

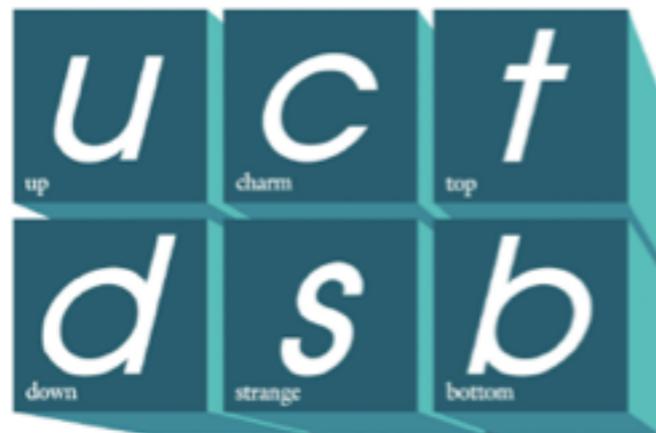
**Unveiling the Secrets of Nature -
An outlook on fundamental
physics in 100 years**

**Planck 2017 - Warsaw
May 23rd, 2017
Markus Klute (MIT)**

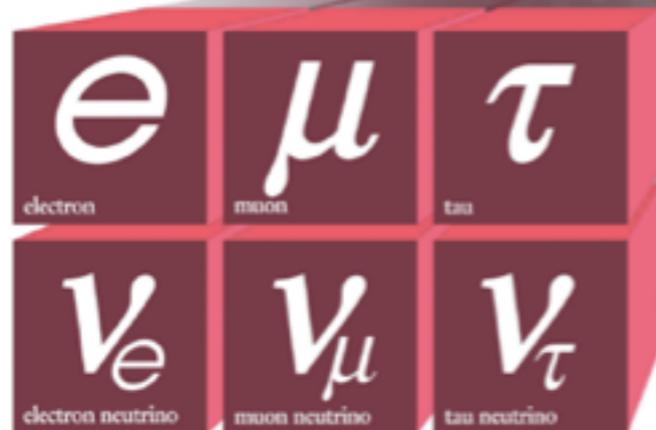
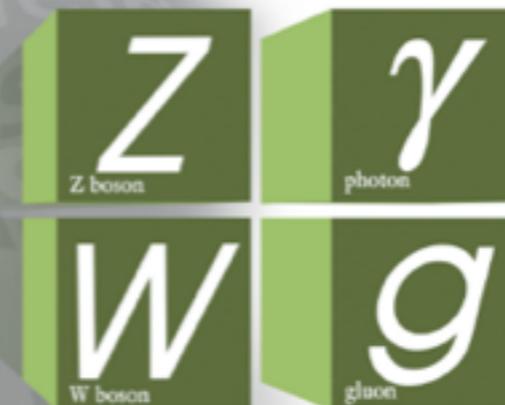
Fundamental Physics Today

Complete theory valid to very high energies

Quarks



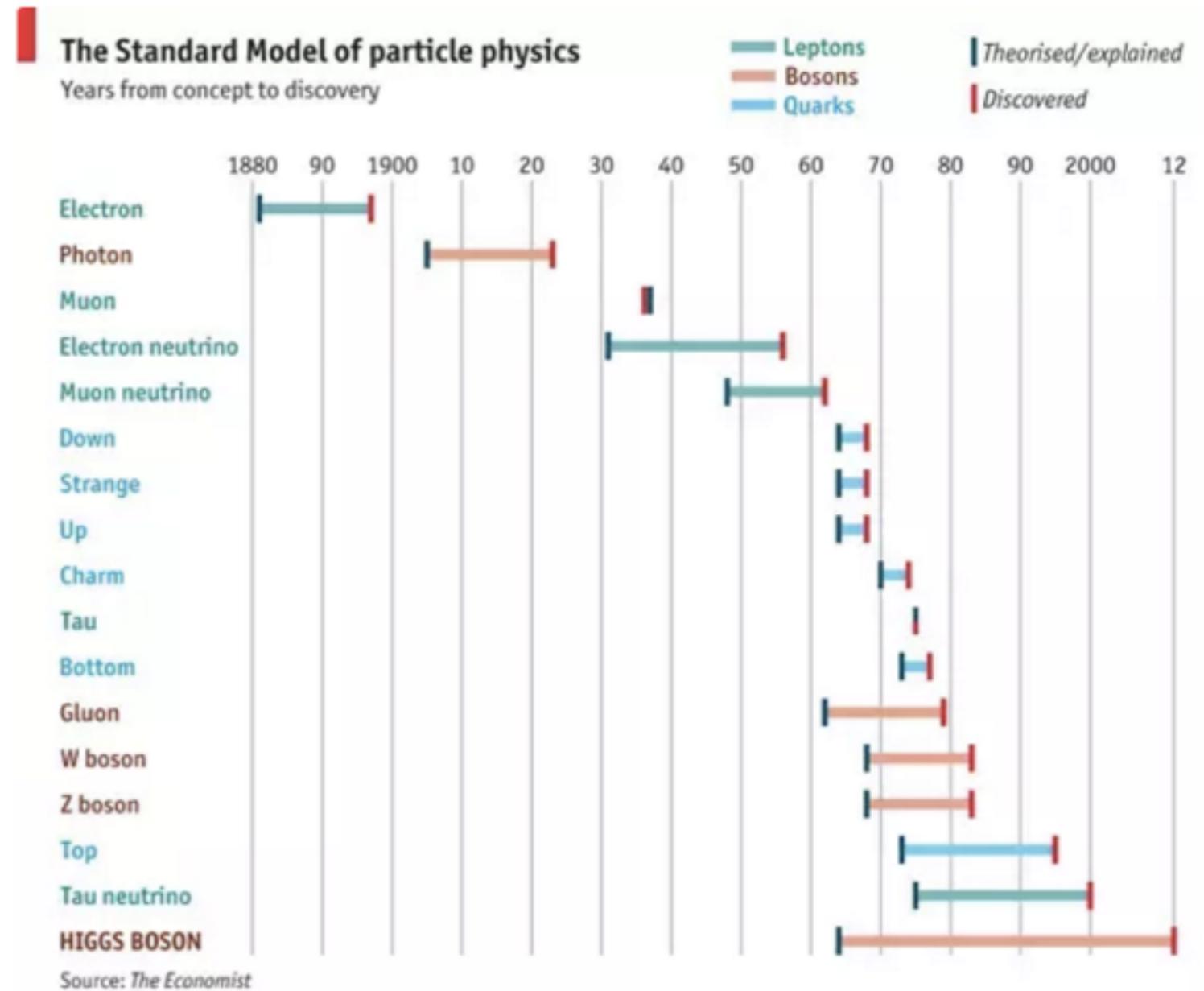
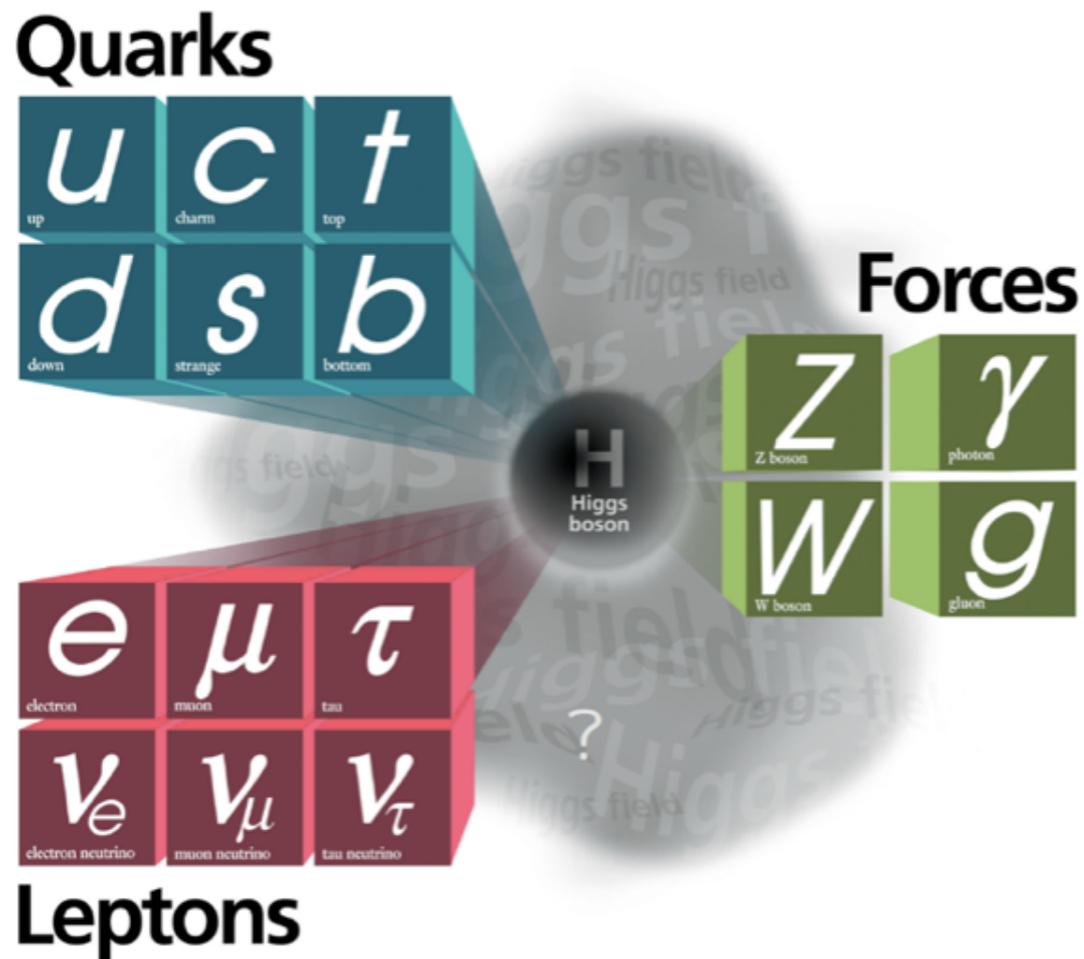
Forces



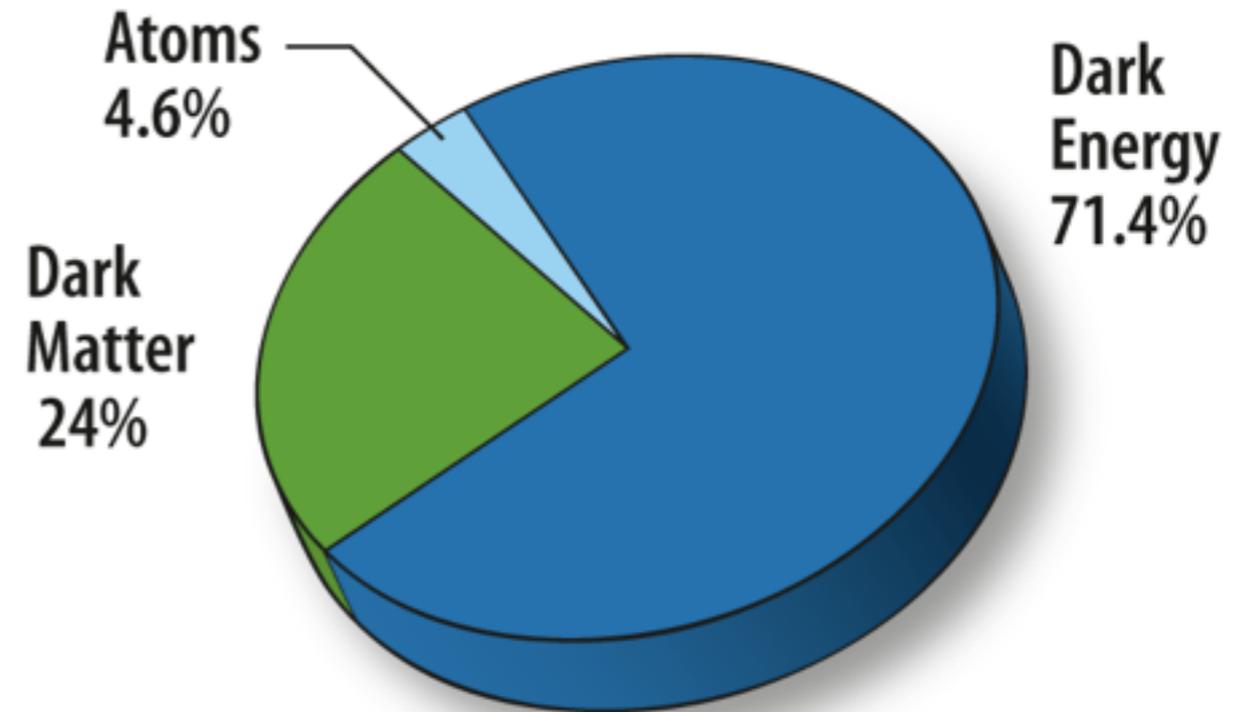
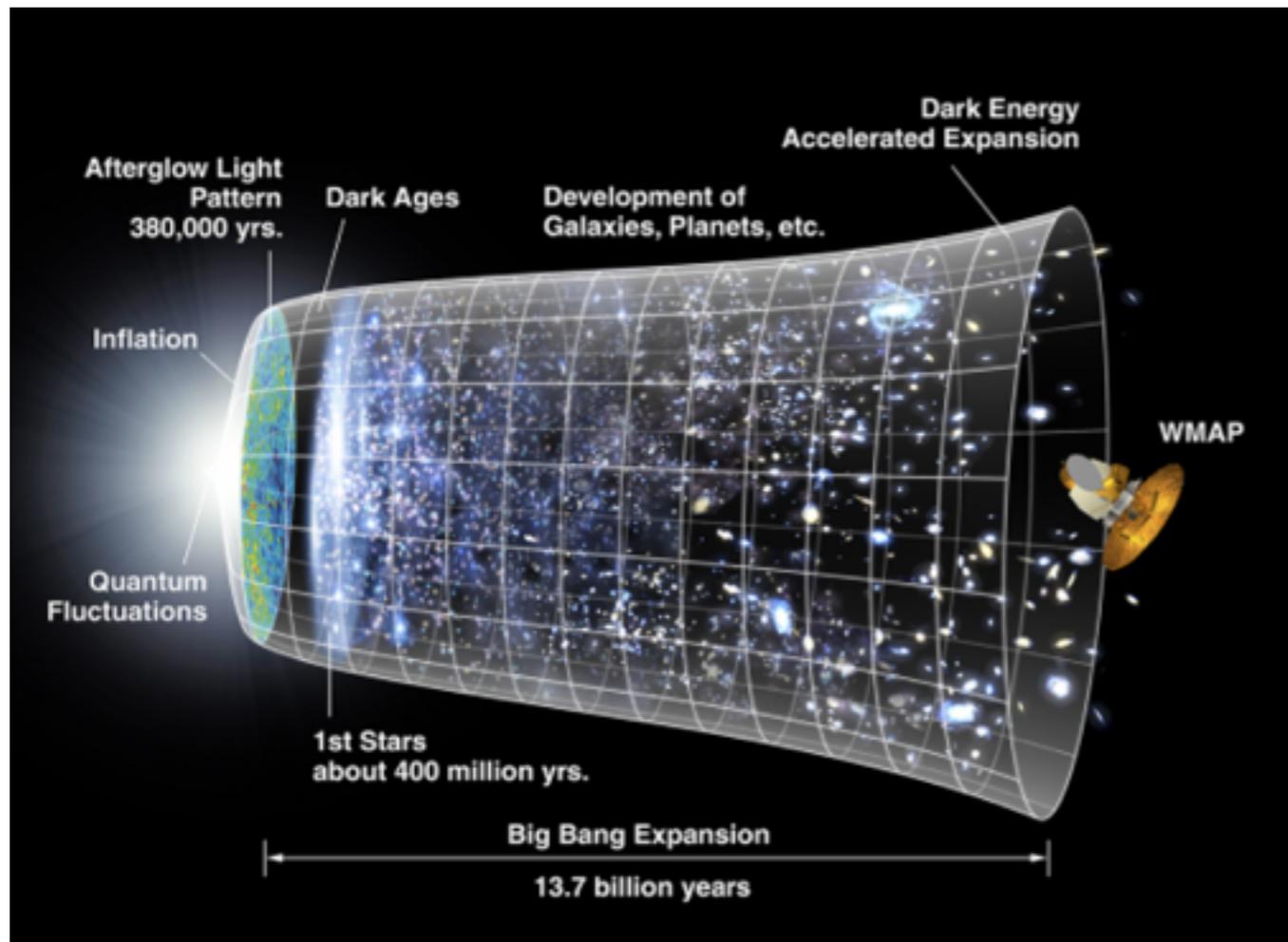
Leptons

Fundamental Physics Today

Complete theory valid to very high energies



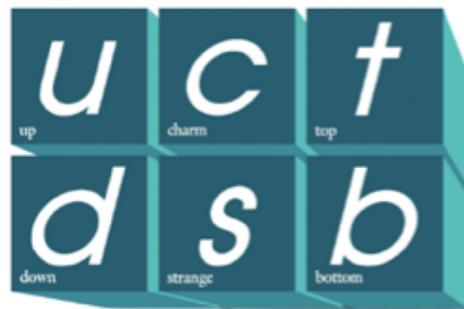
Fundamental Physics Today



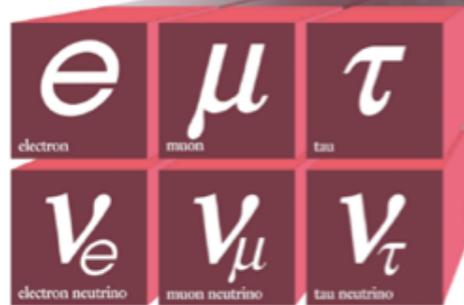
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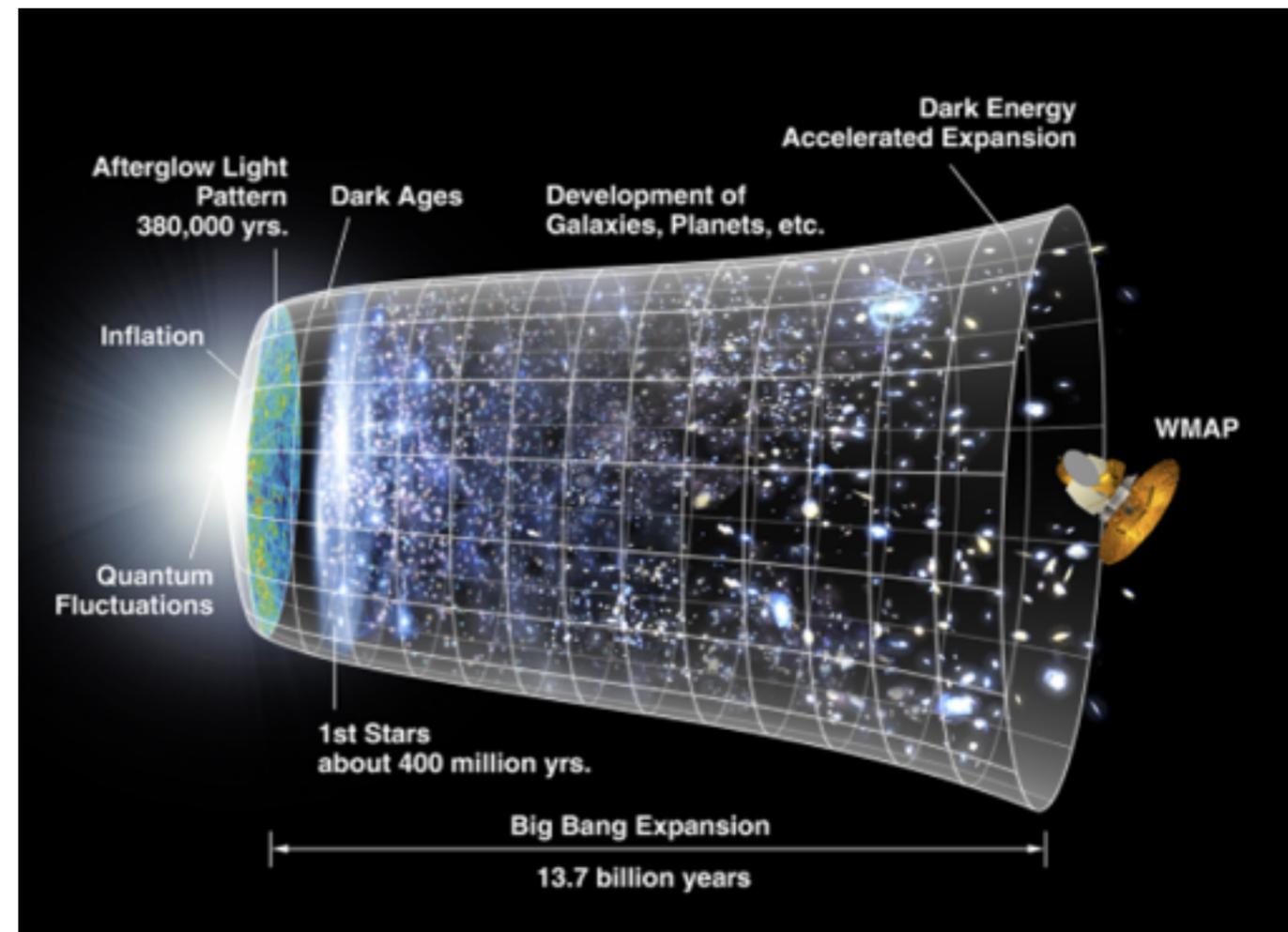
Quarks



Forces



Leptons



Fundamental Physics Today



Is this the end?

Of course not!

Is there anything new to be discovered?

