Building the future together

Open questions in fundamental physics and our main future facilities to address them

Jorgen D'Hondt
Vrije Universiteit Brussel

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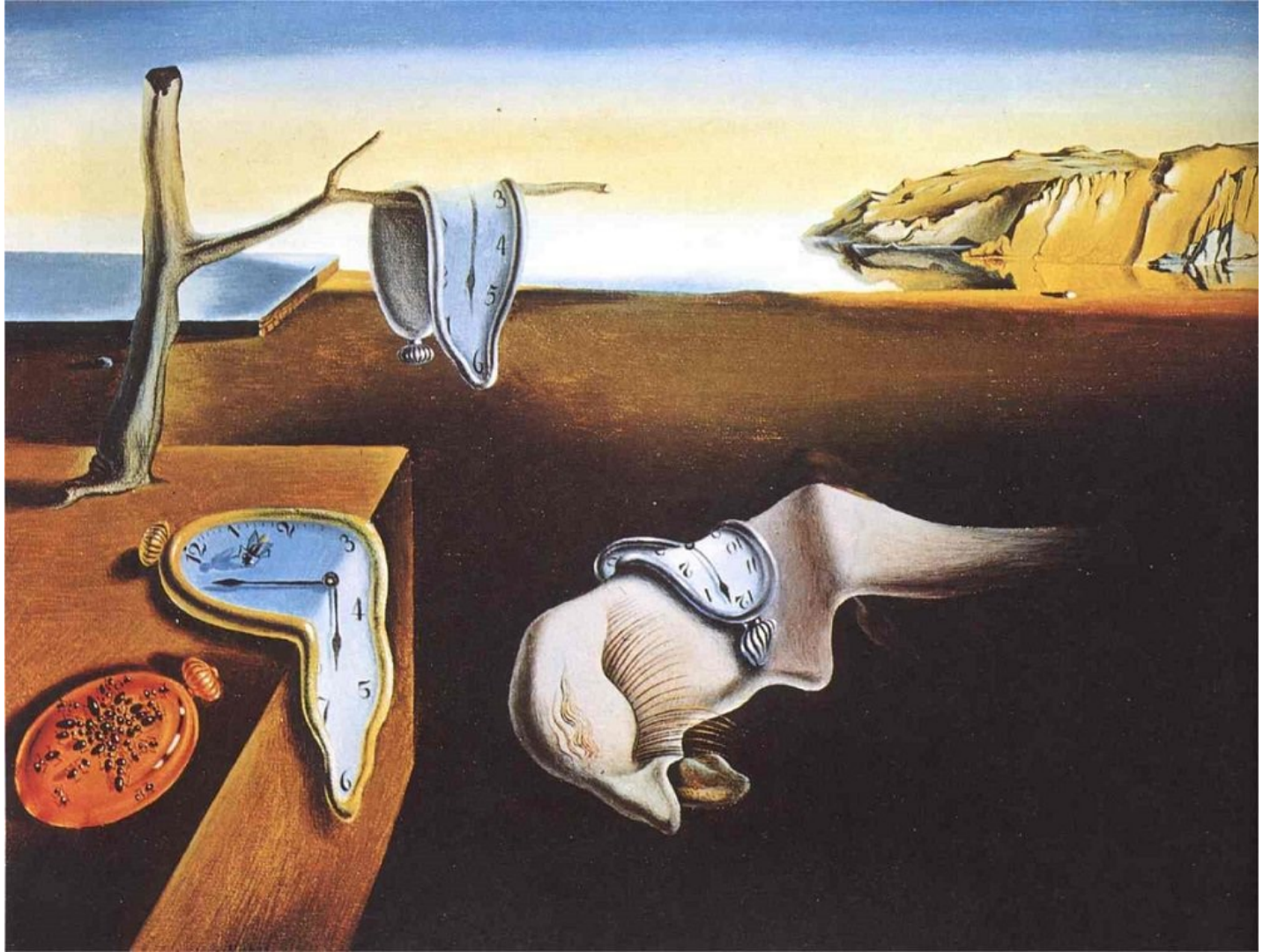
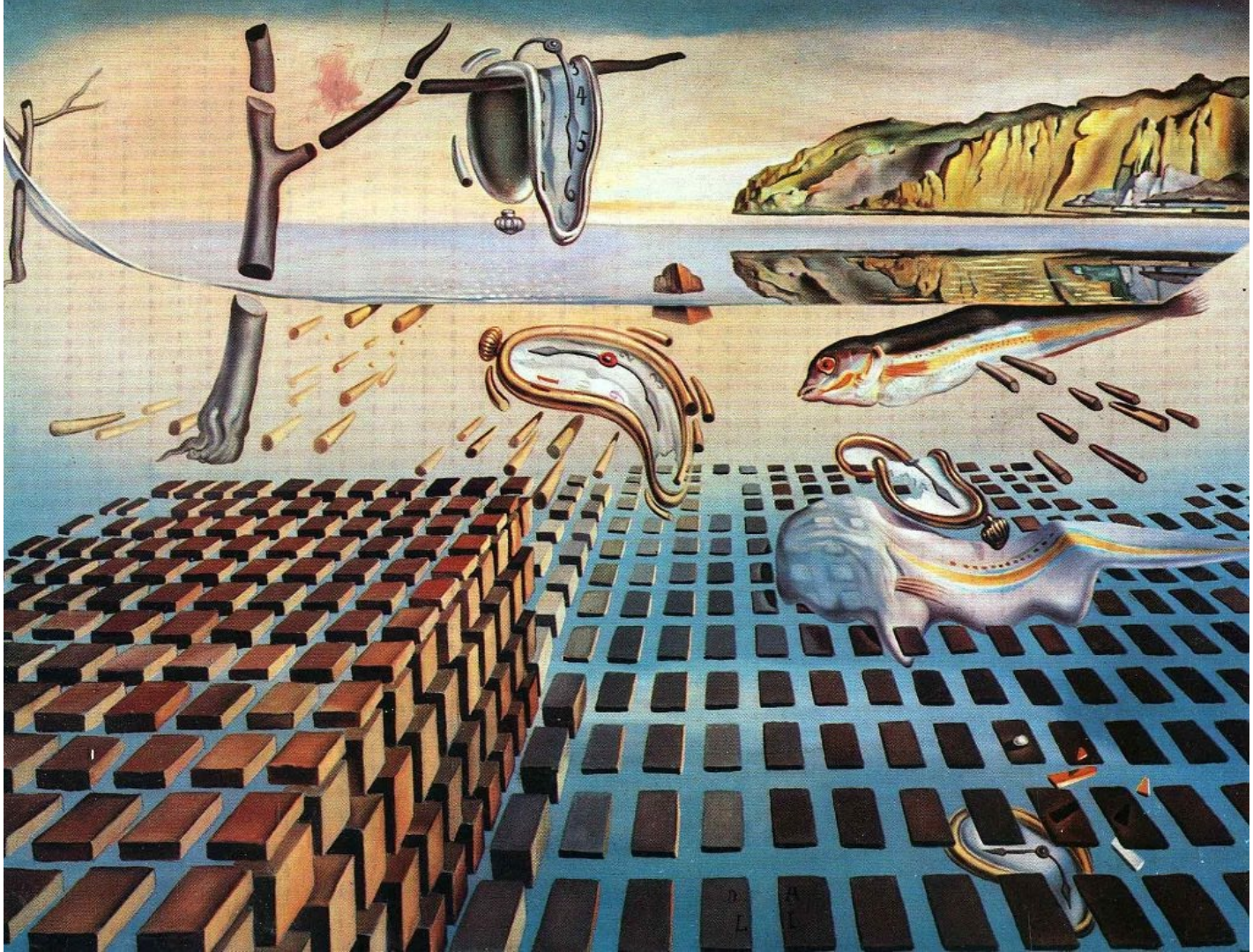
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

beln

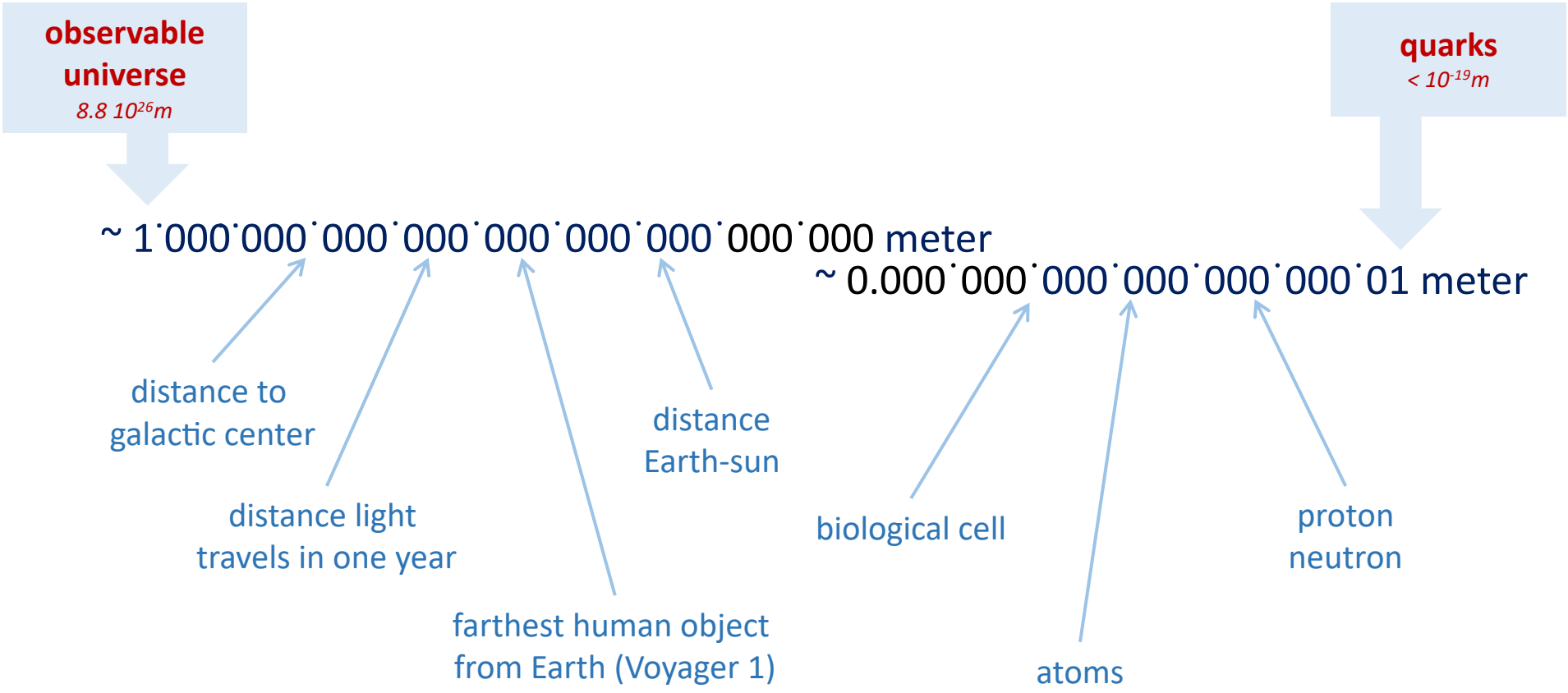
ALICE Collaboration Week, CERN, 6-10 June 2022



S. Dali
1931



S. Dali
1952


observable universe
8.8 10^26 m
quarks
< 10^-19 m
~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter
~ 0.000˙000˙000˙000˙000˙000˙01 meter
distance to galactic center
distance light travels in one year
farthest human object from Earth (Voyager 1)
distance Earth-sun
biological cell
atoms
proton neutron

observable universe
8.8 10^{26}m

visible with our own eyes

quarks
< 10^{-19}m

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

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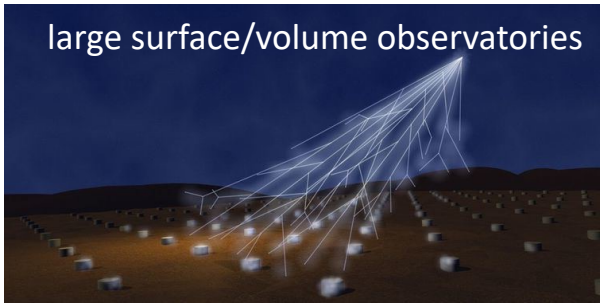
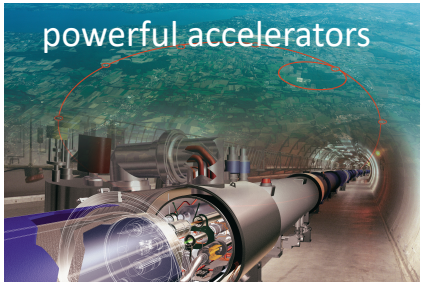


visible with our own eyes



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~ 0.000˙000˙000˙000˙000˙000˙01 meter

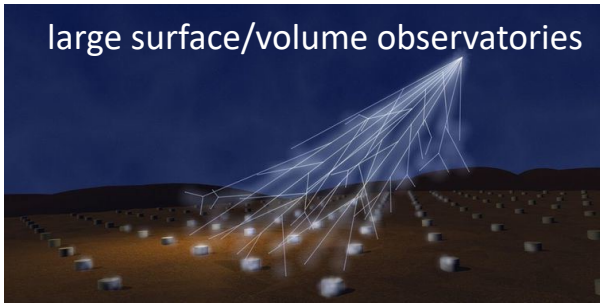
biological cell

atoms

proton neutron

age universe
$4.4\ 10^{18}$ s

observable universe
$8.8\ 10^{26}$m



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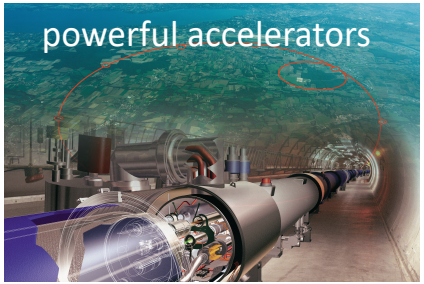


lifetime top quark
$5\ 10^{-25}$ s

quarks
$< 10^{-19}$m

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

atoms

proton
neutron

lifetime star
10^{13}-10^{16} s

duration supernova & GRB
0.1-100 s

lifetime proton
$> 3\ 10^{41}$ s

lifetime kaon ($K^{\pm}$)
$1.2\ 10^{-8}$ s

Develop a model to describe how objects behave in this space and time

Develop a model to describe how objects behave in this space and time

Basic Principles

FROM INTUITION

e.g. the locality principle:
all matter has the same set of constituents

e.g. the causality principle:
a future state depends only on the present state

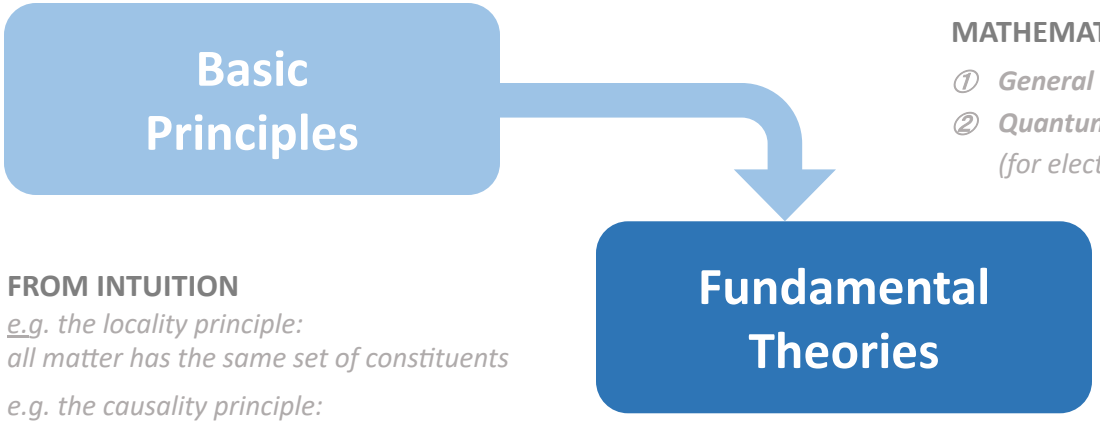
e.g. the invariance principle:
space-time is homogeneous

