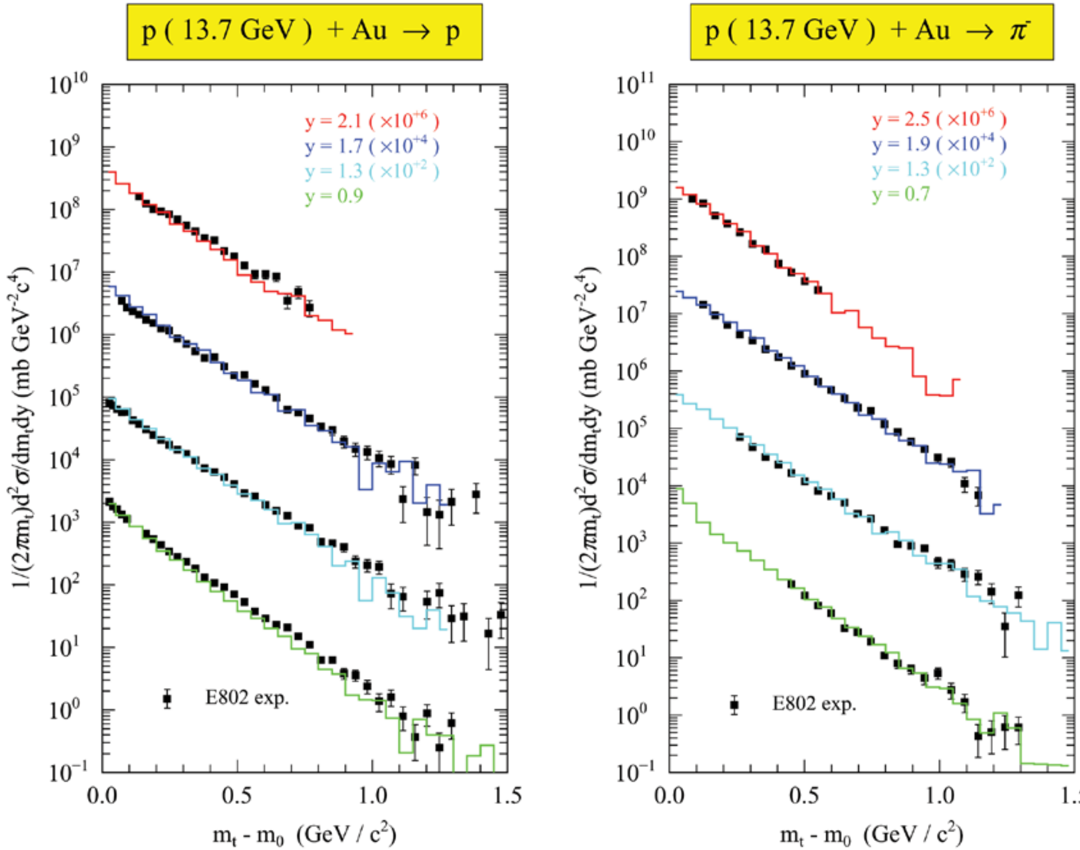
- ***JAM*** is a ***Hadronic Cascade Model***, which explicitly treats all established hadronic states including resonances with explicit spin and isospin as well as their anti-particles.
- We have parameterized all ***Hadron-Hadron Cross Sections***, based on ***Resonance Model*** and ***String Model*** by fitting the available experimental data.



Au+Au 200GeV/n in CM

119 kinds of Mesons

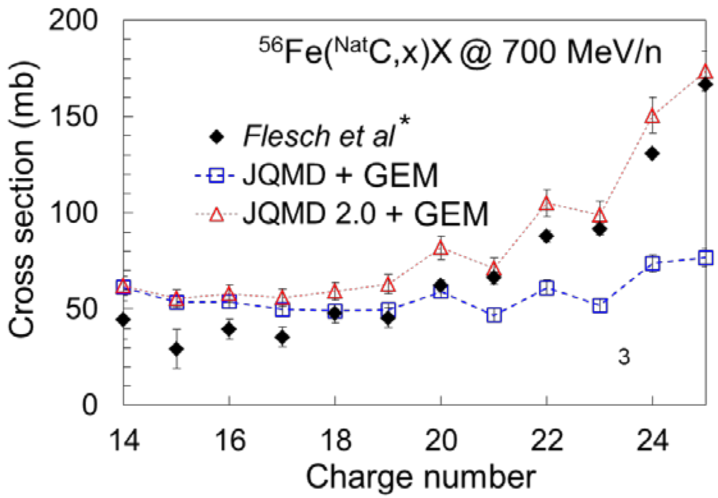
170 kinds of Baryons



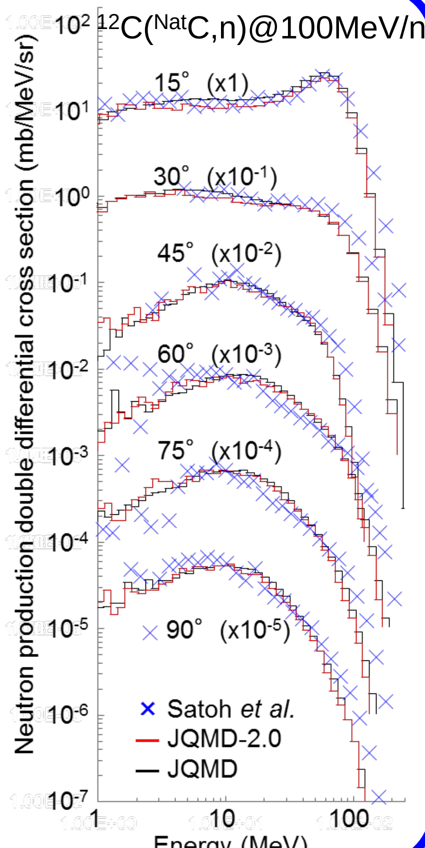
Y. Nara et al, Phys. Rev. C61 (2000) 024901

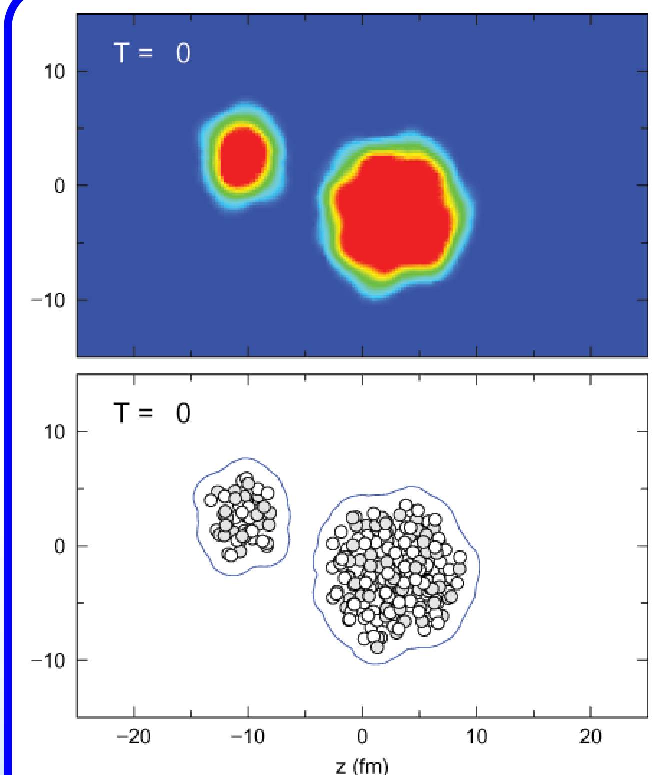
JQMD (JAERI Quantum Molecular Dynamics) Model

- ***JQMD*** can simulate the time evolution of nuclear reactions, considering the correlations between *every combination of nucleons* in the frame.
- Dedicated to simulation of nucleus-nucleus (ion-induced) reactions



- Production of residues and secondaries are simulated
- More accurate JQMD-2.0 is available from PHITS Ver.2.76





^{56}Fe 800 MeV/u on ^{208}Pb

K. Niita et al, Phys. Rev. C52 (1995) 2620, T. Ogawa *et al.*, Phys. Rev. C92 (2015) 024614

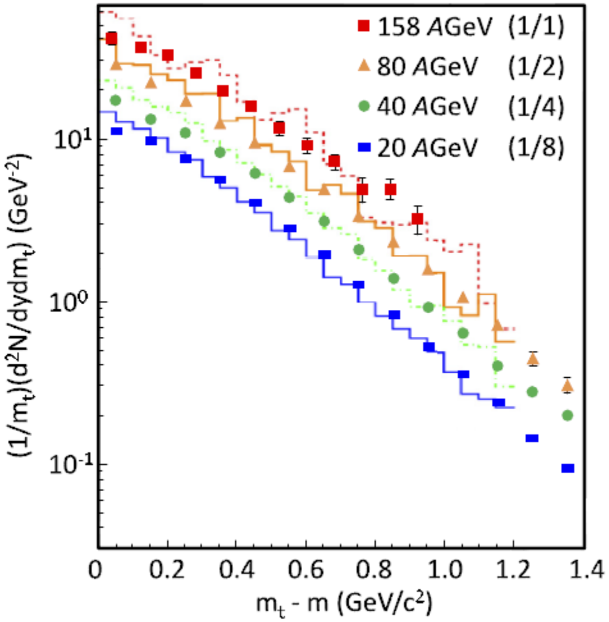
Limitations with QMD

- **QMD calculates the interaction of every single particle and can be used to calculate particle multiplicities and fragment yields.**
- **However, in QMD models, nuclei are often falsely disintegrated or excited during time evolution, mainly owing to a nonrelativistic equation of motion due to a nonrelativistic description of the Hamiltonian.**
  - ➢ **The spurious excitation or decay can suppressed by:**
    - ✓ **introducing Pauli force and freezing the nucleons until impact;**
    - ✓ **disregard peripheral collisions and spurious reactions by limiting the impact parameter.**
    - ✓ **Coalescence models are often used to simulate cluster formation; however, they cannot be applied to the formation of heavy residues.**
  - ➢ **These treatments result in non-conservation of energy, an incorrect specific heat of the nucleus, or inaccurate simulation of peripheral collisions**

Hence, QMD has problems to calculate the residual nucleus production!

JAMQMD

- **JAMQMD is a combination of the JAM and JQMD models and is composed of binary reactions of elastic, resonant and non-resonant channels, a relativistic equation of motion, interaction by mean field, and "clusterization" in the final state.**
- **Artificial corrections are not necessary because nuclei are formed and sustained by the interaction between nucleons.**
- **The calculations are fast and can reasonably well simulate particle production and fragment yield in high-energy nucleus-nucleus reactions of up to 1 TeV/u of incident energy.**



Proton transverse mass distribution in central Pb-Pb collisions at 20, 40, 80, and 158 GeV/u. Symbols are experimental data taken

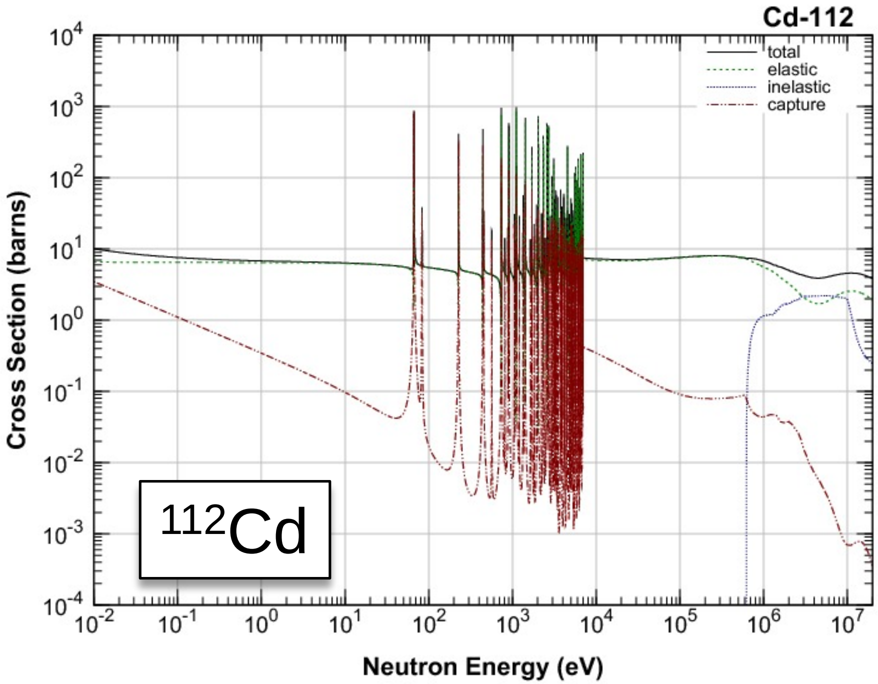
$$m_T^2 = m^2 + p_x^2 + p_y^2 = E^2 - p_z^2$$

