Theoretical and Experimental Investigations of the Strongly Interacting Matter

Gergely Gábor Barnaföldi, group leader

CERN LHC ALICE, Wigner RCP of the Hungarian Academy of Sciences

GGSWBS 2018, TSU, Tbilisi, 20th August 2018.

Grants: THOR, PHAROS, TET 12 CN-1-2012-0016, K120660 (2016-2020), K123815 (2017-2021)

Theory & Computing & Experiment groups

Hungarian ALICE Group

Experiment: Gy. Bencédi, L. Boldizsár, E. Dávid, L. Gáll, Á. Gera, G. Hamar, J. Imrek, T. Kiss, K. Kapás, M. Kőfaragó, P. Lévai, M. Nguyen B. Szilágyi, D. Varga, M. Vargyas, O. Visnyei, R. Vértesi

Wigner GPU Laboratory

Computing: D. Berényi, BM. Nagy-Egri, B Kacskovics

Heavy-ion Theory Group, Department for Theoretical Physics

Theory: D. Berényi, G. Bíró, T.S. Biró, V. Gogokhia, Sz. Karsai, P. Lévai, P. Pósfay, D. Nagy, M. Németh, Á. Takács, M. Gyulassy, G.Y. Ma, G. Papp, K.M. Shen, X.N. Wang, B.W. Zhang.

MOTIVATION

Material properties, phases

- Let’s see a simple material…

Material properties, phases

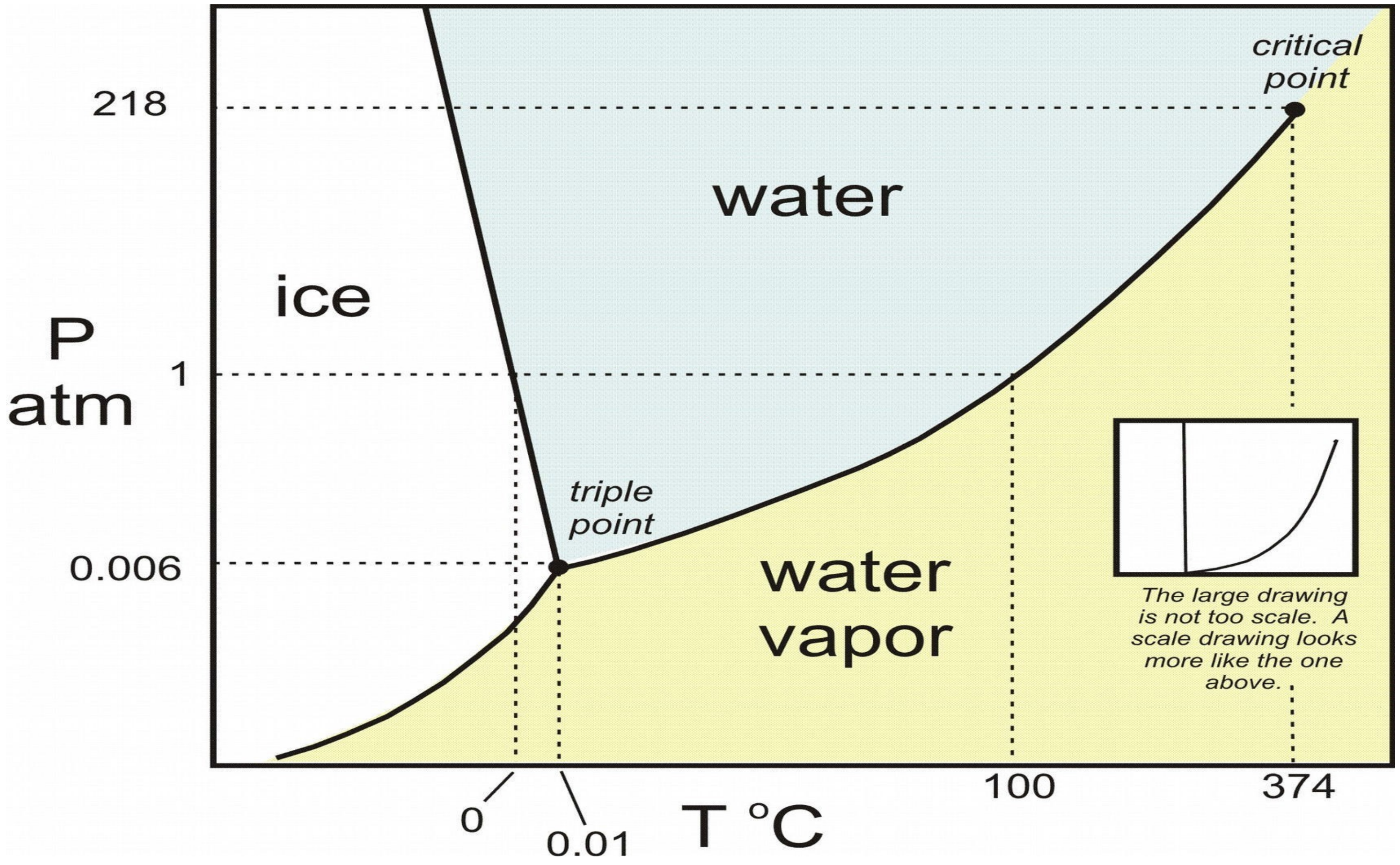
- Let's see a simple material…

Material properties, phases

- Let’s see a simple material…

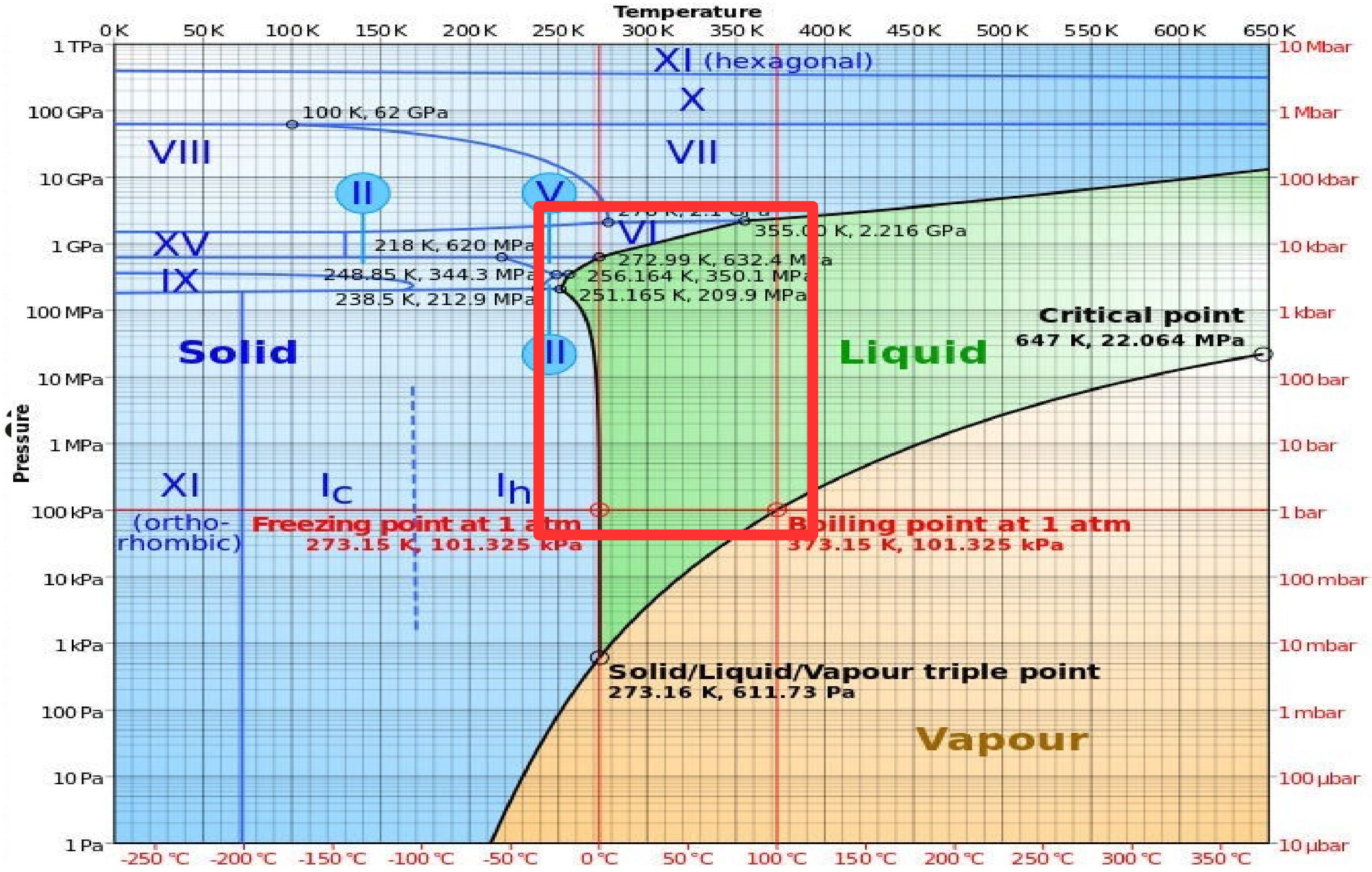
Material properties, phases

- Let's see a simple material…



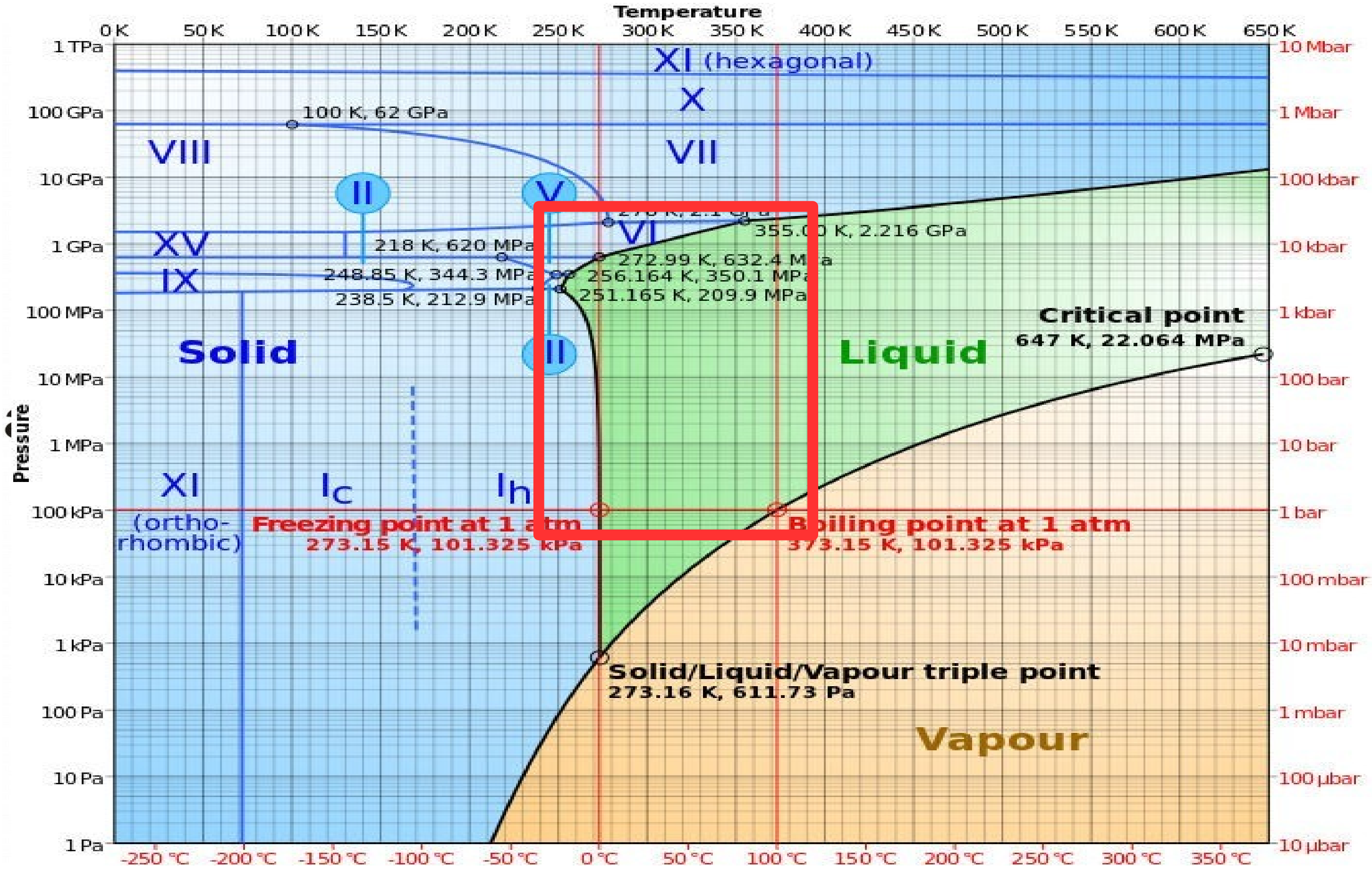
Material properties, phases

- Let’s see a simple material…



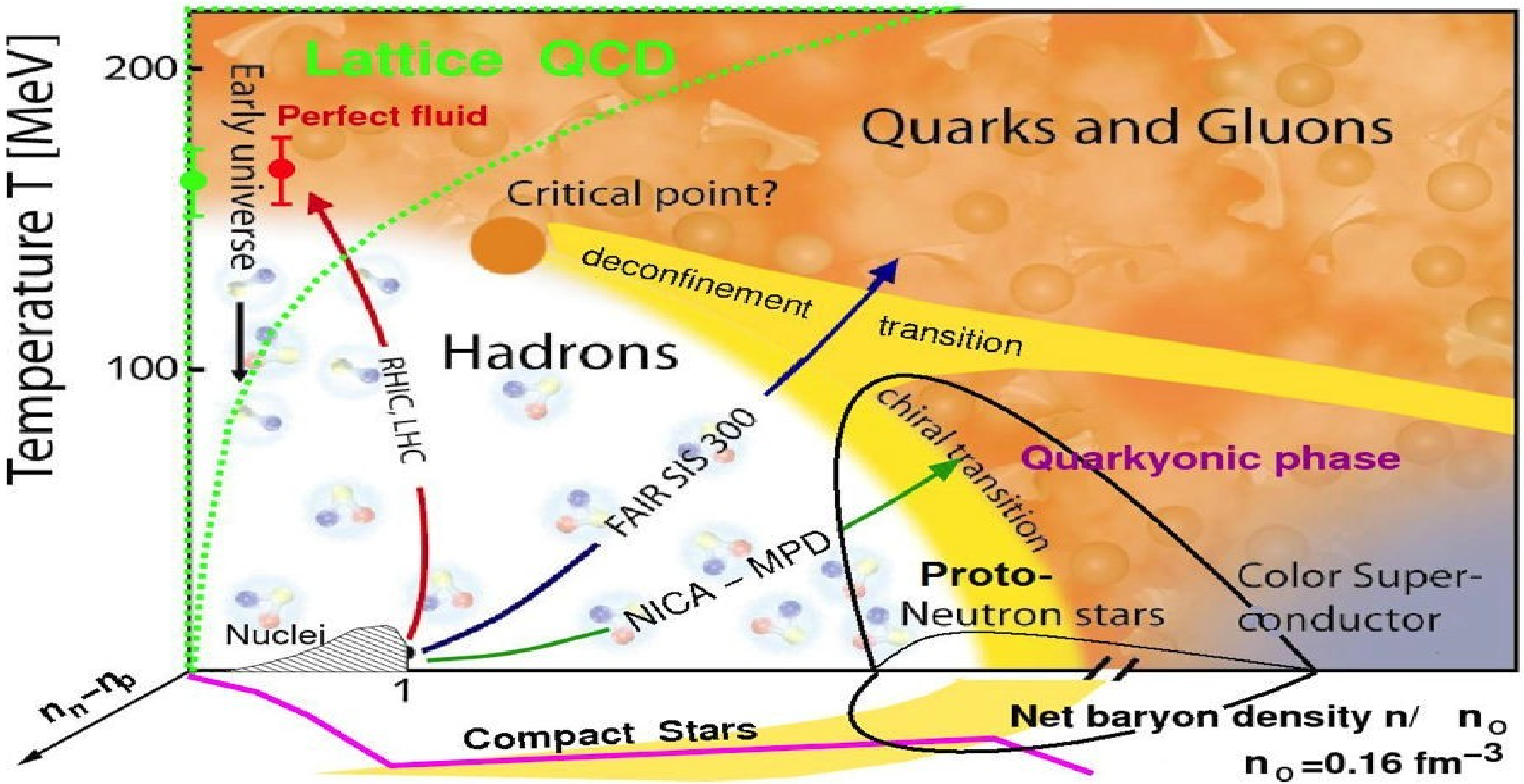
Material properties, phases

- Let’s see a “simple” material at extreme conditions…



Matter of the early Universe: hot & dense matter

- The phase diagram of a complicated matter – in extreme conditions



Theoretical Investigations

Heavy Ion Theory Research Group

- Investigation of Low Energy Hadron Spectra
  - Low energy hadron spectra, SU(3)xSU(3) symmetric sigma model, transport code; GSI HADES experiments theoretical background

    Wolf Gy, Kovács P, Zétényi M, Almási G, Balassa, Jóföldi Zs, Váróczy J.
- Perturbative and non-perturbative QCD
  - Perturbative QCD: nuklear effects in high-energy collisions; Non-perturbative QCD, mass gap, equation of state; theoretical background for ALICE

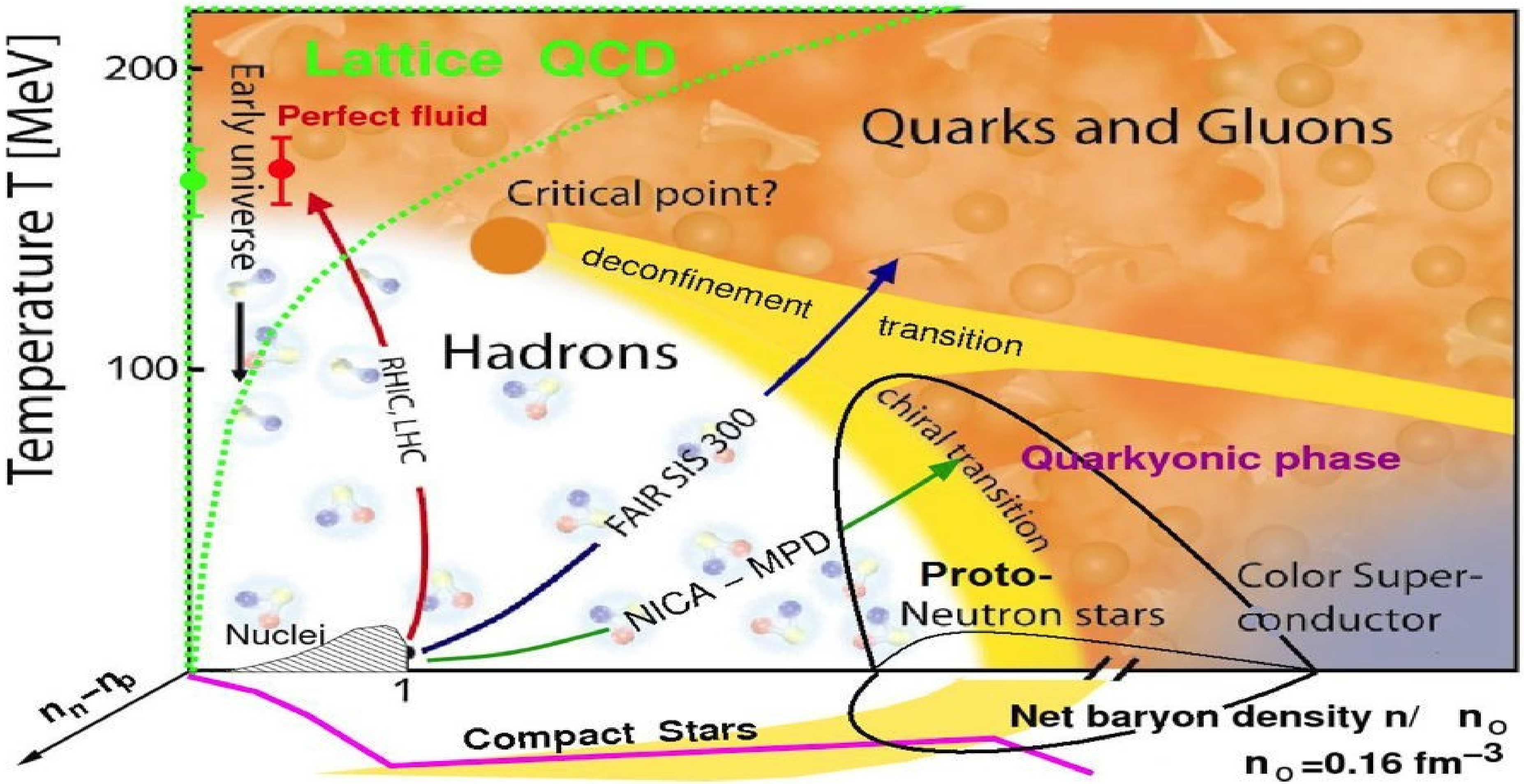
    BGG, Gyulassy M, Vaghtang G, Pósfay P, Karsai Sz, Berényi D, Biro G, Takács Á
- Modelling Hadronization and Fragmentation
  - Hadronization models by Tsallis-Pareto like distributions, jet-fragmentation and fragmentation functions

    BGG, Biró TS, Shen K-M, Bíró G, Takács Á
- New Thermodynamical Approaches
  - Non-extensive thermodynamics, hidrodinamical and statistical approaches, Unruh effect, termodynamics in curved space-time

    Bíró TS, BGG, Ván P, Ürmössy K, Kovács R.

The phases of the strongly interacting matter

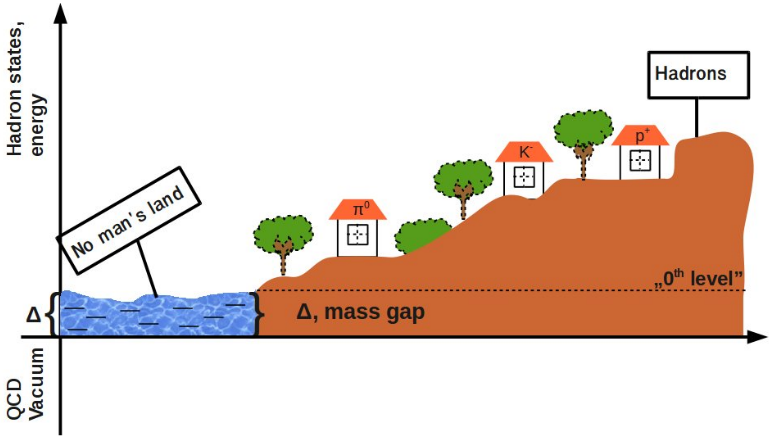
- Extreme dense & cold matter: NORMAL MATTER in QCD

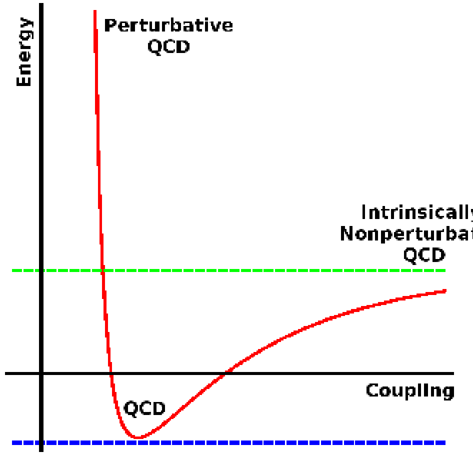


The phases of the strongly interacting matter

- Extreme dense & cold matter: NORMAL MATTER in QCD

- QCD is successful, but main problem: Lagrangian does not contain any mass scale parameter to which we can assign a physical meaning, even after renormalization program is performed.
- Resolving this problem, the mass gap has been introduced by Jaffe and Witten as a mass scale parameter responsible for the large-scale structure of the QCD ground state.
- The mass gap can be introduced via the equation of motion describing the propagation of gluons in the QCD vacuum. Calculation of e.g. bag constant, gluon matter pressure, etc..