FROM LONG-STANDING OBSERVATIONS

the wave-particle duality principle
the quantisation principle
the cosmological principle
the constant speed of light principle
the uncertainty principle
the equivalence principle

} *no obvious reason for these long-standing observations to be what they are…*

Develop a model to describe how objects behave in this space and time



MATHEMATICAL FRAMEWORKS HOW OBJECTS BEHAVE

① ***General Relativity*** *(for gravity)*

② ***Quantum Mechanics + Special Relativity = Quantum Field Theory***
(for electromagnetic, weak and strong forces)

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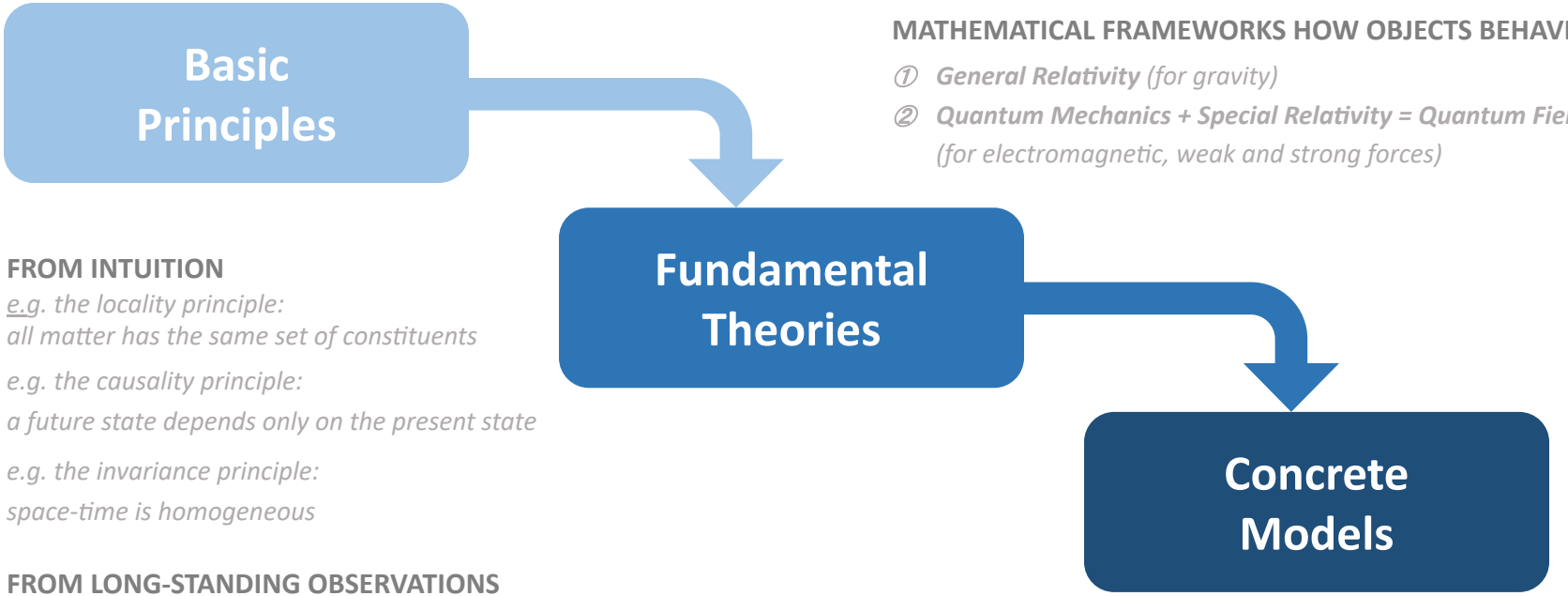

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APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

① *General Relativity* → ***Standard Model of Cosmology***

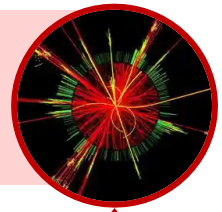
② *Quantum Field Theory* → ***Standard Model of Particle Physics***

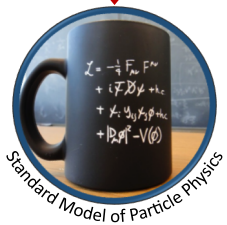
need to be valid into even the tiniest cracks of space and time
and for all energies or masses of the objects… even at the extremes

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

observations how small objects behave in our laboratories





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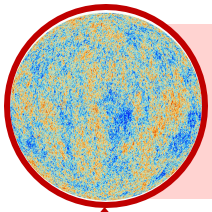
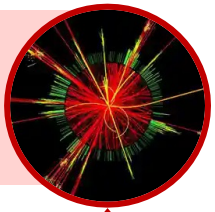
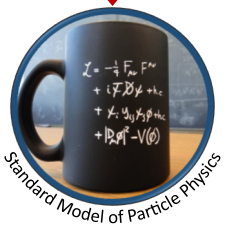


observations how large objects behave in our universe

observations how small objects behave in our laboratories





Einstein's field equations of gravity from which the Friedmann equations are derived to model the evolution of the universe

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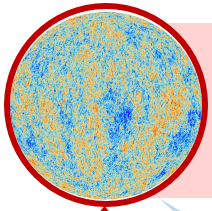
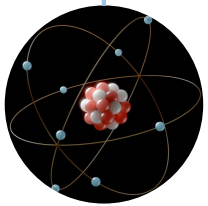
building blocks of life on the human scale



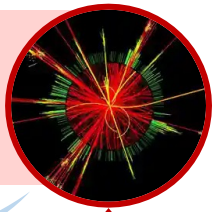
observations how large objects behave in our universe

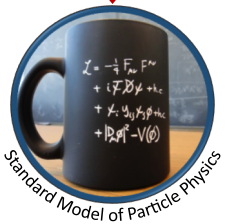
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories



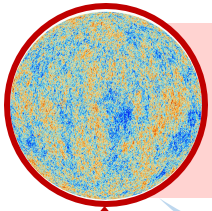


A century of scientific revolutions

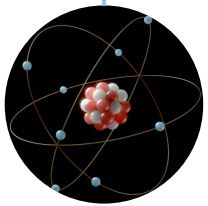
~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

building blocks of life on the human scale



observations how large objects behave in our universe



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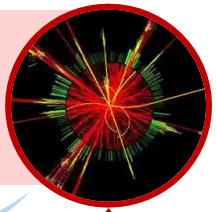
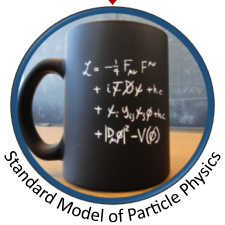
observations how small objects behave in our laboratories





communication
satellites
GPS

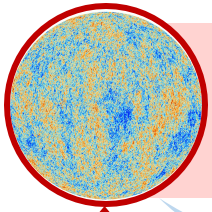
World Wide Web
touchscreens

A century of scientific revolutions

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

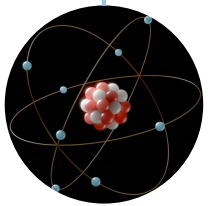
~ 0.000˙000˙000˙000˙000˙000˙01 meter

building blocks of life on the human scale



observations how large objects behave in our universe

production of particles and radiation
nuclear diagnosis and medicine



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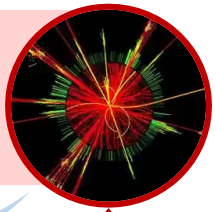

Standard Model of Cosmology

e.g. creation of
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e.g. nuclei built from
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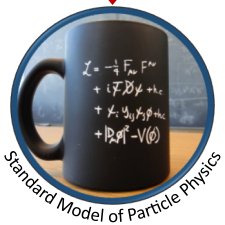
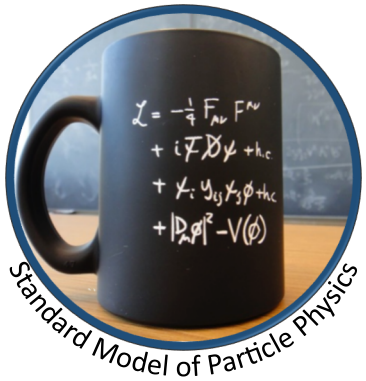


Standard Model of Particle Physics

"Scientific curiosity which ends up in your pocket"

Rolf Heuer (previous Director General of CERN)

The quest for understanding physics

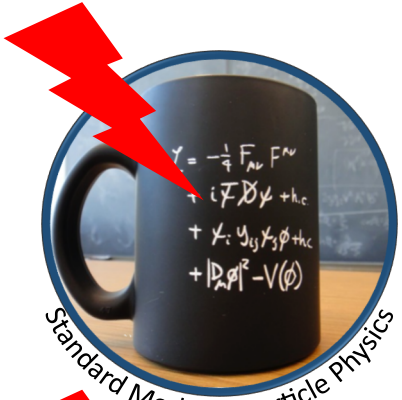


“Problems and Mysteries”

e.g. Abundance of dark matter?

- Abundance of matter over antimatter?
- What is the origin and engine for high-energy cosmic particles?
- Dark energy for an accelerated expansion of the universe?
- What caused (and stopped) inflation in the early universe?
- Scale of things (why do the numbers miraculously match)?
- Pattern of particle masses and mixings?
- Dynamics of Electro-Weak symmetry breaking?
- How do quarks and gluons give rise to properties of nuclei?…

The quest for understanding physics



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Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

higher energy interactions
in the lab

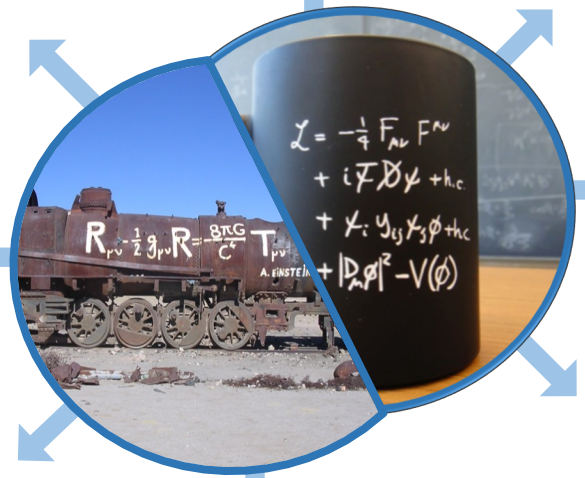
rarer processes

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

higher precision

earlier universe



RF cavities, high-field magnets, plasma wakefield acceleration

higher energy interactions
in the lab

squeezed-light sources to
deal with quantum noise
in gravitational-wave
detectors

earlier universe

rarer processes

solid-state devices with
fast read-out electronics

Innovate Technology
to make the invisible visible

higher precision

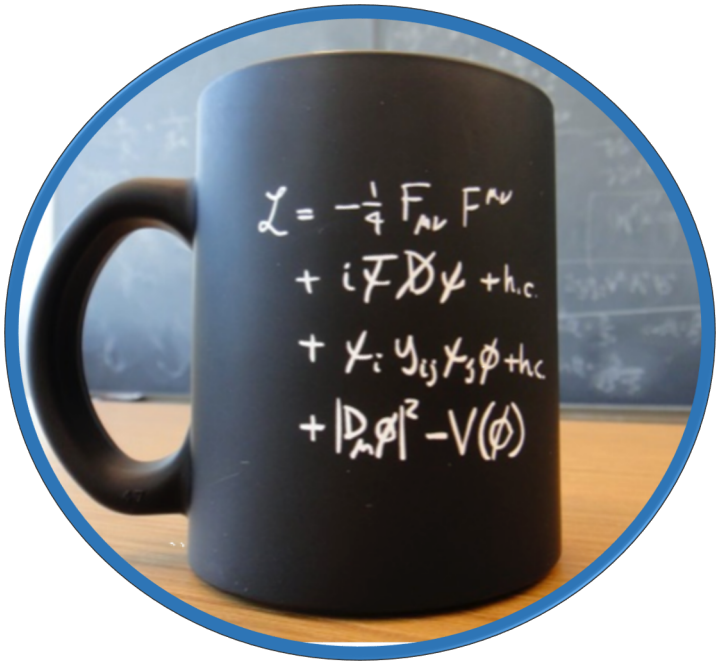
different
observations of the
same phenomenon

higher energetic phenomena
in the universe

computing and software challenge for Multi-Exabyte Data Infrastructures

Extending our models with new phenomena

(assuming our basic principles and theoretical frameworks hold)



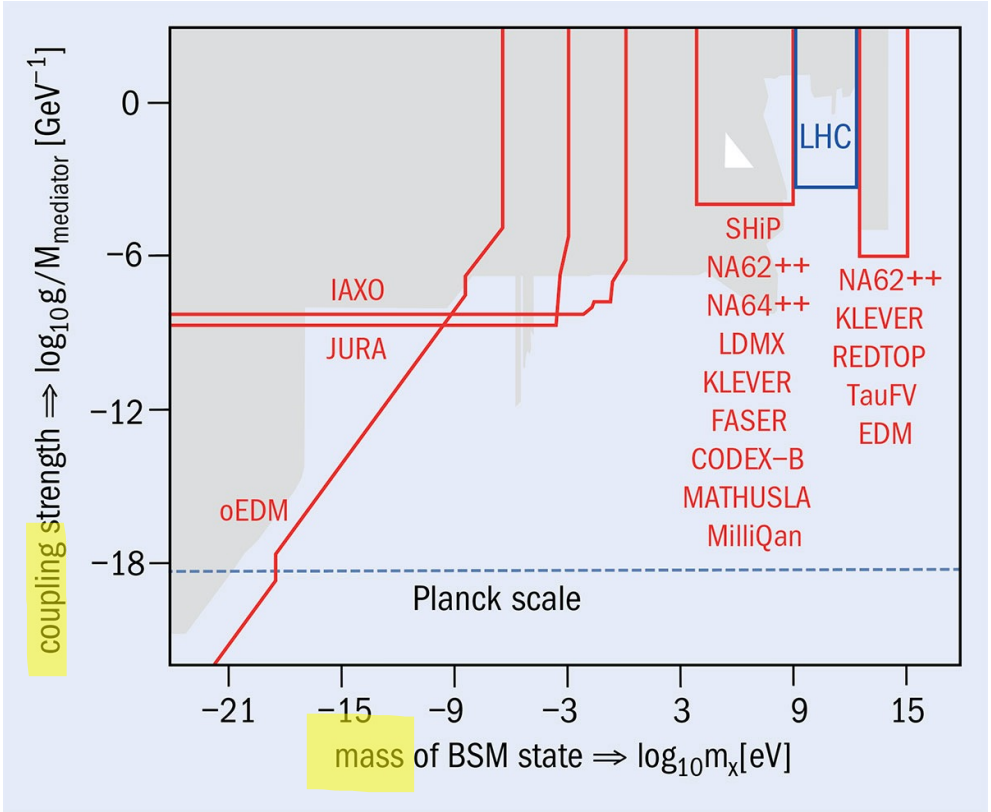
connection

(coupling strength)

Extending our models with new phenomena

(assuming our basic principles and theoretical frameworks hold)

Requires a coherent portfolio of complementary experiments to cover the whole parameter space where new physics can be hiding



