STEAM SUMMER CAMP 2025

Dal 13-17 luglio 2025
presso il Centro Residenziale Universitario
di Bertinoro (Ce.U.B.) - Forlì

INFN
Istituto Nazionale di Fisica Nucleare

Il Summer Camp 2025 ha **104 posti per studentesse e studenti e 20 per i docenti**, così suddivisi:

- 59 studentesse e studenti selezionati dai progetti di divulgazione scientifica dell'Istituto Nazionale di Fisica Nucleare
  - **6 riservati ai partecipanti alle masterclass**
- 45 posti per le studentesse e gli studenti messi a bando #27537 con scadenza 31 marzo 2025 - https://reclutamento.dsi.infn.it
- 20 docenti di Matematica, Fisica e Scienze delle scuole secondarie di II grado italiane selezionati dall'INFN (form per la richiesta di partecipazione dal 24 febbraio 2025)
- 10 ricercatrici e ricercatori dell'INFN.

Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

INTERNATIONAL MASTERCLASSES

hands on particle physics

ALICE & CMS & ATLAS @ Pavia

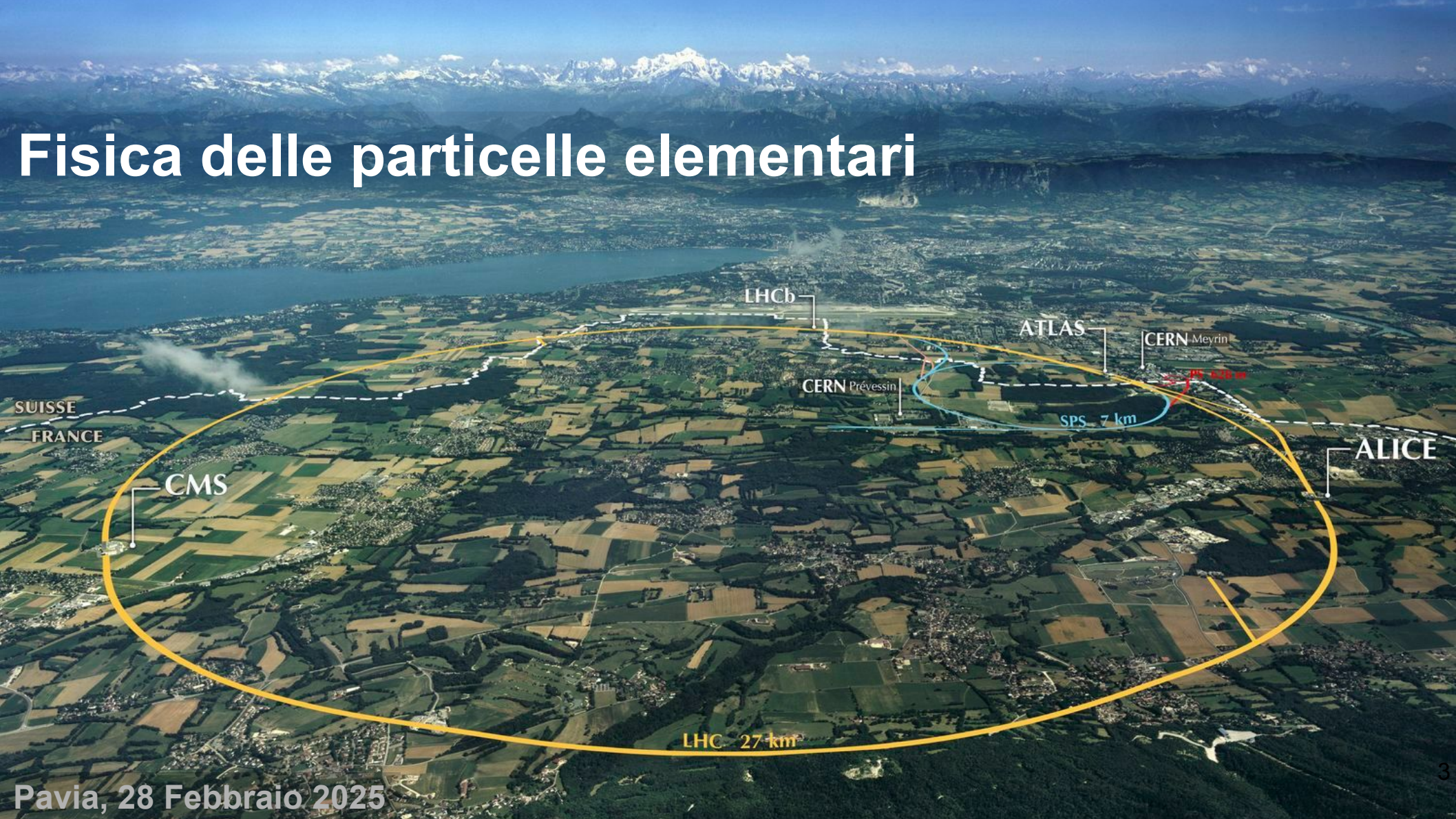
28 Febbraio 2025

Sonia Carrà, Tommaso Cresta

International Particle Physics Outreach Group

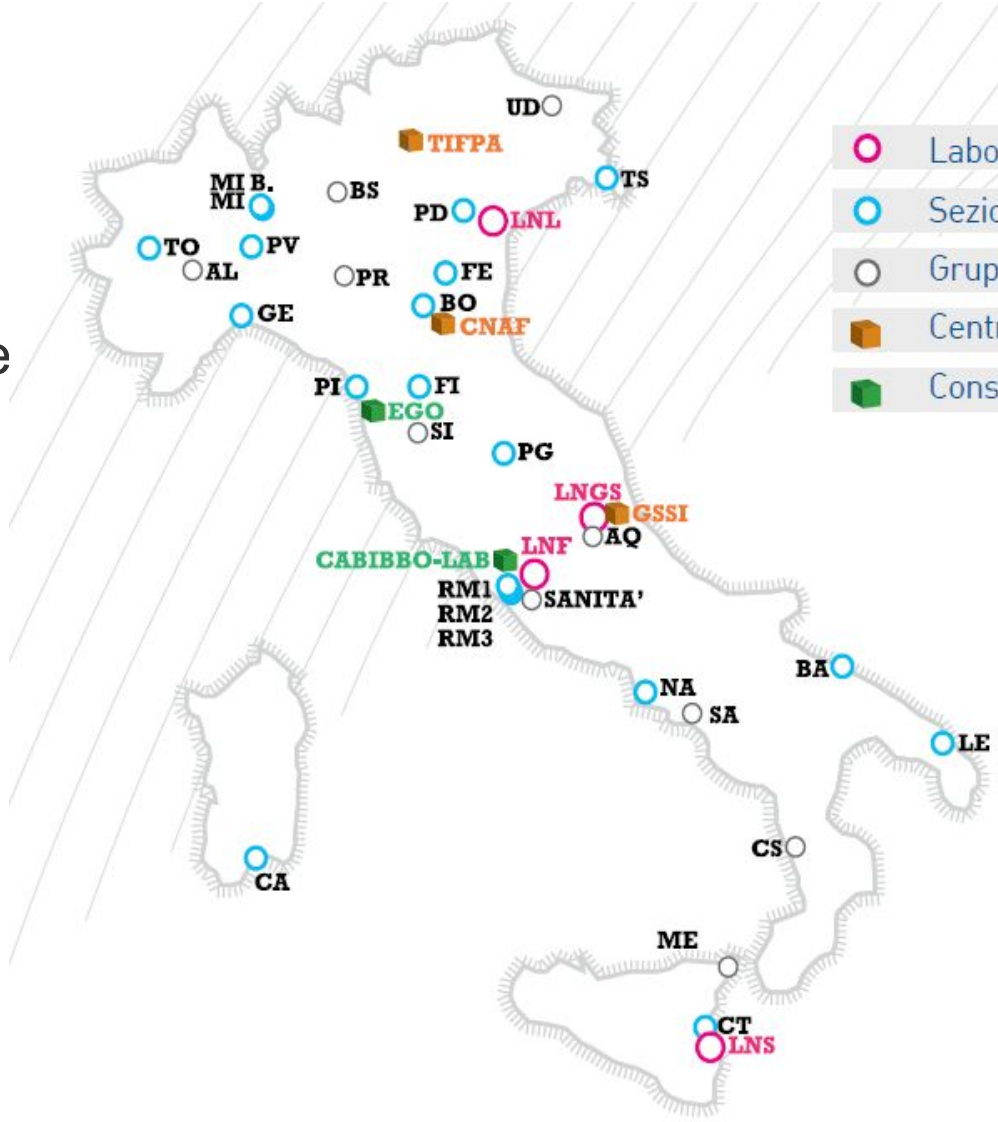
CERN

Fisica delle particelle elementari



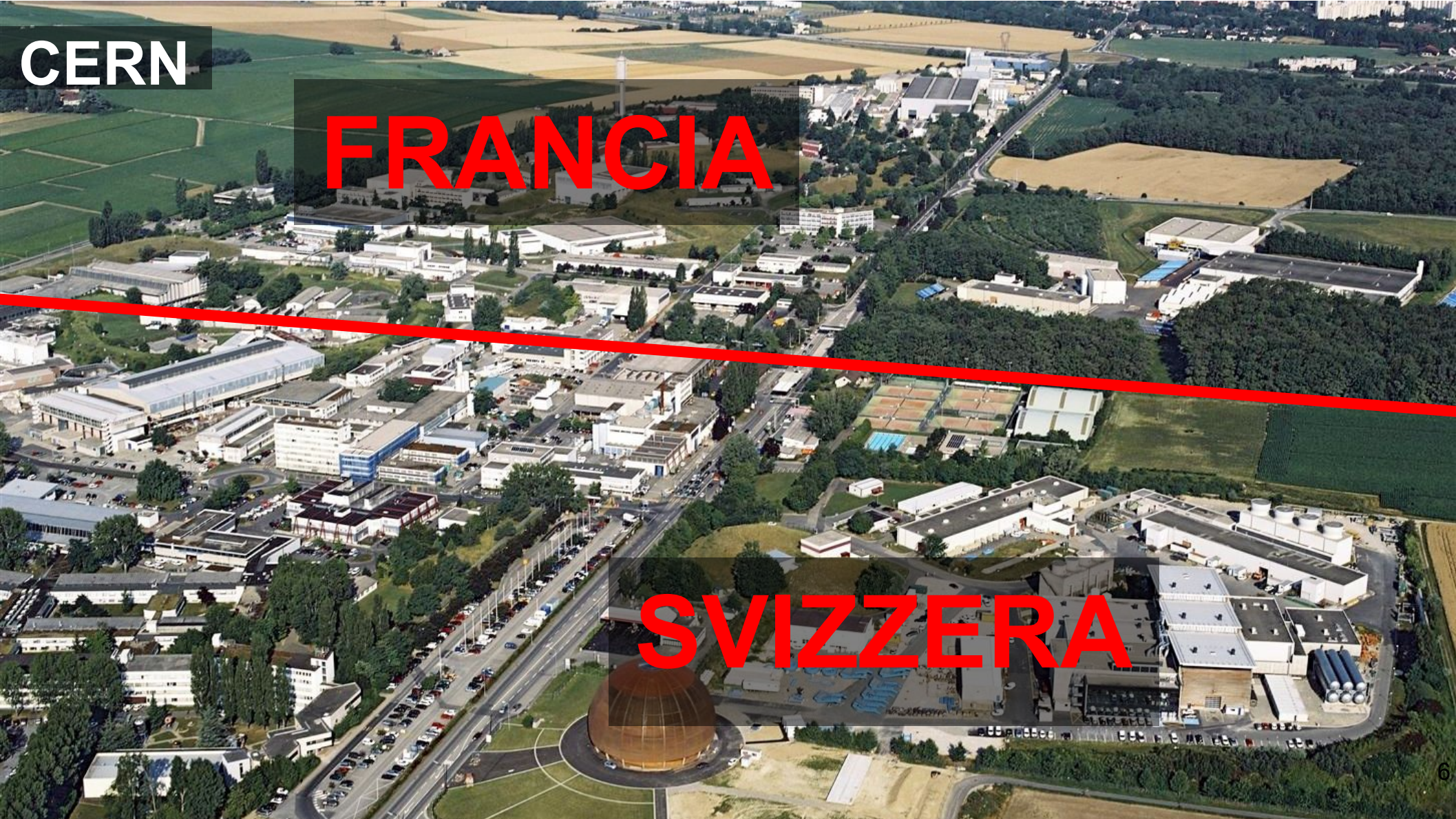
INFN

- **I**stituto **N**azionale di **F**isica **N**ucleare
  - fondi per costruzione apparati e per le trasferte di fisici e tecnici

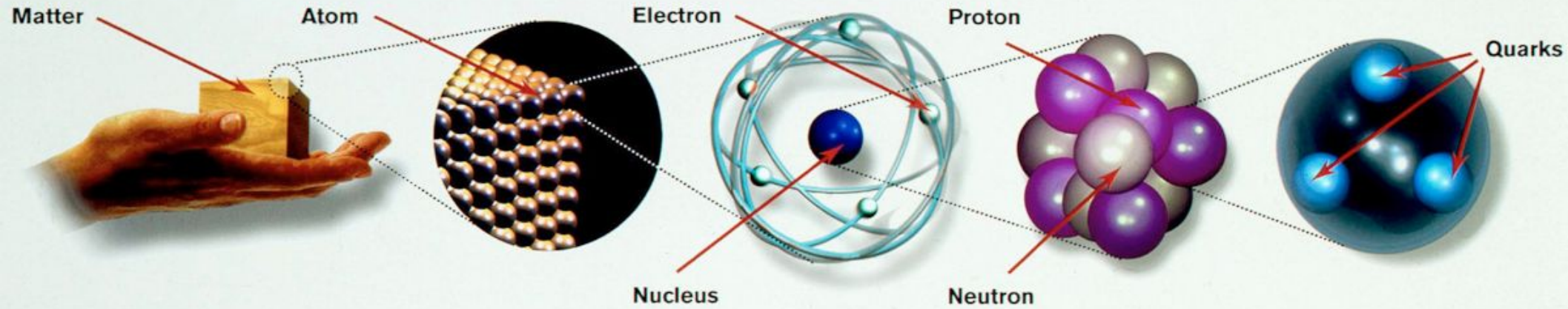


Istituto Nazionale di Fisica Nucleare


CERN


CERN
FRANCIA
SVIZZERA

Fisica delle Particelle Elementari



10^{-10} m

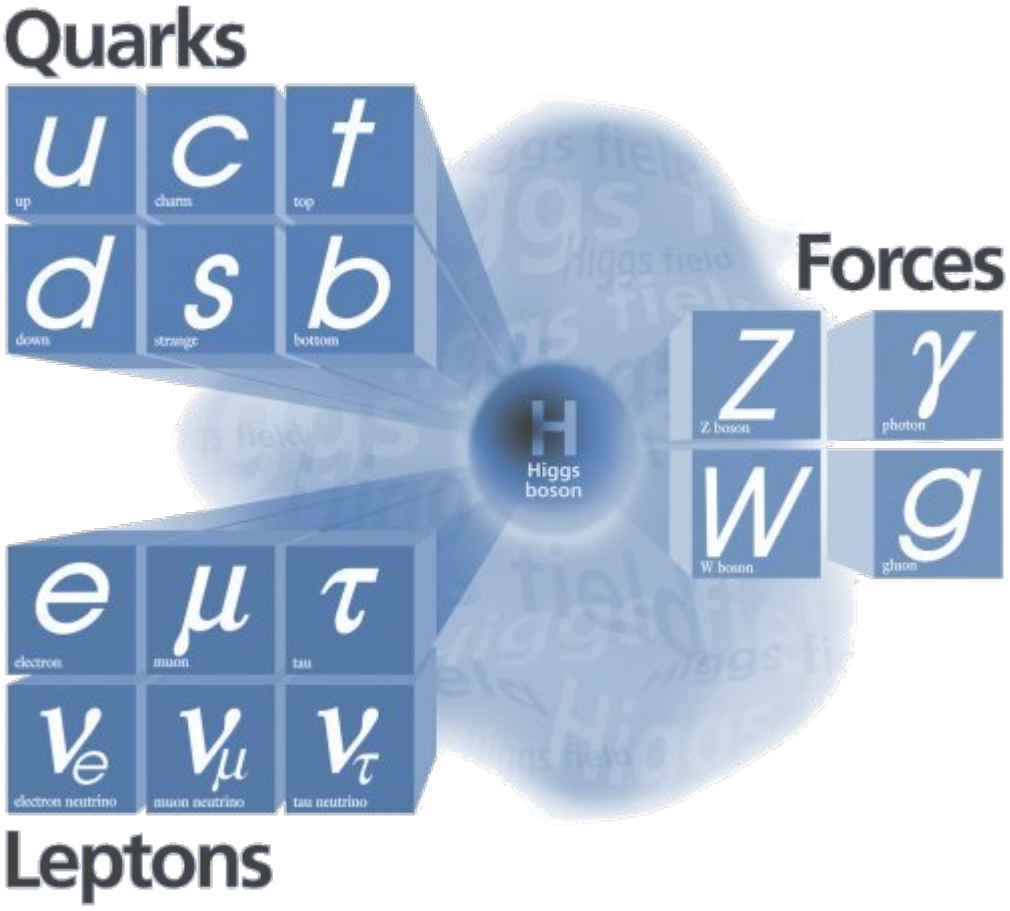
10^{-14} m

10^{-15} m

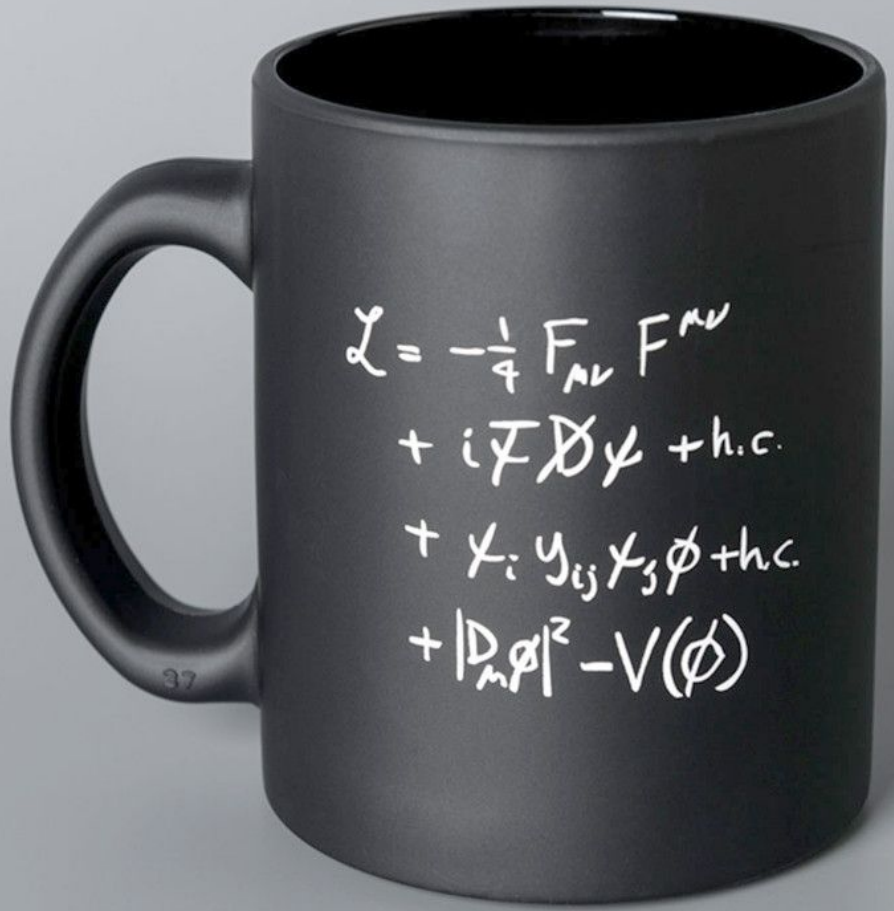
$<10^{-18}$ m

Tutto è fatto di particelle

Tutto è fatto di particelle



Modello Standard



$$\mathbf{L_{SM}} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \tfrac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2}g[W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \tfrac{1}{4}g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2}g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- +$$

ecc...

Alla base della fisica: simmetria

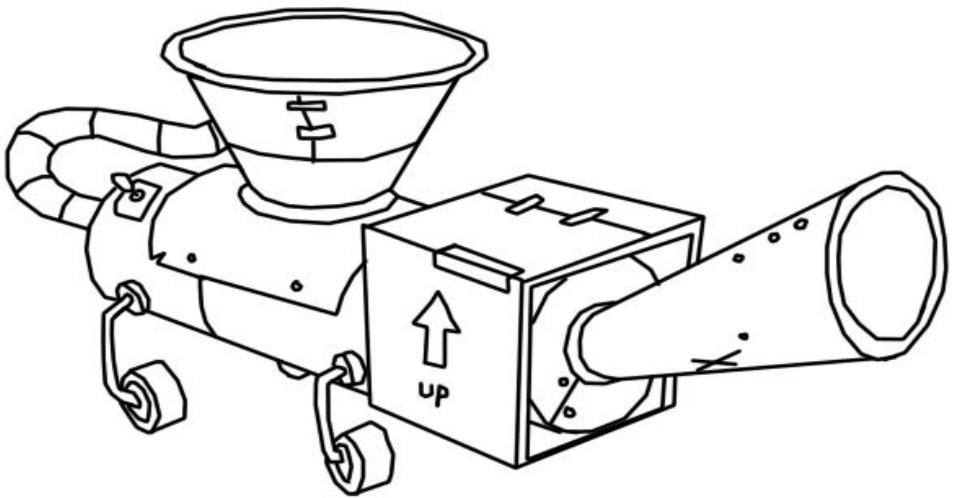
Trasformazione che lascia invariato un oggetto

Simmetria per riflessione

Simmetria per rotazioni

Macchina per teorie

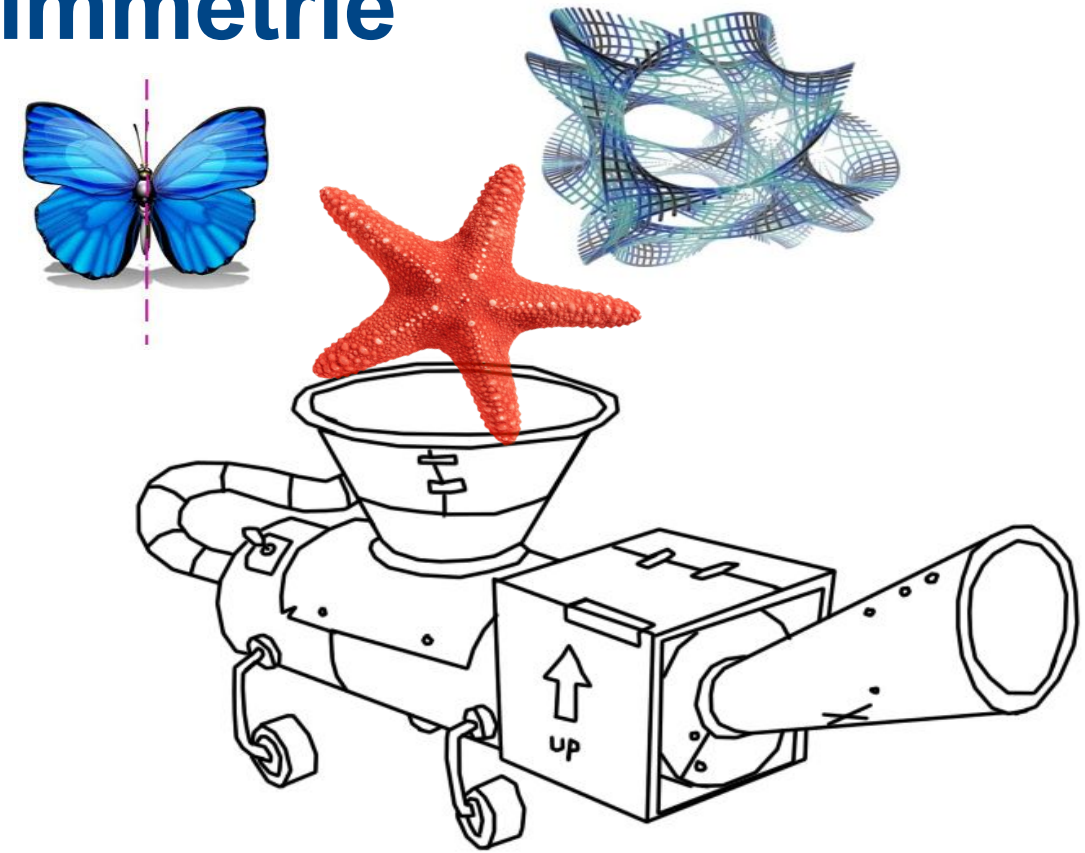
Simmetrie



Equazioni

Macchina per teorie

Simmetrie



$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \Psi_i y_{ij}\Psi_j\Phi + h.c. + |D_\mu\Phi|^2 - V(\Phi)$$

Equazioni

Simmetria

Ad ogni **simmetria** di un sistema fisico è associata una legge di **conservazione**

