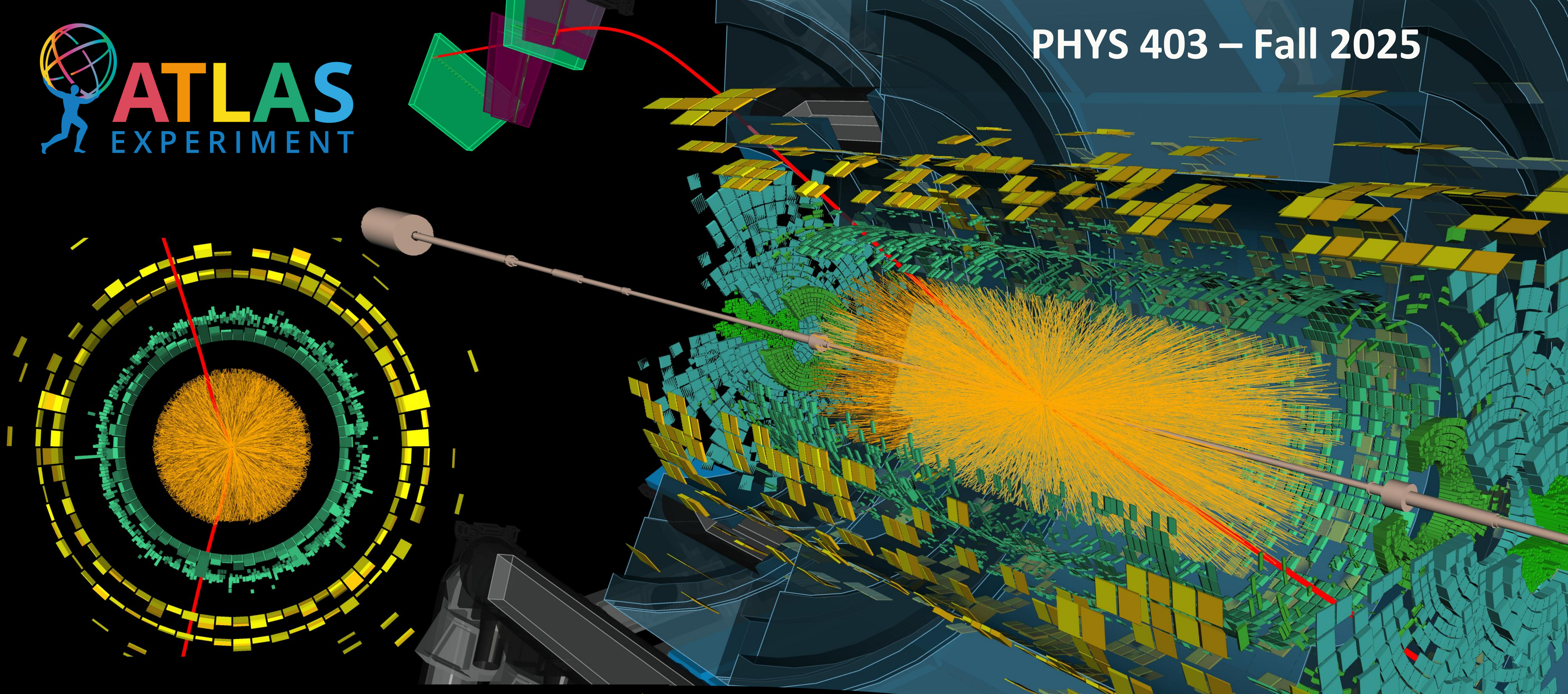
ATLAS EXPERIMENT

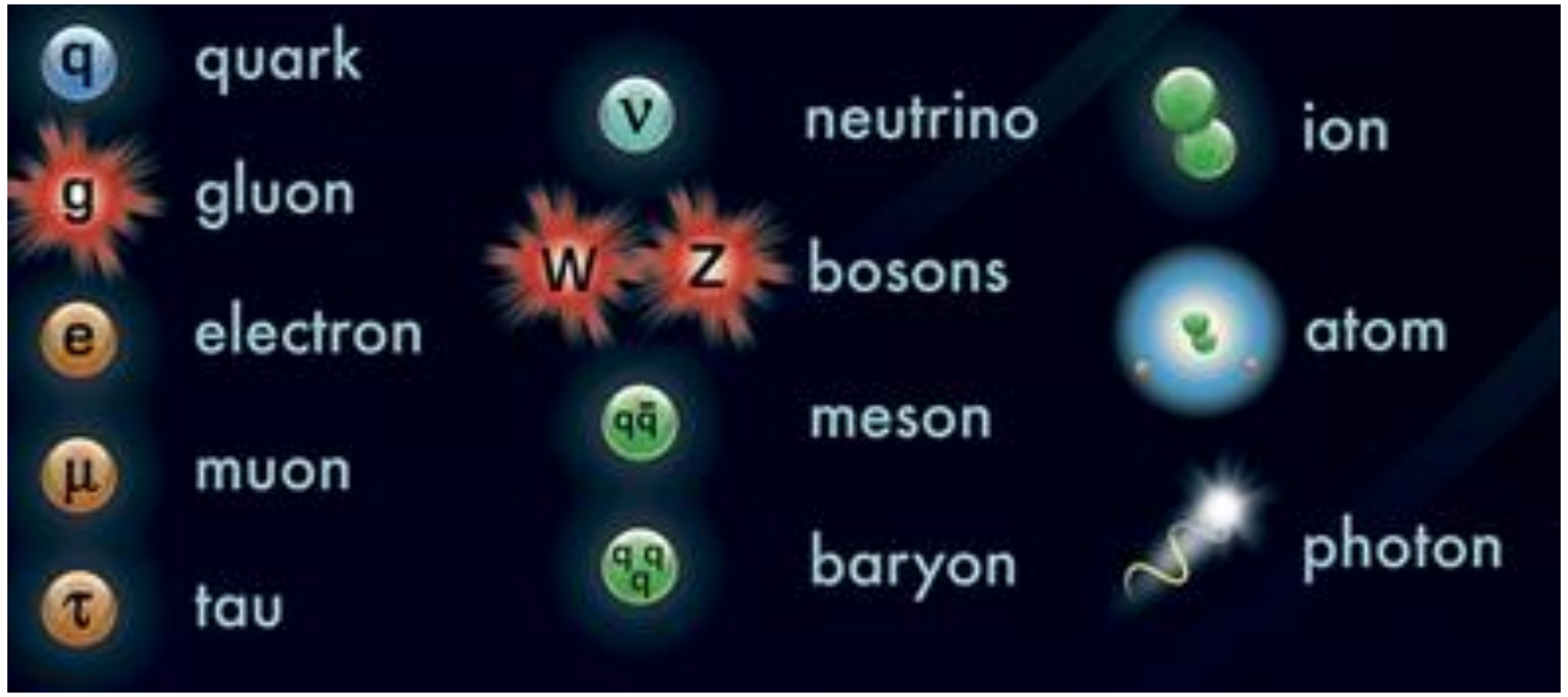
PHYS 403 – Fall 2025

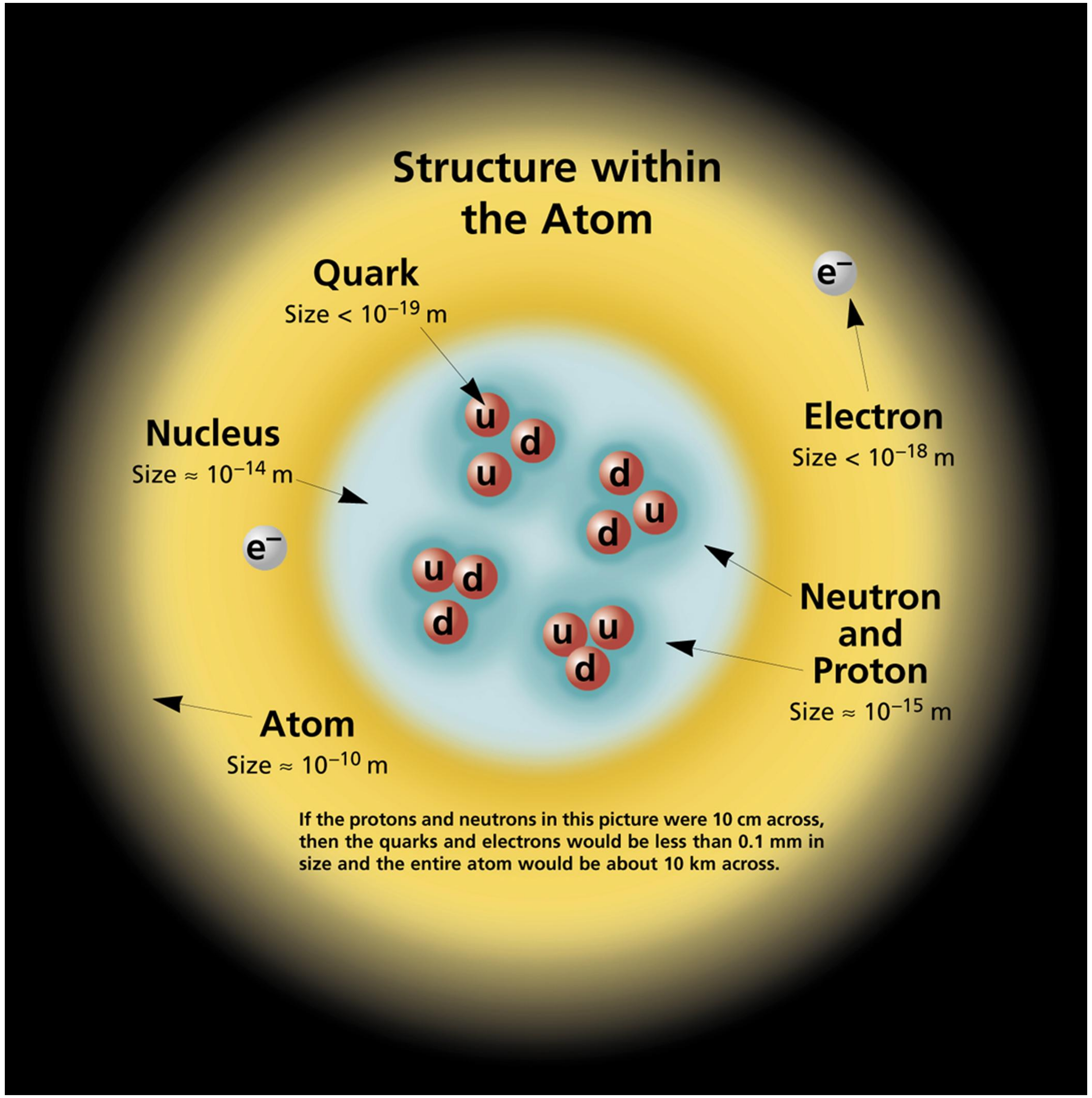


Extreme Matter: Physics at a Trillion Degrees
Exploring the Quark Gluon Plasma
– and the Detectors that can survive it

What matter is made of:

Atoms with electrons and nuclei
Nuclei with protons and neutrons
Protons and neutrons with quarks and gluons



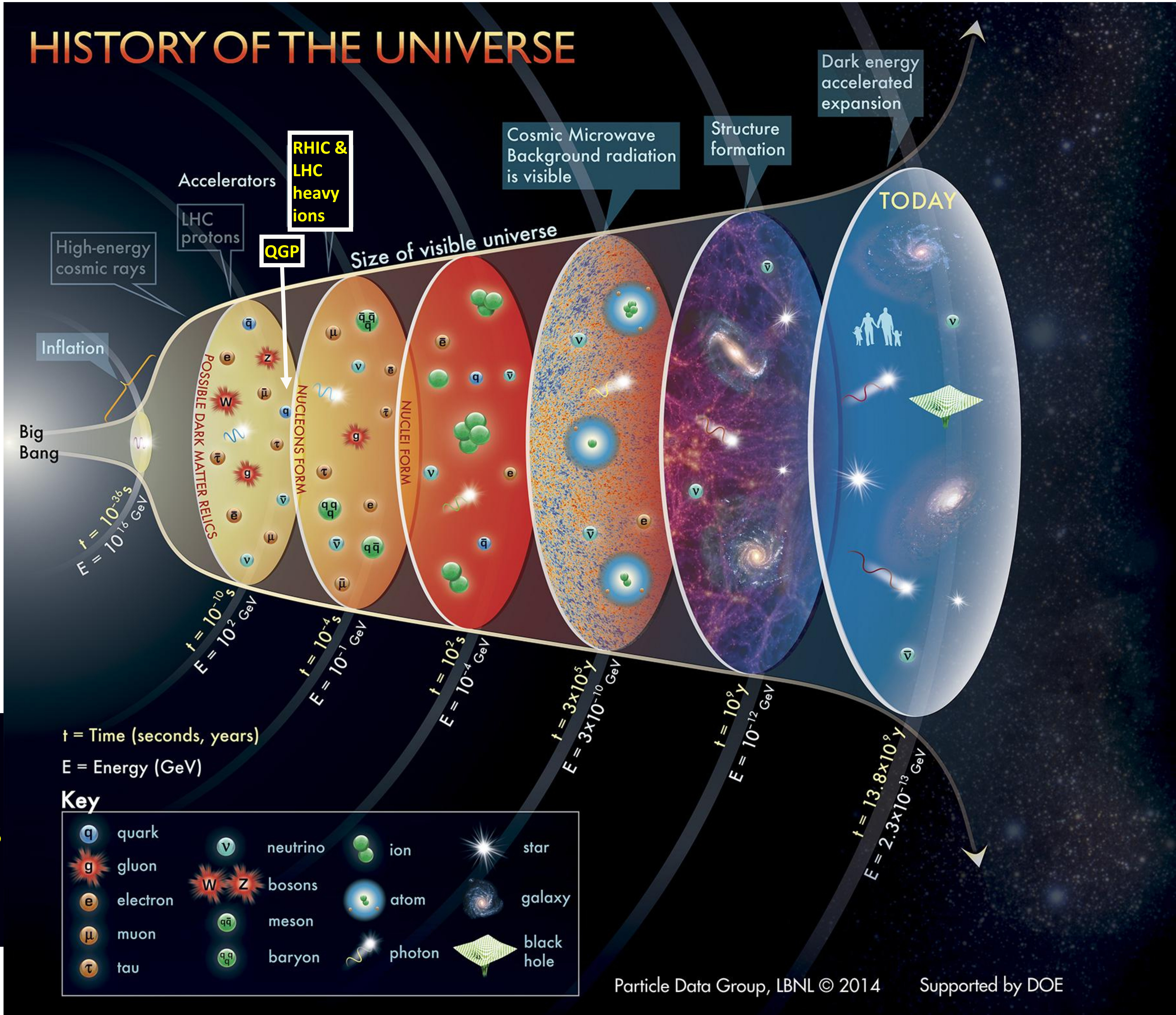


The Quark Gluon Plasma (QGP) is hot matter of free quarks and gluons.

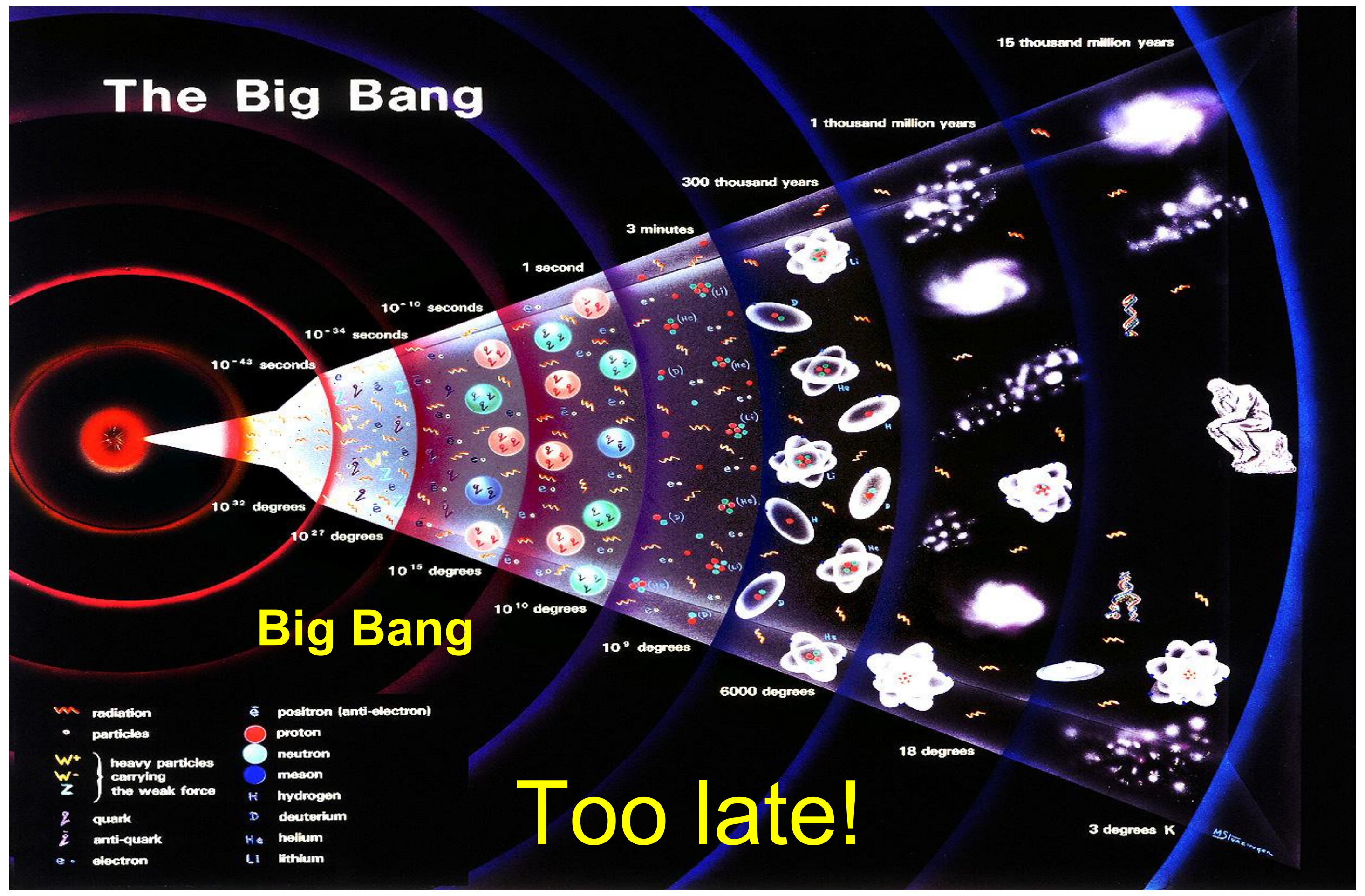
QGP existed at temperatures above 1 Trillion Degrees Celsius in the early Universe.

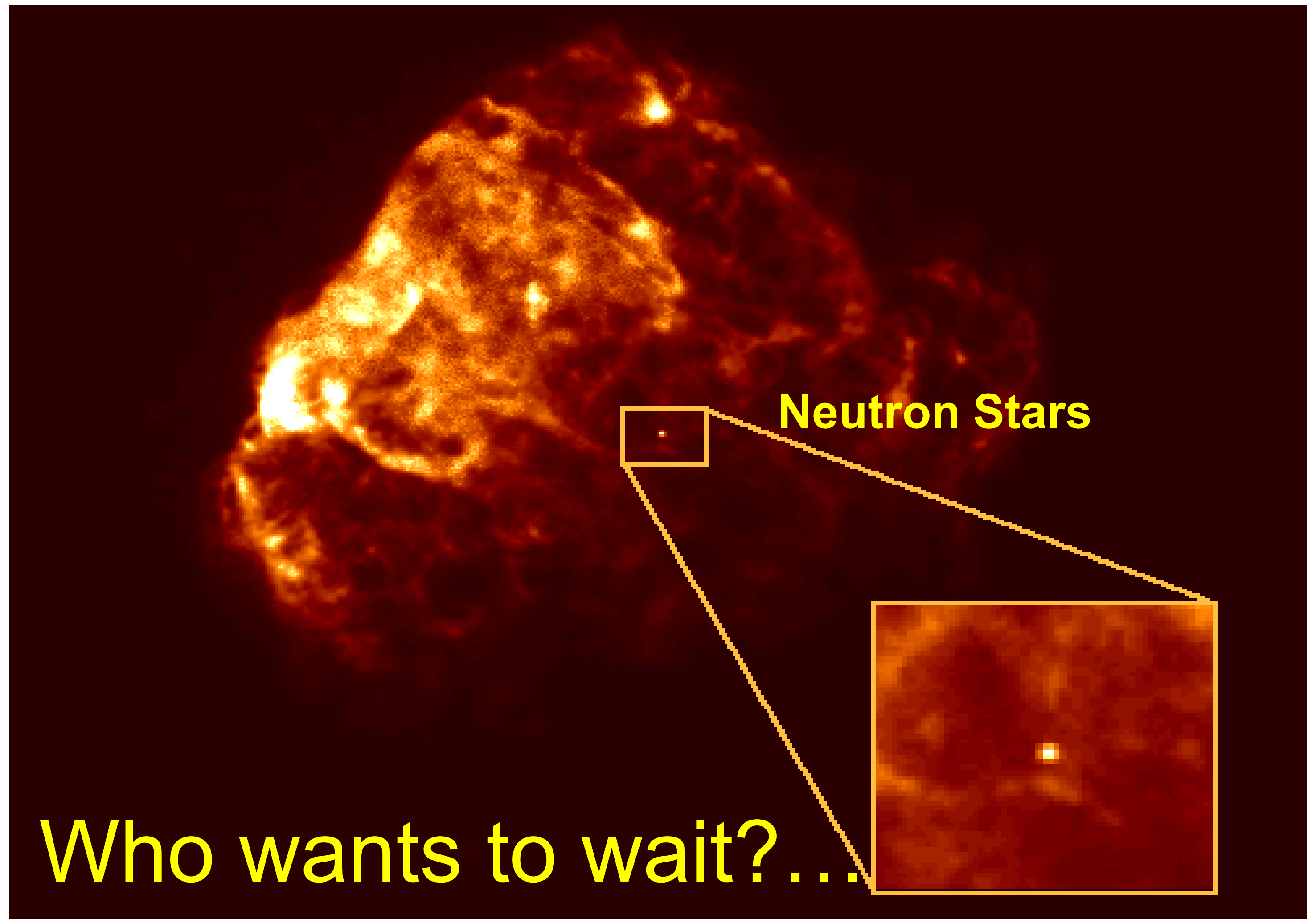
100 micro-seconds after the big bang the QGP ceased to exist, as temperatures cooled and quarks and gluons were bound in protons, neutrons and other baryons and mesons.

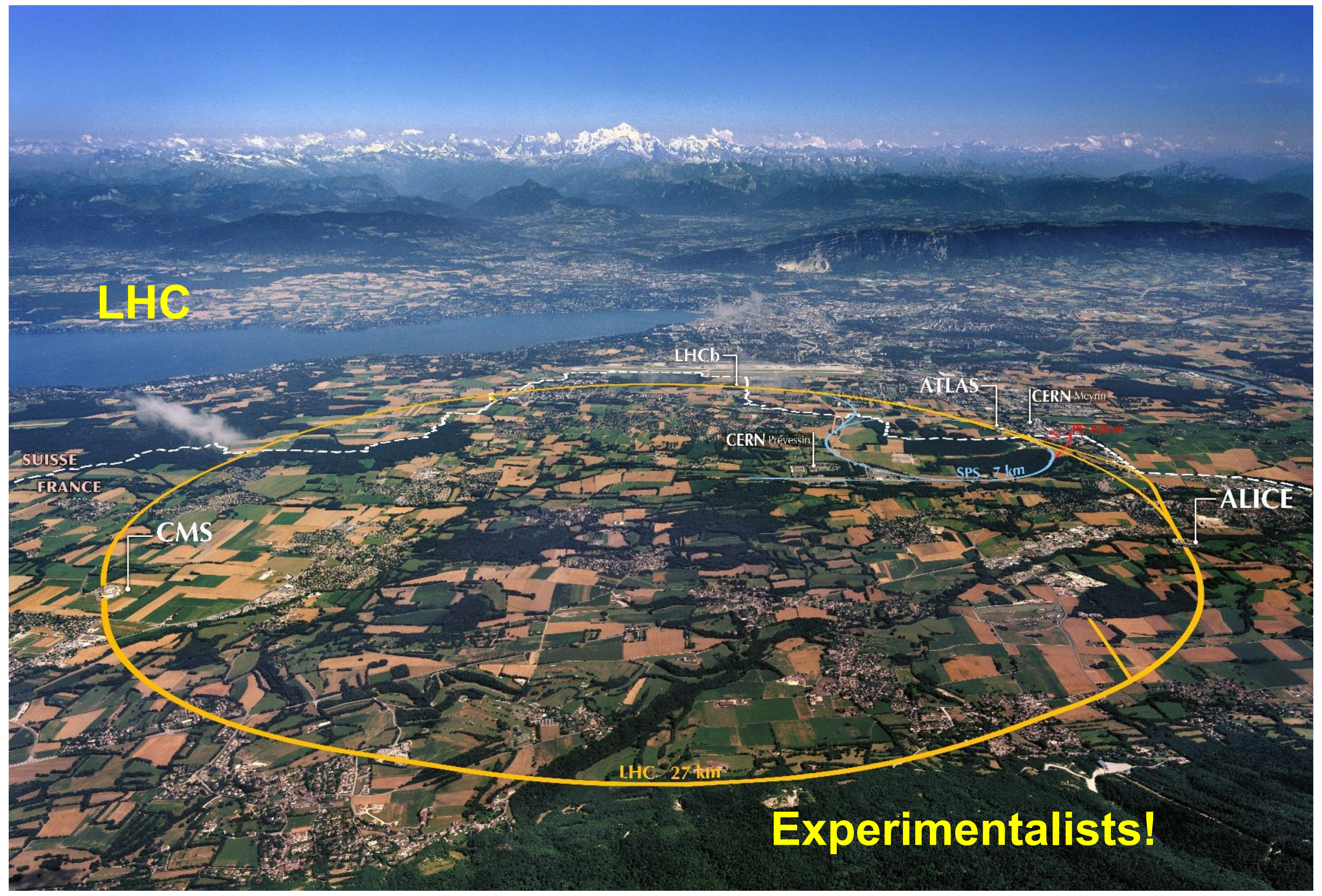
Ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) can re-create temperatures and QGP as it existed 1-20 micro-seconds after the Big Bang.



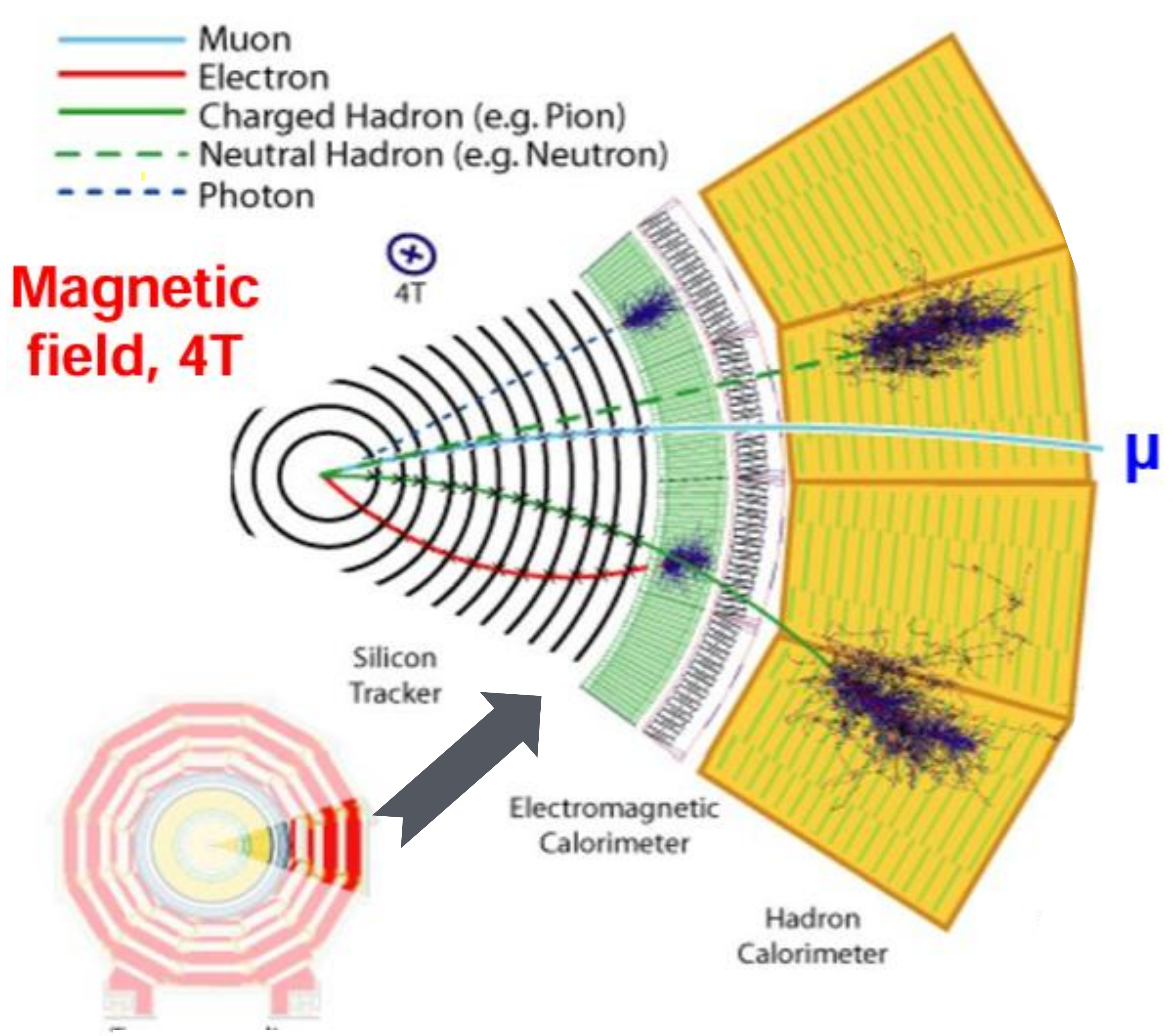
HOW TO STUDY THE QUARK GLUON PLASMA?







CALORIMETERS – MEASURE PARTICLE ENERGY



Transverse view of LHC detector

How do calorimeter measure particle energy?

(1) Primary particles create showers of secondary particles through interactions in dense materials.

(2) Charged secondary particles generate light in optical radiator material.

(3) Light output is measured and recorded.

(4) The instrument is calibrated so that one can infer the particle energy from the light output.