Most recent European Strategies

the large …

weblink

2017-2026 European
Astroparticle Physics Strategy

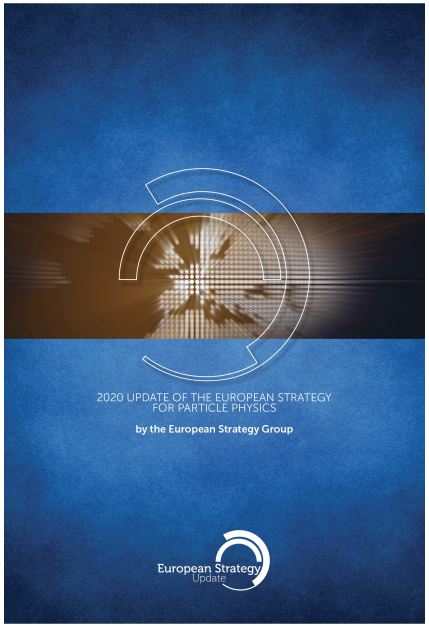
… the connection …

weblink

Long Range Plan 2017
Perspectives in Nuclear Physics

… the small

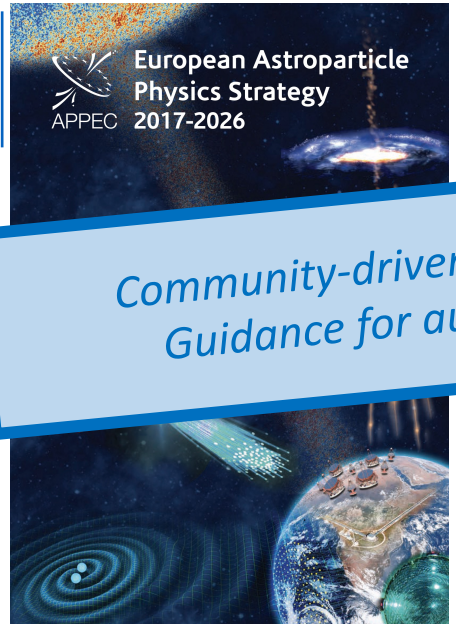
weblink



2020 Update of the European
Particle Physics Strategy

Most recent European Strategies

the large …



2017-2026 European
Astroparticle Physics Strategy

… the connection …

Long Range Plan 2017
Perspectives in Nuclear Physics

… the small

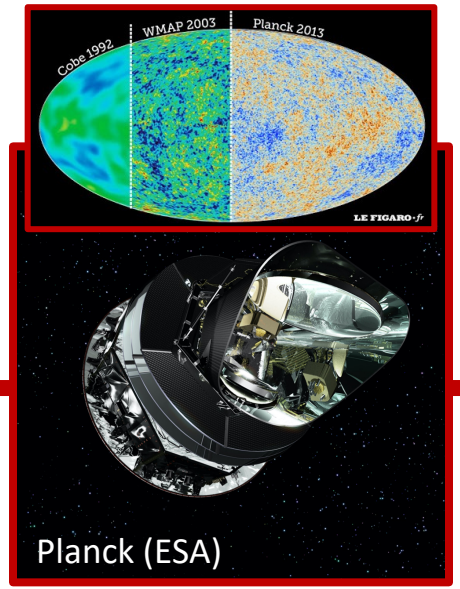
2020 Update of the European
Particle Physics Strategy

Community-driven strategies reflecting our ambition to address open questions.
Guidance for authorities to develop resource-loaded research programmes.

our eyes on the sky

The cosmic frontier: Cosmic Microwave Background precision physics

Previous flagship
impressive science



completed

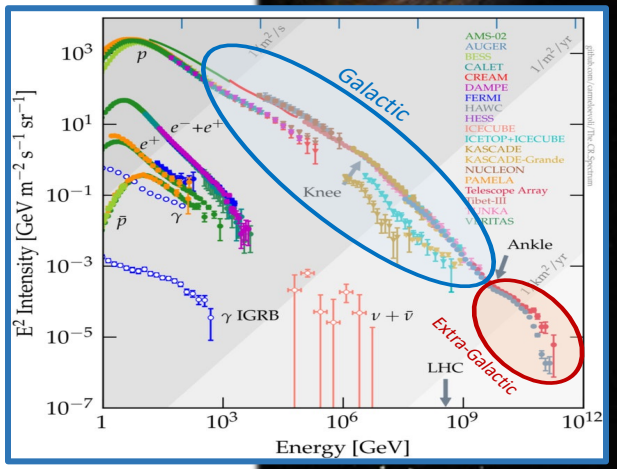
Next generation "Dark Universe" flagship
>30 M spectroscopic redshifts with 0.001 accuracy up to z ~2
to measure the acceleration of the universe

Properties of dark energy, dark matter and gravity

ESA: European Space Agency

A variety of very high-energy particles from our universe

cosmic particles



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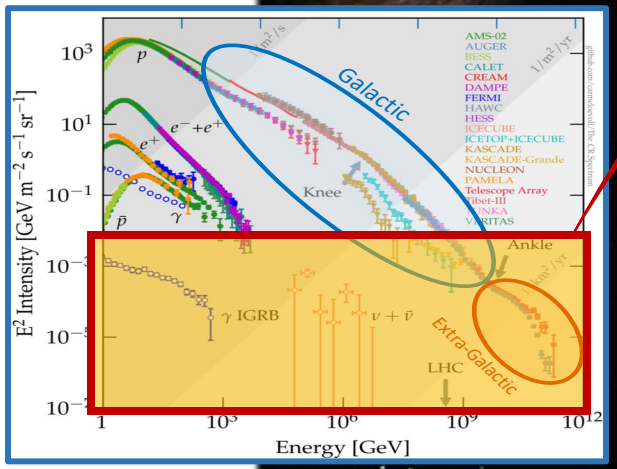
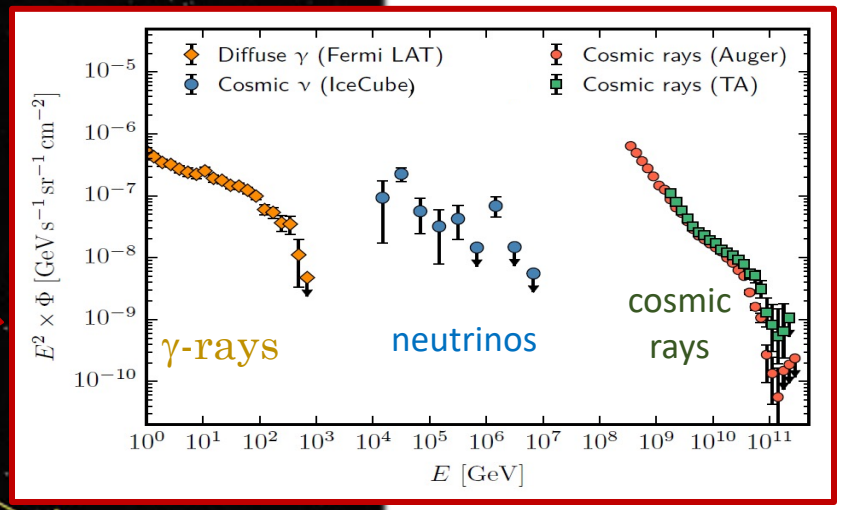


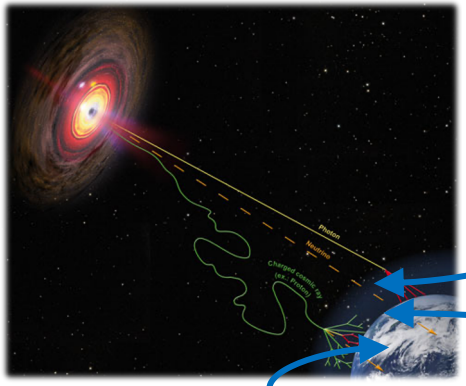


Similar cosmic energy density:
would they have a common origin?

into the global Multi-Messenger Realm for Astronomy to discover the sources

Major Cosmic Particle Facilities in Europe

advance our major participation outside Europe: Pierre Auger Observatory, IceCube(-Gen2), …



observatory in orbit

AMS-2

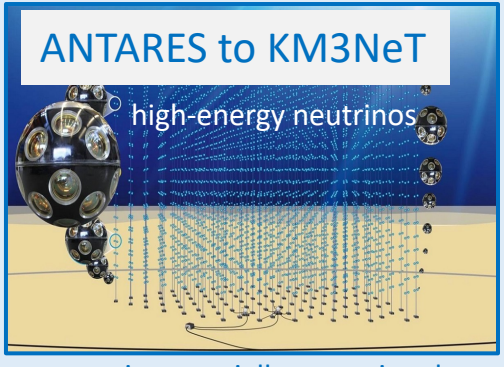
anti-matter in cosmic rays

data taking

observatory below surface

ANTARES to KM3NeT

high-energy neutrinos



construction, partially operational

BAIKAL-GVD

high-energy neutrinos

construction, partially operational

observatory on the surface

H.E.S.S./MAGIC/VERITAS to CTA

high-energy gamma-rays

construction, start observations >2023

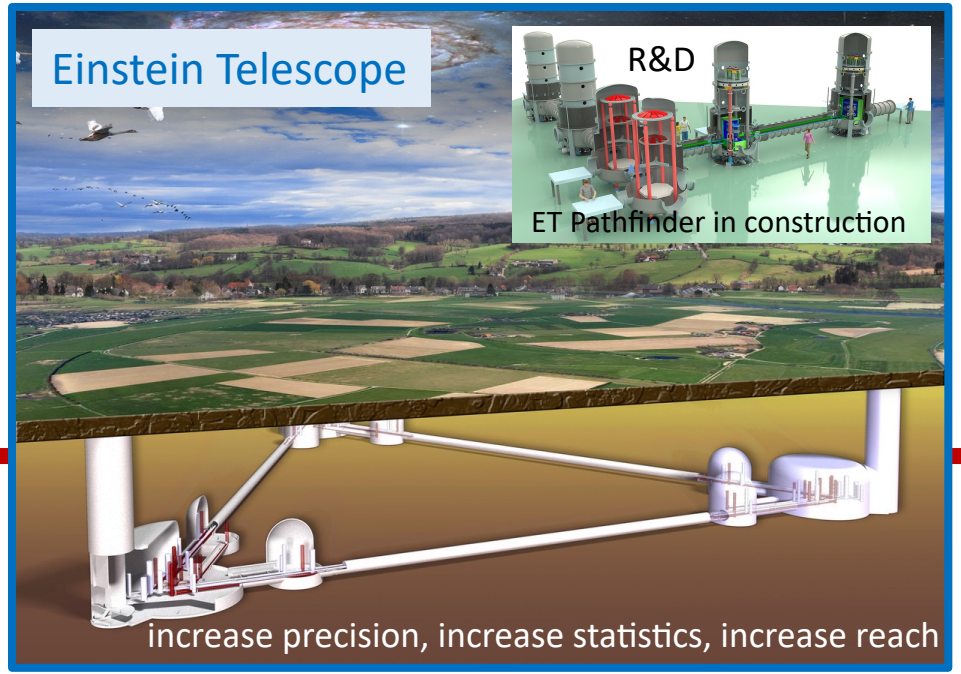
Gravitational Wave Facilities in Europe

Current flagships

Advanced & Plus upgrades up to 2035

3rd generation interferometer, beyond 2035

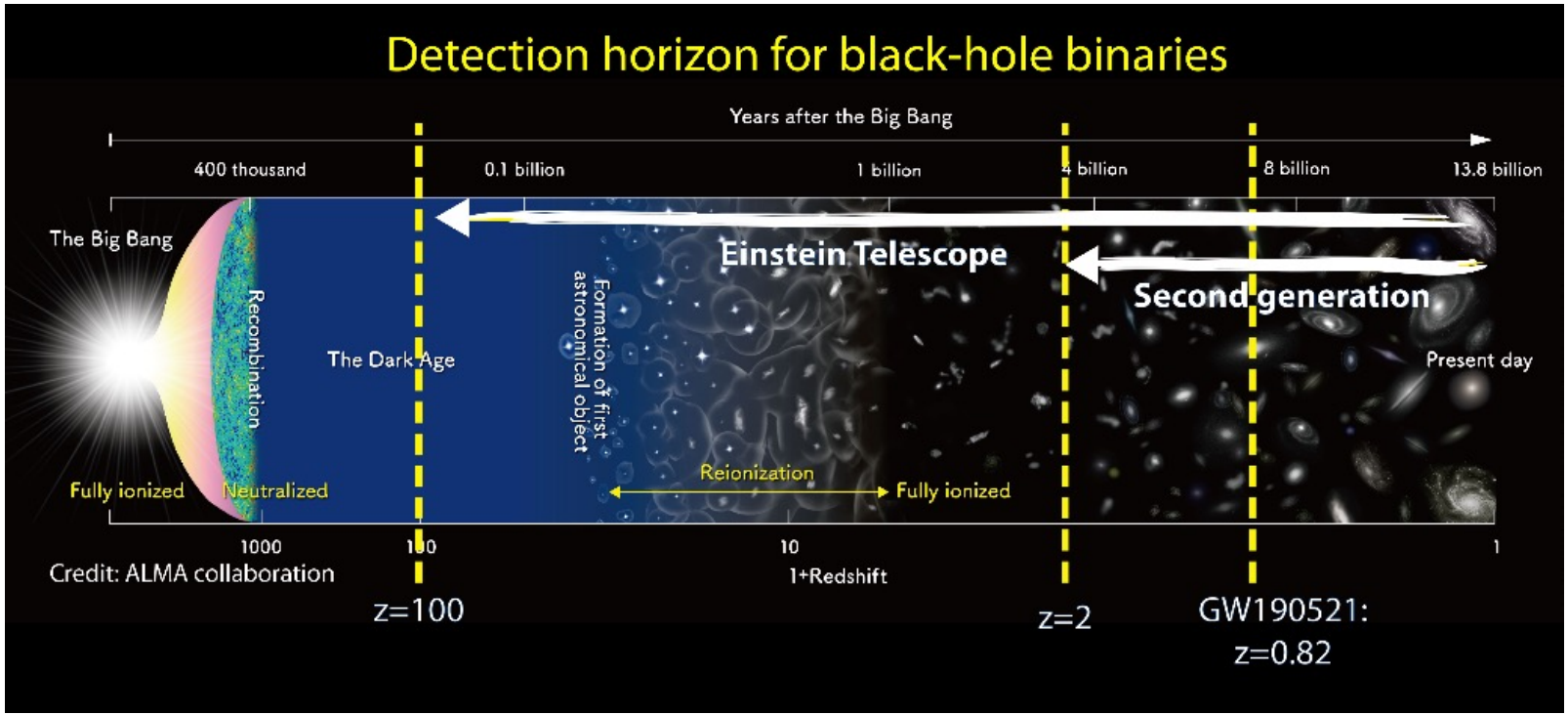
underground – triangle (10km arms) – cryogenic



on the ESFRI Roadmap (EU) *(European Strategy Forum on Research Infrastructures)*

complementary: LISA (ESA) to be launched around 2037

Gravitational Wave with the Einstein Telescope



Will our basic principles and theoretical frameworks hold throughout the cosmic history?