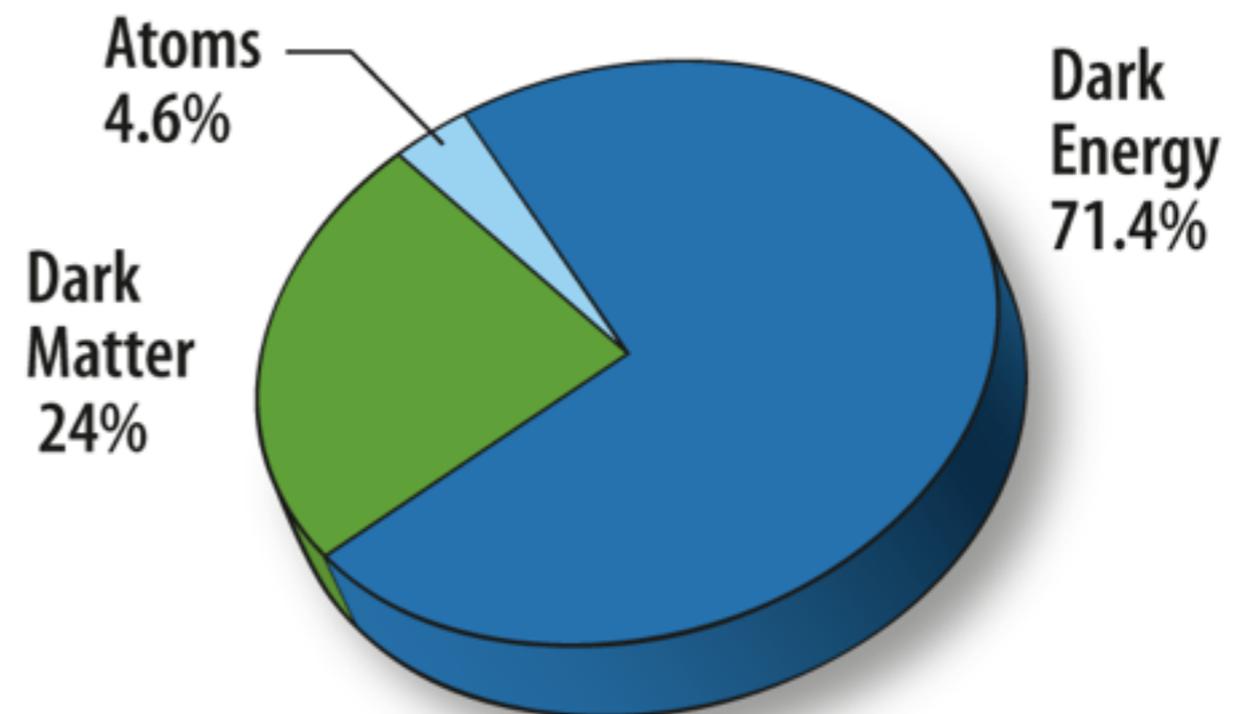
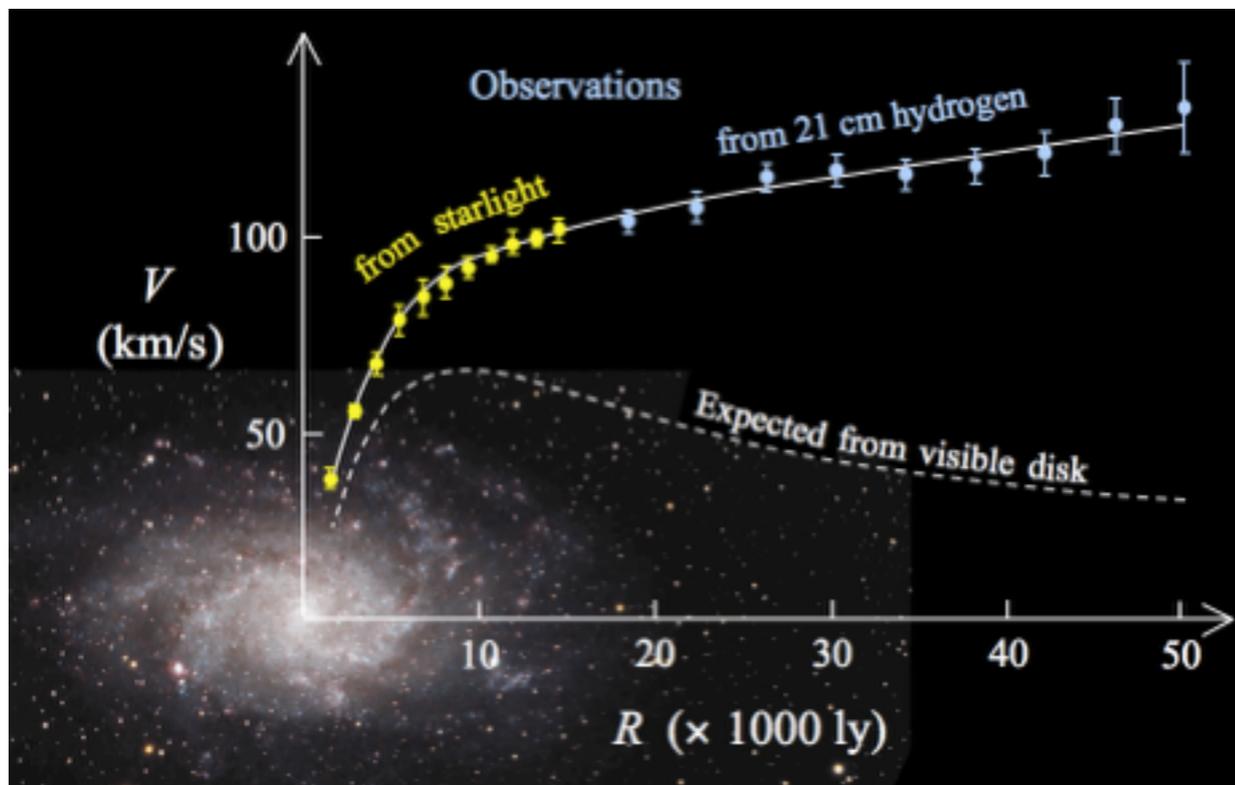
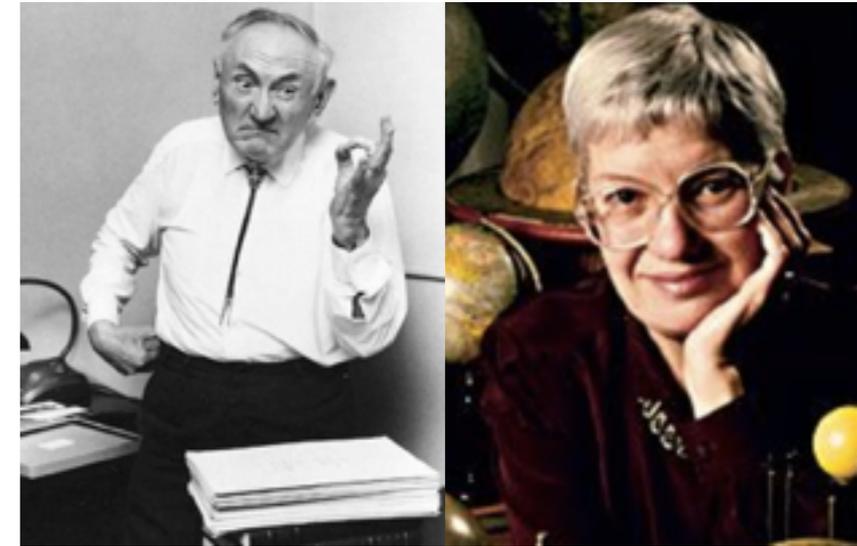
Of course!

- ➔ **The SM fails to explain important observations**
- ➔ **Experimental proof for physics beyond the SM**
 - ⊙ Cosmological dark matter (DM)
 - ⊙ Baryon asymmetry
 - ⊙ Non-zero, but very small neutrino mass
 - ⊙ A hint: the small Higgs boson mass is rather unnatural

Fundamental Physics Today

→ Dark Matter: the matter we can not see

- first proposed as a concept by Oort and Zwicky in the ~1930th
- confirmed by Rubin and Ford in galaxy rotation curves ~1960-70th
- evidence through gravitational effects only
- leading candidate: weakly interacting massive particle



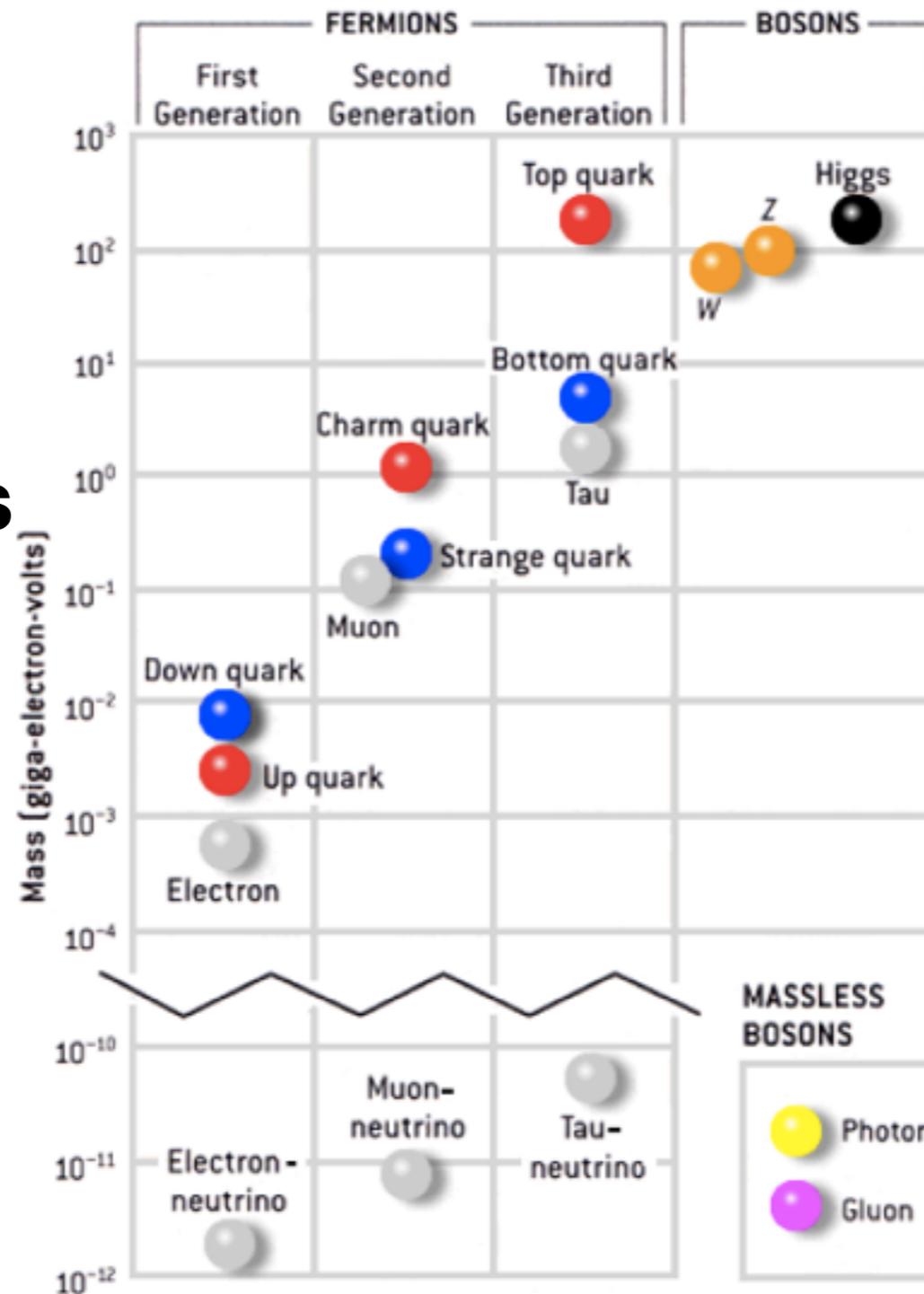
Fundamental Physics Today

➔ Baryon matter asymmetry



Fundamental Physics Today

How do particles acquire mass?



Why do they have these masses?

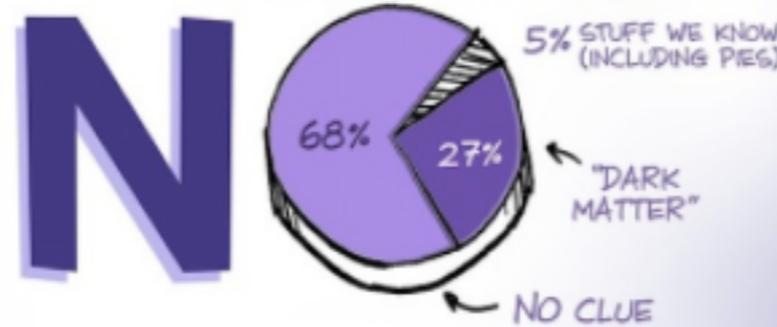
Why are neutrino masses tiny?

JORGE CHAM & DANIEL WHITESON

WE HAVE



THE UNIVERSE: (A PIE CHART)



IDEA

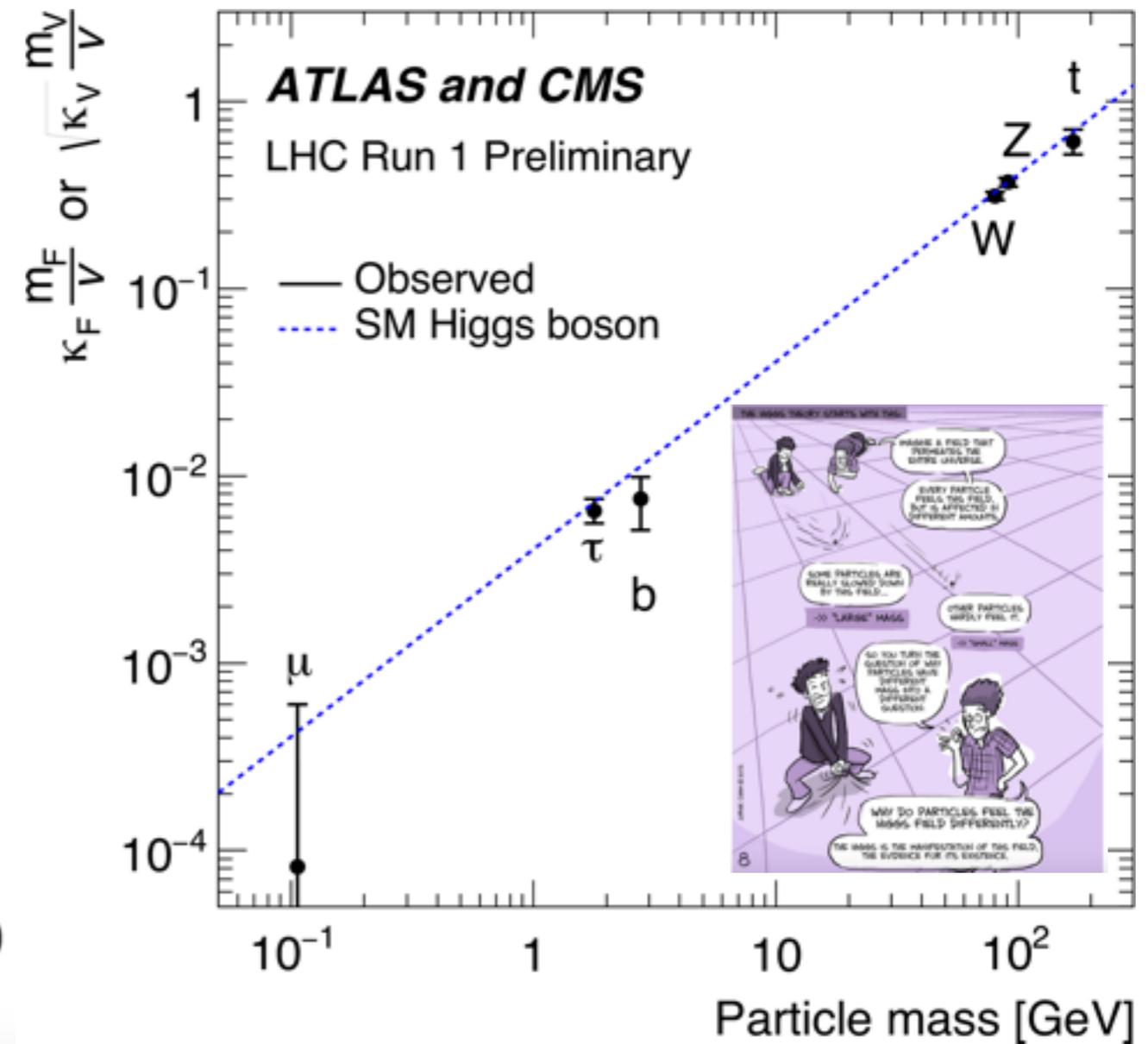
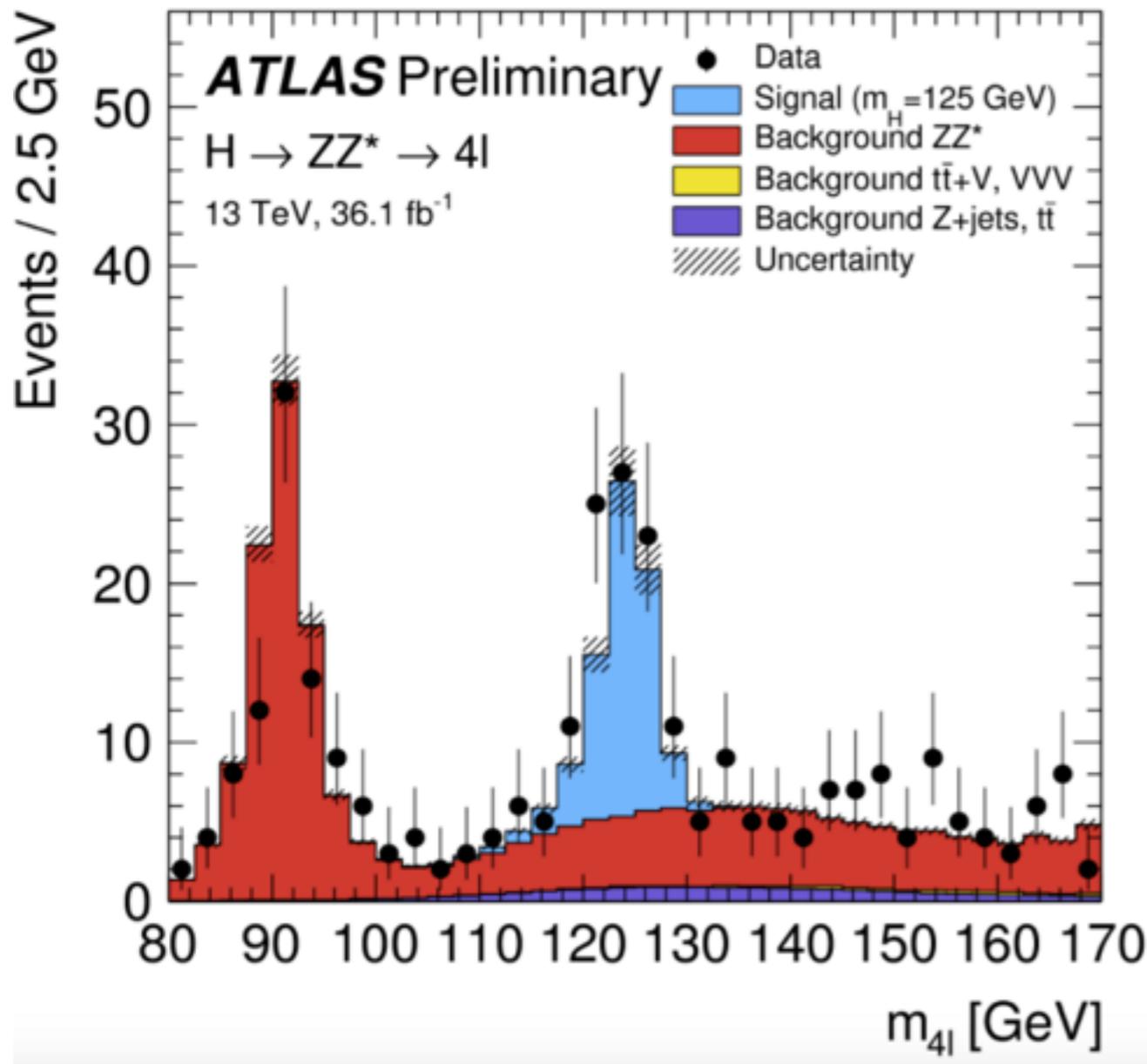


A GUIDE TO
THE UNKNOWN UNIVERSE



Fundamental Physics Today

- ➔ Standard model did not only predict the outcome of scattering experiments, but also the existence of a new particle and its properties - **the Higgs boson**



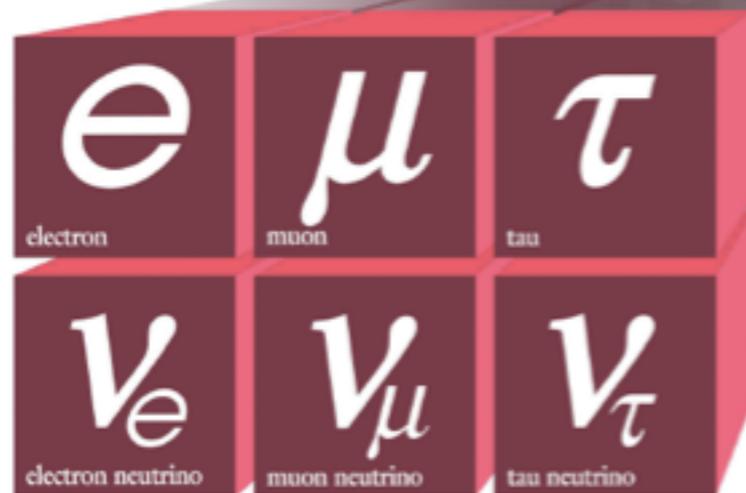
Fundamental Physics Today

Quarks



Complete theory valid to very high energies

Forces



Leptons

... but it is not enough

Experimental Approach

Study particle interaction, resulting reaction products and features
Measure energy, direction and identity of collision products

