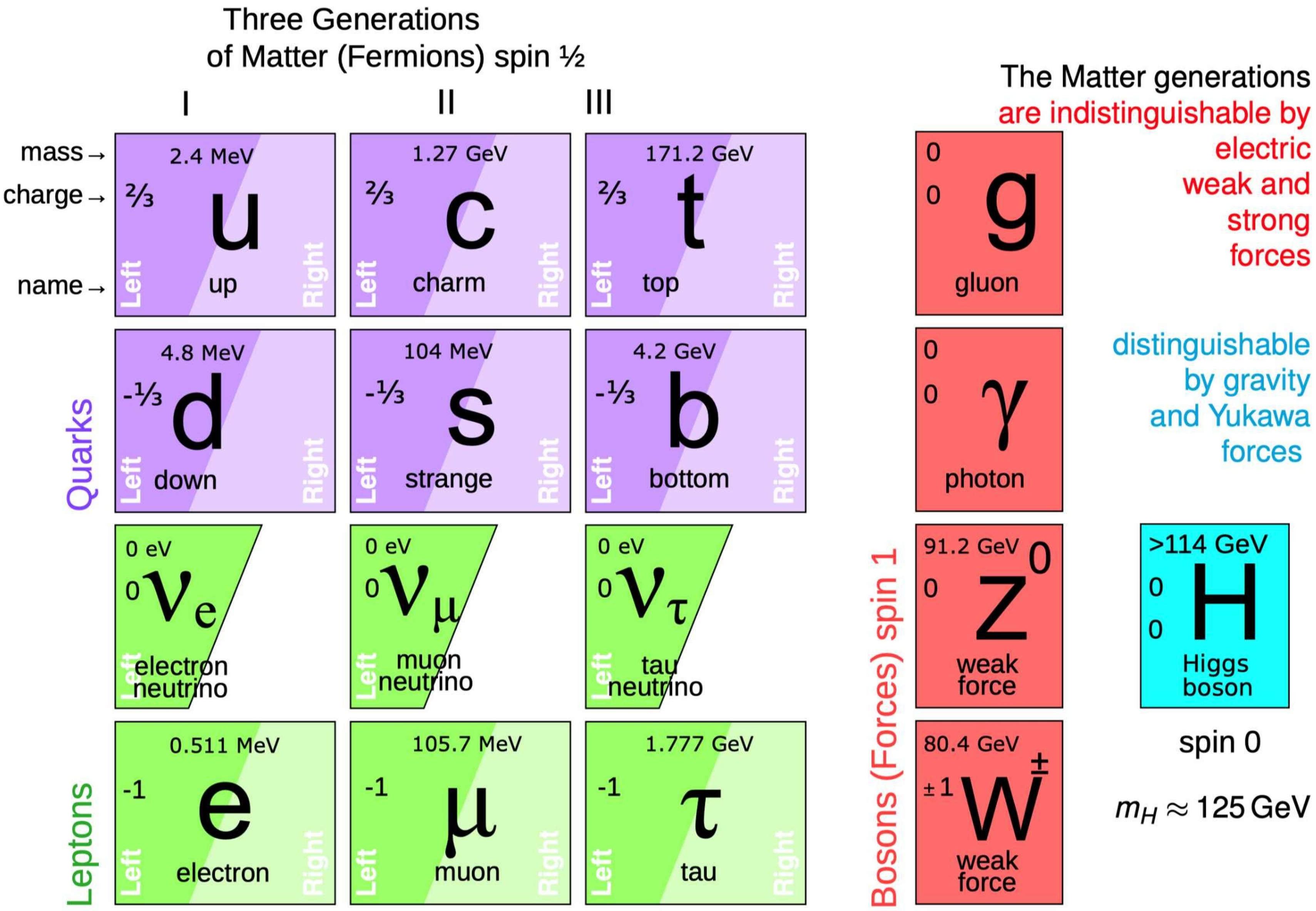
JOINT INSTITUTE FOR NUCLEAR RESEARCH

International Intergovernmental Organization

Future experiments in high energy physics

Grigory Trubnikov, JINR

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\overline{\psi}\not{D}\psi + \psi Y \psi \phi + D_\mu \phi D^\mu \phi - V(\phi)$$



Standard Model + GR : Major Problems

Gauge and Higgs fields (interactions): γ, $W^{\pm}$, Z, g, G, and h

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes all experiments dealing with
  - electroweak and strong interactions (anomalies: $g-2$?, LHC?, B-physics..)
- Does not describe (PHENO)
  - Neutrino oscillations -3 (and anomalies. . .)
  - Dark matter (Ω_{DM}) - ?
  - Baryon asymmetry (Ω_B) -?
  - Why the Universe is flat and homogeneous? -?
  - Where did the matter perturbations come from?-?

(THEORY)-1

- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

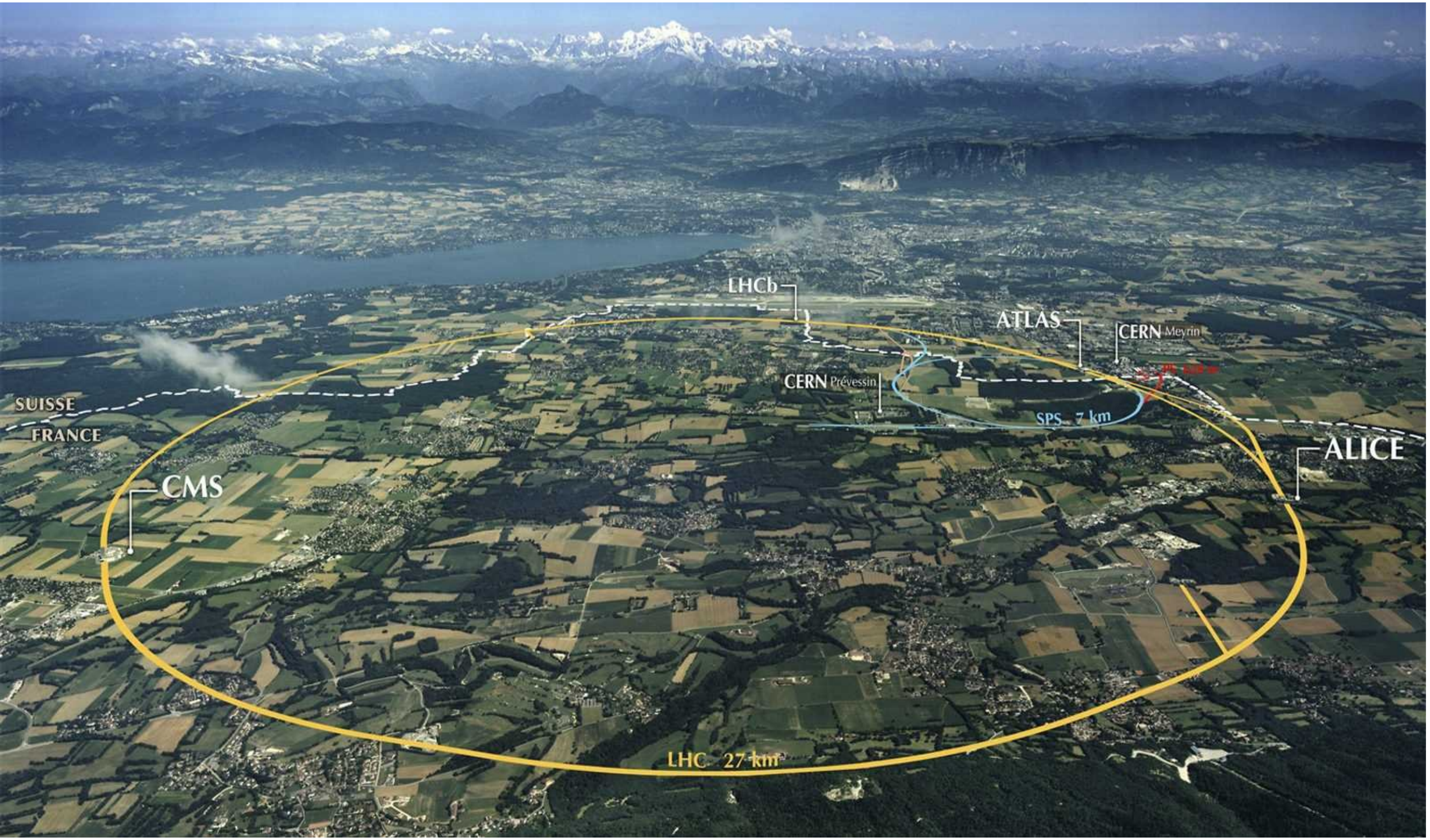
$$\frac{F_{эл}}{F_g} = 2{,}3 \cdot 10^{39}$$

Courtesy of D.Gorbunov, V.Rubakov

Verification of the Standard Model and quest for the New Physics

- Precision tests of the Standard Model: measuring properties of Higgs boson, top quark, search for rare and forbidden decays:
  - Experiments at frontier high energy accelerators;
- Study of CP violation, precision tests of QCD, nucleon structure study:
  - Precision experiments at hadron factories;
- Properties of hadronic matter and physics of critical phenomena in strong interactions (confinement problem, chiral symmetry, quark-gluon plasma):
  - Experiments with relativistic heavy ions;
- Search for New Physics

LHC (CERN, Geneva)

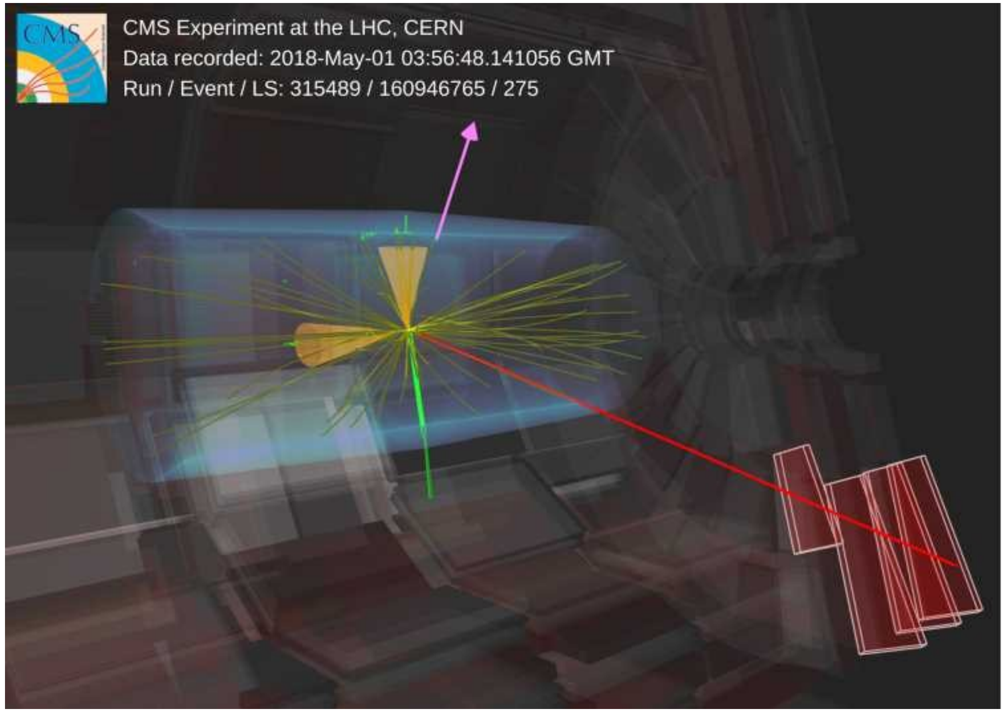


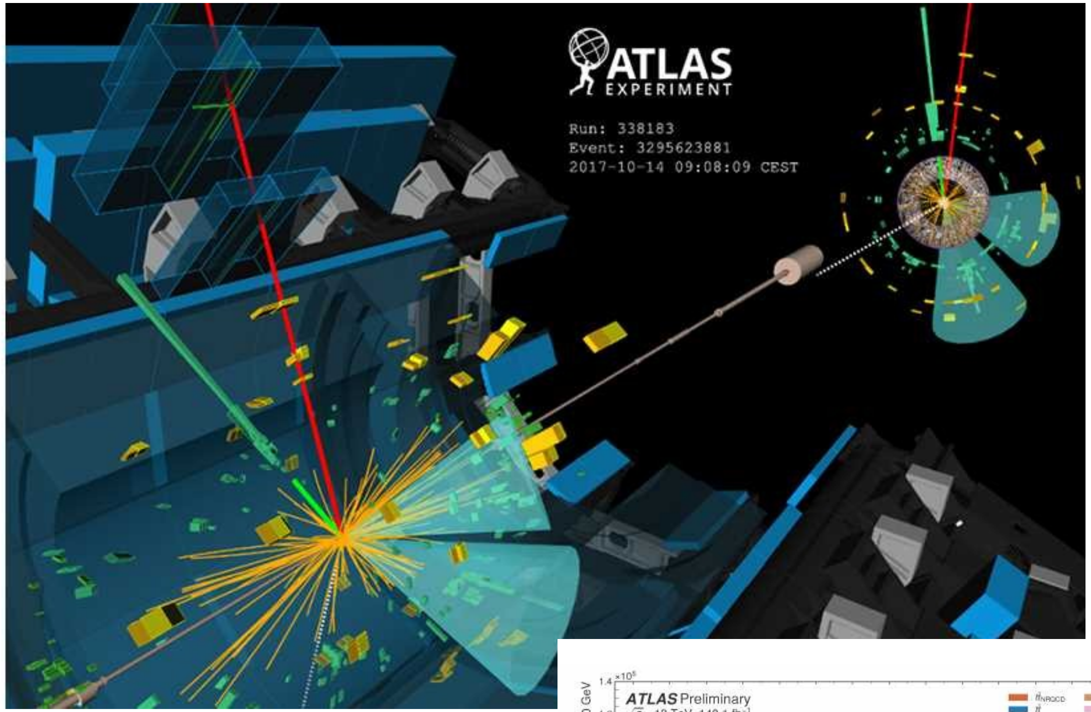
- Large Hadron Collider;
- Runs since 2009;
- Discovery of the Higgs boson. (125 GeV/c^2, quantum numbers correspond to the theory)
- p+p, Pb+Pb;
- up to 13 TeV;
- Remains the main source of HEP experimental data.

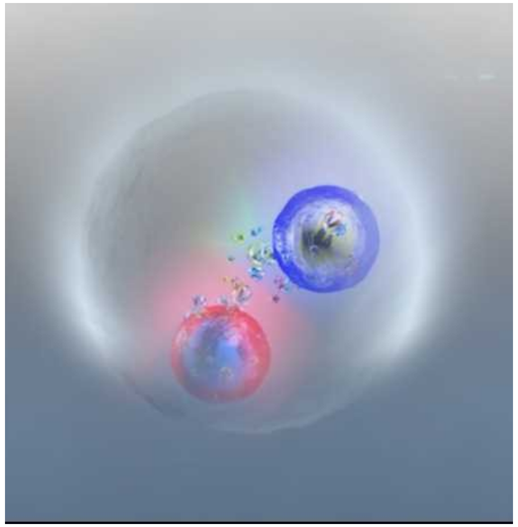
Main LHC results

- Higgs boson discovery (2012) and study of its properties;
- Study of W and Z bosons, and top quark;
- A lot of precise measurements of production cross-sections and decay/branching ratios (for example, rare decay of Bs –> μ+μ-). All those confirmed SM and set hard limits on alternative theories.
- Observation of more than 50 new hadron states, including pentaquarks (2015, LHCb) - hadrons containing 5 quarks (qqqqq̄), and mesons of 4 quarks (qqq̄q̄), observed before only in e^+e^- reactions.
- Confirmation of quark-gluon plasma existence (ALICE: Pb+Pb) with extreme high T and zero viscosity;
- Supersymmetric (SUSY) and exotic particles/objects like microscopic BH or leptoquarks NOT (yet?) observed.

Recent result: evidenice of bound top-antitop state

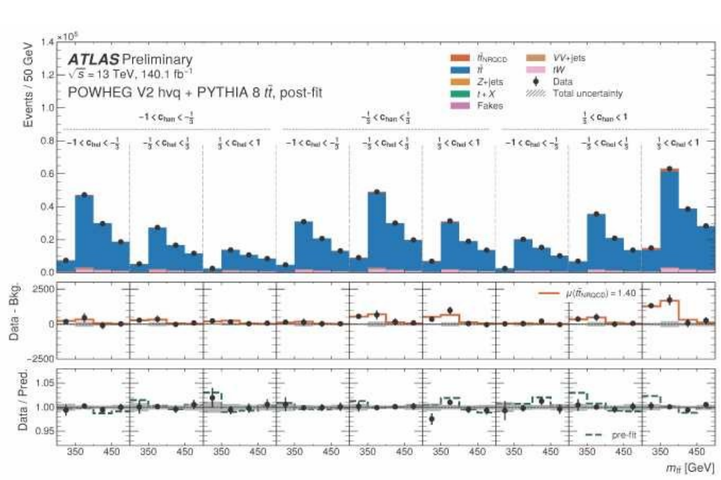




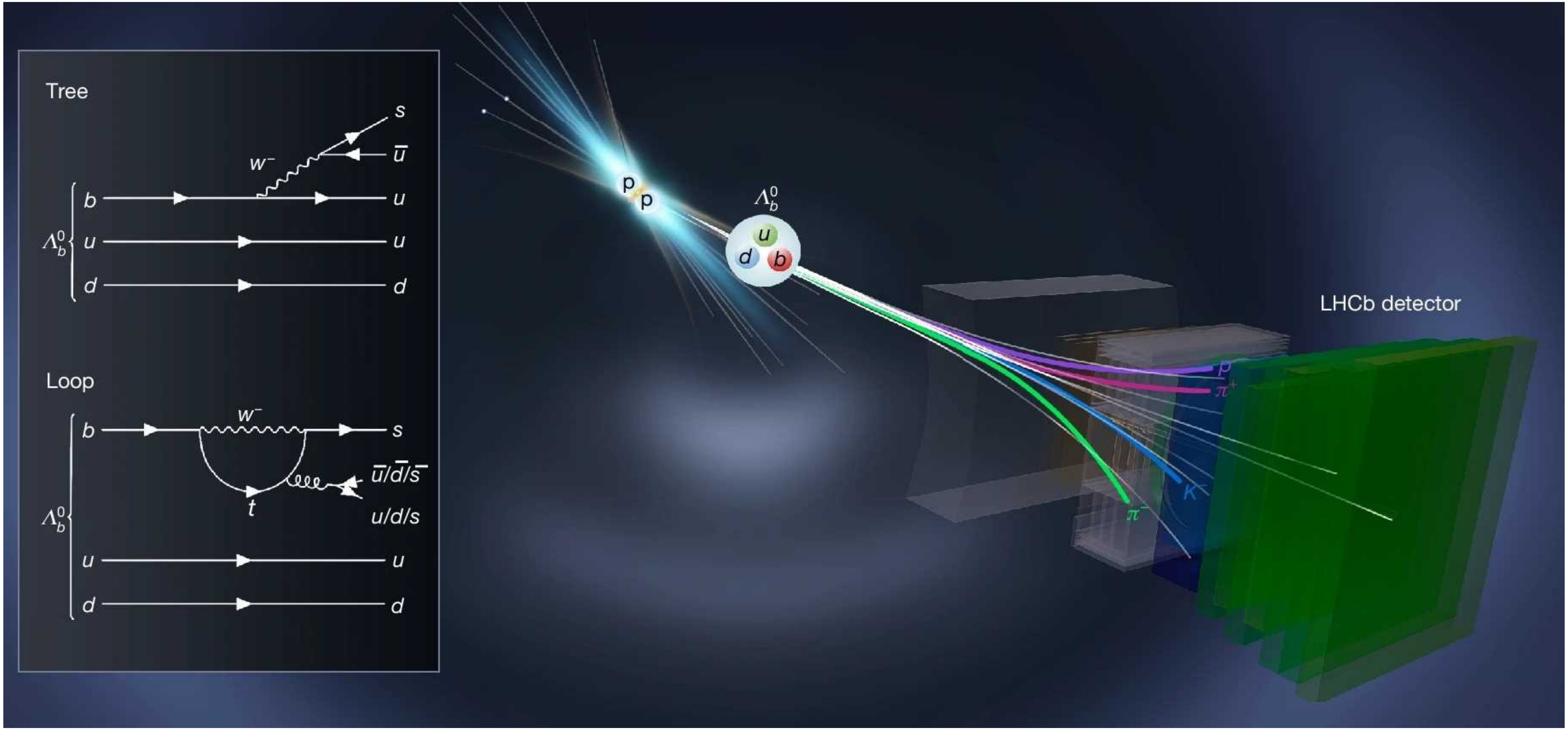


EPS-HEP 2025

Observation of a pseudoscalar excess at the top quark pair production threshold.
https://arxiv.org/abs/2503.22382



https://www.nature.com/articles/s41586-025-09119-3

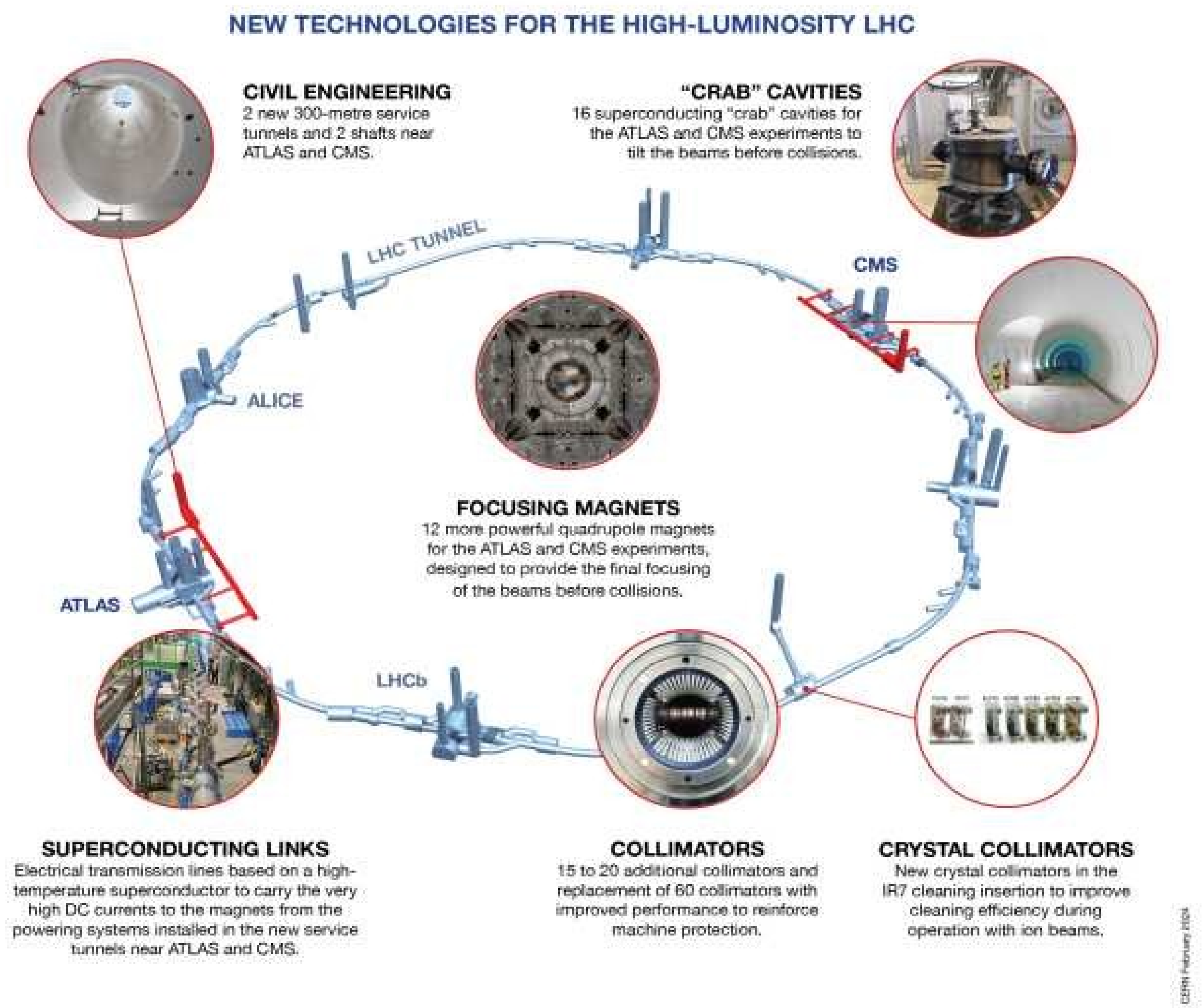


Scientists analyzed almost a trillion decay events of lambda baryons containing the b quark (Λb0) and their antiparticles. These baryons decayed into protons, kaons, and pions. If CP symmetry were preserved, the decay probability should have been the same for a particle and its antiparticle. However, it is recorded a consistent difference of 2.5%, with a statistical significance level of 5.8 sigma — more than enough to officially recognize the discovery.

Where are we now? we attend many experiments

- LHC is the most powerful machine
  No signs of new physics. Consequently, no 5 σ discovery at the ongoing run
- BelleII is the most powerful e^+e^- machine
  Various anomalies (+ LHCb, CMS) in flavor sector. Many disappeared
- Fixed target experiments at CERN SPS
  400 GeV proton beam, various secondary 100 GeV e^-, e^+, μ, π etc beams
  hadronic structure studies, . . . , searches for new physics (NA64, SHiP)
- Fixed target projects at accelerator neutrino experiments
  Fermilab (120 GeV), JPARC (30 GeV)
- Rare processes with light hadrons (kaons, pions, hyperons)
  NA62, KOTO ($K \to \pi\nu\bar{\nu}$), PSI, experiments in Protvino
- e^+e^- low energy colliders: BES-III, experiments in Novosibirsk
  Investigations and precision measurements of hadronic resonances
- low energy accelerators
  electron MeV-GeV scale accelerators (many places), proton sub-GeV scale accelerators (in Troitsk, Dubna, etc) and colliders (SPD at NICA)
- . . .

High Luminosity Run (HL- LHC) - planned after 2029



GOAL – to increase Luminosity

- Target integrated Luminosity: 4000 fb^{-1} for 12 years.
- Peak Luminosity: $5x10^{34} cm^{-2}s^{-1}$ (vs ~$2\times10^{34} cm^{-2}s^{-1}$ in Run 3)

New magnets and infrastructure

- New superconducting magnets (11 T) at the interaction points.
- Upgrade of vacuum chambers and collimators to operate with high intensity beams.
- Optimization of cryogenics (1.9 K) for stable magnet cooling.

Detector upgrade

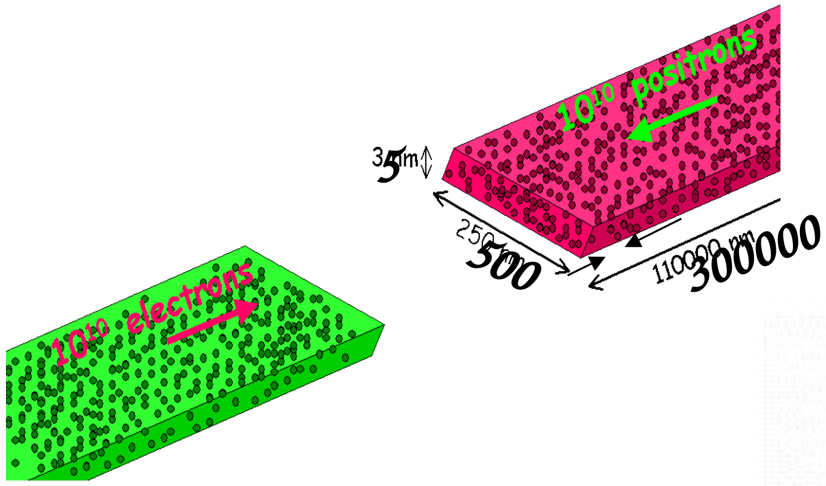
- Replace ATLAS and CMS inner trackers to radiation hard and high granularity detectors.
- Upgrade of trigger and DAQ to handle high data rate.