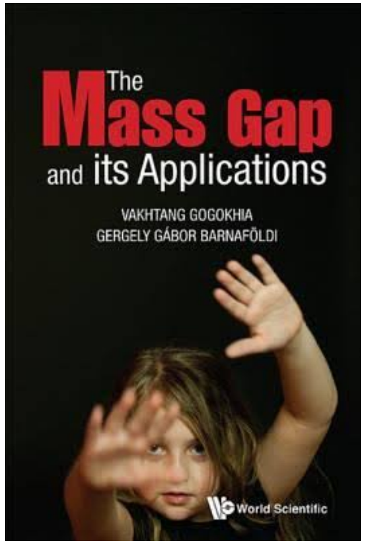




The phases of the strongly interacting matter

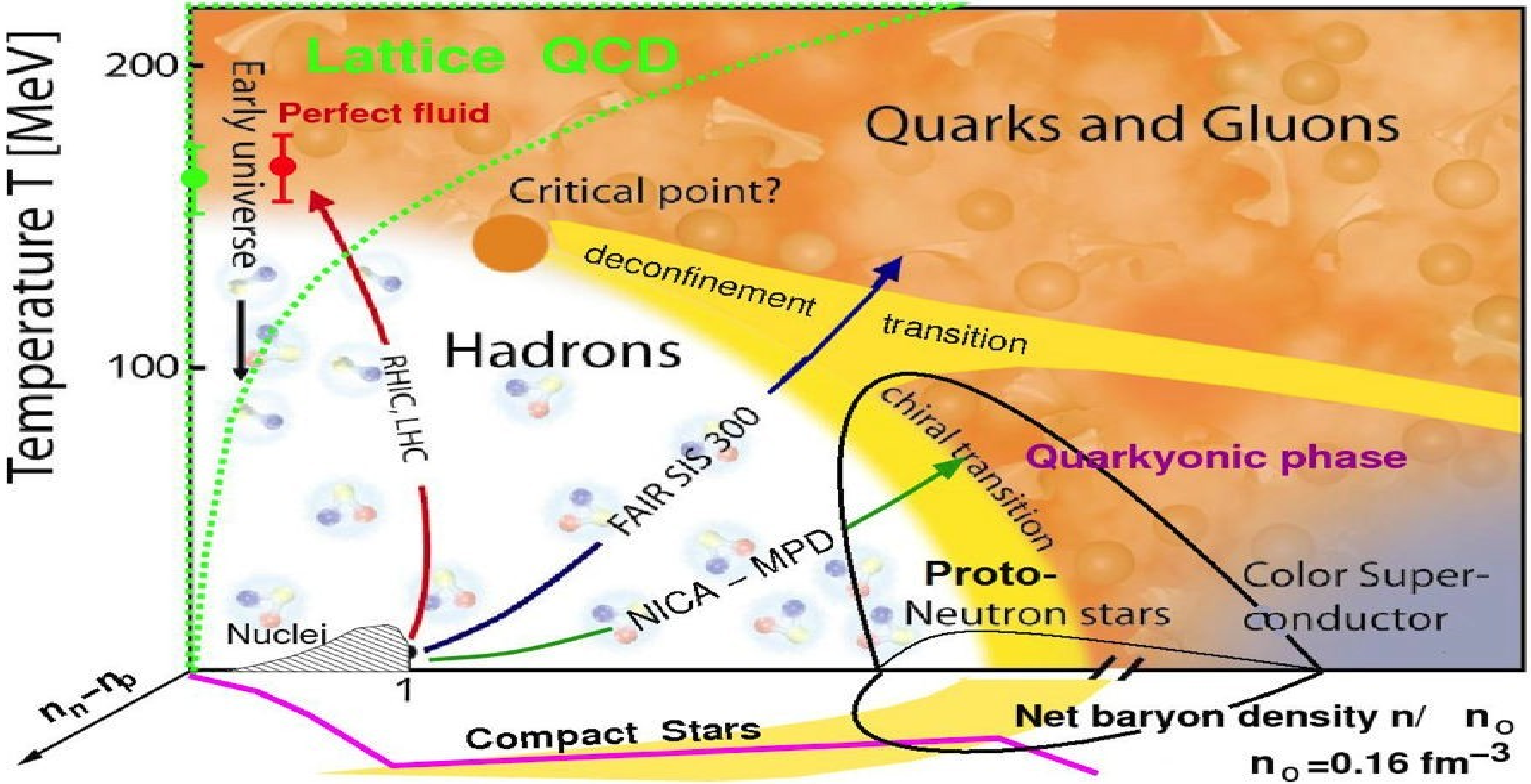
- Extreme dense & cold matter: NORMAL MATTER in QCD

- QCD is successful, but main problem: Lagrangian does not contain any mass scale parameter to which we can assign a physical meaning, even after renormalization program is performed.
- Resolving this problem, the mass gap has been introduced by Jaffe and Witten as a mass scale parameter responsible for the large-scale structure of the QCD ground state.
- The mass gap can be introduced via the equation of motion describing the propagation of gluons in the QCD vacuum. Calculation of e.g. bag constant, gluon matter pressure, etc..

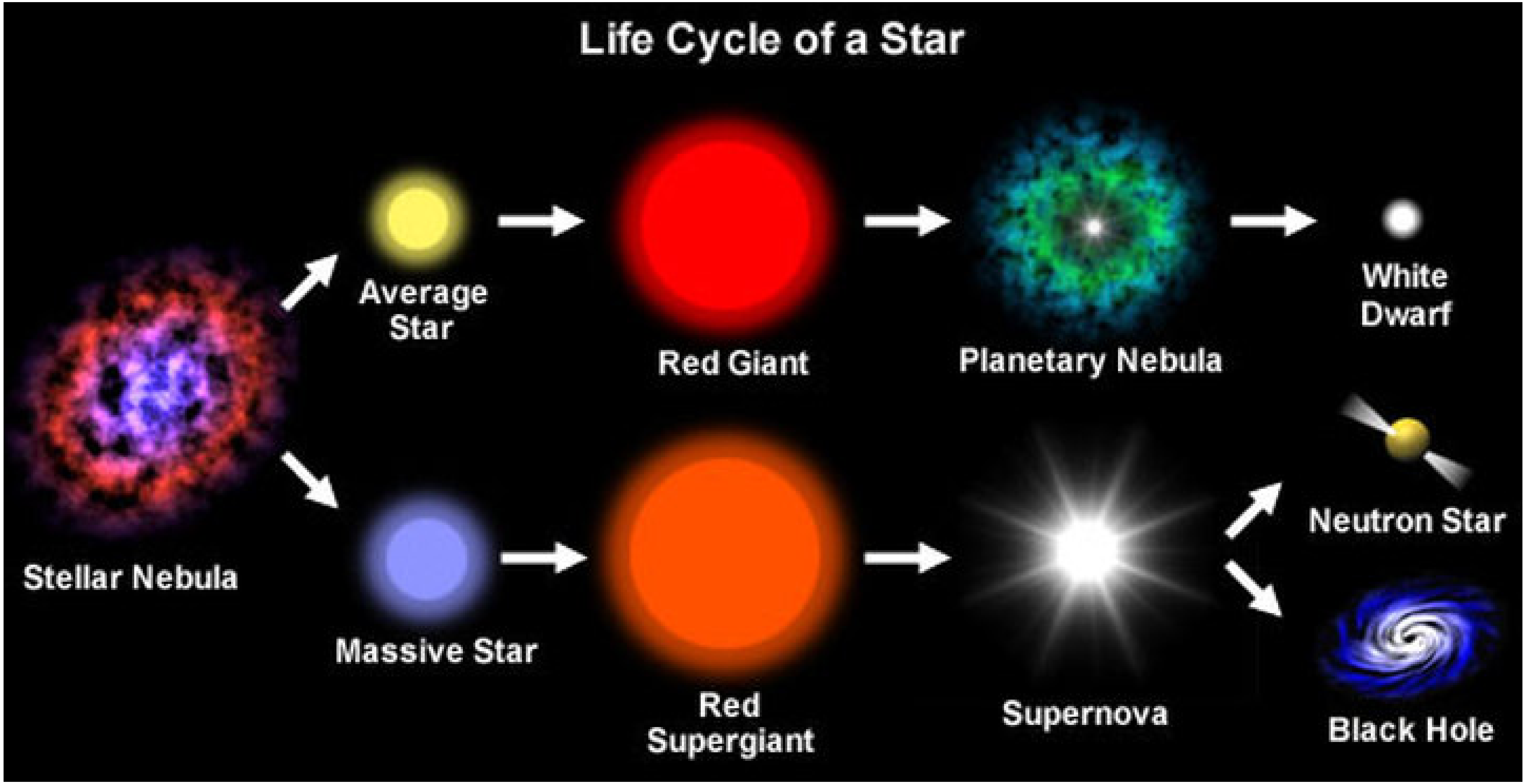


The phases of the strongly interacting matter

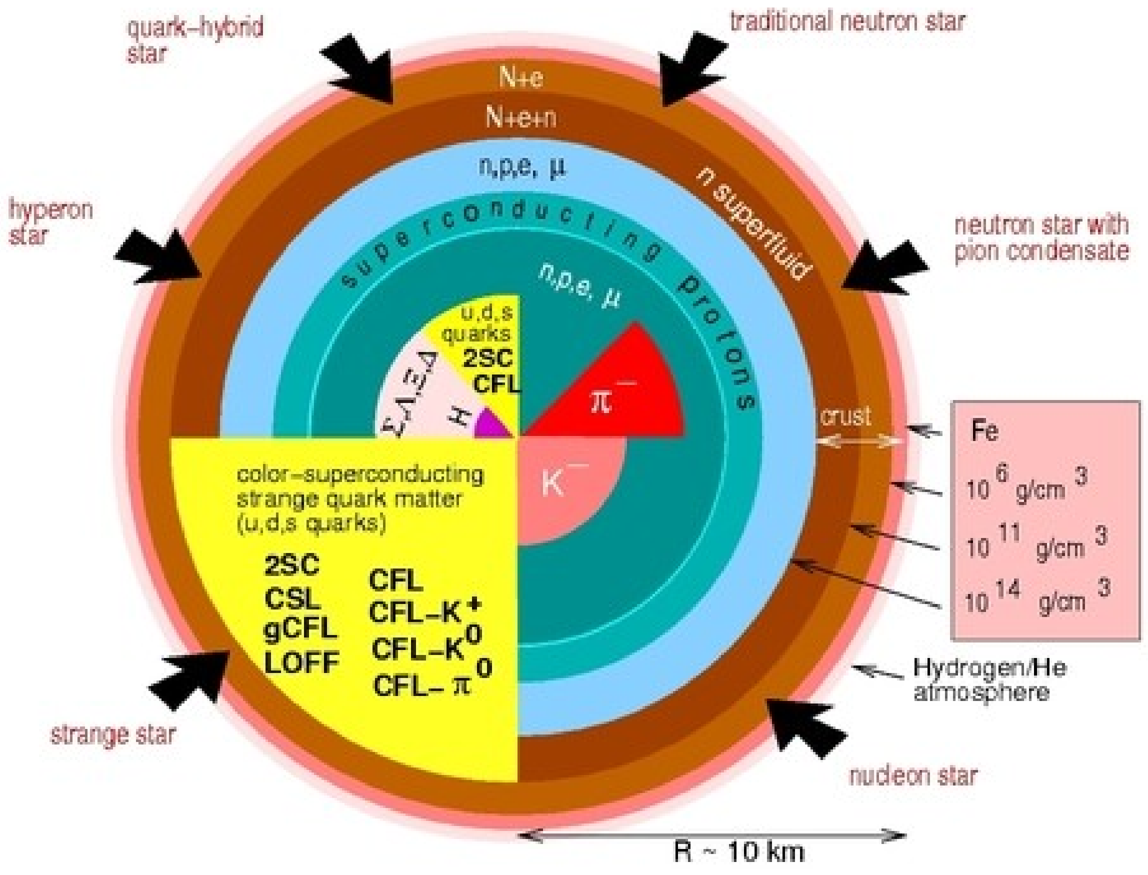
- Extreme dense & cold matter: COMPACT STAR EoS

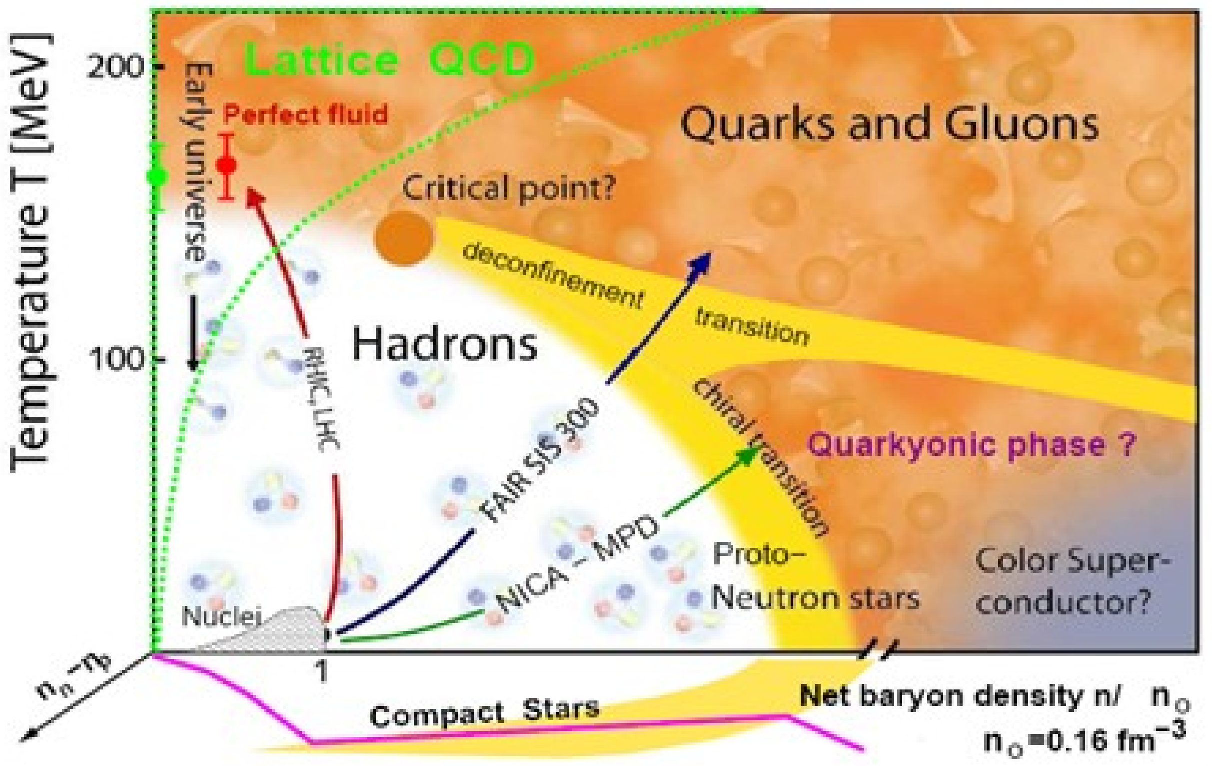


The inner strucutre of compact stars



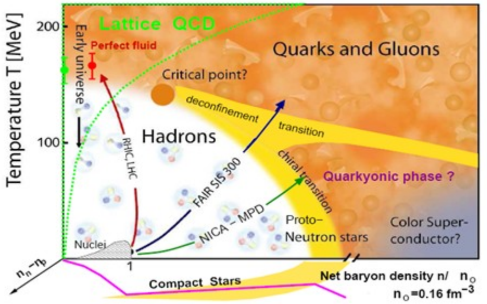
The inner strucutre of compact stars

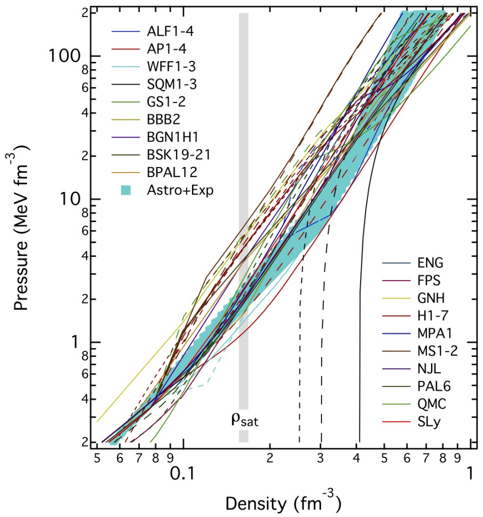




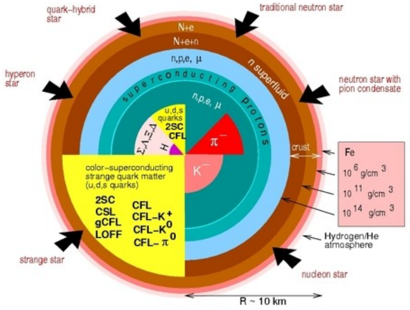
The inner strucutre of compact stars

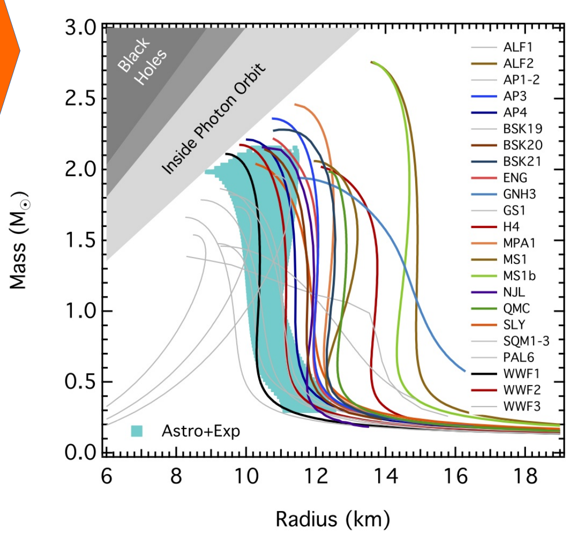
EoS from exp & theory



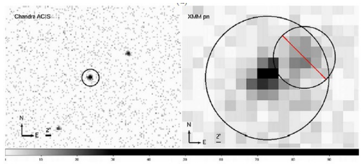


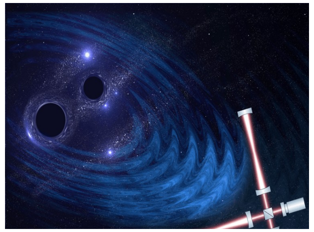
Application in compact stars

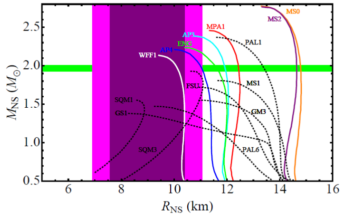


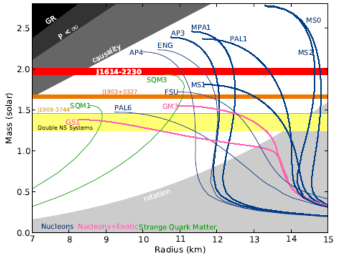


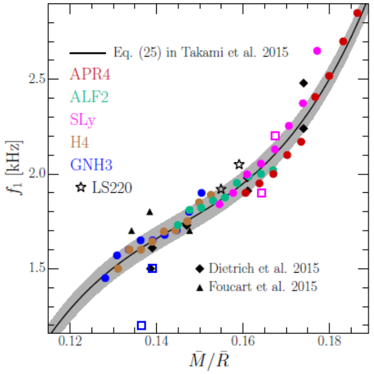
Constraints by astrophysical observations





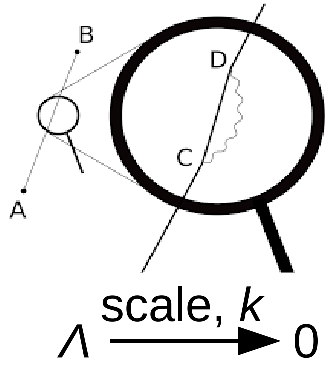


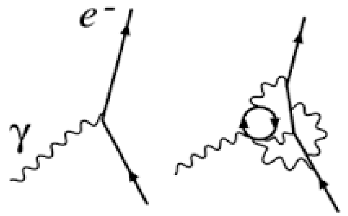


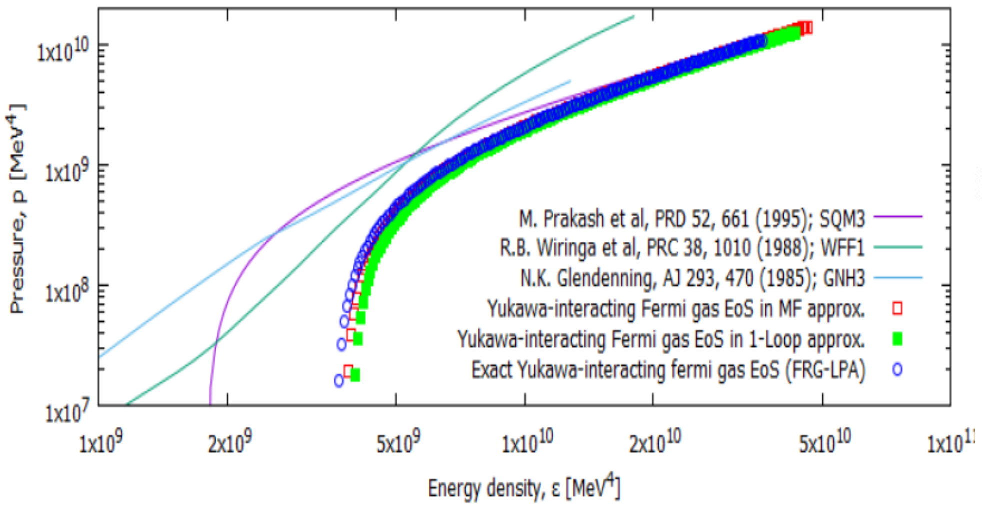


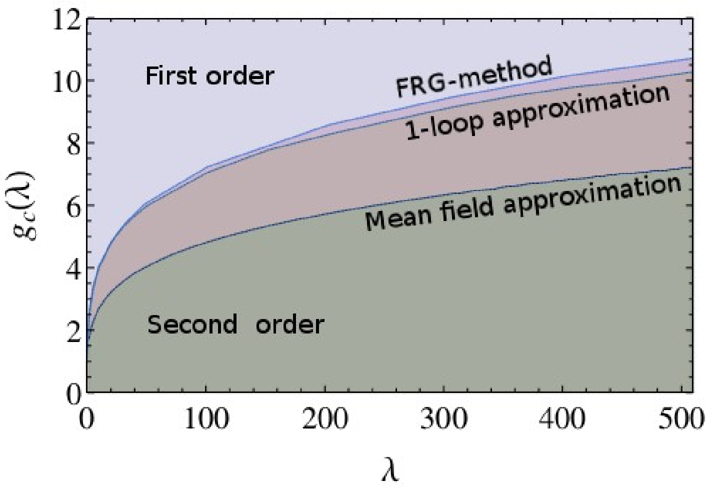
The inner strucutre of compact stars

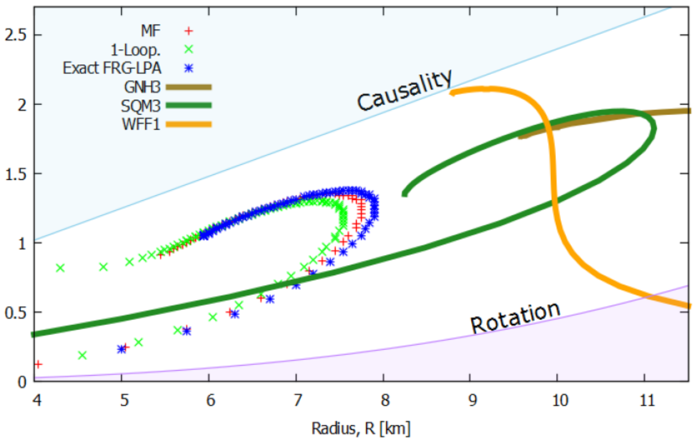
- It is hard to get effective action for an interacting field theory: e.g.: EoS for superdense cold matter ($T \rightarrow 0$ and finite μ)
- Taking into account quantum fluctuations using a scale, k
  - Classical action, $S=\Gamma_{k\rightarrow\Lambda}$ in the UV limit, $k \rightarrow \Lambda$
  - Quantum action, $\Gamma=\Gamma_{k\rightarrow 0}$ in the IR limit, $k \rightarrow 0$
- FRG (non-perturbative) Method: Smooth transition from macroscopic to microscopic world using the scale