Emmy Noether, 1915

Teorema di Nother

Invarianza per traslazioni temporali

$$dU = \delta Q - \delta L$$

Invarianza per traslazioni spaziali

$$\frac{d \sum \vec{p}_i}{dt} = 0$$

Invarianza della velocità della luce

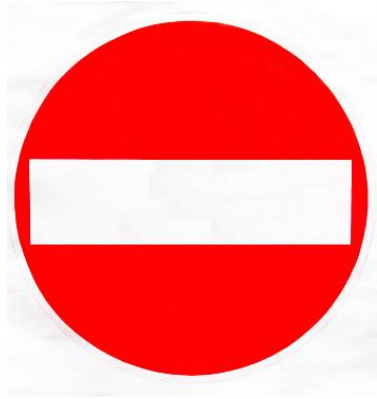
$$E = mc^2$$

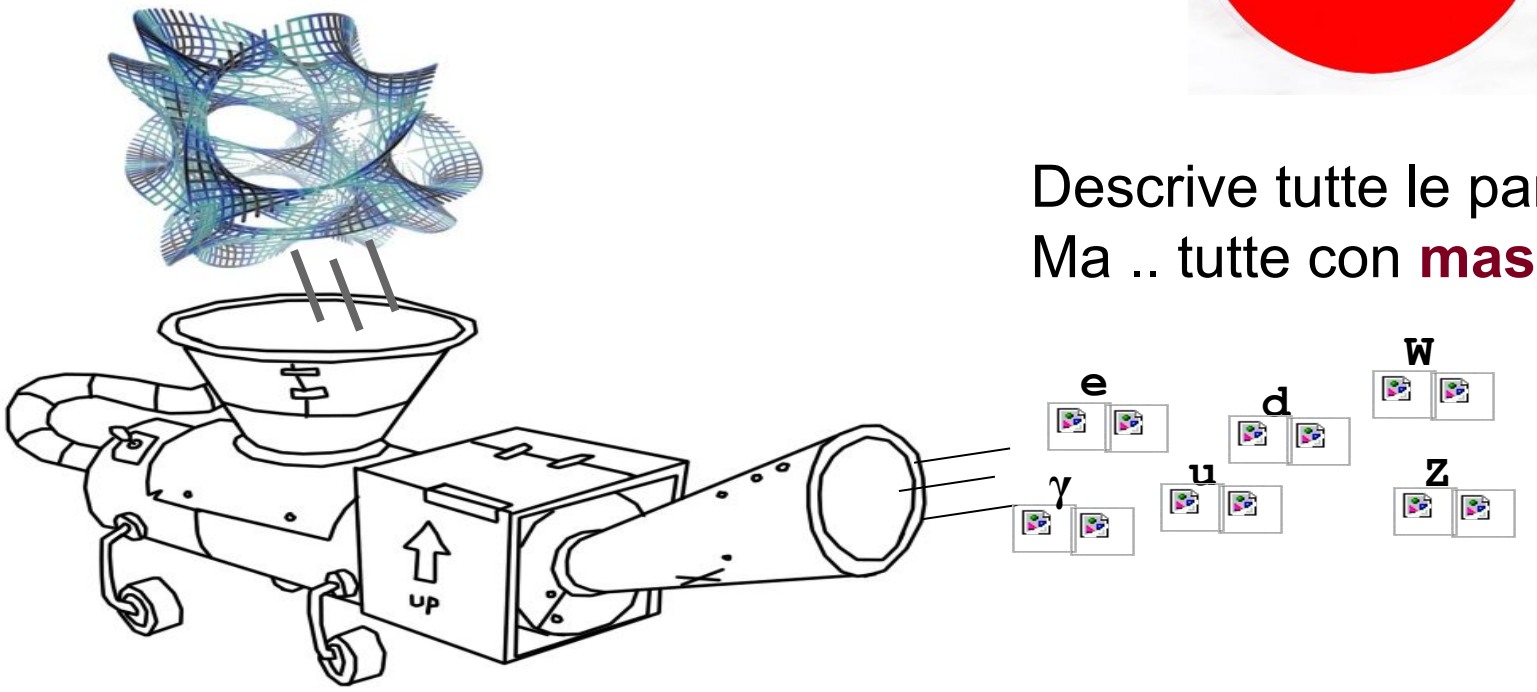
Principio di equivalenza

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8 \pi G T_{\mu\nu}$$

Modello standard delle particelle

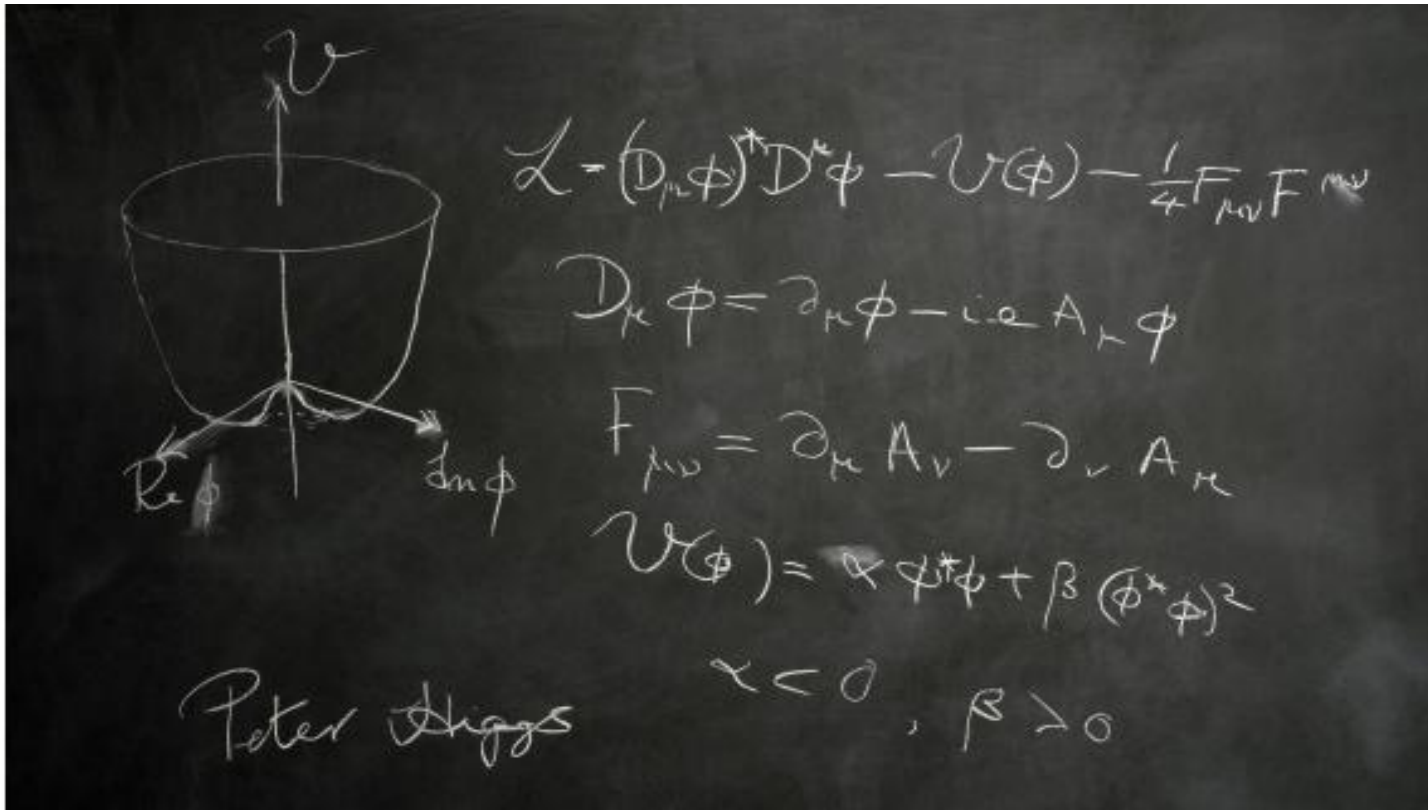
Simmetria **$SU(2)_L$ x U(1)**





Descrive tutte le particelle
Ma .. tutte con **massa nulla**

E se la simmetria fosse rotta?

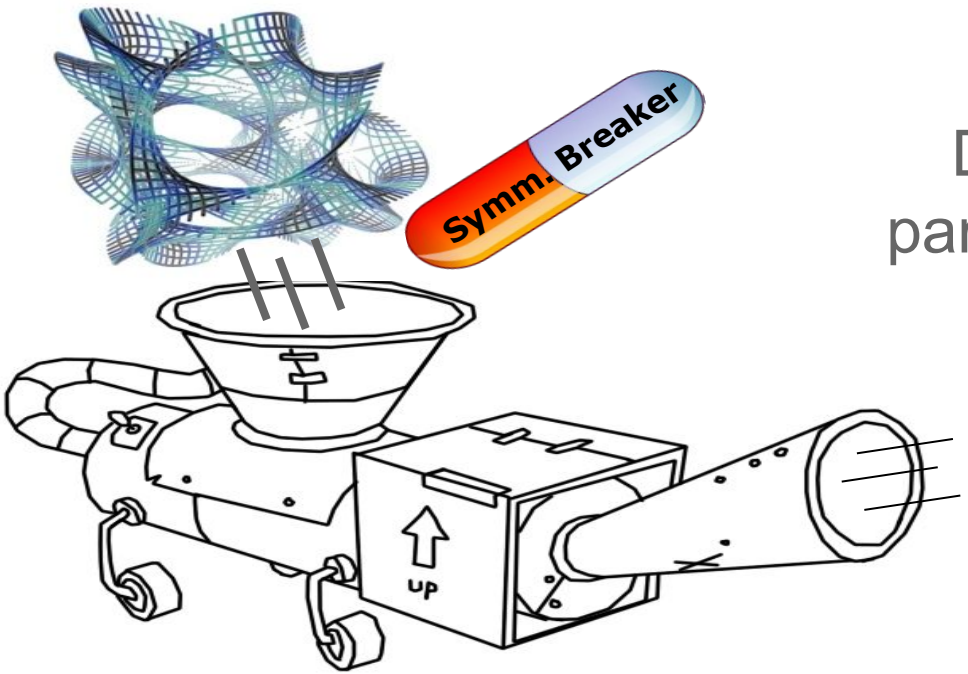


Robert Brout, François Englert, **Peter Higgs @1964**

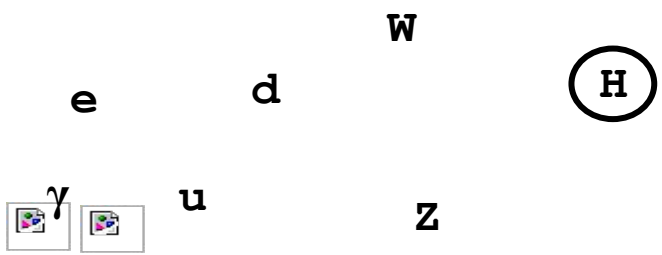
Modello standard delle particelle

Simmetria **$SU(2)_L$ x U(1)**

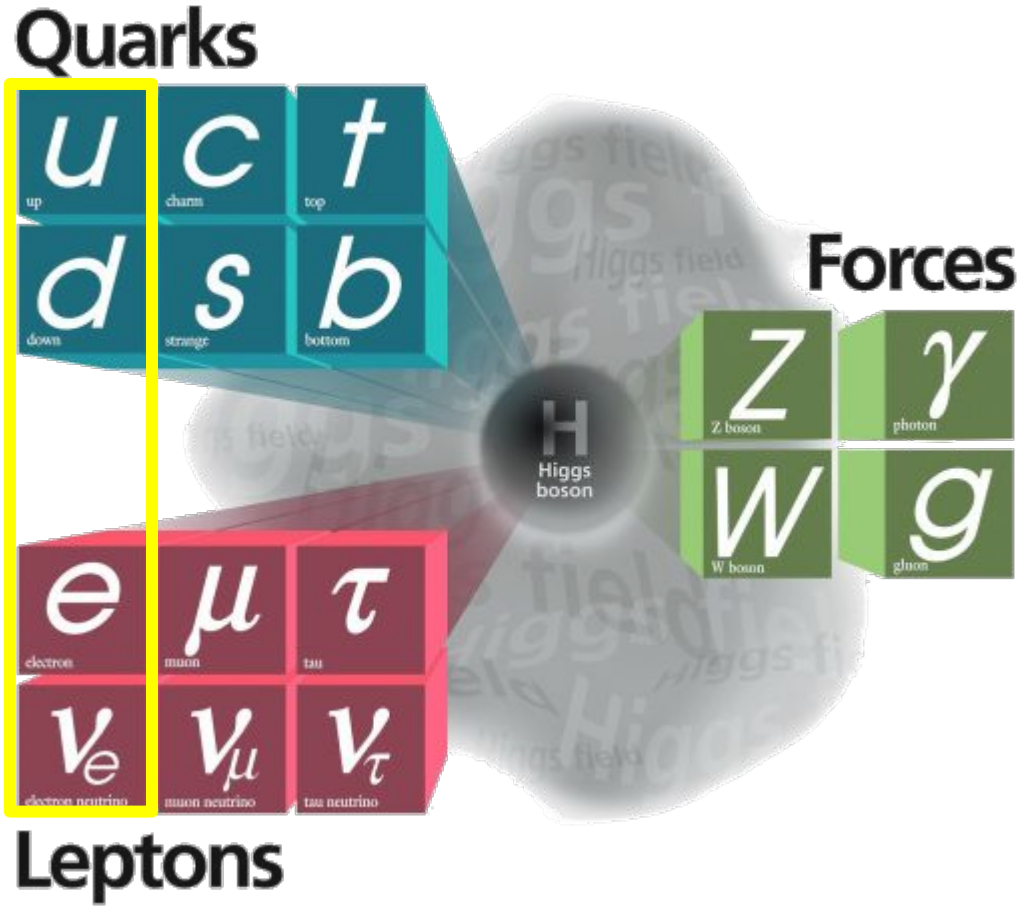
- Meccanismo di **Higgs**:
  in natura la simmetria è "**rotta**"



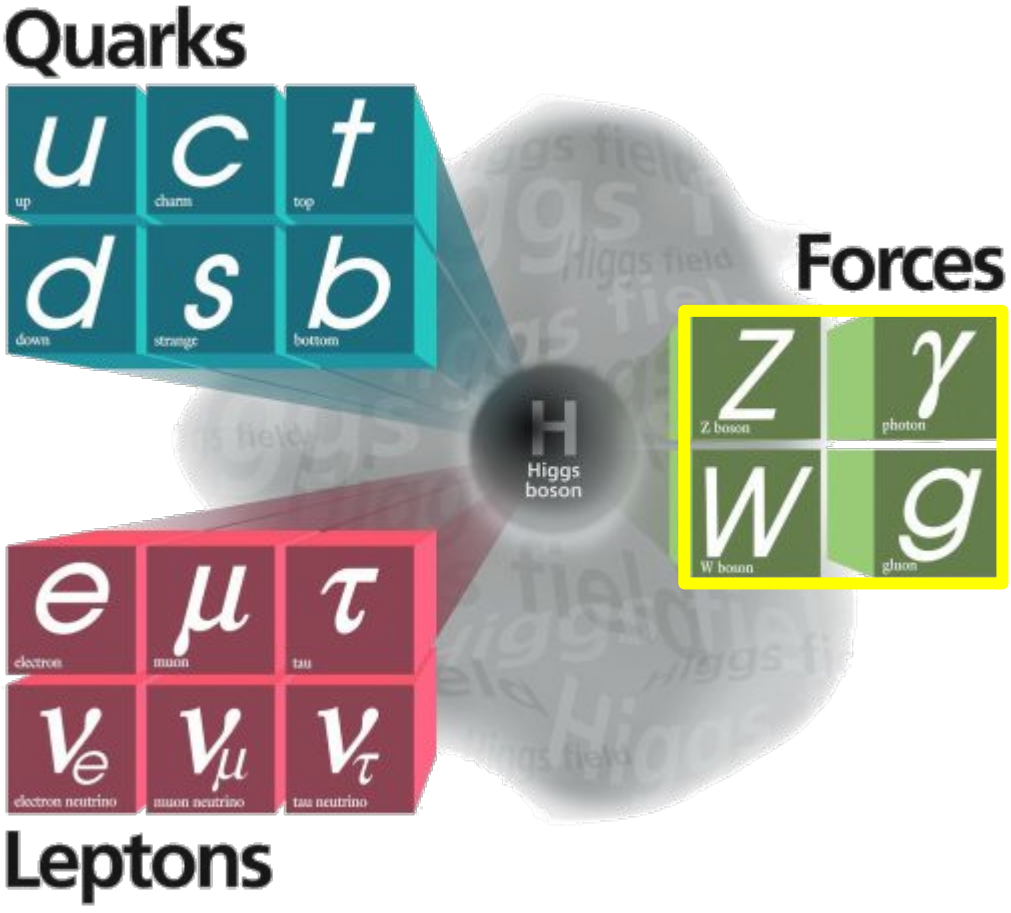
Descrizione corretta delle particelle note + … una nuova



Tutto è fatto di particelle

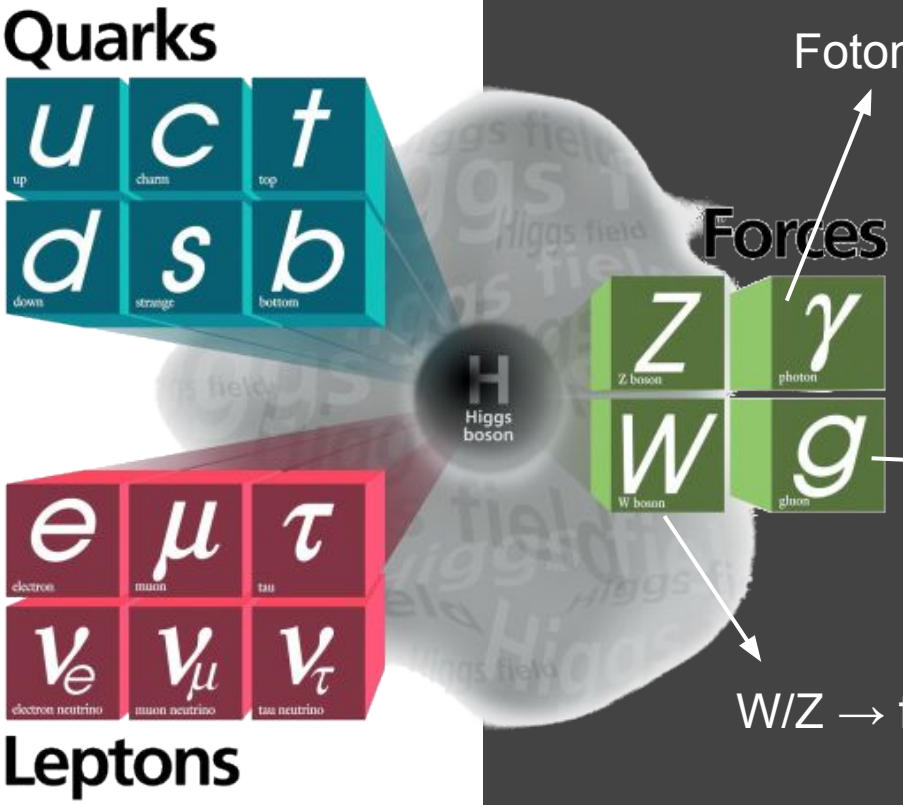


Tutto è fatto di particelle



I fermioni

La materia



I bosoni

Le forze

Fotone → forza elettromagnetica

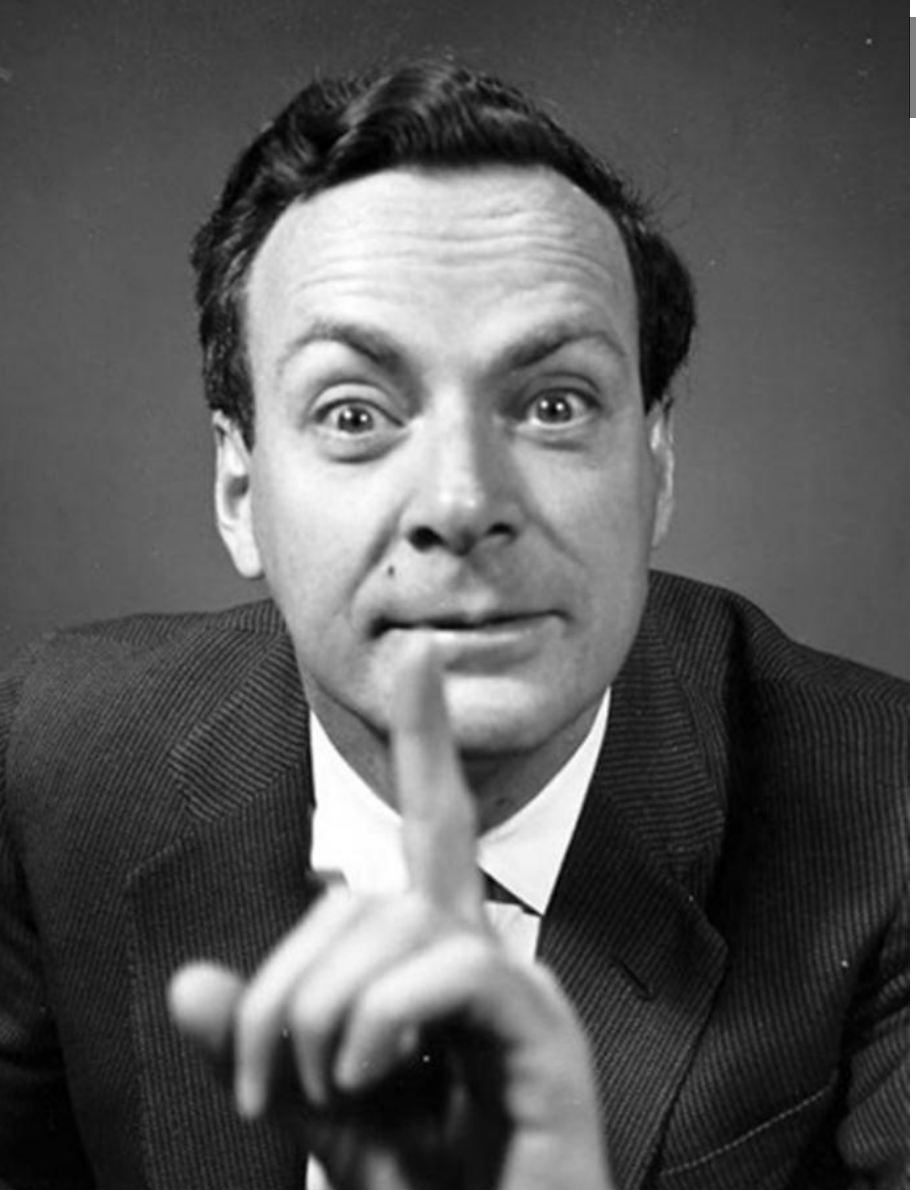
Gluone → forza forte

W/Z → forza debole

Interazioni mediate da bosoni

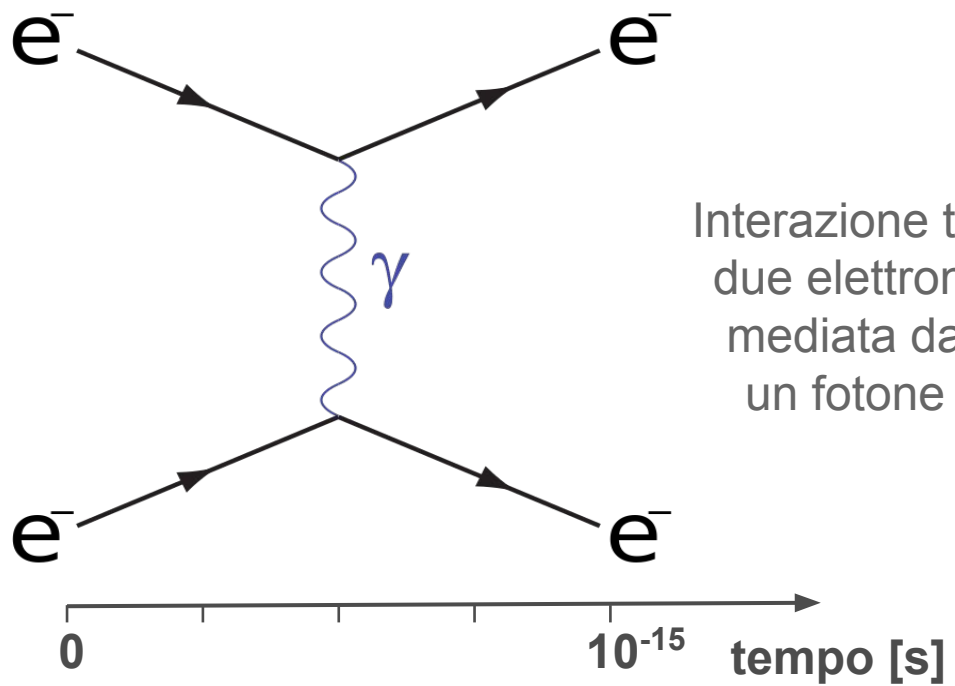
Interazioni mediate da bosoni

A volte la particella emittente si trasforma



Diagrammi di Feynman

- Ogni elemento è un pezzo dell'equazione
- Ad ogni vertice si conserva:
  carica, energia, impulso



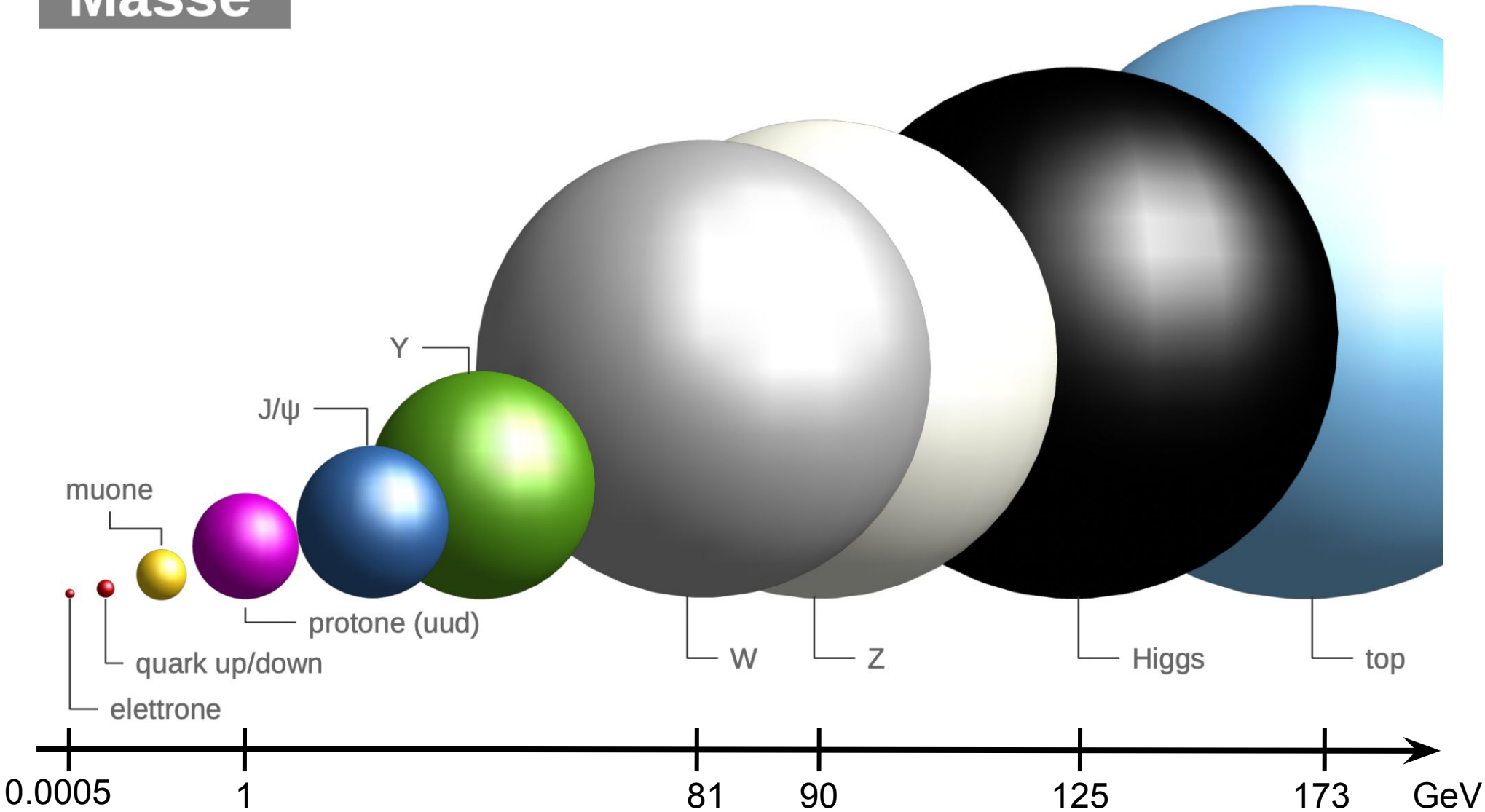
Interazione tra due elettroni mediata da un fotone

Masse

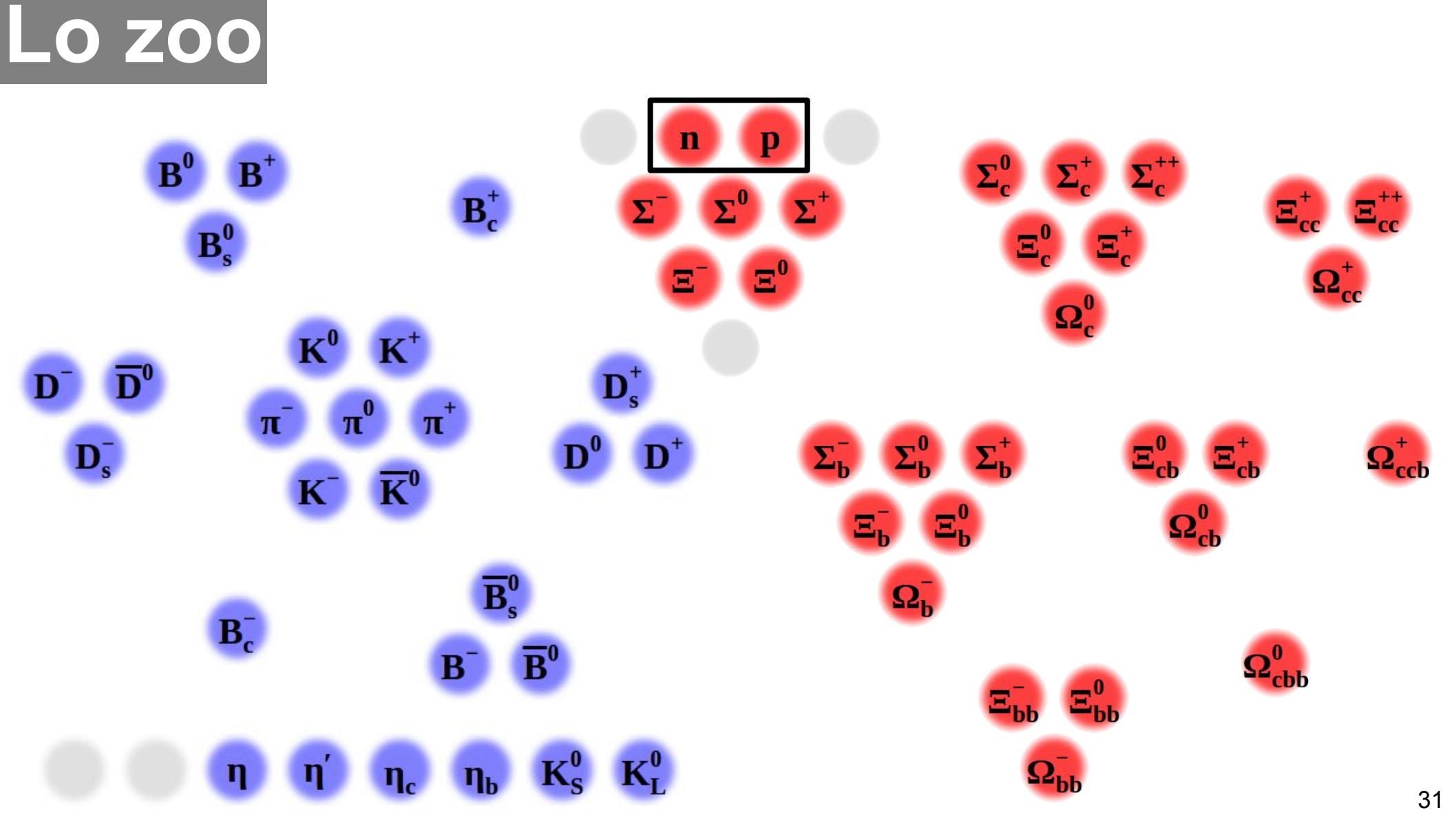
Masse

- Unità di misura di energia
  - $E=mc^2$
- **ElectronVolt**
  - **1 eV** $= 1.6 \cdot 10^{-19}$ J
  - **1 GeV** $= 10^{9}$ eV
  - **1 TeV** $= 10^{12}$ eV
- **Protone = 1 GeV**

Masse


Y
J/ψ
muone
protone (uud)
quark up/down
elettrone
W
Z
Higgs
top
0.0005
1
81
90
125
173
GeV

Lo zoo


B^0 B^+ B_s^0 B_c^+
n p Σ^- Σ^0 Σ^+ Ξ^- Ξ^0
Σ_c^0 Σ_c^+ Σ_c^{++} Ξ_c^0 Ξ_c^+ Ω_c^0
Ξ_{cc}^+ Ξ_{cc}^{++} Ω_{cc}^+
D^- $\overline{D}^0$ D_s^-
K^0 K^+ π^- π^0 π^+ K^- $\overline{K}^0$
D_s^+ D^0 D^+
Σ_b^- Σ_b^0 Σ_b^+ Ξ_b^- Ξ_b^0 Ω_b^-
Ξ_{cb}^0 Ξ_{cb}^+ Ω_{cb}^0
Ω_{ccb}^+
$\overline{B}_s^0$ B_c^- B^- $\overline{B}^0$
Ω_{cbb}^0
Ξ_{bb}^- Ξ_{bb}^0 Ω_{bb}^-
η η' η_c η_b K_S^0 K_L^0

Da ricordare

- La natura è **matematica**
- Equazioni dalle **simmetrie**
- Tutto è fatto di **particelle**
- **Masse** misurate in GeV
  - Protone 1 GeV
  - Bosone Z 90 GeV
  - Bosone Higgs 125 GeV

Decadimenti

Decadimenti

- Poche particelle sono stabili
  - Elettrone, protone e neutrini
- Le altre **decadono** in quelle più stabili
  - Con un tempo caratteristico
- Più tardi vedremo
  - **Z** $\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
  - **J/ψ**(cc)$\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
  - **ϒ** (bb)$\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...