The main parameter of the "accelerator" experiment

Luminosity

$$L = \frac{N_1 N_2 \omega}{S}$$

1 barn = 10^{-24} cm^2



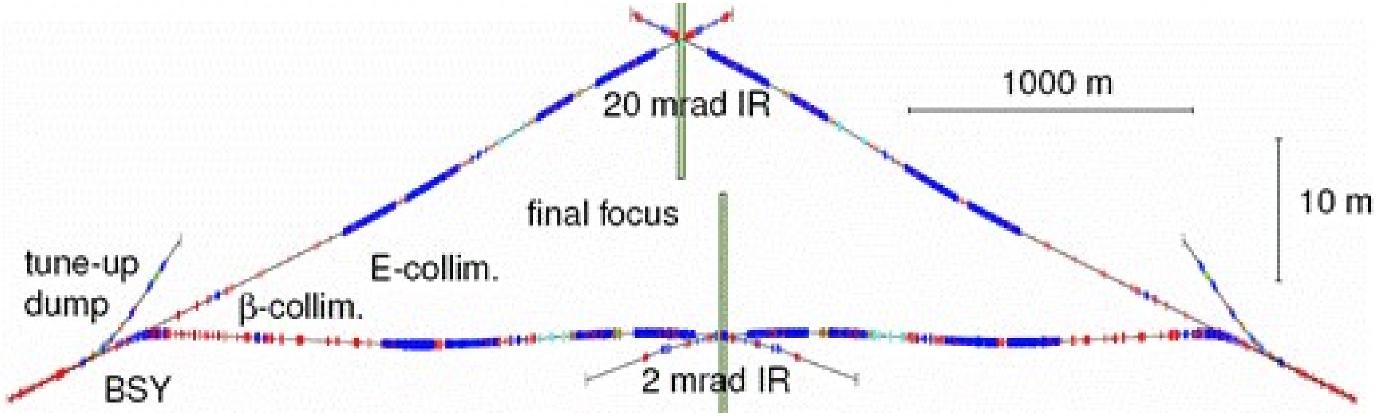
$$L \sim 10^{32} \frac{1}{cm^2 \sec}$$

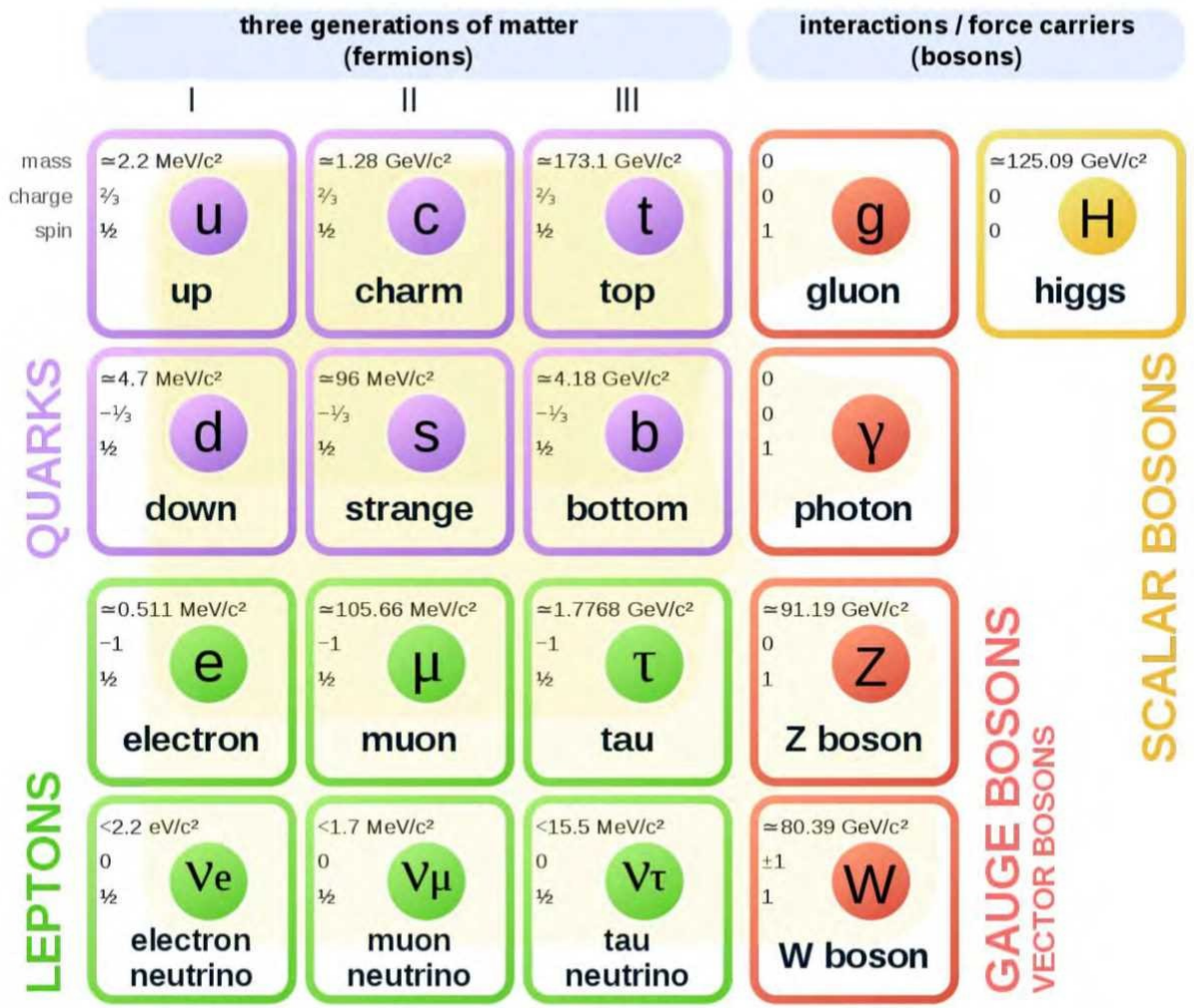
Fixed target

$$E \approx E_{cm} = \sqrt{2(\gamma+1)}mc^2$$

$$E \approx E_{cm} = 2\gamma mc^2 = 2E$$

Colliding beams





- We have to study the Higgs boson it self in as much detail as possible, searching for signs of a larger Higgs sector and the effects of new heavy particles.
- We must search for the imprint of the Higgs boson and its possible partners on the couplings of the W and Z bosons and the top quark.
- We must search directly for new particles with TeV masses that can address important problems in fundamental physics.

Courtesy of A.Bondar'

After LHC

e-p and h-h Colliders : «higgs-factory» and «top-factory»

ILC

Japan

Linear e^+/e^- (polarized)

30-50 km, 0.5 / 1 TeV

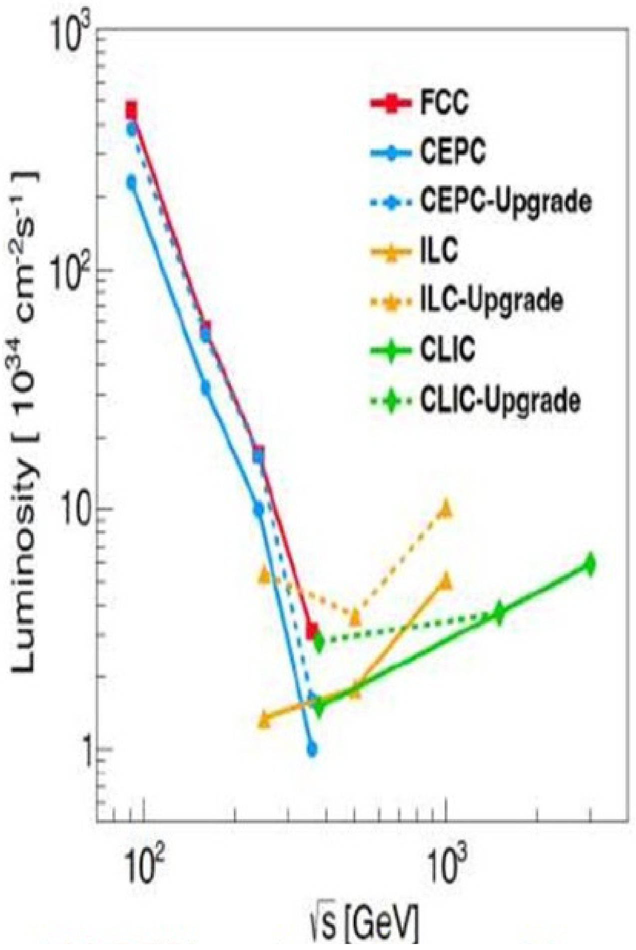
FCC

CERN

90 km circular (16T magnets)

88 ->380 GeV (FCC-ee)

100 TeV (FCC-hh), L ≤ 30×10^{34}



CLIC

CERN

Linear, e^+/e^-

11–50 km, 0.38 / 1.5 / 3 TeV

CEPC

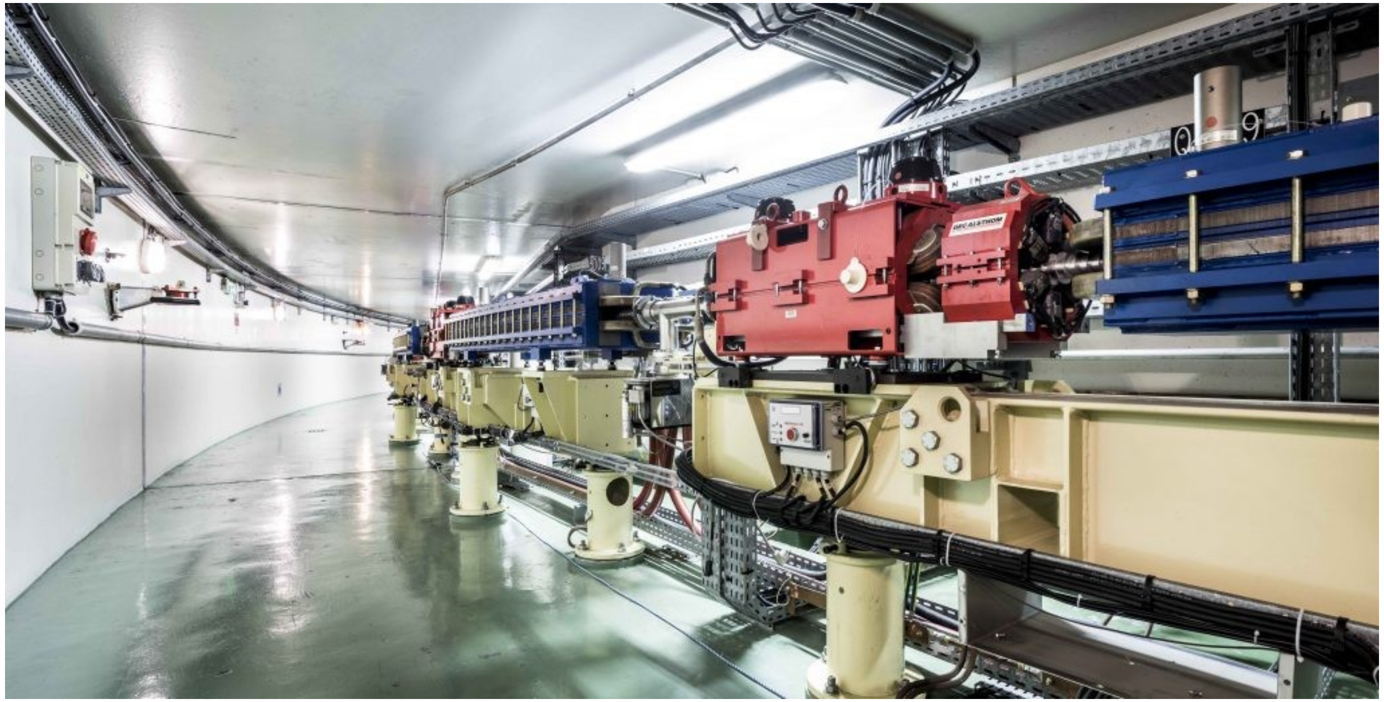
Huairou, China

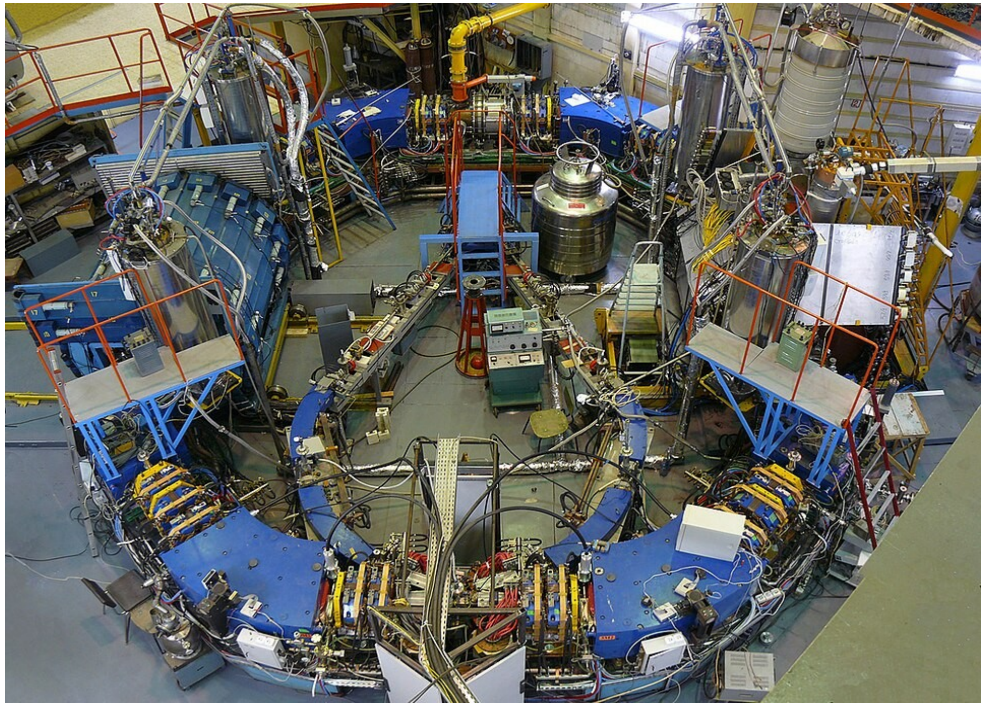
Circular, e^+/e^- , L ~ 2×10^{34}

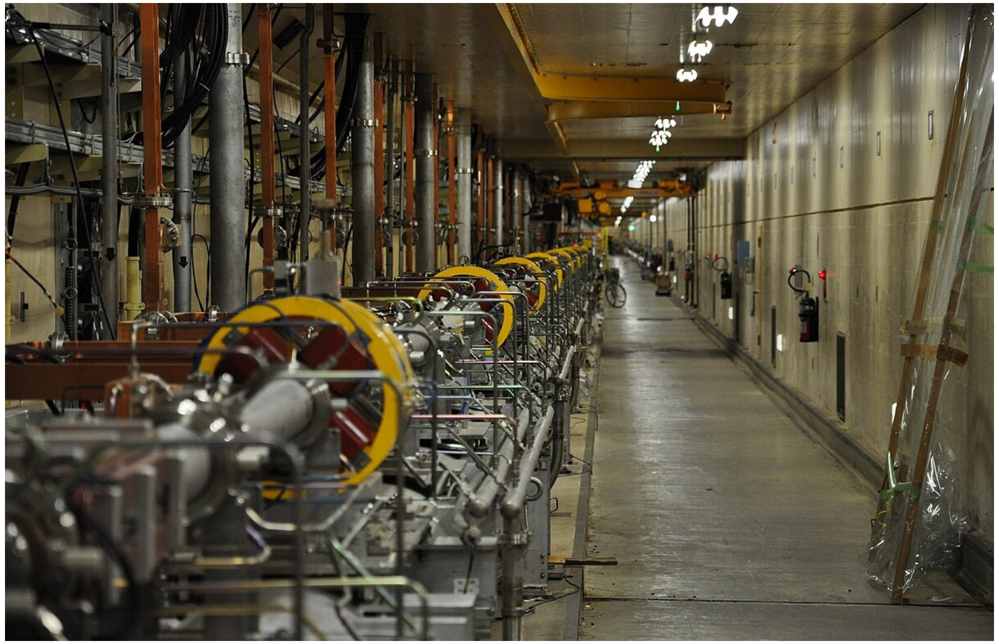
52 ->100 km (7T magnets),

240 GeV (ee), then hh

Протон-протонные (pp), ядро-ядерные(nn) (адронные = hh) коллайдеры

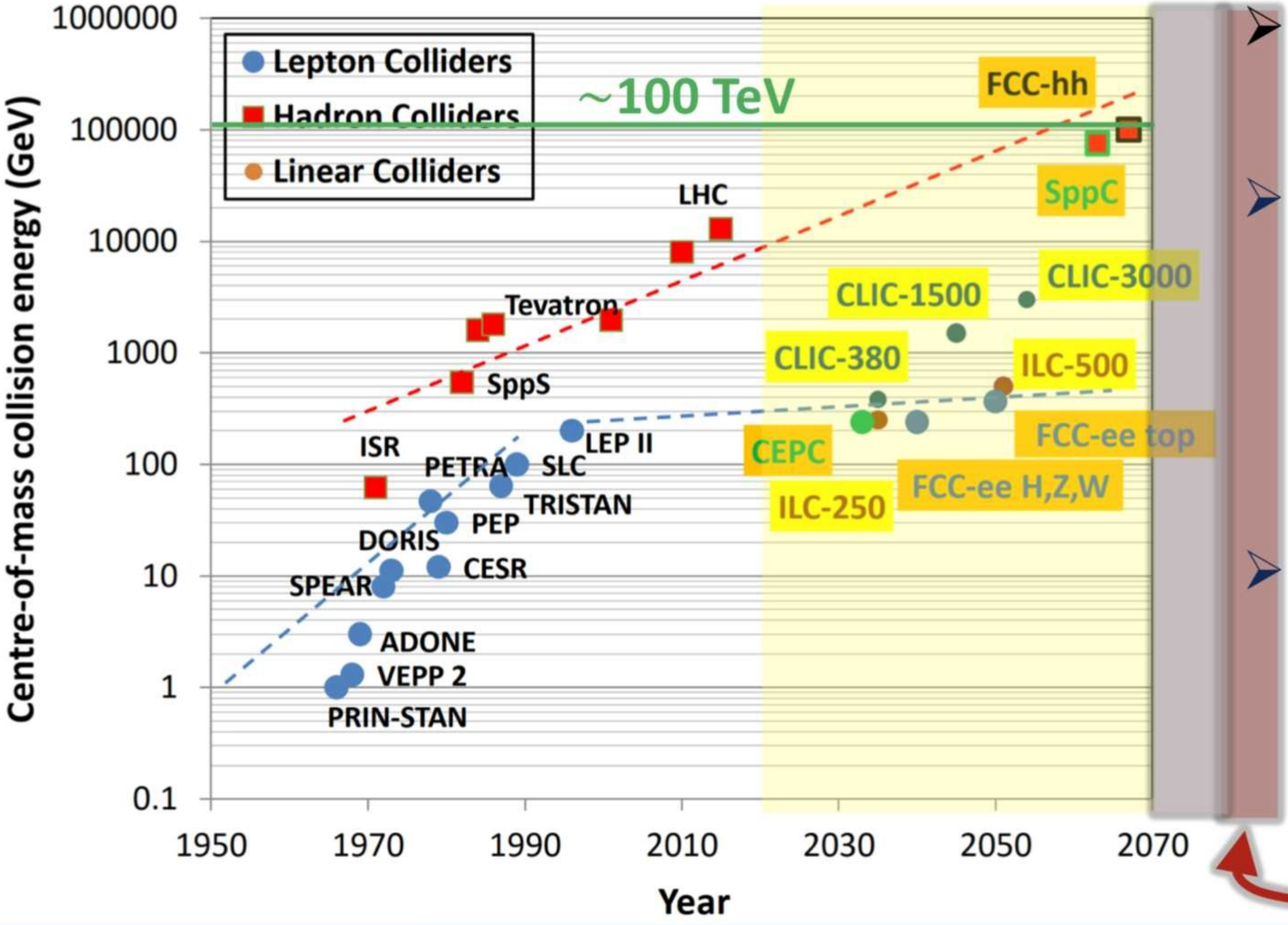






Electron-
positron
(lepton)
colliders

next-generation high energy colliders under study

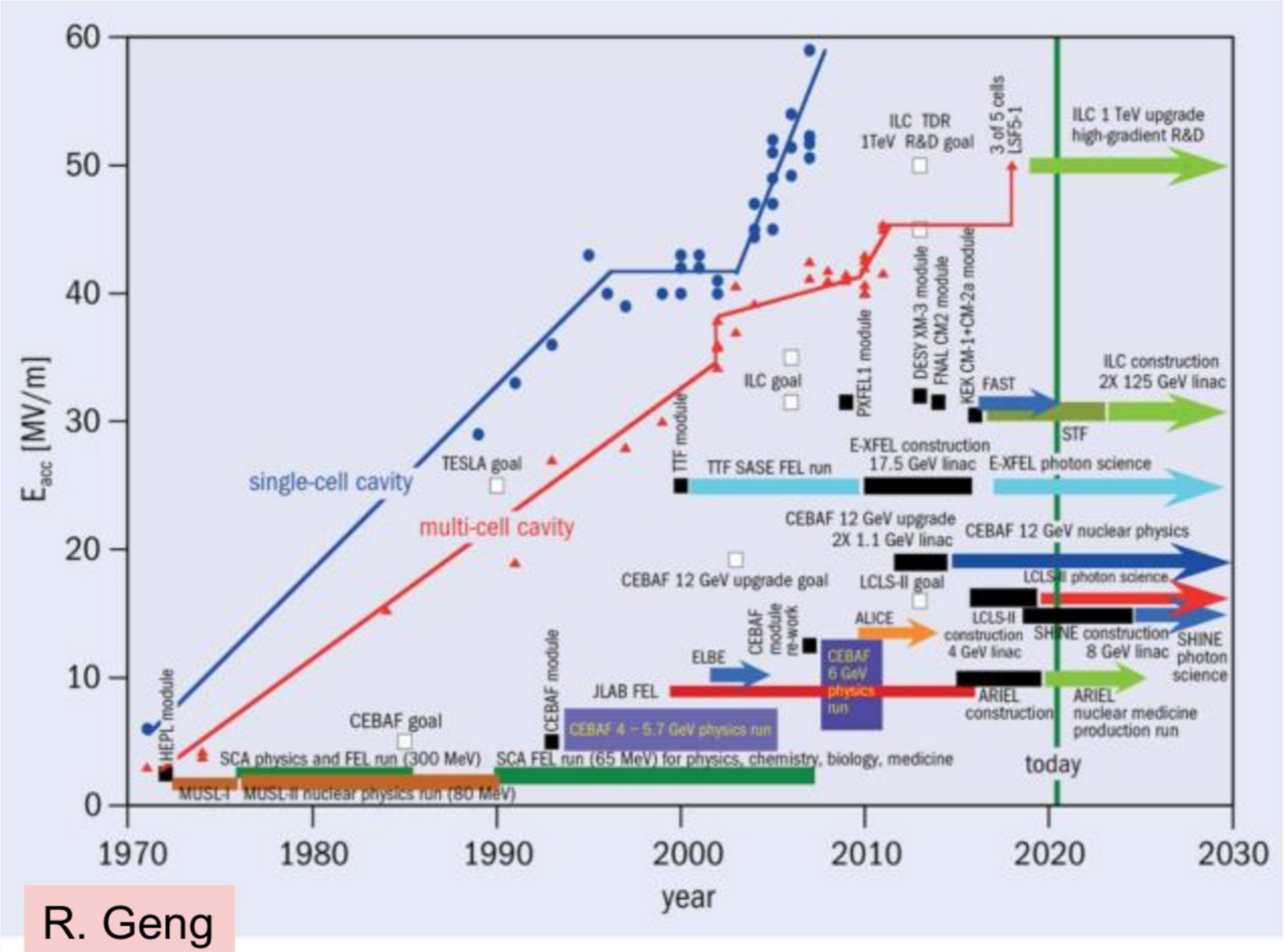


- **Linear e⁺e⁻ colliders** (CLIC, ILC)
  E_{CM} up to ~ **3 TeV**
- **Circular e⁺e⁻ colliders** (CEPC, FCC-ee)
  E_{CM} up to ~ **400 GeV**
  limited by e± synchrotron radiation
  $$\Delta E/\text{turn} \propto \gamma^4/\rho$$
  → **precision measurements**
- **Circular p-p colliders** (SppC, FCC-hh)
  E_{CM} up to ~ **100 TeV**
  energy (momentum) limited by $p = eB\rho$
  → **direct discoveries energy frontier**

next-next(-next) generation:
ERL based colliders?
muon colliders ?
plasma-based colliders?

challenge #1: accelerating gradient

Gradient growth Superconducting RF linac accelerating gradient achievements and applications since 1970. CERN Courier 2020



R. Aßmann

RF Accelerators

> 30,000 operational – many serve for Health

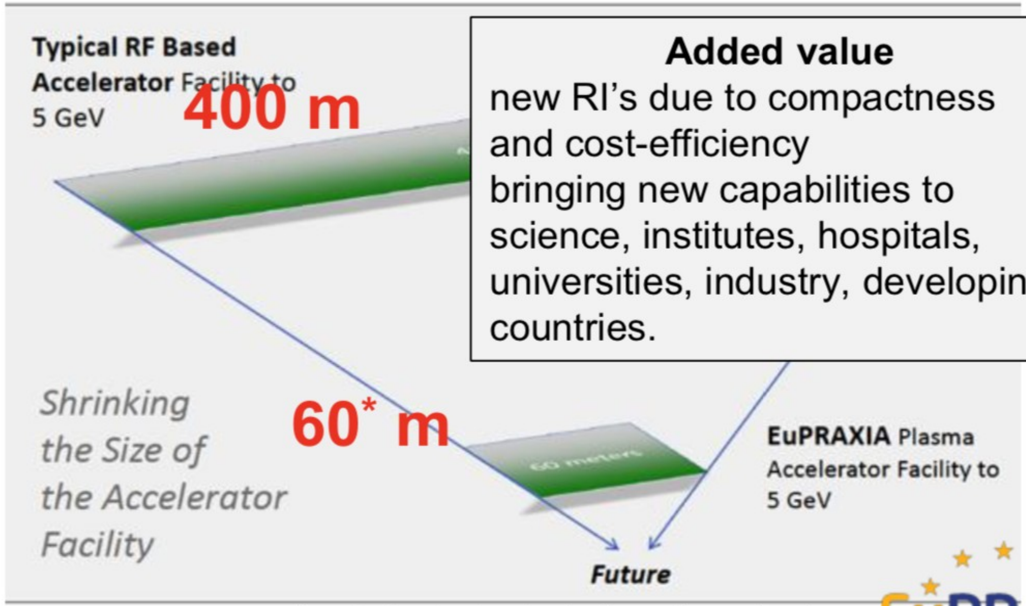
30 million Volt per meter

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt per meter

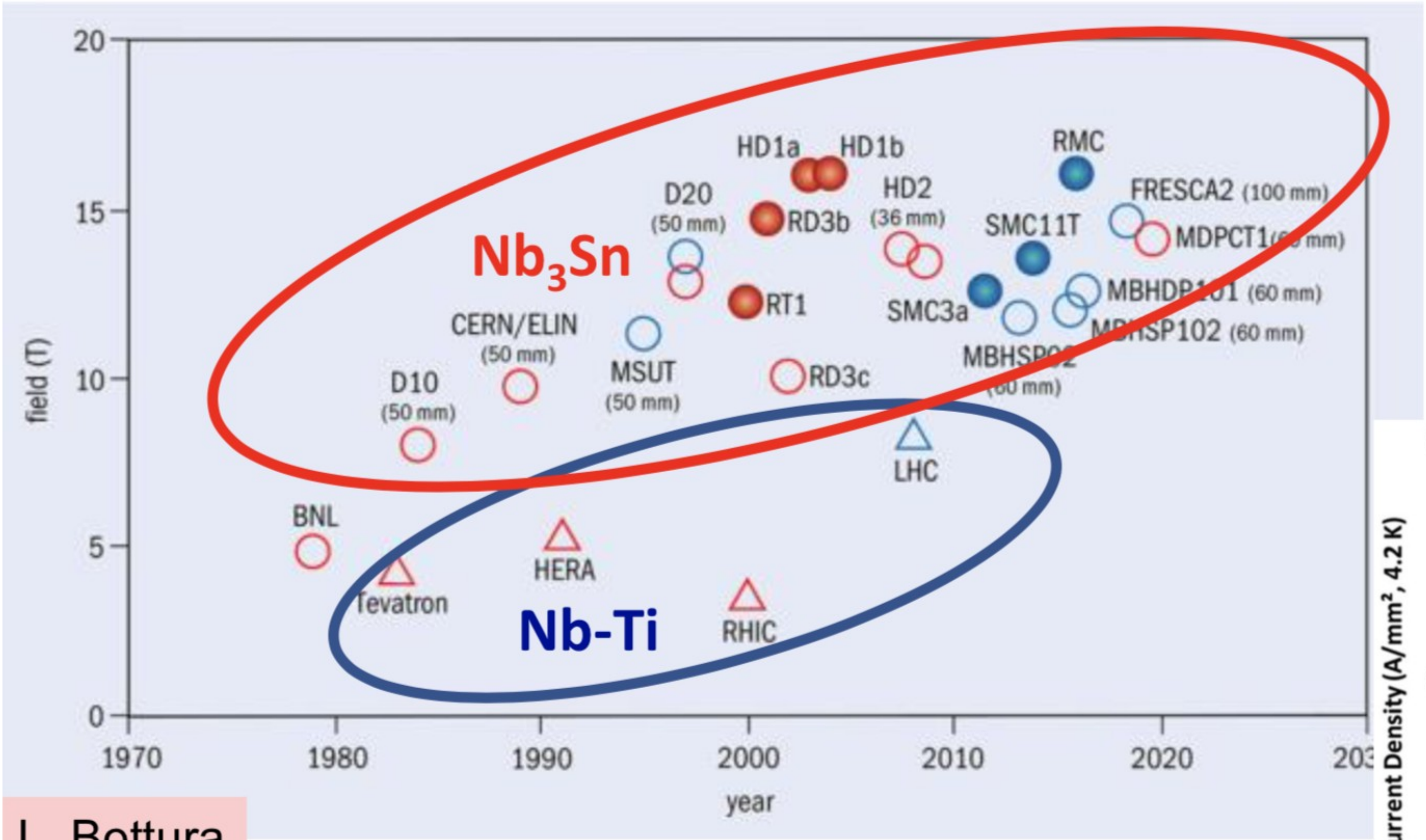


Added value
new RI's due to compactness and cost-efficiency bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

*realistic design including all required infrastructure for powering, shielding,

EuPRAXIA

challenge #2: bending magnetic field



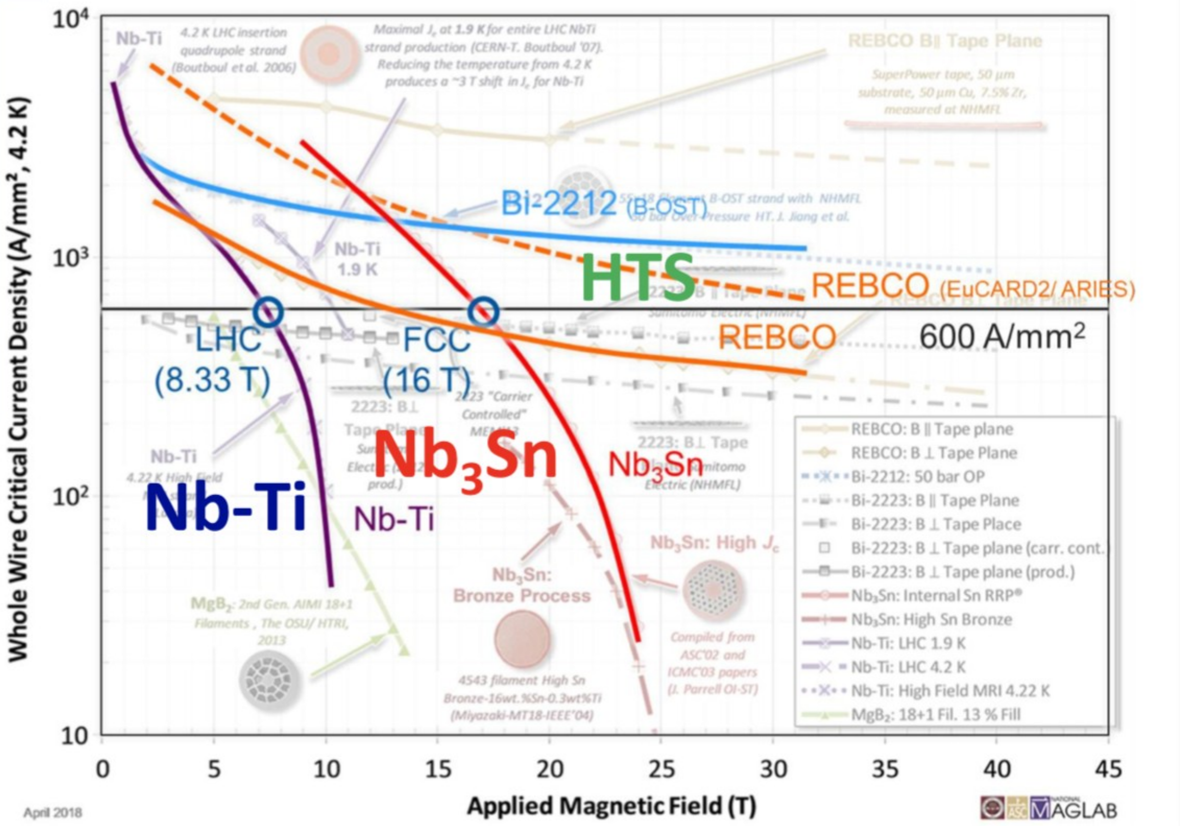
L. Bottura

Record fields attained with dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature.

