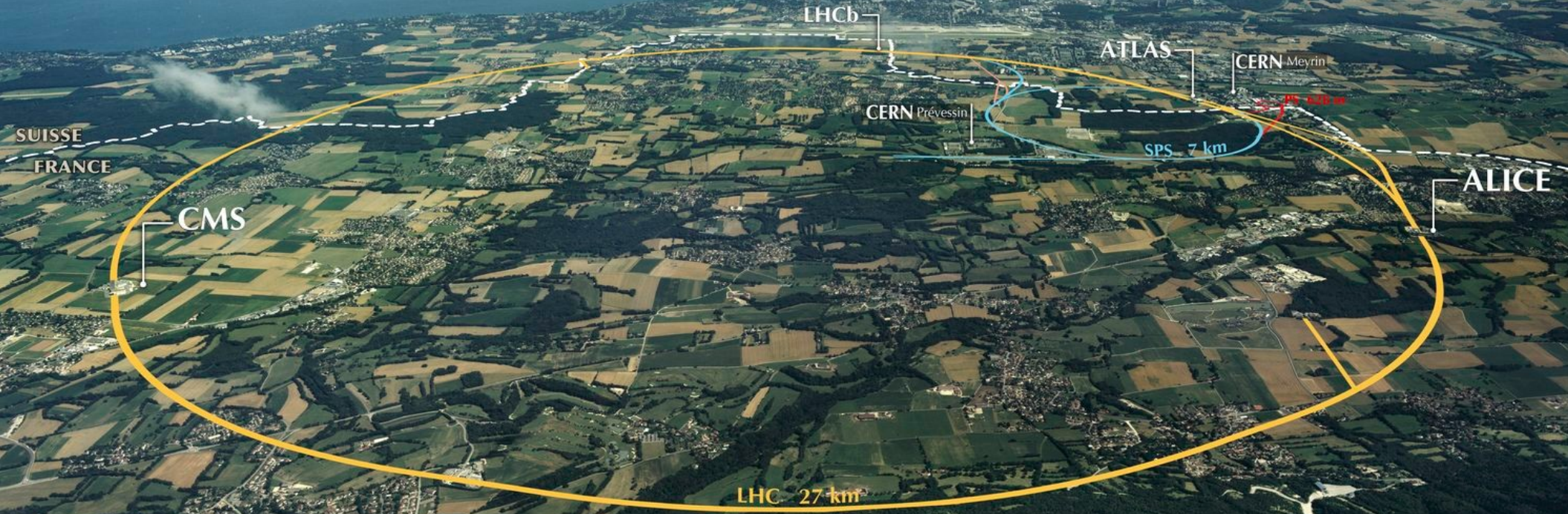


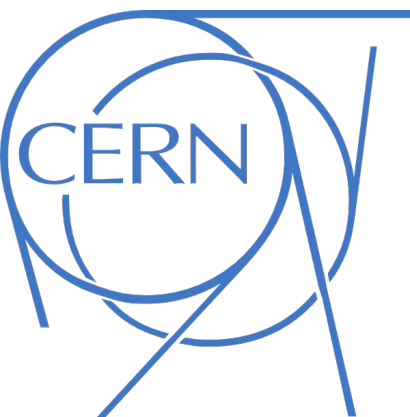
Fisica delle particelle elementari





**INTERNATIONAL
MASTERCLASSES**

hands on particle physics

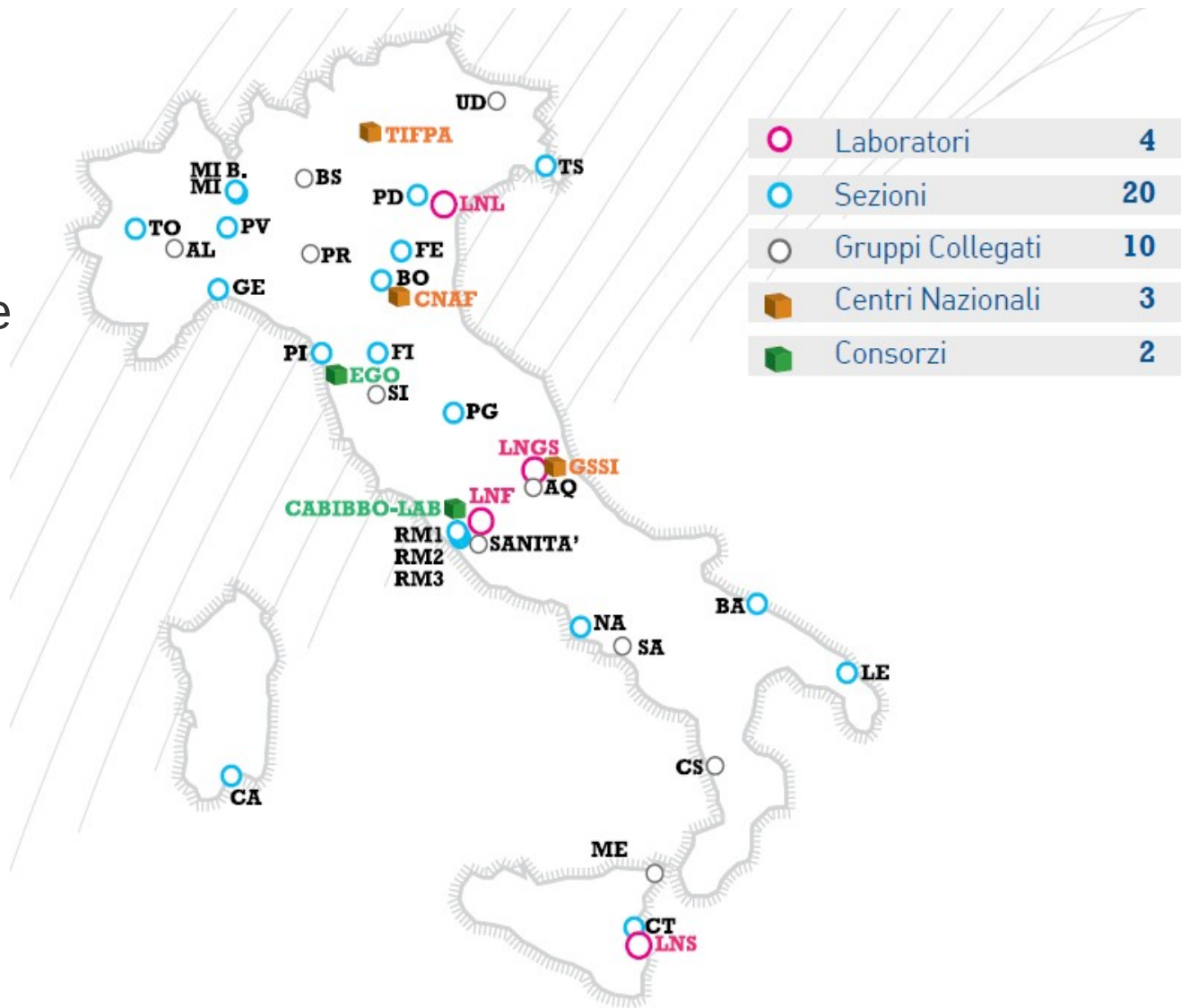


UNIVERSITÀ
DI PAVIA

- Istituto Nazionale di Fisica Nucleare
 - fondi per costruzione apparati e per le trasferte di fisici e tecnici



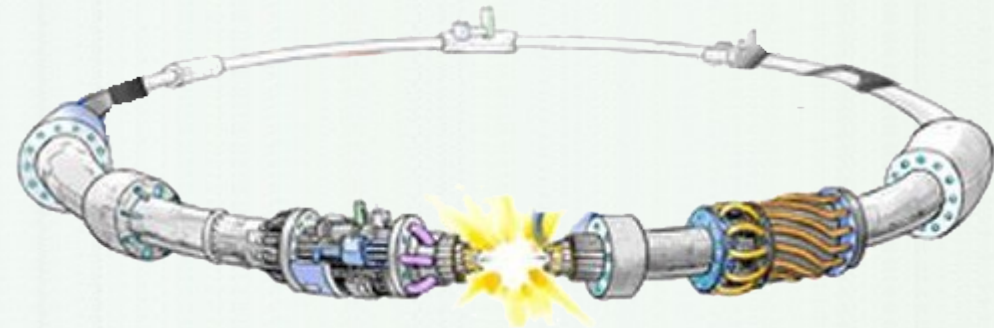
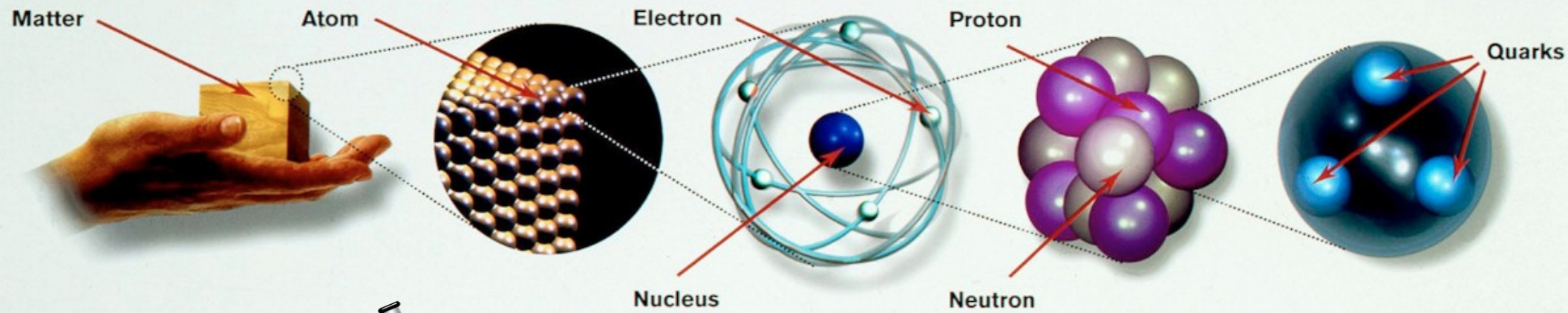
Istituto Nazionale di Fisica Nucleare



CERN



Fisica delle Particelle Elementari





Quale frase contiene il maggior numero di informazioni scientifiche in meno parole?



Quale frase contiene il maggior numero di informazioni scientifiche in meno parole?

Richard Feynman:
“... tutto è fatto di particelle ...”

Tutto è fatto di particelle



Tutto è fatto di particelle

Quarks



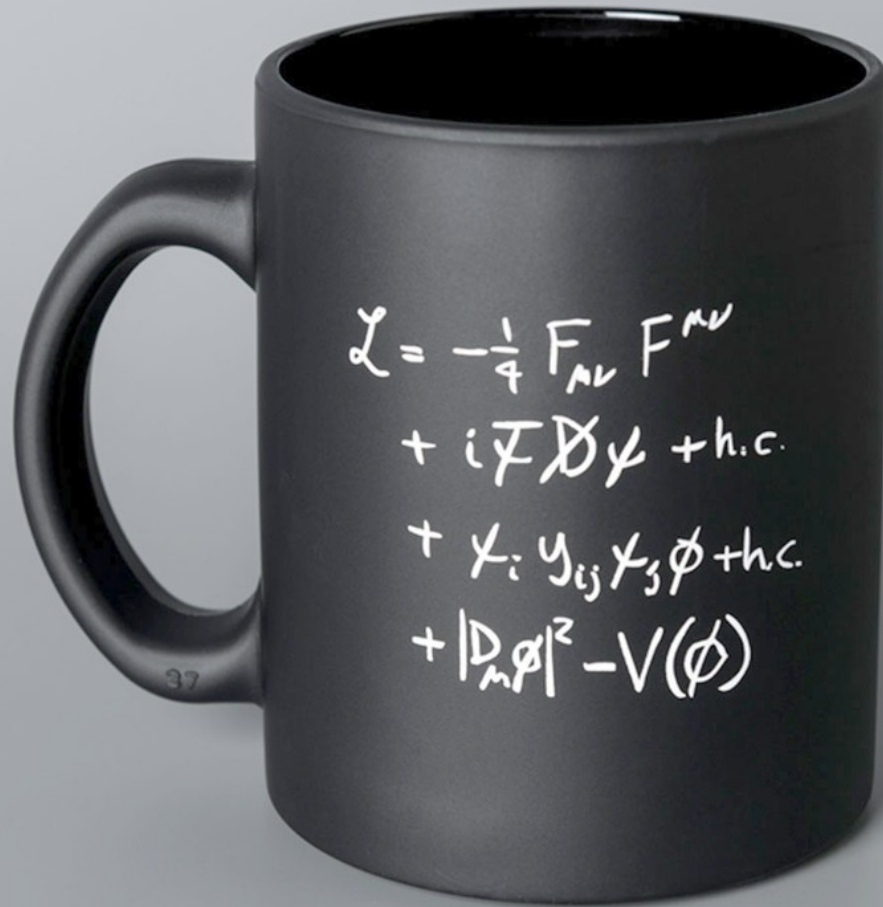
Forces



Leptons



Modello Standard

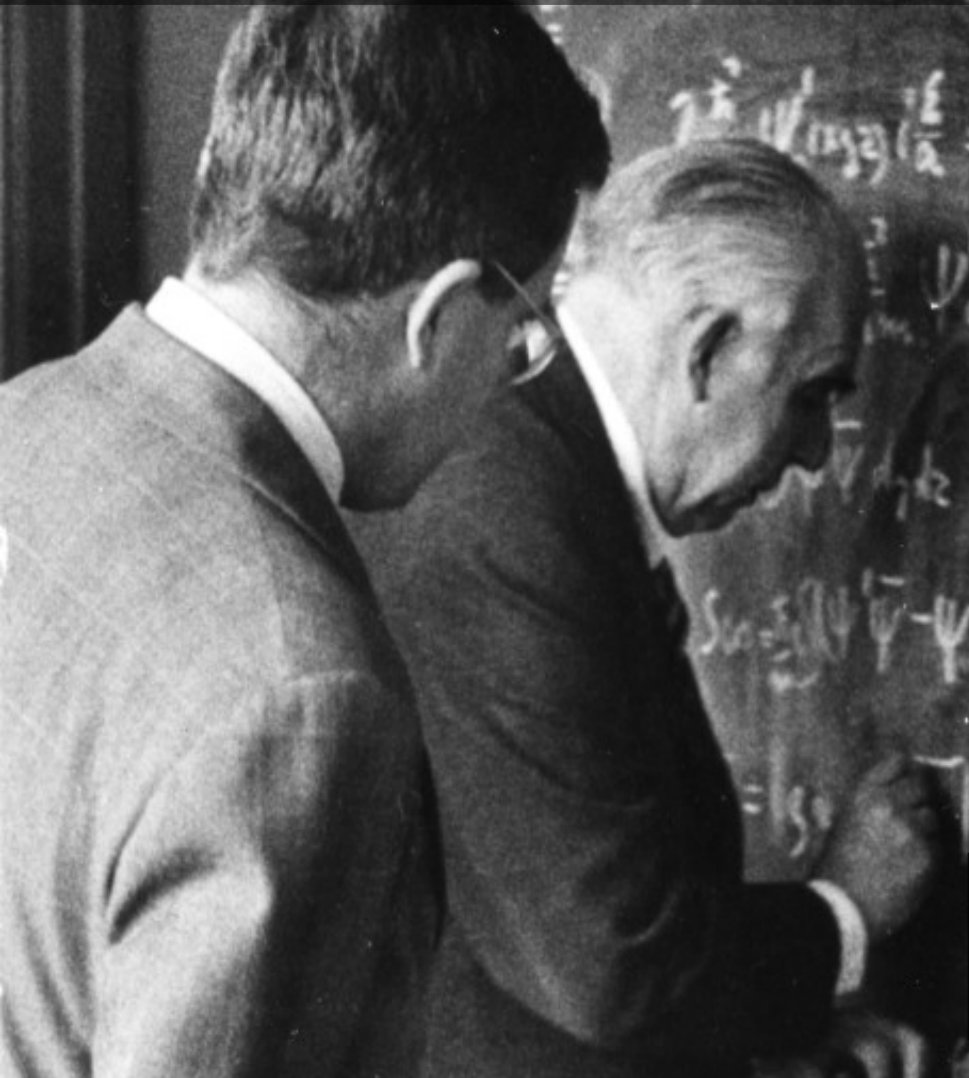


L_{SM}

$$\begin{aligned} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\ & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\ & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\ & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\ & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\ & \frac{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 - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\ & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\ & igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\ & igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\ & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \end{aligned}$$

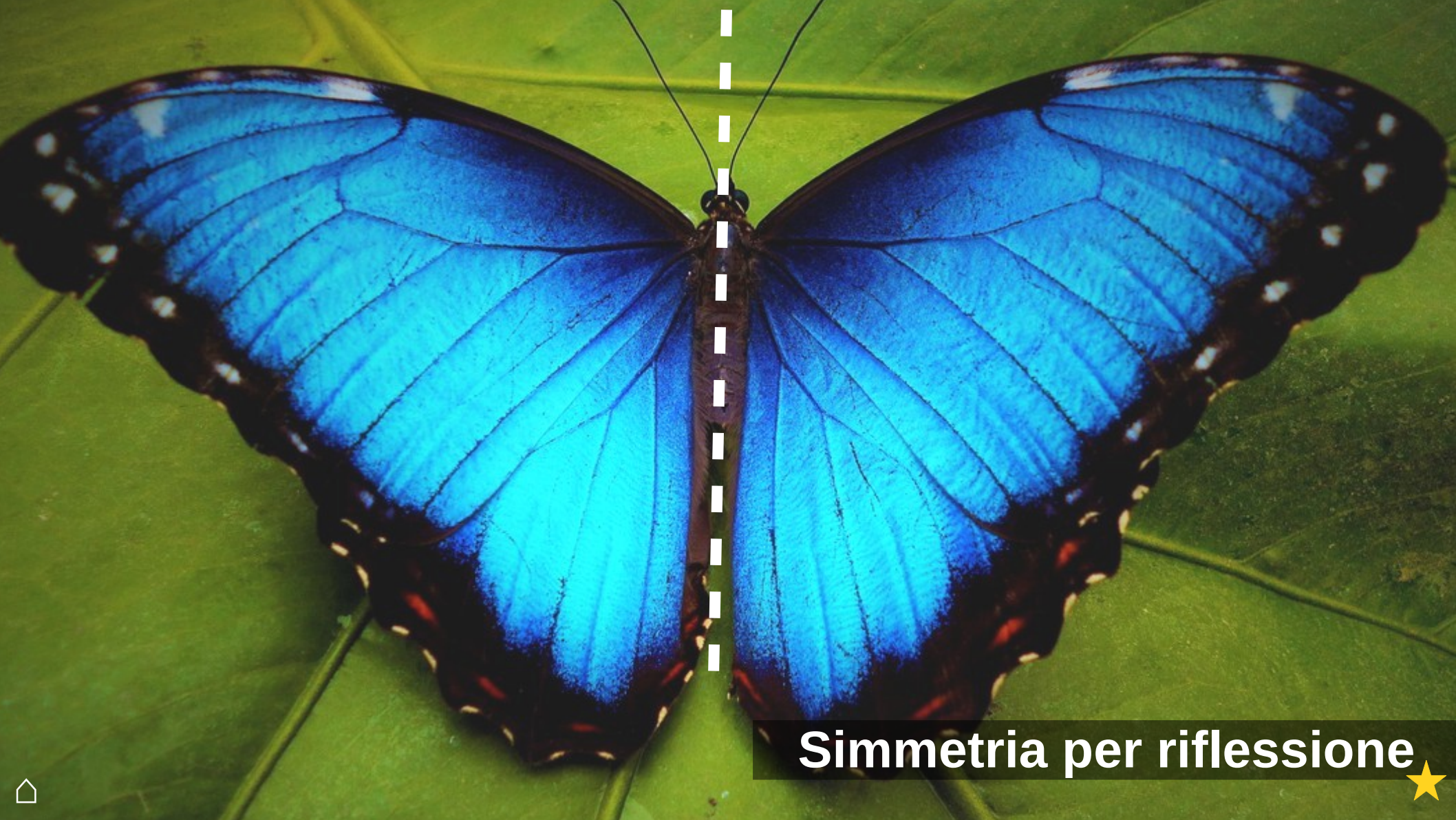
ecc...