➔ **The highest energies allows us to**

- look deep into matter “powerful microscope”: $E \sim 1/\text{size}$



de Broglie

Experimental Approach

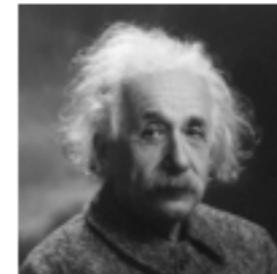
Study particle interaction, resulting reaction products and features
Measure energy, direction and identity of collision products

➔ The highest energies allows us to

- look deep into matter “powerful microscope”: $E \sim 1/\text{size}$
- produce heavy particles: $E = mc^2$



de Broglie



Einstein

Experimental Approach

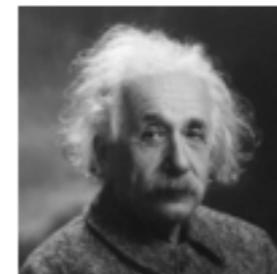
Study particle interaction, resulting reaction products and features
Measure energy, direction and identity of collision products

➔ The highest energies allows us to

- look deep into matter “powerful microscope”: $E \sim 1/\text{size}$
- produce heavy particles: $E = mc^2$
- probe conditions of the early universe: $E = kT$



de Broglie



Einstein



Boltzmann

Experimental Approach

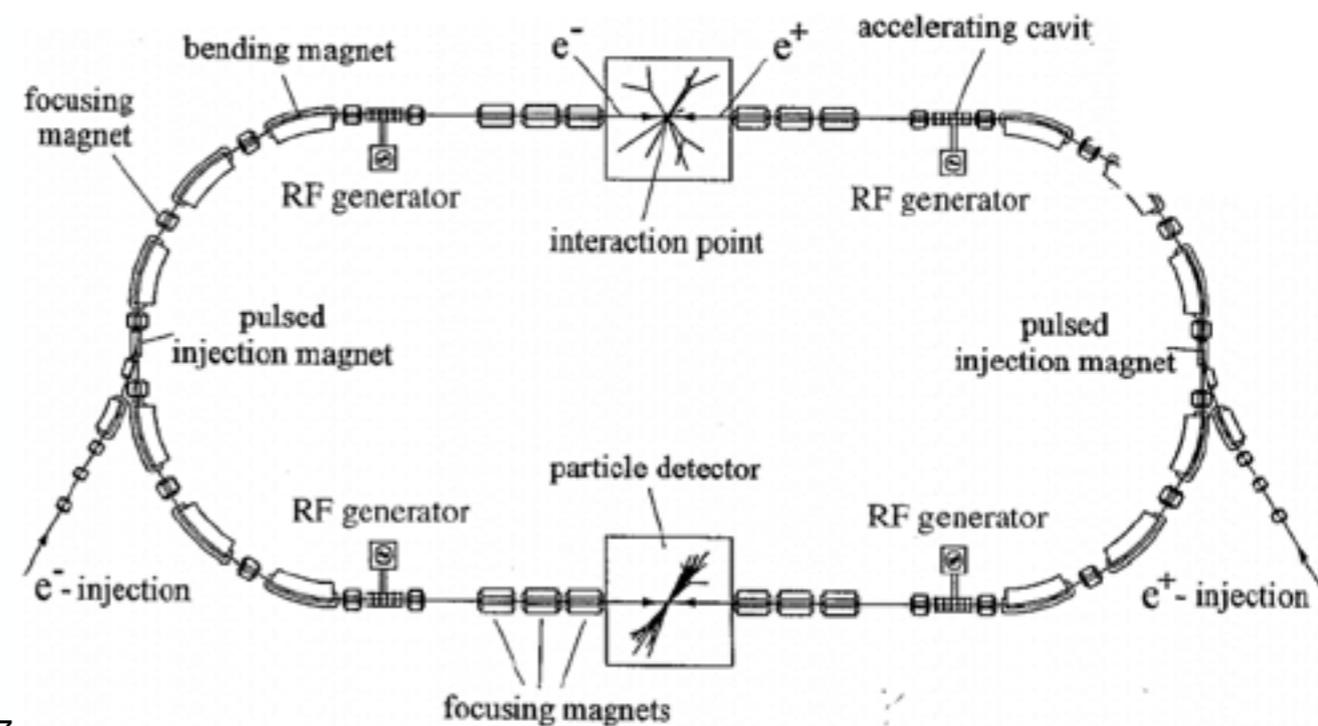
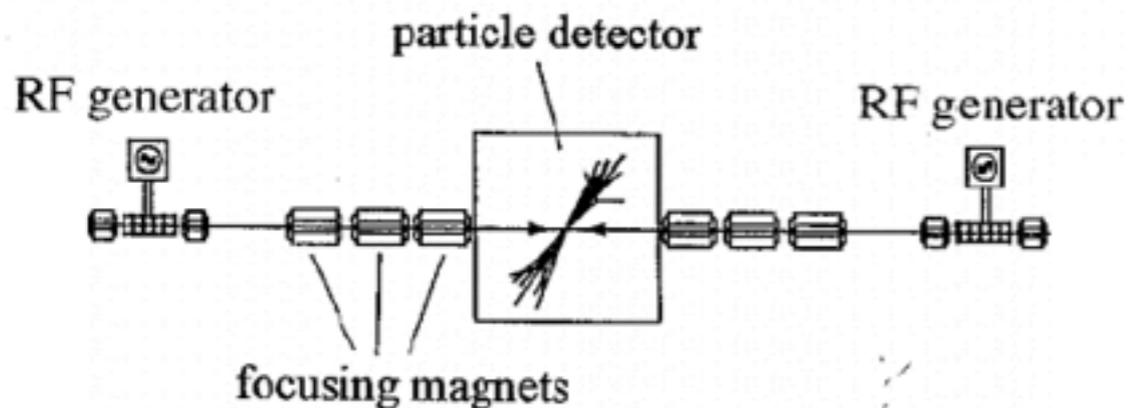
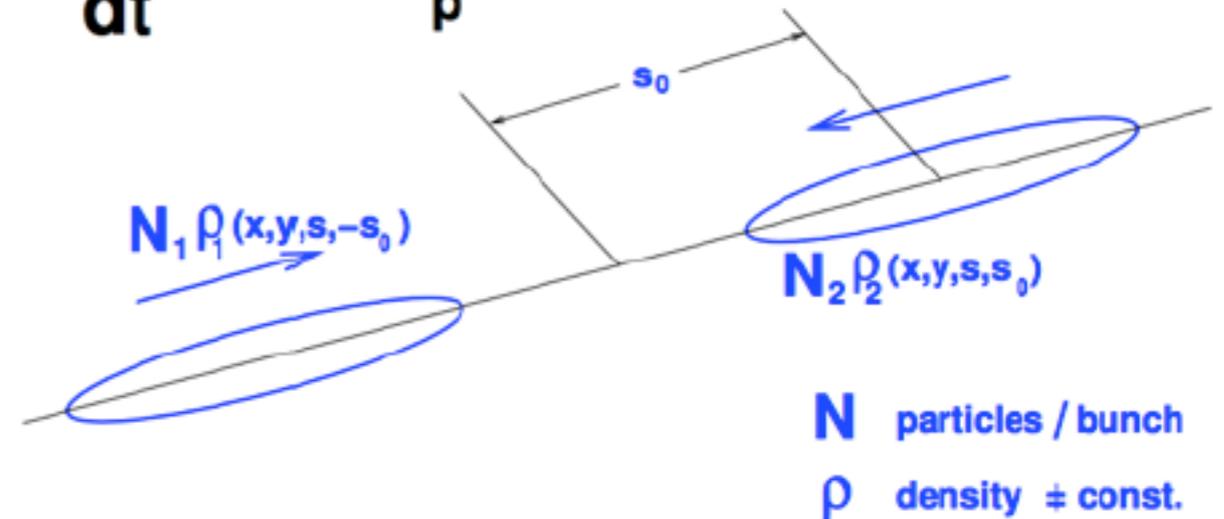
➔ Elements of collider

Key collider parameter

$$E_{\text{cm}}^2 = (E_1 + E_2)^2$$

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

$$\frac{dR}{dt} = L \sigma_p$$



Experimental Approach

➔ Linear vs Circular

- ❖ no synchrotron radiation
- ❖ no bending magnets
- ❖ currents and focusing are limiting L
- ❖ gradients are limiting E
- ❖ limited to one experiment

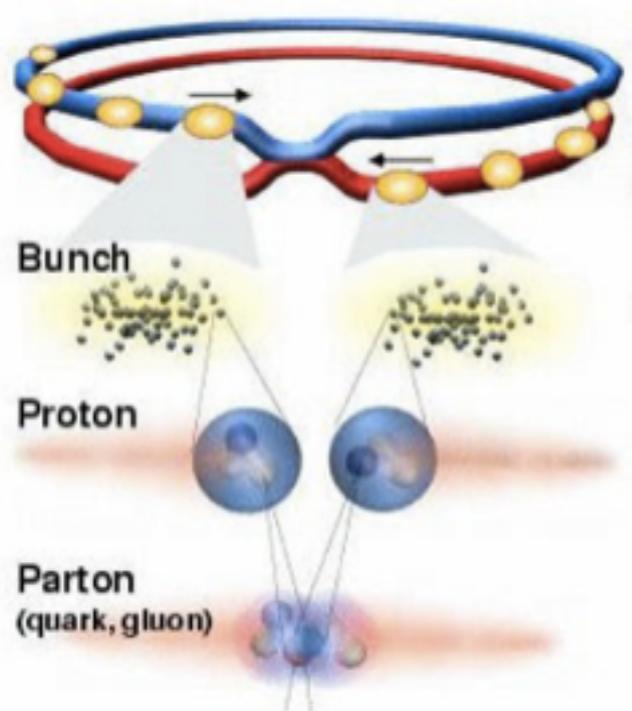
- ❖ accelerate over long distance by repetition
- ❖ recycle particles not used in collisions
- ❖ in principle, this leads to larger L and E

$$P_{\text{radiation}} = \frac{c}{6\pi\epsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

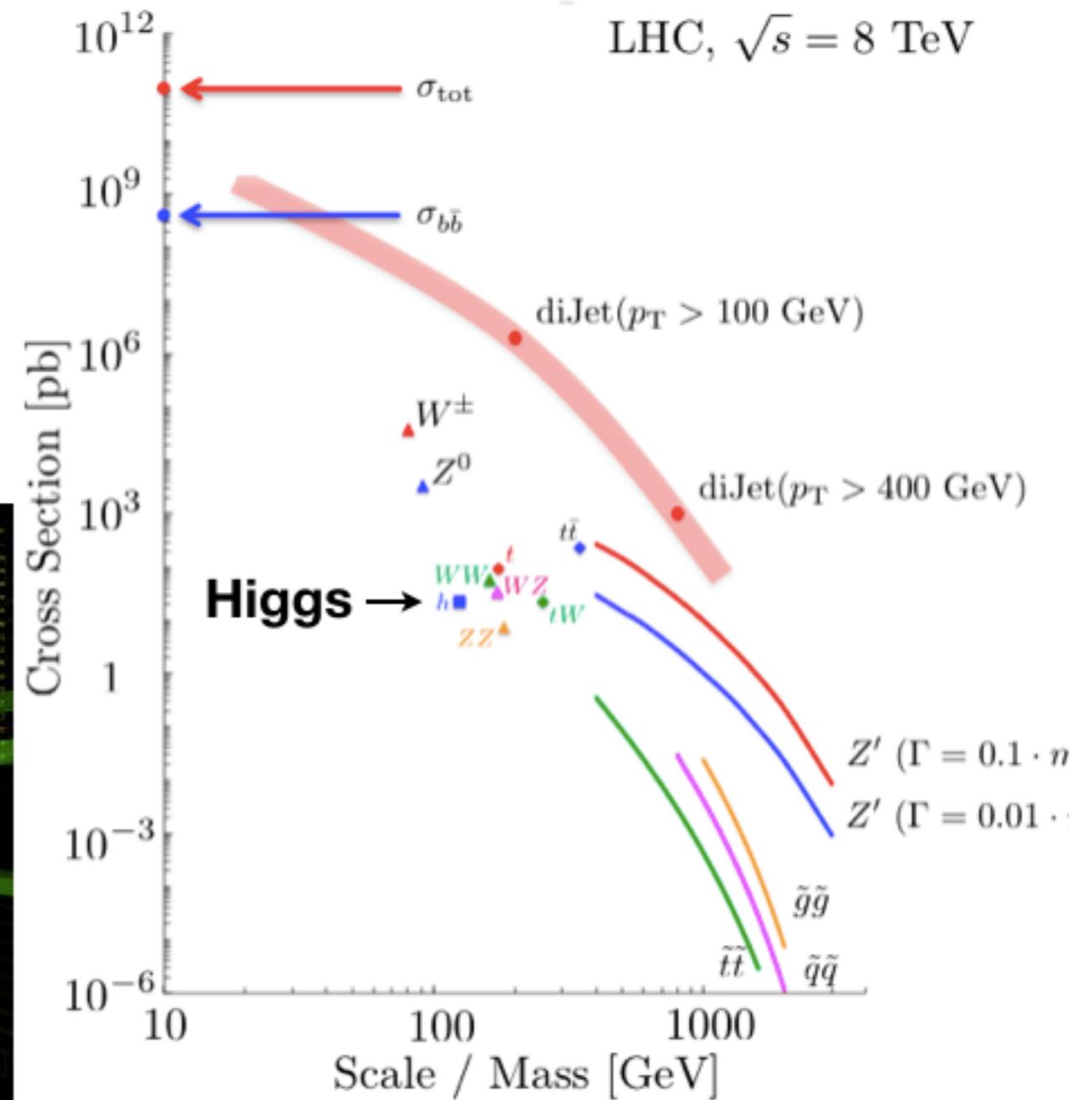
Energy needed to compensate
Radiation becomes too large

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \text{The rings become too long}$$

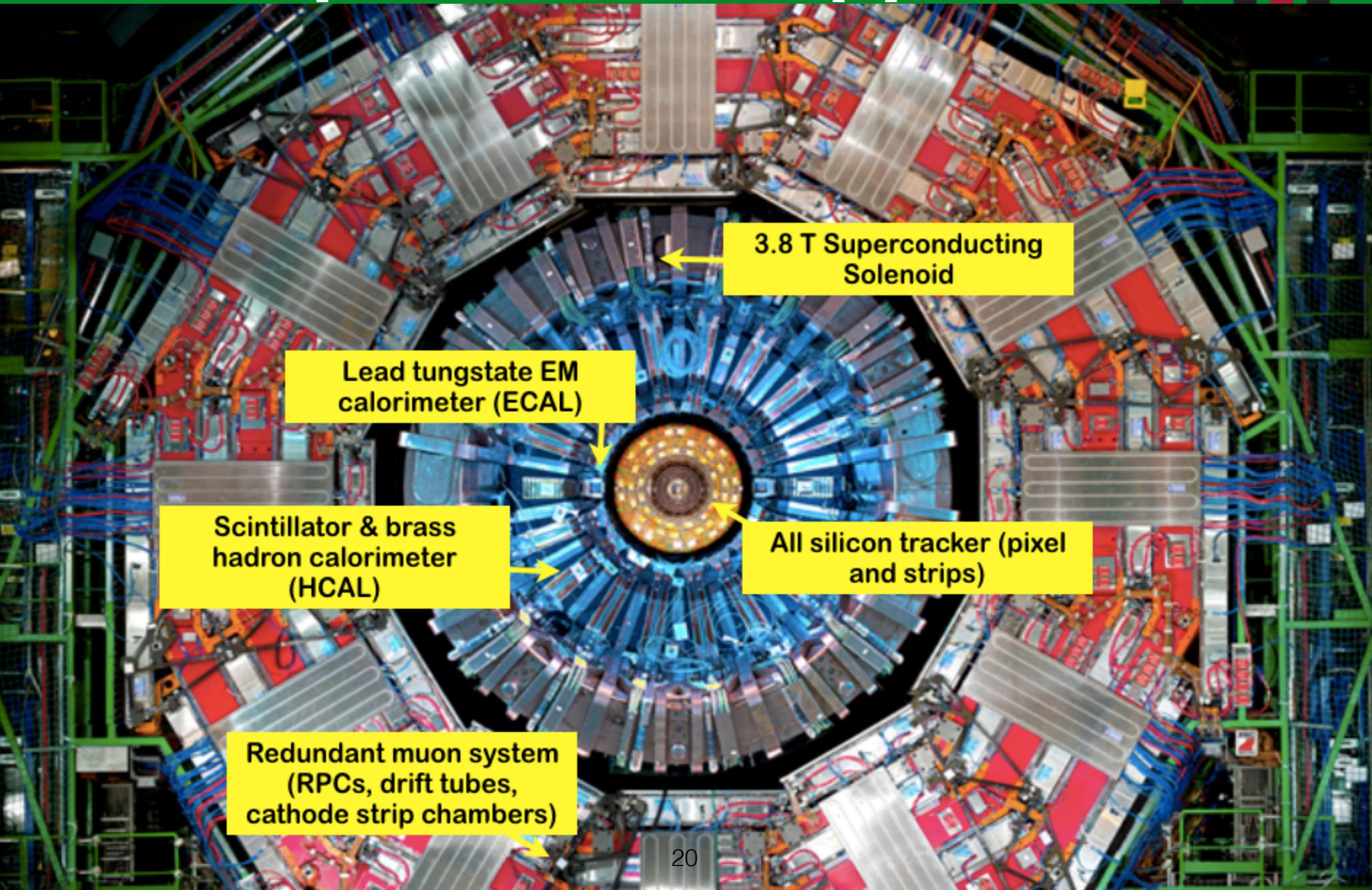
Experimental Approach



1 barn = 10^{-24} cm²



Experimental Approach



3.8 T Superconducting Solenoid

Lead tungstate EM calorimeter (ECAL)

Scintillator & brass hadron calorimeter (HCAL)

All silicon tracker (pixel and strips)

Redundant muon system (RPCs, drift tubes, cathode strip chambers)

Experimental Approach



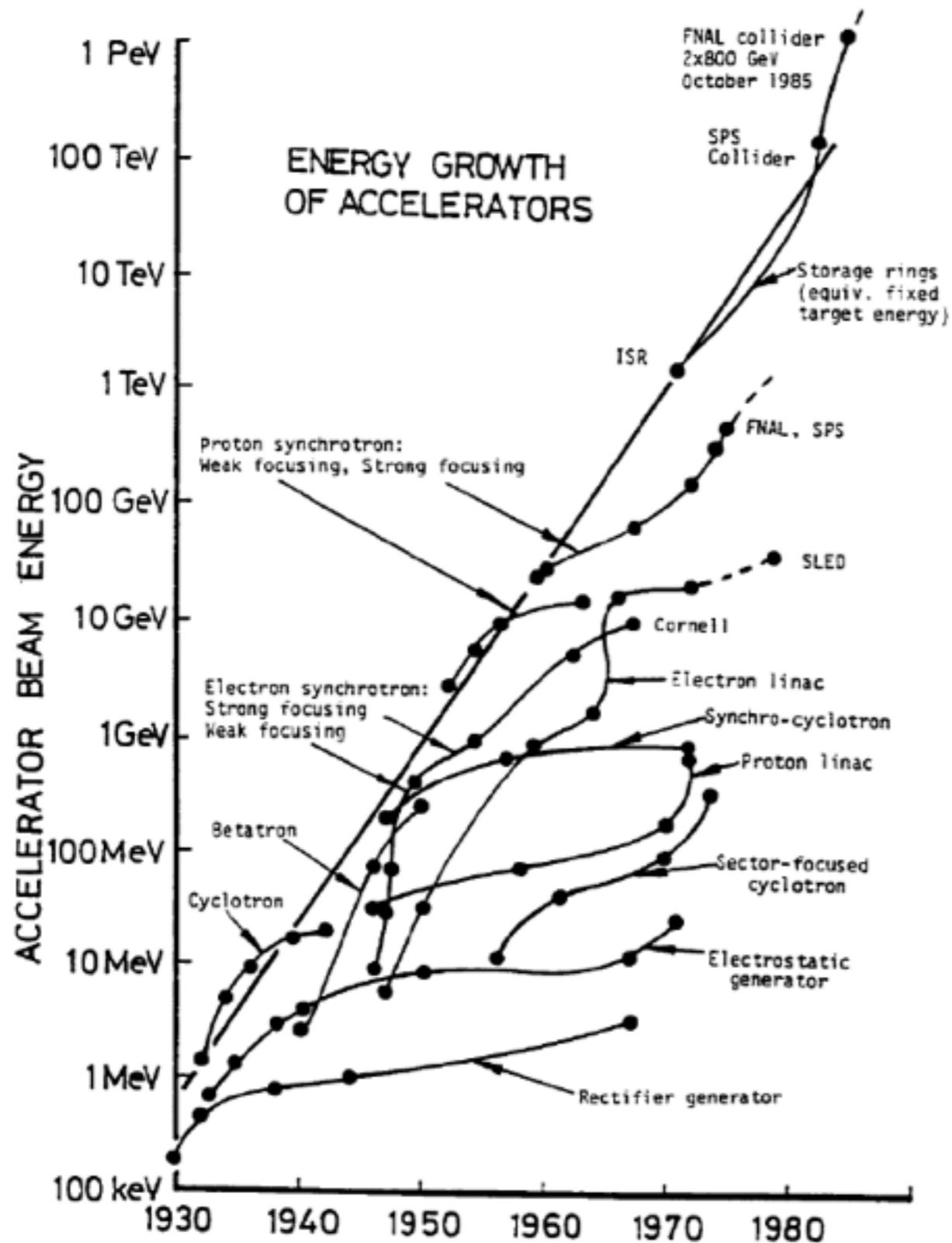
➔ Hadron vs Lepton Collider

"Every event at a lepton collider is physics, every event at a hadron collider is background."