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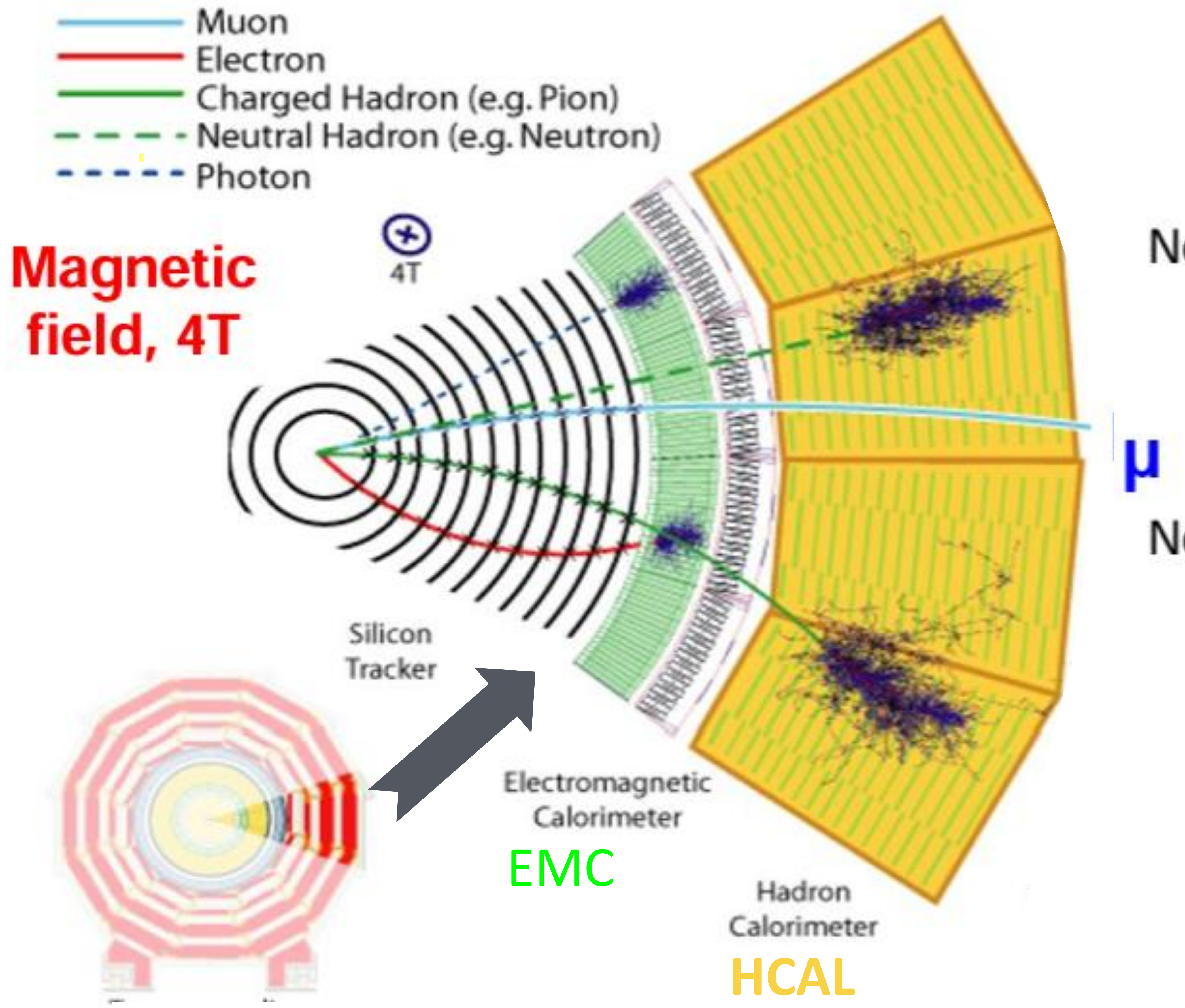
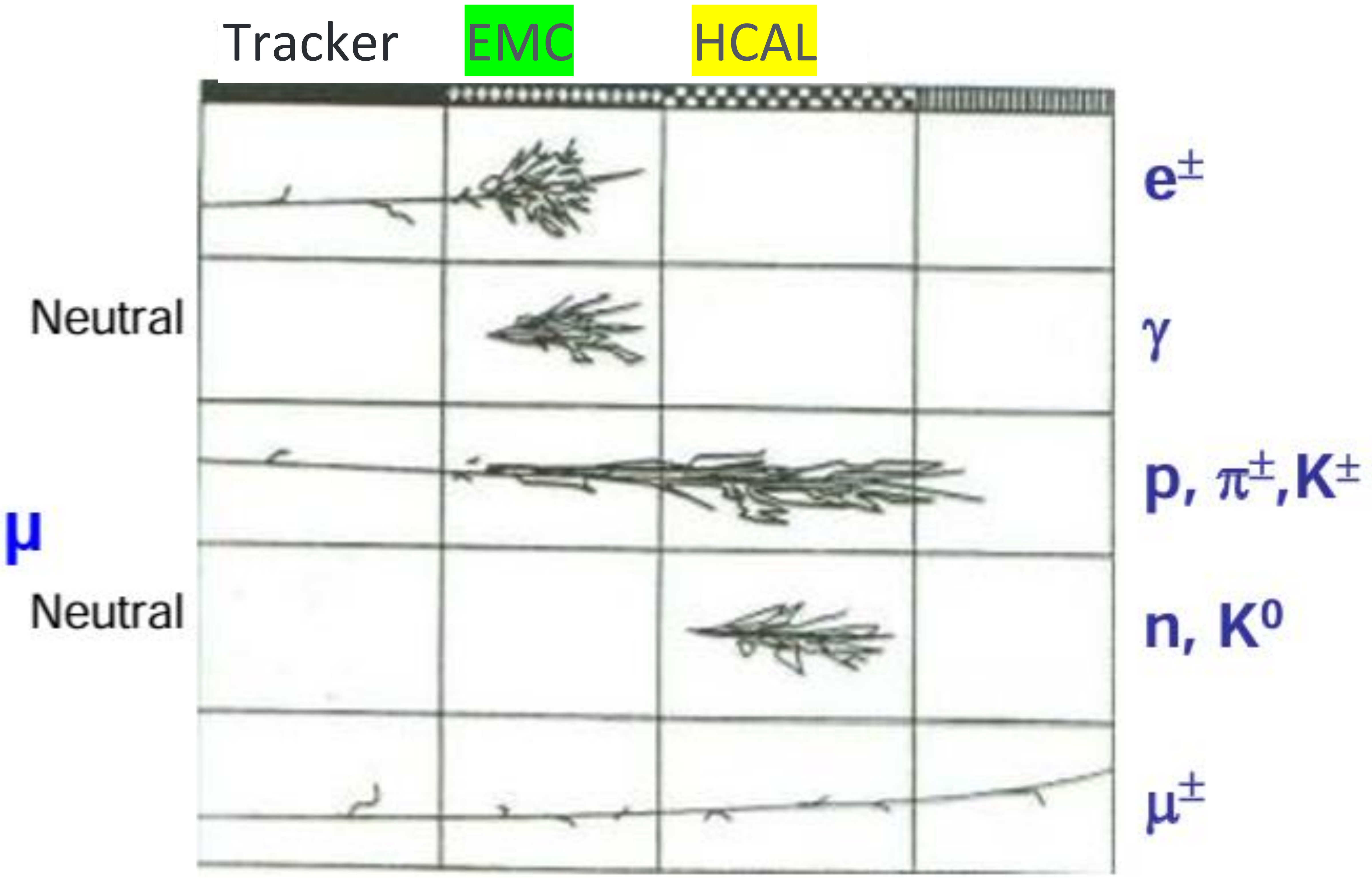


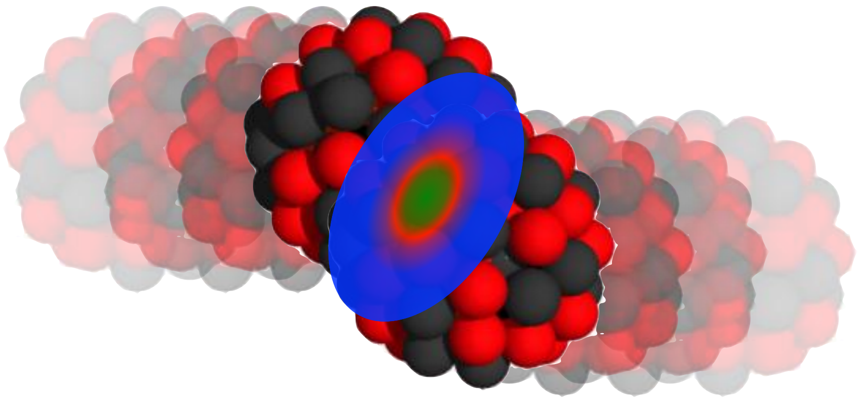
Transverse view of LHC detector

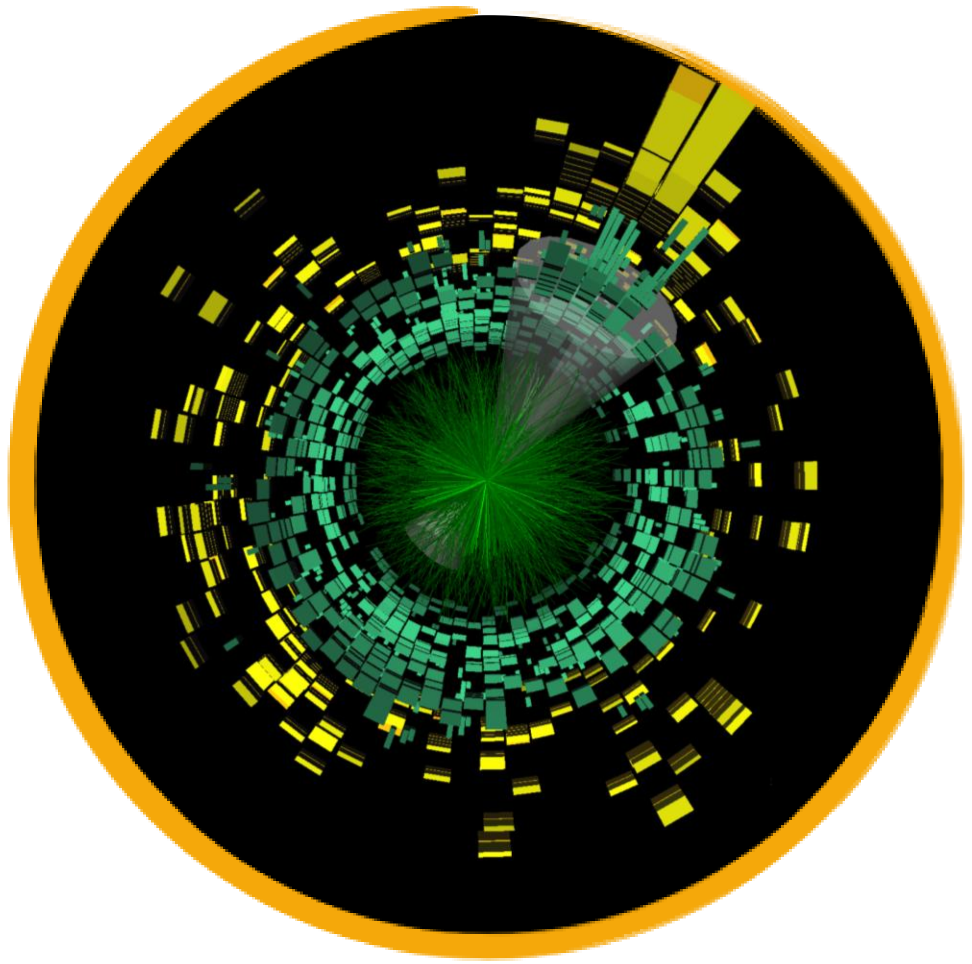


The response of tracker, EMC and HCAL identify electrons, photons, charged hadrons, neutral hadrons and muons

HEAVY IONS - IN A NUTSHELL

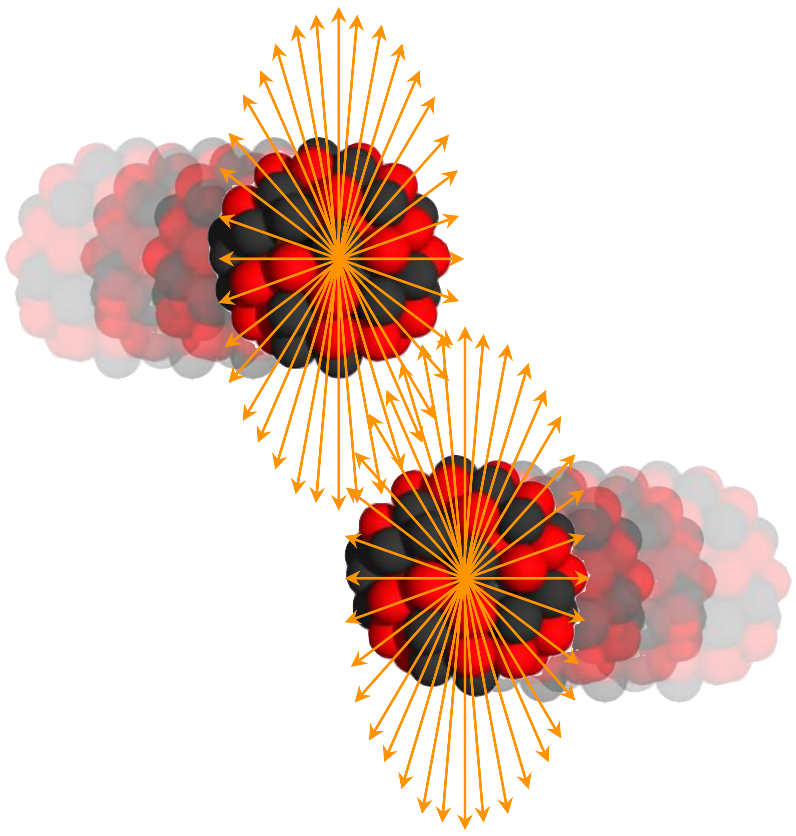
Hadronic A+A collisions

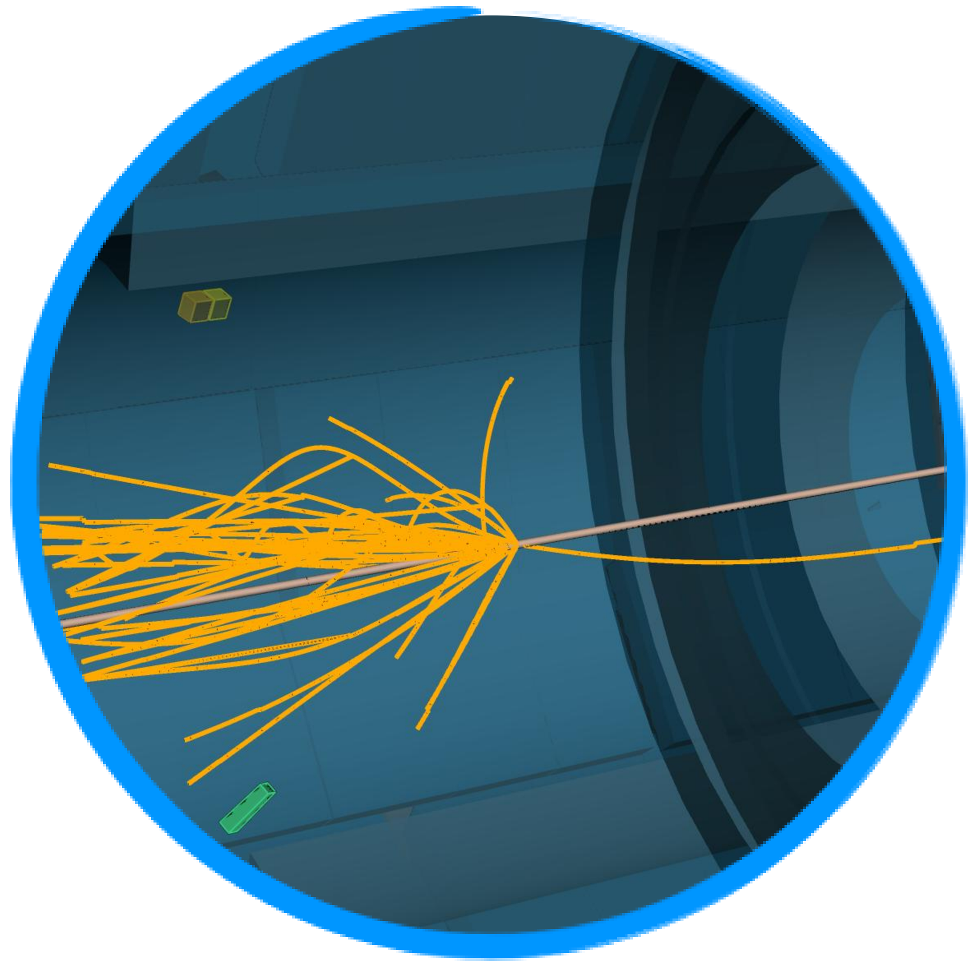


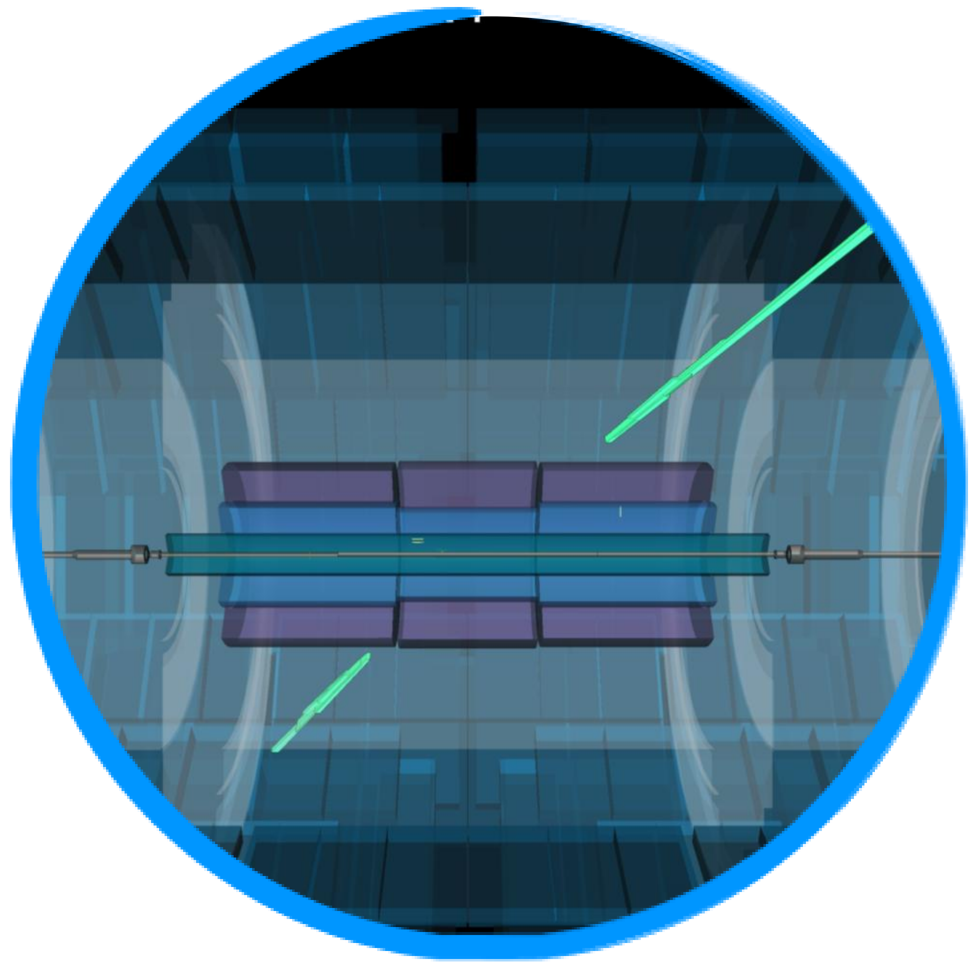


- Investigate the early universe via characterization of the Quark Gluon Plasma (QGP)

Ultra-Peripheral A+A collisions







- Precision Quantum Electro-Dynamics
- Study of the nuclear structure

HEAVY IONS - IN A NUTSHELL

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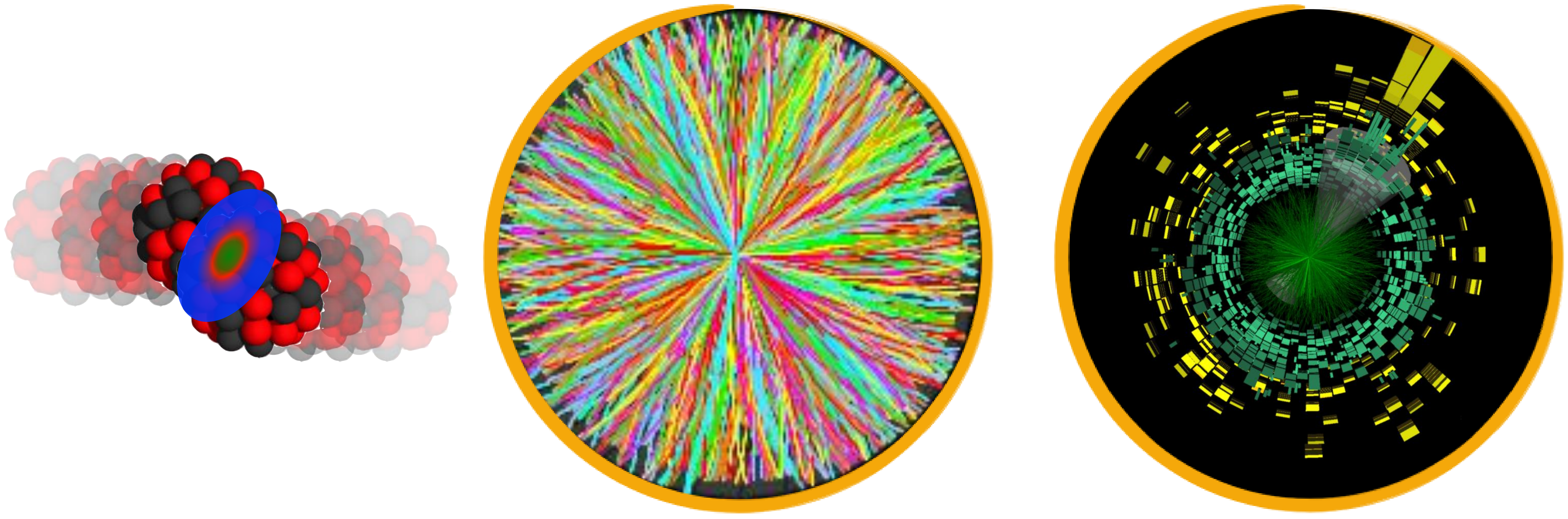

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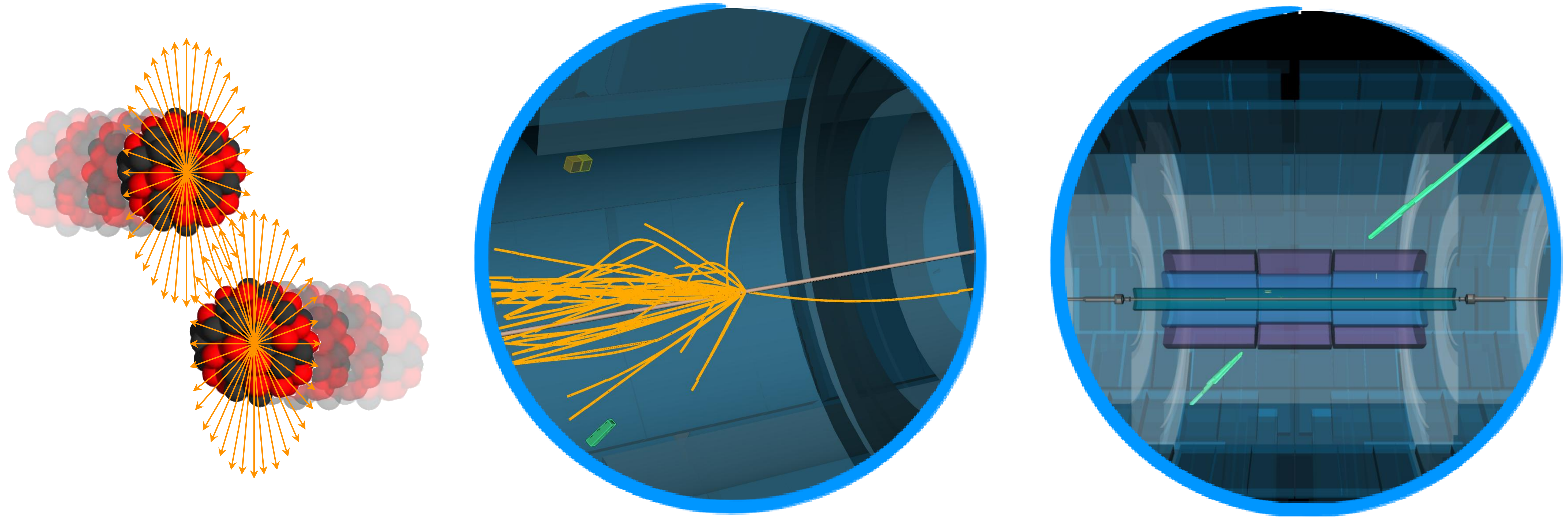
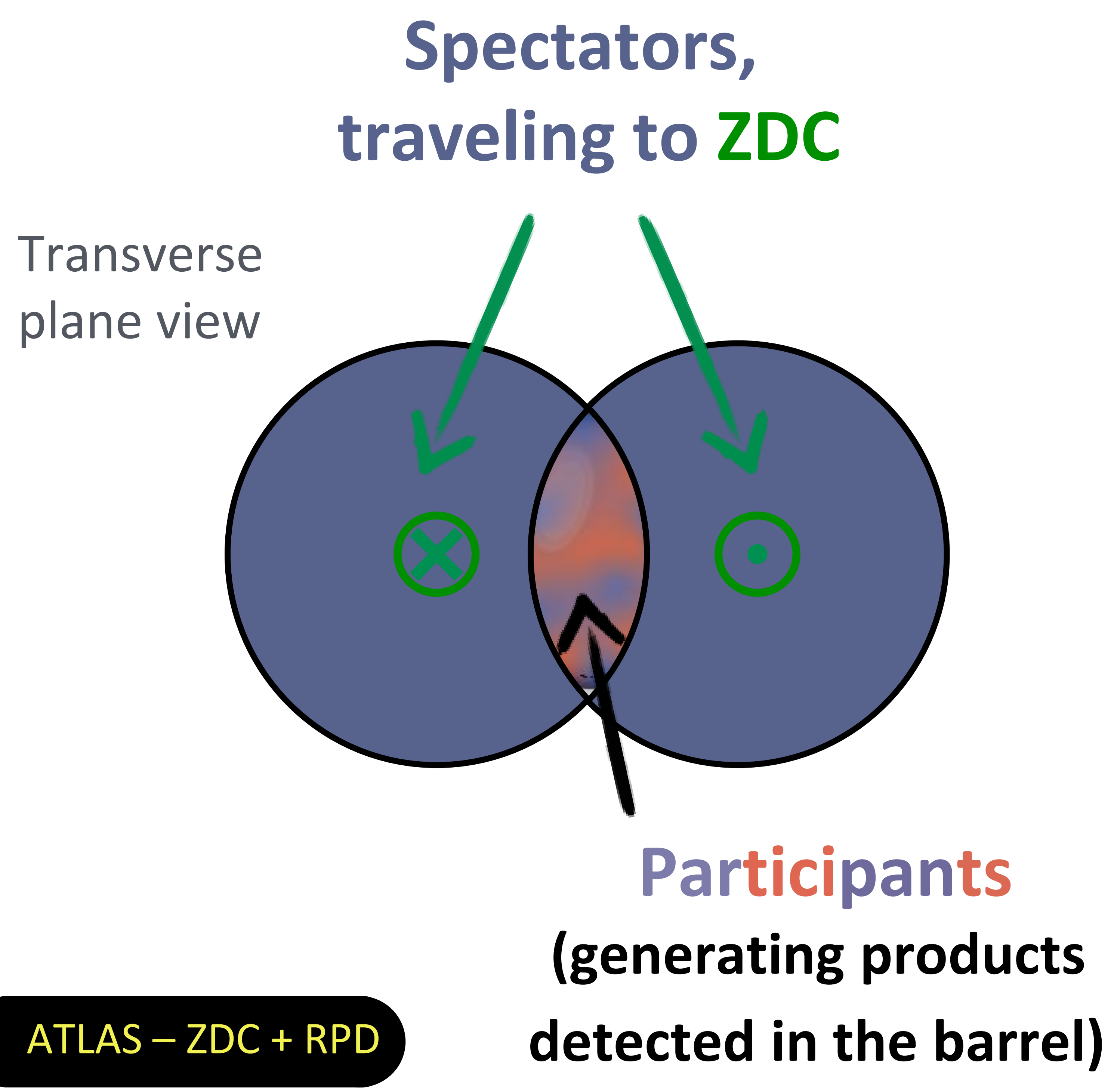


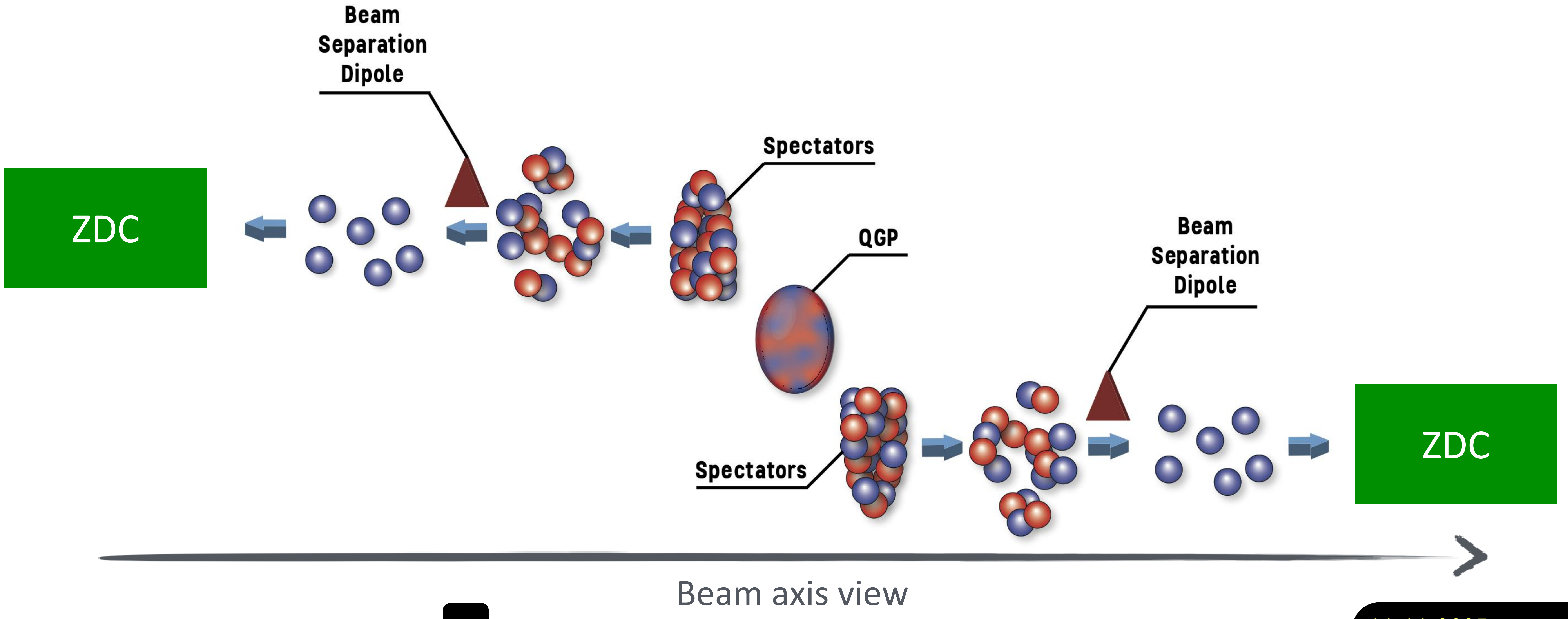
Geometry in these collisions drives nearly everything