Alla base della fisica: **simmetria**



**Trasformazione che lascia
invariato un oggetto**





Simmetria per riflessione ★



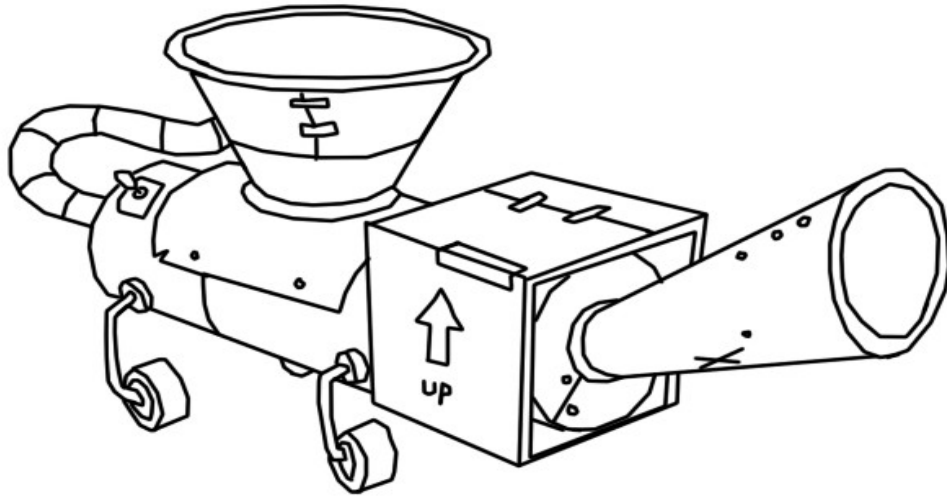


Simmetria per rotazioni



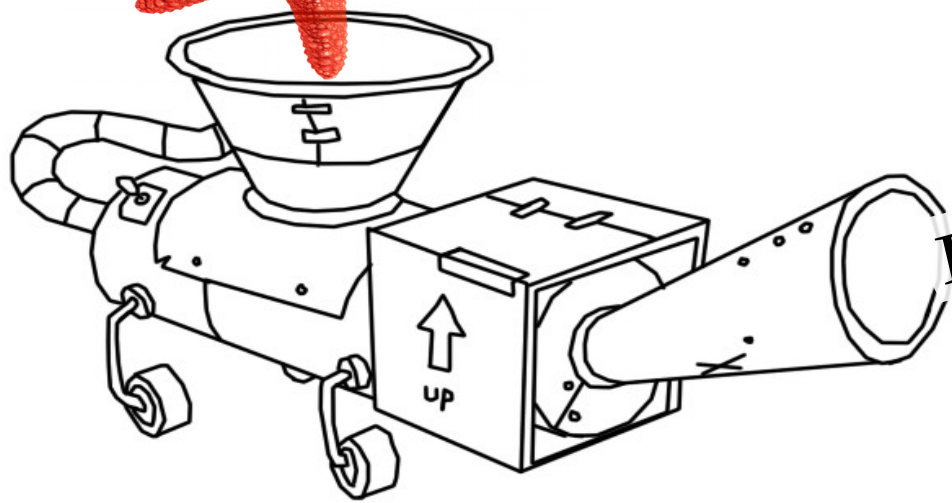
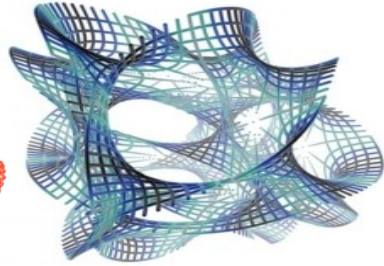
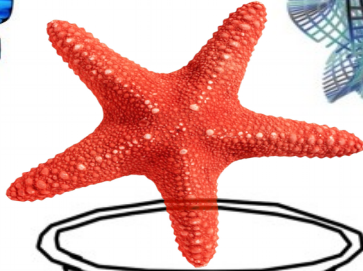
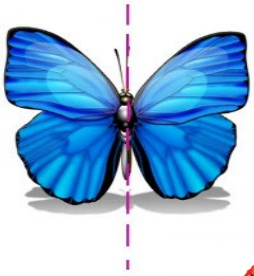
Macchina per teorie

Simmetrie



Equazioni

Simmetrie



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$
$$E = mc^2$$
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{\partial}\psi + \text{h.c.} + \psi_i \gamma_{ij} \psi_j \Phi + \text{h.c.} + |D_\mu \Phi|^2 - V(\Phi)$$
$$dU = \delta Q - \delta L$$

Equazioni



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

Emmy Noether, 1915

Teorema di Noether

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

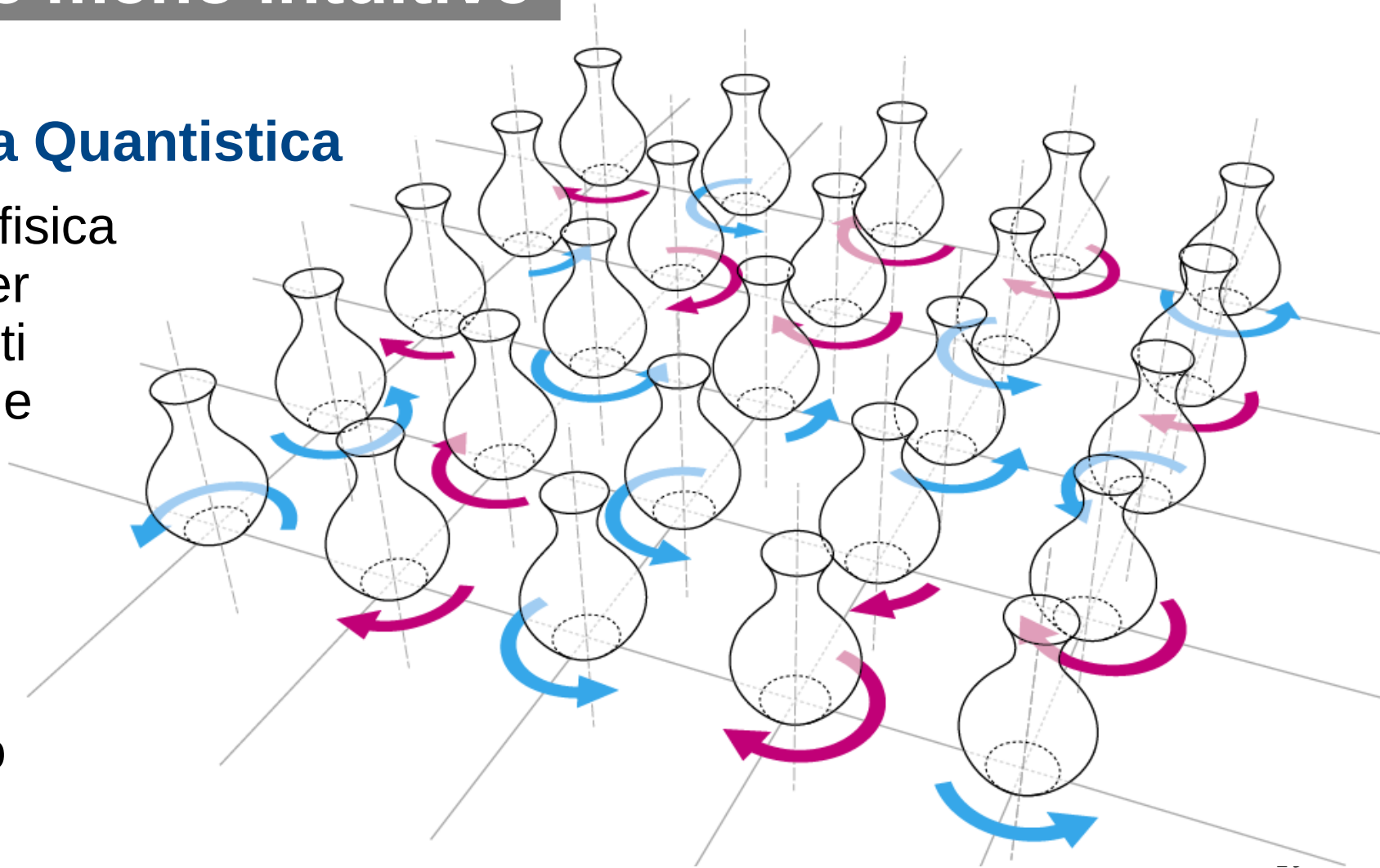


$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Simmetrie meno intuitive

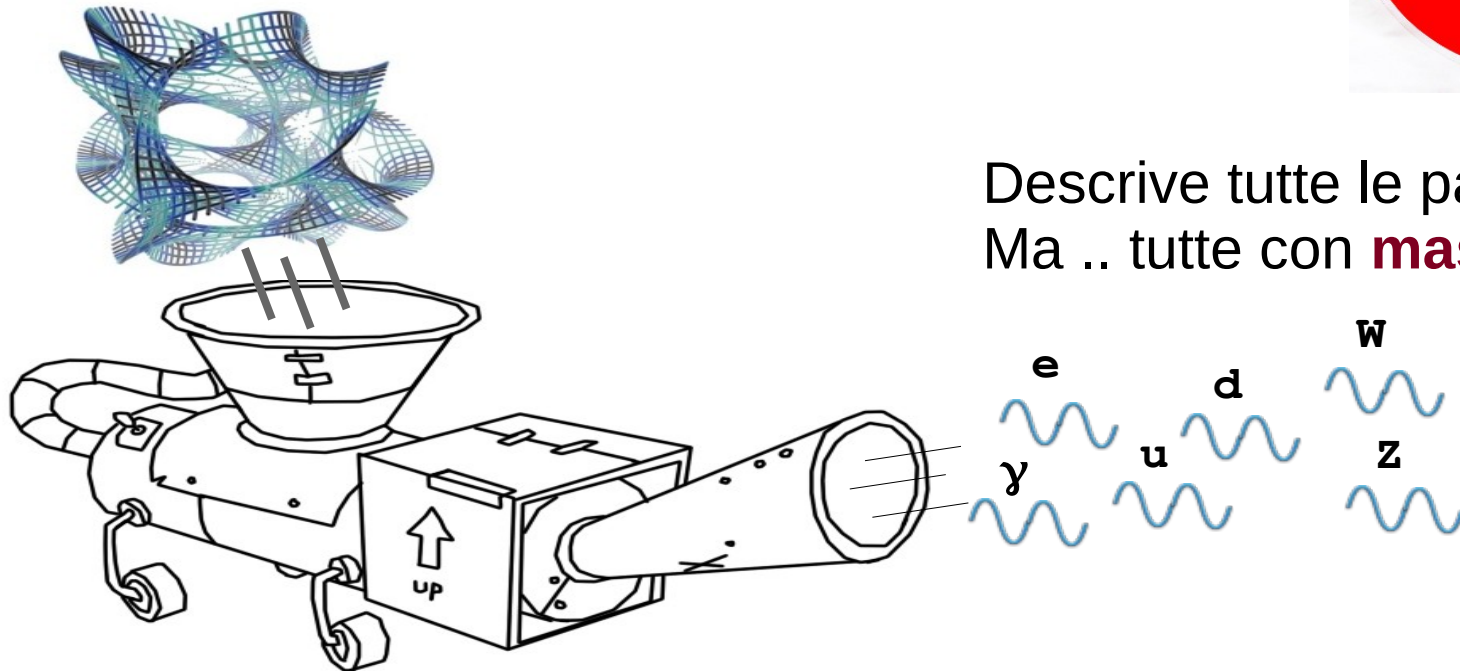
Meccanica Quantistica

Leggi della fisica
invarianti per
cambiamenti
arbitrari delle
fasi della
funzione
d'onda del
sistema in
ogni punto
dello spazio

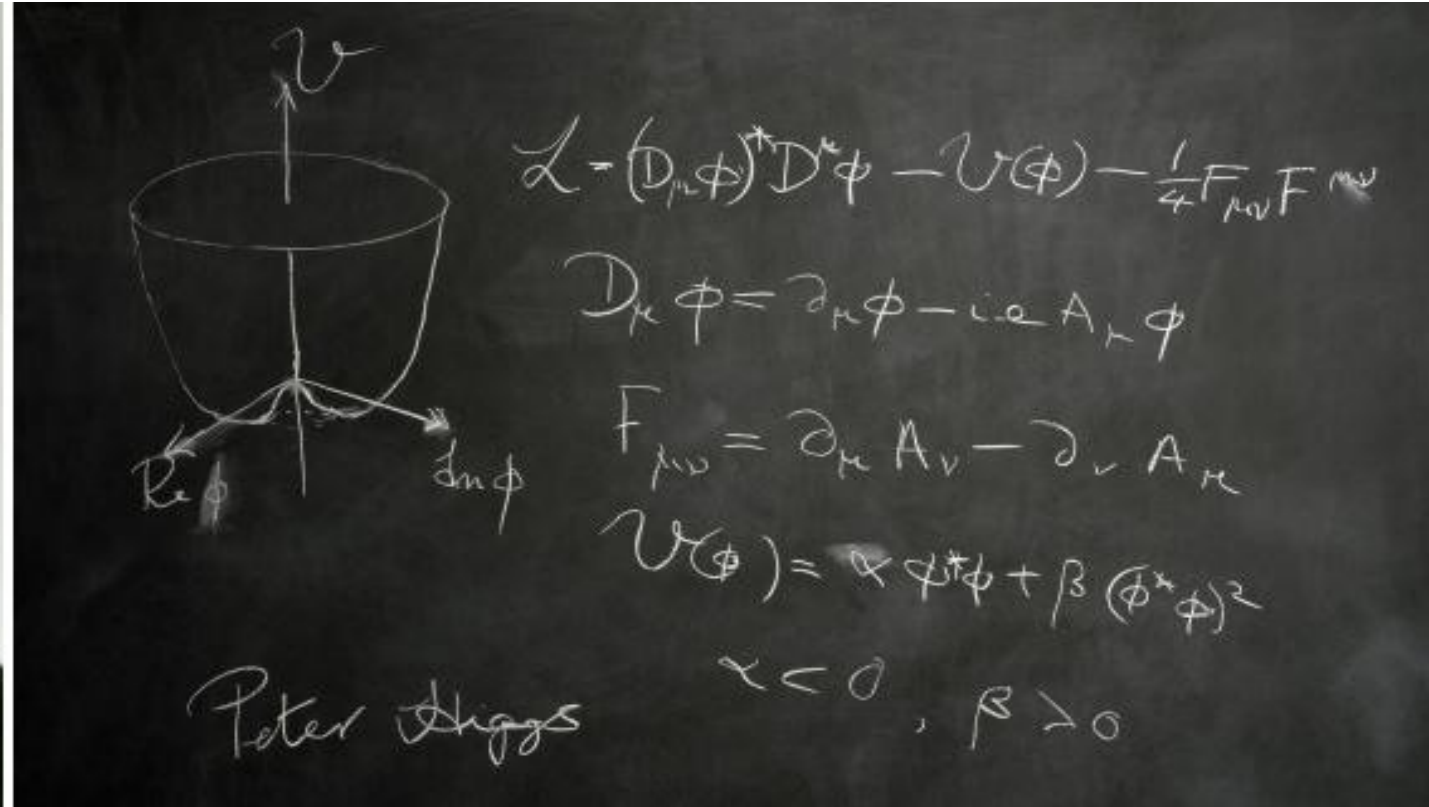


Modello standard delle particelle

Simmetria $SU(2)_L \times U(1)$



E se la simmetria fosse **rotta**?

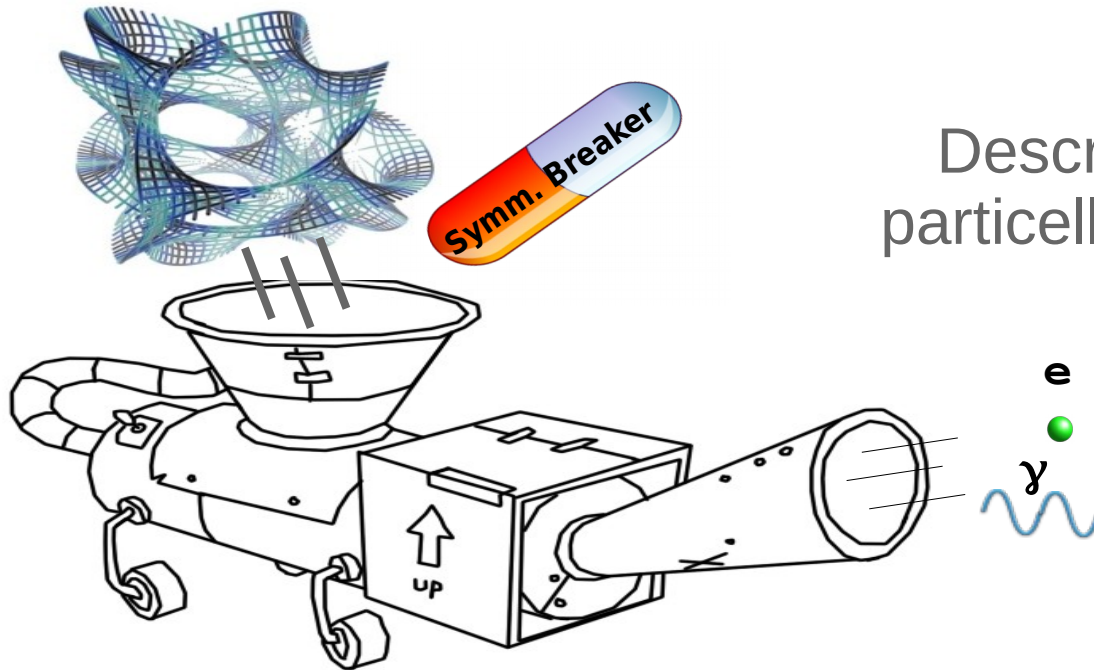


Robert Brout, François Englert, **Peter Higgs** @1964

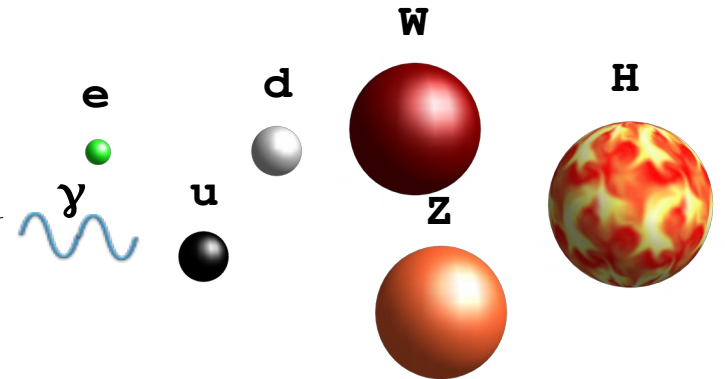
Modello standard delle particelle

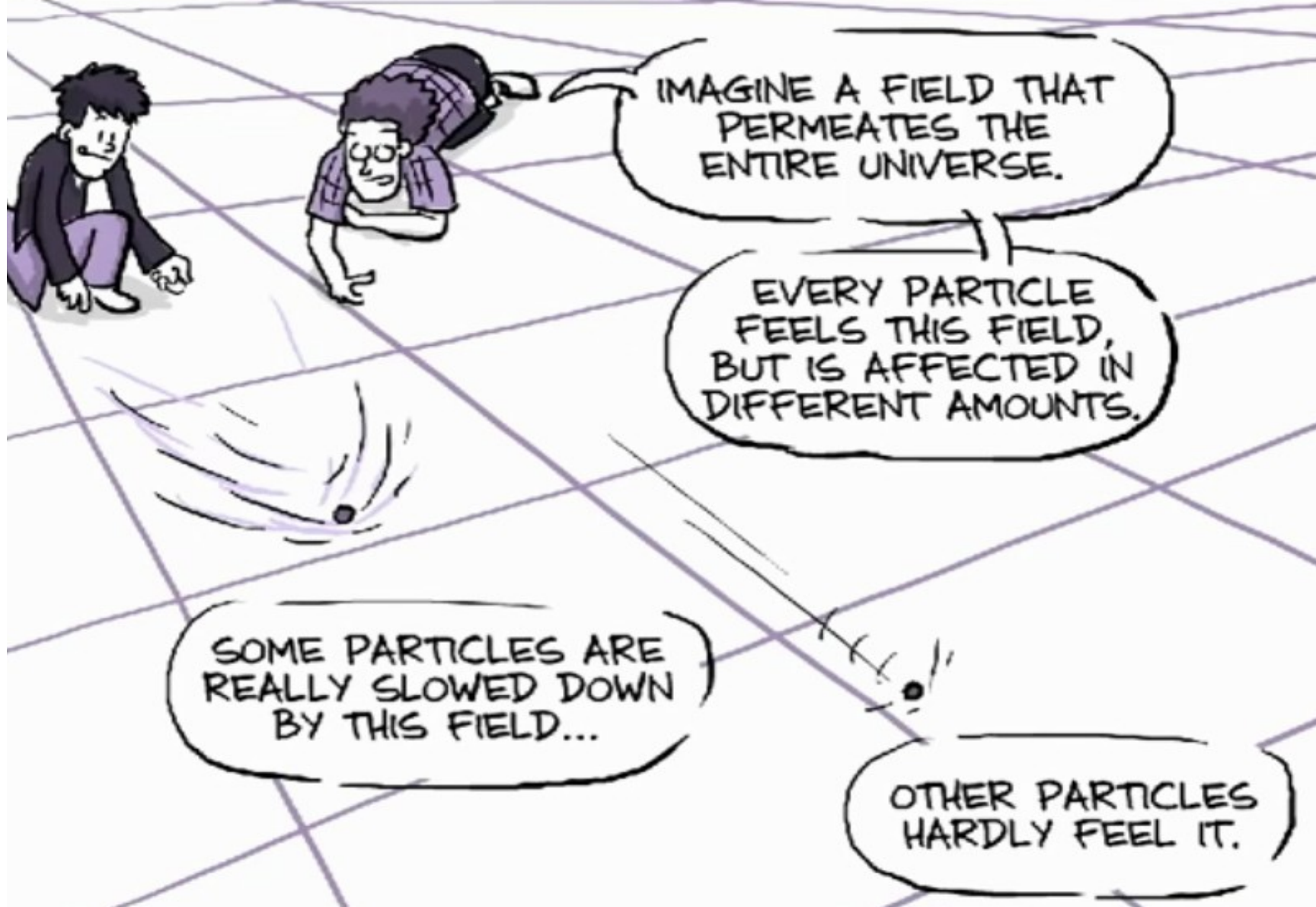
Simmetria $SU(2)_L \times U(1)$

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



Descrizione corretta delle
particelle note + ... una nuova





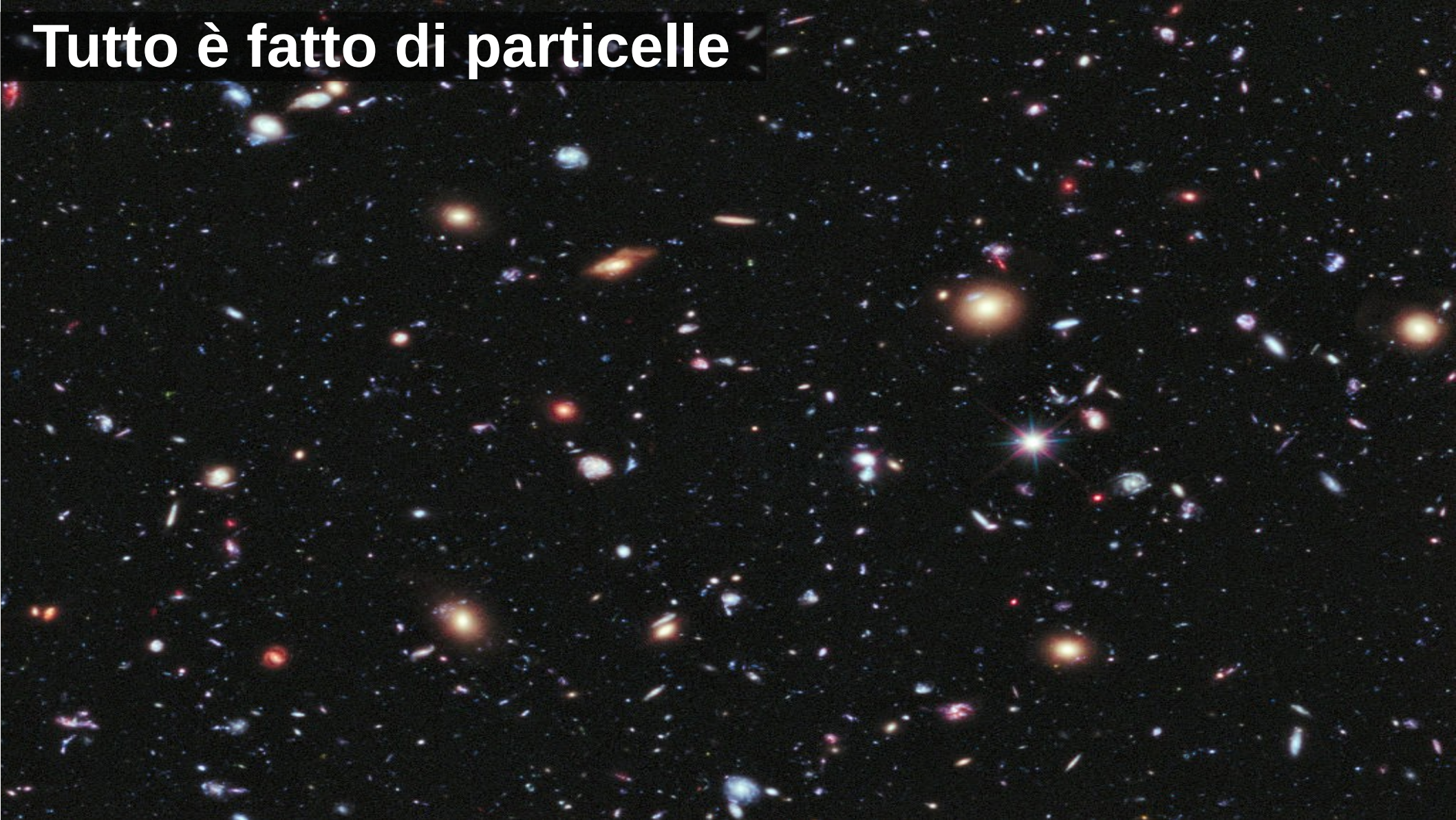
IMAGINE A FIELD THAT PERMEATES THE ENTIRE UNIVERSE.