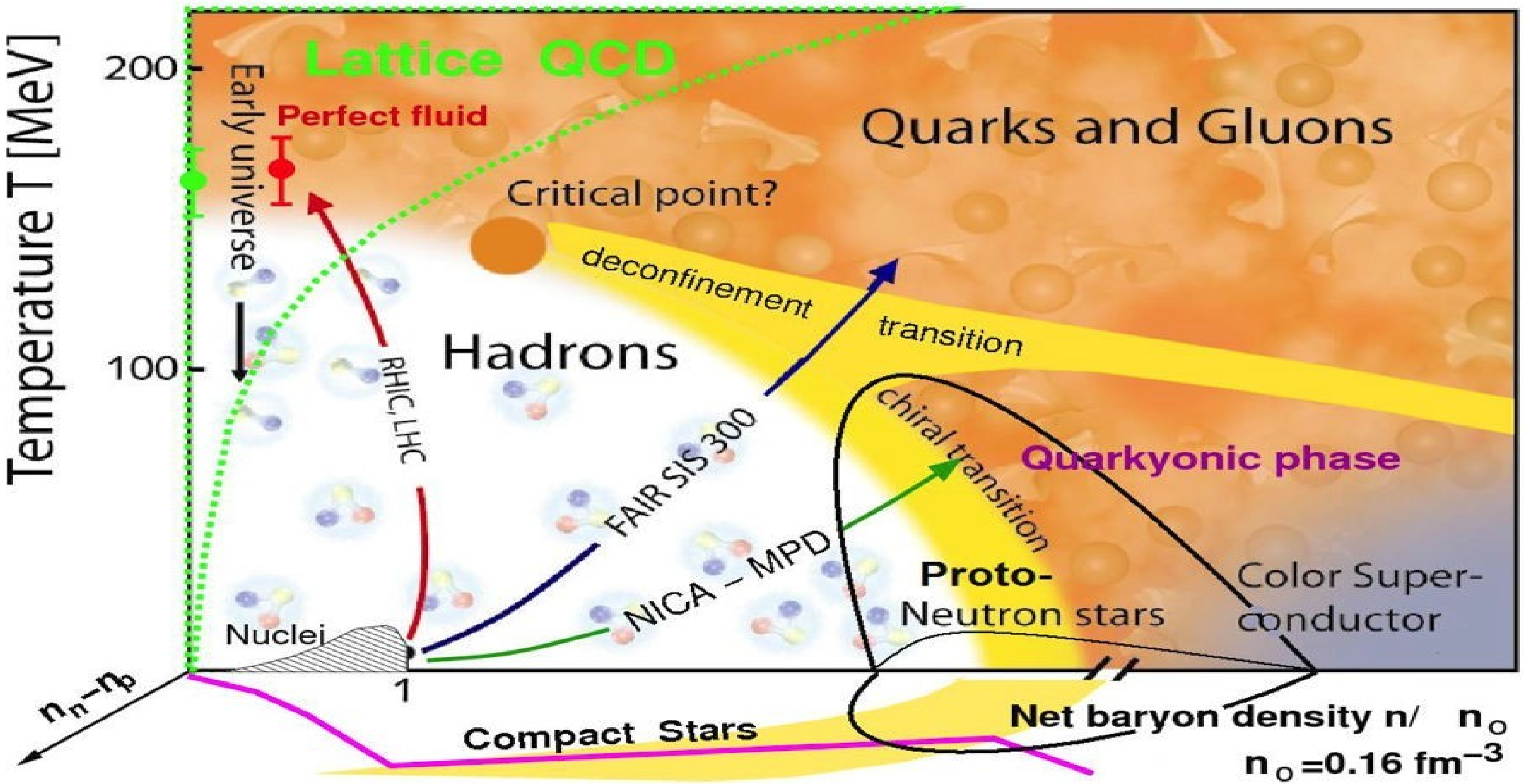






The phases of the strongly interacting matter

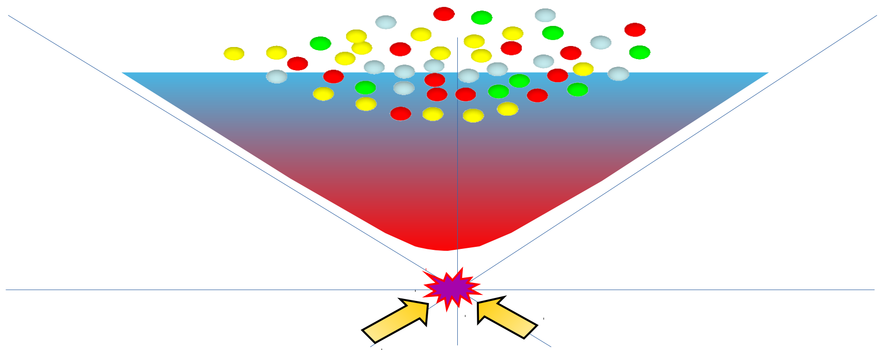
- Extreme hot & dense matter: HADRONIZATION



The phases of the strongly interacting matter

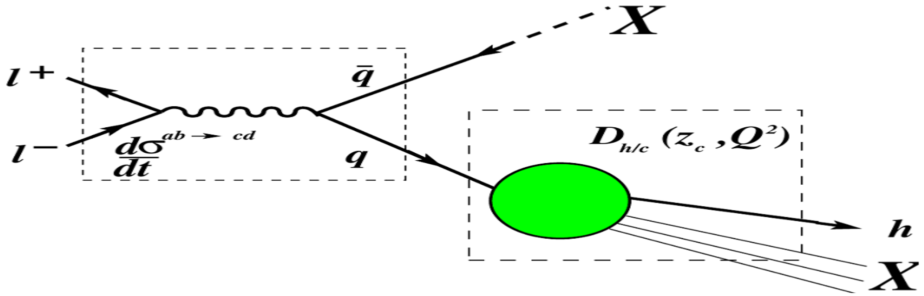
- Extreme hot & dense matter: HADRONIZATION

In high-energy collisions, hadron appears at the end of the partonic (q,g) processes.



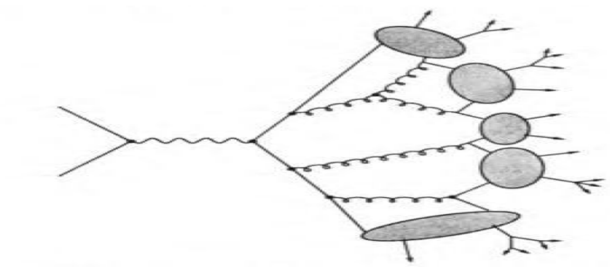
The description of the transition of partons→ hadrons is still a mistery

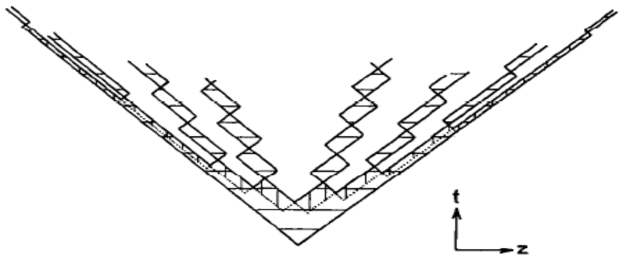
→ phenomenology models are exist



Models for fragmentation:

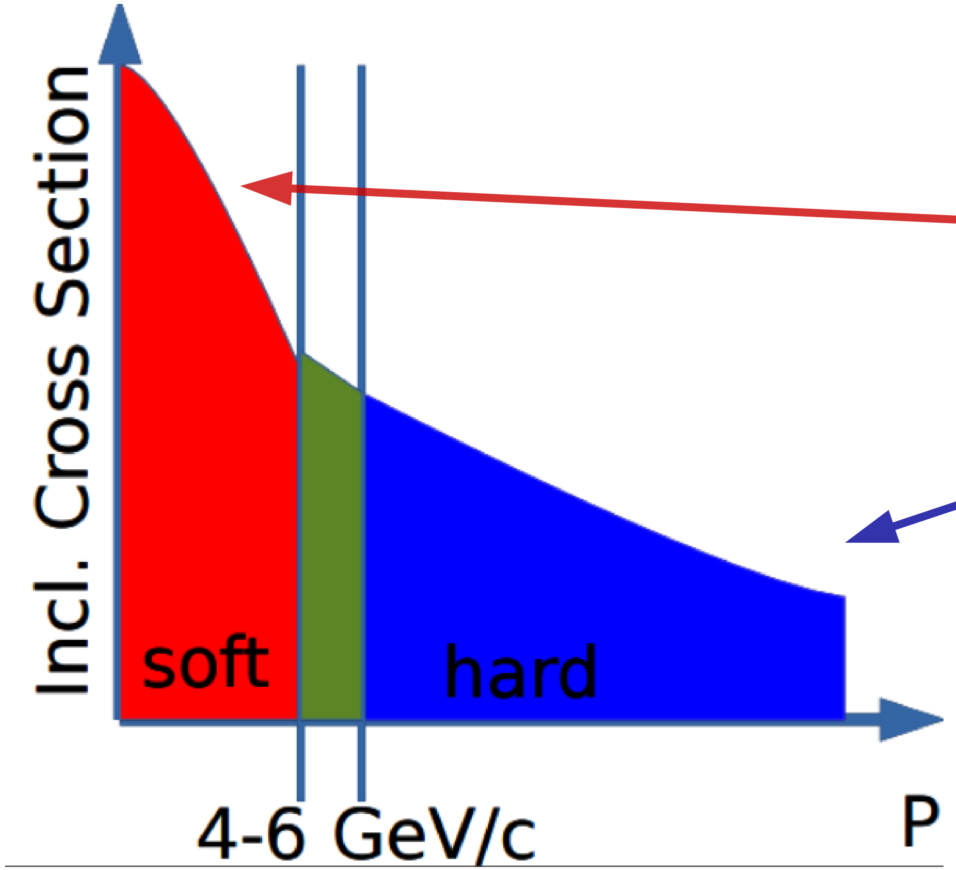
Feynman, Lund, string ,cluster, etc.





Hadronization by Tsallis-Pareto distributions

Proton-proton collisions identified,inclusive hadron spectra



Low p_T ~ Thermal models

$$\sim e^{-\beta p_T}$$

$$\sim p_T^{-\alpha}$$

High p_T ~ pQCD

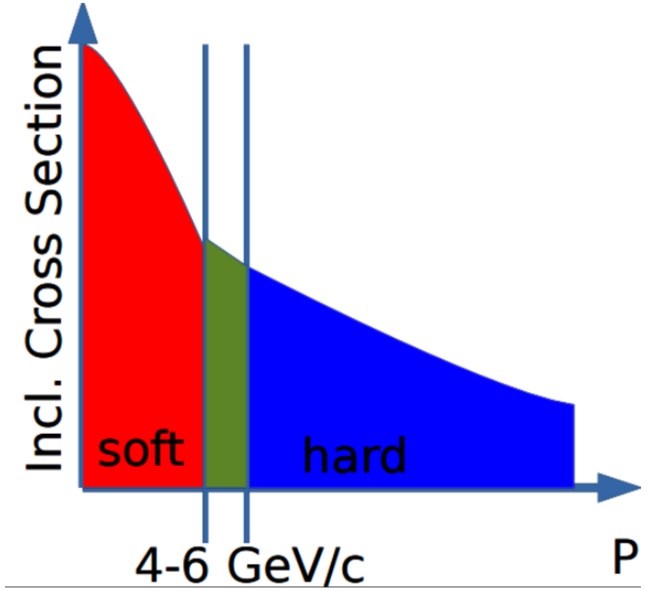
Hadronization by Tsallis-Pareto distributions

Experimental observation: Tsallis-Pareto momentum distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \sim \left[1 + \frac{q-1}{T}\varepsilon\right]^{-\frac{1}{q-1}}$$

Kis p_T: $\sim e^{-\varepsilon/T}$

Nagy p_T: $\sim \varepsilon^{-\frac{1}{q-1}}$



T – parameter (body): Soft p_T

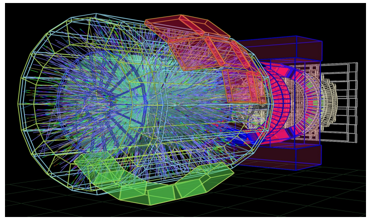
q – parameter (tail): Hard p_T

Hadronization by Tsallis-Pareto distributions

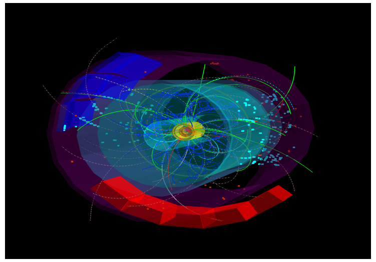
Extensive statistics: $S_{12} = S_1 + S_2$

$S_S = -\sum_i p_i \ln p_i$ Boltzmann-Gibbs distr.: $\sim e^{-\beta\varepsilon}$

Non-extenzive statistic: $S_{12} = S_1 + S_2 + (q-1)S_1 S_2$



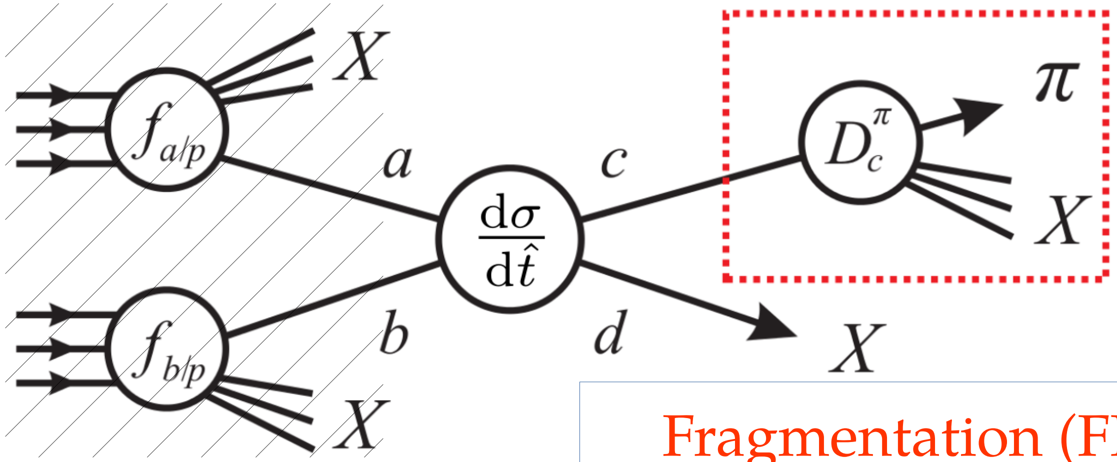
q-entropy: $S_q = \frac{1}{q-1}\left(1 - \sum_1 p_i^q\right)$



Tsallis-Pareto distribution:

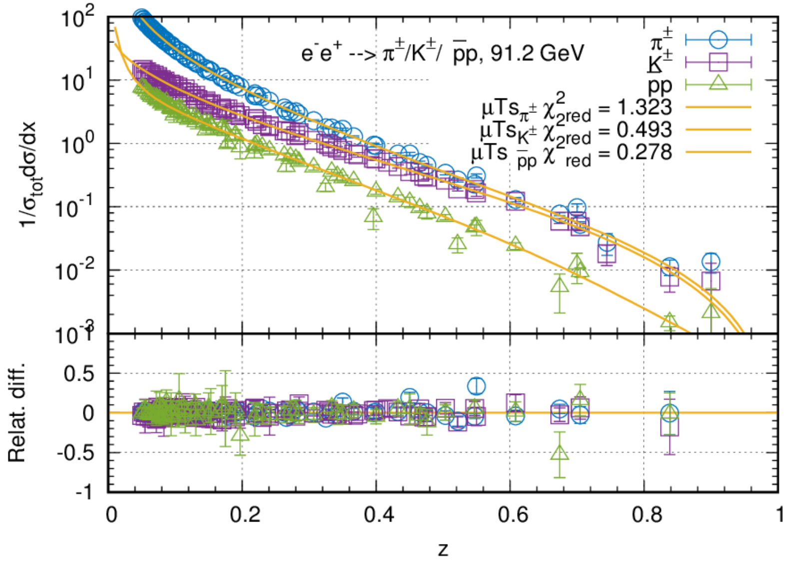
$$\sim \left[1 + \frac{q-1}{T}\varepsilon\right]^{-\frac{1}{q-1}}$$

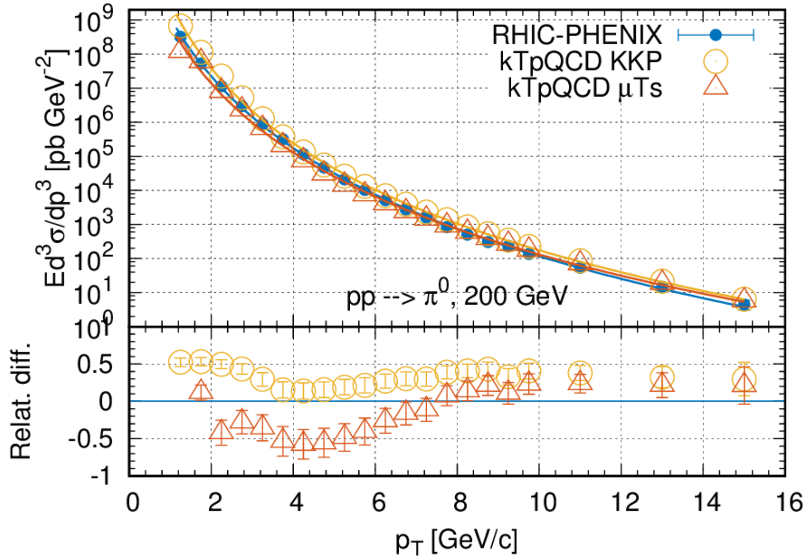
Hadronization by Tsallis-Pareto distributions



Fragmentation (FF)

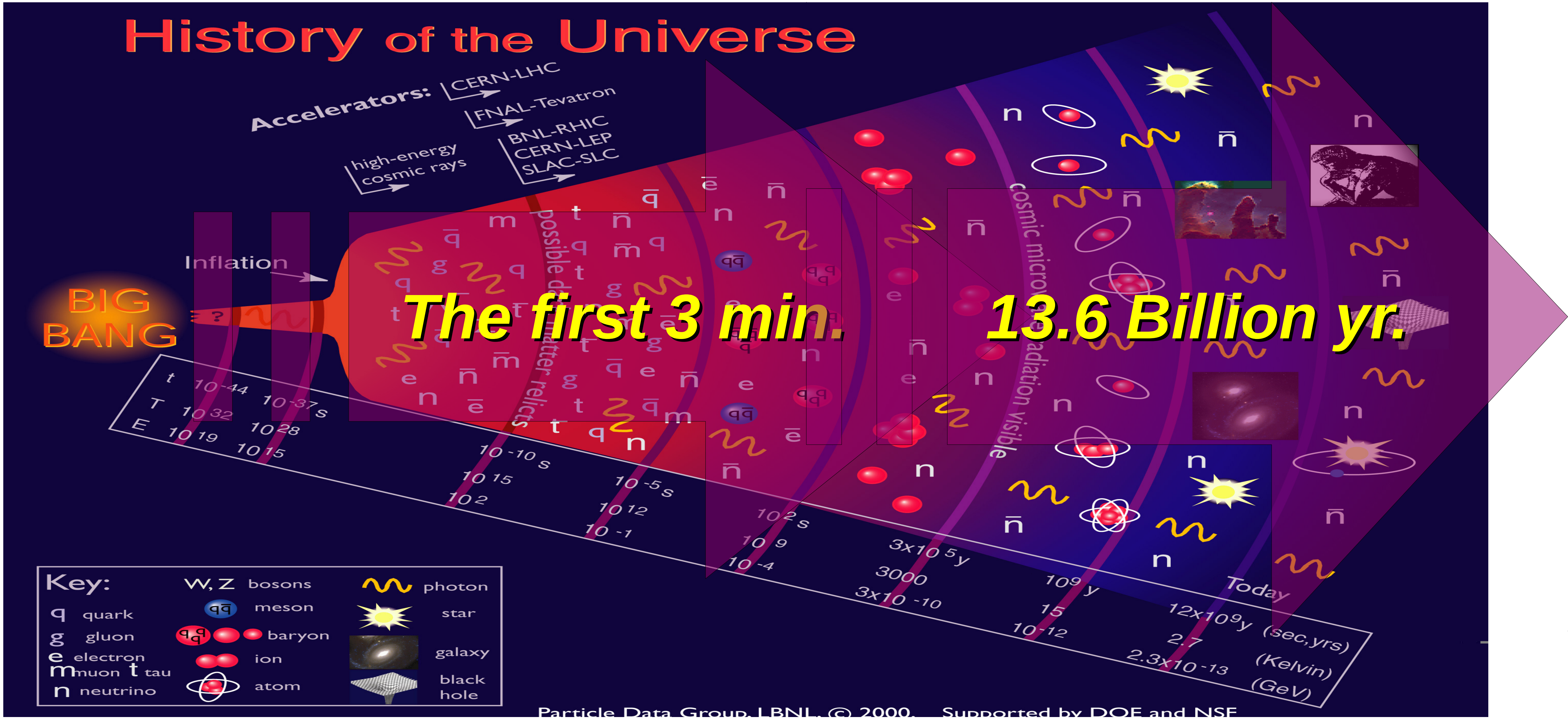
$$\sim (1-z)\left[1-\frac{q-1}{T}\frac{\sqrt{s}}{2}\log(1-x)\right]^{-\frac{1}{q-1}}$$