Distinguishing between these classes of physics processes is key to having a proper trigger for the experiment

ZERO DEGREE CALORIMETERS

- So far - we have discussed calorimeters for large area particle experiments - to be installed in the detector barrel to provide comprehensive particle detection
- When colliding ions - additional calorimeters are usually installed on the beamlines: the **Zero Degree Calorimeters (ZDCs)**
- The ZDCs measure **spectator neutrons** that did not interact in the collision
- The ZDC is installed in the Target Absorber for Neutrals (TAN), at ±140 m from ATLAS IP





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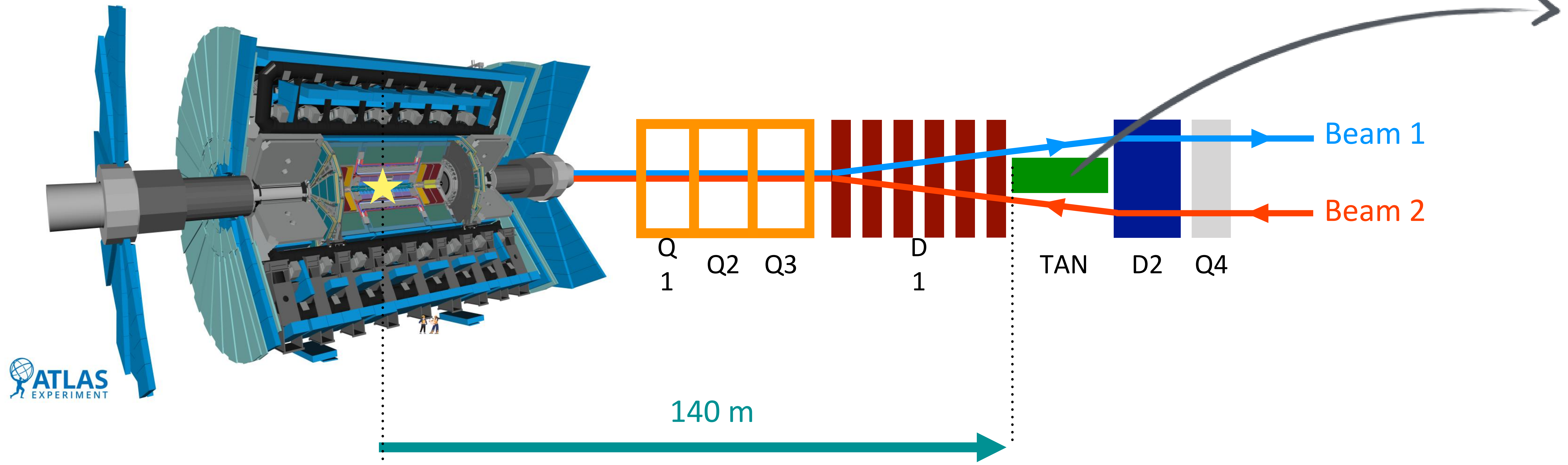
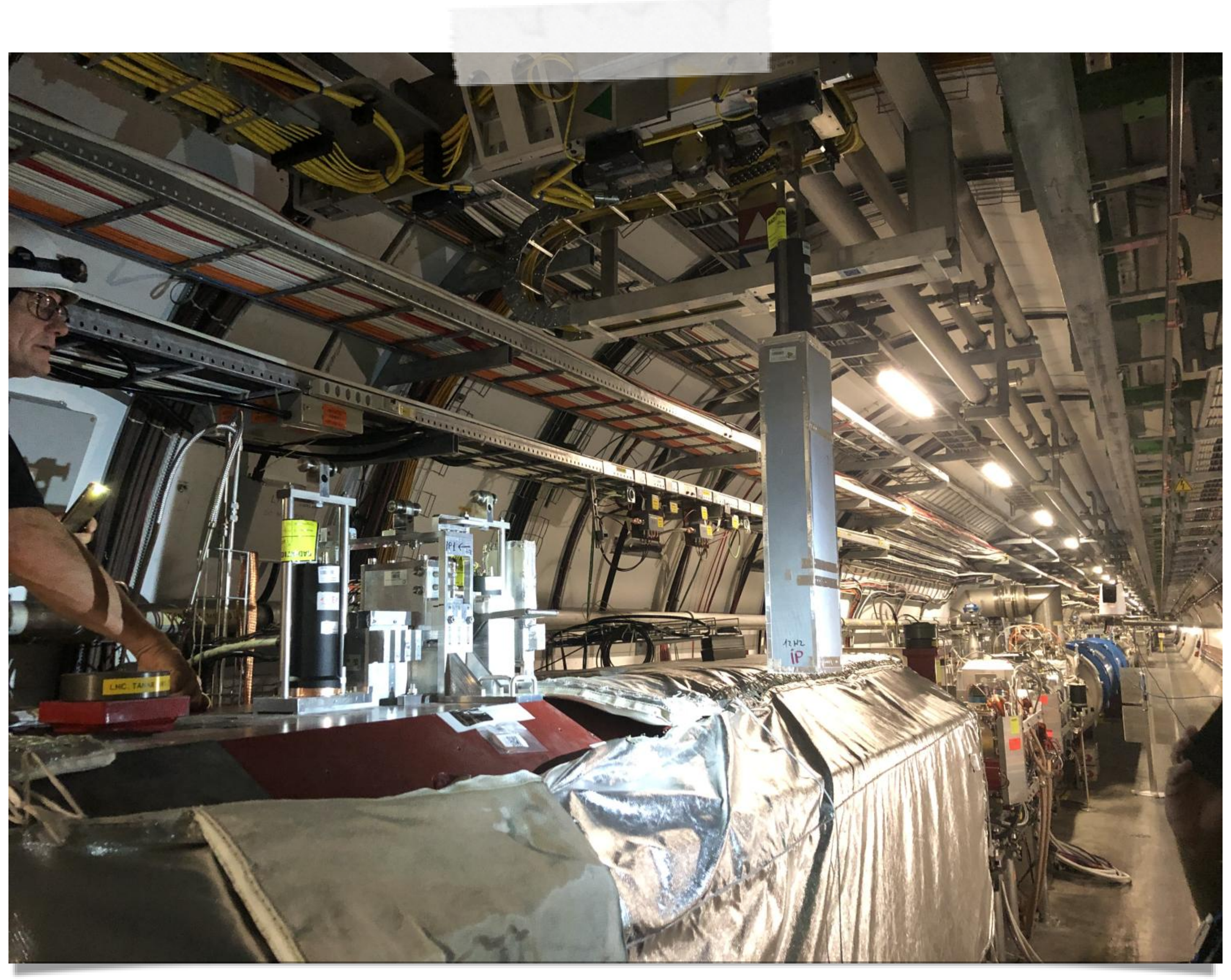
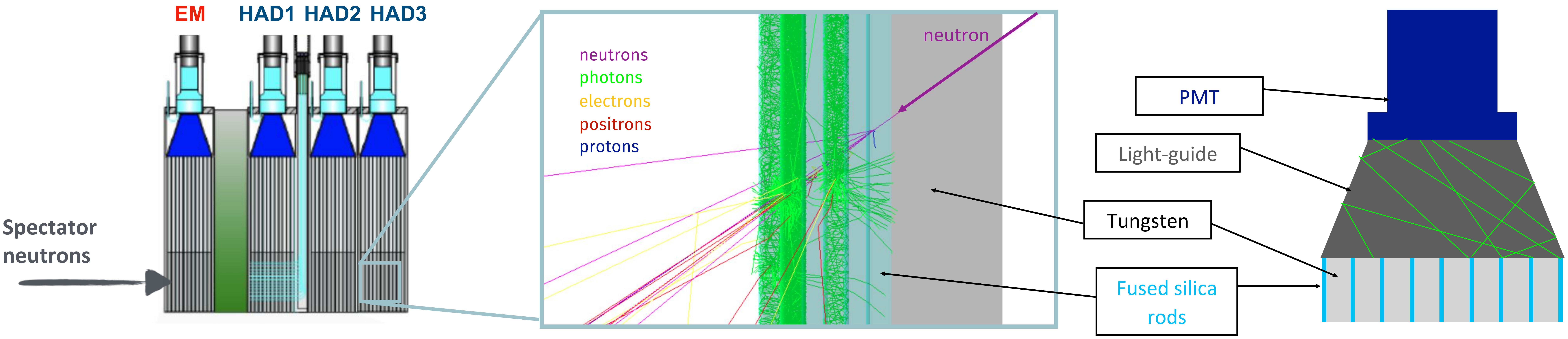
ZDC location in ATLAS





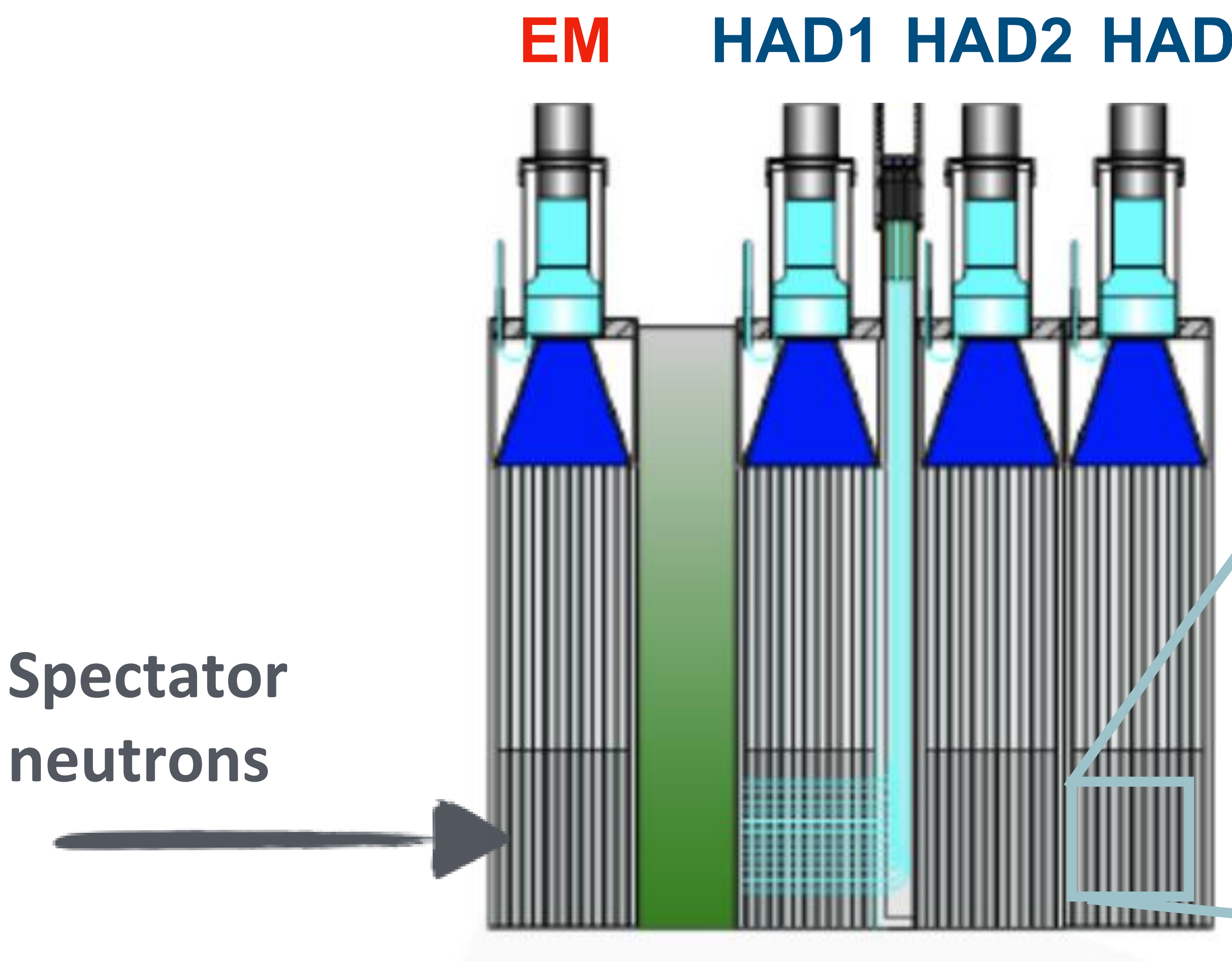
ZDC installation in the TAN
August 2023

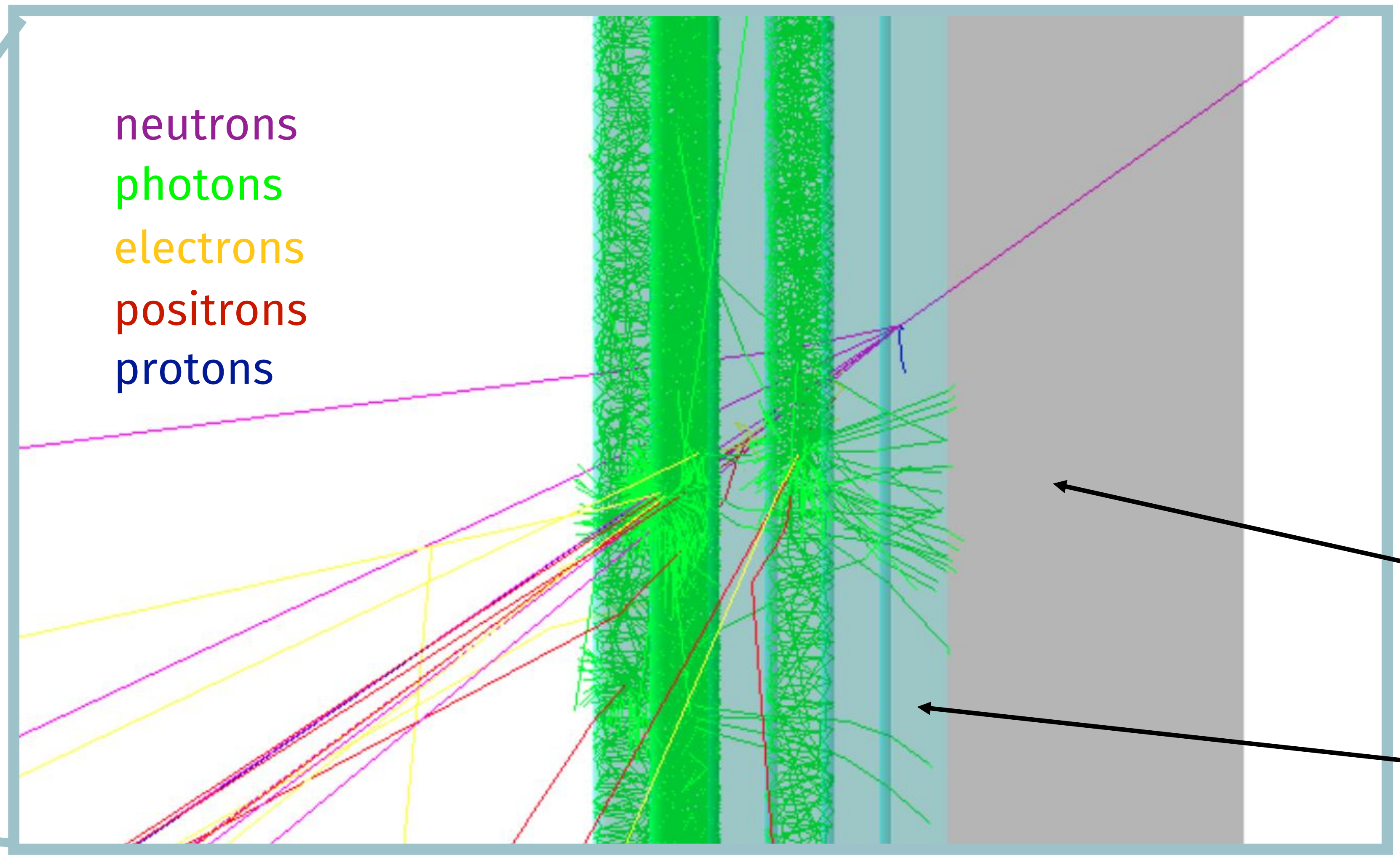
ZDC: FROM NEUTRON TO ELECTRICAL SIGNAL

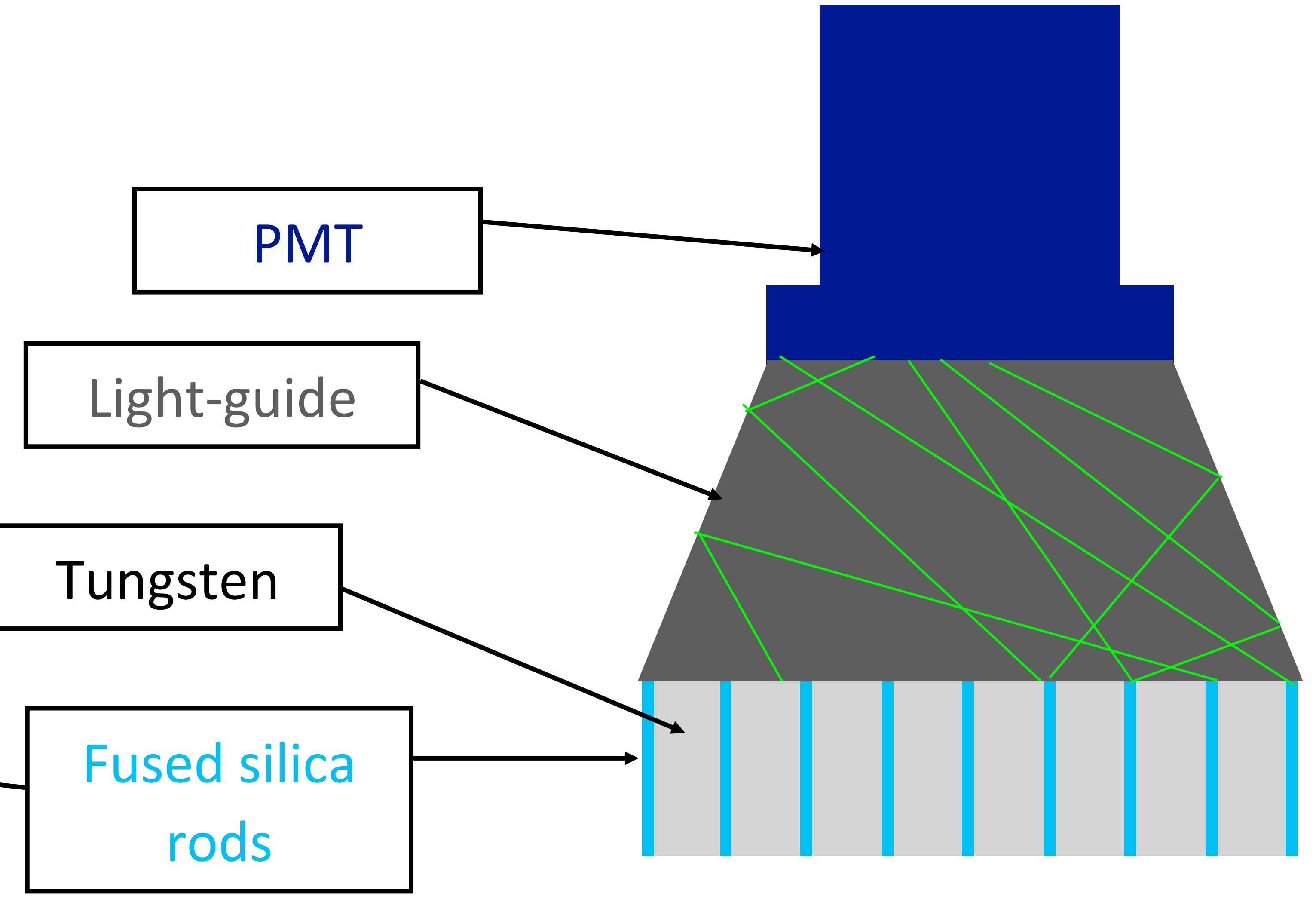


- Nuclei in the W absorber interact with neutrons - generating a high-energy particle shower
- The charged fraction of the shower generates Cherenkov light in the fused-silica rods
- A considerable fraction of the light is retained within the rods by Total Internal Reflection (TIR) and travels towards the extremities of the rods
- At the top of the rods, the light is injected into an air-light guide, that focuses it over a PMT window → the PMT converts the light into an **electrical signal**!