→ hadron collider energy reach

Superconducting wire critical current density versus magnetic field.

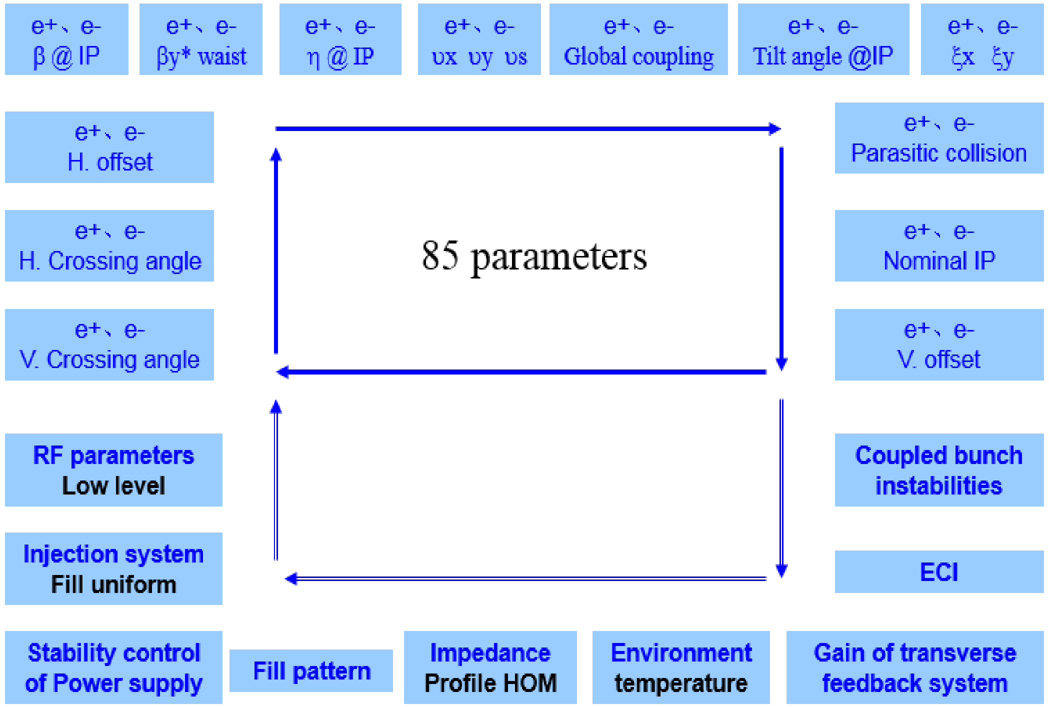
P. Lee



challenge #3: Complexity

The collision tuning system at BES-III (Beijing) was developed from 2003. It consists of solenoid compensation, global coupling correction, X-Y coupling tuning at the IP, relative orbit deviation tuning, optics deviation tuning, chromaticity ($dQ_{x,y}/dE$, $d\beta_{x,y}/dE$, $d\alpha_{x,y}/dE$) knob, etc.

$$L(\mathrm{cm}^{-2}\mathrm{s}^{-1}) = 2.17\times10^{34}(1+R)\xi_y \frac{E(\mathrm{GeV})k_b I_b(\mathrm{A})}{\beta_y^*(\mathrm{cm})} \times F_R$$



The luminosity reduction caused by deviations and multi-bunch instability could be eliminated effectively.

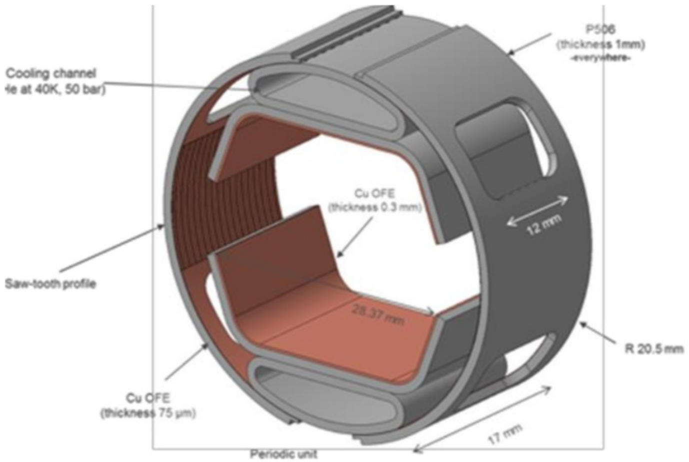
challenge #4: Synchrotron radiation, Power

The main energy/size limitation of any charged particle accelerator is synchrotron radiation (parasitic power loss)

$$\Delta E/\text{turn} \propto \gamma^4/\rho$$

FCC (ee) – energy loss per beam of about 100 MW
FCC (pp) – energy loss per beam of about 5 MW

Energy needs to be taken away somewhere – heat shields in a vacuum chamber

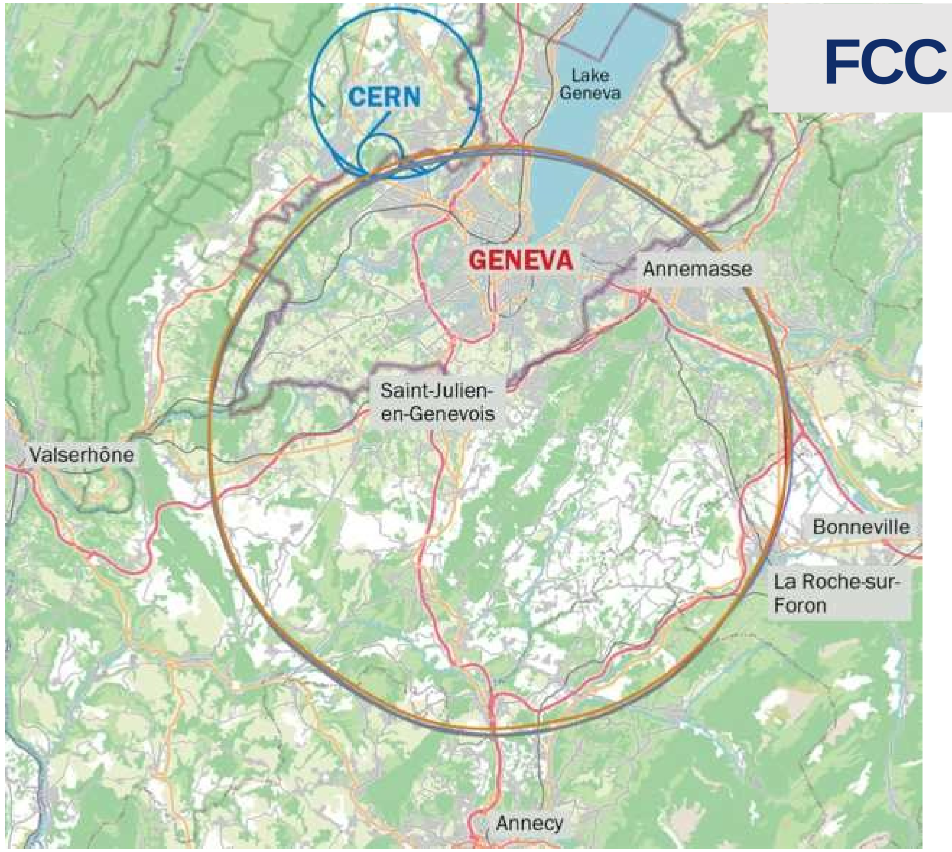


Complex geometry of vacuum beam chambers operating at 2K

Large power consumption…

LHC ~ 200 MW, CERN site ~ 400 MW

FCC and CEPC



2045 (??) +
91 km ring

E_{cm} = 240 GeV, C = ~ 50 km
L = 1.8×10^{34} $cm^{-2}s^{-1}$, I_b = 17 mA, P_{SR} =100 MW
Ready for e+e- in 2030+
For pp ~ 2042 ?

Decision is expected in January 2026

FCC Conceptual Design Study started in **2014** leading to **Conceptual Design Report** in **2018**

2021- 25: Feasibility Study → **2028:** project approval by CERN Council → **2032:** construction starts → **2041:** HL- LHC ends → **2045:** Operation of FCC-ee → **2070:** Operation of FCC-hh

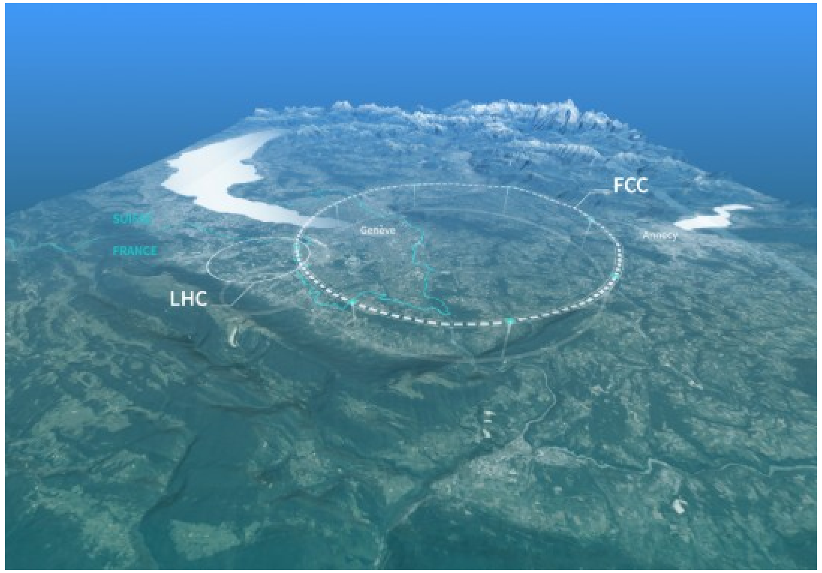
Future **C**ircular **C**ollider (FCC)

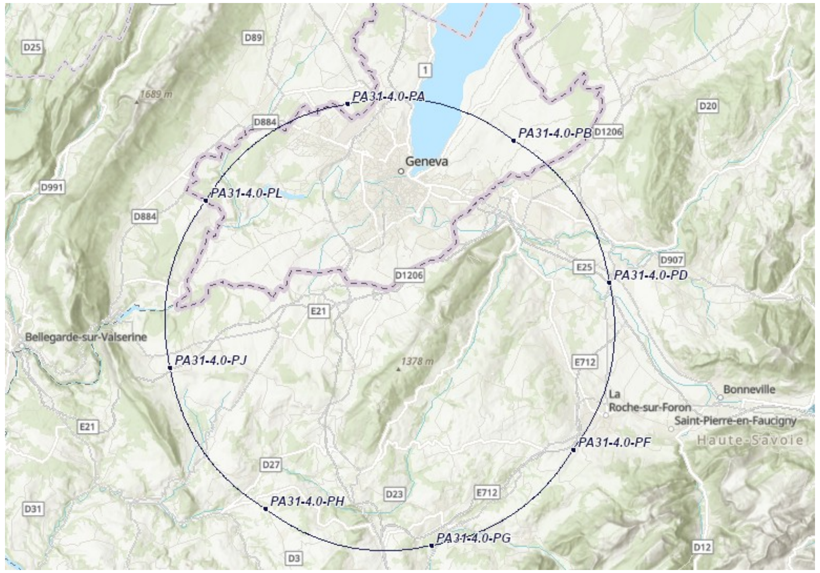
CERN, Switzerland

Partner Countries (collaborations): CERN member states, FCC Collaboration.

Funding: 15 billion CHF **($18,2 billion USD**), spread over about 12 years for FCC-ee with four experiments.

The Future Circular Collider (FCC) study is developing designs for higher performance particle colliders that could follow on from the Large Hadron Collider (LHC). A new underground circular tunnel is planned with a circumference of 90.7 km access shaft depths between 180 and 400 m, with eight surface sites and four experiments. The tunnel would initially house the FCC-ee, an electron–positron collider for precision measurements offering a 15-year research programme from the late 2040s. A second machine, the FCC-hh, would then be installed in the same tunnel, reusing the existing infrastructure, similar to when the LHC replaced LEP. The FCC-hh aims to reach collision energies of 100 TeV, colliding protons and also heavy ions, and running until the end of the 21st century. Once it reaches the end of its High-Luminosity phase. The FCC not yet built and is expected to be operational sometime in the 2040s.





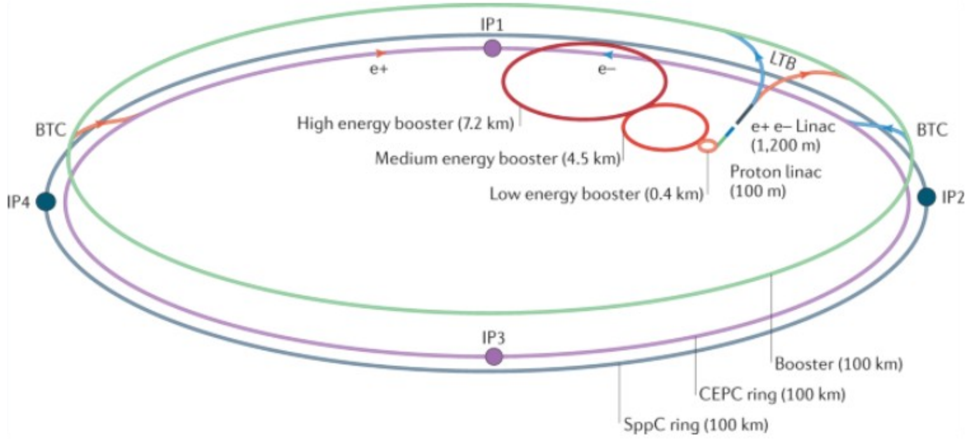
Circular **E**lectron **P**ositron **C**ollider (CEPC)

IHEP CAS, China

Partner Countries (collaborations): China, IHEP CAS, CEPC Collaboration.

Funding: projected cost CN¥36.4 billion (**$5.05 billion USD**), including experiments.

CEPC is a large international scientific facility proposed by the Chinese particle physics community in 2012 to explore the aforementioned physics programme. To be hosted in China in a circular underground tunnel of approximately 50km (and later 100 km) in circumference, is a double-ring collider with electron and positron beams circulated in opposite directions in separate beam pipes, and the detectors are installed at two interaction points (IPs). CEPC is projected to have a maximum centre-of-mass energy of 240 GeV. Commissioning and experiments can begin as early as 2035 when the 17th Five-Year Plan starts. The experiments will continue for about 14 years until 2049, with 1 year for commissioning and 13 years for Higgs, Z and W data taking.



It will be located 100 metres (330 ft) underground, and have two detectors. CEPC enables a wide physics programme. As an electron-positron collider, it is suited to precision measurements, but also has strong discovery potential for new physics. The CEPC is projected to start construction around 2027 and be completed by 2035.

International Linear Collider (ILC)

Japan???

Partner Countries (collaborations): three regions contributing to the ILC effort: Americas, Asia-Pacific and Europe (US, Germany, Japan, Swiss, Australia, etc.).

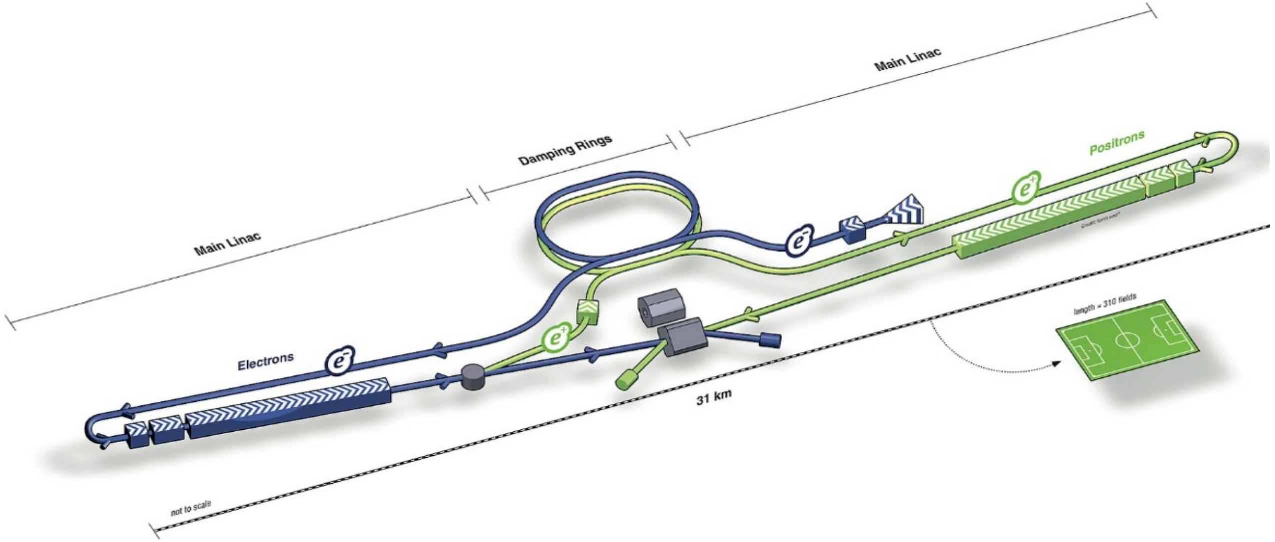
Funding: according to TDR – **$7.8 billion** and **22.6 million** person-hours.

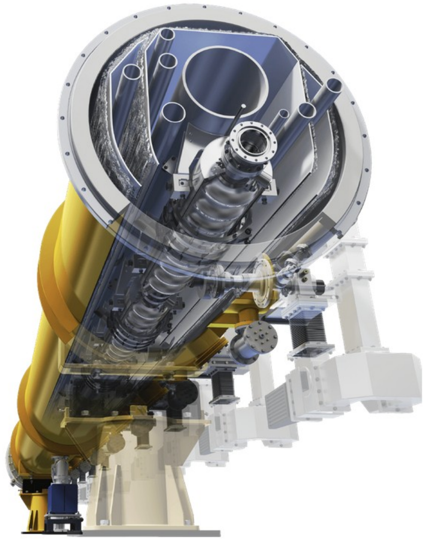
ILC: collision energy of 500 GeV initially, with the possibility for a later upgrade to 1000 GeV (1 TeV).

Year of launch: 2008 – promotion. 2013 – TDR.

Originally, three sites for the International Linear Collider were leading contenders at established High Energy Physics centres in Europe. At CERN in Geneva the tunnel is located deep underground in non-permeable bedrock. This site was considered favorable for a number of practical reasons but due to the LHC the site was disfavored. At DESY in Hamburg the tunnel is close to the surface in water saturated soil. Germany leads Europe for scientific funding and was therefore considered reliable in terms of funding. At JINR in Dubna the tunnel is close to the surface in non-permeable soil. Dubna has a pre-accelerator complex which could have been easily adapted for the needs for the ILC.

Kitakami highland in the Iwate prefecture of northern Japan has been the focus of ILC design efforts since 2013.





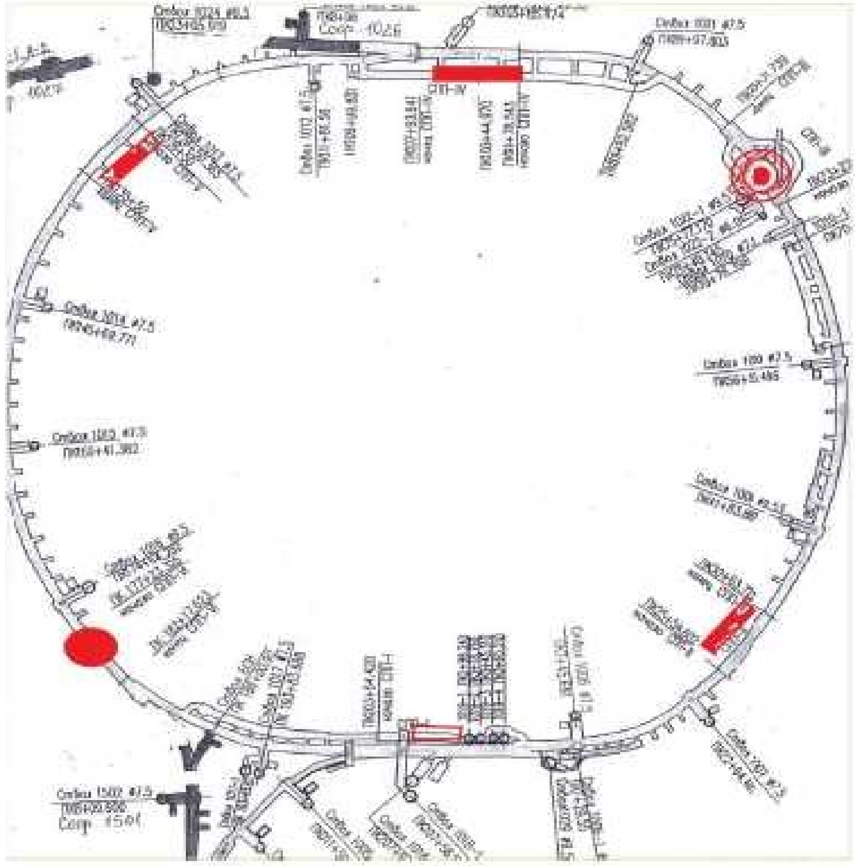
ZUNK: Z - factory in Protvino (Russia)

Proposal by NRC KI and BINP

New e^+-e^- collider in the old UNK tunnel (20 km)

Precision measurements at Z peak
45.6 GeV + 45.6 GeV
Crab Waist

Design luminosity ~10^{35}см$^{-2}$ с$^{-1}$ (4 orders of magnitude above LEP1, ~5% of FCC-ee at Z peak)



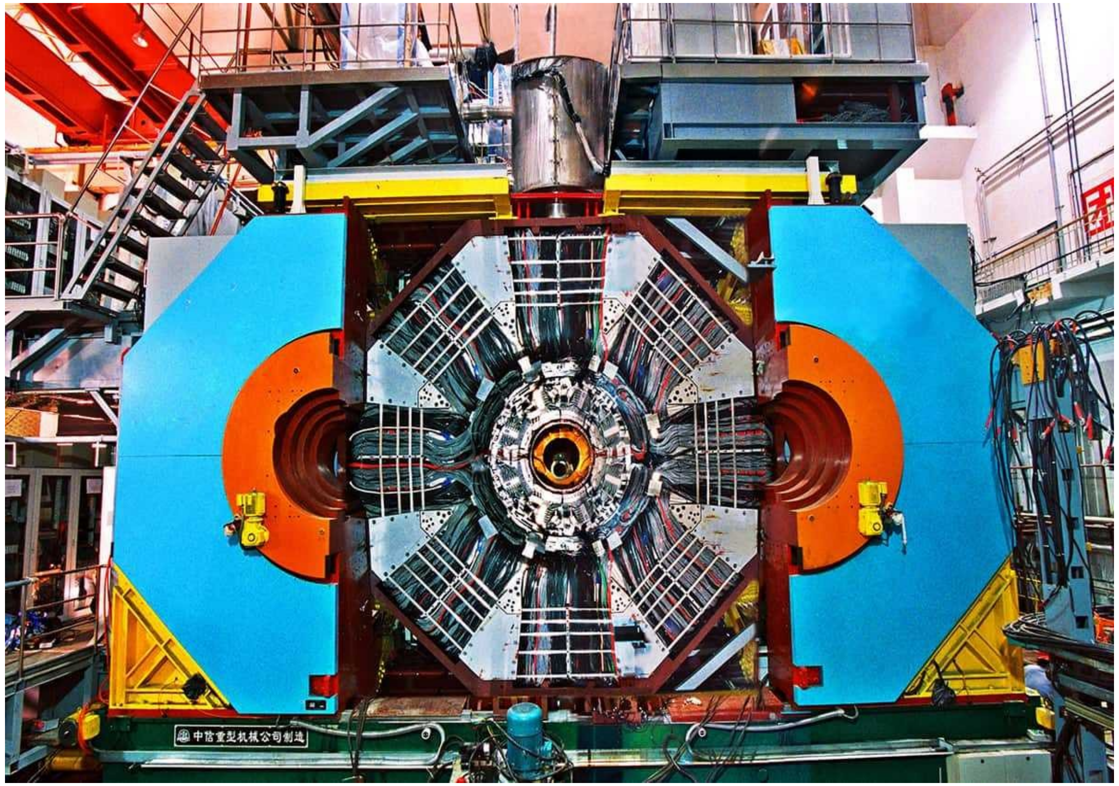
Flavor factories:

ultra high precision with record L, generators of b, c, s particles. Check of SM
QCD with J/psi, psi', psi", exotic hadron states, etc

BES-III (Beijing, China).

E_{cm} 2–5 GeV

Charmonium, D and Ds mesons, hadron spectroscopy, tau leptons

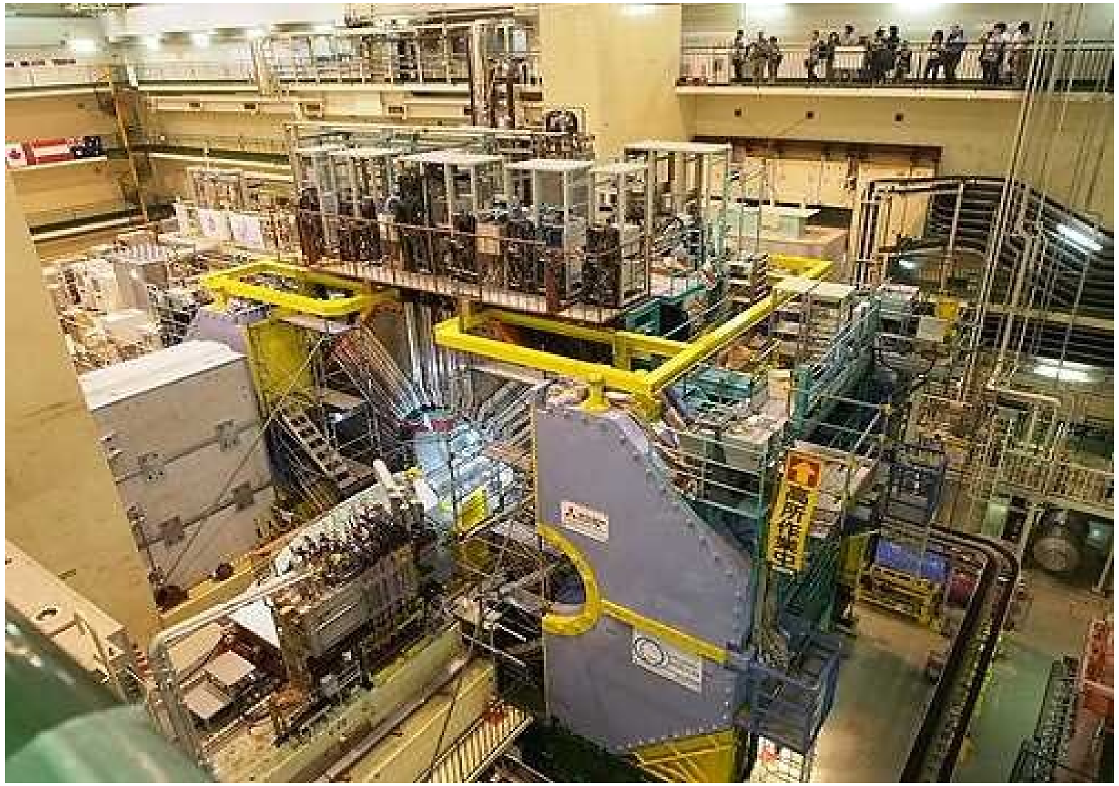


BELLE-II (Tsukuba, Japan).