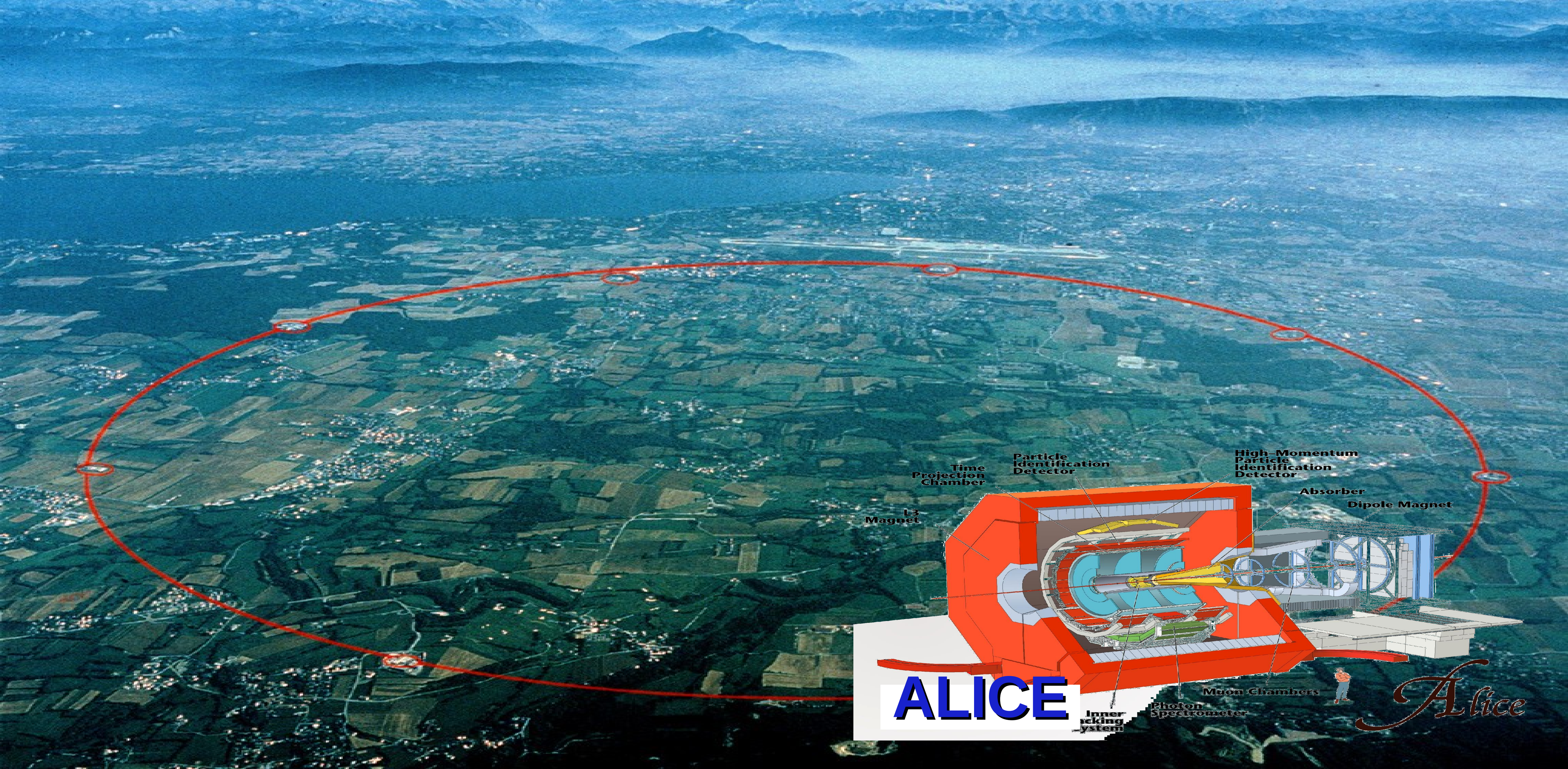


High-energy Heavy Ion Physics with ALICE Experiment at the LHC

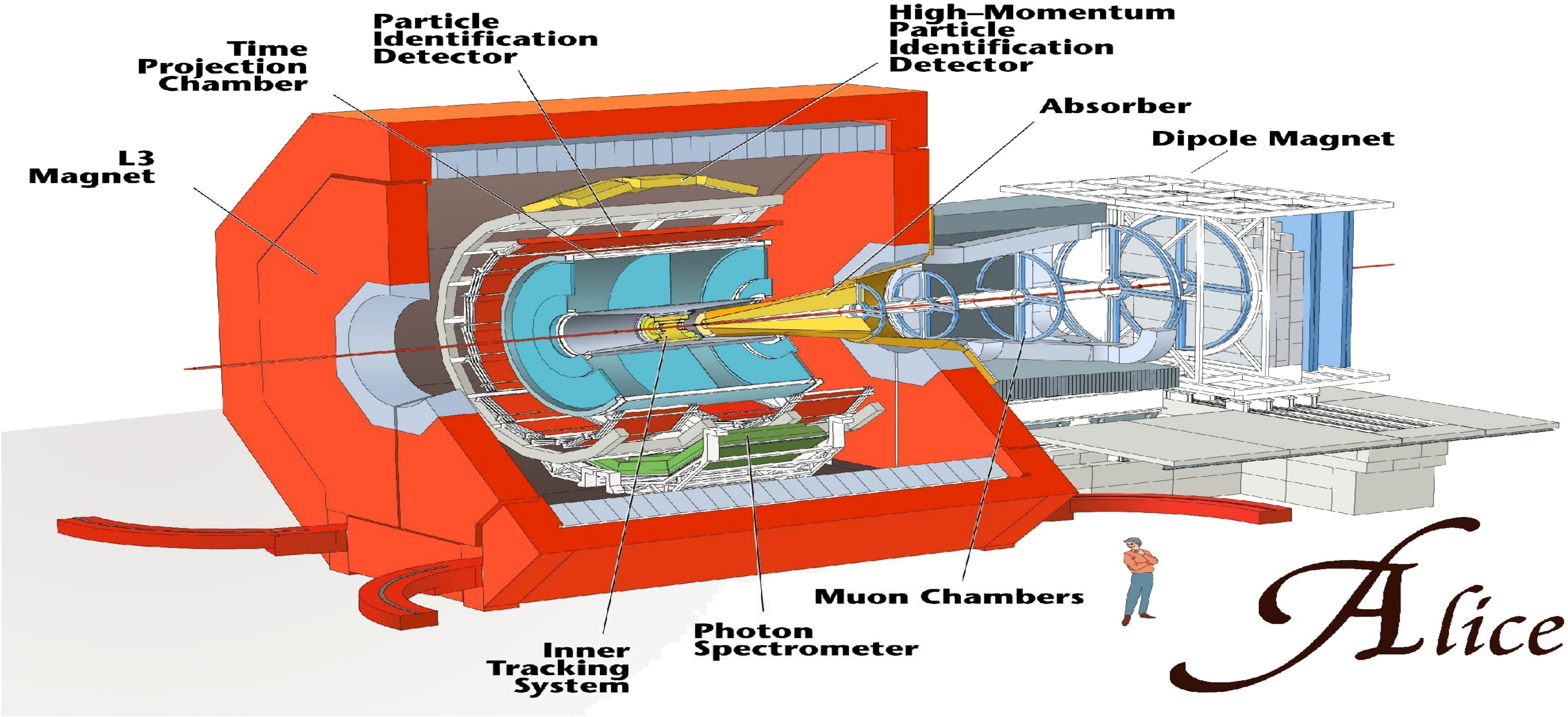
HIC: Research of the early Universe



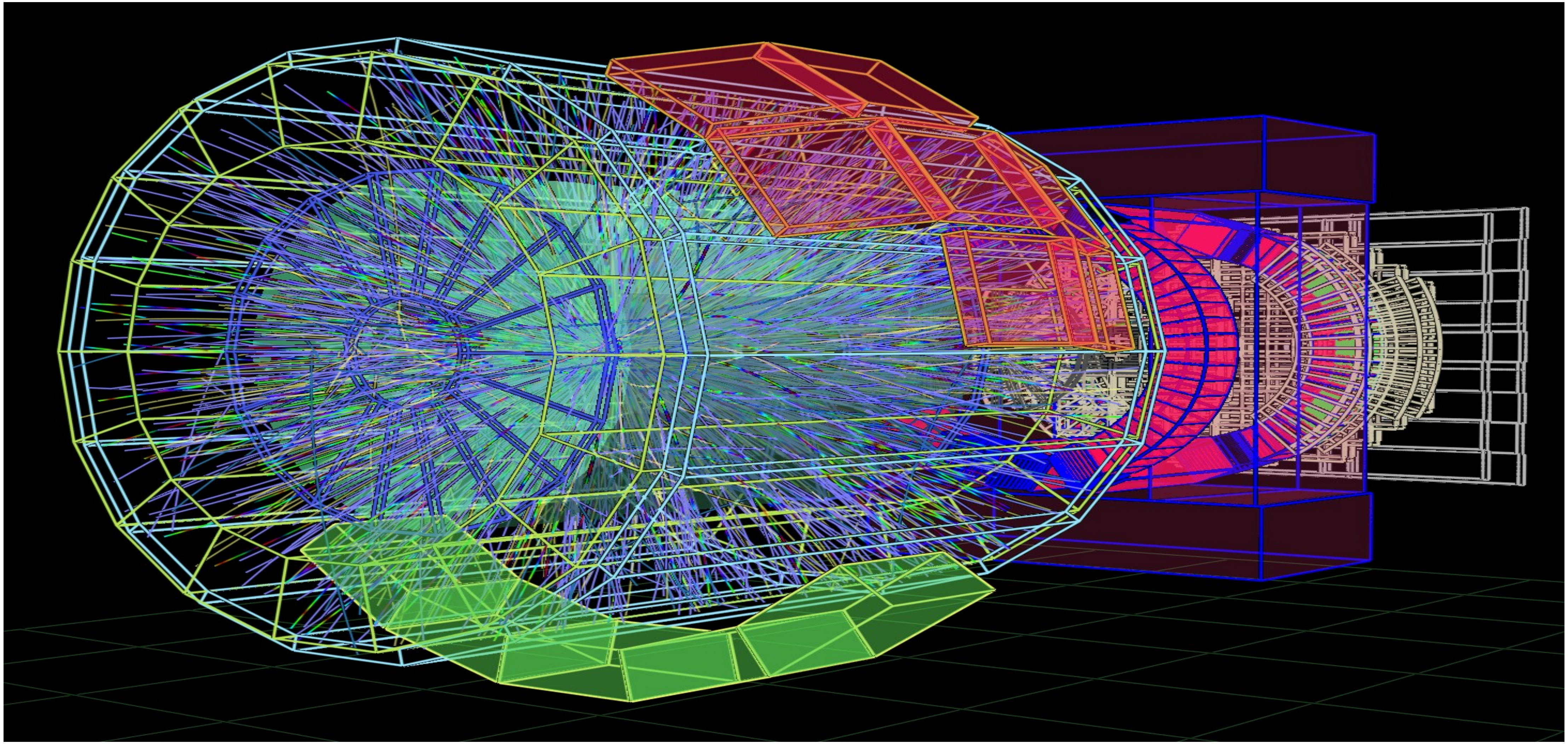
The Big Bang Experiment at P2: ALICE



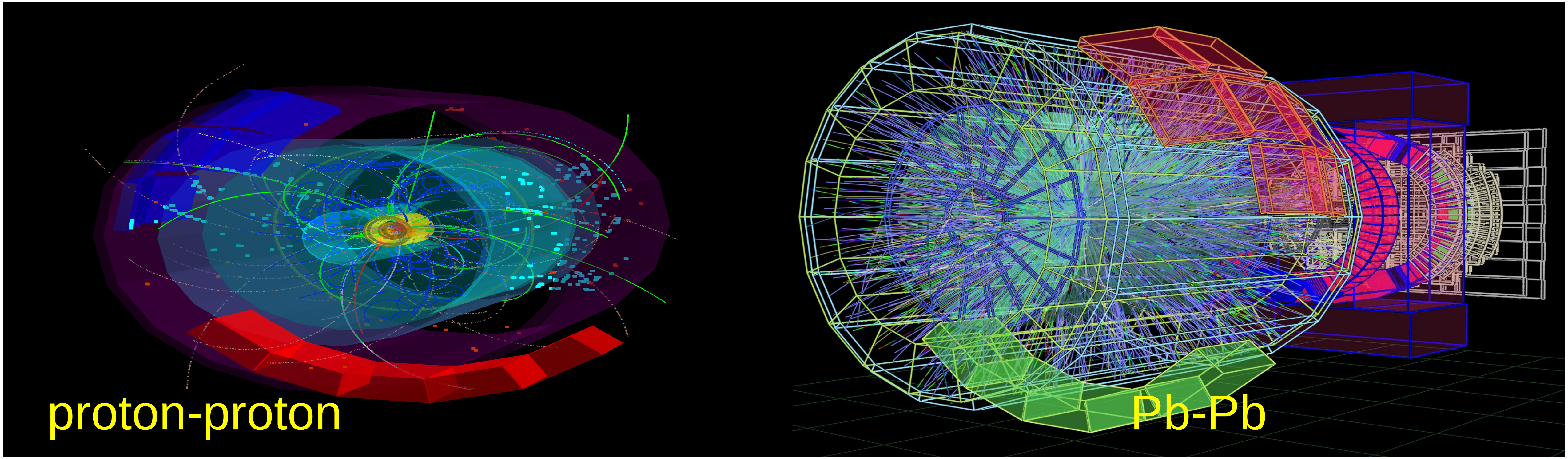
The structure of the ALICE detector



ALICE: Properties of the Primordial Matter



ALICE: Search for the perfect fluid...



Quar-Gluon Plasma (QGP):

- proton-proton vs. Pb-Pb
- hot, color (quark+gluon)
- superfluid
- This is a „perfect fluid“...

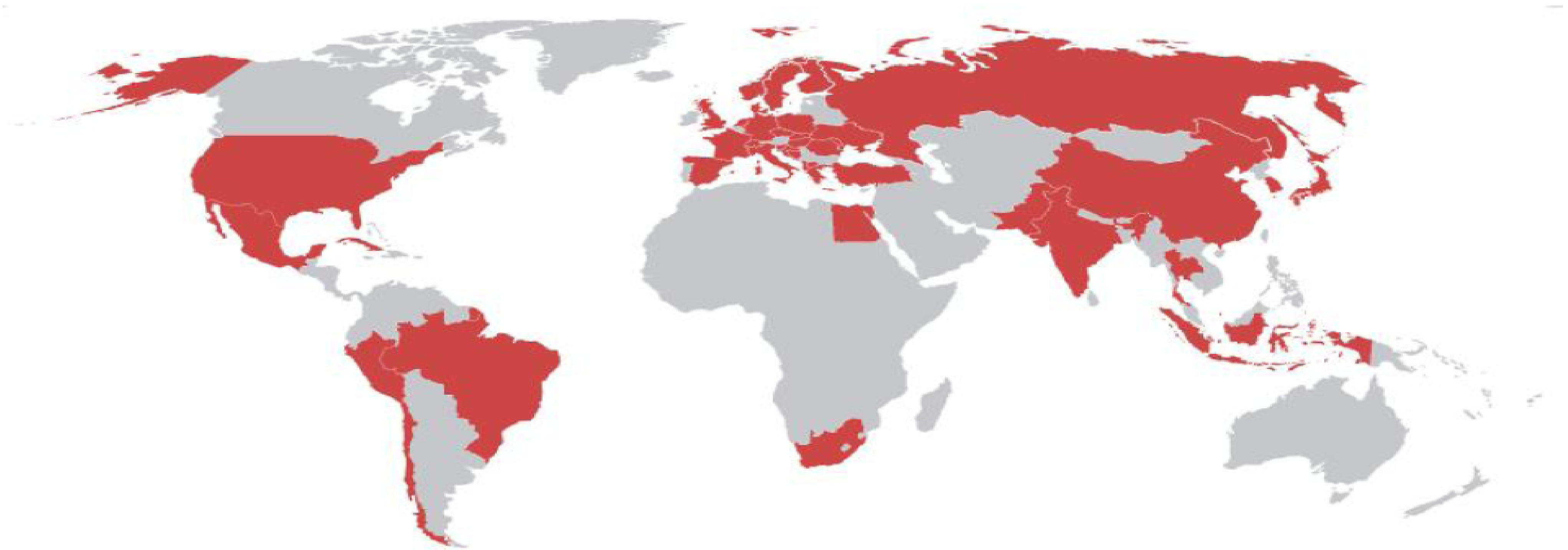
The Hungarian ALICE Group

Hungarian ALICE Group, Wigner RCP
of the HAS, Budapest Hungary

A Large Ion Collider Experiment

THE ALICE COLLABORATION

36 COUNTRIES – 151 INSTITUTES – 161’451 KCHF CAPITAL COST



Hungarian ALICE Group, Wigner RCP of the HAS, Budapest Hungary

A Large Ion Collider Experiment

THE ALICE COLLABORATION

History of the ALICE Experiment:

1990-1996 Design

1992-2002 R&D

2000-2010 Construction

2002-2007 Installation

2008 -> Commissioning

4 TP addenda along the way:

- 1996 Muon spectrometer
- 1999 TRD
- 2006 EMCAL
- 2007 DCAL

2012 LoI for the Upgrade

2012-2014 R&D

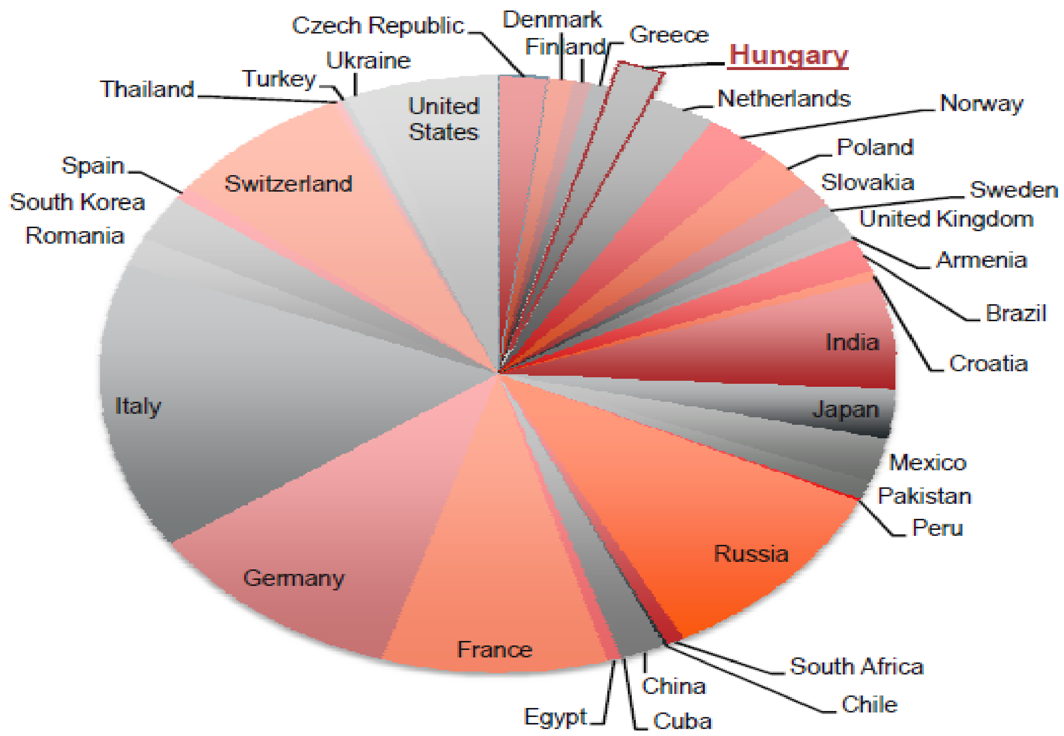
2014-2016 Procurement/Fabrication

2016-2017 Integration, pre-commissioning

2018-2019 Installation, commissioning

2019-2020 Full deployment of DAQ/HLT

The 1472 ALICE Collaborators by country



A Large Ion Collider Experiment

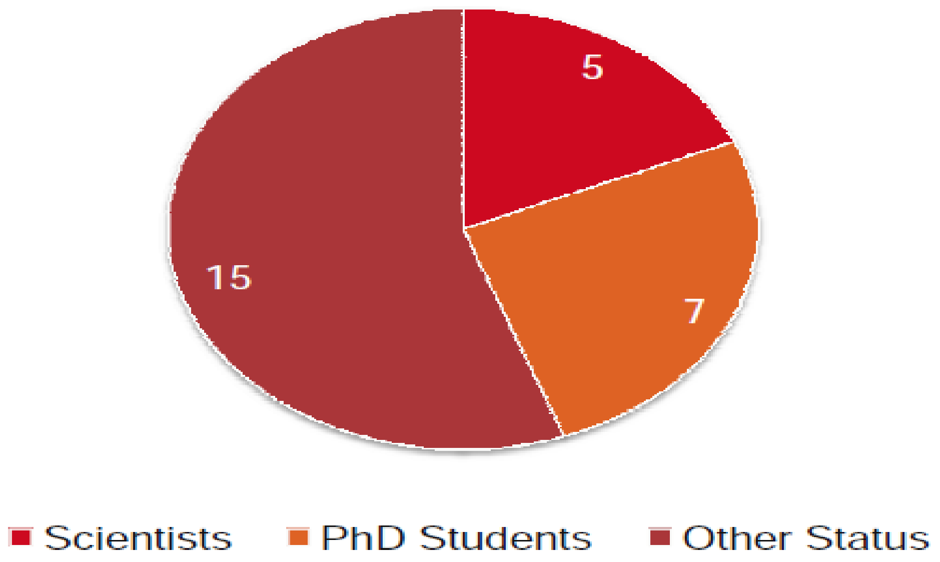
HUNGARIAN COLLABORATORS

27 Collaborators coming from

Wigner Research Centre for Physics

of the Hungarian Academy of Sciences

Collaborators by status



Team leader: Gergely G. Barnaföldi

A Large Ion Collider Experiment

HUNGARIAN FINANCIAL CONTRIBUTION - 1/3

FUNDING AGENCIES: NATIONAL INNOVATION OFFICE (NIH)
NATIONAL SCIENTIFIC RESEARCH FUND (OTKA)

- ✓ Construction: 522 kCHF including 400 kCHF for the Data Acquisition (DAQ) (CERN-RRB-2014-013)
- ✓ 2014 Maintenance and Operation (category A): 38.6 kCHF for 5 Scientists (CERN-RRB-2013-118)
- ✓ Common Fund for Upgrade: 43.7 kCHF for 5 Scientists (ALICE RRB-2013-125)
- ✓ DAQ Upgrade Project: 200 kCHF

HUNGARIAN FINANCIAL CONTRIBUTION - 2/3

FUNDING AGENCIES: NATIONAL INNOVATION OFFICE (NIH)
NATIONAL SCIENTIFIC RESEARCH FUND (OTKA)

Investment into the ALICE project in the WIGNER RCP, Hungary (salary of employed team members and experts, laboratories, etc.) during the 5 year period of 2009-2013:

- ✓ VHMPID project: 1 000 kCHF Letter of Intent, EPJ Plus 129 (2014) 91
- ✓ HMPID project: 200 kCHF (data analysis is running)
- ✓ DAQ Upgrade: 50 kCHF (in the period 2009-2013)
- ✓ TPC Upgrade: 150 kCHF (Wigner Innovative Detector Laboratory, 2013)

HUNGARIAN FINANCIAL CONTRIBUTION - 3/3

FUNDING AGENCIES: NATIONAL INNOVATION OFFICE (NIH)
NATIONAL SCIENTIFIC RESEARCH FUND (OTKA)

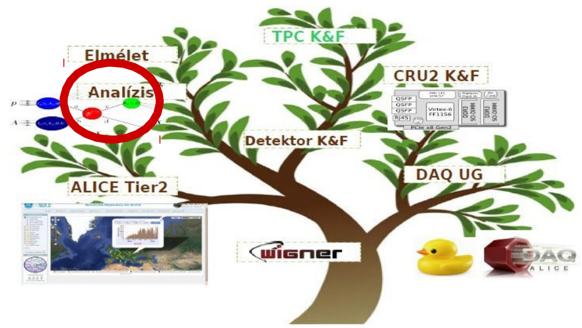
Wigner Research Centre for Physics group joined
to the TPC Upgrade project after the termination of the VHMPID:

- ✓ 5 researchers + students started to work
- ✓ Establishment of the Wigner Innovative Detector Laboratory in 2013
- ✓ 200 kCHF for TPC upgrade expected as yearly local cost (2014 -)

Hungarian ALICE Group, Wigner RCP of the HAS, Budapest Hungary

- DAQ – DAQ UG/service group
  - Strongly involved in the ALICE DAQ UG, CRU2 development
  - Kiss T, Dávid E, Imrek J, T.M. Nguyen
- P/A – Physics/Analysis group
  - High p_T, jets, PID, heavy quarks, correlation
  - BGG, Lévai P, Vértesi R, Varga-Kőfaragó M, Bencédi Gy, Szigeti B
- DDG – Detector Development group
  - Gaseous detector R&D, TPC UG,
  - Varga D, Boldizsár L, Hamar G, Gera Á
- GRID – ALICE Tier-2 Site
  - T2 Budapest: 1000 cores, 750 TB HDD
  - BGG, Bíró G

ALICE data analysis



ALICE data analysis – identified hadron spectra

- Measurement of high-pT hadron spectra
  with particle identfication (pion, kaon, proton)

- Complex task, done by many detector:

  TPC+TOF – Time Projection Chamber+Time of Flight

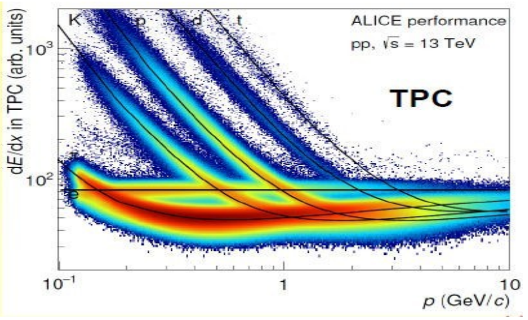
  – low p_T<1 GeV/c & high p_T> 5 GeV/c momentum region

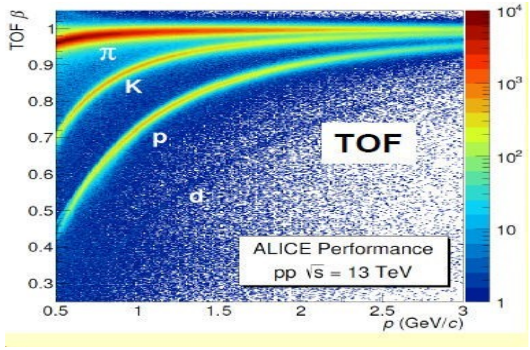
  HMPID – RICH, Cherenkov detector

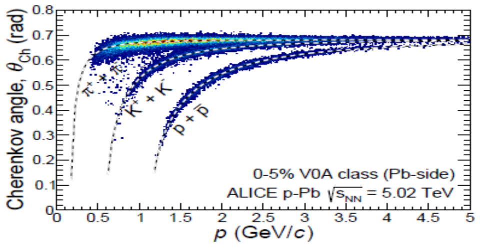
  – 1GeV/c <p_T < 5 GeV/c intermediate momenum region

