Recent trends in **Nuclear** and **Medical physics**

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European Union European Regional Development Fund

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Junior Research Fellow : 2009 – 2011,
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Doctoral Student : 2011 – 2015
Jagiellonian University in Krakow, Poland.
MPD - program

Post Doctoral Fellow : 04/2016 – 03/2017
Warsaw University, Poland

Post Doctoral Fellow : 04/2017 – Present
Jagiellonian University in Krakow, Poland

WHY (NUCLEAR) PHYSICS ???

KEY POINTS

Fundamental Perspectives

Applications in various fields

Nuclear reactions

Categorize in two types (time scale)

Direct reactions :

A projectile and a target nucleus are within the range of nuclear forces for **the very short time** ($\sim 10^{-22}$ s)allowing for an **interaction of a single nucleon only**.

Incident particles interact **on the surface** of a target nucleus rather than in the volume of a target nucleus.

Products of the direct reactions **are not distributed isotropically in angle**, but they are forward focused.

Direct reactions are of importance in measurements of nuclear structure.

Compound reactions :

A projectile and a target nucleus are within the range of nuclear forces for the time 10^{-18} s – 10^{-16} s. allowing for a **large number of interactions between nucleons**.

The compound nucleus reactions is usually created if the projectile has **low energy**. Incident particles interact in the volume of a target nucleus.

Products of the compound nucleus reactions are distributed **near isotropically in angle** (the nucleus *loses memory of how it was created* – the *Bohr's hypothesis of independence*).

The mode of decay of compound nucleus do not depend on the way the compound nucleus is formed.

The large number of collisions between the nucleons leads to a **thermal equilibrium** inside the compound nucleus.

Resonances in the cross-section are typical for the compound nucleus reaction.

Types of nuclear reactions

Elastic : no energy is transferred between the target nucleus and the incident particle.

Inelastic : Energy is transferred. The difference of kinetic energies is saved in excited nuclide.

Capture : Both charged and neutral particles can be captured by nuclei. This is accompanied by the emission of γ-rays. Neutron capture reaction produces radioactive nuclides (. induced radioactivity)

Transfer : The absorption of a particle accompanied by the emission of one or more particles is called the transfer reaction.

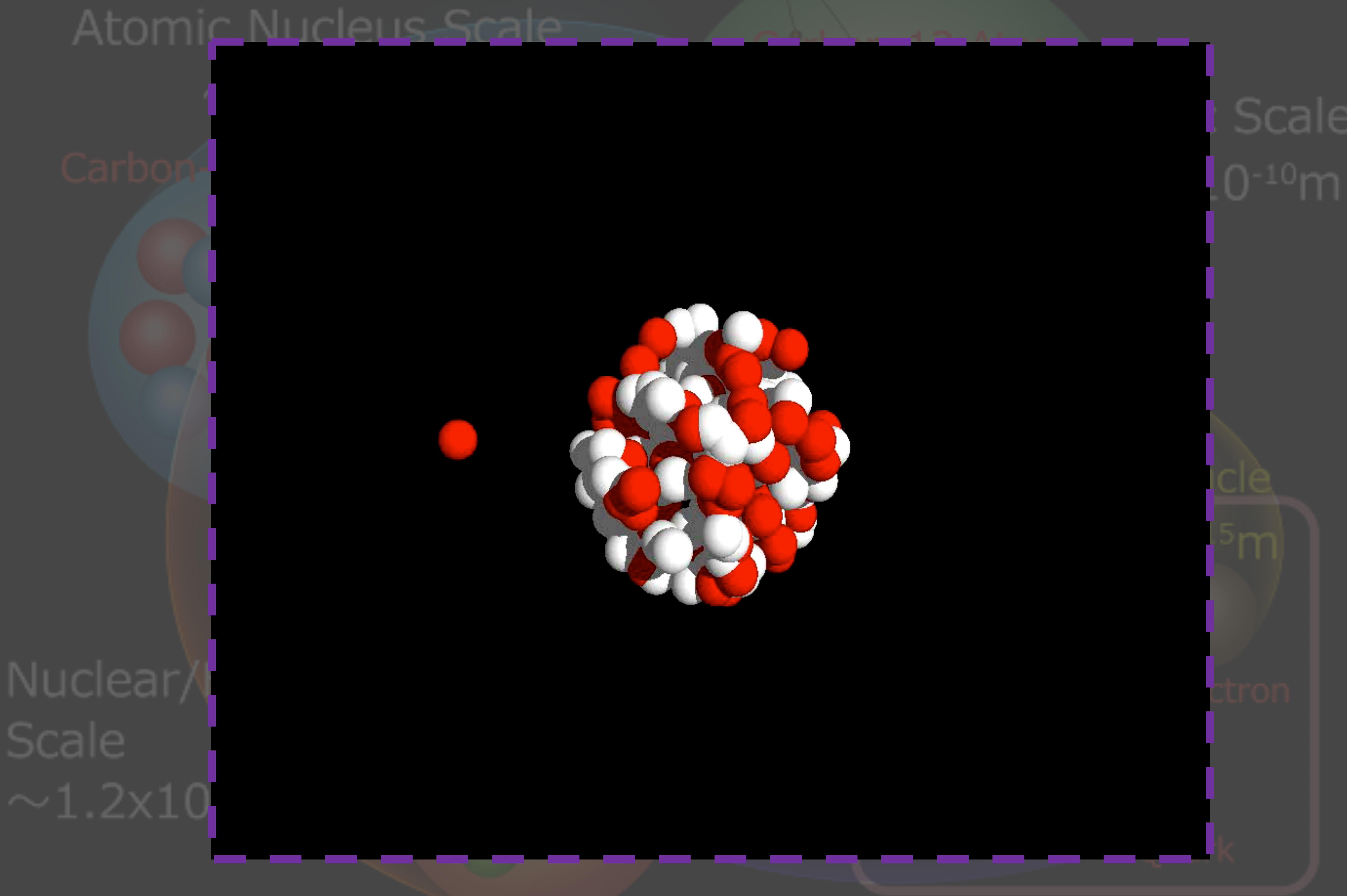
Fission : nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays), and releases a large amount of energy.

Fusion : Two or more atomic nuclei collide at a very high speed and join to form a new type of atomic nucleus.The fusion reaction of deuterium and tritium is particularly interesting because of its potential of providing energy for the future.

Spallation : A nucleus is hit by a particle with sufficient energy and momentum to knock out several small fragments or, smash it into many fragments.

Nuclear decay (Alpha, Beta, Gamma radioactivitY)………

Spallation reactions (proton induced)

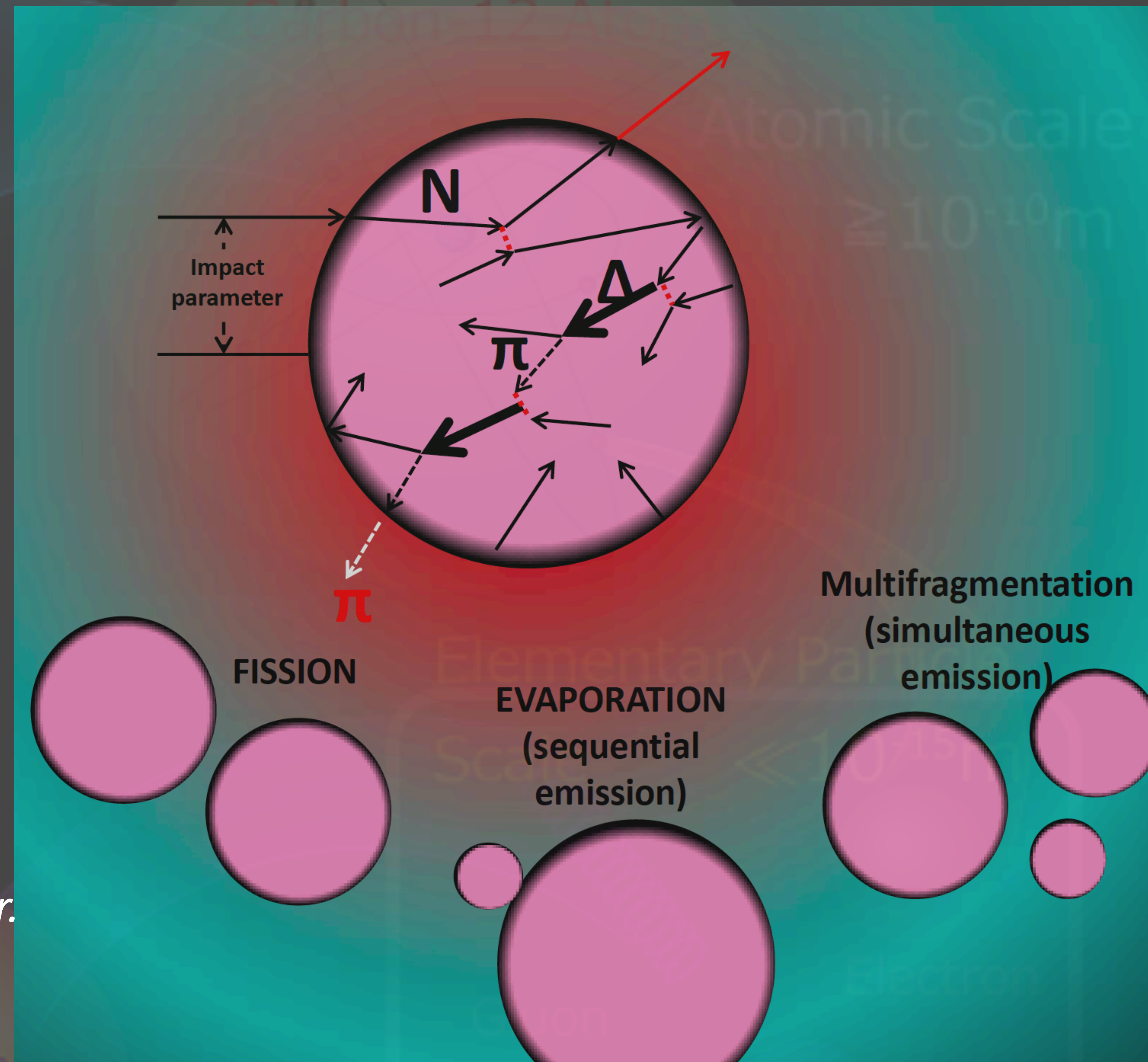


Spallation reactions (proton induced)

The name "spallation" was invented by G. Seaborg:

The incident proton knocks out several nucleons in a series of two-body collisions, leaving behind a highly excited heavy nucleus.

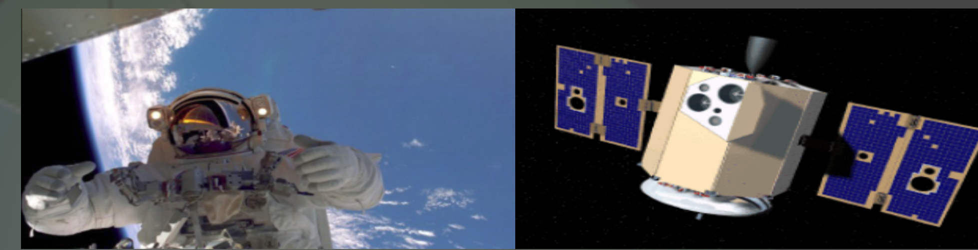
This nucleus decays by the evaporation of charged particles and neutrons, forming a continuous distribution of products ranging downward in A from the target mass number.