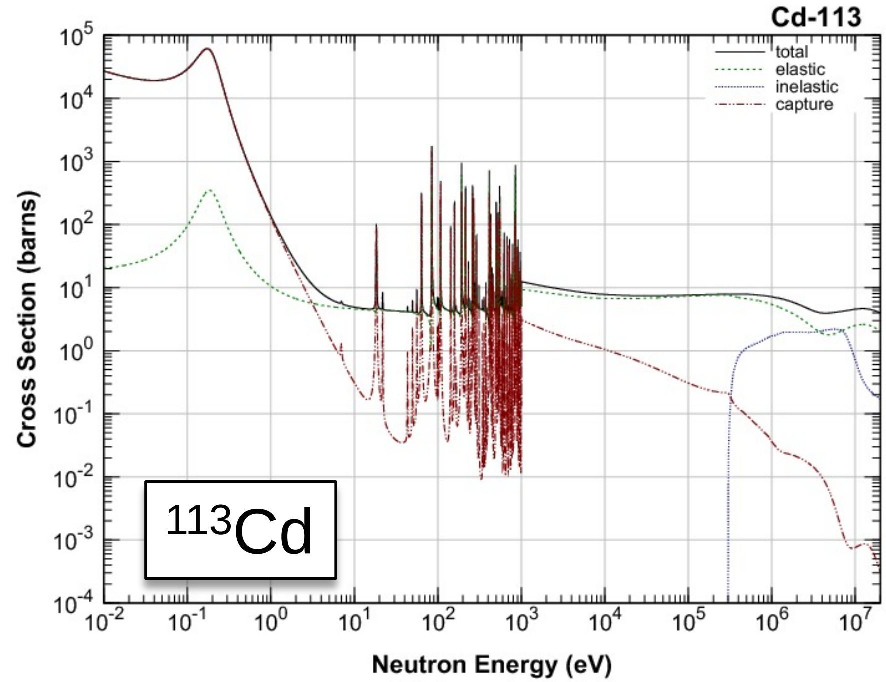
Nuclear Data Library

Cross sections for low energy neutrons strongly depends on nuclear structure

Physics models are inadequate

Isotopic cross section data library is necessary





Neutron reaction cross sections of ^{112}Cd and ^{113}Cd taken from JENDL4.0

http://wwwndc.jaea.go.jp/jendl/j40/J40_J.html

Event Generator Mode

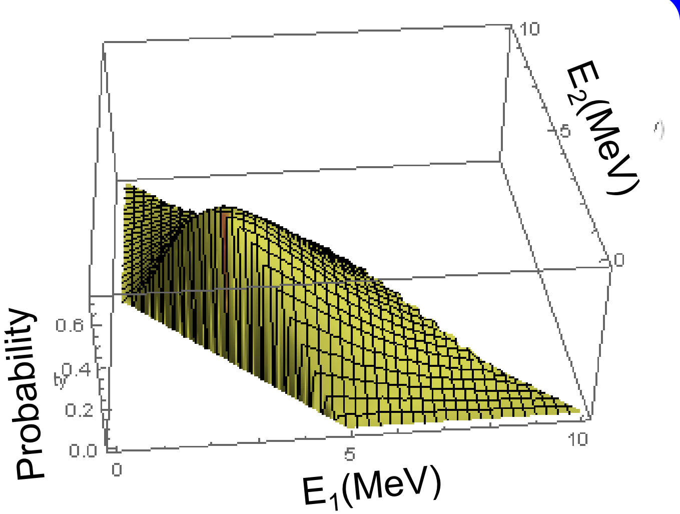
What is event generator mode (EGM)?

Sample all secondary particles from DDX contained in nuclear data library, considering energy & momentum conservation in an event

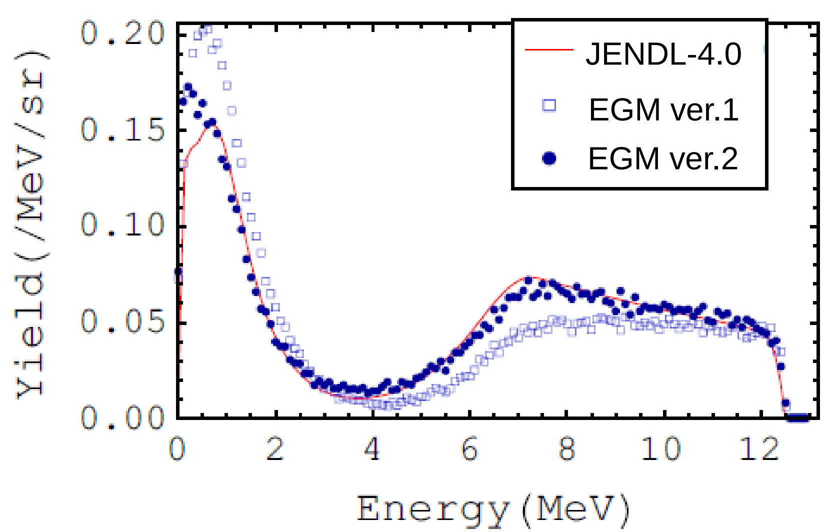
Indispensable for detector response and soft-error rate calculation

How does it work?

- ✓ Conventional method: Sample particle by particle from energy distribution
- ✓ EGM: Sample all particles at once from energy sampling space



Energy sampling space

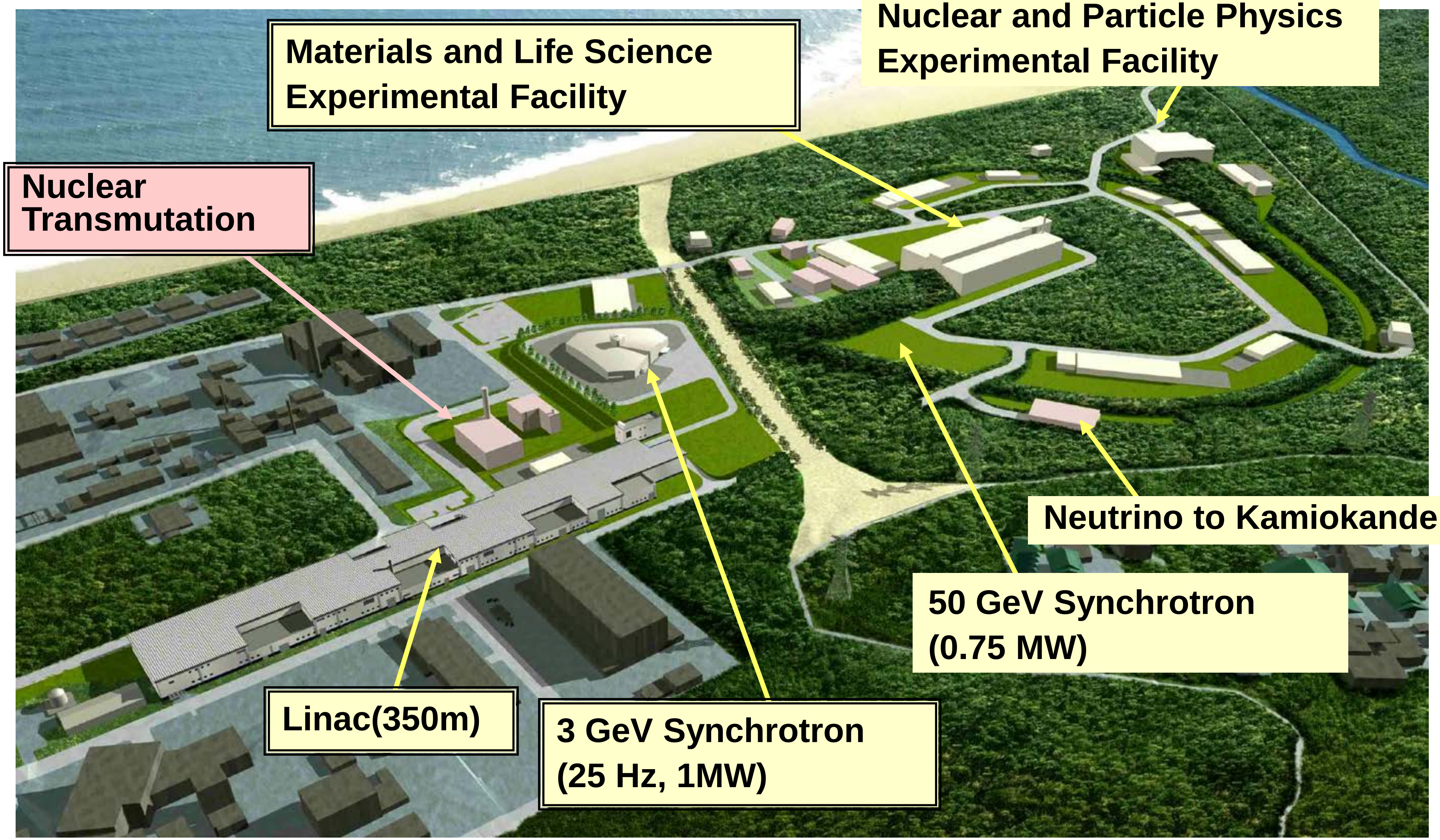


Secondary particle yields from $^{150}Nd(n,2n)$

T.Ogawa *et al.*, *NIM A*, **763**, 575-590 (2014)