E_{cm} 4+7 GeV

Bottomonium, B-mesons,

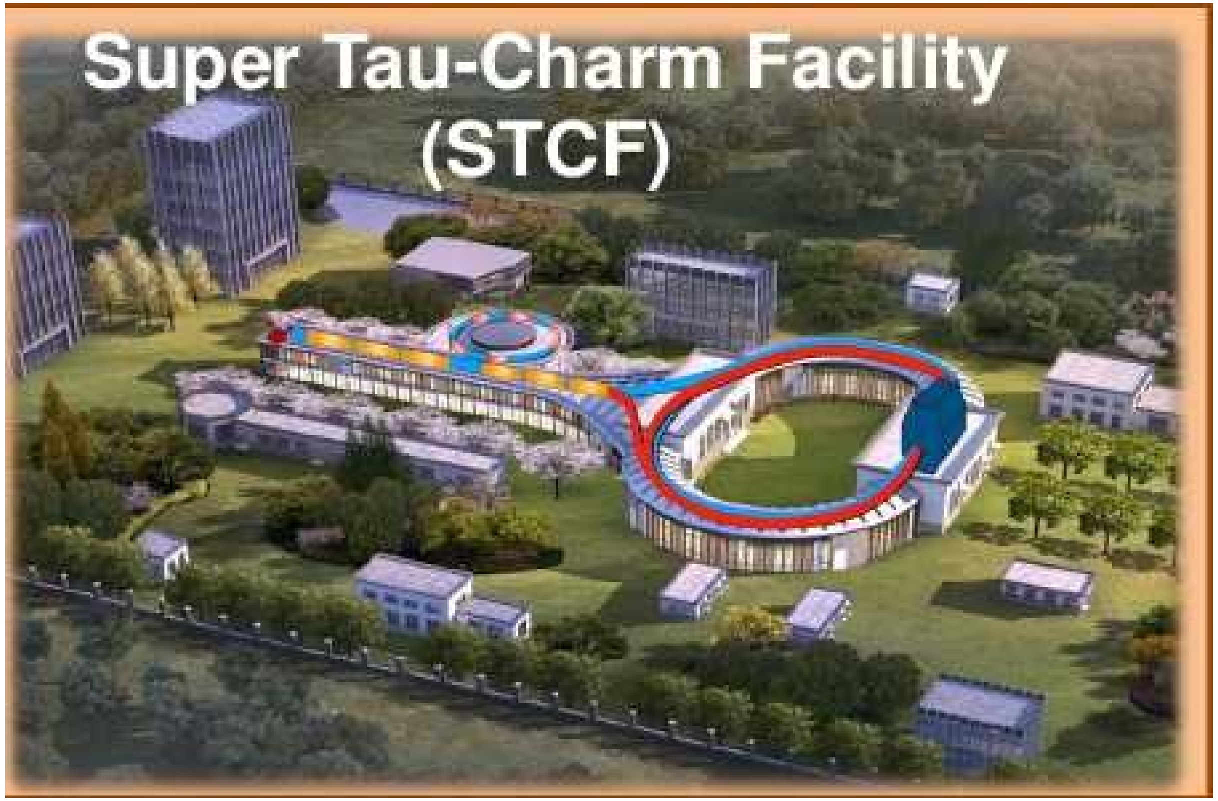
CP-violation in Bs decay, tau leptons



Future flavor factories

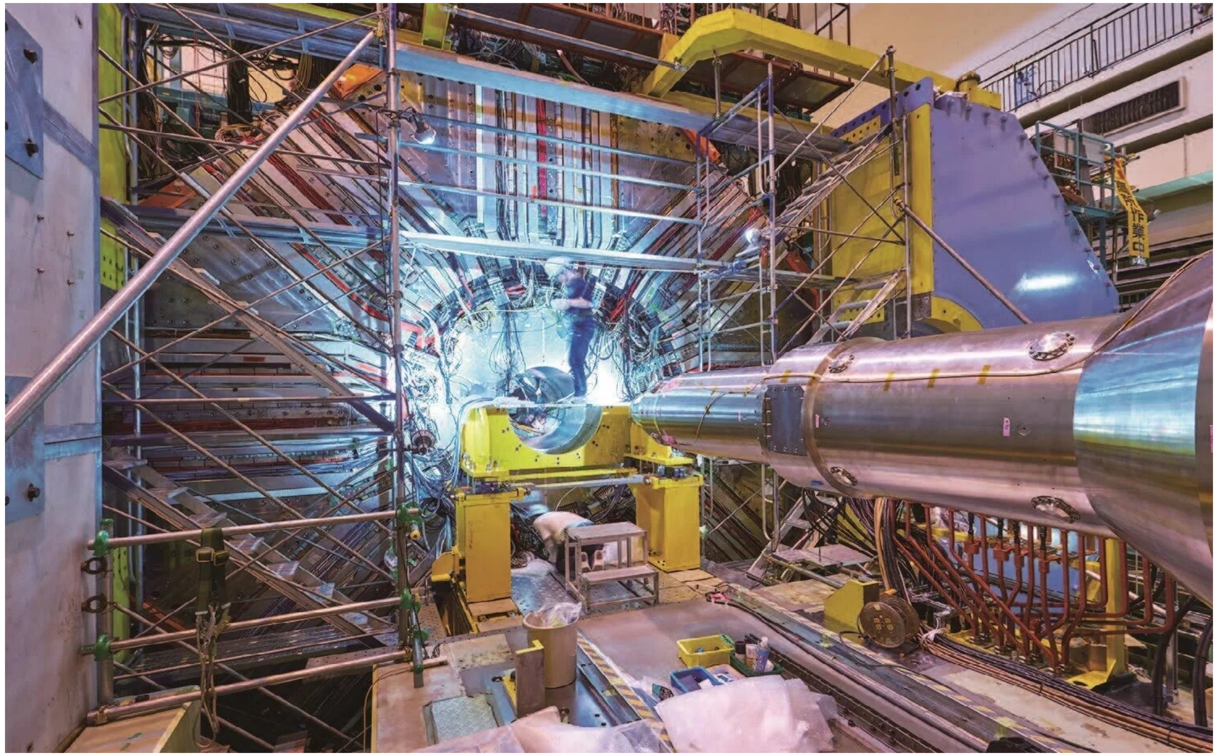
STCF (Hefei, China)

Luminosity: 10^{33} $cm^{-2}s^{-1}$(BESIII) → 5×10^{34} $cm^{-2}s^{-1}$ (STCF)

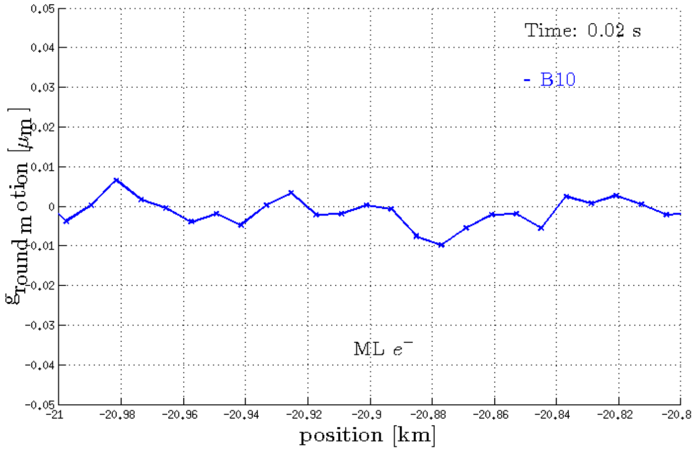


BELLE-II Upgrade

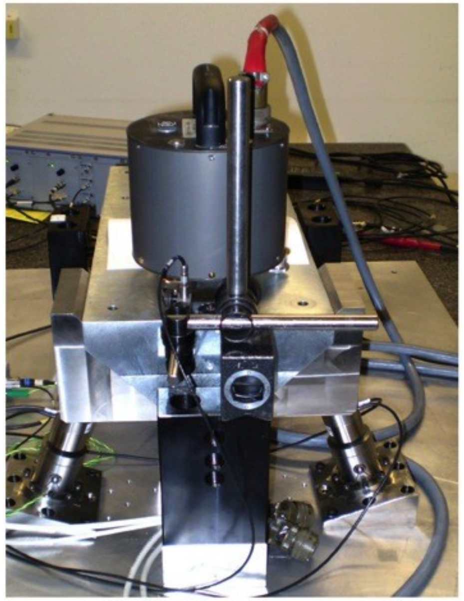
Luminosity: 5.1×10^{34} $cm^{-2}s^{-1}$(2024) → 6×10^{35} $cm^{-2}s^{-1}$ (2030)

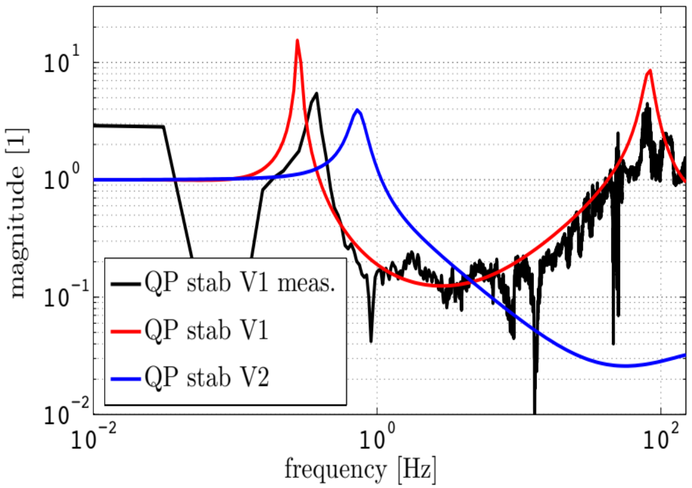


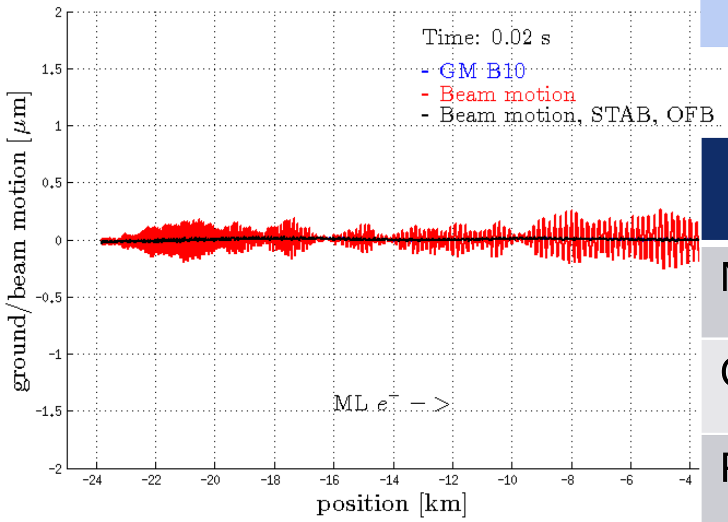
On-line stabilization of the Interaction Point (IP) with dimensions of 10-50 nanometers (!!)



Resulting Beam Jitter

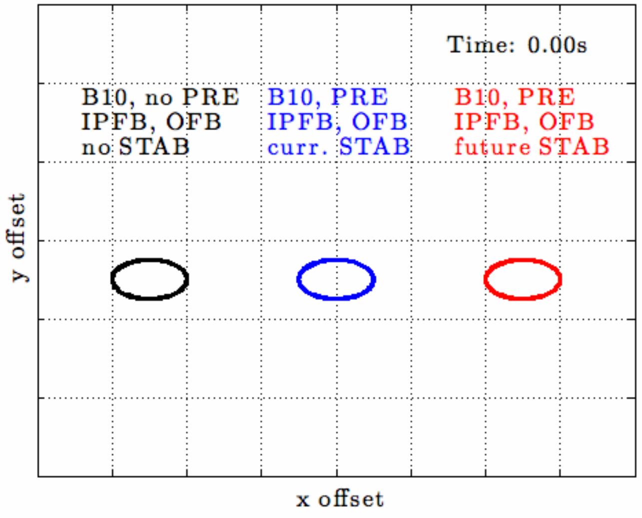






Luminosity achieved/lost [%]

	B10
No stab.	53% / 68%
Curr. stab.	108% / 13%
Future stab.	118% / 3%



D. Schulte, J. Pfingstner

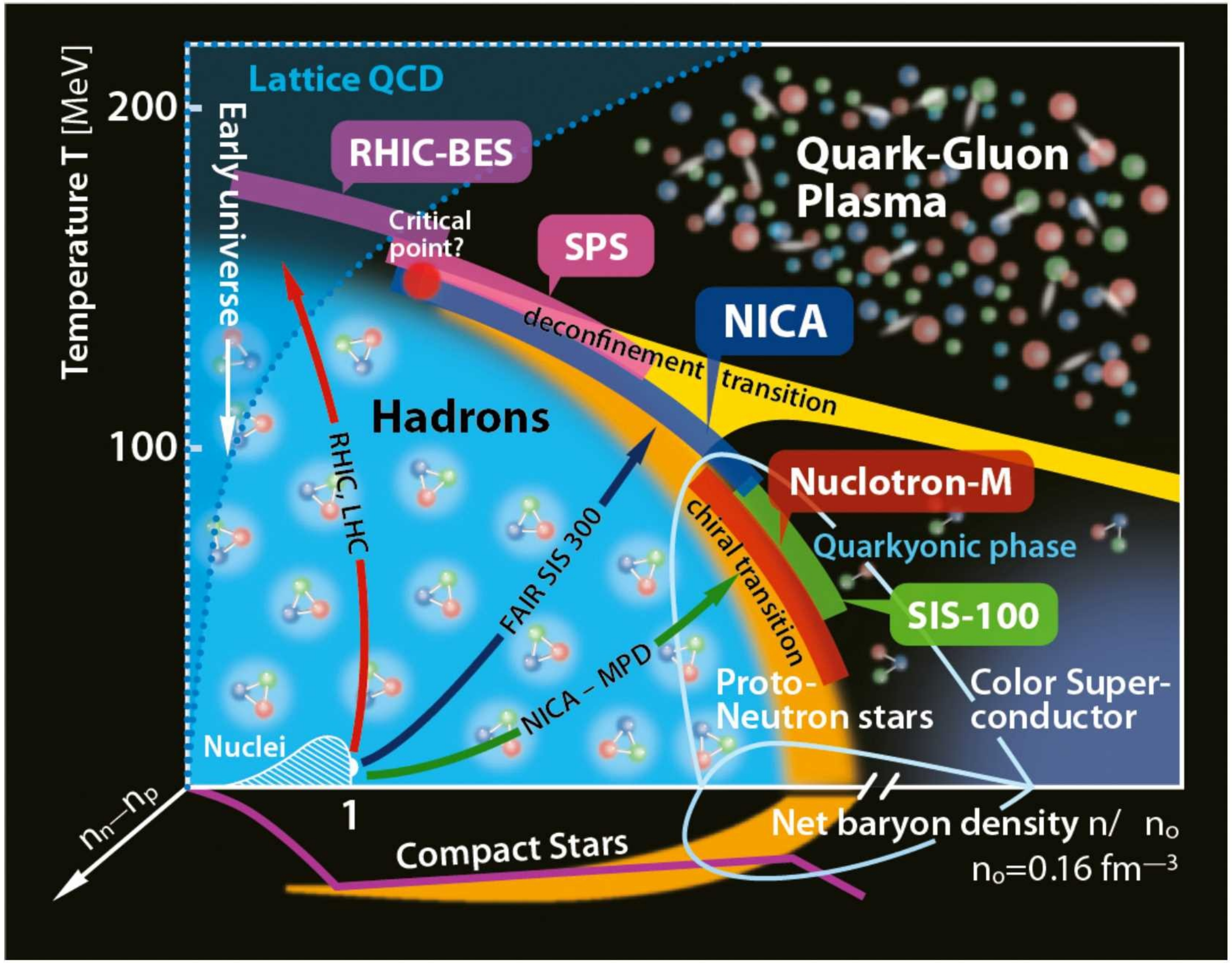
Three Broad Scientific Thrusts of Nuclear Science

Quantum Chromodynamics (QCD) seeks to develop a complete understanding of how quarks and gluons assemble themselves into protons and neutrons, how nuclear forces arise, and what forms of bulk strongly interacting matter can exist in nature, such as the quark-gluon plasma.

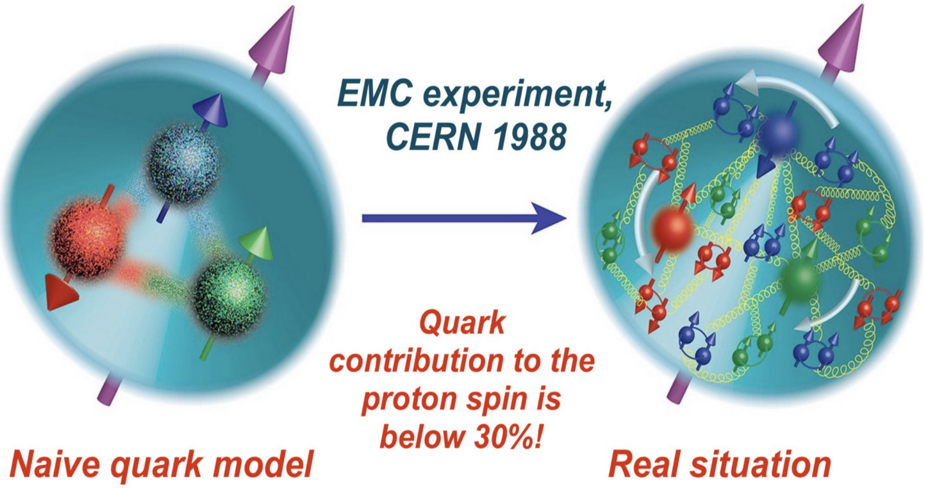
Nuclei and Nuclear Astrophysics seeks to understand how protons and neutrons combine to form atomic nuclei, including some now being observed for the first time, and how these nuclei have arisen during the 13.8 billion years since the birth of the cosmos.

Fundamental Symmetries of neutrons and nuclei seeks to develop a better understanding of fundamental interactions by studying the properties of neutrons and targeted, single focus experiments using nuclei to study whether the neutrino is its own anti-particle.

Experiments with relativistic heavy ions

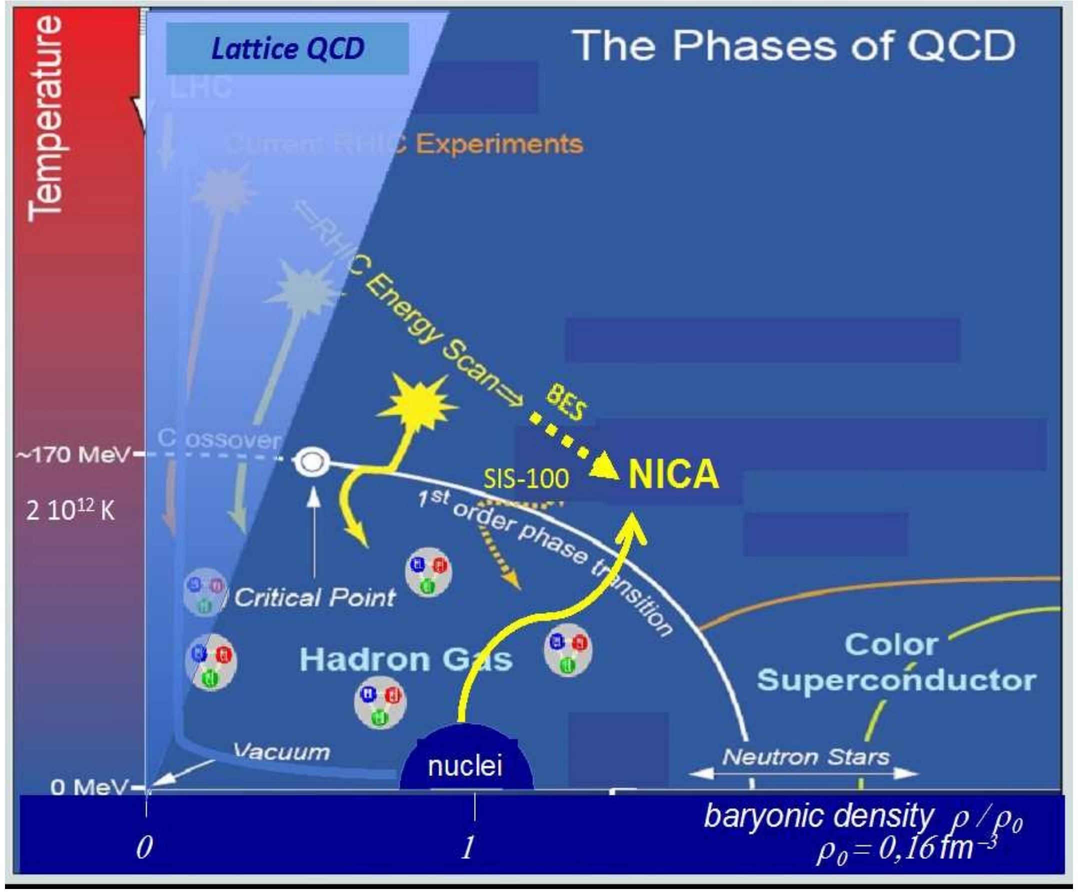


- Hadronic matter in extreme conditions;
- Confinement;
- Chiral symmetry;
- Quark-gluon plasma.



NICA

BM@N & MPD



Achieving the maximum density of nuclear matter, inaccessible to other laboratories in the world: the nature of neutron stars, the early Universe, spin effects.

MPD covers this interesting region providing powerful combination of **large luminosity, collision energy and system size scan** (including isobars), large and consistent **acceptance,** full **centrality** range.

SPD

The SPD experiment is aimed at studying the properties of strong interactions in the nonperturbative region, at measuring the proton and deuteron spin structures, and at the development of a three-dimensional model of the nucleon. It is unique in its methodology, breadth of coverage and variety of tasks.

Experimental facility	SPD @NICA	RHIC	EIC	AFTER @LHC	SpinLHC
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^\uparrow$-$p^\uparrow$ $d^\uparrow$-$d^\uparrow$ $p^\uparrow$-d, p-$d^\uparrow$	$p^\uparrow$-$p^\uparrow$	$e^\uparrow$-$p^\uparrow$, $d^\uparrow$, $^3He^\uparrow$	p-$p^\uparrow$, $d^\uparrow$	p-$p^\uparrow$
Center-of-mass energy $\sqrt{s_{NN}}$, GeV	≤27 (p-p) ≤13.5 (d-d) ≤19 (p-d)	63, 200, 500	20-140 (ep)	115	115
Max. luminosity, 10^{32} cm^{-2} s^{-1}	~1 (p-p) ~0.1 (d-d)	2	1000	up to ~10 (p-p)	4.7
Physics run	>2025	running	>2030	>2025	>2025

NICA
(Nuclotron based Ion Collider fAcility)

4 Major international collaborations have been formed and necessary conditions for their effective functioning at JINR have been created

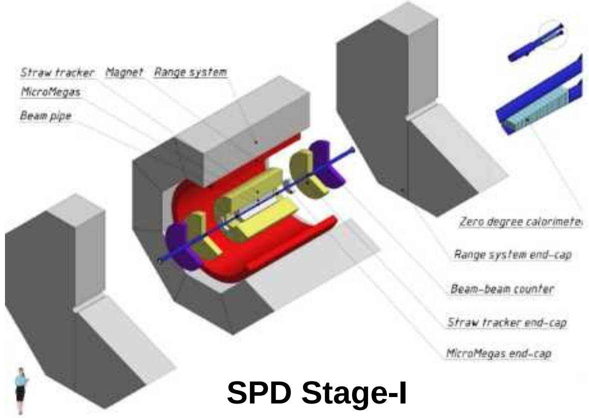
MPD: 15 countries, ~50 institutes, >500 participants

	Year 2023	
12	Jan 15 - April 15th	Preparation for Vacuum test of Solenoid with Cryostat
13	April 20 - May 20th	Vacuum tests
14	May 25 - June 15th	Solenoid cooling down to Liquid Nitrogen temperature (-80K)
15	April 20 June 15th	Electronic Platform construction
16	June 15 – September 15	Activities in the MPD Hall will be stopped
17	October – December	Cooling down to the He temperature
	Year 2024	
18	January. - February 15	Supplying the current to the solenoid and Correction coils
19	March - May 15	Magnetic Field measurements
20	June 1 - June 10	Support Frame installation
21	June 20 – August 30th	Installation ECal sectors, Insertion devices mounting
22	Sept 1 – September 20th	Installation TOF modules, FHCal into poles
23	Sept 15 - Nov 20	TPC installation
24	Sept 18 - Nov 20	Cabling
25	Oct 20 - Nov 25	Installation of beam pipe
26	Nov 30 - Dec 10th	Move the MPD on Collider beam line, Commissioning

116 conference papers
65 publications

SPD: 14 countries, ~40 institutes, ~400 participants

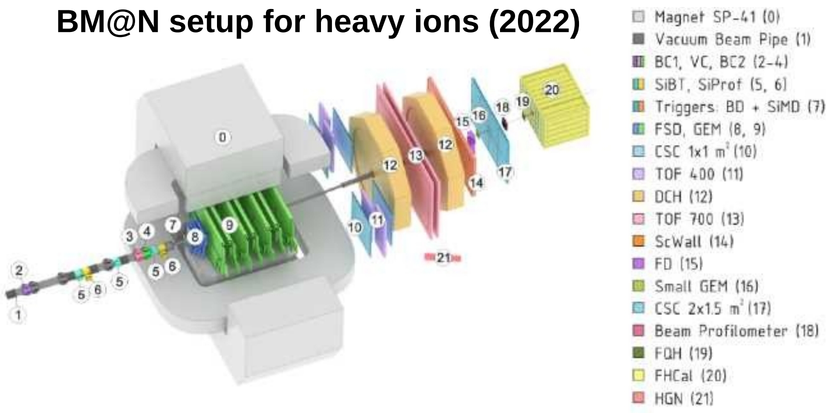
- SPD CDR was approved in Jan'2022;
- detectors prototyping/tests are ongoing;
- new version of **TDR** – Jan'2024;
- start of operation (Stage-I) – **2028**;
- **50** papers and **70** conference reports.



SPD Stage-I

BM@N: 10 countries, 19 institutes, ~300 participants

BM@N setup for heavy ions (2022)



4th NICA run (2022-2023):

- **550M events Xe+CsI at 3.0A, 3.8A GeV;**
- **analysis is ongoing;**
- **so far: 80 publications and 80 reports, including "Quark Matter", "Strangeness in Quark Matter", etc.**

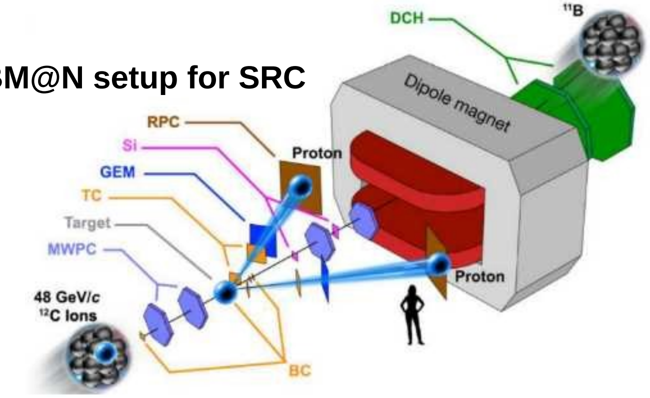
First observation of the Short-Range Correlations in inverse kinematics:

$^{12}C + p \rightarrow 2p + {}^{10}B \,/\, {}^{10}Be + (n\,/\,p)$

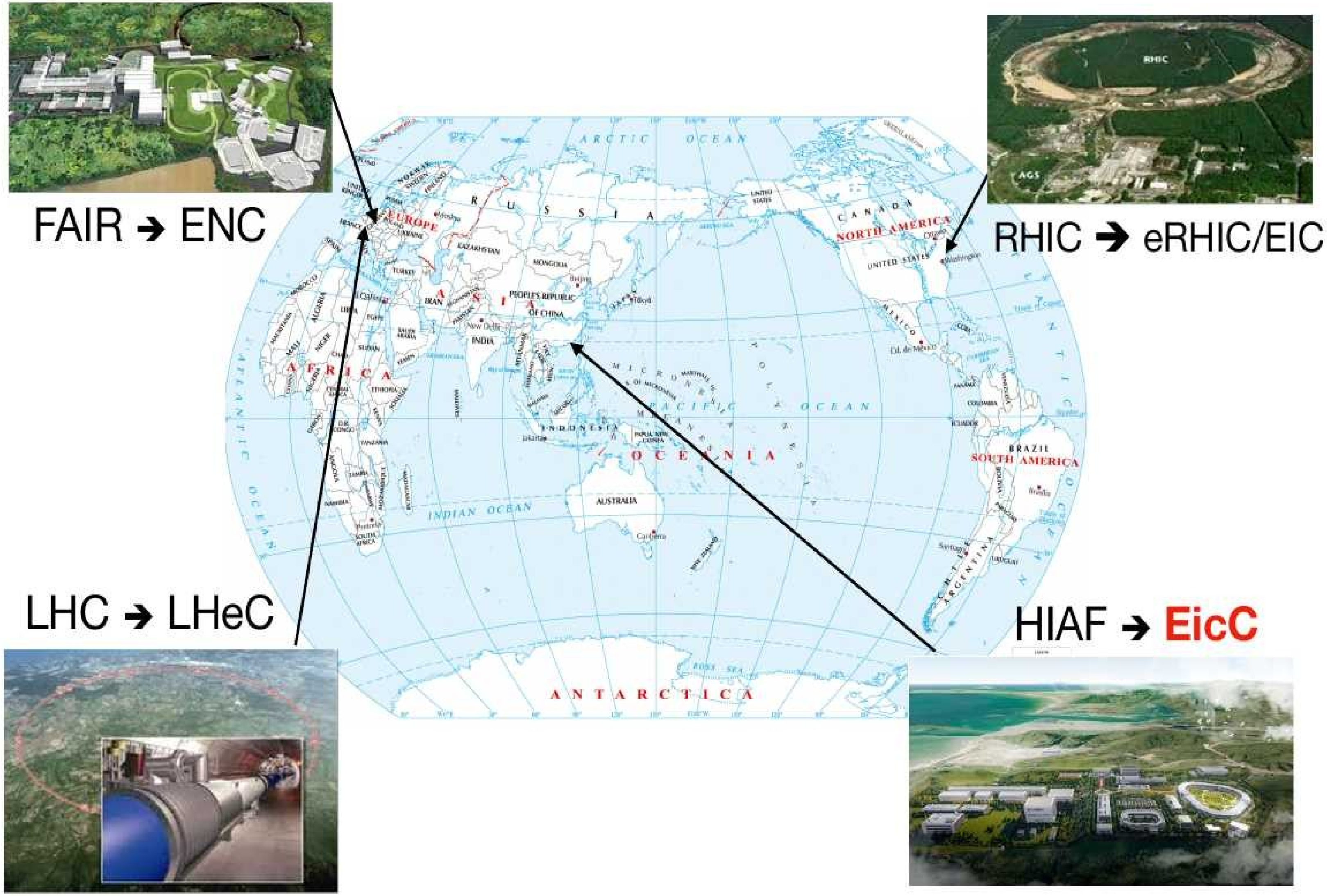
26 ^{10}B **events**
3 ^{10}Be **events** $\rightarrow$ ***np* pair dominance**

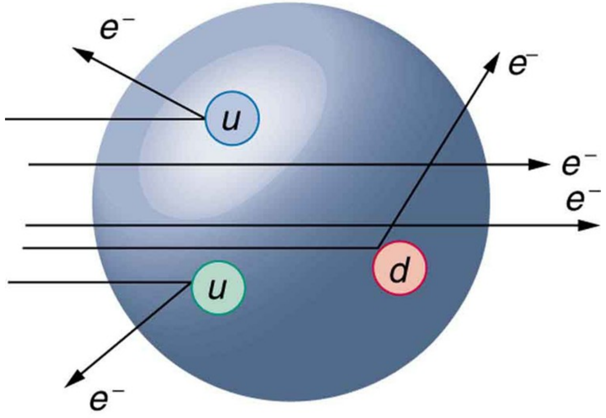
Paper was published in Nature Physics, 17 (2021)

BM@N setup for SRC



Electron - ion colliders





Proton

Program: to collide electrons with energies of 5-20 GeV with protons and heavy ions (up to 100 GeV/nucleon), which will make it possible to study the spatial distribution of partons, including gluons and sea quarks, with unprecedented resolution (~10^{-4} fm). The main physical tasks include measuring the parton distribution functions (TMD, GPD), studying the mechanism of hadronization, and searching for gluon field saturation in the mode of low momentum transmission ($x < 10^{-3}$).