- Sam Ting.

"All events (background) are equal but some events are more equal than others."
- George Orwell (Klute-fied)

Roadmap for Particle Physics



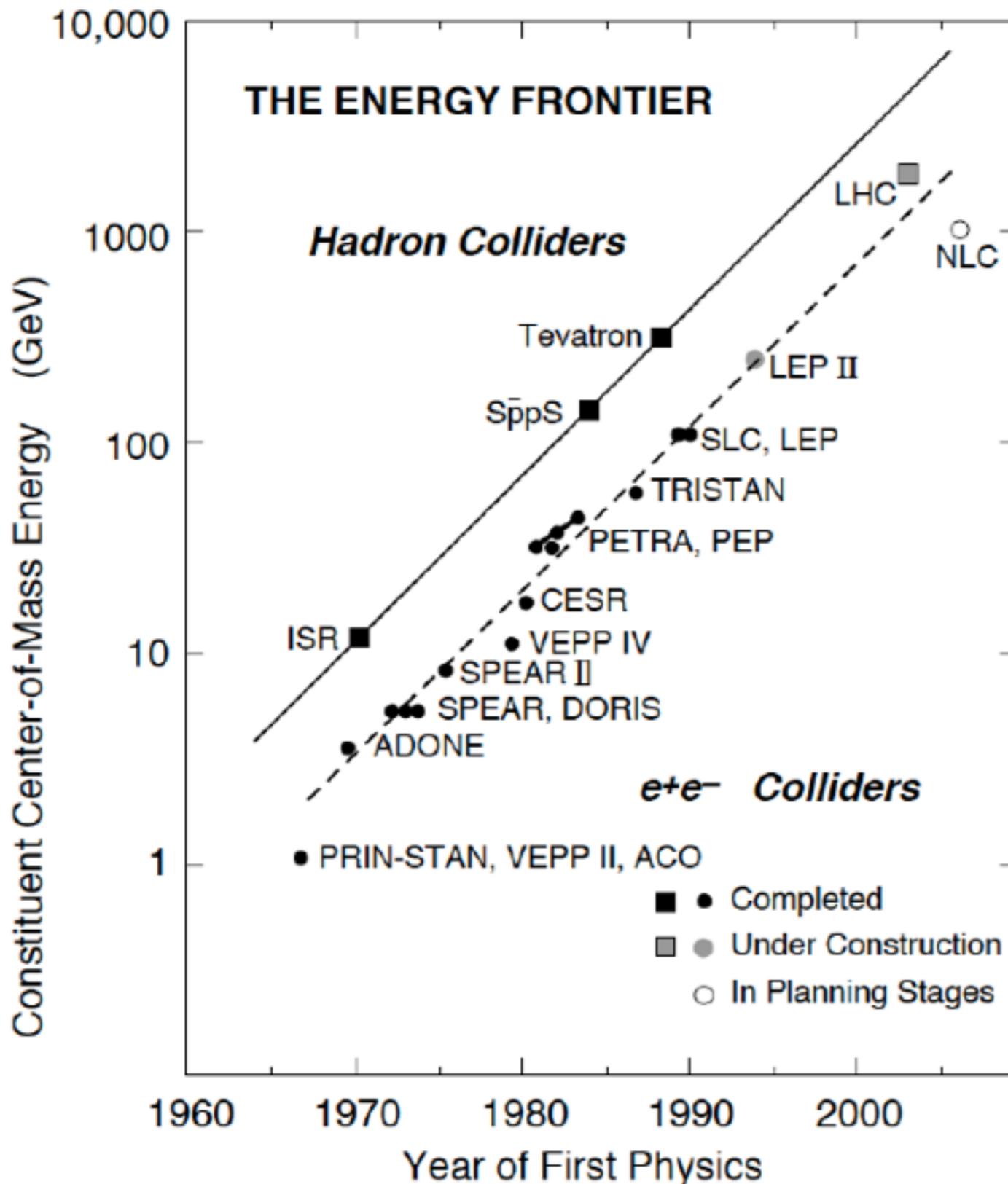
➔ Using history as a guide for the future

- The last ~100 year in particle physics with collider

➔ Livingston Plot ~1985

- nearly 6 decades of growth
- driven by continuous innovation
- pushing energy (discovery) frontier

Roadmap for Particle Physics



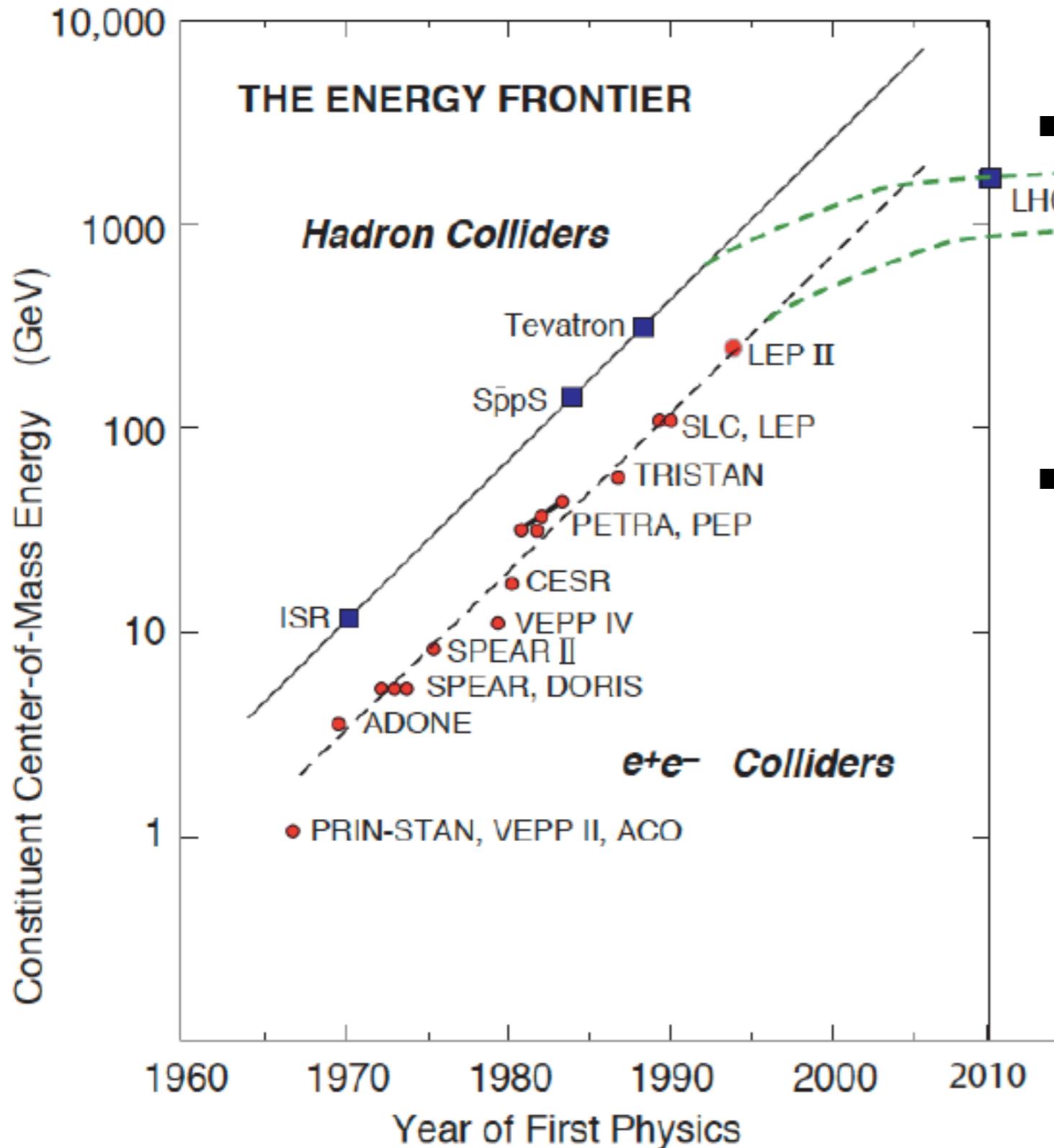
➔ Using history as a guide for the future

- The last ~100 year in particle physics with collider

➔ Livingston Plot ~1996

- It was clear that trend can not be continued into the 21st century
- SSC was meant to fall on the line!
- Two directions
 - ✦ electron-positron collider for precision measurements
 - ✦ energy frontier hadron collider

Roadmap for Particle Physics



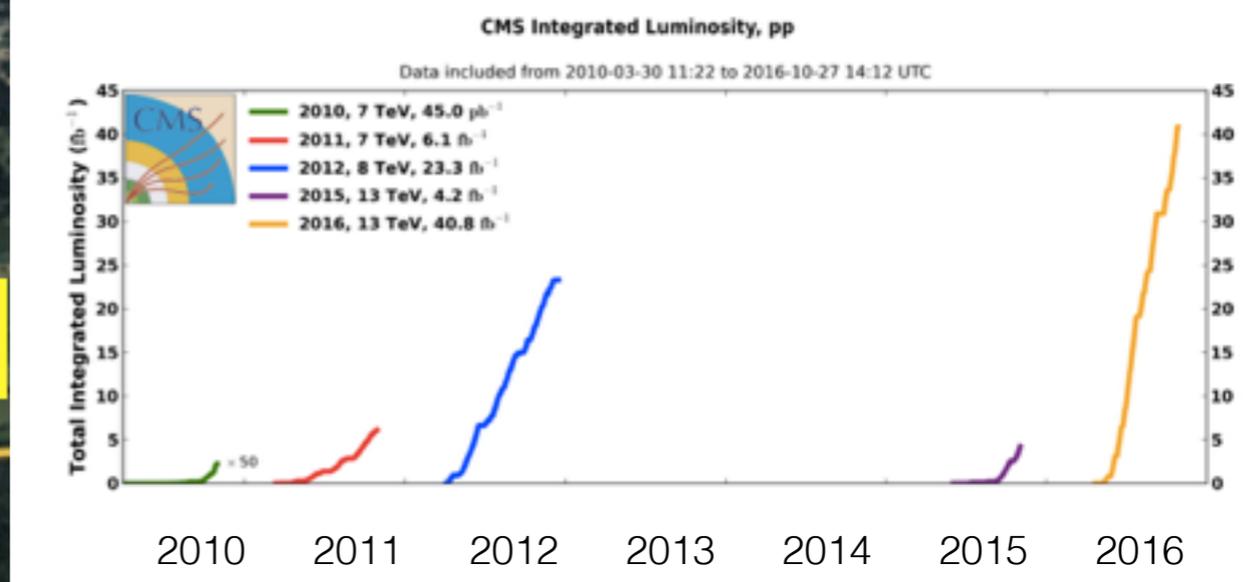
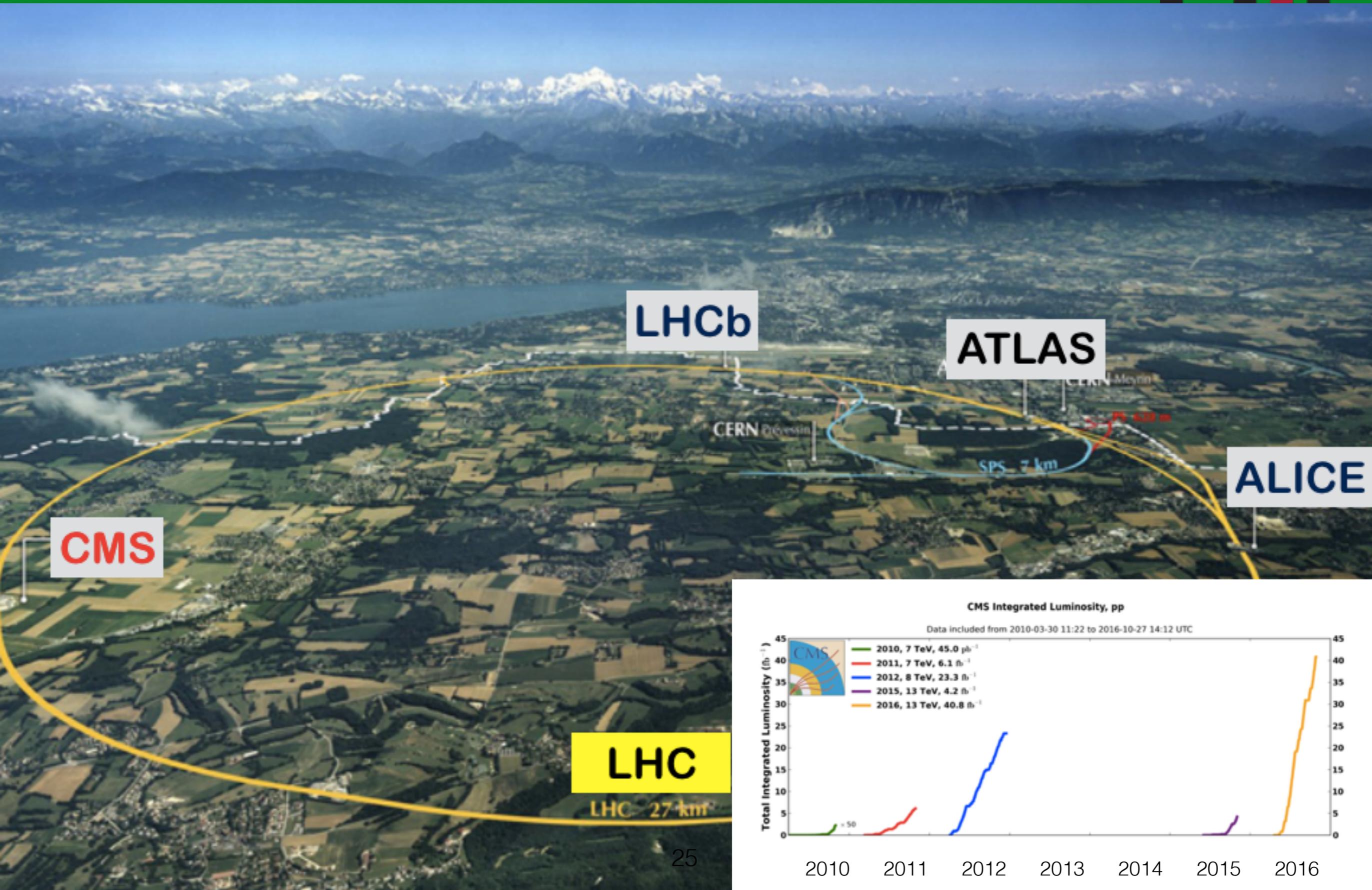
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- The last ~100 year in particle physics with collider

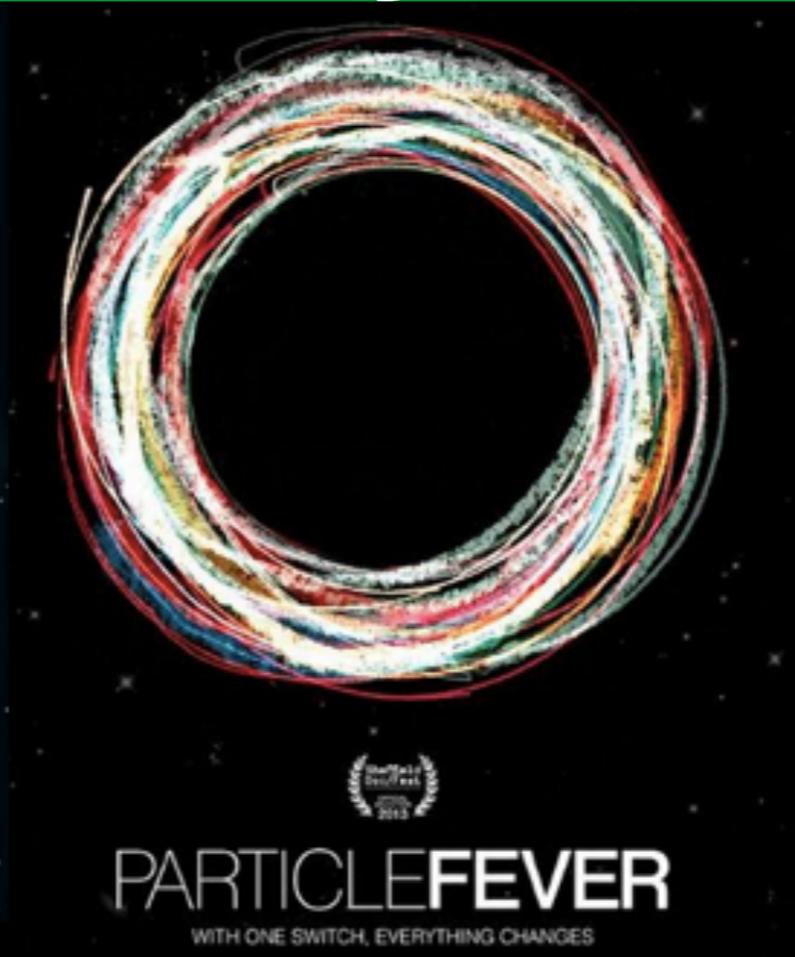
➔ Livingston Plot ~2010

- Progress slowed down considerably
- Investment in accelerator technology is still large, but directed towards tools like light sources
- Limiting factor → cost (size)!

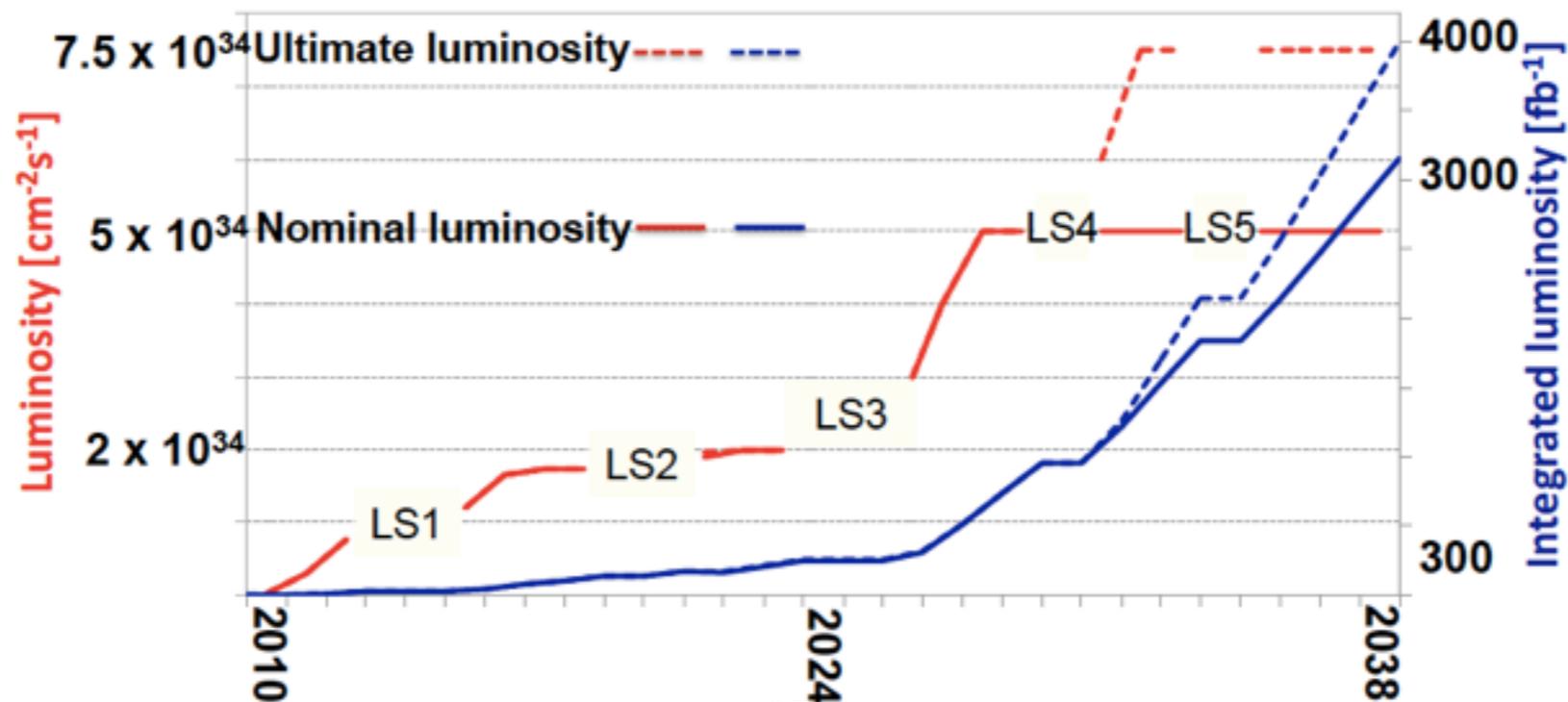
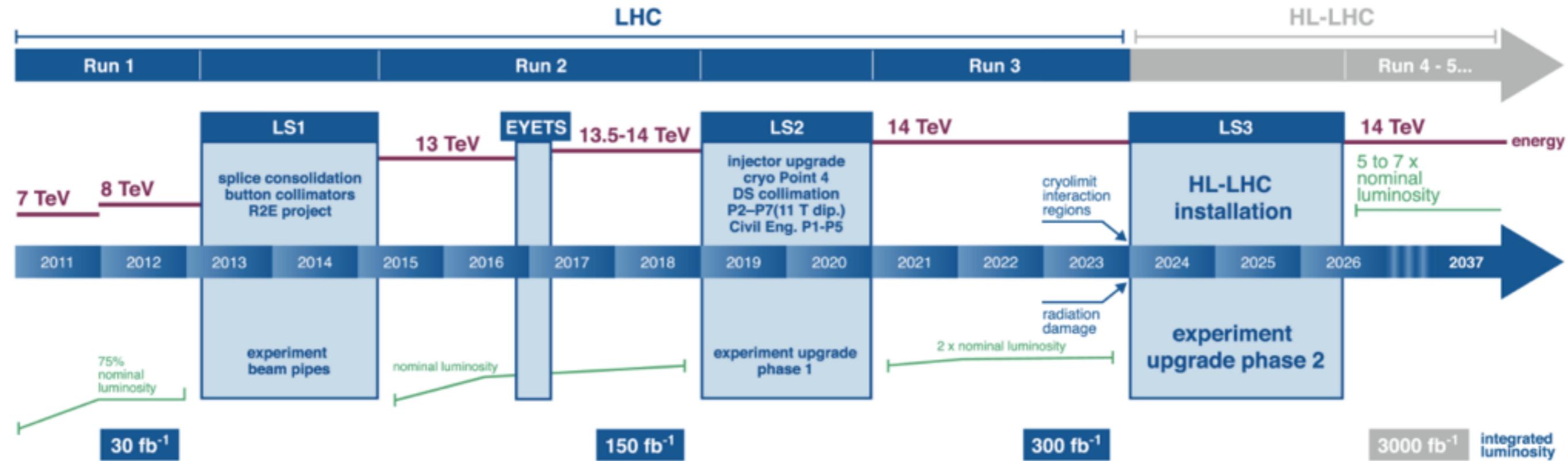
Roadmap for Particle Physics