EVERY PARTICLE FEELS THIS FIELD, BUT IS AFFECTED IN DIFFERENT AMOUNTS.

SOME PARTICLES ARE REALLY SLOWED DOWN BY THIS FIELD...

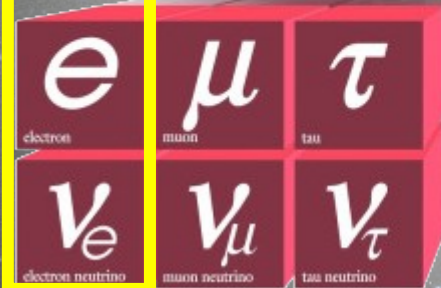
OTHER PARTICLES HARDLY FEEL IT.

Tutto è fatto di particelle



Tutto è fatto di particelle

Quarks



Leptons

Forces



Tutto è fatto di particelle

Quarks



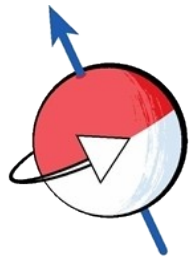
Forces



H
Higgs boson



Leptons



Spin 1/2

I fermioni La materia

Quarks



Leptons



Forces



I bosoni Le forze



Spin 1

Interazioni mediate da bosoni



Interazioni mediate da bosoni

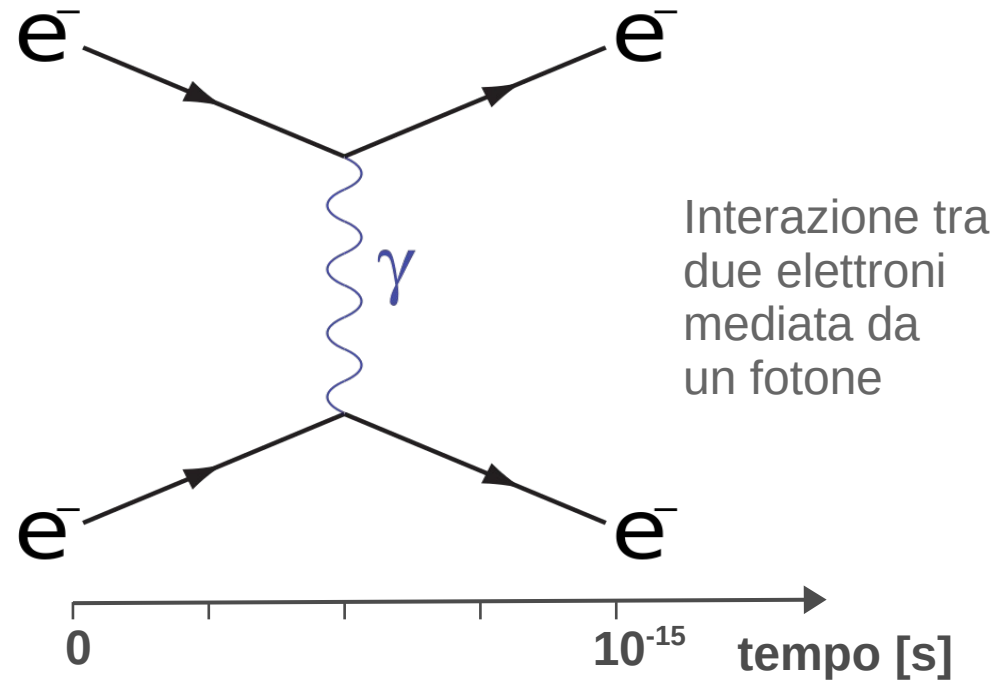


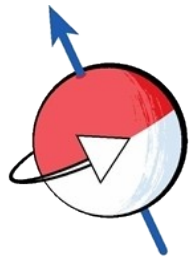
A volte la particella emittente si trasforma



Diagrammi di Feynman

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





Spin 1/2

I fermioni La materia

Quarks



Leptons



Forces



I bosoni Le forze



Spin 1

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**

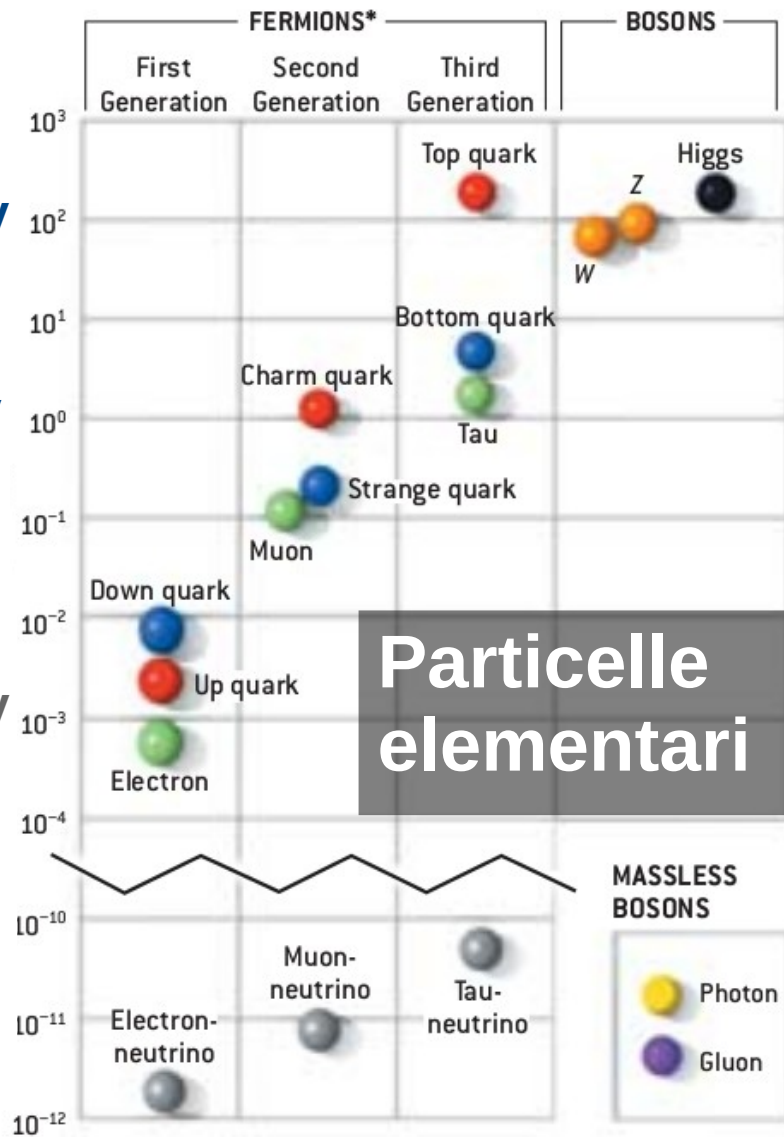


Masse

100 GeV

1 GeV

1 MeV

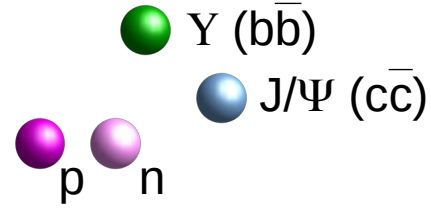
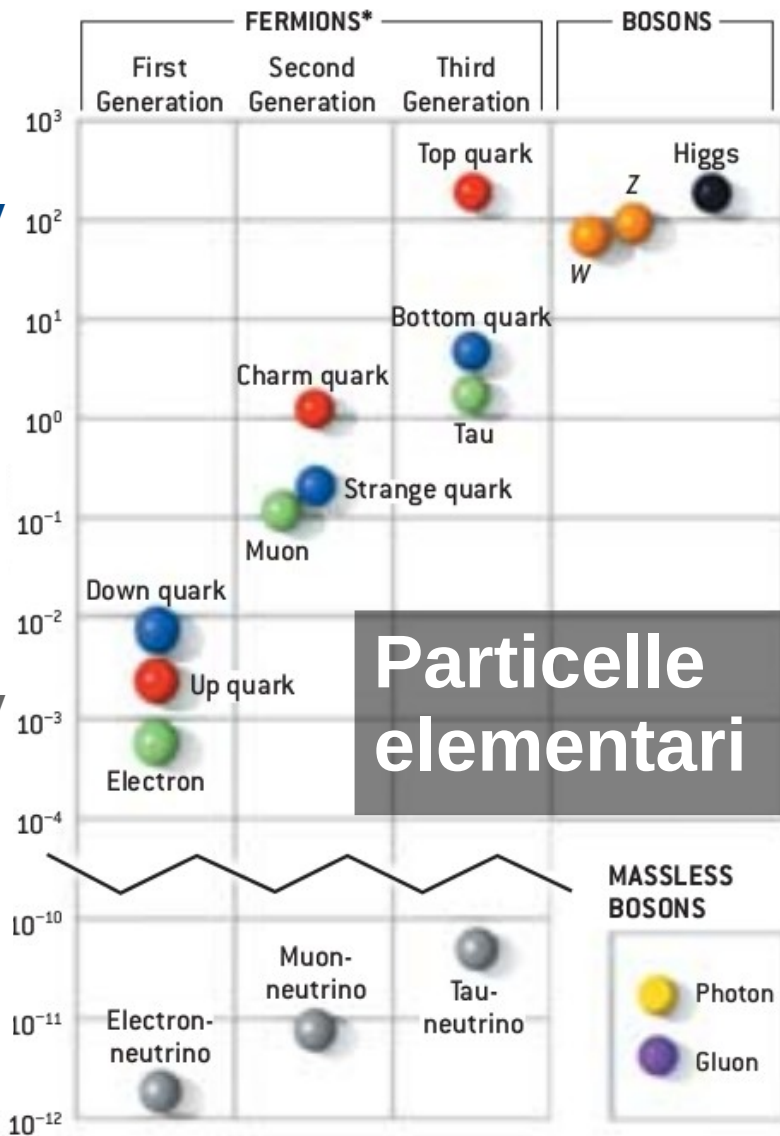


Masse

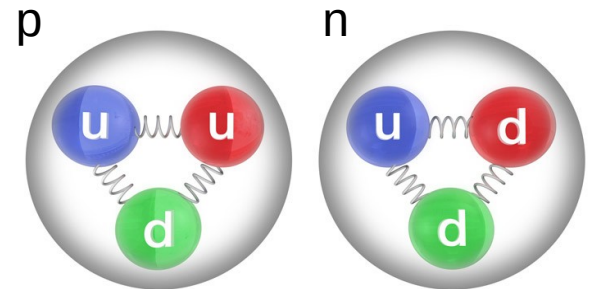
100 GeV

1 GeV

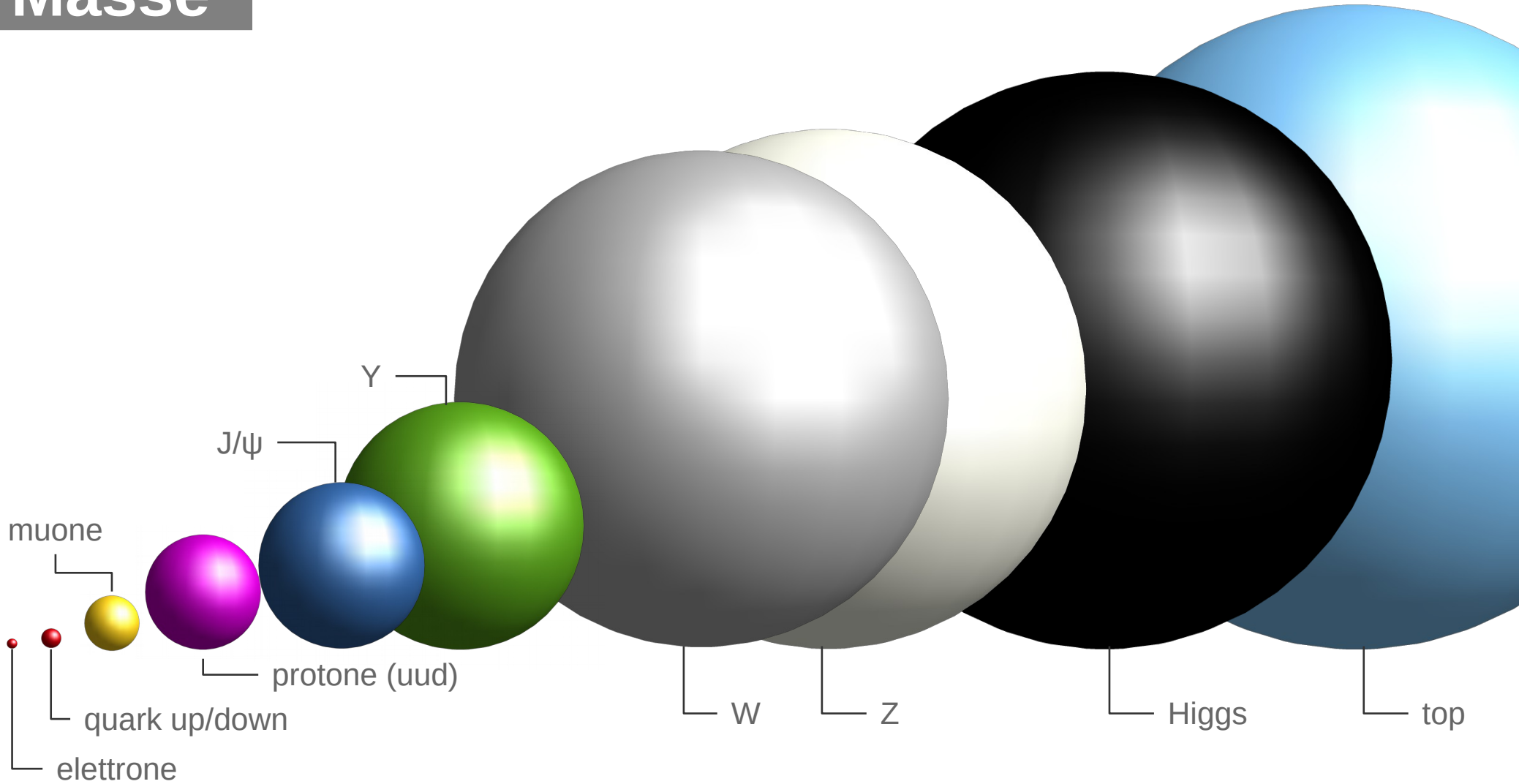
1 MeV



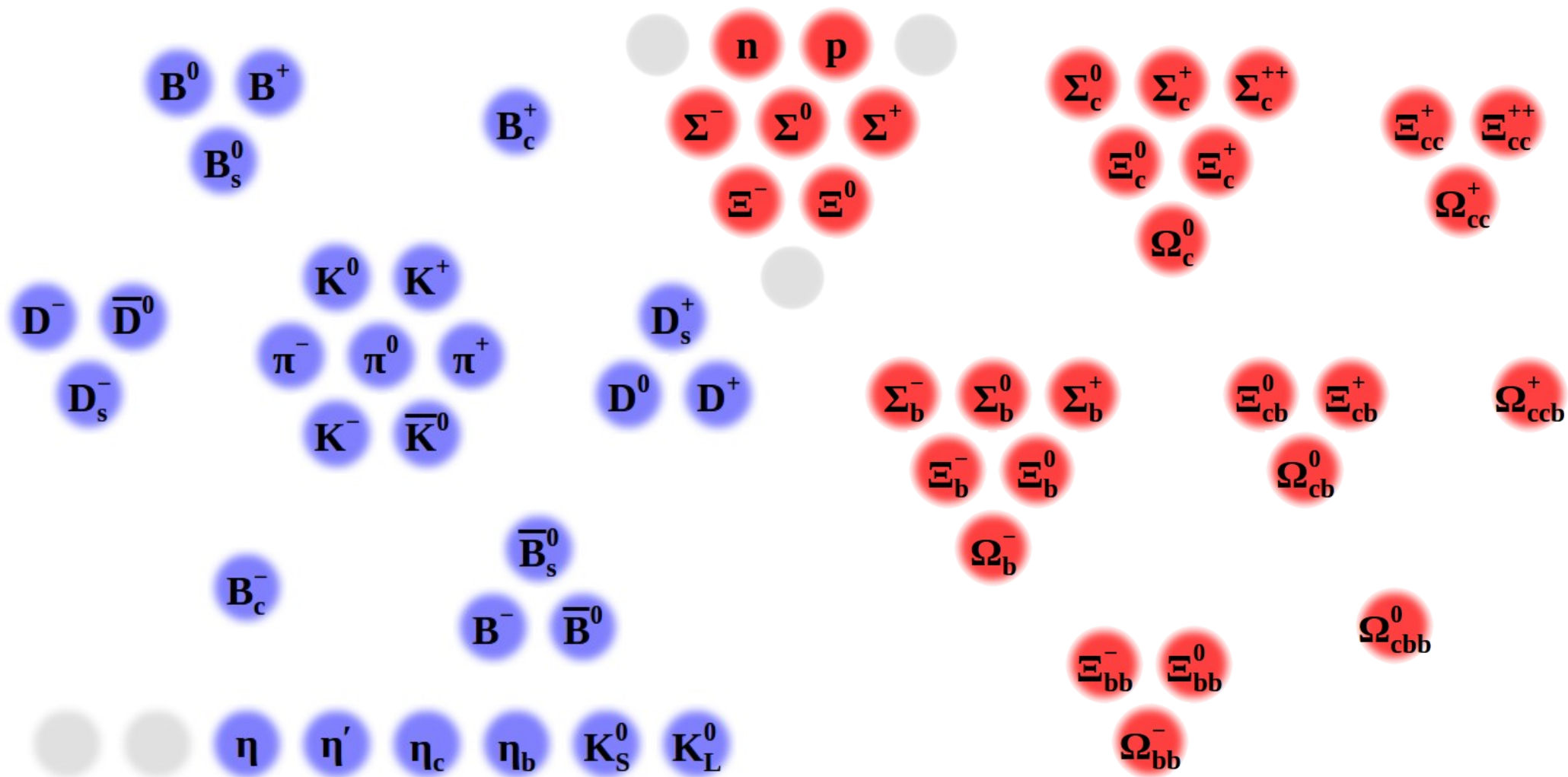
Particelle composte



Masse



Lo zoo



Da ricordare



- La natura è **matematica**
- Formule da principi di **simmetria**
- 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
- Domani vedremo
 - $Z \rightarrow e^+e^-, \rightarrow \mu^+\mu^-, \dots$
 - $J/\Psi(c\bar{c}) \rightarrow e^+e^-, \rightarrow \mu^+\mu^-, \dots$
 - $Y(b\bar{b}) \rightarrow e^+e^-, \rightarrow \mu^+\mu^-, \dots$



Decadimenti

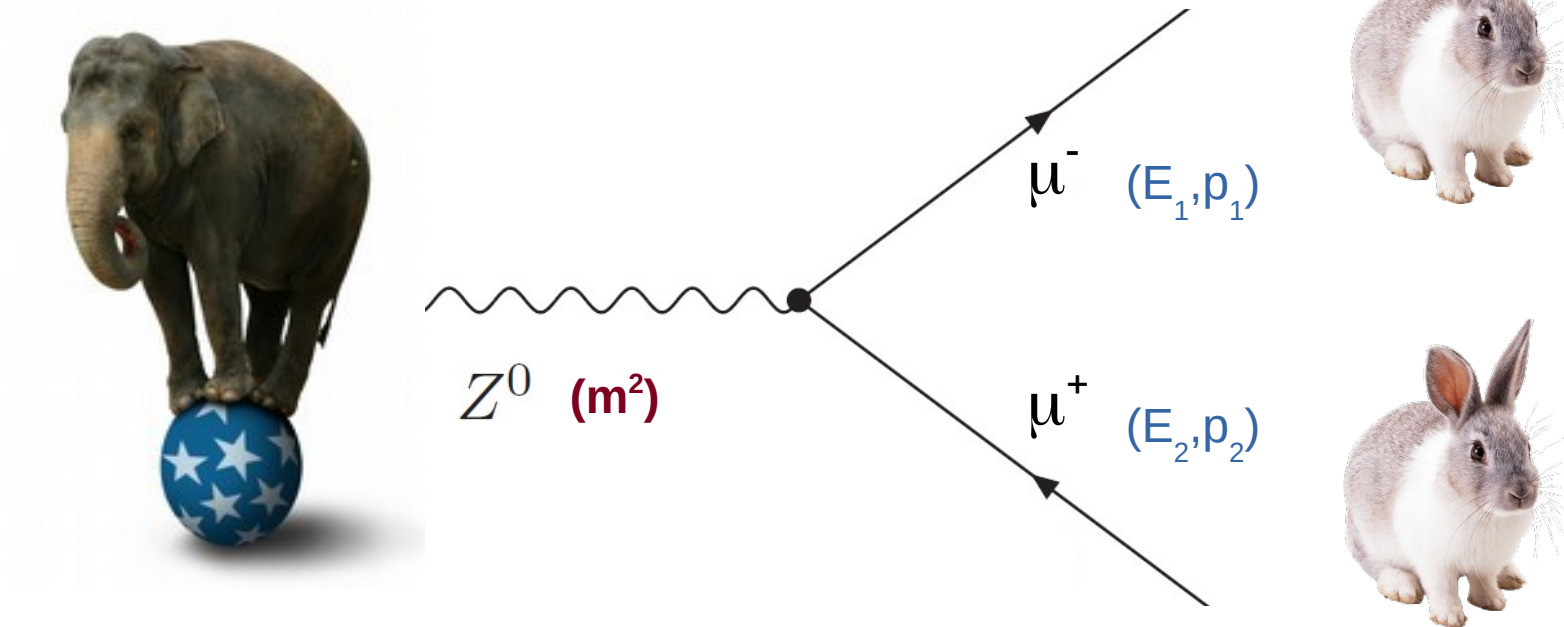
- Poche particelle sono stabili
 - Elettrone, protone e neutrini
- Le altre **decadono** in quelle più stabili
 - Con un tempo caratteristico
- Domani vedremo
 - **Z** $\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
 - **J/ψ**($c\bar{c}$) $\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...
 - **Υ** ($b\bar{b}$) $\rightarrow e^+e^-$, $\rightarrow \mu^+\mu^-$, ...



