Heavy-ion Physics: Present & Future

@Wigner RCP

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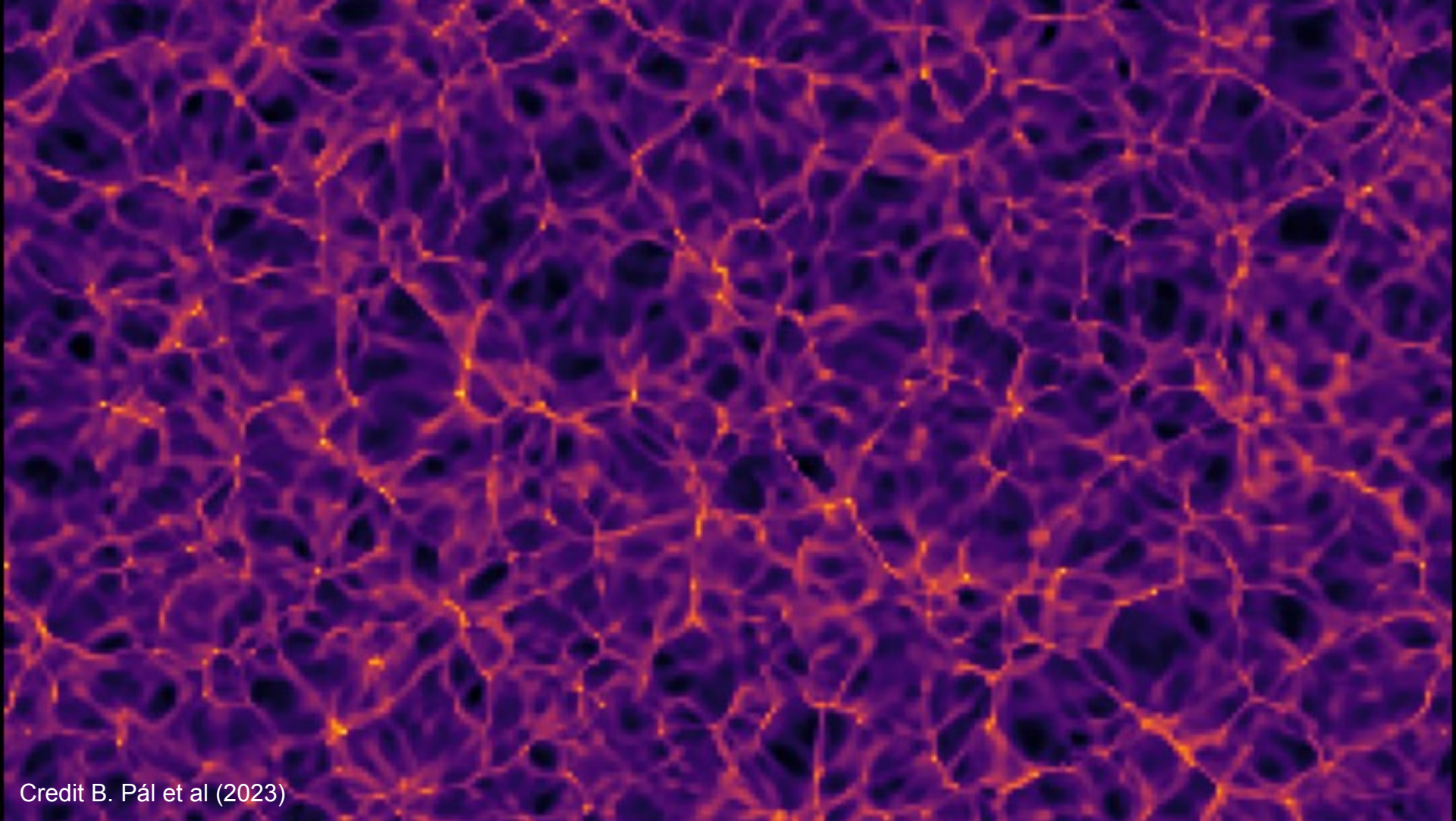
Wigner RCP, ALICE/CERN
Grants: NKFIK OTKA K135515, NEMZ_KI 2022-00009, FK131979

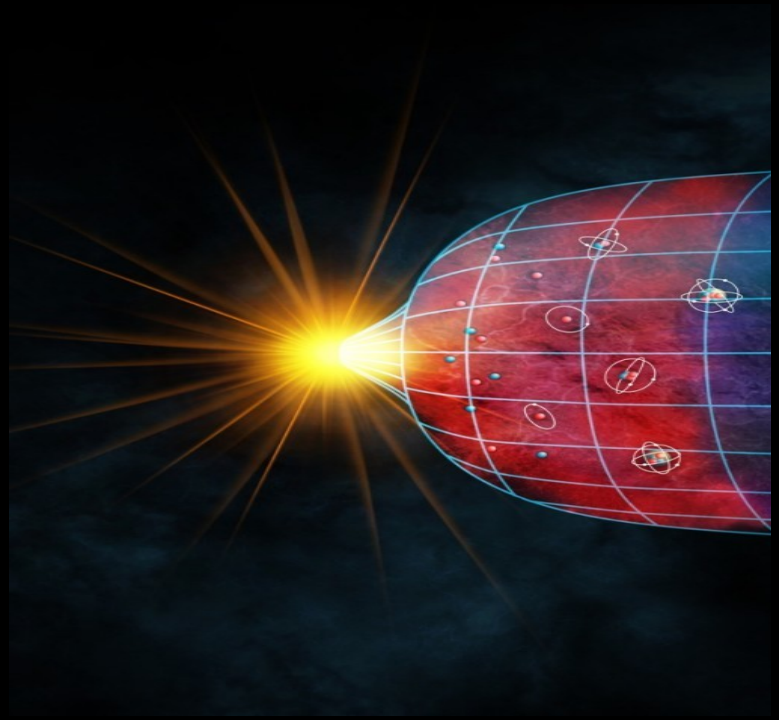
Wigner 121, Margaret Island, Budapest, 18th Sep 2023