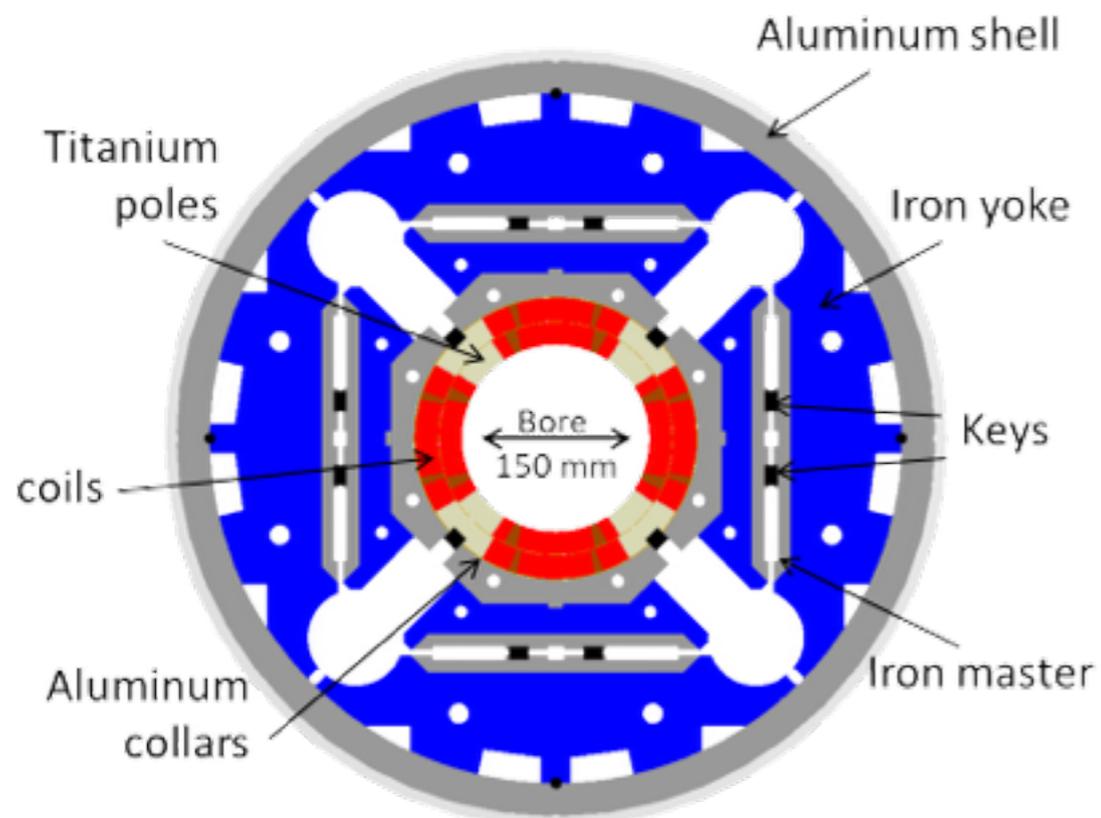
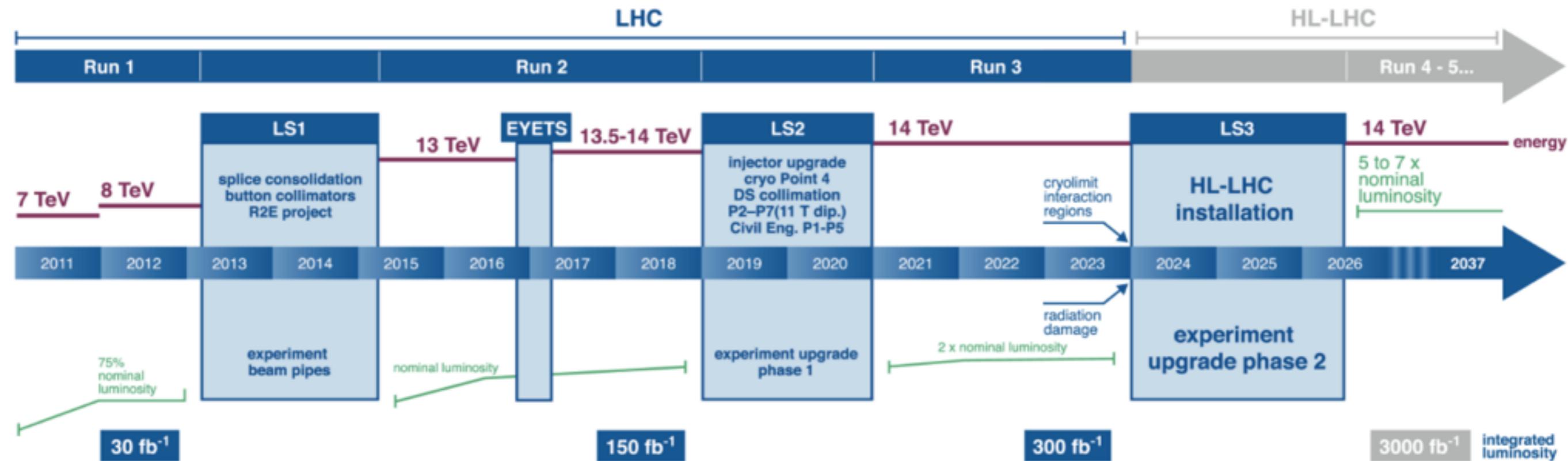
Higgs Discovery 2012



Roadmap for Collider Experiments



Roadmap for Collider Experiments



- ➔ **LHC dipoles stretched NbTi technology to its limit**
 - ⦿ 8.3T in central region via operation at 1.8k
- ➔ **HL-LHC needs **new technology** in iteration region: Nb₃SN**
 - ⦿ 12T quadrupoles with 150mm aperture to shrink β^*
- ➔ **Operating and upgrading the LHC is a very significant investment**

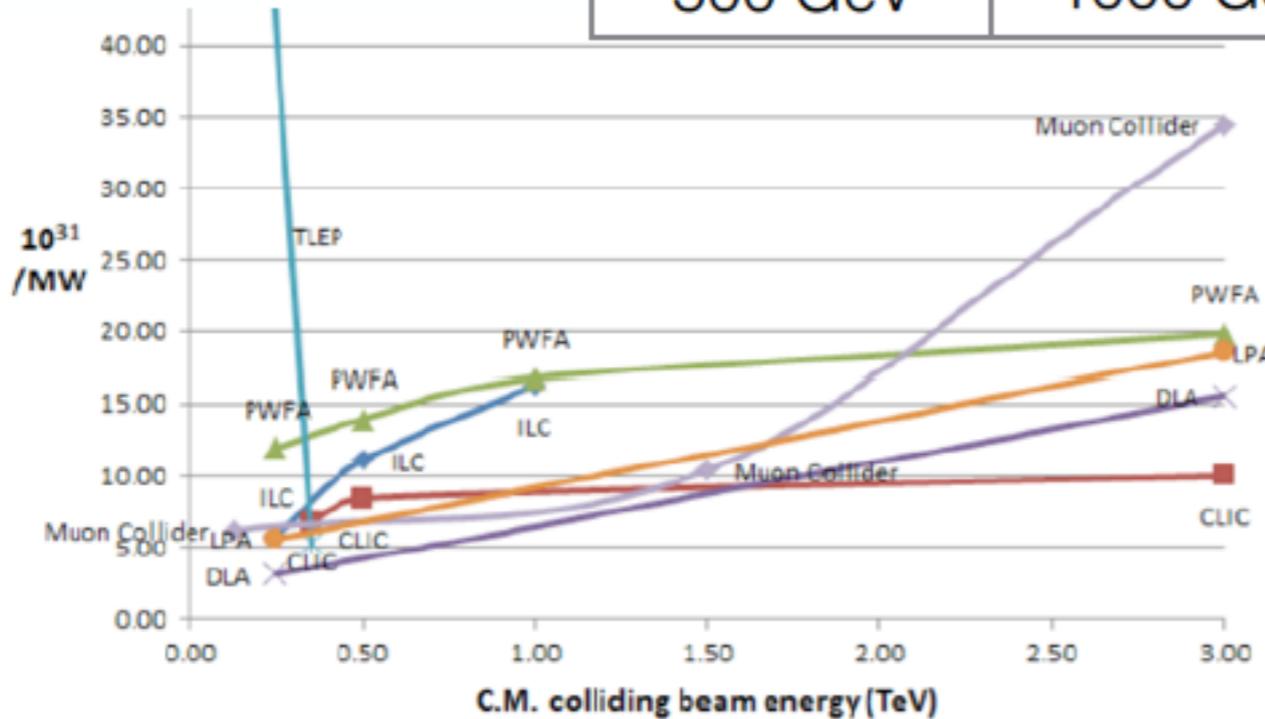
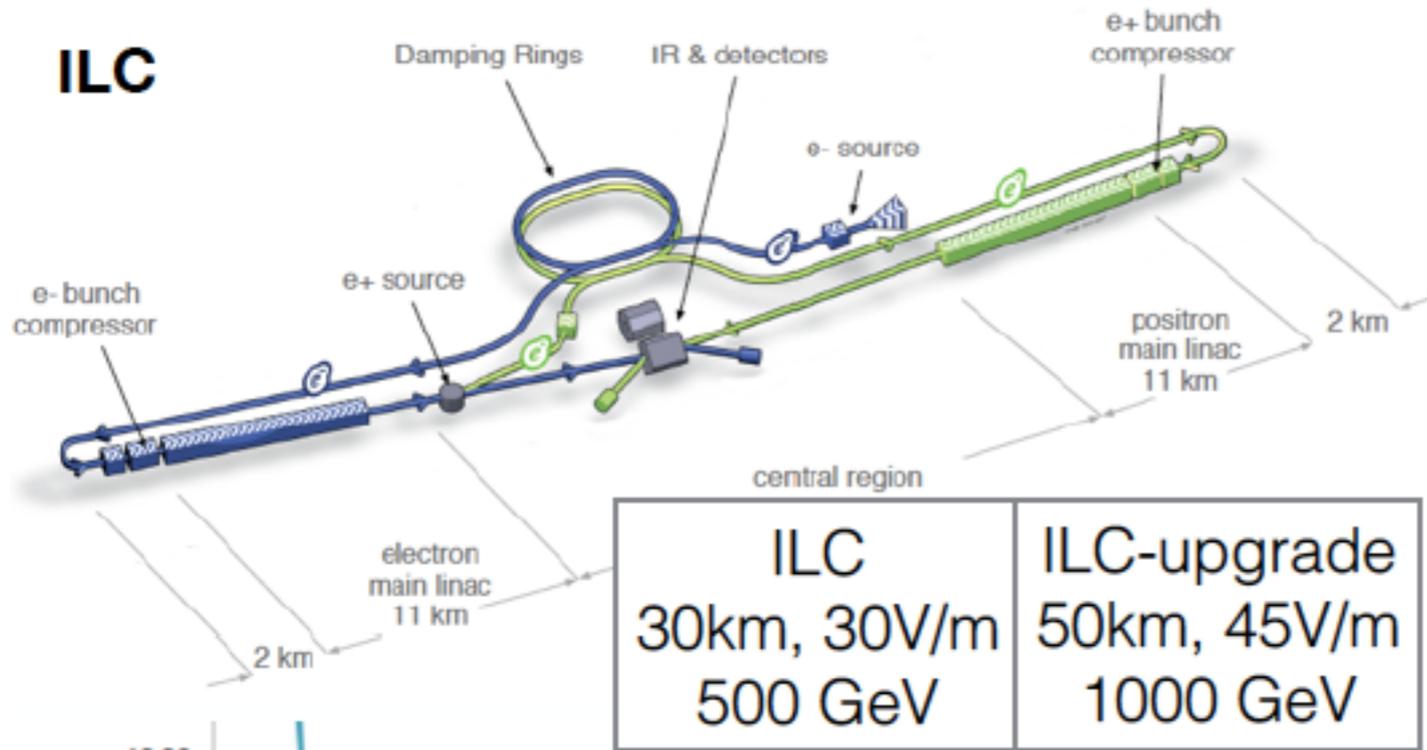
HL-LHC Physics Case



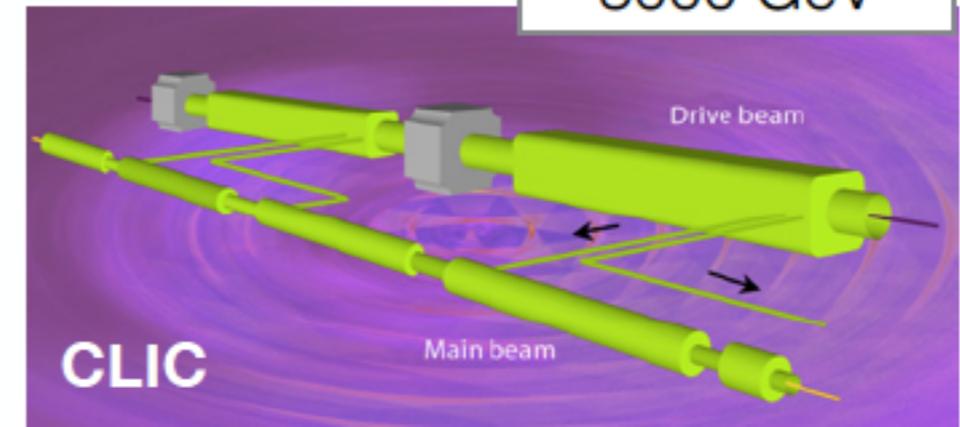
- ➔ **Higgs case at the start of the LHC was exceptional**
 - ⦿ something to built on, not the reference
 - ➔ **Goal for the future LHC and HL-LHC program**
 - ⦿ **Explore the energy frontier**
- ➔ **Precision measurements of SM parameters (including the Higgs boson)**
 - ➔ **Sensitivity to rare SM & rare BSM processes**
 - ➔ **Extension of discovery reach in high-mass region**
 - ➔ **Determination of BSM parameter**

Roadmap for Particle Physics

➔ Future Lepton Collider



CLIC
50km, 100V/m
3000 GeV



CEPC
50km
240 GeV

FCC-ee
100km, 200MV
350 GeV



Future Circular Collider (FCC-ee)
Circular Electron Positron Collider (CEPC)

Roadmap for Particle Physics

➔ International FCC collaboration to study

- ⦿ pp collider (FCC-hh)
- ⦿ e^+e^- collider (FCC-ee)
- ⦿ p-e (FCC-he)

➔ 80-100 km infrastructure in Geneva area

➔ **Goal:** CDR and cost review by 2018

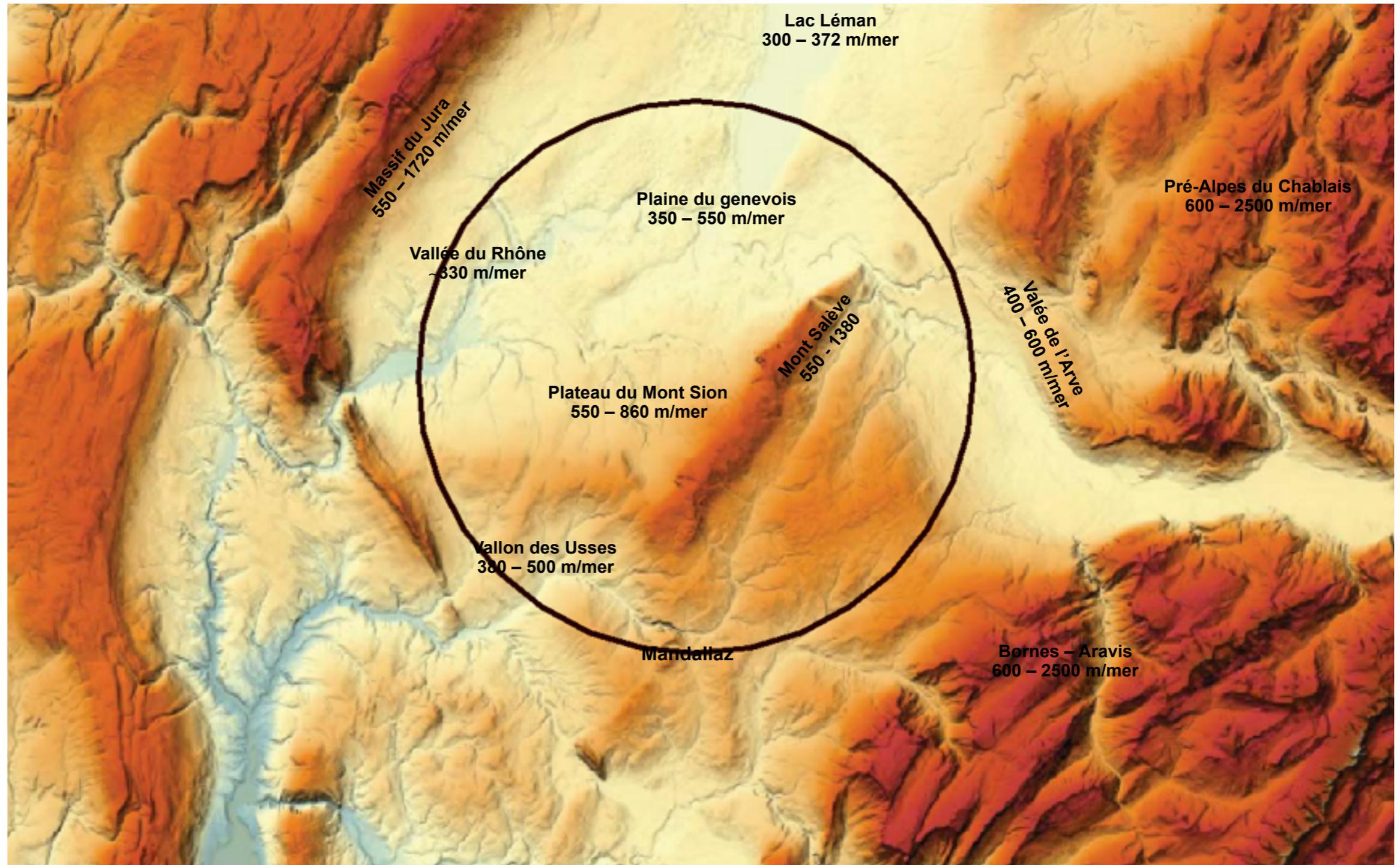
➔ Similar studies in China (50-70 km infrastructure)

- ⦿ pp collider (SppS)
- ⦿ e^+e^- collider (CepC)