Conservazione energia e impulso

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

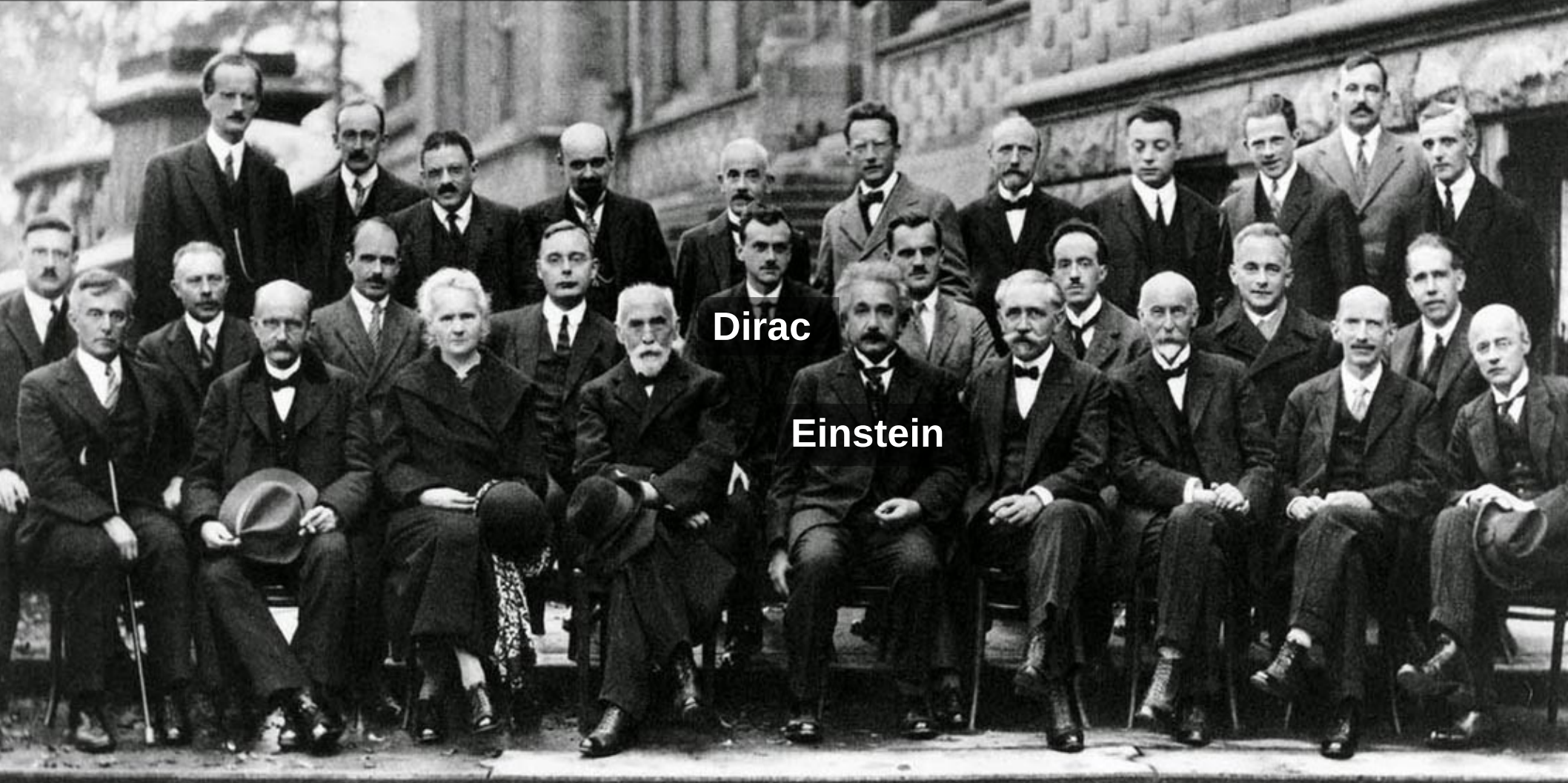
$$m^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$



Come produrre nuove particelle?



Congresso di Solvay 1927



$$i(\gamma^\mu \partial_\mu - m)\Psi = 0$$

Dirac (1928)

Antimateria

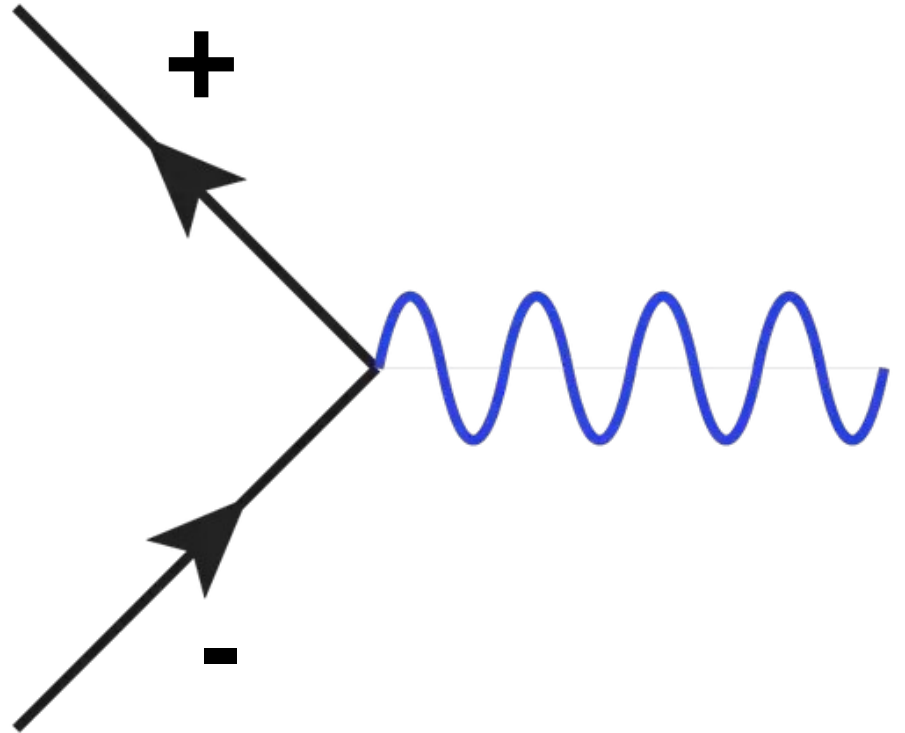


Ogni particella → antiparticella
stessa massa ma carica opposta

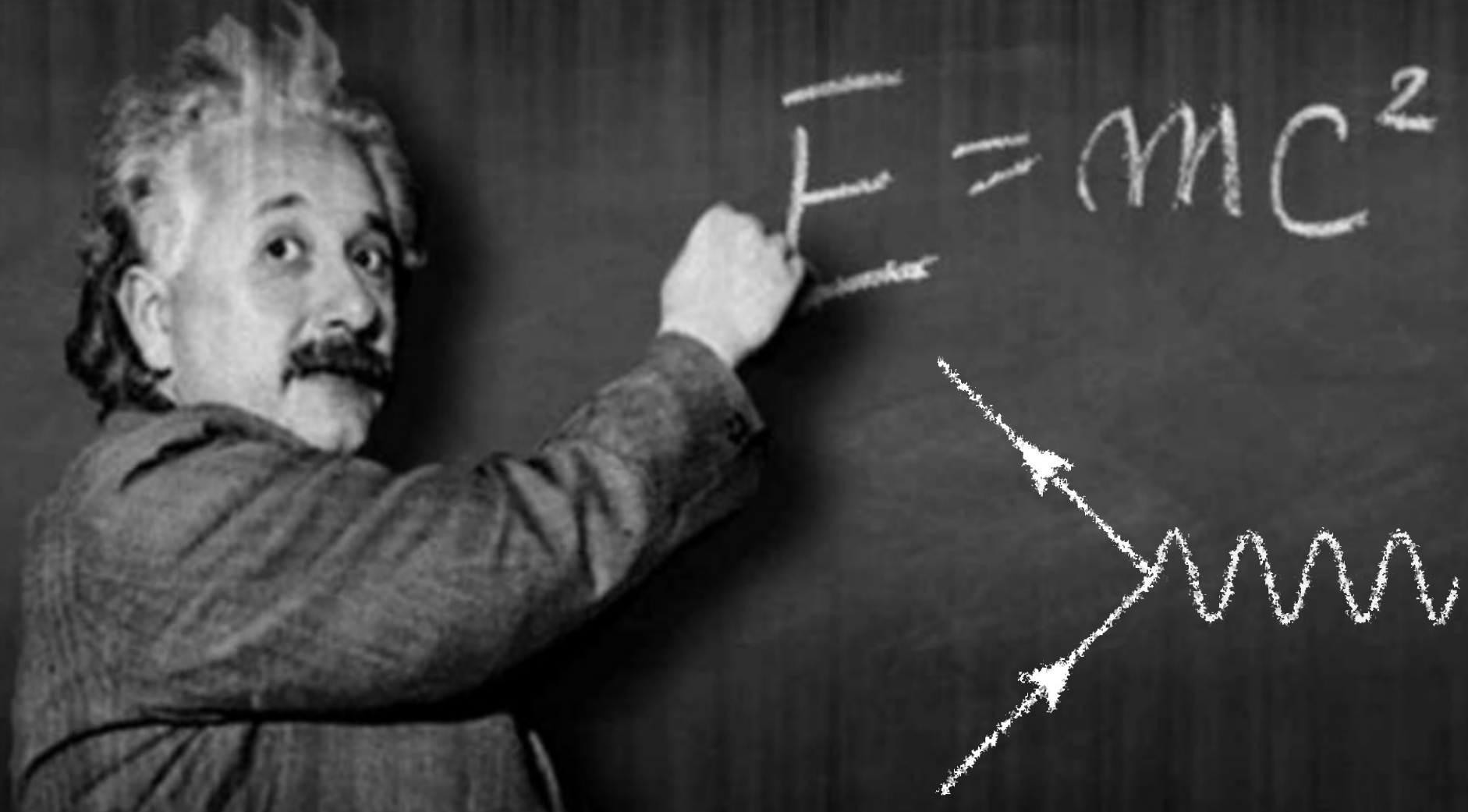
Antimateria

Se una **particella** incontra
la sua **anti-particella**
si **annichilano**

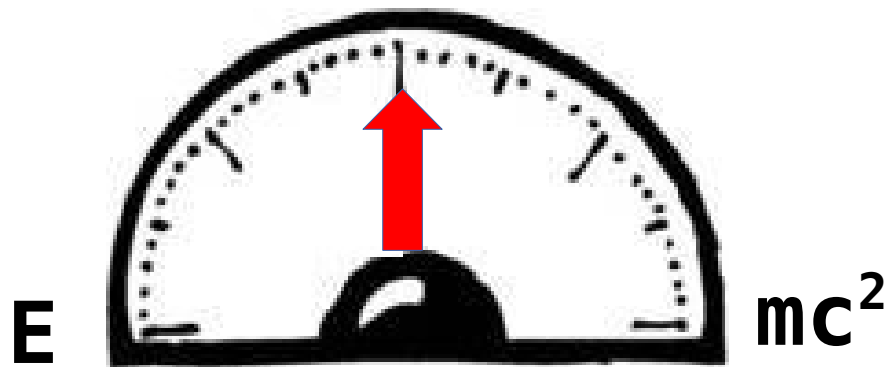
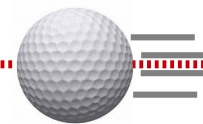
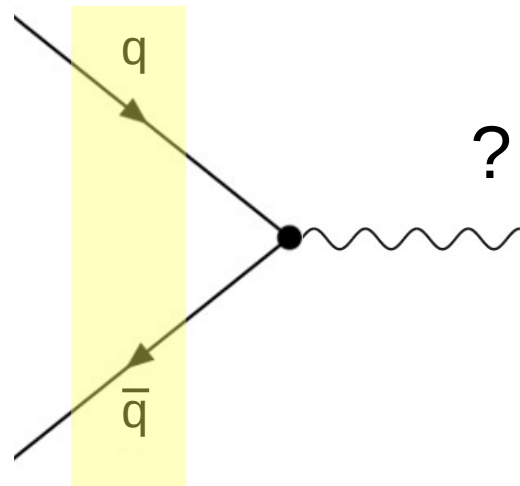
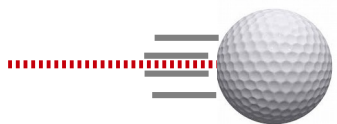
- La **massa** diventa **energia**
 $E=mc^2$
- Particelle a carica neutra:
fotoni, gluoni o il bosone Z



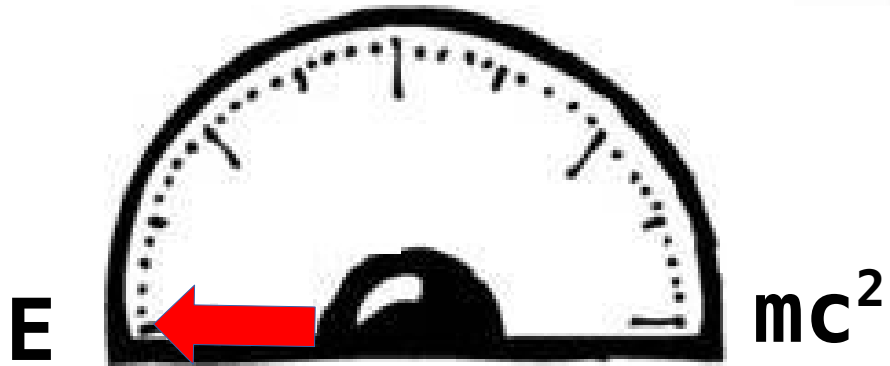
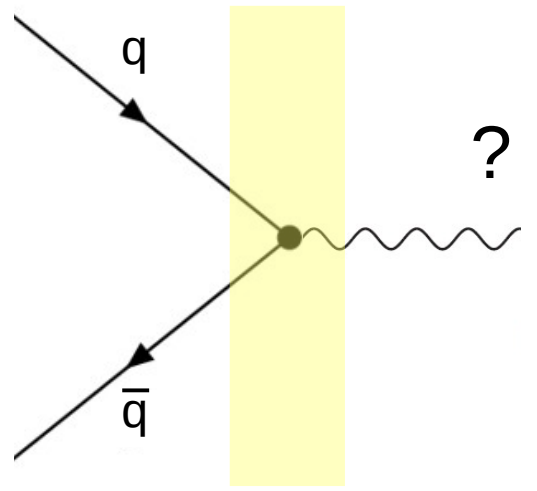
Come produrre nuove particelle?



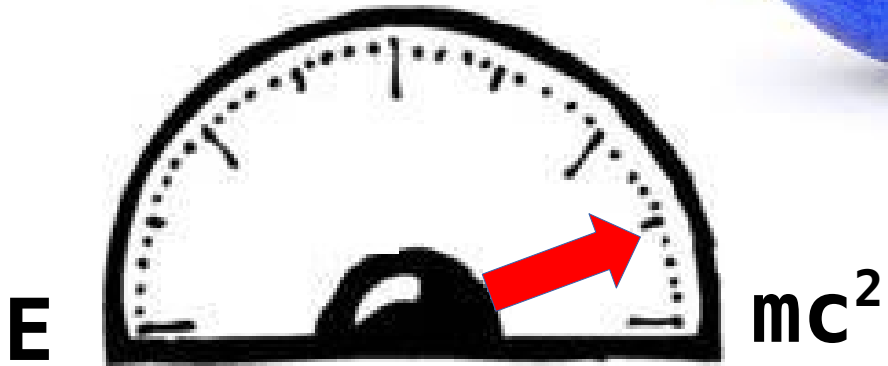
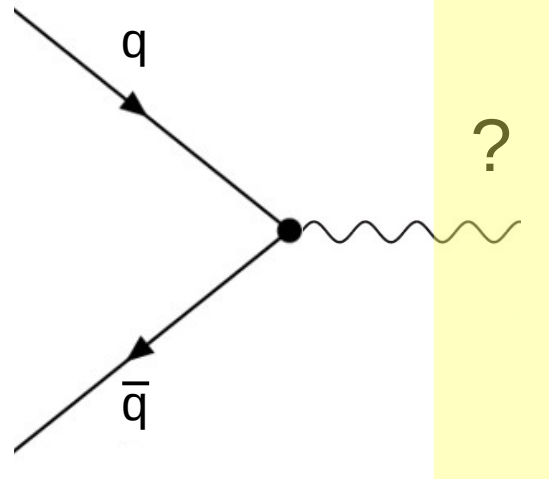
Collider



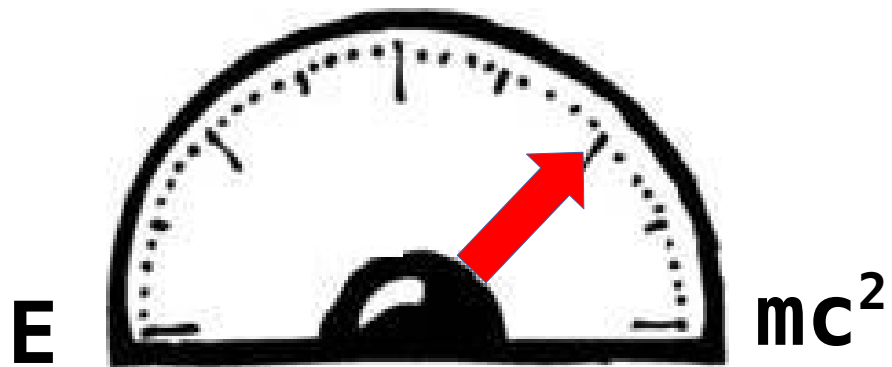
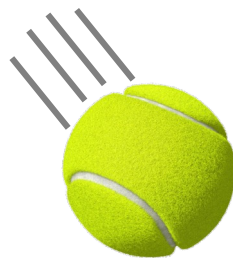
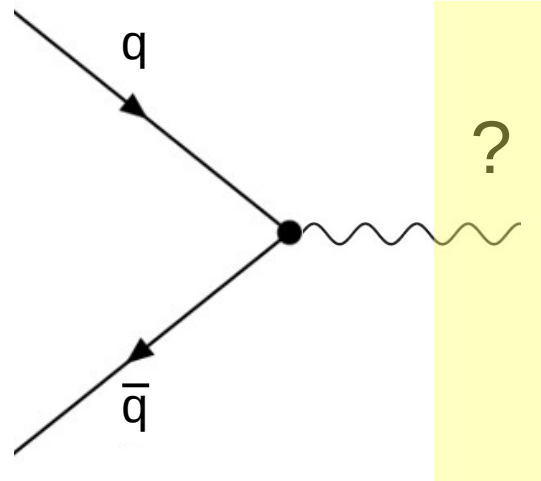
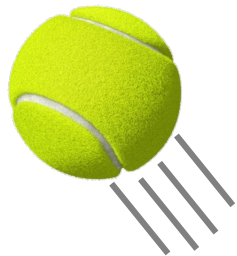
Collider