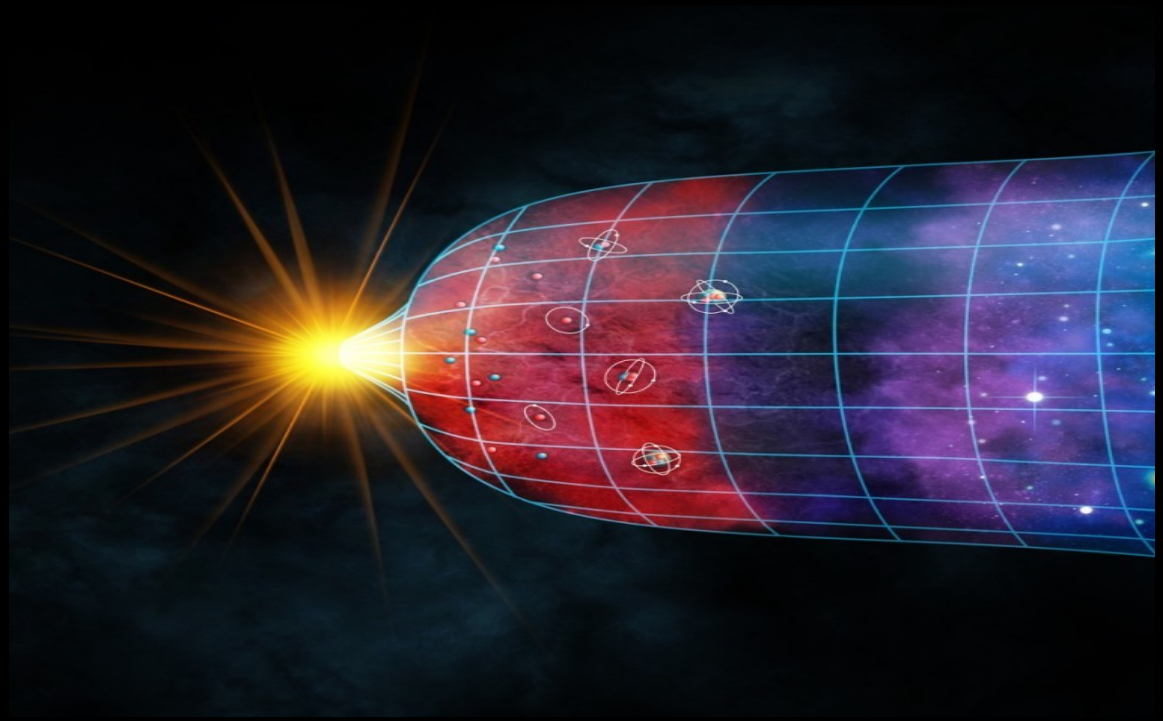
The Universe is 13.7 billion years old…

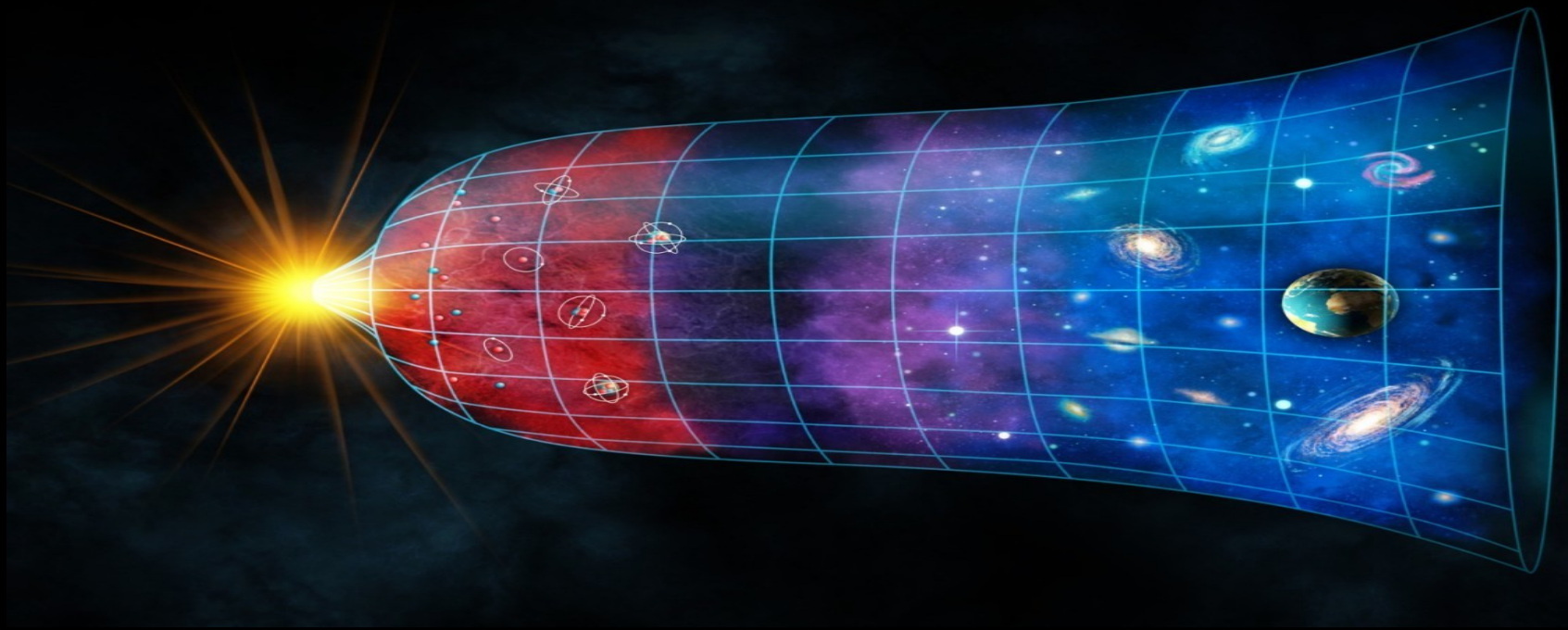


Credit B. Pál et al (2023)

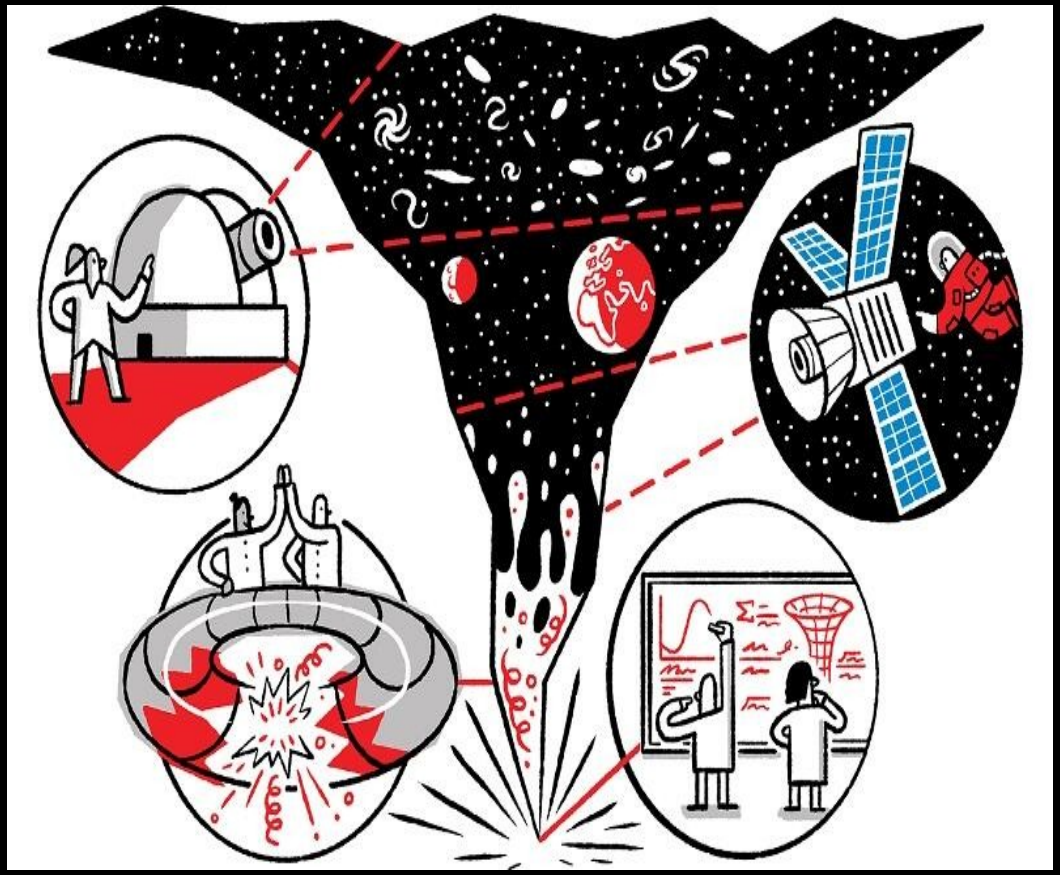
…but it started somehow as like this:





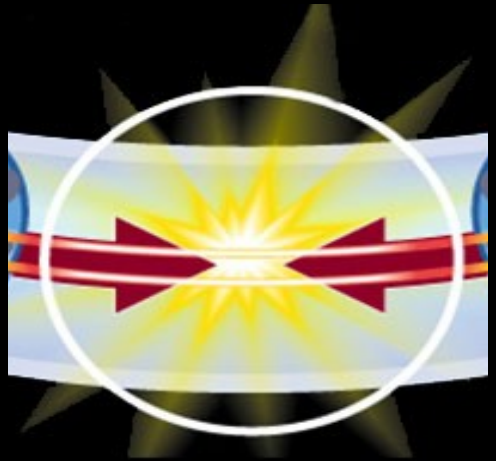


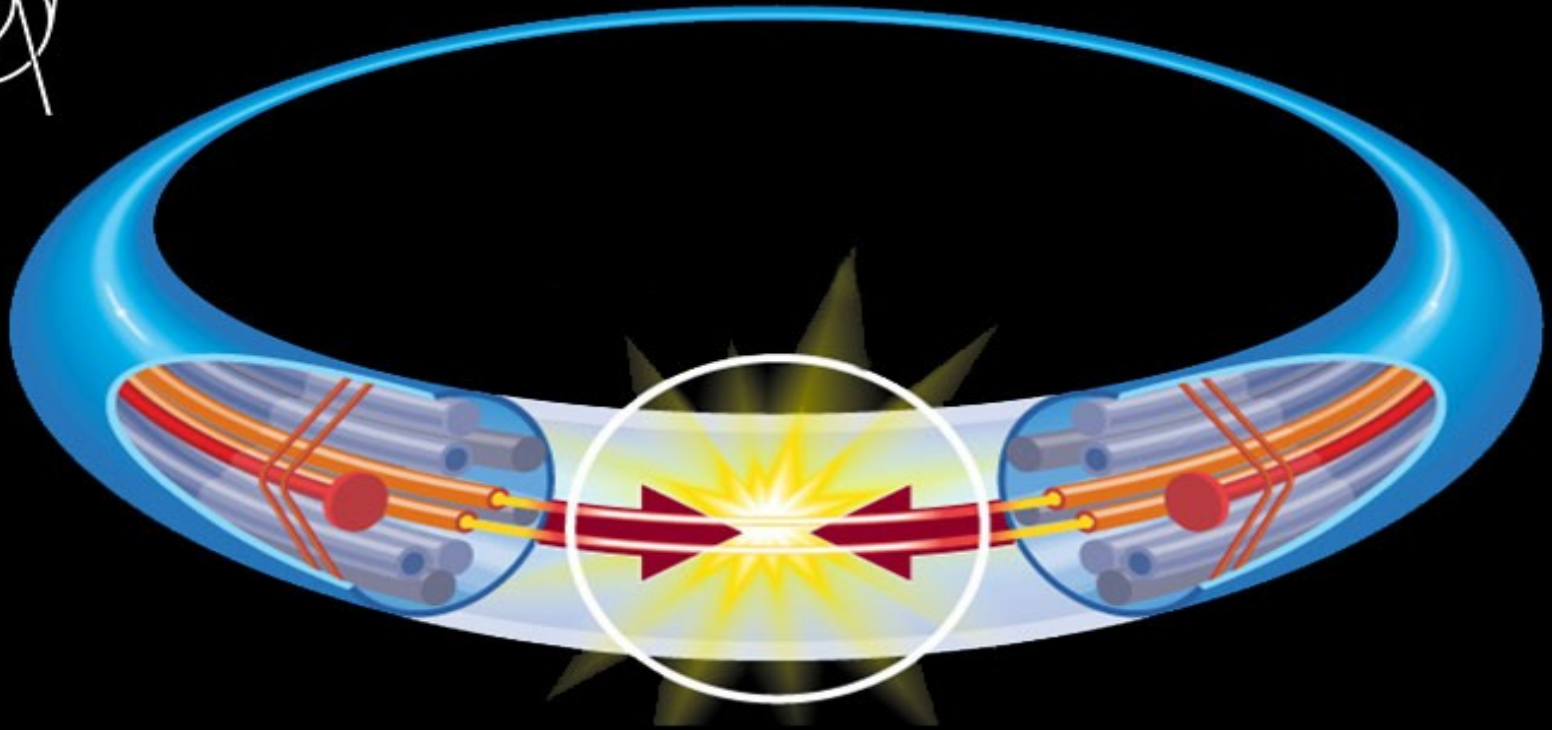
How can we investigate the matter of the Universe?