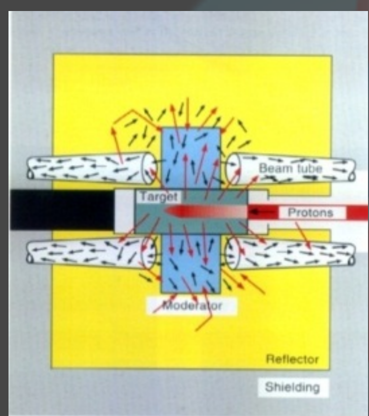


Challenge : ***To understand the reaction mechanism.*** ***HOW WILL BE USEFUL ??***

Spallation reactions (proton induced)

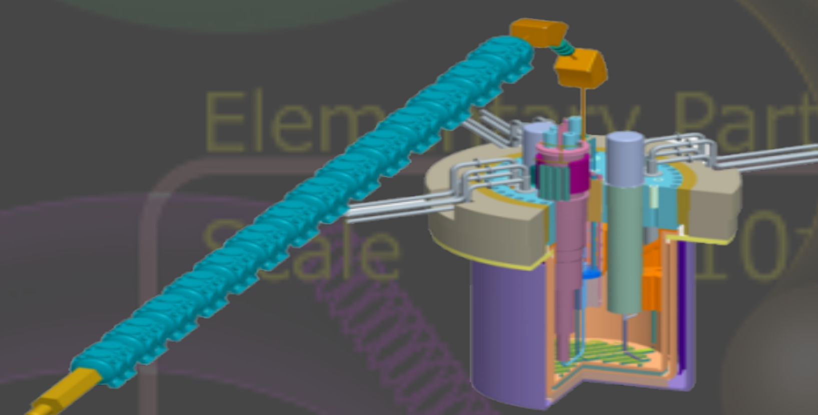
- Radiation protection, damage to electronic circuits in space or near accelerators





- Neutron sources for material science, condensed matter physics (SNS, JPARC, ESS)

- Accelerator-driven sub-critical reactors for nuclear waste transmutation (MYRRHA Belgium)



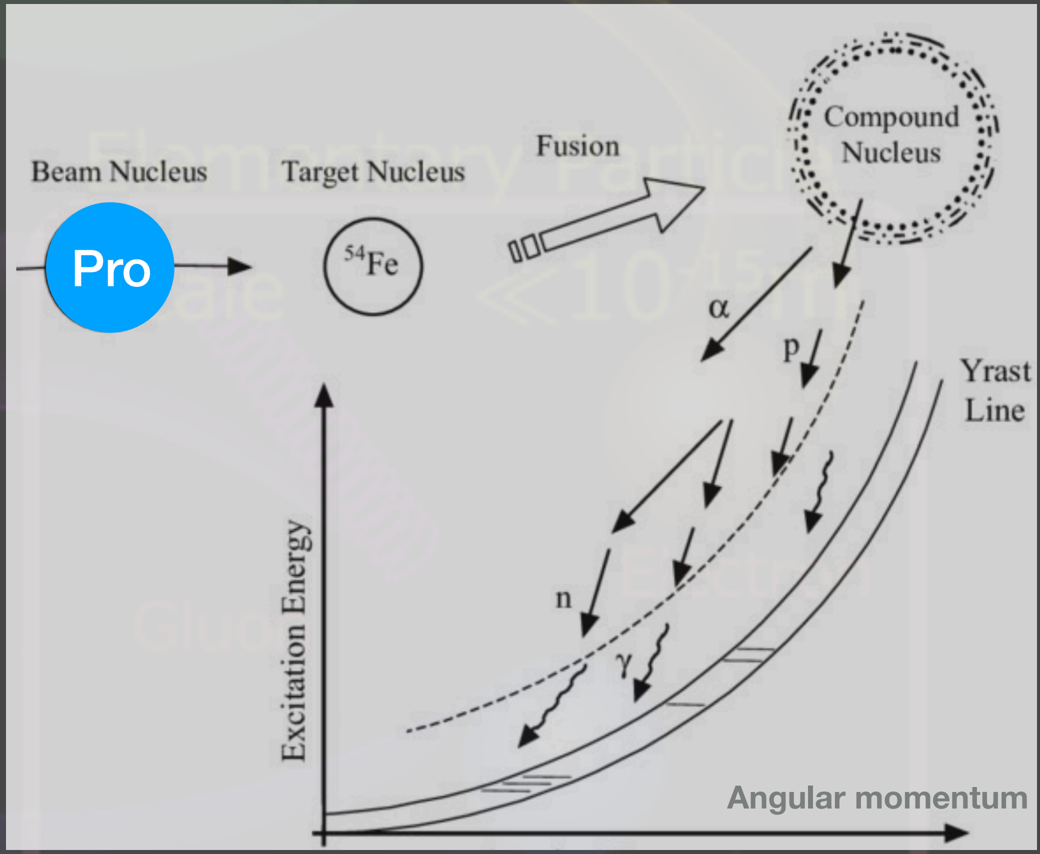
Thus, Very important to understand the reaction mechanism.
One can't measure the data for all the nuclear system(beam and target) and hence to depend on the model calculations.

Nuclear/Gamma Spectroscopy

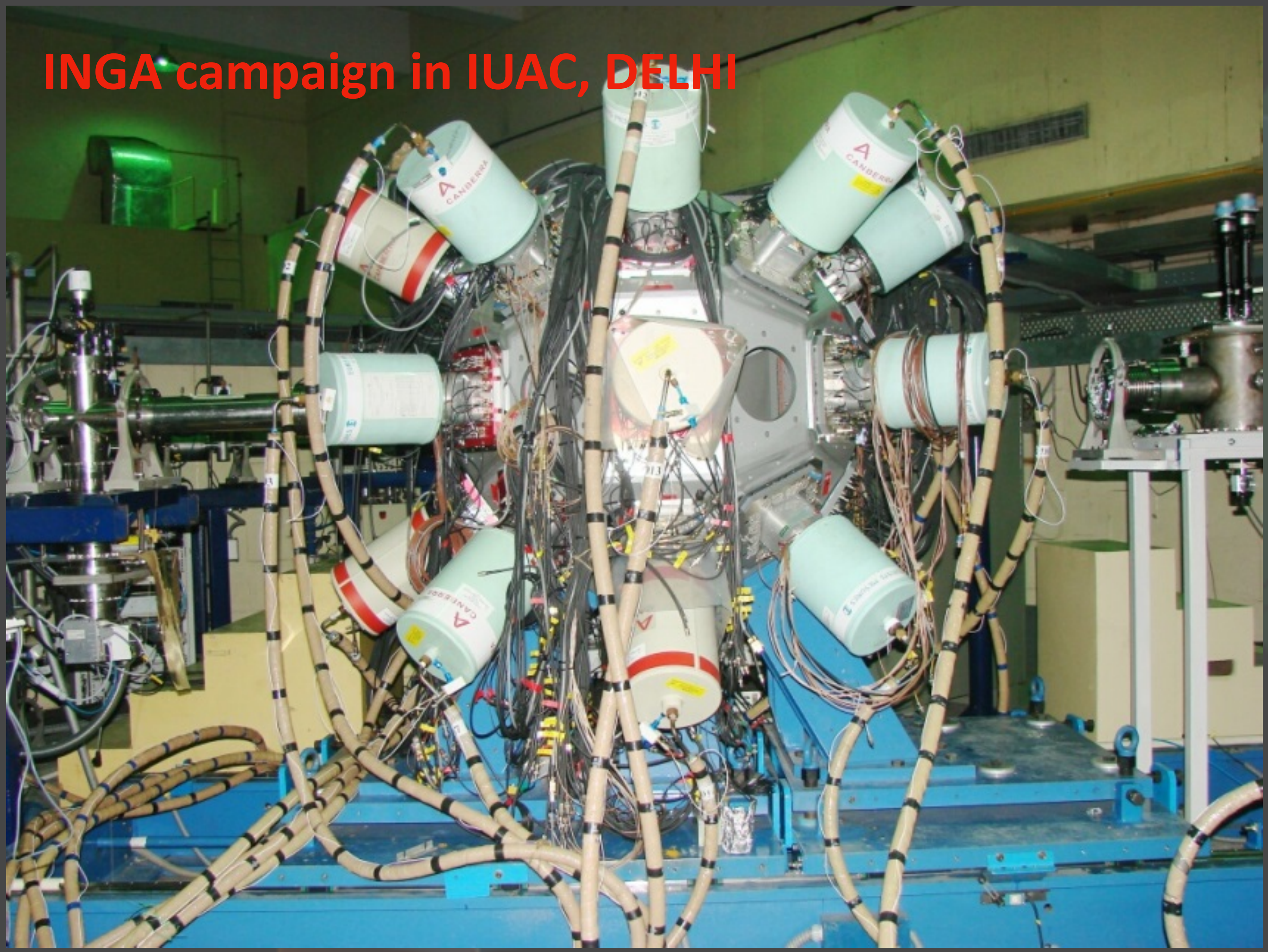
to study the structure of atomic nuclei

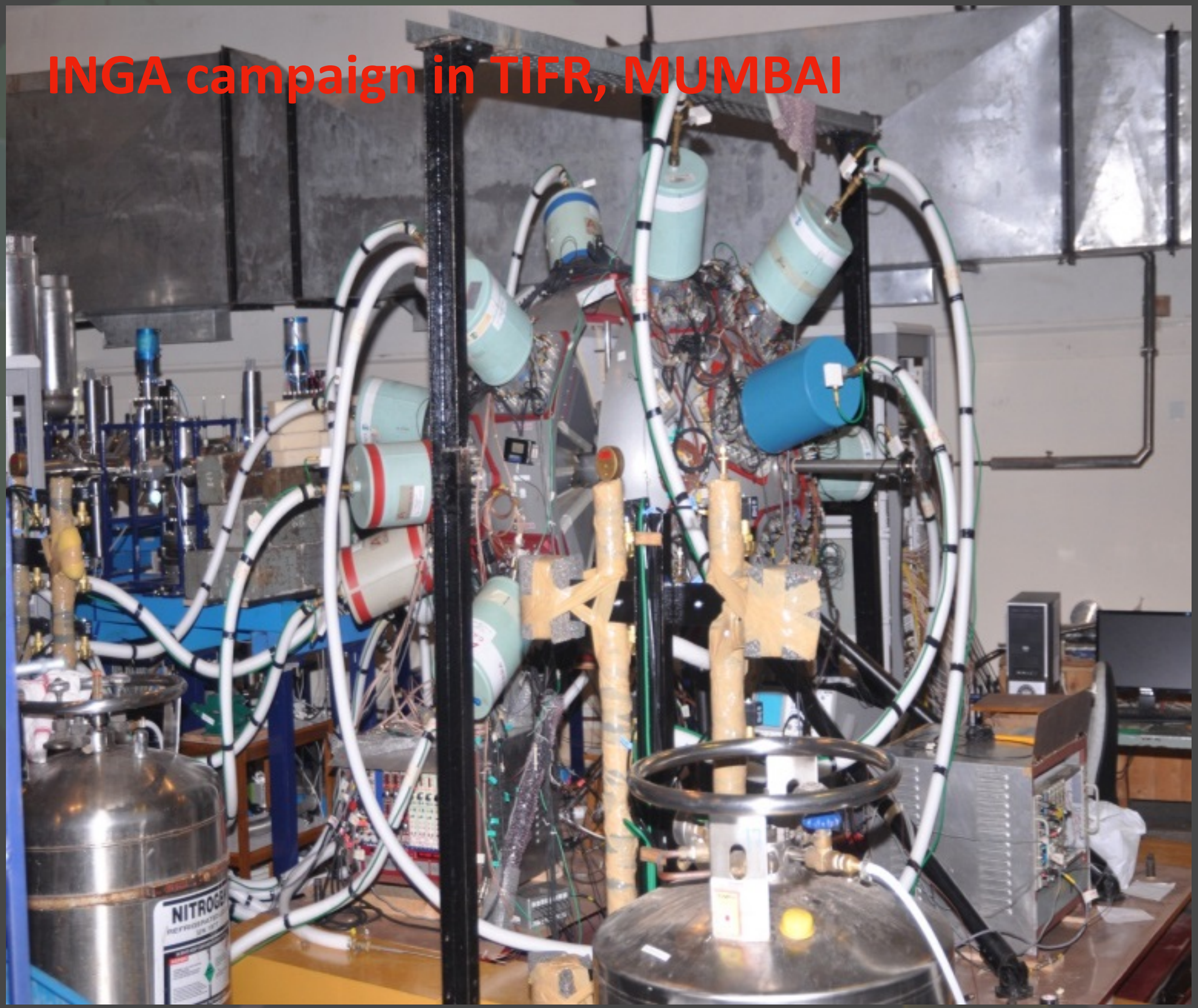
WHY IS IT USEFUL ??????