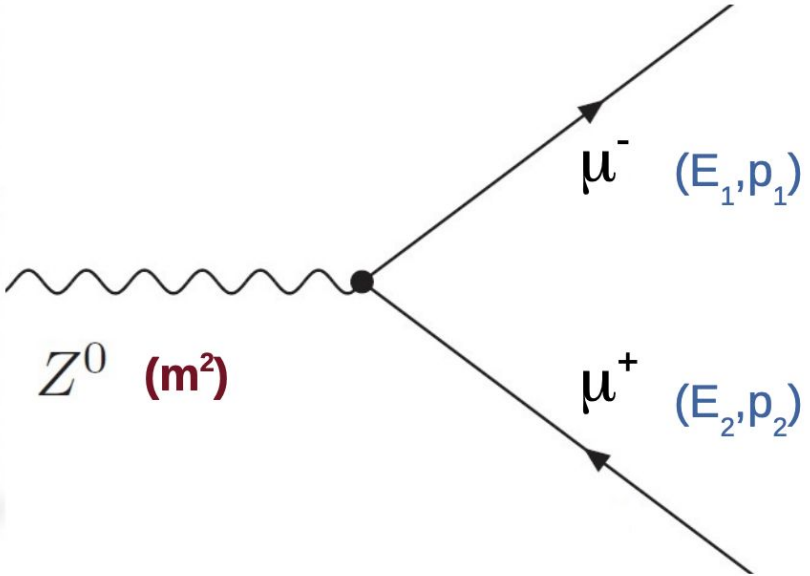
Decadimenti

- Poche particelle sono stabili
  - Elettrone, protone e neutrini
- Le altre **decadono** in quelle più stabili
  - Con un tempo caratteristico
- Più tardi vedremo
  - **Z** $\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
  - **J/ψ**(cc)$\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
  - **ϒ** (bb)$\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...

Conservazione energia e impulso

Misurando **energia** e **impulso** dei prodotti di decadimento
→ si può risalire alla **massa** della particella iniziale

$$m^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$



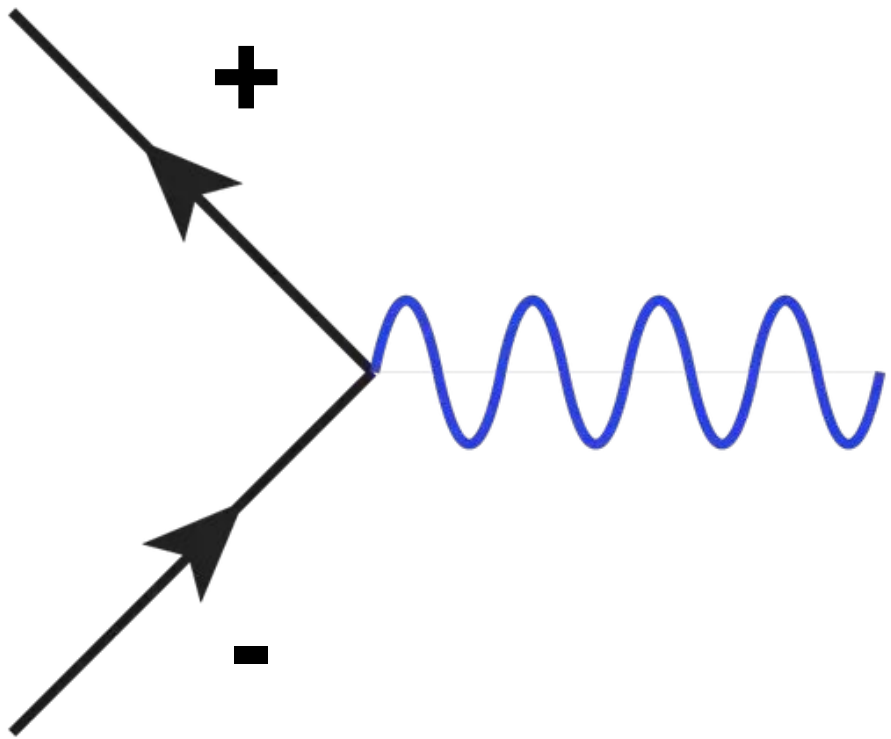
Antimateria

Ogni particella →antiparticella

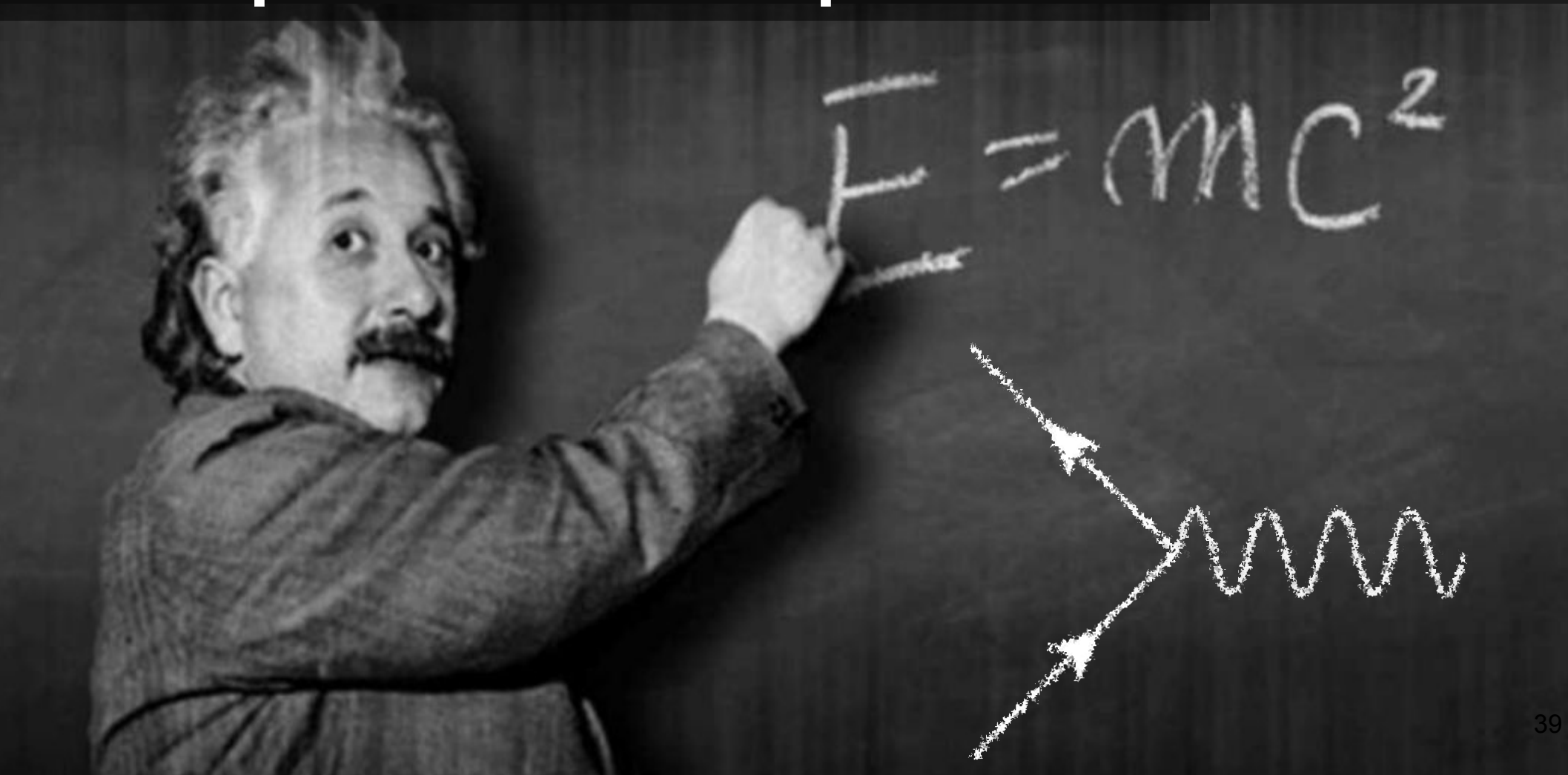
stessa massa ma **carica opposta**

Antimateria

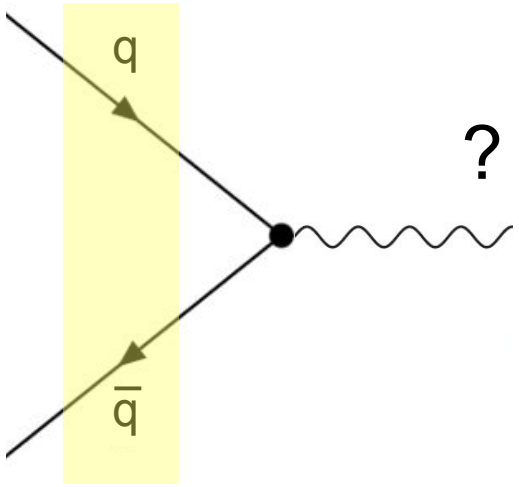
- Se una **particella** incontra la sua **anti-particella** si **annichilano**
  - La **massa** diventa **energia**
    $E=mc^2$
  - Particelle a carica neutra: fotoni, gluoni o il bosone Z

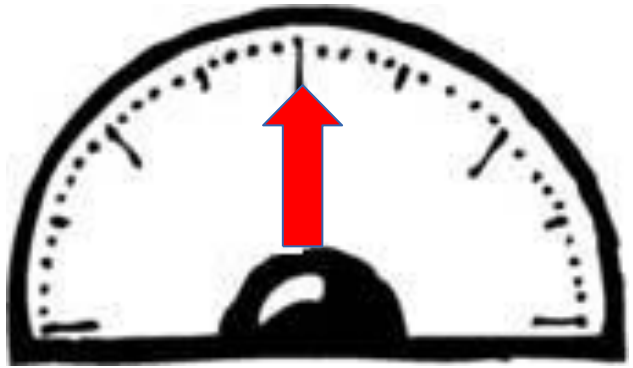


Come produrre nuove particelle?



