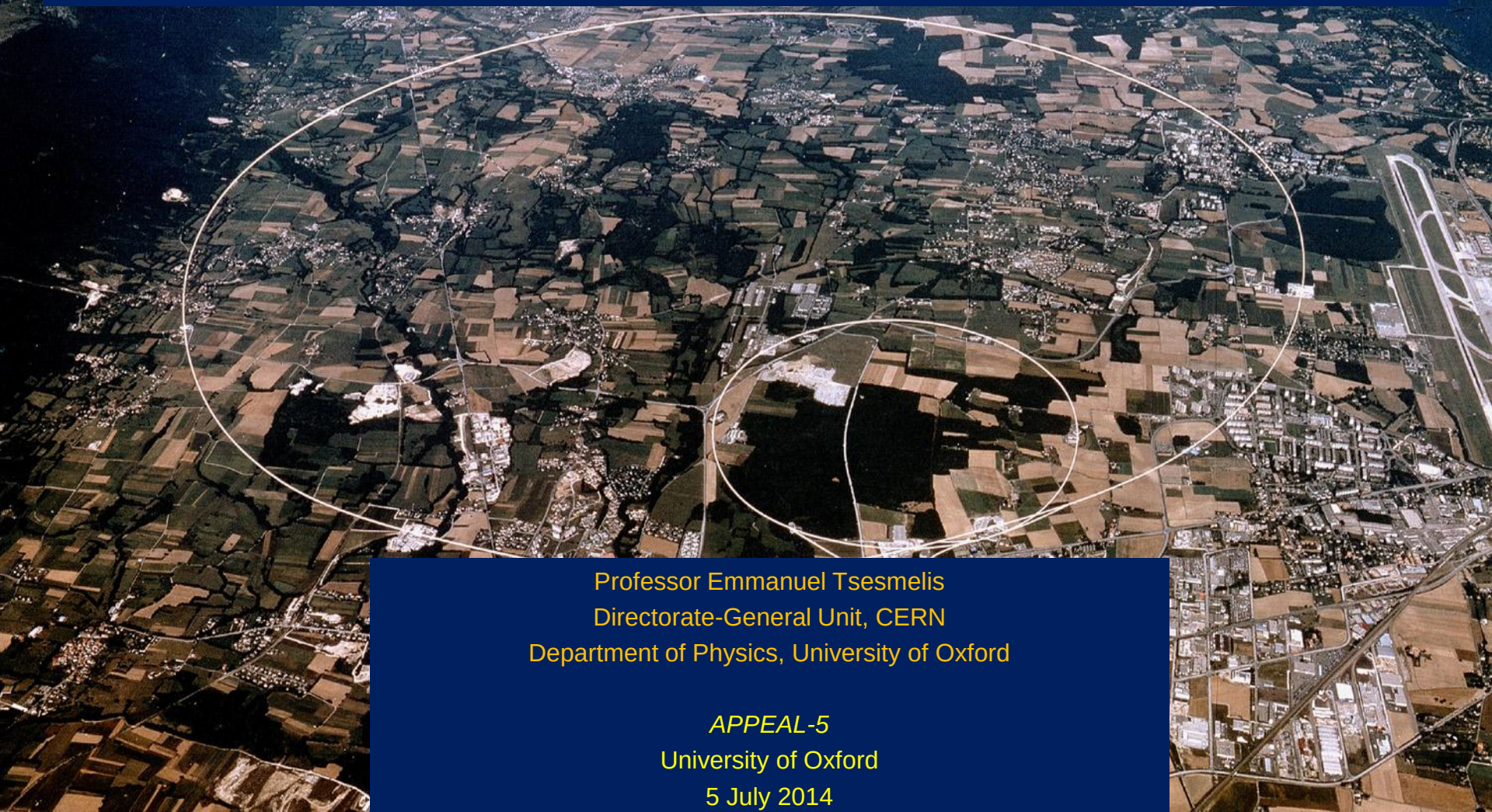
Future Accelerators at the High Energy Frontier



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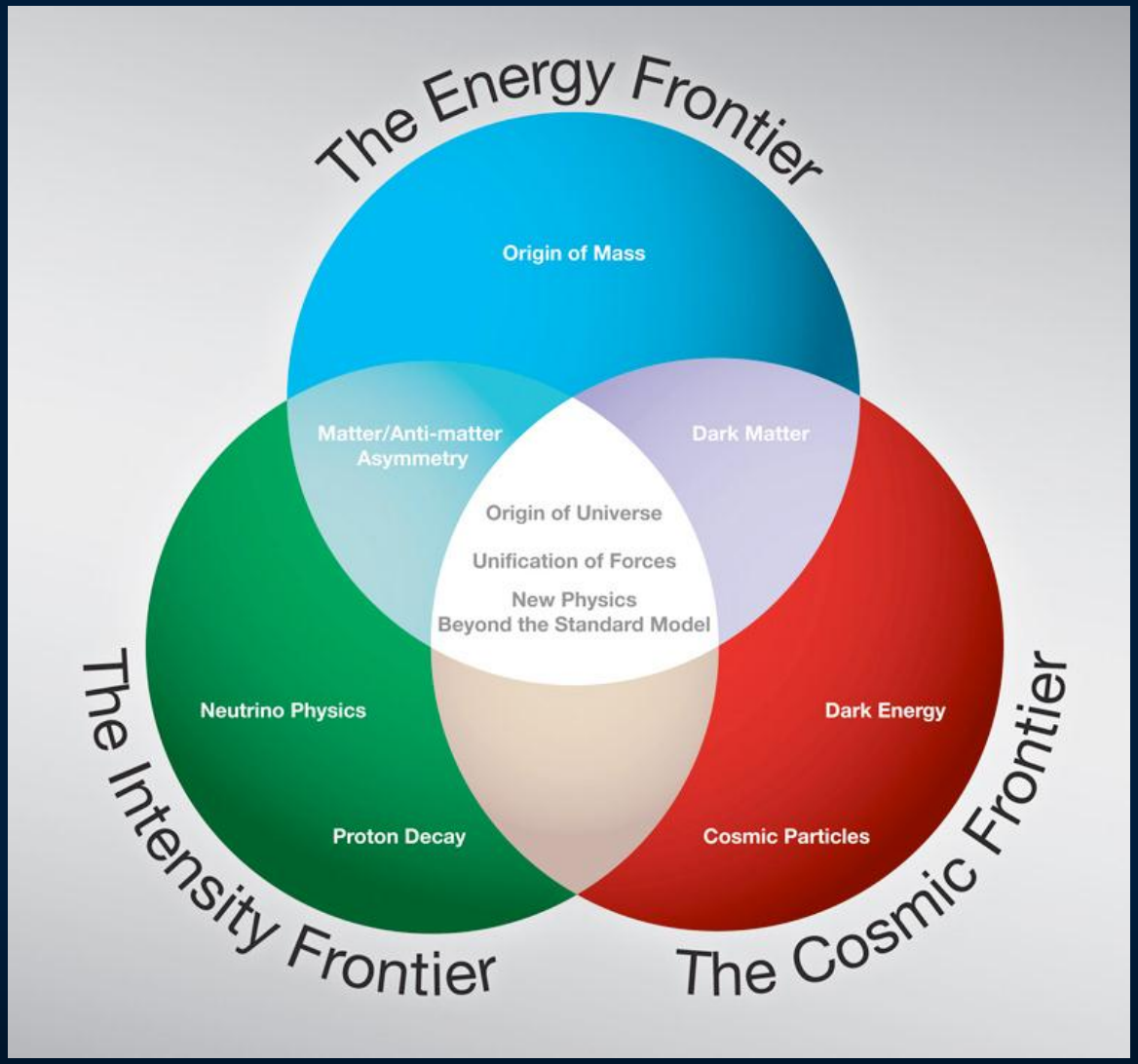
Department of Physics, University of Oxford

APPEAL-5
University of Oxford
5 July 2014

INTRODUCTION

The Three Frontiers



Questions in Particle Physics

- What is the origin of particle masses?
- Why are there so many types of matter particles?
- What is the cause of matter-antimatter asymmetry?
- What are the properties of the primordial plasma?
- What is the nature of the invisible dark matter?
- Can all fundamental particles be unified?
- Is there a quantum theory of gravity?

The present and future accelerator-based experimental programmes will address all these questions and may well provide definite answers.

Introduction - Accelerators

- Historically, HEP has depended on advances in accelerator design to make scientific progress
  - linacs → cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- Accelerators enable the study of particle physics phenomena under controlled conditions
- Costs & time span of today's accelerator projects are high
  - International co-operation and collaboration are obligatory

Colliders at the High-energy Frontier

- HEP typically uses Colliders
  - Counter-propagating beams that collide at one or more IPs
- Today's colliders typically store various types of particles
  - Hadrons (protons, ions)
    - Tevatron (p, anti-p), RHIC (p, ions), LHC (p, ions)
  - Leptons (electrons)
    - CESR-c, PEP-II, KEK-B

Collider Parameters

- Particle accelerators are designed to deliver two parameters to the HEP user
  - Beam energy (and collision centre-of-mass energy)
  - Luminosity
    - Measure of collision rate per unit area
    - Event rate for a given event probability ("cross-section") given by:

$$R = \mathcal{L}\sigma$$

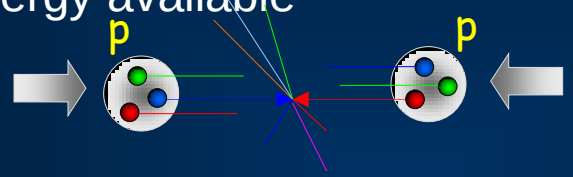
For a Collider luminosity is given by

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- → Require intense beams and small beam sizes at IP

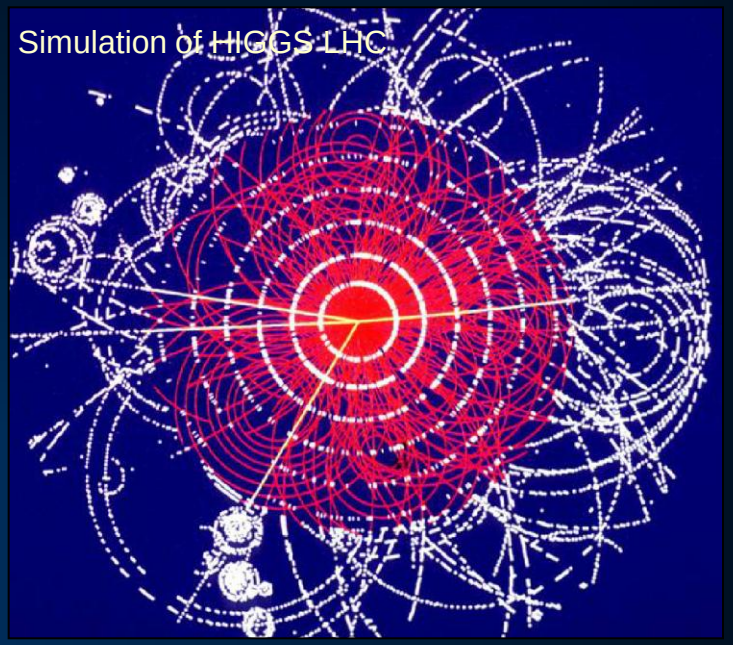
Collider Characteristics

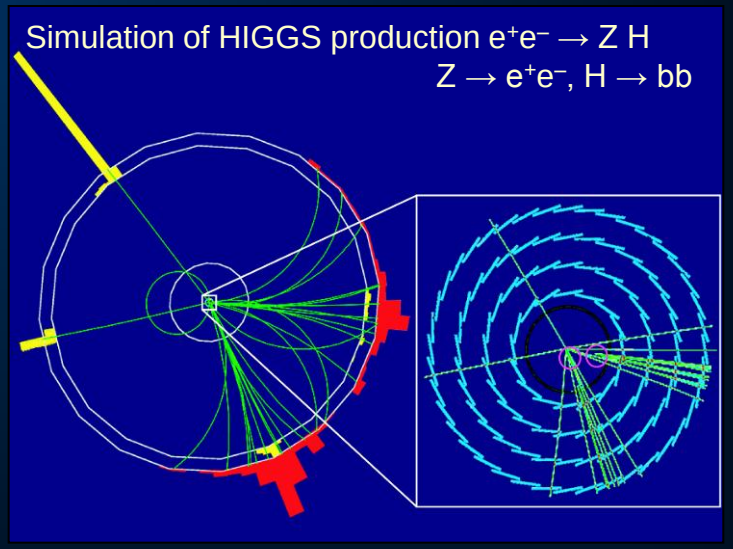
- Hadron collider at the frontier of physics
  - huge QCD background
  - not all nucleon energy available in collision



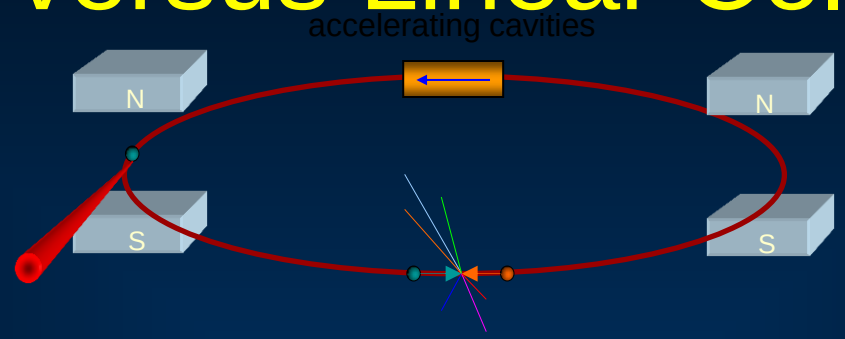
- Lepton collider for precision physics
  - well defined initial energy for reaction
  - Colliding point like particles

- Candidate next machine after LHC
  - e^+e^- collider
  - energy determined by LHC discoveries
  - study in detail the properties of the new physics that the LHC finds