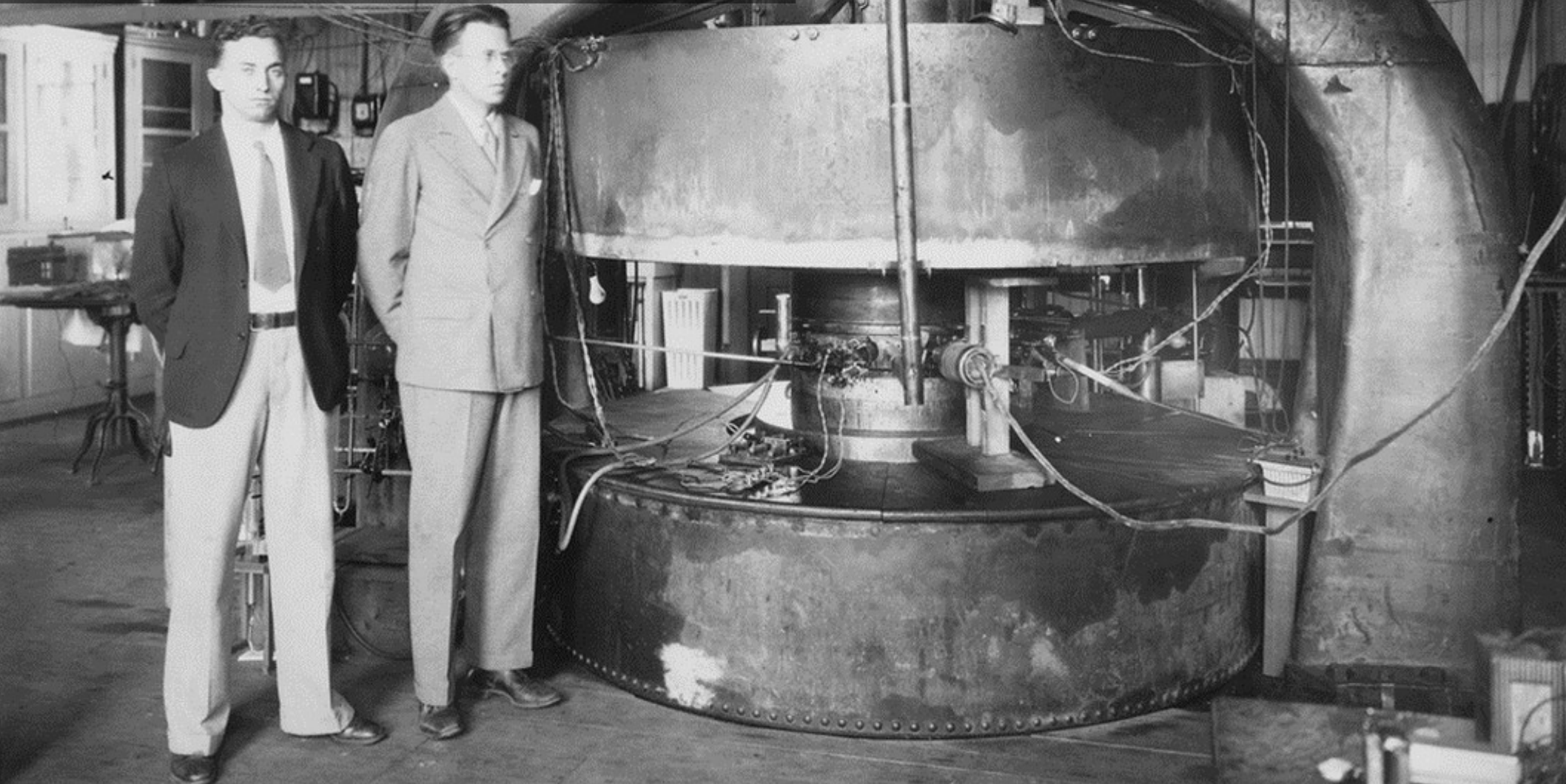
Collider



Collider



Livingstone Lawrence '32



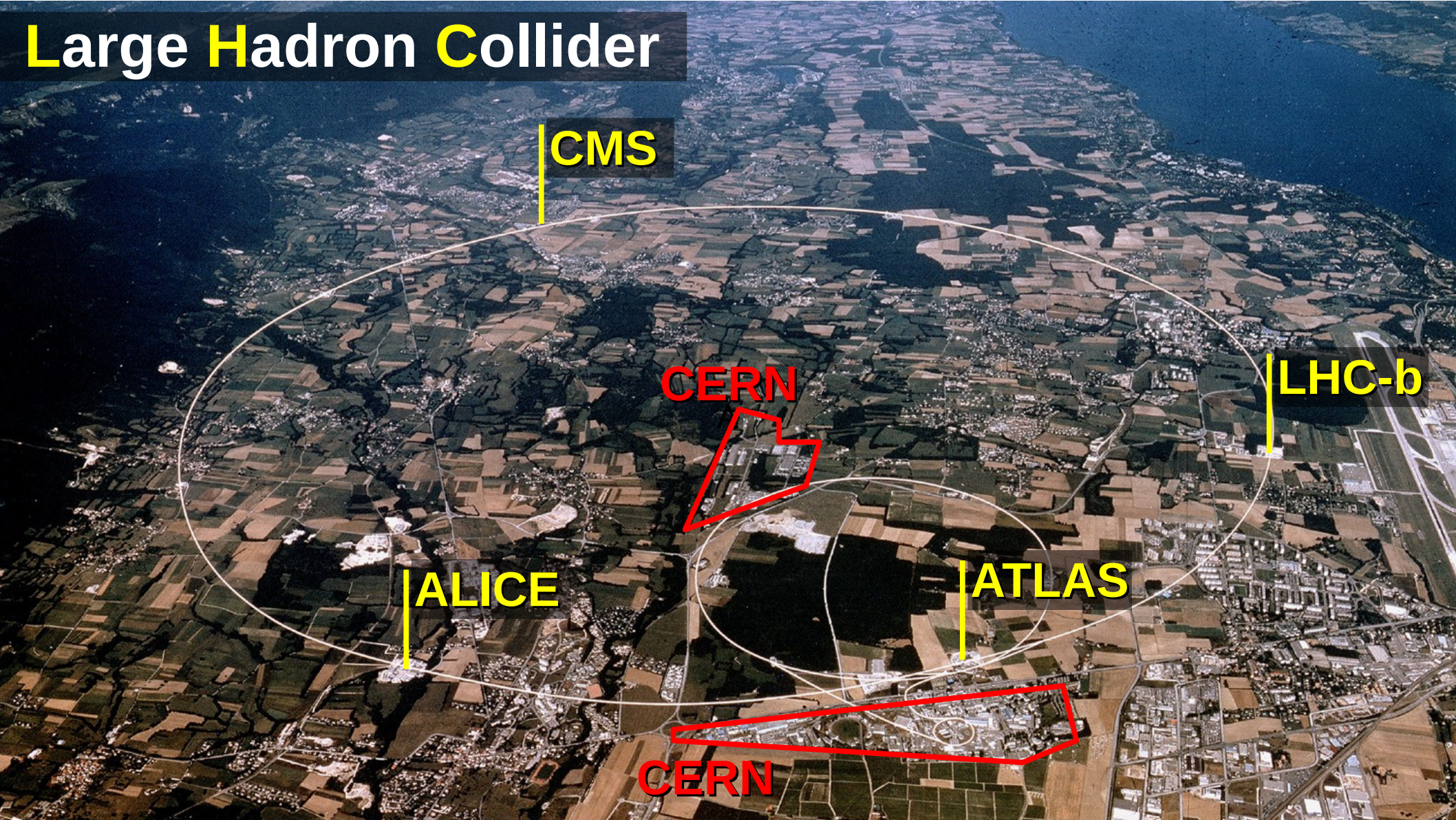
Anello di Accumulazione '60



Large Hadron Collider



Large Hadron Collider



CMS

CERN

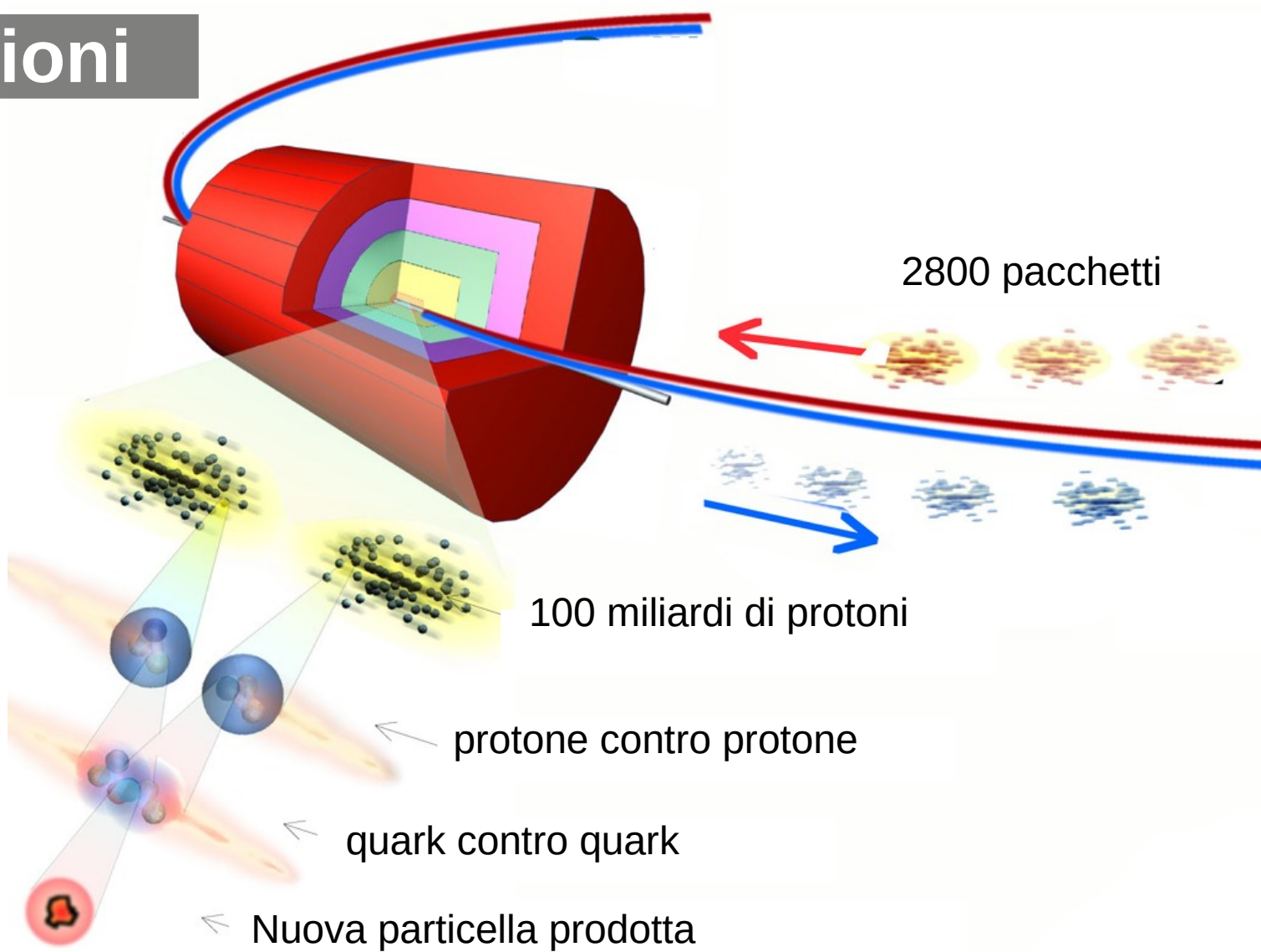
LHC-b

ALICE

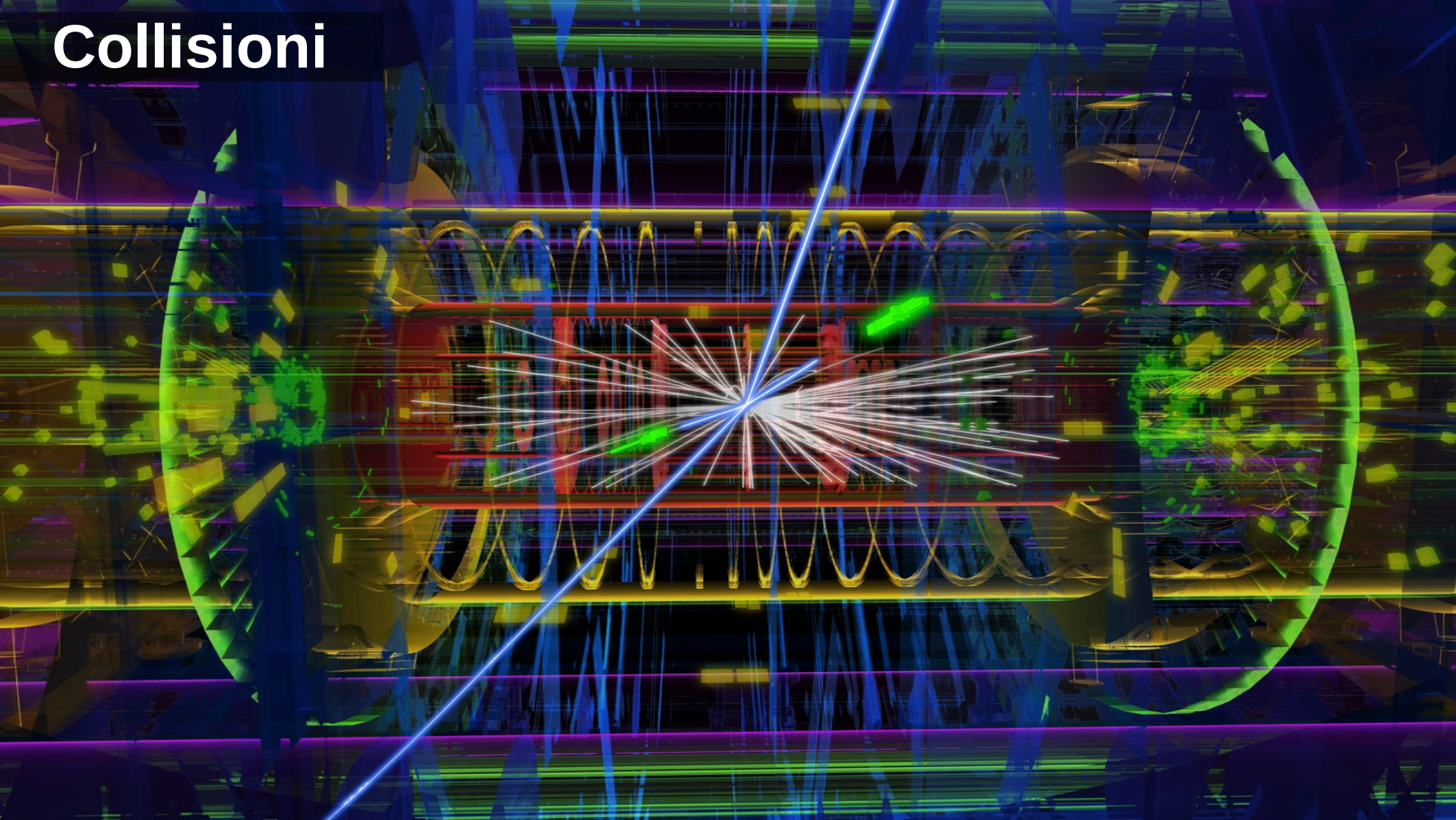
ATLAS

CERN

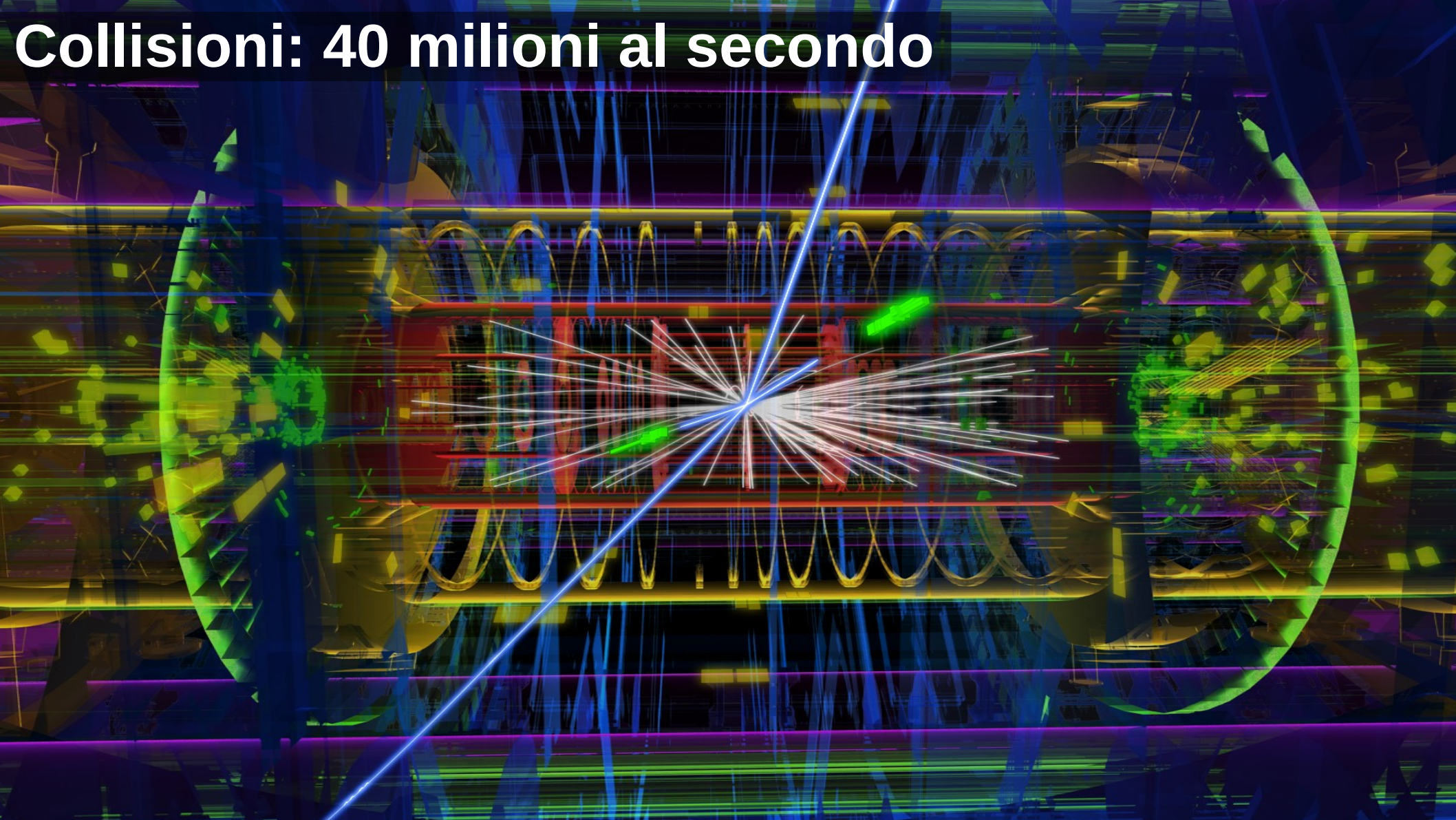
Collisioni



Collisioni



Collisioni: 40 milioni al secondo



Eventi rari

Segnale/fondo:

$1/10^{10}$

- 1 granello ogni 400 secchielli



Da ricordare

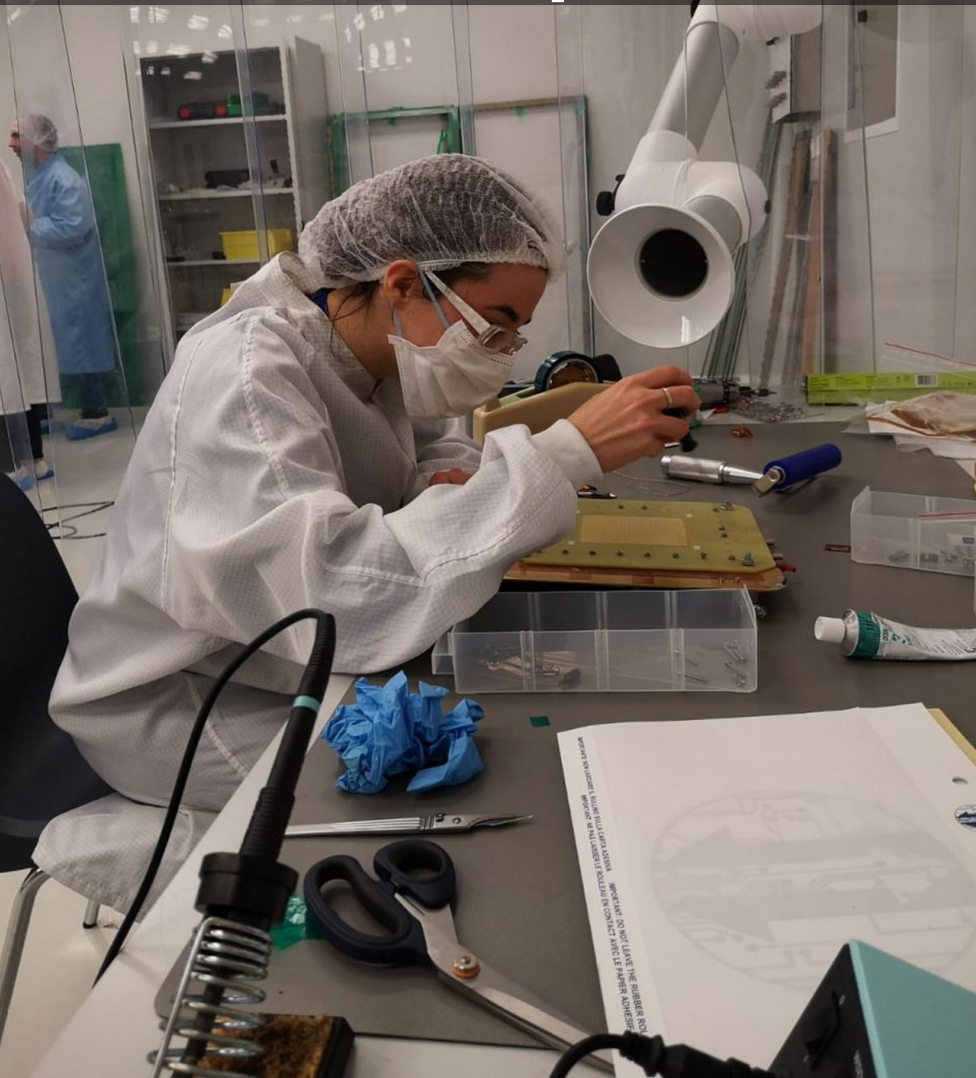


- Acceleratore da **27 km**
 - Per far collidere ad alta energia particelle leggere
- Per produrre **particelle massive**
 - $E=mc^2$ e annichilazione
- Le particelle massive **decadono** in quelle stabili, che riveliamo
- **Eventi rari**, necessari milioni di scontri al secondo

Rivelatori di particelle



Rivelatori di particelle





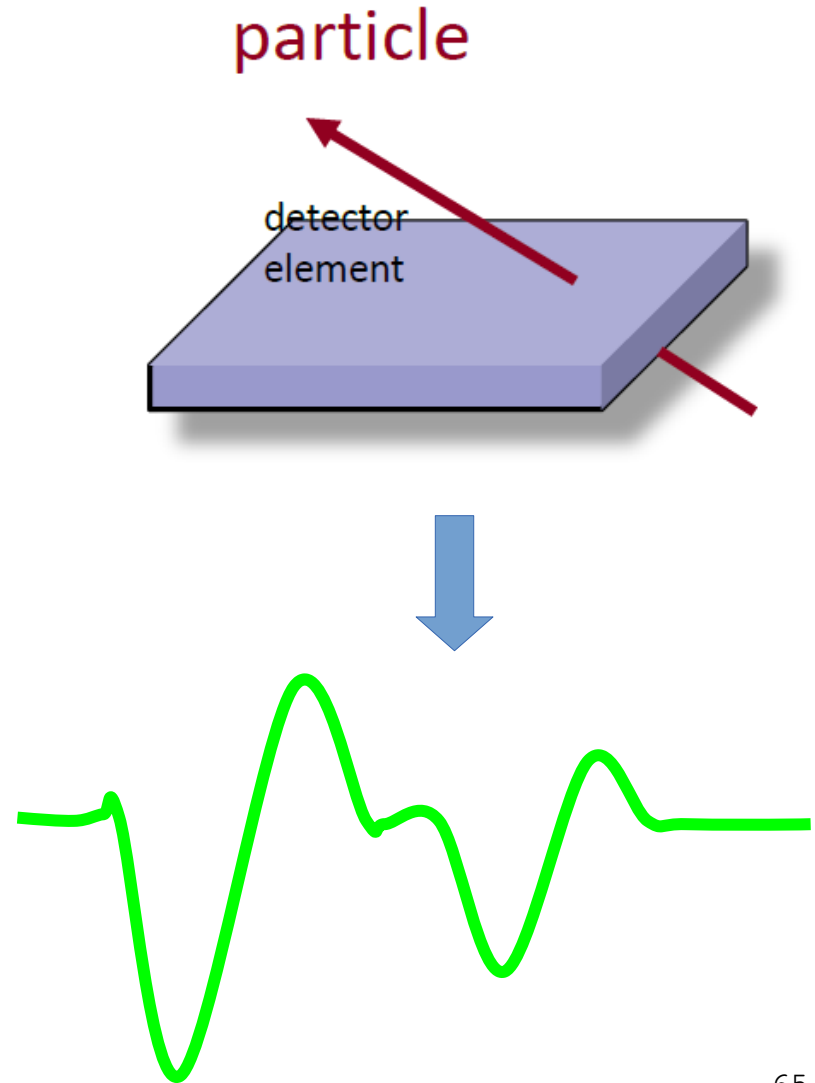
Sempre lui:

“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**

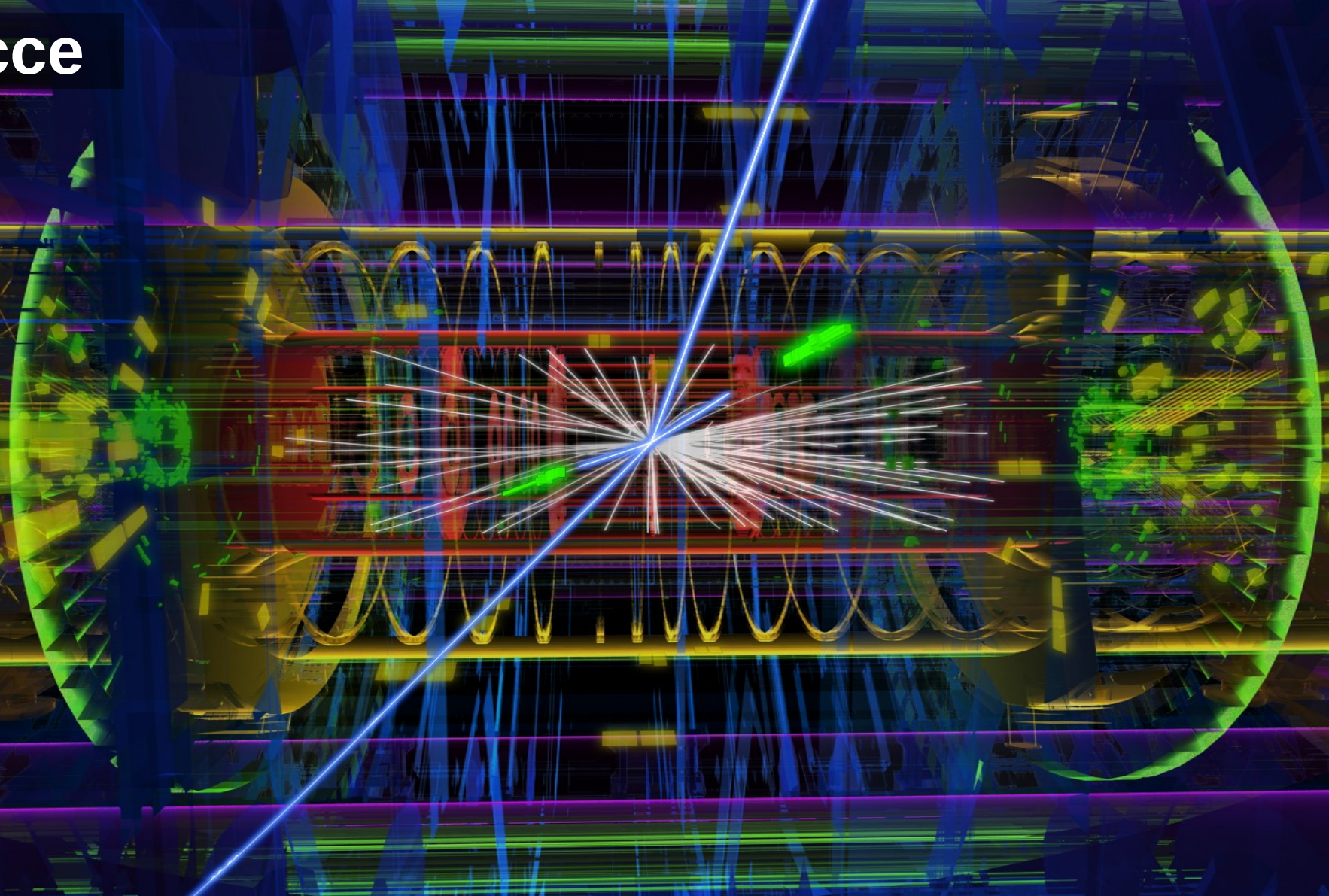


Rivelatori di particelle

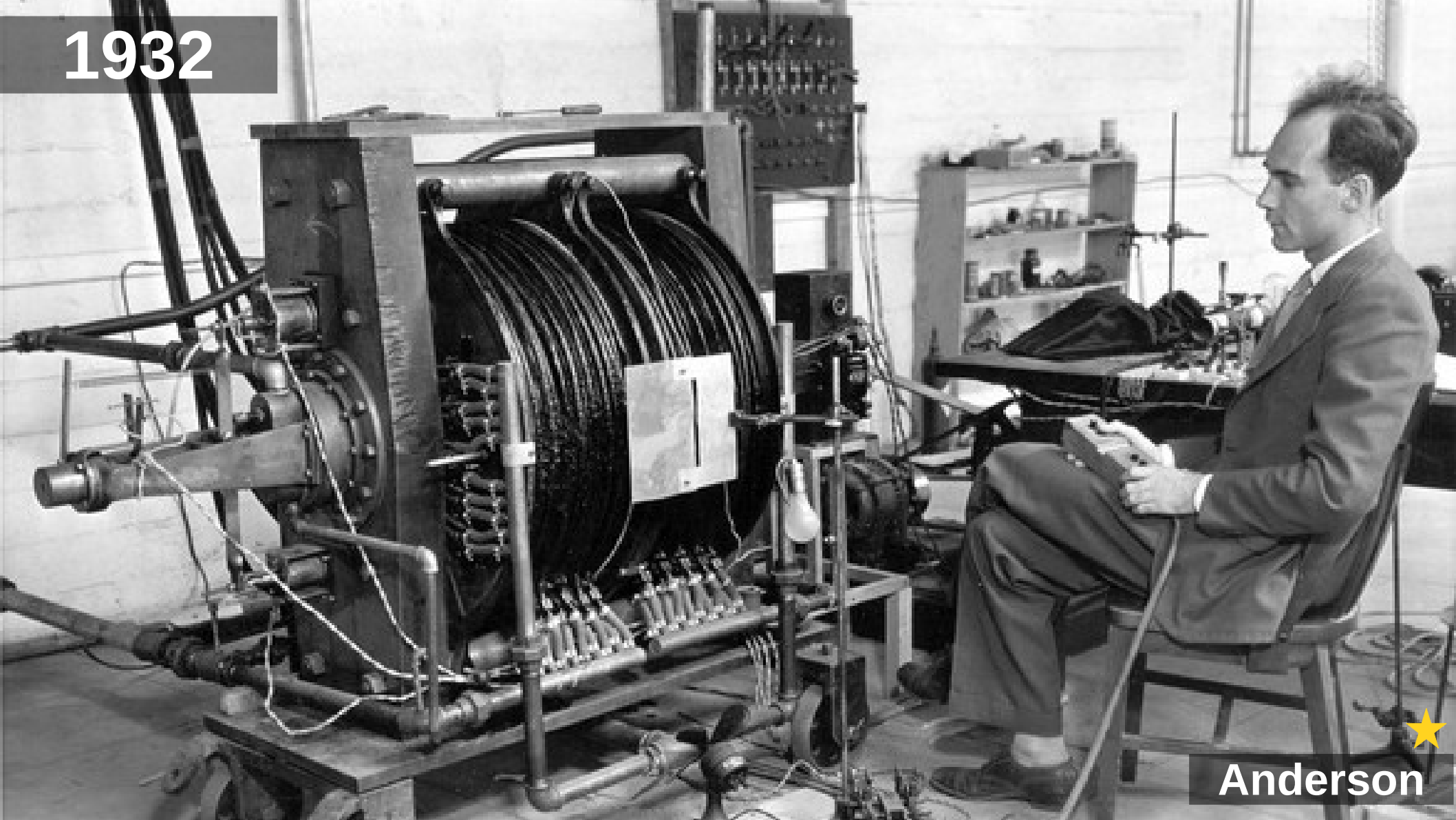


Seguire le scie 

Tracce

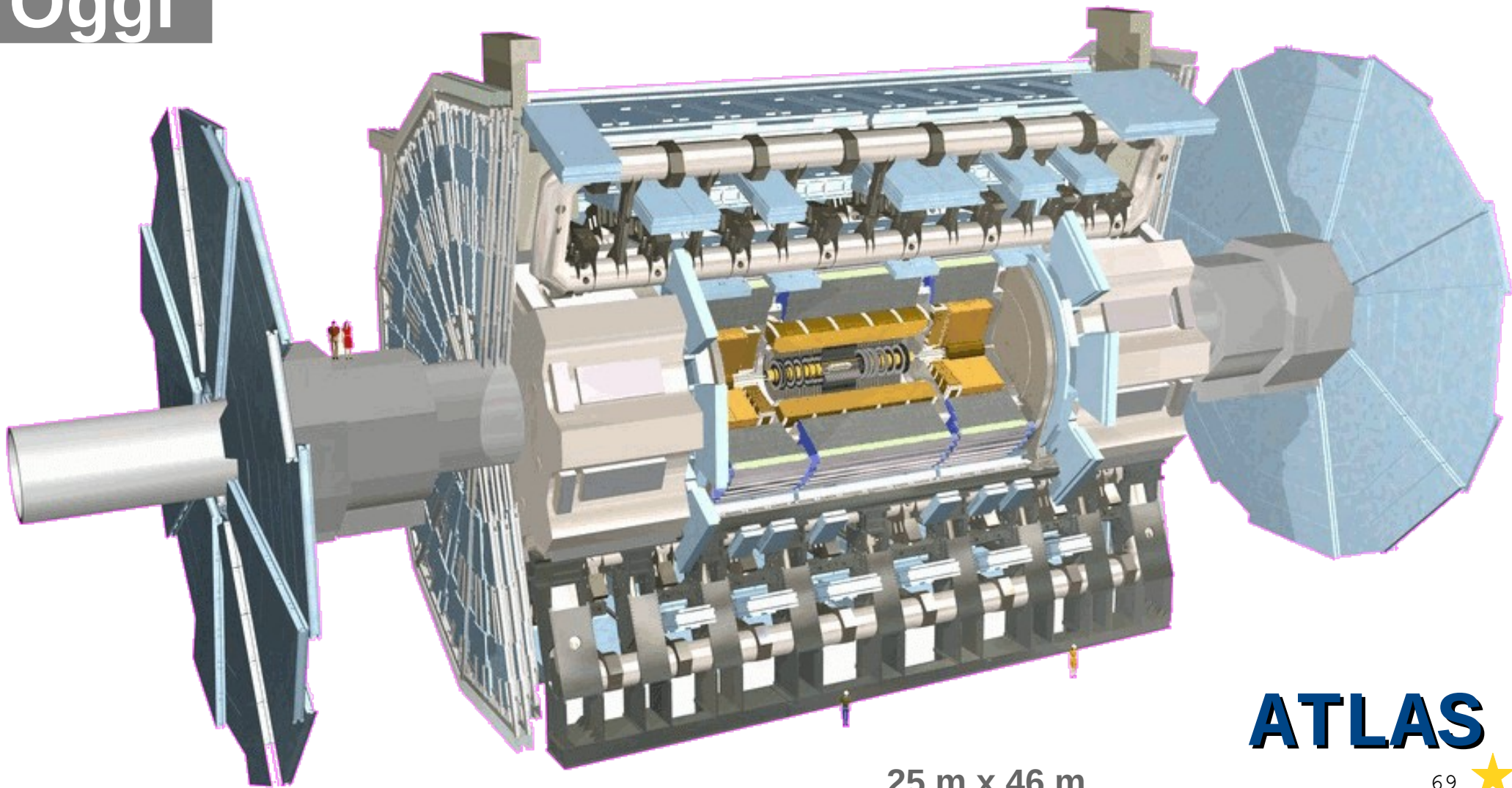


1932



★
Anderson

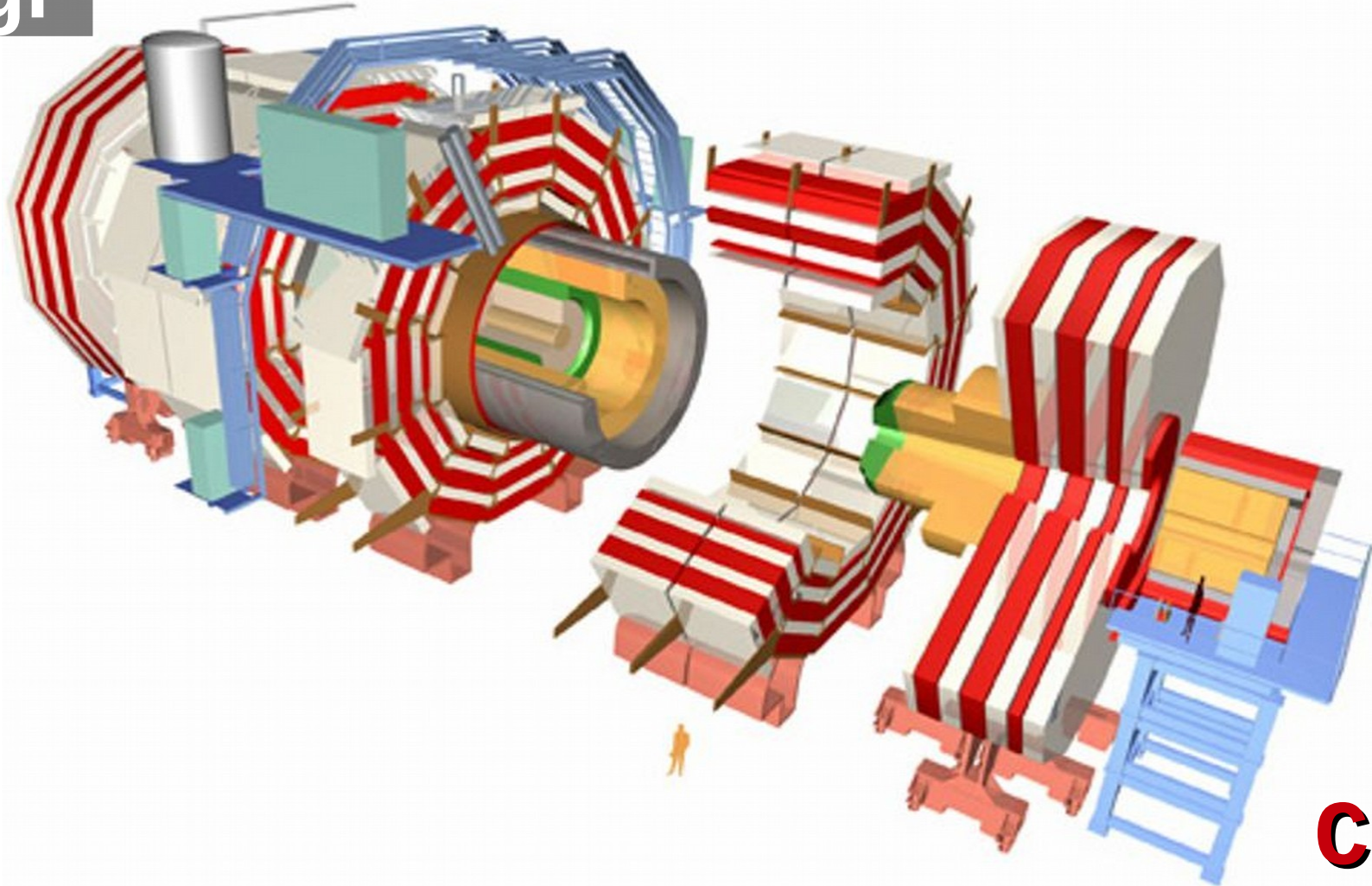
Oggi



25 m x 46 m

ATLAS

Oggi



15 m x 21 m

CMS



Home made



Home made



1996



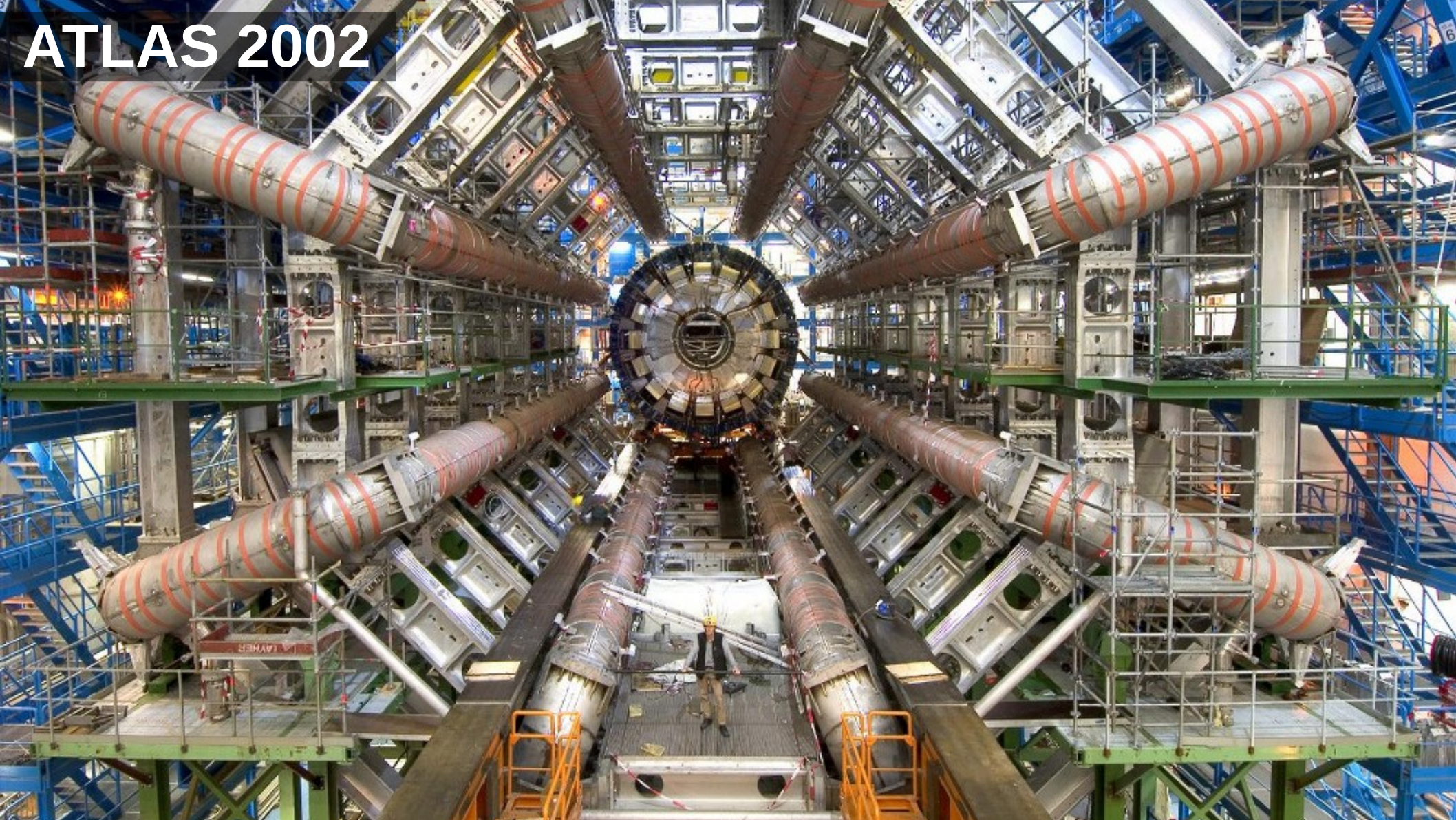
Home made



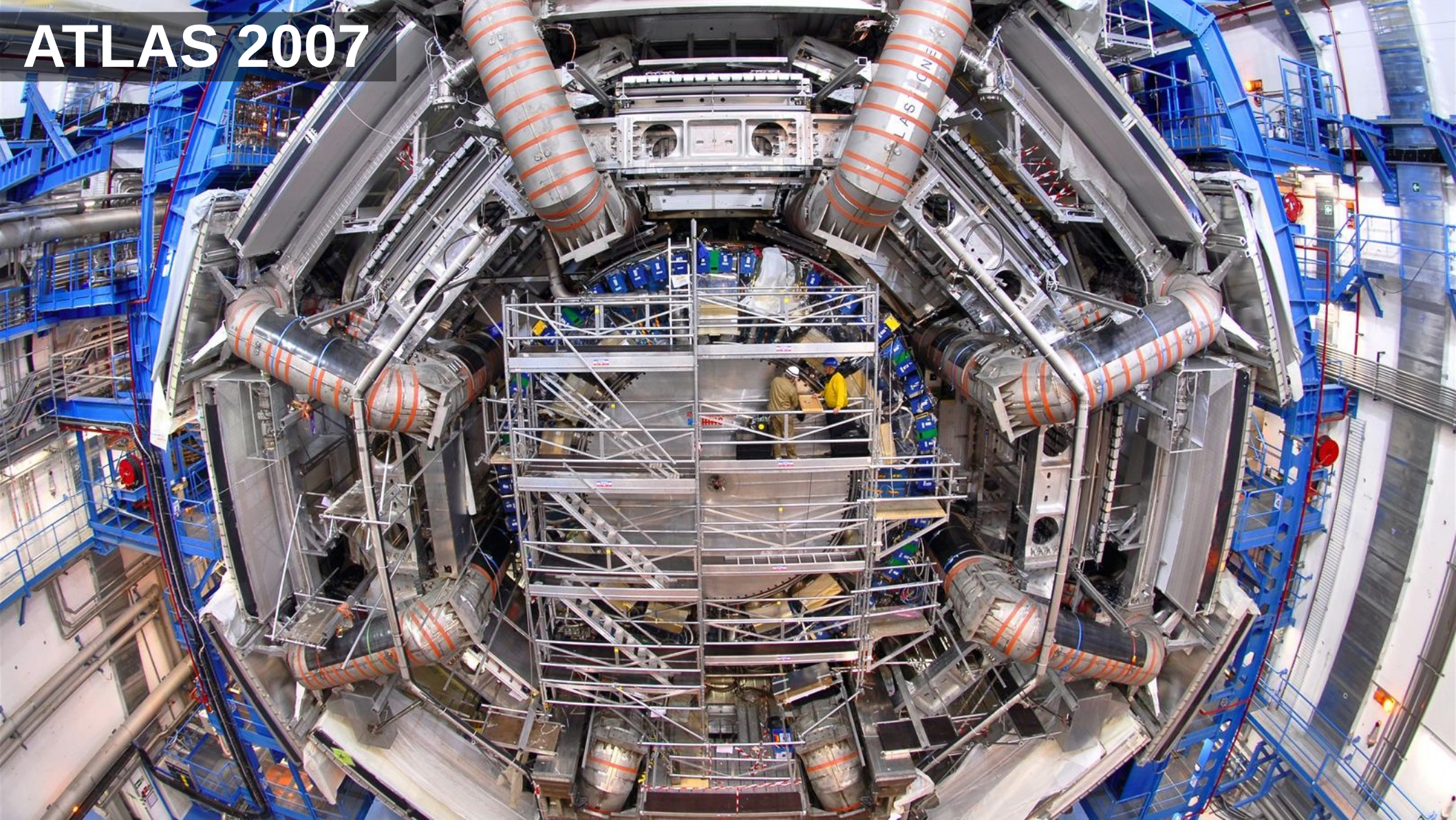
ATLAS 2001



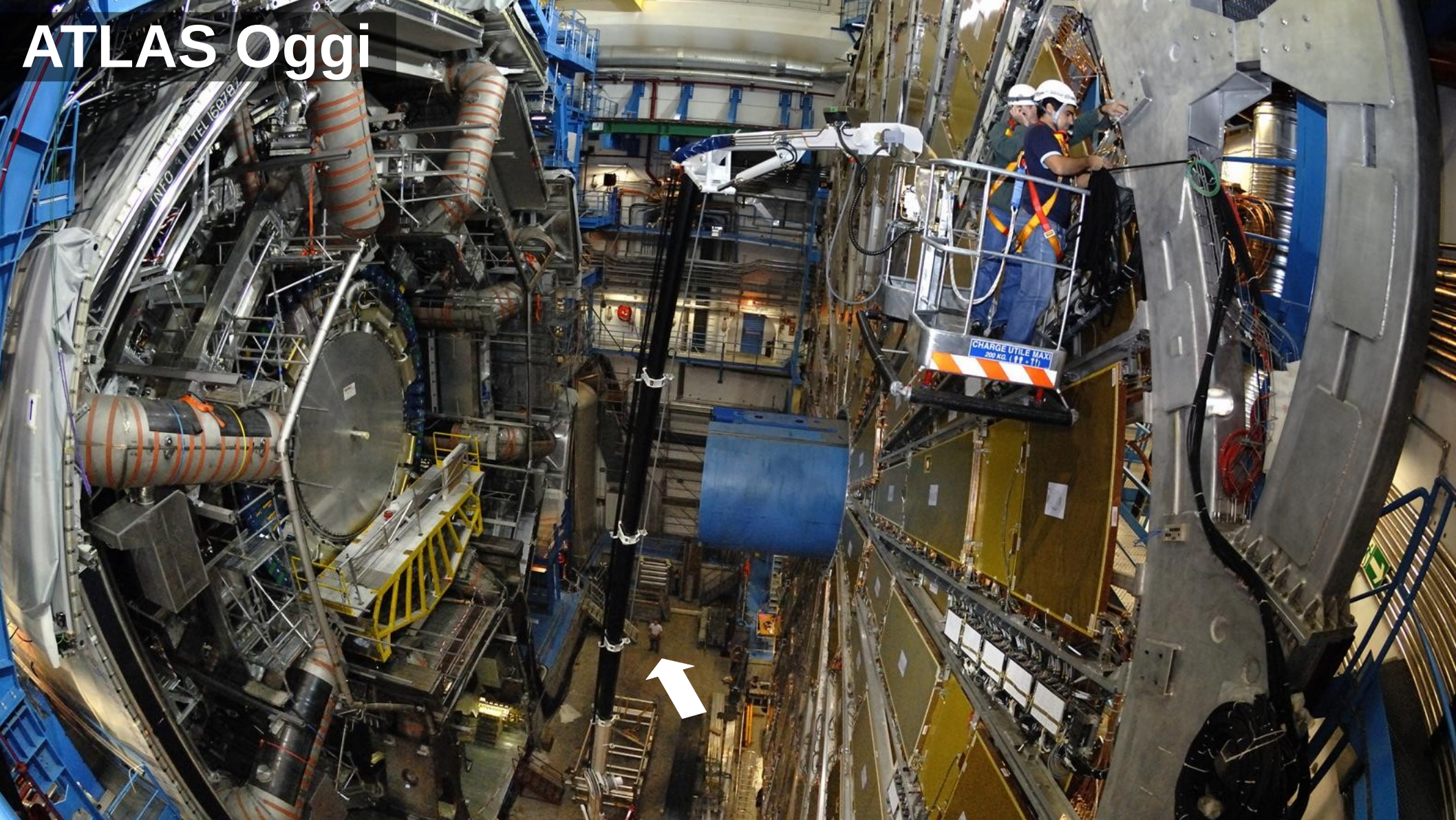
ATLAS 2002



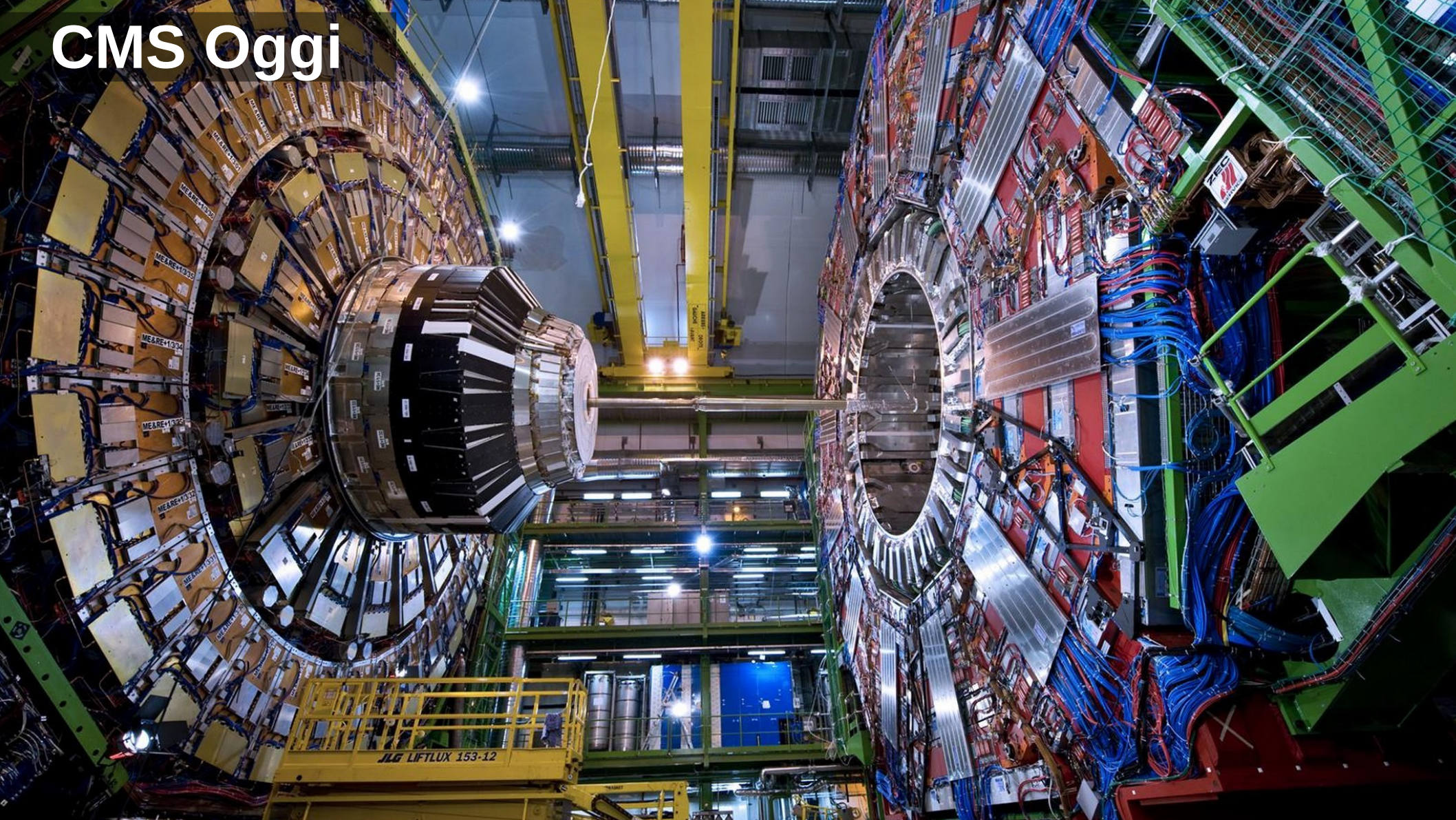
ATLAS 2007



ATLAS Oggi



CMS Oggi



ALICE Oggi





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

Big data

A photograph of a large sand dune under a clear blue sky. The dune is a smooth, golden-brown slope that curves from the left towards the right. A dark shadow is cast on the right side of the dune, indicating the sun is low in the sky. The sky is a deep, clear blue with a few wispy white clouds on the left side.

~10 PB/anno

Analisi dati





CERN
Ginevra