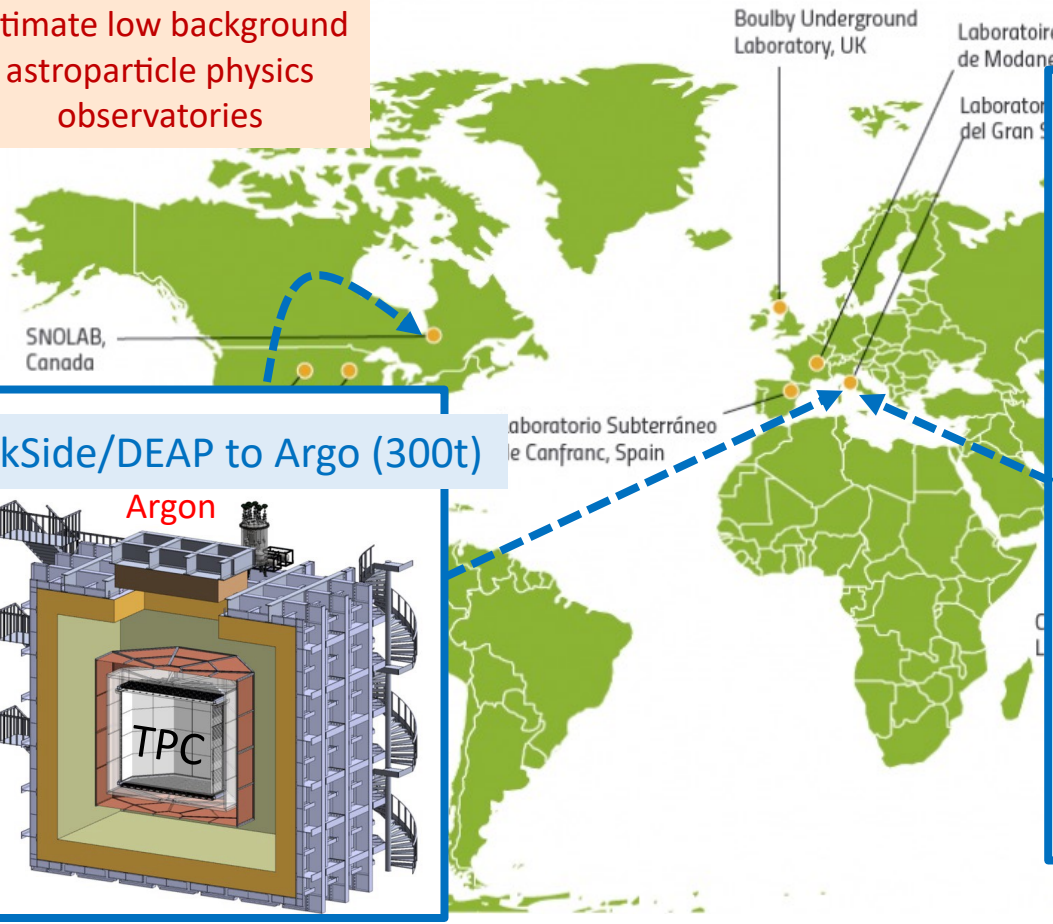
our eyes on the invisible

Major underground Facilities – shielding the visible

image courtesy of Susana Cebrián, "Science goes underground"

Major underground Facilities in Europe – Dark Matter

ultimate low background astroparticle physics observatories



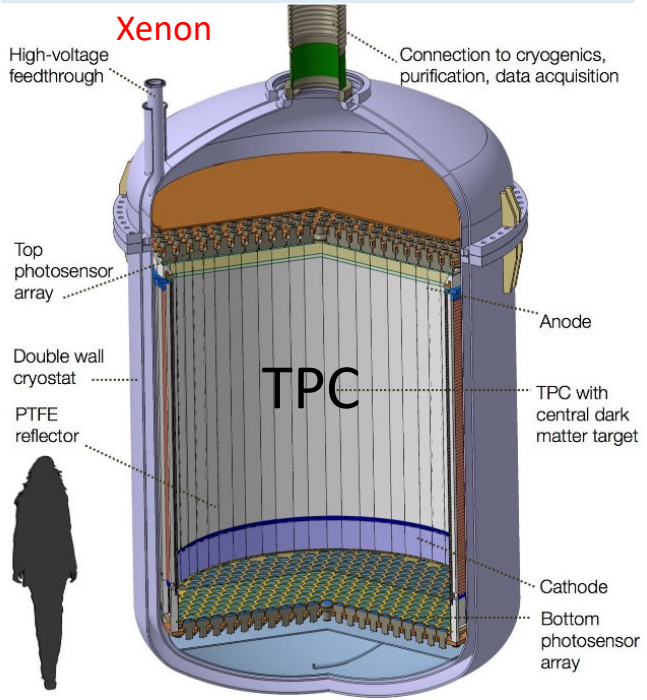
DarkSide/DEAP to Argo (300t)

Argon

proposal

XENON (1-10t) to DARWIN (50t)

Xenon

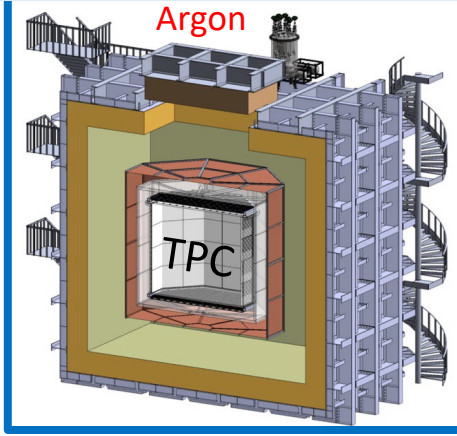


proposal towards CDR (beyond 2027)

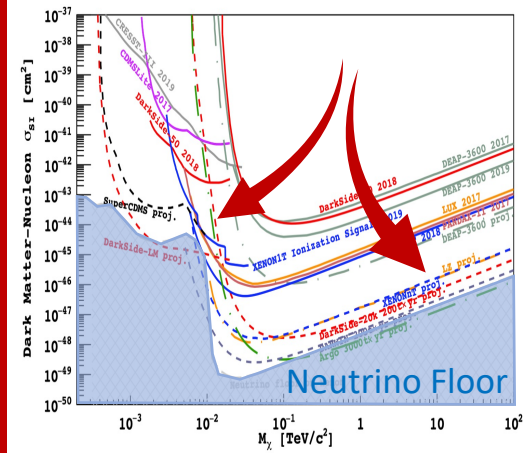
Major underground Facilities in Europe – Dark Matter

ultimate low background astroparticle physics observatories

DarkSide/DEAP to Argo (300t)

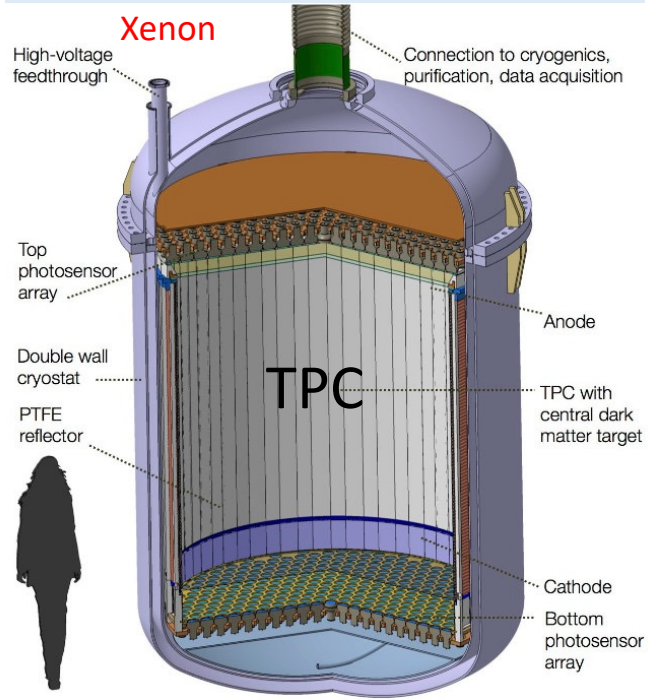


proposal



reaching the "neutrino floor"
where the neutrino backgrounds dominate

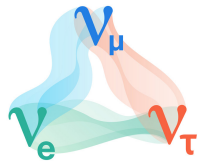
XENON (1-10t) to DARWIN (50t)



proposal towards CDR (beyond 2027)

Neutrino sector extends the Standard Model

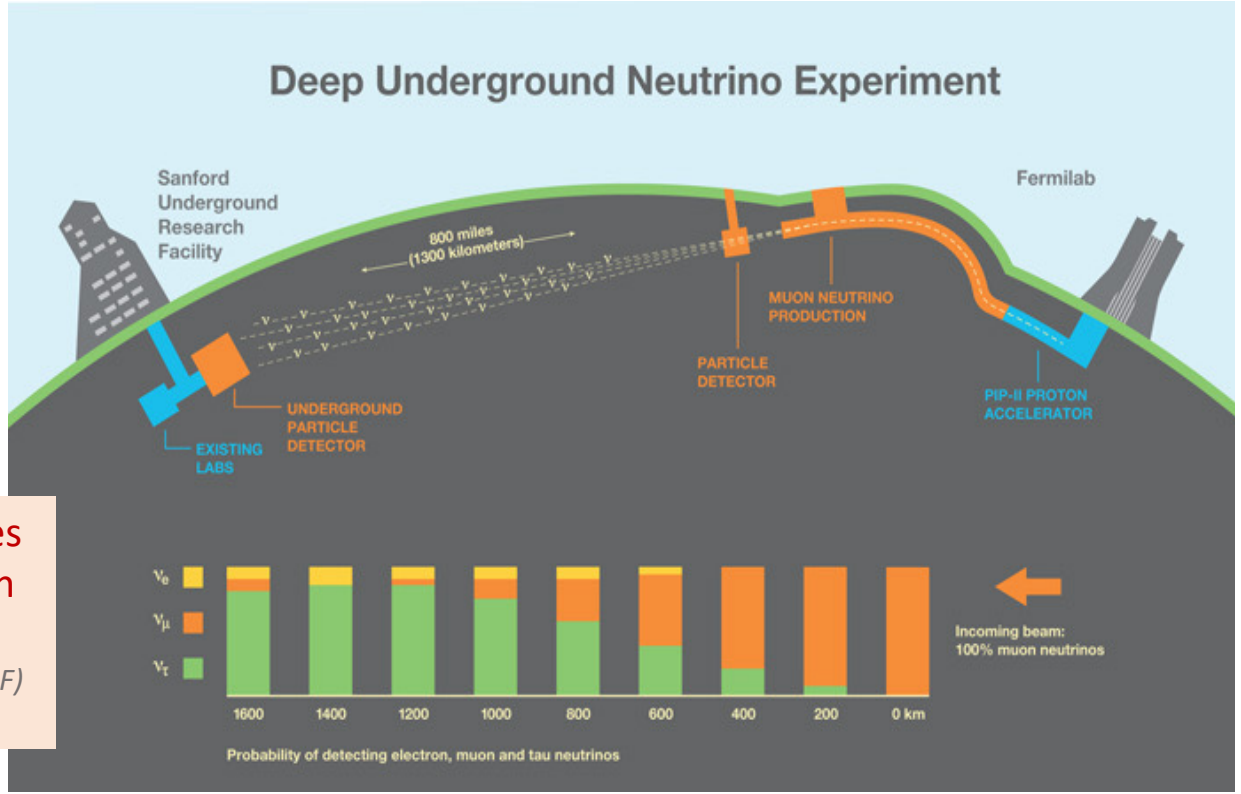
Because neutrinos oscillate, they have mass… but how to extend the Standard Model?



- *Is a neutrino its own anti-particle?*
- *Is there CP violation in the leptonic sector?*
- *What is the absolute mass scale?*
- *How does the neutrino mass spectrum look like?*

Measure the oscillation probabilities of neutrinos and antineutrinos with ultimate precision

e.g. at the Long-Baseline Neutrino Facility (LBNF) with the DUNE experiment

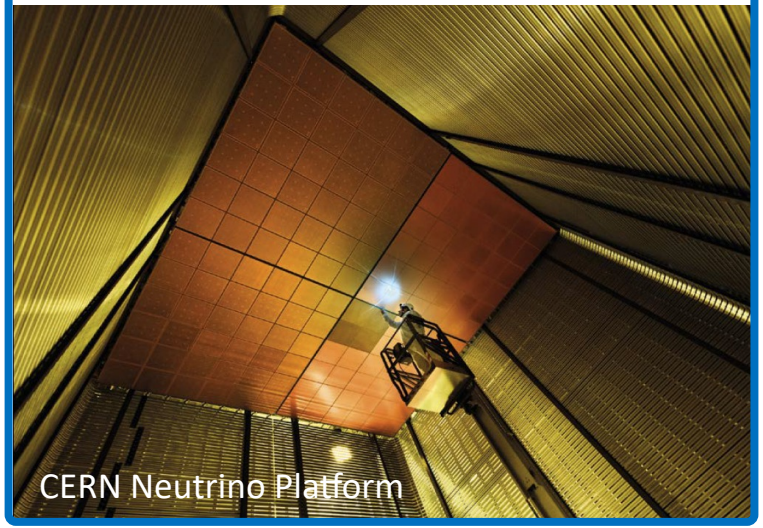


Neutrino beams in Japan and in the US

CERN's Neutrino Platform in LBNF & DUNE (US), and in T2K (Japan)

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC



BabyMIND @ T2K (near detector)

Prototype for Magnetised Iron Neutrino Detector

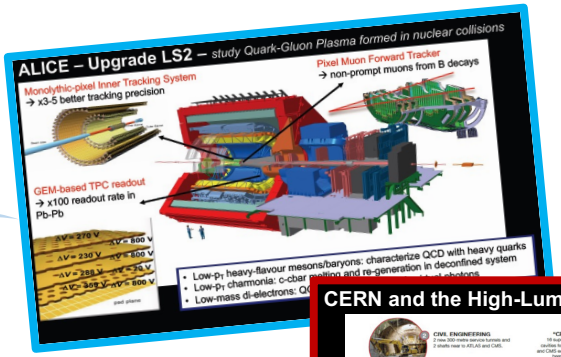
Within the next decade, we will know much more how to develop the neutrino sector to extend the Standard Model

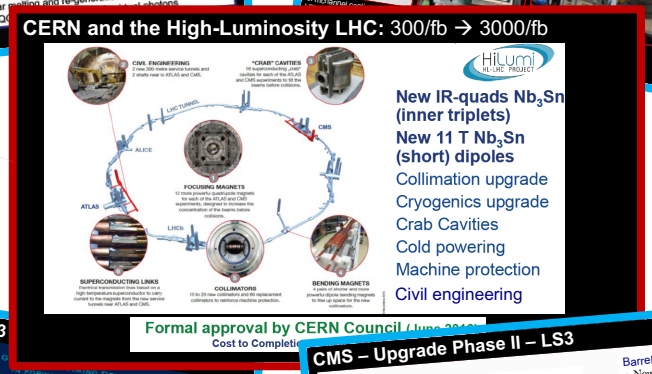
our eyes on direct discoveries

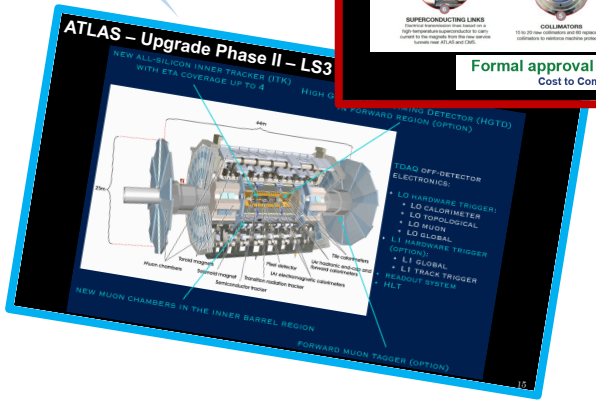
Today's Flagship: from LHC to HL-LHC

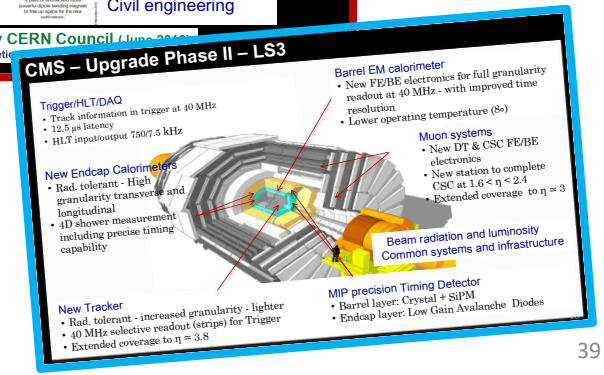
Current flagship (27km)

impressive programme up to 2040









continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

Today's Flagship: from LHC to HL-LHC

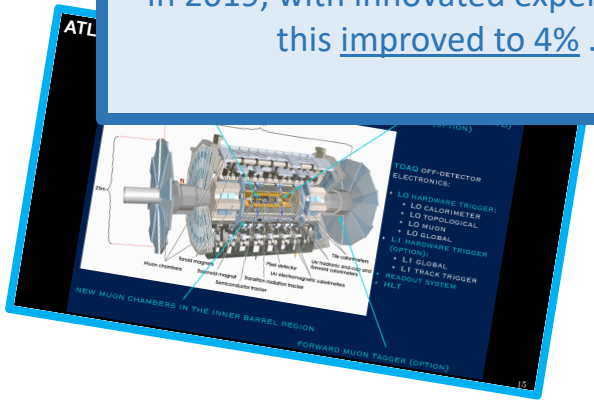
Current flagship (27km)