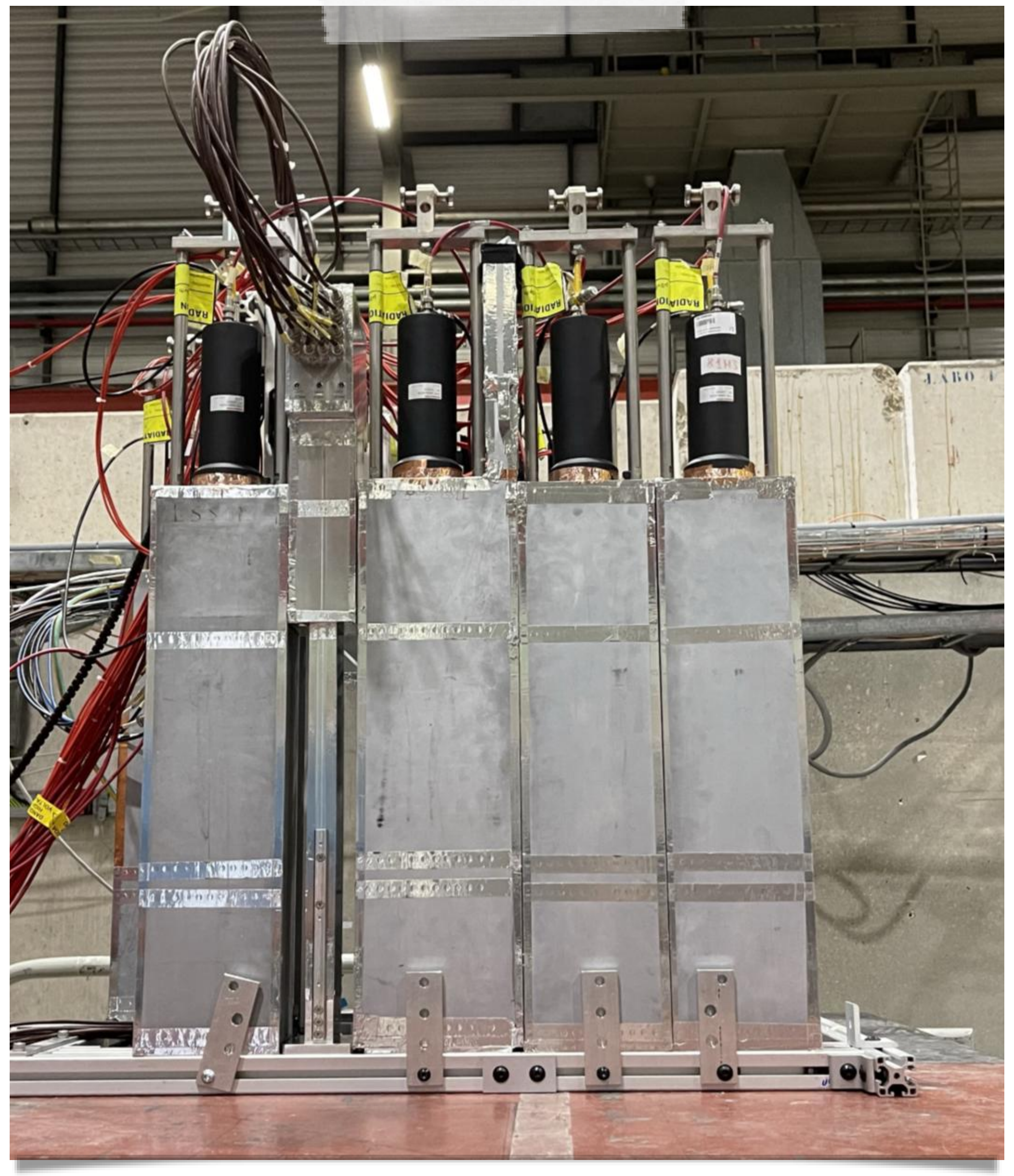
ZDC: FROM NEUTRON TO ELECTRICAL SIGNAL

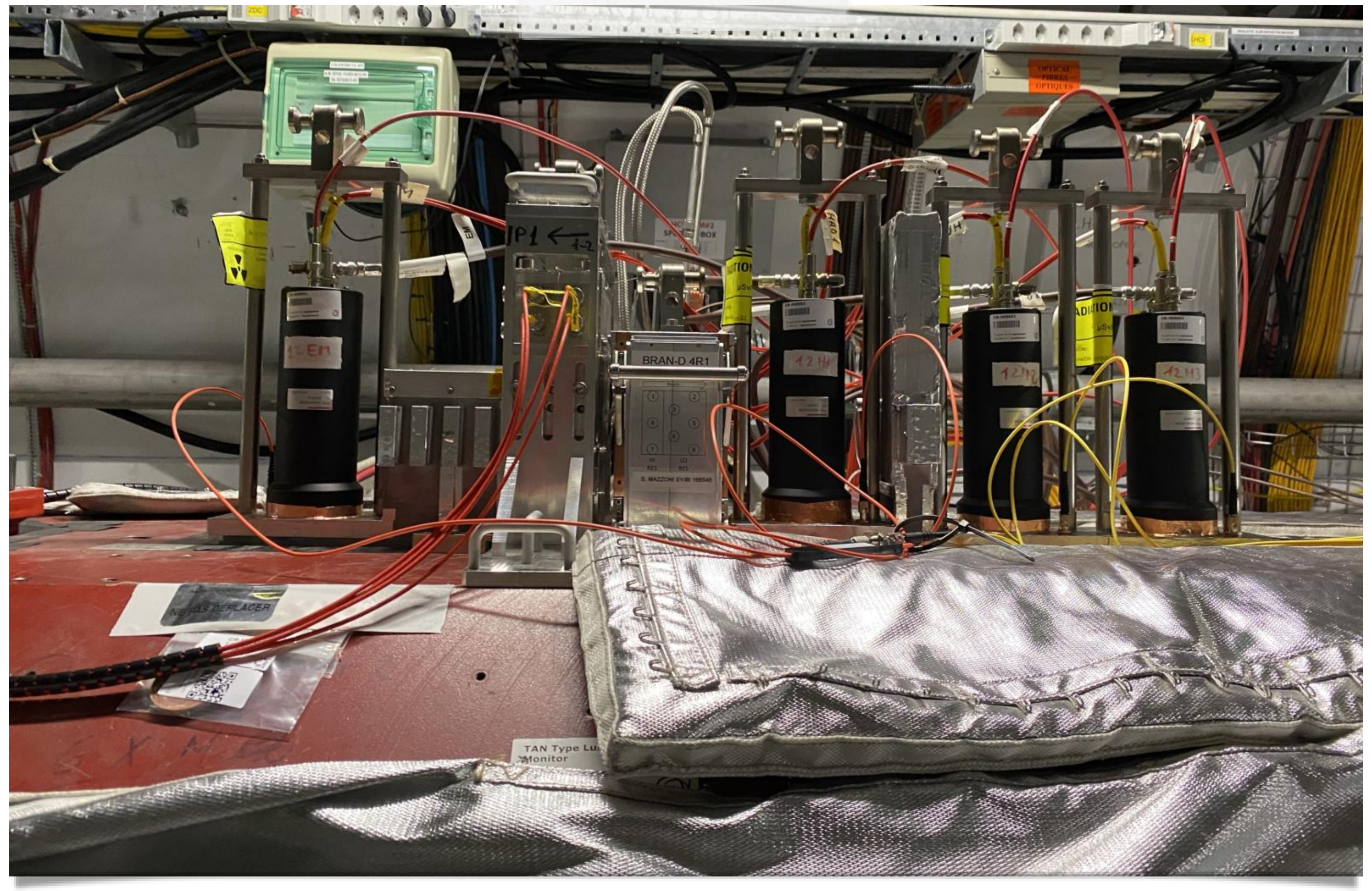






ZDC @ CERN SPS Test Beam, pasty summer



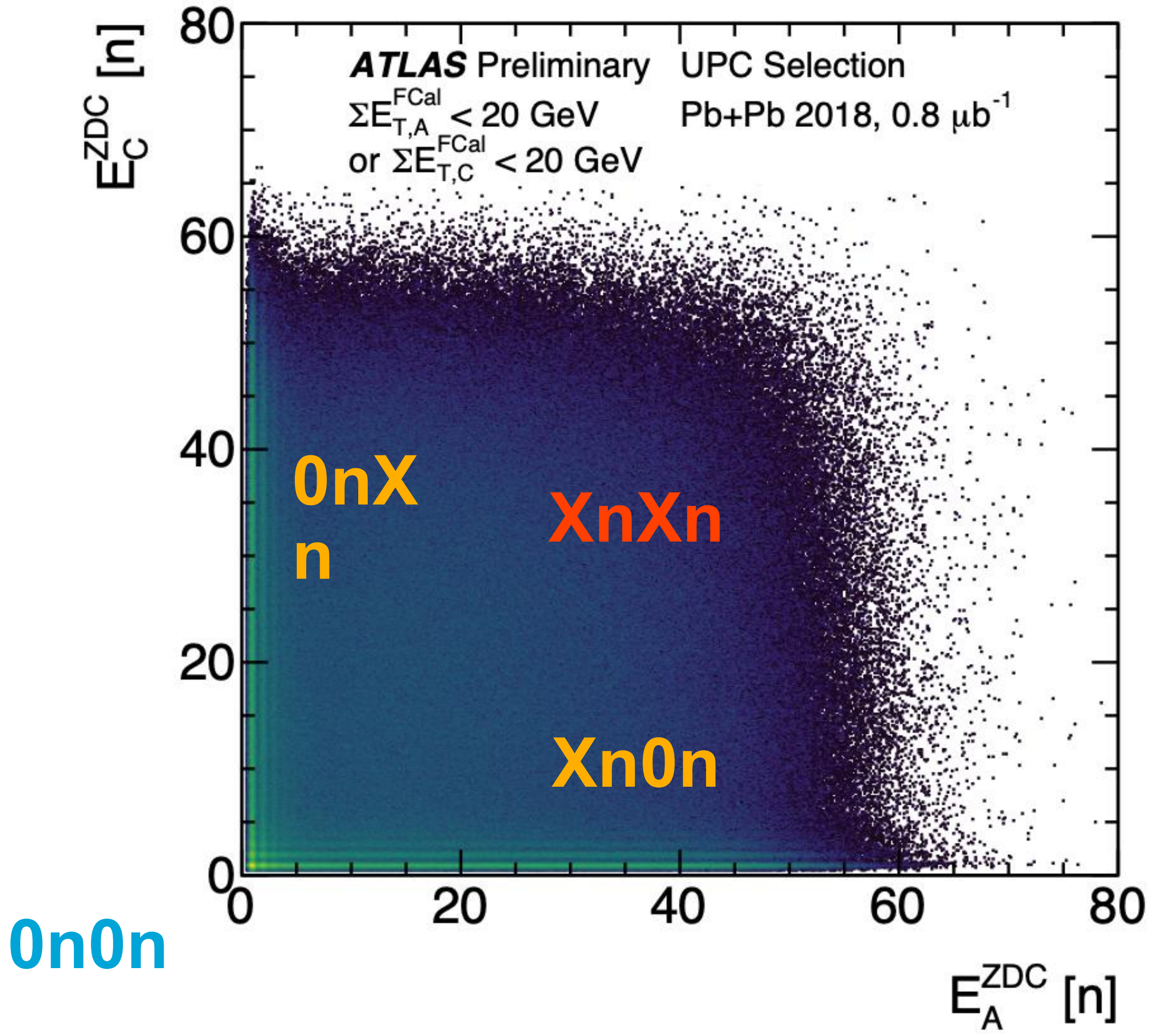


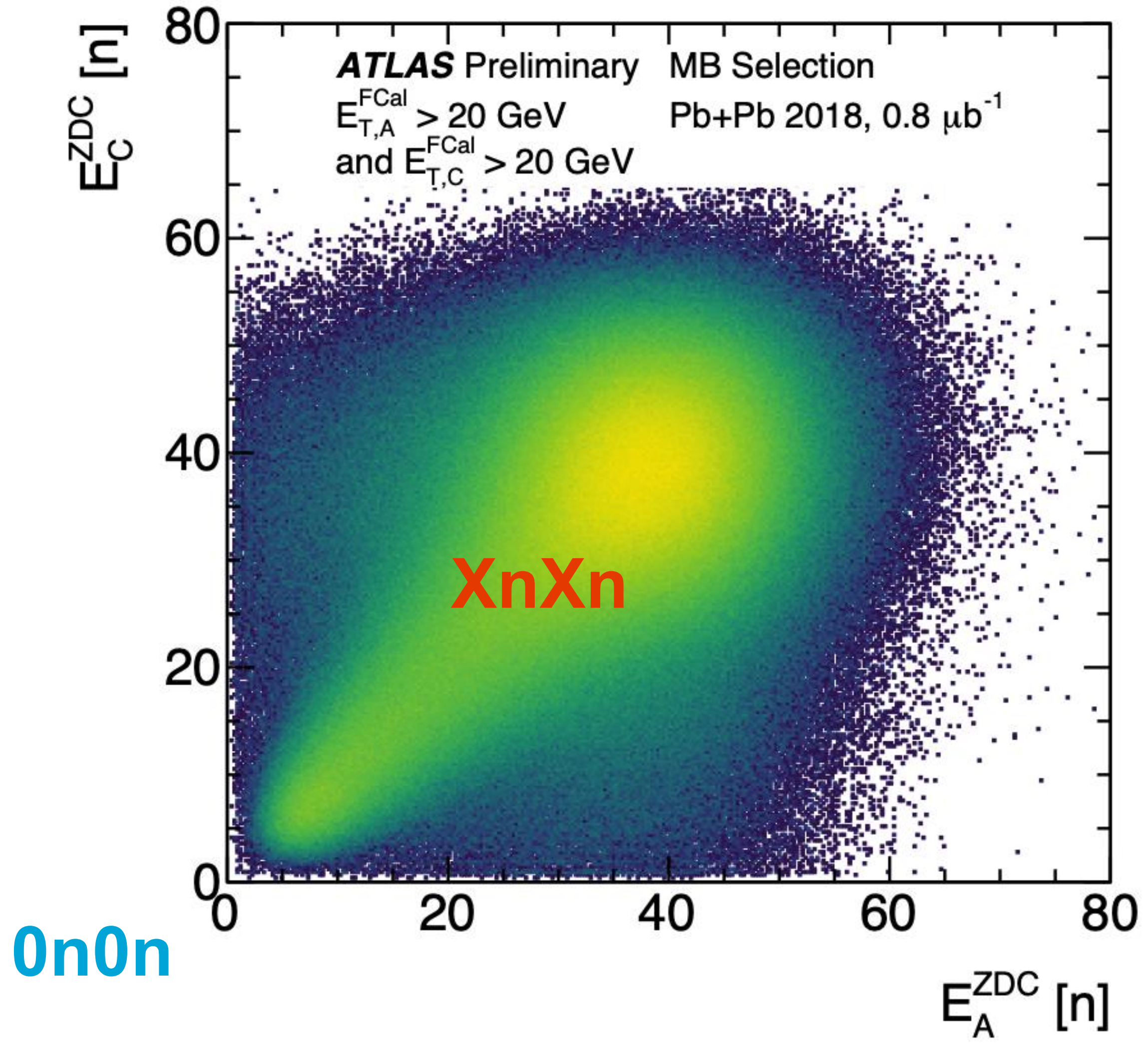
ZDC installed in the LHC

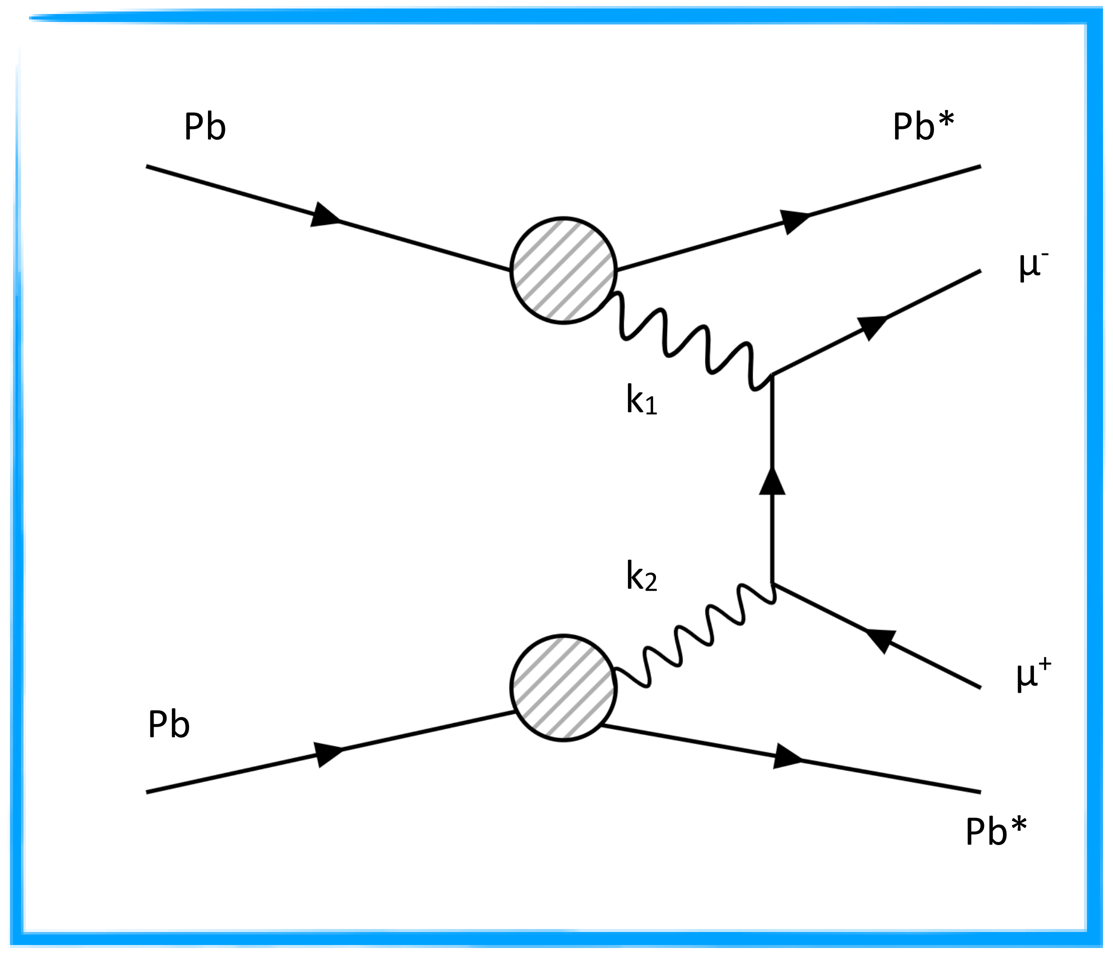
- Why Cherenkov radiation and not directly a detector? With the TAN **radiation environment**, a PMT would not survive too close to the detector core

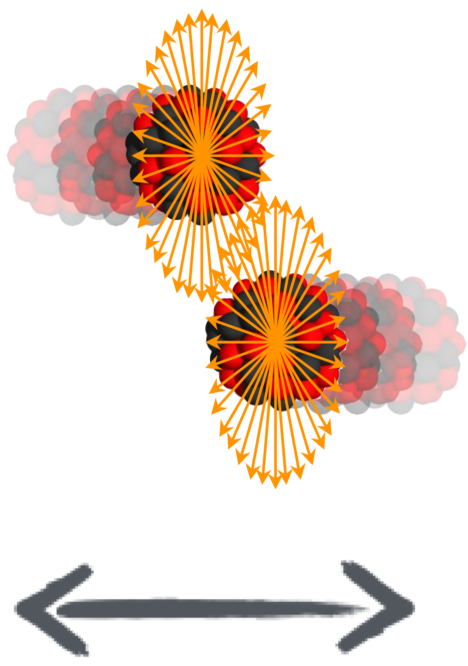
ZDC AS PRIMARY PROCESS TAGGER

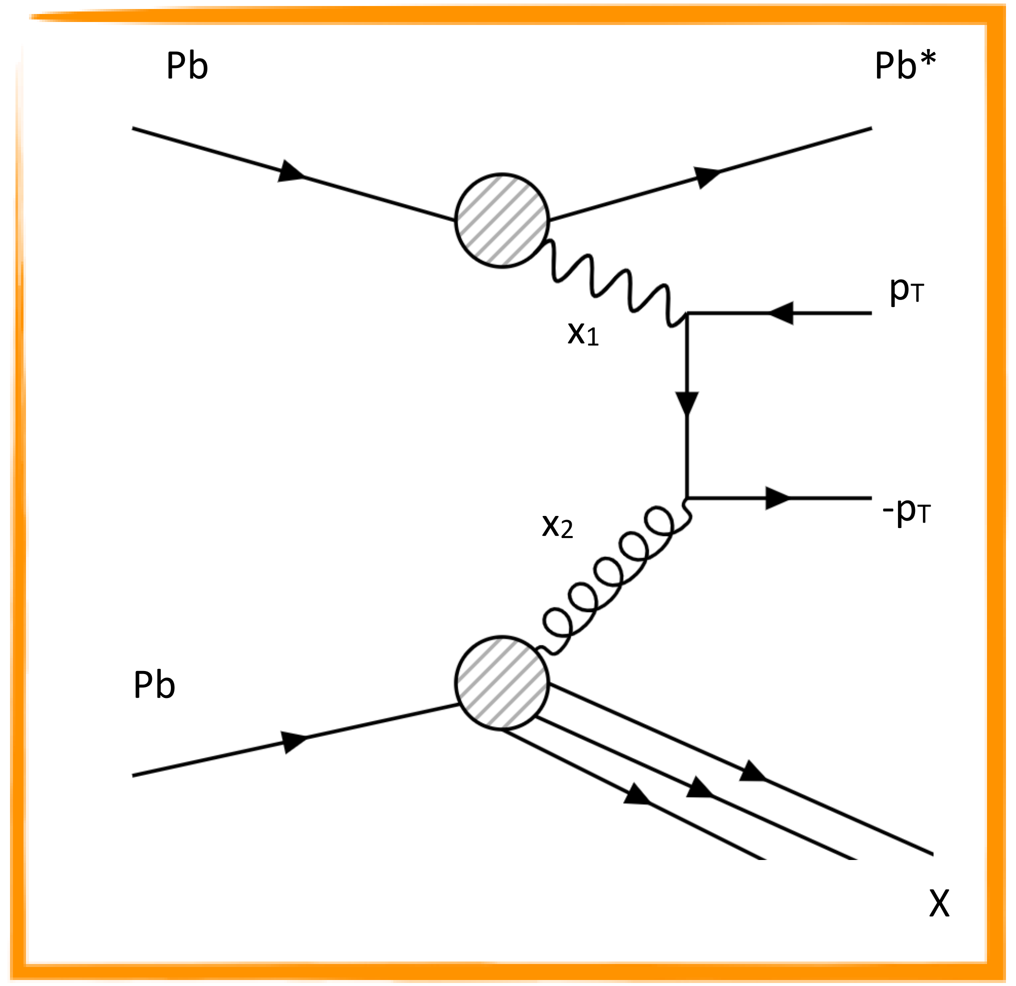
- By counting **spectator neutrons,** the **ZDC** can infer the type of interaction between the ions and the geometry of the collision
  - No neutrons on either side ("0n0n") is typically from γ-γ processes
  - Neutrons only on one side ("Xn0n"/"0nXn") is typically from photonuclear processes
  - Neutrons on both sides ("XnXn") typically come from spectators in hadronic processes

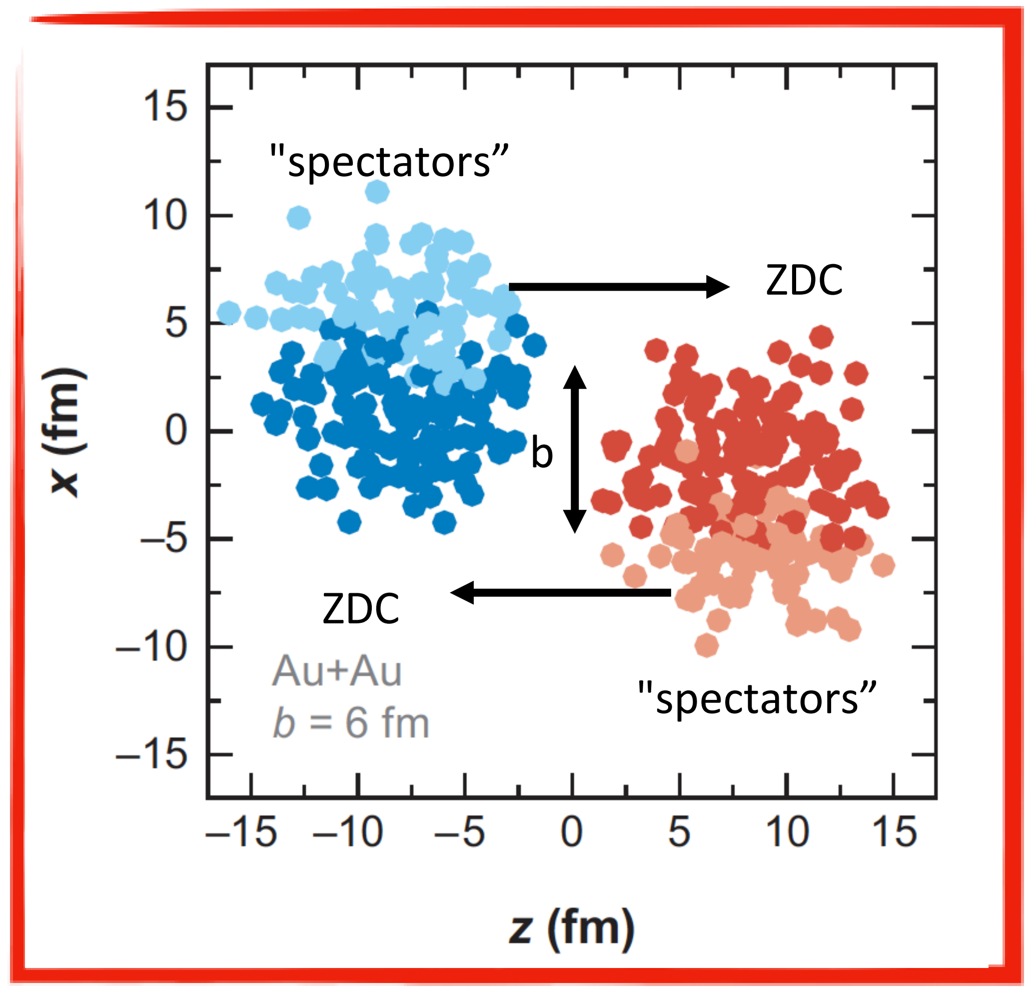


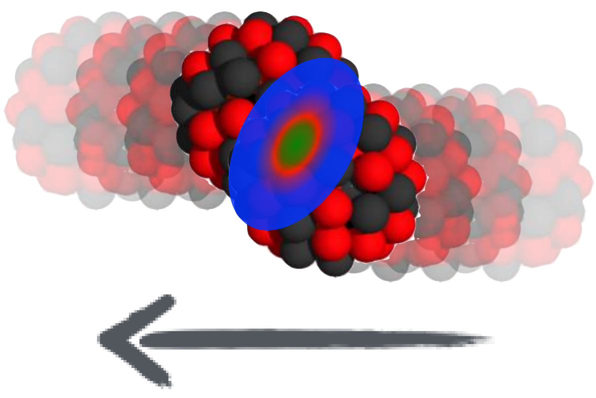






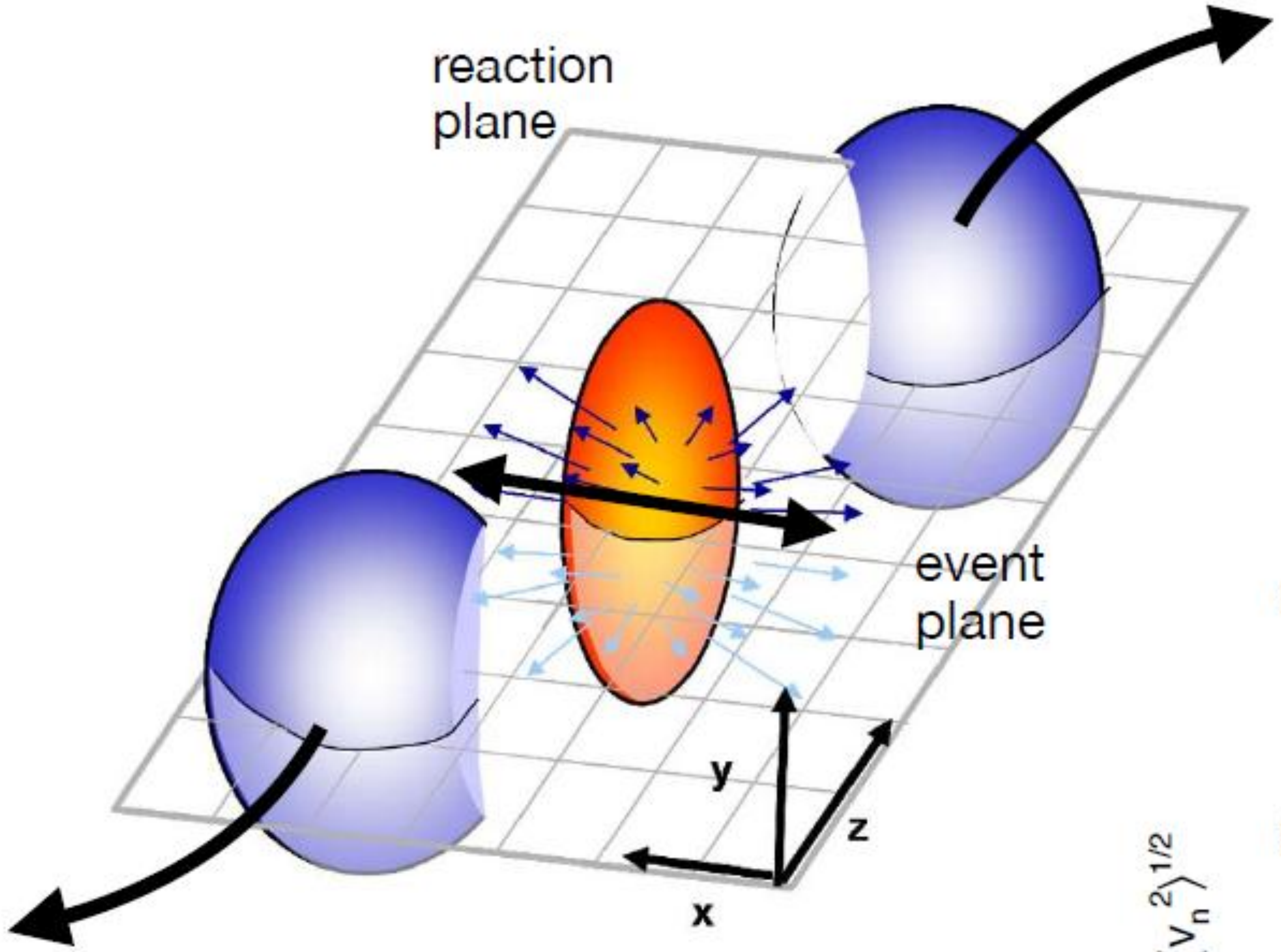






[Ann. Rev. Nucl. Part. Sci. 57 (2007) 205]

REACTION PLANE DETECTOR, RPD, IN THE ZDC



Heavy ion collisions (and pp and p+Pb) show strong evidence for hydrodynamic evolution in the final state, observed with Fourier coefficients of azimuthal distributions v_n relative to "event plane" (defined by angle of maximum particle emission)

Measuring v_1 ("directed flow") is difficult without a direct measurement of the "reaction plane": available using correlated deflection of neutrons (first done at LHC by ALICE in 2015)

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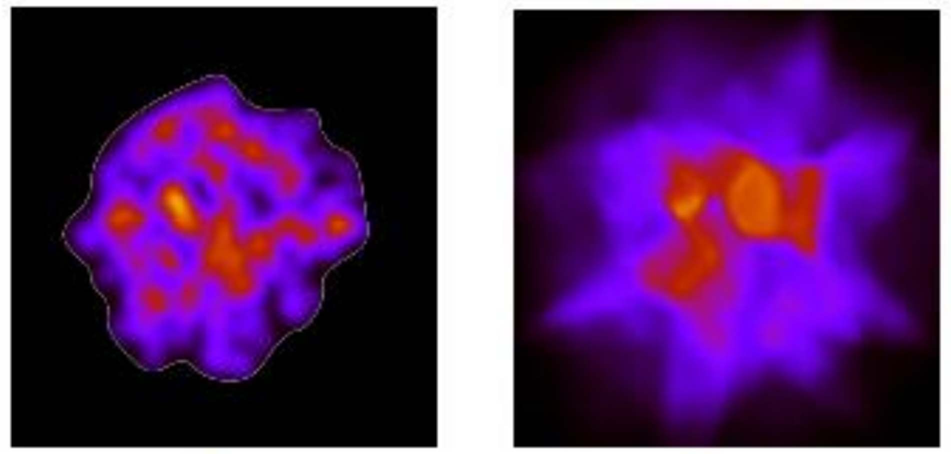

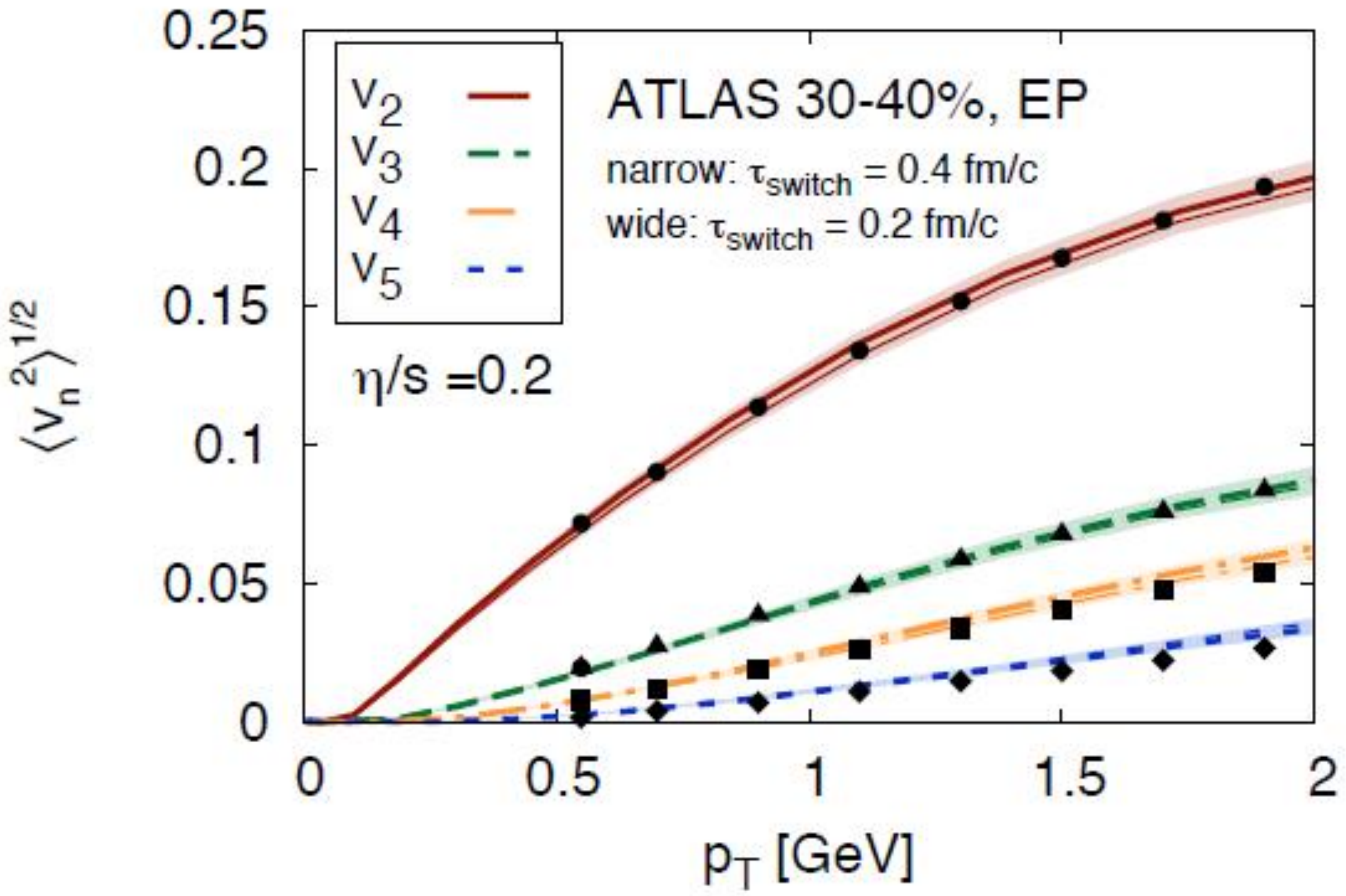

Gale et al, PRL 110 (2012) 012032

ZERO DEGREE CALORIMETERS + RPDS

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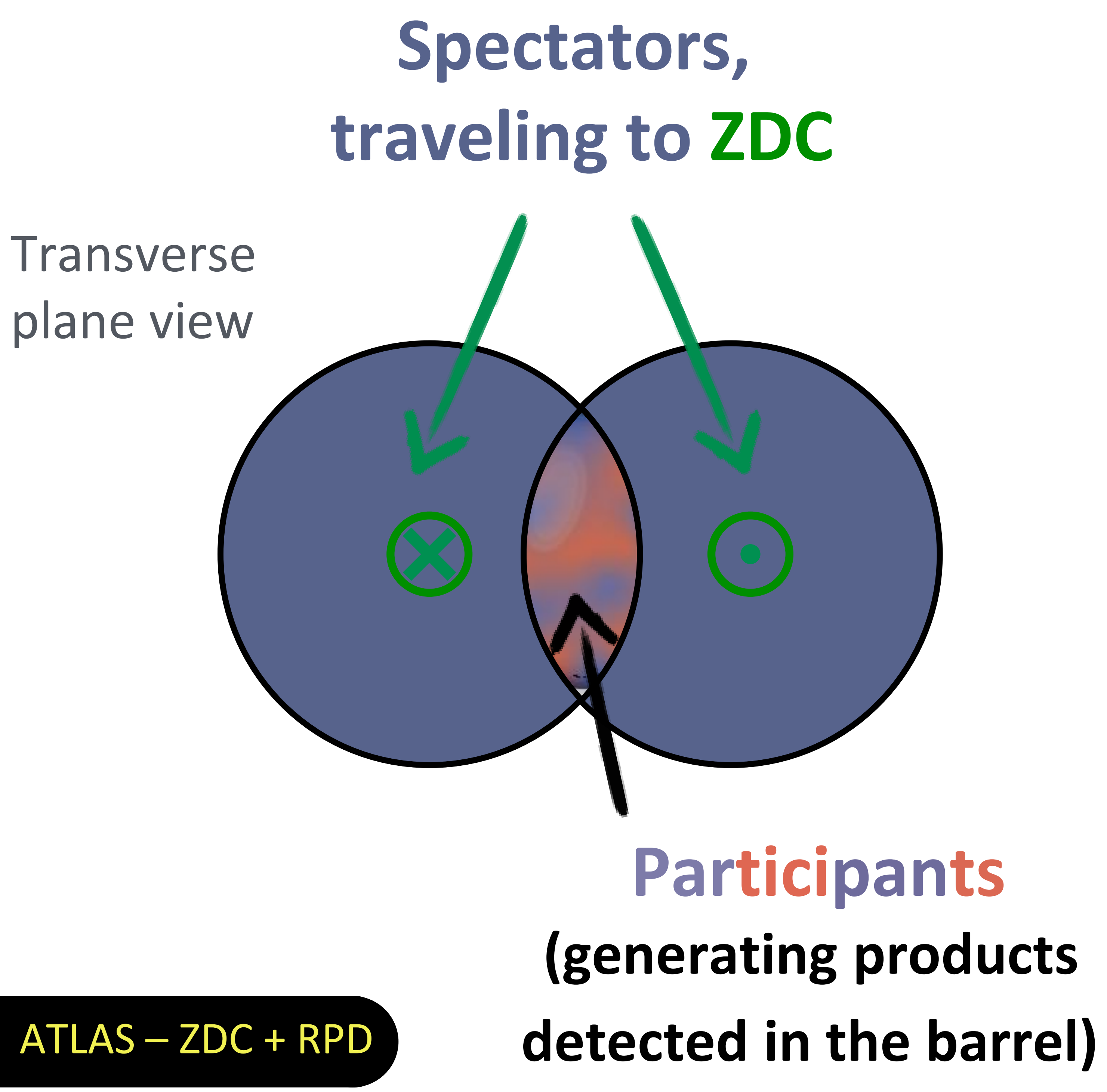