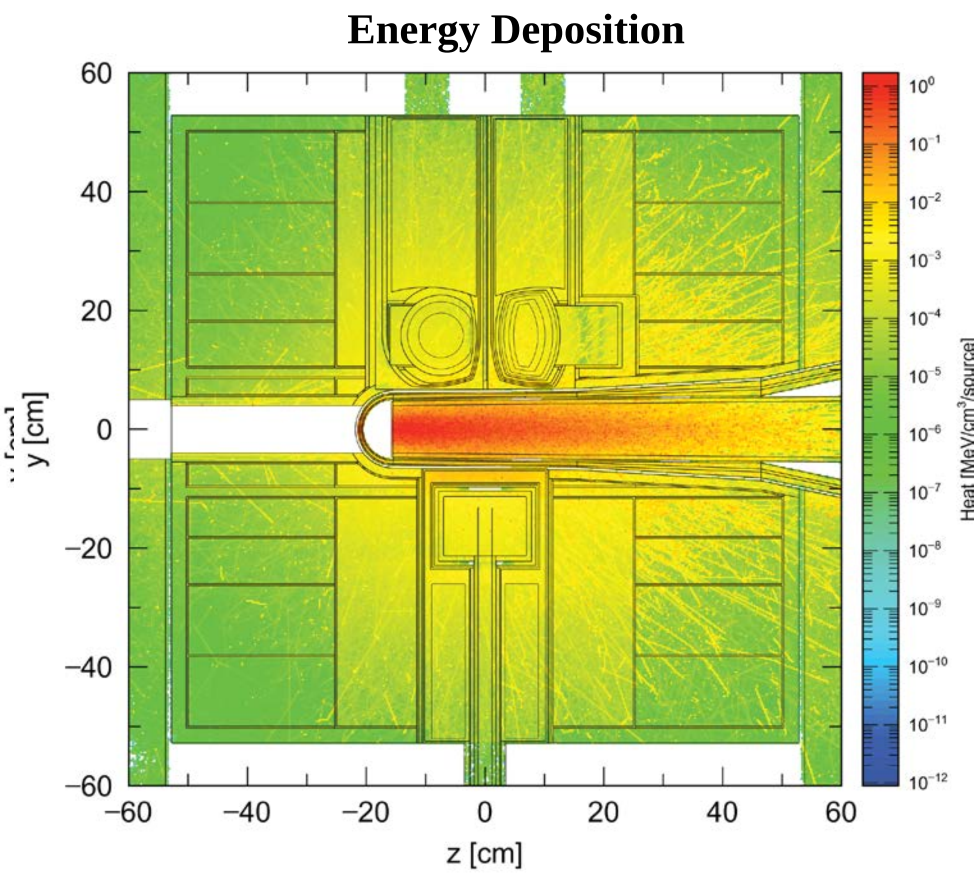
J-PARC

Japan Proton Accelerator Research Complex

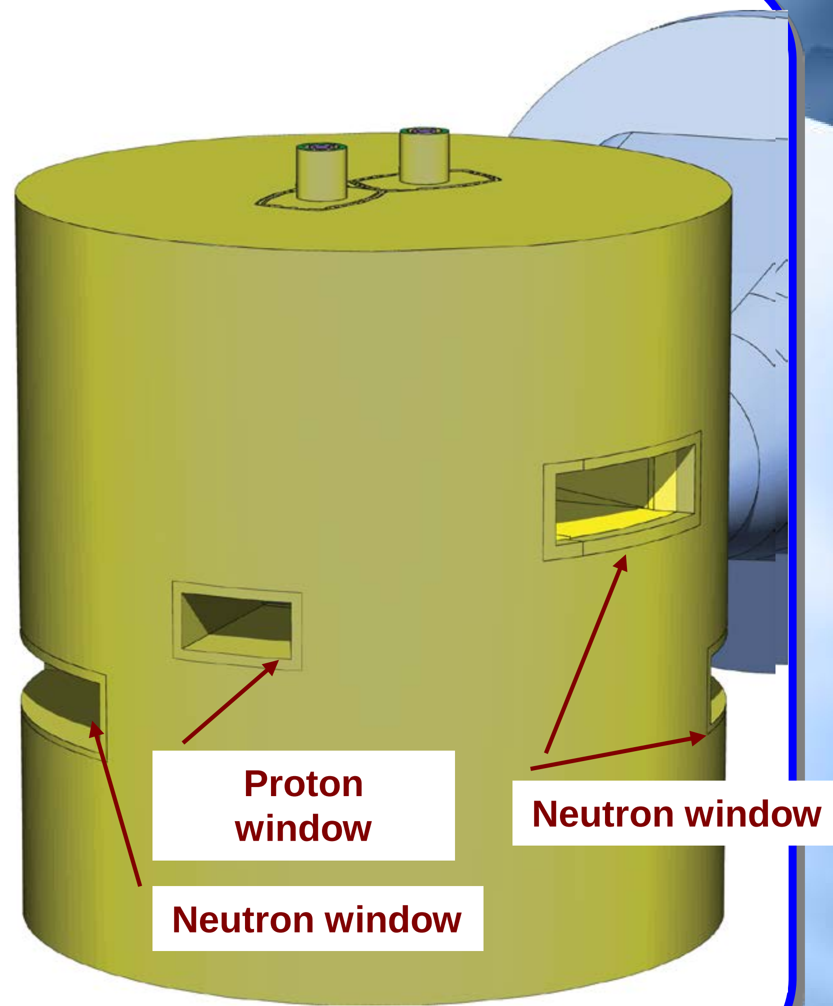


Constructed under joint project of JAEA and KEK in Tokai-mura

Shielding Design around Spallation Target



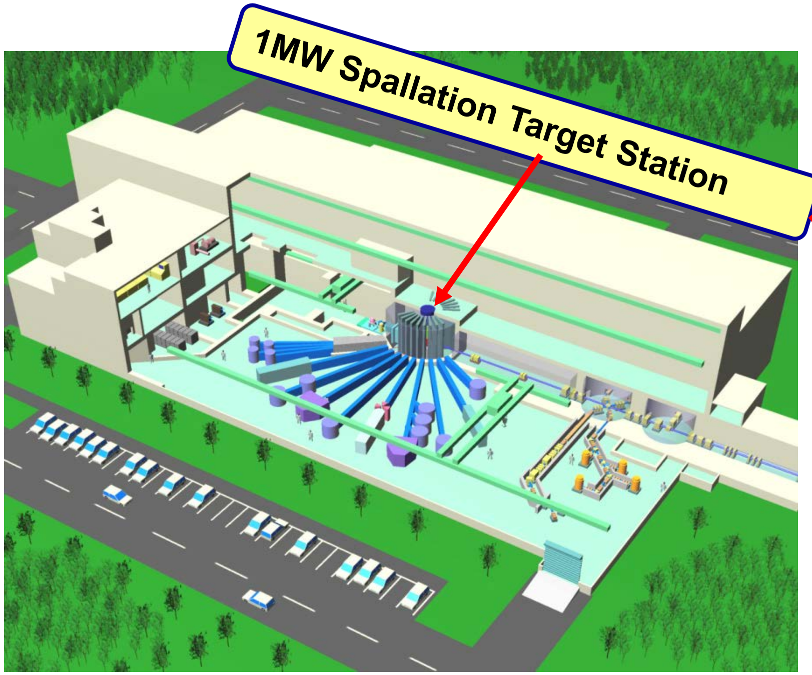
Estimation of Heat around target

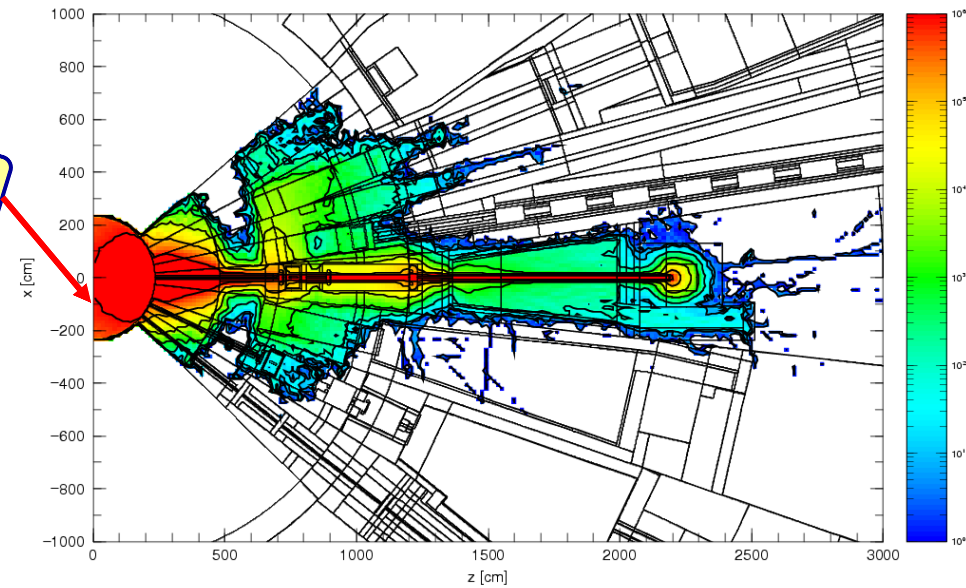


Geometry around Hg target

M. Harada et al. *J. Nucl. Material* **343**, 197 (2005)

Shielding Design around Neutron Beam Line





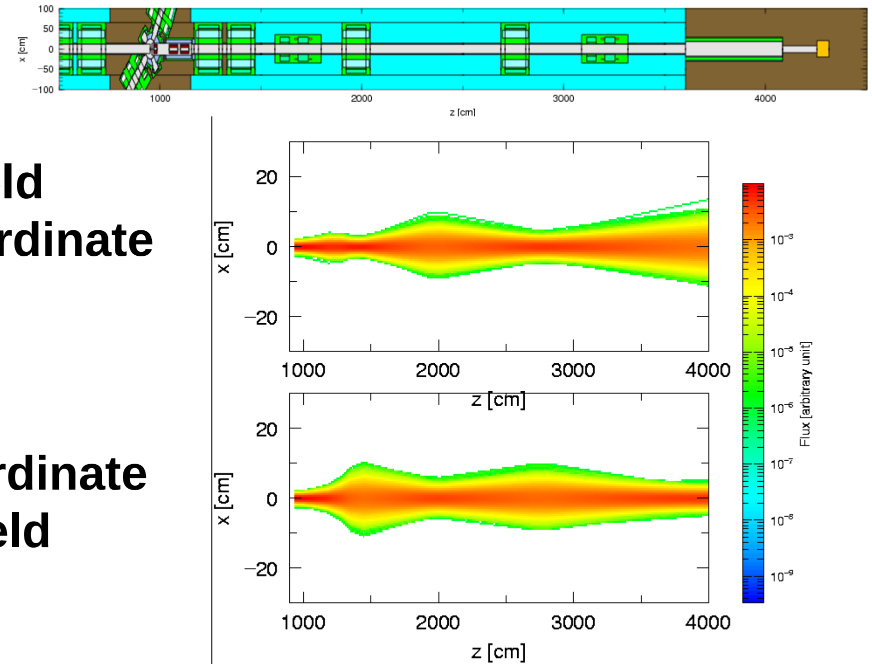
Heat distribution calculated by PHITS

23 neutron beam lines in material and life science facility

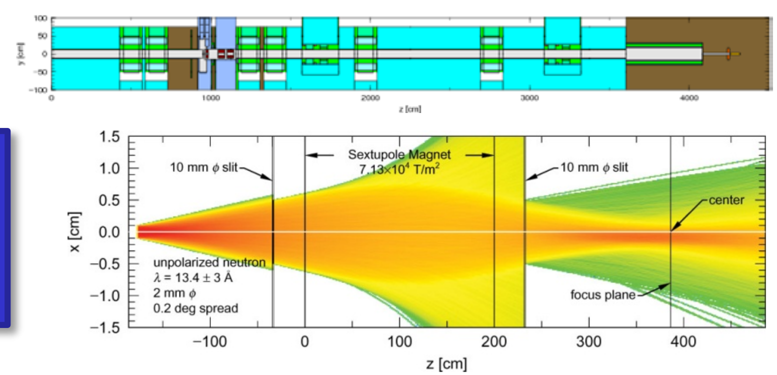
Duct source option

- Source generation program specialized for shielding design of long beam lines
- "Weight" of each source particle is automatically adjusted
- obtain good statistics within reasonable computational time in whole area

Functions for Beam Transport



- **Charged particles**
  - Angular and energy straggling
  - Dipole and Quadrupole Magnetic field
  - Magnetic field map in xyz or r-z coordinate
- **Low energy neutrons**
  - Dipole, Quadrupole and Sextupole
  - Magnetic field map in xyz or r-z coordinate
  - Pulse (Time dependent) Magnetic field
  - Optical devices; Super mirror
  - Mechanical devices; T0 chopper, ….
  - Gravity

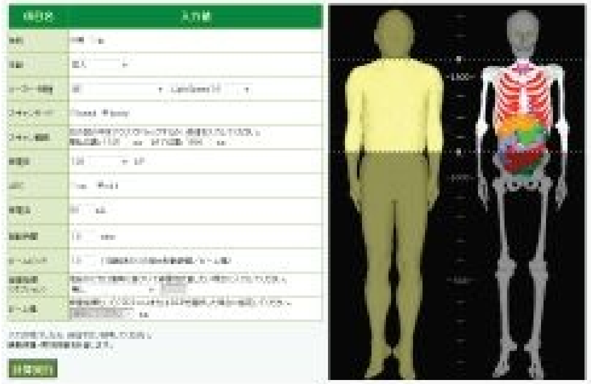


PHITS can simulate not only trajectories, but also collisions and ionization at the same time.

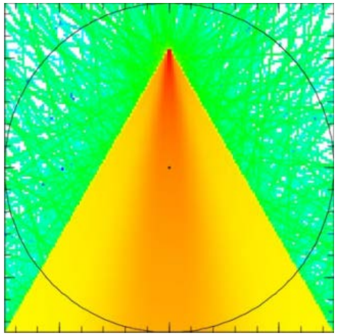
CT Dosimetry System: WAZA-ARI

What is WAZA-ARI?