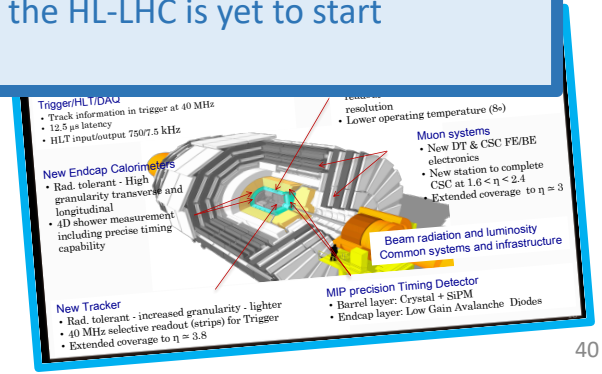
impressive programme up to 2040

Talented researchers make the difference

In 2013, the expected precision on the top quark to Higgs coupling reachable with the HL-LHC programme was estimated 7-10%

In 2019, with innovated experimental and theoretical techniques this improved to 4% ... the HL-LHC is yet to start





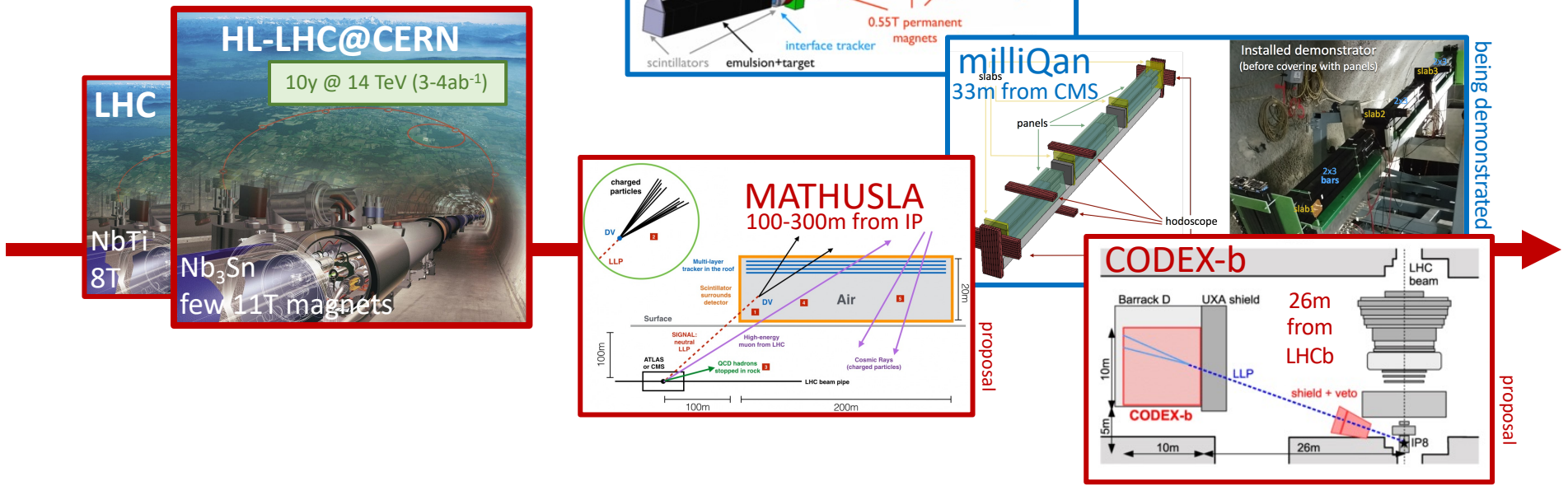
continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

(HL-)LHC as a catalyser for dedicated experiments

Current flagship (27km)

impressive programme up to 2040

Additional opportunities with high-energy proton collisions

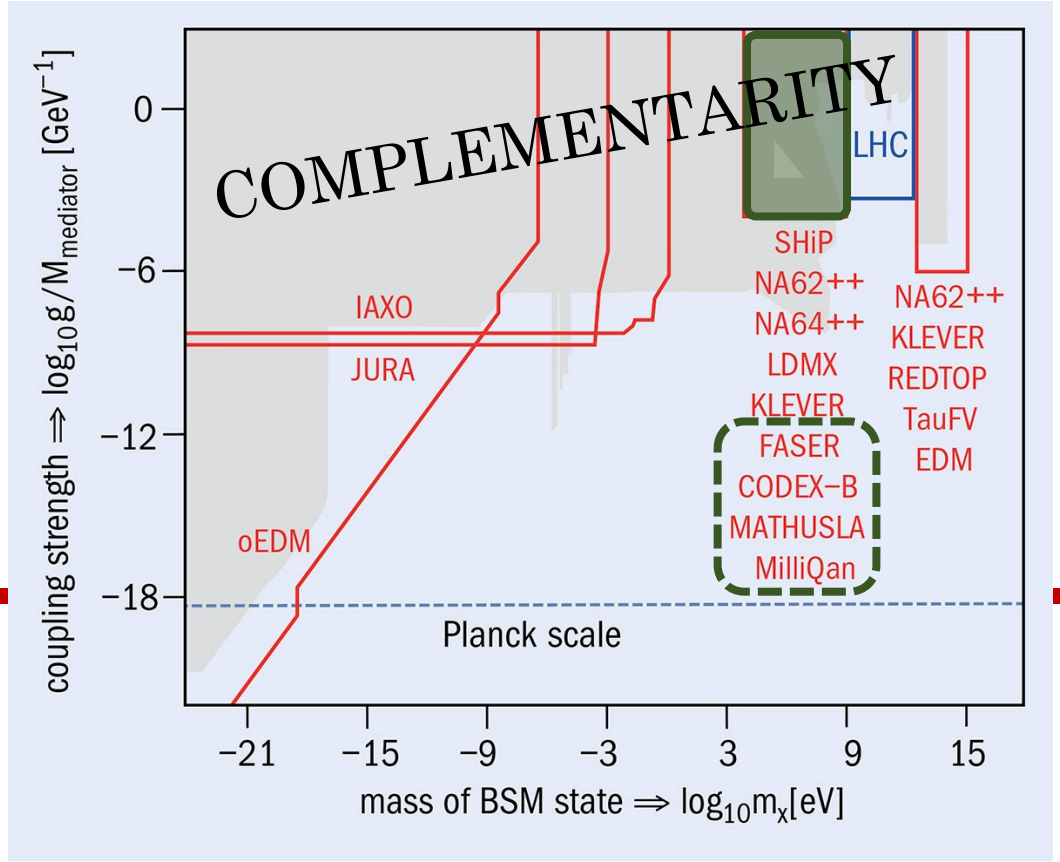


(HL-)LHC as a catalyser for dedicated experiments

Current flagship (27km)

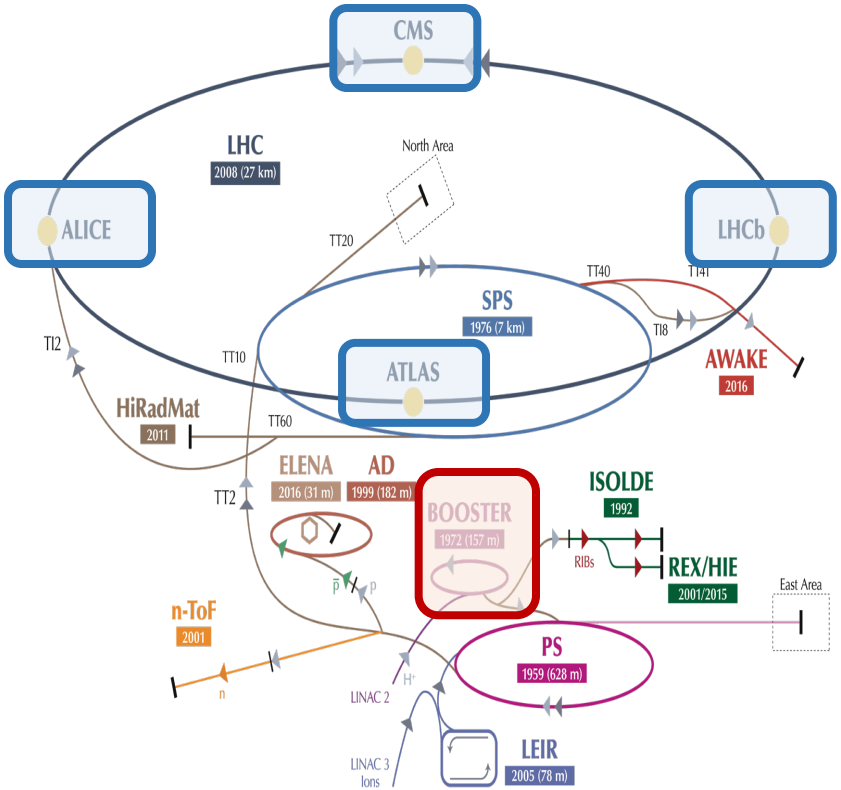
impressive programme up to 2040

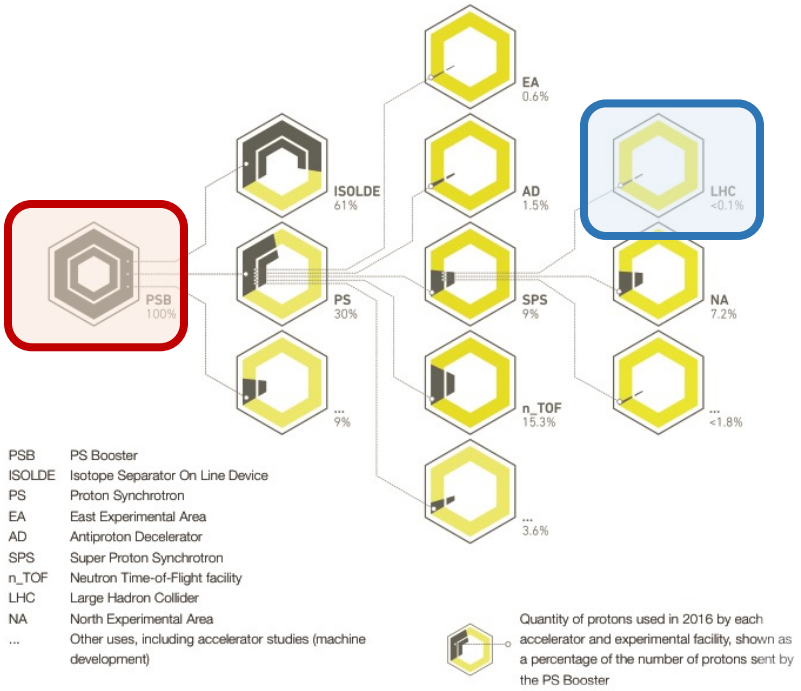
a high-energy proton collider is a catalyser for a unique portfolio of complementary research



While running the (HL-)LHC: Accelerated Beams at CERN

The CERN accelerator complex and the LHC – protons from Booster only <0.1% to LHC



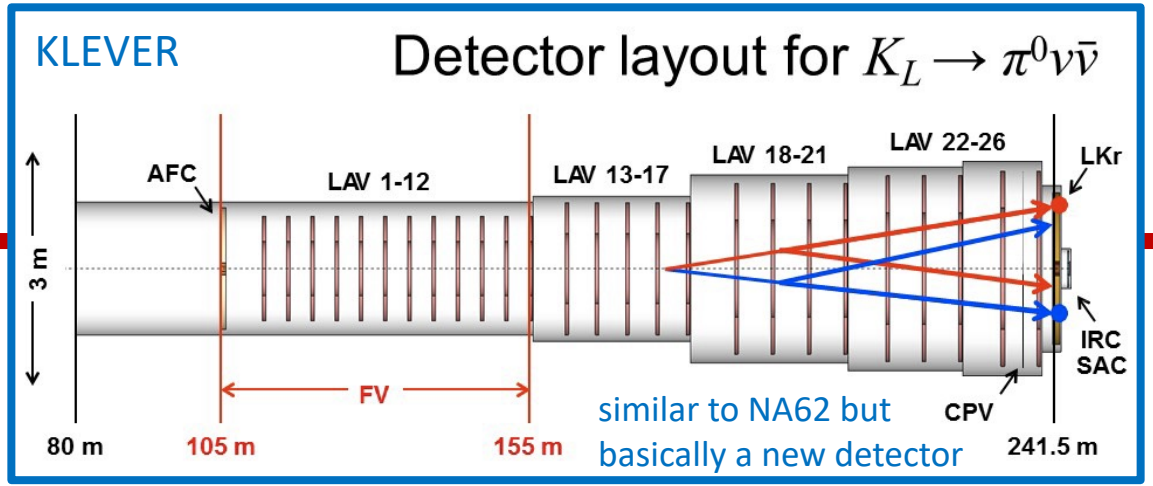


Kaon physics from NA62 to KLEVER @ SPS-CERN

During LHC era

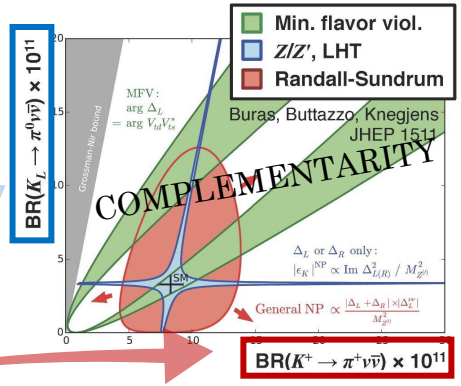
running

During HL-LHC era



proposal

Kaon physics from NA62 to KLEVER @ SPS-CERN



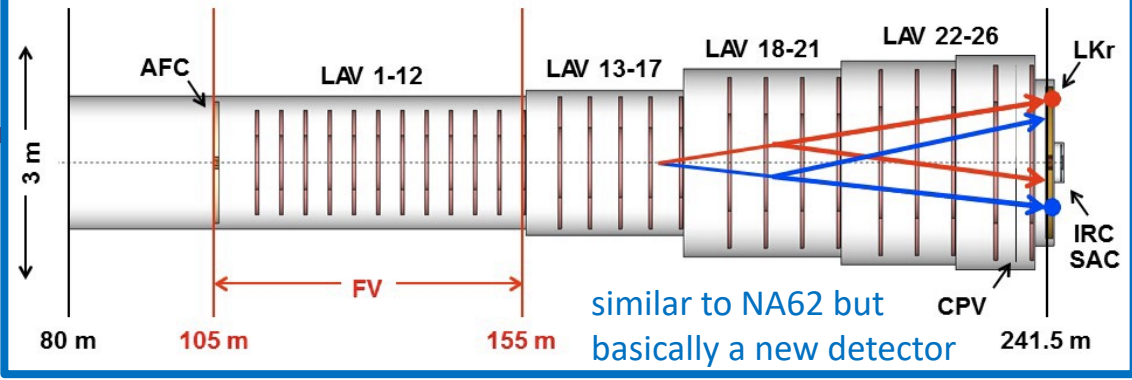
During LHC era

During HL-LHC era

running

KLEVER

Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$



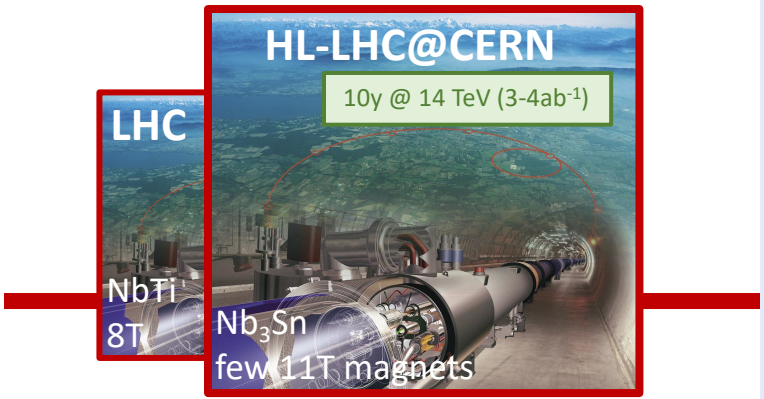
similar to NA62 but basically a new detector