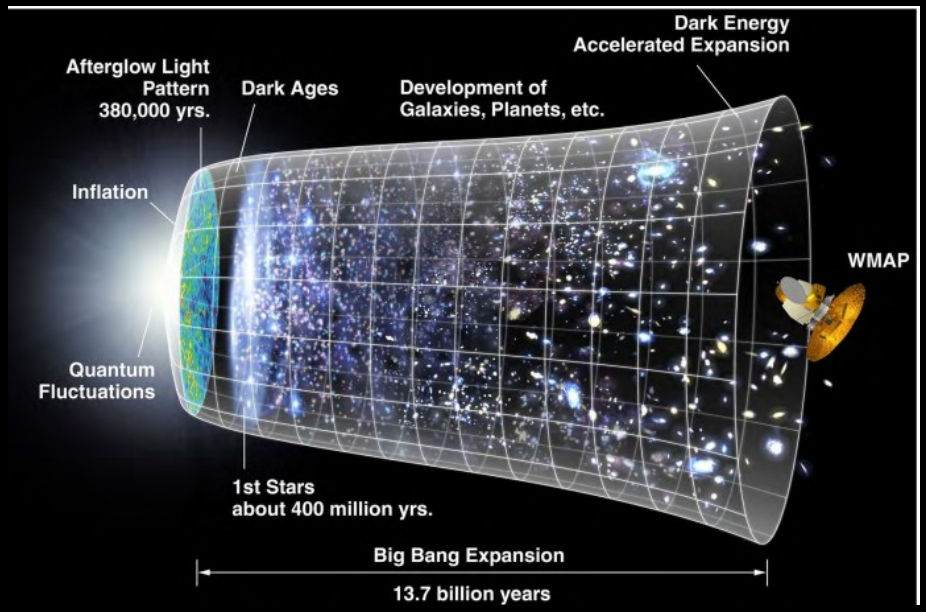
How was it microseconds after the Big Bang?

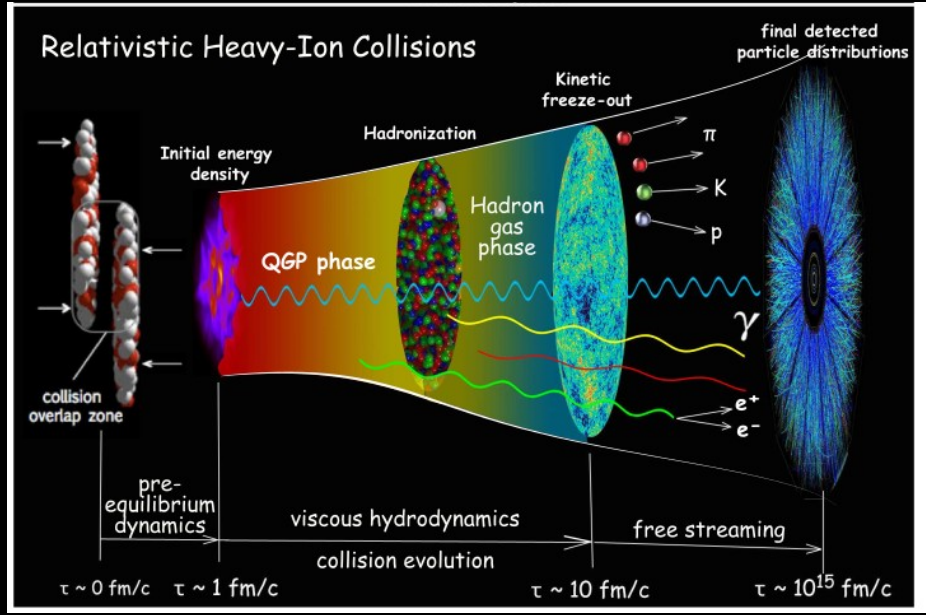
Can we re-create this matter in a laboratory?





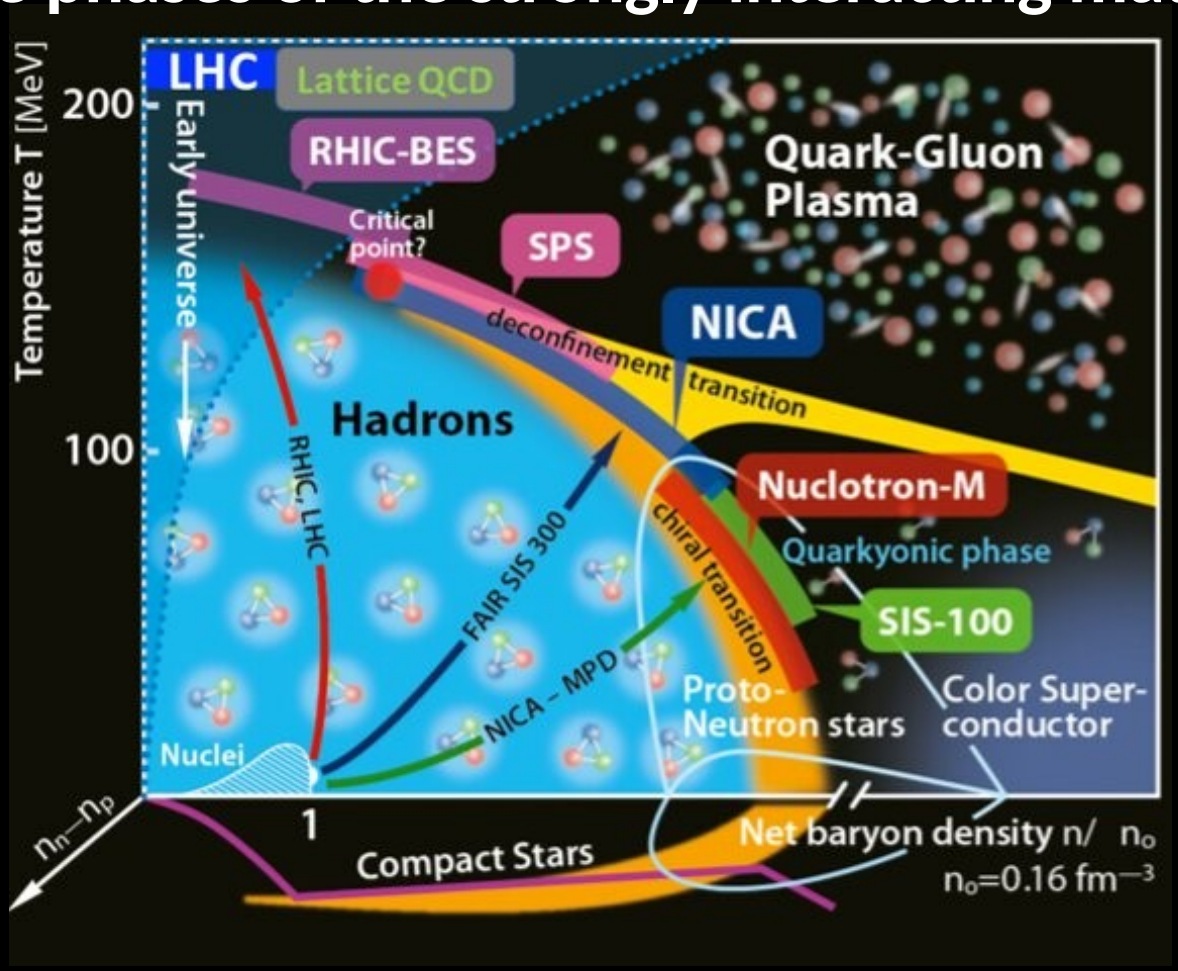
Big Bang vs. Heavy-ion collisions





This is the goal of the high-energy heavy-ion physics.

Exploring the phases of the strongly interacting matter.



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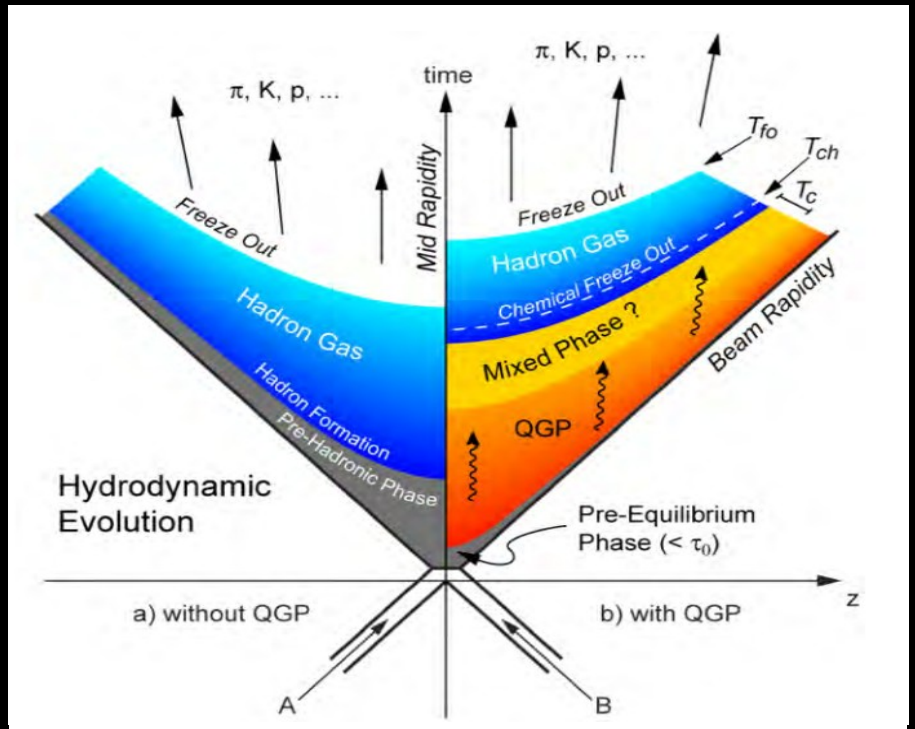
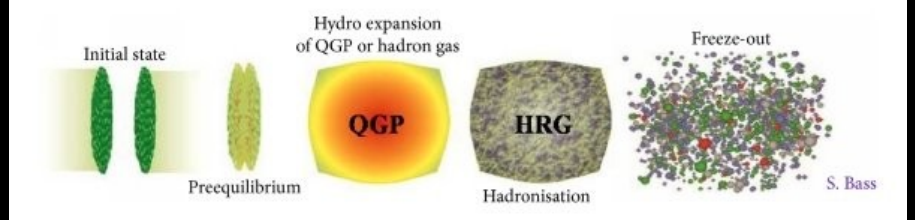
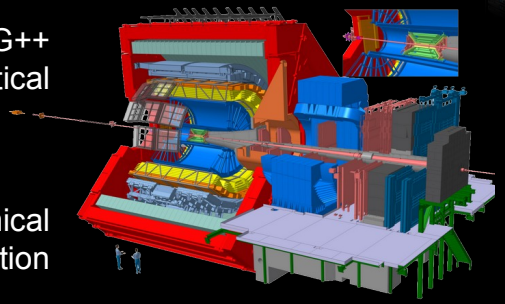