- Web-based system for calculating patient doses from CT examination
- Organ dose data calculated by PHITS coupled with Japanese voxel phantoms for male & female



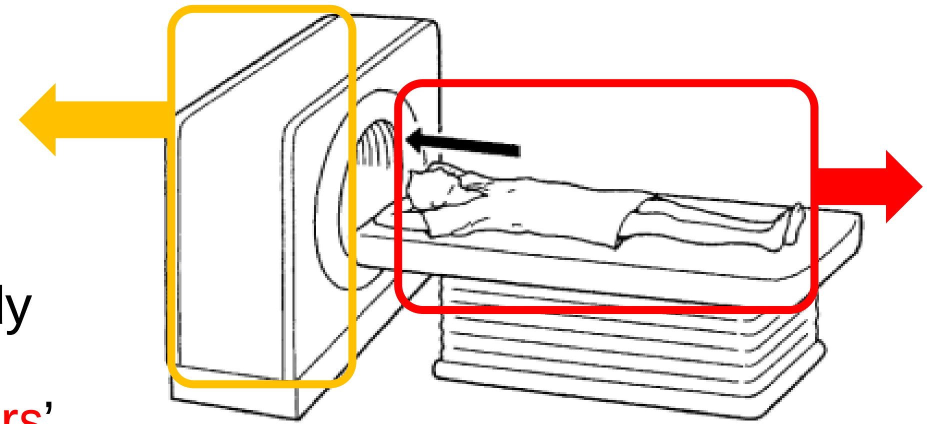
Calculation of CT Dose



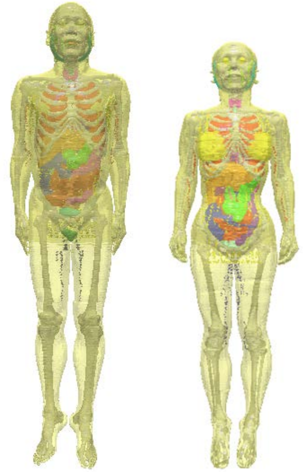
Experimental study

subroutine, ‘usrsors’

Source models



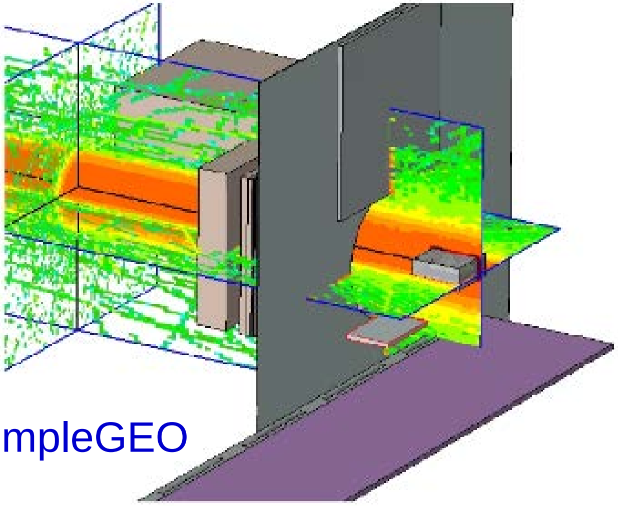
CT examination



Human models

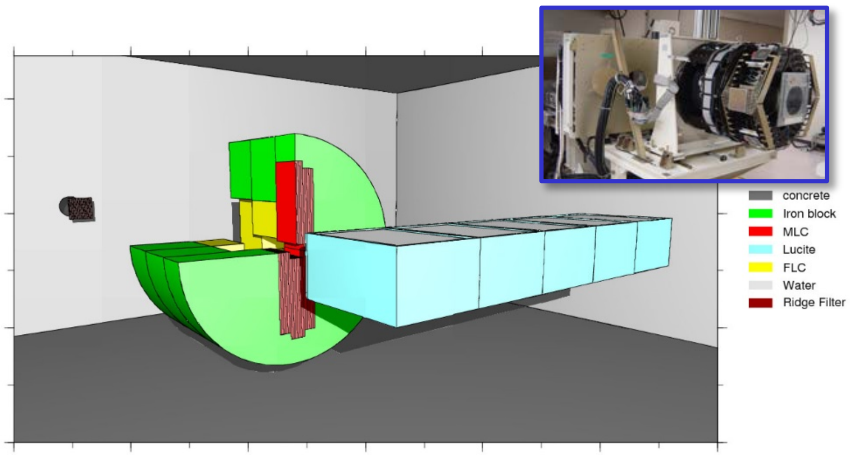
F. Takahashi et al. Health Phys., **109,** 104-112 (2015), https://waza-ari.nirs.qst.go.jp/

Application to Particle Therapy



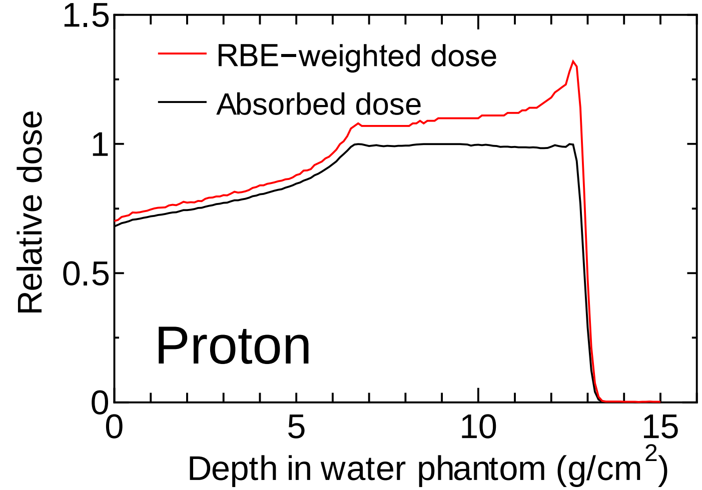
drawn by PHITS+SimpleGEO

O. Ploc et al. IEEE Aerospace Conf. (2017)

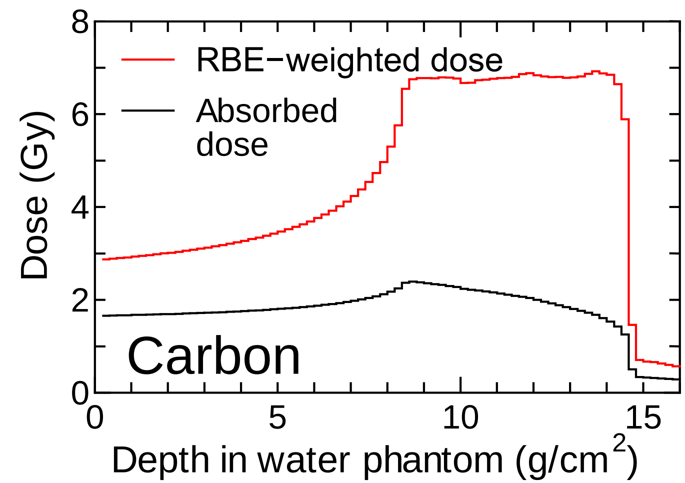


S. Yonai et al. Med Phys. 39, 5028-39 (2012)

Secondary dose estimation



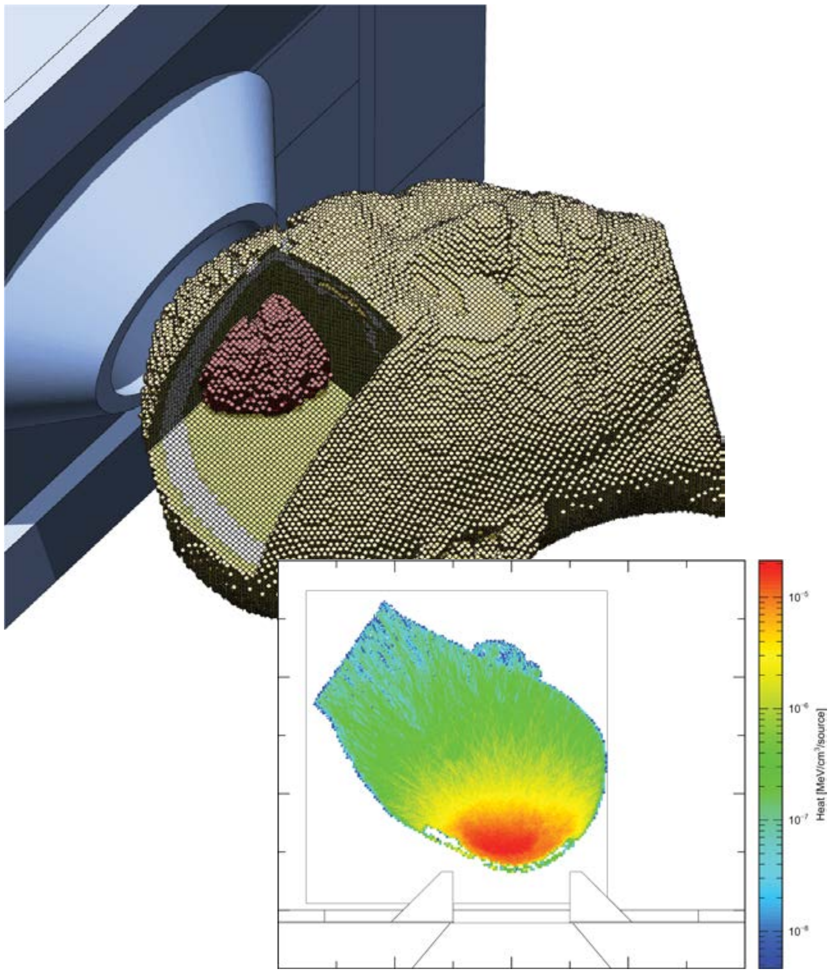
K. Takada et al. JRR 59, 91-99 (2018)



T. Sato et al. Radiat. Res. 171, 107-117 (2009)

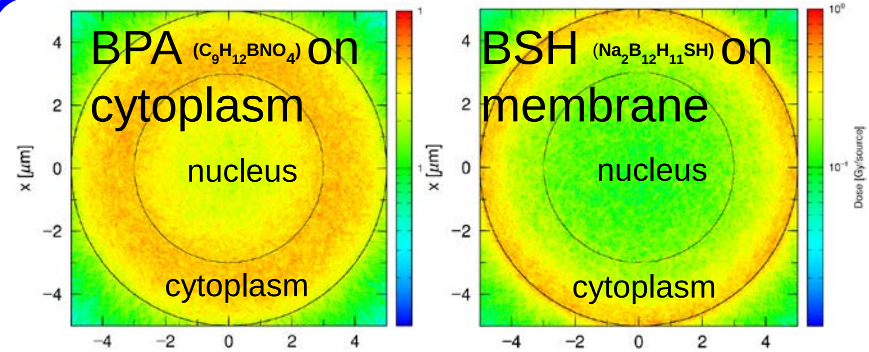
RBE-weighted dose estimation

Application to BNCT

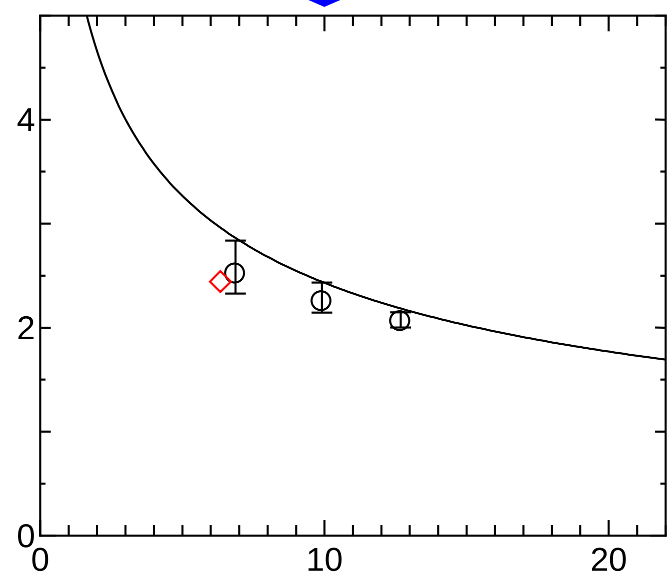


Treatment planning system: JCDS

H. Kumada et al. *J. Phys.: Conf. Ser.* **74**, 021010 (2007)



Dose analysis in cellular scale

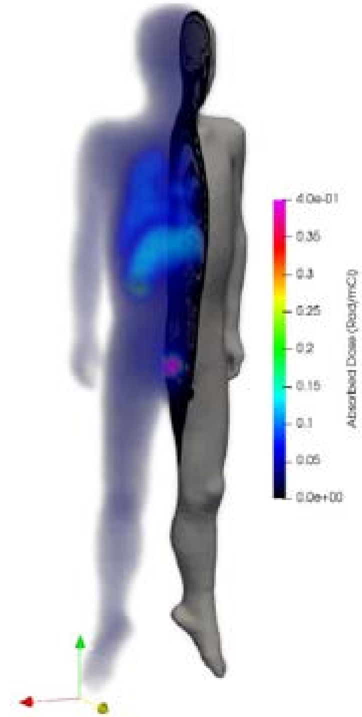


Estimation of therapeutic effect

T. Sato et al. Sci. Rep. 8, 988 (2018)

Application to Nuclear Medicine

PHITS-based Application for Radionuclide Dosimetry In Meshes



ParaVIEW visualization

1. Select human or mouse tetra-mesh phantom
2. Input retention time of Radioiodine (RI) in each organ
3. Automatically generate PHITS input for the condition and execute
4. Visualize the calculated dose distributions in TPS or ParaVIEW

Developed by MSKCC and Opened to Public for free!