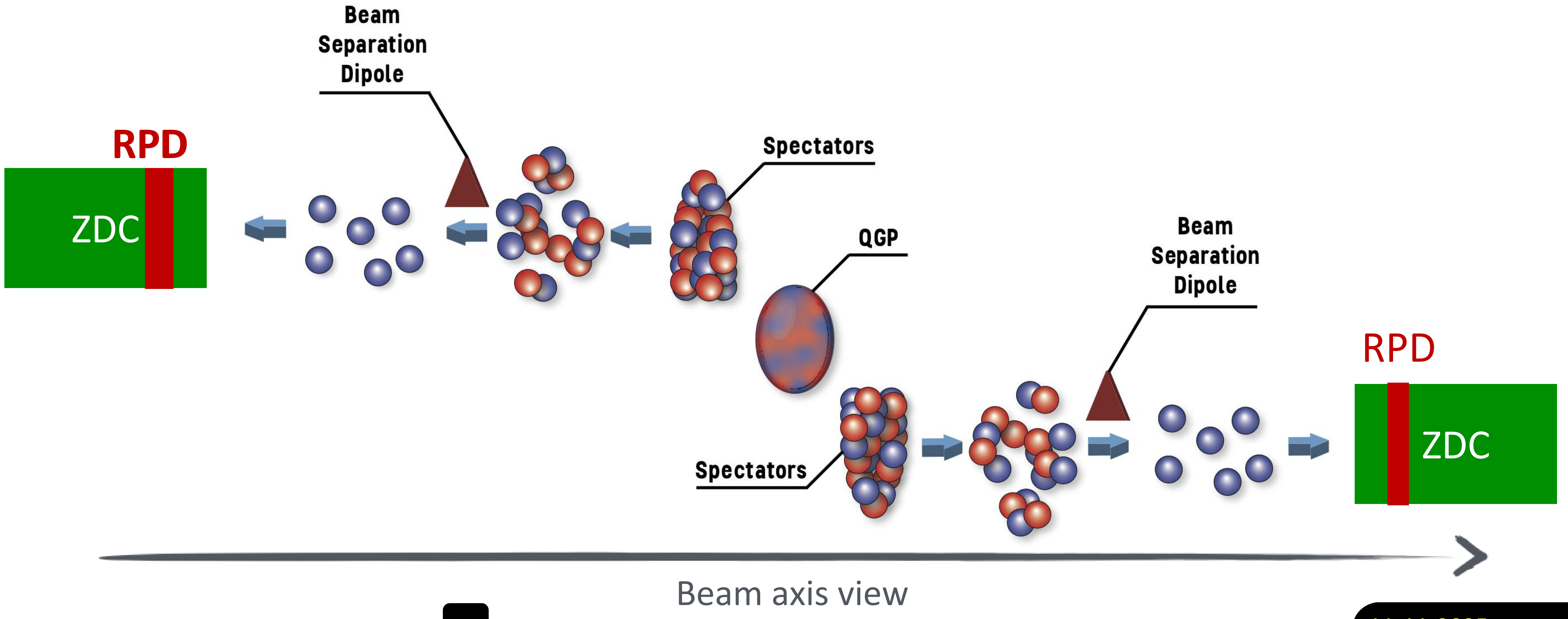

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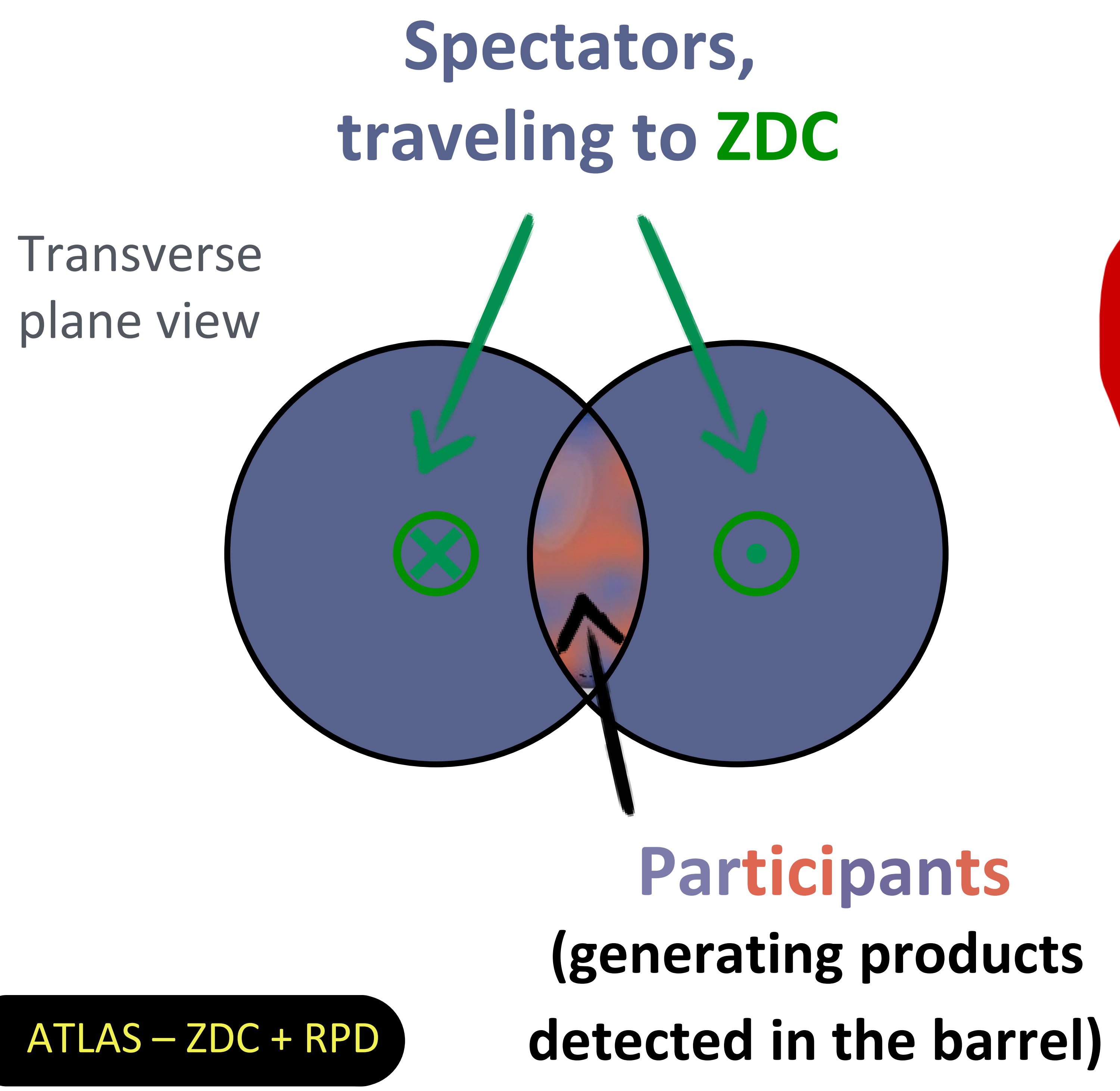
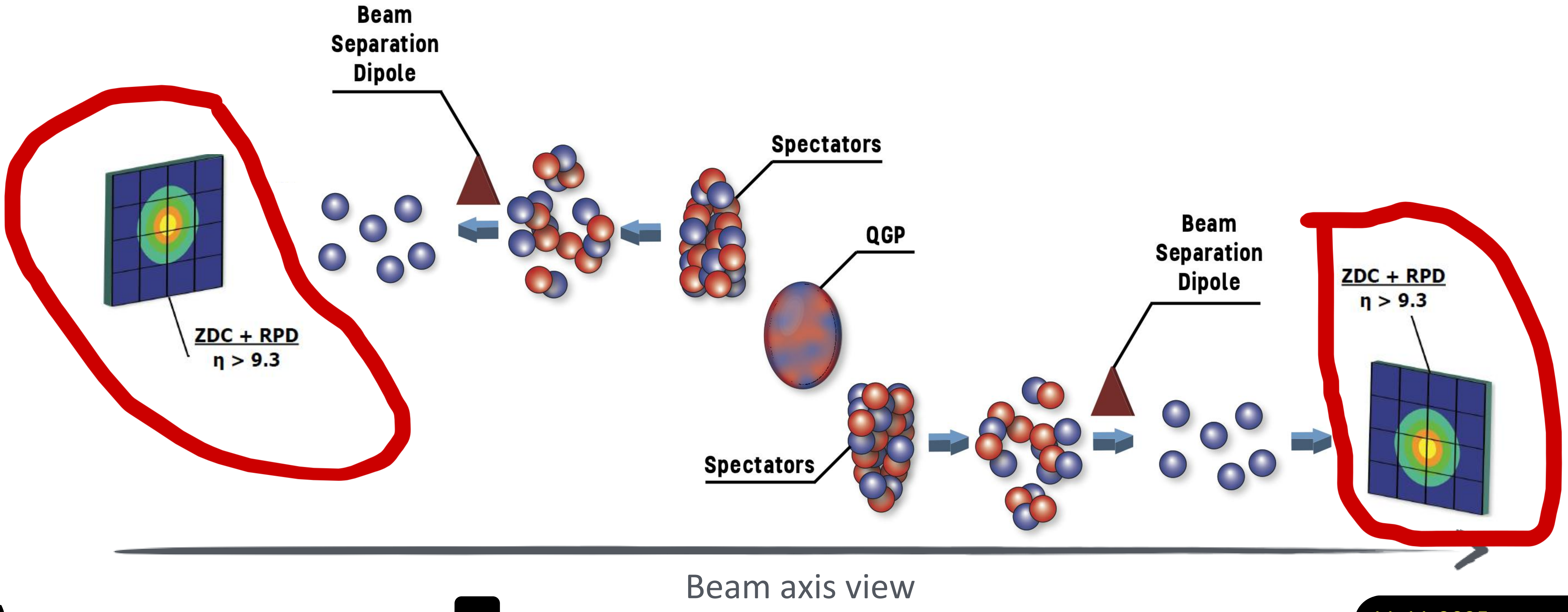




REACTION PLANE DETECTOR, RPD

ATLAS Run 3 RPD – Sheng Yang (NPRE+Physics)

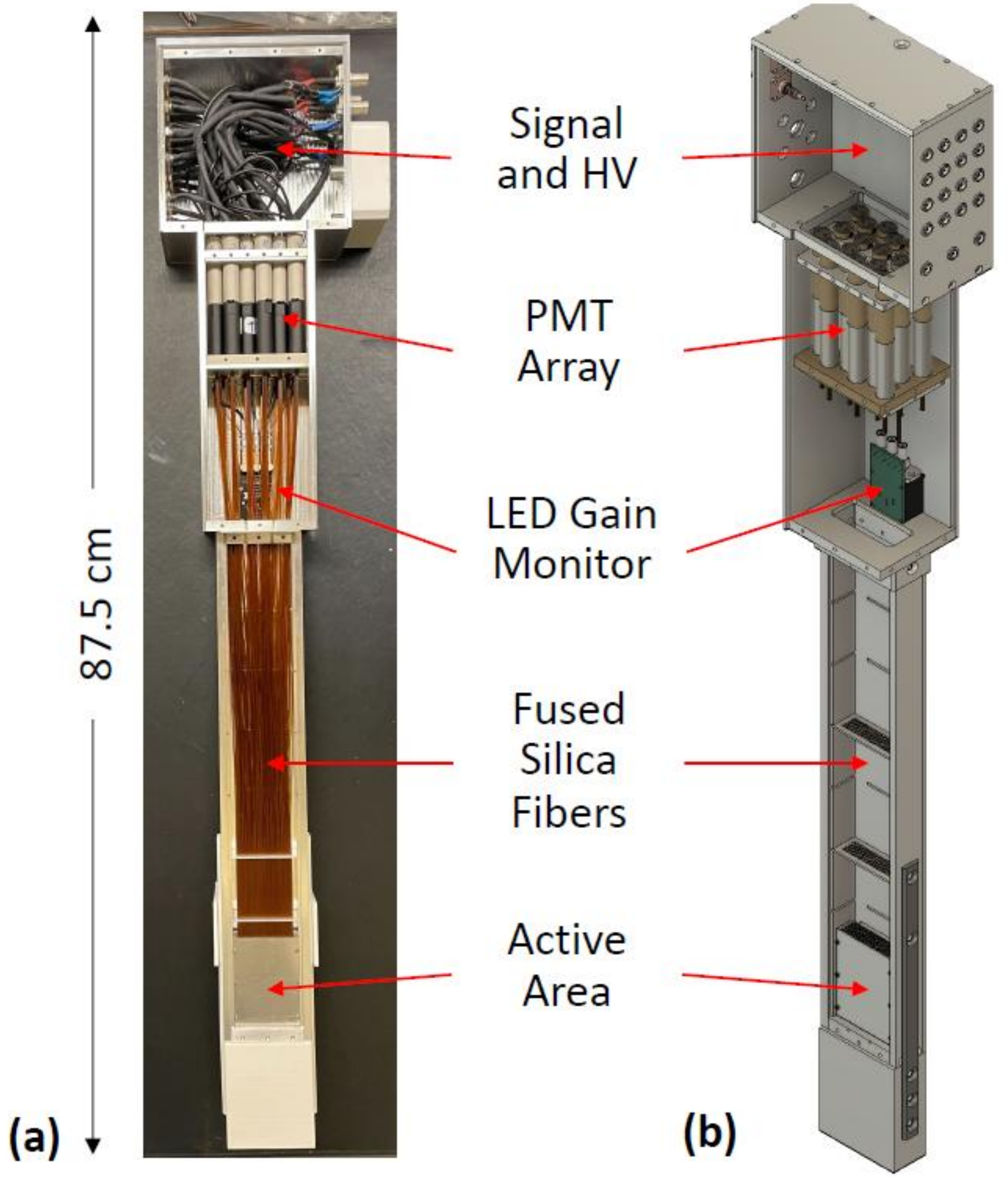
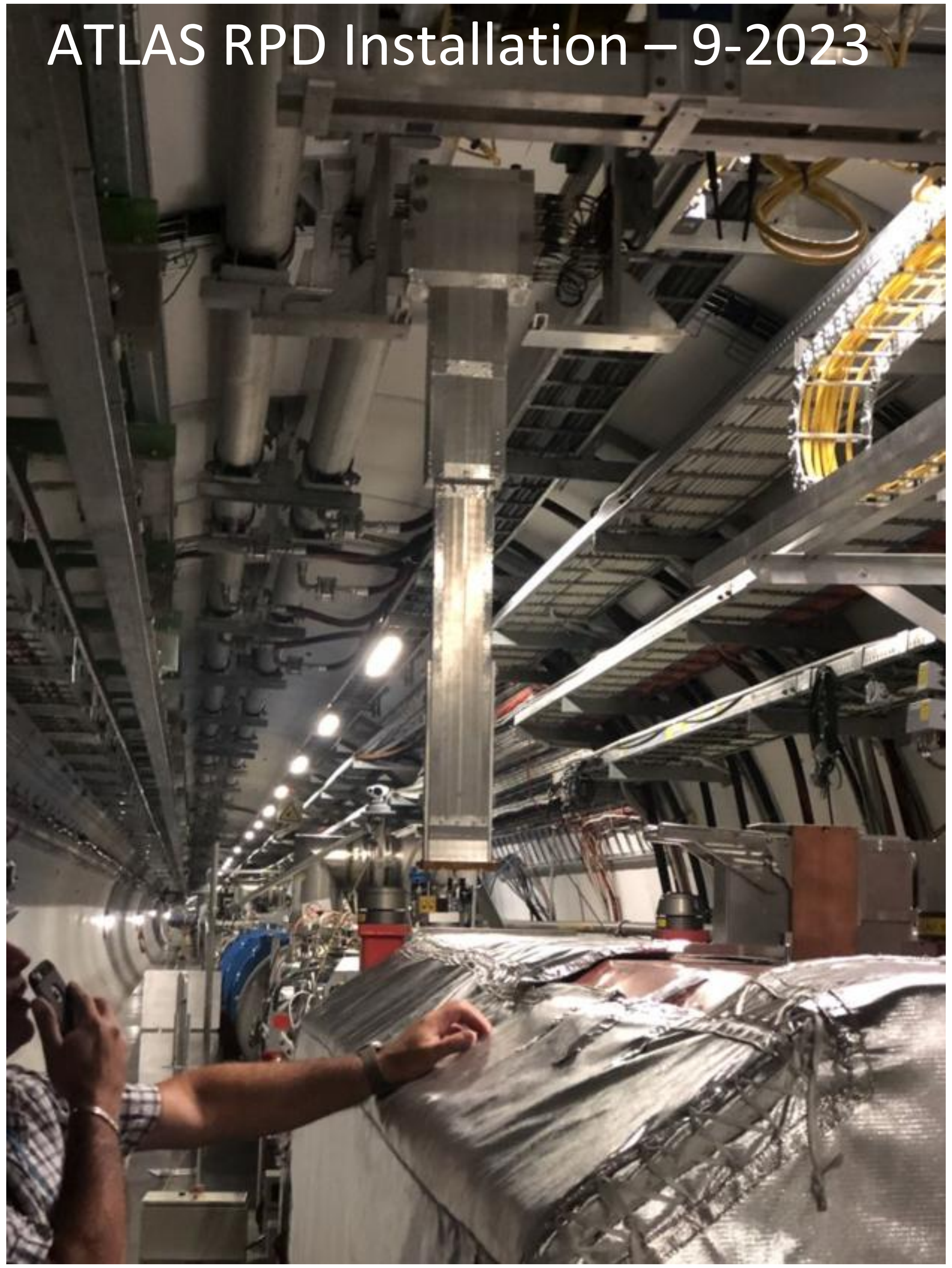


Figure 2.17: Side-by-side diagram of the finalized ATLAS RPD for Run 3 (a) and the corresponding technical drawing (b). Note that the front panel was removed for demonstration. Taken from [39]

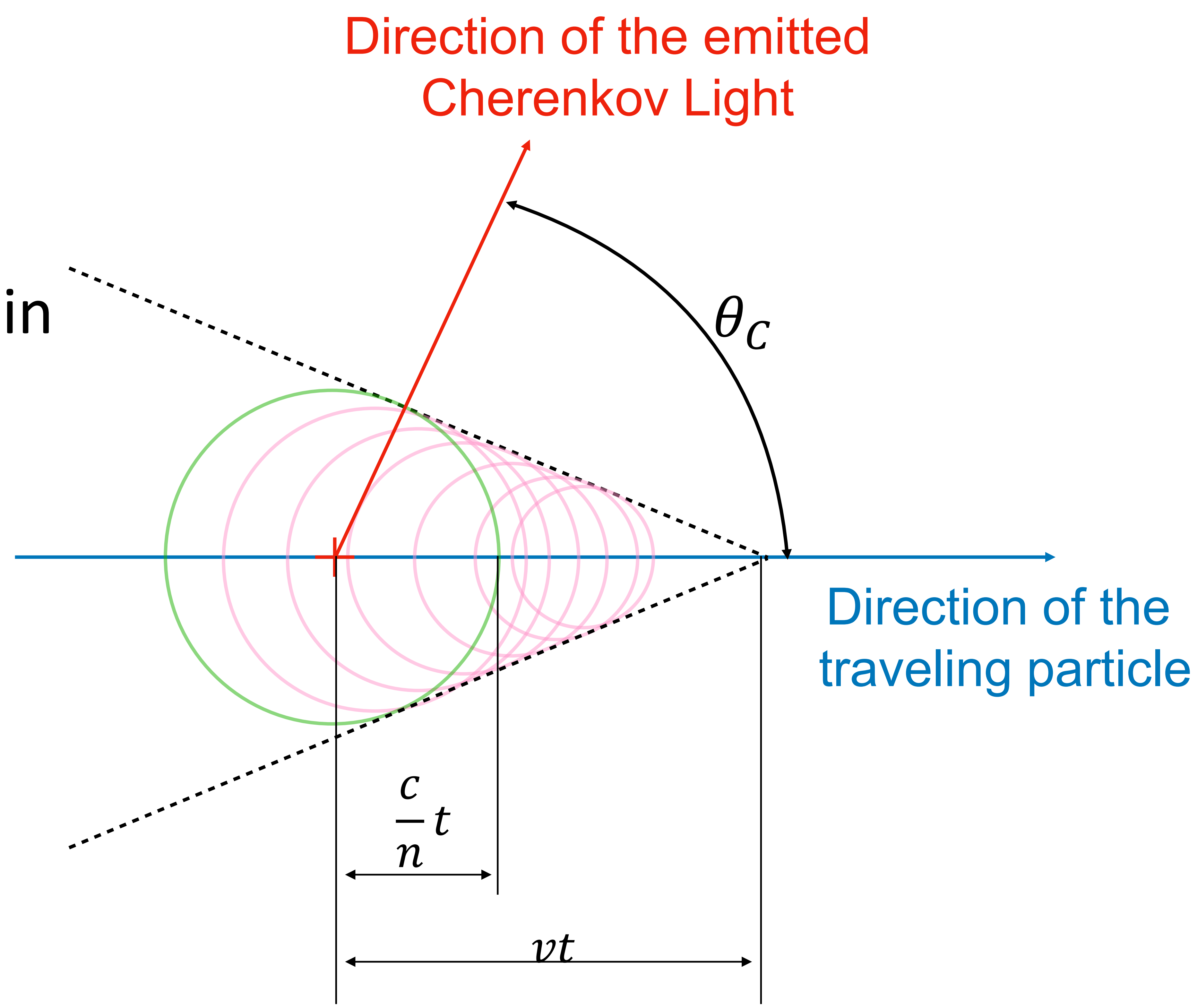


ZDC WORKING PRINCIPLE: CHERENKOV LIGHT

- The ZDCs are tungsten fused-silica **sampling** calorimeters
- W = passive **absorber**; fused-silica = **Cherenkov radiator**

- When a charged particle travels faster than the speed of light in a certain medium (characterized by index of refraction n), it loses energy by **emitting Cherenkov radiation**

Cherenkov light threshold $$v > \frac{c}{n} \rightarrow \frac{v}{c} = \beta > \frac{1}{n}$$



- In a time t, the particle in the medium travels a distance vt, while the light it emits travels a distance ct/n. The wavefronts of the light emitted by such particle form a cone with **half-opening angle** θ_C

$$\theta_C = \arccos(\frac{1}{n\beta})$$

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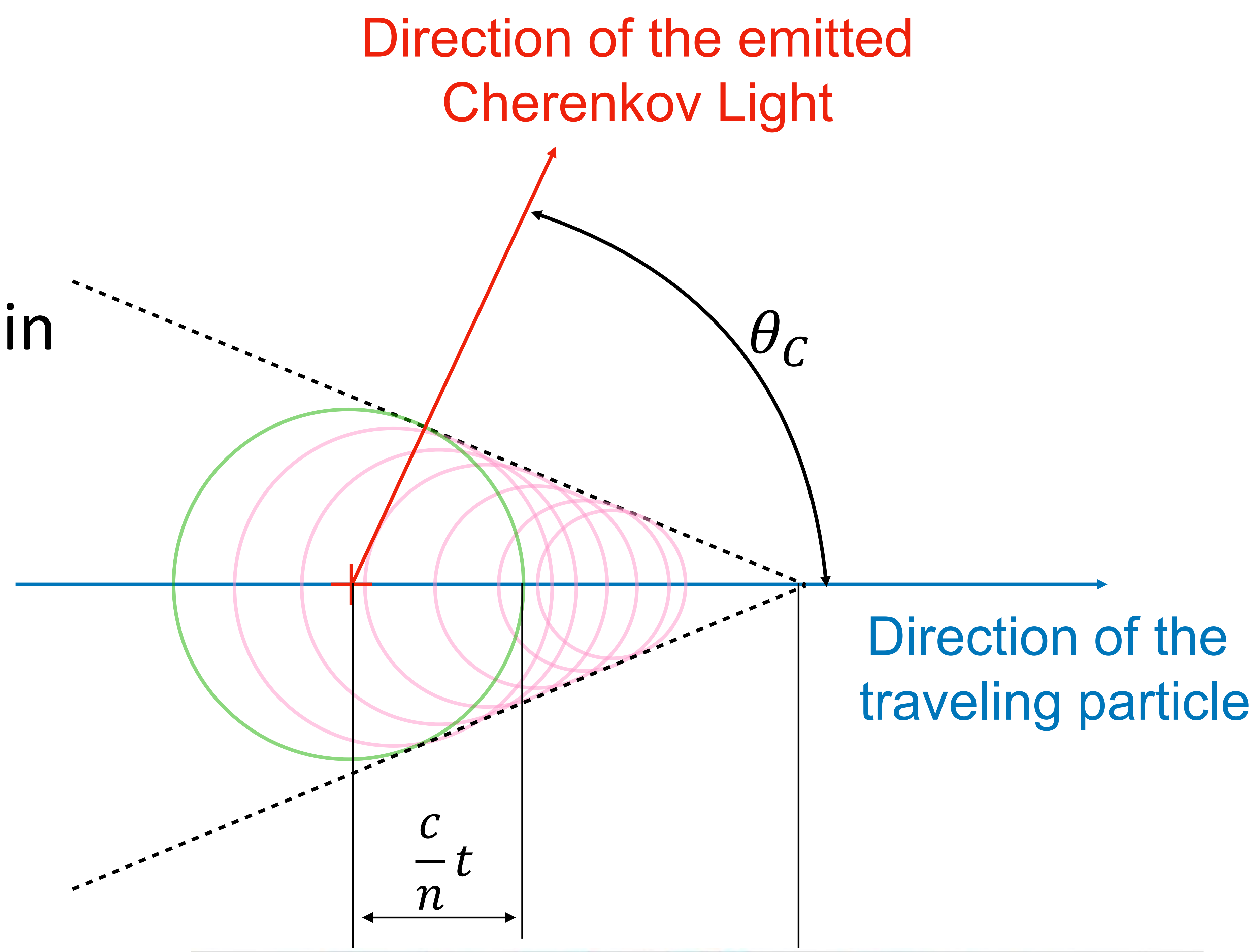
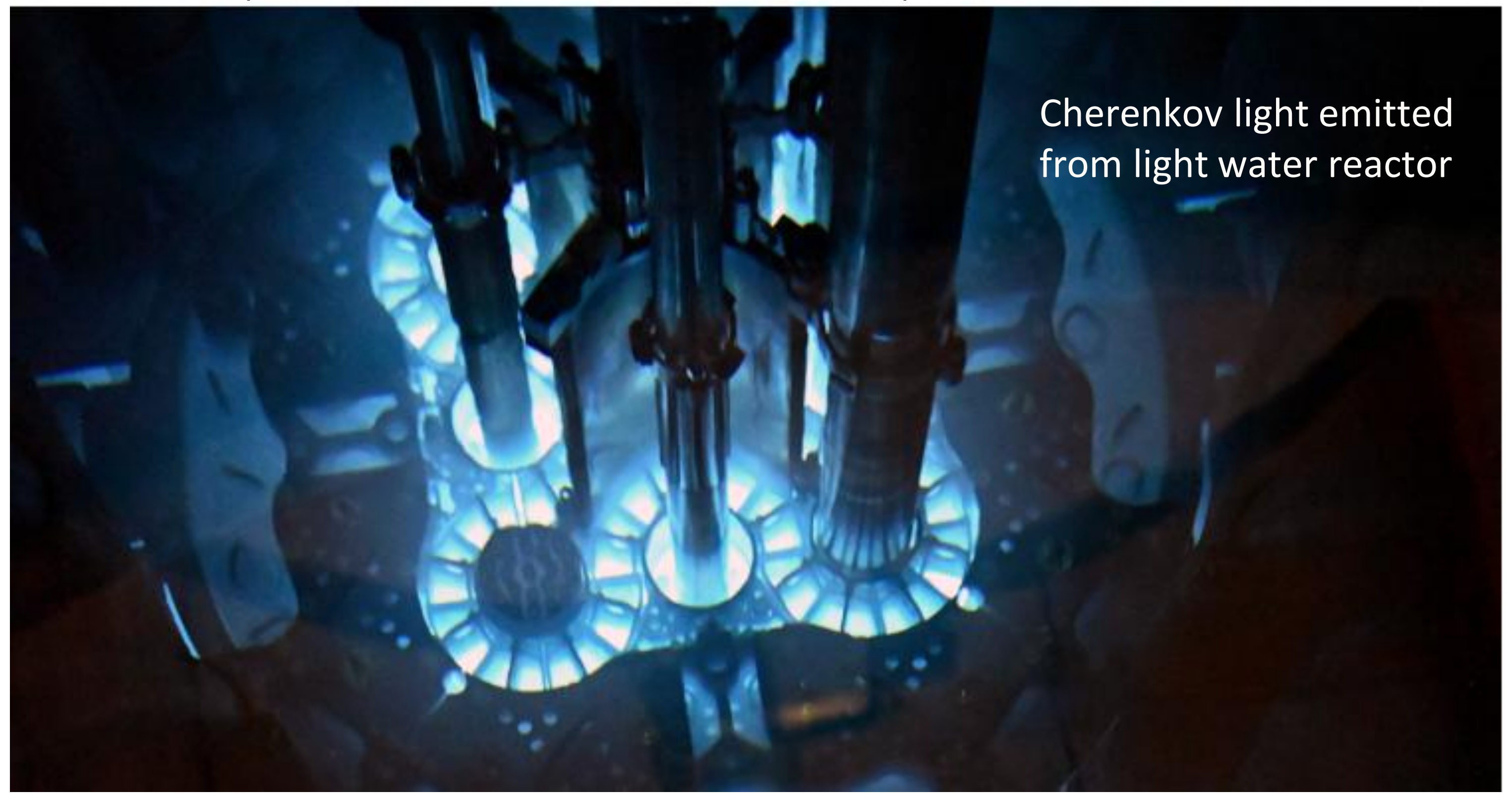
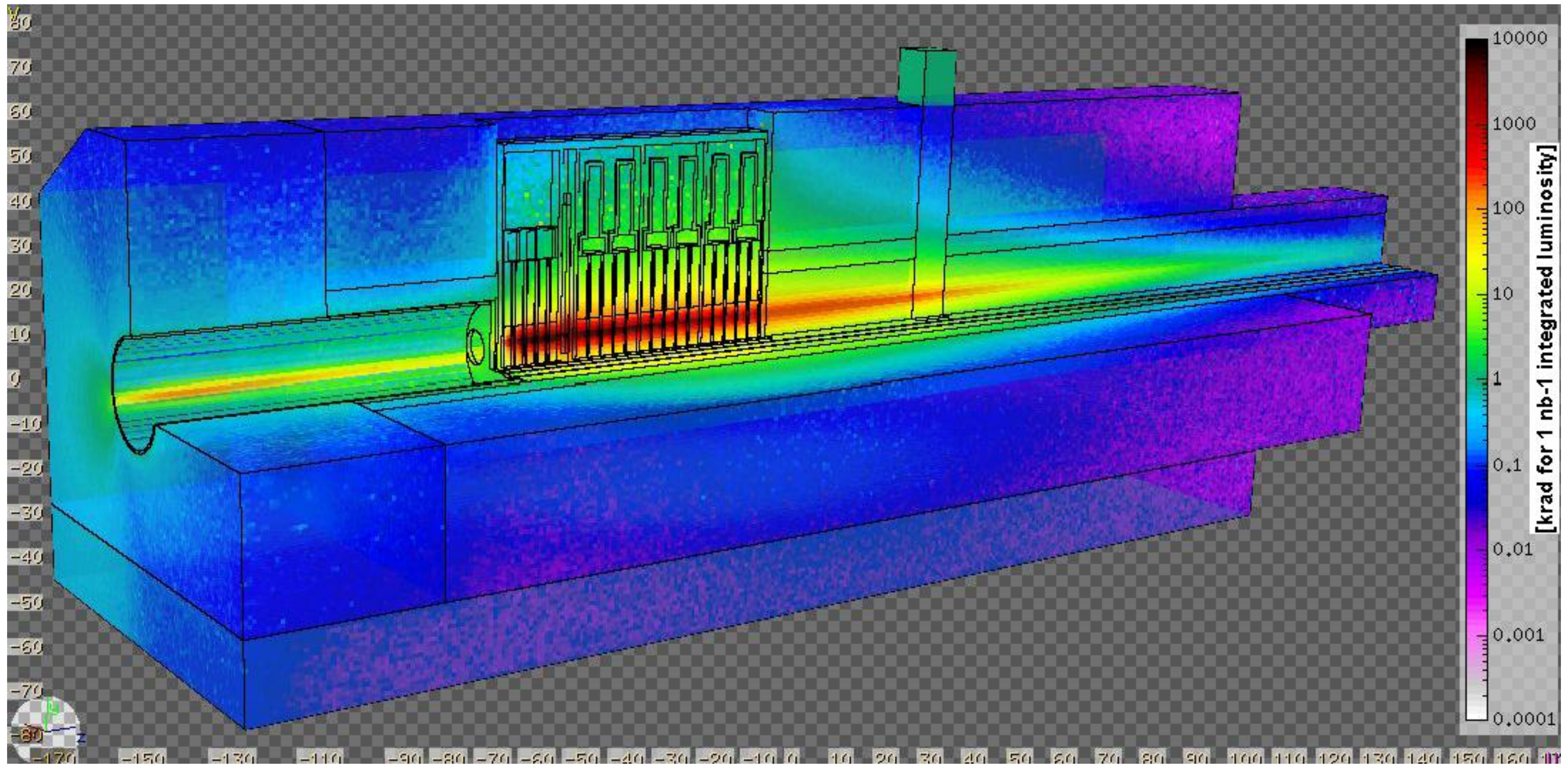
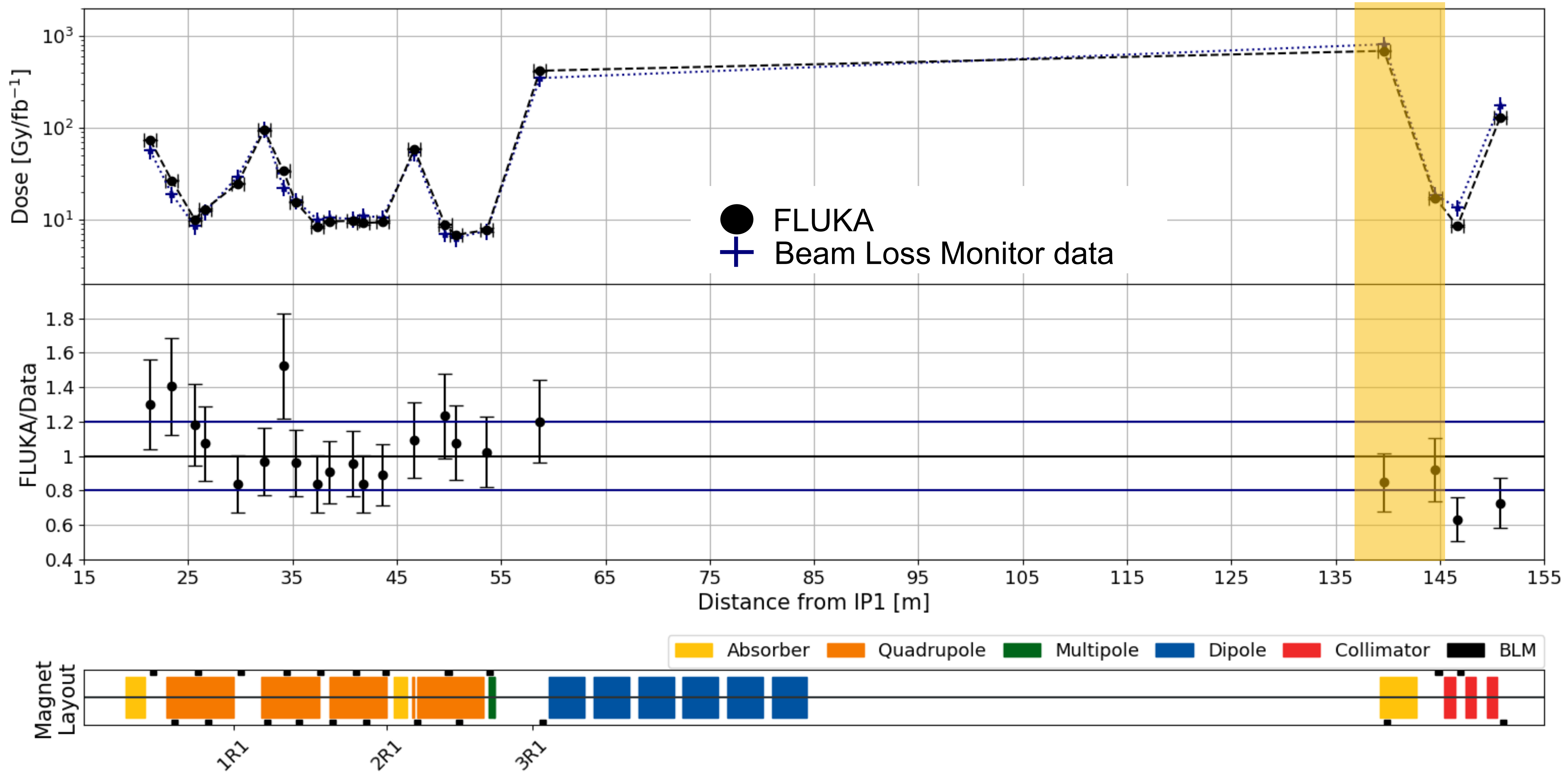