- In atomic nuclei, the interplay of three fundamental forces (electromagnetic, strong and weak) between strongly interacting individual fermions generates an effective nucleon-nucleon interaction. There is a delicate balance between the shell structure and the residual interactions between the nucleons.
- Interplay between single-particle motion, collectivity and pairing in a quantum many-body system.
- To study the structure of atomic nuclei at high spins using energetic beams
- The fast rotating state decays to the ground state, through the intermediate excited states, emitting copious gamma rays that are measured by the detectors
- By populating the nuclei to various shapes and studying their decays, the emergent properties of complex nuclear many-body system are elucidated

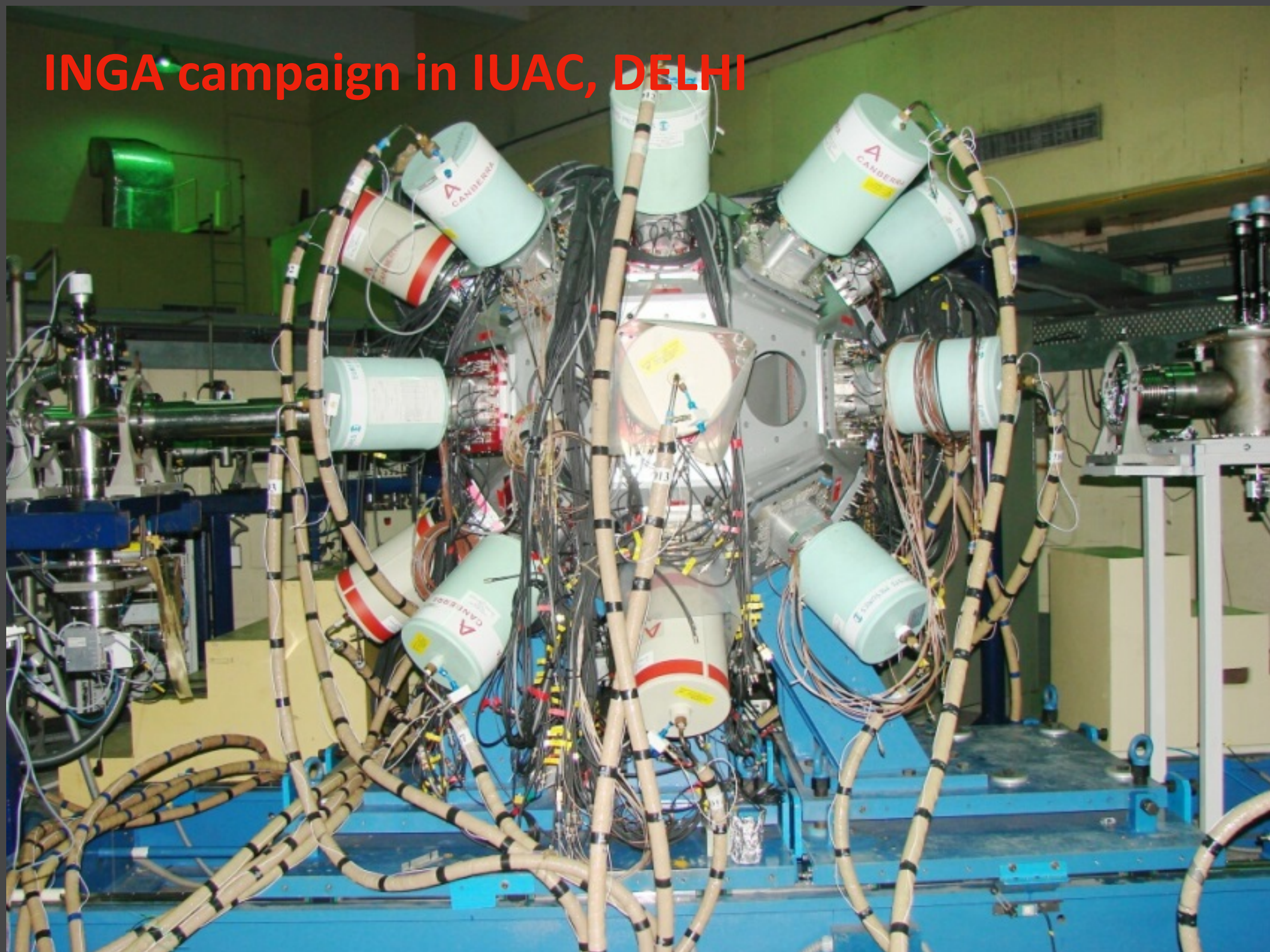


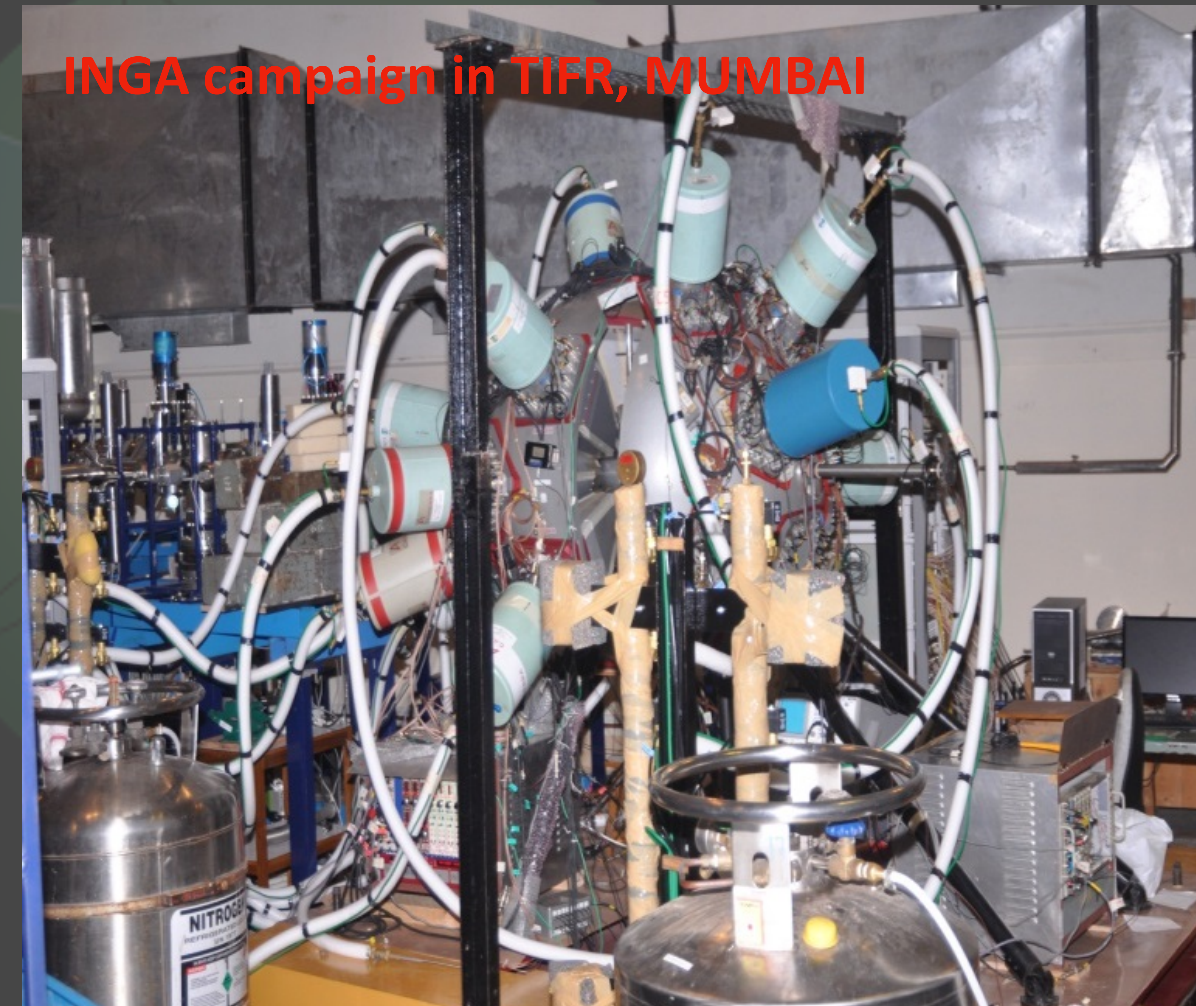
NUCLEAR SPECTROSCOPY Facilities in India



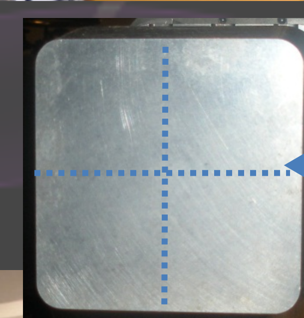


NUCLEAR SPECTROSCOPY Facilities in India



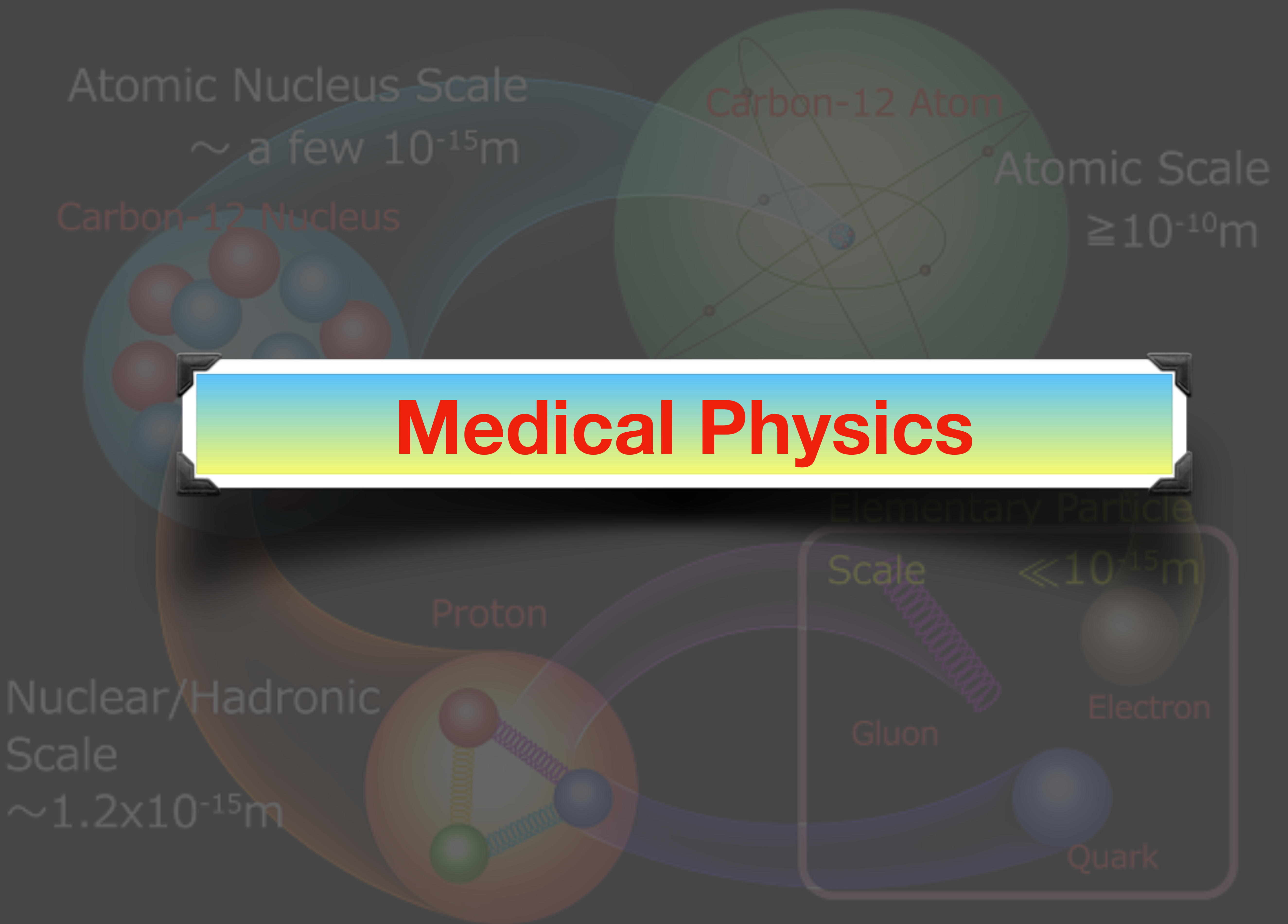


CLOVER DETECTOR



Front view

Medical Physics



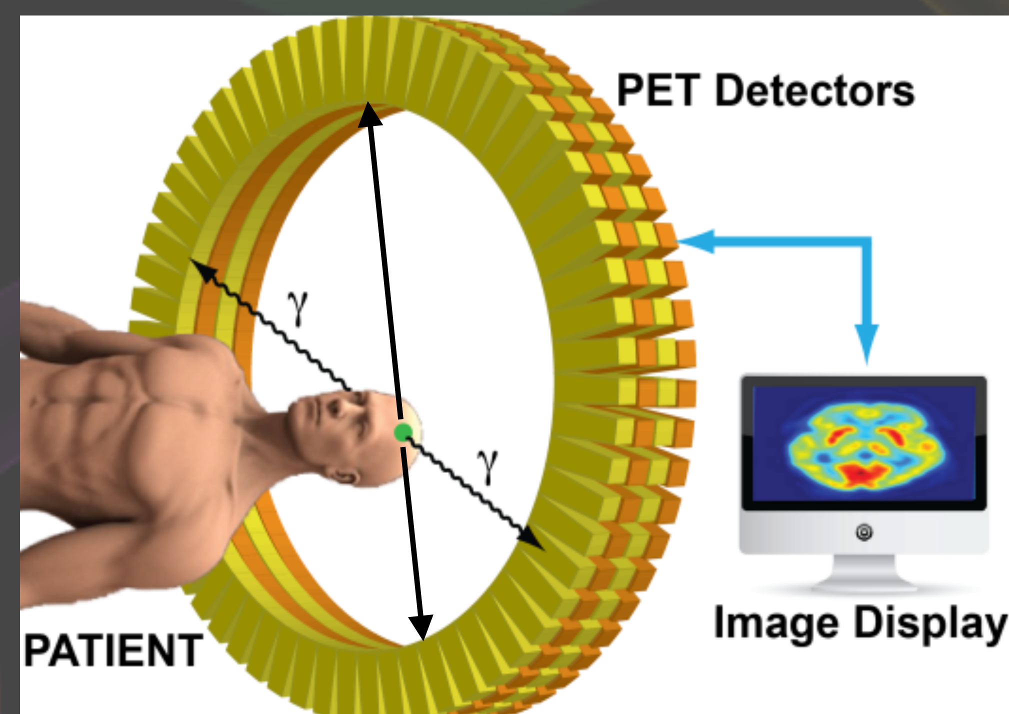
Positron Emission Tomography

RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)

~200 000 000
gamma per second

Study the interaction point of LOR's

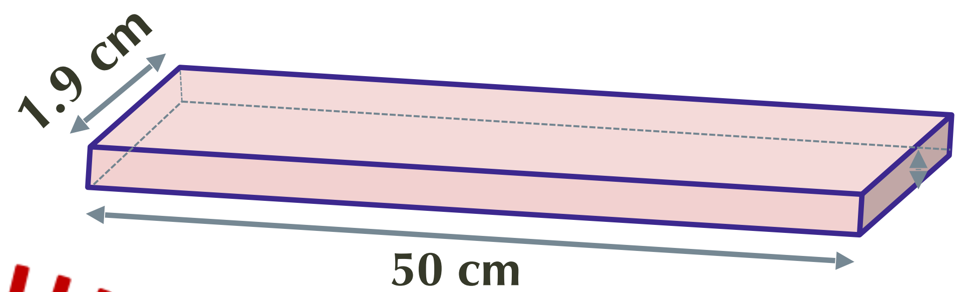


Crystal based tomographs to achieve larger field of view are very costly.