  ITS – Secondary vertex method

- Identified hadron spectra
  → mass & flavor, triggered correlations

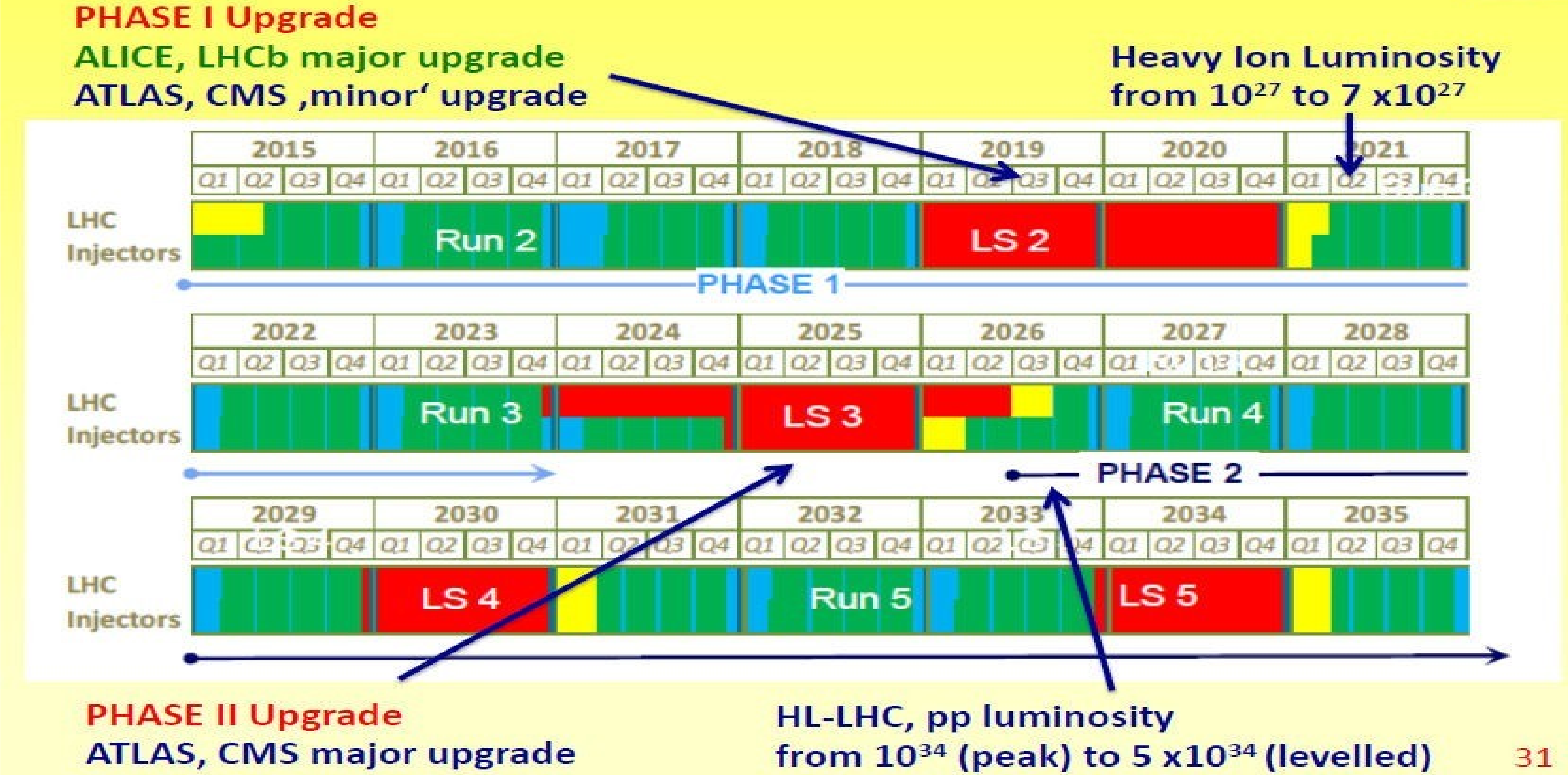




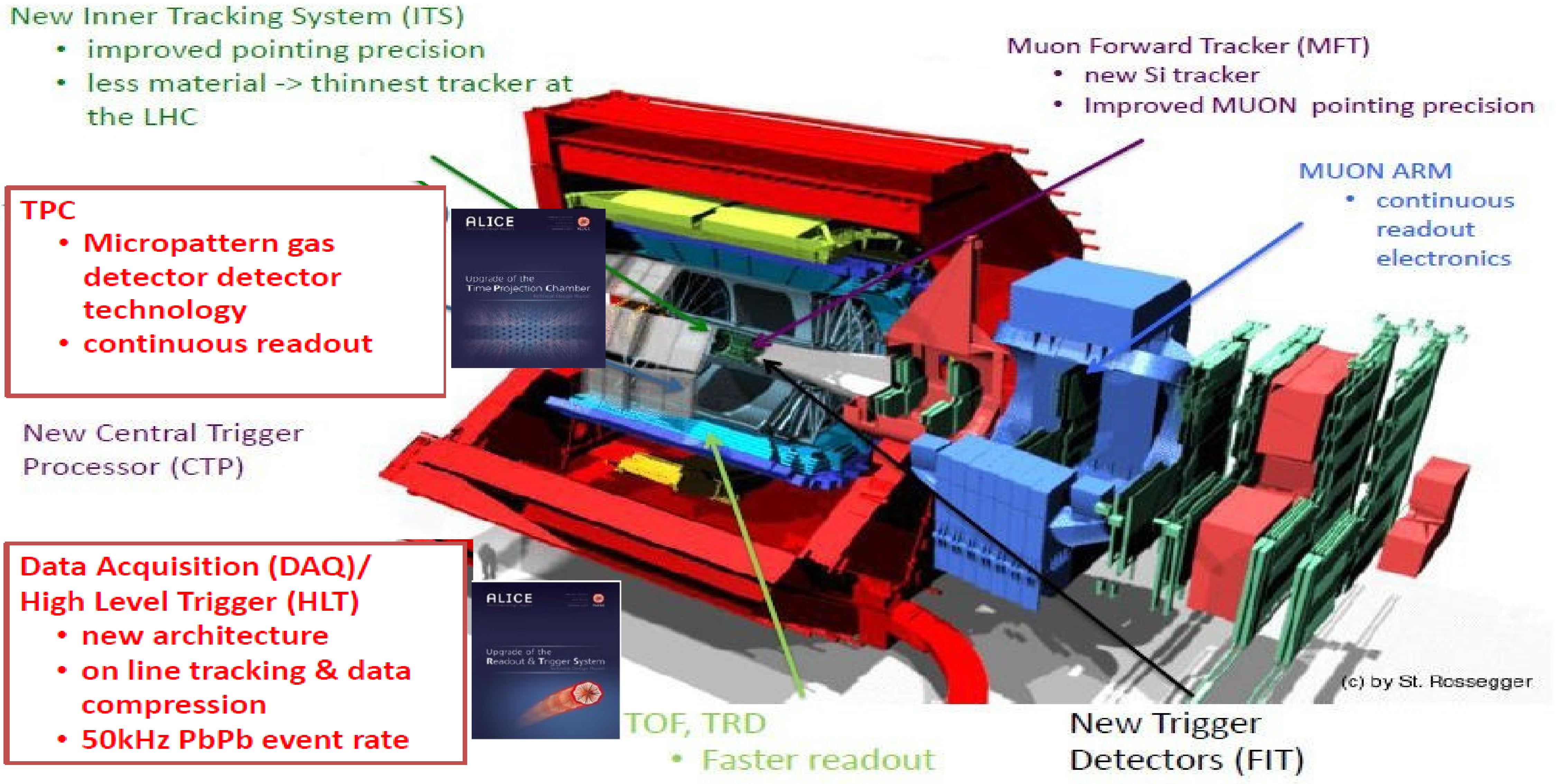


Participation in the ALICE upgrade (2018-2020)

The upgrade plane of the Large Hadron Collider (LHC)

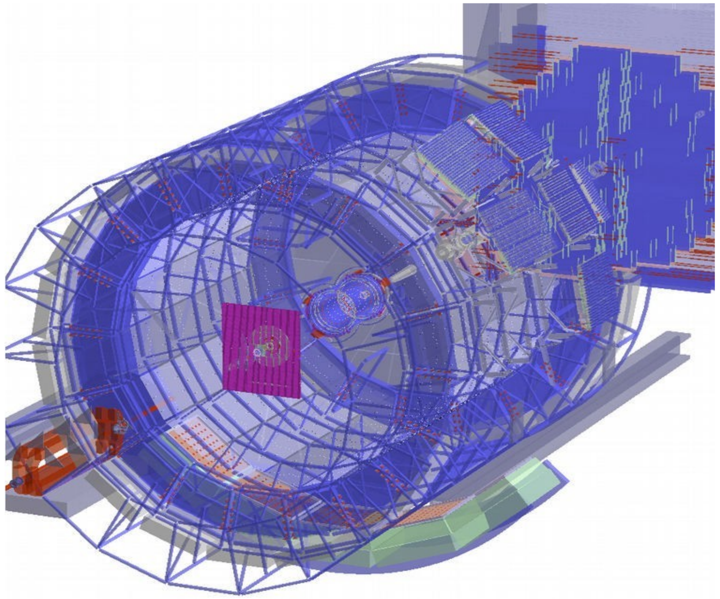


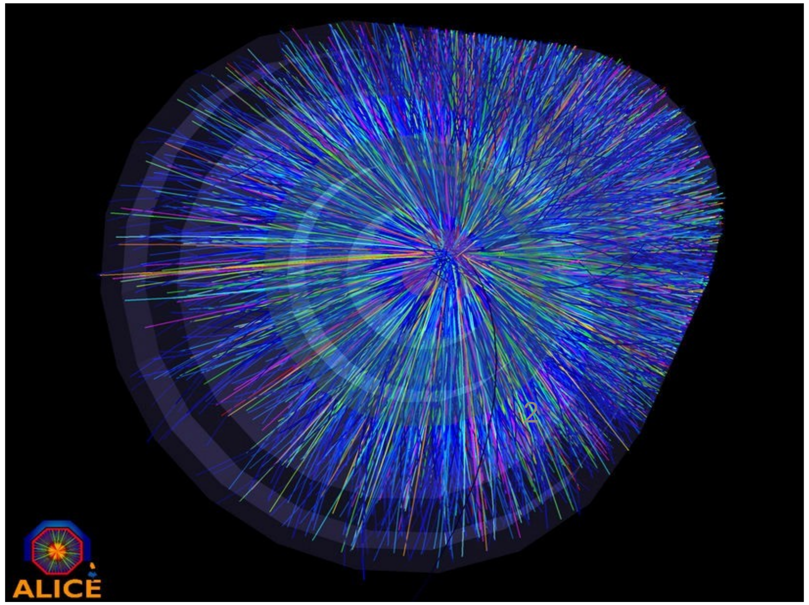
The upgrade of the ALICE detector during LS2



ALICE TPC: World’s Largest TPC

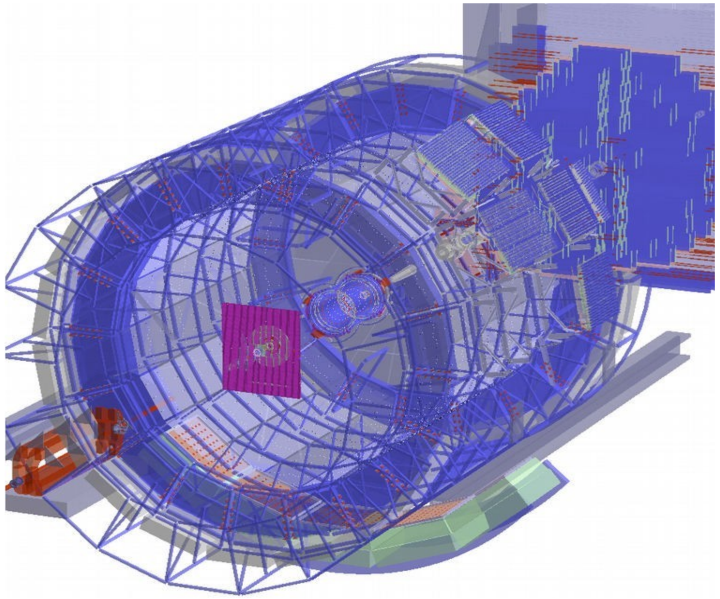
- Measuring the path of the particles with the World’s largest 90m3 Time Projection Chamber

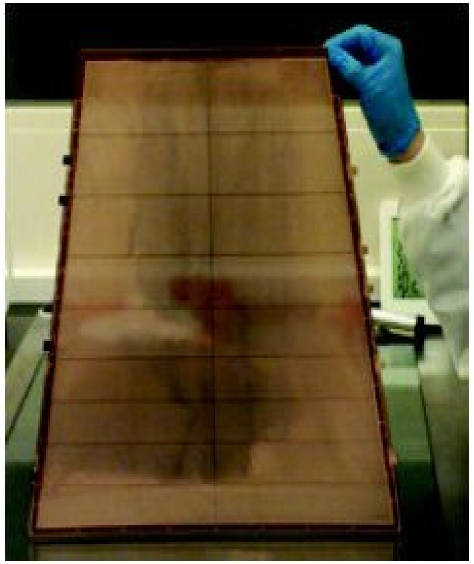


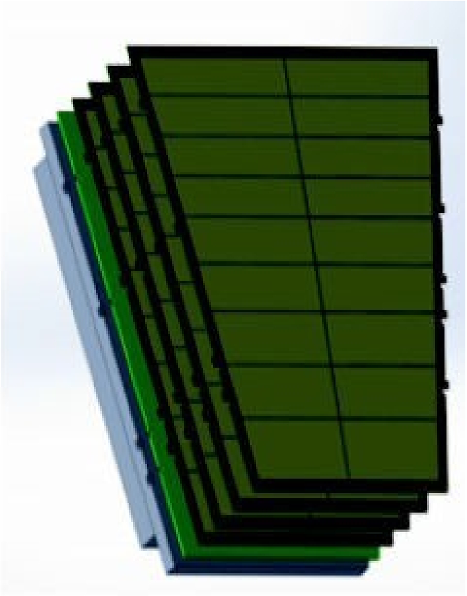


ALICE TPC: World’s Largest GEM-TPC

- Measuring the path of the particles with the World’s largest 90m3 Time Projection Chamber

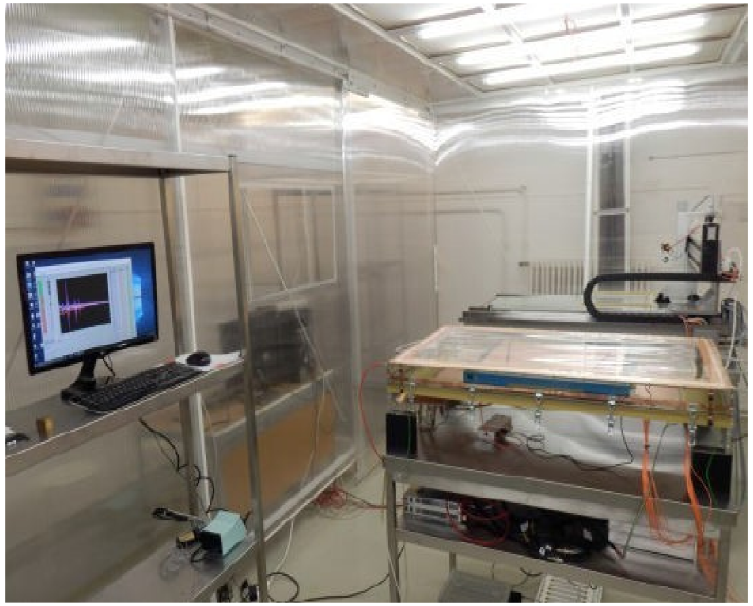


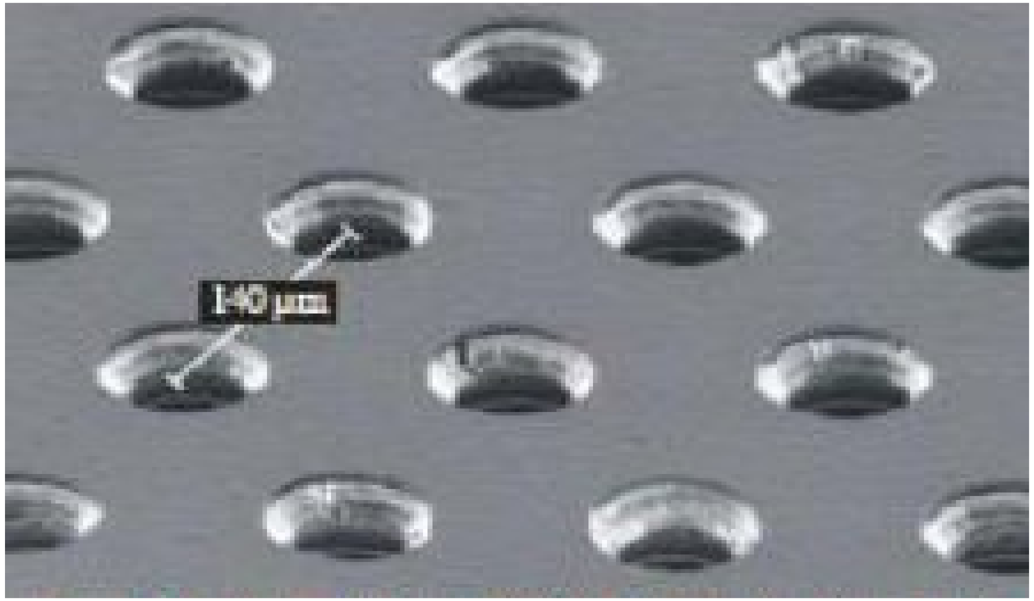




ALICE TPC: World’s Largest GEM-TPC

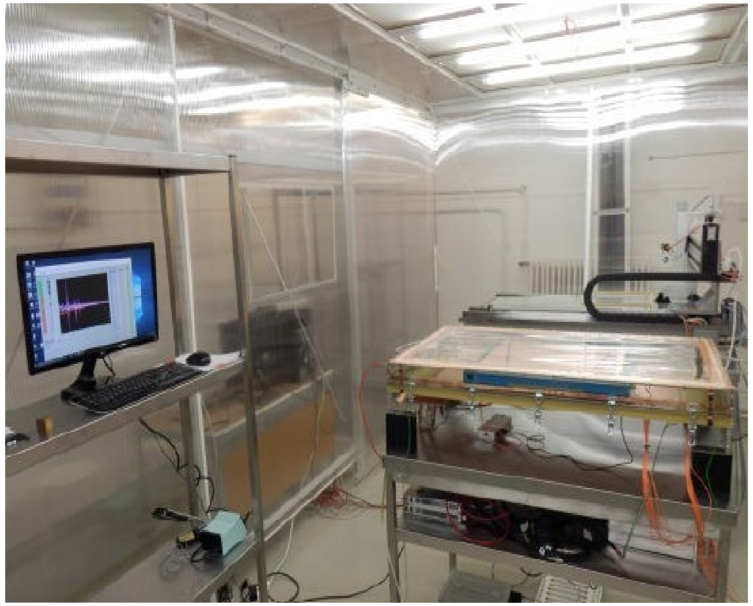
- Measuring the path of the particles with the World’s largest 90m3 Time Projection Chamber

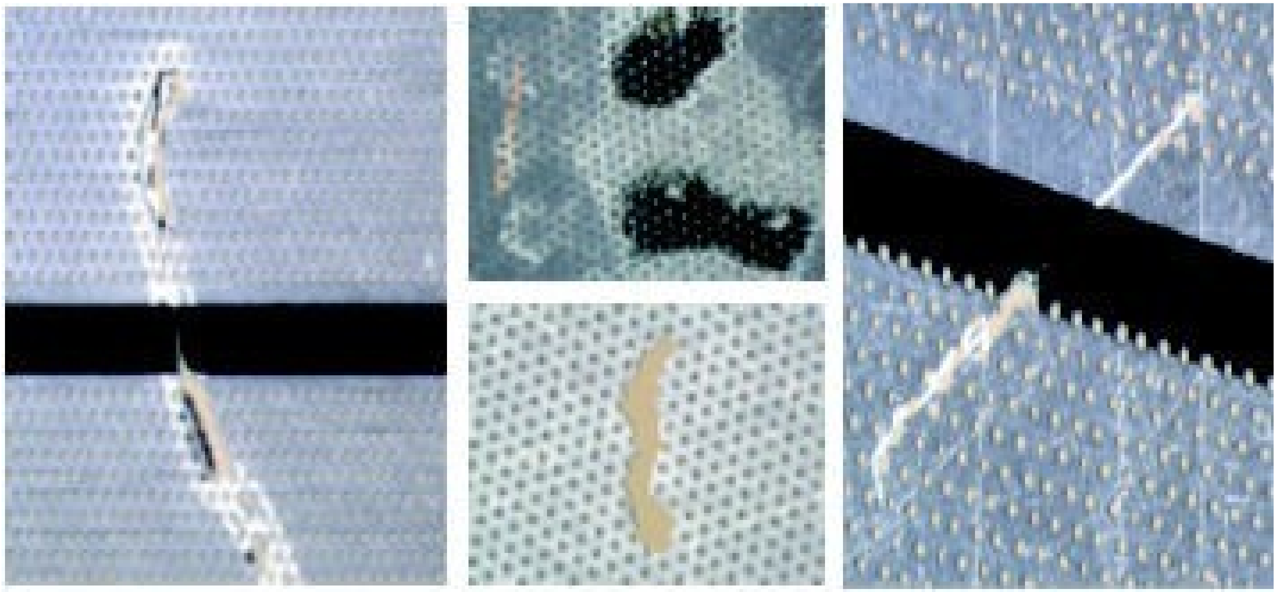




ALICE TPC: World’s Largest GEM-TPC

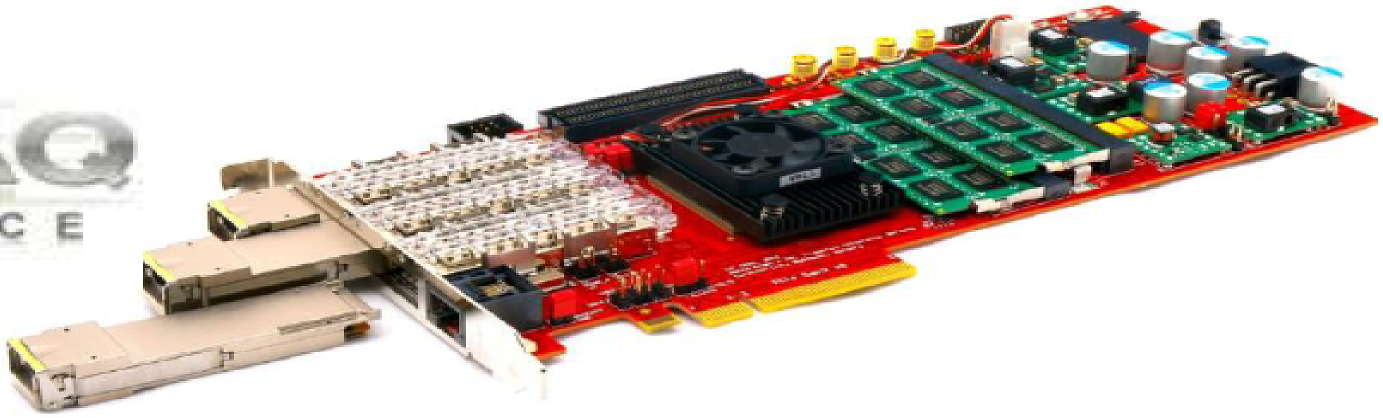
- Measuring the path of the particles with the World’s largest 90m3 Time Projection Chamber





HUNGARIAN CONTRIBUTION TO DATA ACQUISITION (DAQ)

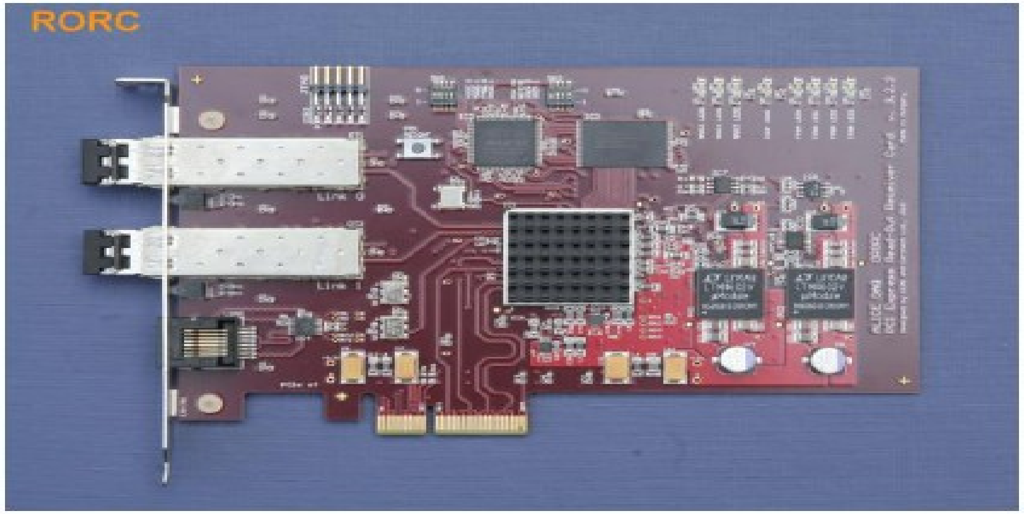
- Major role in the ALICE DAQ system
- Designed and produced the optical links (DDLs) and the computer adapters for these links (D-RORCs) which transmit the data from all the detectors to the DAQ computers. There are currently 500 DDLs running at 2 Gbit/s in use in ALICE.