Carter et al. J. Nucl. Med (2019) (https://www.paradim-dose.org/)

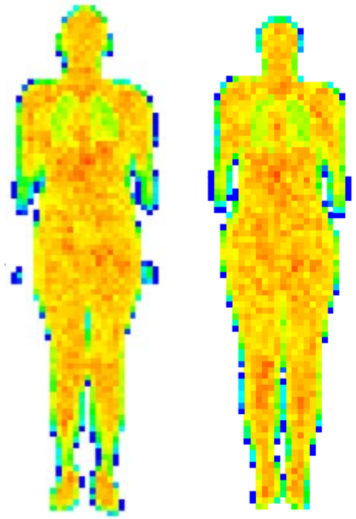
Calculation of Dose Conversion Coefficients

supervision of ICRP C2 Task groups

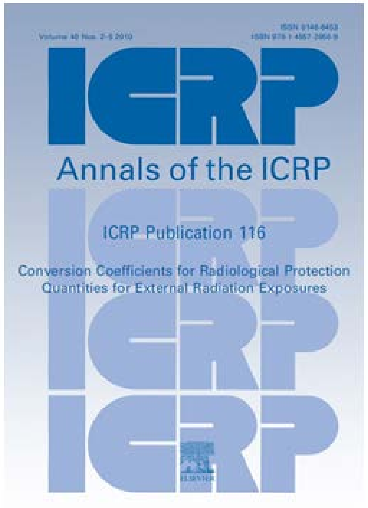
PHITS Simulation Conditions

- Incident particle: neutron, proton, pion, muon, heavy ions (~Ni)
- Incident energy: 1 MeV/n* up to 100 GeV/n
- Irradiation geometry: ISO, AP, PA, LLAT, RLAT, ROT
- Calculated quantity: dose, Q(L),Q(y)&Q_{NASA}-based dose equivalent

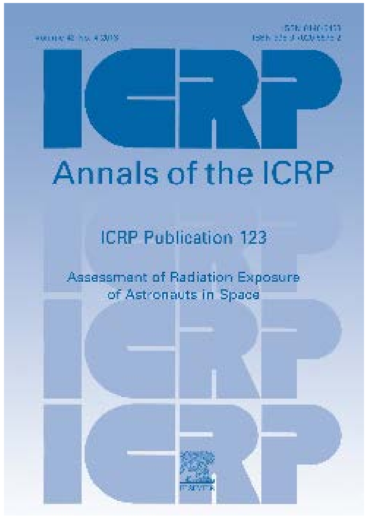
*from 1 meV for neutron



ICRP/ICRU adult reference computational phantoms



ICRP Pub.116

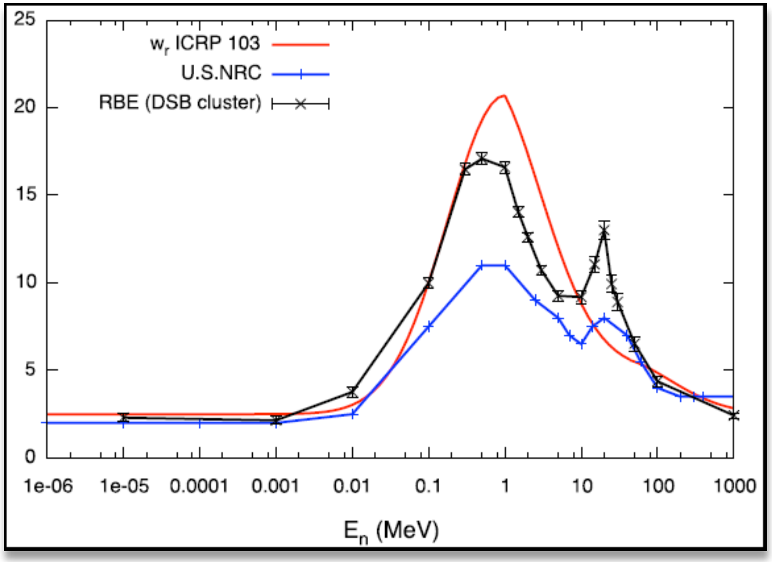


ICRP Pub.123

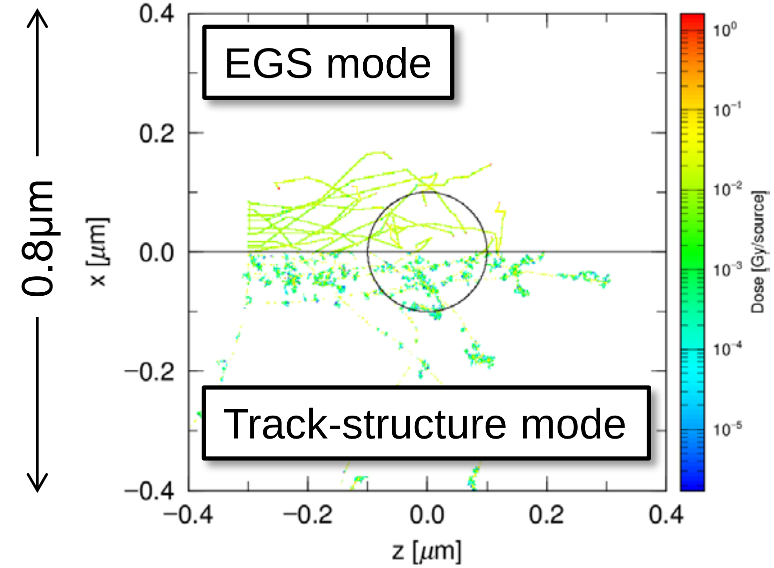
Used for evaluating their reference values

T. Sato et al. *Phys. Med. Biol*. **54**, 1997, (2009), T. Sato et al. *Phys. Med. Biol*. **55**, 2235, (2010)

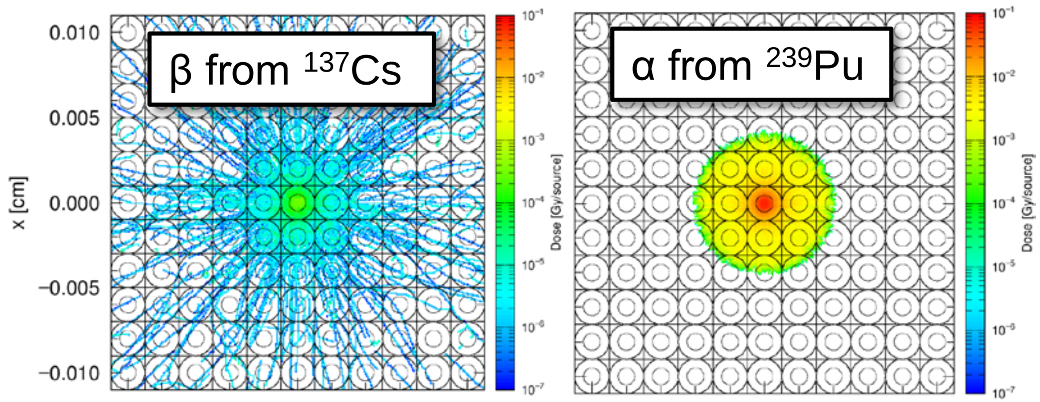
Applications to Radiation Biology



RBE of neutron for DNA damage



Electron track-structure simulation



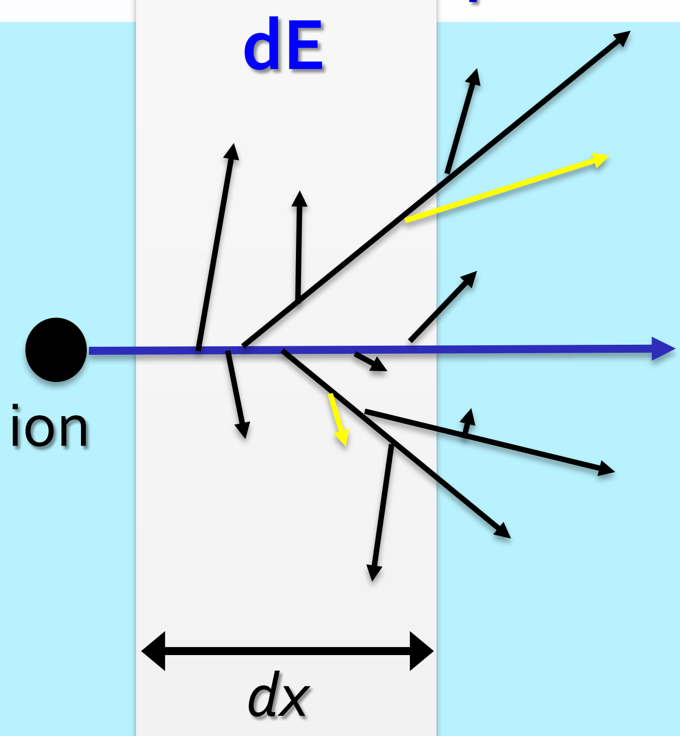
Cellular scale doses calculated by PHITS

Applied to the estimate of DNA damage & risk of internal exposure

T. Sato et al., PLOS ONE 9, e99831 (2014); G. Baiocco et al., Sci Rep 6, 34033 (2016)

Linear Energy Transfer (LET)

Macroscopic: $LET_{\infty}=(dE/dx)_{\infty}$



Independent of radial dose distribution

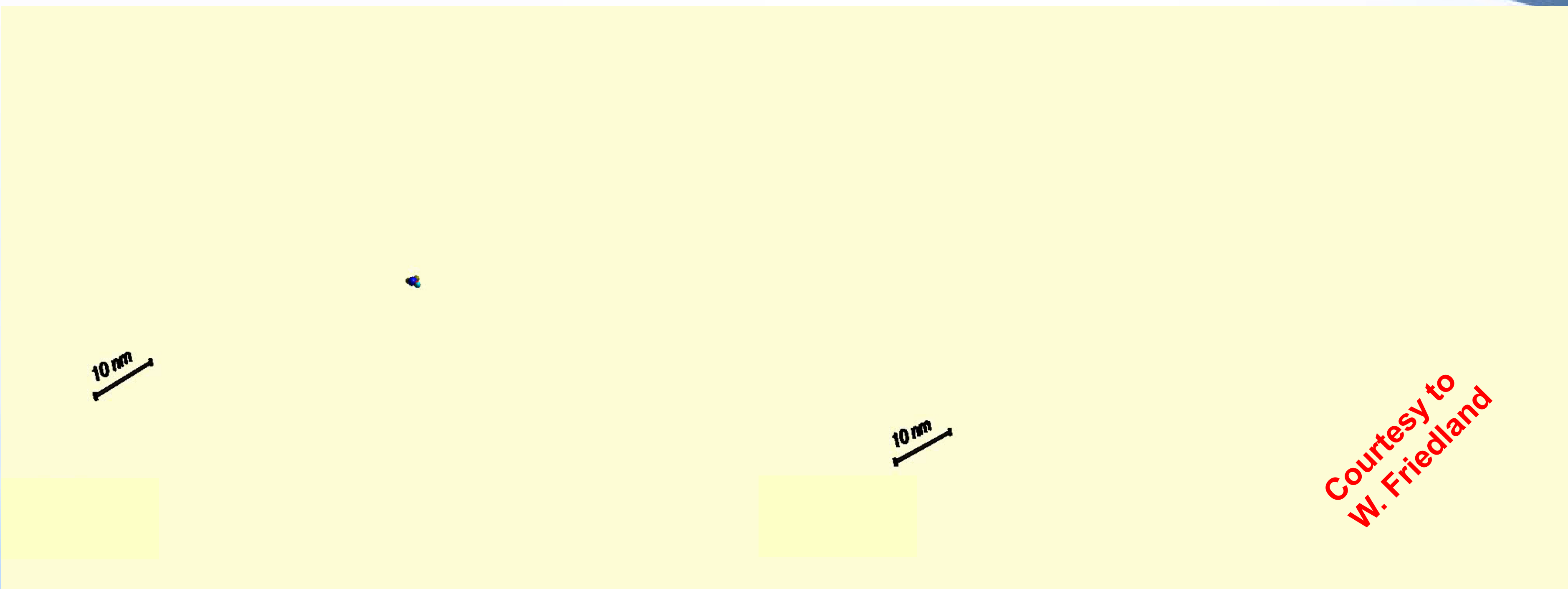
LET_{∞} is the amount of energy deposited per unit length of a material as a charged particle traverses the material

LET_{∞} has the unit MeV/cm (or more common keV/µm)

Track structure is important for Ion beams!