Electron-**i**on **C**ollider (EIC)

BNL, USA

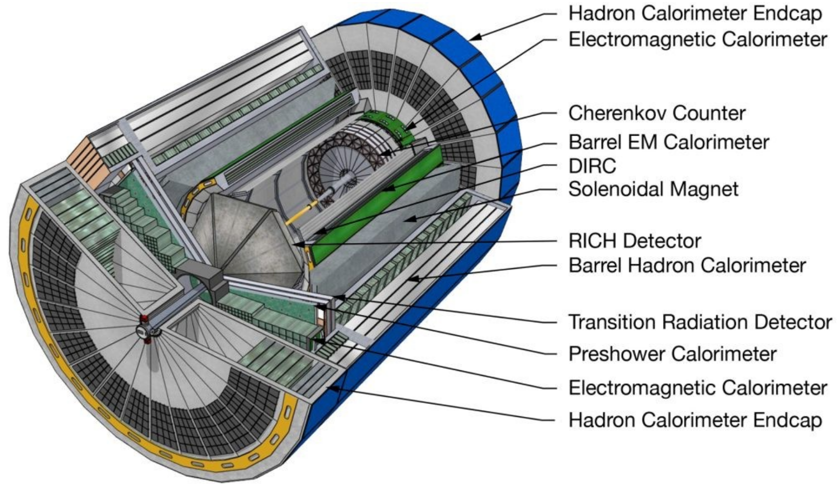
Electron-Ion Collider

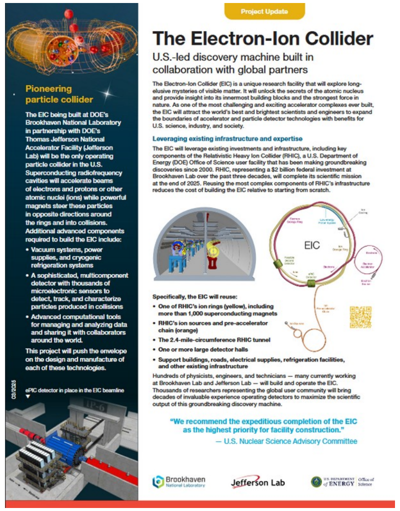
Field of research: nuclear physics, particle accelerator collider for understanding of QCD and nuclear matter.

Partner Countries (collaborations): USA (DOE, BNL, etc.). Electron–Ion Collider user group consists of more than 1500 physicists from over 300 laboratories and universities from 40 countries around the world (Electron-Proton/Ion Collider (ePIC) Collaboration).

Funding: in 2020, The United States Department of Energy announced that an EIC will be built over the next ten years at an estimated cost of between **$1.7** and **$2.8 billion** with a contribution of **$100 million** from New York State.

Electron-Ion Collider will consist of two intersecting accelerators, one producing an intense beam of electrons, the other a high-energy beam of protons or heavier atomic nuclei, which are steered into head-on collisions. Energy Range: Electron Beam: 5–20 GeV, with future plans potentially extending higher. Ion Beam: Proton energies from 41 to 275 GeV; heavy ions (like gold or lead) can reach comparable energies per nucleon. Centre-of-Mass Energy (√s): Ranges approximately from 20 to over 140 GeV, enabling access to a wide kinematic domain. 18 September 2020 officially launching the development and building of the EIC. Commissioning & First Collisions: Anticipated by late 2020s to early 2030s.





Project Update

The Electron-Ion Collider

U.S.-led discovery machine built in collaboration with global partners

The Electron-Ion Collider (EIC) is a unique research facility that will explore long-elusive mysteries of visible matter. It will unlock the secrets of the atomic nucleus and provide insight into its innermost building blocks and the strongest force in nature. As one of the most challenging and exciting accelerator complexes ever built, the EIC will attract the world's best and brightest scientists and engineers to expand the boundaries of accelerator and particle detector technologies with benefits for U.S. science, industry, and society.

Leveraging existing infrastructure and expertise

The EIC will leverage existing investments and infrastructure, including key components of the Relativistic Heavy Ion Collider (RHIC), a U.S. Department of Energy (DOE) Office of Science user facility that has been making groundbreaking discoveries since 2000. RHIC, representing a $2 billion federal investment at Brookhaven Lab over the past three decades, will complete its scientific mission at the end of 2025. Reusing the most complex components of RHIC's infrastructure reduces the cost of building the EIC relative to starting from scratch.

Specifically, the EIC will reuse:

- One of RHIC's ion rings (yellow), including more than 1,000 superconducting magnets
- RHIC's ion sources and pre-accelerator chain (orange)
- The 2.4-mile-circumference RHIC tunnel
- One or more large detector halls
- Support buildings, roads, electrical supplies, refrigeration facilities, and other existing infrastructure

Hundreds of physicists, engineers, and technicians — many currently working at Brookhaven Lab and Jefferson Lab — will build and operate the EIC. Thousands of researchers representing the global user community will bring decades of invaluable experience operating detectors to maximize the scientific output of this groundbreaking discovery machine.

"We recommend the expeditious completion of the EIC as the highest priority for facility construction."
— U.S. Nuclear Science Advisory Committee

Pioneering particle collider

The EIC being built at DOE's Brookhaven National Laboratory in partnership with DOE's Thomas Jefferson National Accelerator Facility (Jefferson Lab) will be the only operating particle collider in the U.S. Superconducting radiofrequency cavities will accelerate beams of electrons and protons or other atomic nuclei (ions) while powerful magnets steer these particles in opposite directions around the rings and into collisions. Additional advanced components required to build the EIC include:

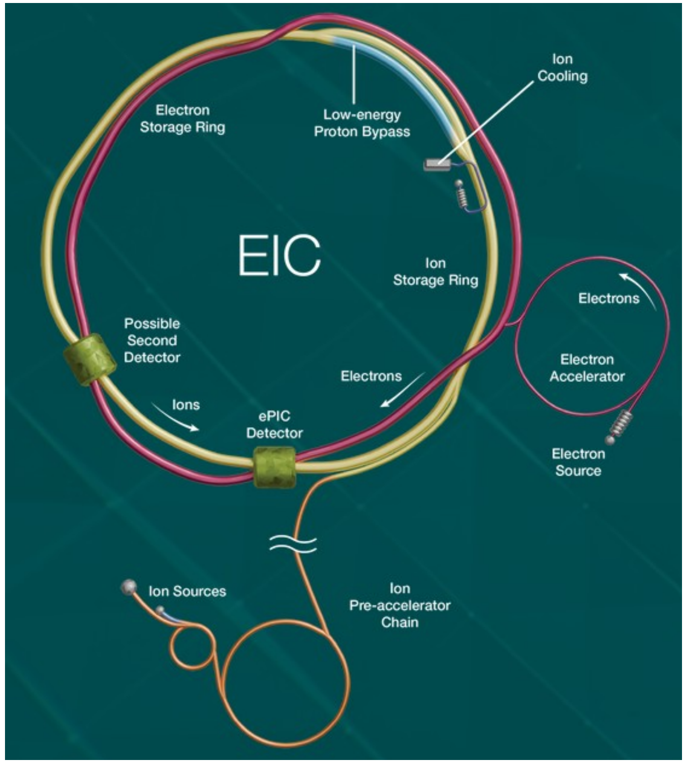
- Vacuum systems, power supplies, and cryogenic refrigeration systems
- A sophisticated, multicomponent detector with thousands of microelectronic sensors to detect, track, and characterize particles produced in collisions
- Advanced computational tools for managing and analyzing data and sharing it with collaborators around the world.

This project will push the envelope on the design and manufacture of each of these technologies.

03/2025

ePIC detector in place in the EIC beamline

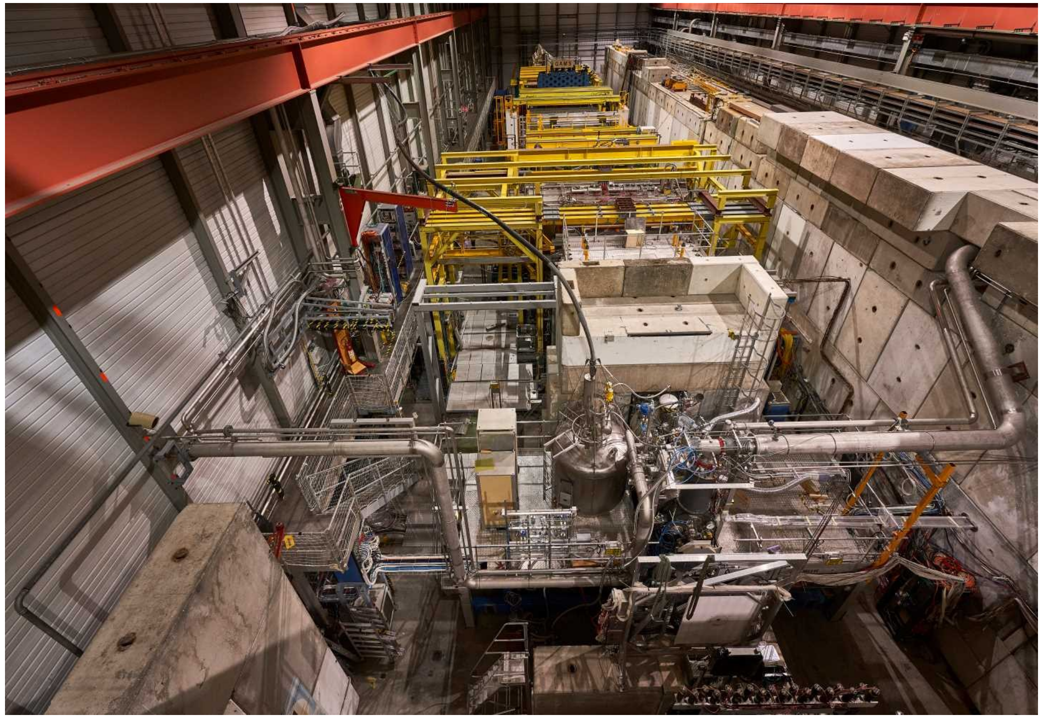
Brookhaven National Laboratory · Jefferson Lab · U.S. Department of Energy Office of Science



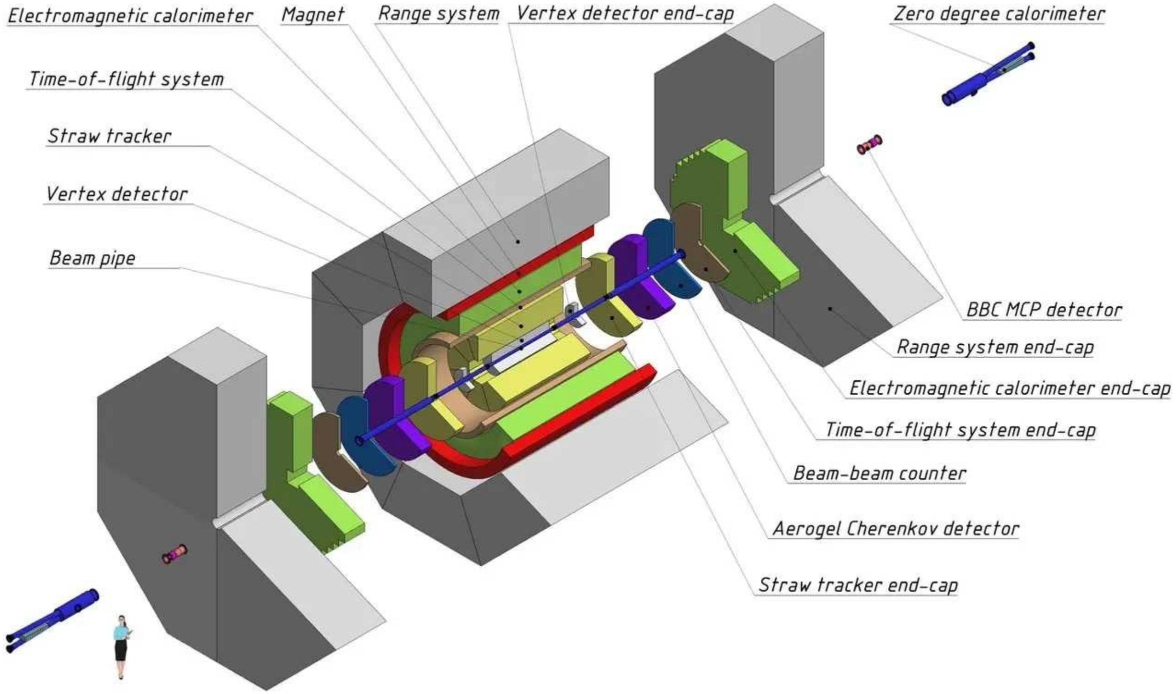
Precise study of nucleon structure

The AMBER experiment (Apparatus for Meson and Baryon Experimental Research) is designed for precision measurements in the field of hadron physics, studying the distribution of partons using muon beams from SPS in the energy range of 100-280 GeV. Measuring the electromagnetic form factors of the proton, studying Compton scattering on protons through the Primakov effect, and searching for exotic hadron states. SPD is the study of the spin structure of nucleons and hyperons, with an emphasis on the measurement of birth–asymmetric particles using polarized beams. Both: studies of the structure of hadrons and spin dynamics in various energy ranges, providing data for QCD in the nonperturbative mode and refinement of the parameters of the PDF.

AMBER (CERN)



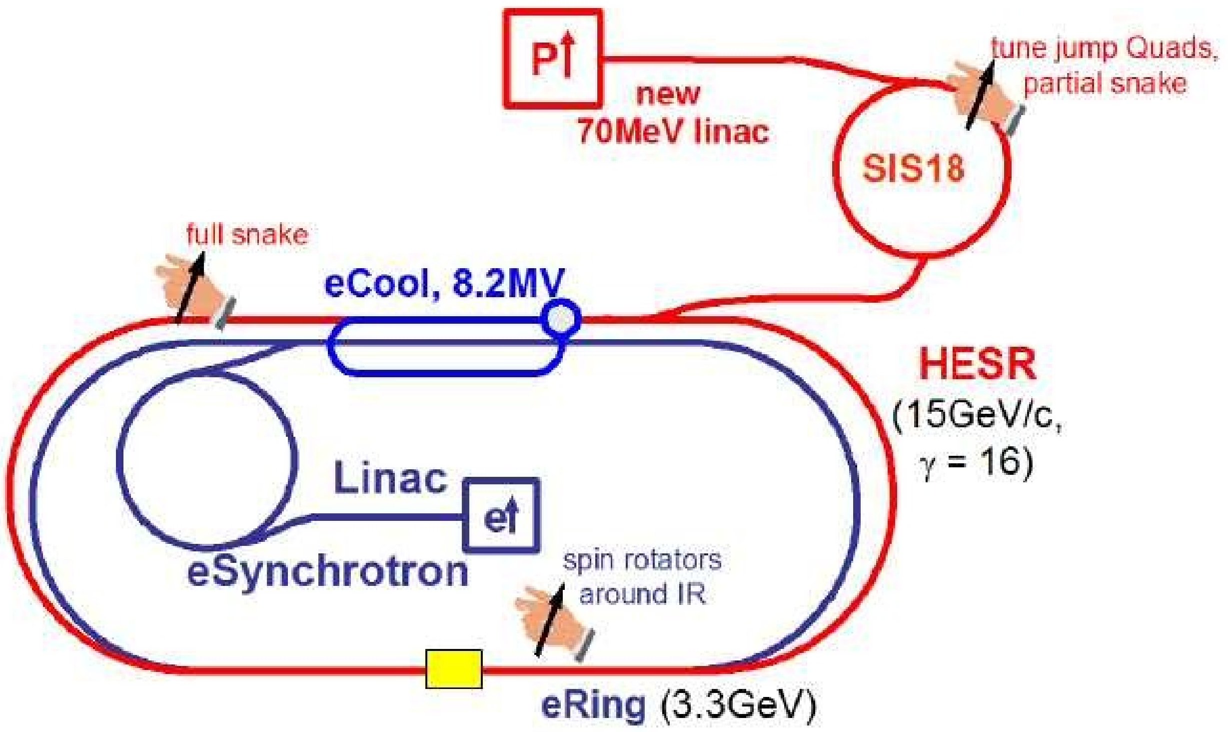
NICA/SPD (JINR)



Also LHCspin at CERN

The polarized electron-nucleon collider project ENC at GSI/FAIR

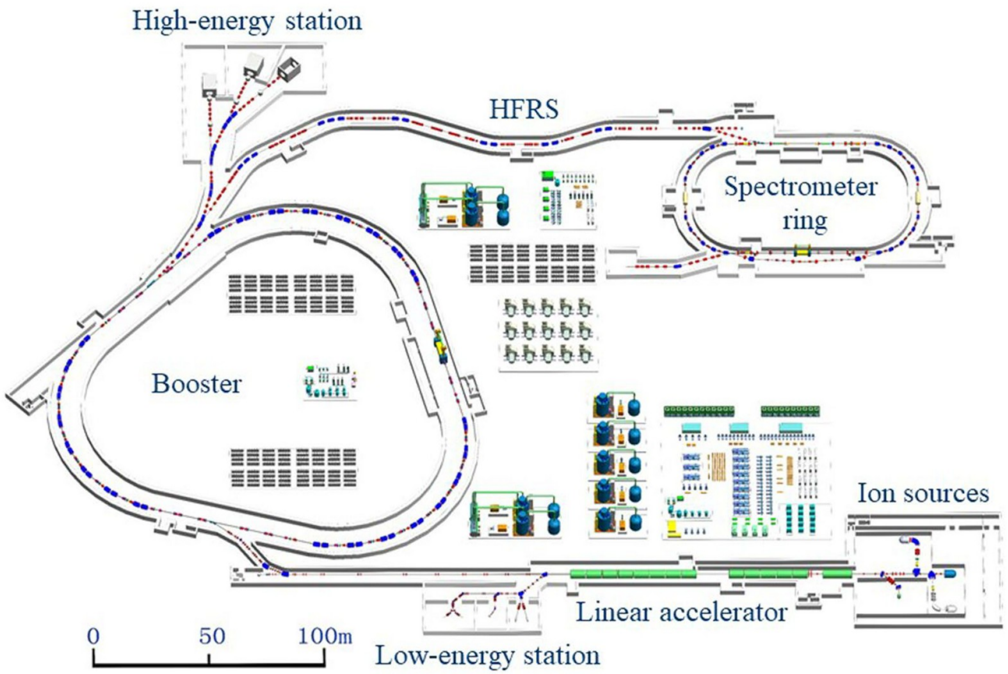
- New 3.3 polarized electron ring in HESR tunnel and polarized ion beam from HESR
- E_{cm} ~14 GeV for e-p and ~9 GeV for e-d
- Design luminosity 2 - $6x10^{32}$ $cm^{-2}s^{-1}$
- Modified PANDA setup is proposed as a detector



High **I**ntensity Heavy-ion **A**ccelerator **F**acility (HIAF)

Huizhou, China

The HIAF accelerator complex includes a linear accelerator and two rings designed to produce beams of stable and radioactive nuclei up to uranium in a wide range of energies up to 800 MeV/nucleon.
The project started in 2018 and is expected to be launched in 2025.
PROJECT BUDGET: CNY 2.5 billion (US$350 million).



Scientific objectives of the HIAF project:

Studies of the limits of the existence of nuclei at the boundaries of neutron and proton stability;
Studies of the structure of exotic weakly bound nuclei;
The origin of nuclei from iron to uranium in the Universe;

- Studies of the critical point of the QCD phase diagram of strongly interacting matter.

Japan **P**roton **A**ccelerator **R**esearch **C**omplex (J-PARC)

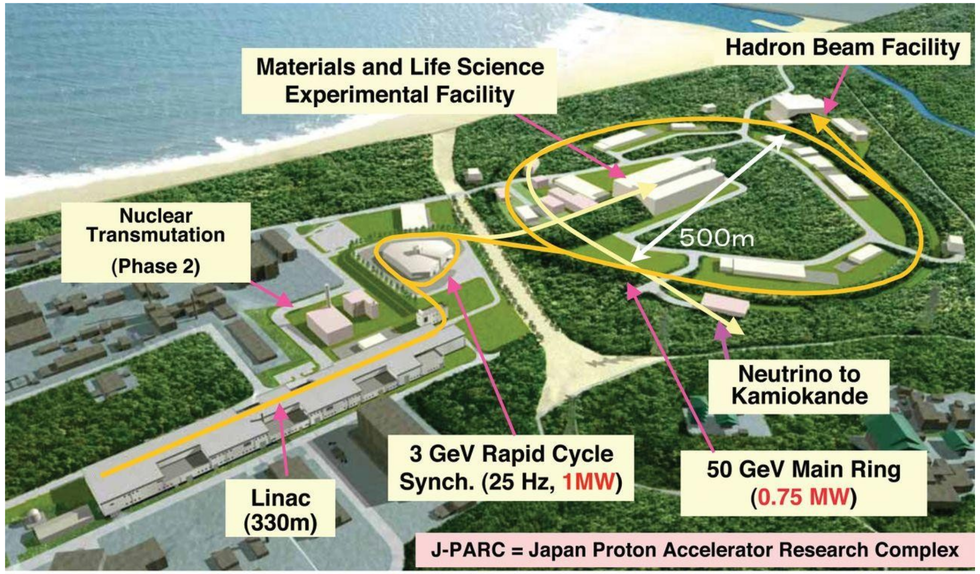
Tokai, Japan

Field of research: accelerator science, neutron scattering, and neutrino physics.

Partner Countries (collaborations): United States, Germany, the United Kingdom, France, China, and Switzerland.

Funding: the budget of the first phase (about **151 billion yen**) included the main components of the accelerator and part of the experimental facilities. Annual Budget (2023-2024): Around 30–40 billion JPY (**~200–270 million USD**).

J-PARC – The J-PARC stands for Japan Proton Accelerator Research Complex and is an accelerator-based research facility with intense proton beams at Tokai-mura, Ibaraki, Japan. J-PARC has three proton accelerators and three research facilities with using MW-class high power proton beams, which generate neutrons, muons, mesons and neutrinos for experiments, to underlie the development of advanced science.



Joint Project between KEK and JAEA

China **S**pallation **N**eutron **S**ource (CSNS)

Dalang Town of Dongguan City, China

Field of research: it includes a powerful linear accelerator, a rapid circling synchrotron, a target station and three Phase I neutron instruments. It aims to provide a powerful platform for both fundamental scientific research and high-tech development in many application fields such as material science, life science, resource environment, new energy, etc.

Partner Countries (collaborations): > 400 scientists and engineers working together in Dongguan on the CSNS project. CSNS-ISIS Neutron and Muon Source MoU (2021).

Funding: intended budget for the project is **1.5 billion CNY**. Total budget is **323 million U.S. dollars** for construction of the accelerator, the spallation neutron target and 3 neutron spectrometers. The local government will support free land, additional budget of **$57M**, infrastructure, dedicated high-way and power transformer station. Construction of the CSNS project started in 2011 under the direction of the IHEP, with a total investment of **2.3 billion yuan**.

CSNS is a new facility under construction at IHEP's Dongguan campus, due to start running in 2018. Consisting of an H-linac and a proton rapid cycling synchrotron, it is designed to accelerate proton beam pulses to 1.6 GeV kinetic energy at 25 Hz repetition rate, striking a solid metal target to produce spallation neutrons.

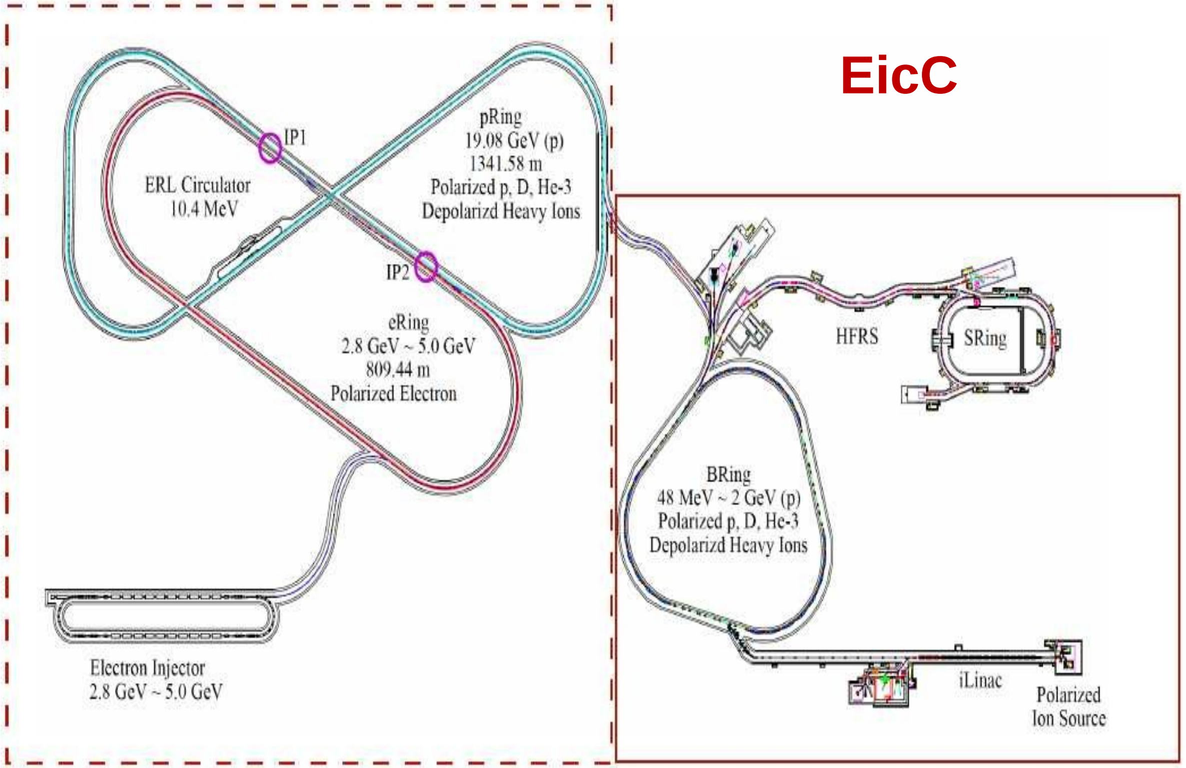
Chinese initiatives

4th gen High Energy Photon Source (HEPS), Beijing, China

Partner Countries (collaborations): International Advisory Committee (more than 20 countries and 50 institutes).

Funding: HEPS project is estimated about **$676.7 million**.

HEPS one of the key projects listed in the “13th Five-year Plan for national major scientific and technological infrastructure”. Diffraction-limited storage ring synchrotron light source with a beam energy of 6GeV and an ultra-low emittance of better than 0.06nm×rad, SR with circumference of 1360 m.



+ JUNO, LHAASO, HXMT, ... China is striving to become a leader in high-energy physics!

European **S**ynchrotron **R**adiation **F**acility **E**xtremely **B**rilliant **S**ource (ESRF-EBS)

Grenoble, France

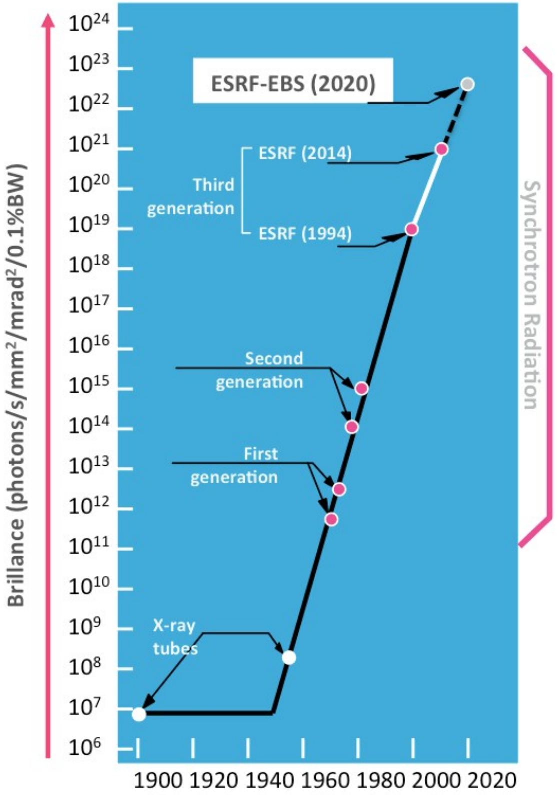
Field of research: low-emittance, high-energy synchrotron light source and new, cutting-edge beamlines.

Partner Countries (collaborations): joint research facility, supported by 19 countries (13 member countries: Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Russia, Spain, Sweden, Switzerland, and the UK; and 6 associate countries: Austria, the Czech Republic, Israel, Poland, Portugal and South Africa).

Funding: 150M€ facility upgrade, ESRF-EBS expenditure budget **40M€/year**.