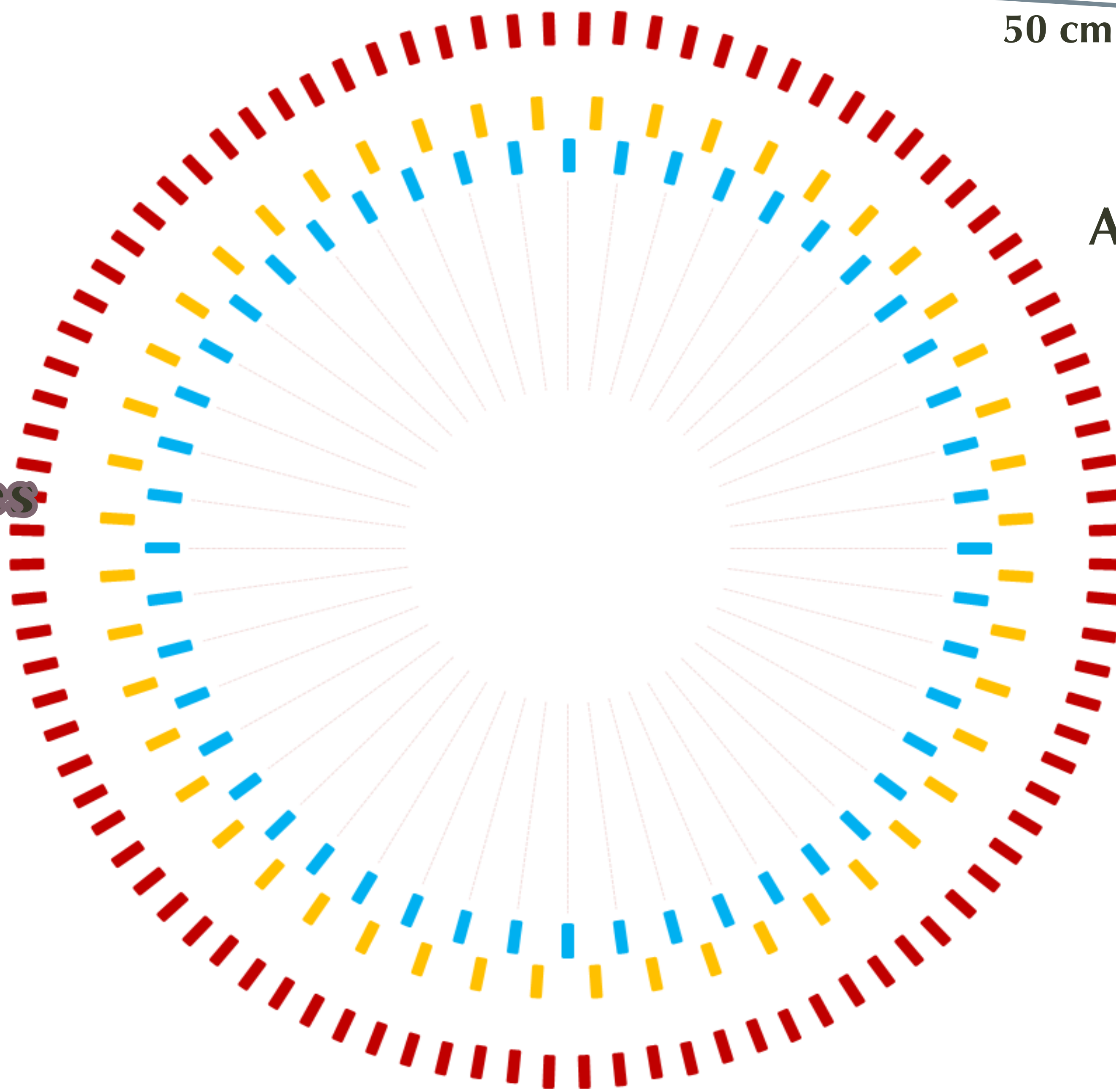
What are alternatives ????

Jagiellonian Positron Emission Tomograph

Plastic Scintillator



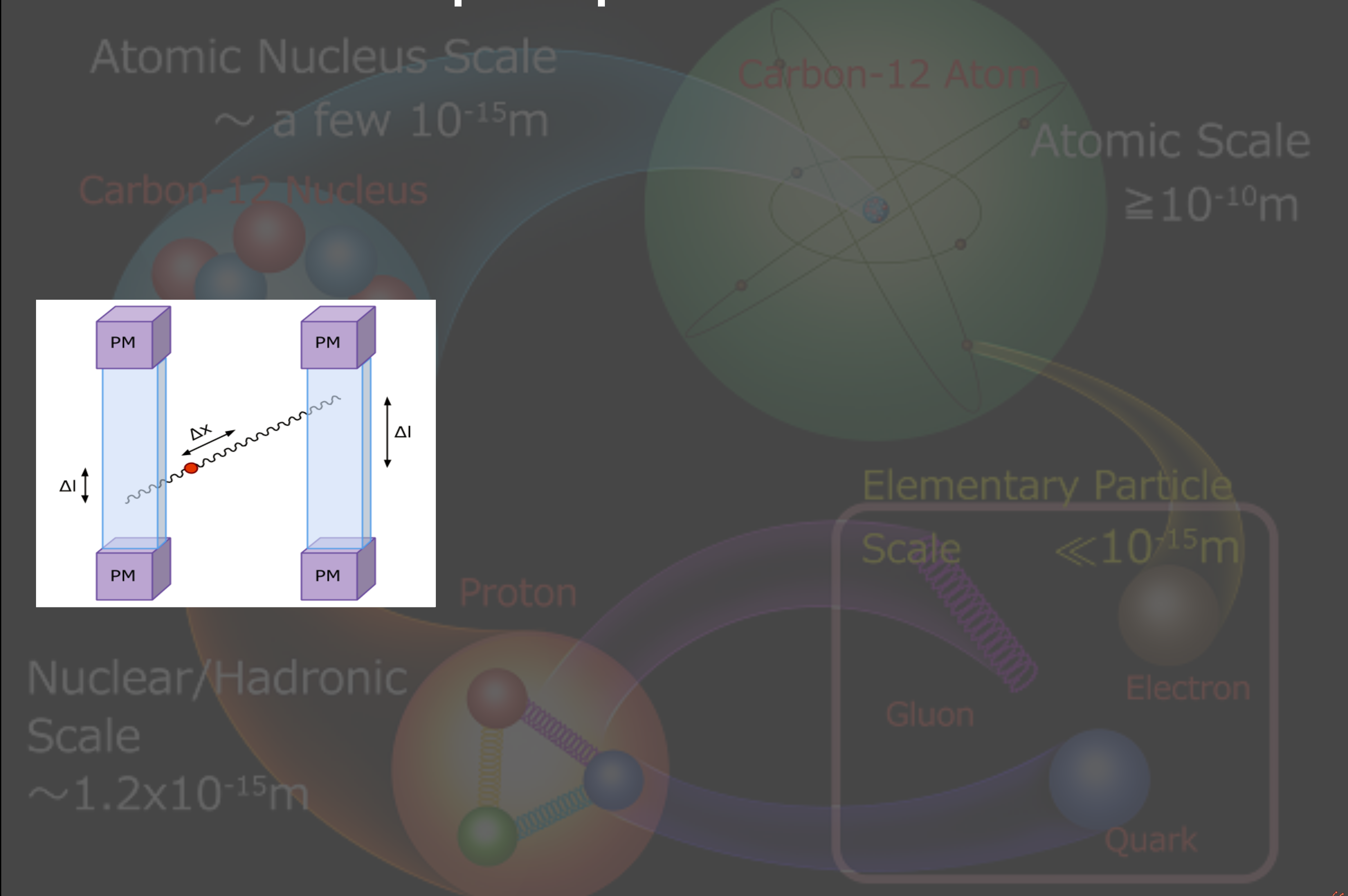
192 Modules



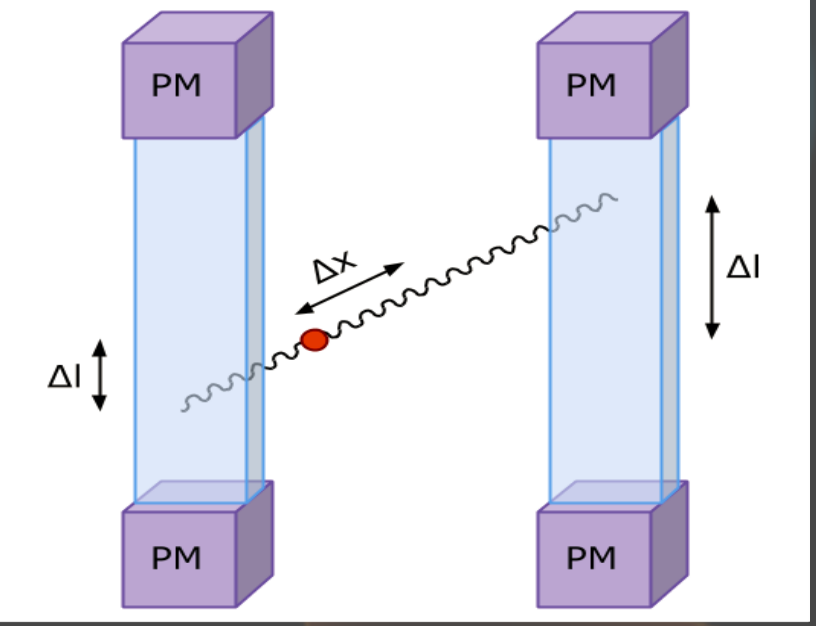
Arranged axially in
3 layers

(48,48,96)

Principle of photon's detection

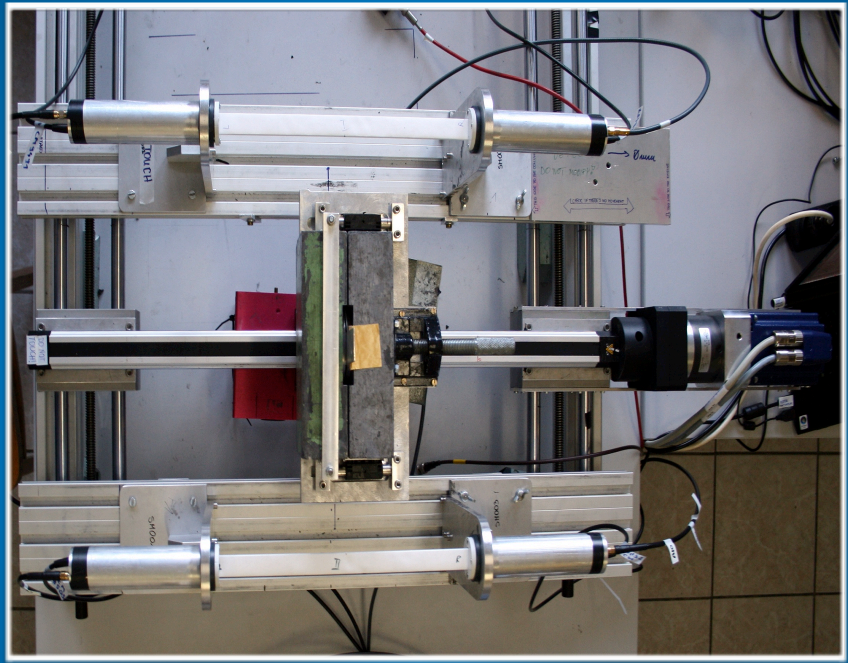


Principle of photon's detection



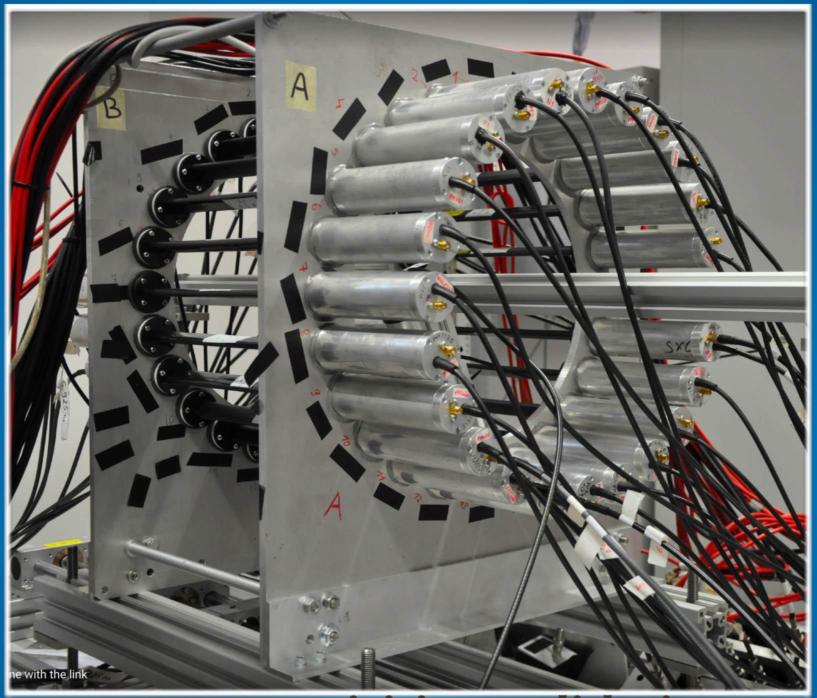
Historical review of J-PET

2
0
1
2



Characterize scintillator properties
Energy resolution, hit time, ..