HUNGARIAN CONTRIBUTION TO DATA ACQUISITION

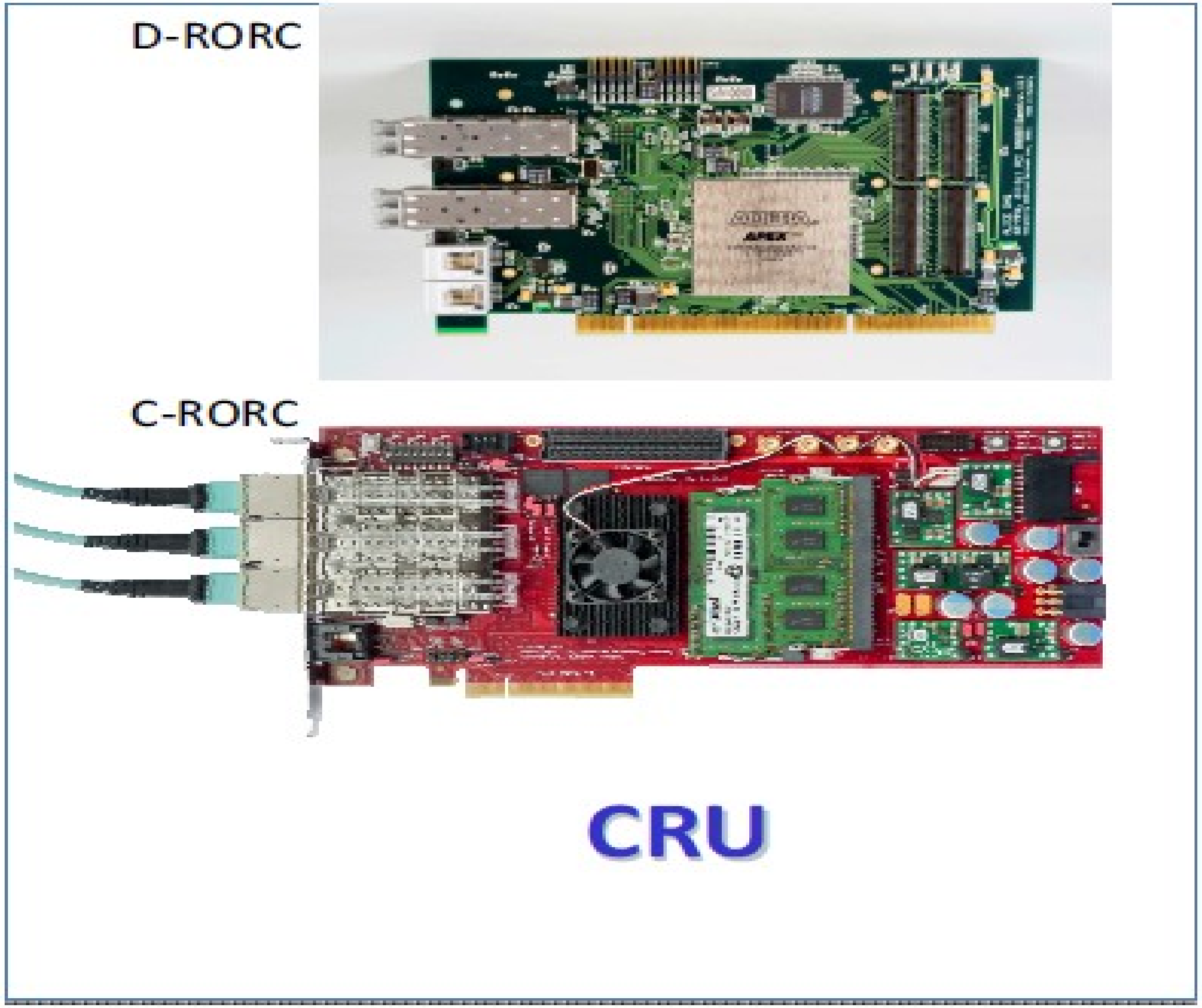
ALICE

- Providing a **readout bandwidth of 1 Tbit/s**. They are also used in the reverse direction to configure the electronics of some detectors (e.g. TPC or MCH). The same links are used to transmit the data to the HLT computers.
- Developed the system drivers used with the DDLs and the DRORCs.
- Funded the DDLs and part of the D-RORCs.



SIU

ALICE DDL/DAQ: data on the Highway



- Standardised detector data links (DDL) as the common interface between the detectors read-out and the DAQ (online system)

- Run1:
- **2.125 Gb/s custom DDL & D-RORC**

- Run2:
- **4.25 Gb/s custom DDL2 & C-RORC**

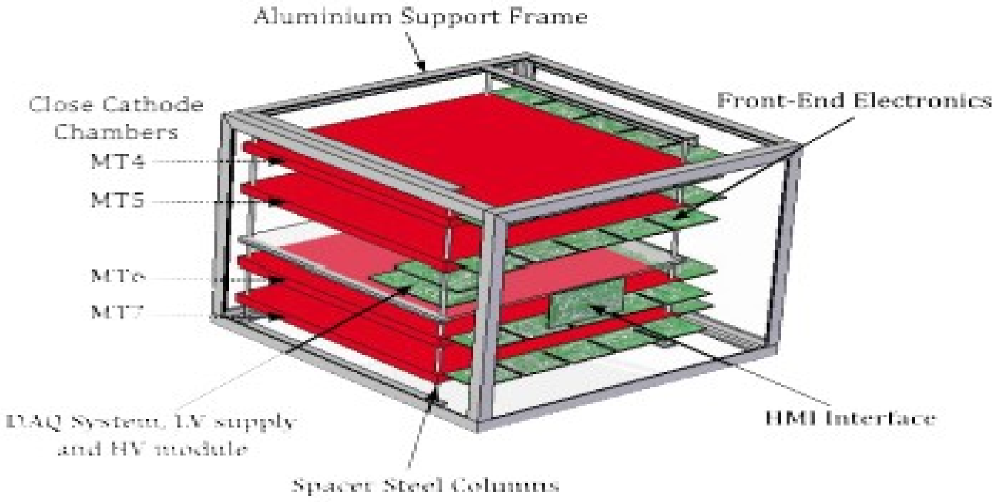
- Run3:
- **Common Read-out Units (CRUs) as common detector, an trigger, and control interface**
- **10..40 Gb/s commercial DDL3**
  (10 GbE or PCI Express over fiber)

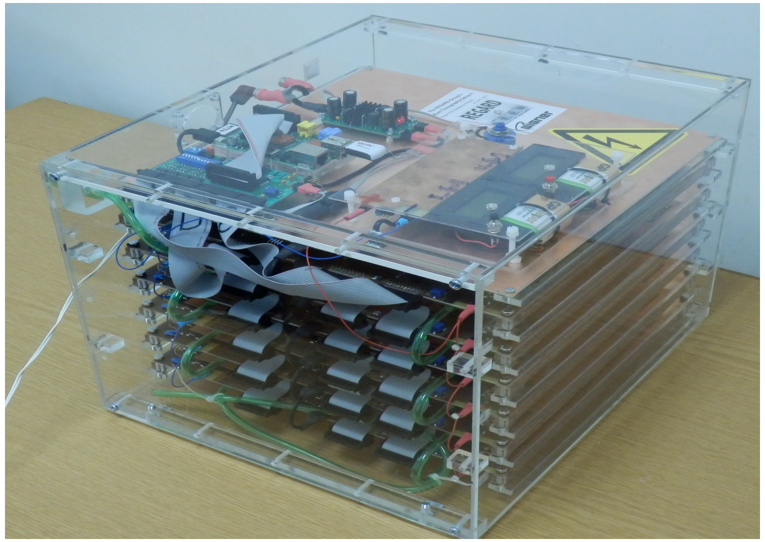
Collaborations in Applied Physics

Cosmic Muon Tomography

Mountomograph

- Size: 50x50x50 cm3
- Sensitive area: about a A4 page
- Resolution < 10 mrad
- Mass: 10-13 kg
- Power consumption: < 5W
- Gas Ar+CO2 1l/hour
- For sale 3000 EUR+TAX+shipment

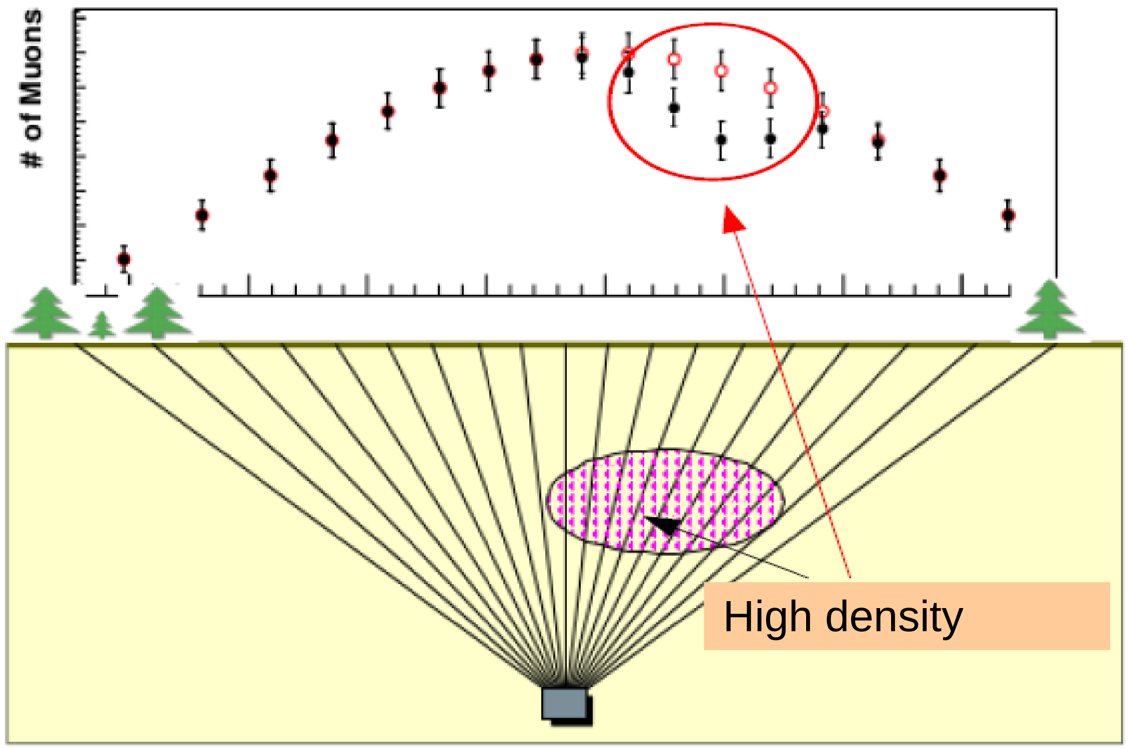




Cosmic Muon Tomography

Mountomograph – the idea

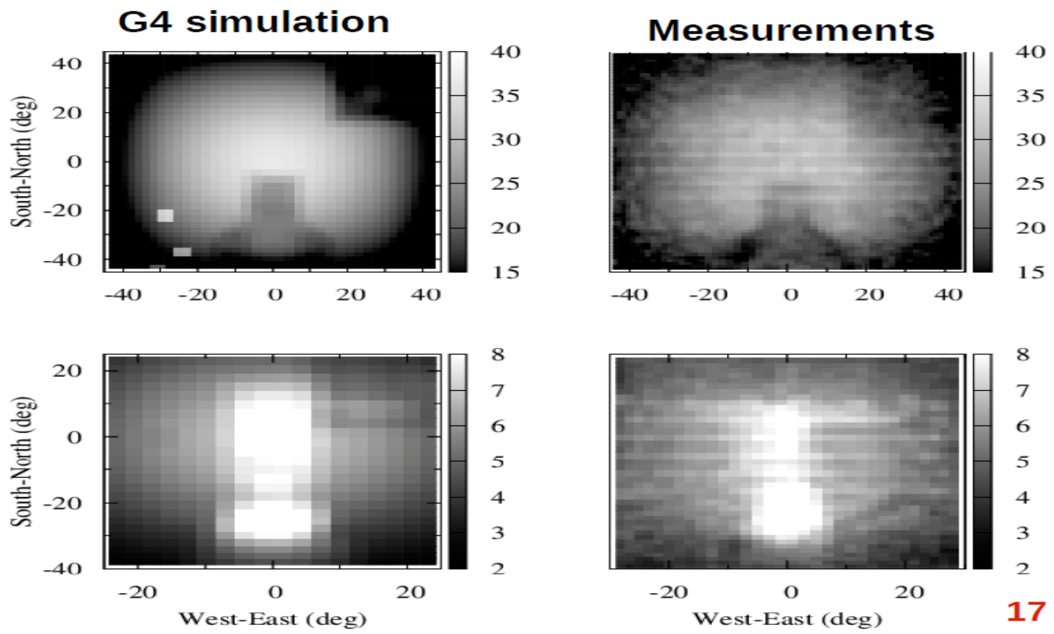
- Cosmic muon angular distribution & flux is well known
- Underground measurements can be done to measure large-scale inhomogenities
- It can be used to explore undergound structures: caves, pyramids, pipes, mines, volcanoes..

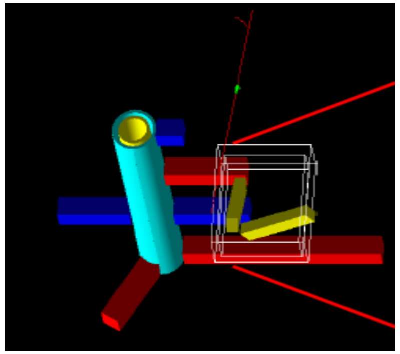


Cosmic Muon Tomography

Mountomograph references

- HZDR Dresden, Germany
  Underground Laboratory background
- Saud Arab Emirates
  Archeology & mine technology
- University of Tokyo, Japan
  Volcano Scanning for eruption research
- Hungary
  Speleology (cave research)
  Civil Engineering
  Homeland Security

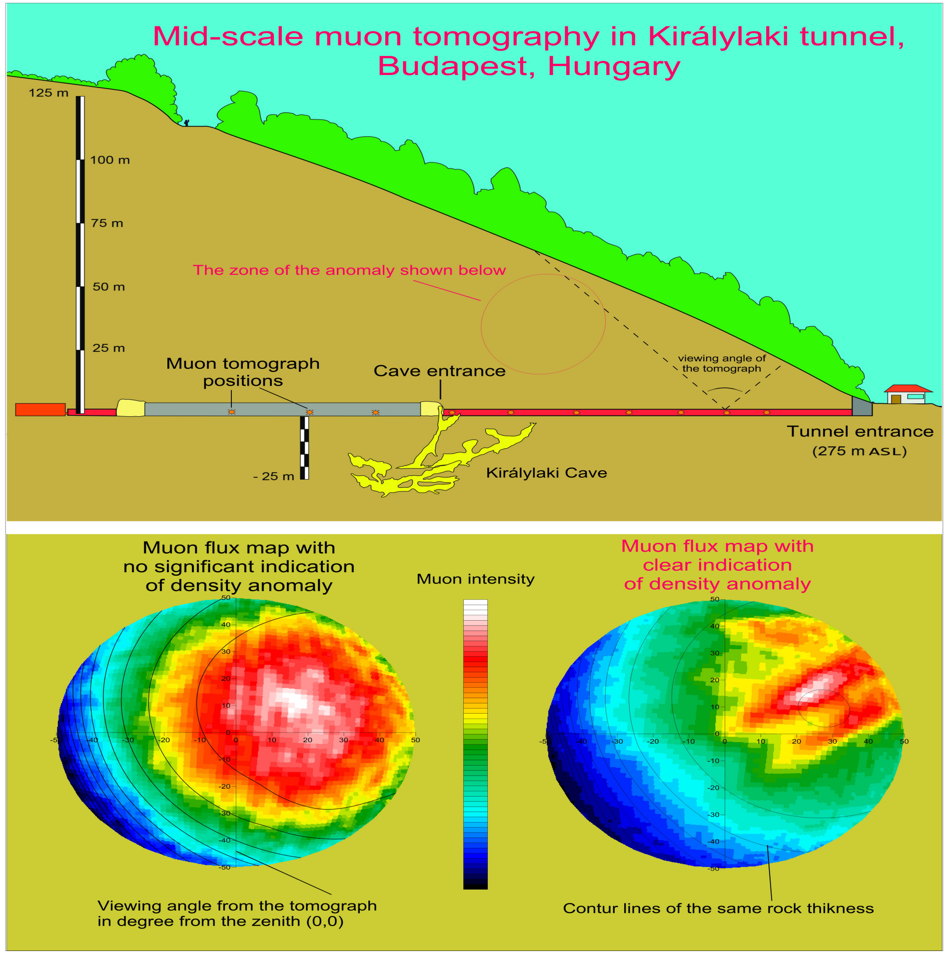




Cosmic Muon Tomography

Mountomograph references

- HZDR Dresden, Germany
  Underground Laboratory background
- Saud Arab Emirates
  Archeology & mine technology
- University of Tokyo, Japan
  Volcano Scanning for eruption research
- Hungary
  Speleology (cave research)
  Civil Engineering
  Homeland Security



Particle physics against cancer...

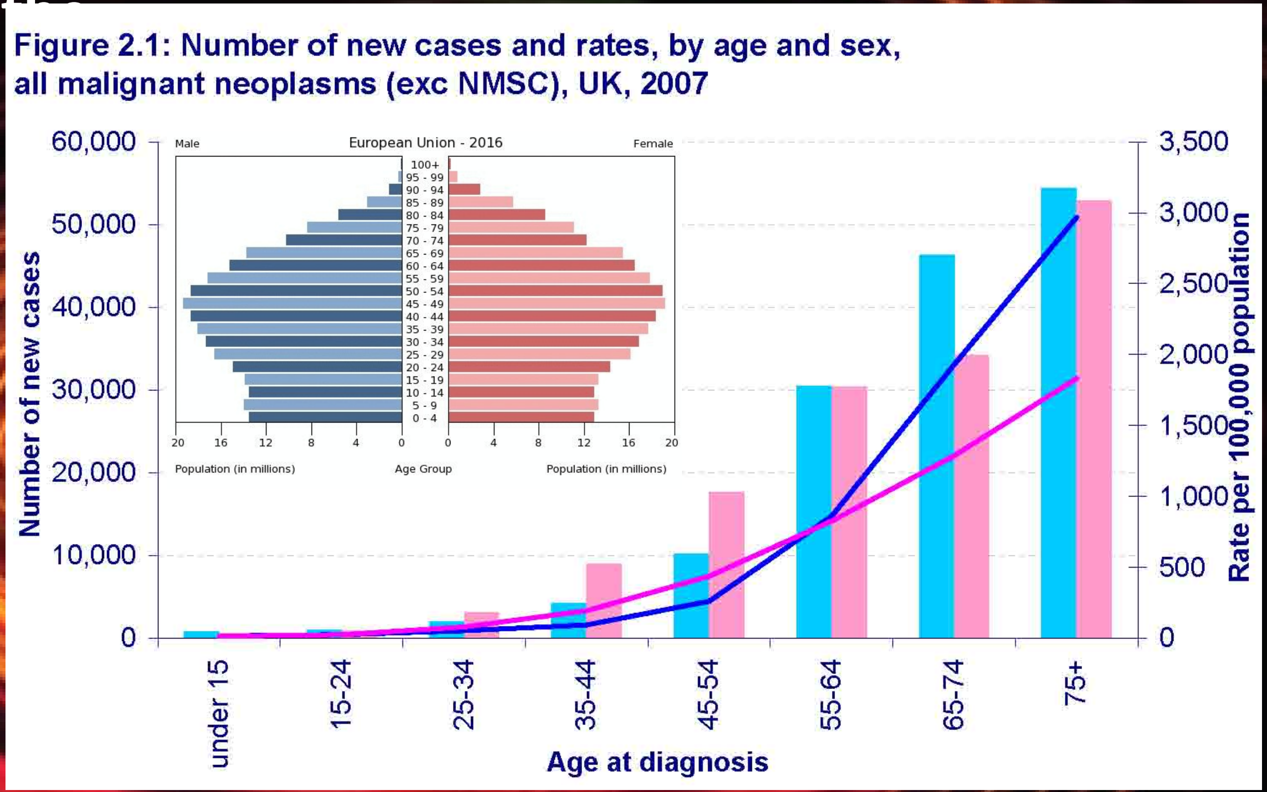
Radiotherapy is an important weapon in the battle against cancer

Contributions to successful treatment of cancer

45-50% surgery

40-50% radiotherapy

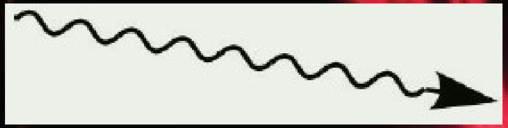
10-15% chemotherapy



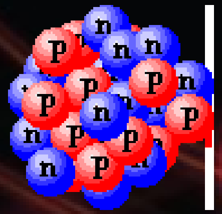
Particle physics against cancer...

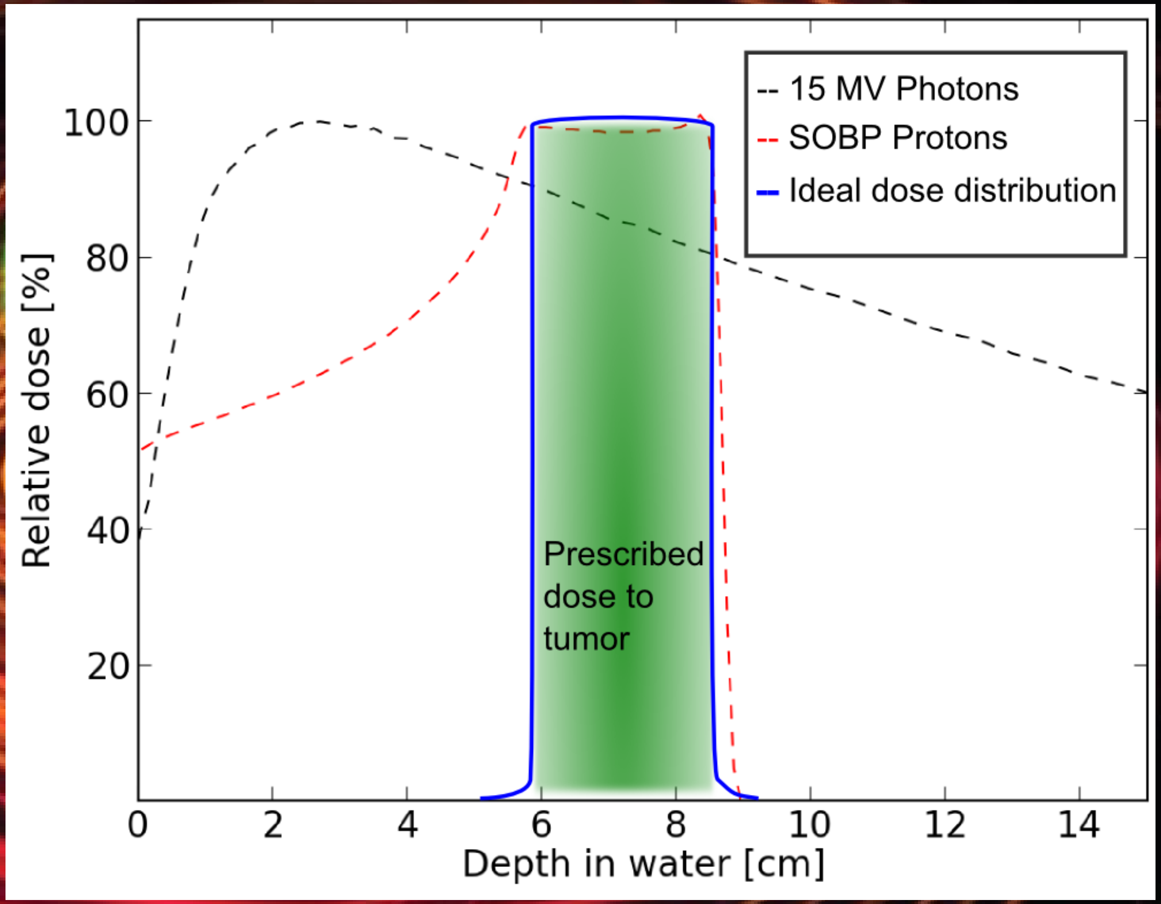
The goal of radiation therapy is to irradiate the tumor with the prescribed dose and minimize the dose to healthy tissue

Photons (electromagnetic):



Hadrons (proton, nuclei):

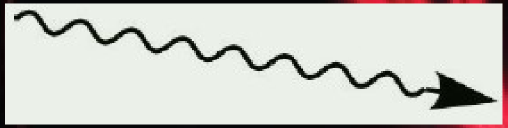




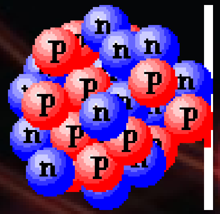
Particle physics against cancer...