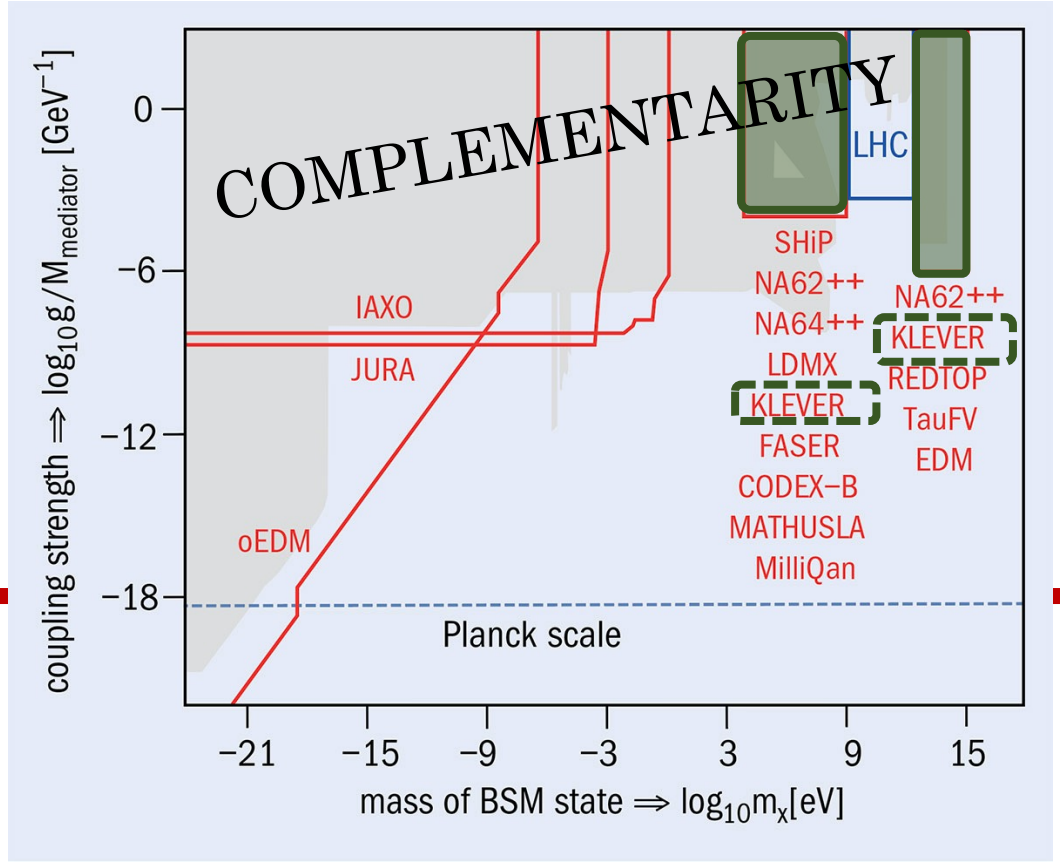
proposal

While running the (HL-)LHC: Accelerated Beams at CERN

Current flagship (27km)

impressive programme up to 2040

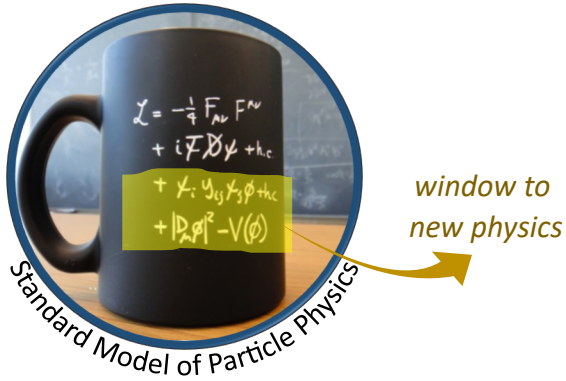




Future high-energy particle colliders

Essentially all problems of the Standard Model are related to the Higgs sector, hence the argument to built new colliders dedicated to produce copiously Higgs bosons in order to map precisely its interactions with other particles.

An electron-positron Higgs factory is the highest-priority next collider.



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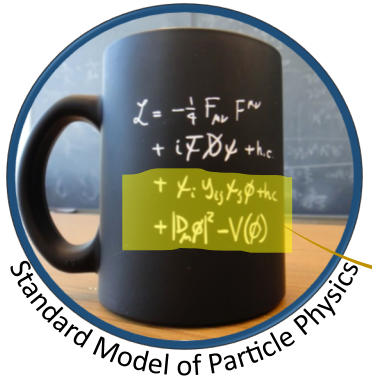
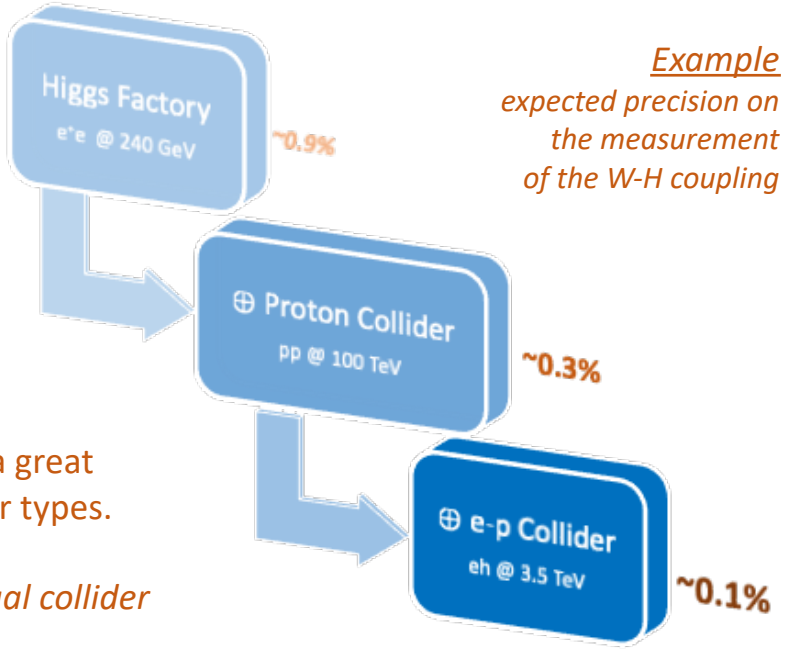


window to new physics



Example
expected precision on the measurement of the W-H coupling

In the search for answers to open questions, we discovered a great complementarity among the science reach of different collider types.

the combined precision is much better than that of each individual collider

We need a coherent program allowing for a variety of future colliders

Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

ep-option with HL-LHC: LHeC

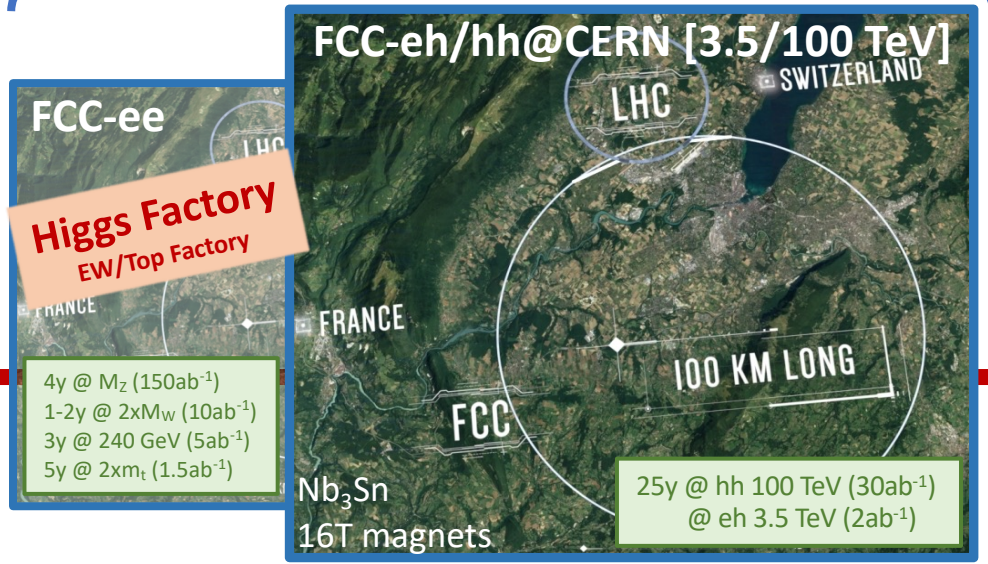
10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



numbers assume 2 IPs for each collider (only one for FCC-eh)

by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

our eyes on the structure of things

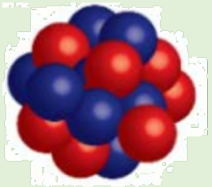
Hadrons & Ions are made up of Quarks & Gluons

colour confinement
coupling ~1

low energy

high energy

asymptotic freedom
coupling <<1



Equation-of-State

Parton Distribution Functions

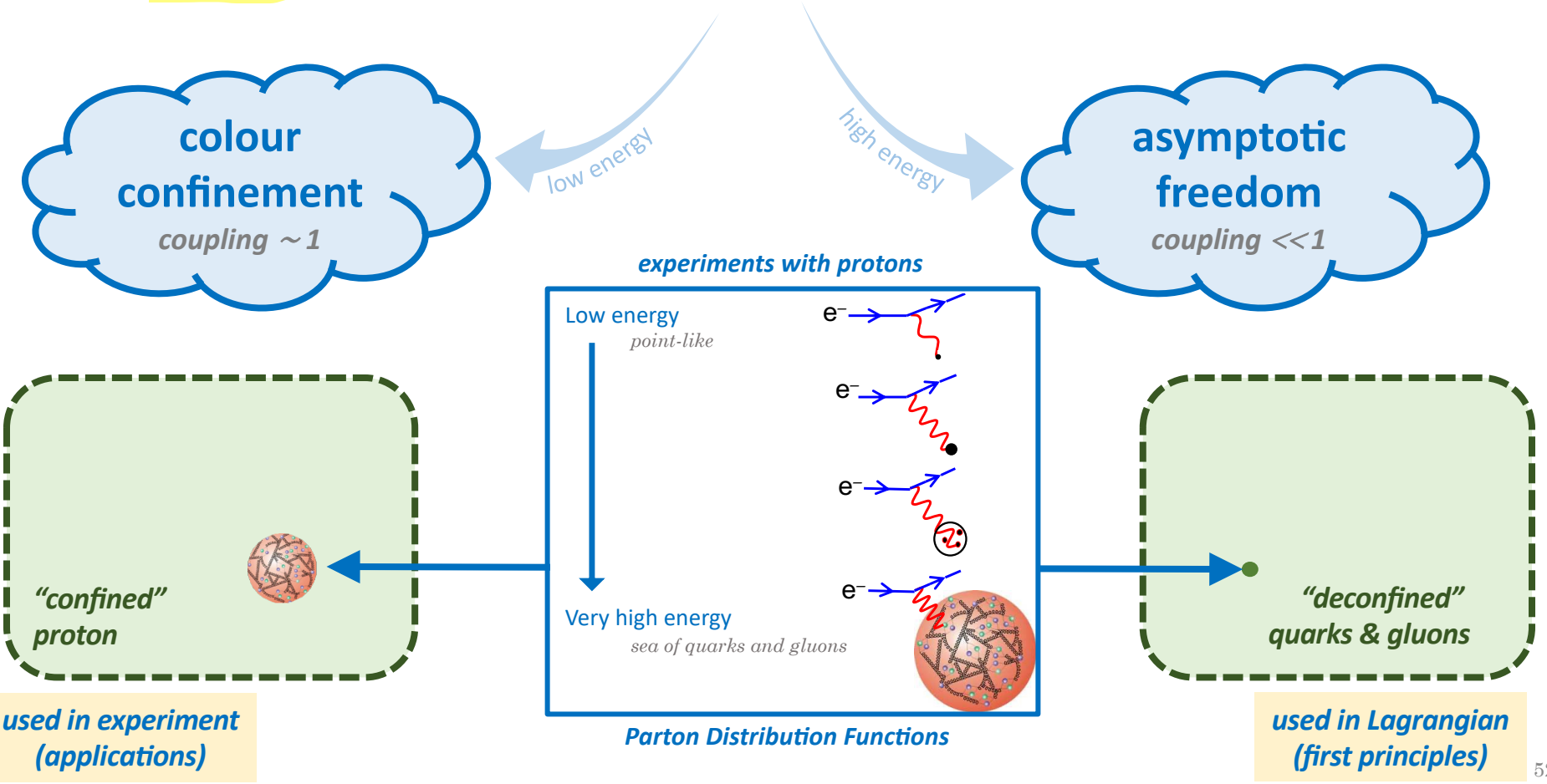
"confined" hadrons & ions

"deconfined" quarks & gluons

used in experiment (applications)

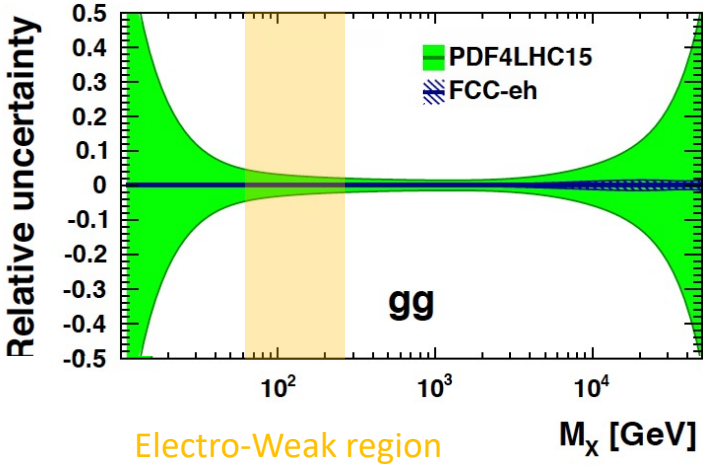
used in Lagrangian (first principles)

Hadrons & Ions are made up of Quarks & Gluons



Empowering the FCC-hh program with the FCC-eh

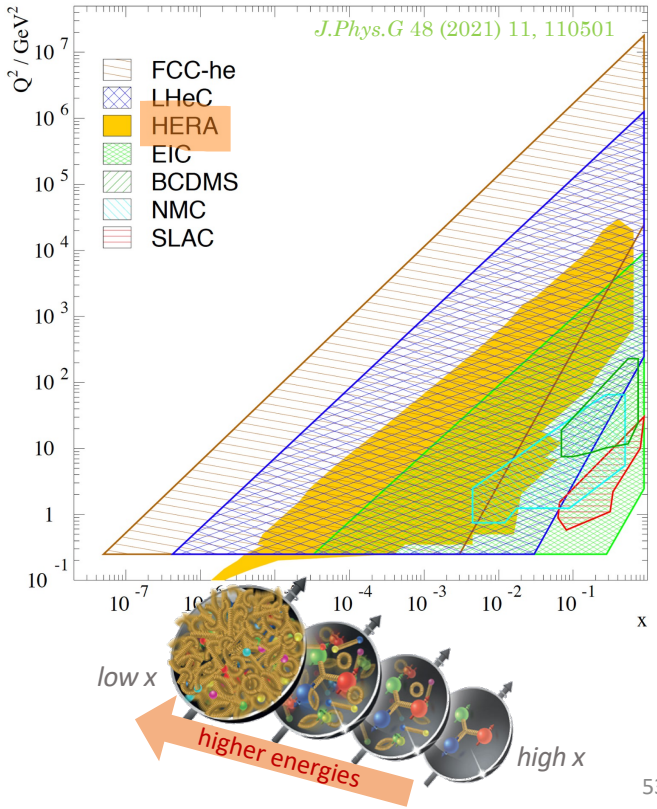
pp @ 100 TeV



Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

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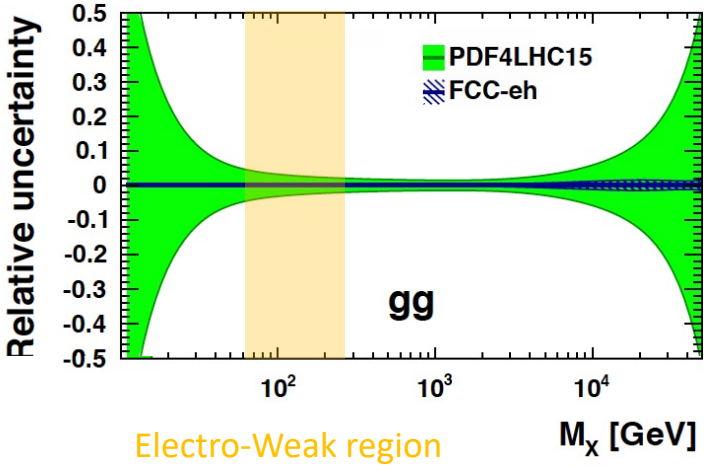