Circular versus Linear Collider

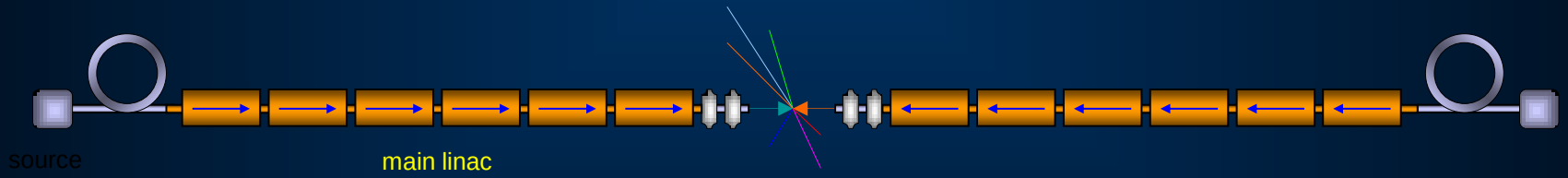


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

Accelerator Characteristics

- Hadron Colliders
  - Protons are composite particles
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale
      - Desired high energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Anti-protons difficult to produce if beam is lost
    - Use proton-proton collisions instead
    - Demand for ever-higher luminosity has led LHC to choose proton-proton collisions
    - Many bunches (high bunch frequency)
    - Two separate rings that intersect at select locations

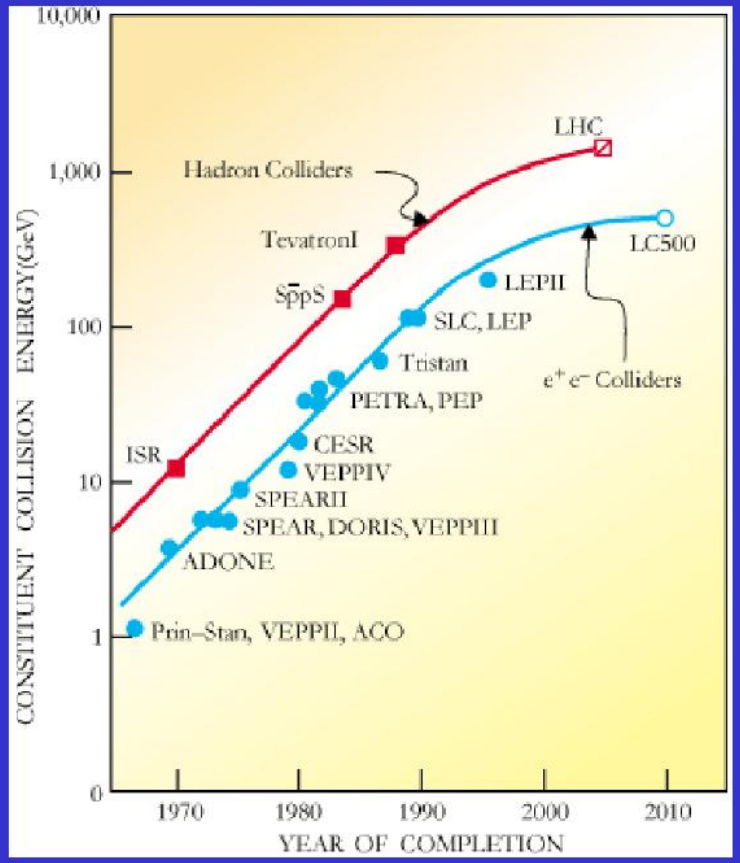
Accelerator Characteristics

- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}] I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

    - For a 1 TeV CM energy Collider in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
      - Would need to replenish radiated power with RF
      - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider (ILC,CLIC)

Colliders – Energy vs. Time



M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

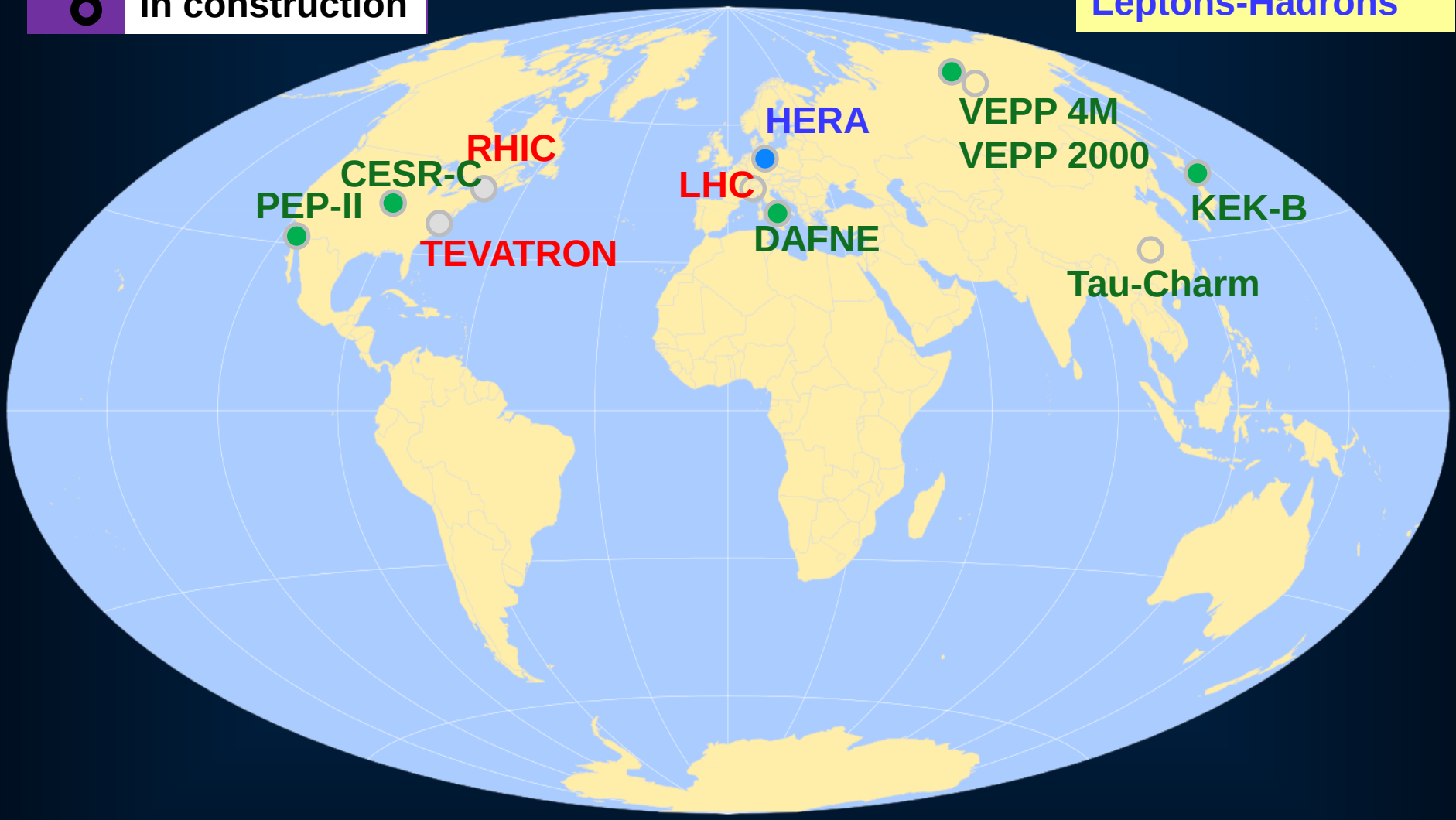
Not enough: Project cost increased by factor 200!