Investigating the strongly interacting matter @ Wigner RCP.

High-enegy Heavy-ion Research @ Wigner RCP

- **Effective filed theory of the strongly interacting matter in matter**
  - Low-energy hadron spectra, BUU transport code development, GSI/FAIR CBM, PANDA, FOPI, HADES data analysis, simultation models and theoretical background development.
- **High-energy collisions and fragmentation**
  - Hadronization with Tsallis-Pareto-like fragmentation, HIJING++ software development, RHIC/LHC/FCC-energy theoretical model development
- **New thermodynamical and hydrodynamical approaches**
  - Nonextensive statistical thermodynamics, new hydrodynamical methods, thermodynamics in curverd space-time propagation in elastic matters
- **High-energy physics & gravity, the physics of compact stars**
  - Cold, extreme dense matter in compact stars, alternative gravitational theory
- **Participation in the large-scale experimental collaborations**
  - CERN LHC ALICE, GSI FAIR, NA61, HW & SW development, GPU, Cloud Computing, Big Data Science.



Theory highlights: DNN predicted elliptic flow

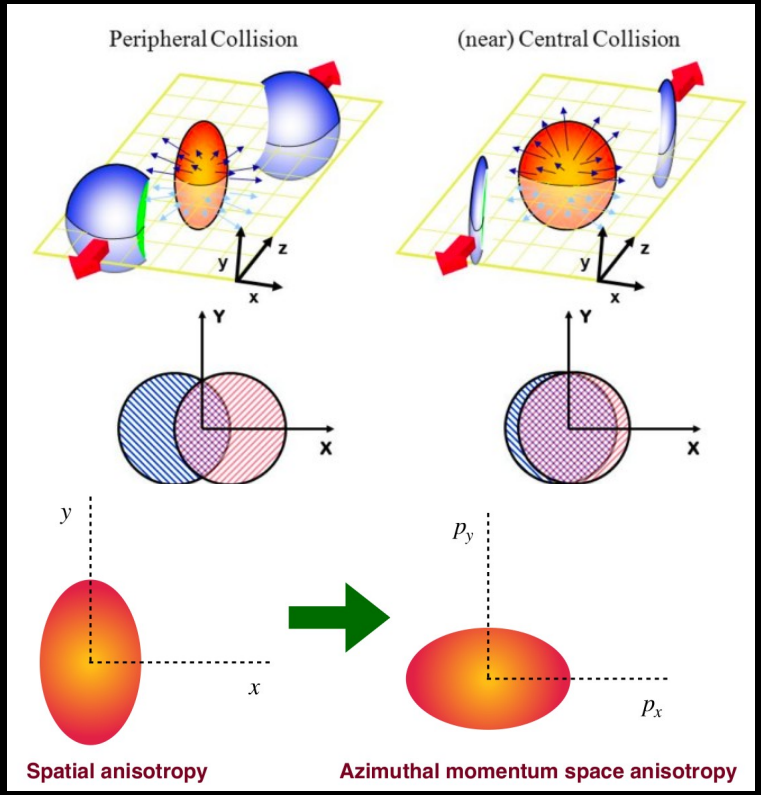
Elliptic flow is one of the signature of the strong collectivity → Quark Gluon Plasma

The measure is the strong asimuthal anisotropy in the momentum space 'elliptic flow' → 2nd harmonic of the Fourier expansion:

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

Converting the hadron's momemta, mass, and c.m. energy to pictures → A DNN network is able to recognize the inner scaling properties.

N. Mallick et al: PRD



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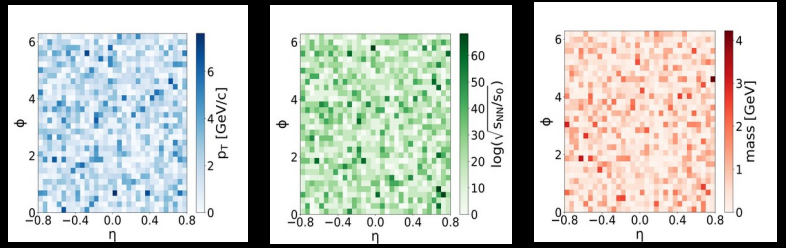

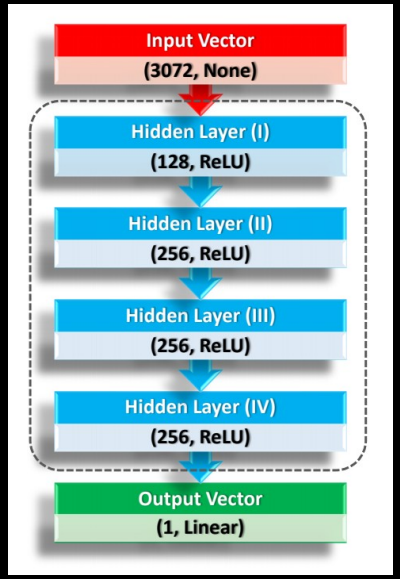

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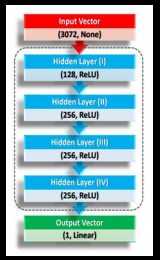
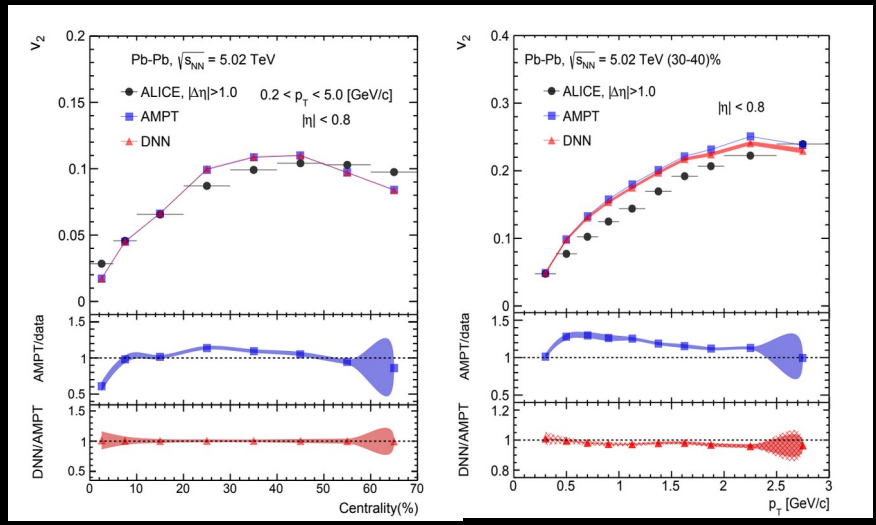




Theory highlights: QGP in small systems?

Can we have QGO in small systems, where thermodynamics is no longer valid? → Test the non-extensive statistical approach.