Roadmap for Particle Physics

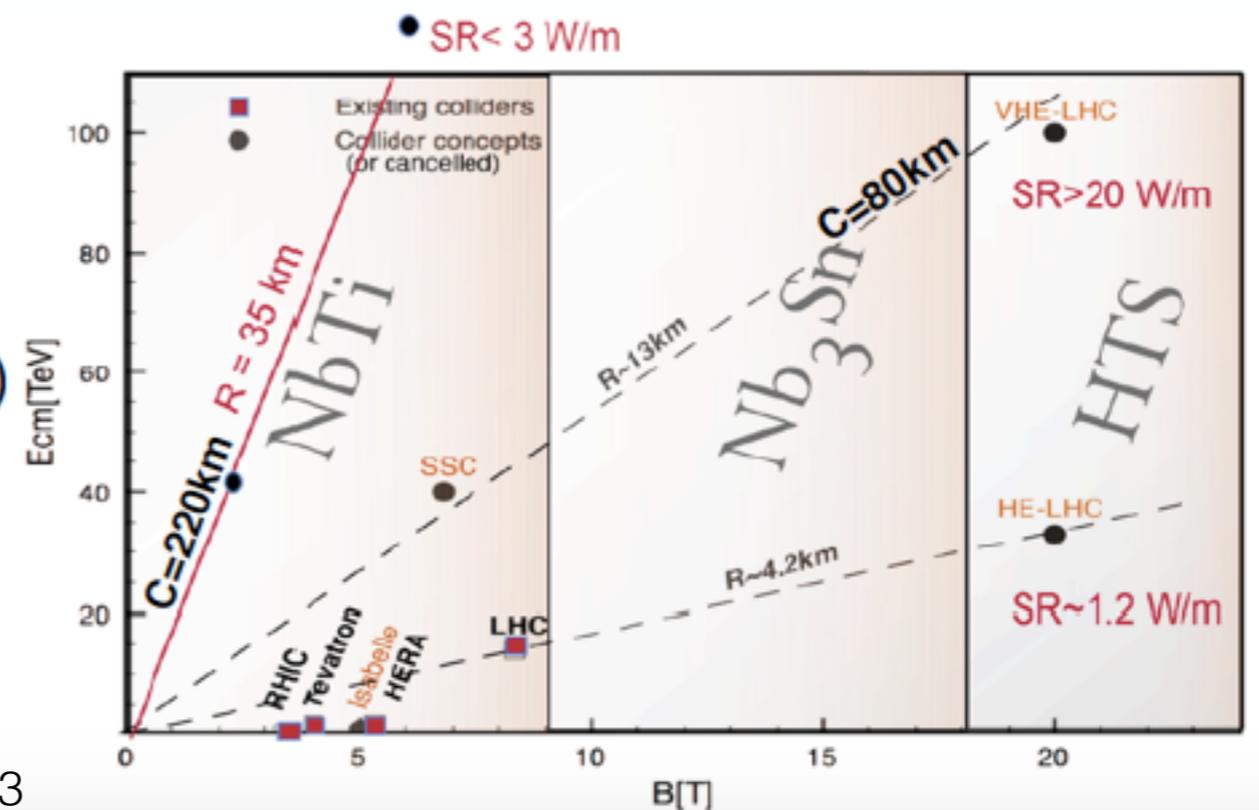
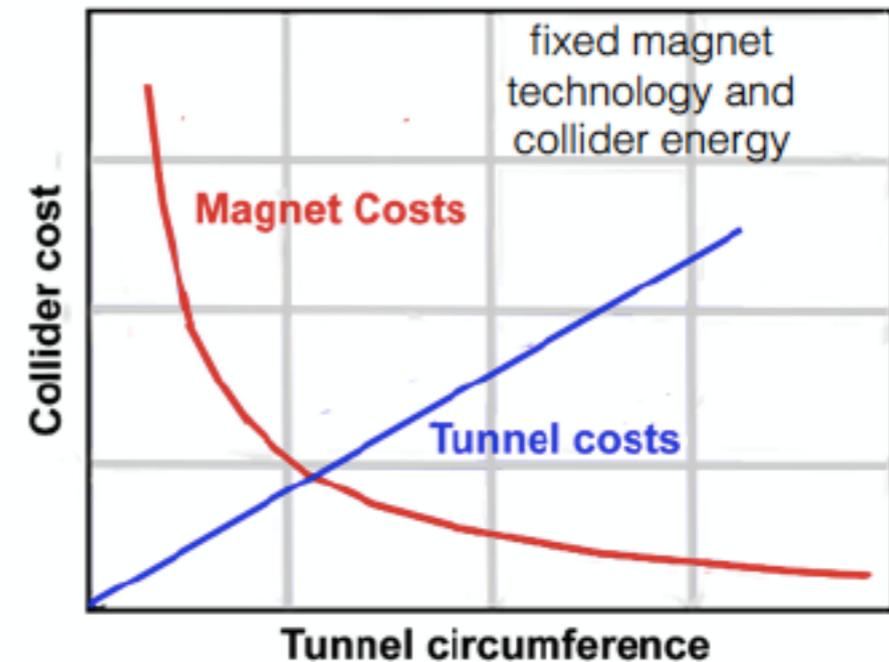
➔ Future Hadron Collider



Roadmap for Particle Physics

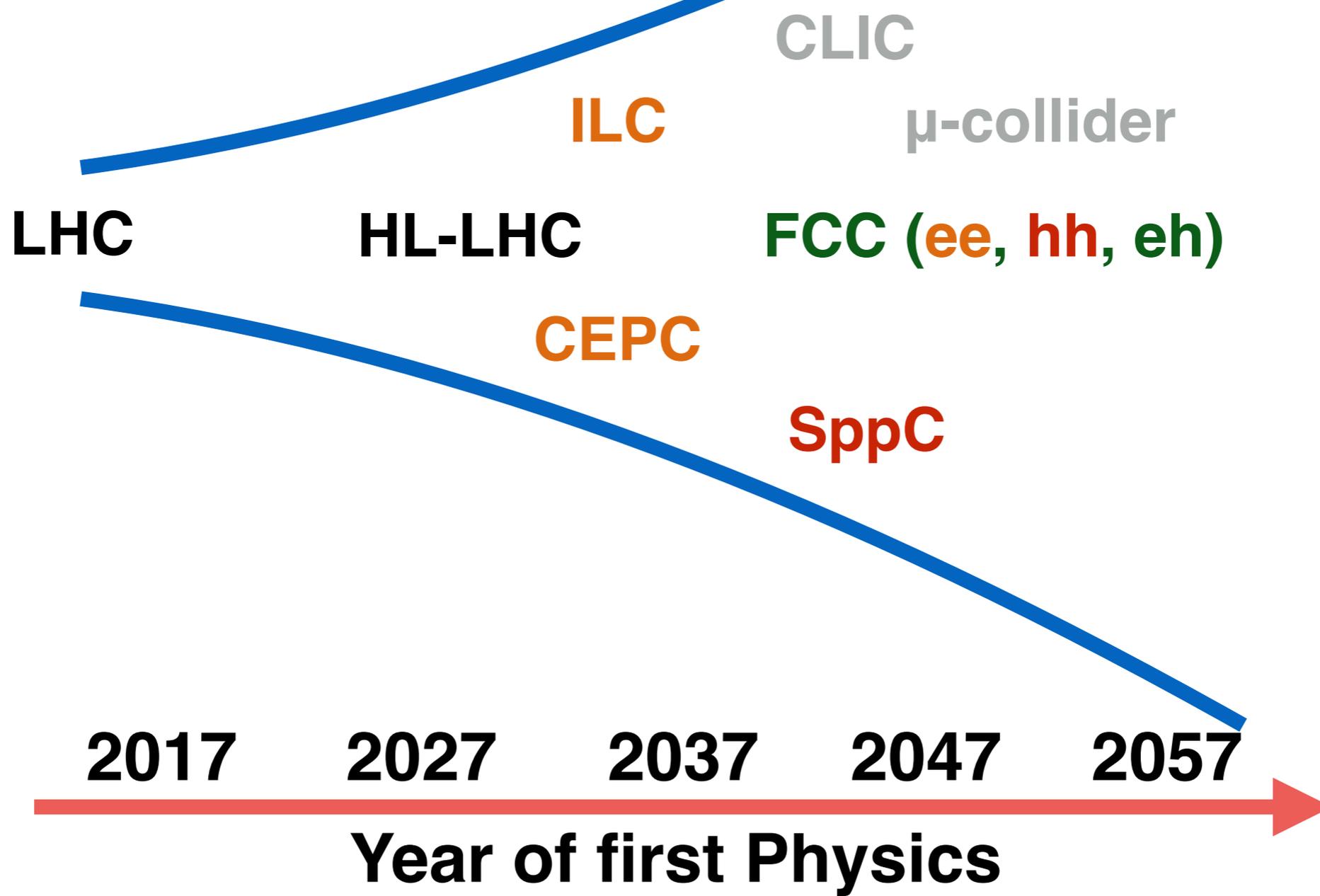
➔ Future Hadron Collider Challenges

- ❖ **Overall construction cost**
 - ❖ cost driver are magnets and the tunnel
 - ❖ depend on magnet technology
 - ❖ tunnel cost highly geology dependent
- ❖ **Magnet technology**
 - ❖ Nb₃Sn foreseen for HL-LHC
- ❖ **Total energy stored**
 - ❖ for 100km, 20T machine
 - ❖ ~200 GJ in magnet
 - ❖ ~10 GJ in beam,
 - ❖ both are very challenging (~20*LHC)
- ❖ **Proton synchrotron radiation**



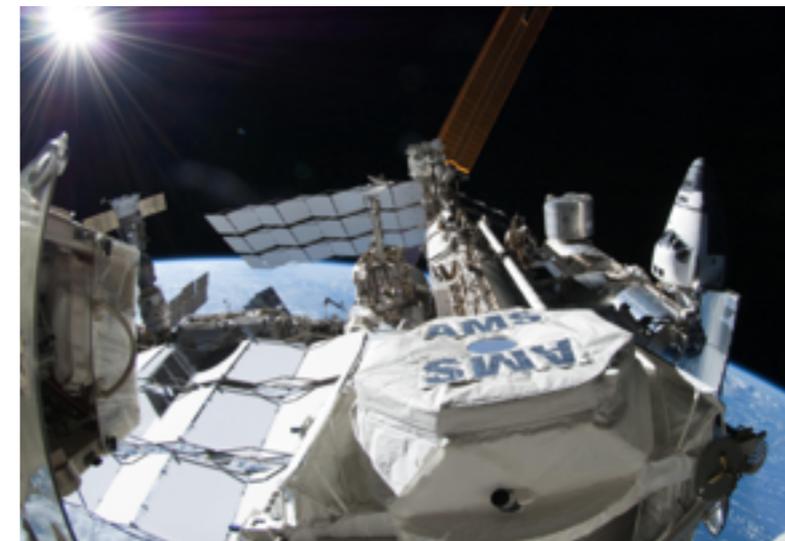
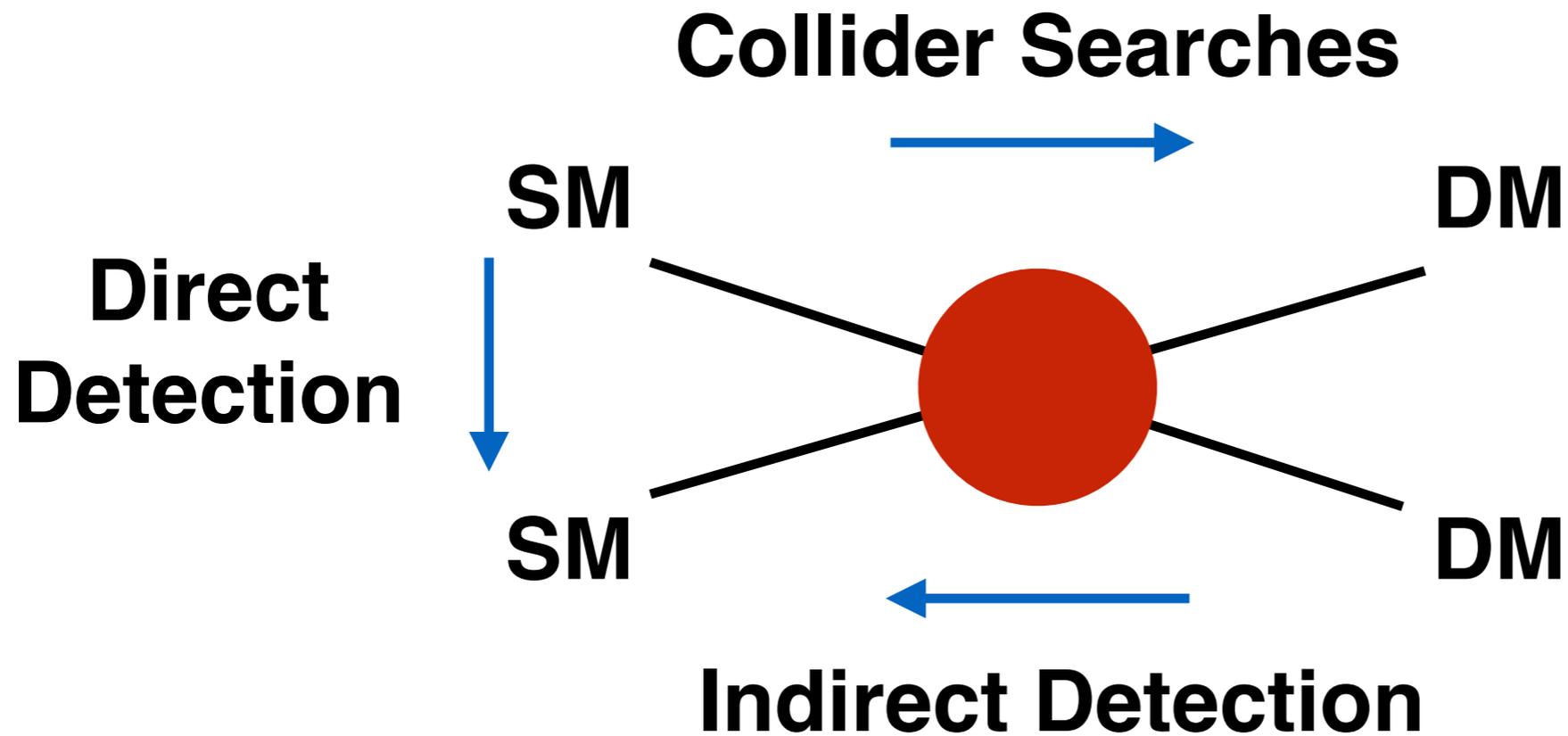
Roadmap for Particle Physics

➔ Beyond the HL-LHC



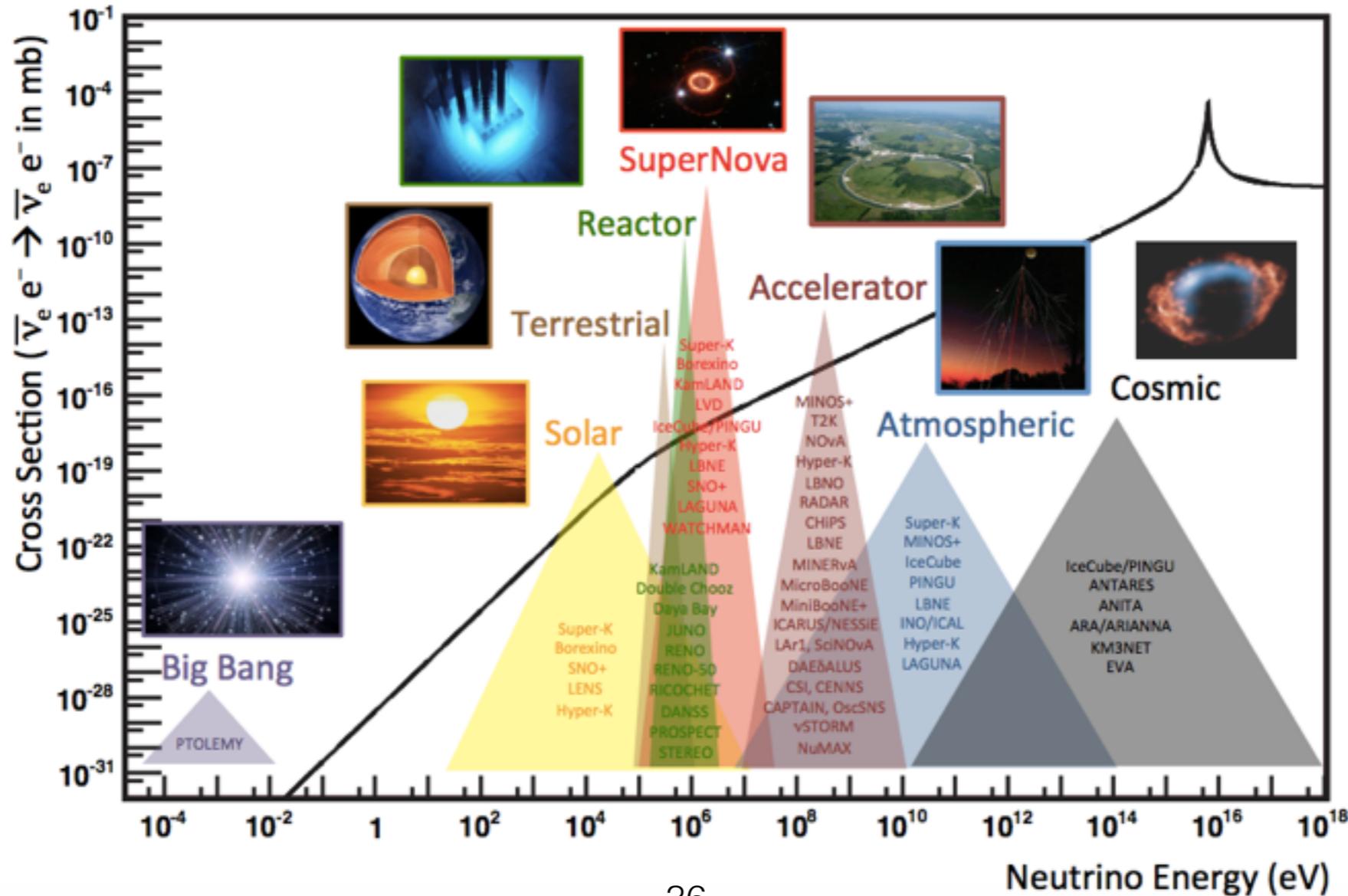
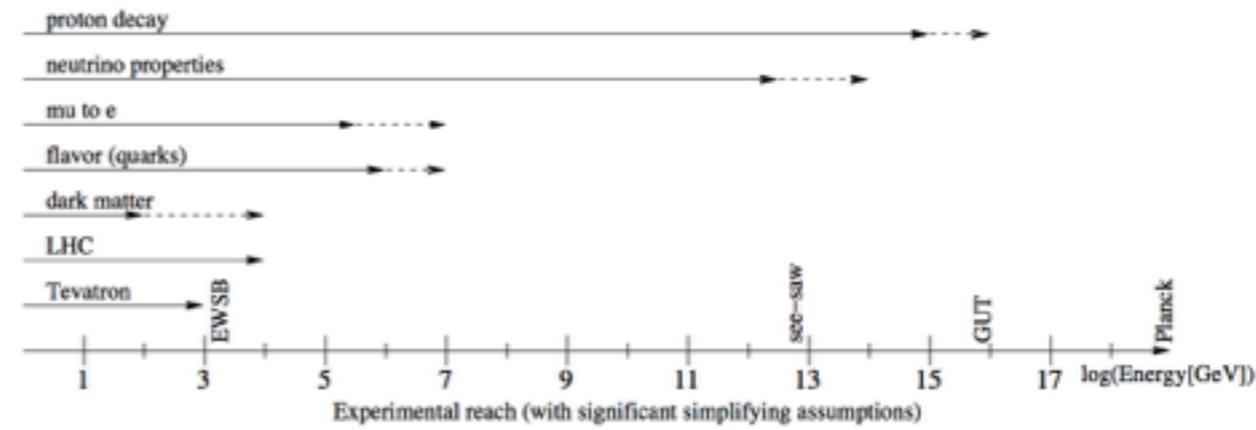
Roadmap for Particle Physics