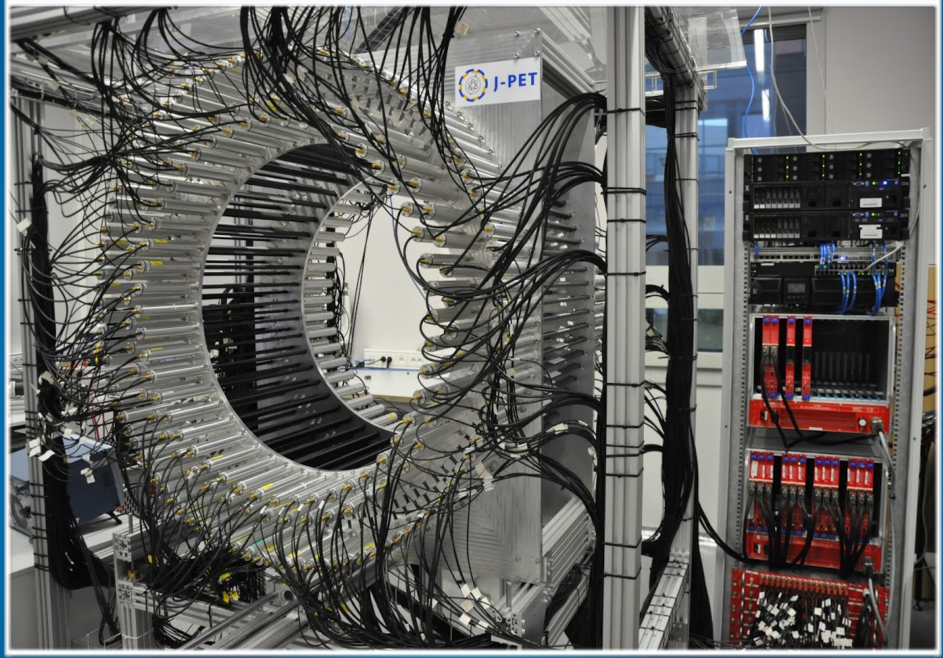
2
0
1
4



24 strips

Data acquisition validation
for multi-modules

2
0
1
6



Current version
Fundamental symmetries test and Positronium imaging

2
0
1
8

24 modules

Modular PET : Ready for first data campaign
J-PET's Plastic Revolution - CERN COURIER
https://cerncourier.com/a/j-pets-plastic-revolution/

Modular J-PET

Studies in the framework of J-PET collaboration

Investigating the decay of the Positronium atoms:

- First time detected **positronium** in Gas : Martin Deutsch

  Nobel prize in 1956 for discovering **Ps**
- **Positronium** is like hydrogen atom without nuclei consist of electron and positron

  Purely Leptonic object !!!
- Eigenstate for C,P, CP operators
- Undergoes self-annihilation into gamma quanta

$n\gamma$ (n=2,4,6,..)

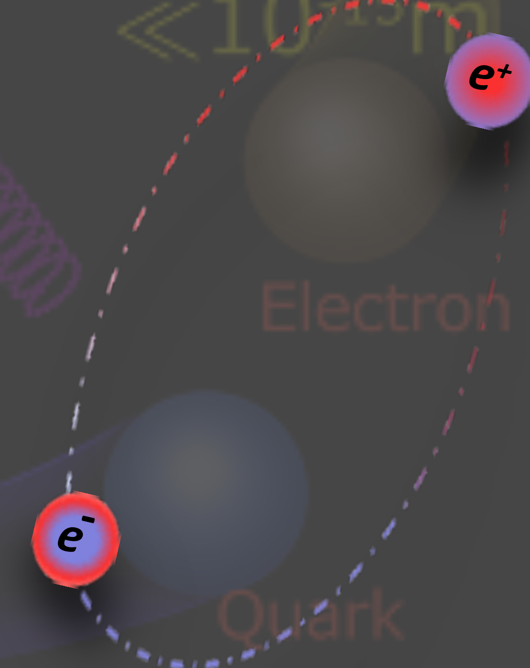
S=0 $\downarrow\uparrow - \uparrow\downarrow$ **Para**–positronium (**p - Ps**), **τ(vac)** = **0.125** ns, $^1S_0$

$\uparrow\uparrow$

$(2n+1)\gamma$ (n=3,5,..)

S=1 $\uparrow\uparrow + \downarrow\downarrow$ **ortho** – positronium (**o - Ps**), **τ(vac)** = **142**ns, $^3S_1$

$\downarrow\downarrow$



Selected Recent Publications

- ☆P. Moskal et al., *Nature Reviews Physics* 1 (2019) 527
- ☆Beatrix C. Hiesmayr, Pawel Moskal; ***Nature scientific reports 9*** (2019) 8166
- ☆P. Moskal et al., **Phys. Med. Bio. 64** (2019) 055017
- ☆P. Kowalski et al., **Phys. in Med. & Bio. 63** (2018)
- ☆G. Korcyl et al., **IEEE Trans. on Med. Imag.** (2018)
- ☆B.C. Hiesmayr, P. Moskal; ***Nature Scientific reports 7*** (2017) 15349
- ☆L. *Raczyński et al.*, **Phys. Med. Bio. 62** (2017) 5076
- ☆A. Wieczorek et al., **PLoS ONE 12 (11)**: E0186728 (2017)
- ☆P. Moskal et al., **Phys. in Med. & Bio. 61** (2016) 2025
- ☆ A. Gajos et al., **Nucl. Inst. & Meth. In Phys. Res. A 819**(2016) 54
- ☆D. Kaminska et al., **Eup. Phys. J. C 76** (2016)
- ☆……….

More than 70 articles and 18 patents applications
<u>For more information</u> : http://koza.if.u.edu.pl

Geant4

GEometry ANd Tracking

Geant4 is a platform for "the simulation of the passage of particles through matter" using Monte Carlo methods**

**** Monte Carlo Simulation is a mathematical technique that generates random variables for modeling risk or uncertainty of a certain system**

Geant4

GEometry ANd Tracking

Geant4 is a platform for "the simulation of the passage of particles through matter" using Monte Carlo methods**

Applications in :

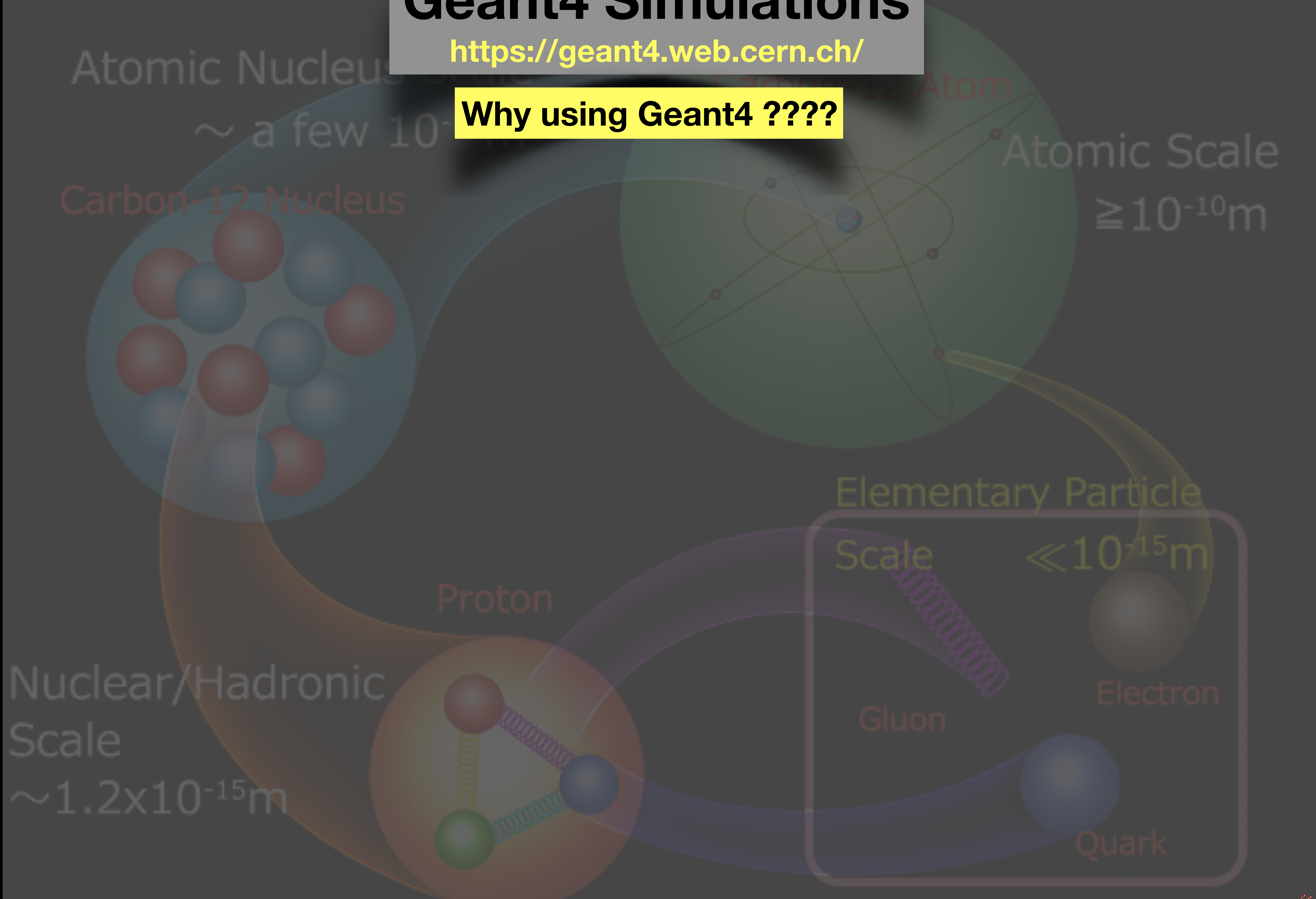
- **High energy Physics (ATLAS, CMS, ALICE experiments - LHC (CERN), AEgIS in CERN, Fermilab, BABAR, etc…)**
- **Nuclear and accelerator physics (e.g., HADES in GSI , Germany)**
- **Medical imaging and radiation doses (e.g., Medical group in INFN labs in Italy, J-PET)**
- **Space science…..**

**** Monte Carlo Simulation is a mathematical technique that generates random variables for modeling risk or uncertainty of a certain system**

Geant4 Simulations

https://geant4.web.cern.ch/

Why using Geant4 ????



Geant4 Simulations

https://geant4.web.cern.ch/

Why using Geant4 ????

All experiments have a (more or less detailed) full-scale Monte Carlo simulation to estimate the outcome and uncertainties.

Optimize the geometry of detector and maximize the detection of the required outcomes.

Estimate the detector characteristics : Efficiency, coincidences, shielding and dosimetry purpose.