Light vs. Heavy Ions at the same LET (140 keV/μm)

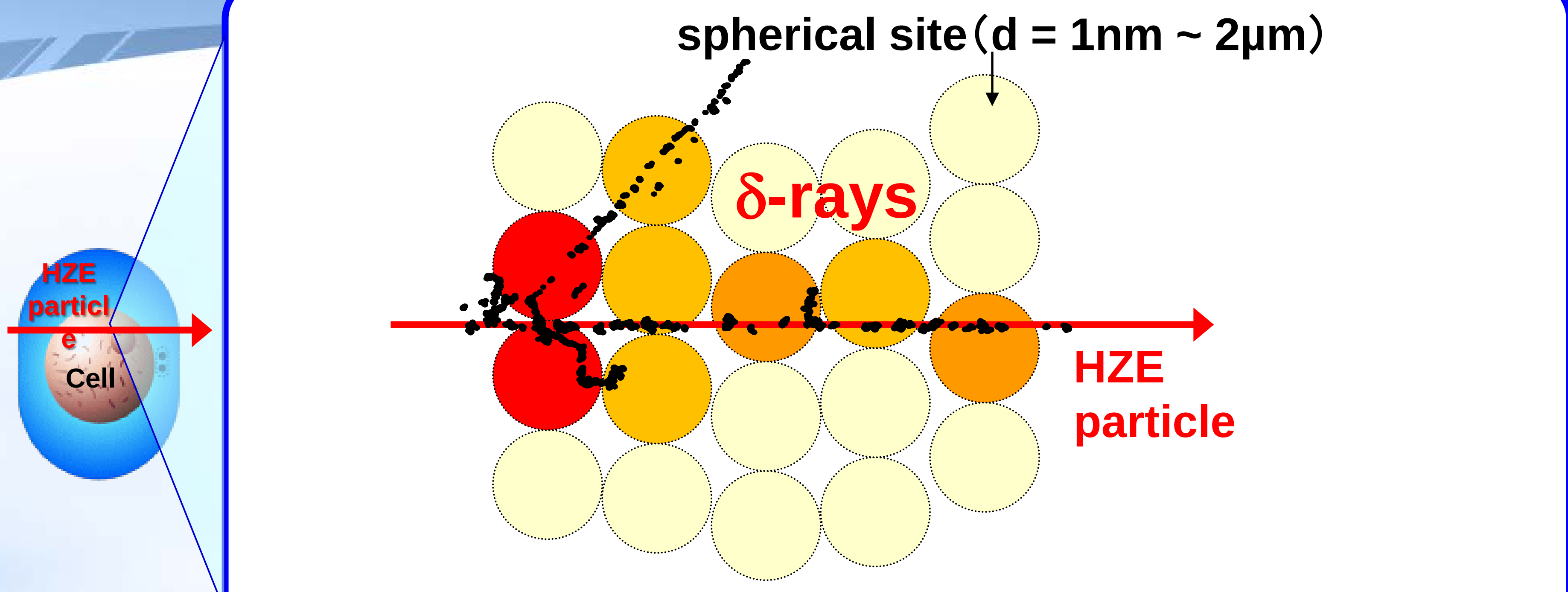
α-particles, 2 MeV | **Fe-ions, 1 GeV/u**



LET_∞: Transferred energy within a certain distance ➡ SAME

***y*: Transferred energy within a certain small volume ➡ DIFFERENT**

Microscopic Track Structure Simulation



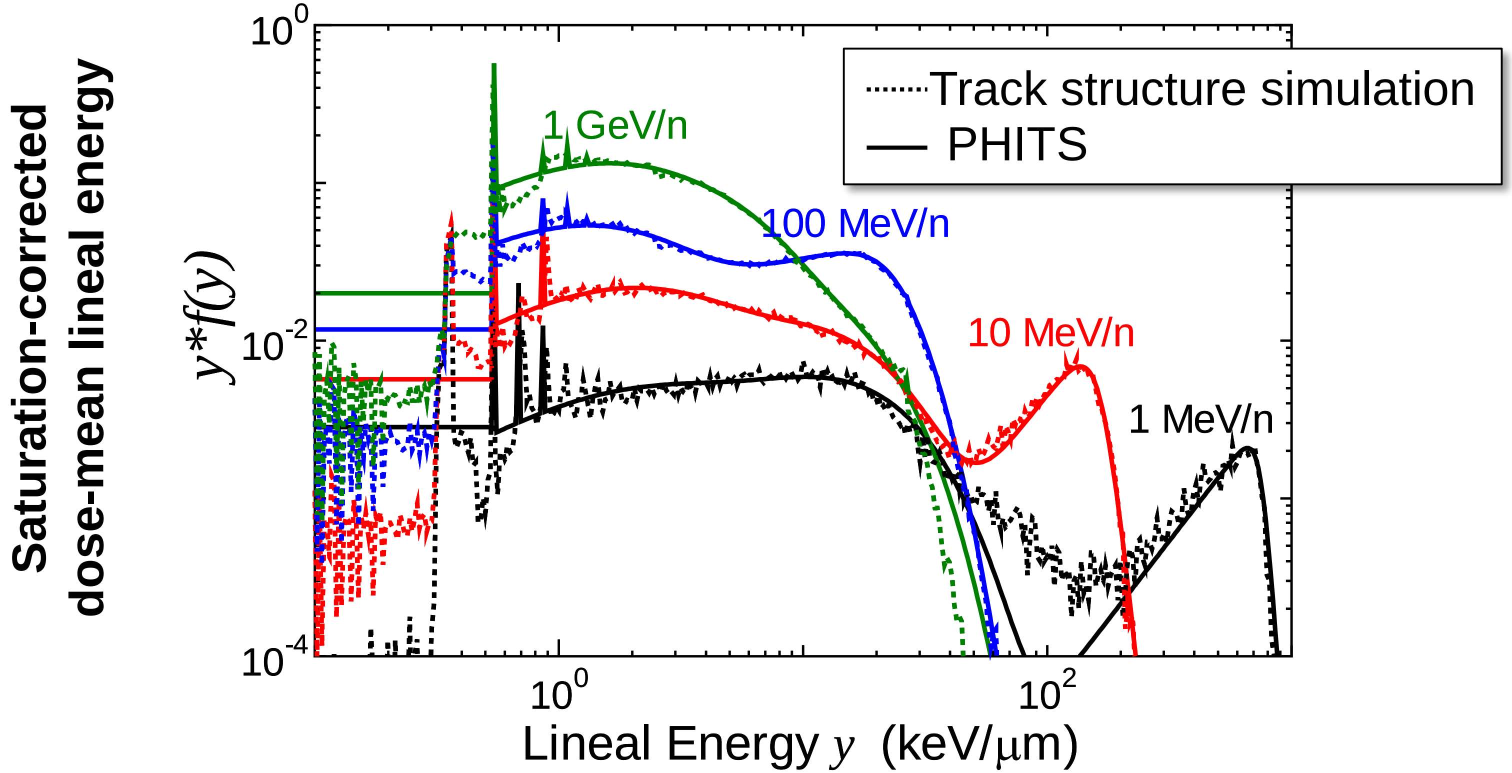
Track structure around the trajectory of HZE particle in water

Simulate the track structures for proton, He, C, Fe up to 100 GeV/u, using TRACEL*

Estimate *yf(y)* around their trajectories by calculating deposition energies in each spherical site

Too time-consumptive to be directly incorporated into a macroscopic simulation !!!!

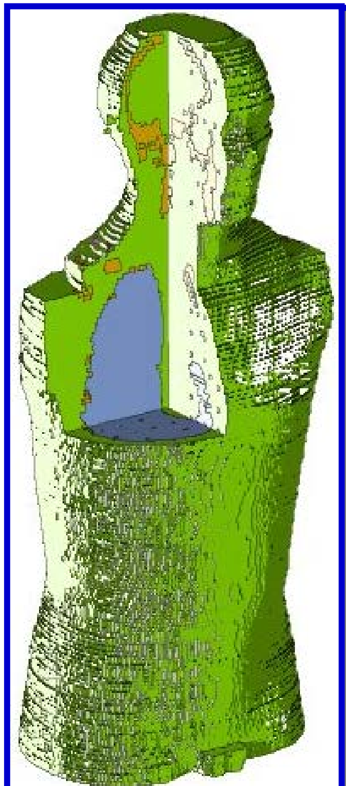
Microdosimetric Function
~ Comparison with Track Structure Simulation ~

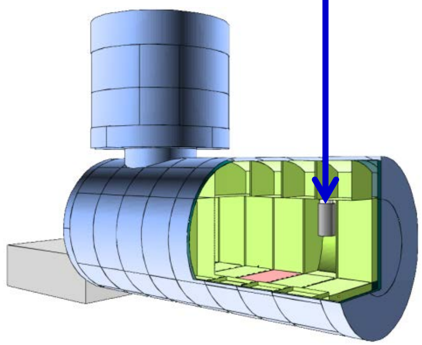


yf(y) for C ions (E = 1, 10, 100 and 1000 MeV/u, d = 30 nm)

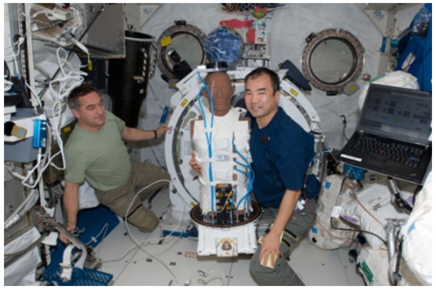
- **PHITS can almost perfectly reproduce the track structure simulation data**
- **Computational time: PHITS << Track structure simulation (~10^{-6})**