➔ Beyond the energy frontier



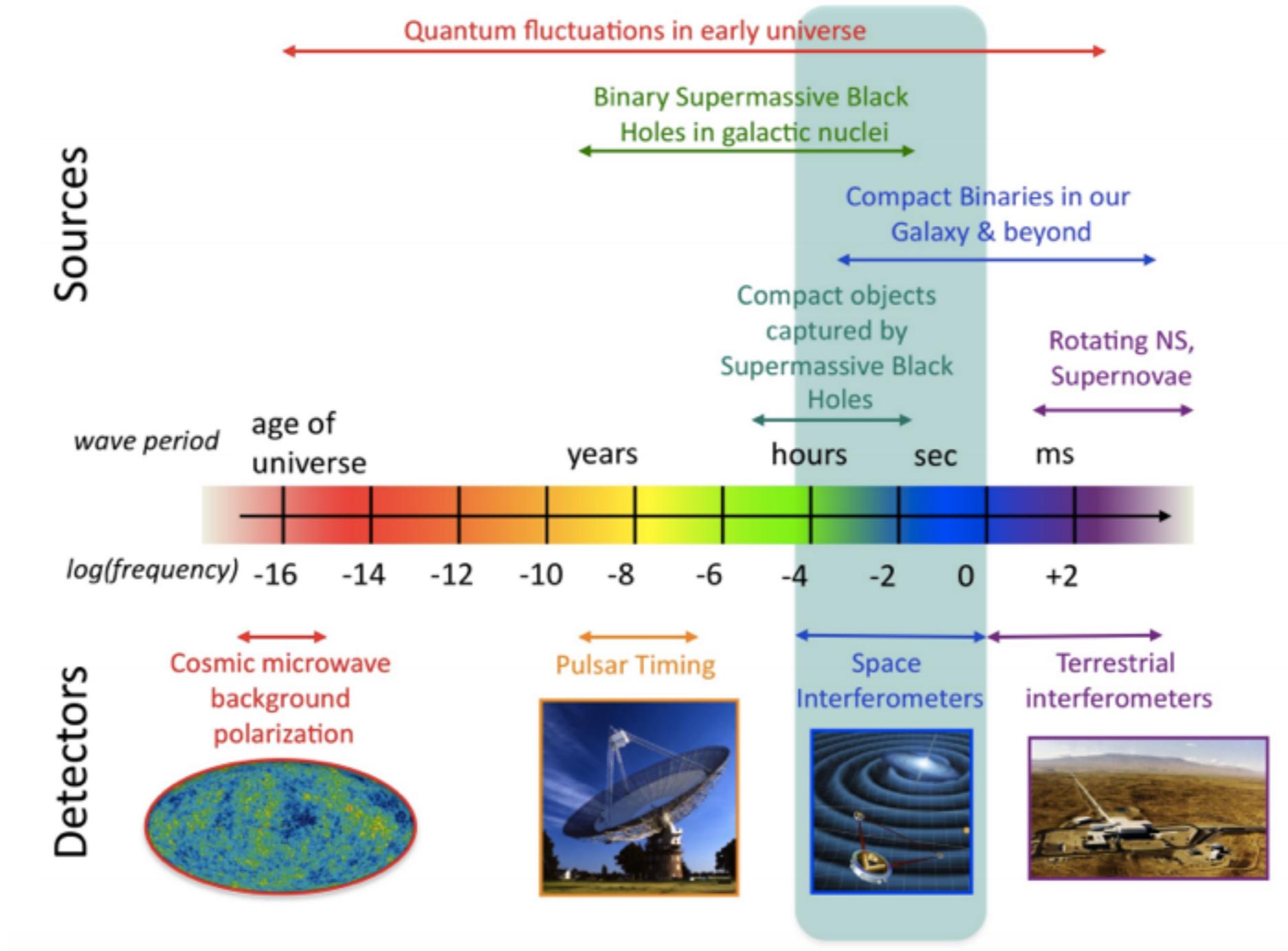
Roadmap for Particle Physics

➔ Beyond the energy frontier



Roadmap for Particle Physics

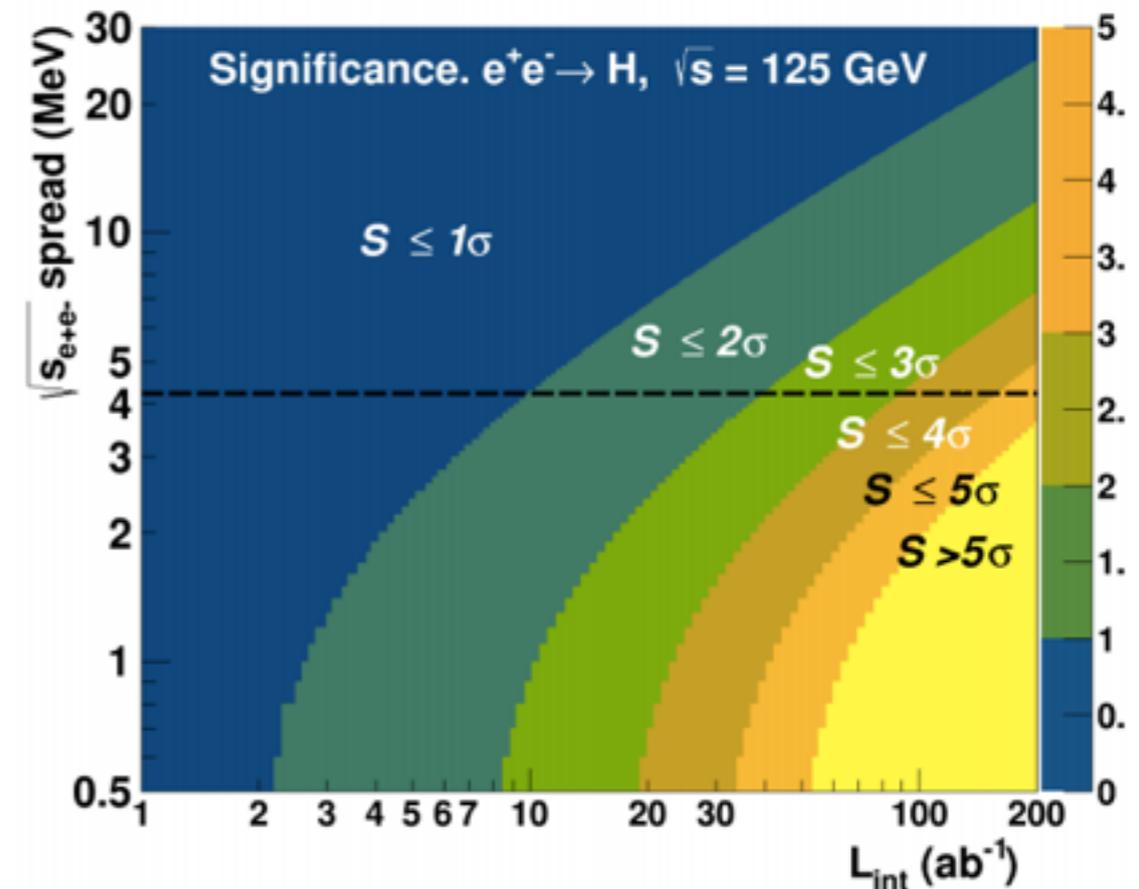
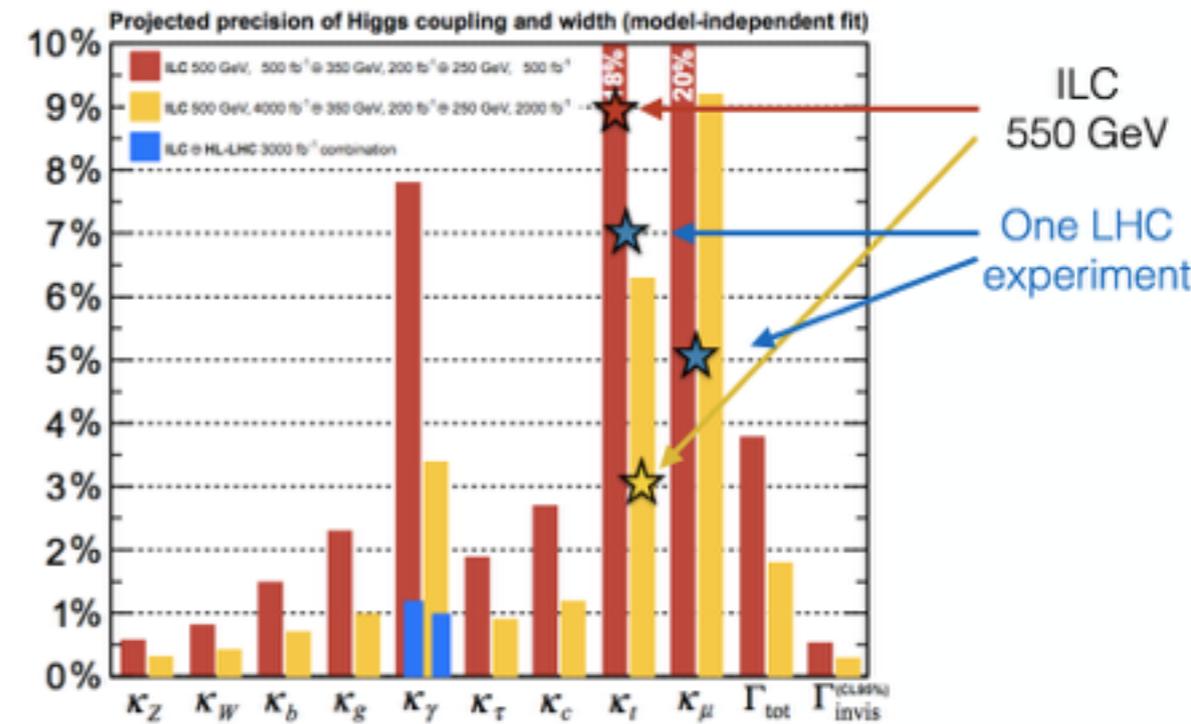
➔ Beyond the energy frontier



Prospects

➔ Example: the Higgs boson (mechanism)

- predicted in 1964
- discovered in 2012
- today's knowledge
 - ✦ consistent with SM prediction ~20% level
 - ✦ Spin-0
 - ✦ gives mass to W and Z bosons
 - ✦ gives mass to 3 generation fermions
- in 100 years we will know
 - ✦ consistent (or not) with SM prediction ~0.1% level
 - ✦ gives mass to 2 and 1 generation fermions
 - ✦ whether there is more than one Higgs boson

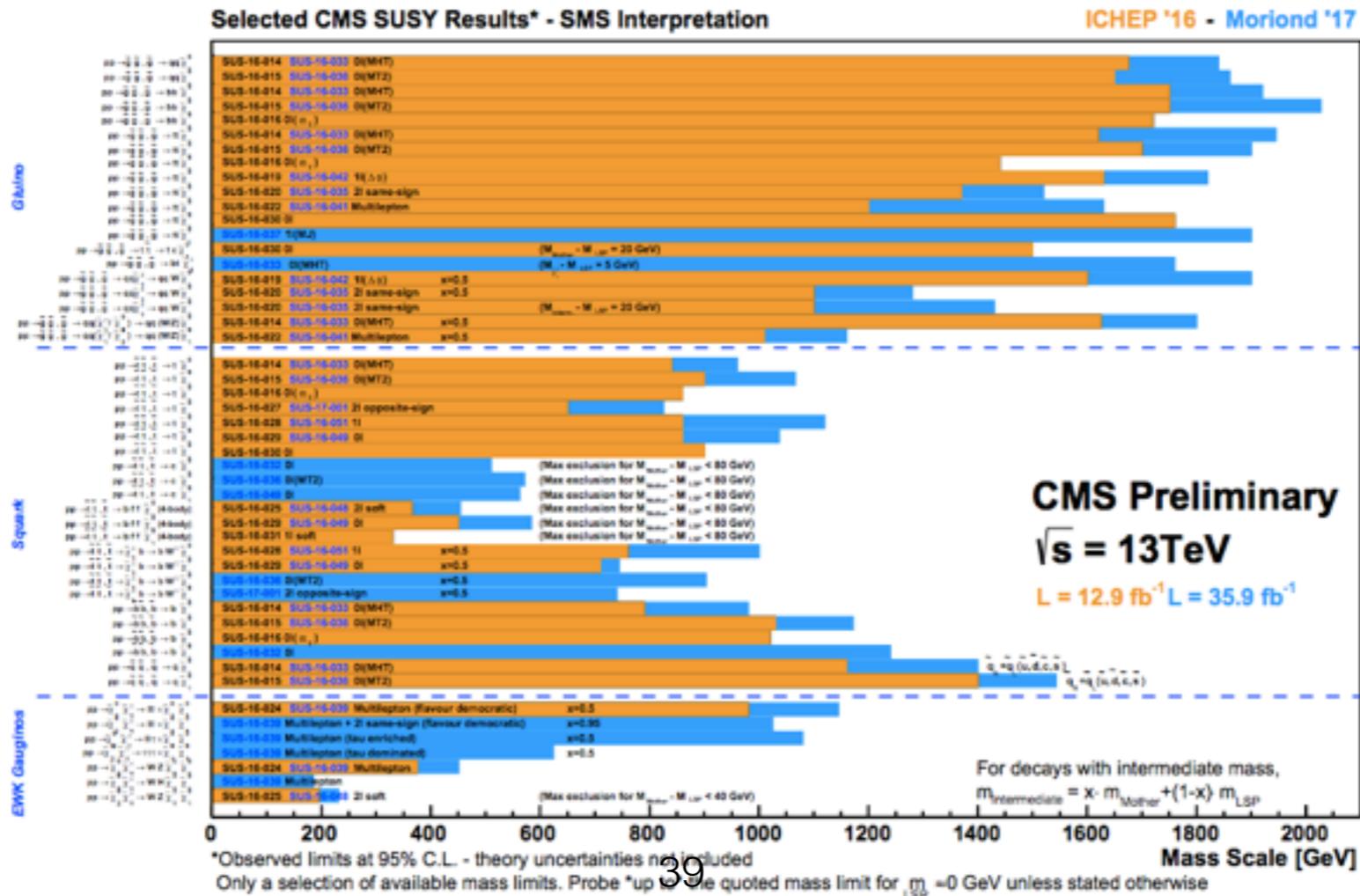
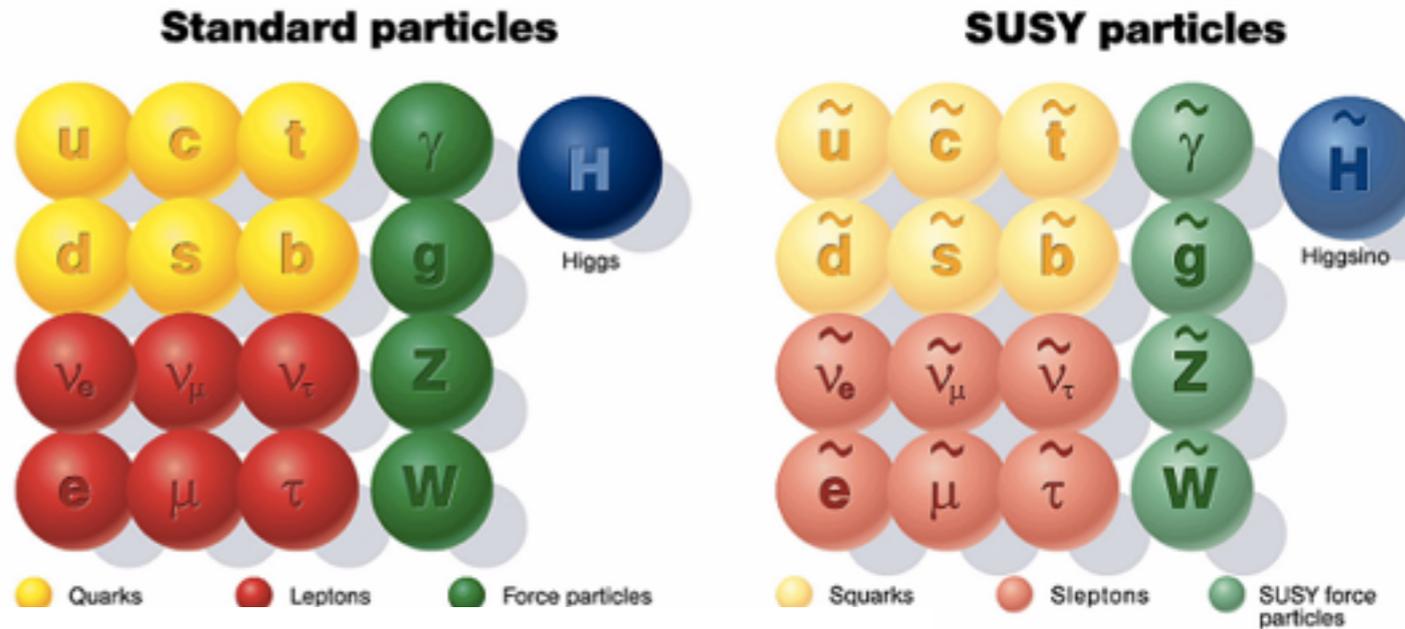


Prospects



➔ Example: Supersymmetry

- ◉ proposed in ~1974 (by Wess & Zumino)
- ◉ today's knowledge
 - ◉ Supersymmetry must be broken
- ◉ discovery in ...
- ◉ in 100 years we will know



Prospects



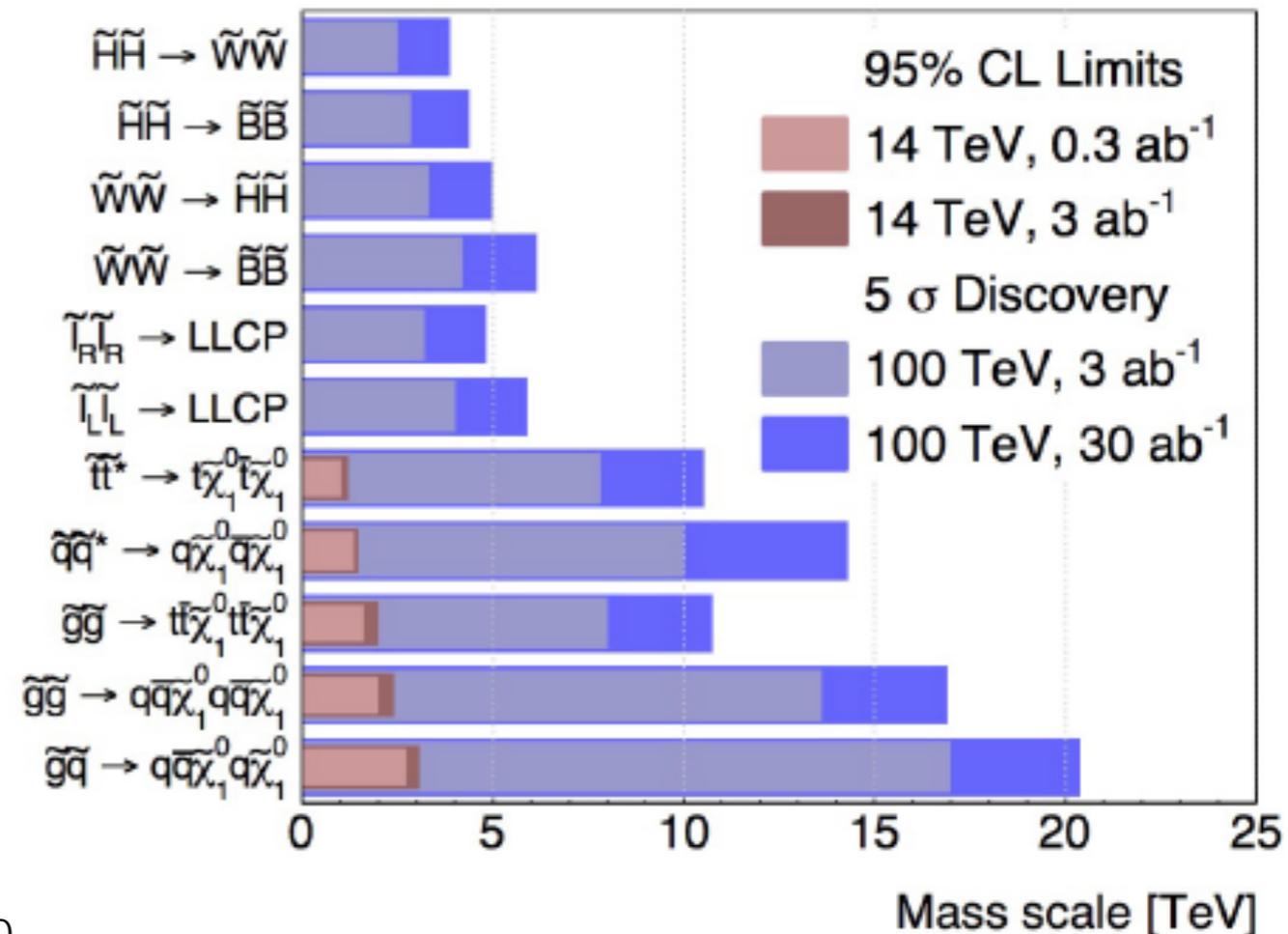
➔ Example: Supersymmetry

- ◉ proposed in ~1974 (by Wess & Zumino)
- ◉ today's knowledge
- ◉ **discovery in ...**
- ◉ in 100 years we will know

HL-LHC

Analysis	Luminosity (fb ⁻¹)	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300					
	3000					
all-hadronic (MT2) search	300					
	3000					
all-hadronic \tilde{b}_1 search	300					
	3000					
1-lepton \tilde{t}_1 search	300					
	3000					
monojet \tilde{t}_1 search	300					
	3000					
$m_{\ell\ell}$ kinematic edge	300					
	3000					
multilepton + b-tag search	300					
	3000					
multilepton search	300					
	3000					
ewkino WH search	300					
	3000					