Free available software

Free Regular, development, updates , bug fixes and validation

Can be customized To different requirements

Can handle complex geometries

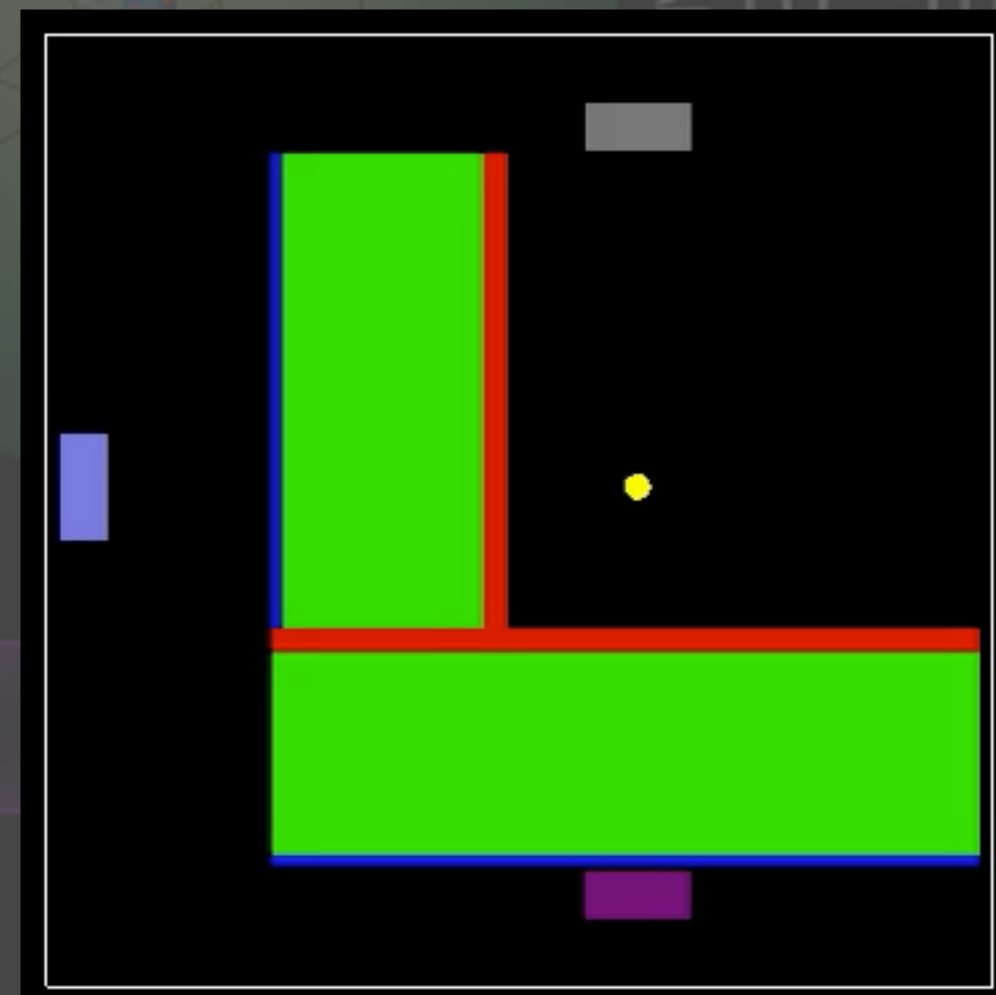
Many physics models and data/evaluated sets

Salient features in Geant4

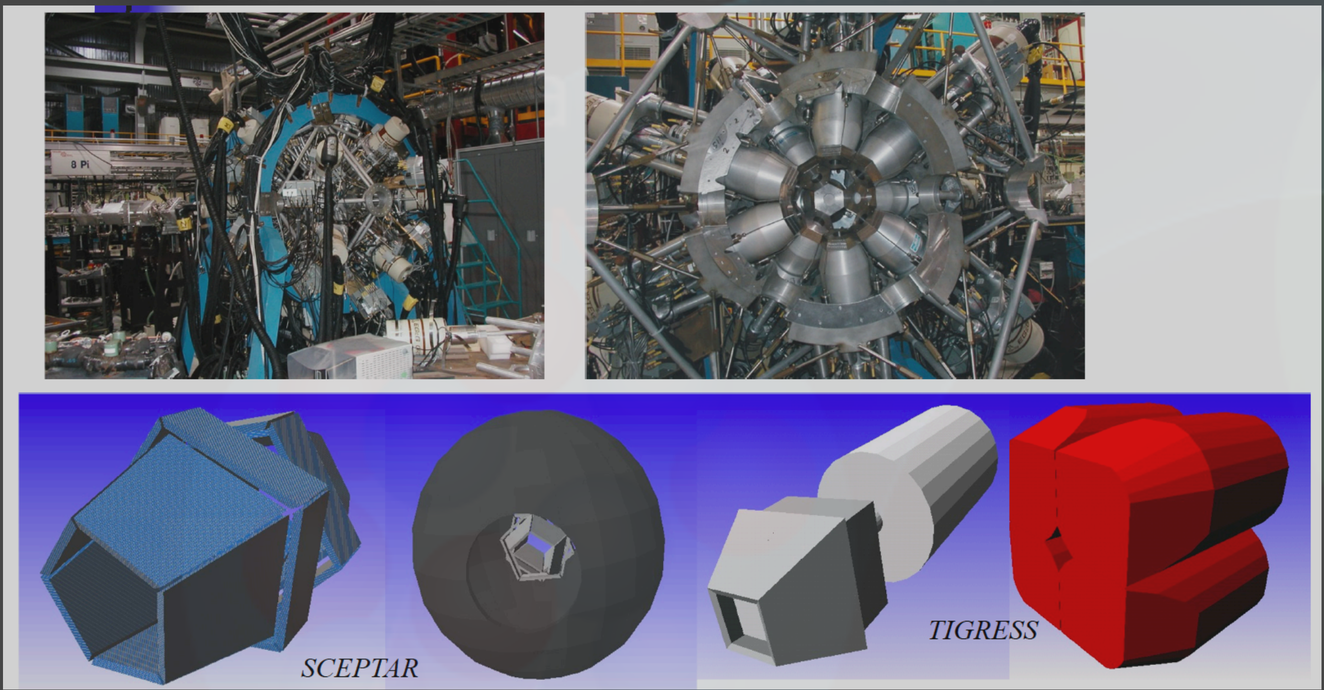
Describe the experimental set-up

Provide the projectile as input

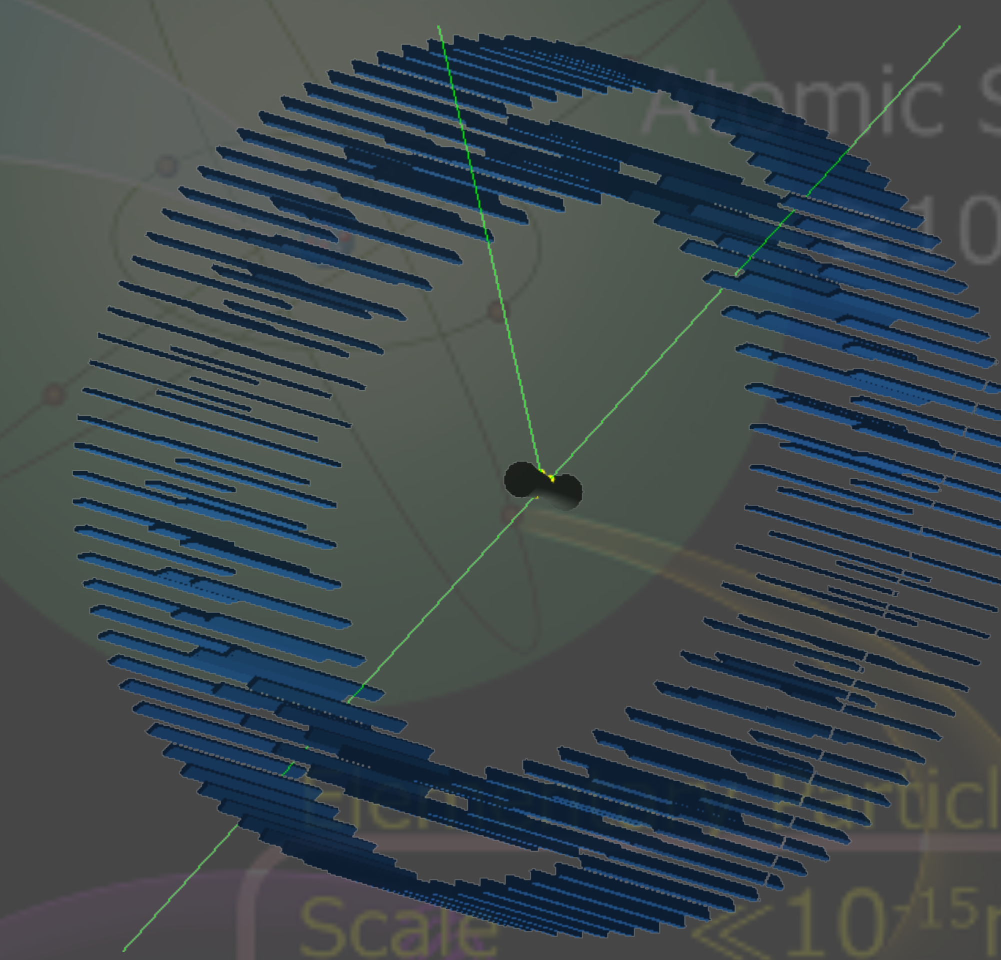
Decide the detector / Physics models / Cuts (which particles to produce and which cuts down



Geant4 Applications in various facilities

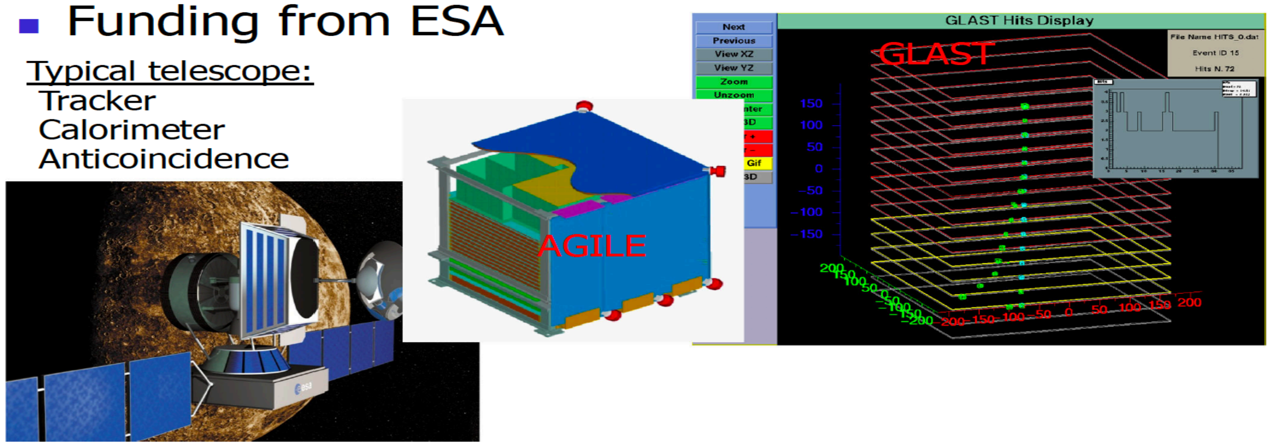


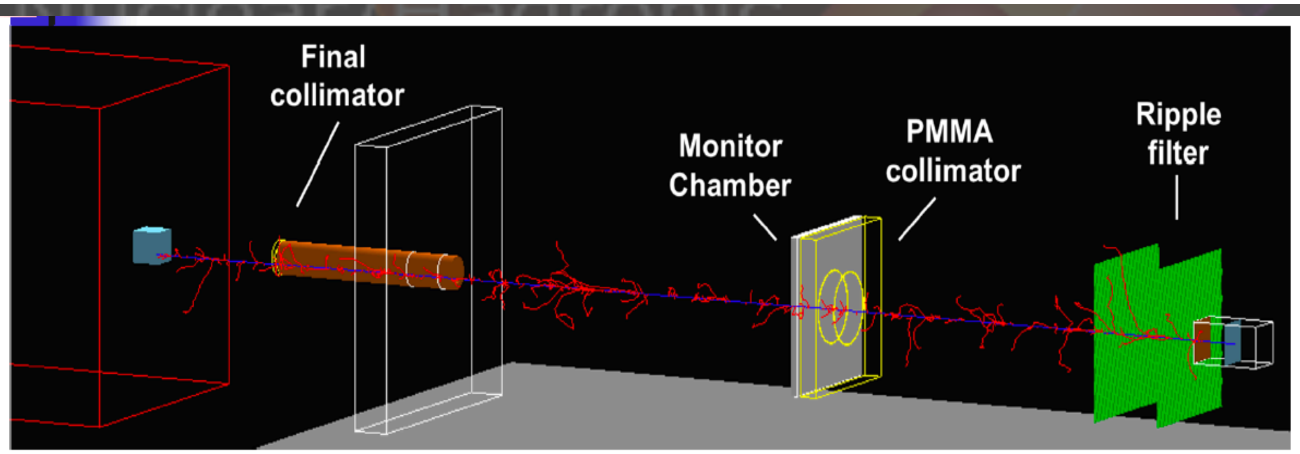
J-PET



- Satellites (γ astrophysics, planetary sciences)
- Funding from ESA

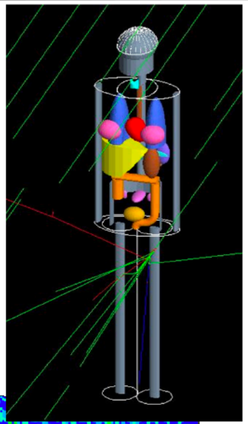
Typical telescope:
Tracker
Calorimeter
Anticoincidence