Electro-Weak region

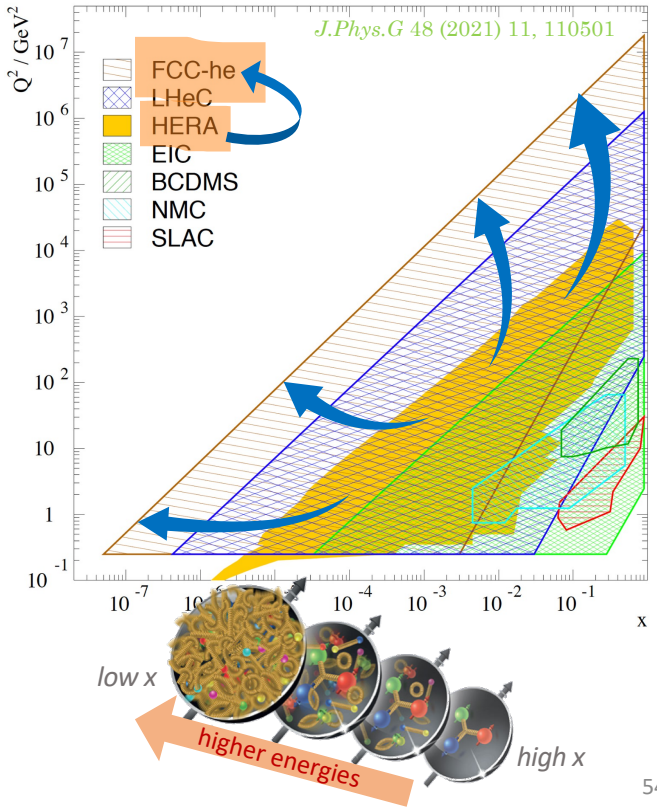
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

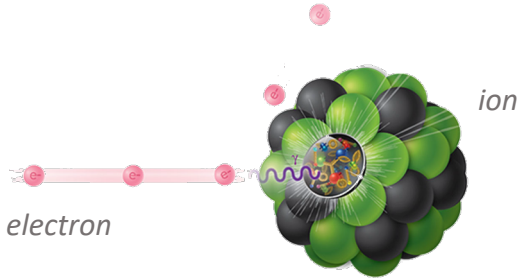
Kinematic range Parton Distribution Functions



Electron-Ion Collider (EIC)

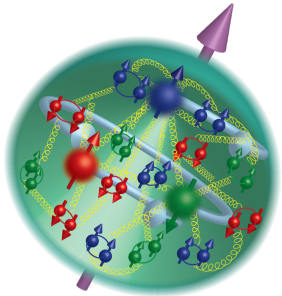
World's 1st polarized e-p/light-ion & 1st eA collider

User Group >1000 members: http://eicug.org

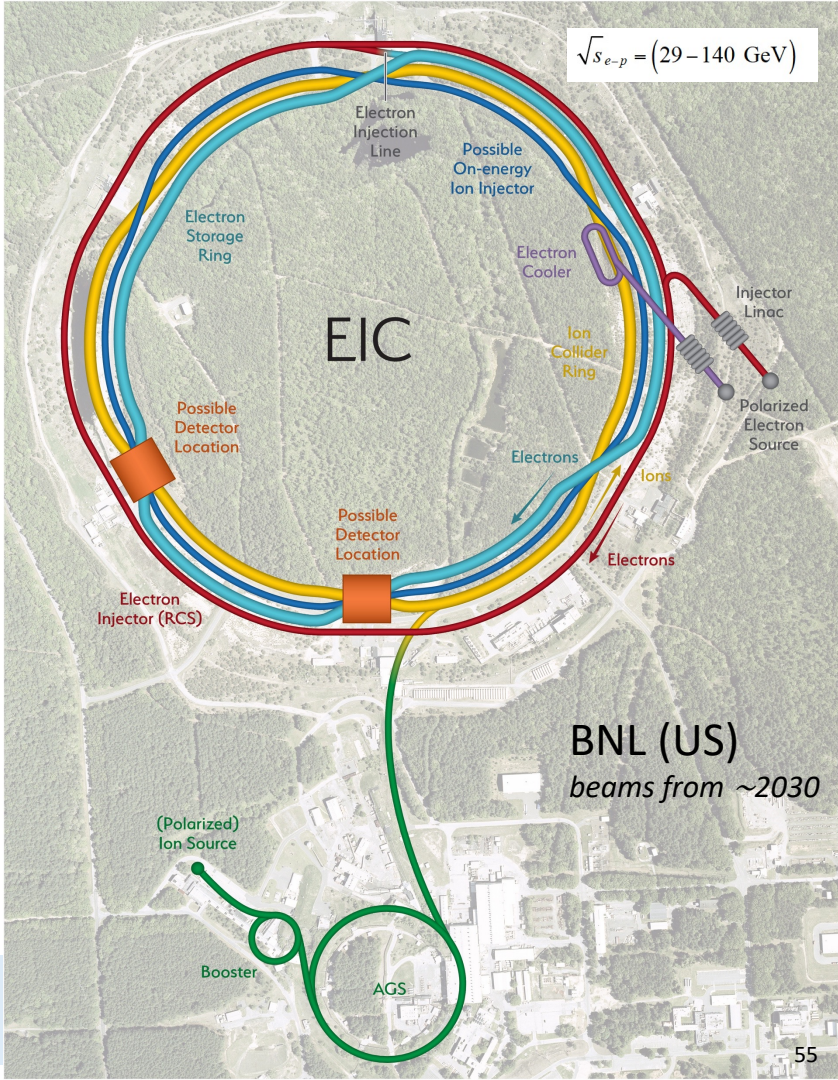


How do the properties of protons and neutrons arise from its constituents?

Towards a 3D partonic image of the proton



Many other running and emerging low-energy scattering facilities are key to understand the structure of hadrons



Hadrons & Ions are made up of Quarks & Gluons

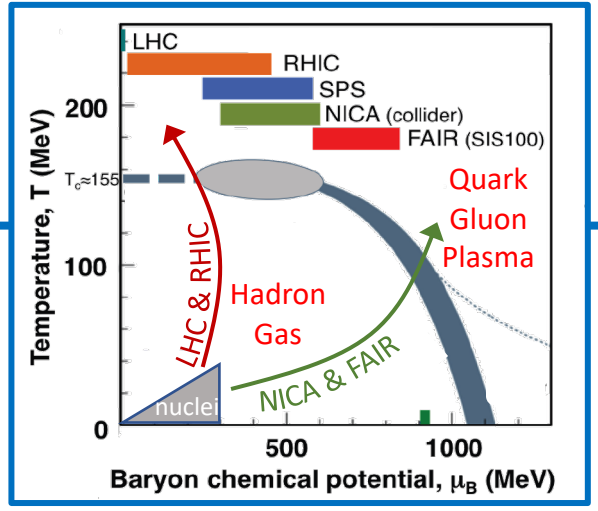
colour confinement
coupling ~1

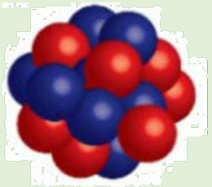
low energy

high energy

asymptotic freedom
coupling <<1

experiments with heavy ions





"confined" ions

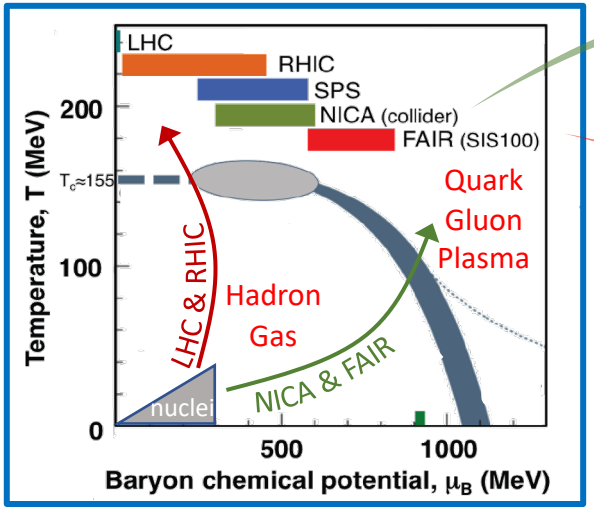
"deconfined" quarks & gluons

used in experiment (applications)

Equation-of-State (from a gas state to a quark-gluon plasma)

used in Lagrangian (first principles)

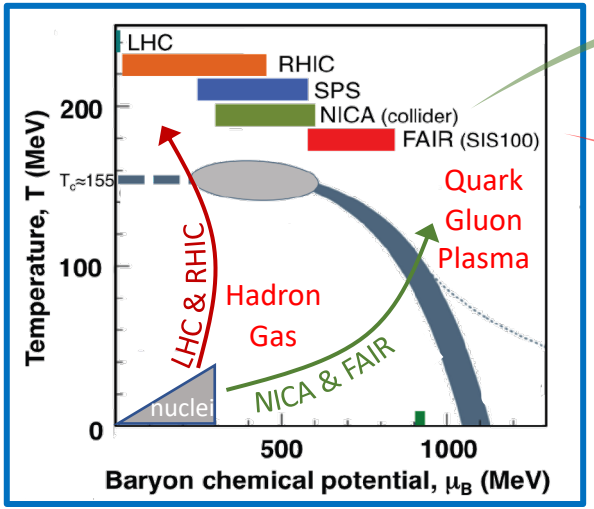
Heavy Ion physics from RHIC & SPS to NICA & FAIR



Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

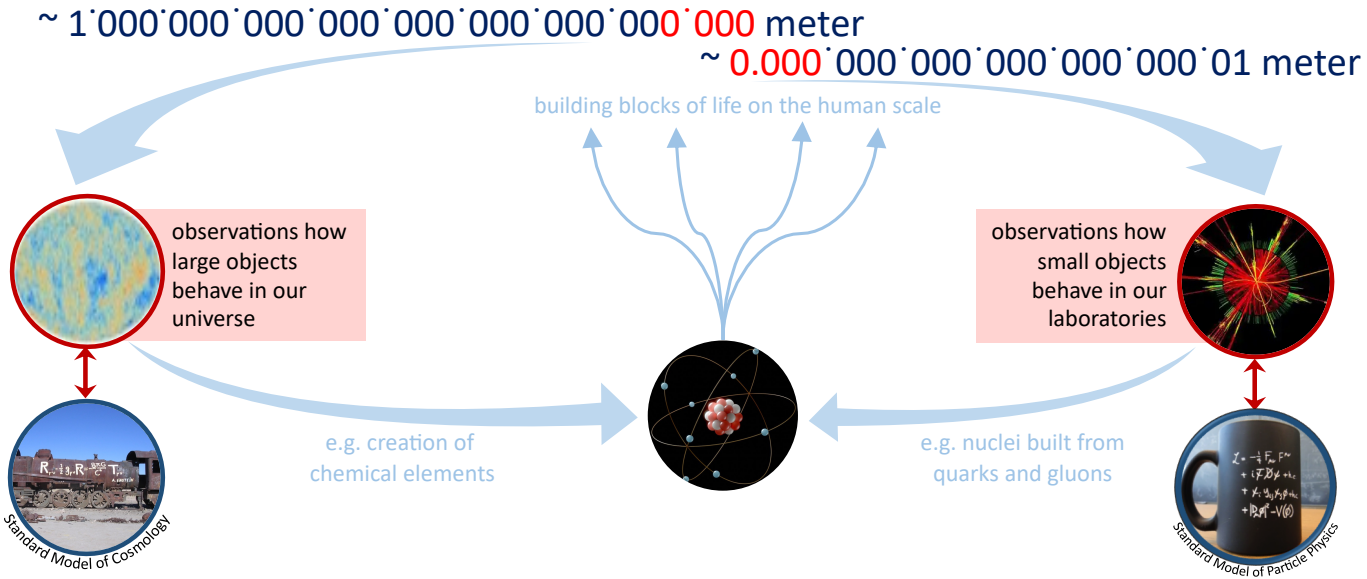
Heavy Ion physics from RHIC & SPS to NICA & FAIR



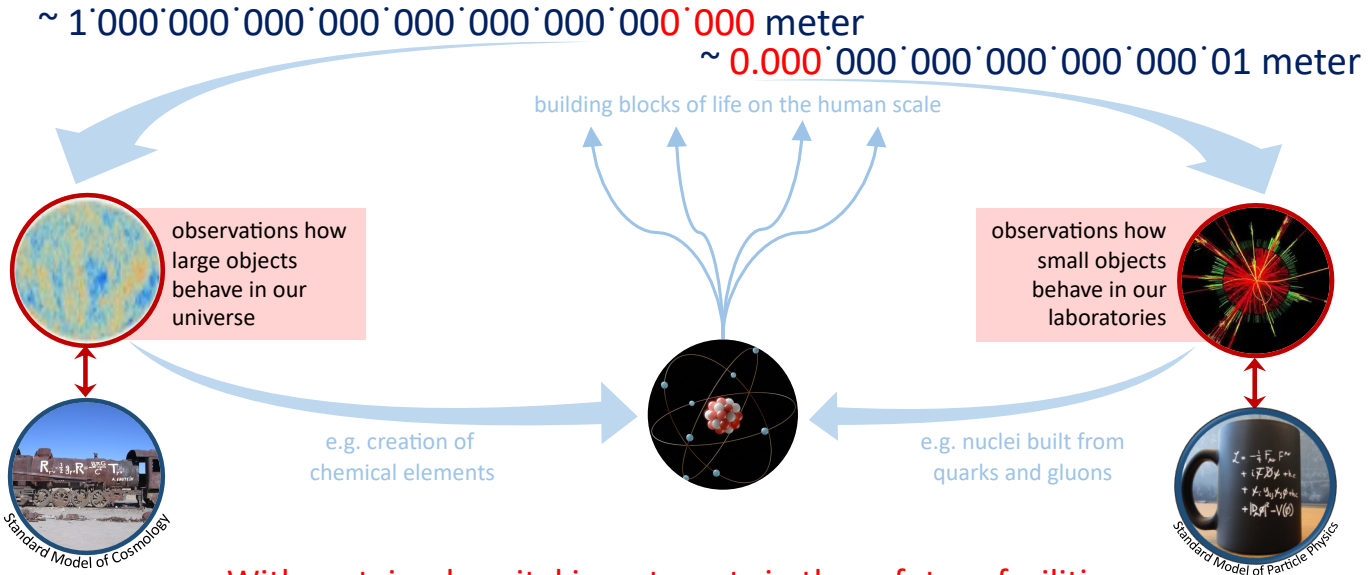
Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

- how matter and complexity emerge
- evolution of our Universe
- origin of the chemical elements


~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter
~ 0.000˙000˙000˙000˙000˙000˙01 meter
building blocks of life on the human scale
observations how large objects behave in our universe
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

Building the future together



With sustained capital investments in these future facilities,
we know that we must discover new physics phenomena to add to our standard models.
… if not, we might have to revisit our theoretical frameworks and/or our basic principles.