ZDC CHALLENGES: RADIATION





- CERN FLUKA team (F.Cerutti, M.S.Gilarte) provides detailed simulations of the radiation environment in the TAN
- Peak radiation load on the ZDC estimated to be of several **5++ MGy !!!**

To have stable operation - the zdc needs radiation hard materials

[Phys. Rev. Accel. Beams 25, 091001 (2022)], Yang (NPRE grad), Tate (NPRE grad), RL et al

- Benchmark against LHC Beam Loss Monitor data: **FLUKA can describe radiation levels in the LHC tunnel within 20% uncertainty**

RADIATION DAMAGE IN FUSED SILICA

from Sheng Yang's thesis

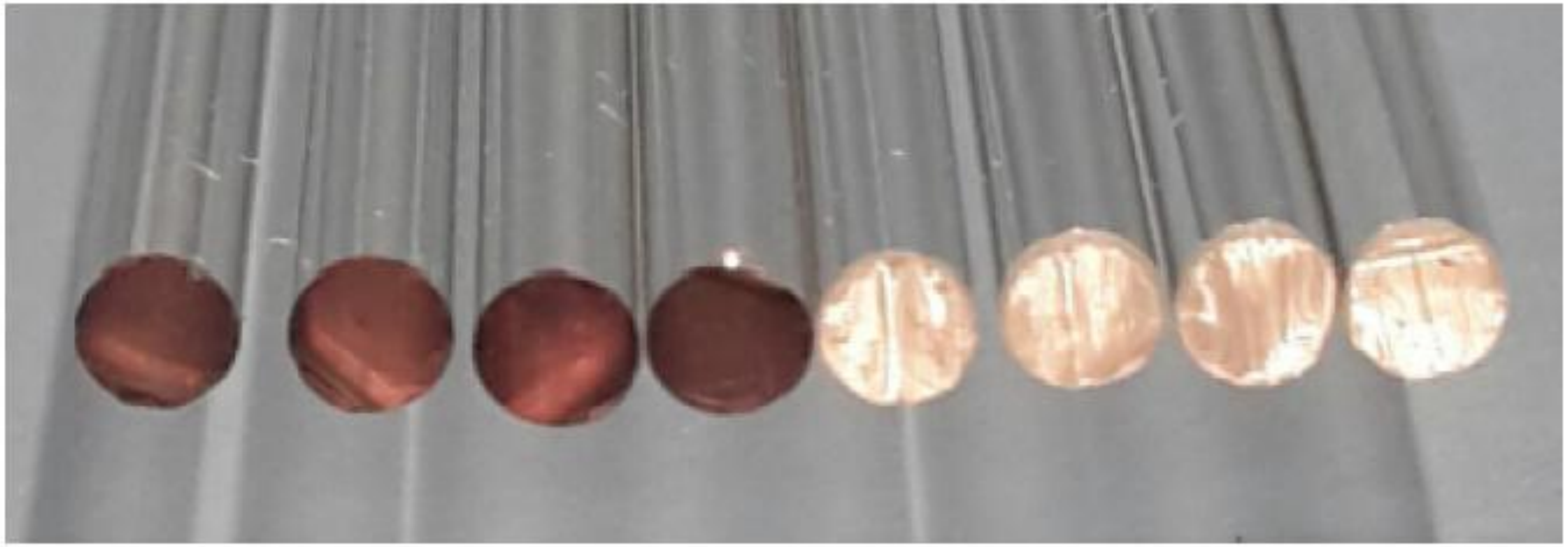
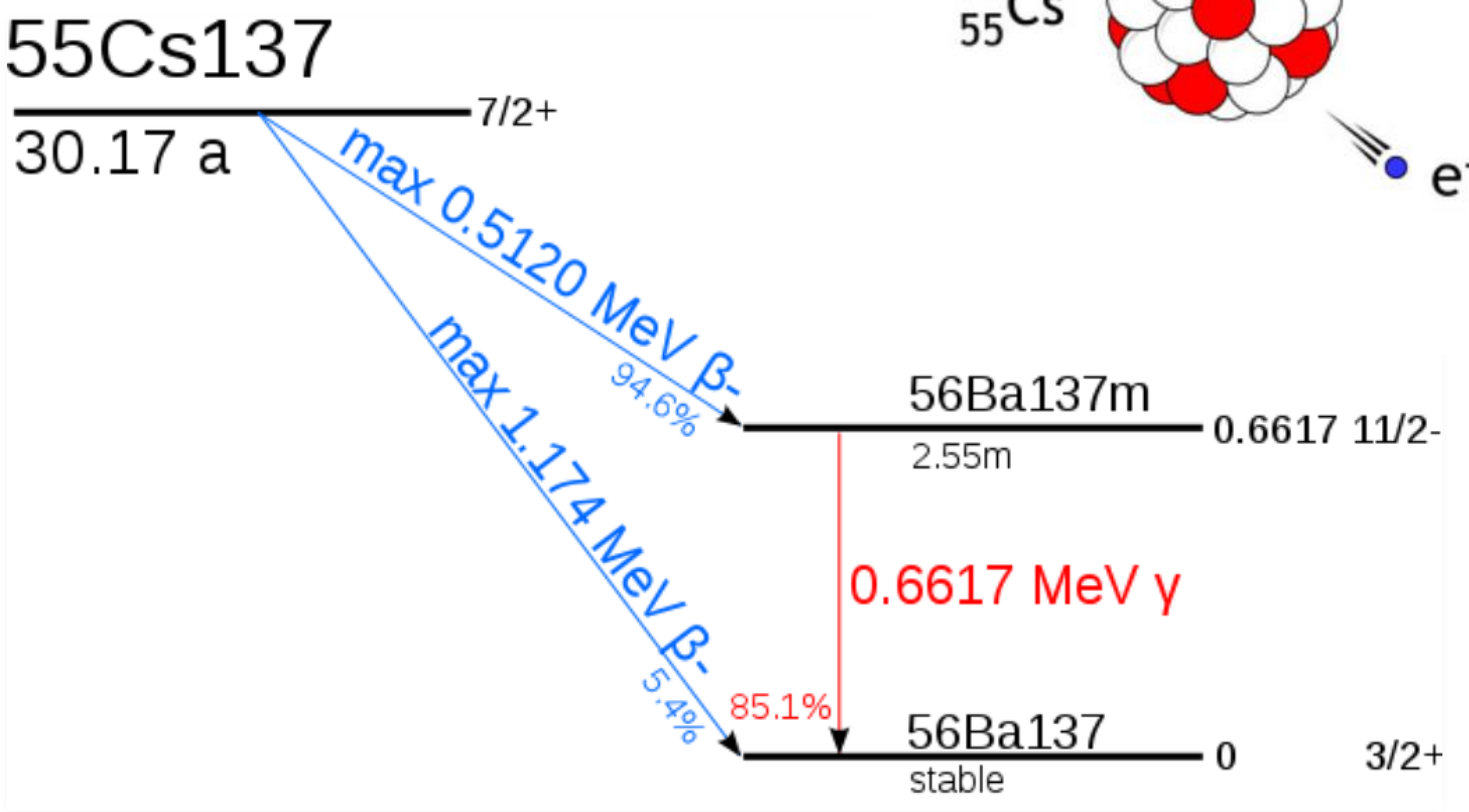
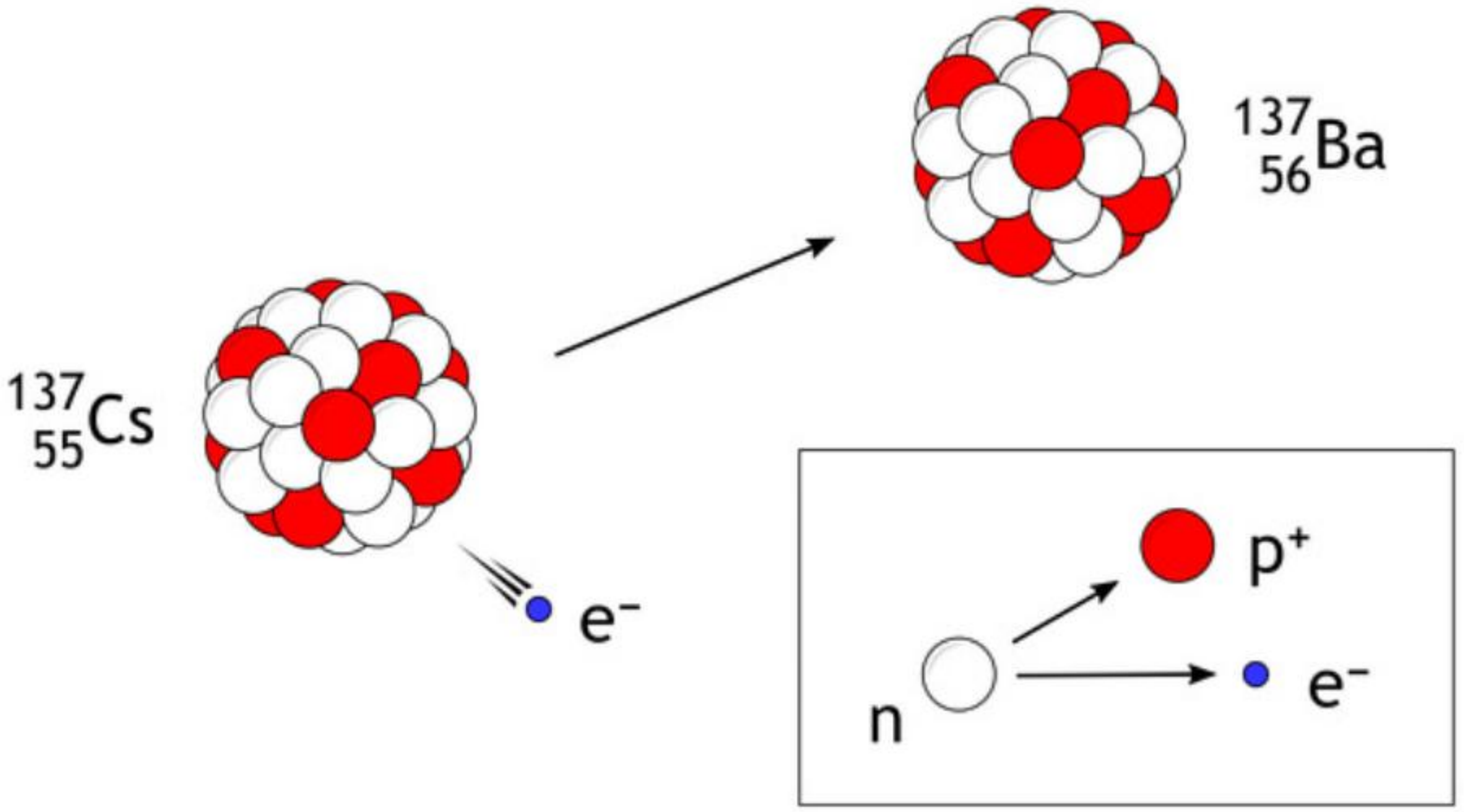


Figure 2.18: Comparison between brand new GE214 [41] fused quartz rods (right) and the same type of rods irradiated in the LHC during Run 1 (∼ 10 MGy, left).

COMPARE TO TYPICAL SOURCE FOR DETECTOR CALIBRATION – CS-137

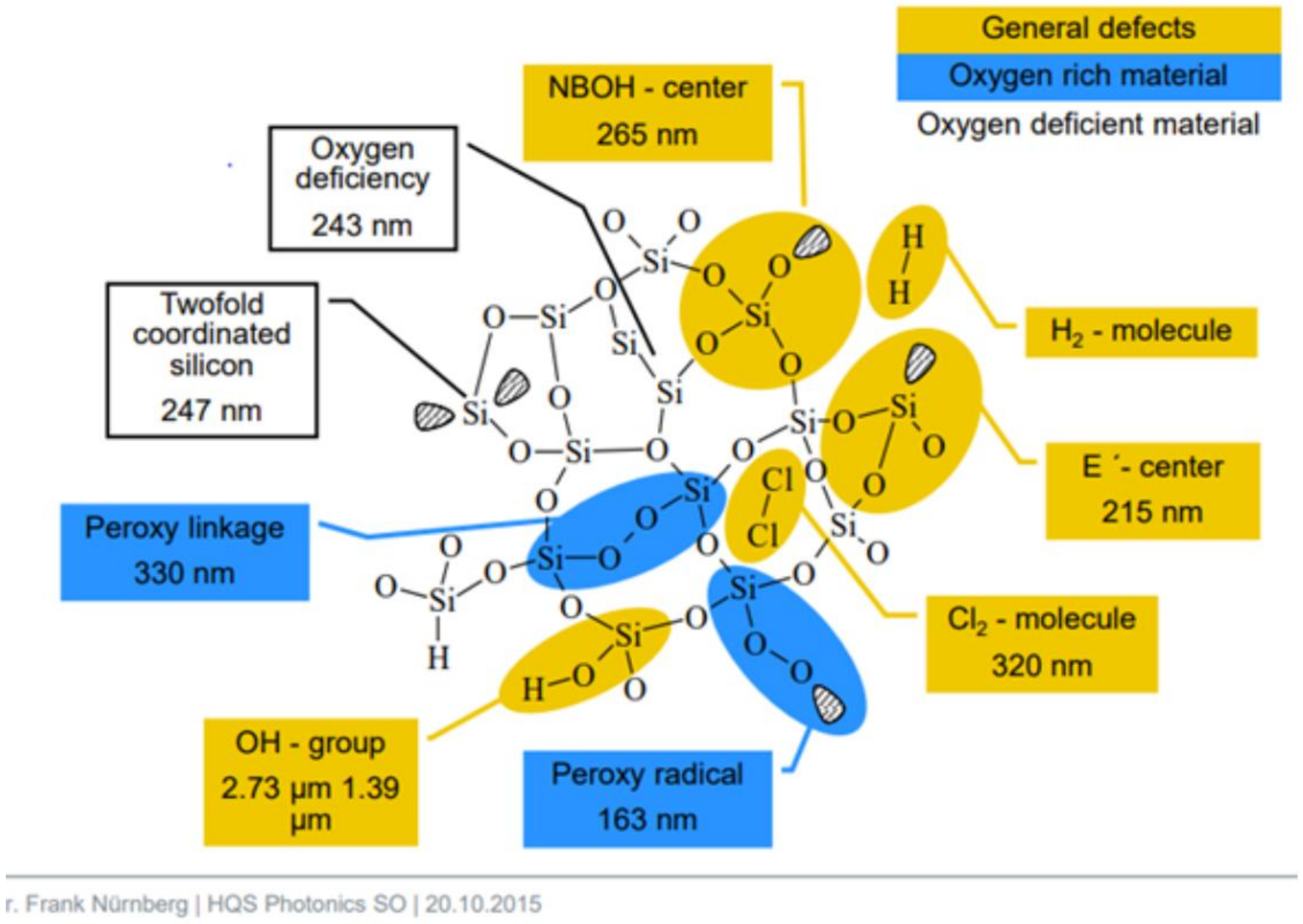




Source ~ 0.00006 Gy/h

ZDC ~ Run-1 4,000 Gy/h
Run-4 120,000 Gy/h (lethal does, LD50, is ~ 5 Gy)

RADIATION DAMAGE IN FUSED SILICA



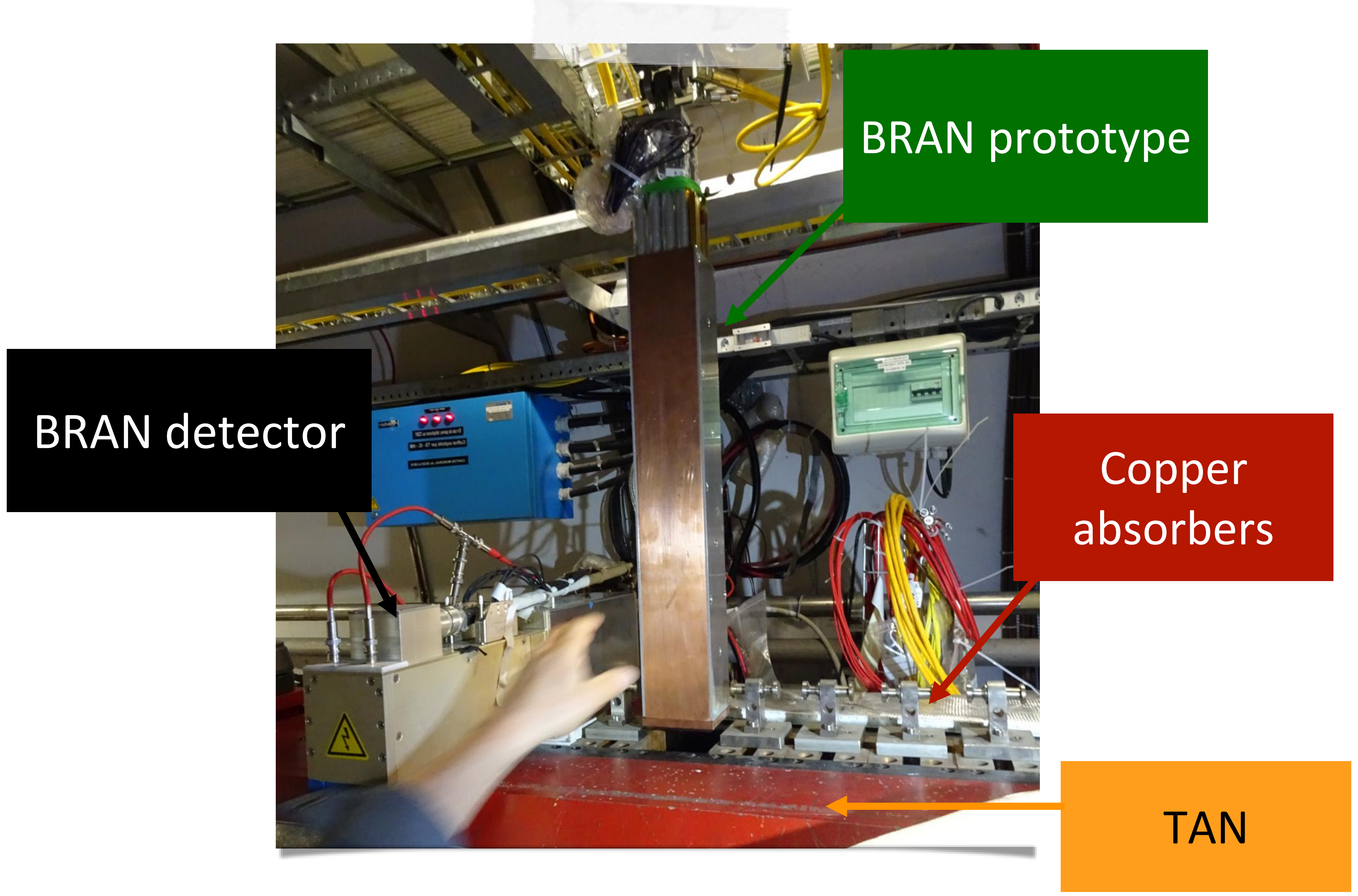
Schematics showing known defects to SiO4 tetrahedral characteristics (courtesy of Frank Nuernberg [Heraeus])

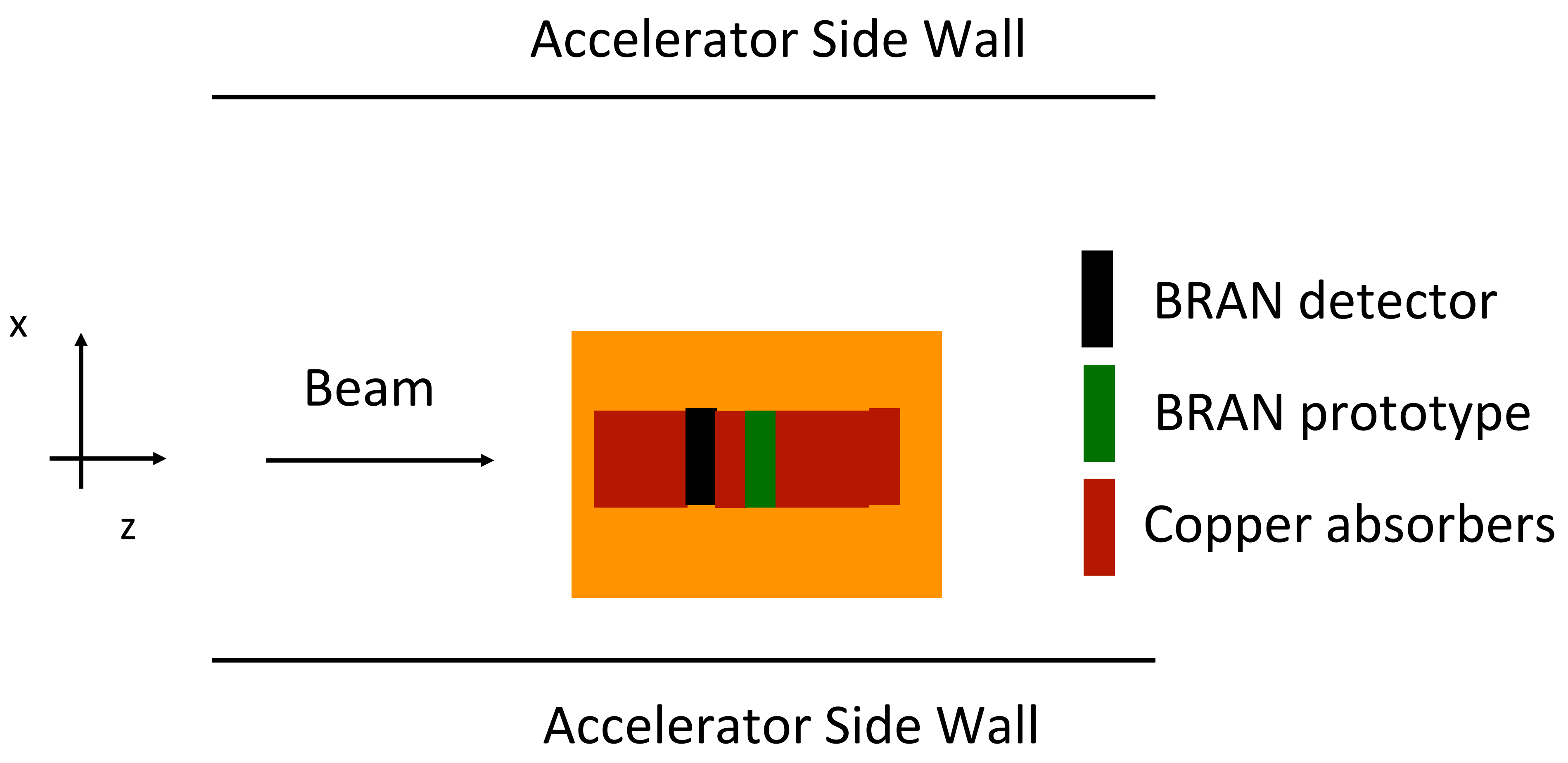
- Increasing number of defects and color centers induced by radiation damage decreases the transmission
- Materials with a high purity level show a lower absorption and a better radiation hardness.
- In the UV region:
  - Saturation of absorbing defects by H_2
  - Decrease in transmittance more pronounced/rapid
- Our results represent the first study of radiation hardness of fused silica exposed to **high energy hadron cocktail**