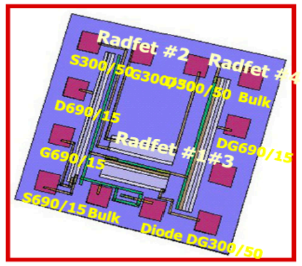




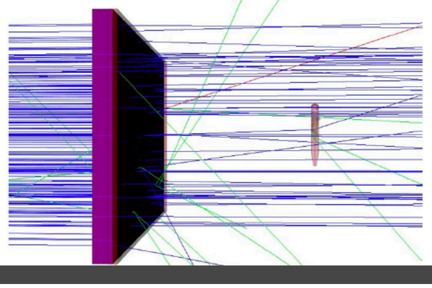
Space science

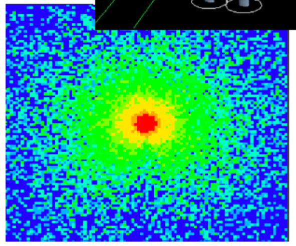
Radiotherapy

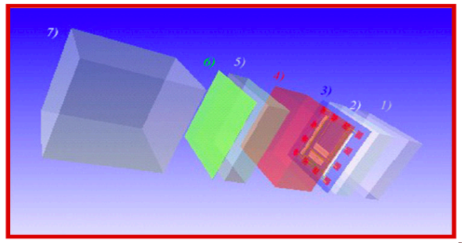




Effects on electronics components

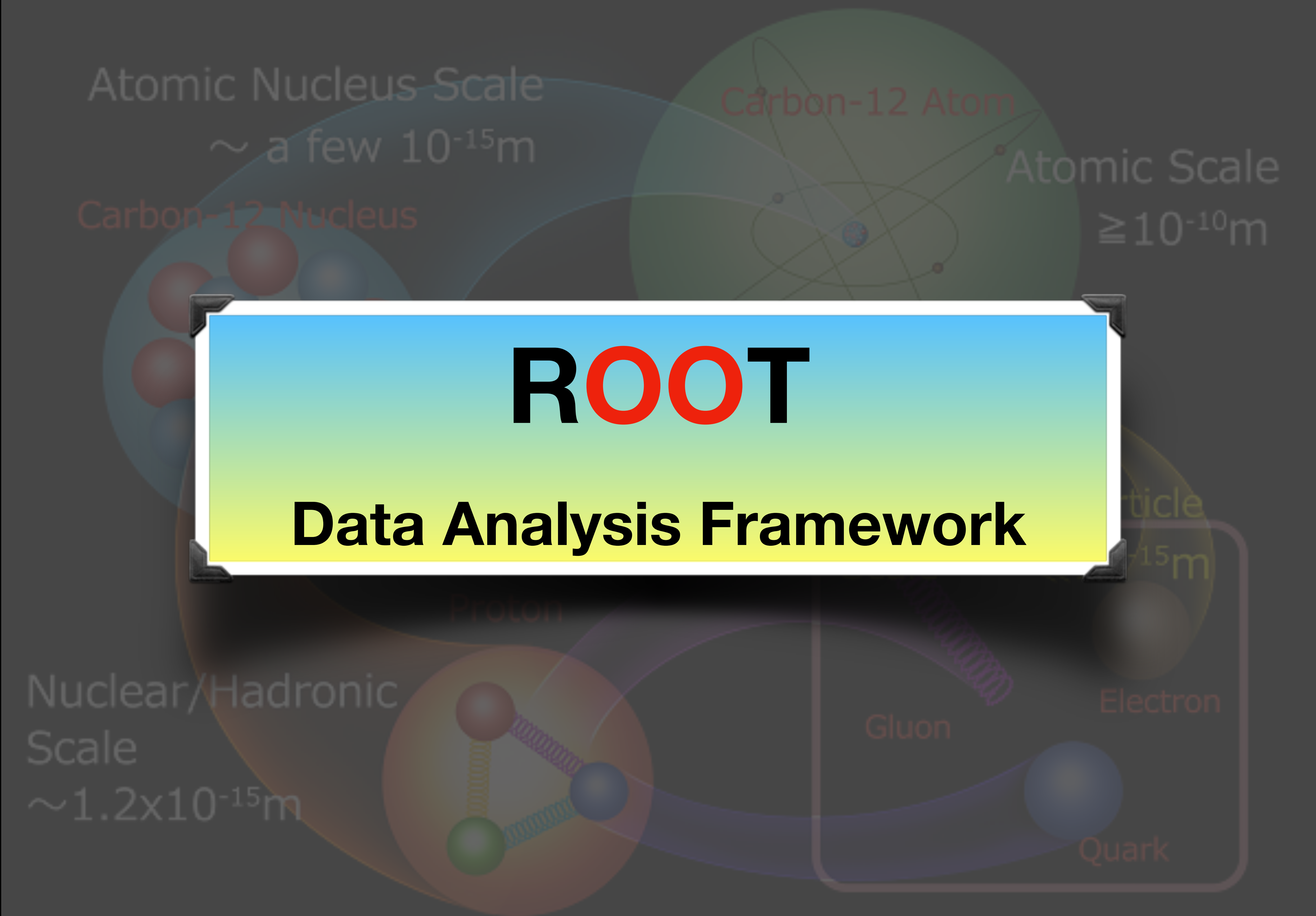




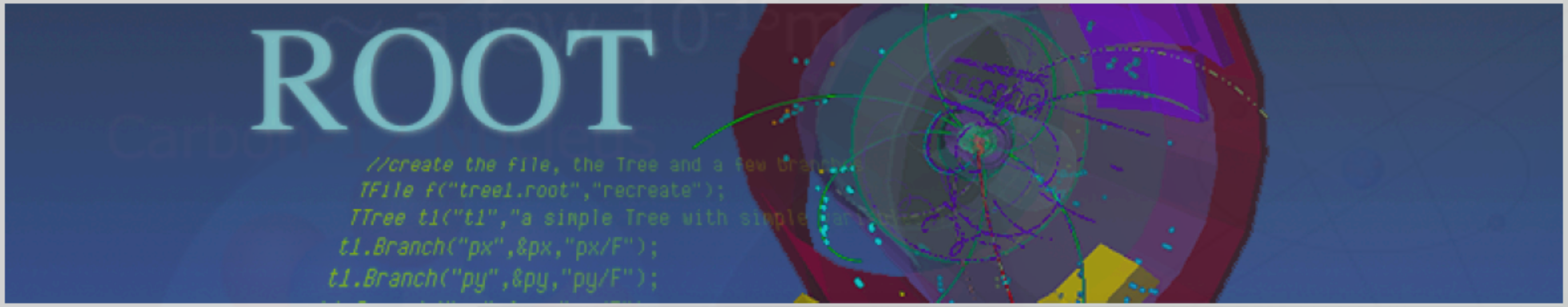


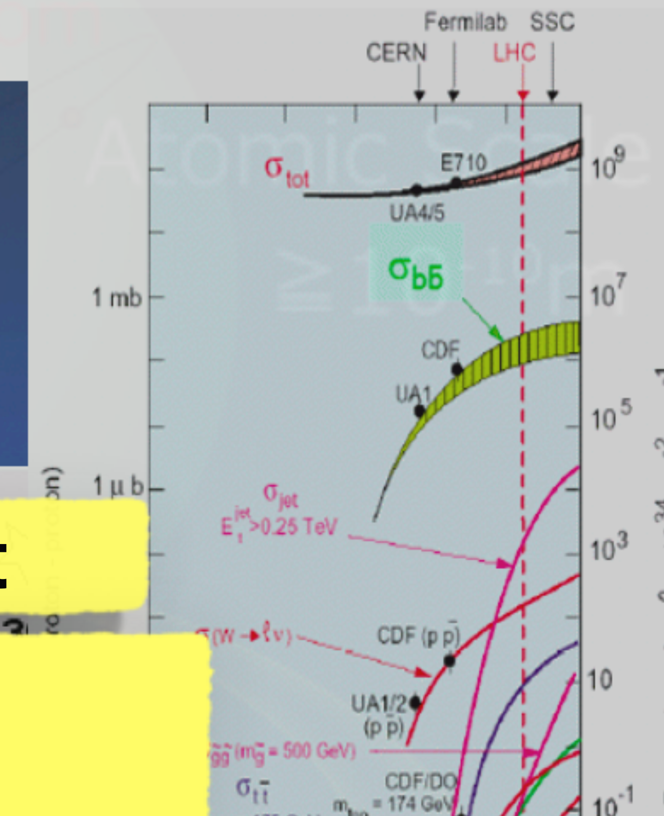
ROOT

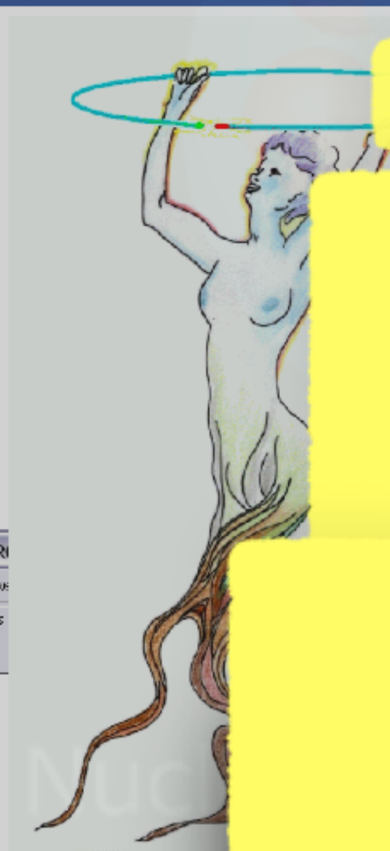
Data Analysis Framework



What is ROOT? http://root.cern.ch/







A modular scientific software toolkit

Object Oriented Framework
Mainly written in C++

Large scale data processing,
statistical analysis / inferences
visualisation and storage
Integrated with Python and R

HOW TO USE THE ROOT

ROOT: a set of reusable **classes** and **libraries**

ROOT in **interactive mode**

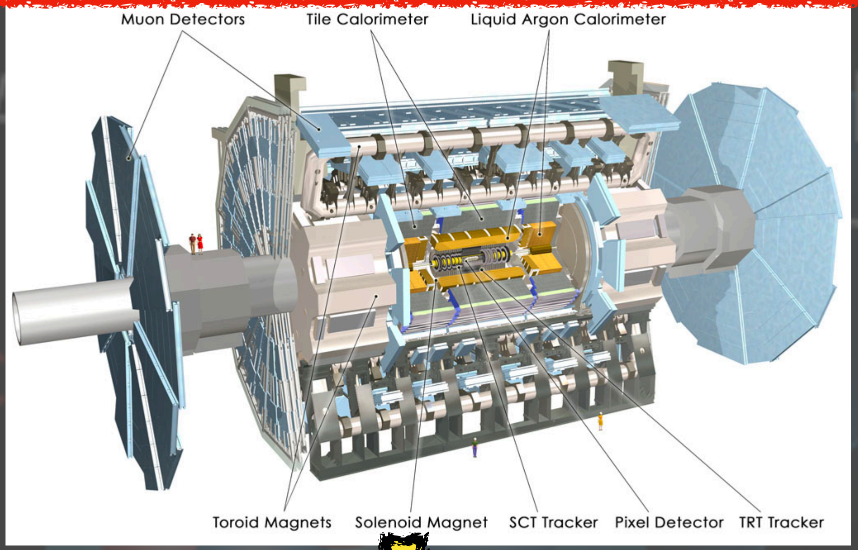
```
cate@catelenovolinux:~$ root -l
root [0]  TF1 *myFunction = new TF1("myFunction
","[0]+[1]*x",0,10);
root [1]
```

cate - root

ROOT in **compiled code**

```
#include "TF1.h"

int main() {

  TF1 *myFunction =
  new TF1("myFunction","[0]+[1]*x",0,10);

  delete myFunction;

  return(0);

}
```