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, Karlsruhe - Stoccarda, GER
- Fermilab - Chicago, USA
- Triumf - Vancouver, CAN
- Brookhaven - Long Island, USA
- Nordic - SVE-FIN-NOR
- Pic - Barcellona, SPA
- Ascc - 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

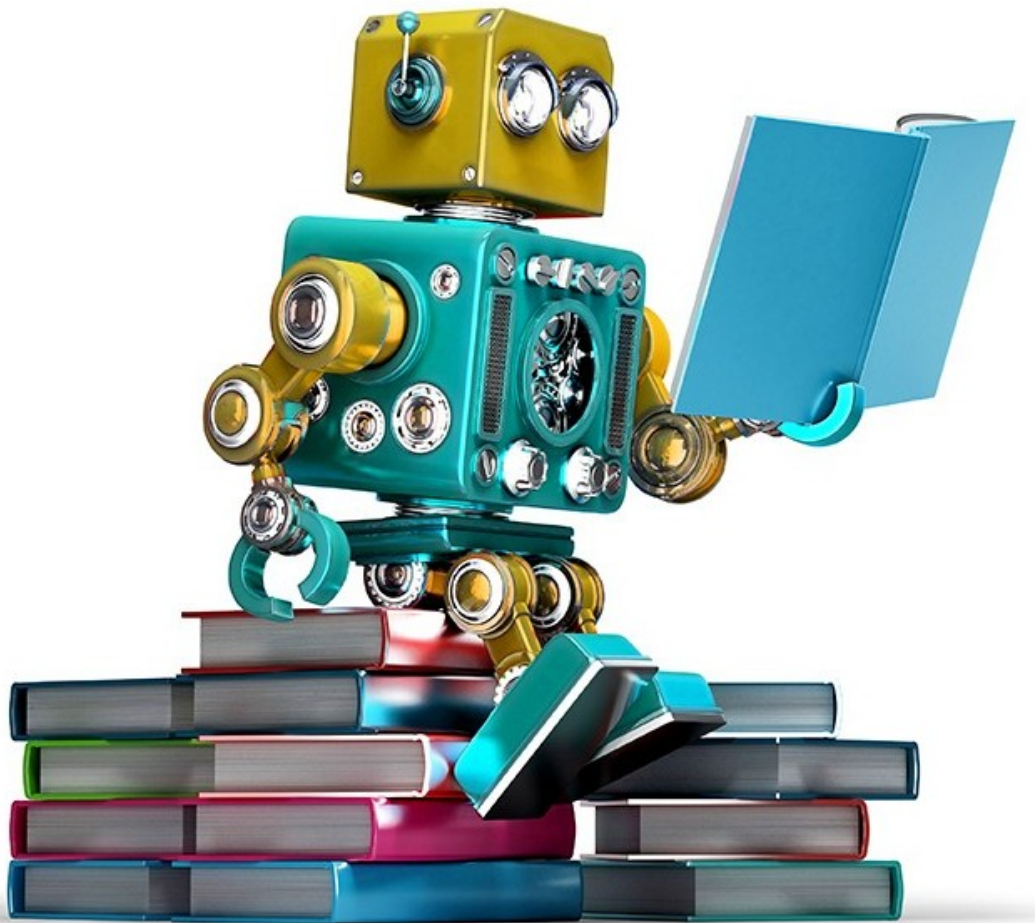


Oltre 10.000
gli utenti che
utilizzano Grid



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>



Organization committee

Balázs Kégl - *Apollon-LAL*
Cécile Germain - *TAC-LRI*

David Rousseau - *Atlas-LAL*
Glen Cowan - *Atlas-RHUL*

Isabelle Guyon - *Chaleam*
Claire Adam-Bourdarios - *Atlas-LAL*

Advisory committee

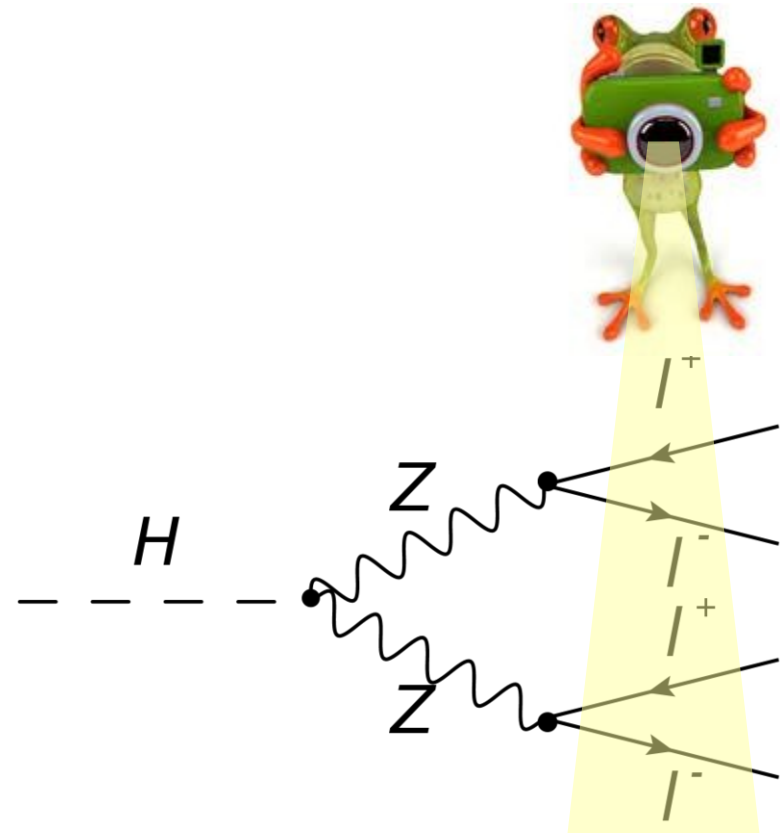
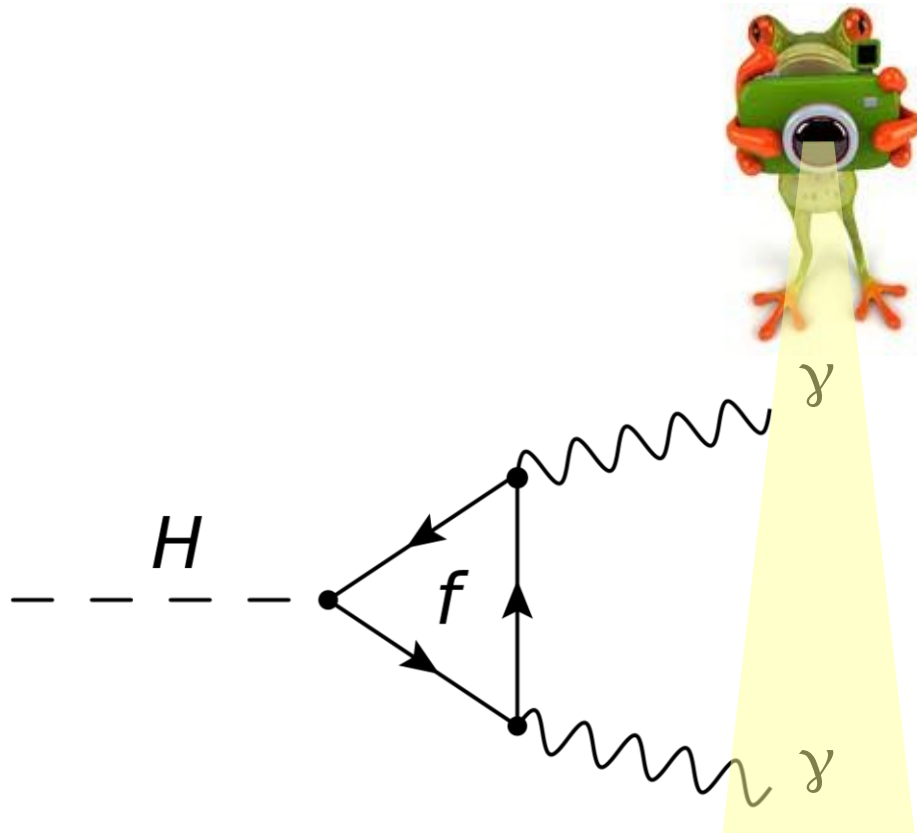
Thorsten Wengler - *Atlas-CERN*
Andreas Hoecker - *Atlas-CERN*

Joerg Stelzer - *Atlas-CERN*
Marc Schoenauer - *INRIA*

Ricerca bosone di Higgs

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

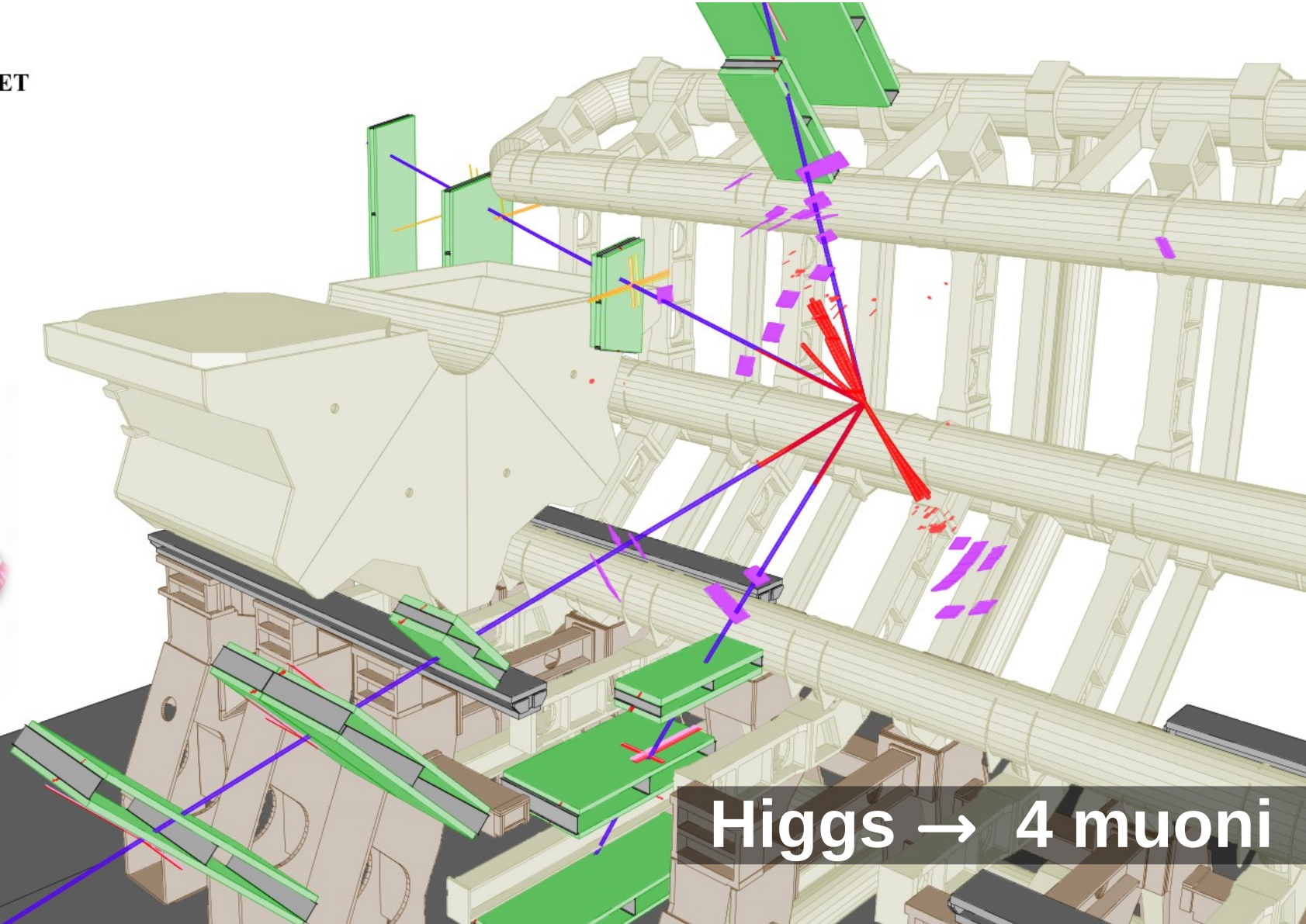
- Identificato partendo dai prodotti del suo decadimento



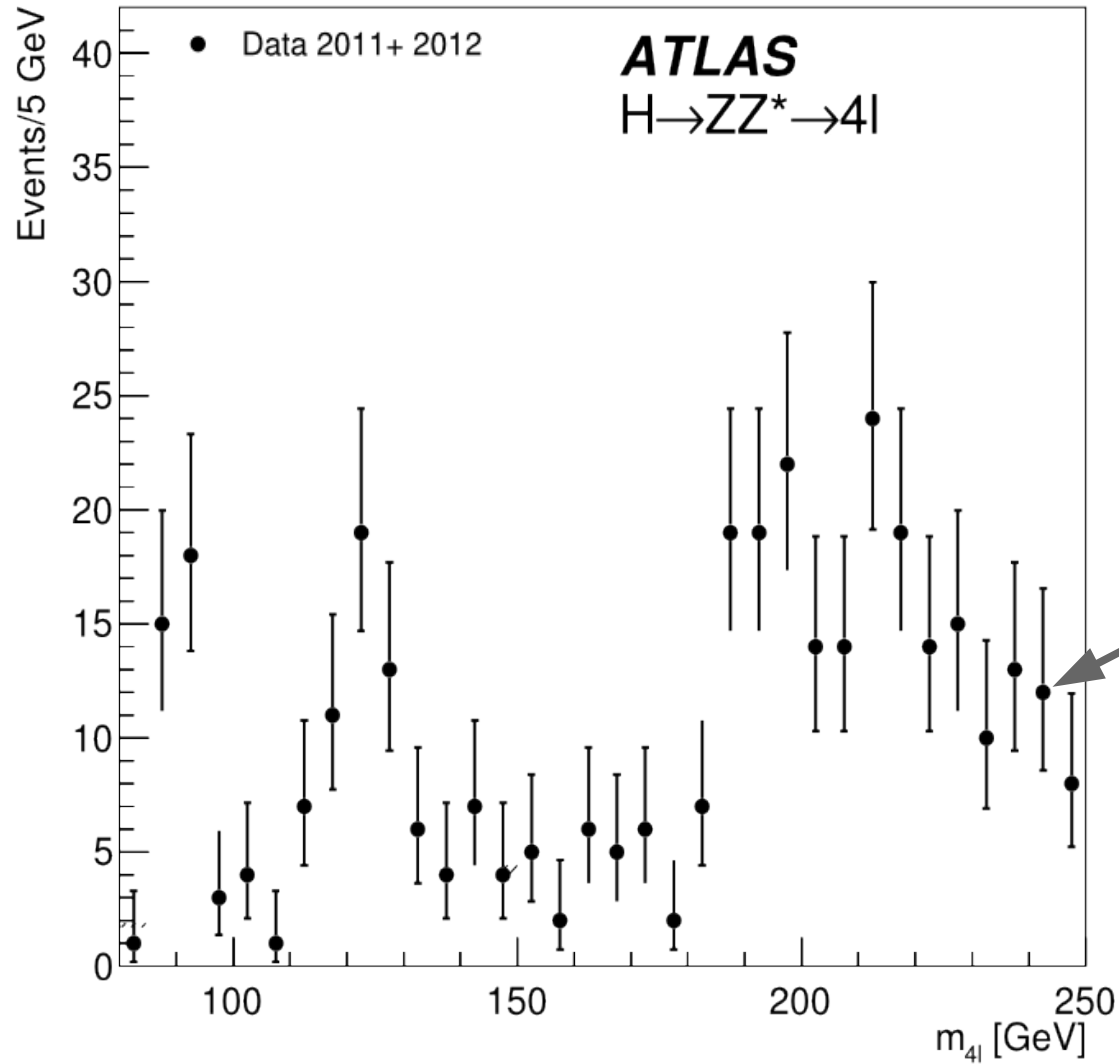
Run Number: 189280,
Event Number: 143576946
Date: 2011-09-14, 11:37:11 CET