Tsallis-Pareto distriputiuns fits well the identified hadron spectra → Thermodynamical consistency & scaling properties

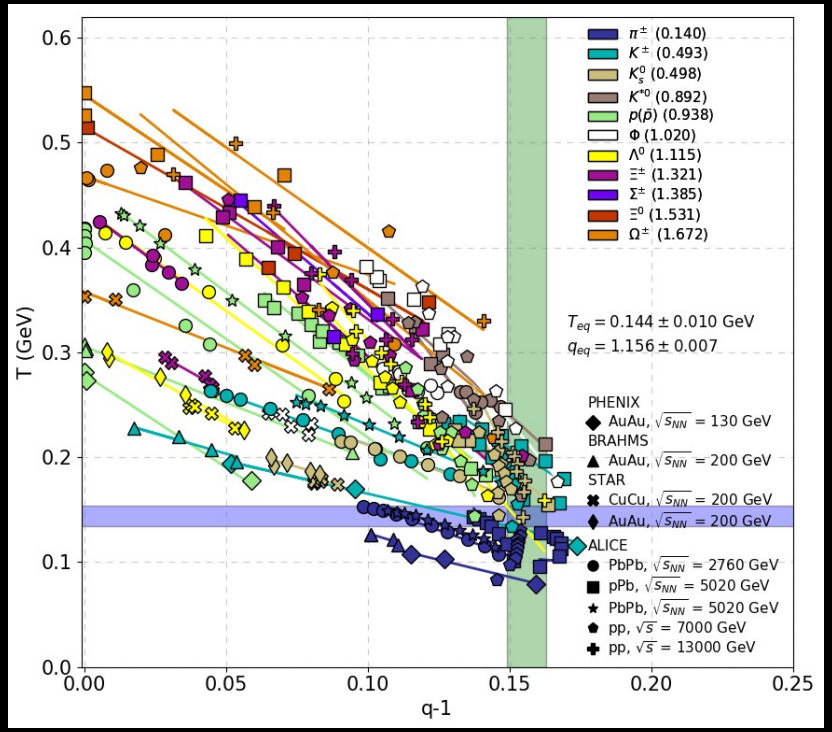
$$\left.\frac{d^2N}{2\pi p_T dp_T dy}\right|_{y\approx 0} = Am_T\left[1+\frac{q-1}{T}(m_T-m)\right]^{-\frac{q}{q-1}}$$

$$T(\sqrt{s_{NN}},\langle N_{ch}/\eta\rangle,m) = T_0 + T_1\ln\frac{\sqrt{s_{NN}}}{m} + T_2\ln\ln\langle N_{ch}/\eta\rangle,$$

$$q(\sqrt{s_{NN}},\langle N_{ch}/\eta\rangle,m) = q_0 + q_1\ln\frac{\sqrt{s_{NN}}}{m} + q_2\ln\ln\langle N_{ch}/\eta\rangle,$$

New measures: quantifying small systems → Tsallis thermometer

G. Bíró et al



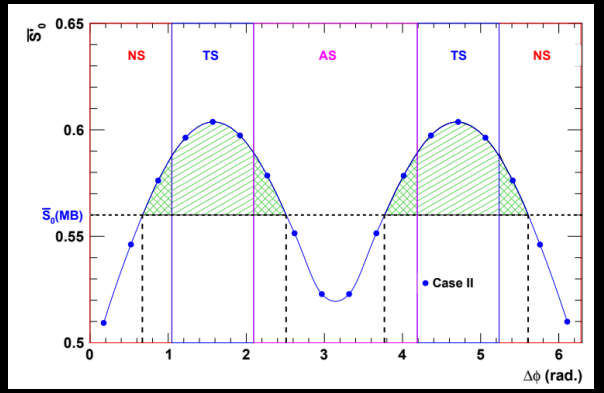
Theory highlights: Quantifying the underlying event

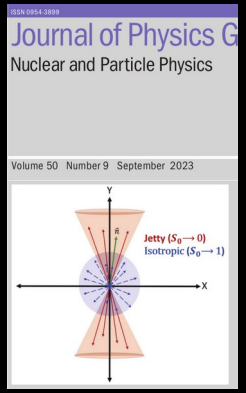
Event classification help to separate jetty and isotrop events → Different physics, better separation of the bulk from the jet part.

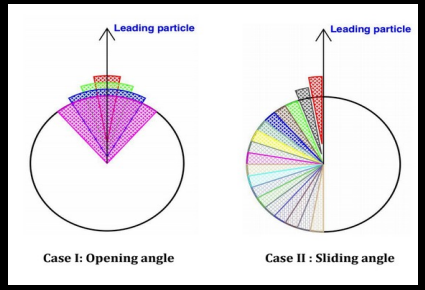
The CDF definition use to be a drastic method → this can be extended by 40 degrees

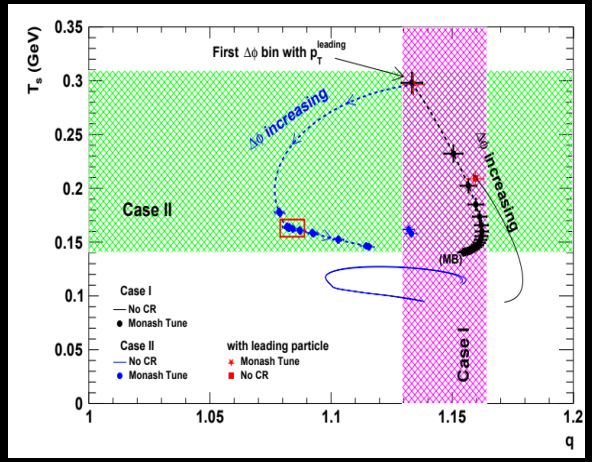
Tsallis thermometer was able to quantify the underlying event by its parameter → Tsallis parameters were correlated with spherocity-classified events.

A.N. Mischra. JPG

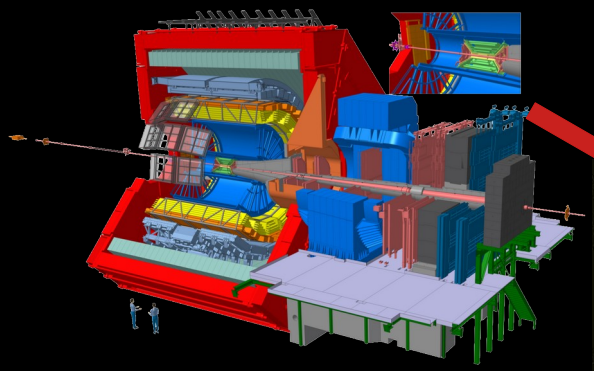


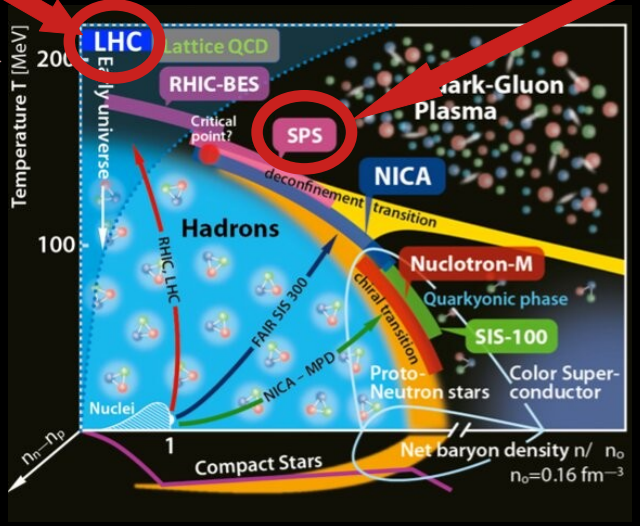


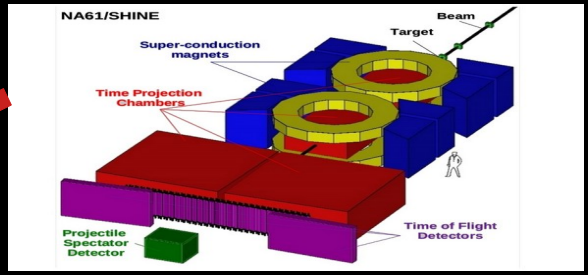




Experimental activity: in heavy-ion collisions

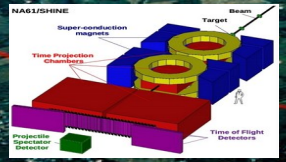






SHINE NA61

Experimental activity: NA61 & A Large Ion Collider Experiment



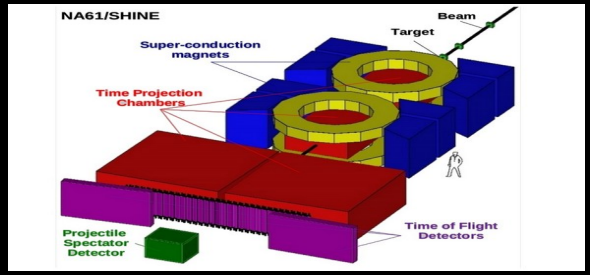
NA49 → NA61/shine (CERN SPS)

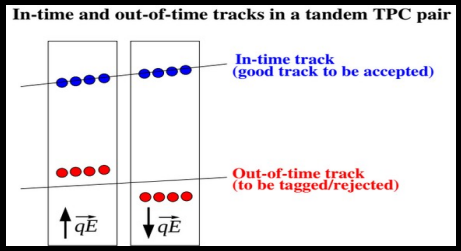
NA49 is the dedicated HI experiment at CERN SPS → Hungary joined for the fist time

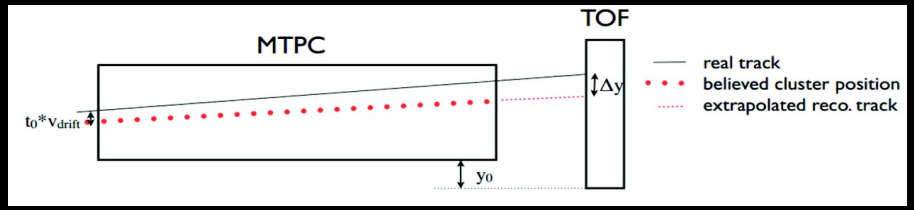
NA61 is a continuation: large acceptance hadron spectrometer experiment at the CERN SPS. Main tracking components: 40m^3 TPC system.