The goal of radiation therapy is to irradiate the tumor with the prescribed dose and minimize the dose to healthy tissue

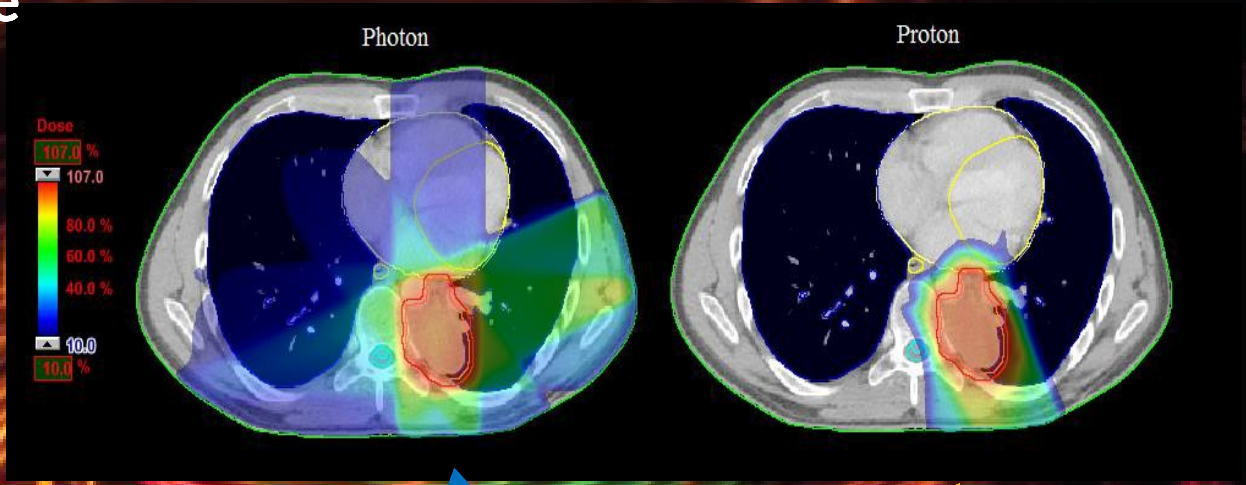
Photons (electromagnetic):

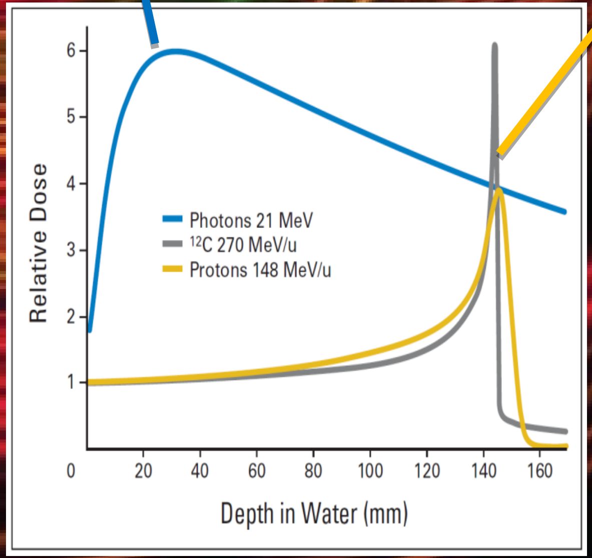


Hadrons (proton, nuclei):

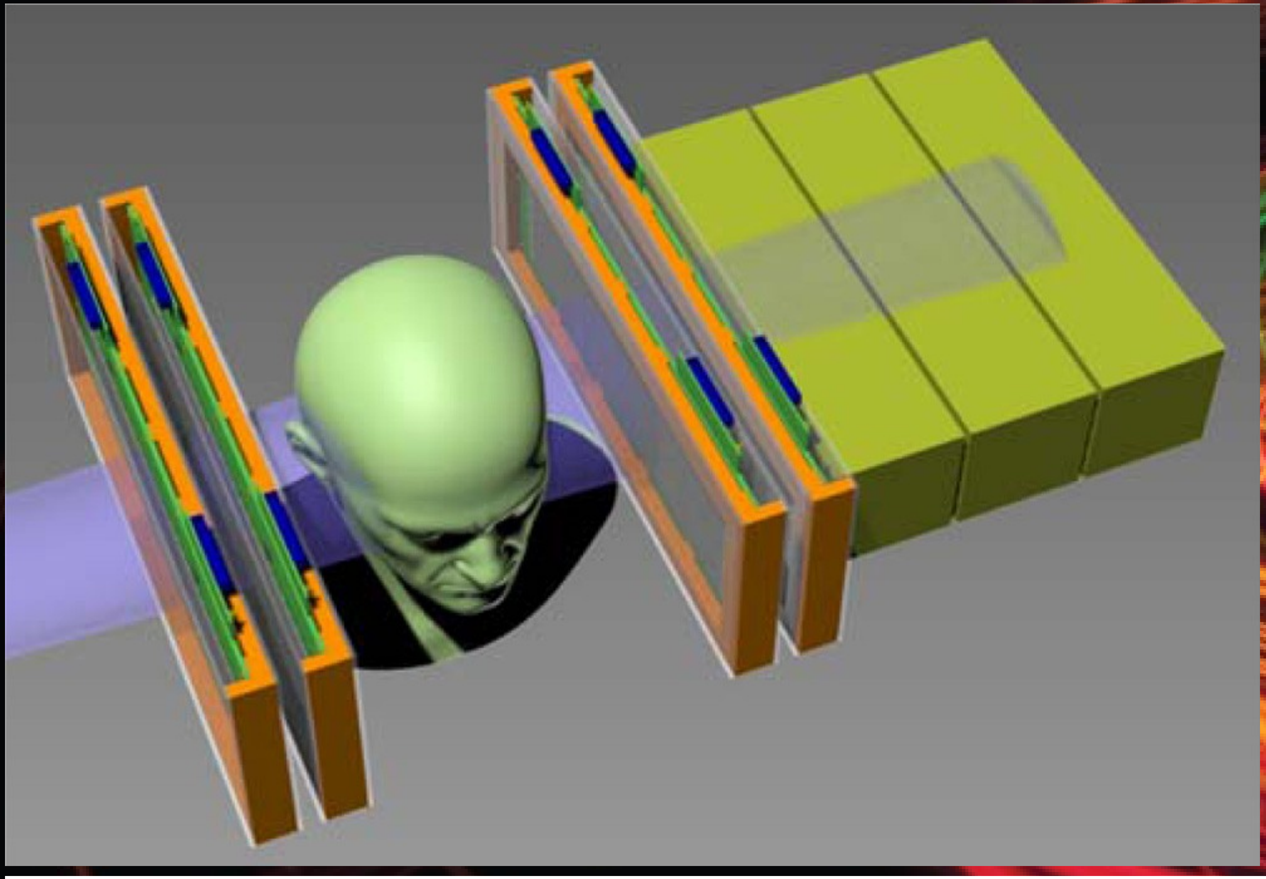


Figur fra Engeseth, GM (Haukeland)





pCT project



H.F.-W. Sadrozinski / Nuclear Instruments and Methods in Physics Research A 732 (2013) 34–39

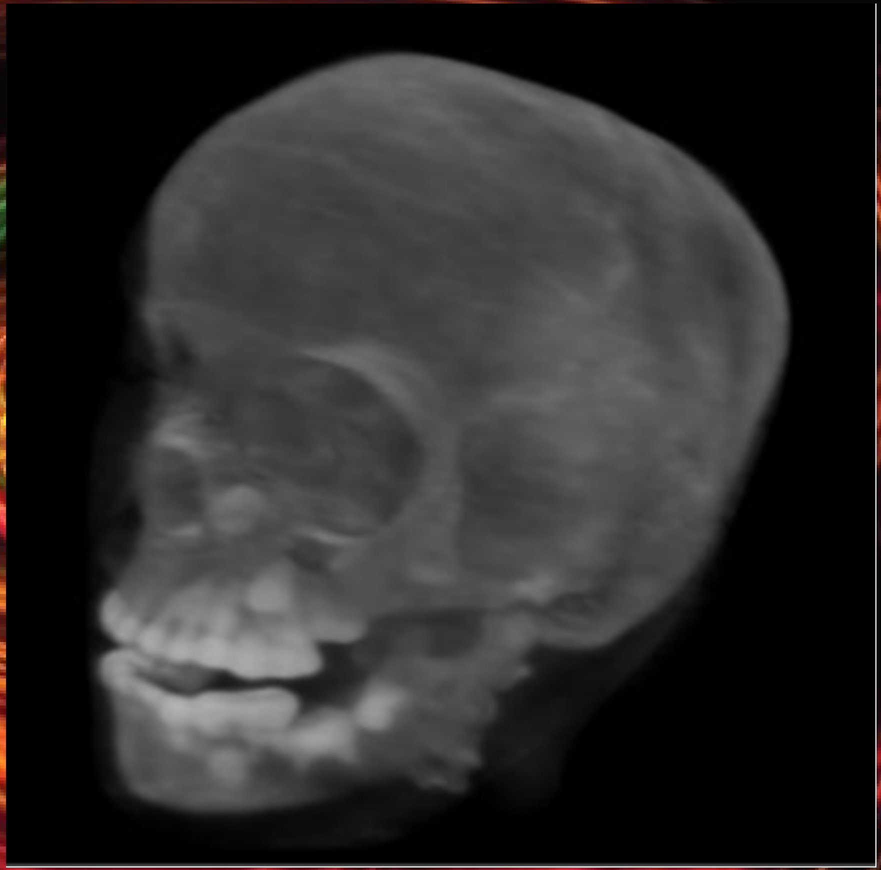
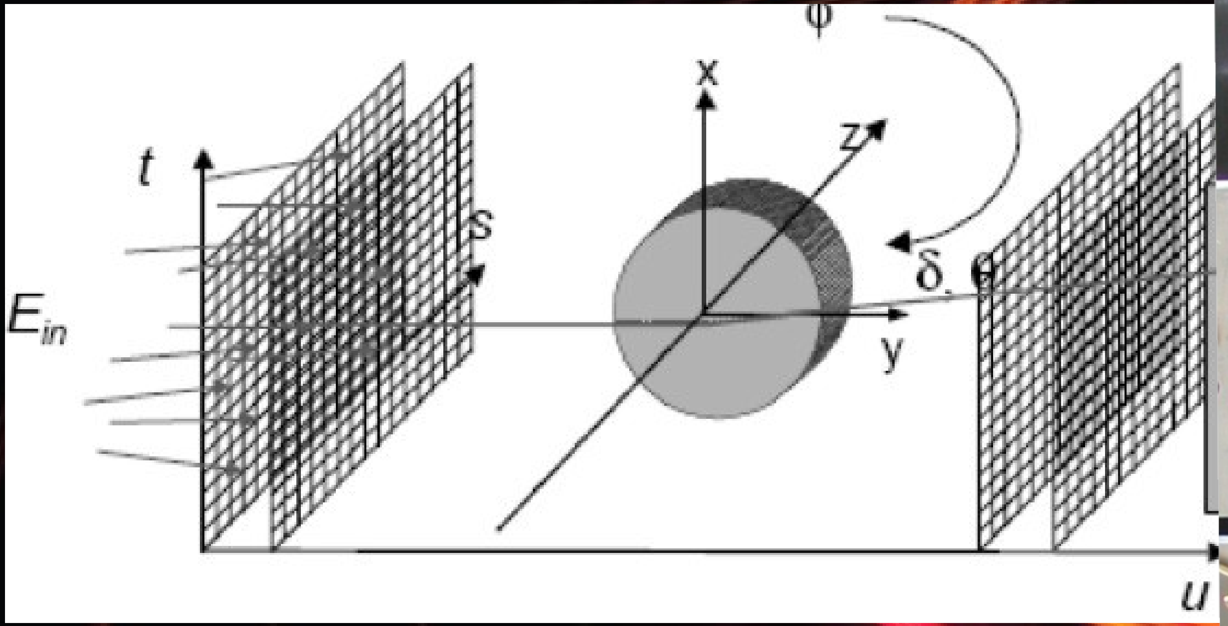
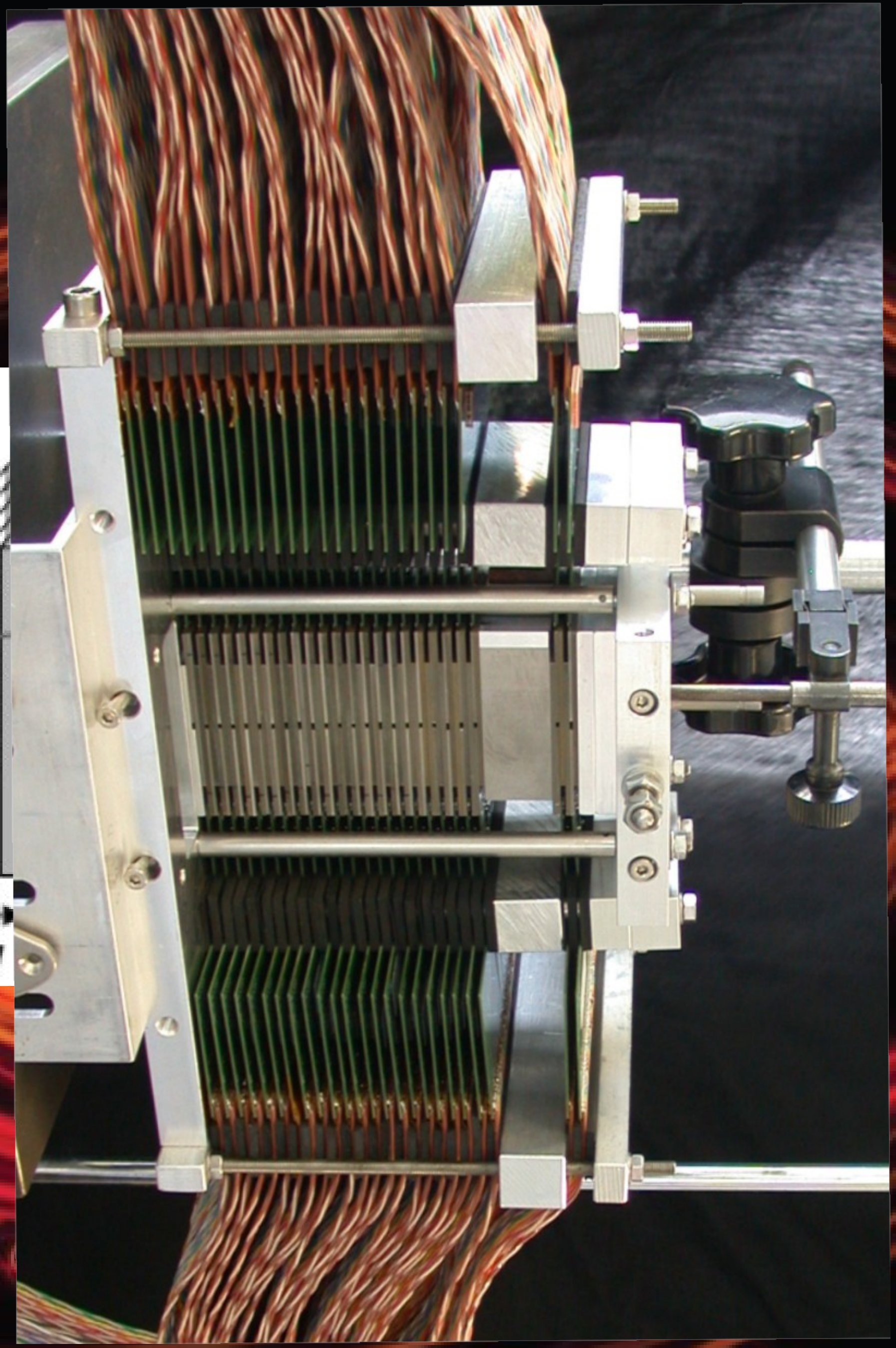


Fig. 14. 3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom.

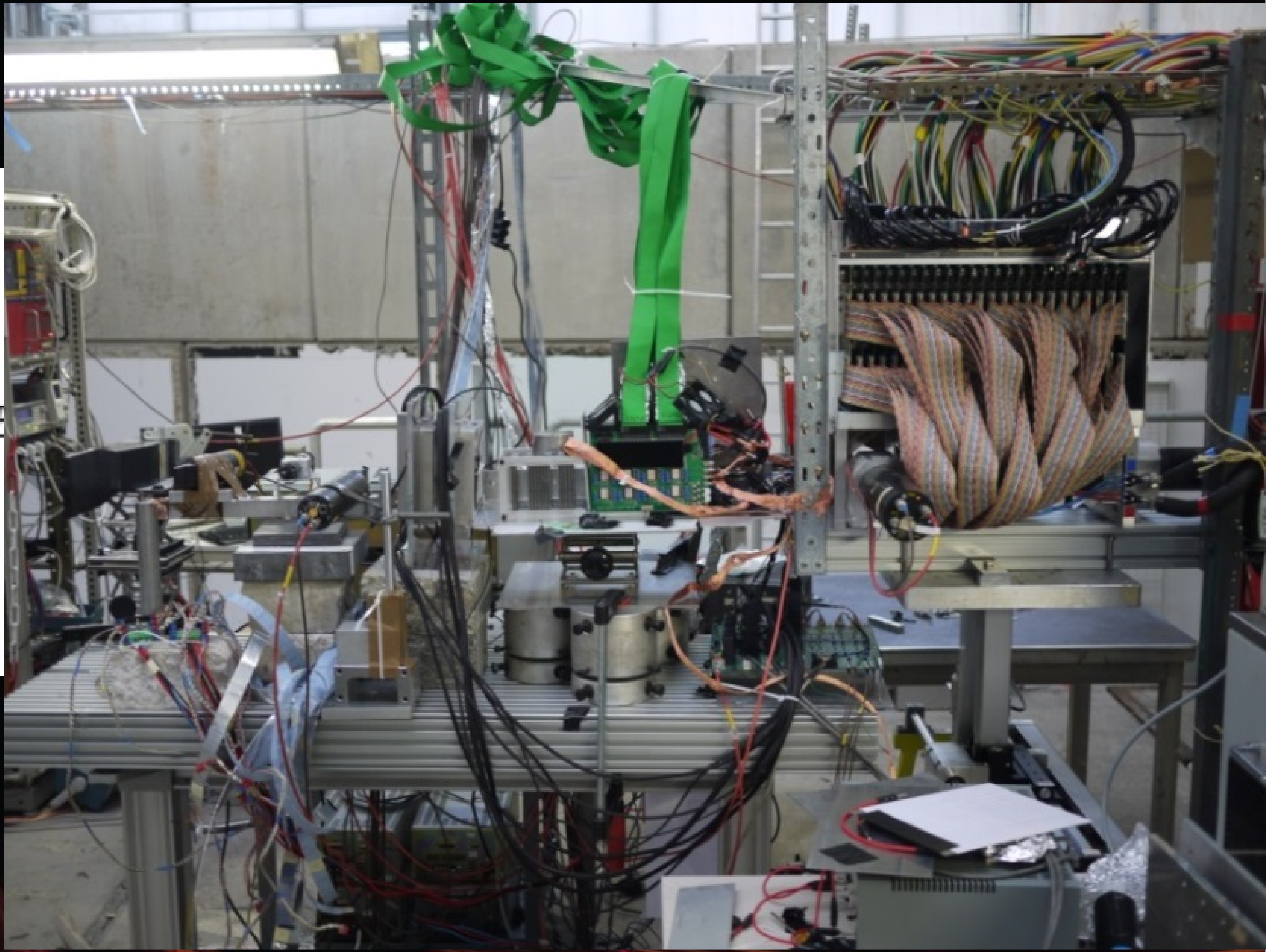
V.A. Bashkirov et al. / Nuclear Instruments and Methods in Physics Research A 809 (2016) 120–129

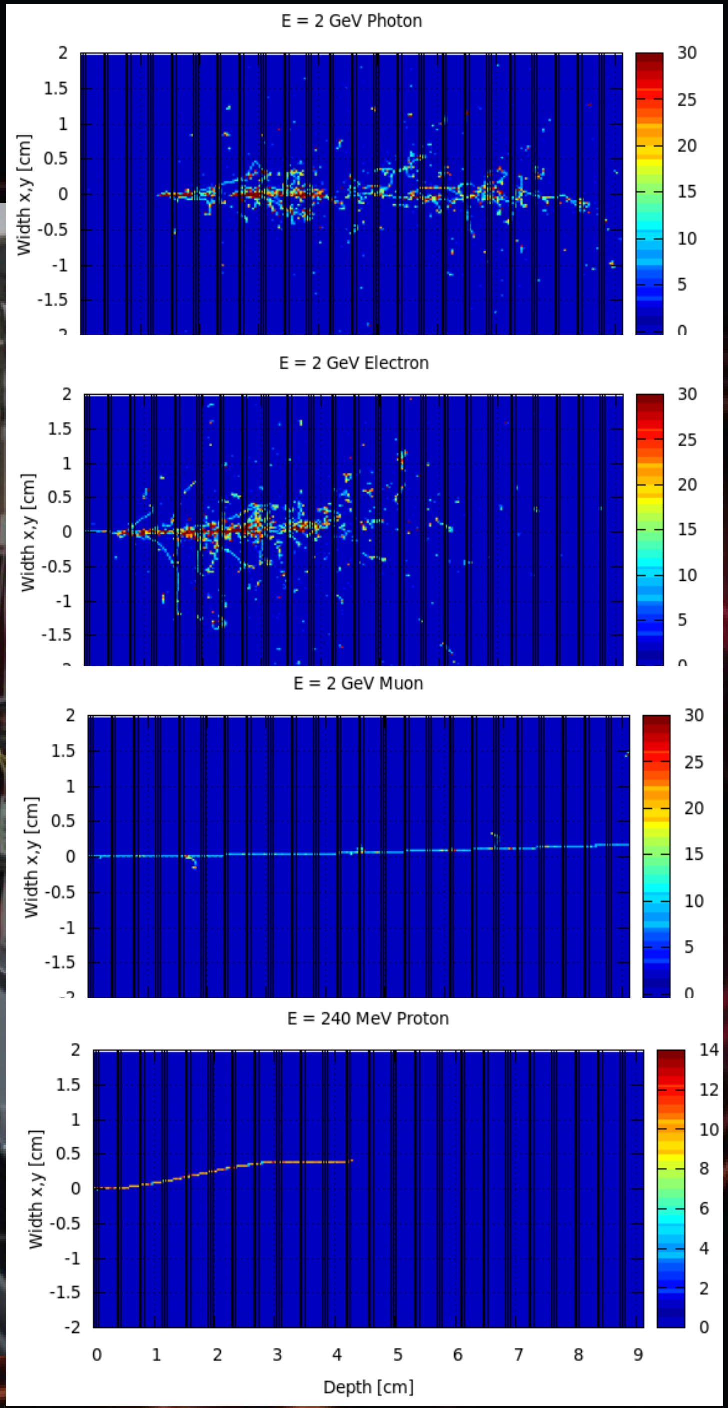
pCT project





pCT project





E = 2 GeV Photon
E = 2 GeV Electron
E = 2 GeV Muon
E = 240 MeV Proton
Width x,y [cm]
Depth [cm]

Computing: Wigner GPU Laboratory

Software R&D for parallel computing

Wigner GPU Laboratory

- gpu.wigner.mta.hu
- GPU Day – Schools & Workshops
- Support of projects
- Academy: WDC, CERN Openlab
- Partners: Lombiq,KHRONOS
- ColSpotting: CERN IT as USER(!)
- 2 years of running:
  - Fellowships (1-2 month)
  - 10 IF papers
  - 3-5 ongoing projects

We Offer

Development environment for GPU codes

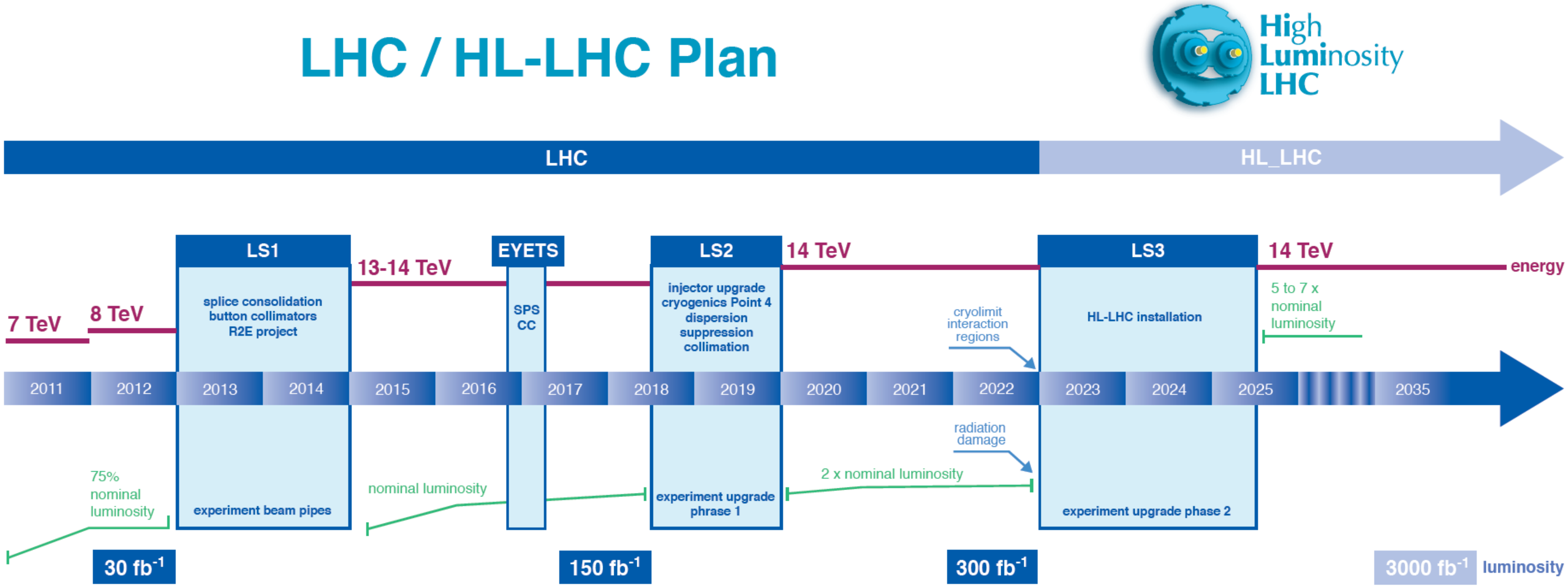
The machines of the GPU Lab are built to be a testbed for experimenting with the different GPU technologies and to test algorithms utilizing multiple cards. There are configurations hosting NVIDIA cards with CUDA support and OpenCL capable devices in the form of AMD GPUs and Intel Xeon Phis

Developer assistance and consulting

The associates of the GPU Lab are keen to help in understanding the architecture of CPU and GPU hardware and answer the questions arising in programming and API usage.