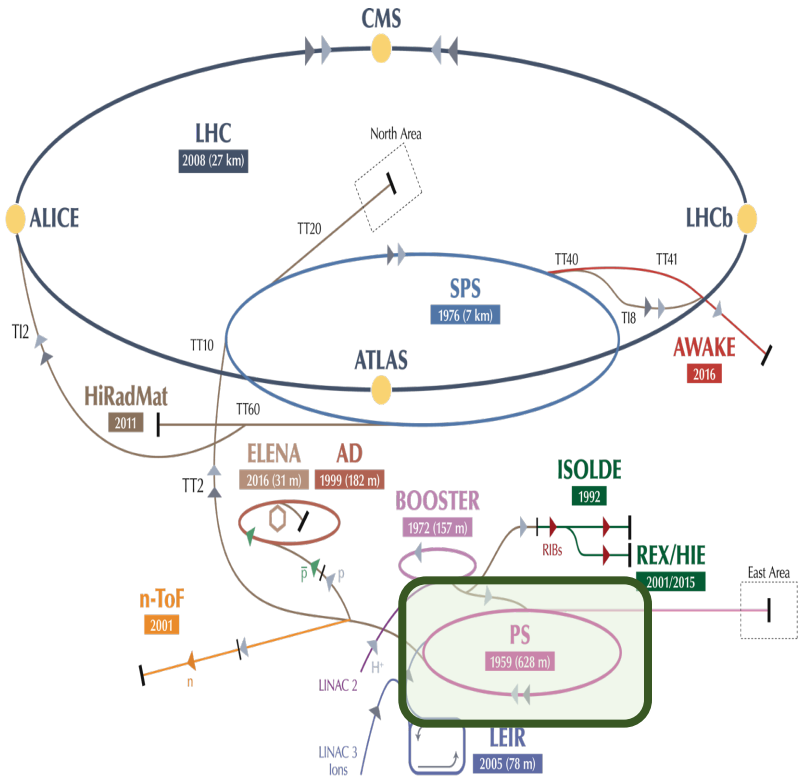
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

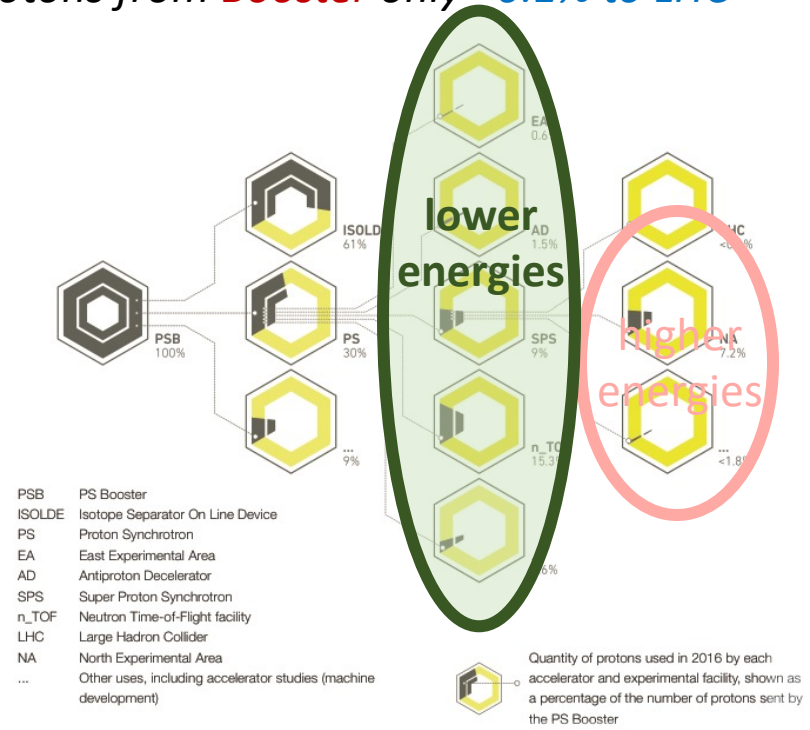
Thank you for your attention!

Jorgen.DHondt@vub.be

While running the (HL-)LHC: Accelerated Beams at CERN

The CERN accelerator complex and the LHC – protons from Booster only <0.1% to LHC

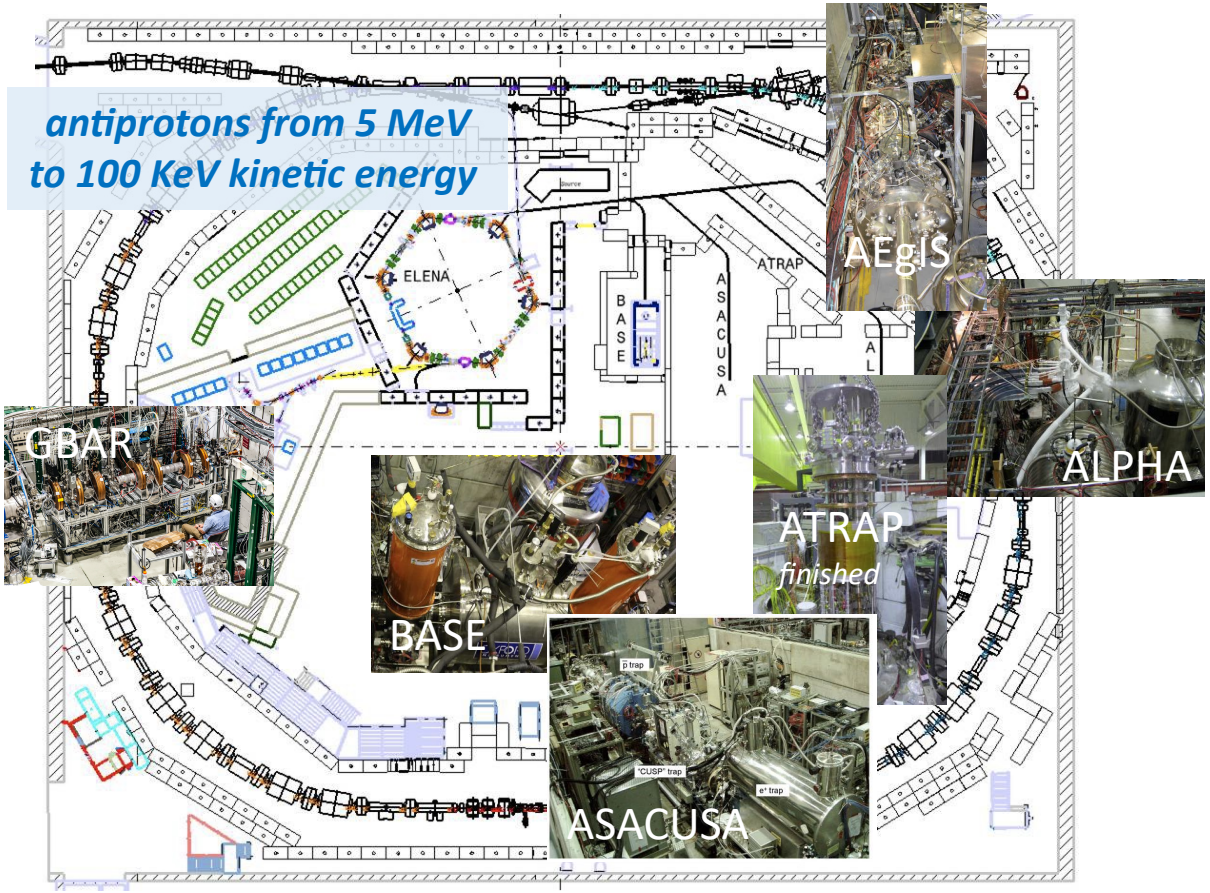




PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

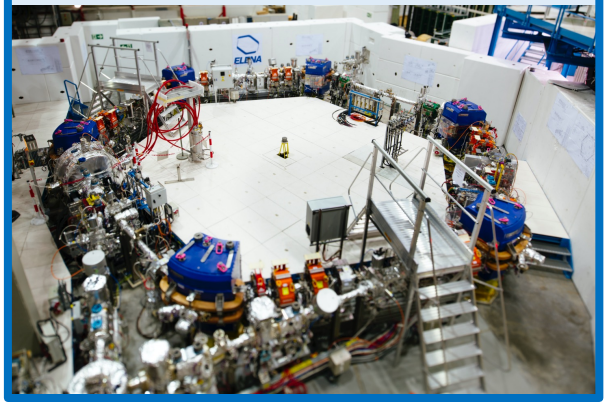
Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

Precision physics with antimatter @ CERN



Devoted to antiproton and antihydrogen properties

ELENA secures antimatter physics for the next decade

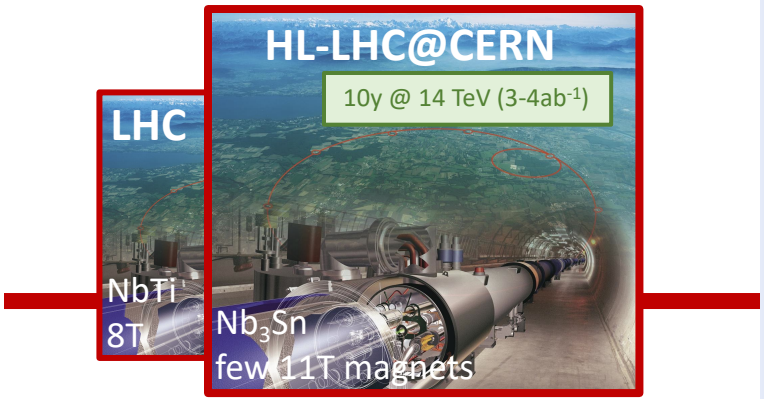


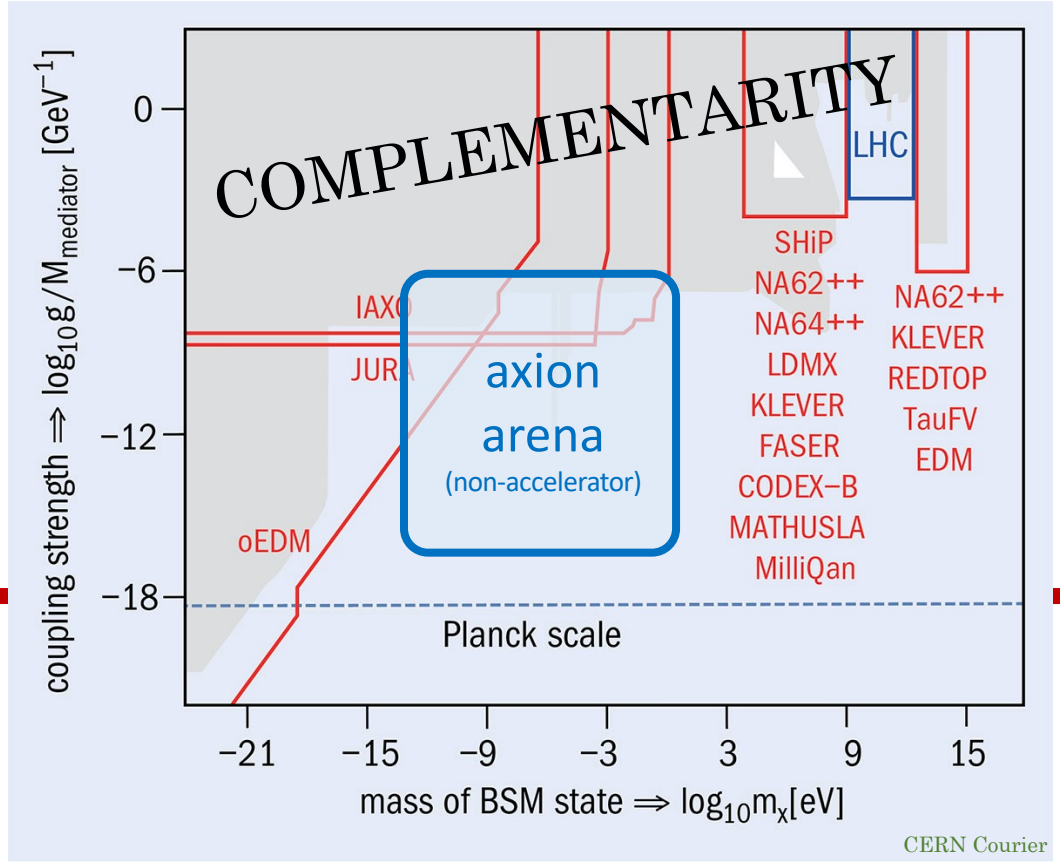
AEgIS – Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy
ALPHA – Antihydrogen Laser PHysics Apparatus
ASACUSA – Atomic Spectroscopy And Collisions Using Slow Antiprotons
ATRAP – Antihydrogen TRAP
GBAR – Gravitational Behaviour of Antihydrogen at Rest
BASE – Baryon Antibaryon Symmetry Experiment

More complementarity beyond particle accelerators

Current flagship (27km)

impressive programme up to 2040

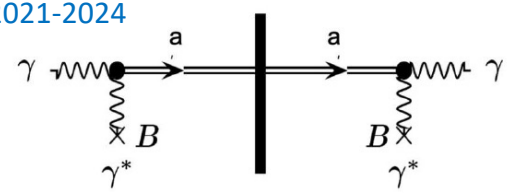




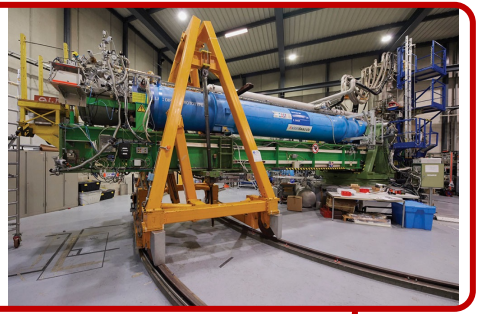
"portal" representation of physics potential to demonstrate complementarity

Axion Physics with “old” and new magnets in Europe

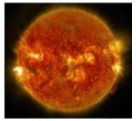
Light-shine-through-Wall
ALPS-II @ DESY
2021-2024

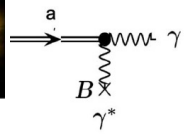


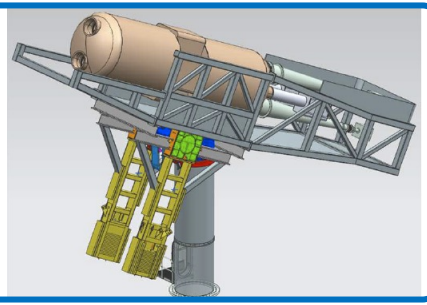
CAST @ CERN
(helioscope)
running



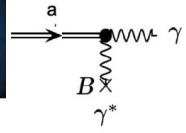
BabyIAXO & IAXO @ DESY
looking at the Sun, helioscope
2024-2030+

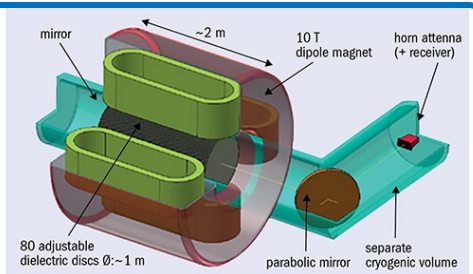


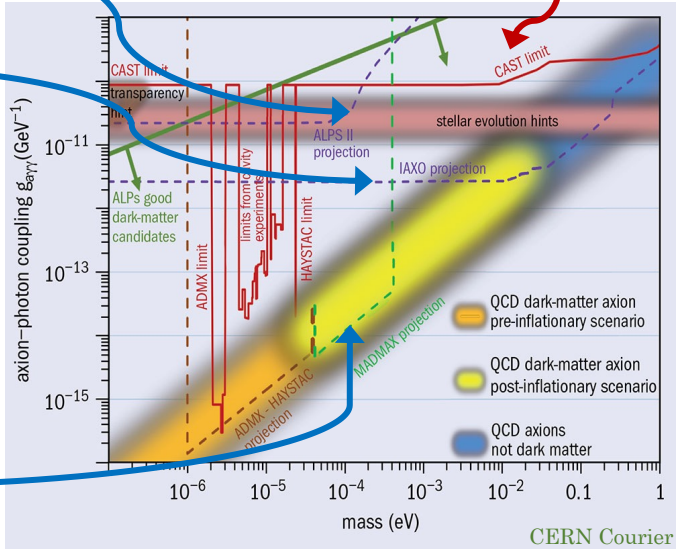




MADMAX @ DESY
looking at the galactic halo, haloscope
2026-2030+







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