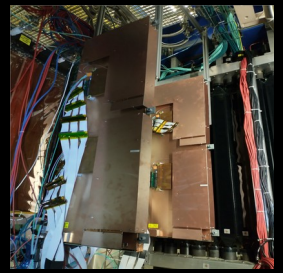
Conceptualization, development, building of Forward TPCs: novel tandem-TPC concept for higher rates

Special auxiliary detector (Geometry Reference Chamber) for in-situ drift velocity determination in large TPCs









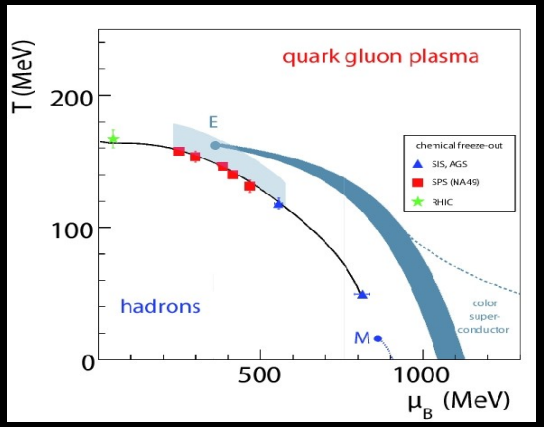
NA49 → NA61/shine (CERN SPS)

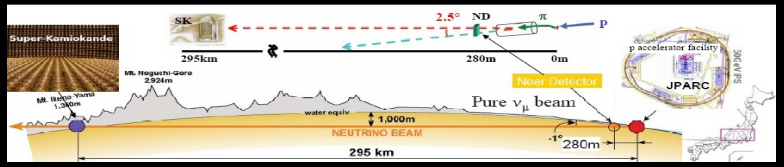
Main physics goals:

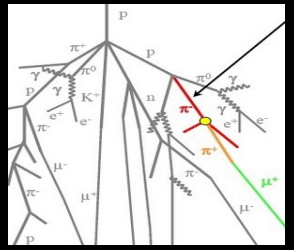
Hadronic spectra and fluctuactions in A+A for studying Onset of Deconfinement and searching for Critical Point in strong interactions, intermediate p_T physics in p+p,p+A,A+A, open charm measurement

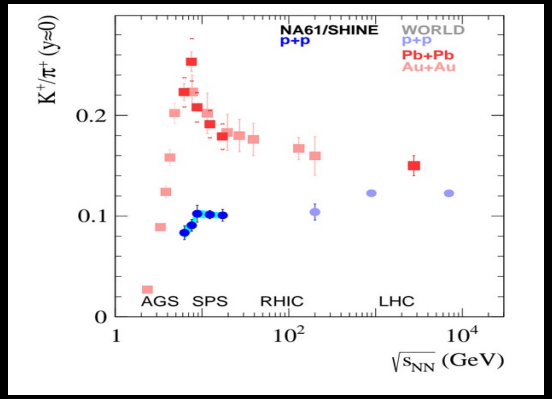
Reference hadron spectra in p+A for DUNE, T2K (ν-beams)

Reference hadron spectra in π^-+A for the Pierre Auger Obs.

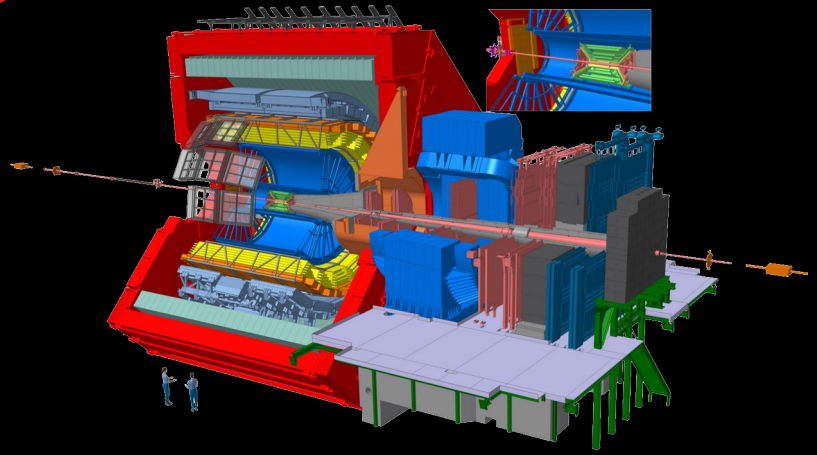


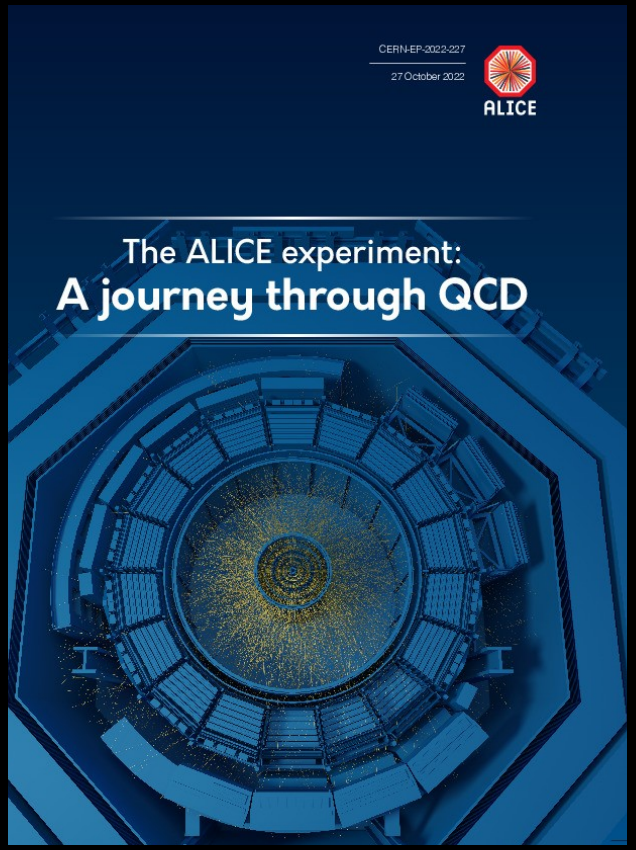






A Large Ion Collider Experiment, CERN LHC





Hungarian ALICE Group @ Wigner RCP

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

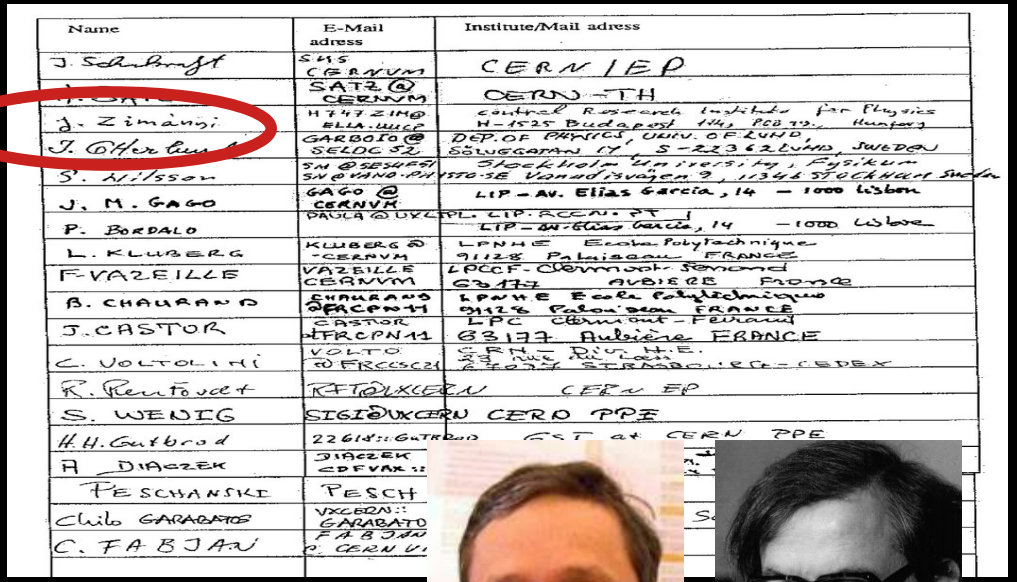
2012-2014 R&D

2014-2016 Procurement/Fabrication

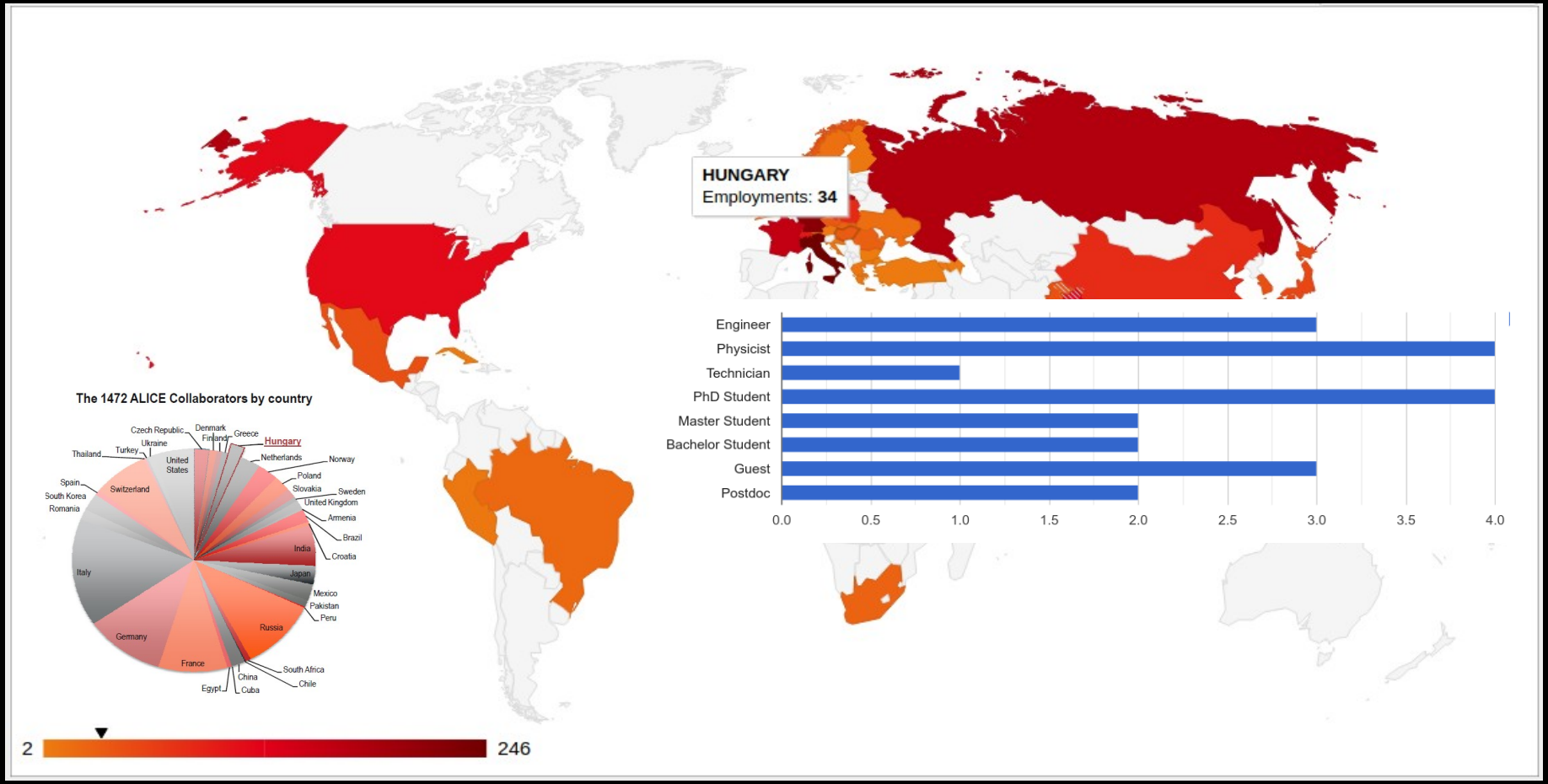
2016-2017 Integration, pre-commissioning