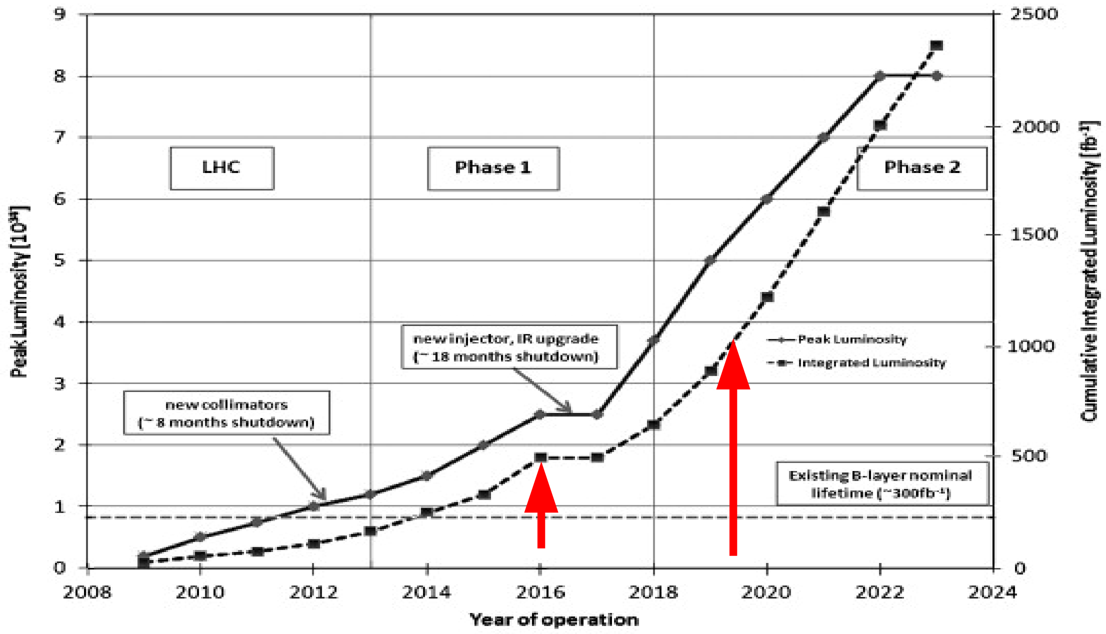
HI data from the Large Hadron Collider

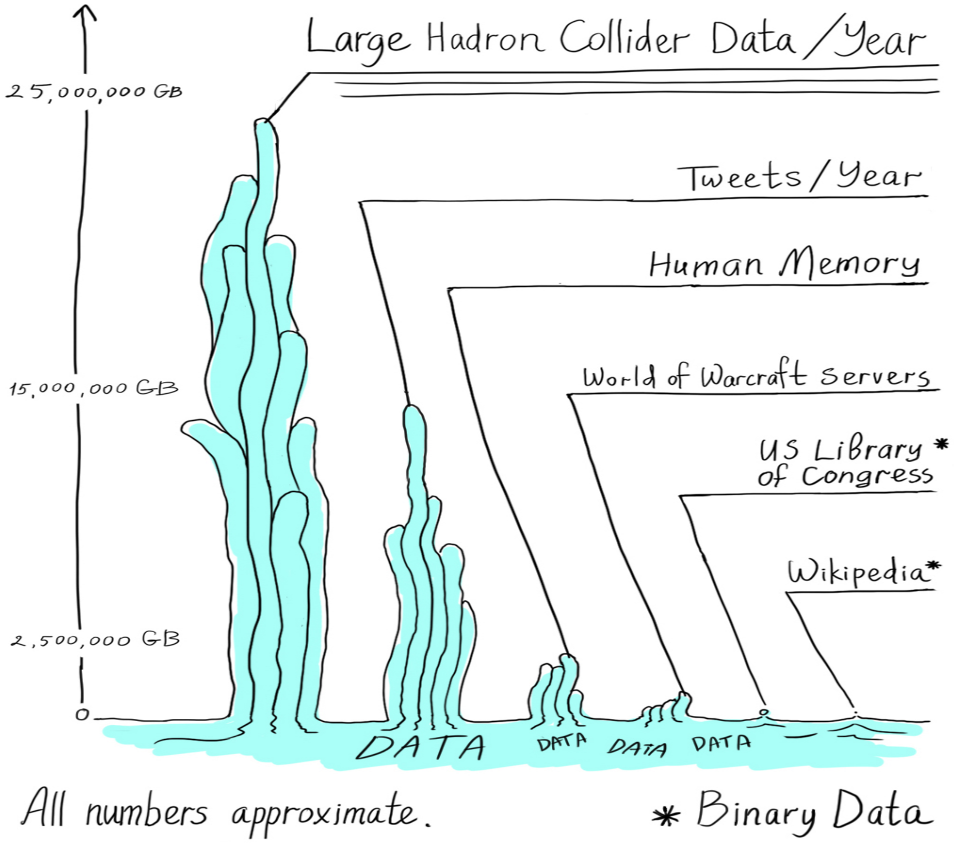
- LHC upgrades & theories required more and faster HI simulations



HI data from the Large Hadron Collider

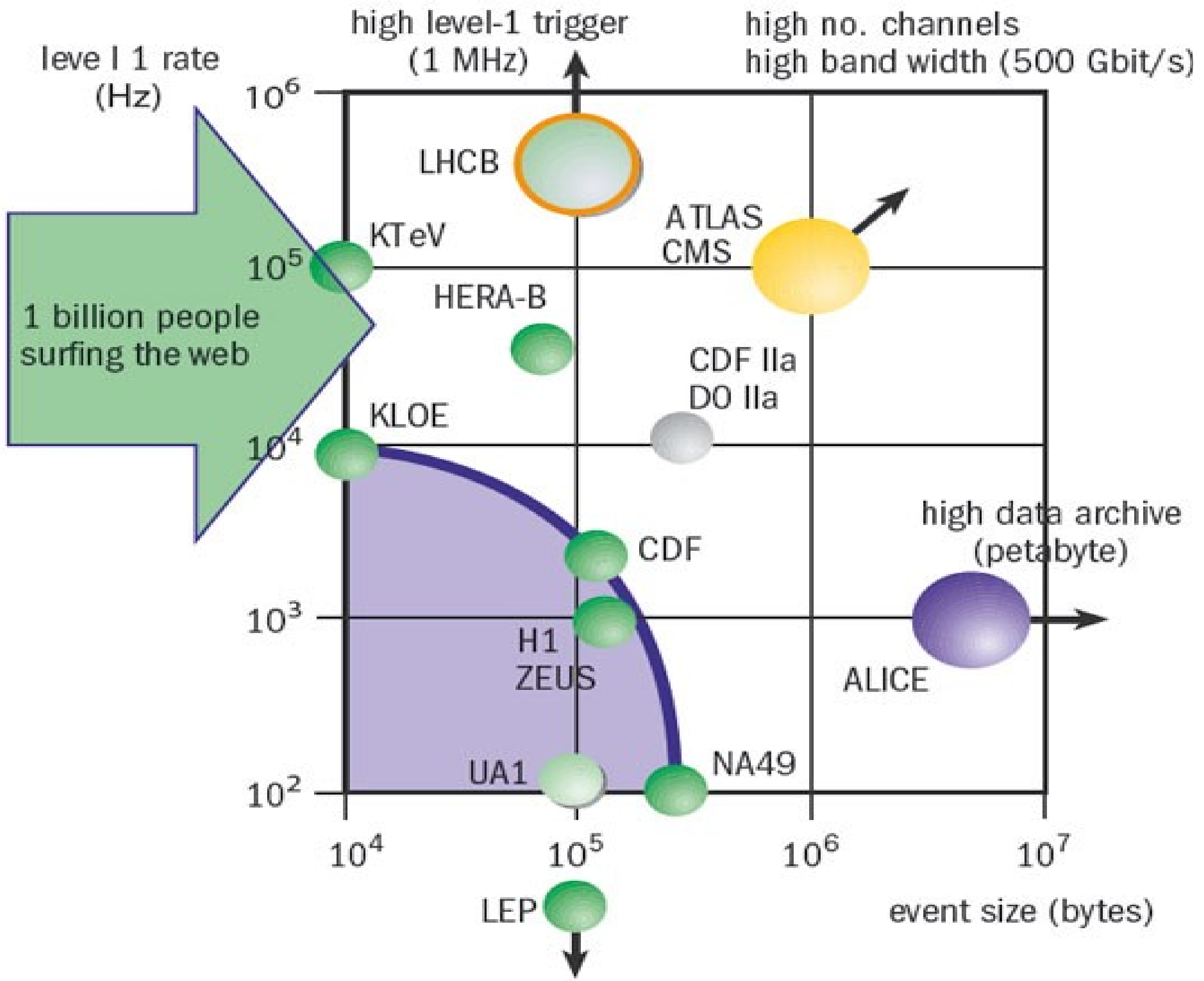
- WLCG – Worldwide LHC Computing GRID:
  - LHC made 15-20 PB data per year
  - ...and now before HL-LHC 2PB/day





More data: motivation for fast computing at CERN

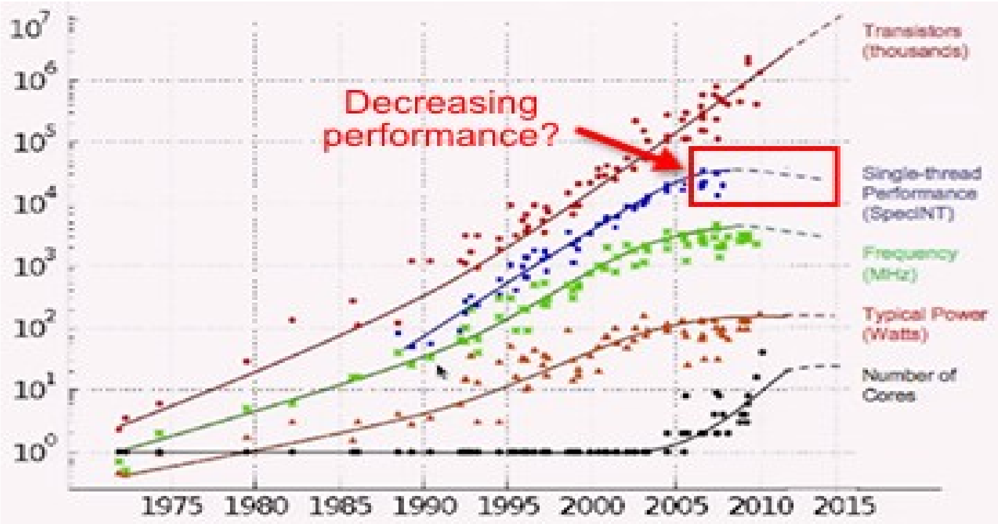
- Ideal: amount of simulated data ≈ real data
  - Number of events at LHC: $\mathcal{O}(10^8)$ / s
  - Necessary time for Monte Carlo with ALICE geometry: $3.8\ ms/track$
- Necessary time to simulate 1 s of ALICE data: $\mathcal{O}(days)$



Fast computing = parallel computing

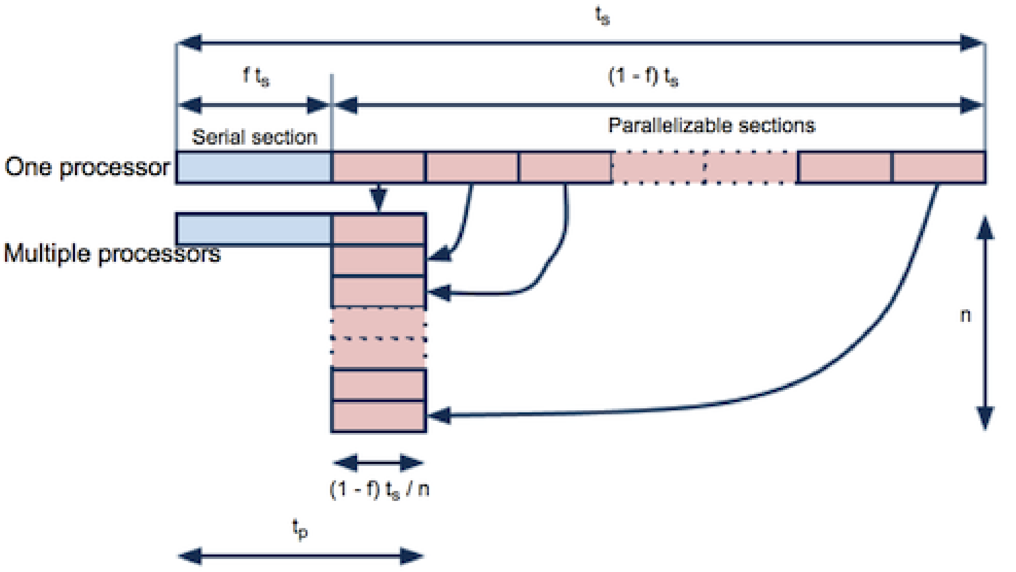
- Moore's law:

Every 2nd year the number of transistors (integrated circuits) are doubled in computing hardwares.



- Amdalh's law:

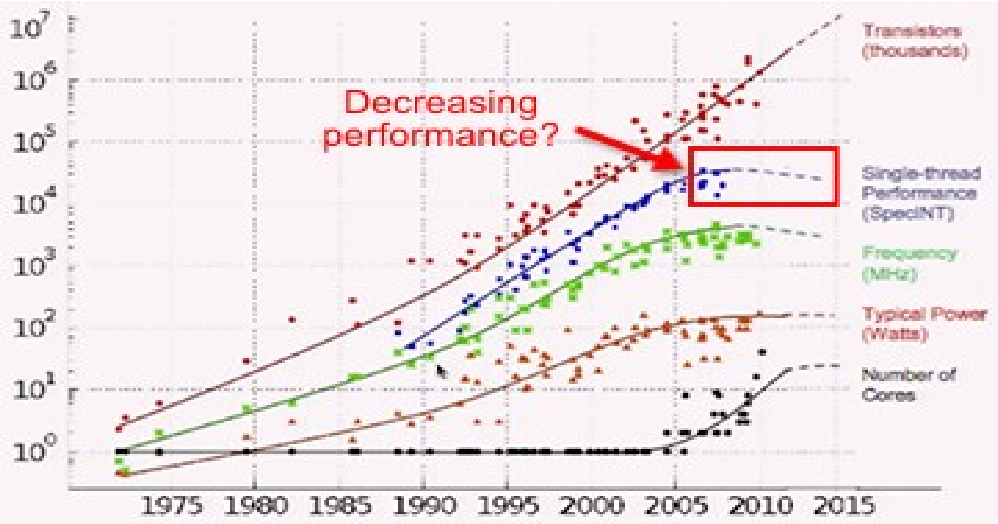
The theoretical speedup is given by the portion of parallelizable program, p, & number of processors, N, is:



Fast computing = parallel computing

- Moore's law:

Every 2nd year the number of transistors (integrated circuits) are doubled in computing hardwares.



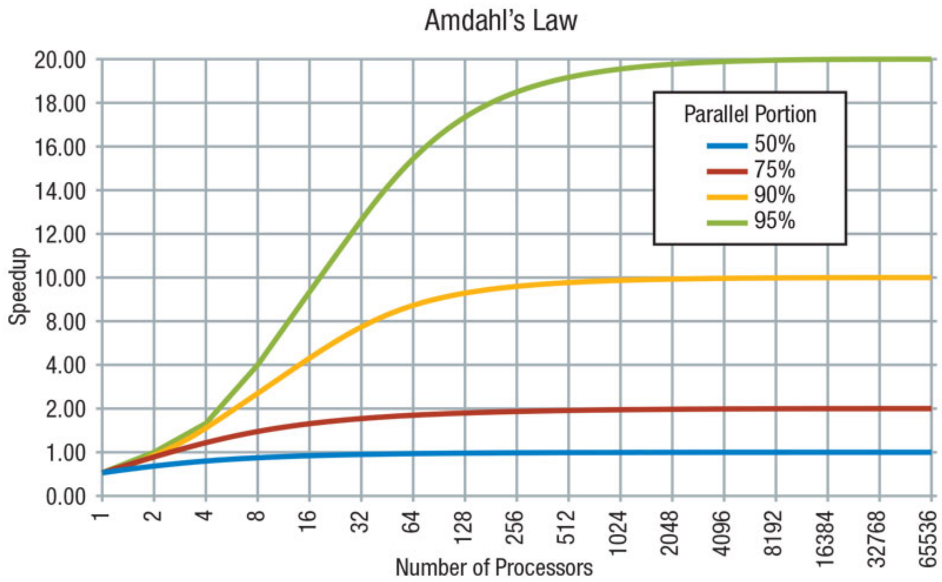
- Amdalh's law:

The theoretical speedup is given by the portion of parallelizable program, p. & number of processors, N, is:

$$\text{Speedup}(N) = \frac{1}{(1-P)+\frac{P}{N}}$$

Serial part of job = 1 (100%) - Parallel part

Parallel part is divided up by N workers



The HIJING++

HIJING(Heavy-Ion Jet INteraction Generator)

易經

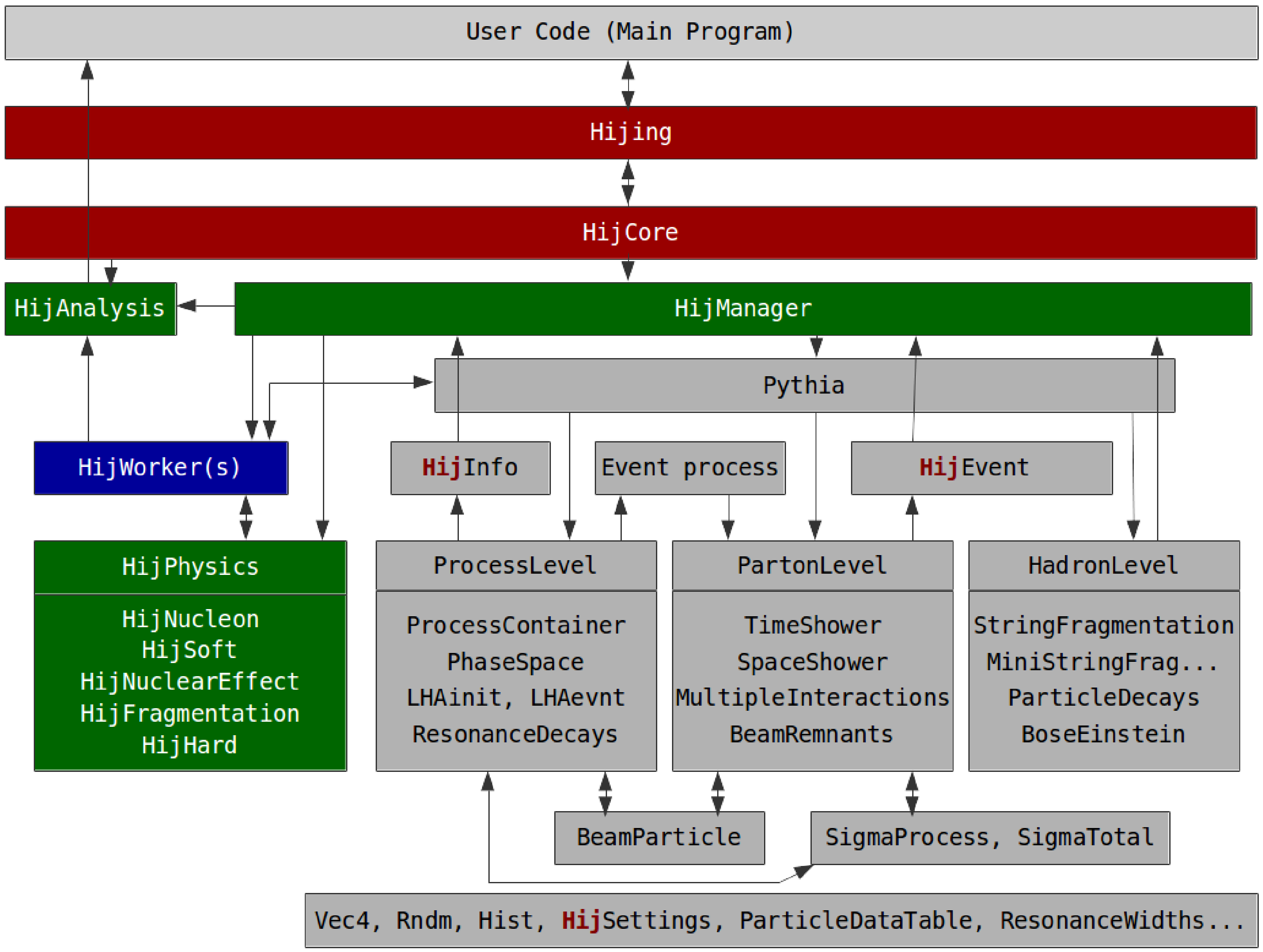
Bagua (eight simbols)

fundamental principles of reality

adjoint representation 8 of *SU(3)*

Program Structure

- Pythia8 namespace containers
- Structure similarities
- Actual program flow is more complicated
- New: HijManager



Join us

THOR EU COST Action CA15213

- Theory of Hot Matter and Relativistic Heavy Ion Collisions
- http://thor-cost.eu

PHAROS EU COST Action CA16214

- The multi-messenger physics and astrophysics of neutron stars

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Wigner GPU Laboratory

- Highly-parallel computing techniques
- http://gpu.wigner.mta.hu