New technology needed…

Colliders - 2006

In operation
In construction

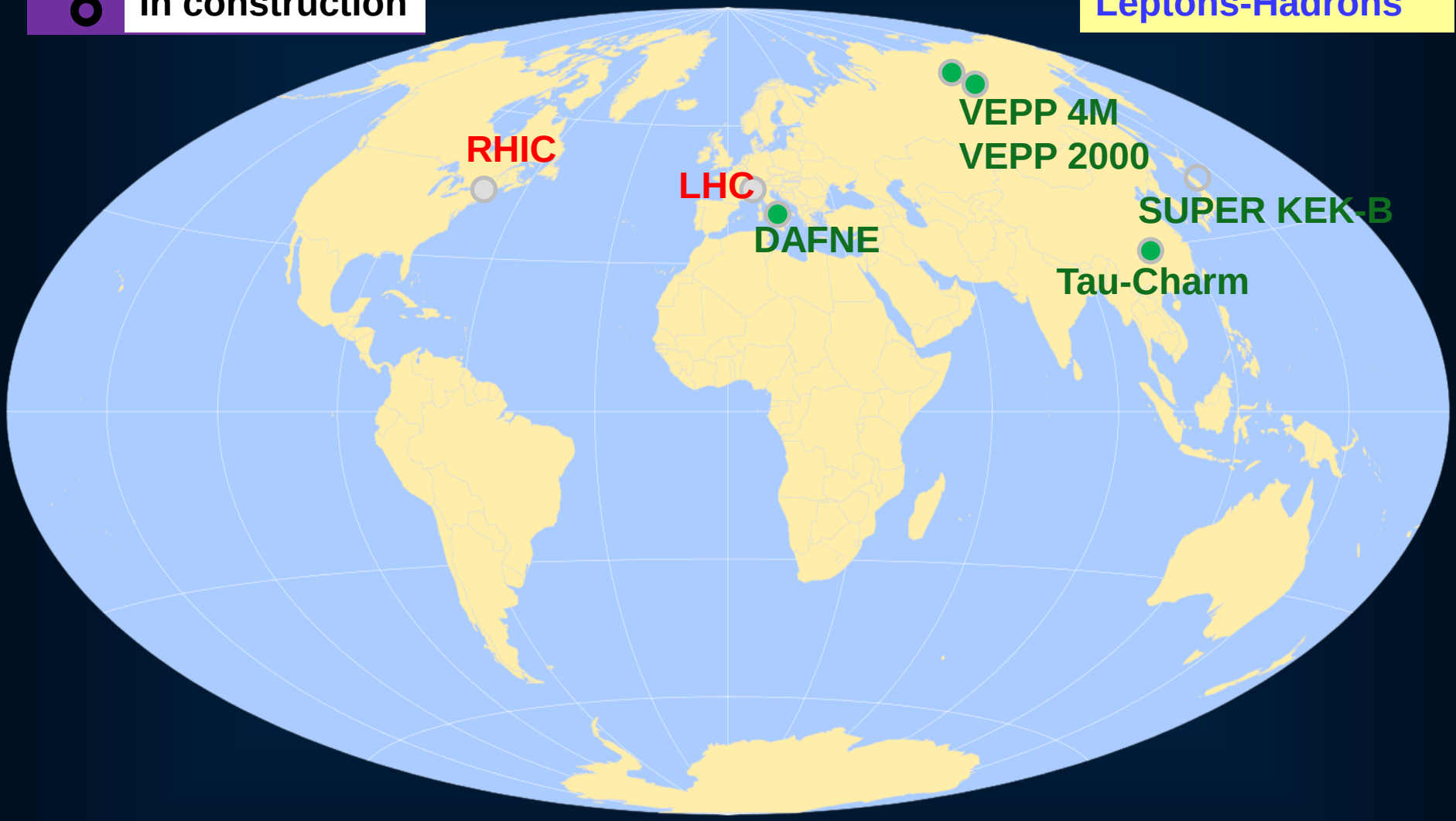
Hadrons
Leptons
Leptons-Hadrons



Colliders - 2012

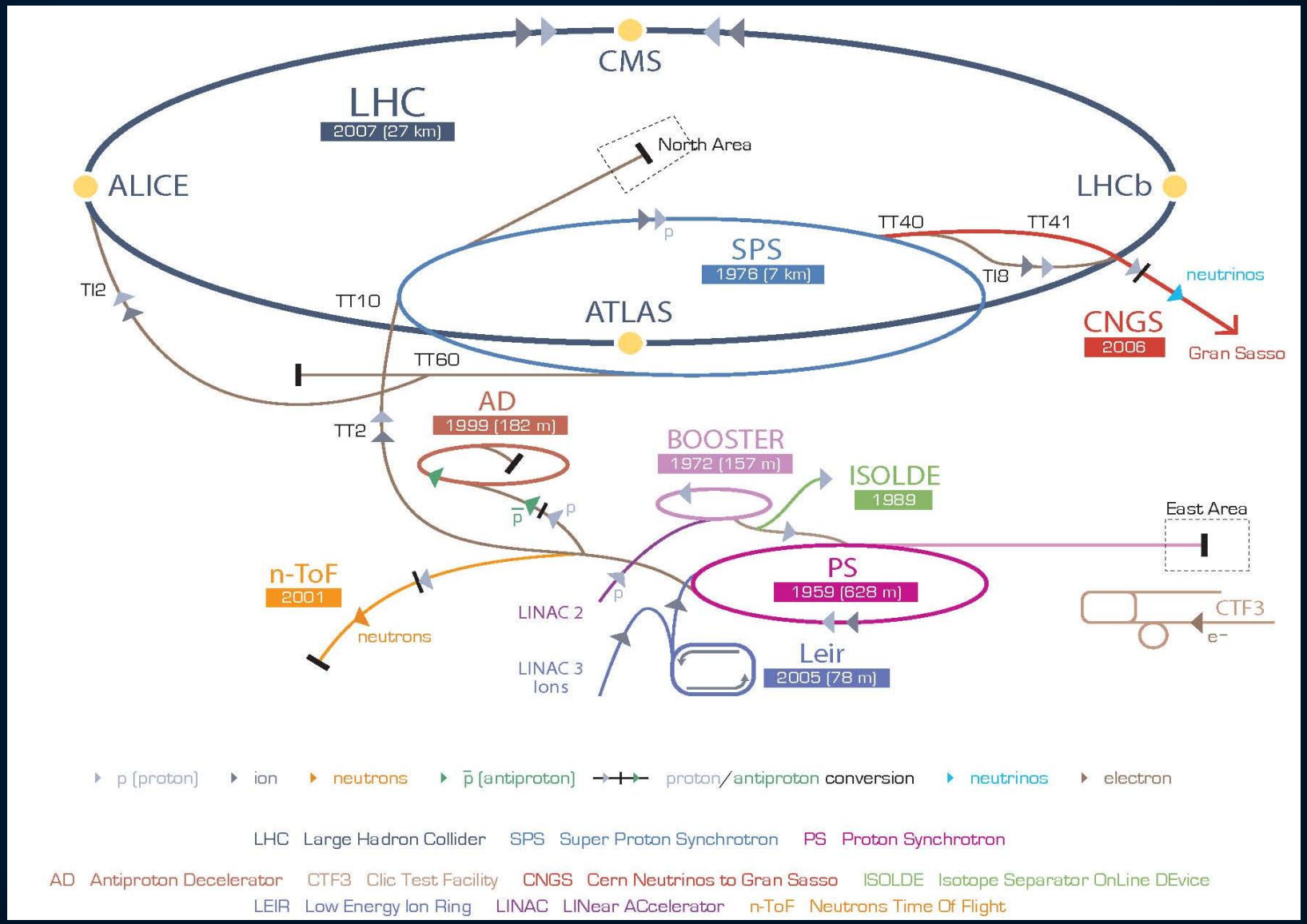
In operation
In construction

Hadrons
Leptons
Leptons-Hadrons

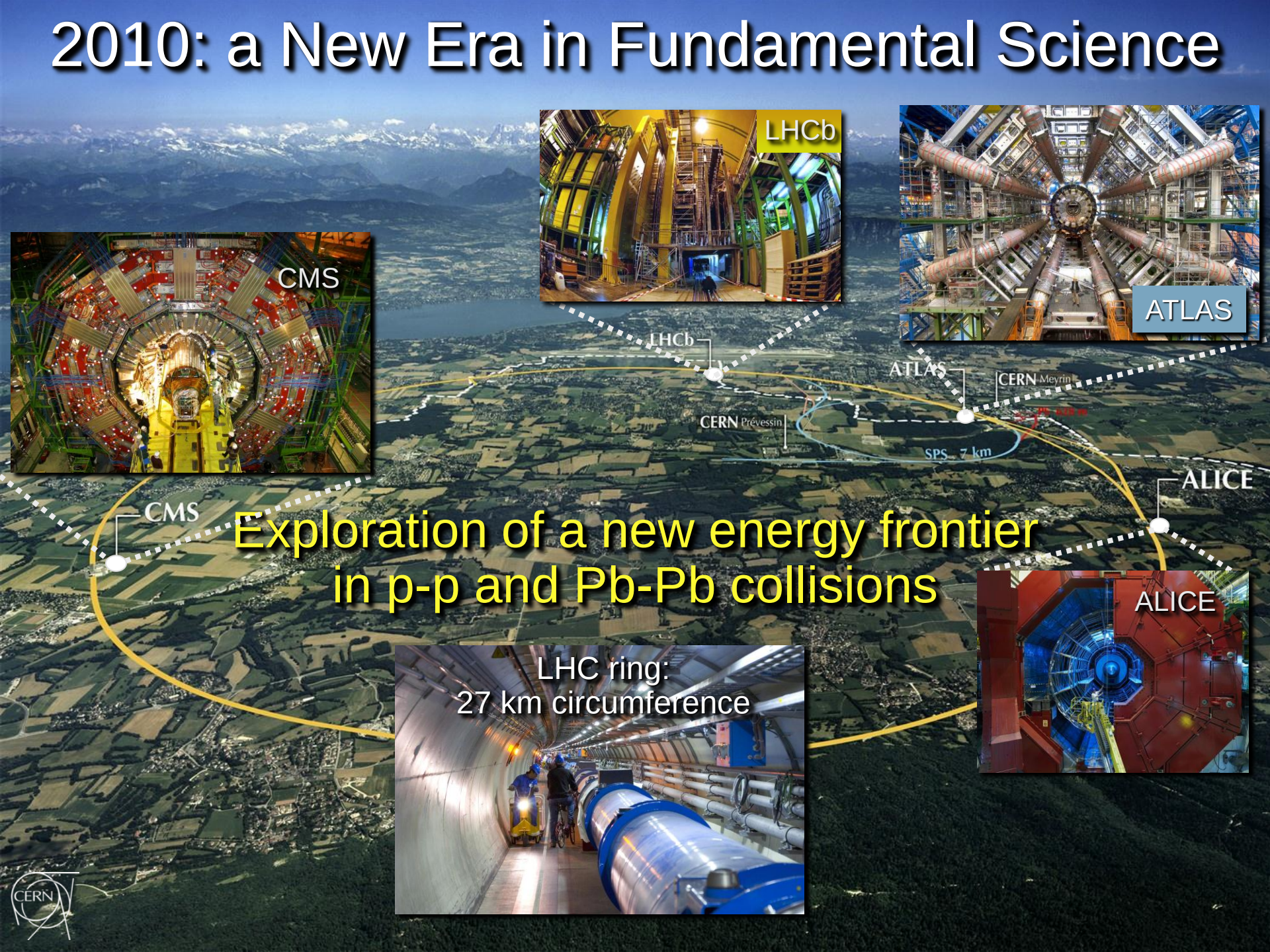


HADRON COLLIDERS

CERN Accelerator Complex

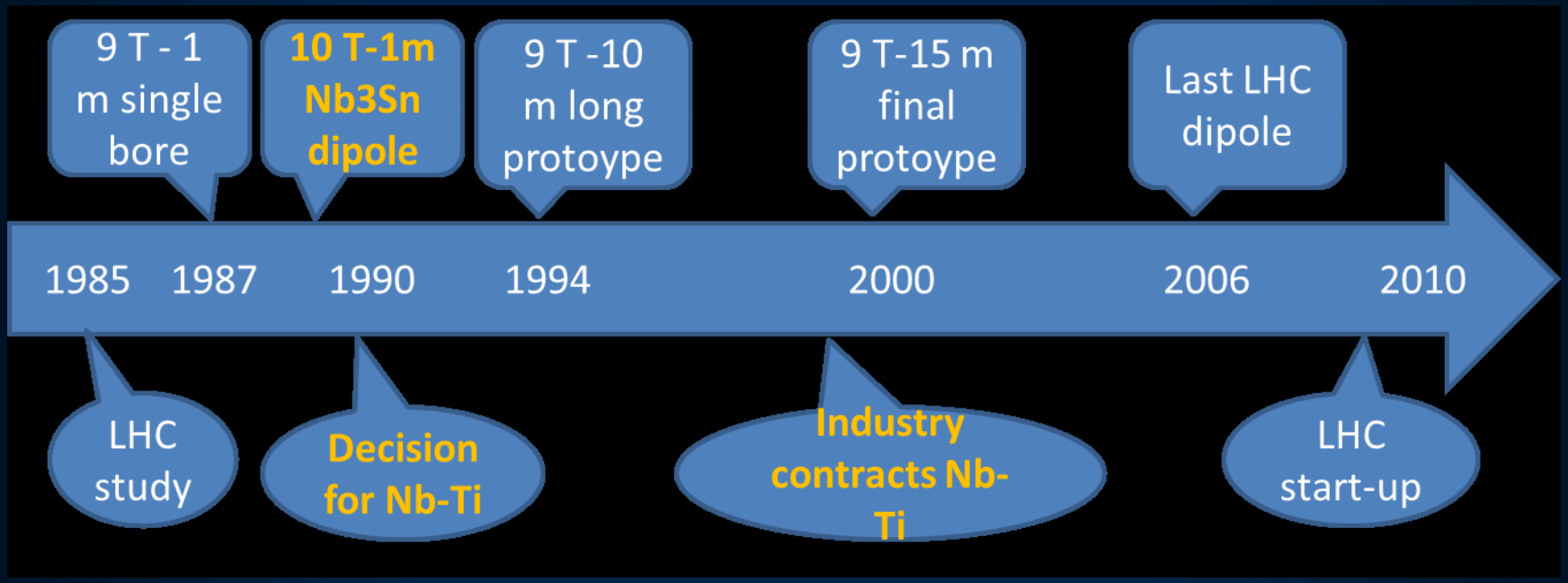


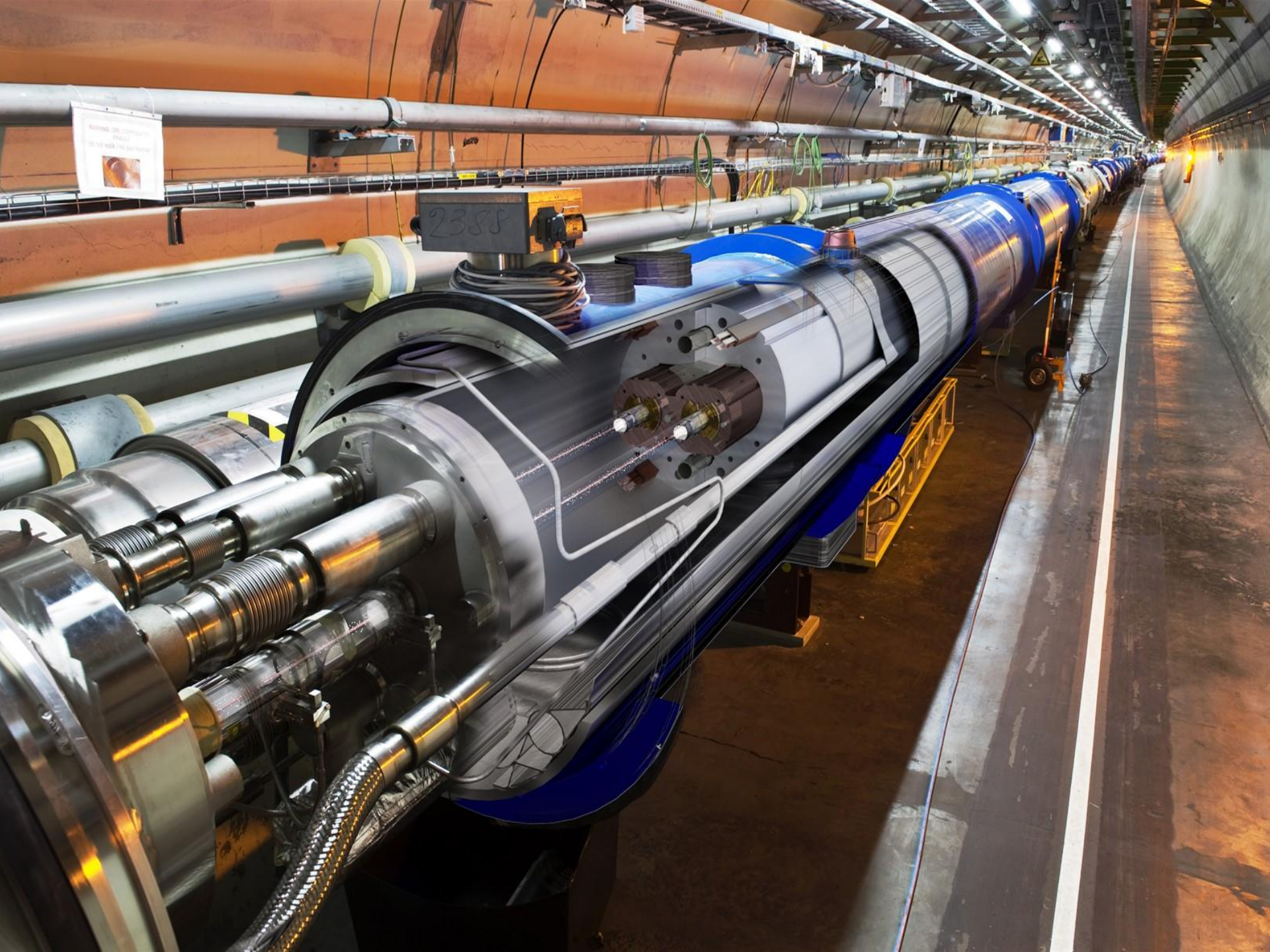
2010: a New Era in Fundamental Science



Exploration of a new energy frontier
in p-p and Pb-Pb collisions

LHC – 25-year Project

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The LHC Arcs

Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Studying the Higgs boson…

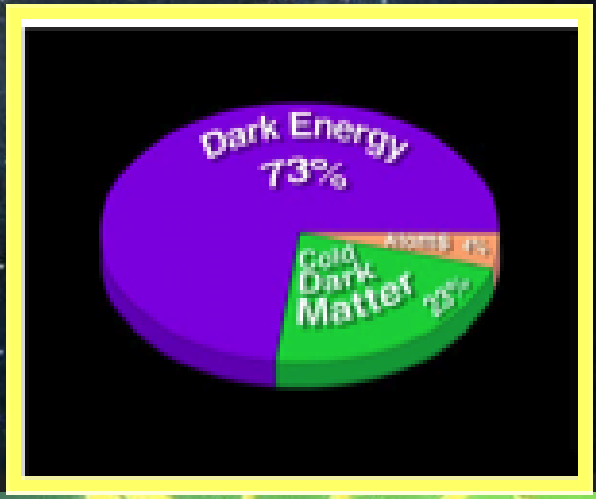
…in the years to come.

Dark Matter in the Universe

Astronomers say
that most of the matter in the Universe is invisible

‘Supersymmetric’ particles ?