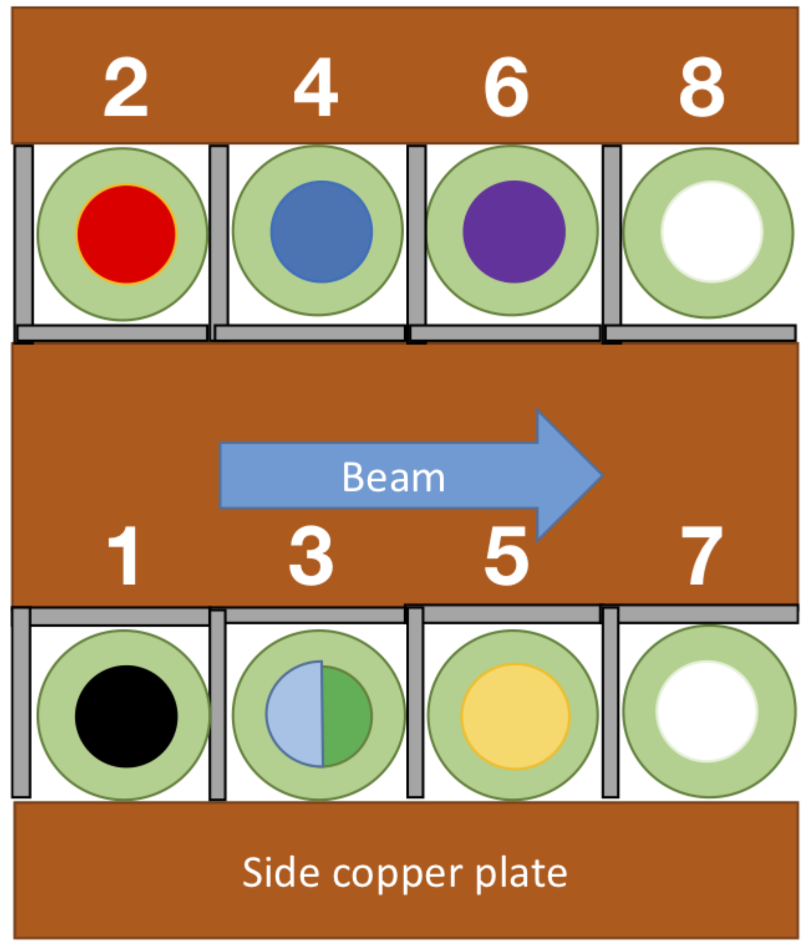
IRRADIATION OF FUSED SILICA MATERIALS

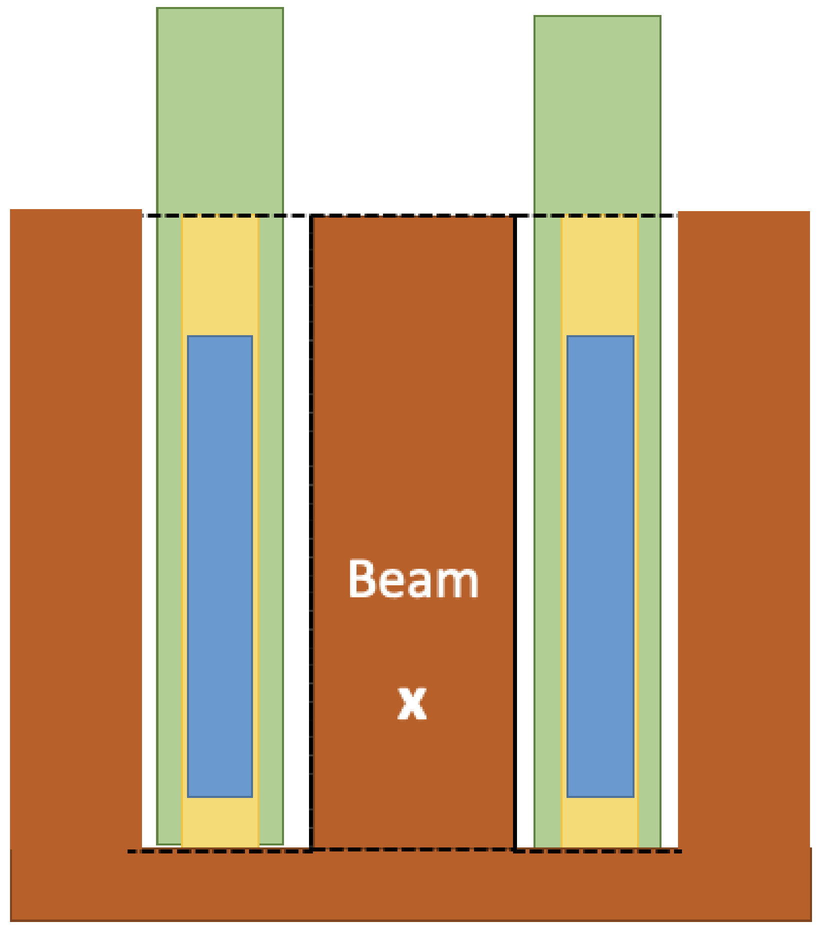
- **Fused silica rods irradiated over 3 years (2016-2018) in the TAN (IP1), in a BRAN detector prototype**
  - Installed in addition to the **actual BRAN detector** (ion chamber) for p+p running only
    - During HI the ZDC replaces the copper bars
  - Equipped w/ **different fused silica materials**

Collaboration with Heraeus





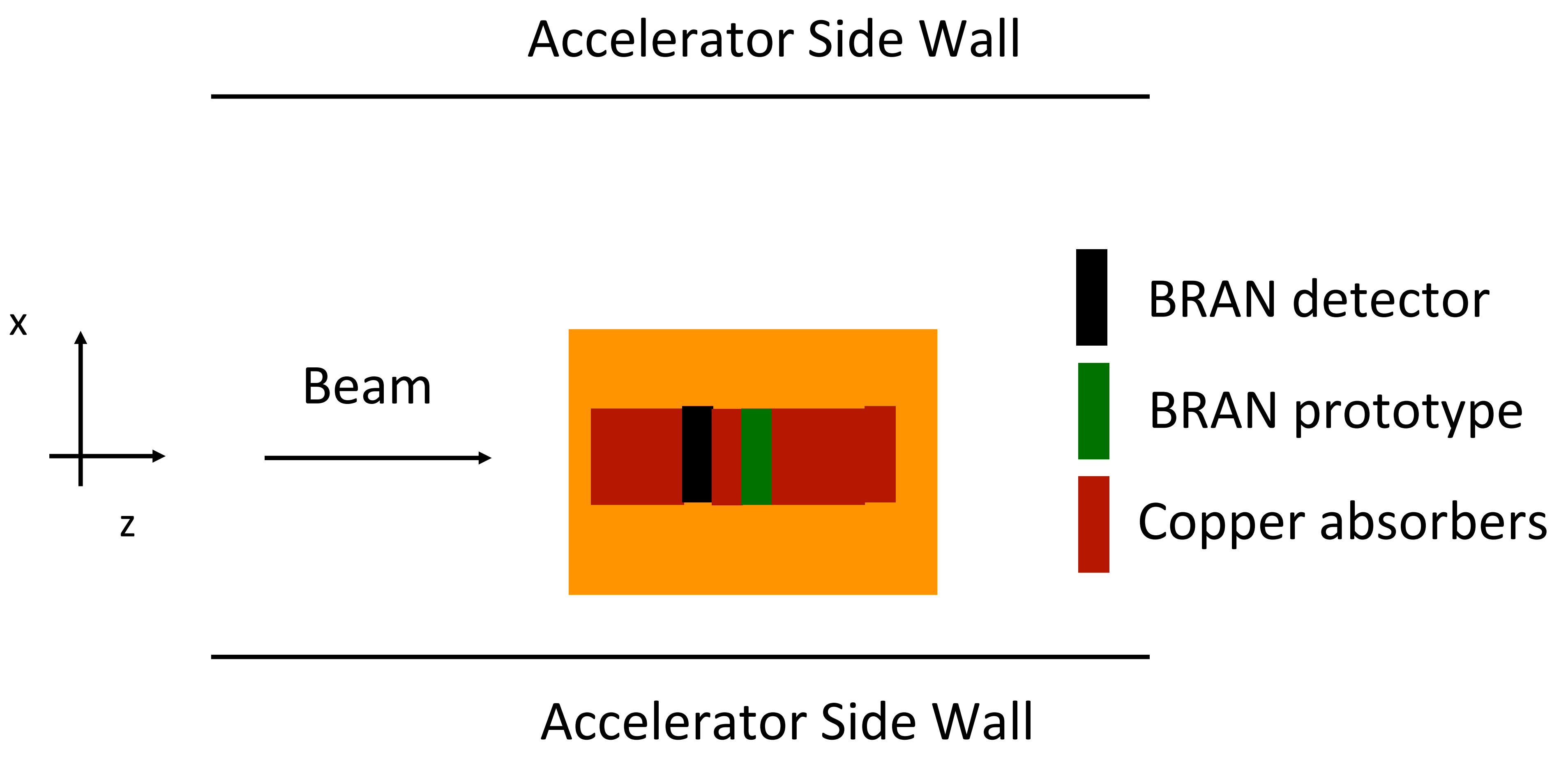


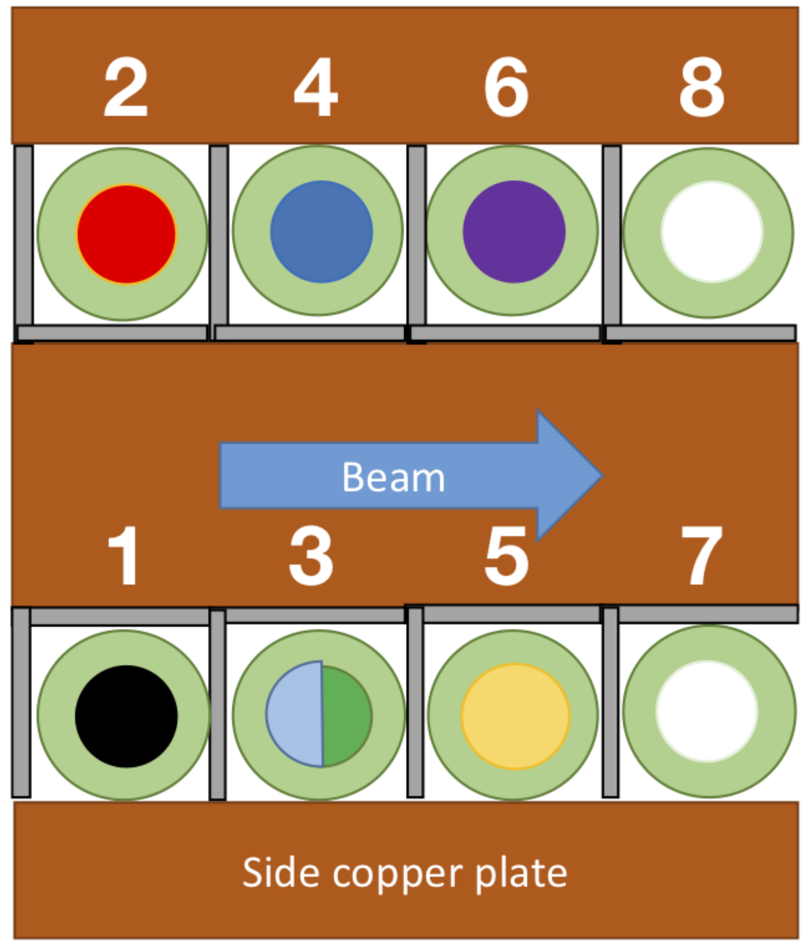


IRRADIATION OF FUSED SILICA MATERIALS

- **Fused silica rods irradiated over 3 years (2016-2018) in the TAN (IP1), in a BRAN detector prototype**
  - Installed in addition to the **actual BRAN detector** (ion chamber) for p+p running only
    - During HI the ZDC replaces the copper bars
  - Equipped w/ **different fused silica materials**

Collaboration with Heraeus

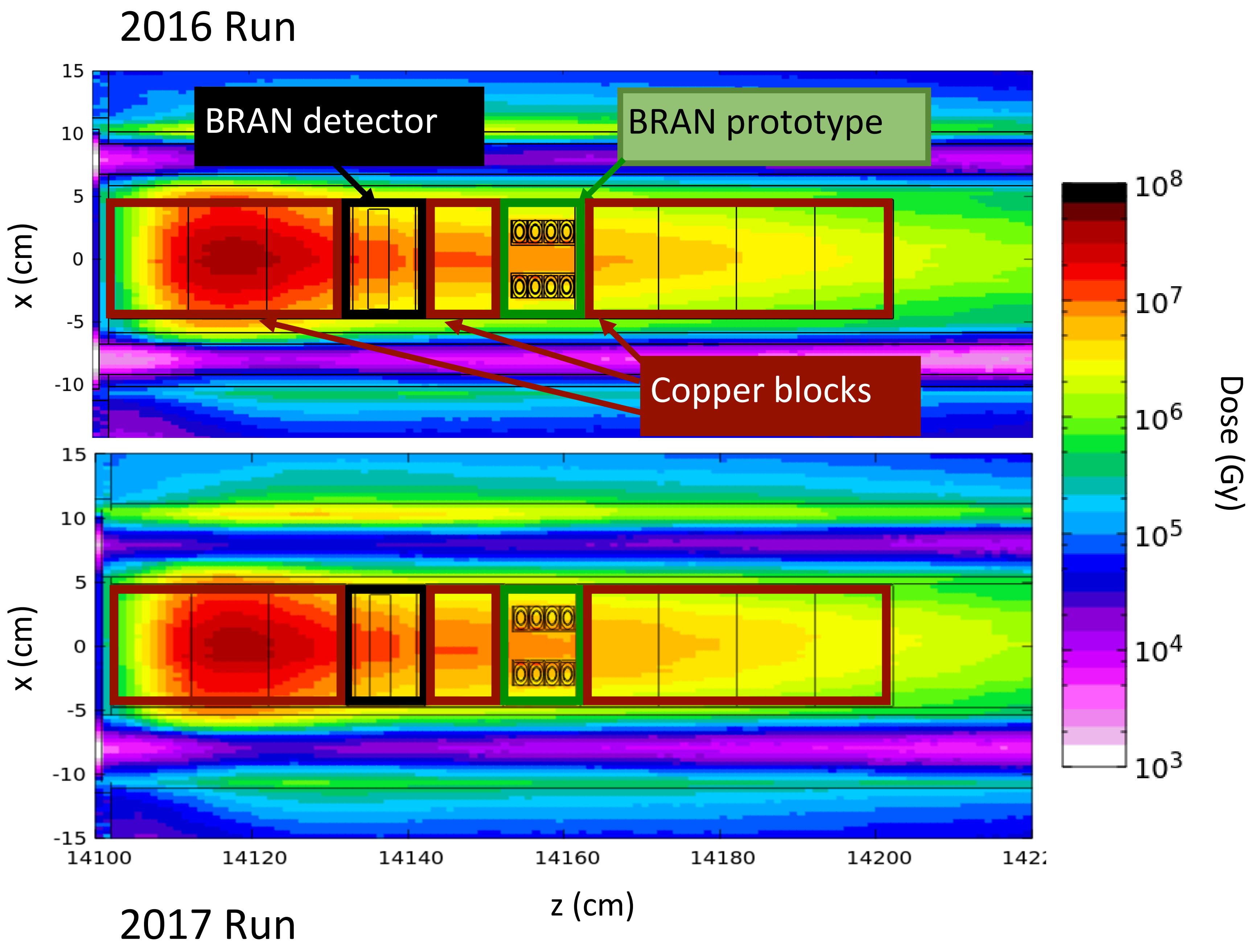


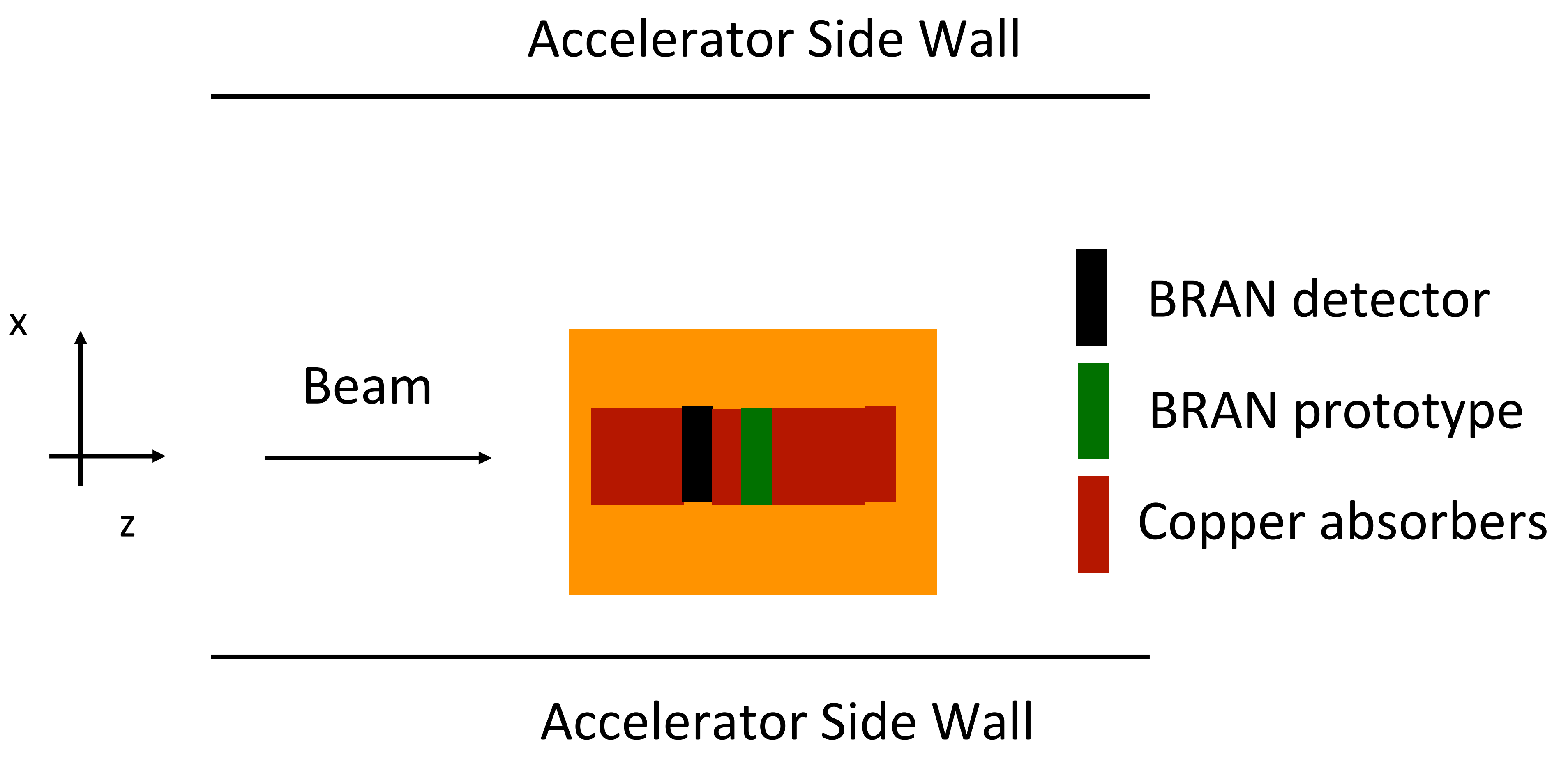


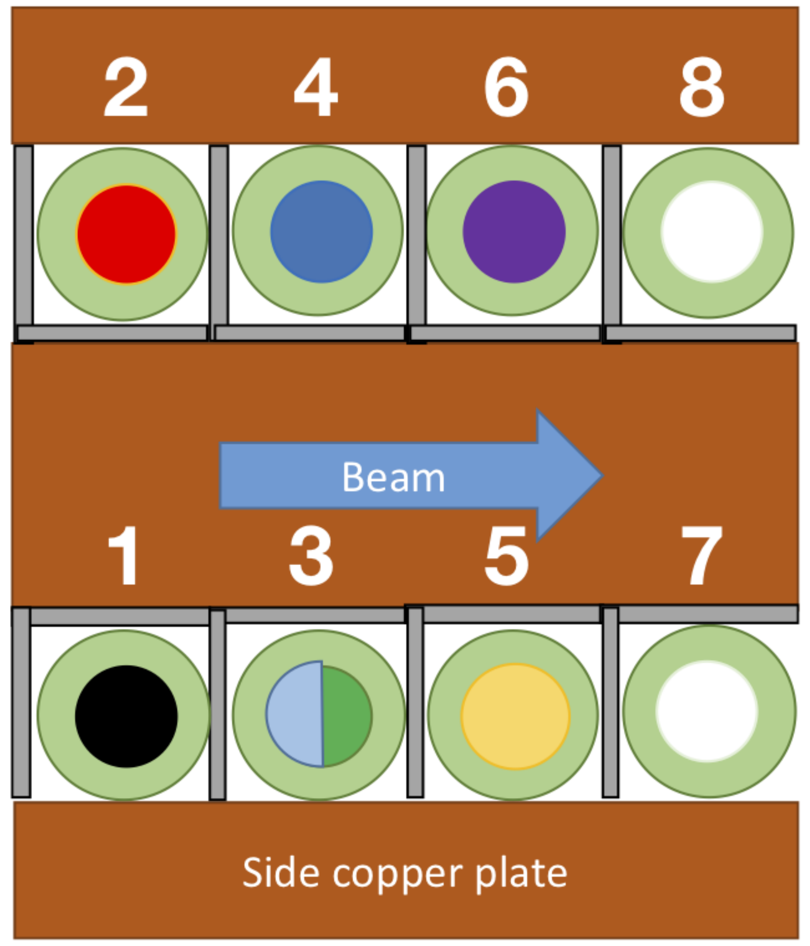
Bran Position	Irradiation Period	Max. Dose (MGy)	Material
Control	None	0	Spectrosil 2000 (High OH, Mid H_2)
1	04/2016 - 12/2018	18	Spectrosil 2000 (High OH, Mid H_2)
2	04/2016 - 12/2017	10	Spectrosil 2000 (High OH, Mid H_2)
3a	04/2016 - 12/2016	5	Spectrosil 2000 (High OH, High H_2)
3b	04/2017 - 12/2018	16	Spectrosil 2000 (High OH, Mid H_2)
4	04/2016 - 12/2017	9	Spectrosil 2000 (High OH, H_2 free)
5	04/2016- 12/2017	8	Suprasil 3301 (Low OH, High H_2)
6	04/2016 - 12/2018	17	Suprasil 3301 (Low OH, H_2 free)

ANALYSIS OF IRRADIATED SAMPLES

- **Detailed FLUKA simulations of the TAN allow for precise evaluation of dose deposited in the fused silica rods**
  - ➞Possibility to determine the dose received by each rod segment







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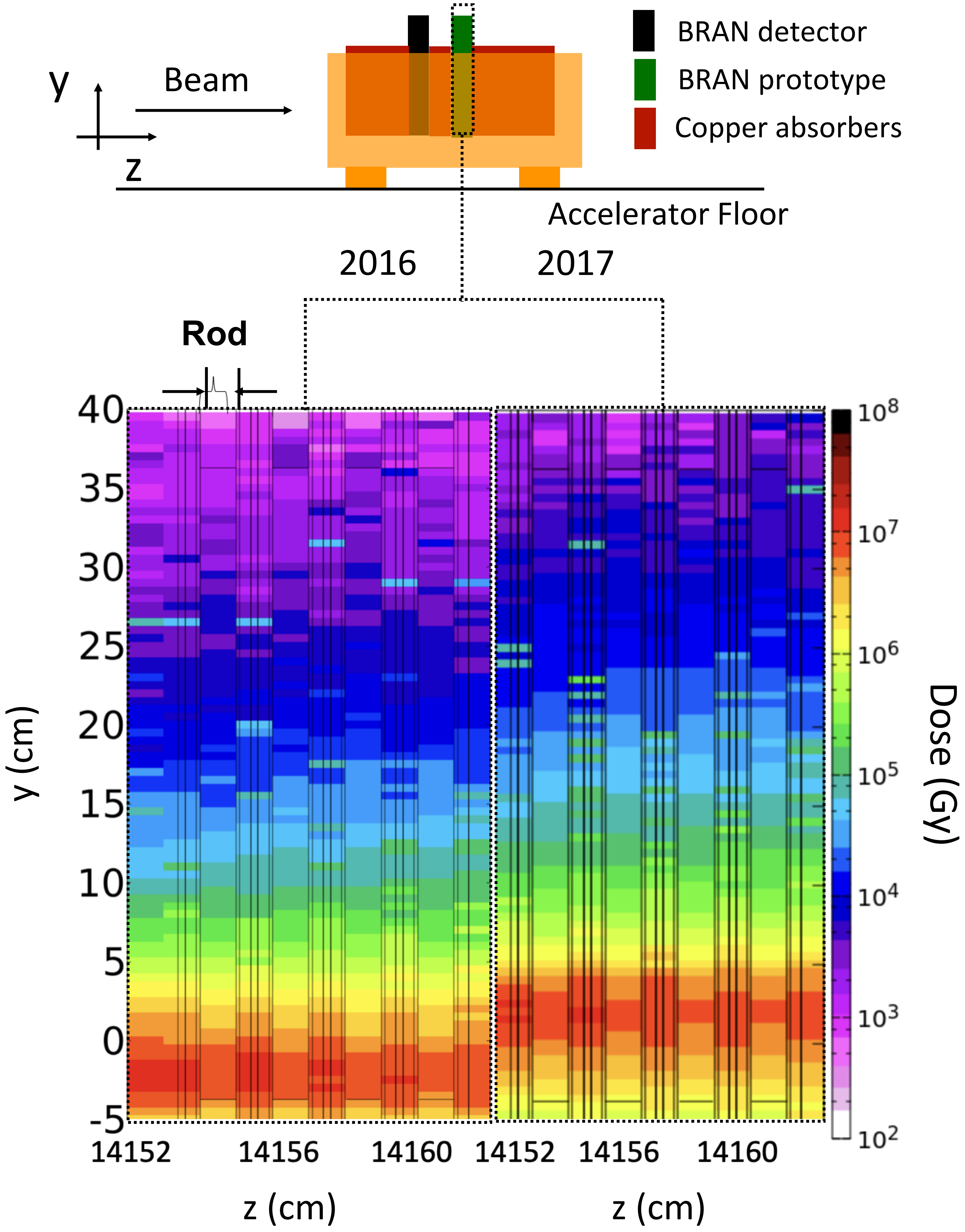
ANALYSIS OF IRRADIATED SAMPLES

- The TAN is characterized by a **steep dose profile in the vertical direction**
  - ➞BRAN rods received dose spanning **over four orders of magnitude**
- Simulation of the **whole particle propagation from the interaction point to the TAN**
  - ➞Beam configuration reproduced for every year of running - crucial input to describe the dose profile along the rods



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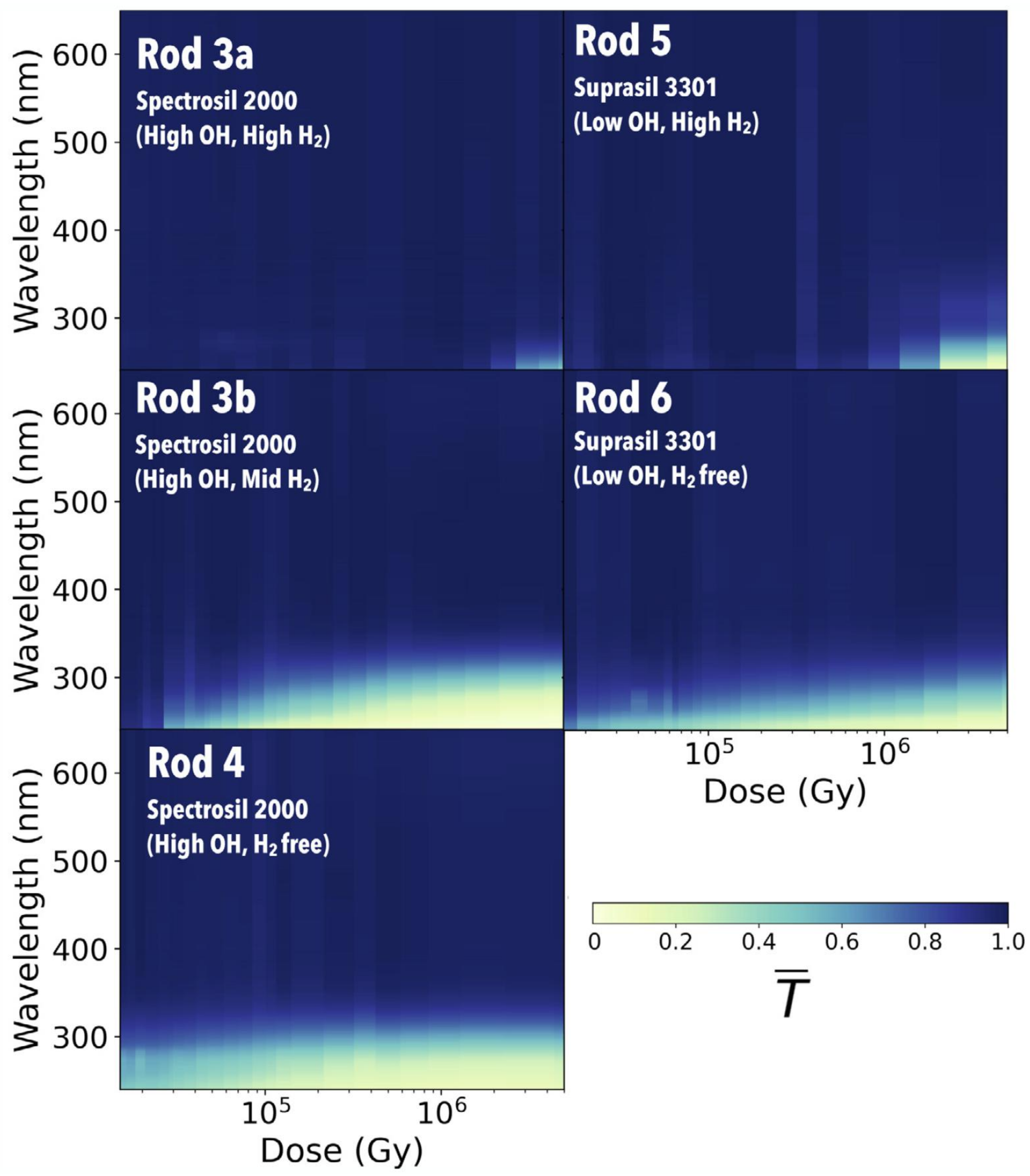
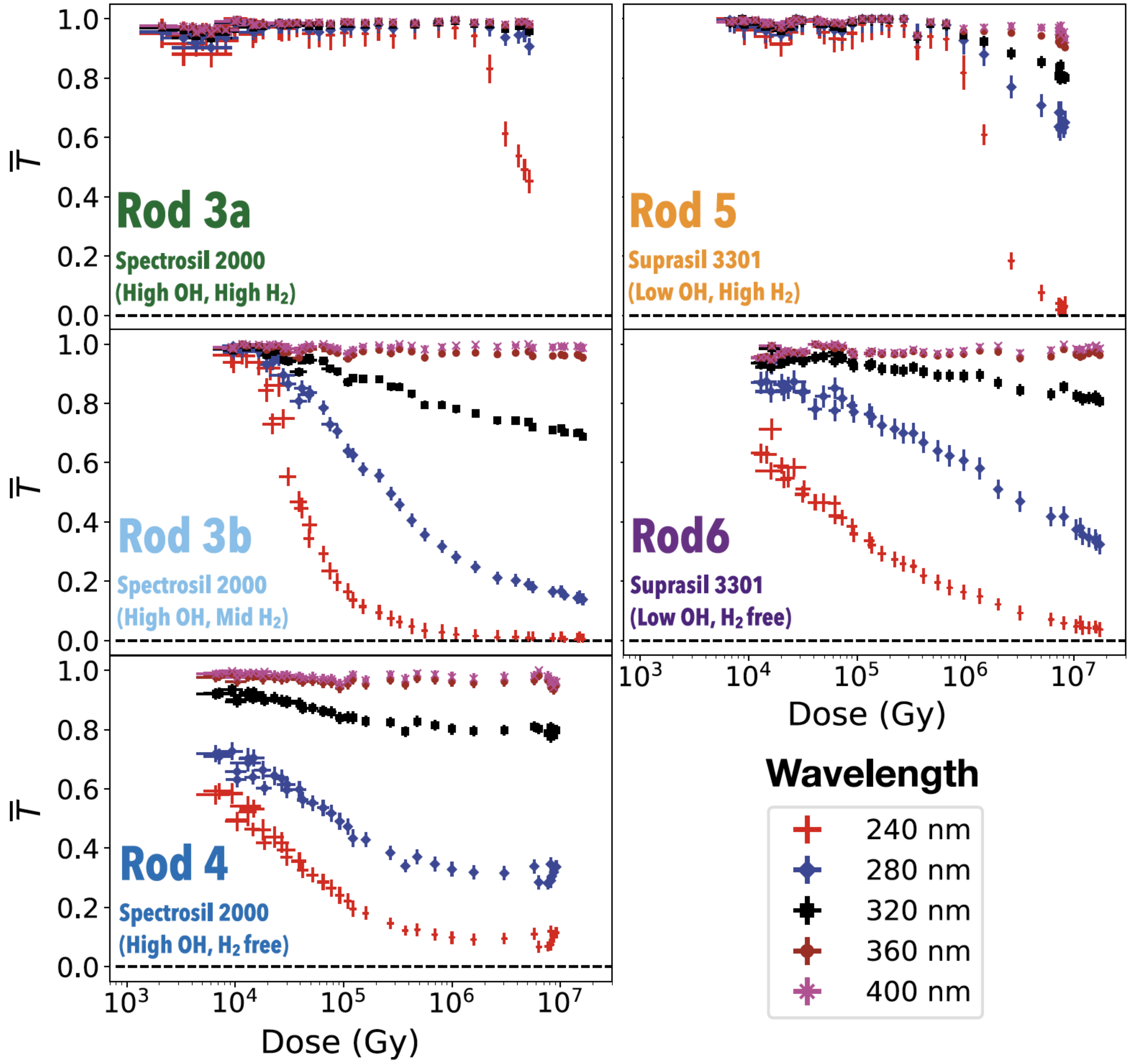
RAD-HARD FUSED SILICA MATERIALS: RESULTS