A new storage ring based on an ESRF-developed hybrid multi-bend achromat (HMBA), producing extremely brilliant X-rays and open to users in 2020. Four brand-new flagship beamlines, in addition to the refurbished and upgraded beamlines, covering a multitude of scientific techniques, making it possible to study the structure of matter at the atomic level in greater detail, with higher quality, much faster:

- EBSL1-ID18: Coherent X-rays dynamics and imaging;
- EBSL2-ID03: Dark field X-ray microscopy;
- EBSL3-BM18: High-throughput large-field phase-contrast tomography,
- EBSL8-ID29: Serial macromolecular crystallography.



Siberian Ring Photon Source (SKIF)

Boreskov Institute of Catalysis, Koltsovo, Novosibirsk, Russia

СКИФ
СИБИРСКИЙ КОЛЬЦЕВОЙ ИСТОЧНИК ФОТОНОВ

Field of research: chemistry, physics, materials science, biology, geology, and the humanities.

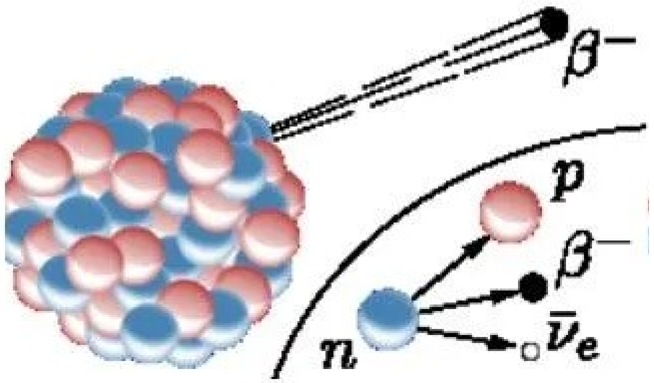
Partner Countries (collaborations): a number of Russian institutes and research organizations.

Funding: as of October 2022, the project cost was **47.3 billion rubles**. Initially, the construction was estimated at **37.1 billion rubles**.

SKIF is a 4+ generation synchrotron radiation source with an energy of 3 GeV and an emittance of 75 pm·rad under construction in Siberia in the Koltsovo science city (Novosibirsk Region, Russia). SKIF represents one of the largest research infrastructure projects in Russia in recent decades. A linear accelerator shoots a beam of electrons at a relatively small annular booster accelerator. There, the particles accelerate to near-light speed and enter a synchrotron storage device measuring almost half a kilometer, from which dozens of output channels to user stations extend along the perimeter. The construction is scheduled to be completed by the end of 2025.

Neutrino physics

- Neutrino mass hierarchy;
- Direct neutrino mass measurement;
- Search for CP violation in the lepton sector;
- Dirac or Majorana?
- Neutrino properties (cross-section, etc).



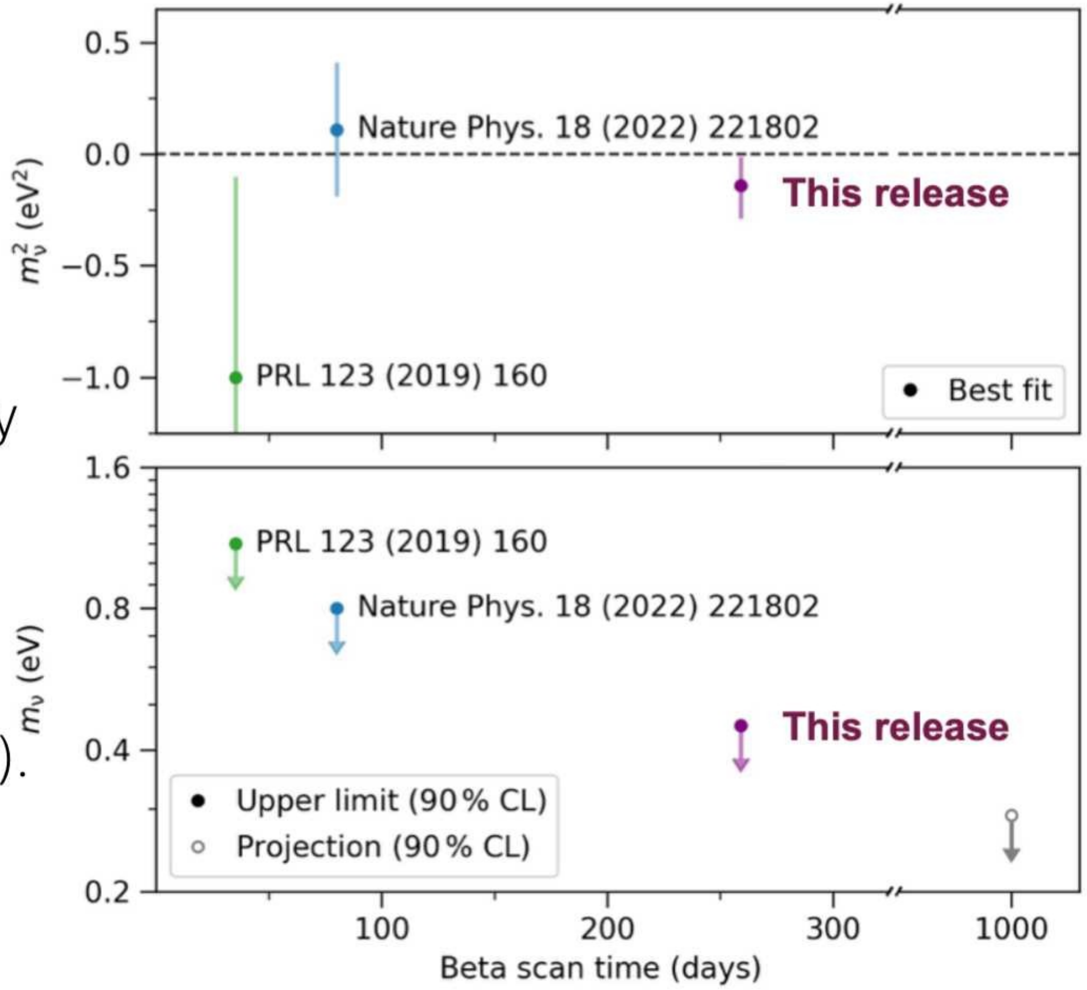
Identification of ultra-high-energy neutrino astrophysical sources, mechanisms of galaxy formation and evolution, determination of the neutrino mass hierarchy, neutrino mass origin, constraints on the CP violation phase, direct search for dark matter, precision study of coherent elastic neutrino scattering on nuclei, etc.

Neutrino mass measurement

KATRIN latest results

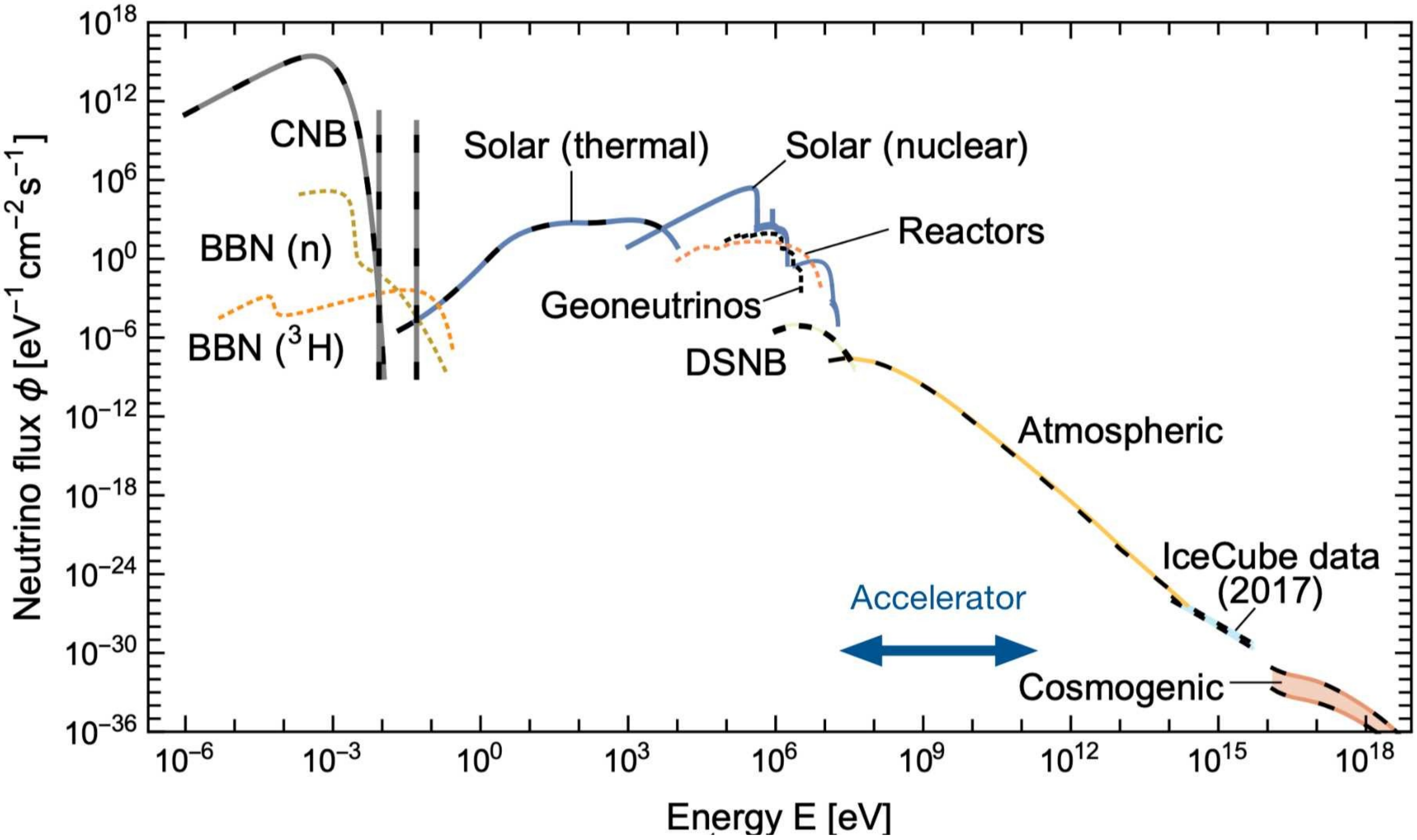
- ✳ 259 measurement days collected in 2019 – 2021;
  - ✳ already has x4 more data to analyse.
- ✳ New upper limit $m_\nu < 0.45$ eV (90% CL).
- ✳ Future plans:
  - ✳ Ongoing data taking through 2025, target sensitivity below 0.3 eV (90% CL).
  - ✳ 2026 – 2027: TRISTAN@KATRIN for sterile keV neutrino search.
  - ✳ 2028 – 2034 R&D for the next apparatus (< 0.045 eV).

Technique limitation: gaseous tritium source is already nearly opaque to the electrons.



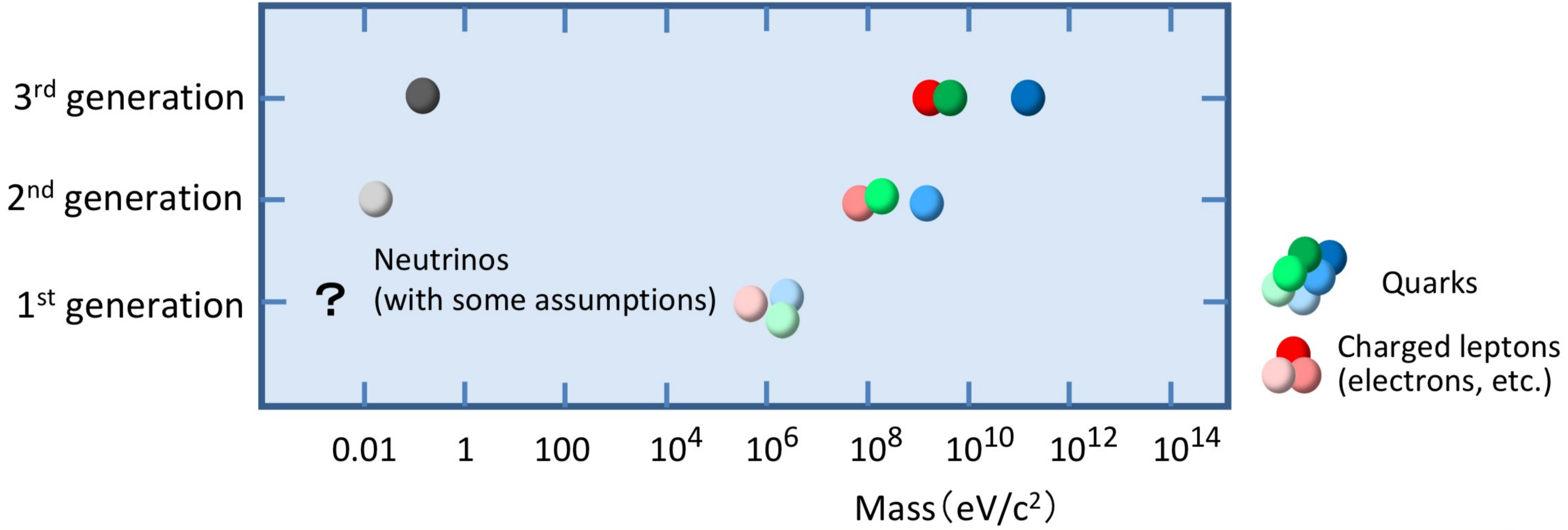
Courtesy of L.Kolupaeva

Neutrino sources



Courtesy of L.Kolupaeva

What have we learned?
Why are neutrinos important?



The neutrino mass is approximately (or more than) 10 billion times (10 orders of magnitude) smaller than the corresponding mass of quarks and charged leptons!
We believe this is the key to better understand elementary particles and the Universe.

Courtesy of T.Kajita

Neutrino mass ordering

Mass hierarchy/ordering plays important role for:

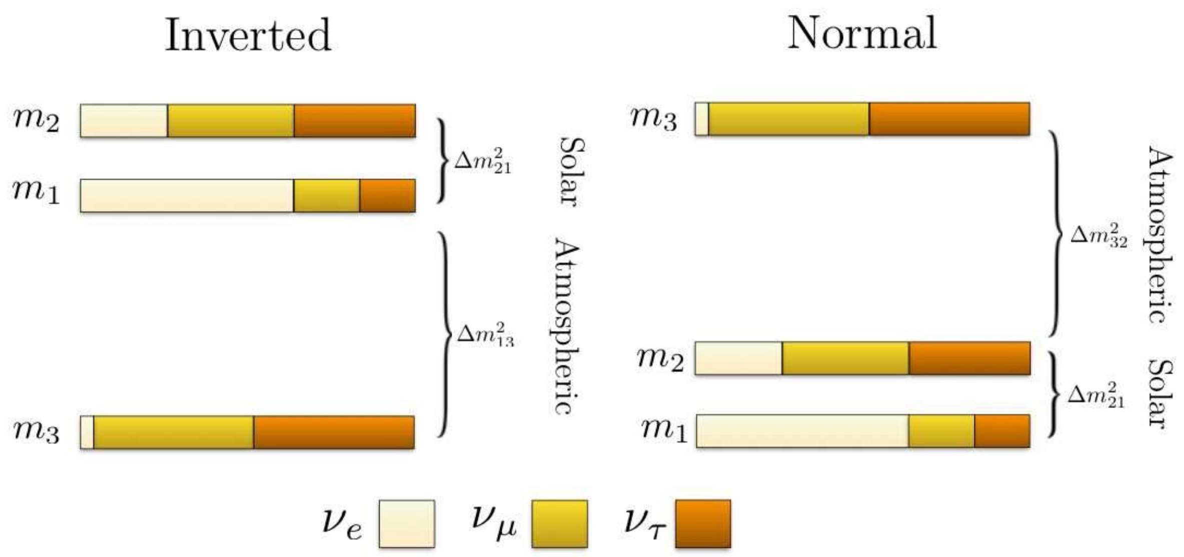
✳ neutrinoless double beta-decay searches,

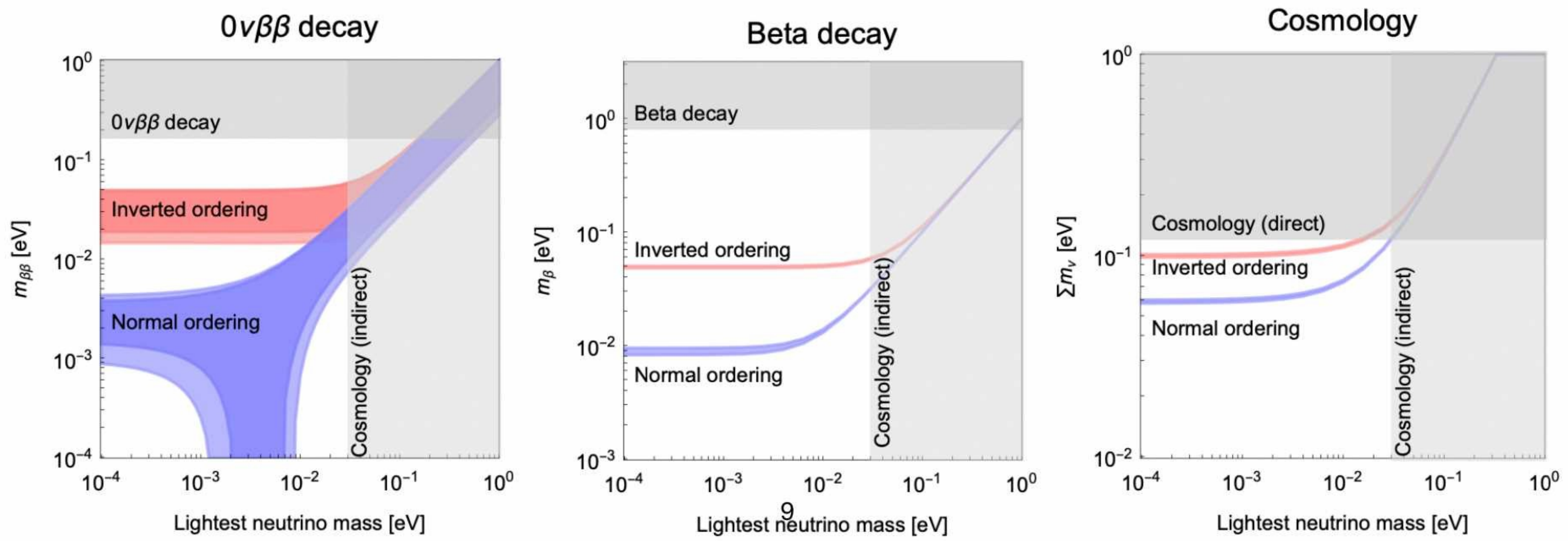
✳ supernova simulations,

✳ relic neutrinos searches,

✳ absolute ν mass measurements etc.

So it affects everything connected with ν masses





Courtesy of L.Kolupaeva

Accelerator-based experiments (protons 2-120 GeV)

Oscillation parameters and how precisely do we know them:

$\theta_{12} \approx 34^\circ$ (4.4%)

$\theta_{23} \approx 49^\circ$ (5.2%)

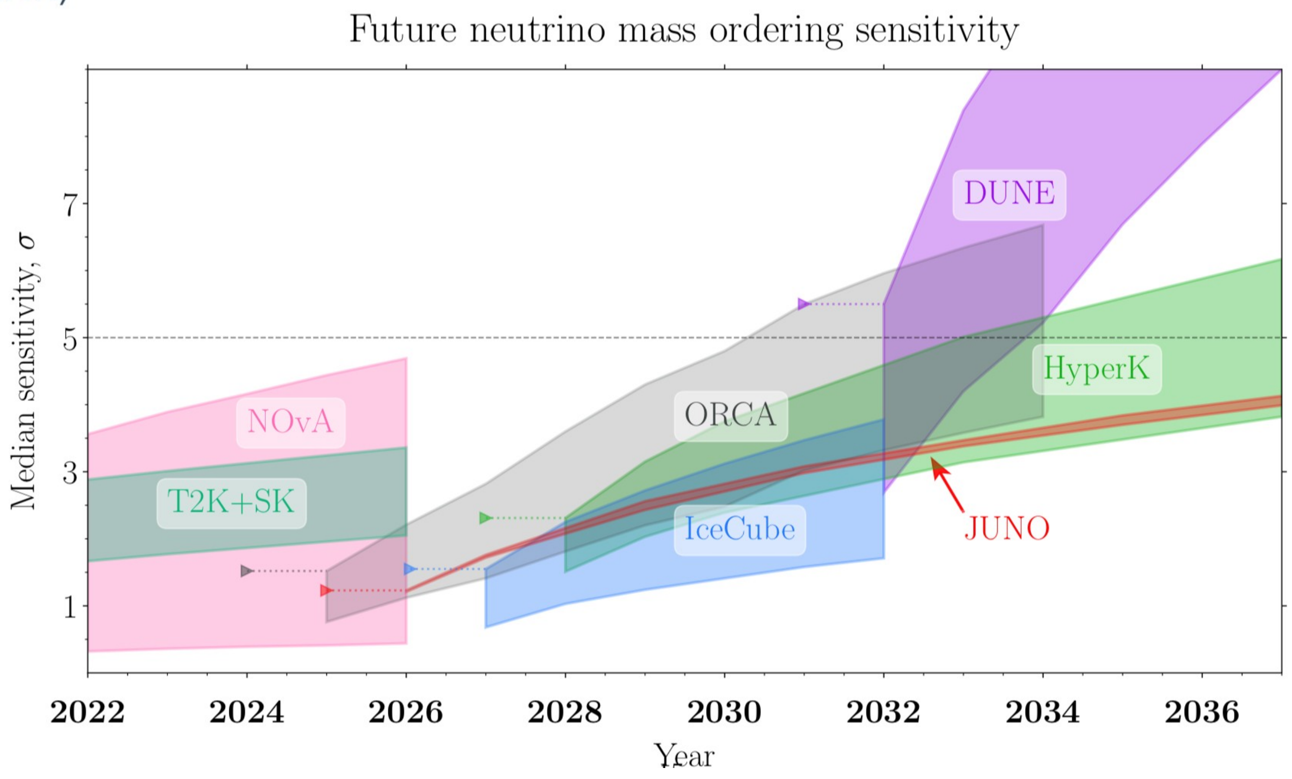
$\theta_{13} \approx 9^\circ$ (3.8%)

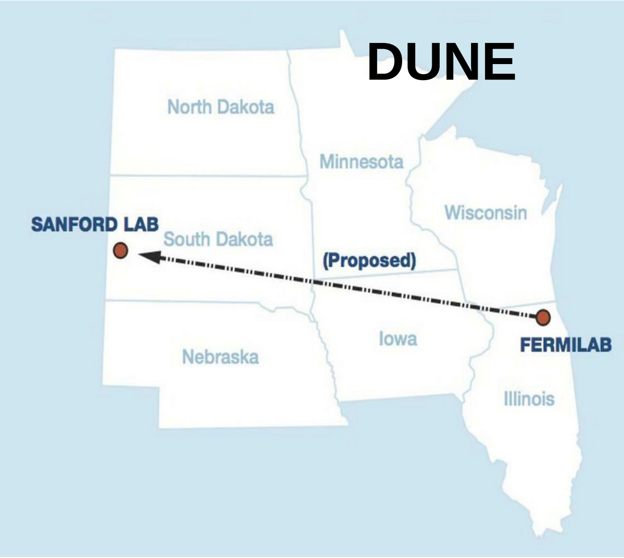
$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \mathrm{eV}^2$ (2.2%)

$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \mathrm{eV}^2$ (1.4%)

atmospheric accelerator	short baseline reactor accelerator	solar long baseline reactor

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left|\begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}\right\rangle$$





JUNO

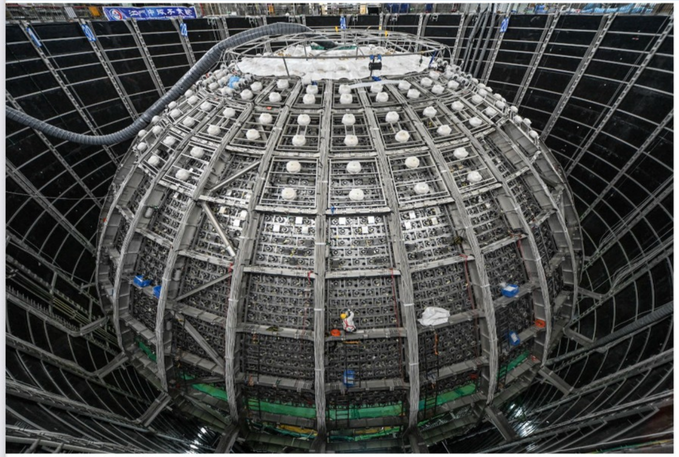
Modern detectors (Daya Bay, RENO, Double Chooz) use liquid scintillators doped with gadolinium or lithium. JUNO's largest reactor experiment (20 kt liquid scintillator), already built in China and has started data collection, aims to determine the hierarchy of masses through spectrum distortions using high energy resolution reaching 3% at 1 MeV, accurate measurement of Δm^2_{21} и θ_{12}, study of atmospheric and solar neutrino oscillations, search for sterile neutrinos.

20 kt of liquid scintillator, 18000 PM's

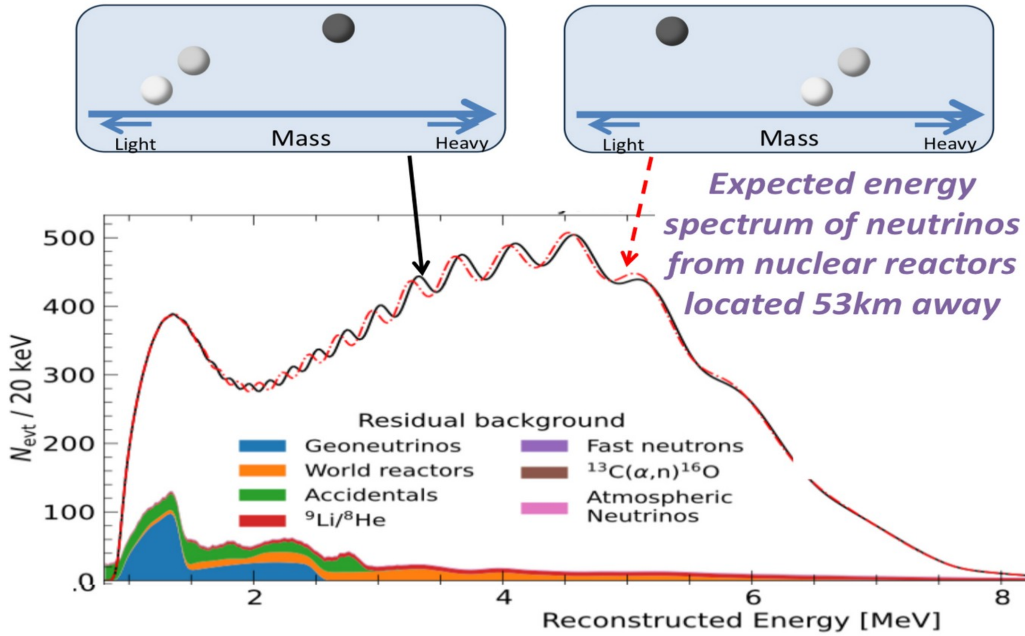
Started in September 2025 !!!

JUNO

Jun Cao, Neutrino2024
Marco Grassi, NNN2023



JUNO detector (world largest (20kton) liquid scintillator detector, located "near" Haikou)



Astroparticle physics

- Ultra high energy cosmic rays;
- High energy neutrino from space;
- The nature of dark matter;
- Gravitational waves.

$$\frac{F_{эл}}{F_g} = 2{,}3 \cdot 10^{39}$$

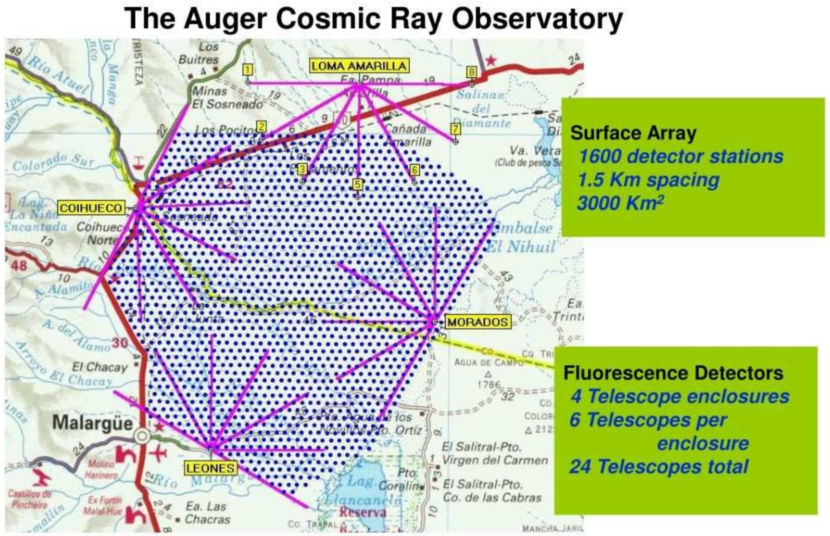
Further progress in understanding the evolution of the Universe lies:
- in experiments at accelerators and colliders, including the search for dark matter;
- in astrophysical and cosmological observations and studies of gravitational waves, multi-channel astronomy and the dark sector in non-accelerator experiments;
- in experimental and theoretical definition of models beyond the Standard Model;

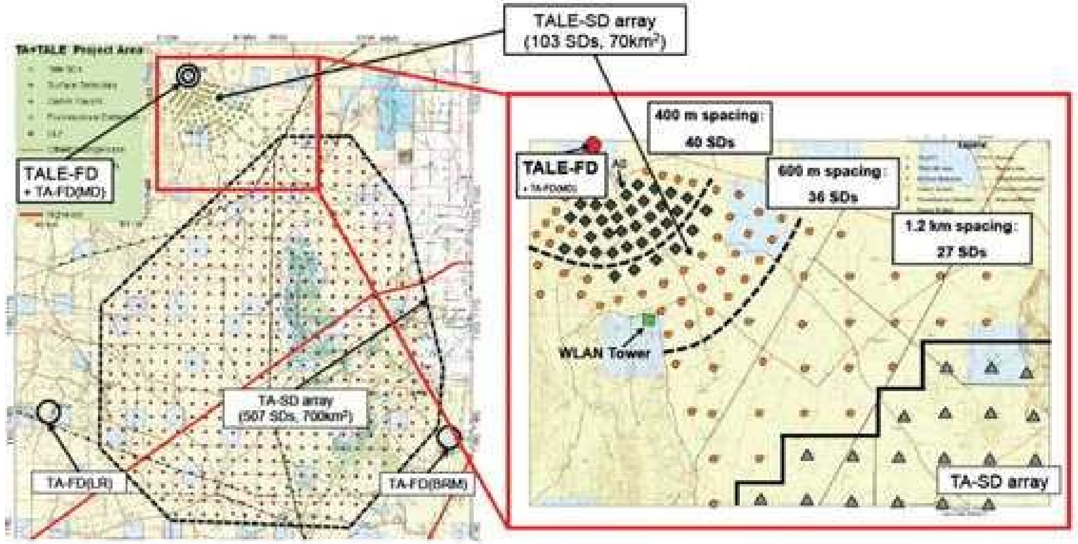
Studying the Universe on gigantic scales of distances

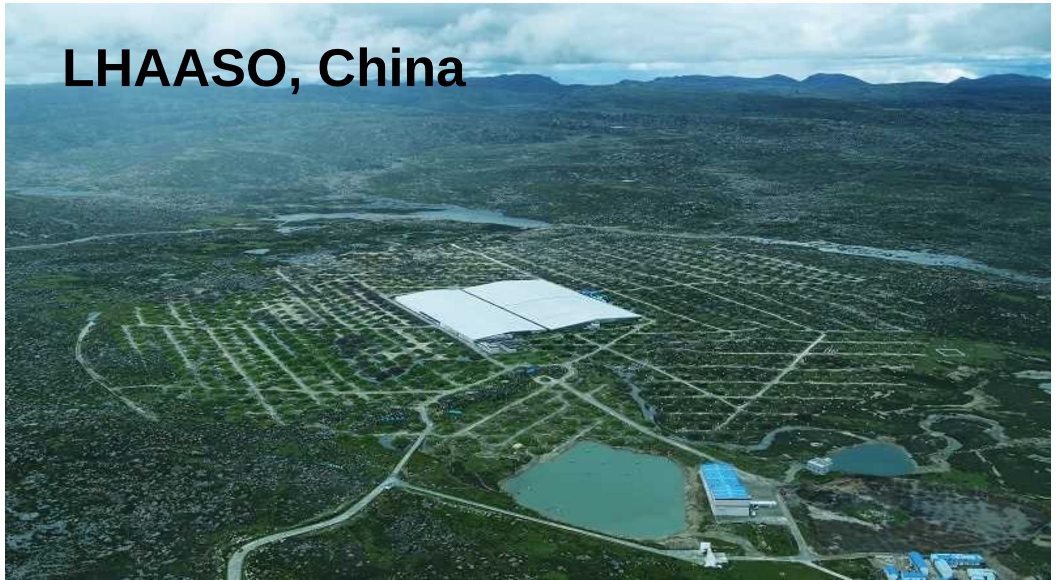
(hundreds of millions and billions of light years),

We expect to learn about the first moments of its evolution and the processes that took place at ultra-high energies.