We are looking for them with the LHC



The Predictable Future: LHC Time-line

2009 — Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to few 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14 — LHC shut-down to prepare machine for design energy and nominal luminosity

Run 2: Ramp up luminosity to no[illegible] to 100 fb^{-1}) and centre-of-mass energy ([illegible]

2018 — Injector and LHC Phas[illegible] ate luminosity

Run 3: [illegible] x nominal, reaching ~100 fb^{-1} / year ac[illegible]

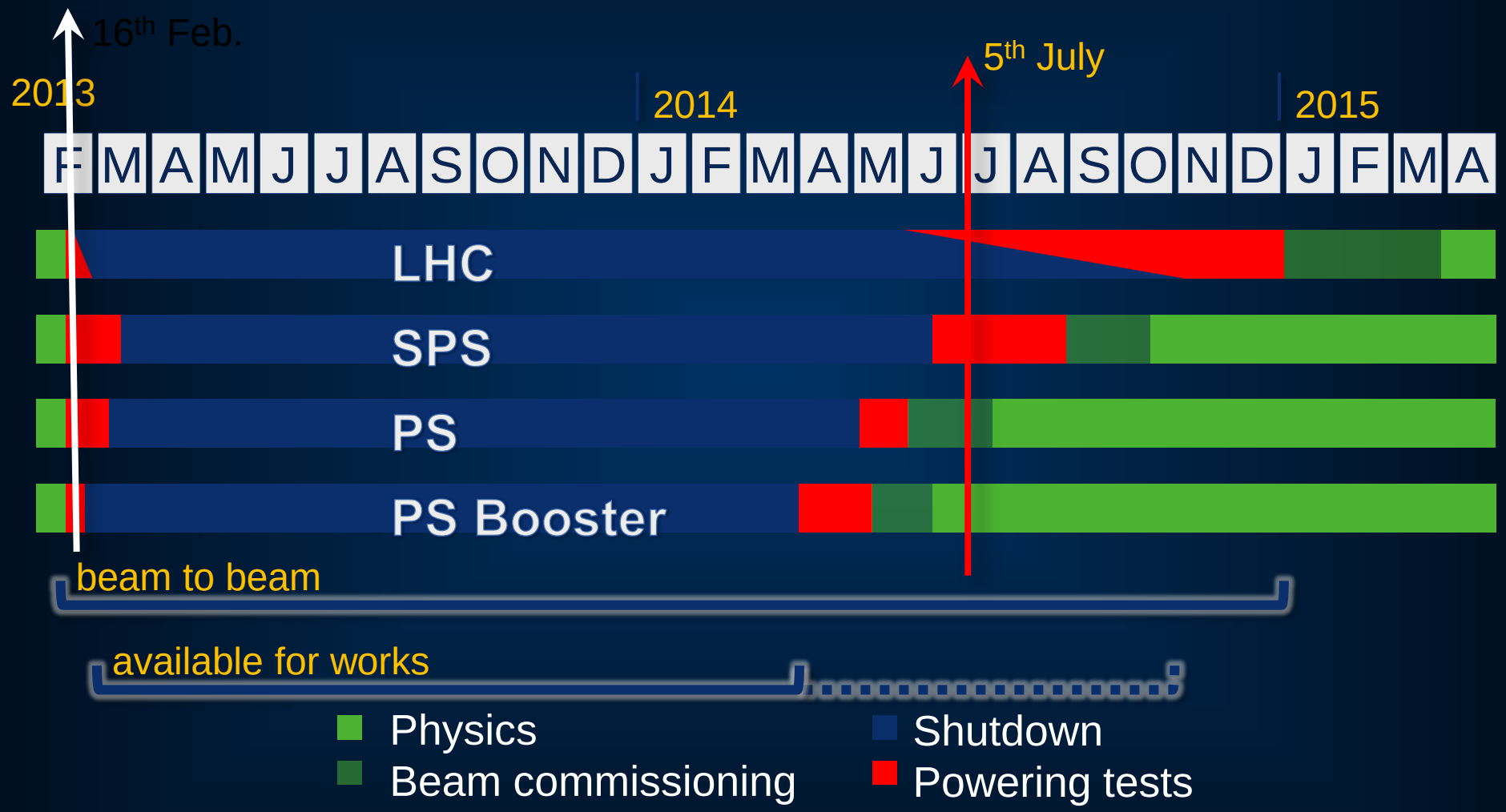
~2023 — Phas[illegible] inosity LHC. New focussing magnets and CRAB [illegible] for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

>2030 — HE-LHC?

Study of the properties of the Higgs Boson
and
Physics beyond the Standard Model

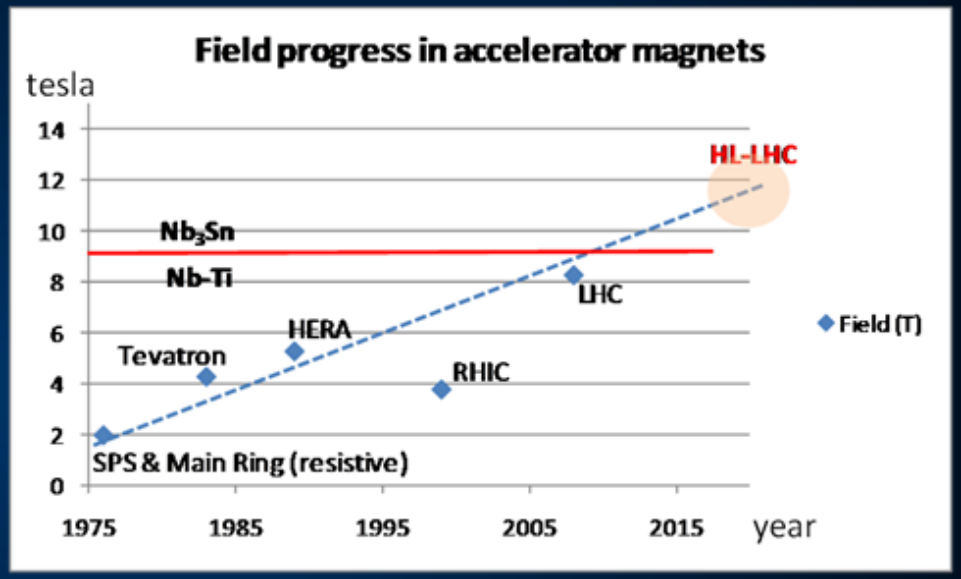
LS1 from Feb. 2013 to Dec. 2014



LHC Schedule Beyond LS1

Beam Focusing
High-Field SC Magnets

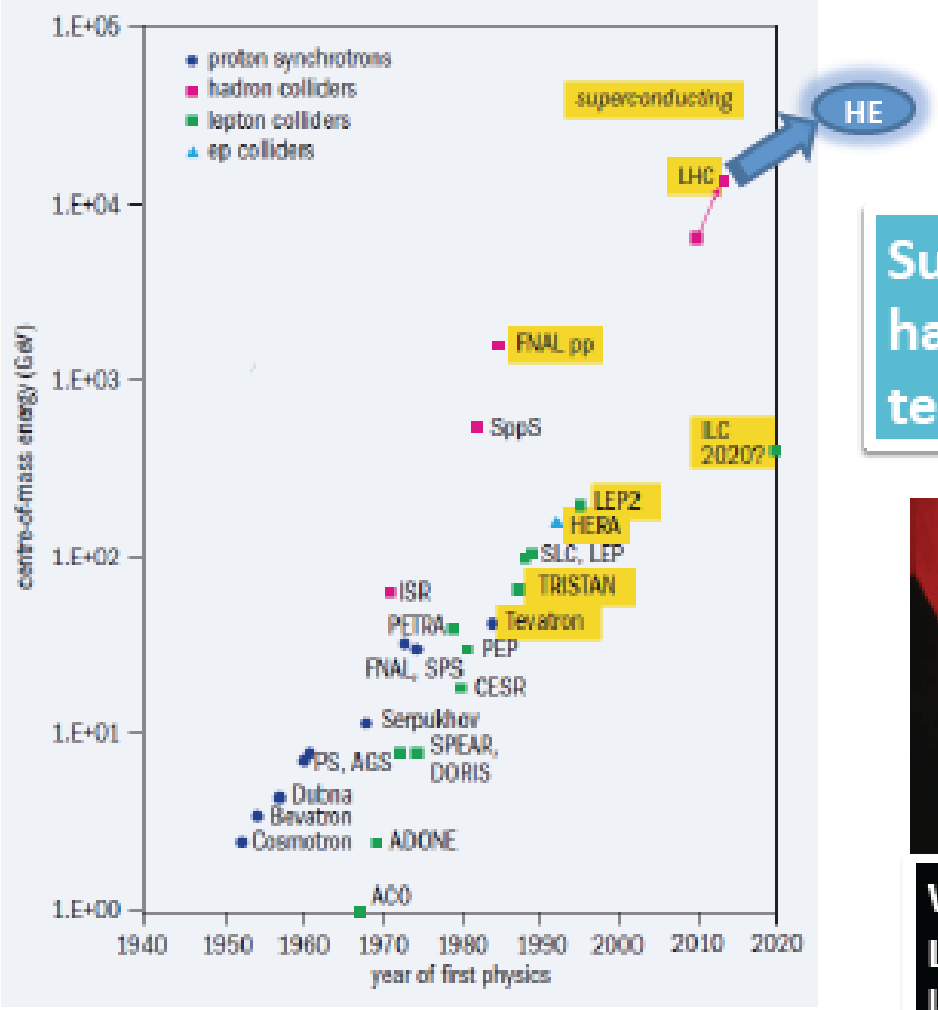
- 13 T, 150 mm aperture quadrupoles for the inner triplet:
  - LHC: 8 T, 70 mm.
- More focus strength, β* as low as 15 cm (55 cm in LHC).
  - In same scheme even β* down to 7.5 cm considered.
- Dipole separators capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)



Goal:

Enable focusing of the beams to β^*=0.15 m in IP1 and IP5.

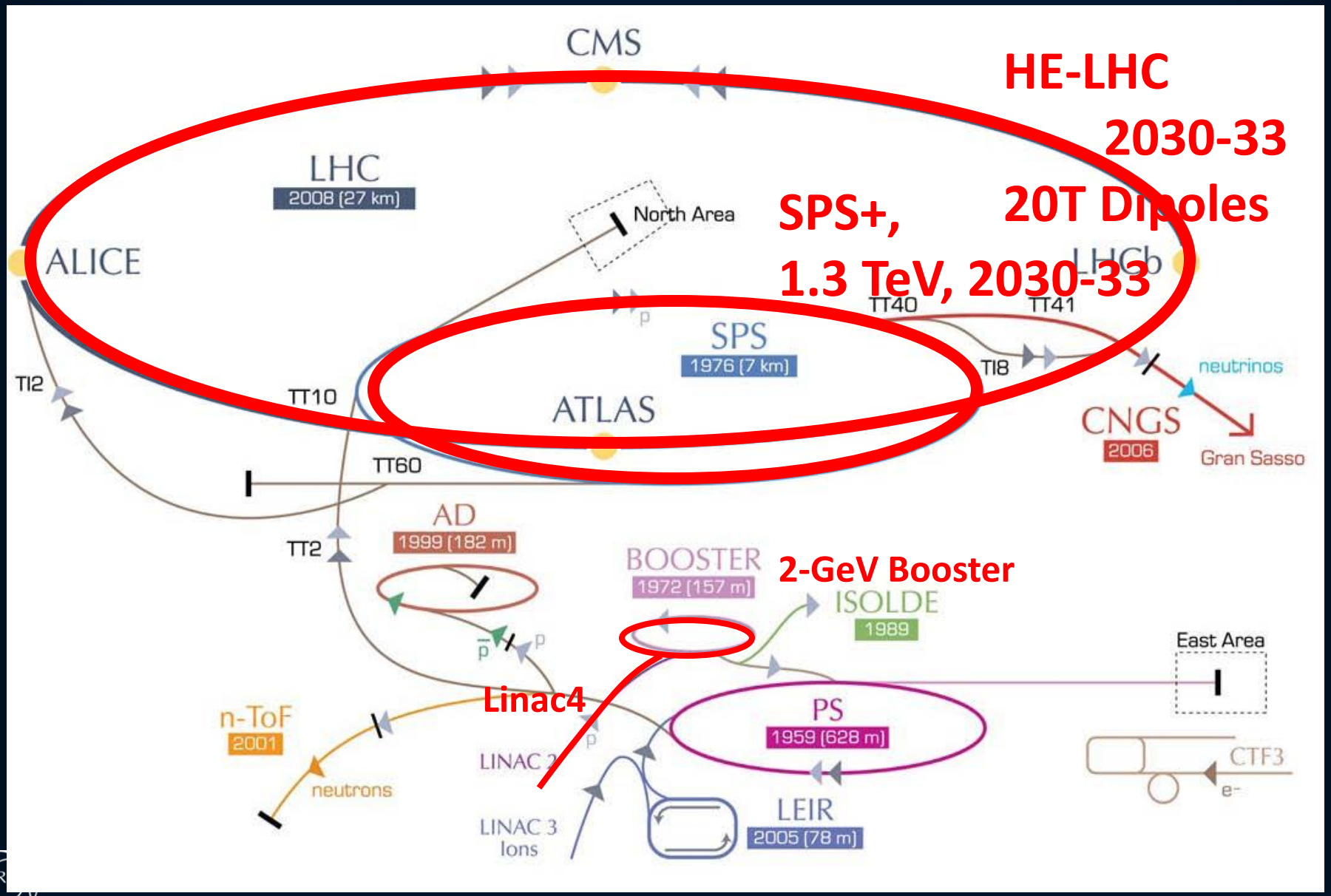
Thirty Years of SC Accelerators



Superconductivity has been an enabling technology

Without SC technology LHC would be 100 km long and 900 MW !