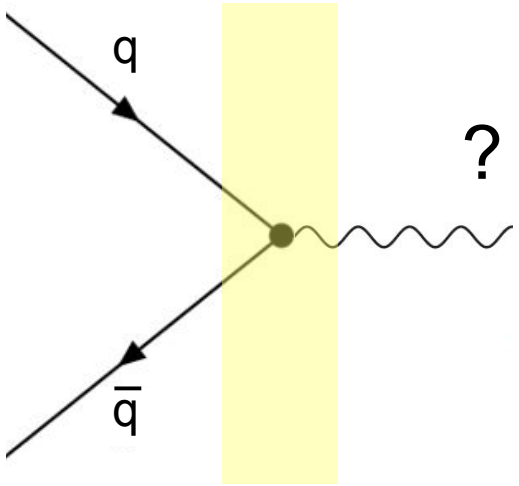
Collider

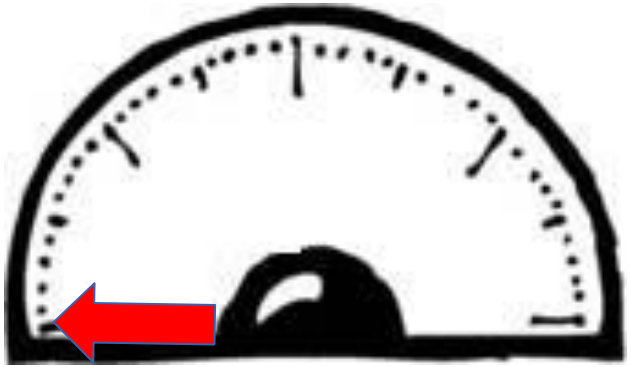




$E = mc^2$

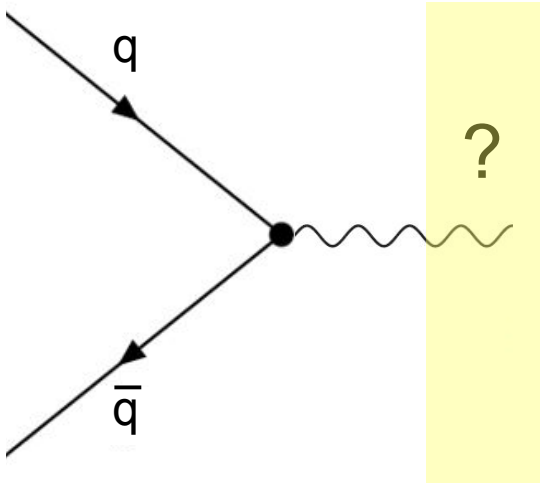
Collider

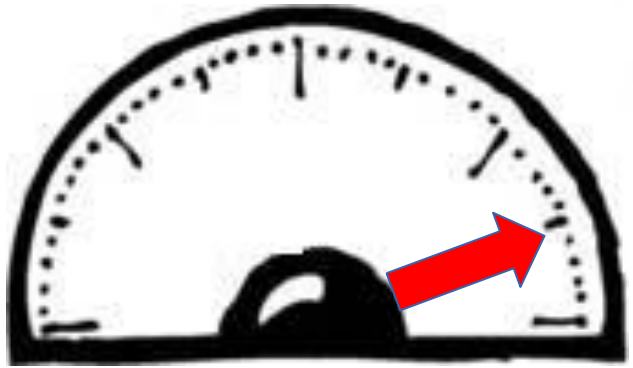




$E = mc^2$

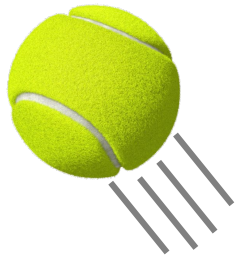
Collider

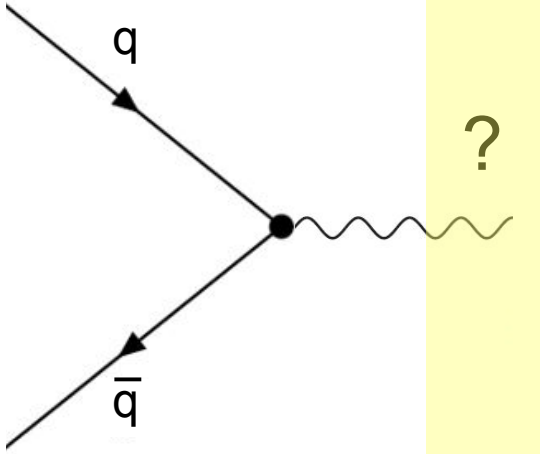


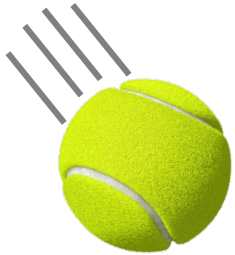


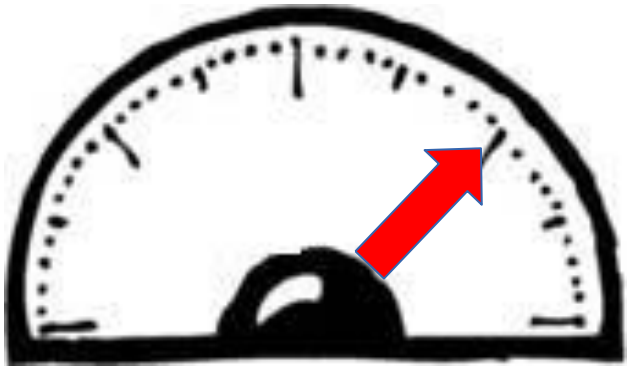
$E = mc^2$

Collider







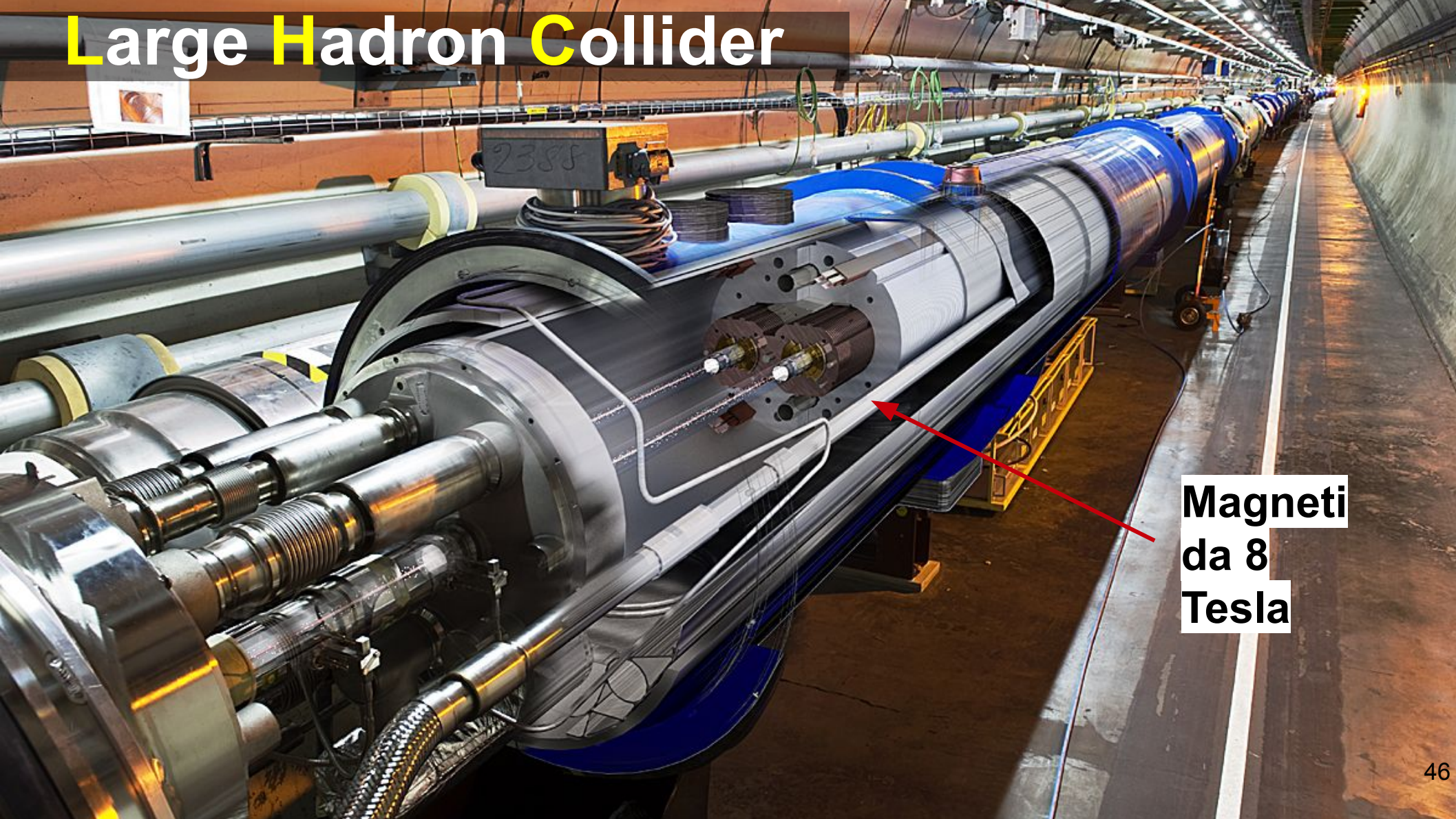


$E = mc^2$

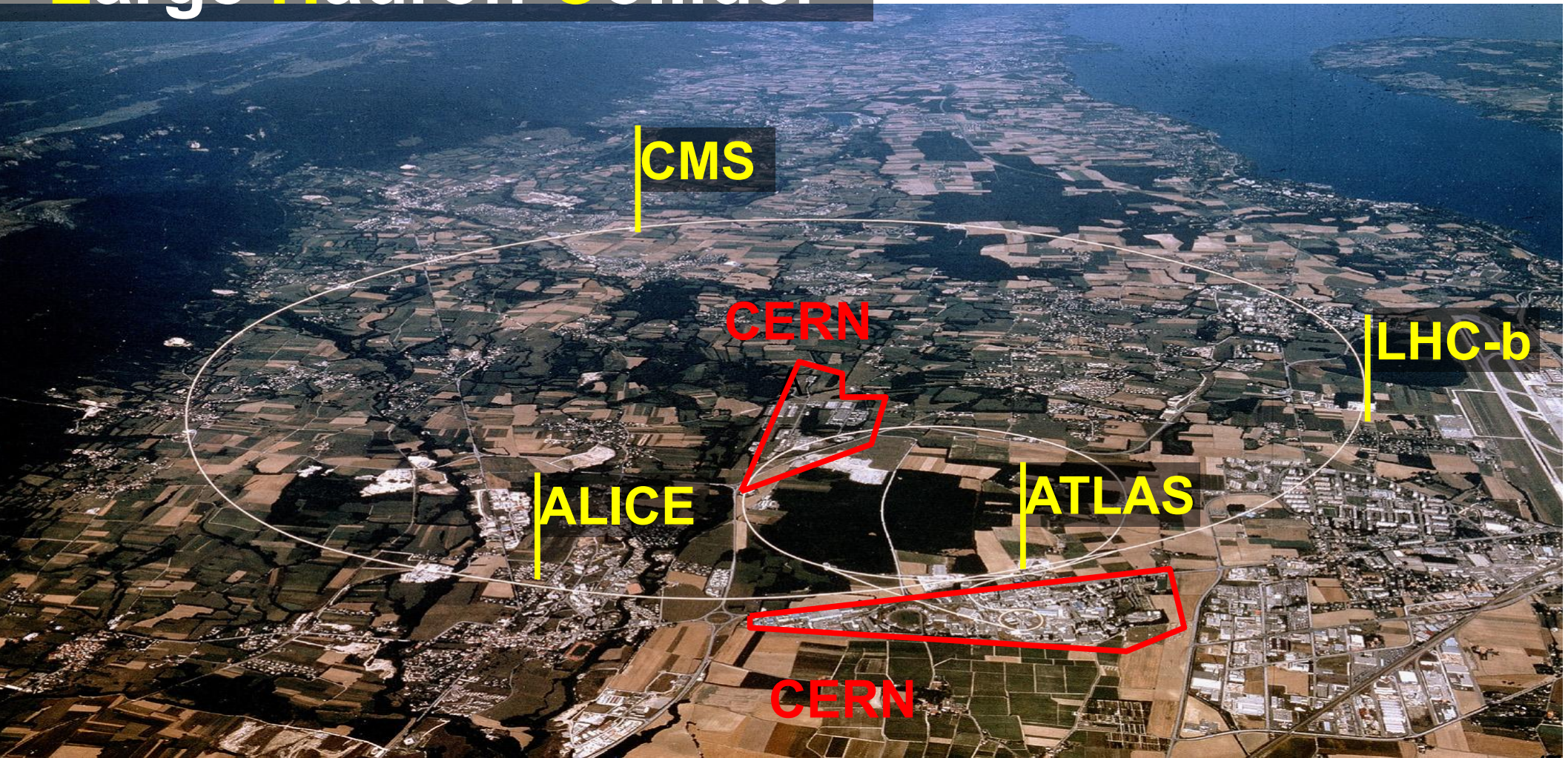
Livingstone Lawrence ‘32

Anello di Accumulazione ‘60

Large Hadron Collider

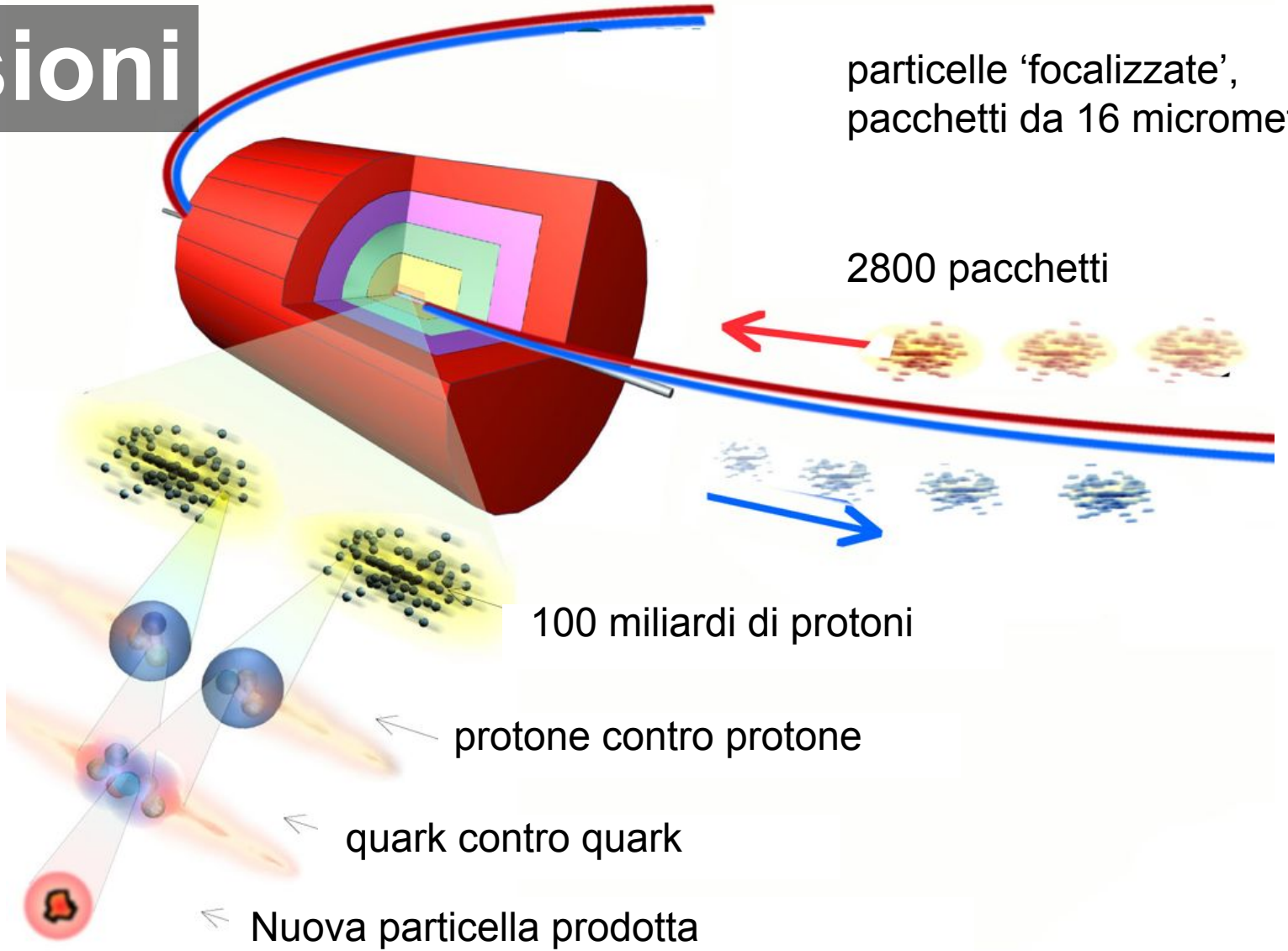


Large Hadron Collider

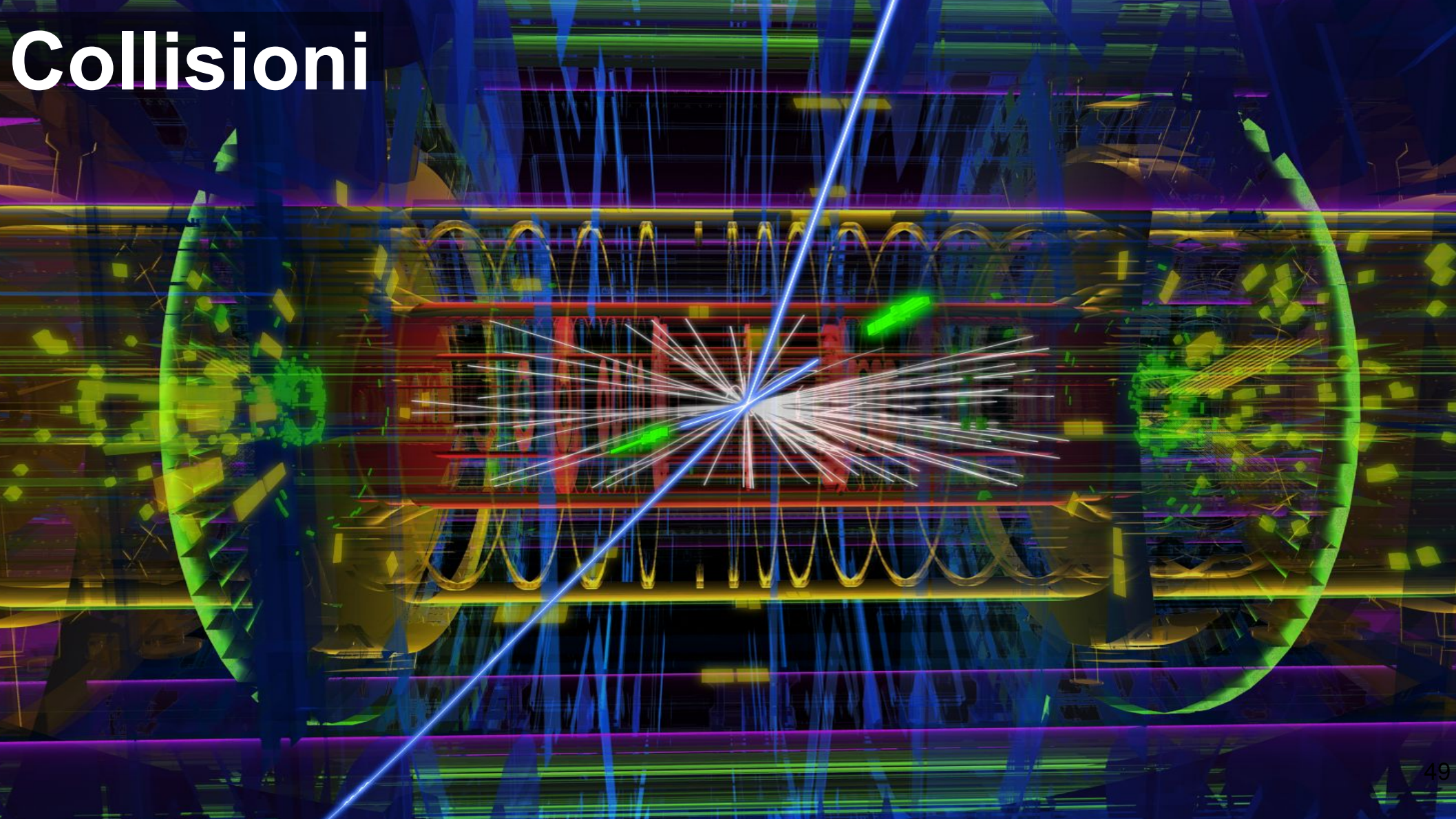


Collisioni

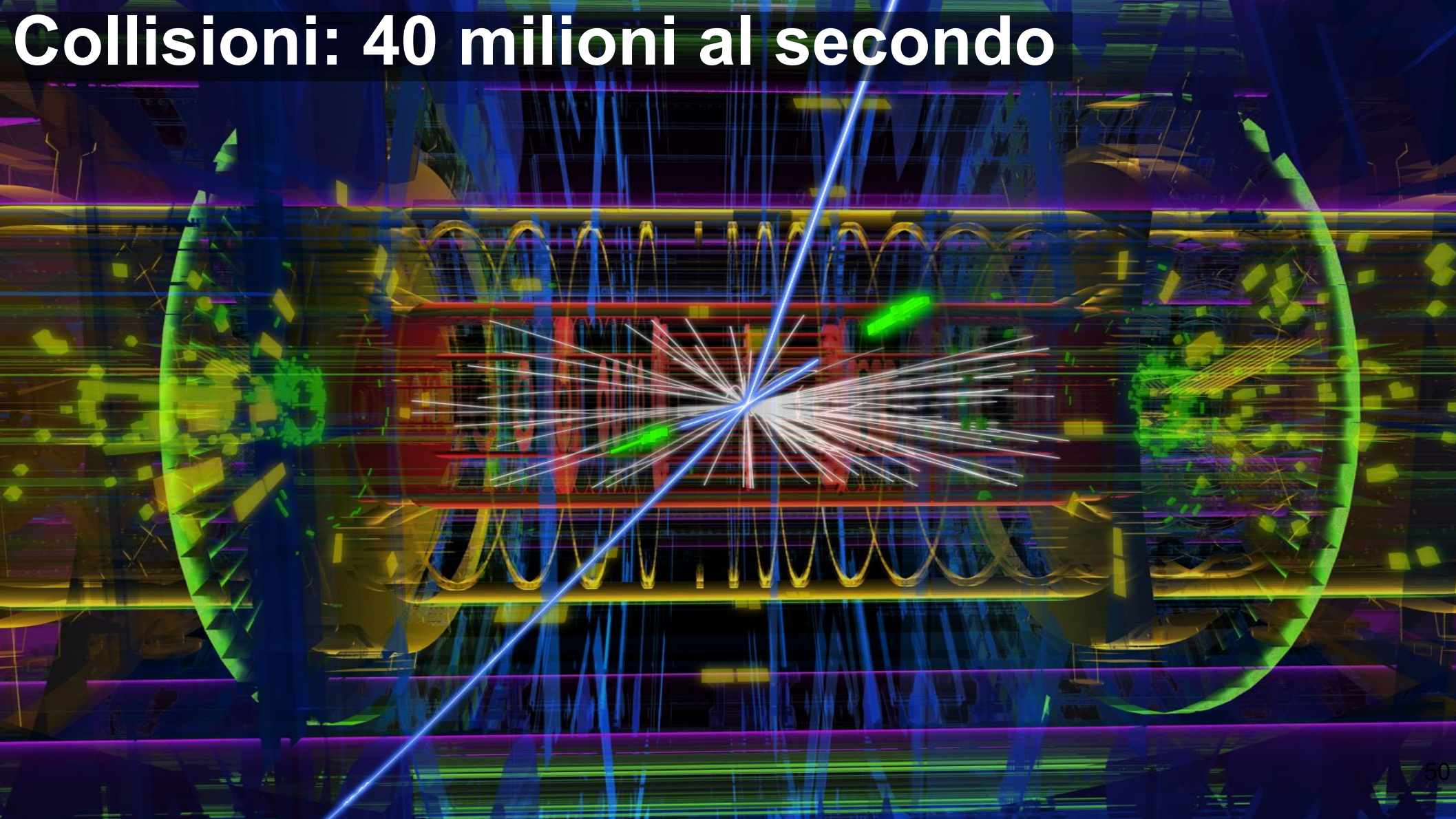
particelle ‘focalizzate’,
pacchetti da 16 micrometri x 10 cm



Collisioni



Collisioni: 40 milioni al secondo



Eventi rari

Segnale/fondo:
$1/10^{10}$

- 1 granello ogni 400 secchielli

Da ricordare

- Acceleratore da **27 km**
  - Per far collidere ad alta energia particelle leggere
- Per produrre **particelle massive**
  - $E=mc^2$ e annichilazione
- Le particelle massive **decadono** in quelle stabili, che riveliamo
- **Eventi rari**, necessari milioni di scontri al secondo

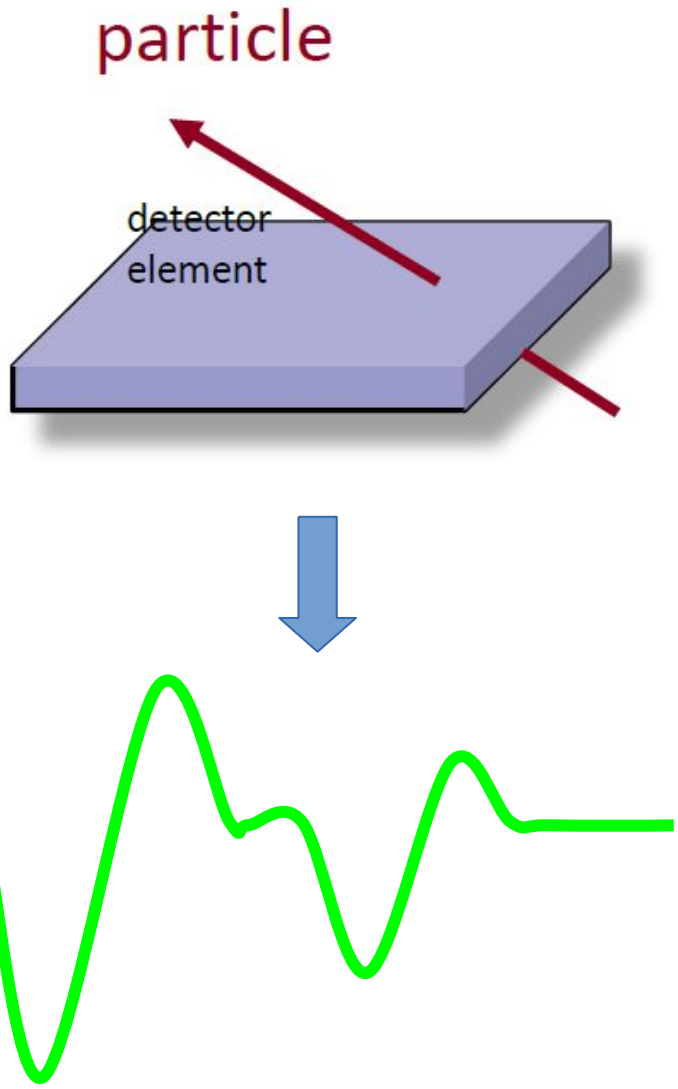
Rivelatori di particelle

Sempre lui:

“It doesn’t matter how beautiful your theory is. If it doesn’t agree with experiment, it’s wrong.”

Rivelatori di particelle

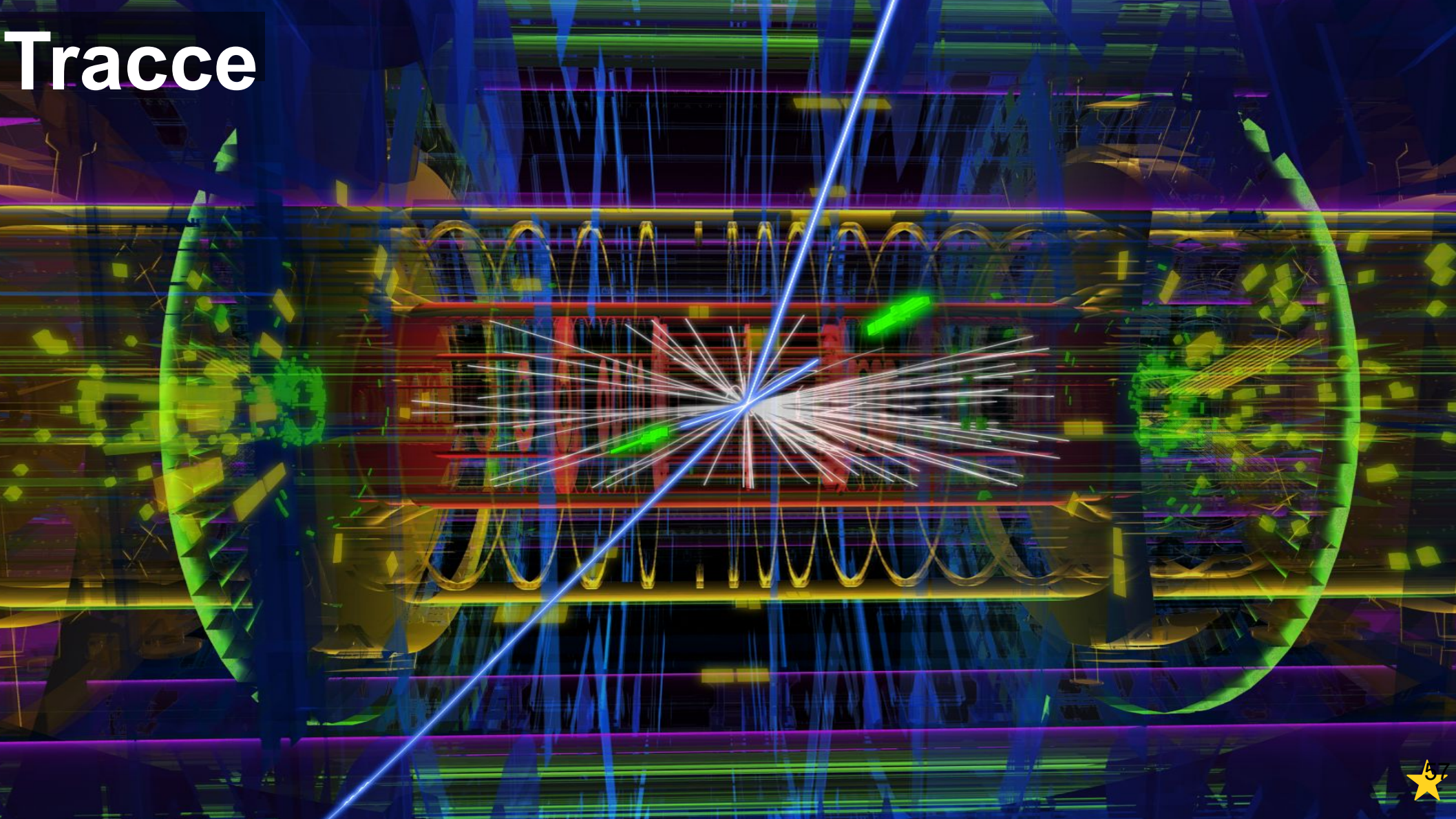
- **Interazione** delle particelle con la materia
- Liberazione di elettroni, ioni, fotoni
- Raccolta di **segnali elettrici**

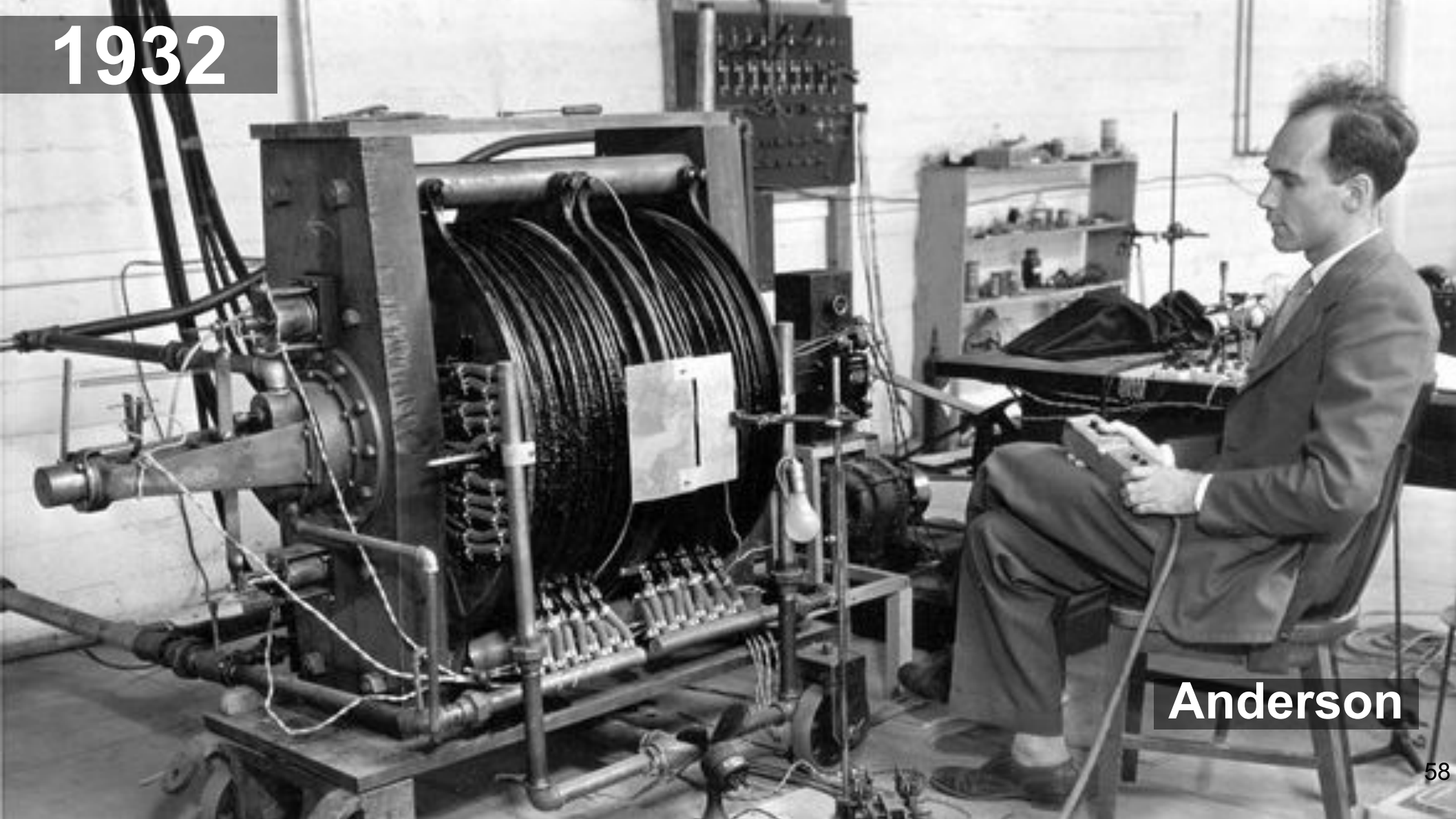


Rivelatori di particelle

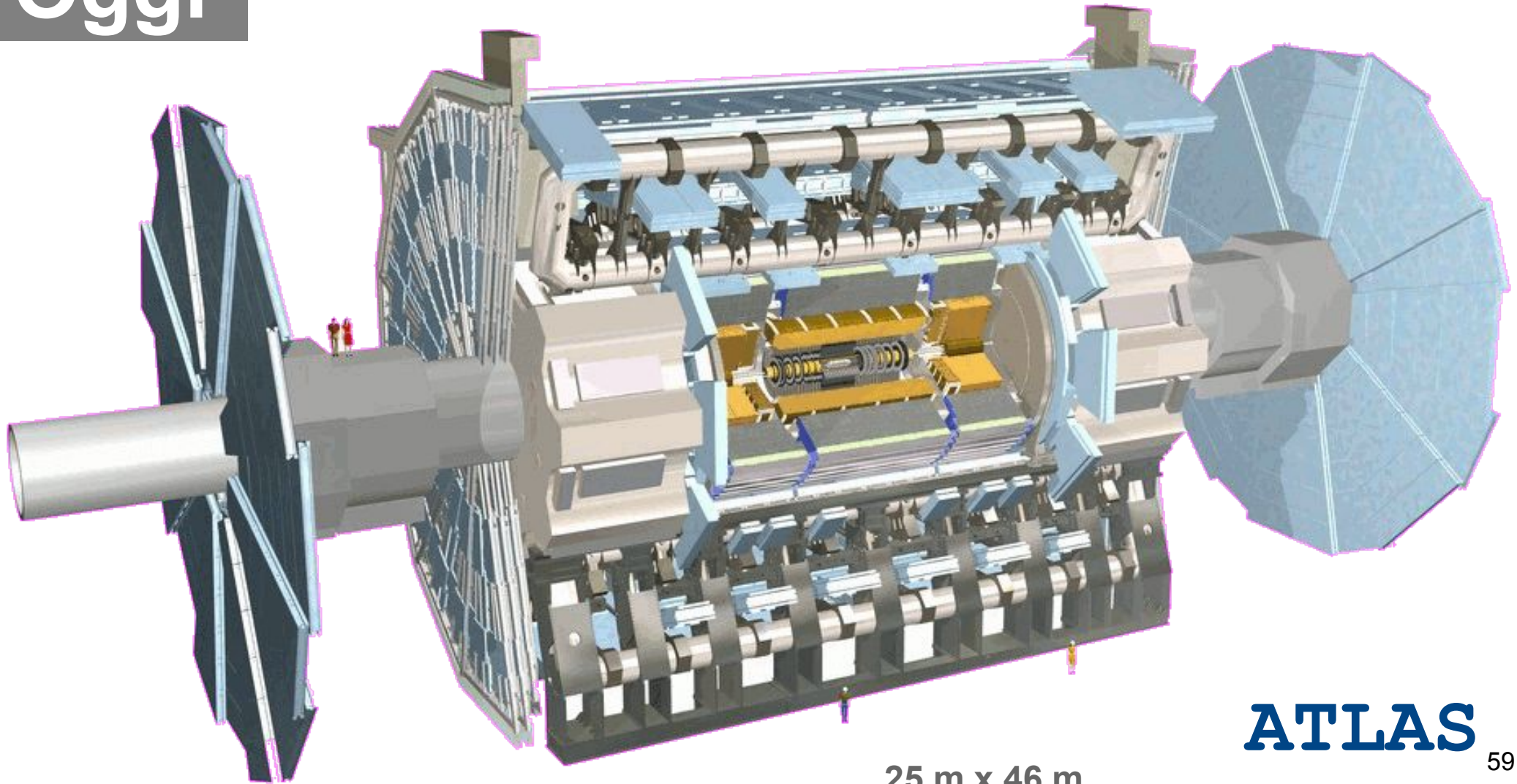
Seguire le scie

Tracce




1932
Anderson

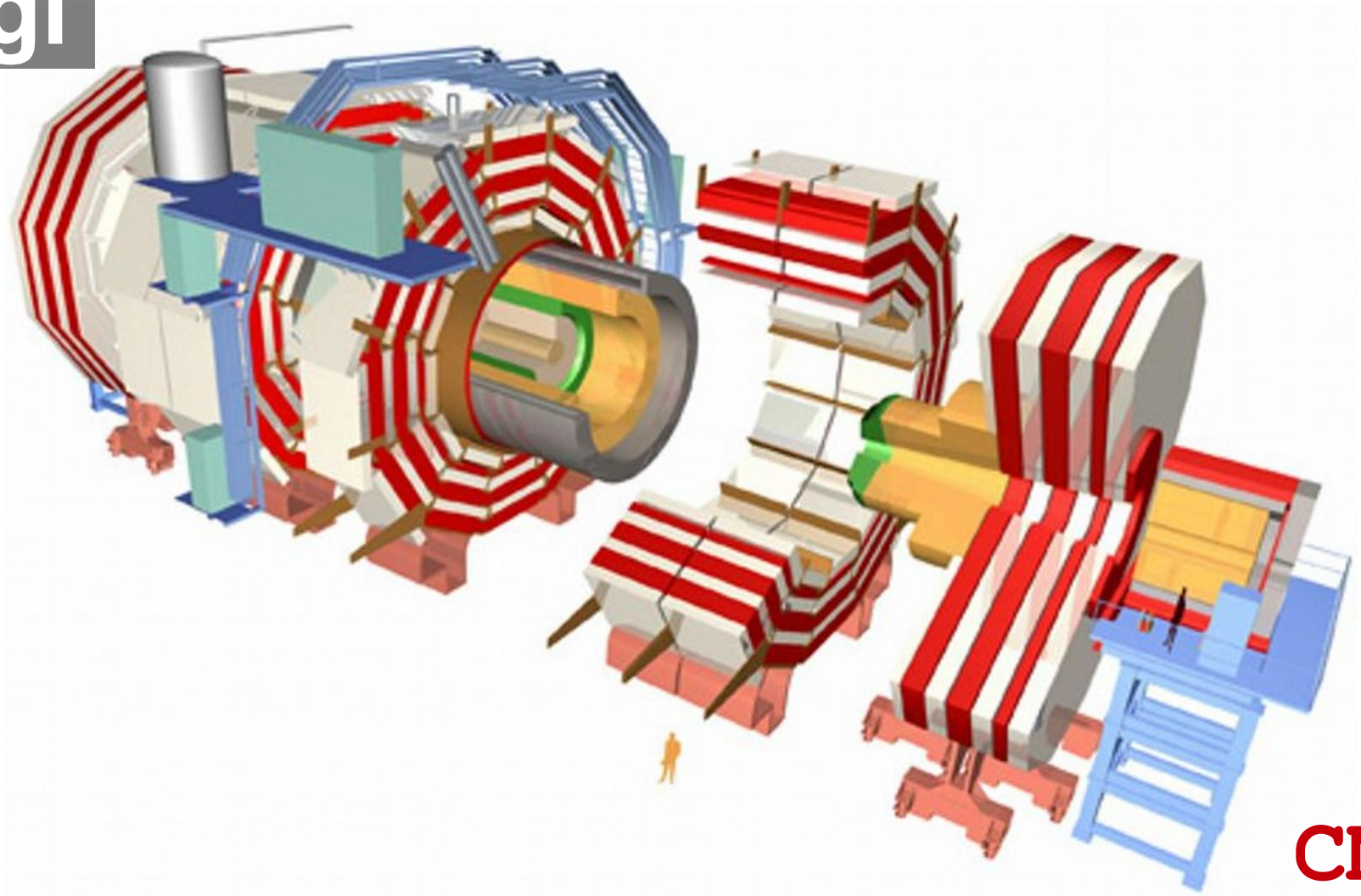
Oggi



ATLAS

25 m x 46 m

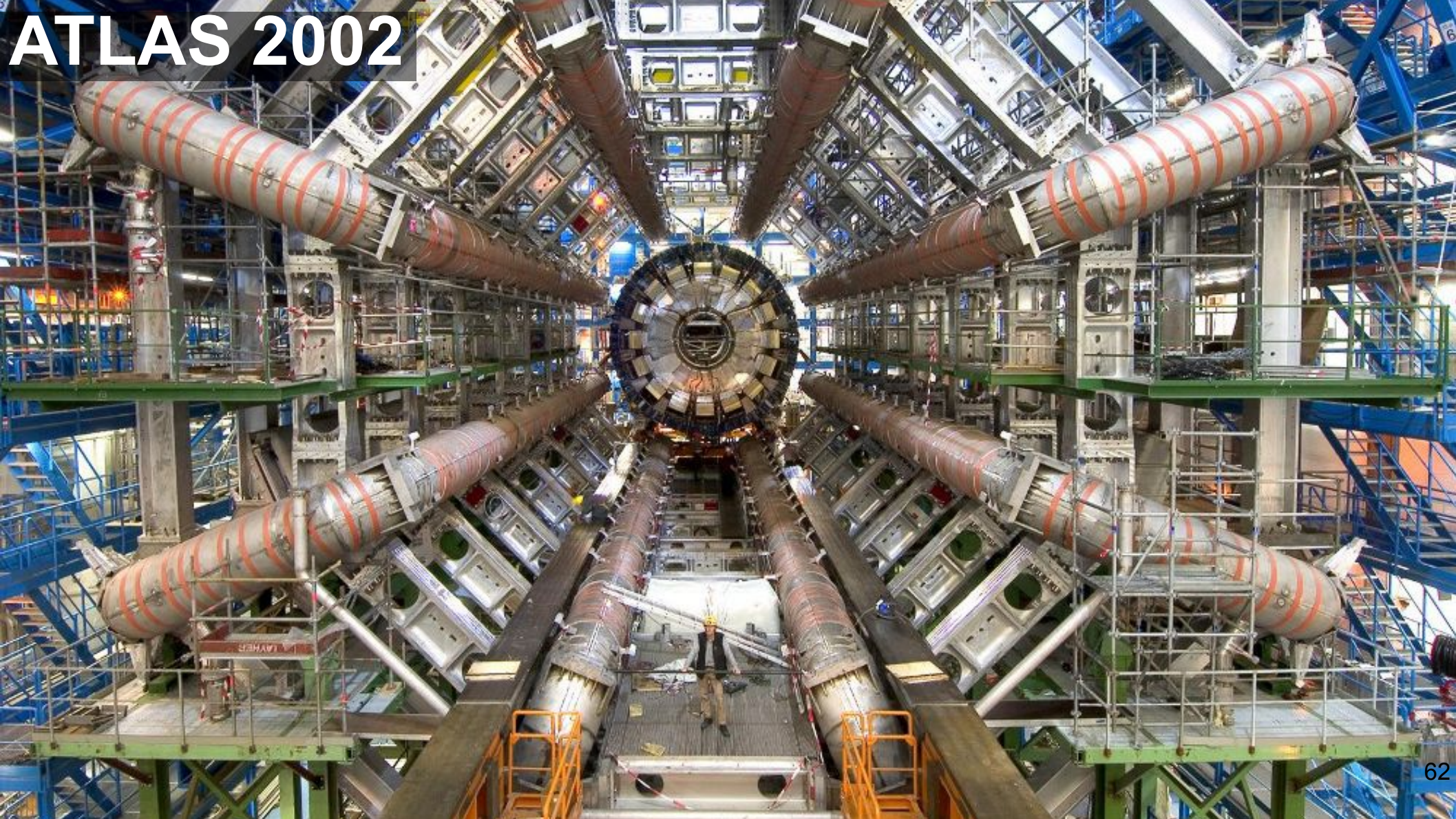
Oggi

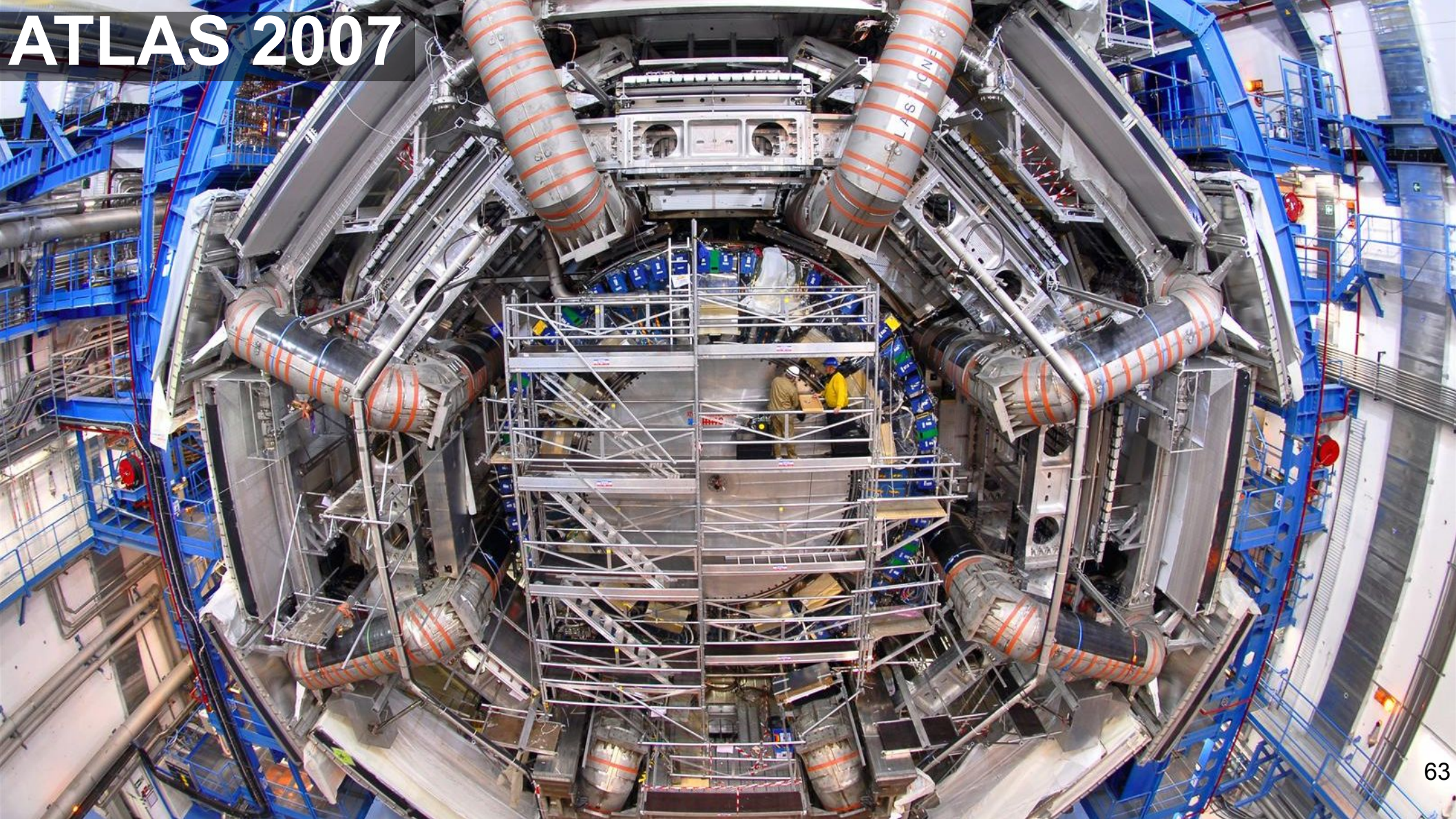


CMS

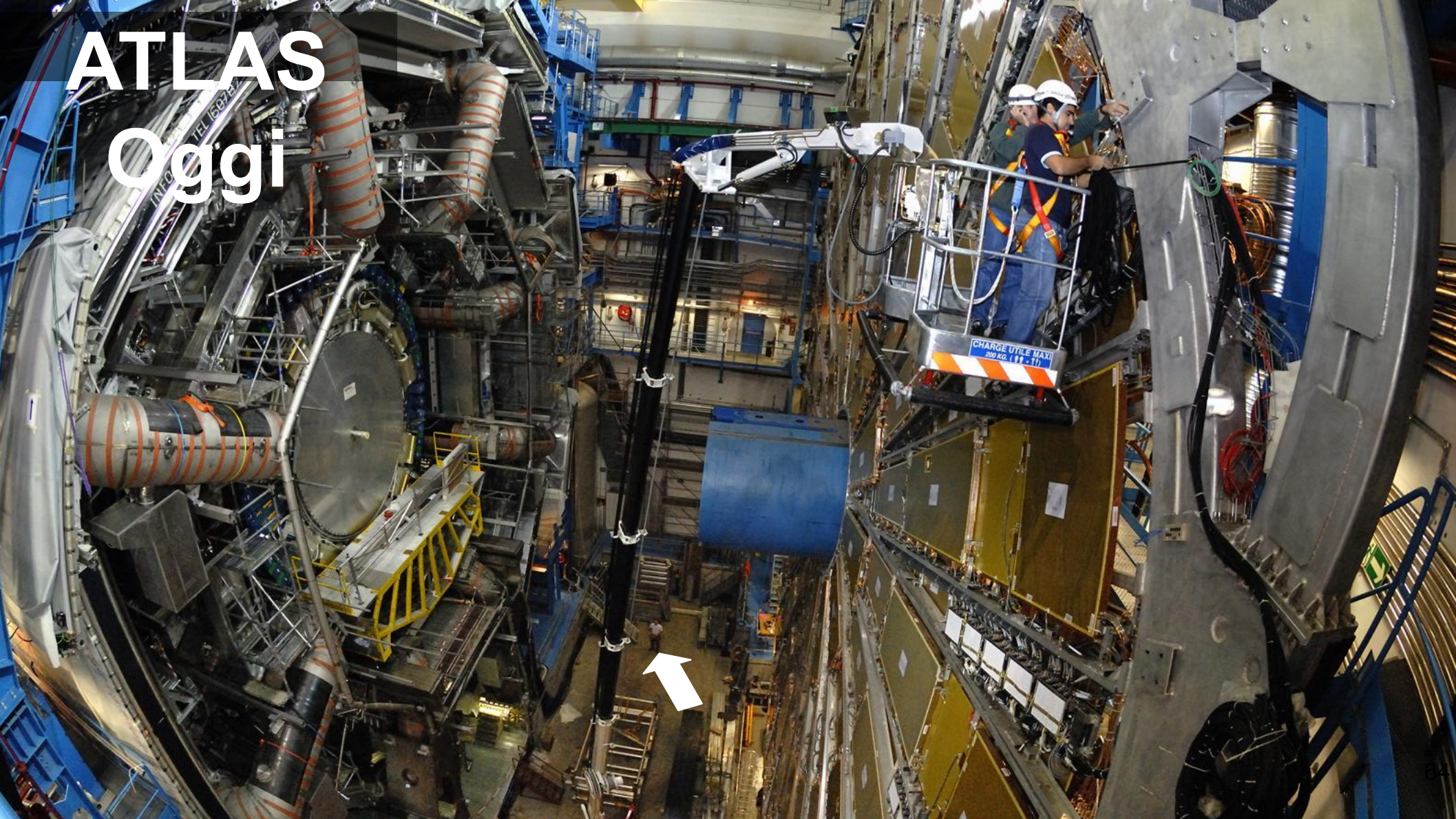
15 m x 21 m


ATLAS 2001

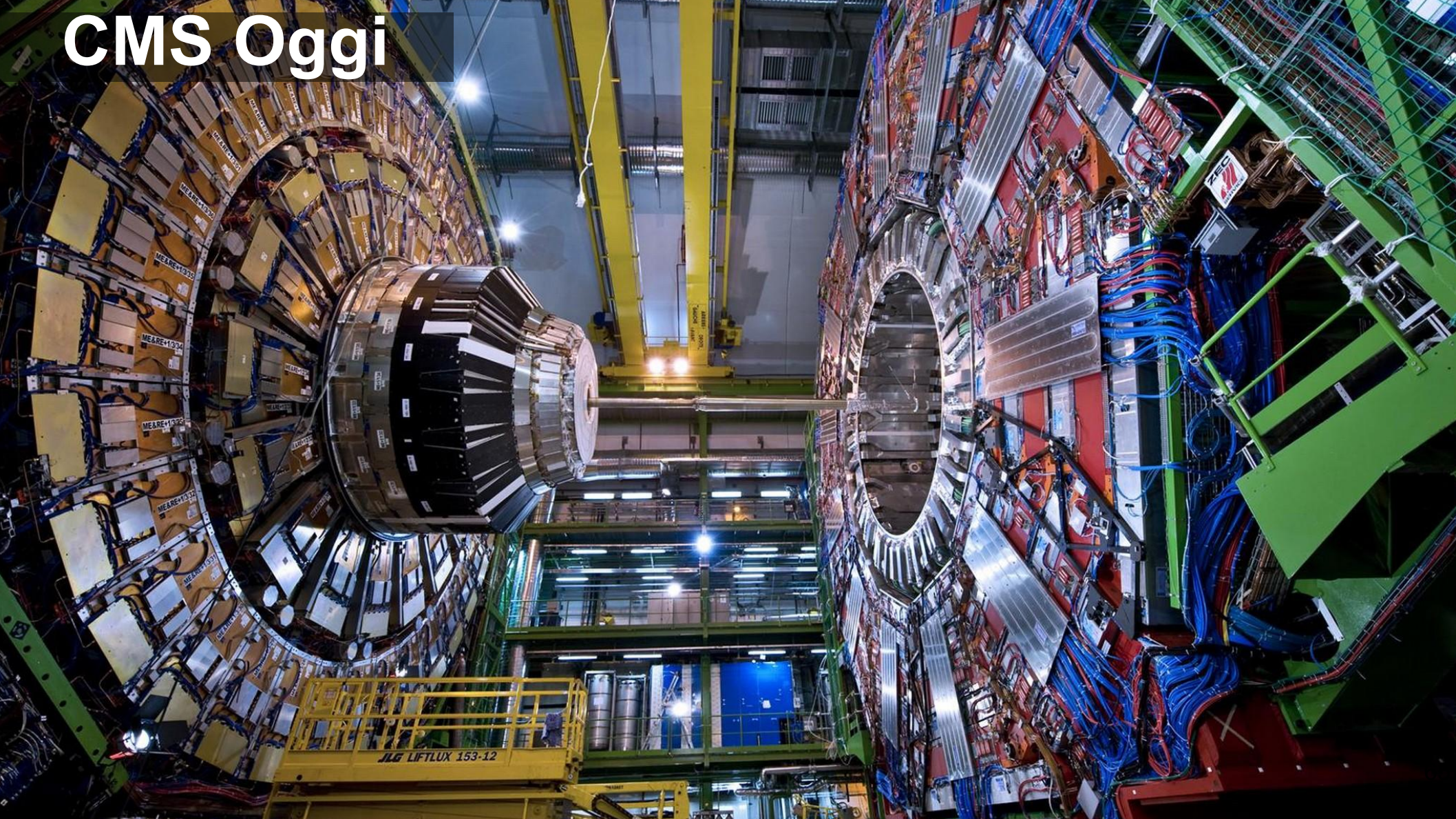

ATLAS 2002


ATLAS 2007

ATLAS Oggi



CMS Oggi



ALICE Oggi

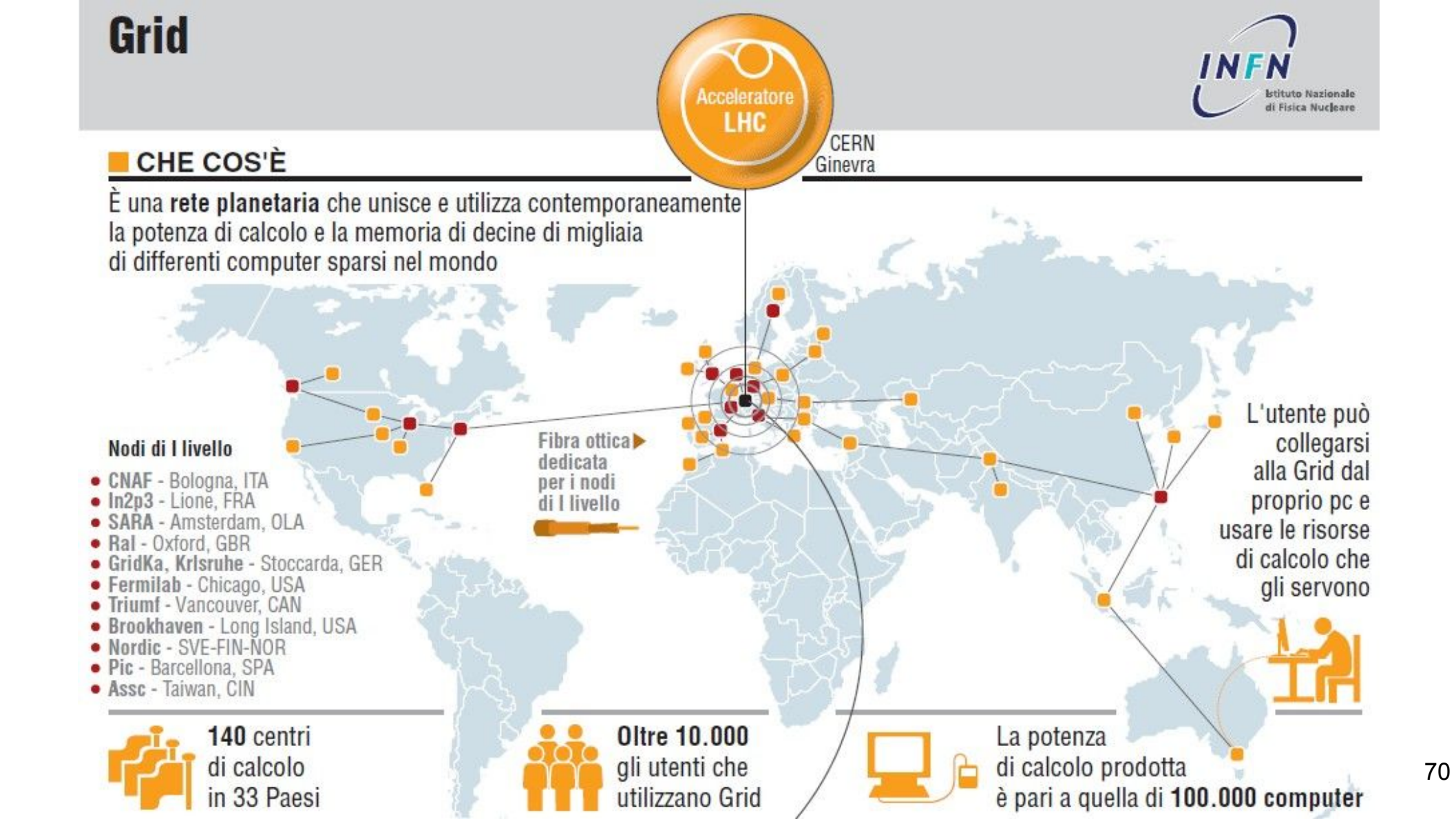
Presa dati: 2010-12, 2015-18, 2022-2025 ... 2038

Big data

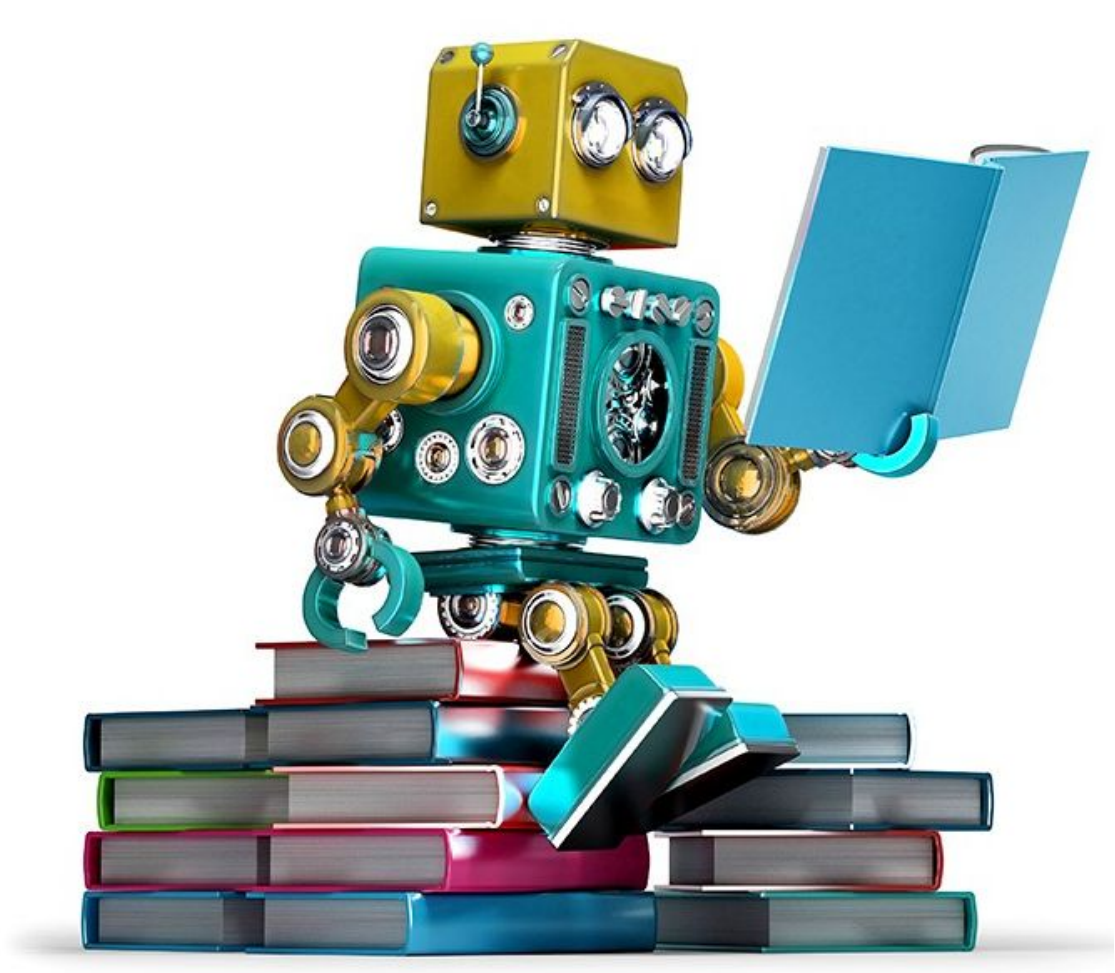
~10 PB/anno

Analisi dati

Grid


Acceleratore LHC
CERN Ginevra
INFN Istituto Nazionale di Fisica Nucleare
CHE COS'È
È una rete planetaria che unisce e utilizza contemporaneamente la potenza di calcolo e la memoria di decine di migliaia di differenti computer sparsi nel mondo
Nodi di I livello
CNAF - Bologna, ITA
In2p3 - Lione, FRA
SARA - Amsterdam, OLA
Ral - Oxford, GBR
GridKa, Krlsruhe - Stoccarda, GER
Fermilab - Chicago, USA
Triumf - Vancouver, CAN
Brookhaven - Long Island, USA
Nordic - SVE-FIN-NOR
Pic - Barcellona, SPA
Assc - Taiwan, CIN
Fibra ottica dedicata per i nodi di I livello
L'utente può collegarsi alla Grid dal proprio pc e usare le risorse di calcolo che gli servono
140 centri di calcolo in 33 Paesi
Oltre 10.000 gli utenti che utilizzano Grid
La potenza di calcolo prodotta è pari a quella di 100.000 computer

Machine Learning



Higgs challenge

the HiggsML challenge

May to September 2014

When **High Energy Physics** meets **Machine Learning**

info to participate and compete : https://www.kaggle.com/c/higgs-boson

ATLAS EXPERIMENT · LAL · Inria · kaggle · ParisSaclay Center for Data Science · CERN · Google

Organization committee

Balázs Kégl - *AppStat-LAL*
Cécile Germain - *TAO-LRI*
David Rousseau - *Atlas-LAL*
Glen Cowan - *Atlas-RHUL*
Isabelle Guyon - *Chalearn*
Claire Adam-Bourdarios - *Atlas-LAL*

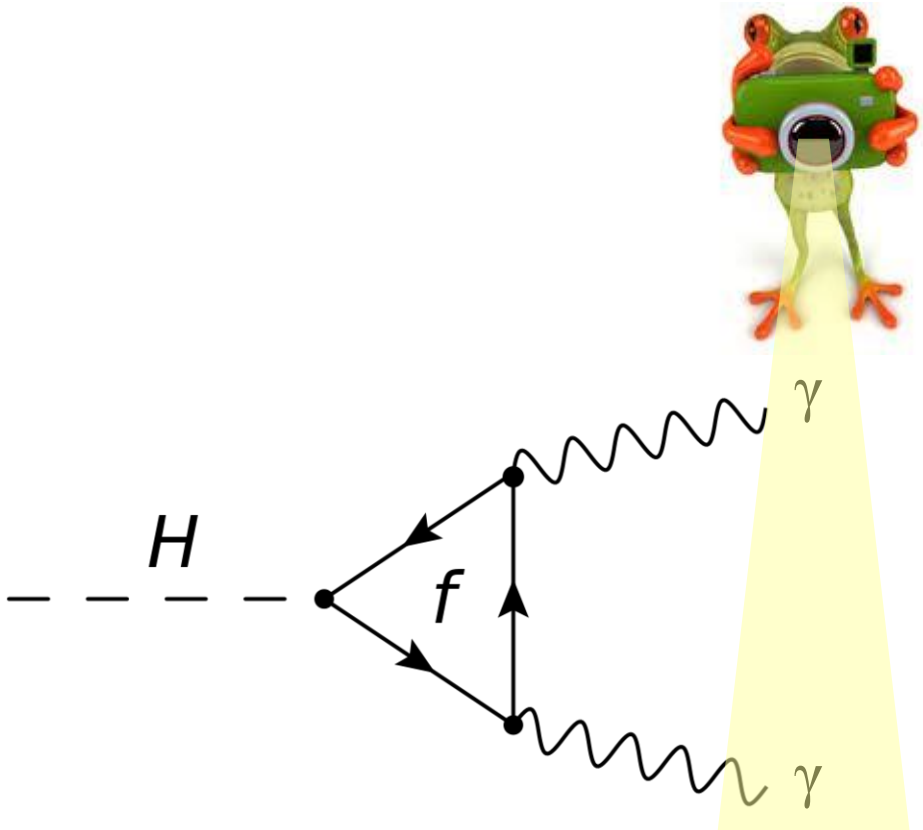
Advisory committee

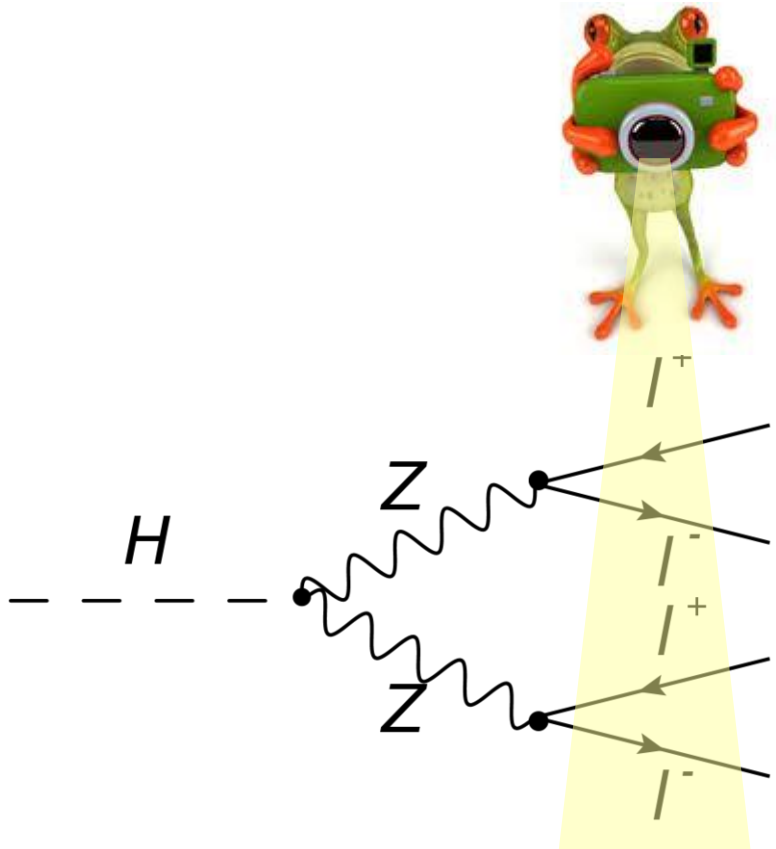
Thorsten Wengler - *Atlas-CERN*
Andreas Hoecker - *Atlas-CERN*
Joerg Stelzer - *Atlas-CERN*
Marc Schoenauer - *INRIA*

Ricerca bosone di Higgs

L'Higgs non è stabile, **decade** in fotoni o leptoni

- Identificato partendo dai prodotti del suo decadimento



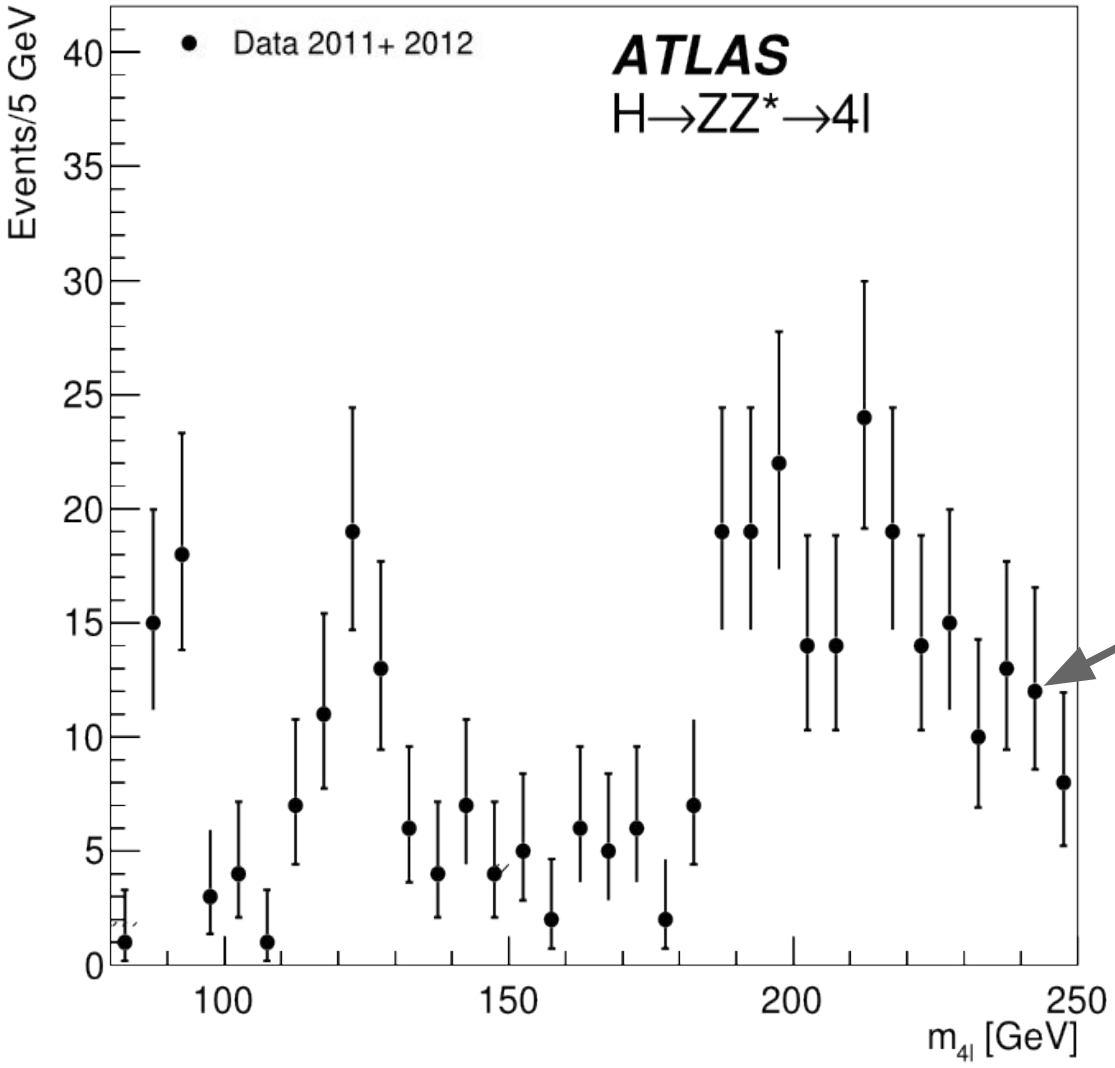


Run Number: 189280,
Event Number: 143576946
Date: 2011-09-14, 11:37:11 CET

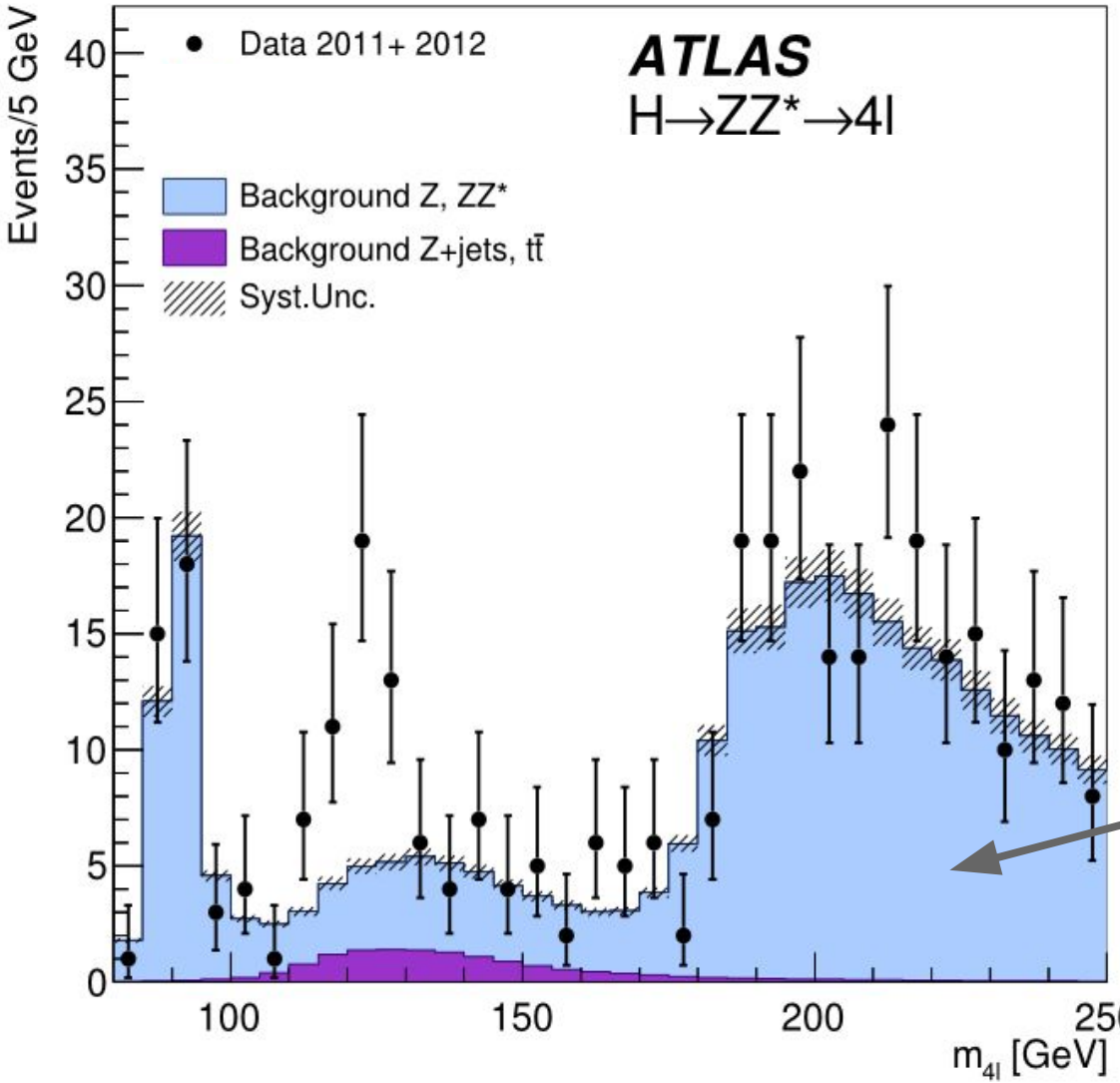
EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm

Muon: blue
Cells: Tiles, EMC

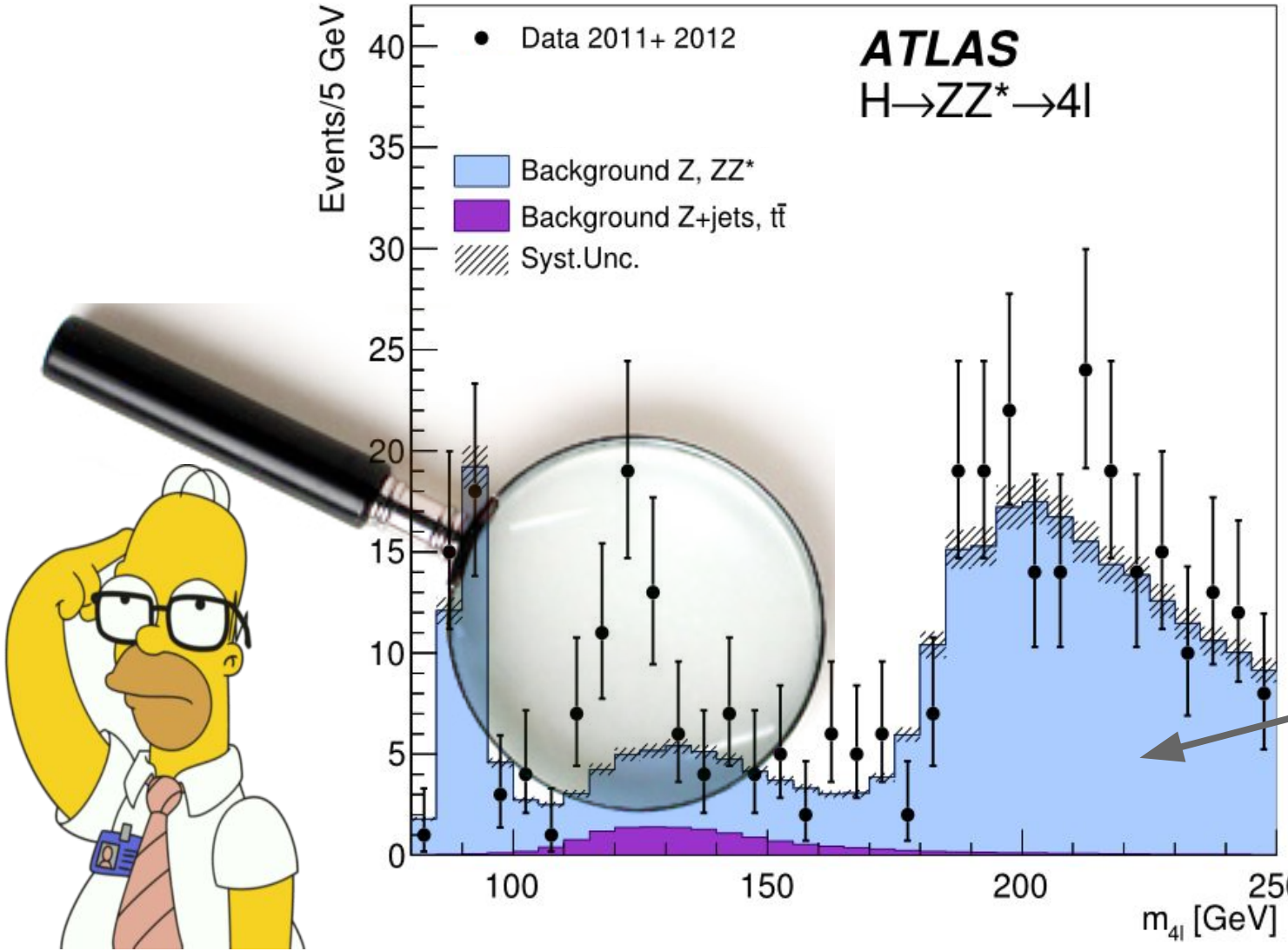
Higgs → 4 muoni



Dati sperimentali

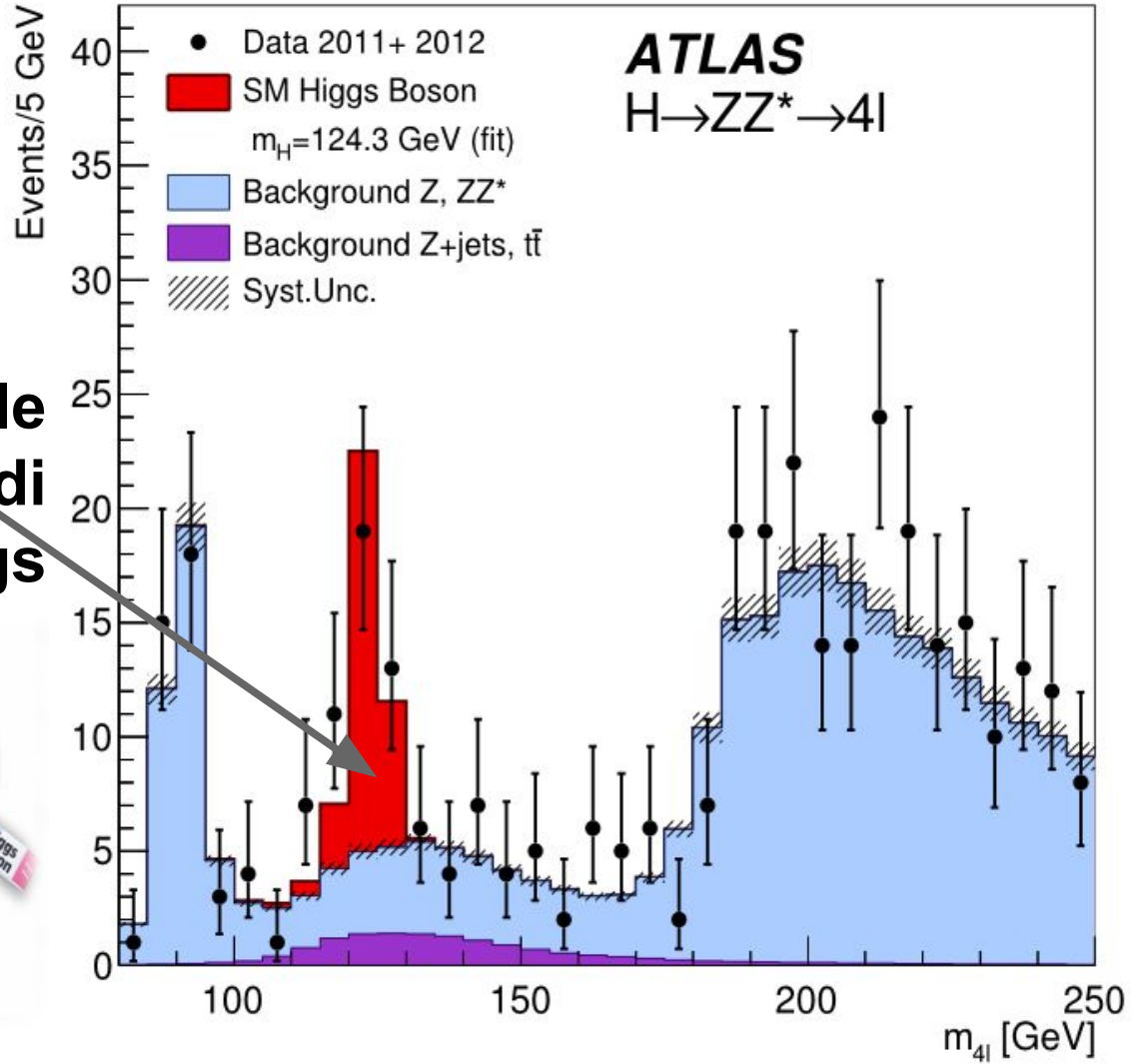


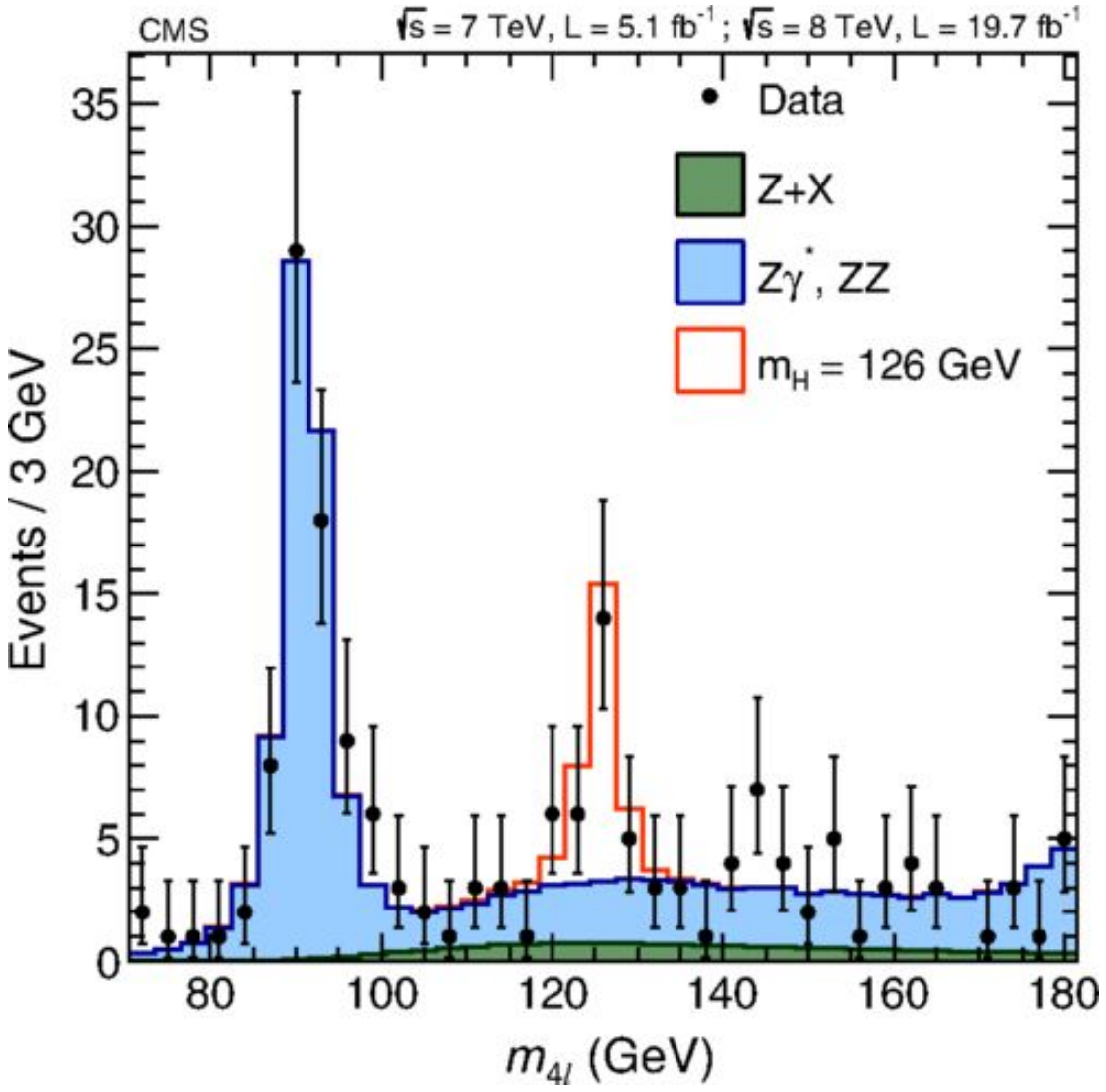
Fondo atteso



Fondo atteso

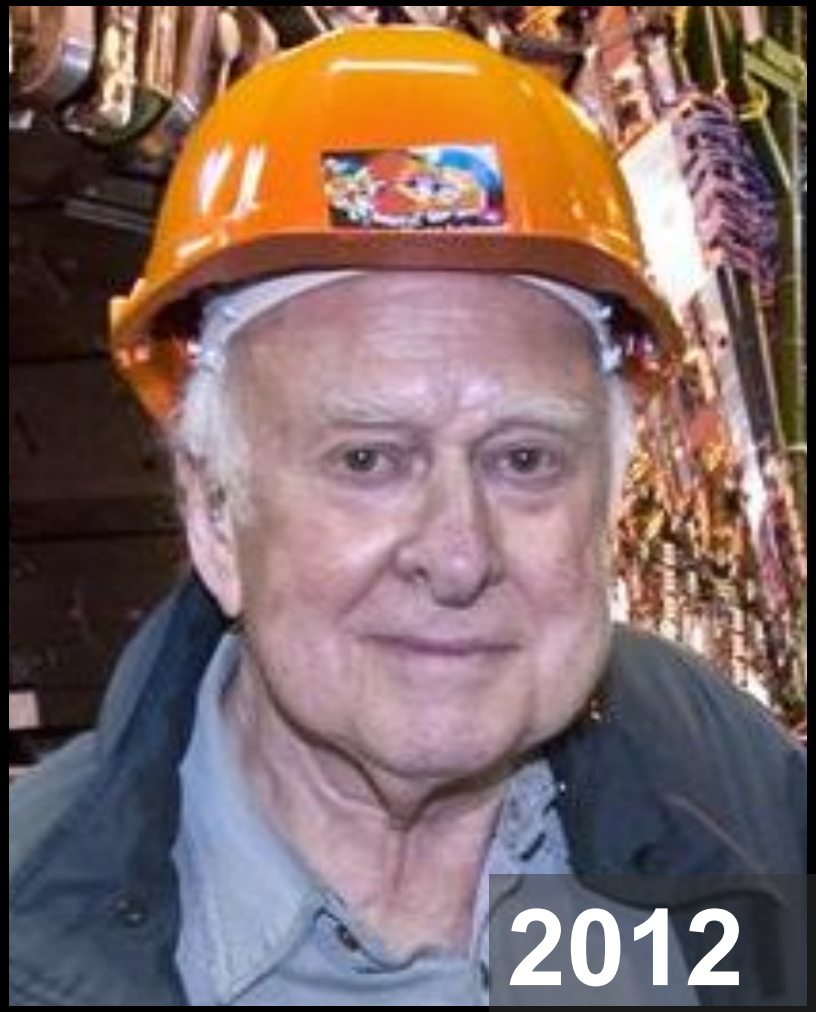
Segnale atteso di Higgs




CMS
√s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.7 fb-1
Data
Z+X
Zγ*, ZZ
mH = 126 GeV
Events / 3 GeV
0
5
10
15
20
25
30
35
80
100
120
140
160
180
m4l (GeV)

Bosone di Higgs

Prof. Peter Higgs



Premio Nobel 2013

PRESSMEDDELANDE
Press release

8 October 2013

The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"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"


u
c
t
γ
g
g
d
s
b
Z°
g
g
ν_e
ν_μ
ν_τ
W^+
g
g
e
μ
τ
W^-
g
Higgs

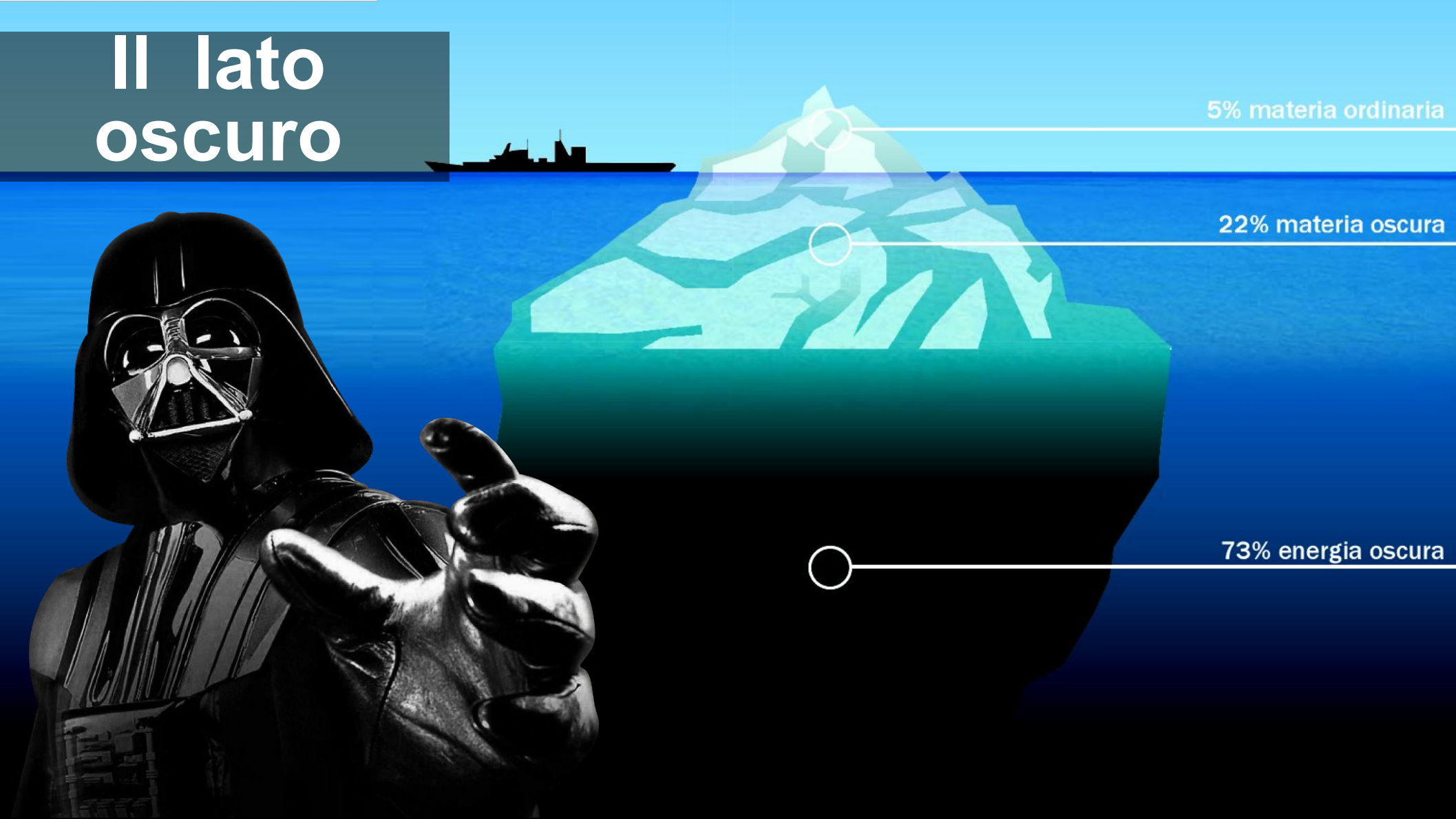

u c t γ g g
d s b Z° g g
ν_e ν_μ ν_τ W^+ g g
e μ τ W^- g h

Cosa sappiamo?

Cosa sappiamo? Poco

- I quark sono **indivisibili**?
- Dov'è finita l'**antimateria**?
- Esistono altre dimensioni?
- Esiste una teoria che **unisca tutte** le forze fondamentali?
- Cos'è la **materia oscura**?
- Cos'è l' **energia oscura**?

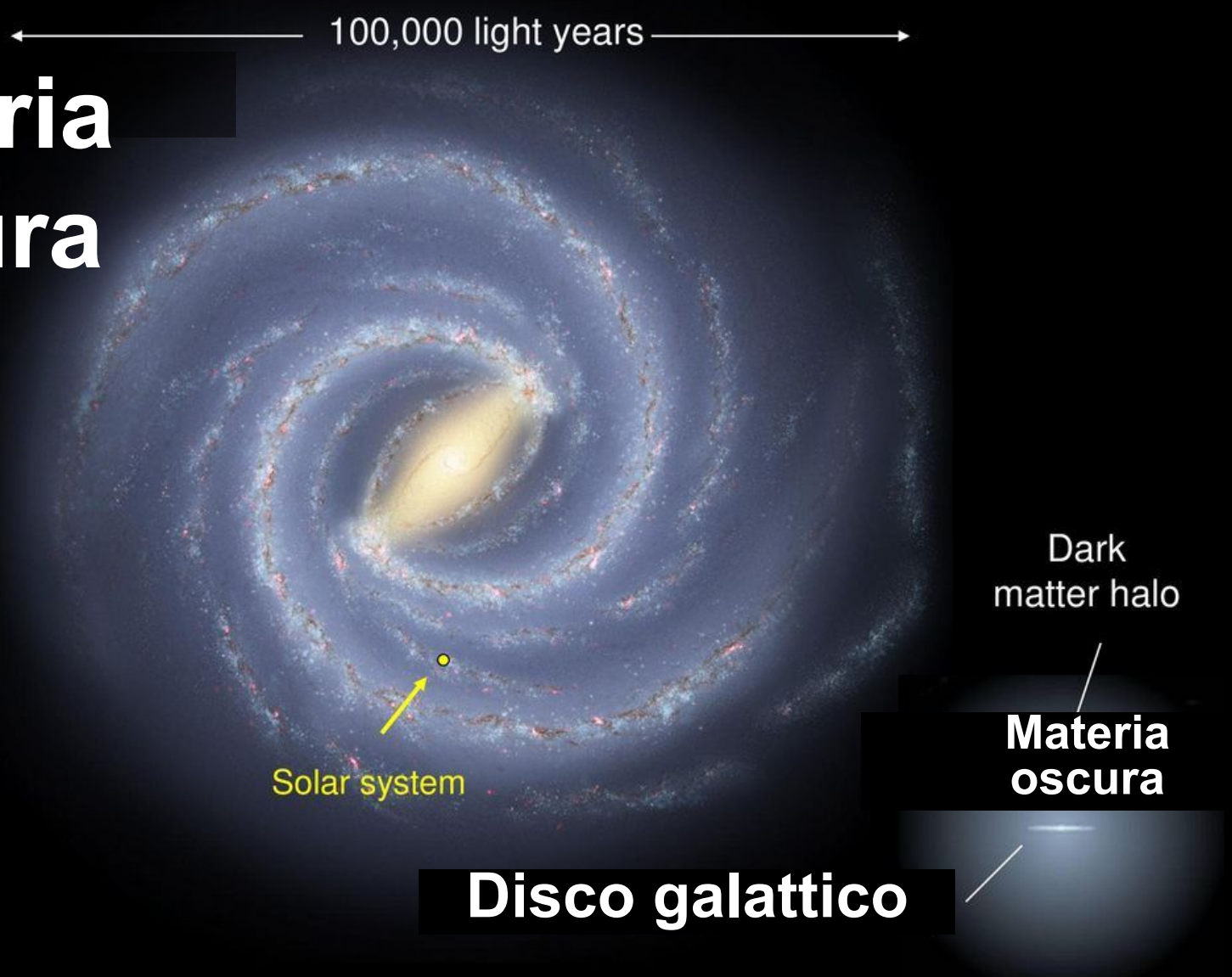
Il lato oscuro

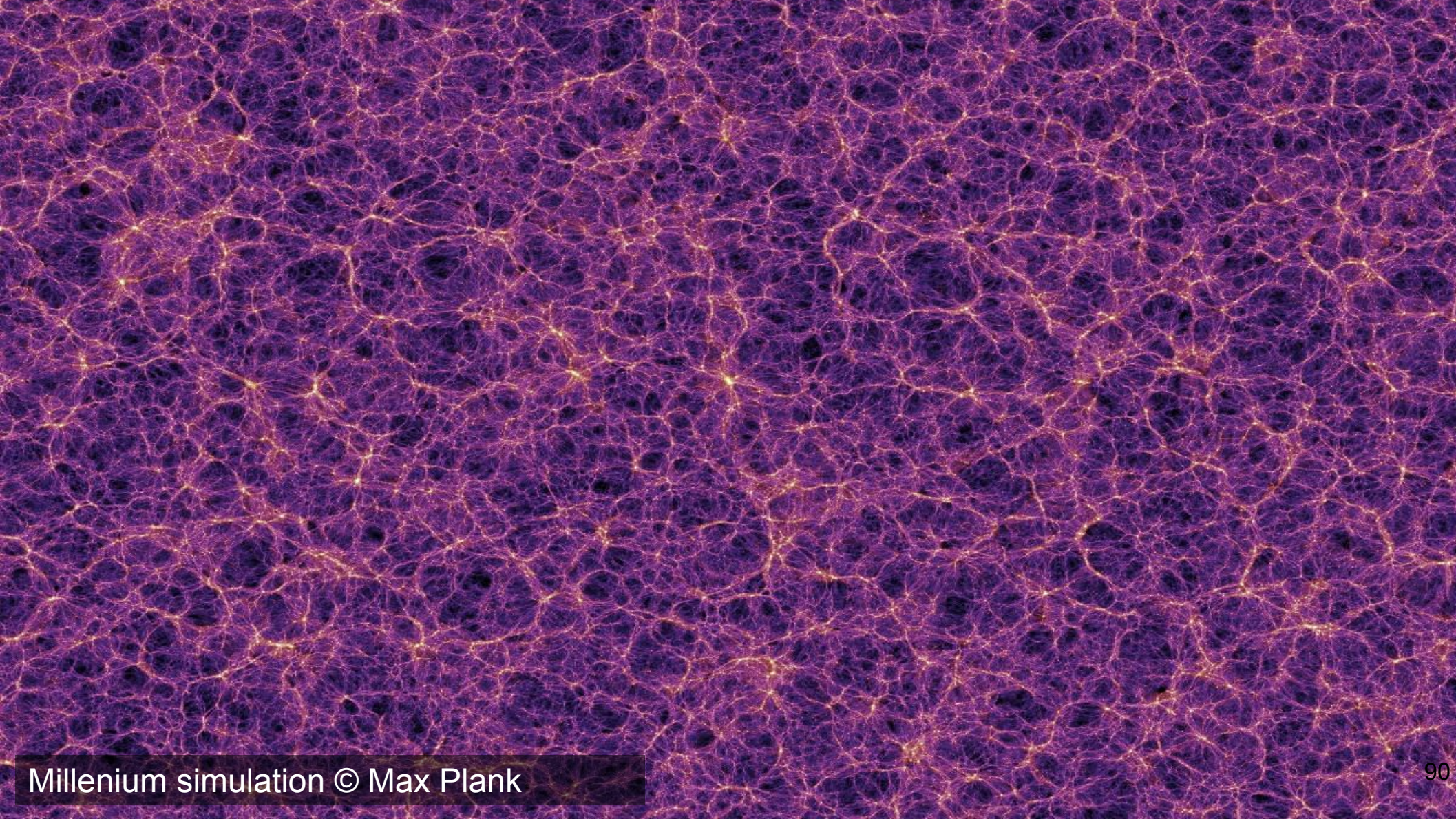


La massa mancante

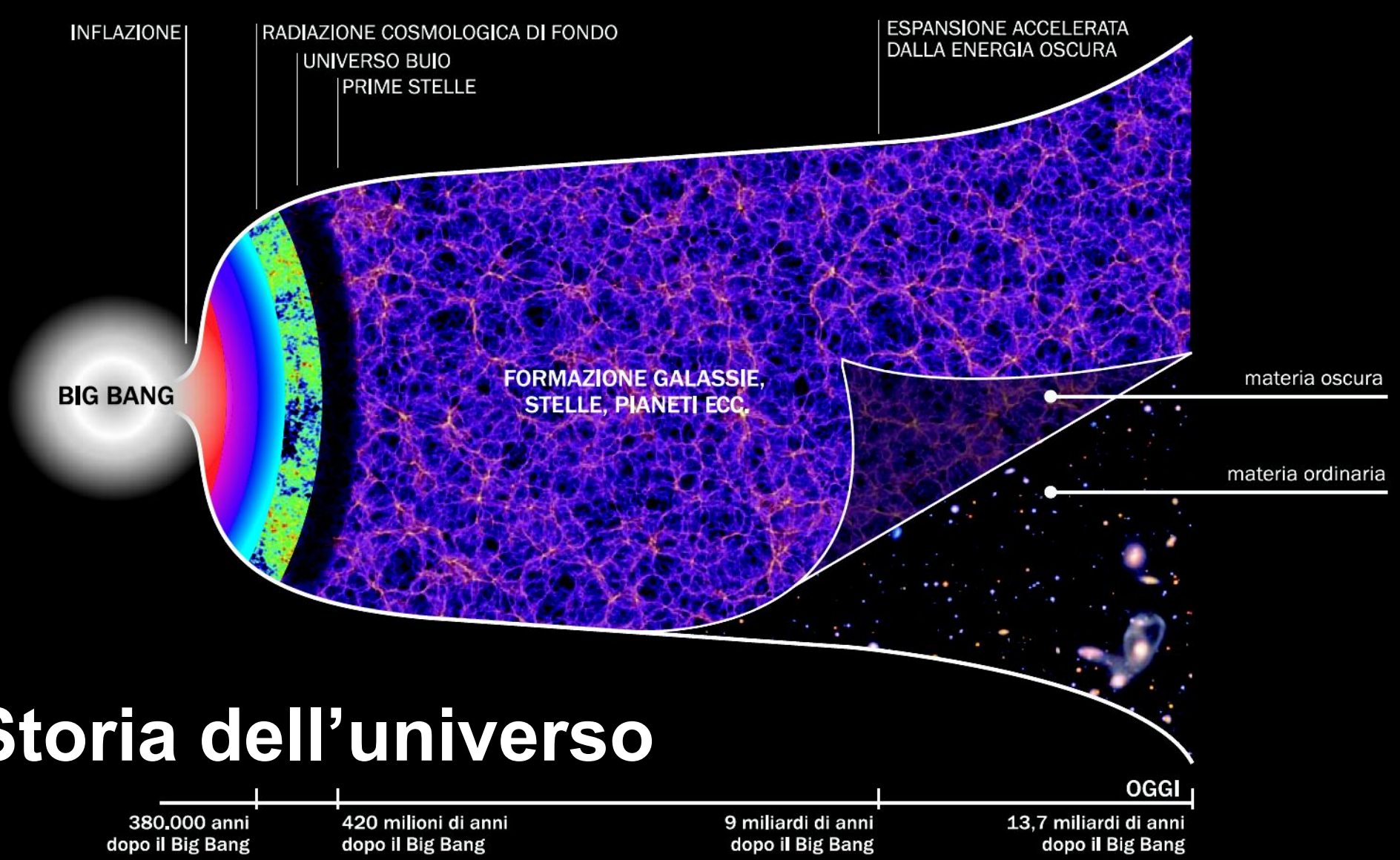
'30: Ian Ort, Fritz Zwicky
'60: Vera Rubin

Materia oscura





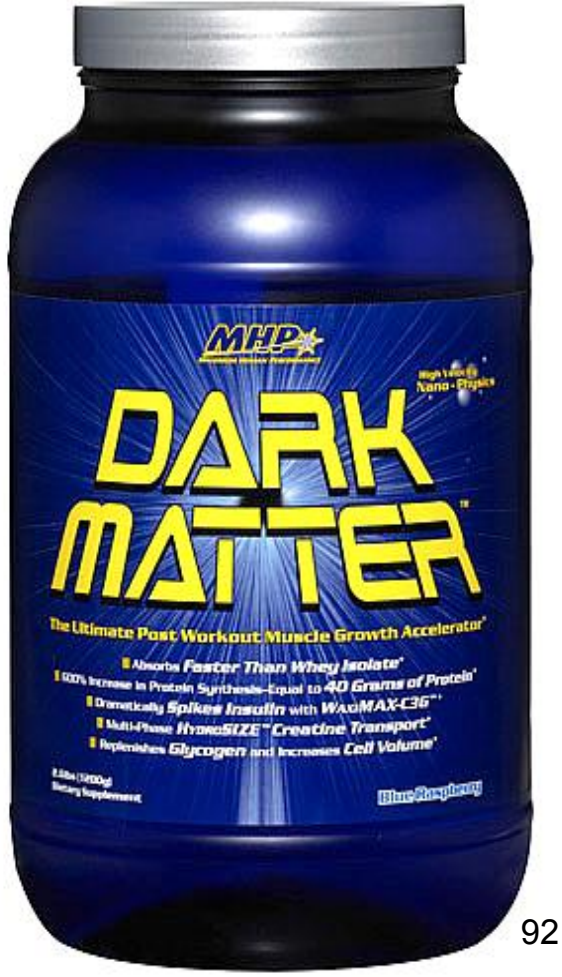
Millenium simulation © Max Plank



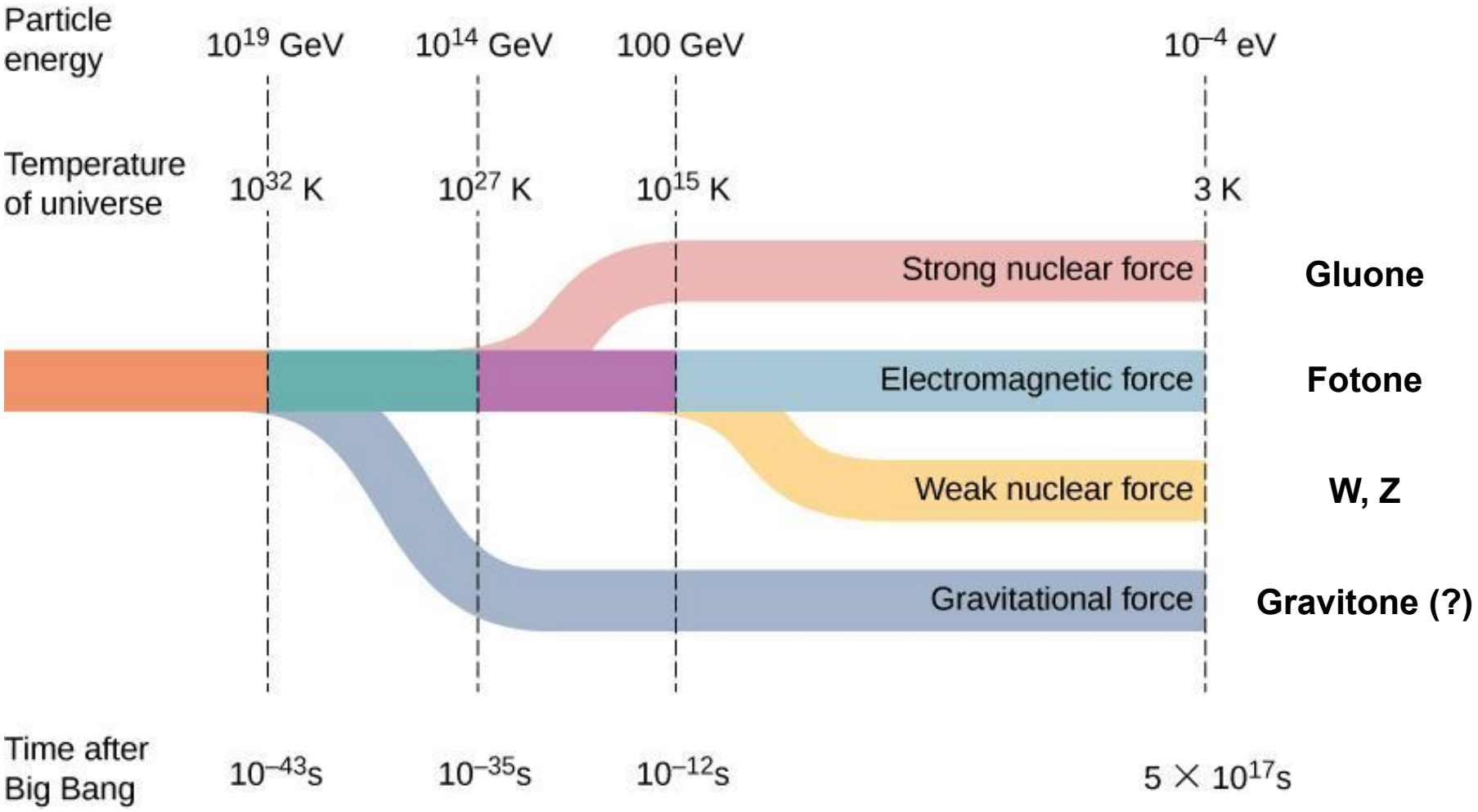
Storia dell'universo

Materia oscura

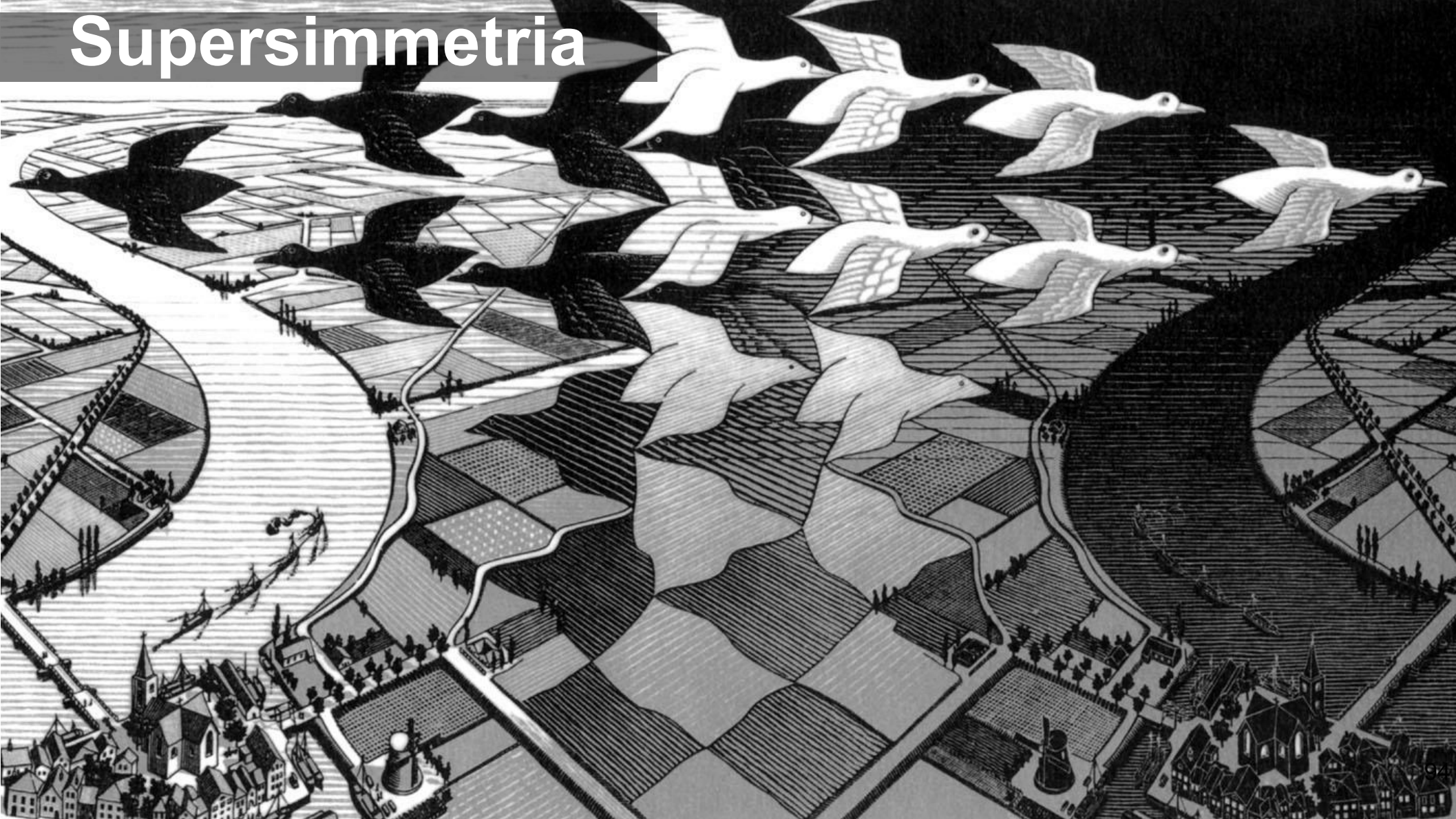
- **Permea** lo spazio
- Interagisce solo **gravitazionalmente**
- Seme per formazione **galassie**
- **Non compatibile** con il modello standard delle particelle elementari
  - Possibili spiegazioni nelle teorie di unificazione delle forze



Teorie di unificazione



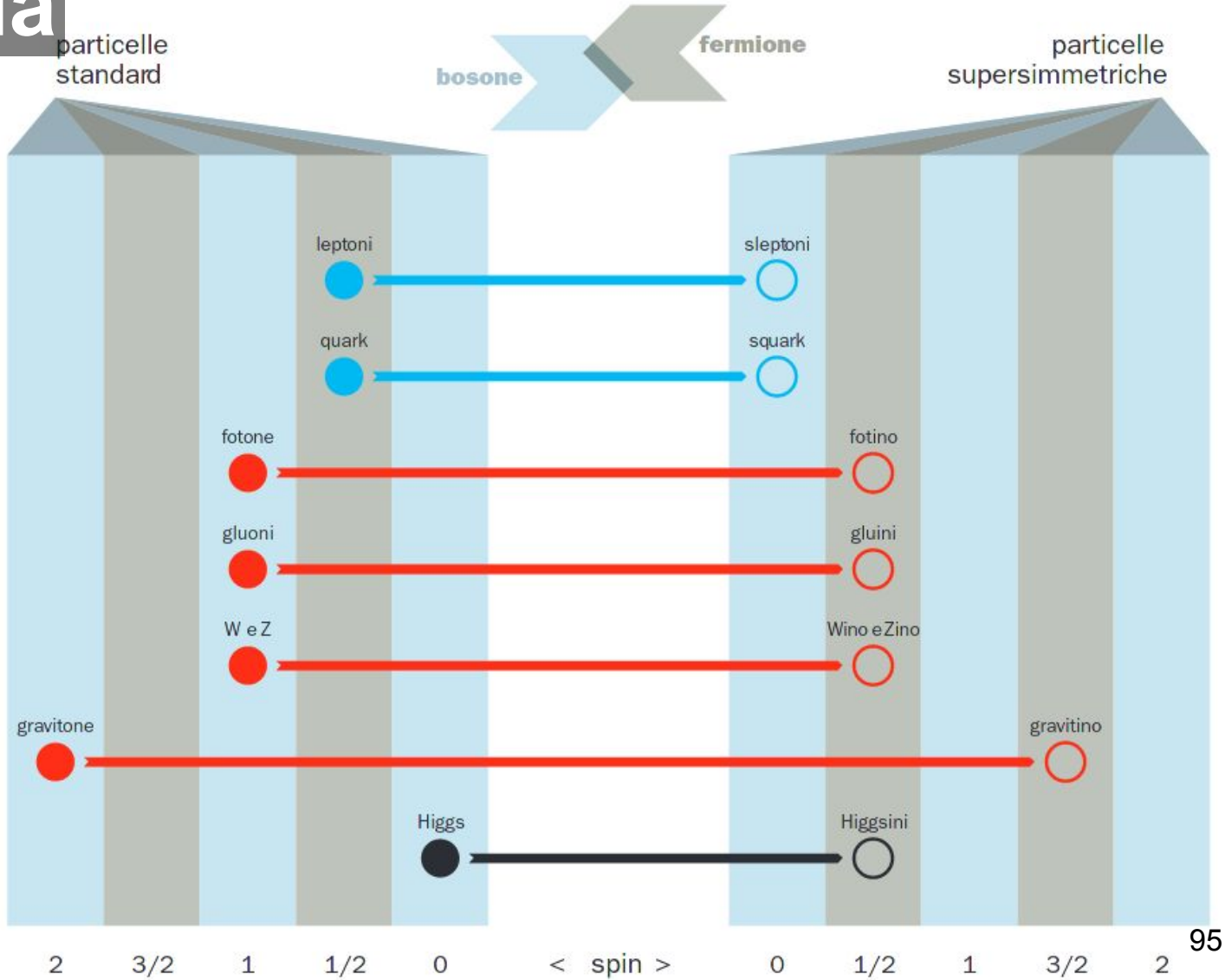
Supersimmetria



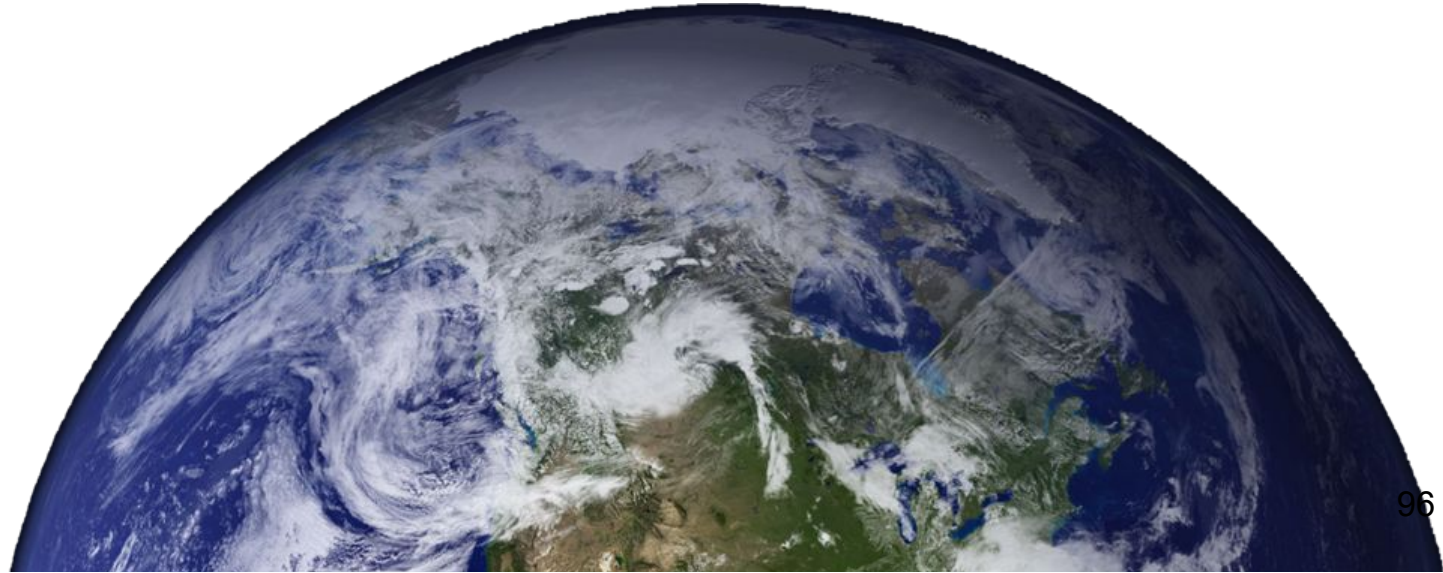
Supersimmetria

mediatori

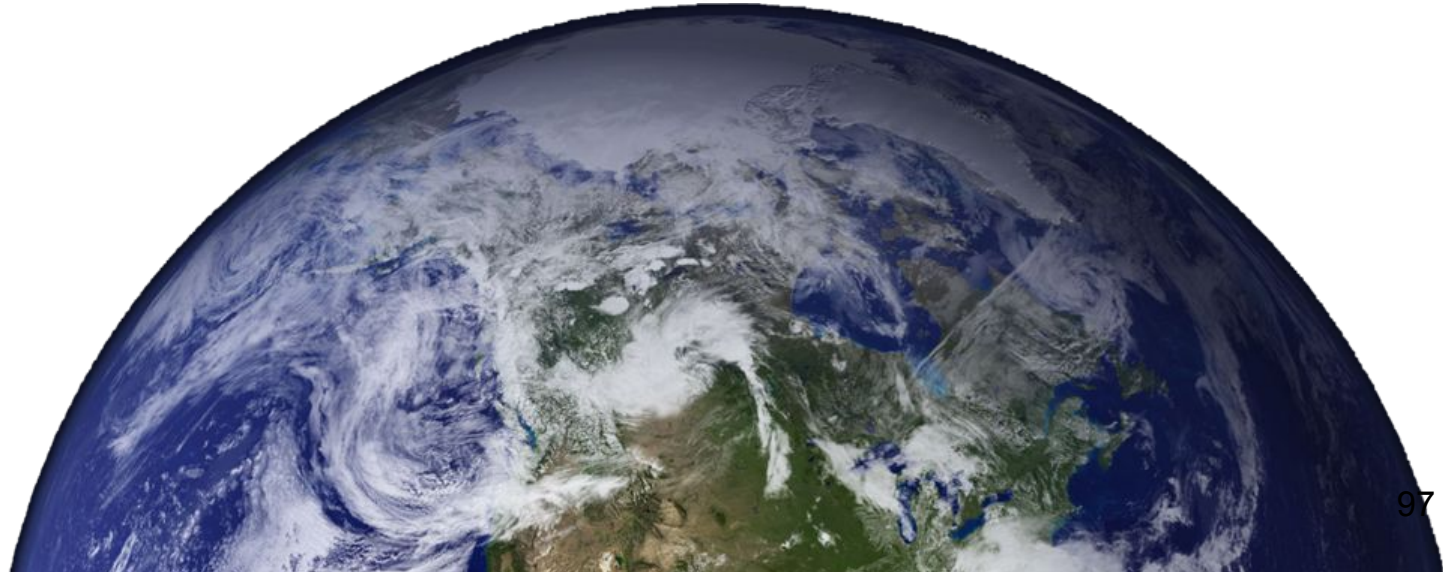
massa



La gravità è …?



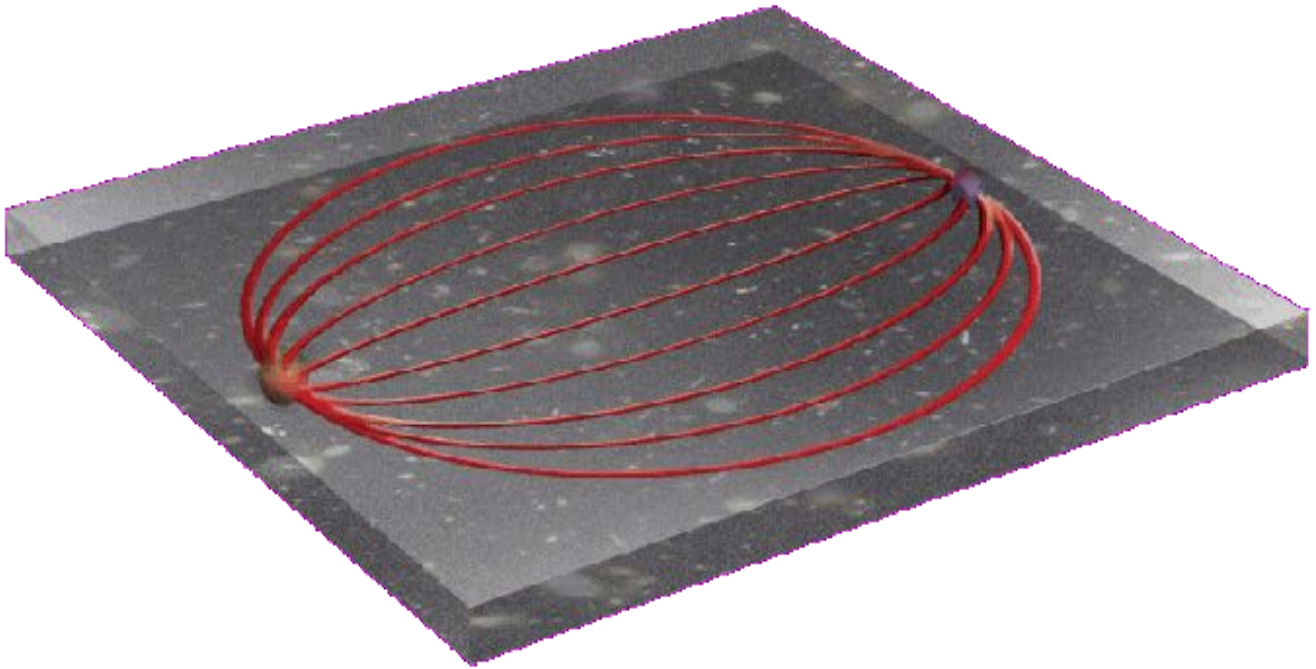
La gravità è debole!



Dimensioni addizionali?

Potrebbero spiegare debolezza forza gravitazionale

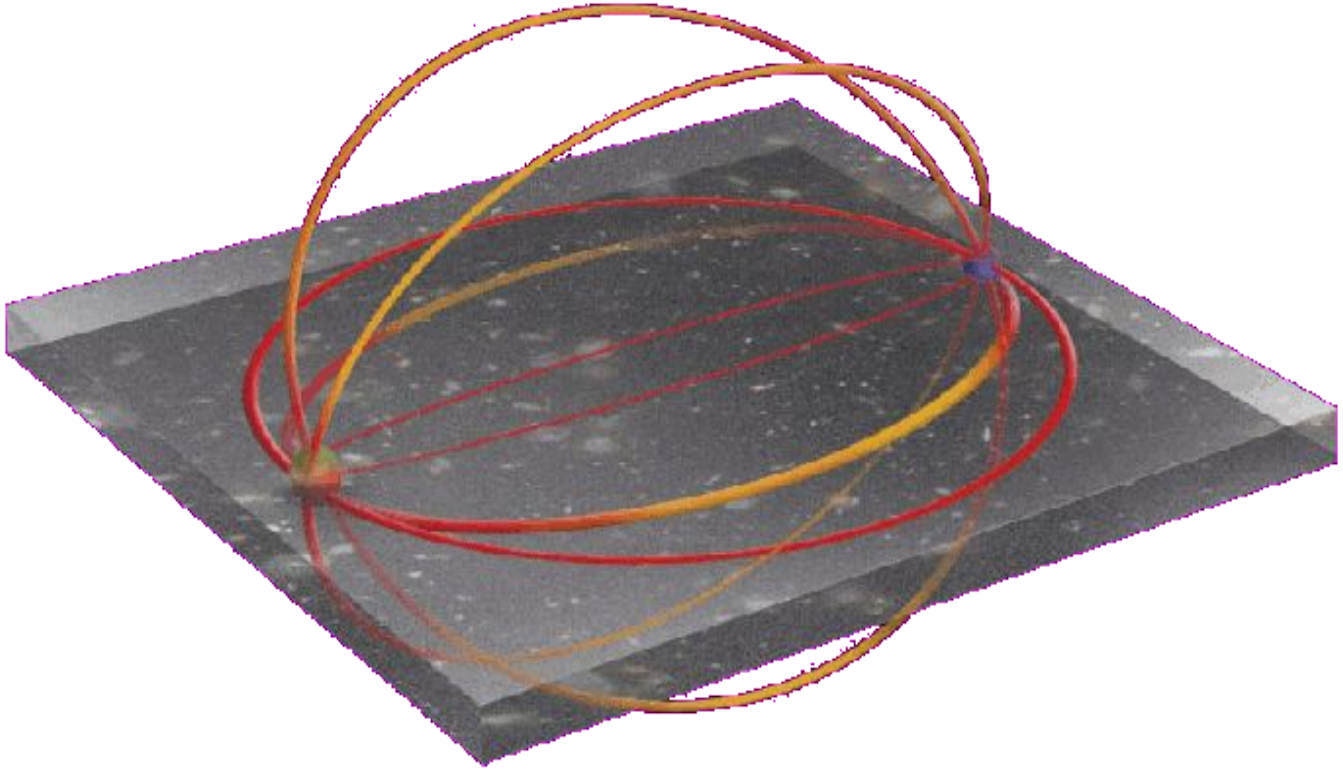
- Le altre forze sono **confinate** in 3D
- La gravità si **distribuisce** invece in tutte le dimensioni



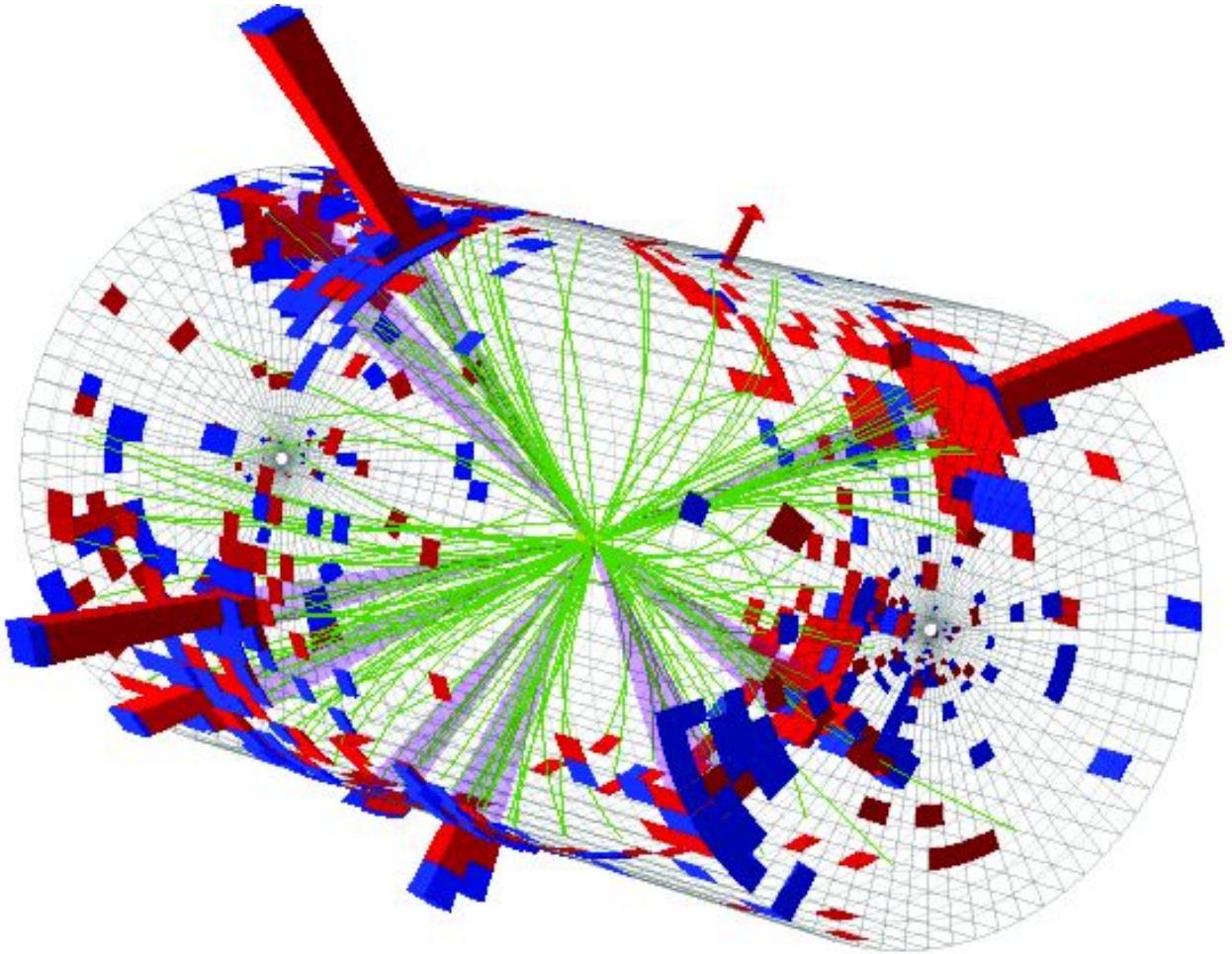
Dimensioni addizionali?

Potrebbero spiegare debolezza forza gravitazionale

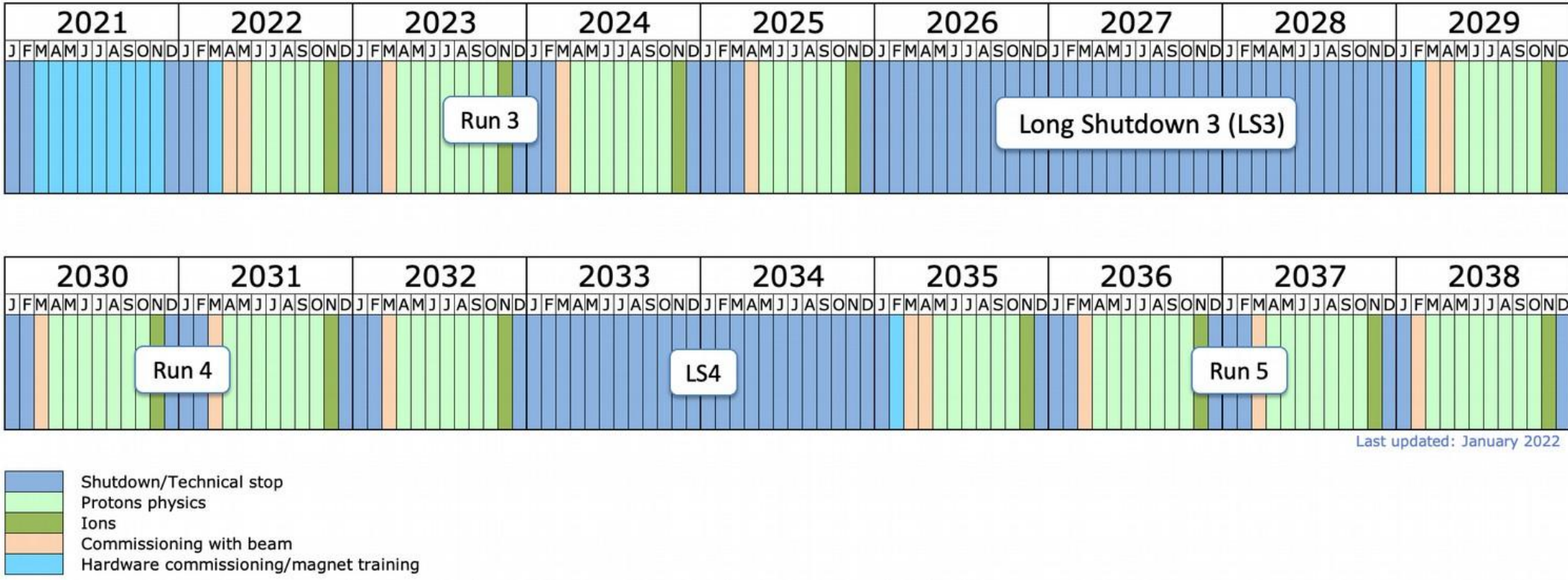
- Le altre forze sono **confinate** in 3D
- La gravità si **distribuisce** invece in tutte le dimensioni



Micro buchi neri

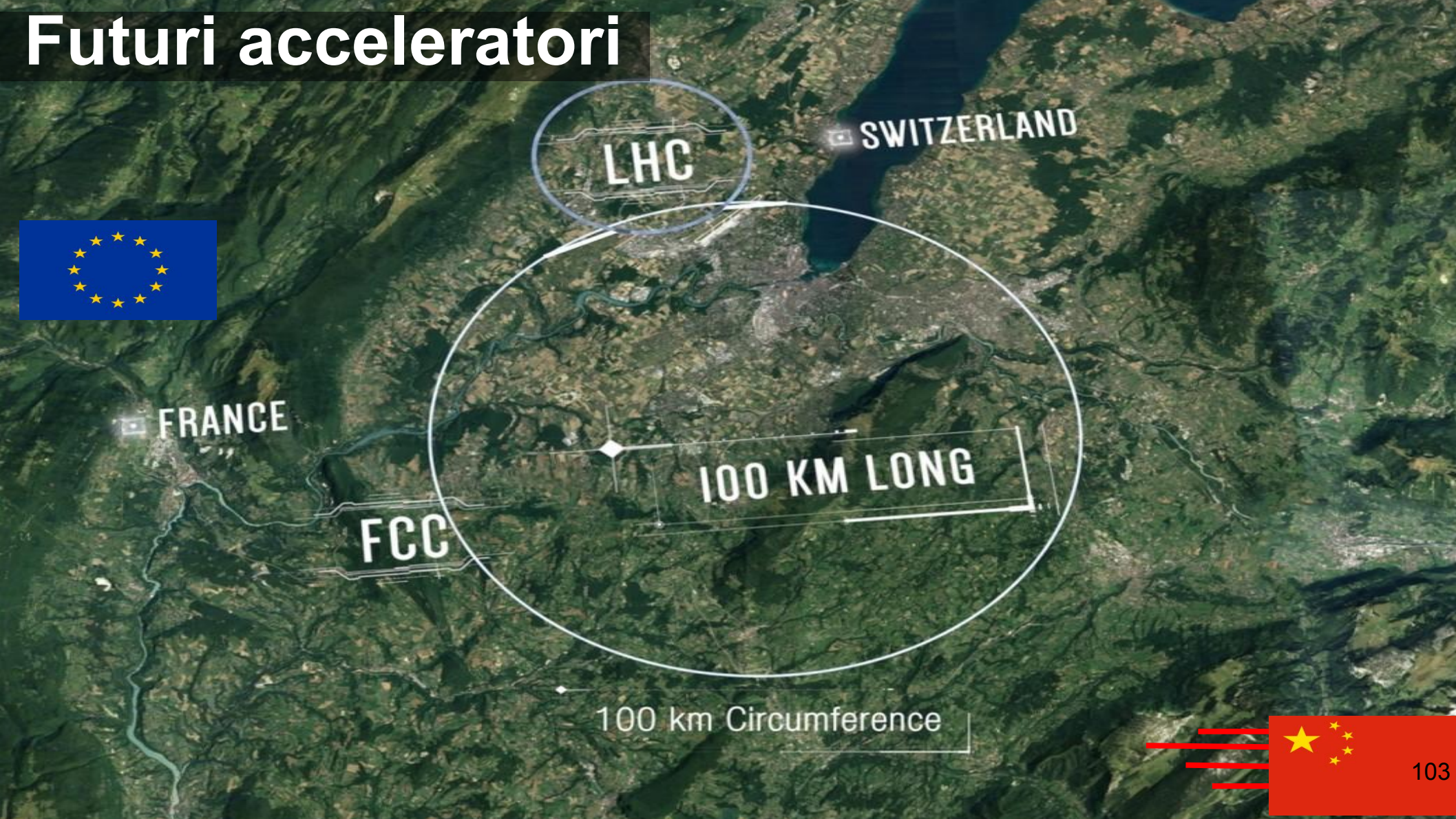


LHC fino a 2038



LHC fino a 2038

Futuri acceleratori



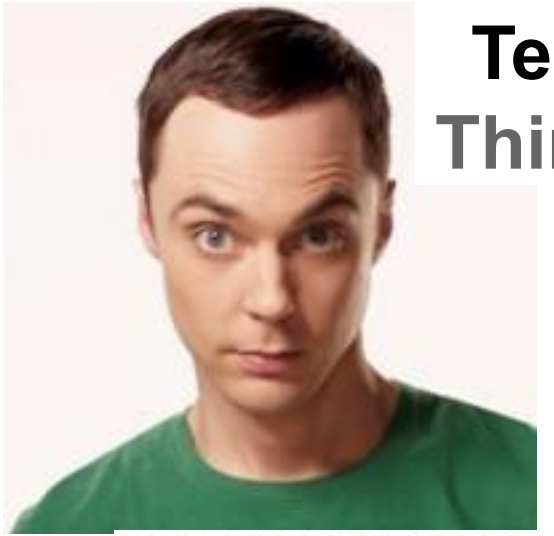
Al lavoro

UNIVERSITÀ DI PAVIA

Al lavoro

Al lavoro

Ricadute sulla società



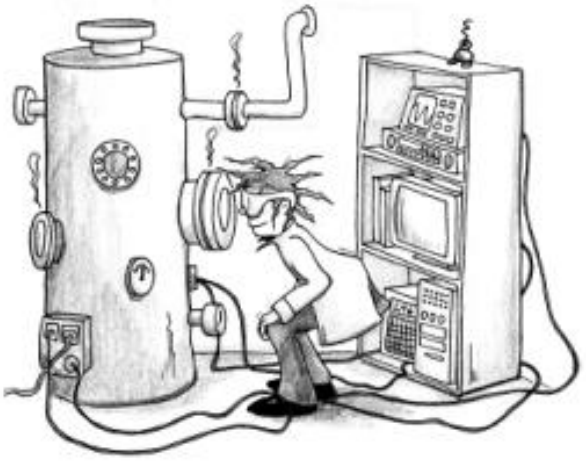
Teorici

Thinkers

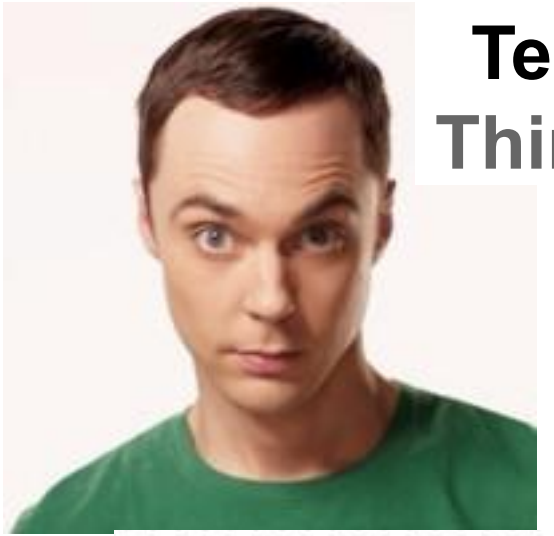
Sperimentali

Makers

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \Psi_i y_{ij}\Psi_j\Phi + h.c. + |D_\mu\Phi|^2 - V(\Phi)$$



Ricadute sulla società



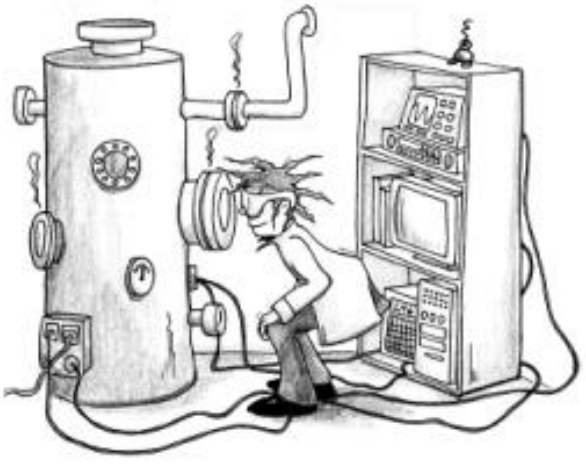
Teorici

Thinkers

Sperimentali

Makers

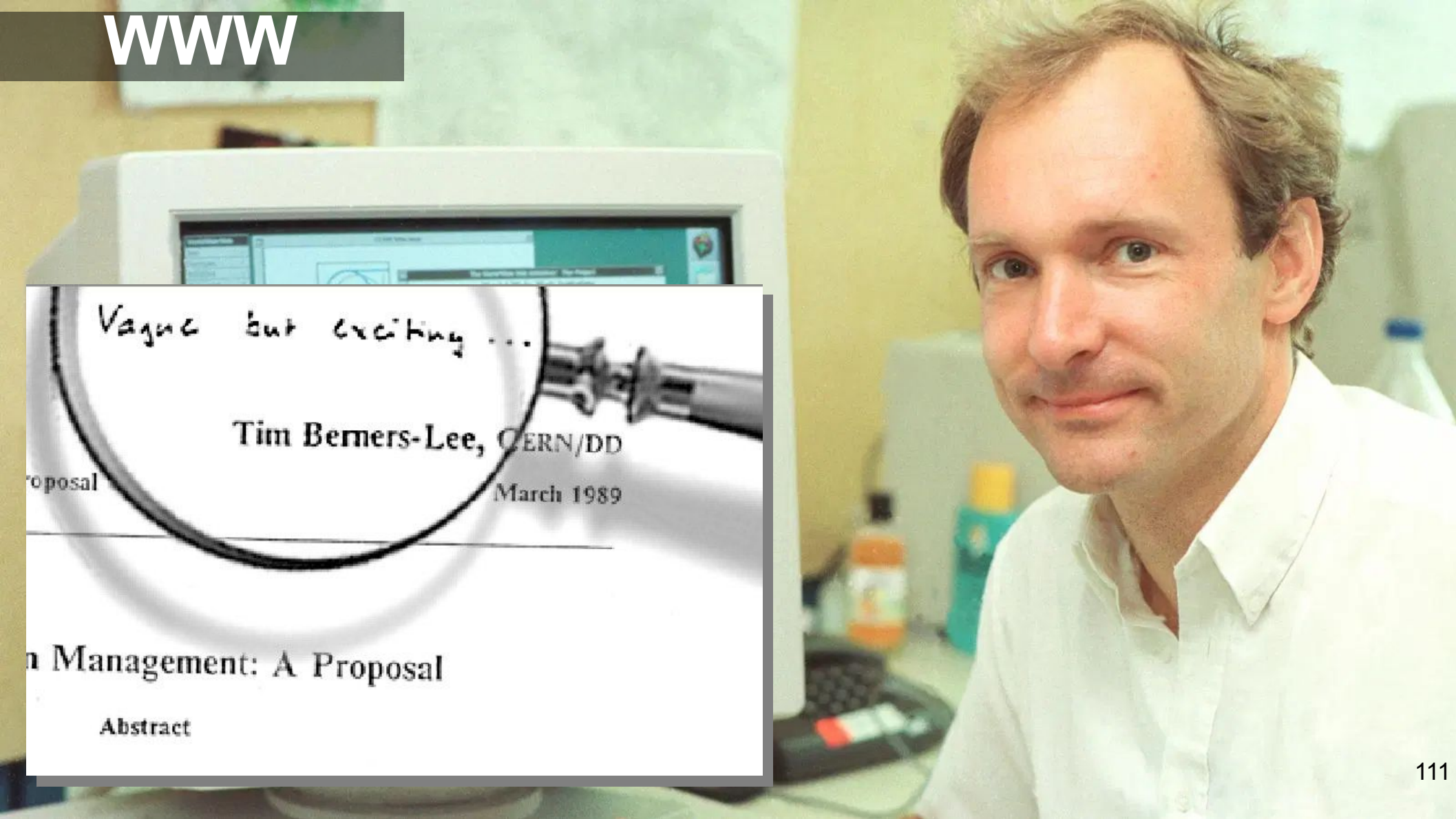
$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \Psi_i y_{ij}\Psi_j\Phi + h.c. + |D_\mu\Phi|^2 - V(\Phi)$$



Disegnare il futuro

WWW

WWW


Vague but exciting ...
Tim Berners-Lee, CERN/DD
March 1989
roposal
n Management: A Proposal
Abstract

Centro Nazionale Adroterapia Oncologica

Ricerca di base

Non un **frutto** pronto

Ricerca di base

Ma un **seme** che produrrà un albero con frutti inimmaginabili