Ground-based observatories of extensive atmospheric showers

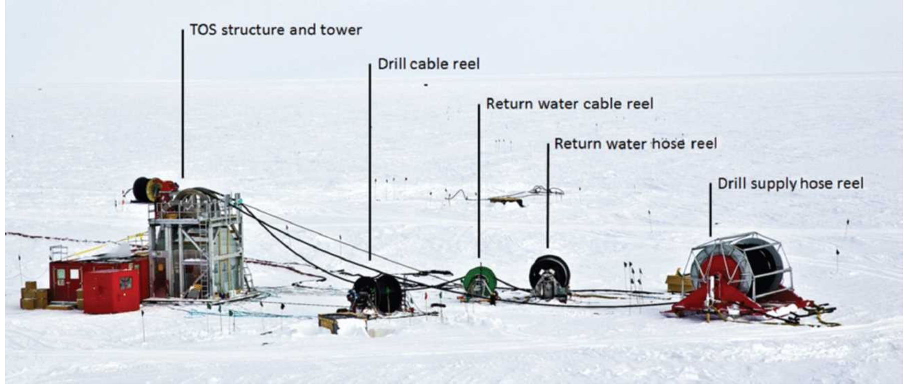


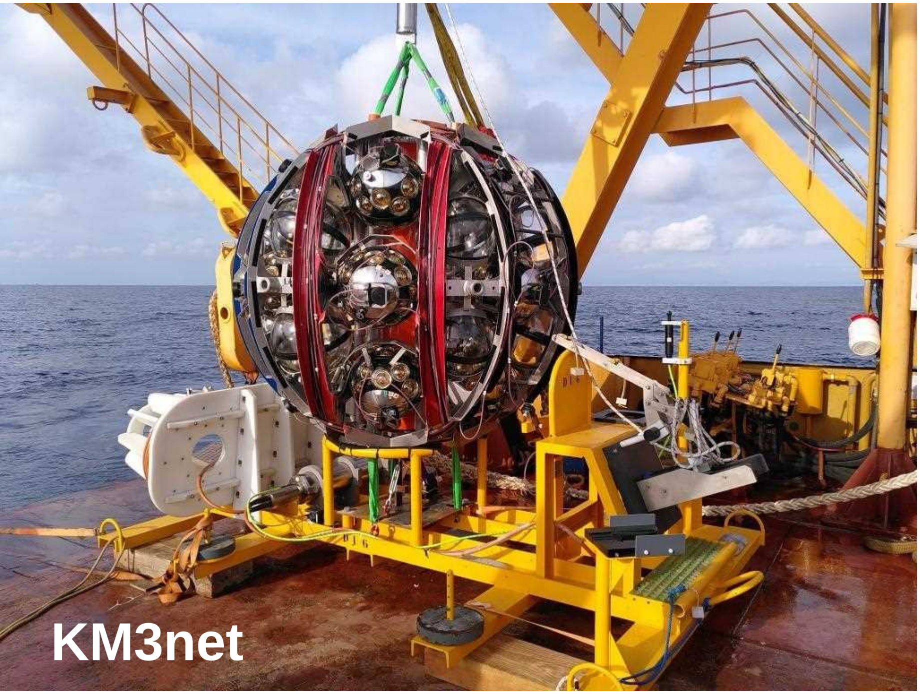




Deep water neutrino telescopes

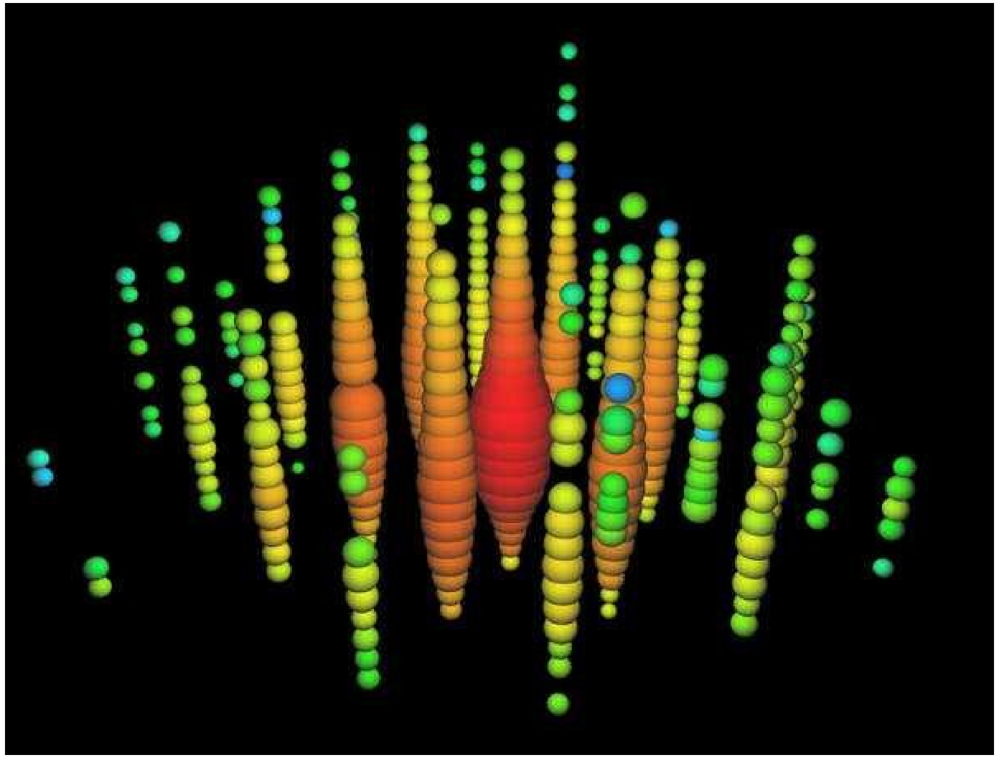
Diffuse fluxes of astrophysical neutrinos and identification of point sources (blazars).
The goal: a fiducial volume of ≥1 cubic kliometer.



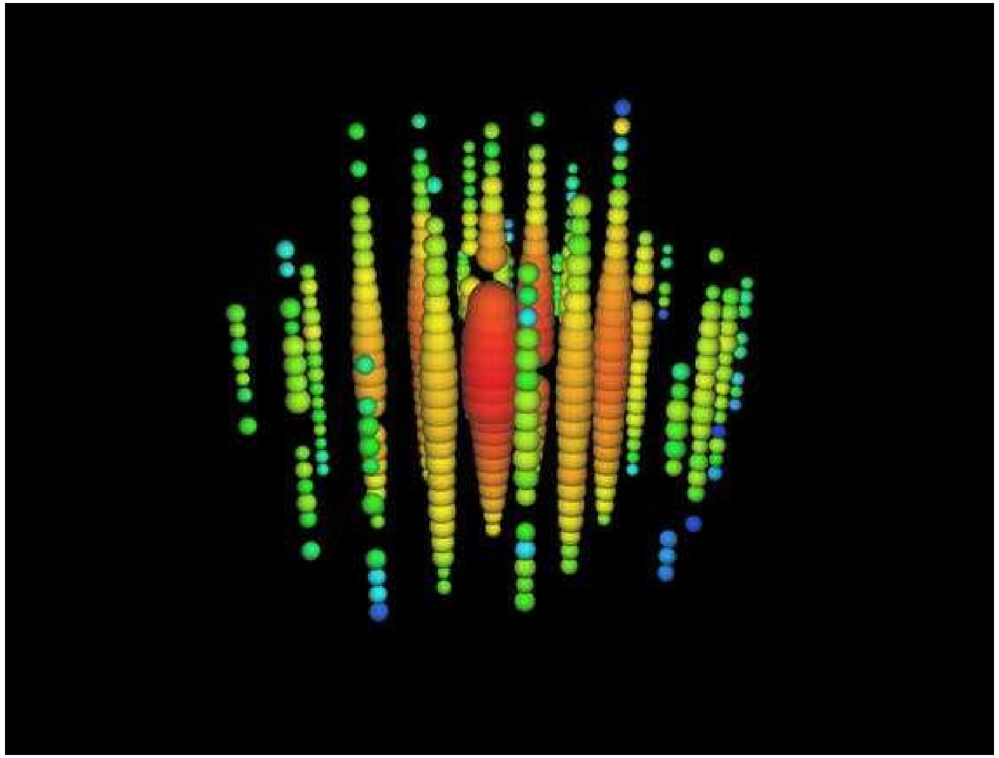


Events with the energy of ~ 1 PeV

August 2011



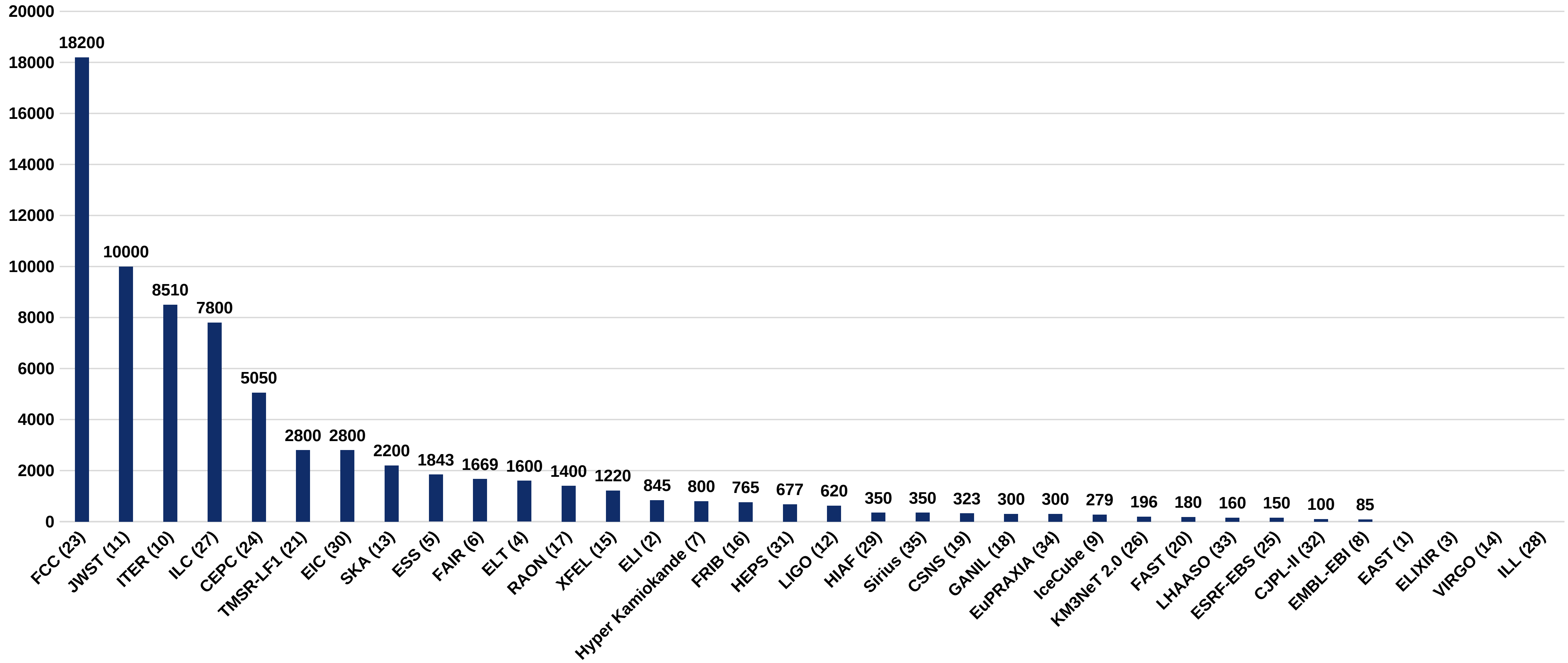
January 2012

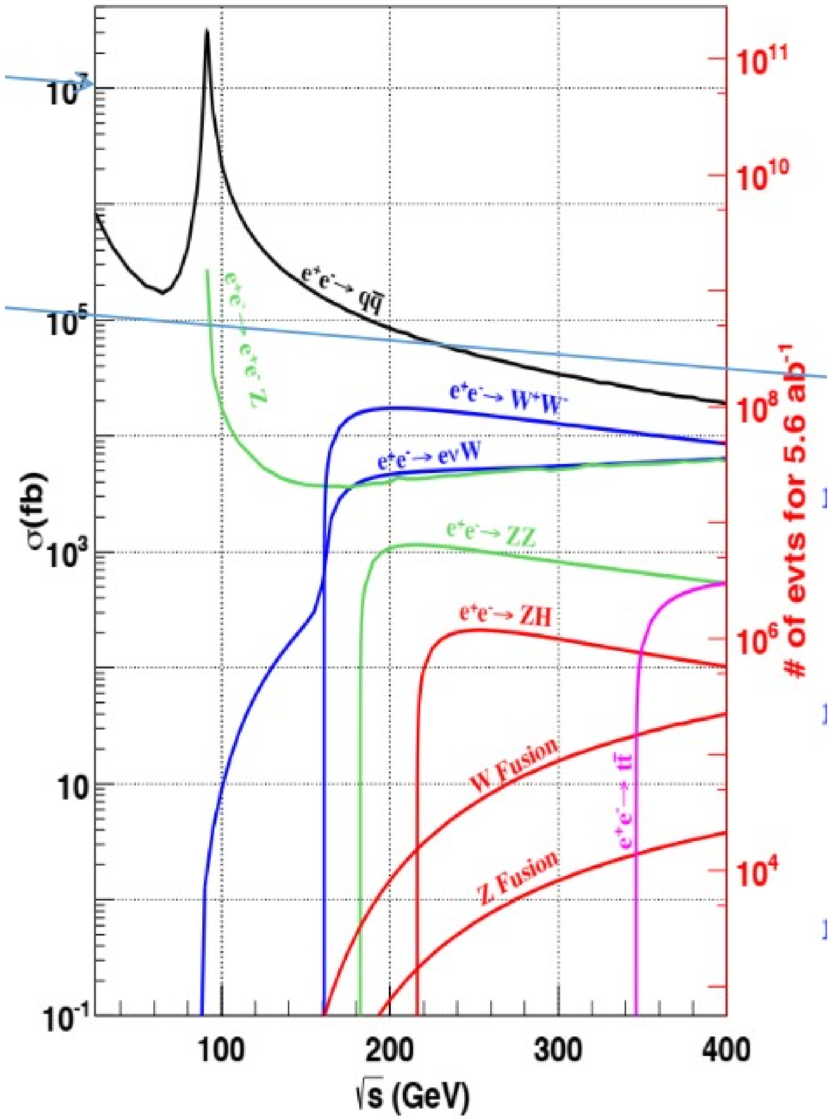


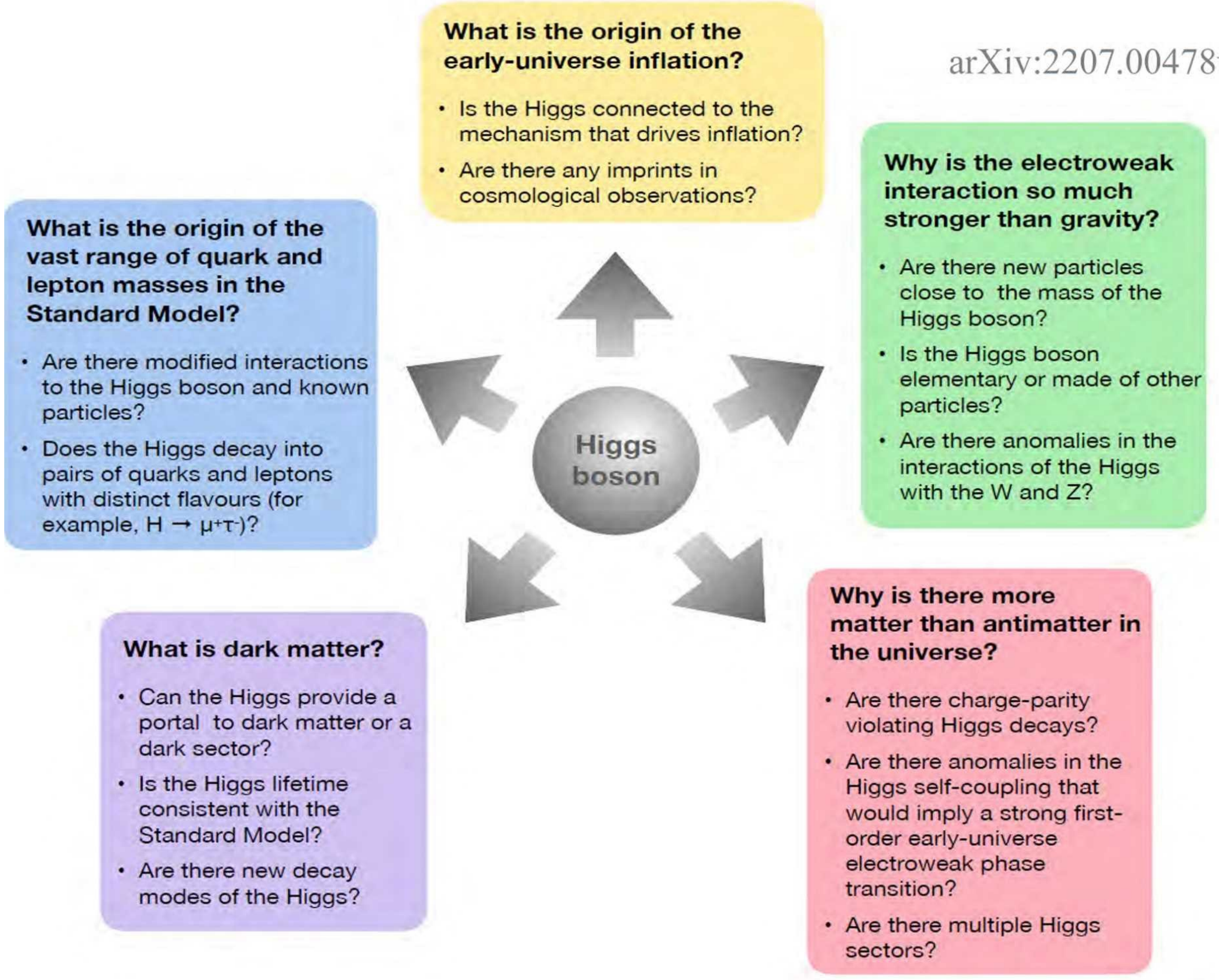
"First observation of PeV-energy neutrinos with IceCube."
IceCube Collaboration. MG.Aartsen et al. Physical Review Letters 111 (2013)

VLRI projects total cost of construction

(in millions of dollars, US$)

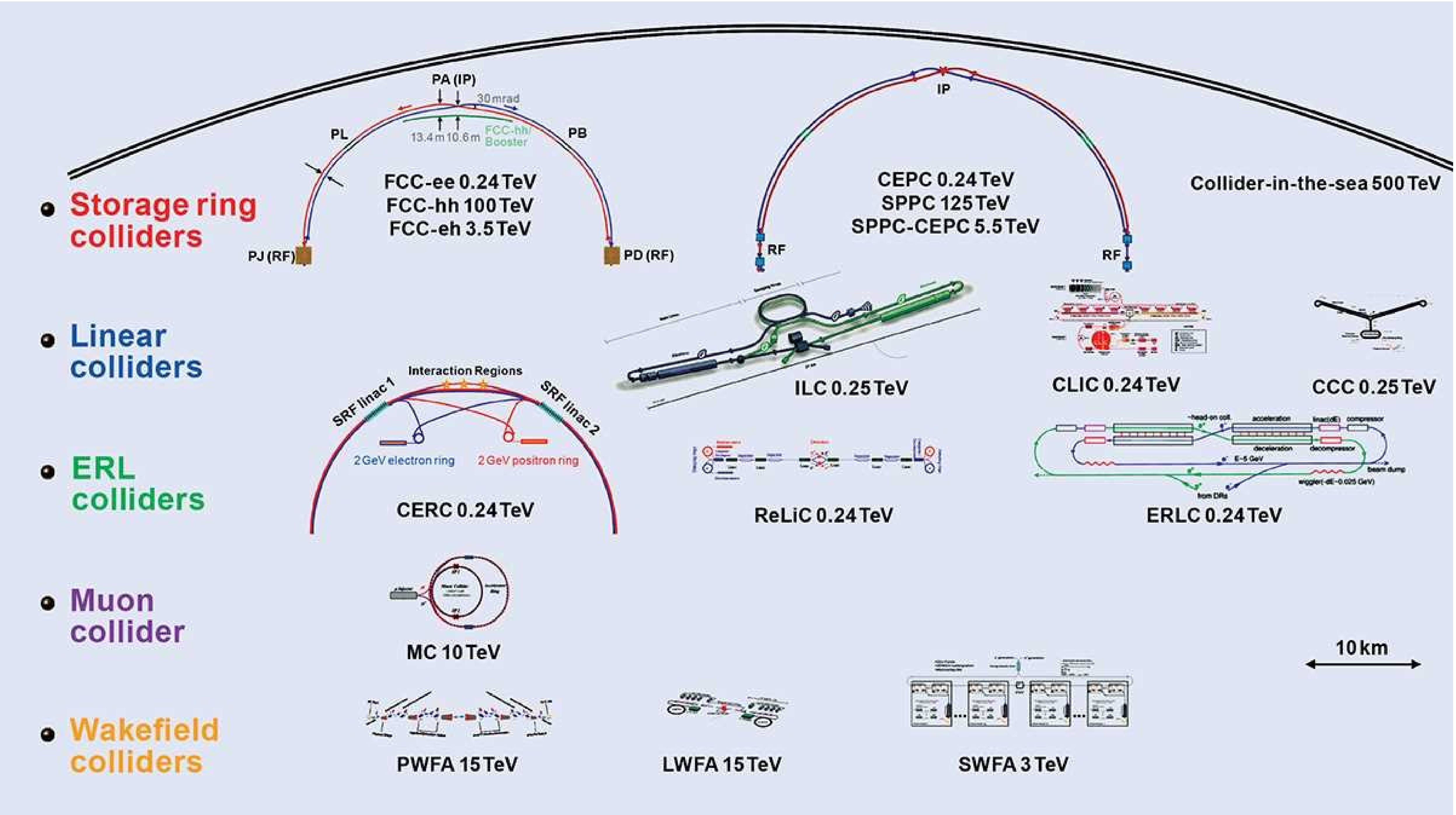






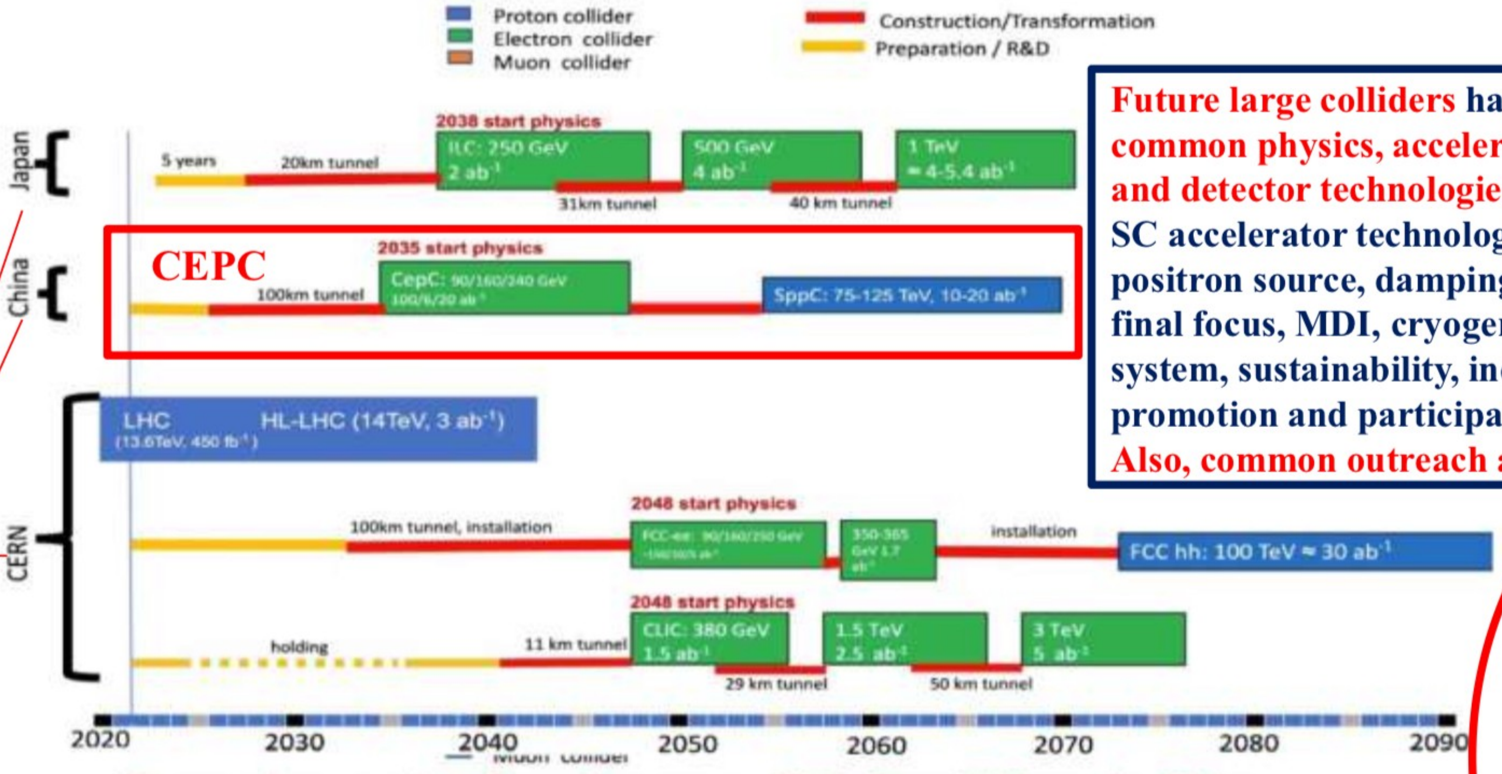
arXiv:2207.00478

- Colliders continue to drive precision tests of the Standard Model
- Further progress in this direction is associated with e+e- colliders in the energy region from the Z-boson to the production threshold of the *tt* quark pair
- Lower energy colliders remain and will remain an essential research tool