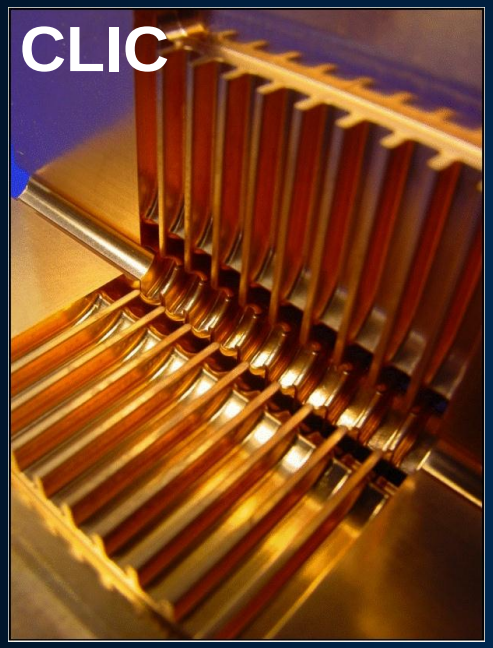
High-Energy LHC (HE-LHC)



LEPTON COLLIDERS

International Linear Collider (ILC) & Compact Linear Collider (CLIC)

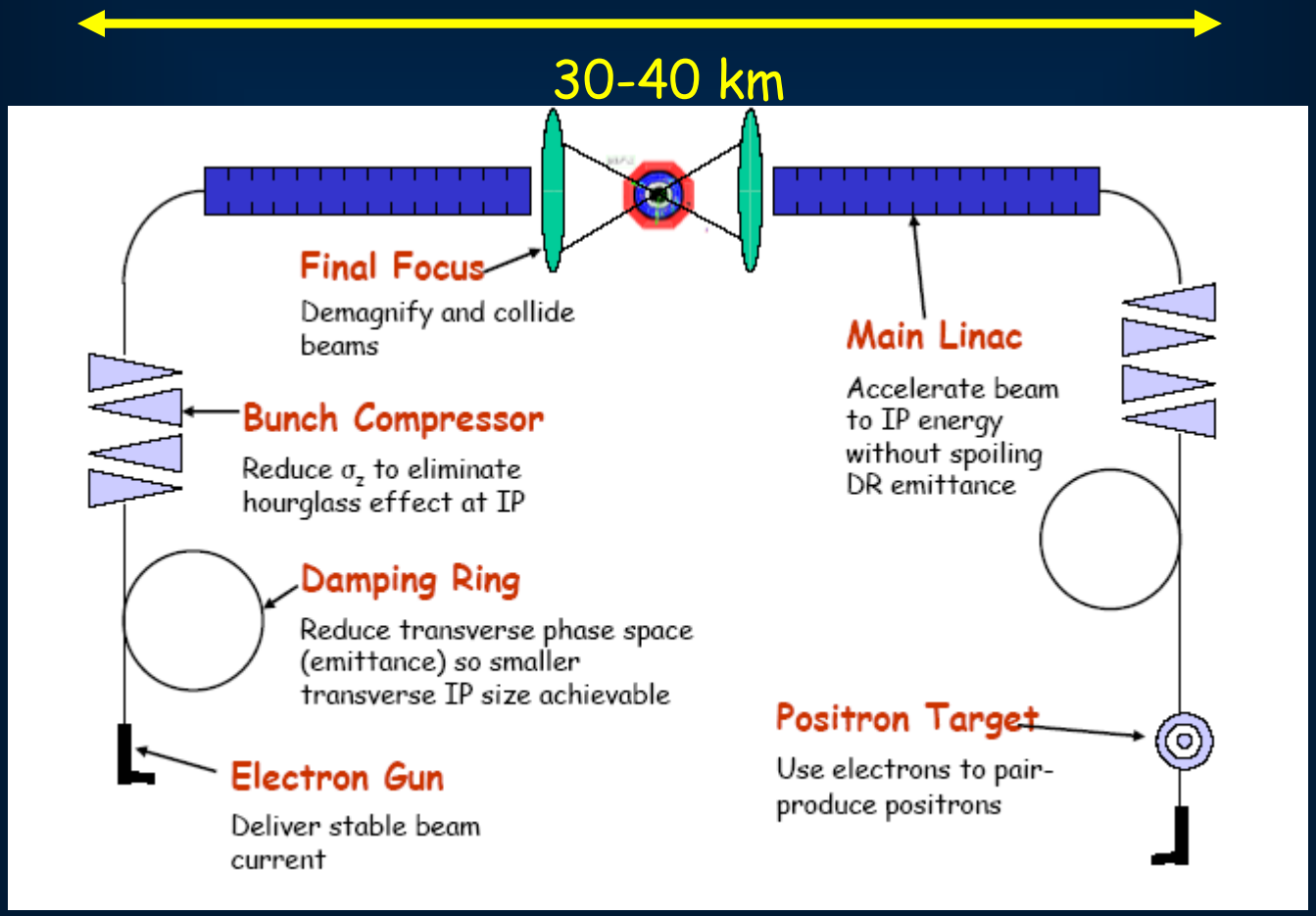
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$



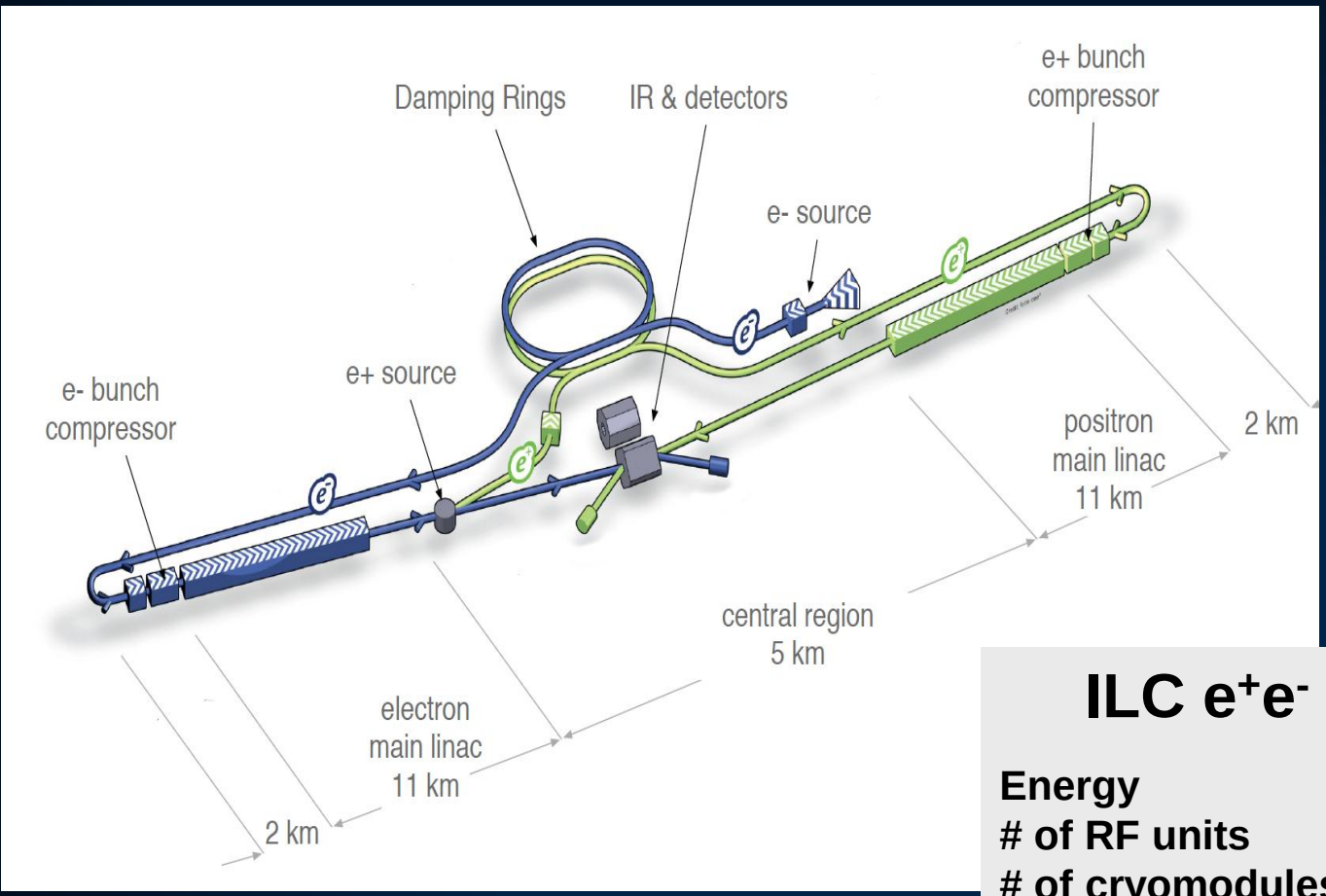
- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

A Generic Linear Collider

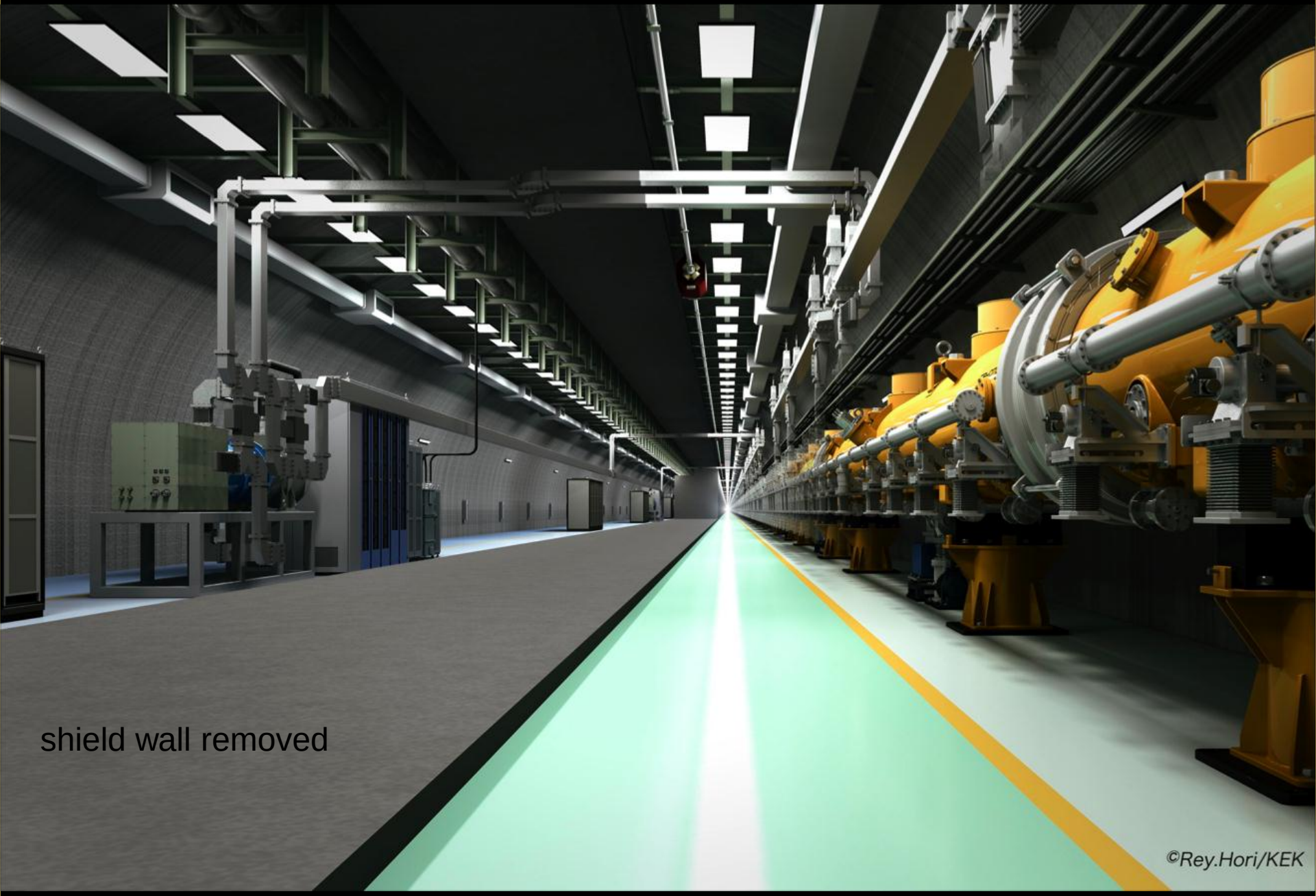


The International Linear Collider ILC (in Japan?)

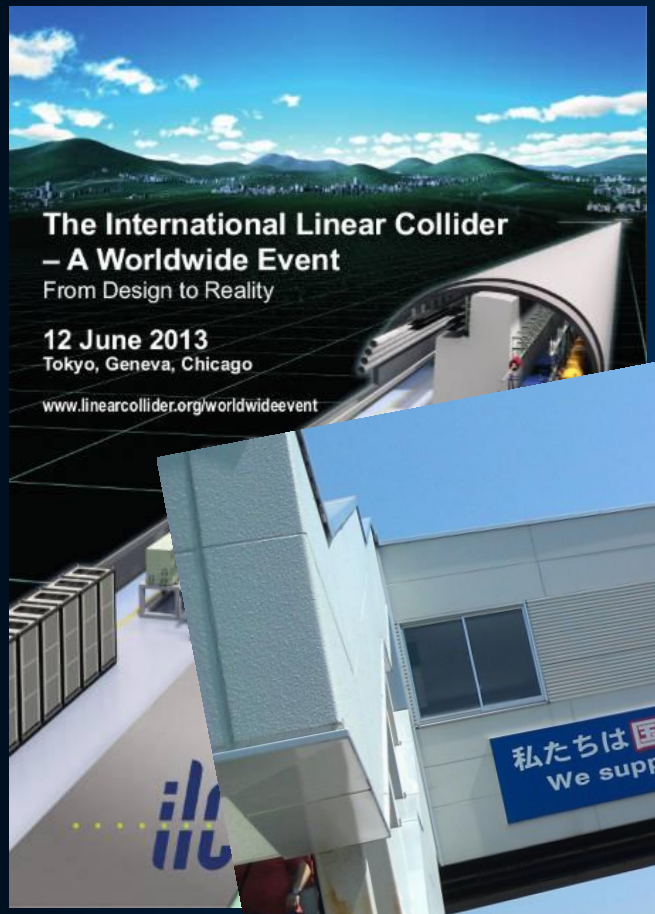


ILC e^+e^- Linear Collider

Energy	250 GeV x 250 GeV
# of RF units	560
# of cryomodules	1680
# of 9-cell cavities	14560
2 detectors push-pull	
Peak luminosity	$2\ 10^{34}$
5 Hz rep rate, 1000 -> 6000 bunches	
IP : σ_x 350 – 620 nm; σ_y 3.5 – 9.0 nm	
Total power	~230 MW
Accelerating gradient	31.5 MeV/m


shield wall removed
©Rey.Hori/KEK

ILC


The International Linear Collider
– A Worldwide Event
From Design to Reality
12 June 2013
Tokyo, Geneva, Chicago
www.linearcollider.org/worldwideevent

- Japanese Mountainous Sites -
Site-A
KITAKAMI
SEFURI
Site-B
FUKUOKA
SAGA
IWATE
Tokyo
TOHOKU district

私たちは国際リニアコライダー計画を応援しています
We support the International Linear Collider Project.

CLIC Conceptual Design

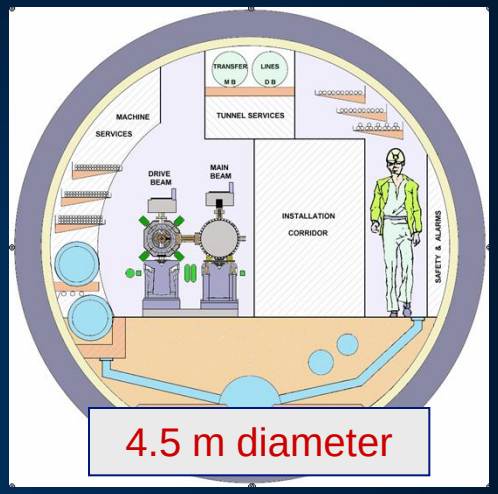
- Site independent feasibility study aiming at the development of the technologies needed to extend e+ / e- linear colliders into the multi-TeV energy range.
  - E_{cm} range complementary to that of the LHC & ILC
    - E_{cm} = 0.5 – 3 TeV
  - L > few 10^{34} cm^{-2} s^{-1} with low machine-induced background
  - Minimise power consumption and costs

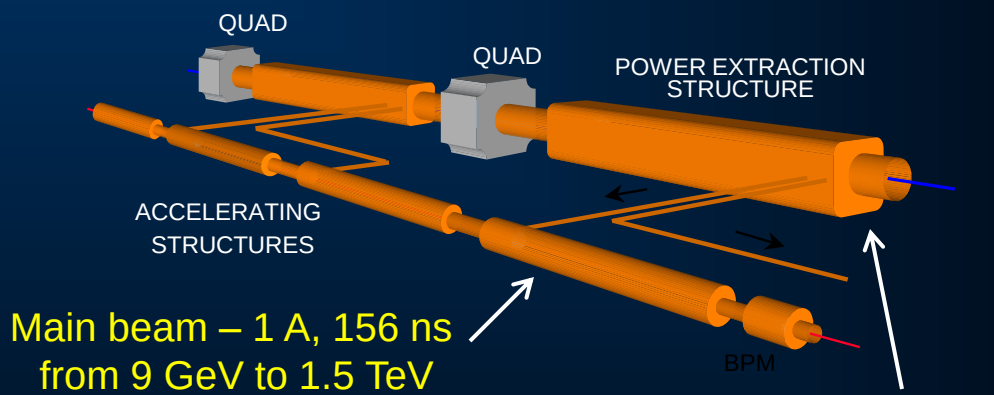
Basic Features

- **High acceleration gradient: > 100 MV/m**
  - "Compact" collider – total length < 50 km at 3 TeV
  - Normal conducting acceleration structures at high frequency

- **Novel Two-Beam Acceleration Scheme**
  - Cost effective, reliable, efficient
  - Simple tunnel, no active elements
  - Modular, easy energy upgrade in stages

CLIC TUNNEL CROSS-SECTION





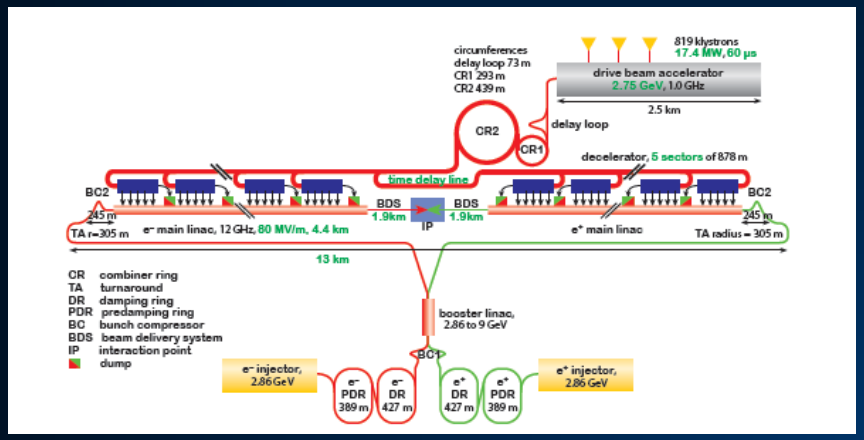
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

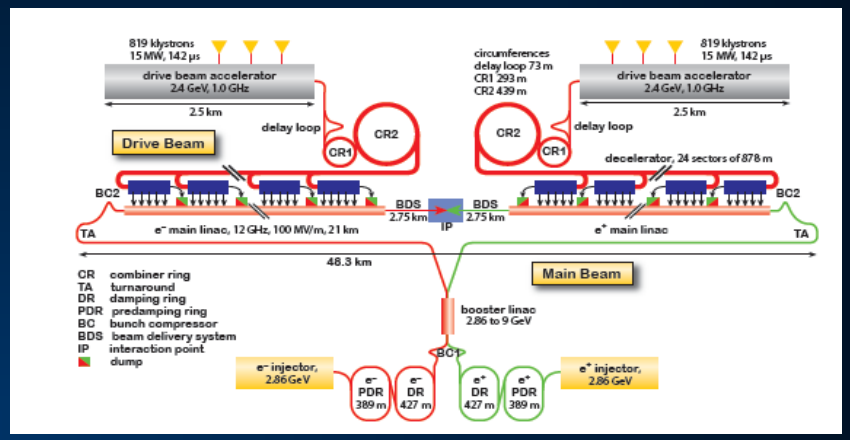
12 GHz – 64 MW

Proposed CLIC Lay-outs

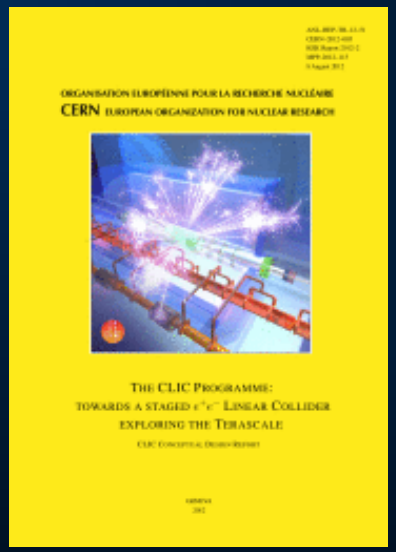
Centre-of-mass energy 500 GeV



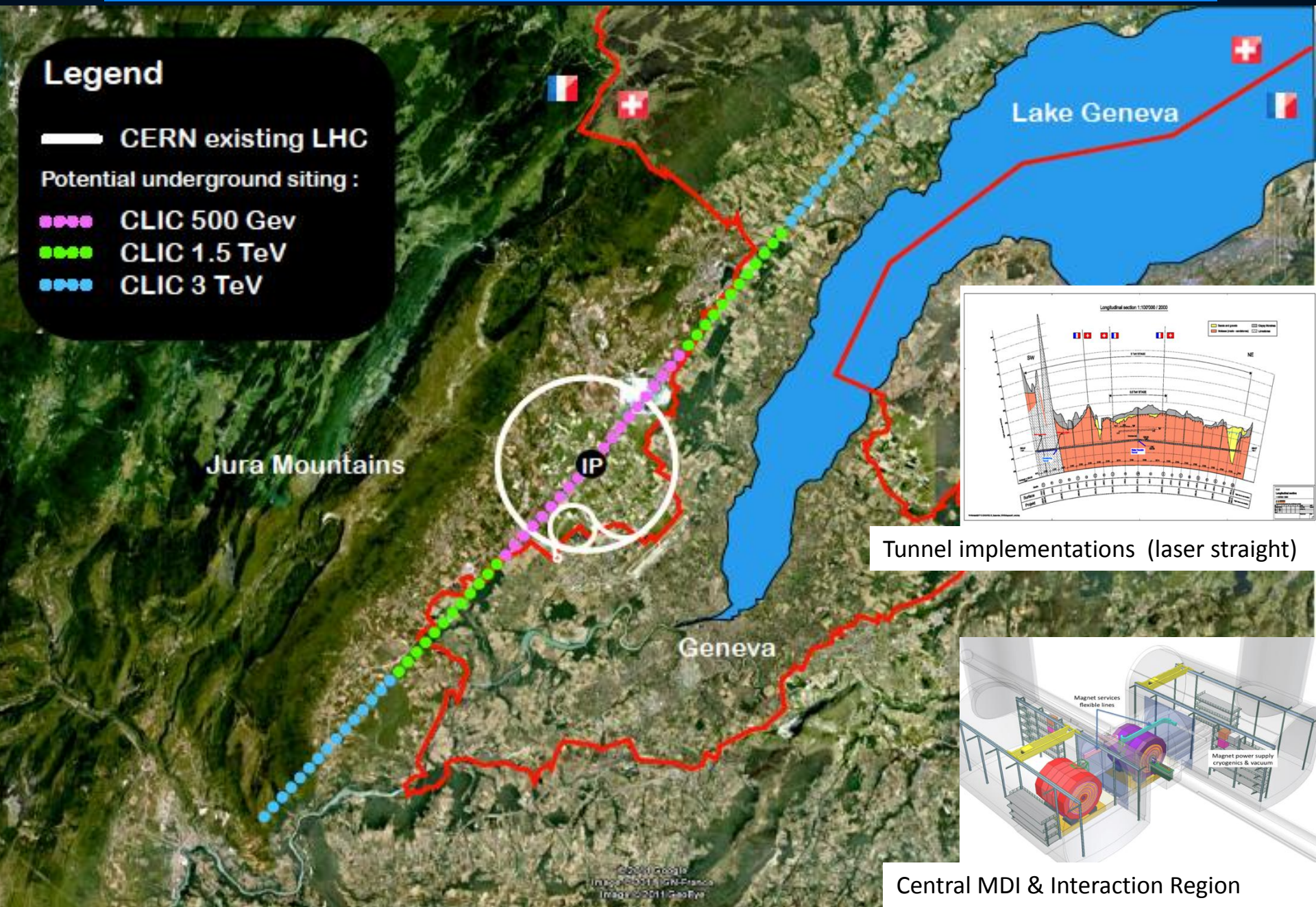
Centre-of-mass energy 3 TeV



Documented in conceptual design reports for the accelerator & detectors

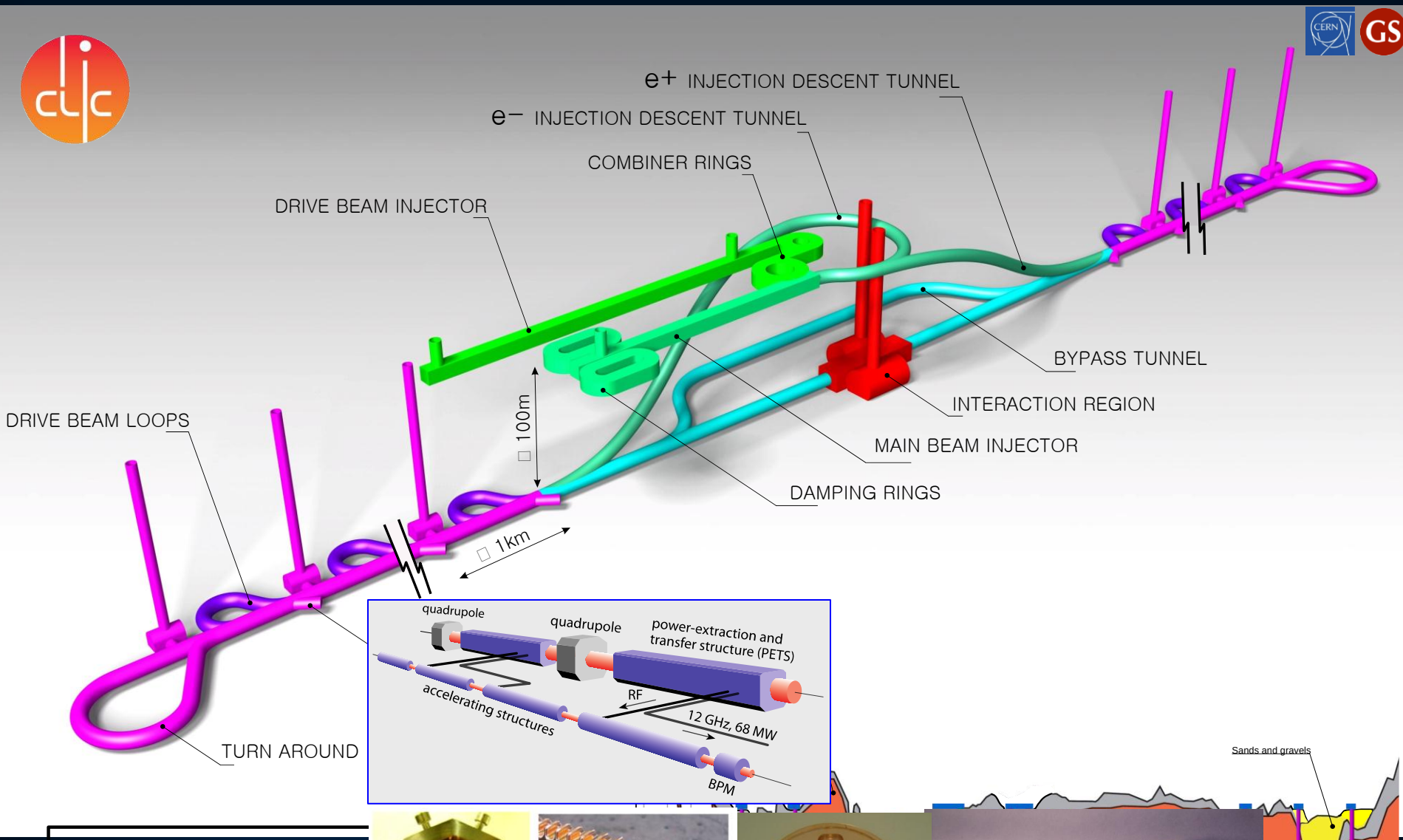


CLIC in the CERN region



CLIC SCHE

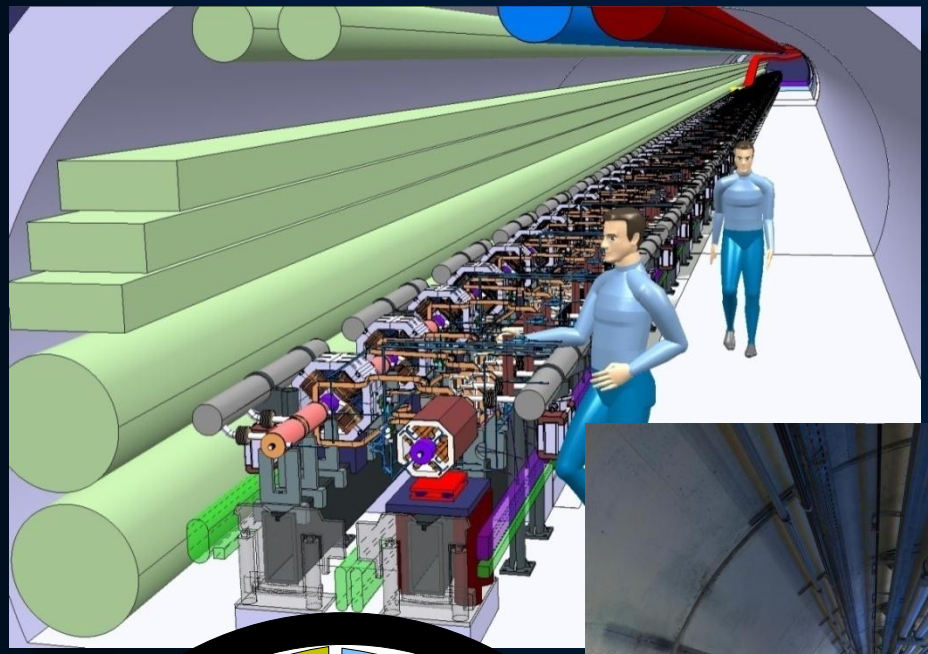
(not to scale)

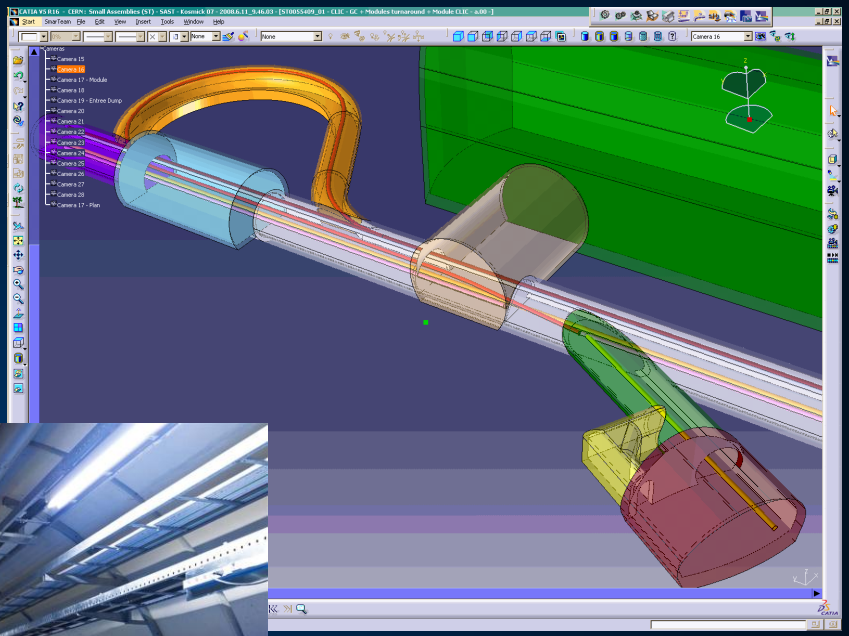


CLIC Parameters

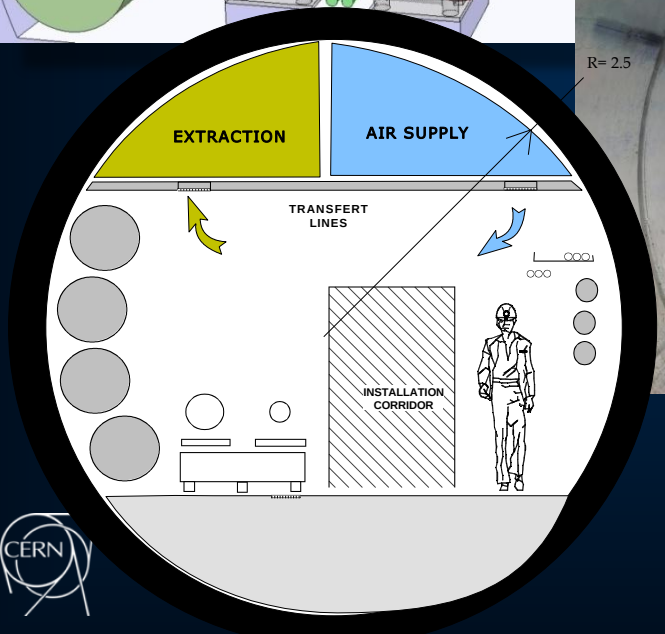
Center-of-mass energy	3 TeV
Peak Luminosity	$7 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	41.7 km
Bunch charge	$4 \cdot 10^{9}$
Beam pulse length	200 ns
Average current in pulse	1 A
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	53 / ~1 nm
Total site length	48.25 km
Total power consumption	390 MW

Tunnel Integration





(Courtesy John Osborne)



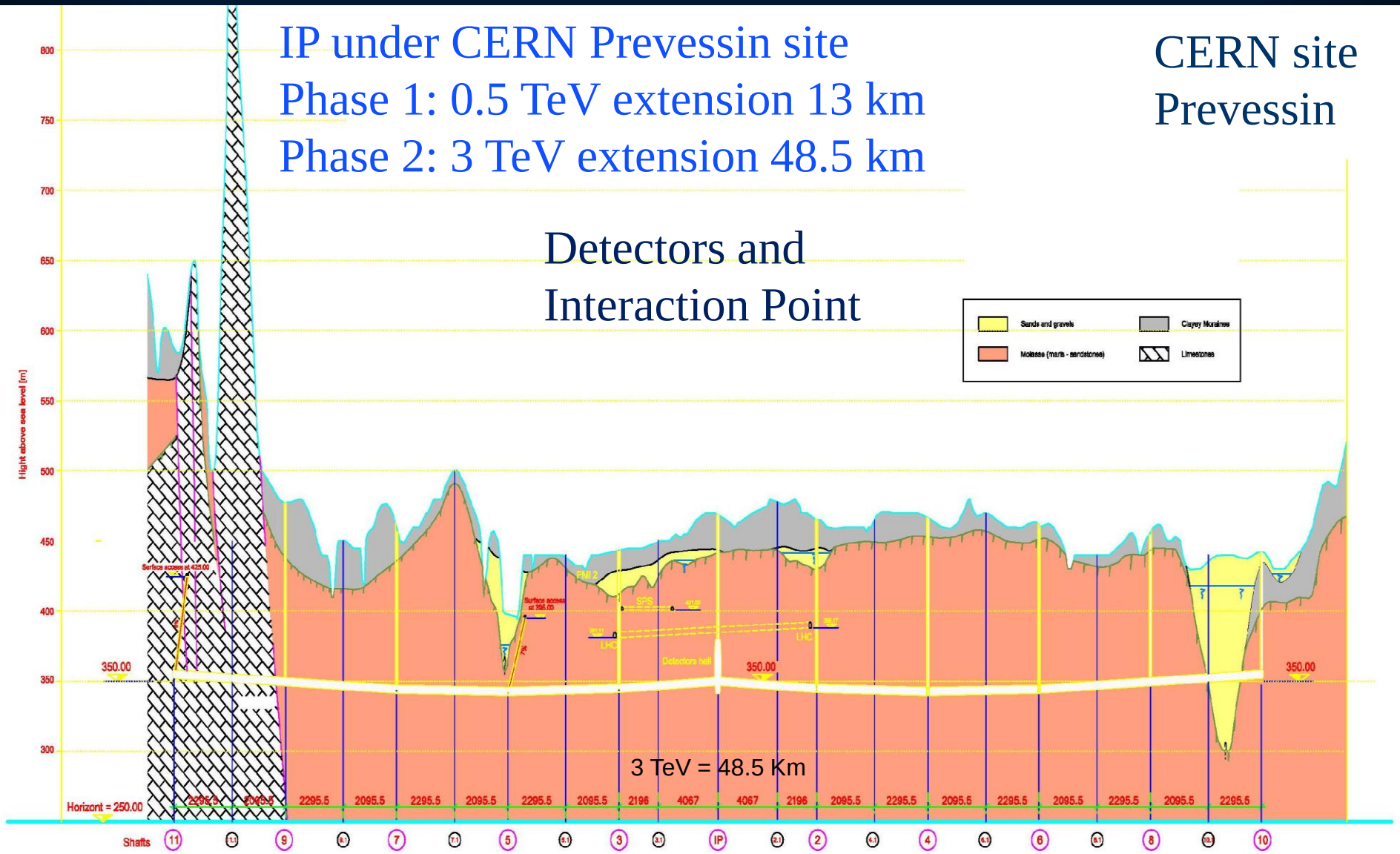
Standard tunnel with modules

Potential Machine Site

IP under CERN Prevessin site
Phase 1: 0.5 TeV extension 13 km
Phase 2: 3 TeV extension 48.5 km

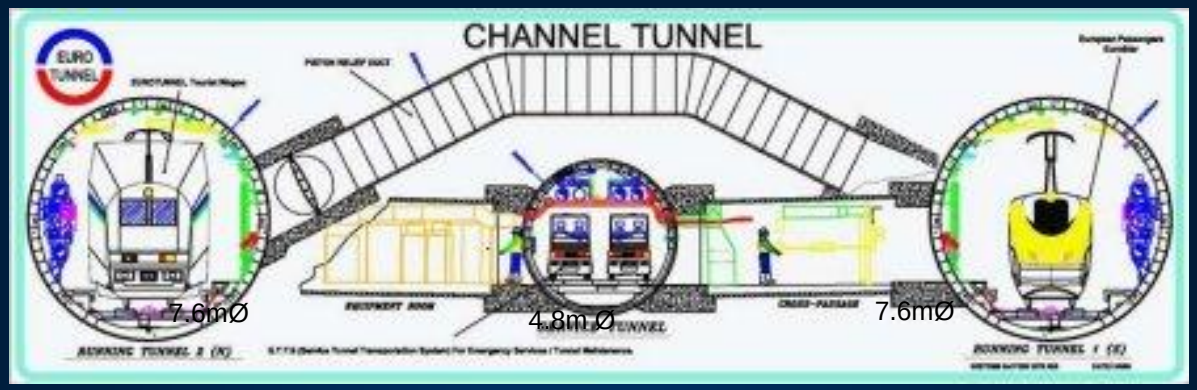
CERN site
Prevessin

Detectors and
Interaction Point

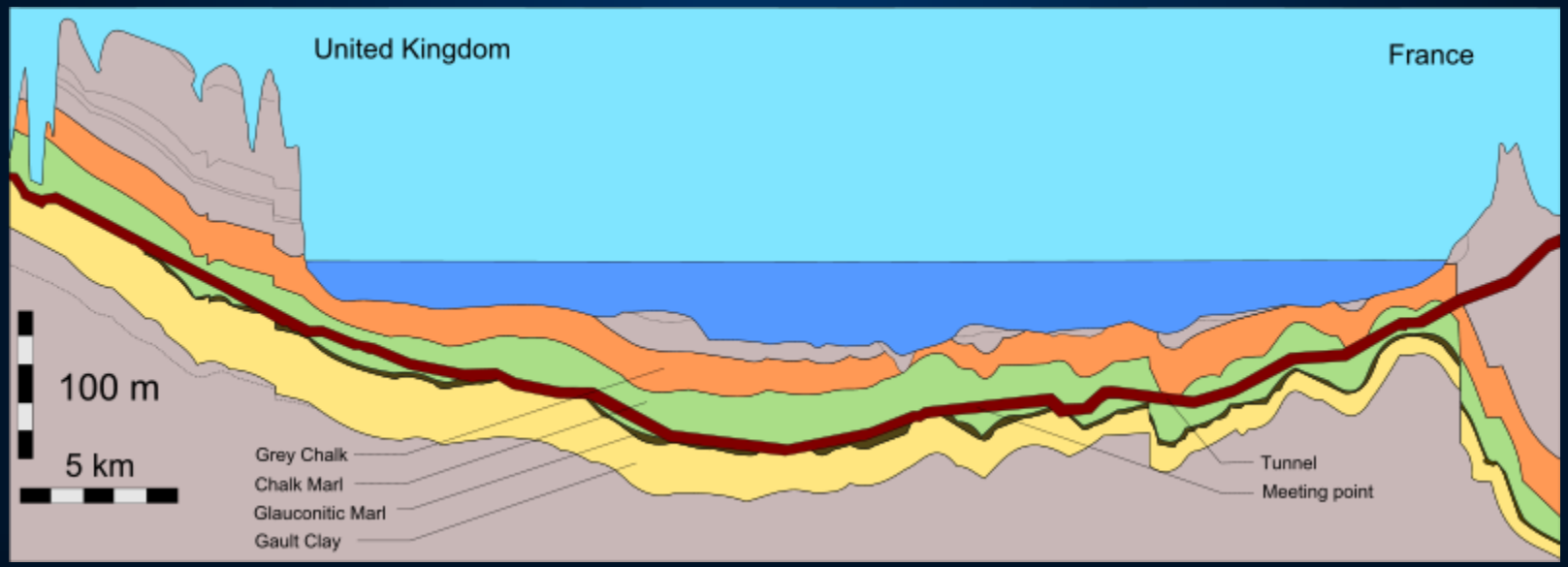


Longitudinal section of a laser straight Linear Collider on CERN

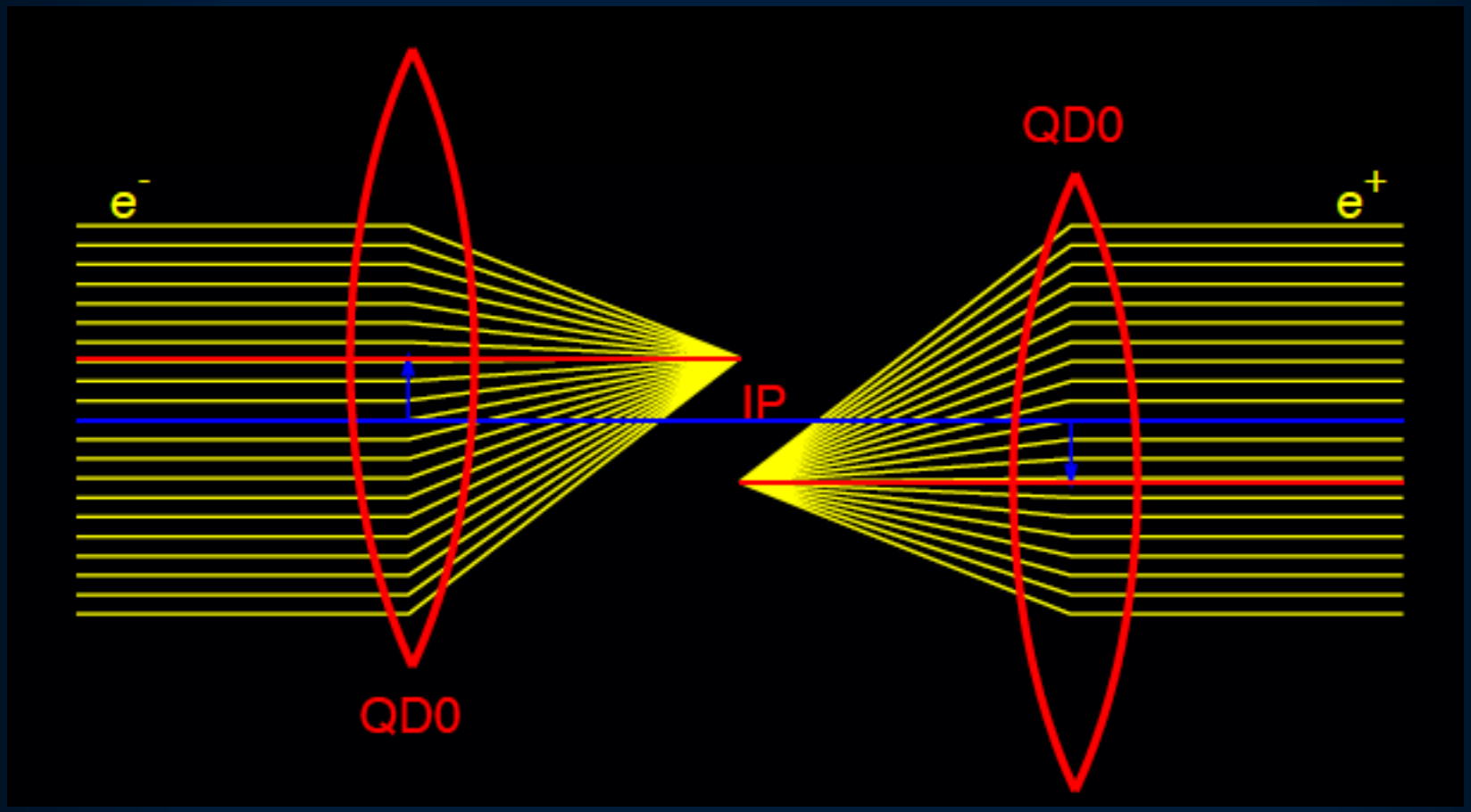
CLIC & ILC - Similar World Projects: Channel Tunnel



50Km



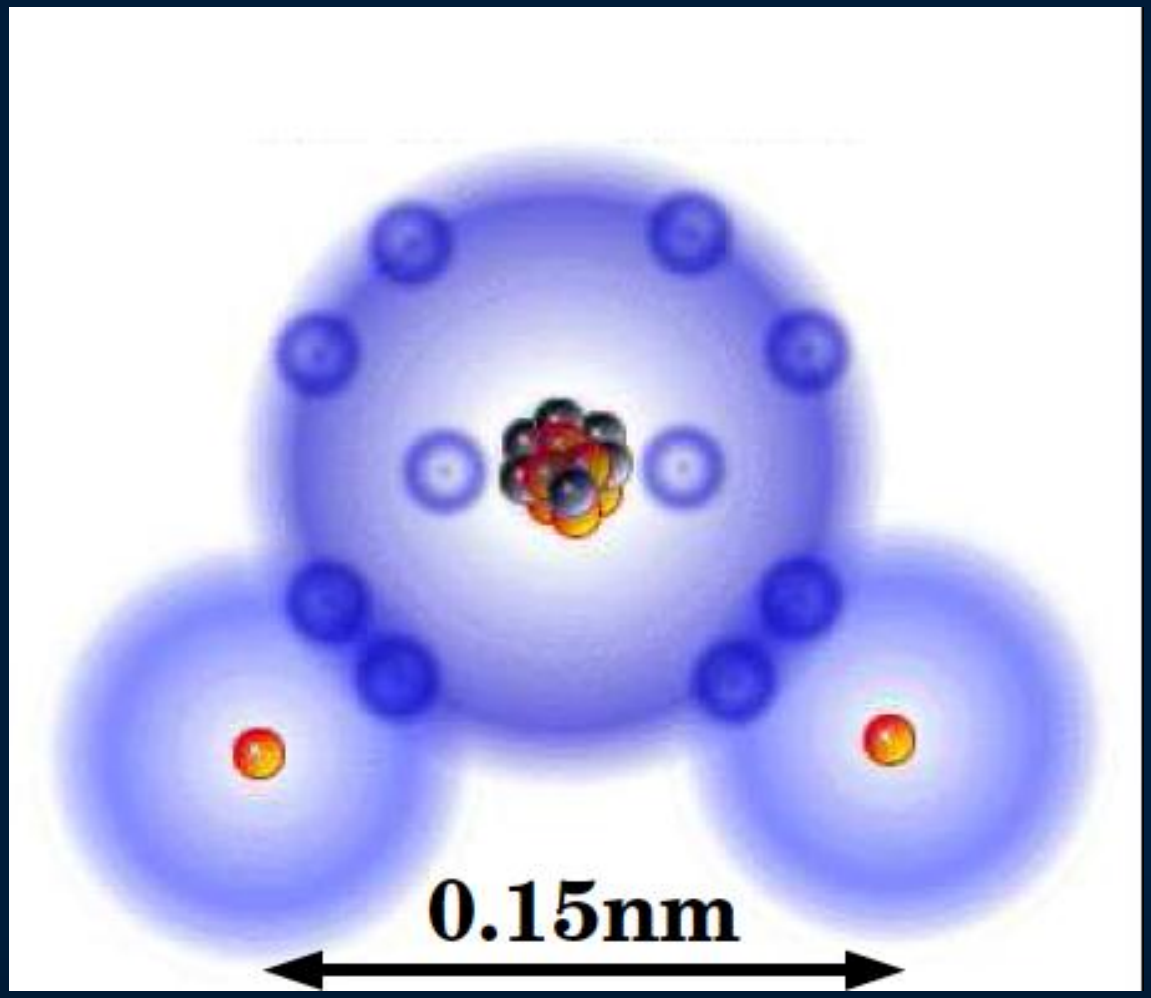
Other Technological Challenges



The final focusing quadruple should be stabilized to 0.15 nm

for frequencies about 4 Hz

Other Technological Challenges



0.15 nm, small as a H_20 molecule !

CIRCULAR COLLIDERS AFTER THE LHC

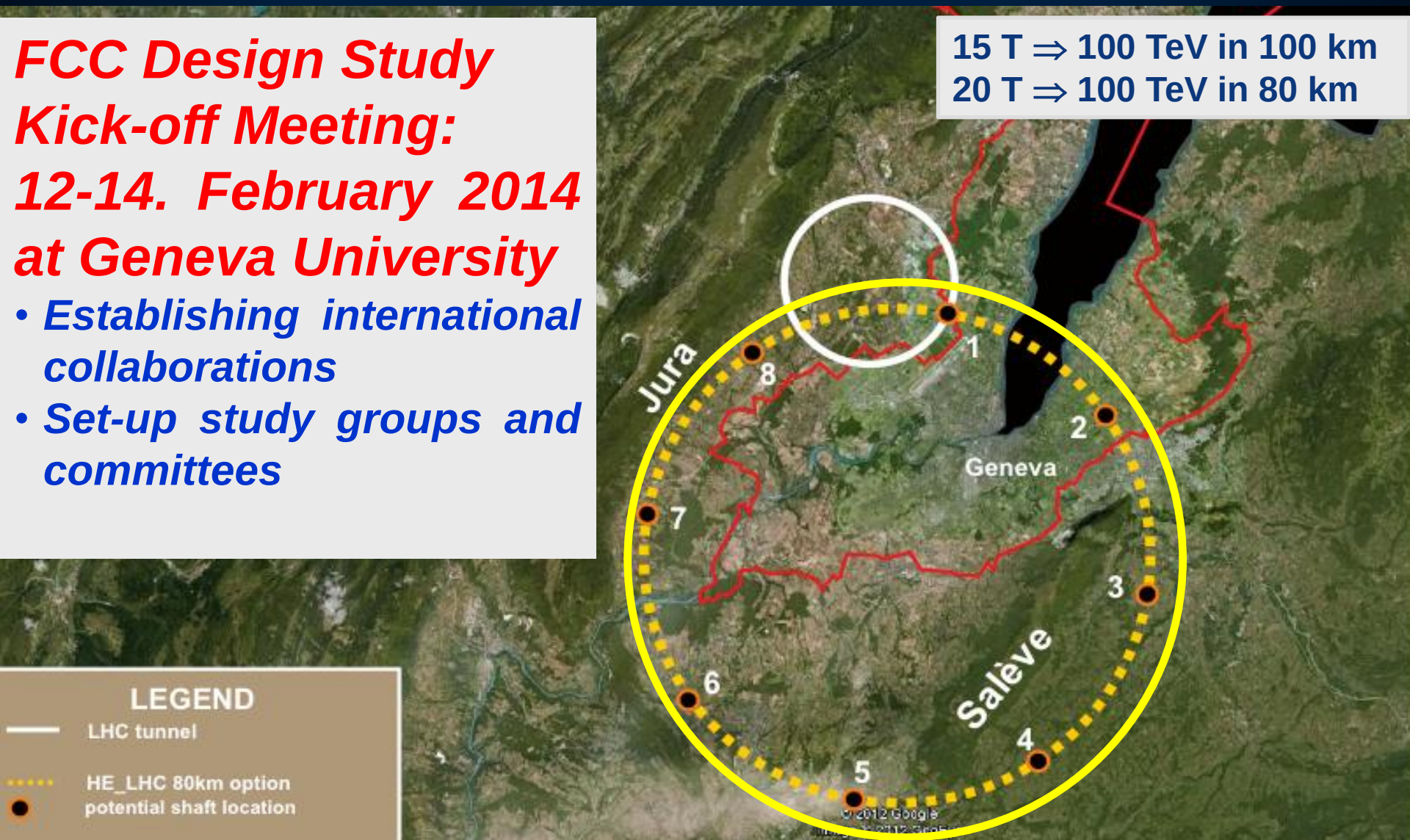
80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

with possibility of e+-e- (TLEP) and p-e (VLHeC)

FCC Design Study Kick-off Meeting: 12-14. February 2014 at Geneva University

- ***Establishing international collaborations***
- ***Set-up study groups and committees***

15 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km

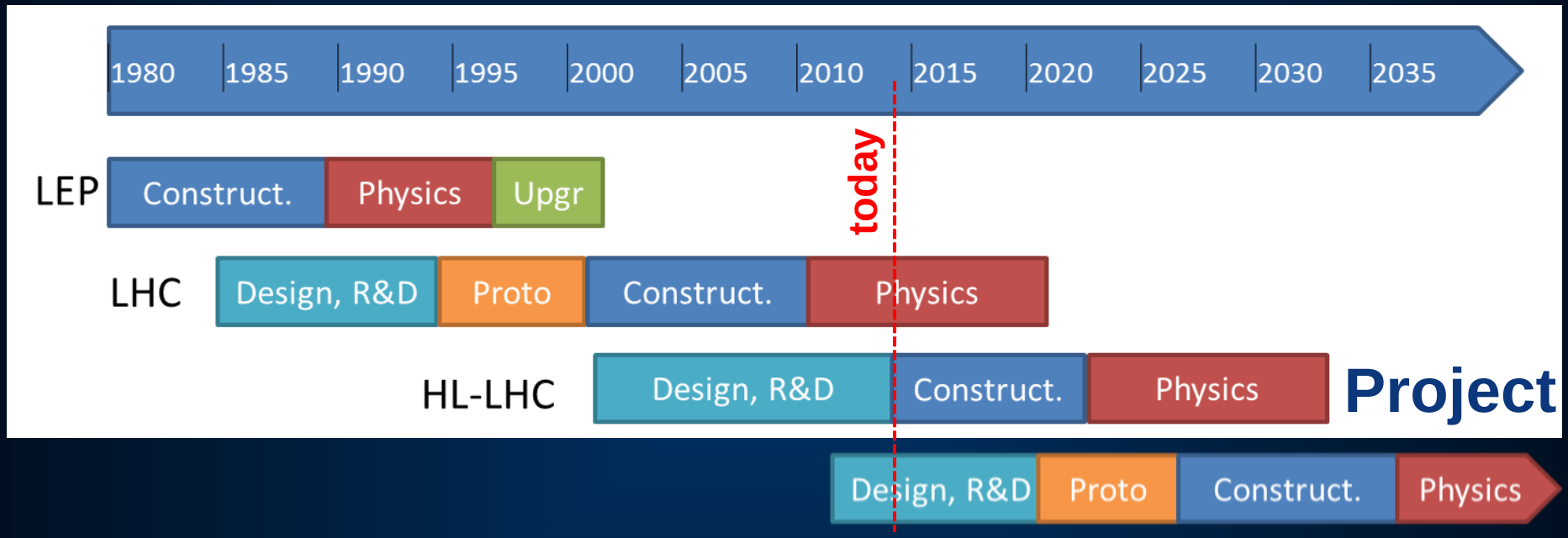


CEPC (China)

- Circular accelerator 50-70 km.
- Focus on simple design and low cost
- Initially designed for an e^+e^- machine and later for a proton machine.

- Possible location: Qinhuangdao (秦皇岛)

High-energy Physics Colliders



FCC Study : p-p towards 100 TeV

Concluding Summary
Next Decades

Road beyond Standard Model

LHC results will guide the way at the energy frontier

through synergy of

hadron - hadron colliders (LHC, HL-LHC, HE-LHC, FCC, CEPC)

lepton - hadron colliders (LHeC)

lepton - lepton colliders (LC (ILC or CLIC), Muon Collider)