2018-2019 Installation, commissioning

2019-2020 Full deployment of DAQ/HLT



Hungarian ALICE Group @ Wigner RCP



Activities (2010-2023): Wigner's Contributions

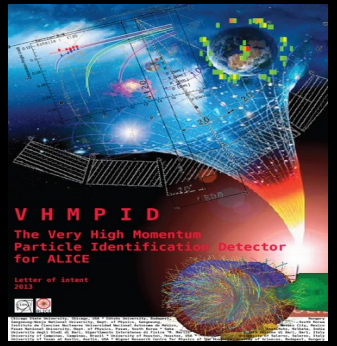
Strong theoretical background in heavy-ion physics → Experiment & Theory

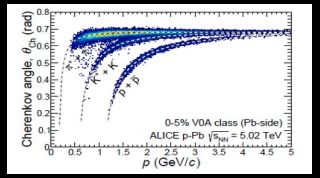
Strong participation in R&D activity → LoI preparation and deliverables

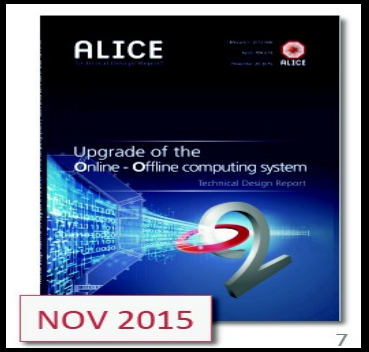
Strong participation in data analysis → QGP: PID hadron spectra, Heavy Flavor physics, jet physics, correlations

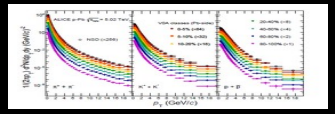
Active in data taking → ALICE ROS, Remote Operation Site @ Wigner

Strong in Computing at large scale → Software & hardvare developemnt









Recent: ALICE LS2 R&D – Wigner's Contributions

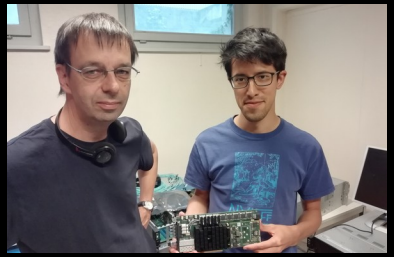
The upgrade of the ALICE's DAQ system, CRU2 R&D → 4TB/s speed

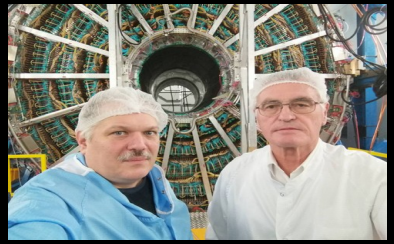
QA & building the new, GEM-based ALICE TPC R&D → World record: 90m^3

Inner tracking system (ITS2) upgrade (silicon-pixel MAPS technology) test → 10m^2 & 13Gpixel

Big Data: First large scale Specialized Analysis Facility @ WDC → 100 PB adat

Data Analysis & software developments → 100 000 line of code





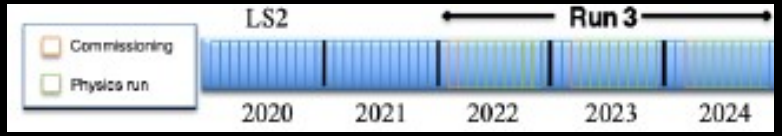
Now: ALICE LS2 R&D + Ongoing Run3

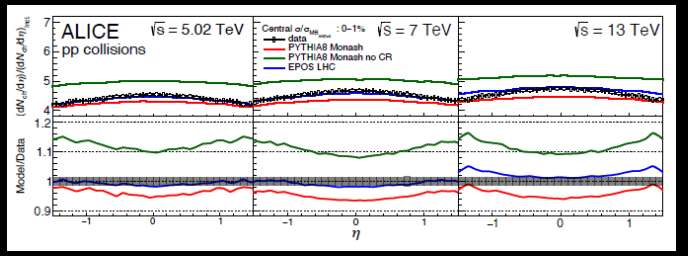
More precise pesudo-rapidity distributiuon measurememnts, **PID hadron spectra**

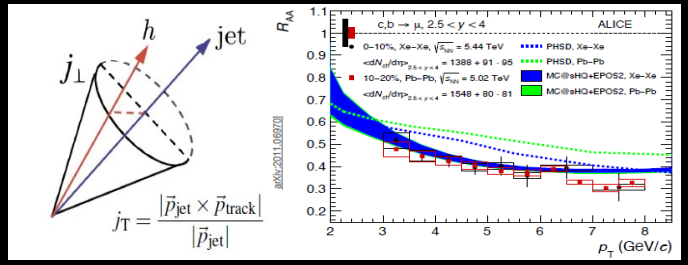
- **Jet-structure measurements:** jet-fragmentation, hadronization, pp, pPb

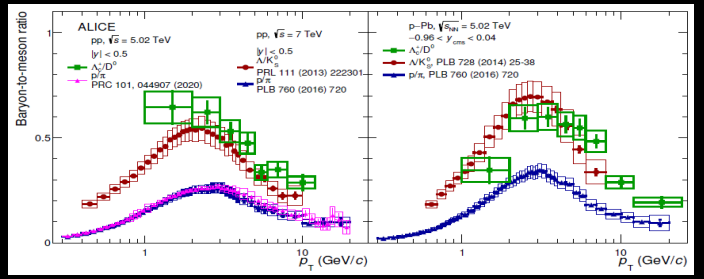
Deuteron-production: testing coalescence model

- **Investigating the charm hadron production** (Λc/D ratio & DD correlations)
- **Heavy flavor production in** XeXe and PbPb collisions









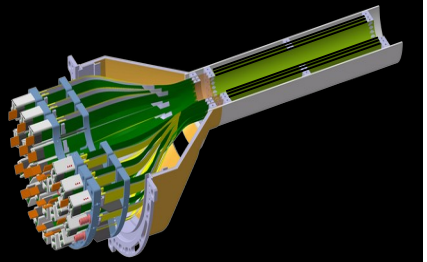
Next: R&Ds for the LS3 period

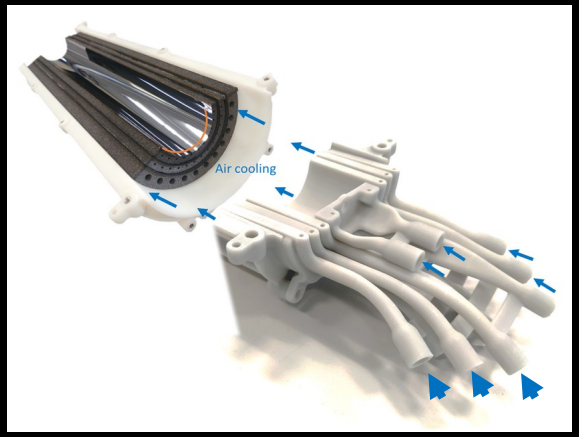
FOCAL and ITS3 R&D in ALICE

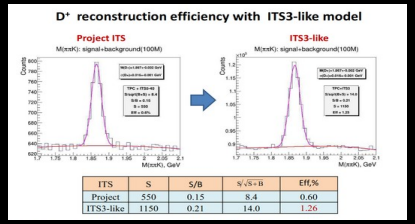
ITS3: bendt silicon pixel detector technology: MAPS has been tested at DESY. (Our task: Cooling simulations ITS3 WP5)

Detector-part tests + DAQ-system R&D

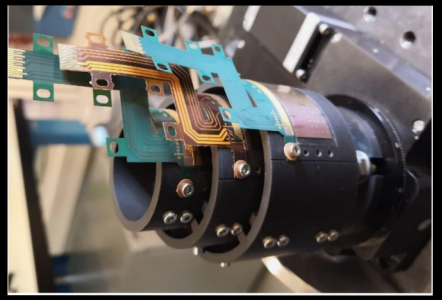
Better then 2x more precise heavy flavor measuremetns: fine structure of the jets, measuring fragmentation & hadronization.