MATROSHKA Experiment





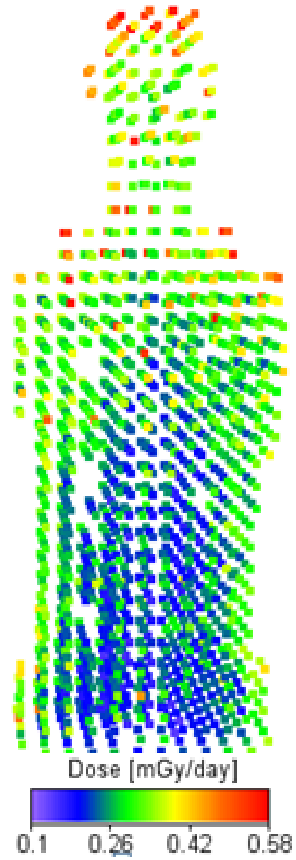
Virtual Kibo Module

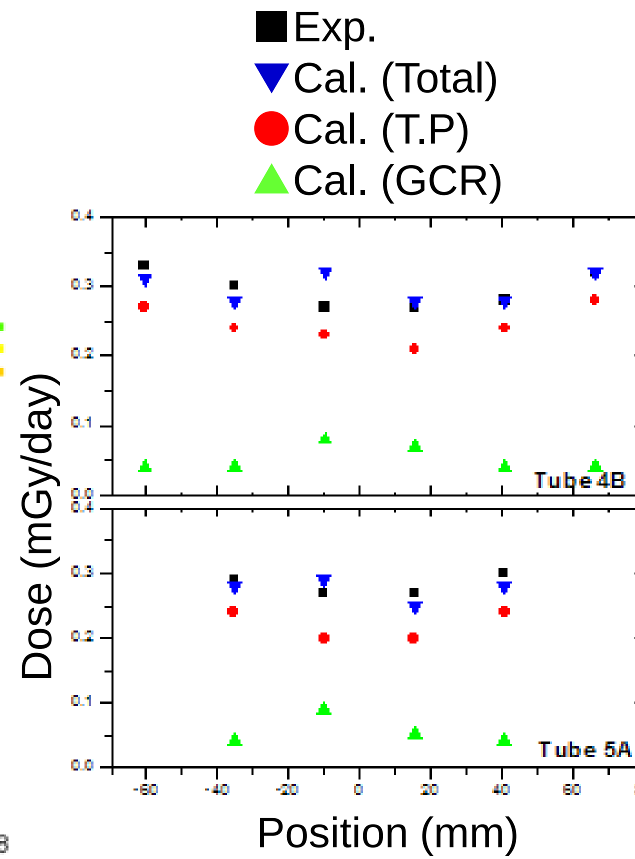


JAXA

MATROSHKA Experiment

- **Measure astronaut doses inside and outside ISS**
- **Lead by G. Reitz of DLR**

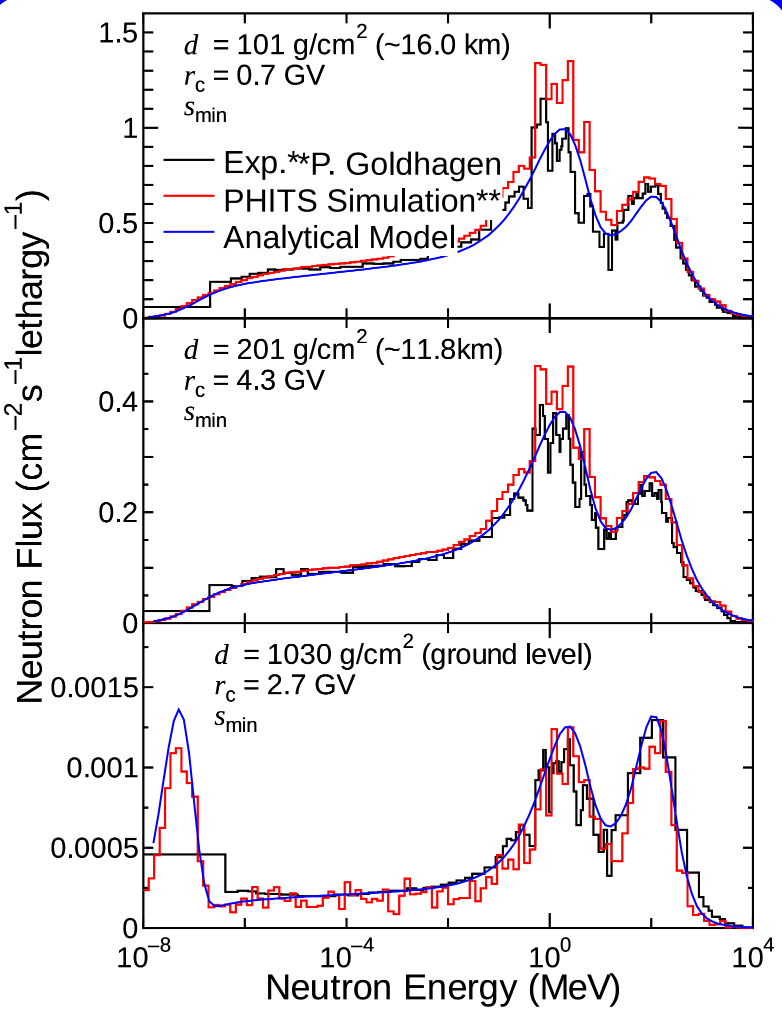




Calculated dose inside the phantom using PHITS

L. Sihver et al. *Radiat. Environ. Biophys*. **49**, 351 (2010), M. Puchalska et al., Adv. Space Res. (2012)

Aircrew Dose Estimation



Atmospheric Neutron Spectra

PHITS simulation

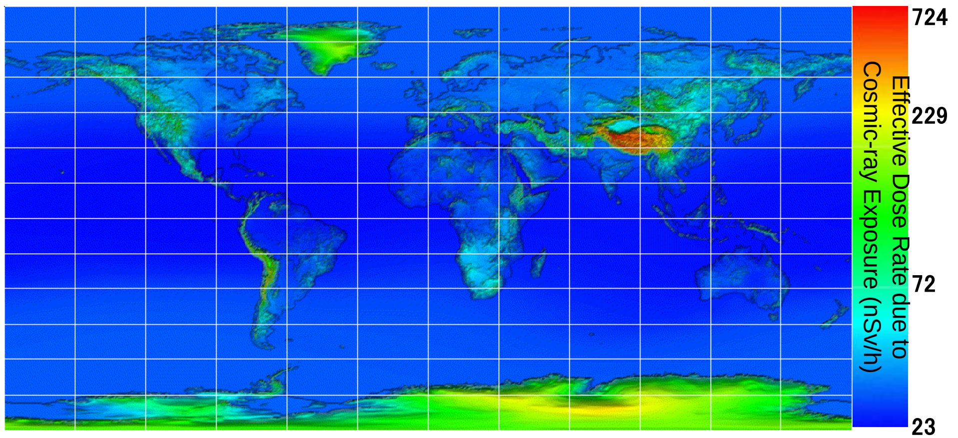
- Transport of cosmic ray in atmosphere considering solar activity and geomagnetism

Modeling

Flux and dose in arbitrary location/time can be predicted

Available as online software EXPACS

http://phits.jaea.go.jp/expacs



Dose distribution at the ground level

Currently used in the Japanese aircrew dose estimation for regulatory purpose

T. Sato, *PLOS ONE*. **10**, e0144679 (2015), T.Sato, Sci Rep 6, 33932 (2016)

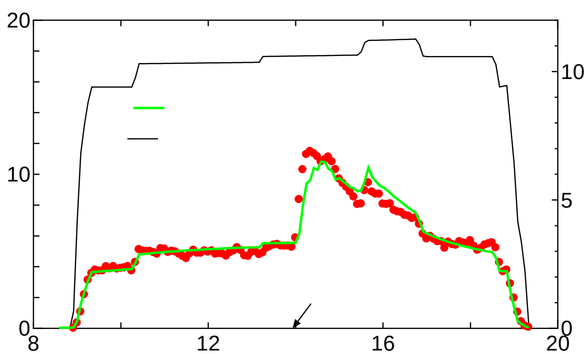
Impact of Solar Flares on Earth

WArning System for AVIation Exposure to Solar Energetic Particle

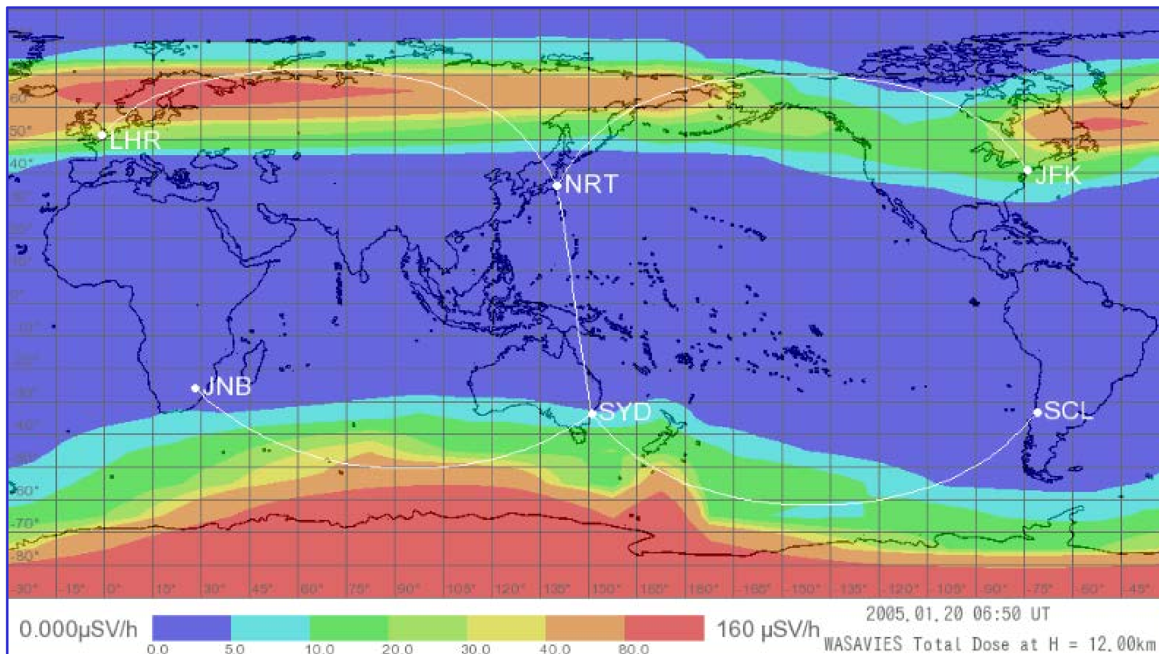
WASAVIES

- ✓ Nowcast radiation doses during large solar particle events based on the satellite observation and ground-level neutron monitors
- ✓ PHITS was used for analyzing the motion of solar particles in the atmosphere

http://wasavies.nict.go.jp



Validation results



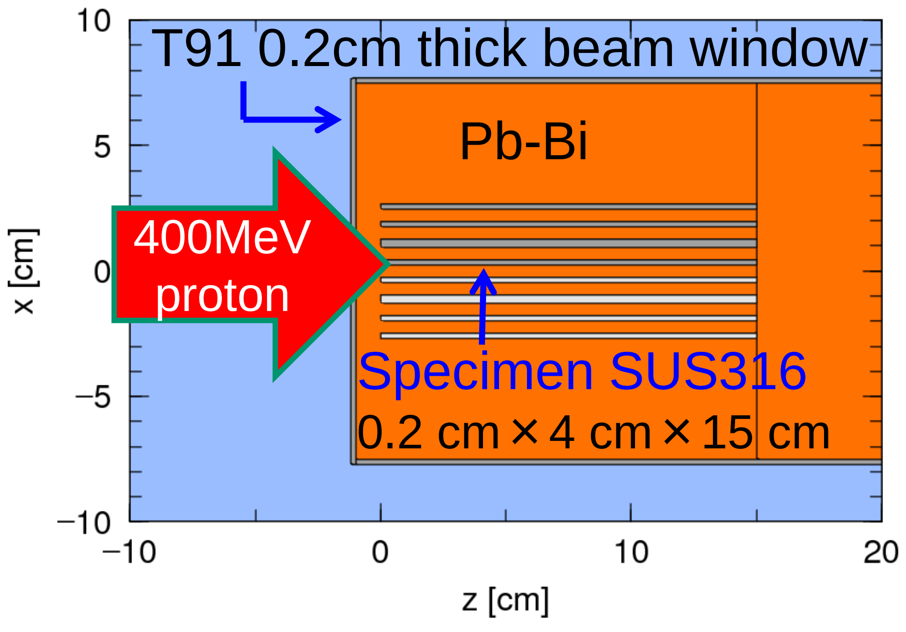
Radiation dose rate map at flight altitude during solar flare on Jan. 2005

R. Kataoka et al. Space Weather (2018); T. Sato et al. Space Weather (2018)

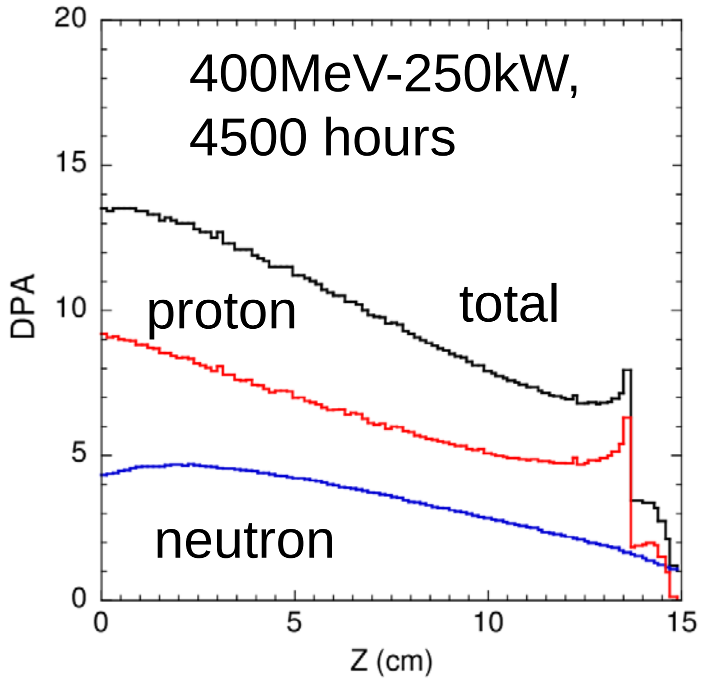
Calculation of Radiation Damage: DPA

What is DPA?