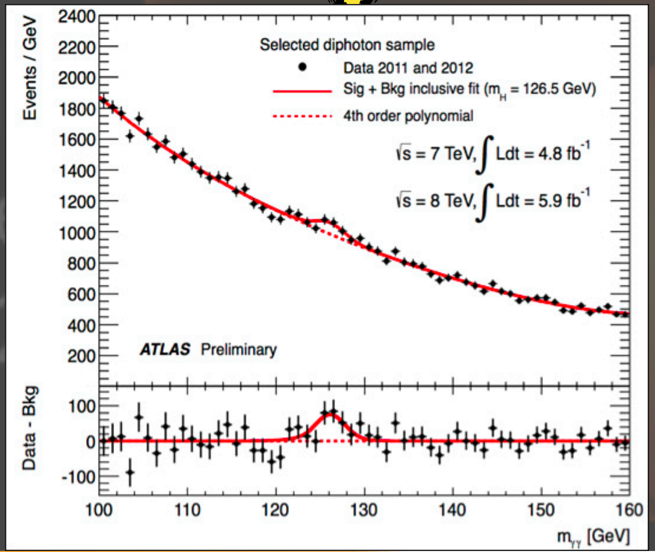
DATA ANALYSIS -> Physics outputs



Raw data

Reconstructed/calibrated physics objects

NTuples



Analysing data involves:

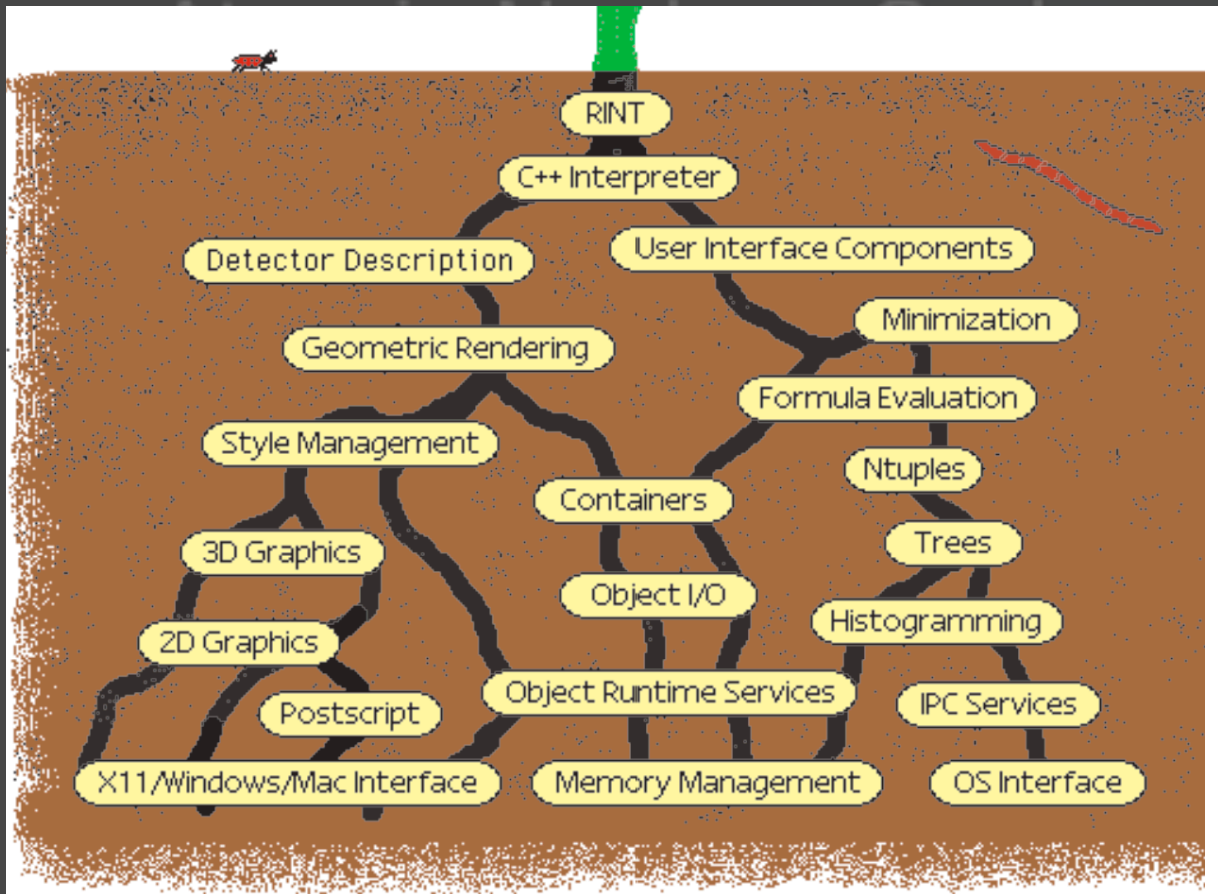
- ☑ Recording and storage of data/MC
- ☑ Reconstruction of **physics objects**
- ☑ **Discrimination** of **signal from background** (e.g. using cuts)
- ☑ Quantitative **comparison of predictions to experimental results**

Presentation results (usually using plots)

...and much more:

ROOT is used to do all of this

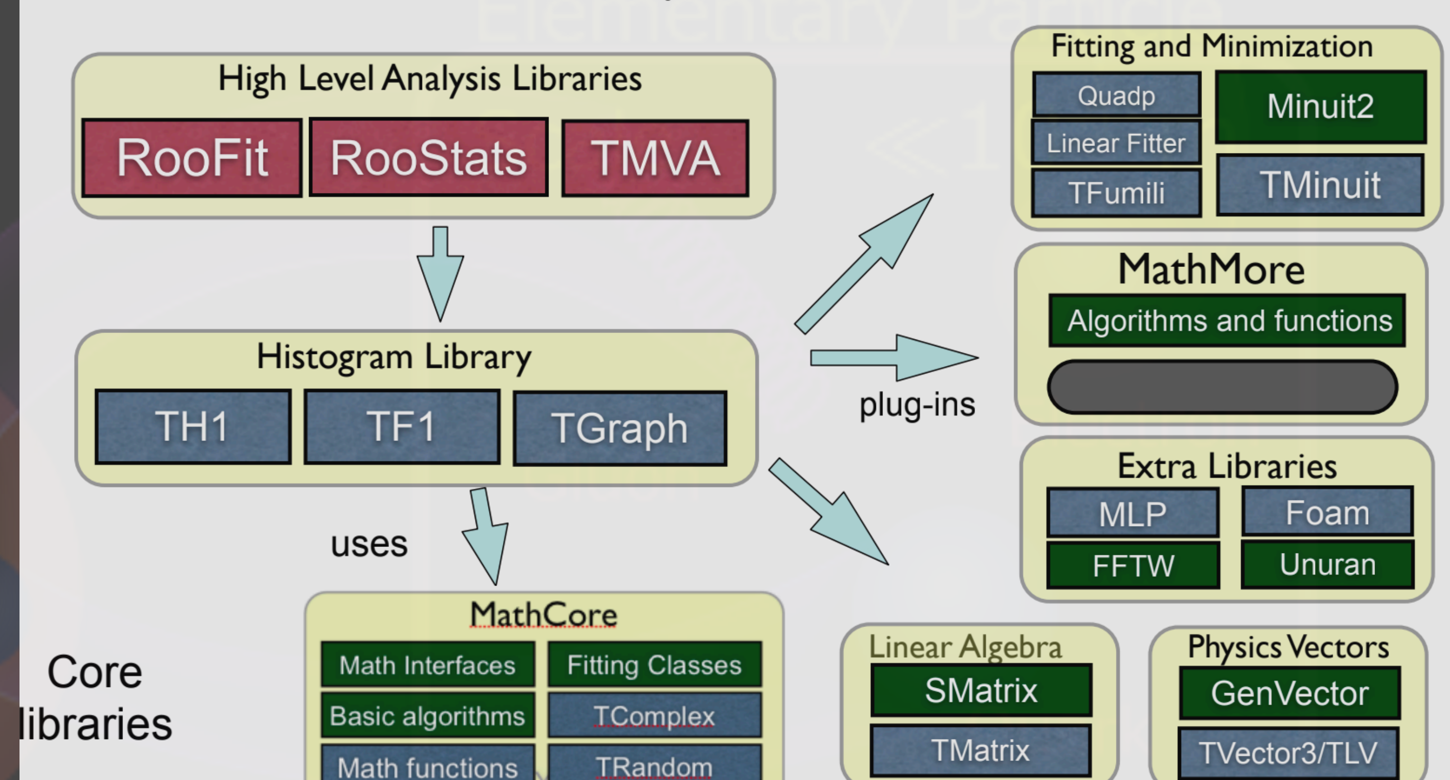
Salient features of ROOT



Root classes and libraries

Statistical software tools
RootFit, Root Stats ....

- Large set of mathematical libraries and tools needed for event reconstruction, simulation and statistical data analysis



Fundamental knowledge of Subject

Habit To read

Scientific updates Literature, Biographies

Statistical Inferences

Monte Carlo, Stat tools,…

!!!!! Take Away Message !!!!

Programming Languages

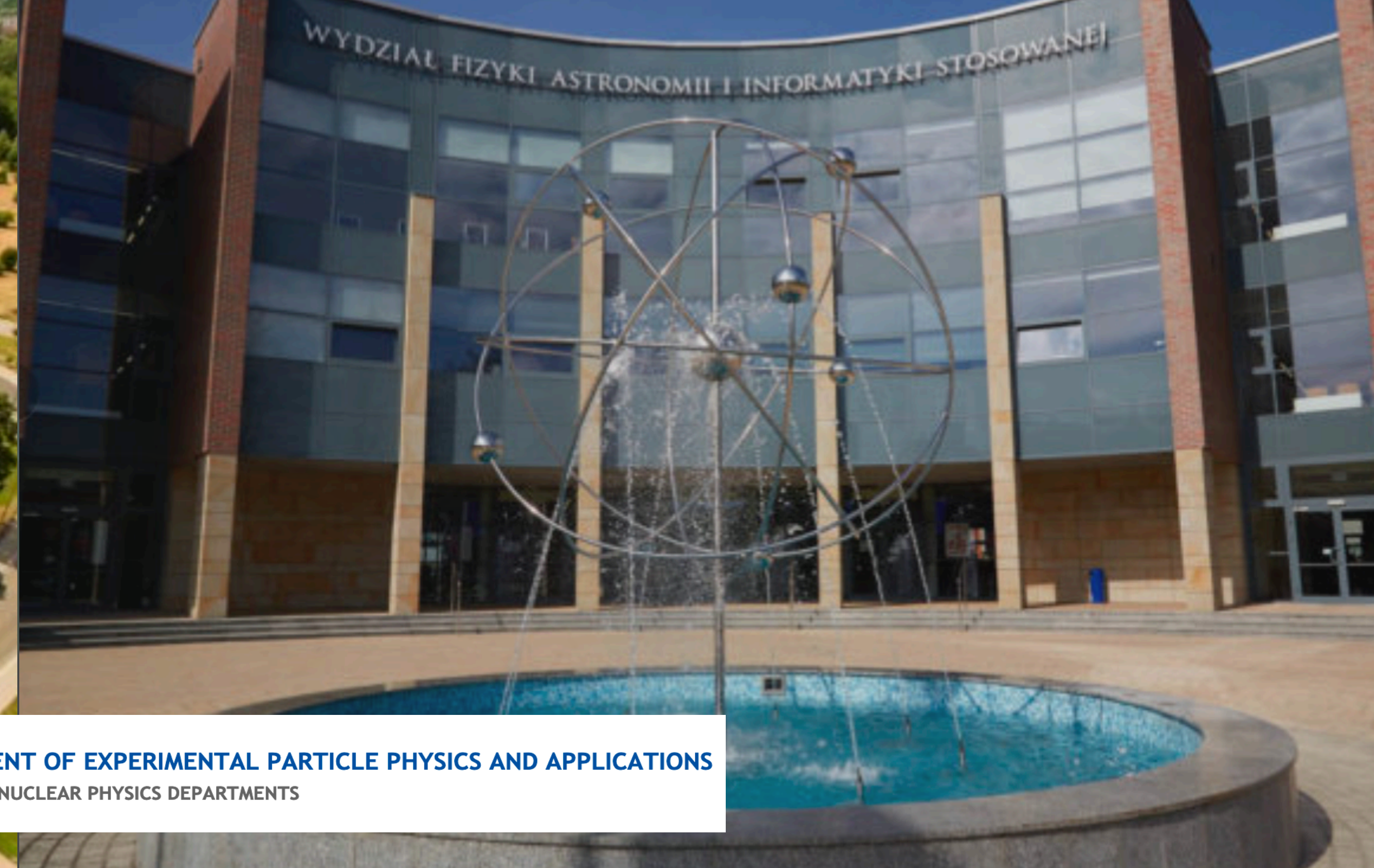
C++(OOPs)/Python

Scientific tools

ROOT, Geant4, Latex, GATE, Mathematica..

Visualization Tools

Blender, GIMP, Inkscape, FreeCAD..



Marian Smoluchowski Institute of Physics
Jagiellonian University in Kraków

DEPARTMENT OF EXPERIMENTAL PARTICLE PHYSICS AND APPLICATIONS
CLUSTER OF NUCLEAR PHYSICS DEPARTMENTS

ध्यान देने के लिए आपका धन्यवाद !!!!