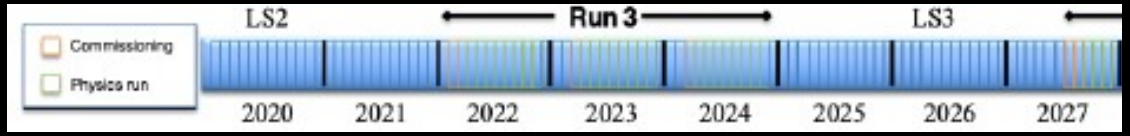






ITS	S	S/B	$S/\sqrt{S+B}$	Eff,%
Project	550	0.15	8.4	0.60
ITS3-like	1150	0.21	14.0	1.26

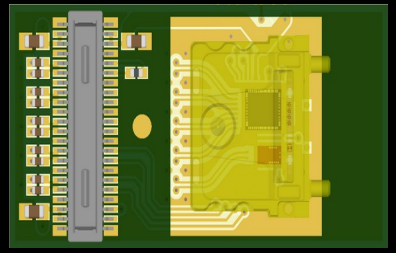


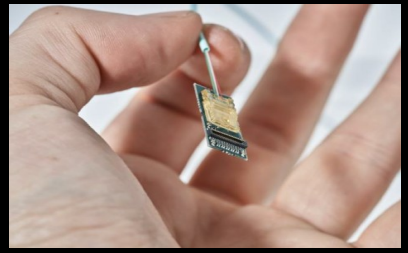


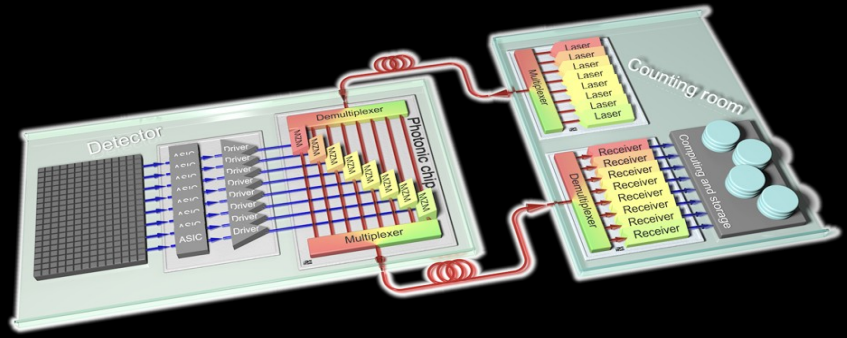
Next: R&Ds for the LS3 period

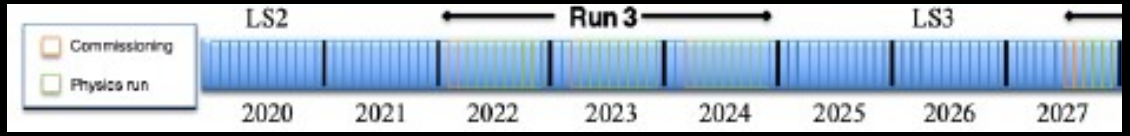
New radiation tolerant DAQ system R&D

- **Versatile+ link optical receiver**
  - **20x10x2,5 mm**
  - **4x5-10 Gb/s download + 1x2,5 Gb/s upload**
  - **Between -35C and 60C**
  - **Radiation tolerance: 1 MGy or 1000+hadron/cm2**
- **Optoelectronic data transfer: 28/56 Gb/s**









Future: ALICE3 Letter of Intent

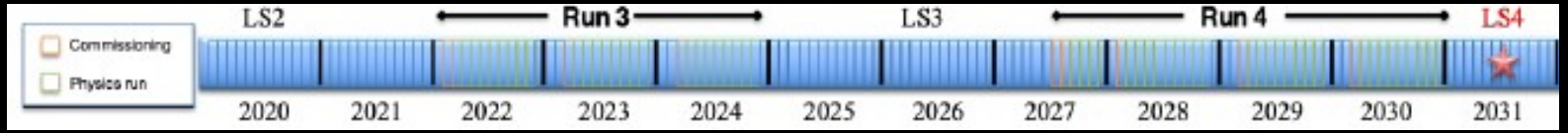
Physics: Test of principles of quantum field theory (QFT), in medium effects (QCD chiral symmetry restoration, exotic hadrons, DM).

Large Acceptance: Δη = 8

PID: TOF 20 ps time resolution, aeroge-based RICH

Zero momentum detector: $p_T \lesssim$ 50 MeV/c (at mid rapidity); $\lesssim$ 10 MeV/c (forward)

MAPS detector systems: 12 layer + CMOS-disks + Cherenkov detectors



Future: ALICE3 Letter of Intent

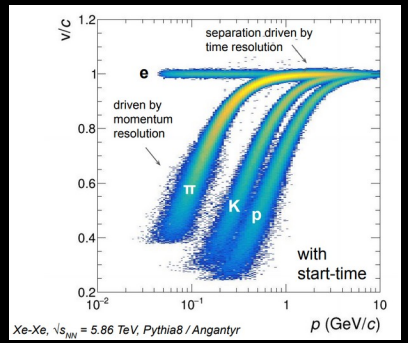
Electron ID: Low-mass di-electron spektum:
50 MeV/c < pT < 3 GeV/c

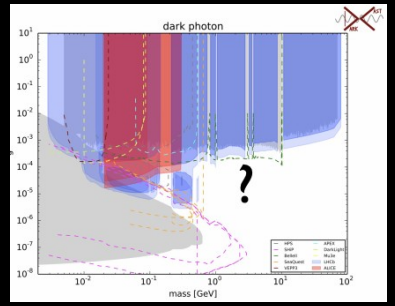
Hadron ID: Heavy Flavor (secondary vertex)
50 MeV/c < p_T < 5 GeV/c, π/K/p ID with 3sigma

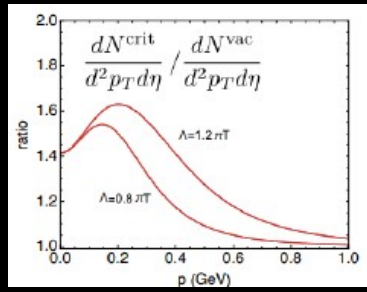
Photon detection: ultra low energy photons, calorimetry for 10 MeV/c < p_T < 100 MeV/c

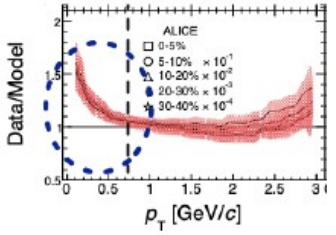
Primary vertex: with mm resolution: bendt silicon pixel technology

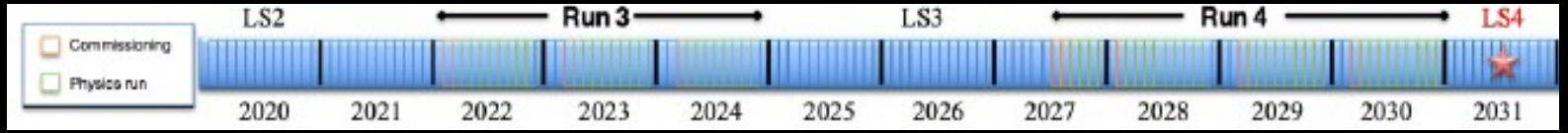
MuonID: Search for quarkonia & exotic hadrons: precise muon detection around ~1 GeV/c









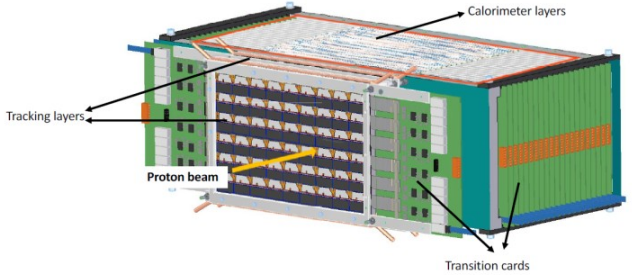


ALICE Technology Transfer → Medical Application

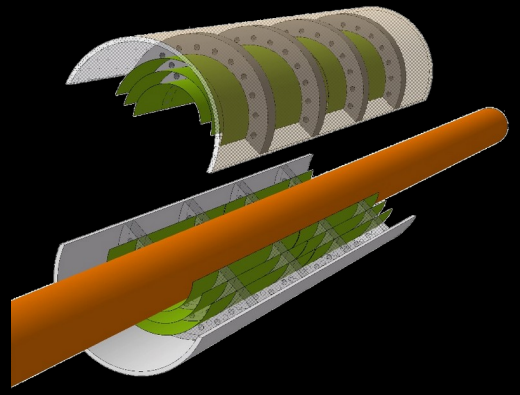
HADRON THERAPY R&D

Detector UG & Medical applications

- ITS3 → ALICE3 MAPS technology, DAQ systems, cooling
- Bergen Proton CT collaboration
- RICH technologies (earlier HMPID/VHMPID group)



Front. in Phys. Med. Phys. Im. ID: 568243,
Nucl. Instrum. Methods Phys. Res. Im. ID: 162626



Summary: Heavy-ion Research at the Wigner RCP

Heavy-ion@Wigner is well planned

- Well-defined physics program
- Strong R&D with NL & NI
- New technology challenges
- Strong & active local group
- Theory background
- Computing resources