- Average number of displaced atoms per atom of a material
- PHITS-DPA considers not only Coulomb scattering of charged particles but also nuclear interactions.



J-PARC TEF-T for ADS target



Depth-DPA distribution in specimen

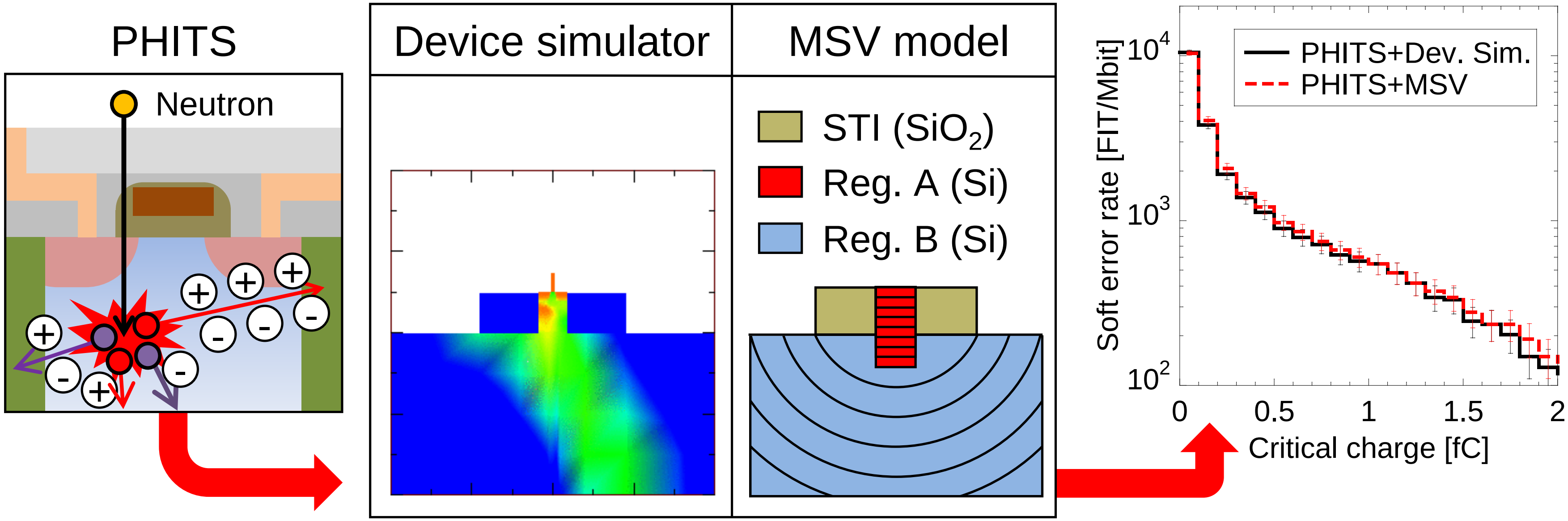
Y. Iwamoto et al., Nucl. Instr. and Meth. B, 274 (2012) 57.
Y. Iwamoto et al., J. Nucl. Sci. Technol. 51 (2014) 98.

Semiconductor soft error rate evaluation

Semiconductor soft error ?

- The information stored in semiconductor memory is flipped by incident radiations through the energy deposition process
- At ground level, errors are induced by reactions of cosmic ray neutrons

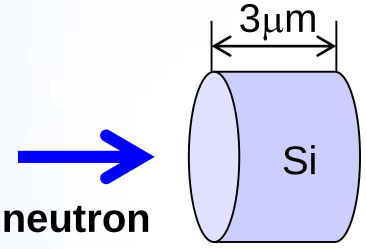
Simulation of secondary particle production by neutrons is necessary

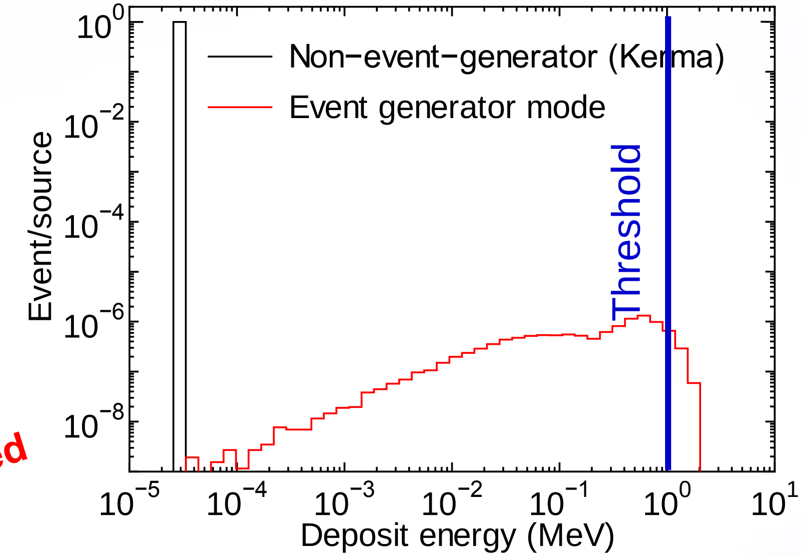


SER analyses with device simulator or multiple sensitive volume model

S. Abe et al. *J. Nucl. Sci. Technol. 53, 451-458* (2015)

Semiconductor soft error rate evaluation





Deposition energy distribution in 3 mm Si

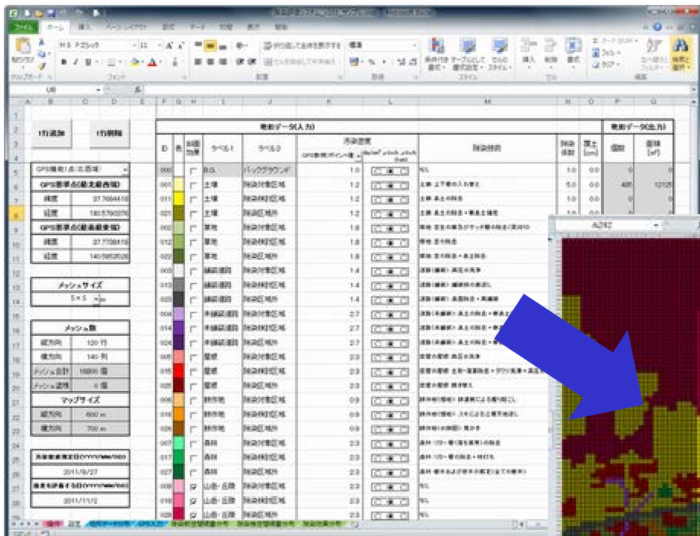
Also indispensable in estimating neutron contribution of RBE-weighted dose!

Single Event Upset (SEU) of Semi-conductor Devices

- **SEU occurs when deposition energy exceeds a certain threshold**
- **SEU probability = 0 from non-event generator simulation** **→ Critical mistake!**
- **SEU probability = 10^{-6}/source from event generator simulation**

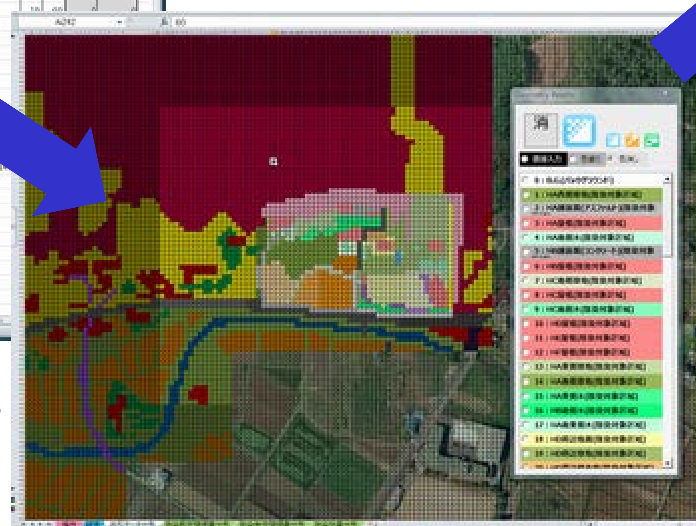
Decontamination effect estimation system

- Software to evaluate decontamination effect based on ambient dose
- PHITS was used to calculate ambient dose in contaminated environment

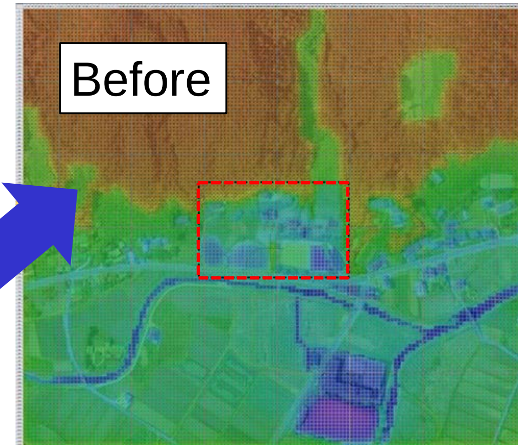


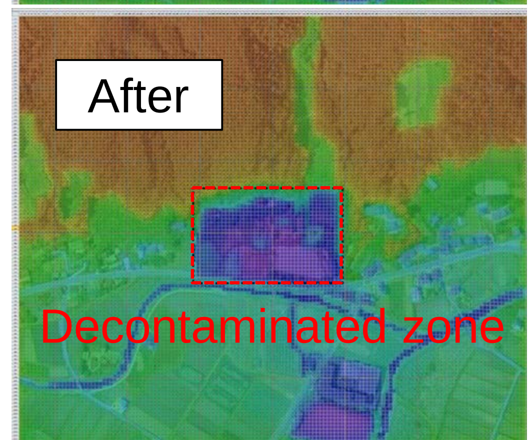
Provided as spreadsheet

Dose calculation
Visualization



Input activity distribution





http://nsed.jaea.go.jp/josen/ （←Provided as freeware）

Typical Features of PHITS

- **Capability of transporting nearly all particles**
  Over a wide energy range in any materials
- **Simple user interface and graphical output tools**
- **Sophisticated nuclear reaction models and libraries**
  INCL4.6, INC-ELF, JQMD, JAM, JAMQMD, JENDL-4, EGS5 etc.
- **Special functions for various purposes**
  - Event generator mode
  - Microdosimetric function
  - Beam transport functions

PHITS has been used by more than 4,000 users in many countries

Future Plans

- **Improve nuclear reaction models and data library**
  - Full set of JENDL-4.0/HE
  - Fission & intra-nuclear cascade models
- **Implement new functions**
  - Improvement of track-structure model
  - Estimation of uncertainties using the high-energy particle induced radioactivity calculation code DCHAIN-SP
  - Estimation of systematic uncertainties
- **Improve user support functions**
  - Special editor for making PHITS input file
  - Completion of error & warning ID lists

Subscribe to PHITS mailing list for update information

see http://phits.jaea.go.jp/howtoget.html
and Email to phits-office@jaea.go.jp

Thank you very much for your kind attention!!