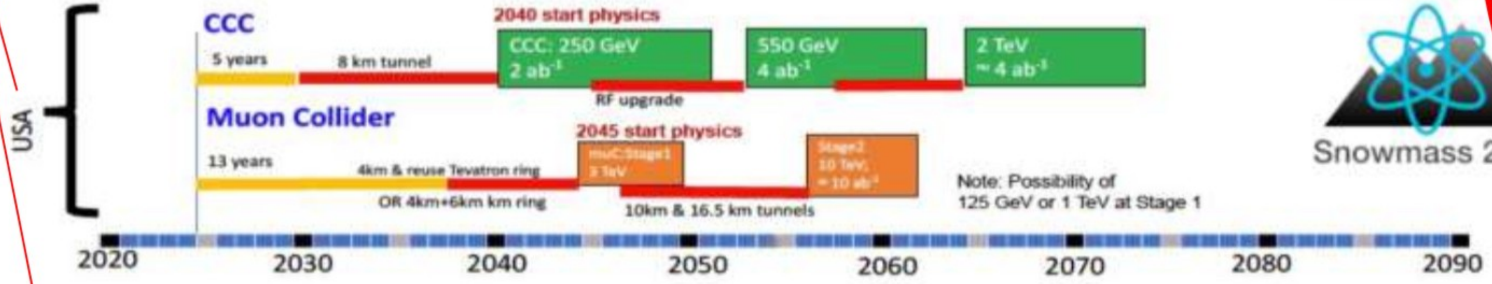


Courtesy of V.Shiltsev

Worldwide High Energy Physics Goal Timelines and Common Efforts



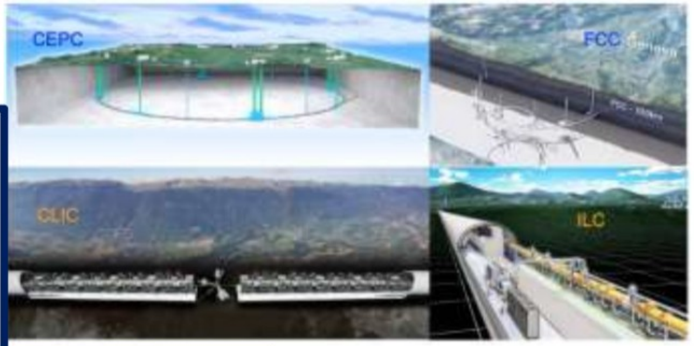
Proposals emerging from Snowmass 2021 for a US based collider

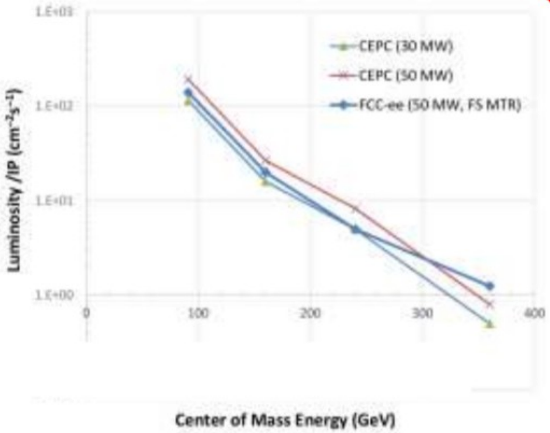


Snowmass 2021

The common physics goals in complementary

Future large colliders have the common physics, accelerator and detector technologies:
SC accelerator technologies, positron source, damping ring, final focus, MDI, cryogenic system, sustainability, industrial promotion and participation.
Also, common outreach activities





	Operation mode			
	H	Z	W	$t\bar{t}$
CEPC (TDR, 30 MW)	5	115	16	0.5
CEPC (TDR, 50 MW)	8.3	192	26.7	0.8
FCC-ee (FS MTR, 50 MW)	≥ 5.0	140	20	1.25

HALHF was proposed in 2023 as a Higgs factory based on plasma accelerator technology

Courtesy of J.Gao

JINR research Infrastructure in the global scientific Landscape today

IUPAP

IUPAP Report 41

A Worldwide Perspective of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9

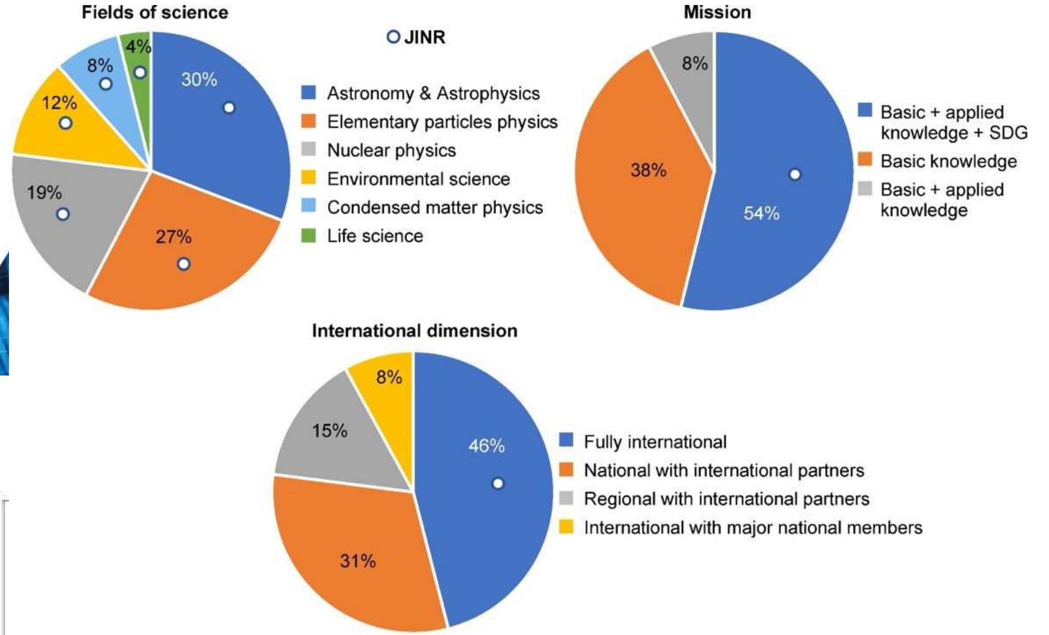
VERY LARGE RESEARCH INFRASTRUCTURES

POLICY ISSUES AND OPTIONS

OECD SCIENCE, TECHNOLOGY AND INDUSTRY **POLICY PAPERS**

July 2023 **No. 153**

OECD BETTER POLICIES FOR BETTER LIVES

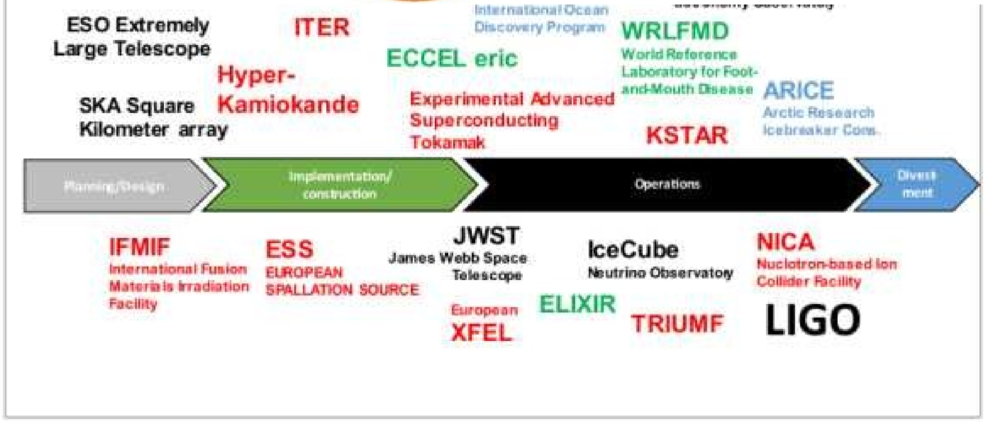


Taking beam energies of 1 GeV or greater, one has:

- fixed target heavy-ion experiments (CERN-SPS, SIS-GSI/FAIR);
- fixed target proton-nucleus studies (Fermilab, J-PARC);
- heavy ion collider experiments (BNL-RHIC, CERN-LHC and in the future NICA);
- fixed target-lepton DIS experiments (CERN, JLab-CEBAF);
- DIS collider experiments (were at DESY, in the future possibly at

Superheavy element search: The future race hunting for the 119th and 120th elements will continue at the SHE factory at Dubna and RIKEN.

Baikal-GVD: ... the study of the flux of high-energy neutrinos and the construction of a telescope with a volume of 1 km^3...



The analysis shows that almost half of modern projects in the field of basic sciences have accompanying programmes of applied research aimed at Sustainable Development Goals (SDG). Worldwide international dimension, the multi-disciplinary scientific programme and large infrastructure projects of JINR harmoniously complement the global scientific agenda and the worldwide landscape of mega-science infrastructure, assuming, along with the main goals in the field of fundamental research, the achievement of certain Sustainable Development Goals.

Summary

- High-energy physics has made significant progress over the past two decades and continues to be a key area in the study of the fundamental properties of matter.
- However, science faces large-scale challenges, the solution of which will require the construction of next-generation experimental facilities and research infrastructure.
- Today, CERN remains the world leader in experimental high-energy physics. In the US, the scale of research has decreased, with efforts focused primarily on studying neutrinos and astrophysical phenomena. China is emerging as a promising new player: if implemented, its projects could significantly influence the development of this field. JINR is looking seriously and ambitious with home projects in PP/NP (NICA, BAIKAL, SHE, IBR-2M), also being large contributor to CERN, FNAL, JUNO, BES-III, and intending to contribute to HyperK, CePC, HIAF, etc.

Thank you for your attention !

Four accelerator and beam physics grand challenges were identified:

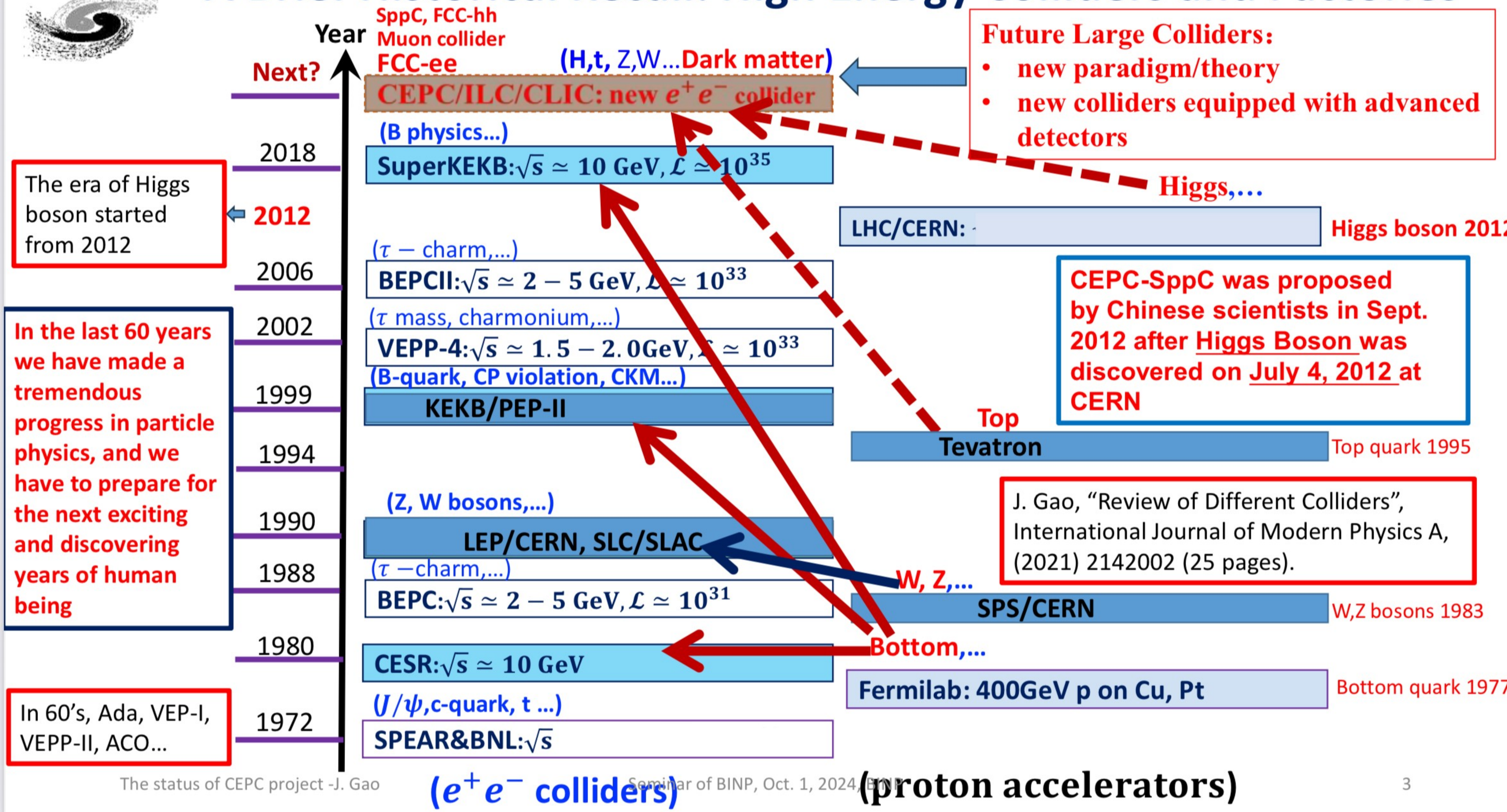
Grand Challenge #1: Beam Intensity – "How do we increase beam intensities by orders of magnitude?"
- Deliver an order of magnitude increase or more in secondary particle fluxes from proton and heavy-ion driver applications;
- Enable ultrashort electron bunches for collider applications;
- Enable first generation of accelerator-driven energy systems;

Grand Challenge #2: Beam Quality – "How do we increase the beam phase space density by an order of magnitude, towards the quantum degeneracy limit?"
- Create new paths for dramatically increased collider luminosity;
- Enable compact wakefield-based colliders;
- Significantly enhance the brightness and wavelength reach of modern X-ray sources;

Grand Challenge #3: Beam Control – "How do we measure and control the beam distribution down to the individual particle level?"
- Substantially increase luminosity in future colliders;
- Mitigate beam losses;
- Enable table-top coherent light sources;
- Enable quantum science experiments.

Grand Challenge #4: Beam Prediction – "How do we develop predictive 'virtual particle accelerators'?"
- Deliver an integrated ecosystem of predictive tools for accurate, complete and fast modeling of particle accelerators and beams;
- Enable virtual accelerators to predict the behavior of particle beams in accelerators;
- Develop mathematical and algorithmic tools that benefit from — and contribute to

A Brief Historical Recall: High Energy Colliders and Factories



Российская Академия Наук

Отделение Физических Наук
Секция Ядерной Физики

ПРОЕКТ

Программа развития исследований физики фундаментальных свойств материи в Российской Федерации на 2026-2032 годы

2025 г.

Scientific directions of the Program implementation

Based on the priority areas of scientific and technological development established by the Strategy and the national development goals of the Russian Federation, outlined in the Decree of the President of the Russian Federation of July 21, 2020 No. 474 "On the National Development Goals of the Russian Federation for the Period up to 2030", the following scientific areas for the implementation of the Program have been identified:

- the nature of strong interactions in the physics of elementary particles and atomic nuclei (NICA and VEPP-6, the JINR Cyclotron Complex, the Compton radiation source of the IKI NCFM, NEVOD-DÉCOR-TREK.)
- search for new elementary particles and fundamental interactions (NICA, VEPP-6 e-r collider (INP SB RAS), Complex of low-background facilities of the Baksan NO, Creation of a modern management company of the Troitsk Meson Factory (TiMoFey project), experiments on the study of reactor neutrinos, CASH axion haloscope project, Projects for the search for the electric dipole moment of the neutron and measurement of asymmetry in neutron decays at the PIK reactor complex, Theoretical research, Projects for long-term development, Experiments at CERN, at the operating colliders BESIII (China), BelleII (Japan), participation in FCCee (Switzerland), CEPC (China). Experiments on the direct search for dark matter particles, on the study of neutrino oscillations: Japan, China, USA;
- study of processes with extreme energy release in the Universe and related fundamental physics (Multichannel High-Energy Observatory (MVO) Project, Neutrino Channel: Baikal-GVD+ , Photon Channel and Charged Particles: TAIGA-100, Ultra-High Energy Hadron Channel: Extreme Relativistic Astrophysics (ERA) Project)
- application of methods of physics of fundamental interactions in other fields of knowledge, industry and medicine.

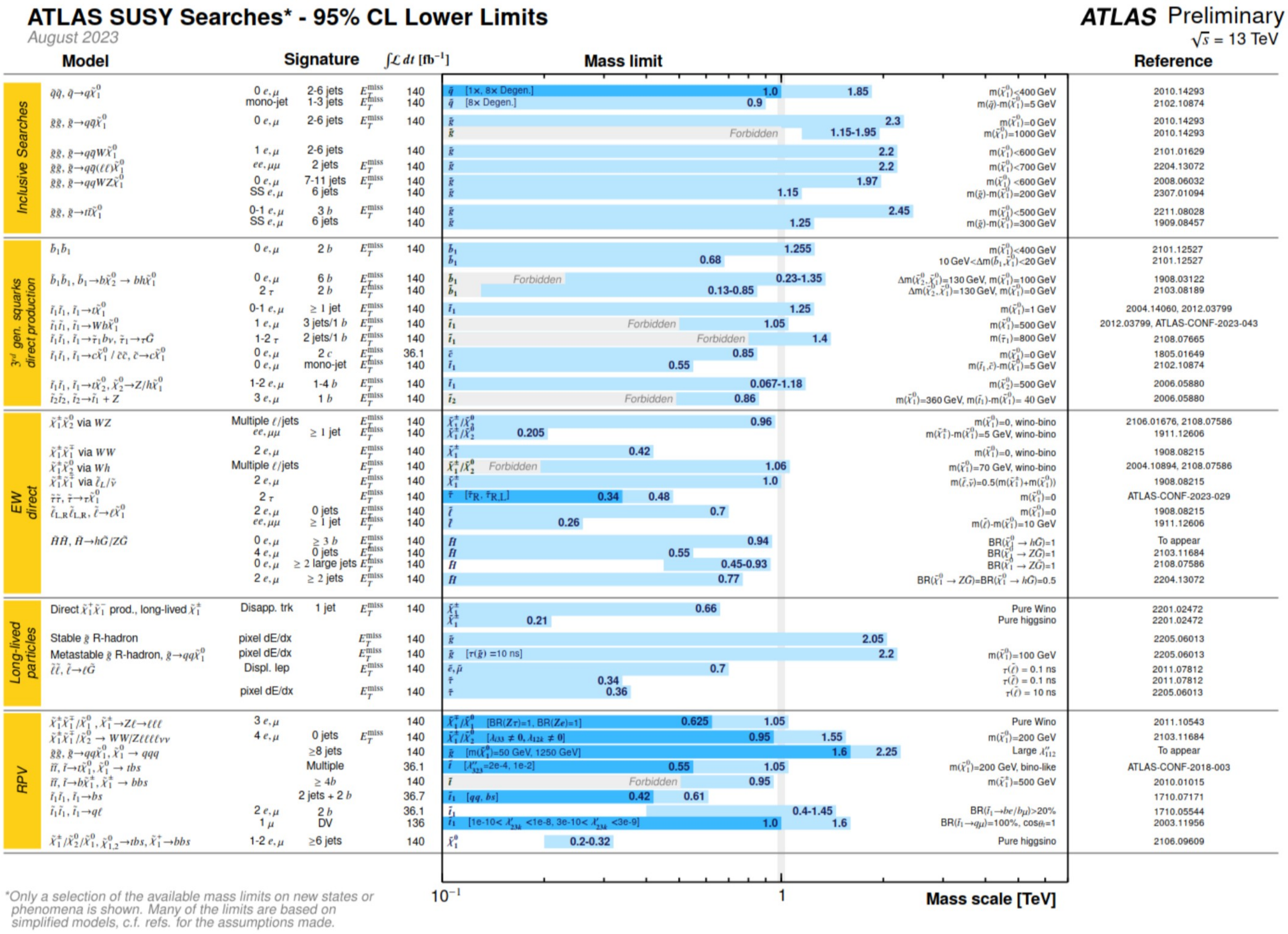
Lepton Number Violation in B-decays (LHCb)

Eur. Phys. J. Spec. Top. 233, 225–240 (2024)

Decay mode	Data analysed	Limit at 90% CL
$B^0 \to K^{*0}\mu^\pm e^\mp$	9 fb^{-1}	9.9×10^{-9}
$B_s \to \phi\mu^\pm e^\mp$	9 fb^{-1}	15.9×10^{-9}
$B^+ \to K^+\mu^- e^+$	3 fb^{-1}	7.0×10^{-9}
$B^+ \to K^+\mu^+ e^-$	3 fb^{-1}	6.4×10^{-9}
$B^+ \to K^+\mu^- \tau^+$	9 fb^{-1}	3.9×10^{-5}
$B_s \to \mu^\pm \tau^\mp$	3 fb^{-1}	3.9×10^{-5}
$B^0 \to \mu^\pm \tau^\mp$	3 fb^{-1}	1.2×10^{-5}
$B_s \to \mu^\pm e^\mp$	3 fb^{-1}	5.4×10^{-9}
$B^0 \to \mu^\pm e^\mp$	3 fb^{-1}	1.0×10^{-9}
$\tau \to 3\mu$	3 fb^{-1}	4.6×10^{-8}

Searches for SUSY particles

ATL-PHYS-PUB-2023-025



Search for gravitational waves

Next generation of detectors

IUPAP Report, WG-9 and C-12 (Summer 2023):

Key problems in physics that should determine the development of new facilities and programs in nuclear science:

- Nuclear physics: nuclear structure and nuclear reactions, formation of elements in the Universe, including superheavy elements
- Structure of the nucleon, consisting of quarks and gluons within the Standard Model
- Fundamental symmetries leading to physics beyond the Standard Model and to the study of neutrino properties (study of neutrinoless double beta decay and neutrino oscillations)
- Nuclear energy in the era of climate change and global warming
- Application of nuclear physics for the benefit of society, e.g. nuclear medicine.

Objectives and Prospects at JINR:

- Borders of the existence of nuclear matter, extreme states of nuclear matter: neutron “paste”, quark matter and color superconductivity. The nature of neutron stars and “deconfinement energy”.
- Study of nuclear structure, nuclear reactions and properties of new nuclei at ultra-small cross sections (up to 1 fb) and ultra-short lifetimes (< μsec);
- Obtaining record intensities of beams of highly charged heavy ions and operating with them (beam power, high luminosity, backgrounds);
- Highly active targets and beams;
- Superconducting technologies and devices (ion sources, linacs, cyclotrons, synchrotrons, channels and detectors);
- High-intensity sources of heavy ions;
- Highly intelligent beam cooling and beam gymnastics (ultra-short times < 1 sec, and maximum intensities up to 10^10).

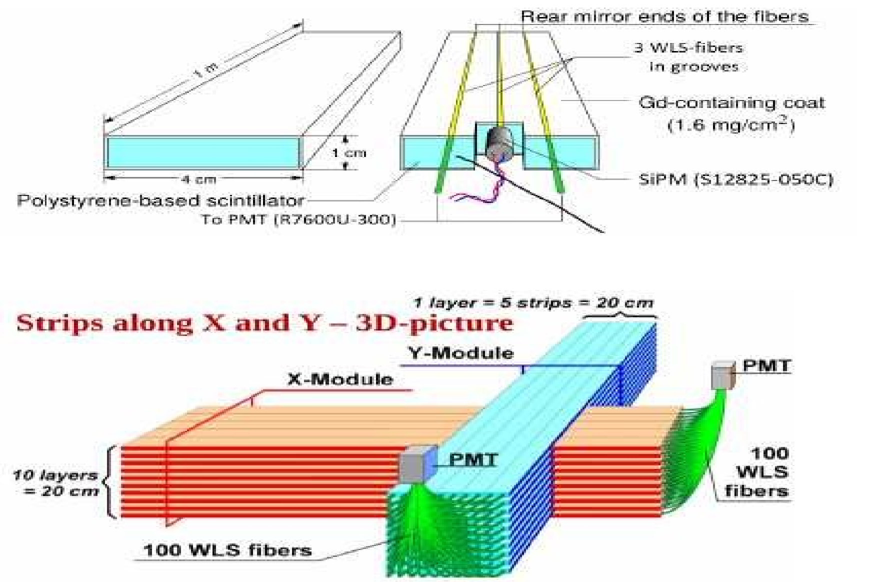
Experiments at Kalinin NPP

DANSS

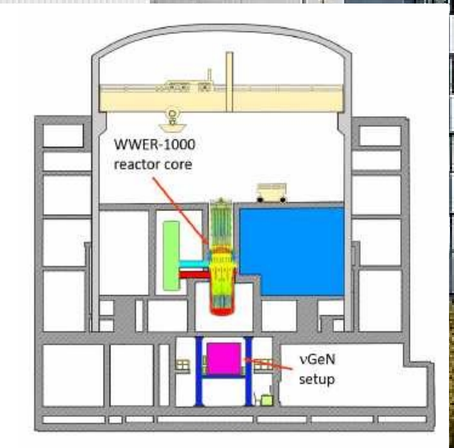
Search for electron neutrino oscillation at the very short range

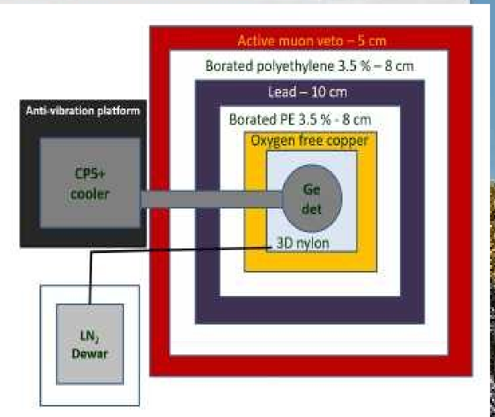
νGen

Search for coherent elastic neutrino scattering on nuclei



- Double PMT (groups of 50) and SiPM (individual) readout
- SiPM: 18.9 p.e./MeV & 0.37 X-talk
- PMT: 15.3 p.e./MeV
- 2500 strips = 1 m^3 of sensitive volume
- Inverse beta decay reaction is used





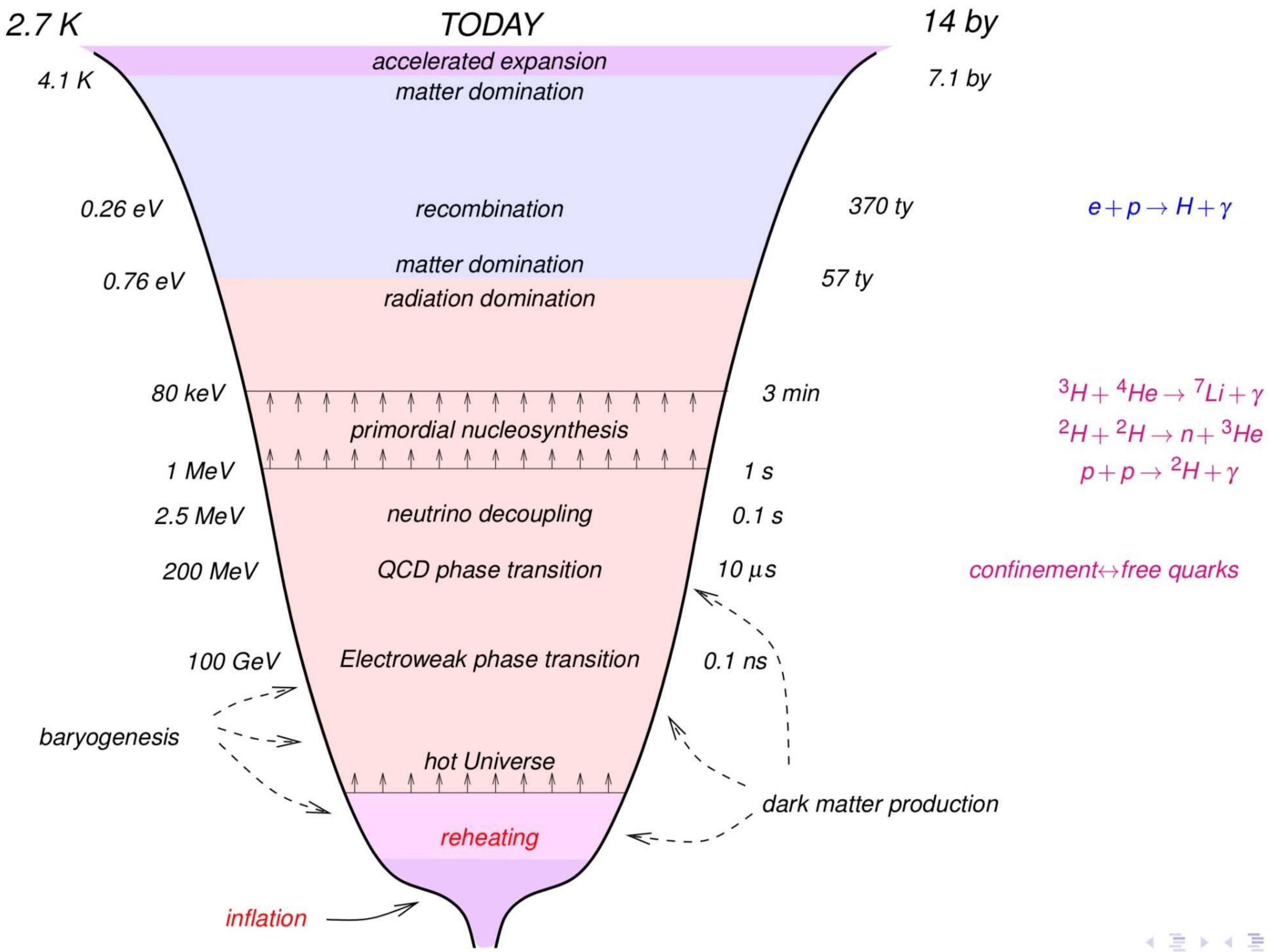
Neutrino physics challenges

Modern facilities (GERDA, CUORE, EXO-200, KamLAND-Zen) use various detection techniques: enriched isotopes of ^{76}Ge (germanium detectors), ^{130}Te (cryogenic bolometers) and ^{136}Xe (liquid xenon).

Key technological challenges include suppression of the radioactive background to 10⁻ events/kg/year (LEGEND-200, 200 kg ^{76}Ge) and improvement of energy resolution (2-3% FWHM at Qßß≈2.5 MeV).

Perspective projects (nEXO, CUPID, NEXT) plan to increase the mass of detectors to a ton scale with a further reduction in the background, which will achieve sensitivity of m~0.01 eV, covering the area of the normal hierarchy.

In parallel, alternative mechanisms of 0vßß (heavy particle exchange, Lorentz invariance violation) are being investigated through the analysis of angular correlations and spectral shapes. Confirmation of the 0nbb observation would have fundamental implications for physics beyond the Standard Model, including the lepton number and the origin of neutrino masses.


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
7.1 by
matter domination
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.76 eV
57 ty
radiation domination
80 keV
3 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation