International Teachers Program 2019

Future Accelerators

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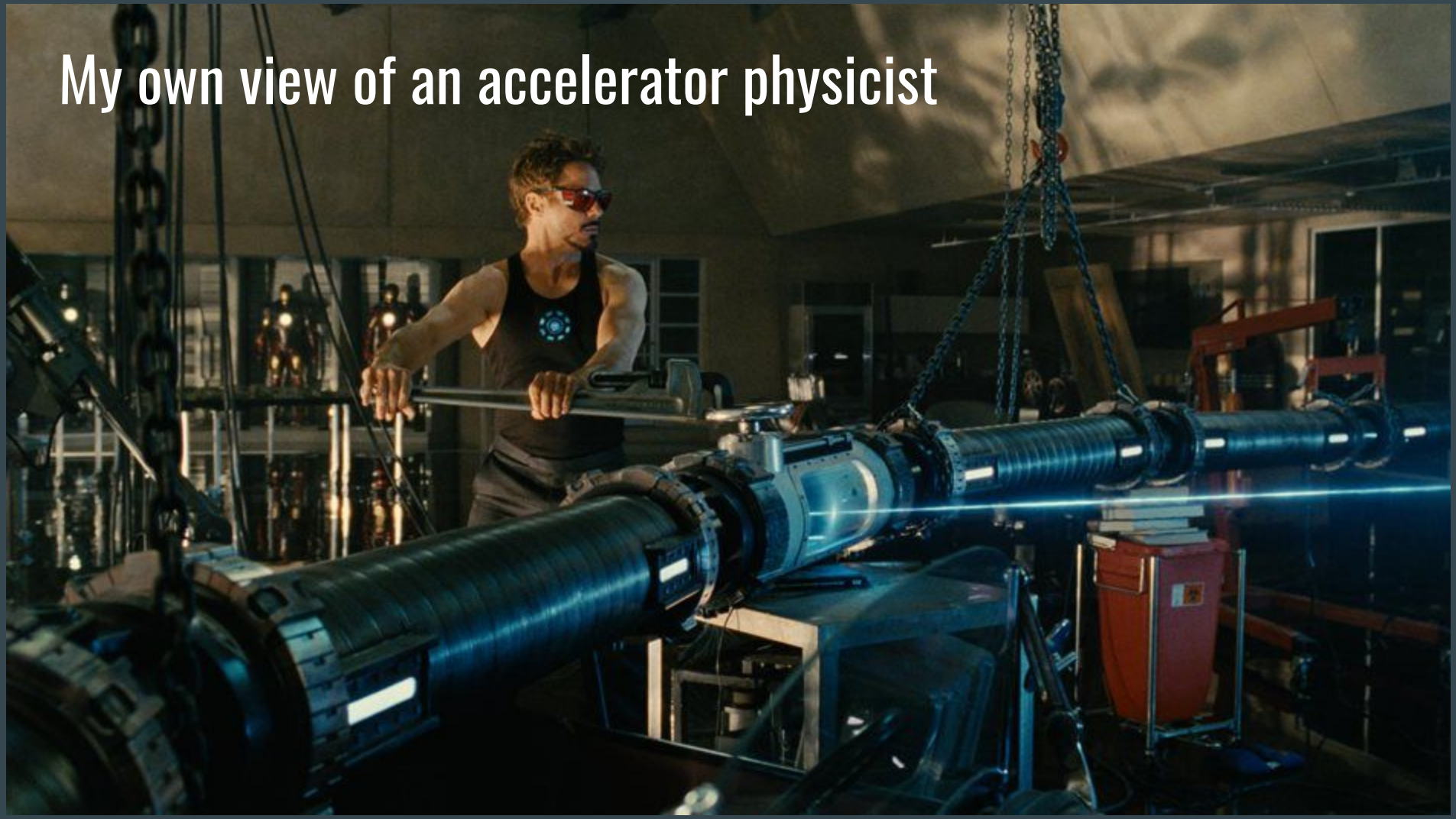
“Trying to predict the future is a mug’s game. But [...] it’s a game we all have to play because the world is changing so fast and we need to have some sort of idea of what the future’s actually going to be like because we are going to have to live there, probably next week.”

Douglas Adams, The Salmon of Doubt

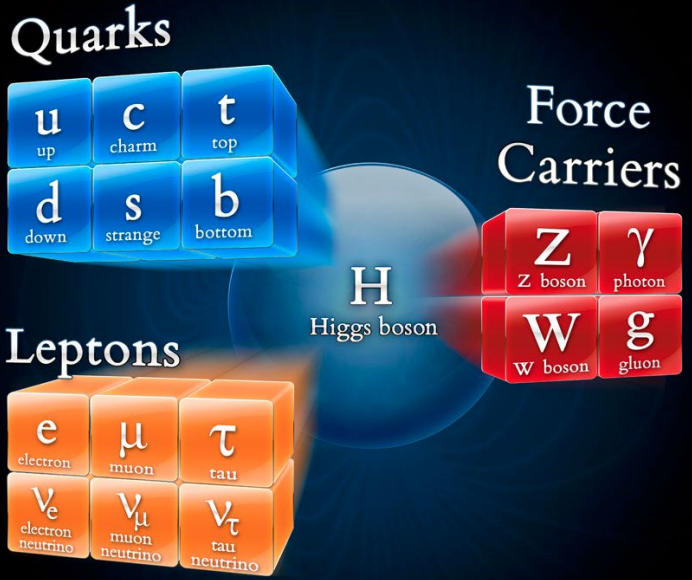
My own view of an accelerator physicist



We only need 2 things to build new machines

1

Physics Motivation


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
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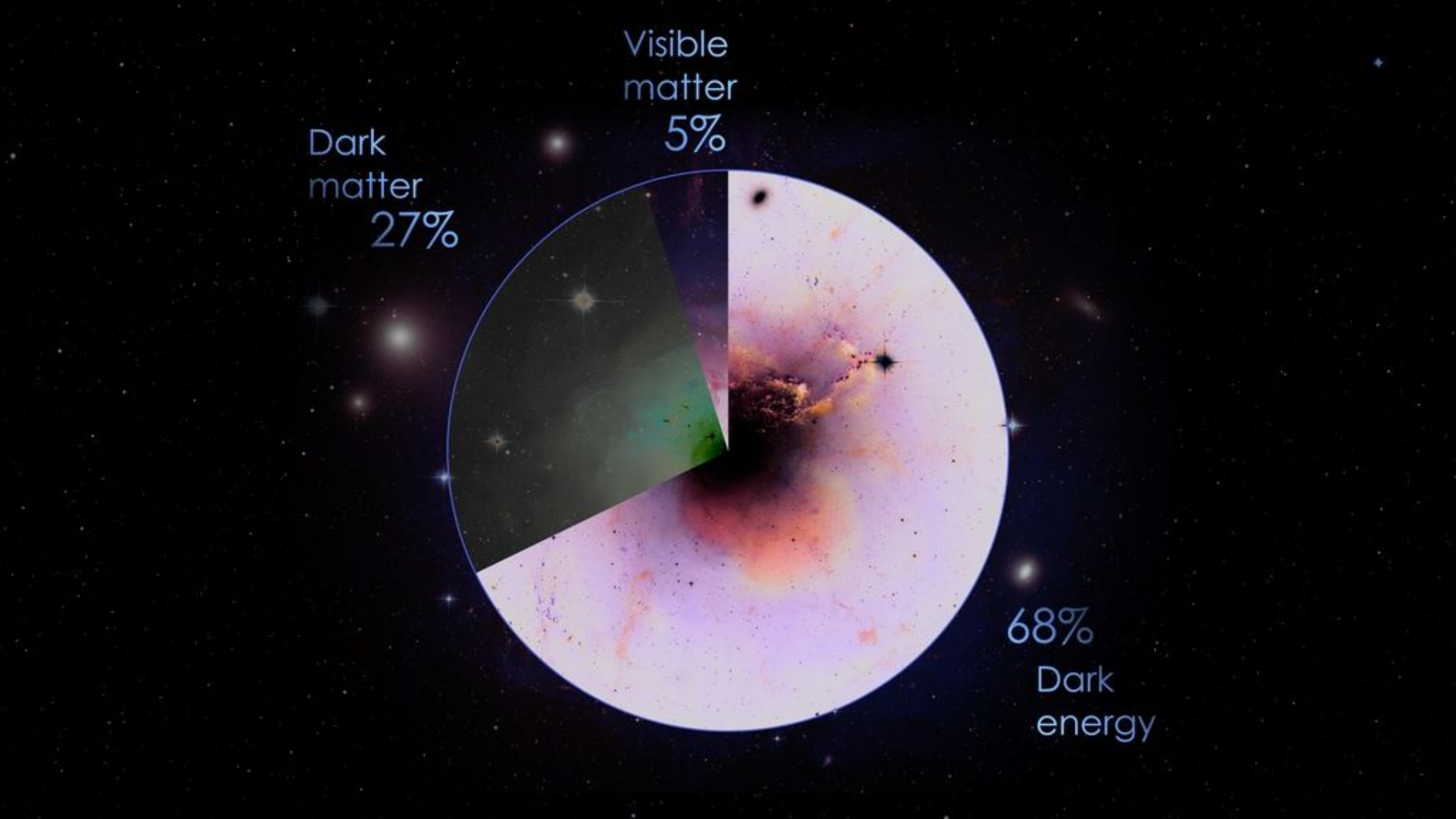
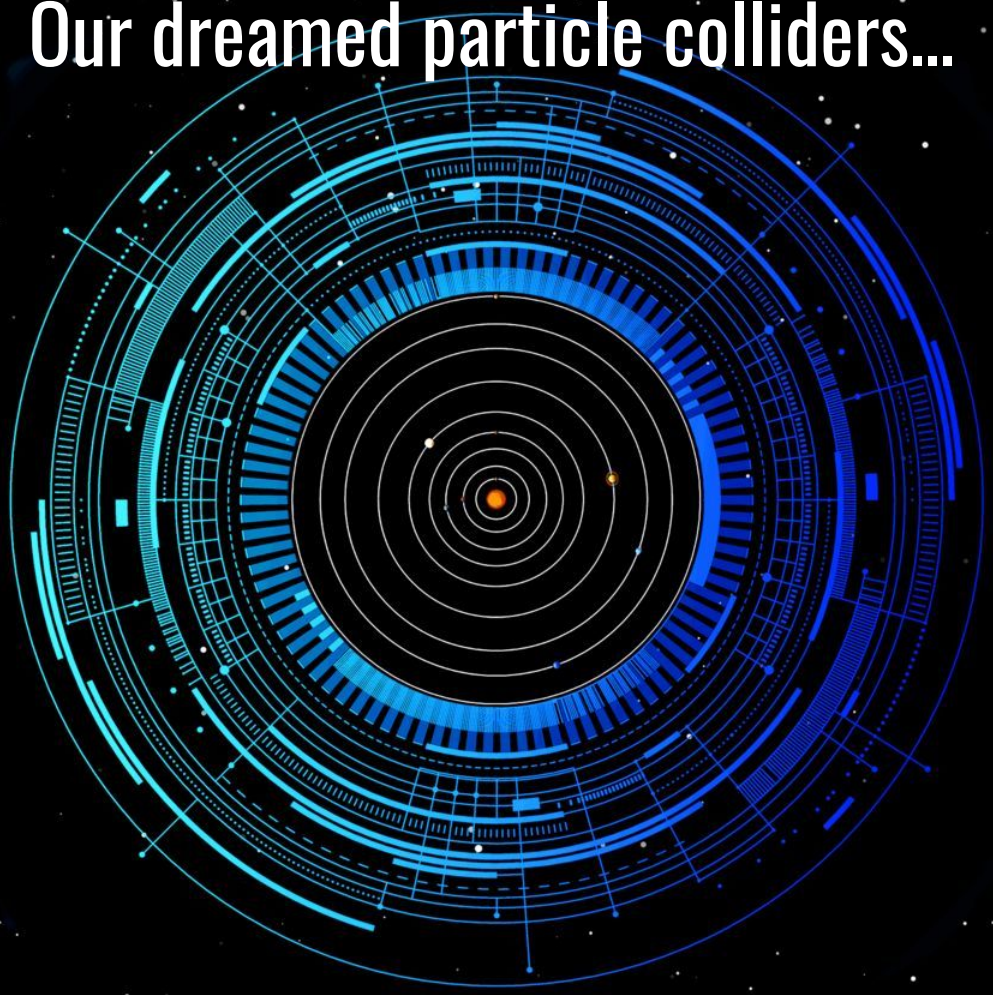
ντ
tau neutrino
H
Higgs boson
Force Carriers
Z
Z boson
γ
photon
W
W boson
g
gluon


Visible
matter
5%
Dark
matter
27%
68%
Dark
energy

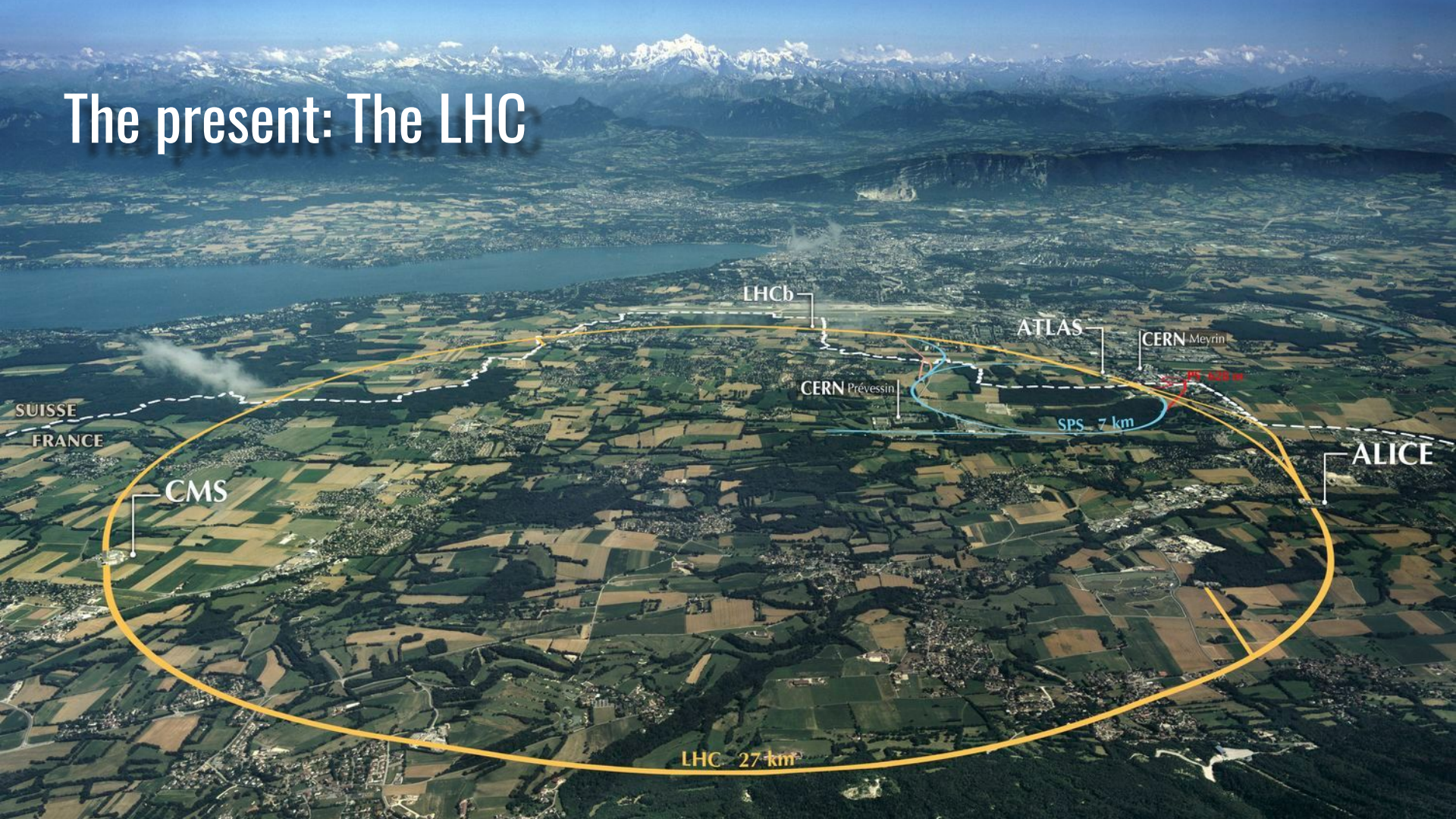
2


FUCKING
MONEY MAN

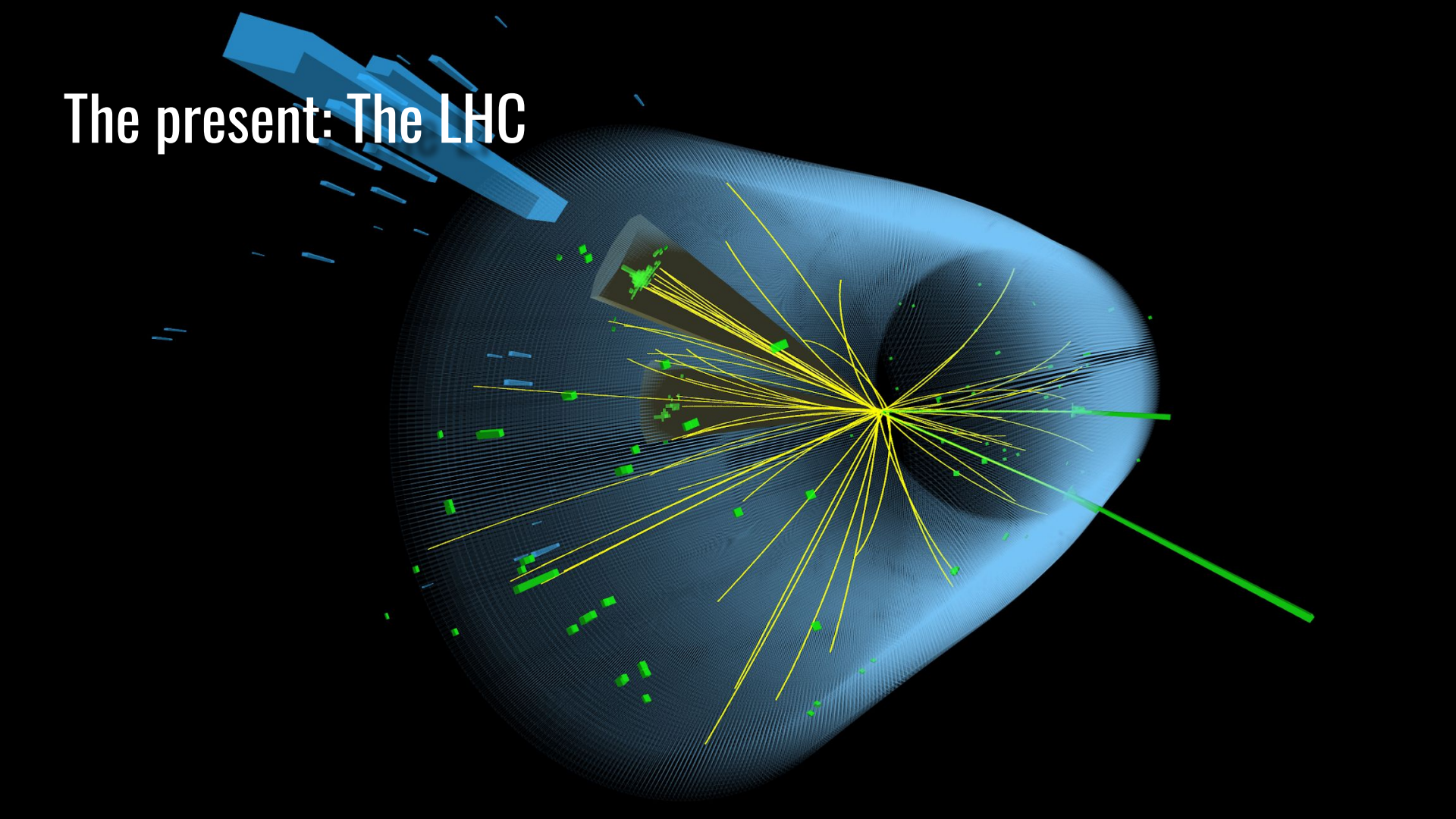
Our dreamed particle colliders...



The present: The LHC



The present: The LHC



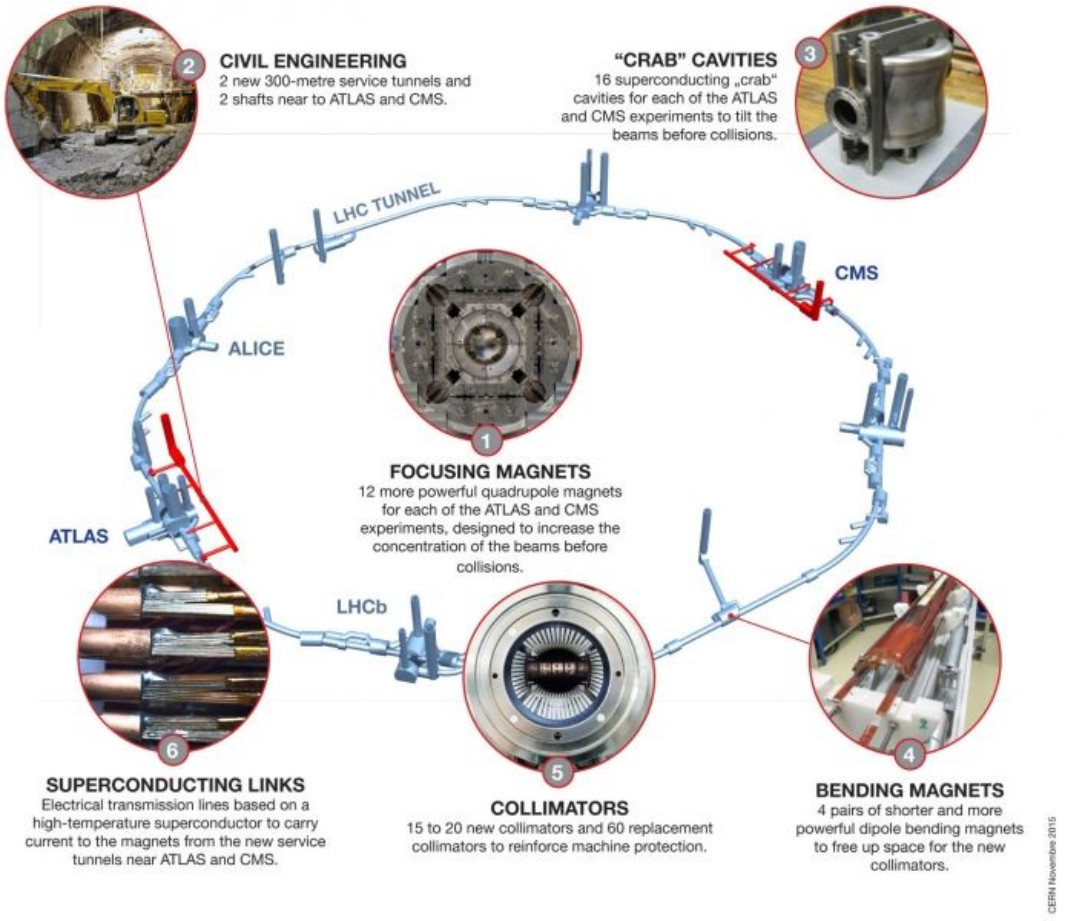
Nature is a bit tricky and this seems not to be enough...

The obvious option: upgrading the LHC

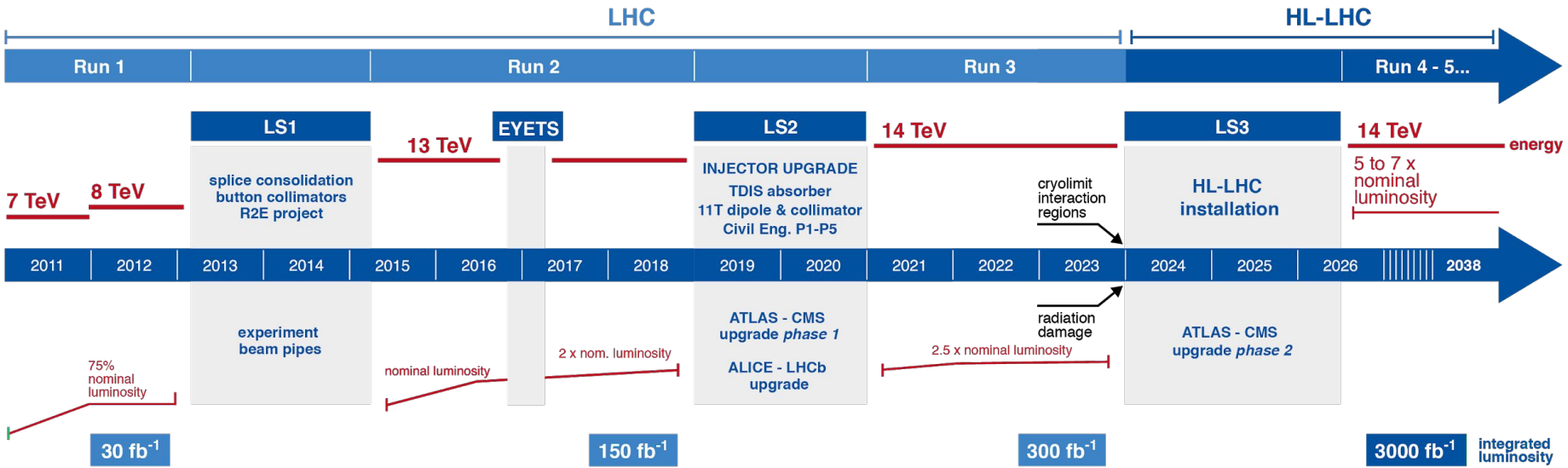
High Luminosity LHC (HL-LHC)

- GOAL: Increase the amount of collisions per second (luminosity)
  - Higher number of particles per bunch
  - Smaller beamsize at the Interaction Point (IP)
- Currently, the largest collider being built.

High Luminosity LHC (HL-LHC)

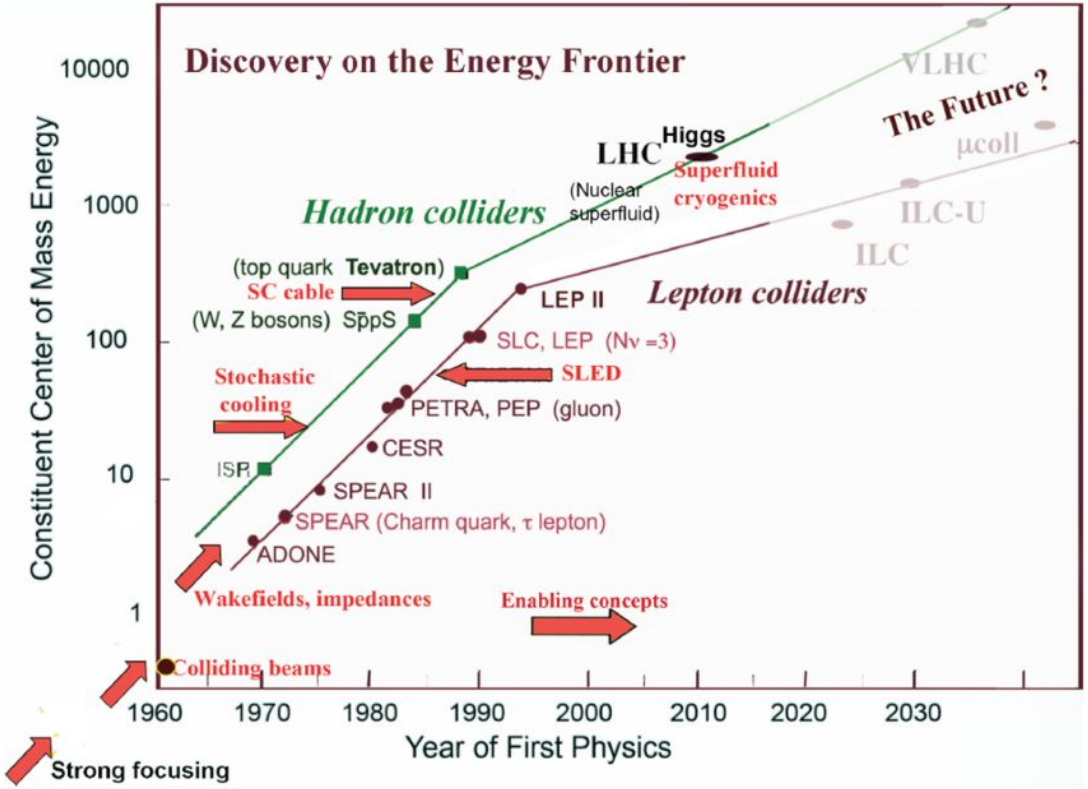


LHC / HL-LHC Plan

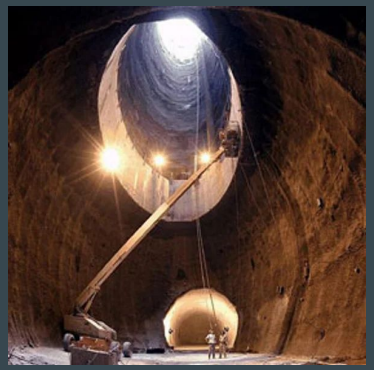


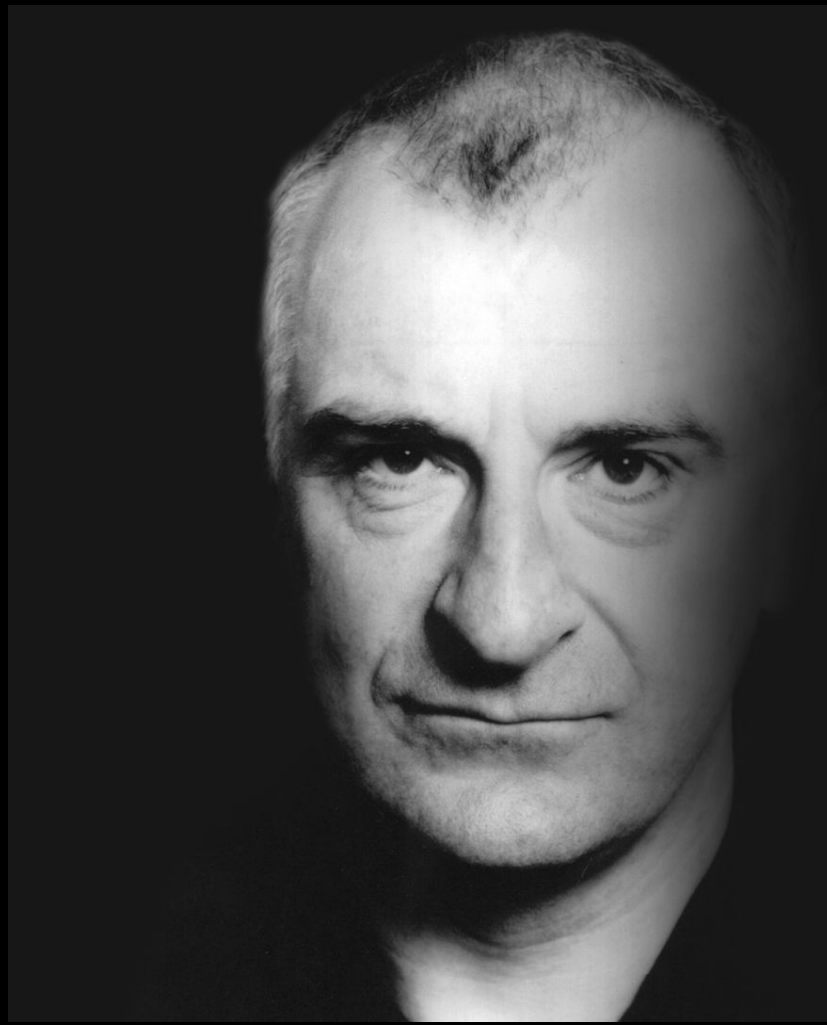
Why do we need to build larger colliders?

Evolution of Particle Colliders



A short digression: The SSC





Human beings, who are almost unique in having the ability to learn from the experience of others, are also remarkable for their apparent disinclination to do so.

-Douglas Adams

What should be the next collider?

Linear or circular colliders?

Linear colliders

- Relatively simpler machine
- Less magnets
- Single pass machine
  - All the energy must be given in one shot
- One collision per bunch
- Lower luminosity
- No synchrotron radiation emission
- Only one experiment
- Mainly for colliding electrons

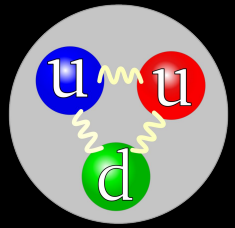
Circular Colliders

- Quite complex machine
- Many magnets
- Multi-turn machine
- Higher luminosity
- Synchrotron radiation emission
- Multiple experiments installed
- Electrons, protons and ions

Protons or electrons?

Protons

- Composed of quarks and gluons
- Heavy (~1GeV)
- Low synchrotron radiation emission

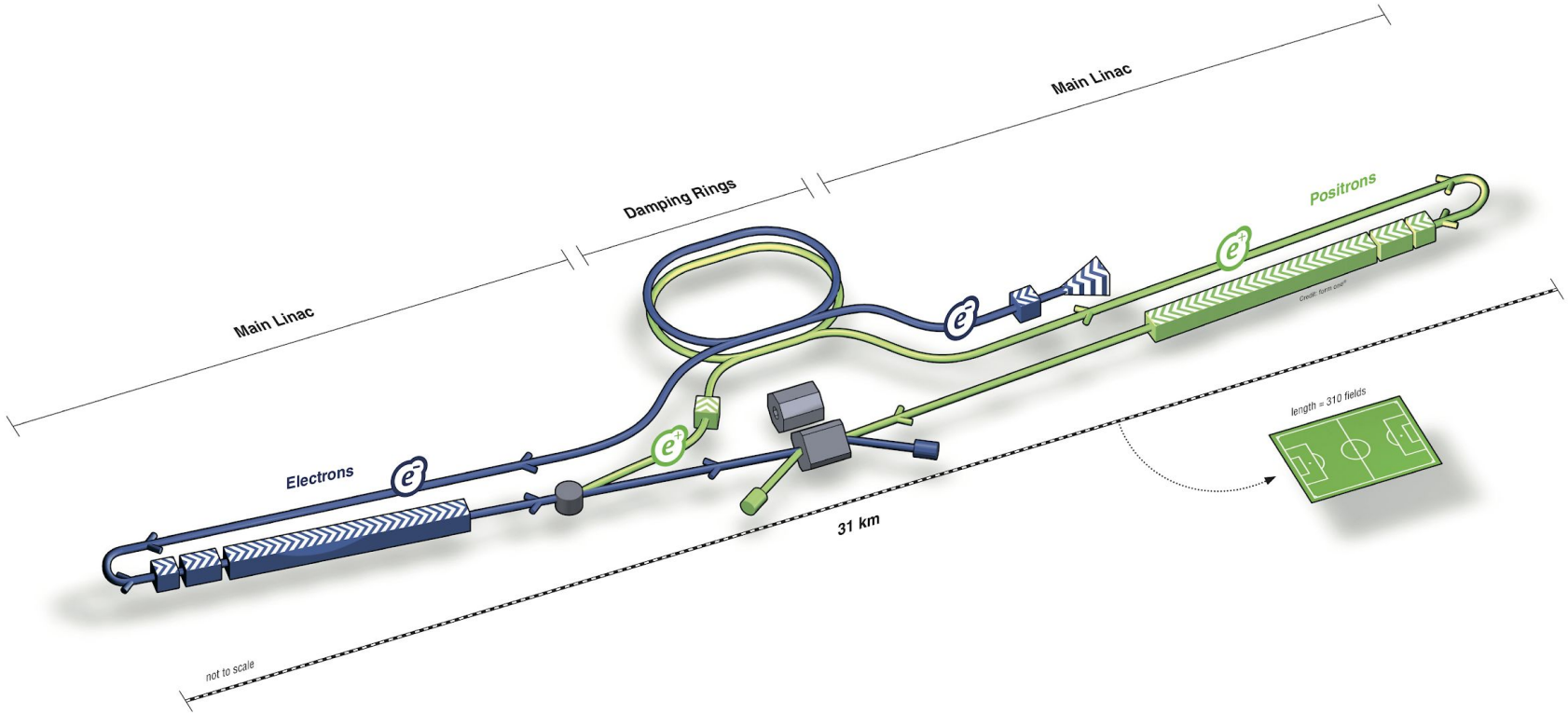


Electrons

- Elementary particles
- Light (511 keV)
- High synchrotron radiation emission

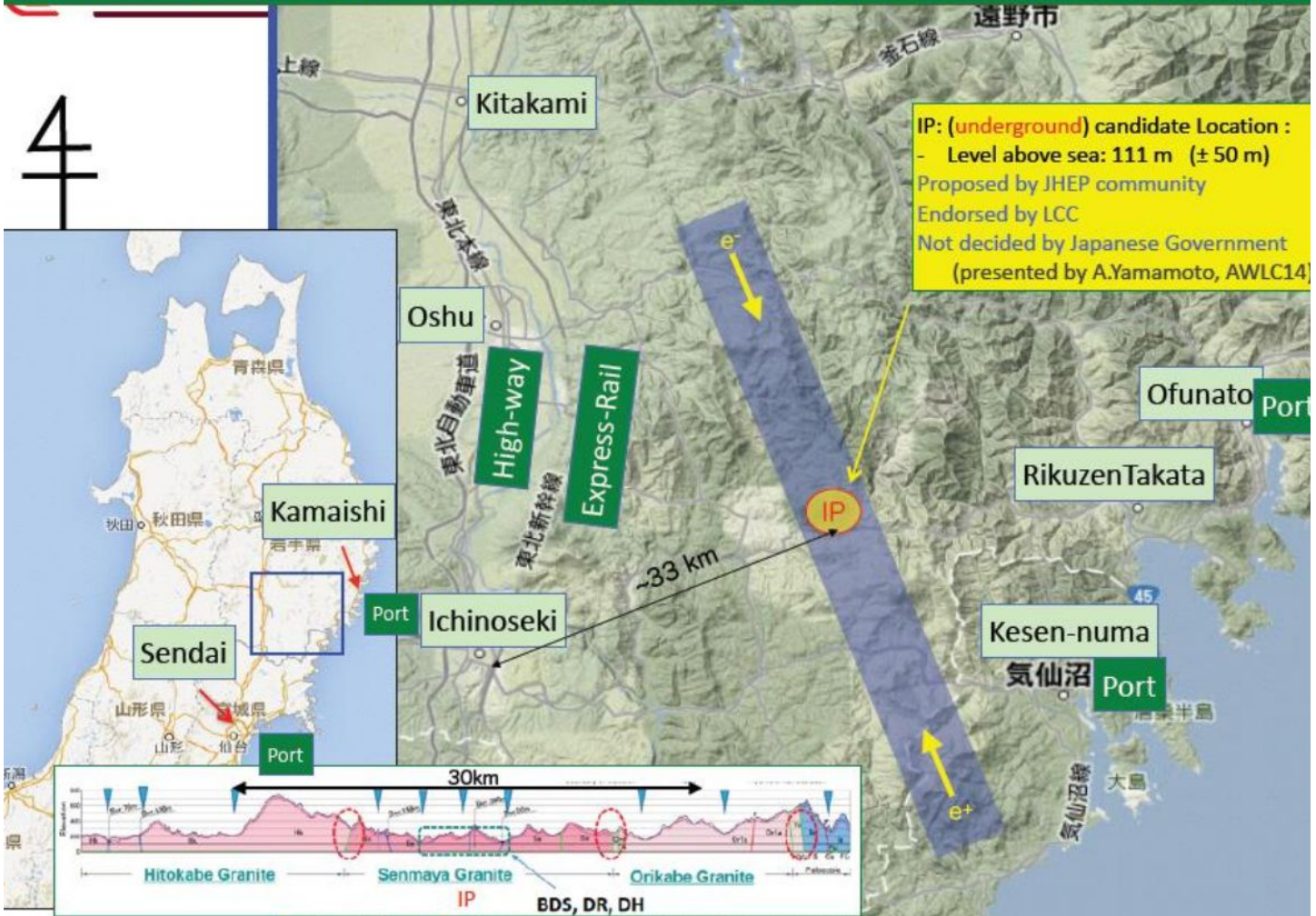
Linear Colliders

International Linear Collider (ILC)

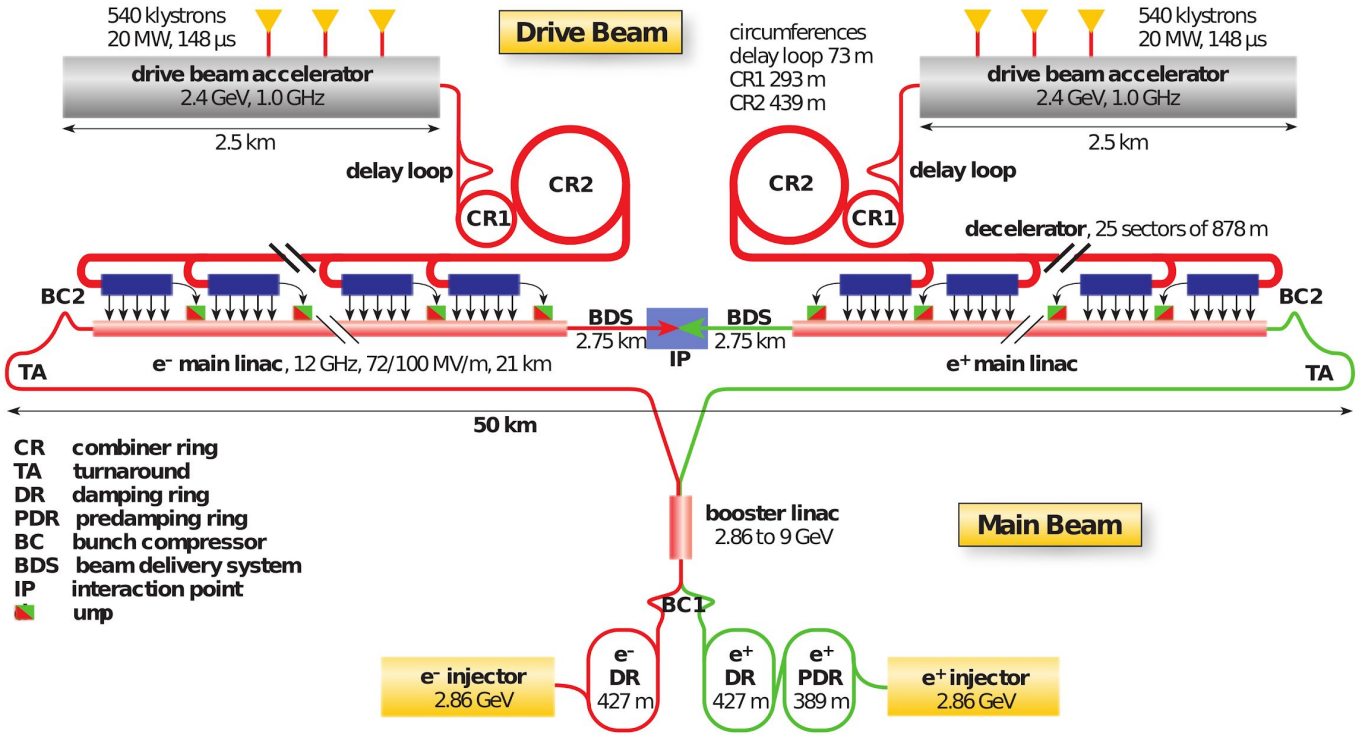


	ILC (500)	
Electrons/bunch	0.75	10**10
Bunches/train	2820	
Train repetition rate	5	Hz
Bunch separation	308	ns
Train length	868	us
Horizontal IP beam size	655	nm
Vertical IP beam size	6	nm
Longitudinal IP beam size	300	um
Luminosity	2	10**34

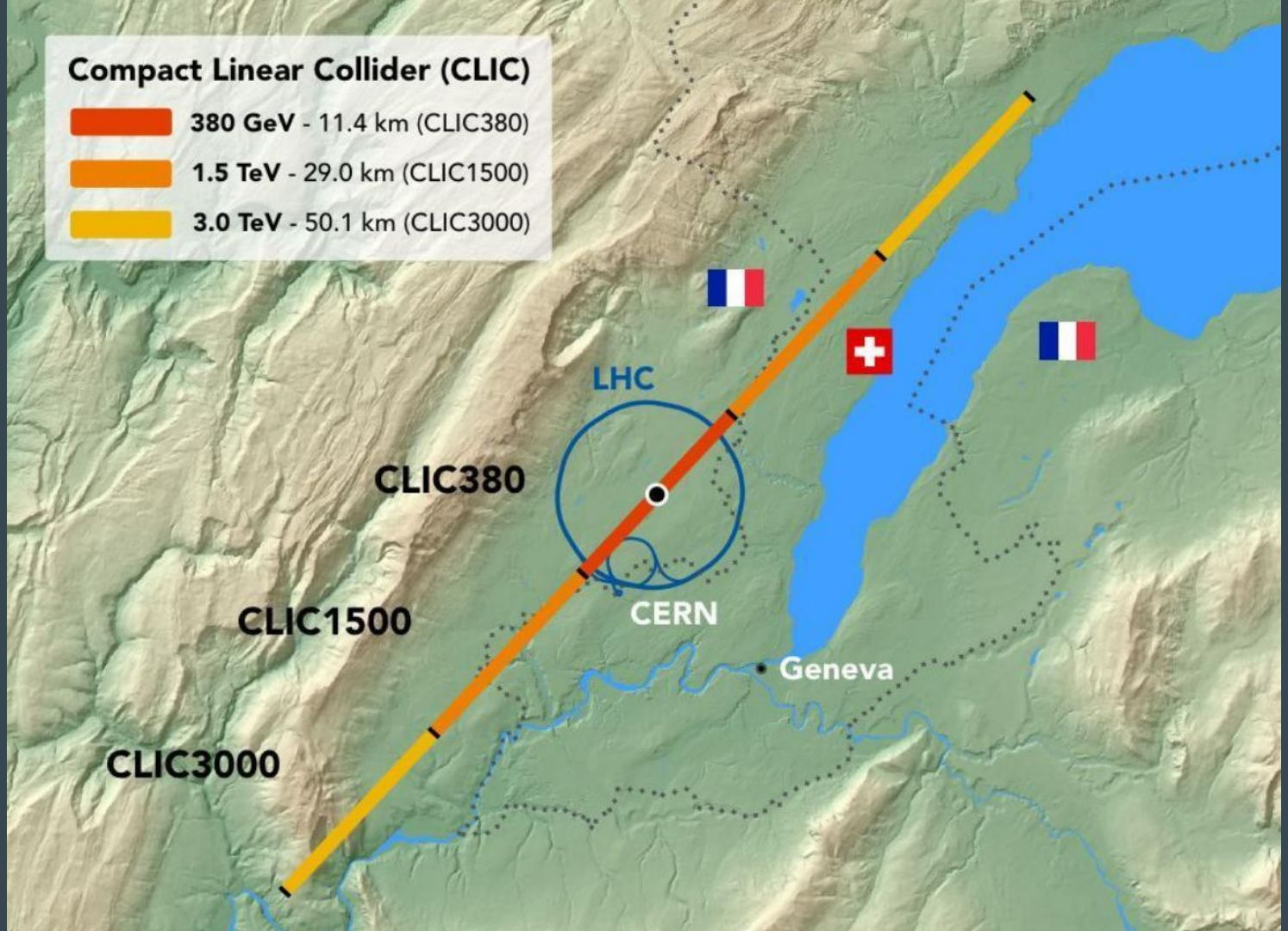
ILC Candidate Location: Kitakami Area



Compact Linear Collider (CLIC)

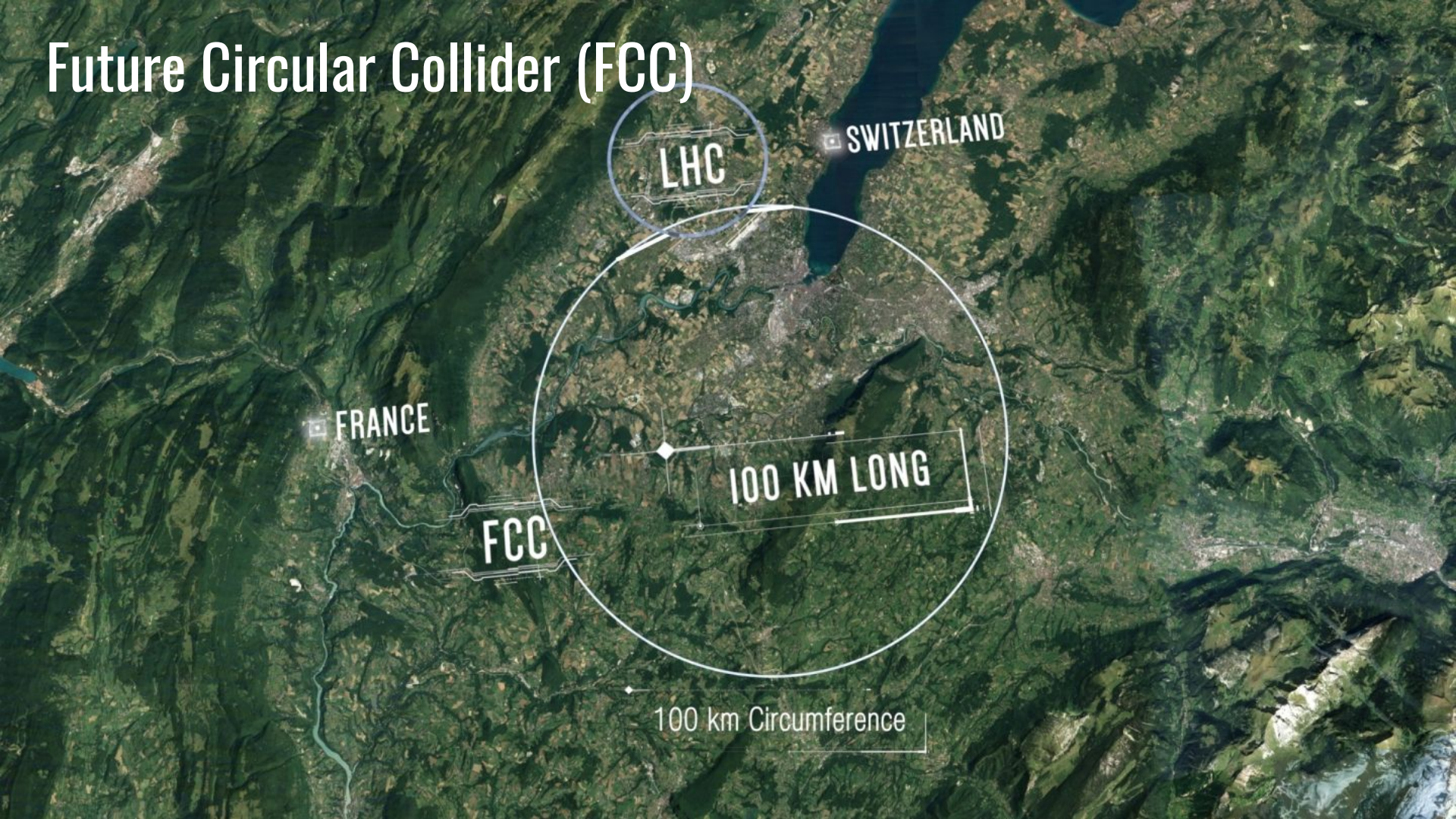


Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_{b}		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^{9}	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

Circular Colliders

Future Circular Collider (FCC)



Two (or three) options: electrons and protons

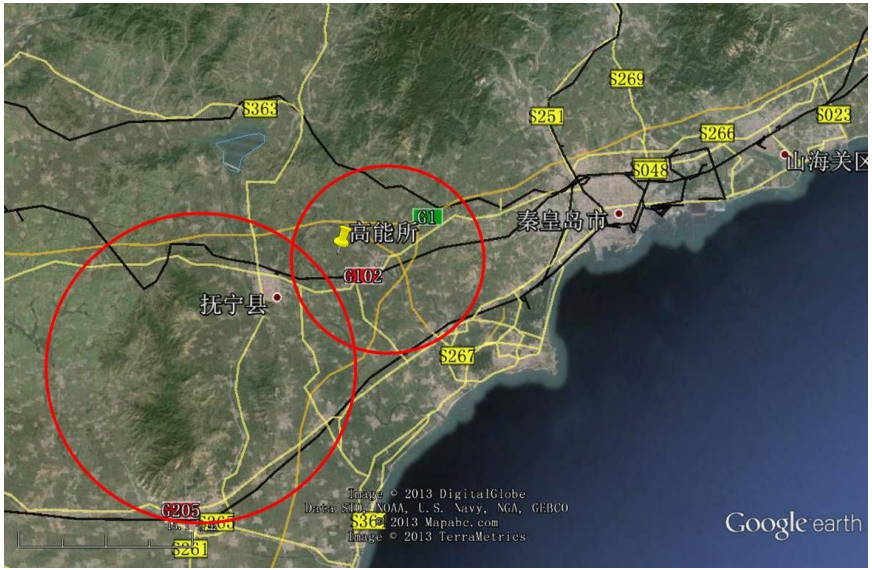
Future Circular Collider (FCC-ee)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4

Future Circular Collider (FCC-hh)

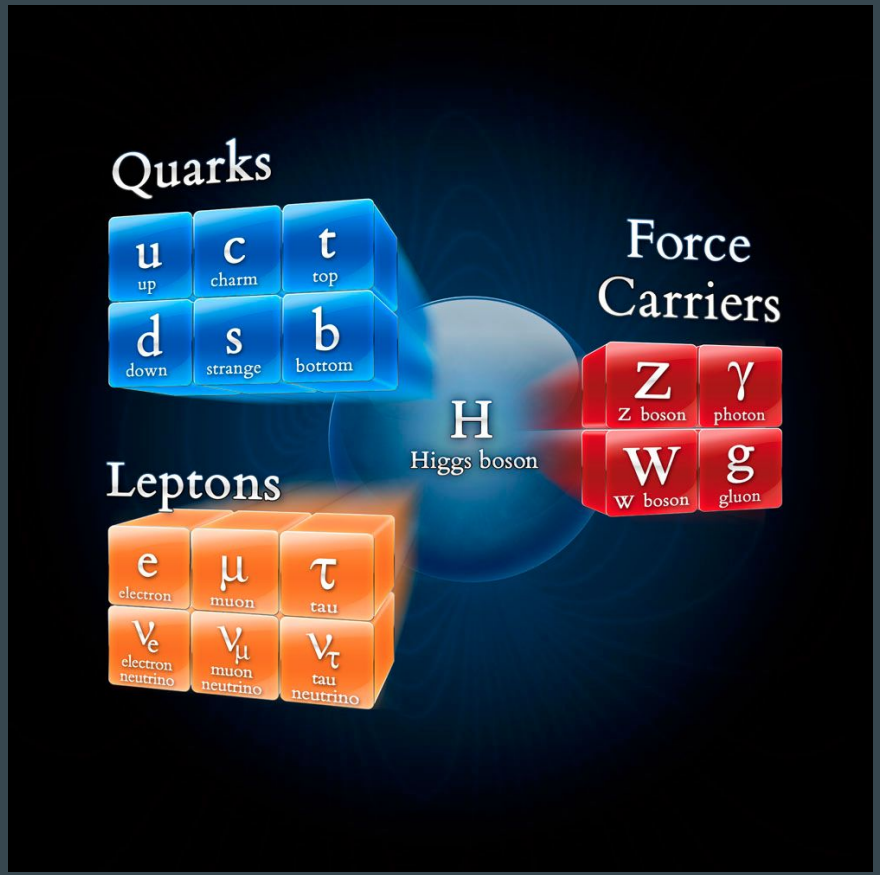
	LHC / HL-LHC	HE-LHC (tentative)	FCC-hh Initial	FCC-hh Ultimate
Cms energy [TeV]	14	27	100	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1 / 5	28	5	20-30
Machine circumference	27	27	97.75	97.75
Arc dipole field [T]	8	16	16	16
Bunch charge	1.15 / 2.2	2.2	1	1
Bunch distance [ns]	25	25	25	25
Background events/bx	27 / 135	800	170	<1020
Bunch length [cm]	7.5	7.5	8	8

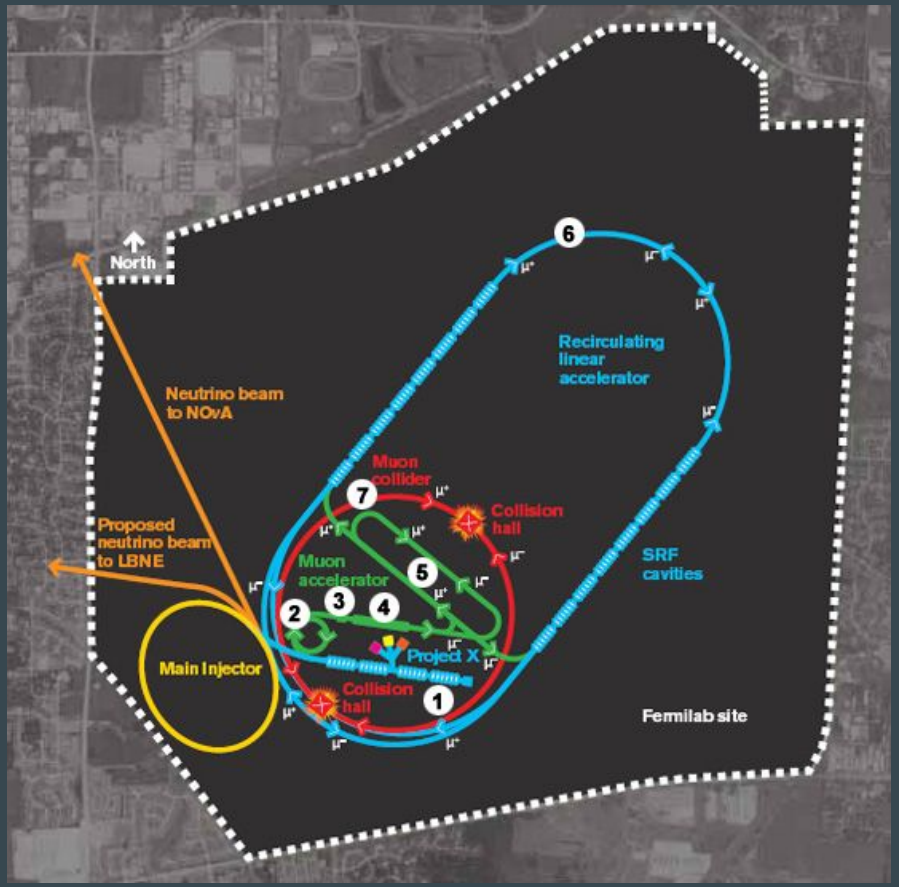
Made in China colliders (CepC and SppS)



Para.	Unit	Value	Para.	Unit	Value
Energy	GeV	120	Circum.	km	54.752
N_e	10^{11}	3.79	N_b/beam		50
Beam current	mA	16.6	SR power /beam	MW	51.7
ε (x/y)	nm	6.12/ 0.018	Bending radius	km	6.094
β_{IP} (x/y)	mm	200/1	σ_x/σ_y (@IP)	μm	70/0.15
$\xi_{x,y}$		0.118/ 0.083	SR loss /turn	GeV	3.11
α_p	10^{-4}	0.336	σ_z	mm	2.88
V_{rf}	GV	6.87	No. of IP		2
ν_s		0.181	f_{rf}	GHz	0.65
δ_{SR}		0.0013	Harm. No.		118712
δ_{BS}		0.0008	$\delta_{BS,\,tot}$		0.00177
n_γ		0.23	τ_{BS}	hr	12.2
F_H		0.692	L /IP	/cm^2/s	2.0×10^{34}

None of the above: the muon collider



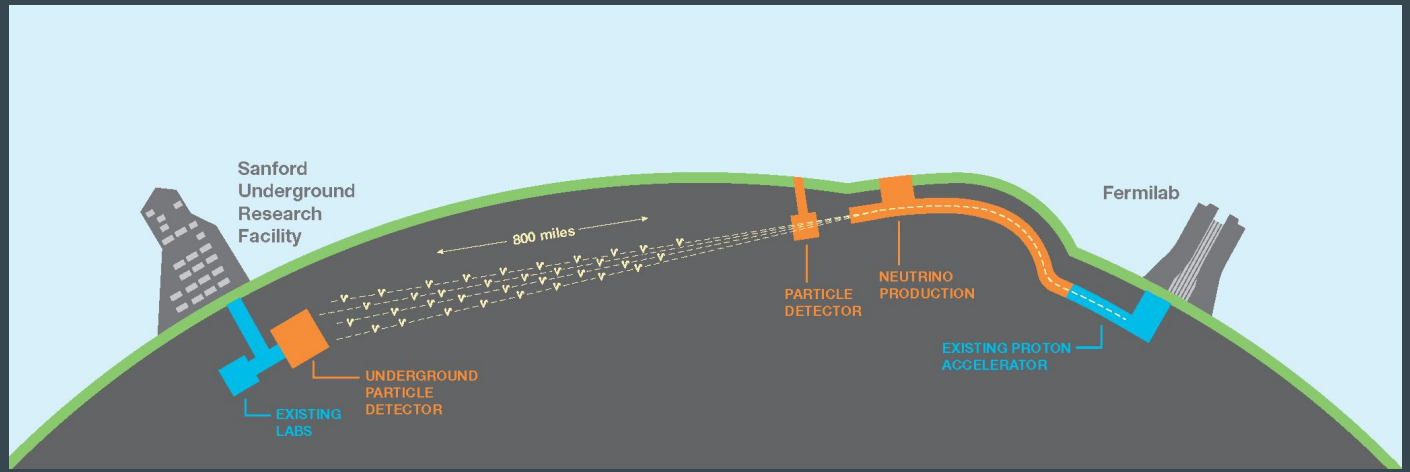


Project comparison

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

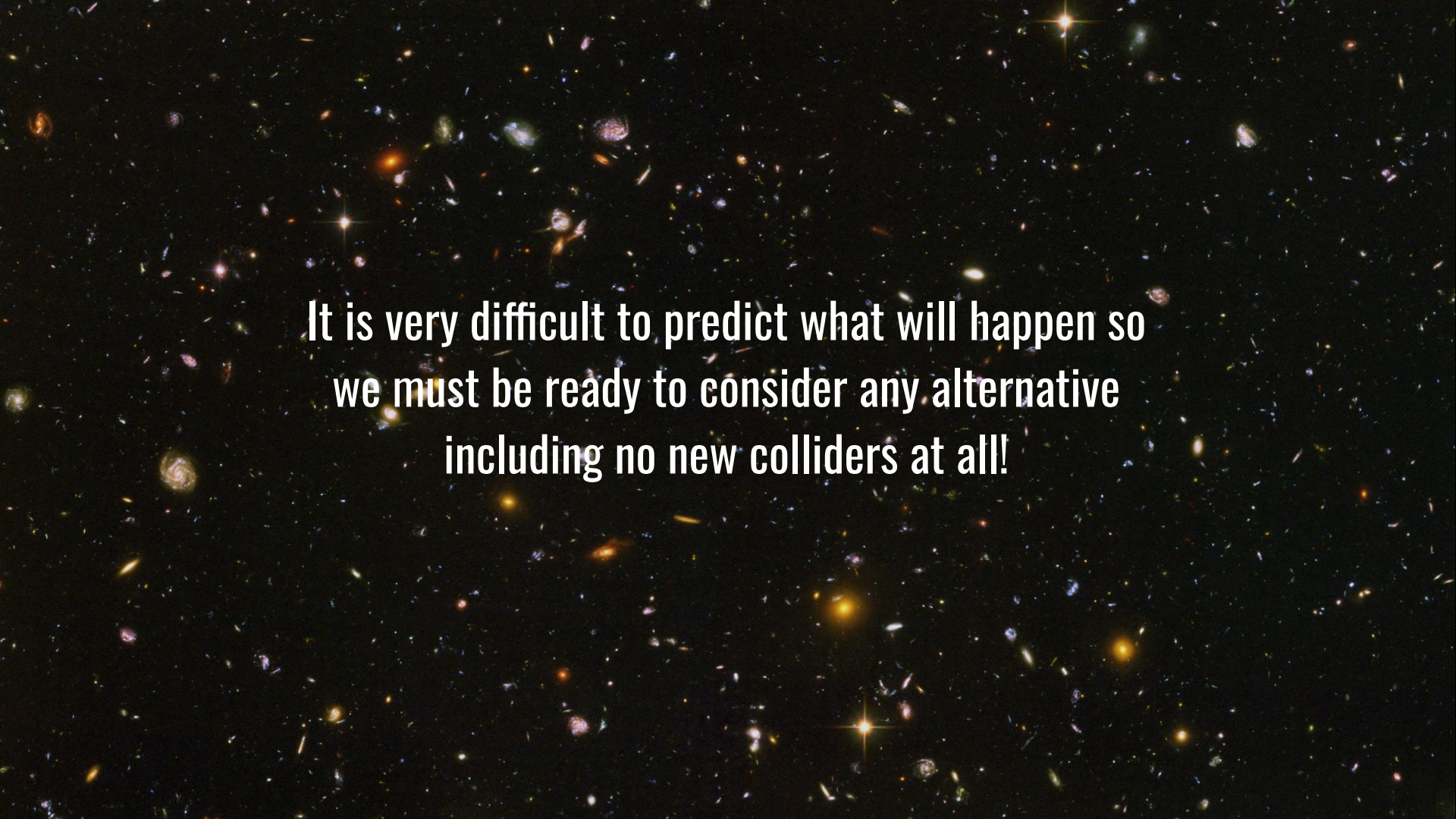
Other options not included in this talk

- Novel acceleration techniques: AWAKE (previous session)
- Neutrino platforms (DUNE)



Summary

- Many options considered (circular, linear, protons, electrons...)
- In different formats (energy, size, technology)
- Preliminary designs are ready for final consideration.
- European Strategy on Particle Physics will be updated next year.


It is very difficult to predict what will happen so
we must be ready to consider any alternative
including no new colliders at all!

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Thank you very much!

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