[*Nuclear Inst. and Methods in Physics Research, A 1055 (2023) 168523, S.Yang, A.Tate, RL et al.*]

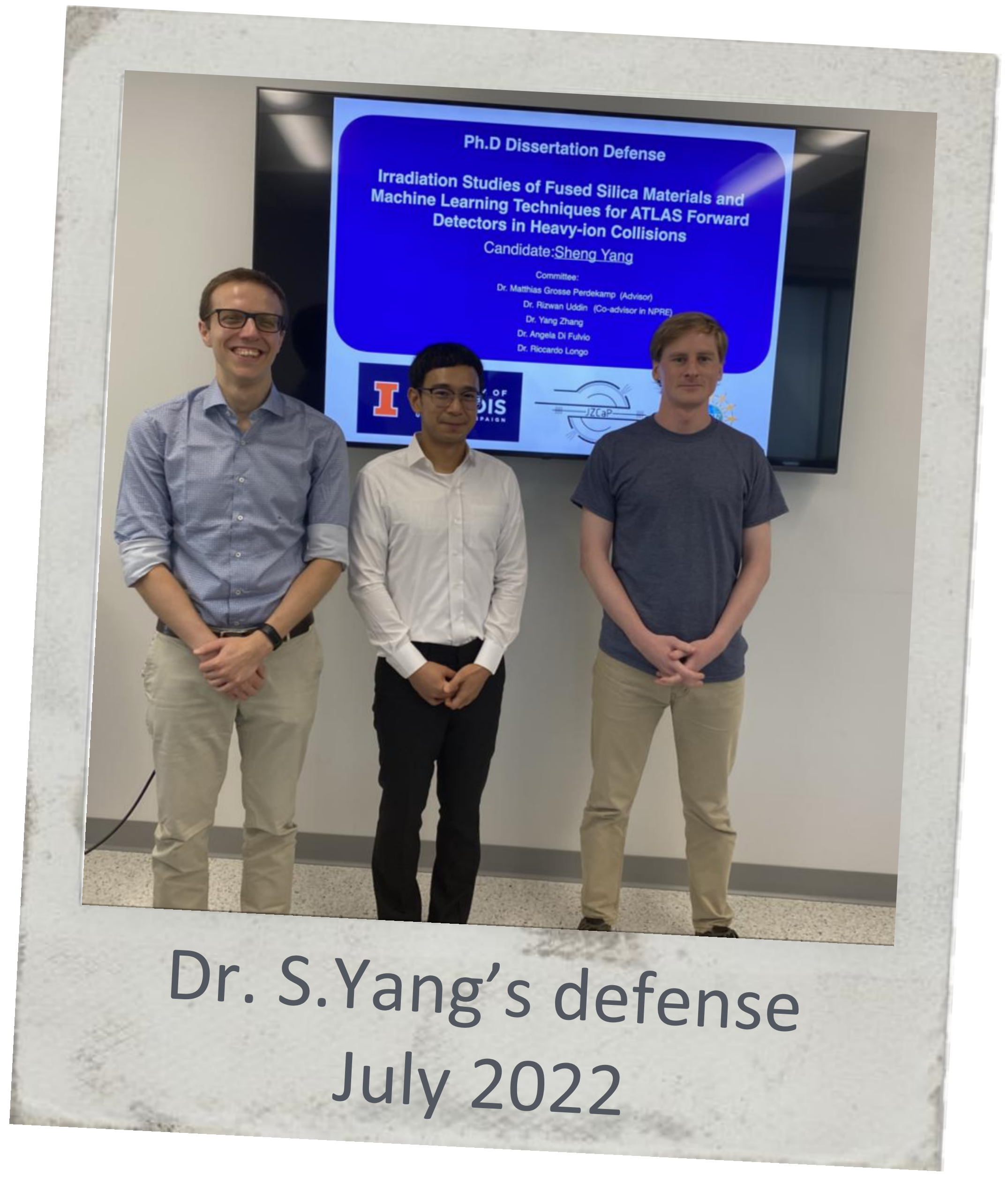
- Unprecedented characterization of fused silica transmittance as a **function of irradiation, wavelength and material composition**
- Samples irradiated up to several MGy

RAD-HARD FUSED SILICA MATERIALS: RESULTS



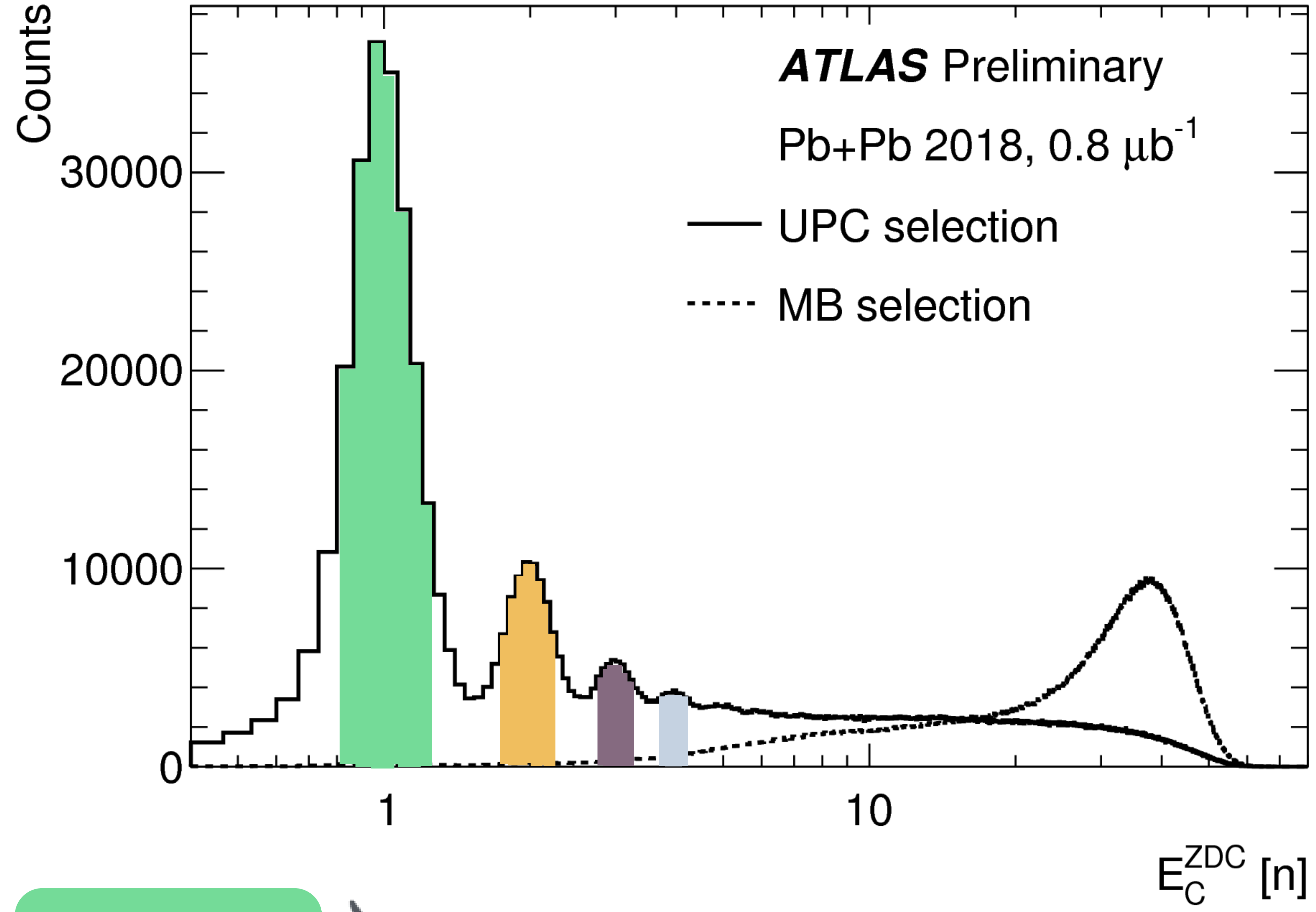
[Nuclear Inst. and Methods in Physics Research, A 1055 (2023) 168523, S.Yang, A.Tate, RL et al.]

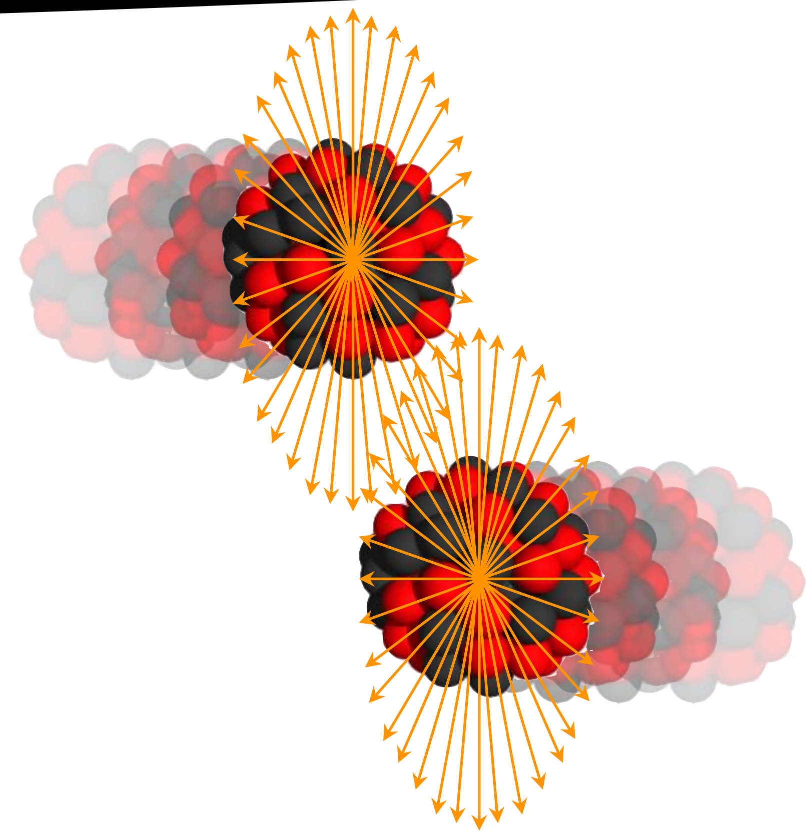
- Unprecedented characterization of fused silica transmittance as a **function of irradiation, wavelength and material composition**
- Samples irradiated up to several MGy
- **Remarkable radiation hardness of high-H2 load Spectrosil 2000** (very little damage up to the MGy scale)
- Interesting **plateau for H2-free materials** after initial fast damage



Dr. S.Yang's defense
July 2022

ZDC DATA DRIVEN CALIBRATION



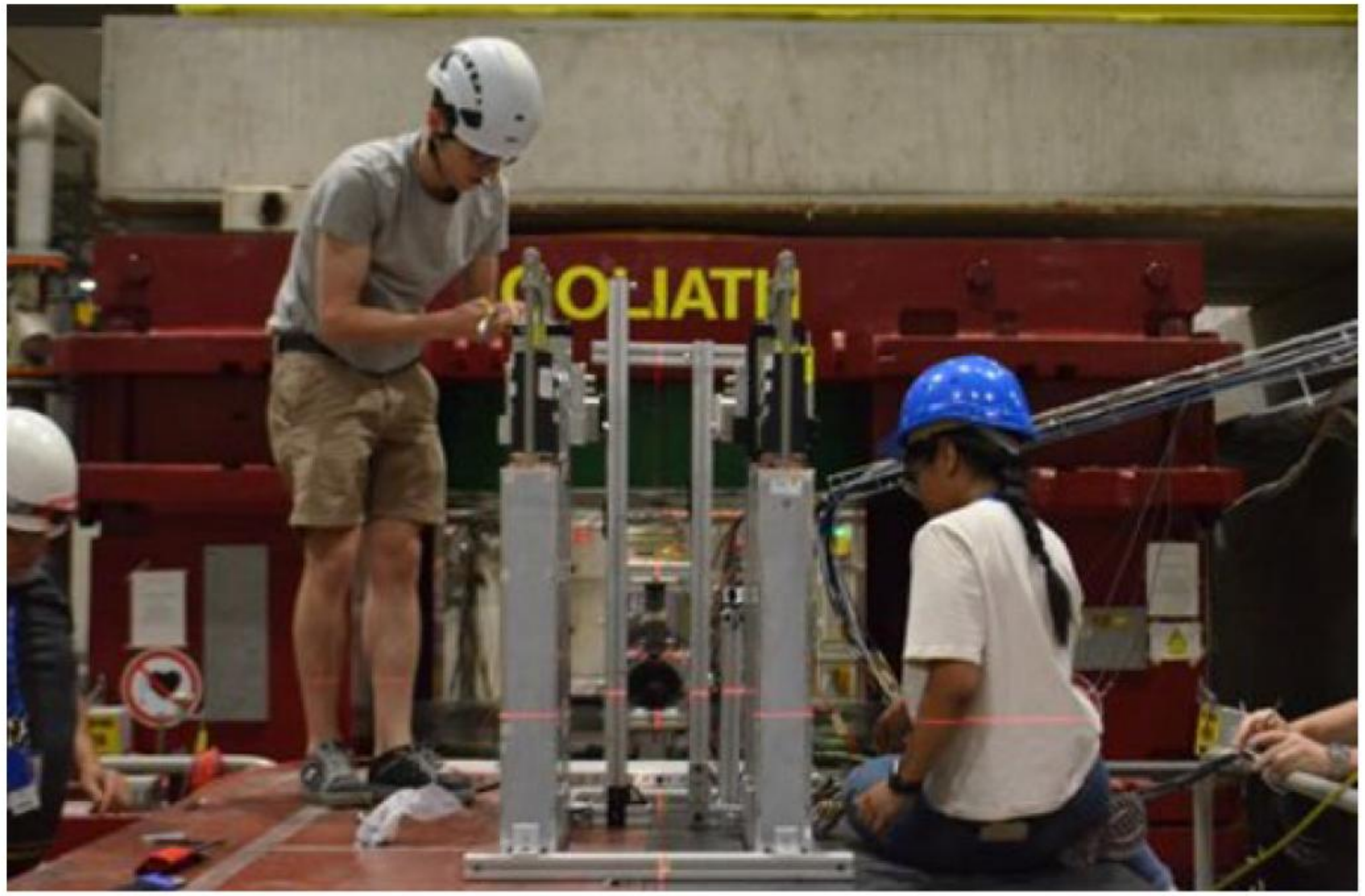


- 1 n peak
- 2 n peak
- 3 n peak
- 4 n peak

→ Simultaneous fit to determine data-driven **single neutron resolution,** **~17-18%** in this case

- When two ultra relativistic Pb ions cross, their strong EM fields can interact even without nuclear overlap
- The large photon fluxes at very low photon energies give a cross section for forward neutron production from EM dissociation (EMD) in each arm of about 200 barn
- This process provides plenty of events with low number of neutrons, that can be used for **data driven calibration procedures**

TECHNOLOGY



Illinois Physics undergraduate student Farah Mohammed Rafee and mentor Illinois Physics postdoctoral researcher Riccardo Longo make final adjustments to the detector setup before data taking.

Exploring the Quark Gluon Plasma in Ion-Ion collisions at CERN requires instrumentation operating in a radiation environment far exceeding the radiation levels post nuclear accident or attack!

Over the past 8 years the HL-ZDC team in NPL has developed instrumentation with optical materials that can function at radiation levels more than 10x larger than commercially available instruments!

UNPLANNED RESEARCH/TECHNOLOGY OPPORTUNITIES

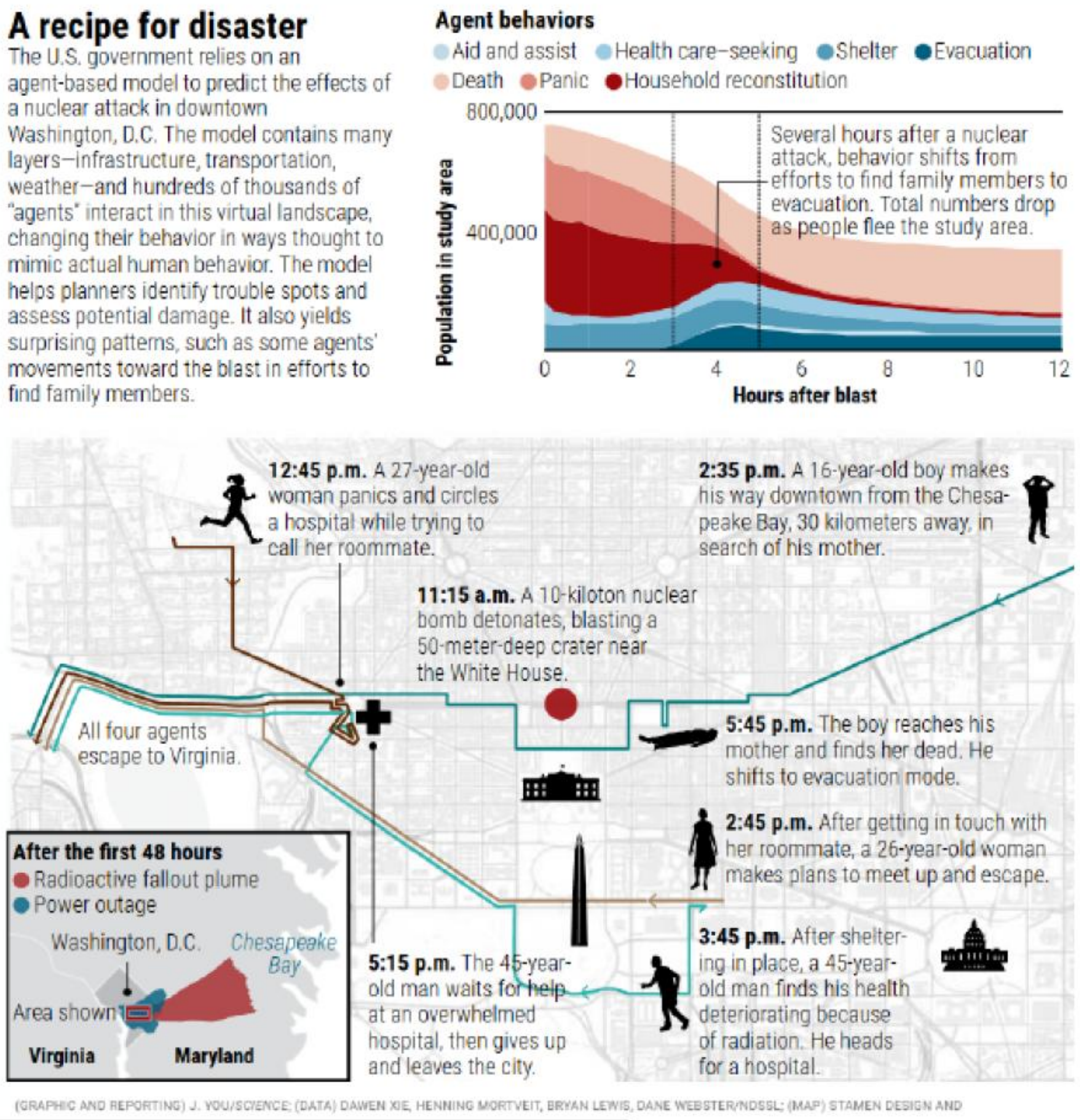
Extreme environments for radiation monitoring:

- Post nuclear (terrorist) attack
- Consider agent simulation:
  - "What if as nuke goes off Washington D.C.? Simulations of artificial societies help planners cope with the unthinkable".

Science, April 12th, 2018, M. Mitchell Waldrop
https://www.science.org/content/article/what-if-nuke-goes-washington-dc-simulations-artificial-societies-help-planners-cope

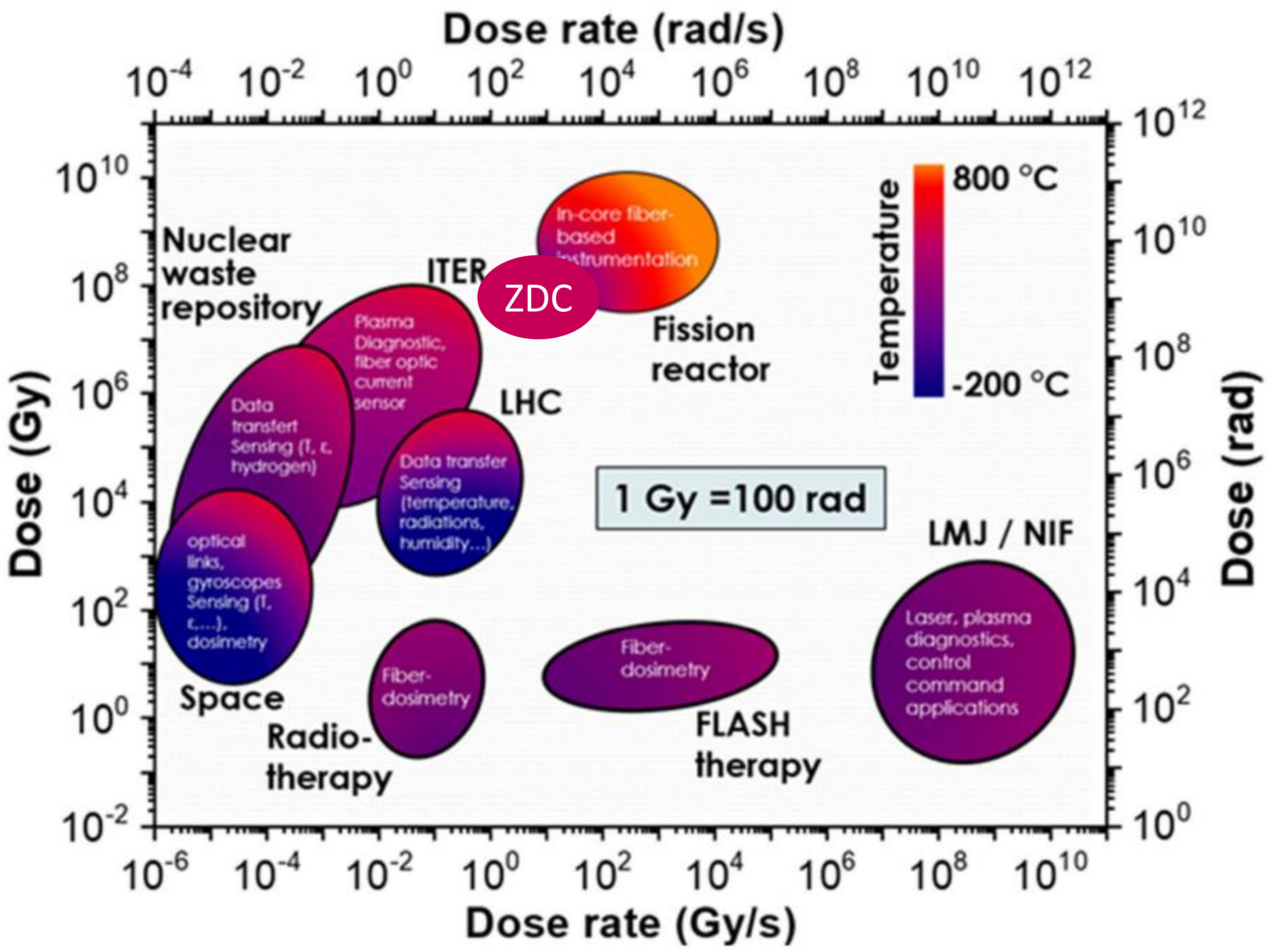
➔ household reconstitution, aid and assist and health care-seeking activities contribute to increase in radiation dose to population in the impacted area!

HL-ZDC detectors can be used for reliable post nuclear accident or attack radiation monitoring



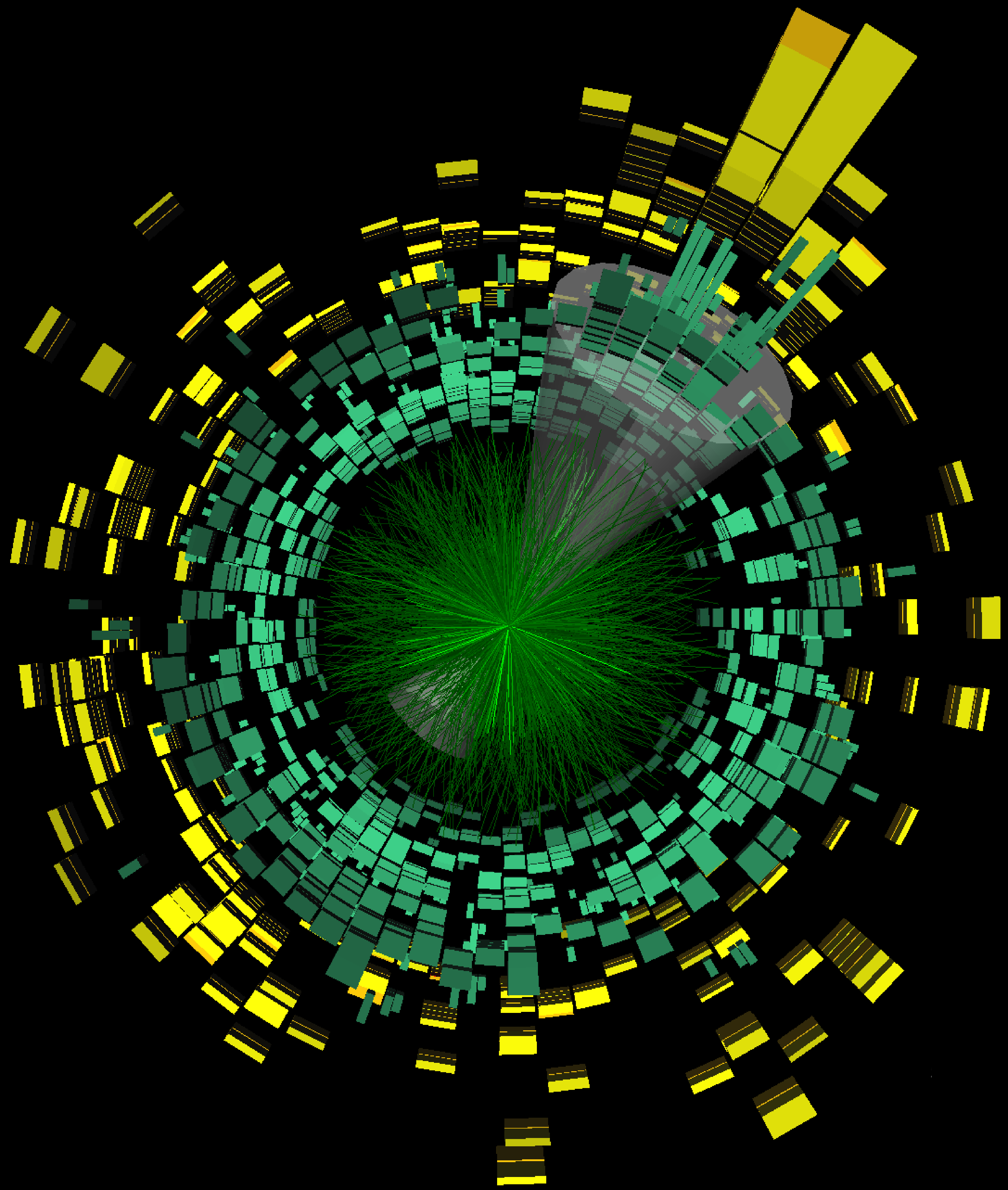
UNPLANNED RESEARCH/TECHNOLOGY OPPORTUNITIES

Radiation hard fused silica materials potentially can be used for optics and optical fibers in a broad range of applications!



THE TEAM: HL-ZDC UNDERGRADUATE RESEARCHERS

Undergraduate Researchers for HL-ZDC at NPL
(last grant period, 2021-2025)



Contact: mgp@illinois.edu

THANK YOU !