< 3σ
3 – 5σ
> 5σ

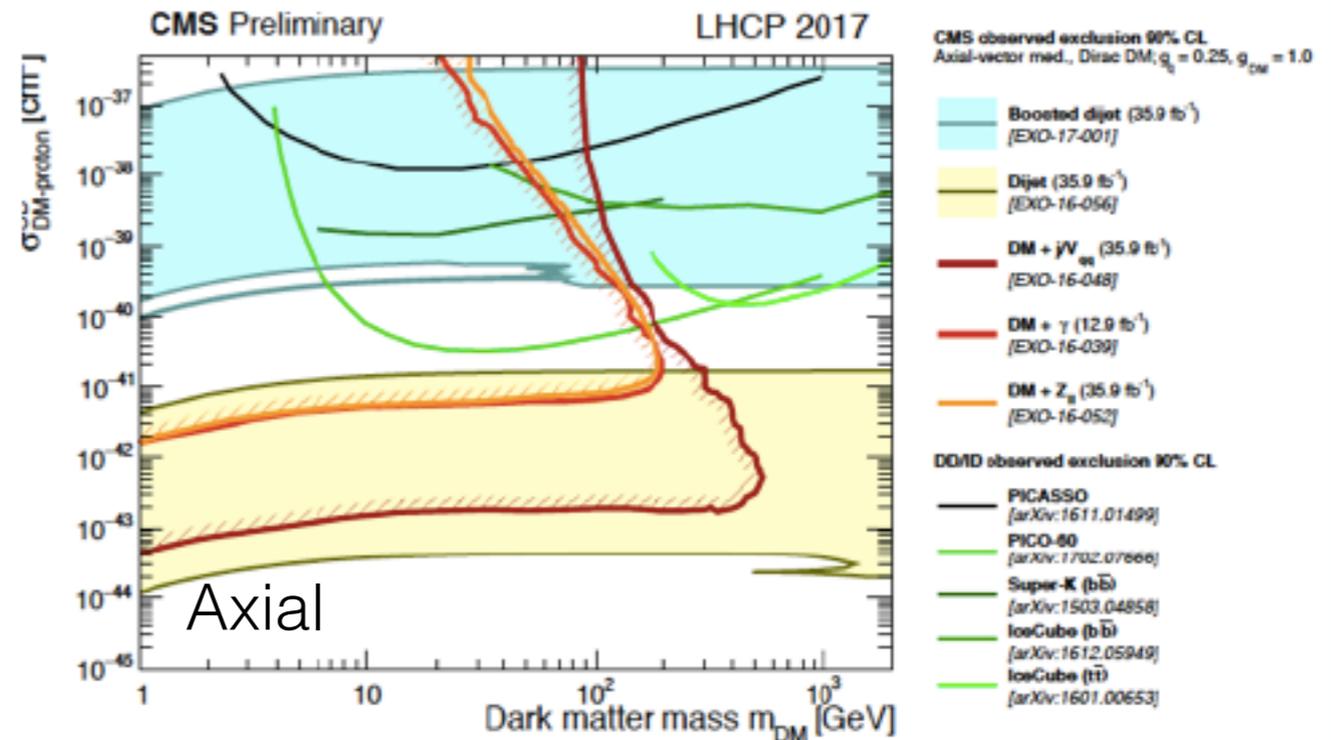
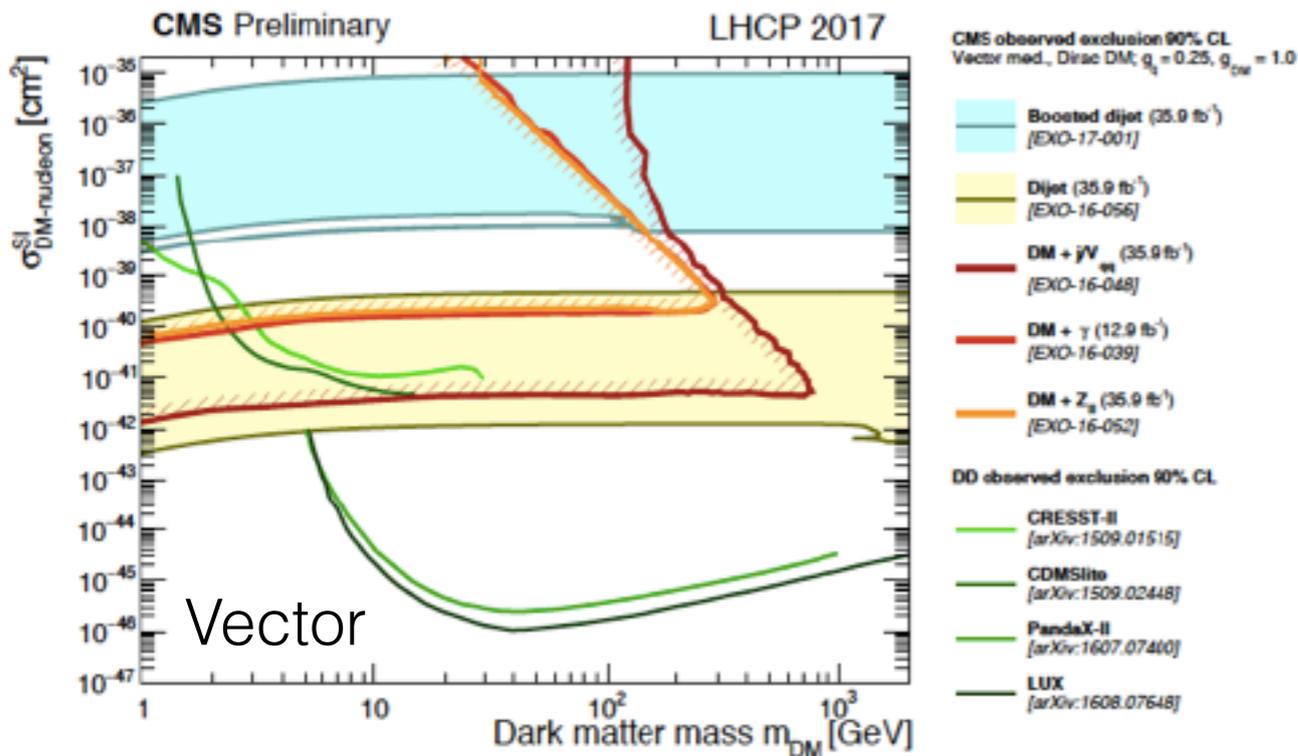
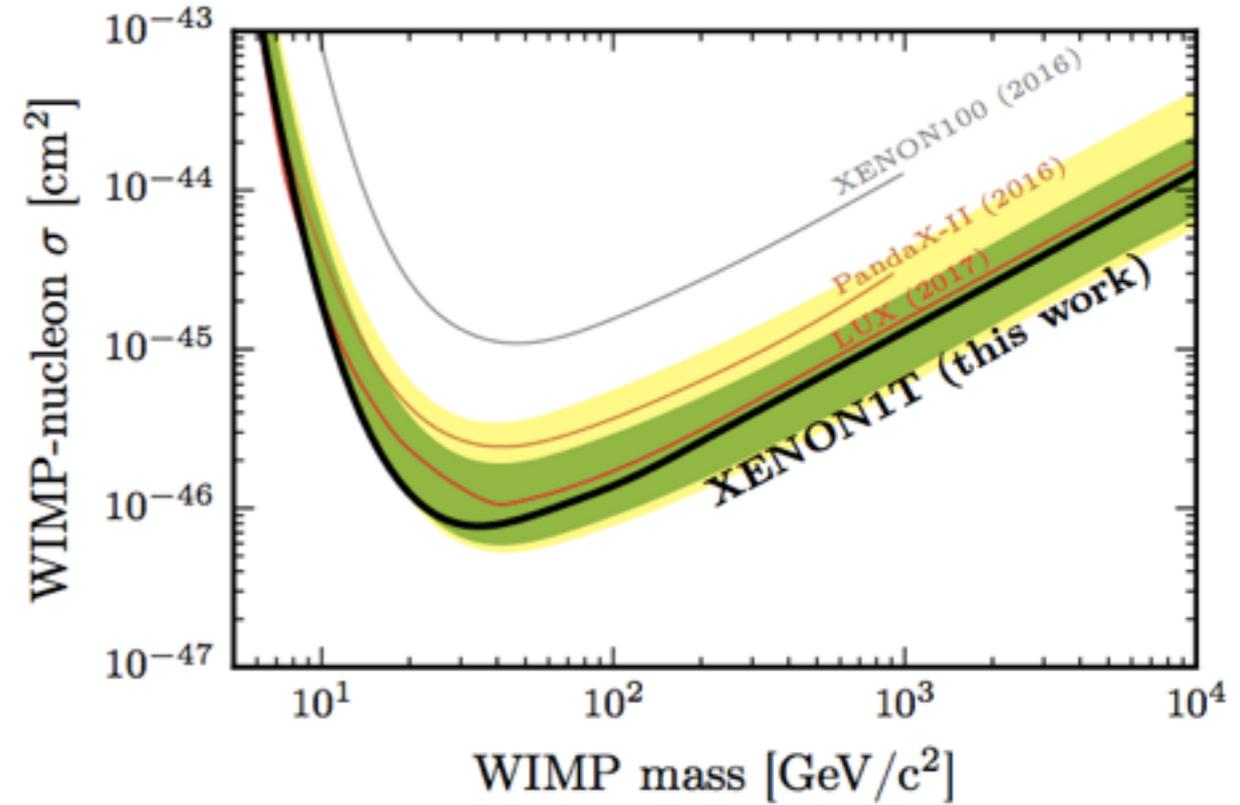


Prospects



➔ Example: dark matter

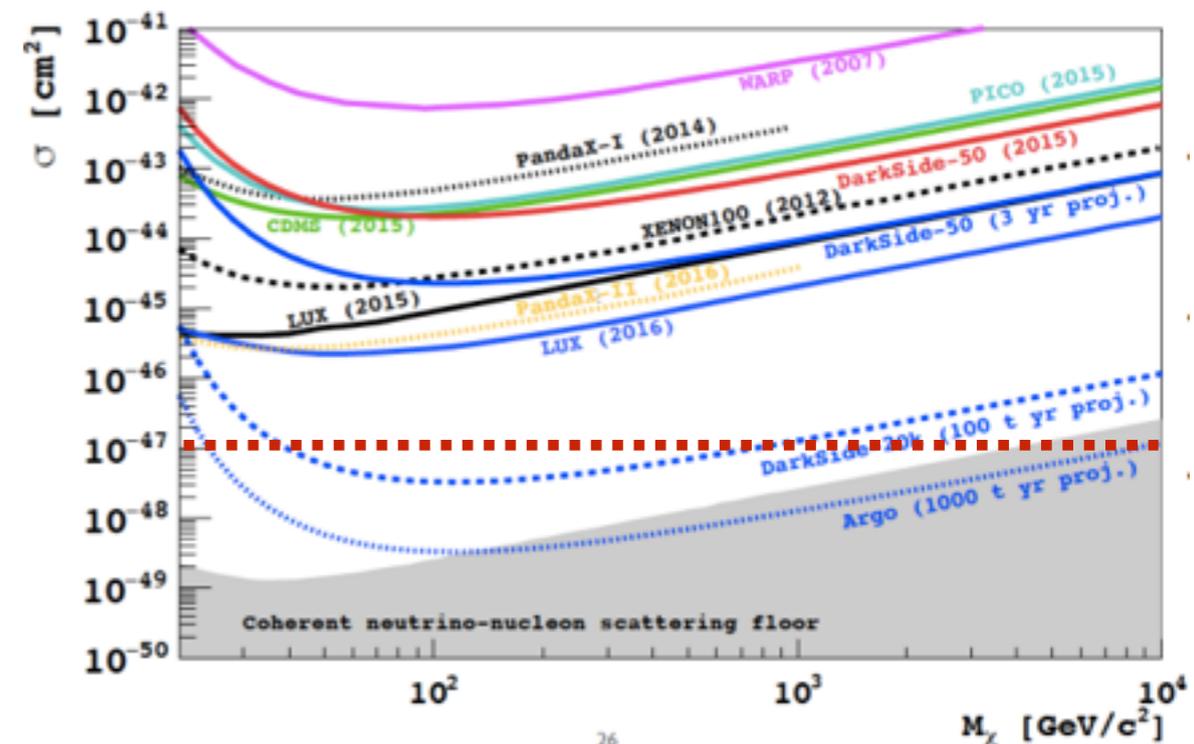
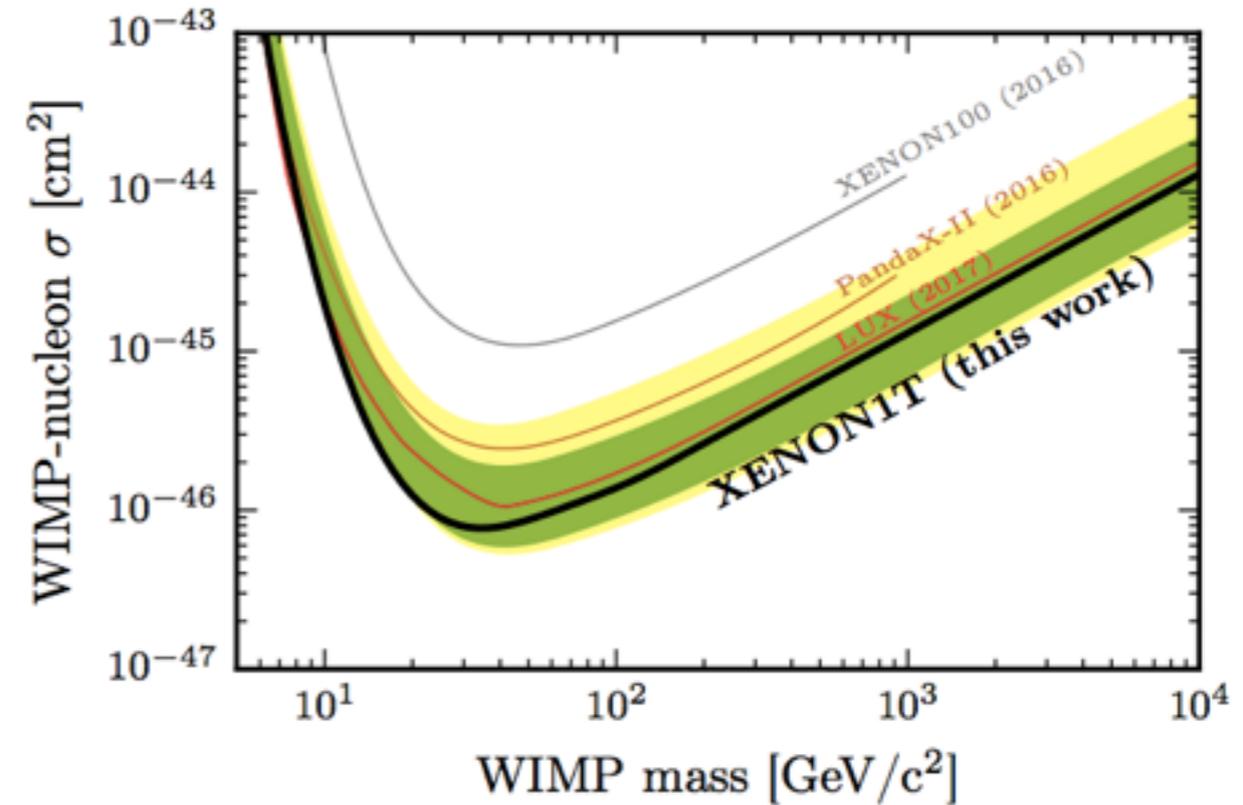
- proposed in ~1930
- confirmed in ~1970
- today's knowledge
 - dark matter is very very weakly interacting
- discovery in ...



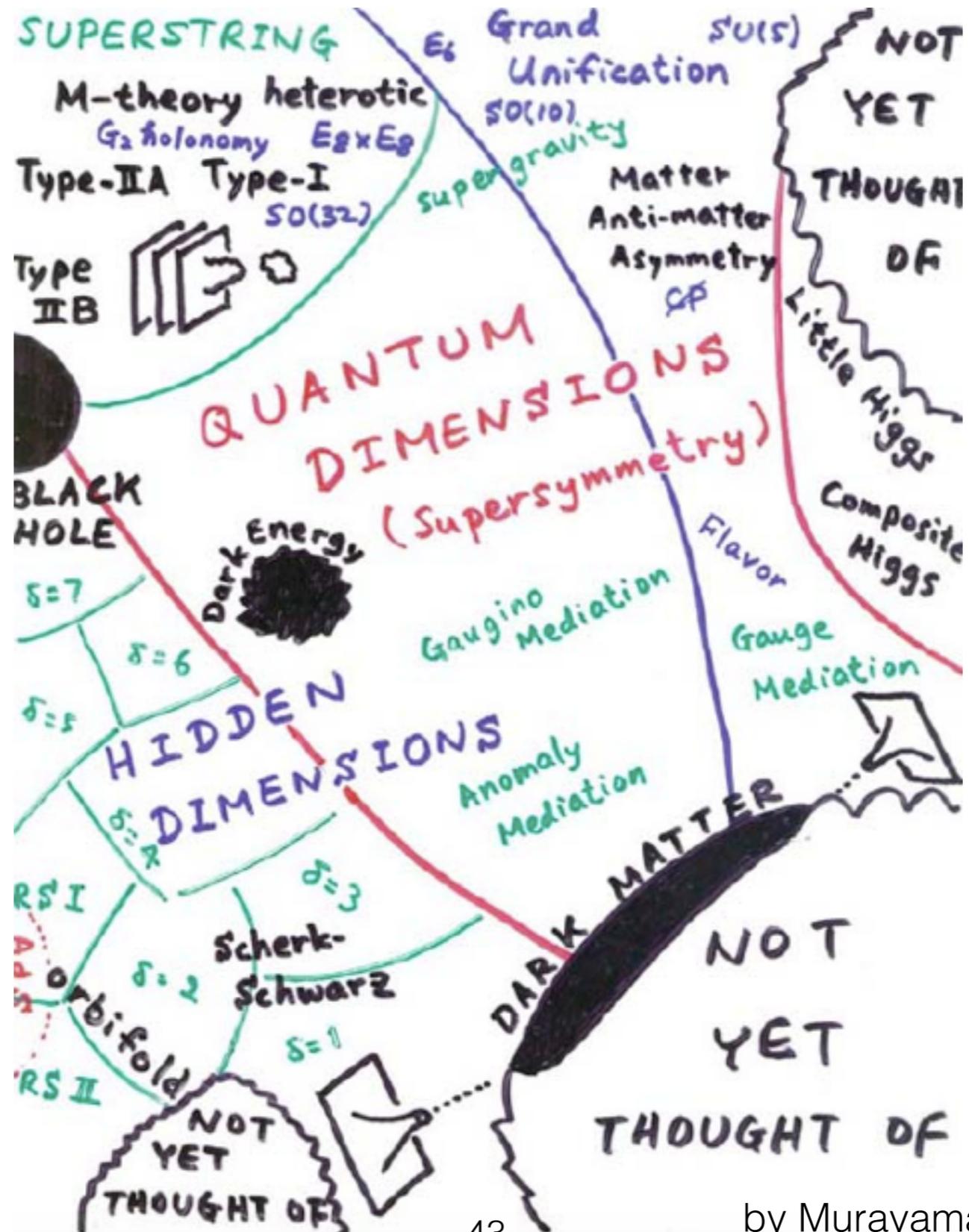
Prospects

➔ Example: dark matter

- proposed in ~1930
- confirmed in ~1970
- today's knowledge
- discovery in ...
- **in 100 years we will know**
 - whether (or not) WIMPs exist
 - and have answers for alternative ideas

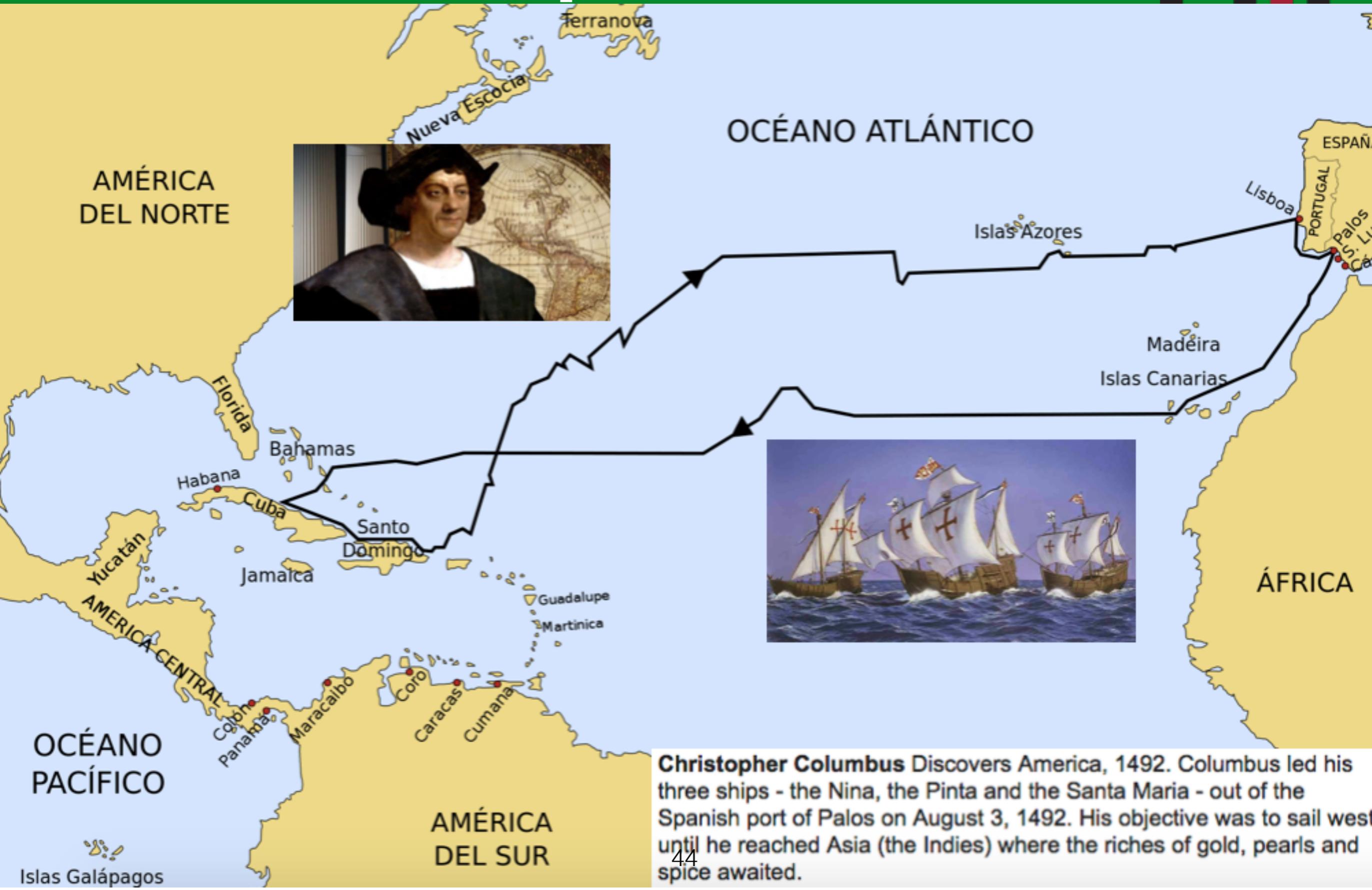


Landscape



Large space of "Not Yet Thought Of"

Exploration



Christopher Columbus Discovers America, 1492. Columbus led his three ships - the Nina, the Pinta and the Santa Maria - out of the Spanish port of Palos on August 3, 1492. His objective was to sail west until he reached Asia (the Indies) where the riches of gold, pearls and spice awaited.

Conclusion



**Unveiling the Secrets of Nature -
An outlook on fundamental
physics in 100 years**

Concluding Remarks



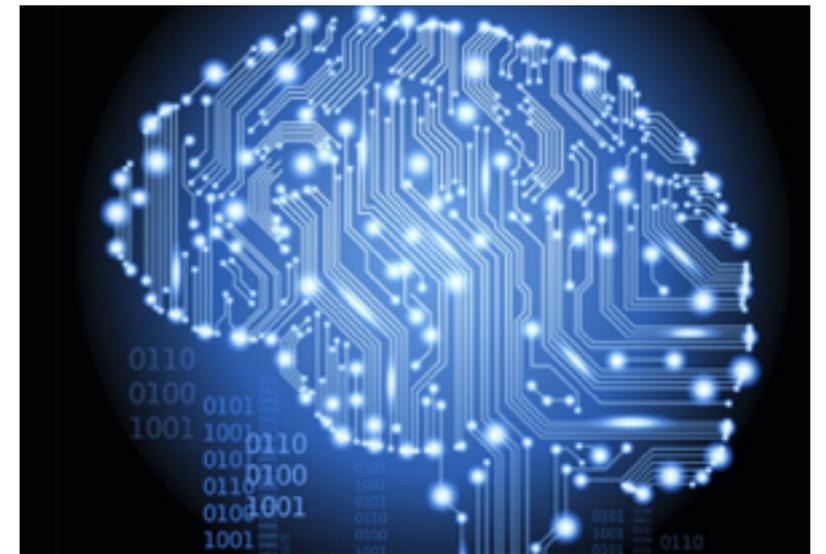
➔ Prediction

- Niels Bohr: “it is very difficult to predict - especially the future”



➔ Progress through technology and new ideas

- Continuous innovation (investment) is crucial



➔ Spirit of exploration

- It is in the nature of fundamental research that we do not know what's beyond our current knowledge