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

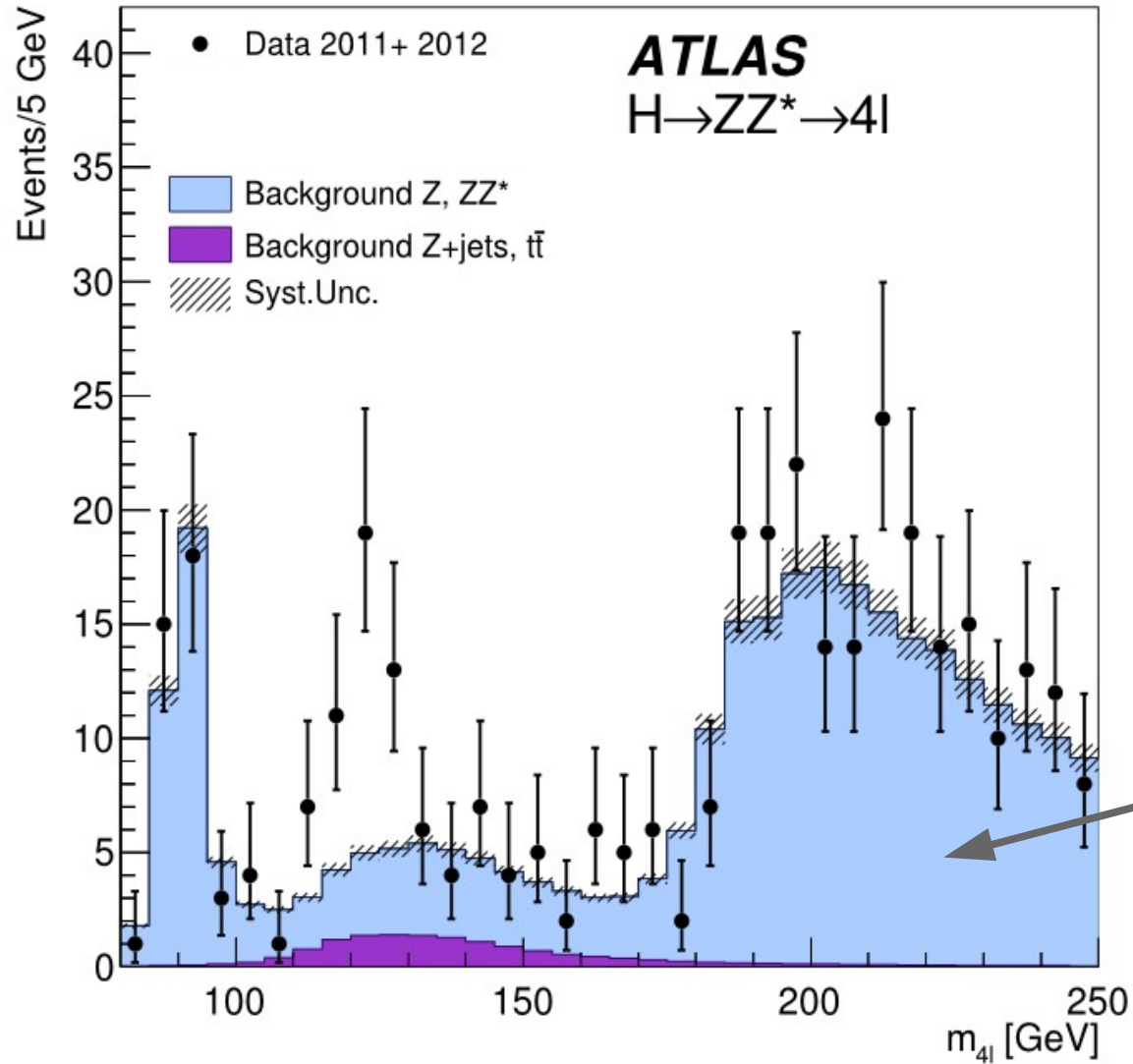
Muon: blue
Cells: Tiles, EMC



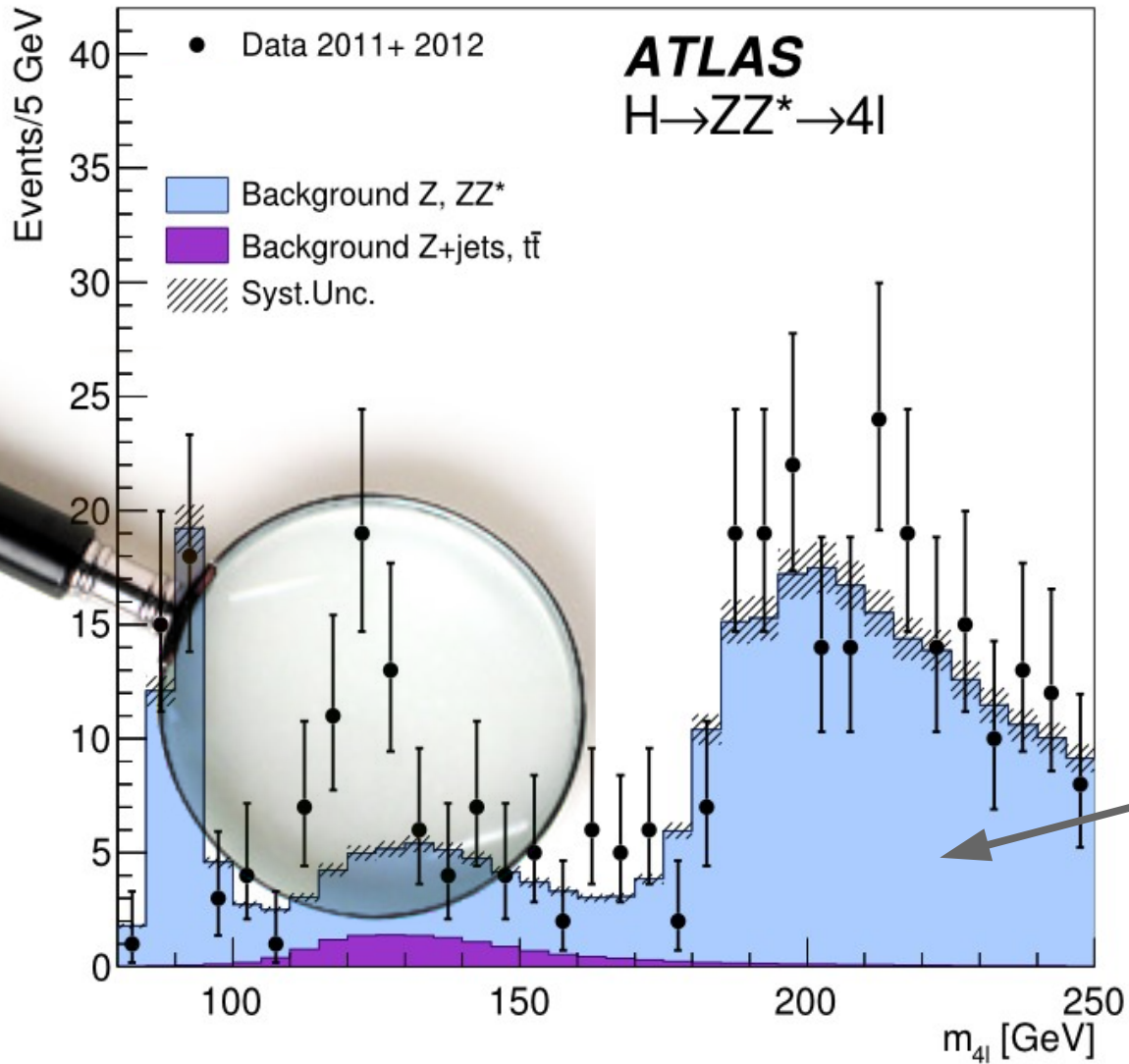
Higgs \rightarrow 4 muoni



**Dati
sperimentali**

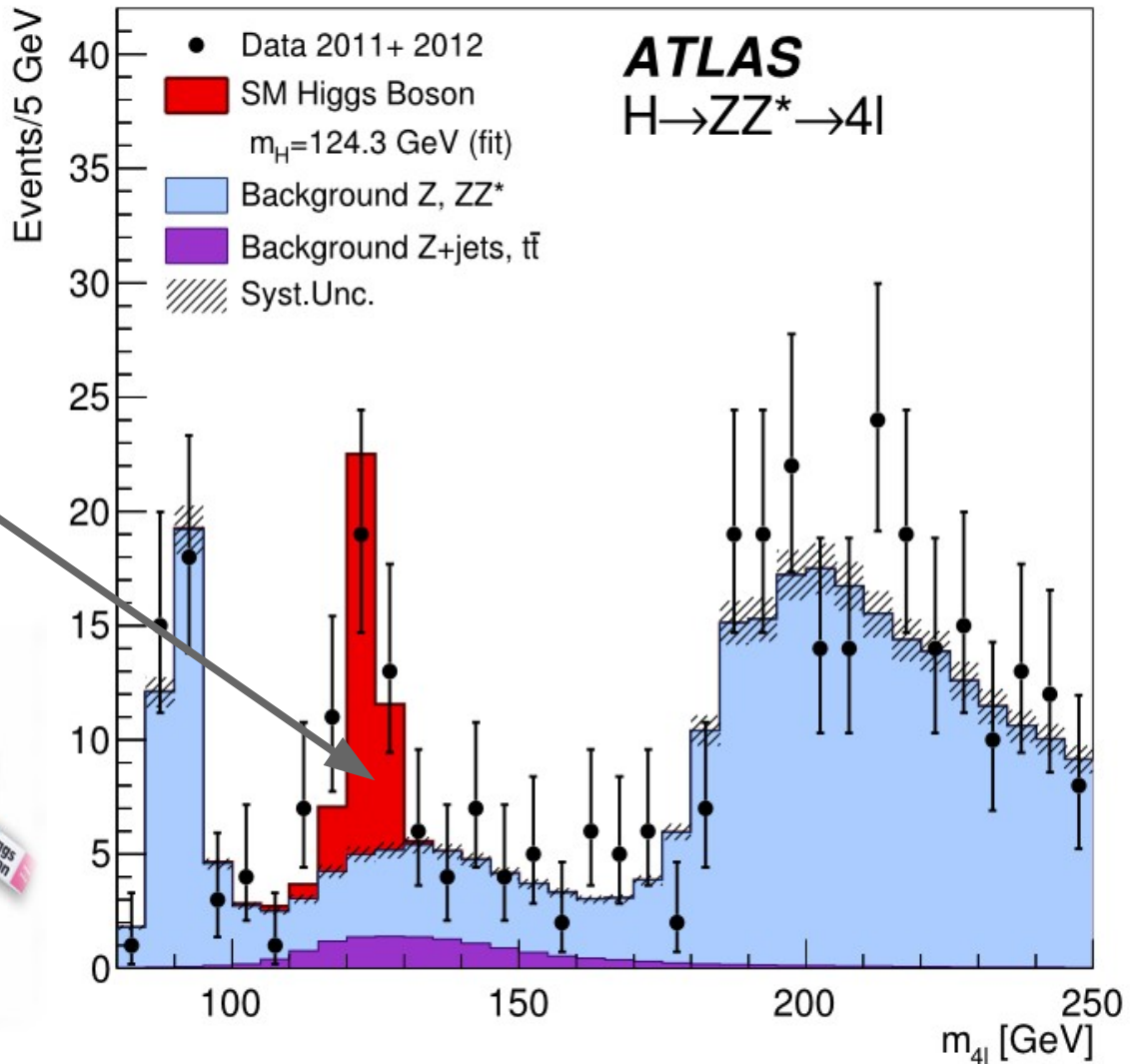


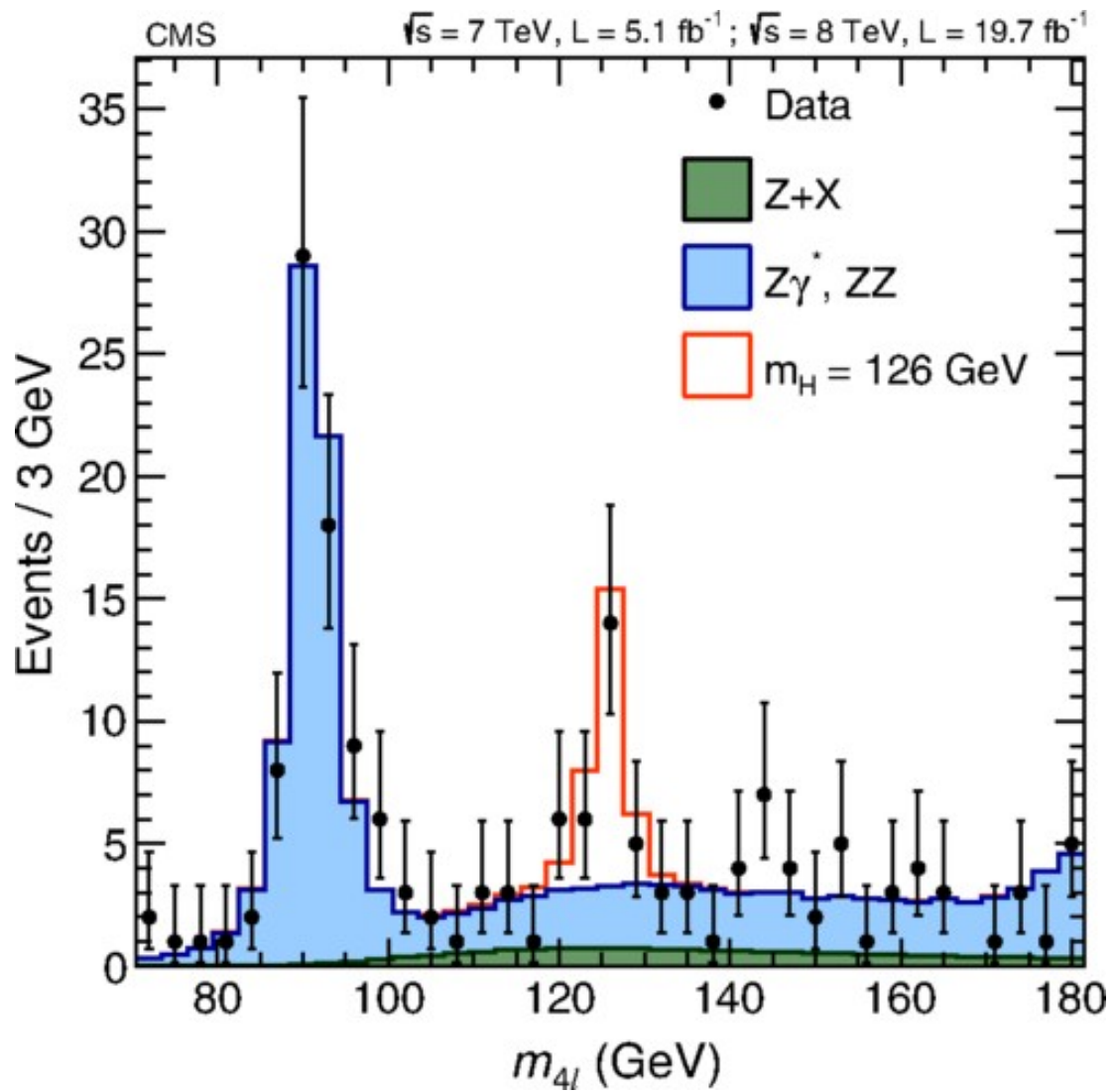
Fondo atteso



Fondo atteso

Segnale
atteso di
Higgs





Bosone di Higgs



Prof. Peter Higgs



1964



2012



Premio Nobel 2013



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”

A photograph of George Clooney in a dark pinstriped suit, looking directly at the camera with a slight smile. He is leaning forward with his hands on a dark surface.

Higgs boson. What else?



u	c	t	γ	g	g
d	s	b	Z^0	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^0

g

g

ν_e

ν_μ

ν_τ

W^+

g

g

e

μ

τ

W^-

g

h



Cosa sappiamo?



Cosa sappiamo? Poco

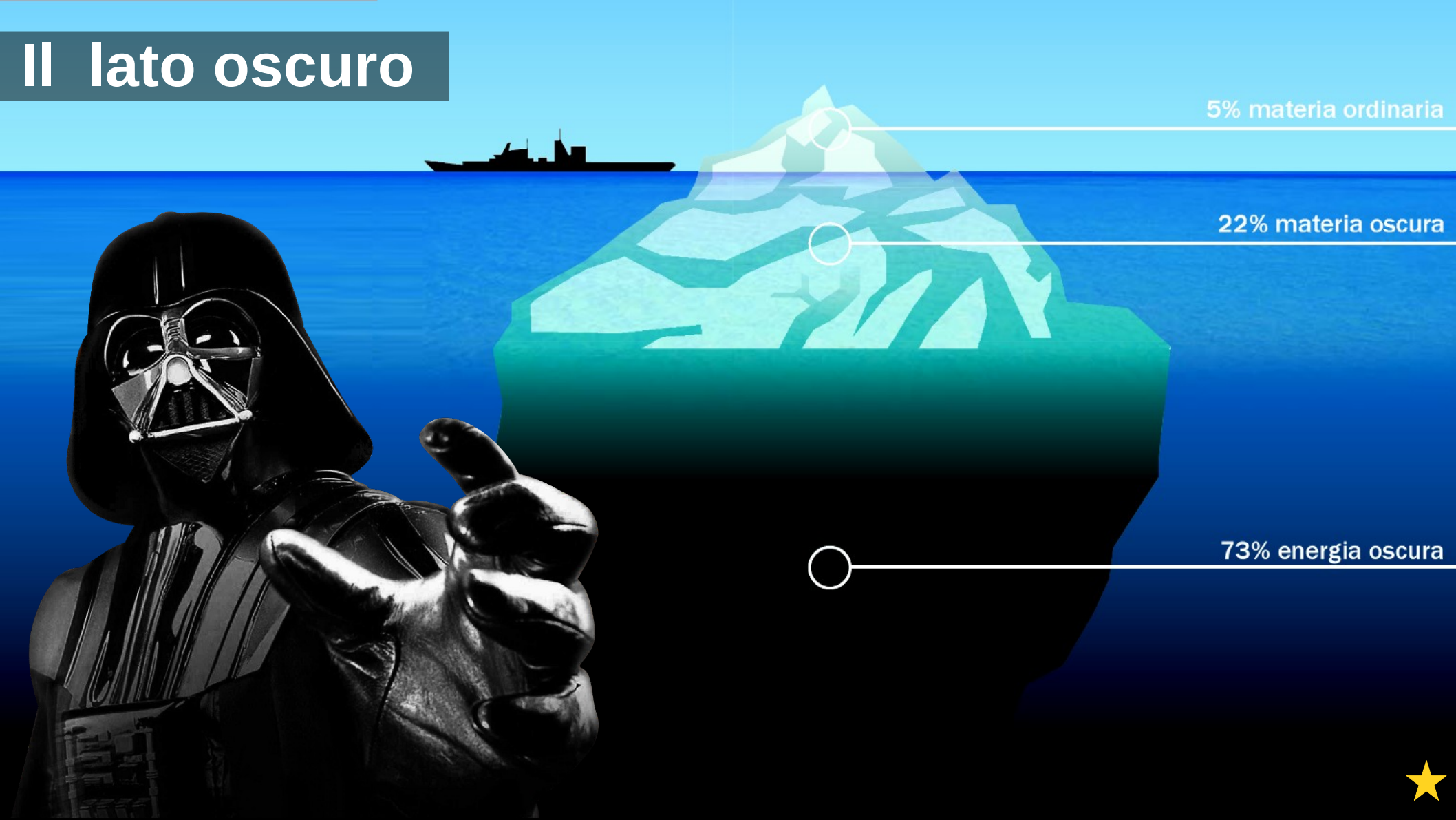
- I quark sono **indivisibili**?
- Dov'è finita l'antimateria?
- Esistono altre **dimensioni**?
- Esiste una teoria che unisca tutte le forze fondamentali?
- Cos'è la **materia oscura** ?
- Cos'è l' **energia oscura** ?



Il dubbio è conoscenza



Il lato oscuro



5% materia ordinaria

22% materia oscura

73% energia oscura



La massa mancante

A composite image of a galaxy, likely the Andromeda Galaxy, showing a central bright core and a diffuse, elongated structure. The image is overlaid with a dark, semi-transparent region that represents the distribution of dark matter, which is much more extensive than the visible stars and gas. The background is filled with numerous stars of various colors, including yellow, blue, and red.

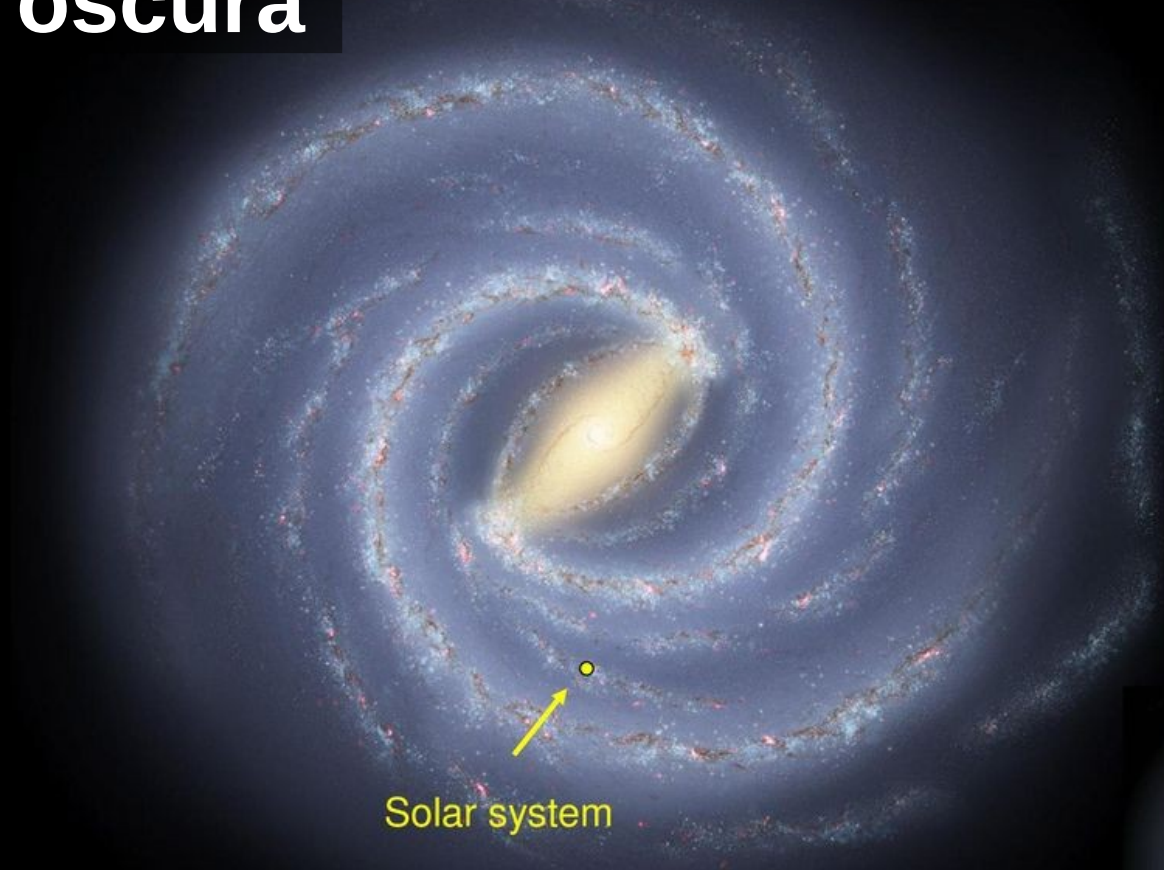
'30: Ian Ort, Fritz Zwicky

'60: Vera Rubin



← 100,000 light years →

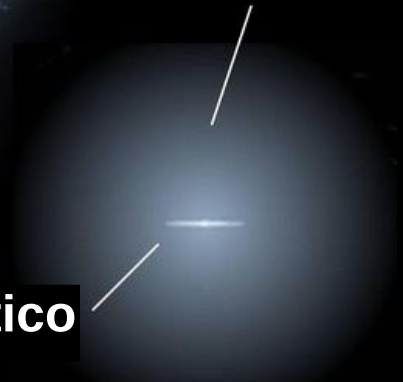
Materia oscura

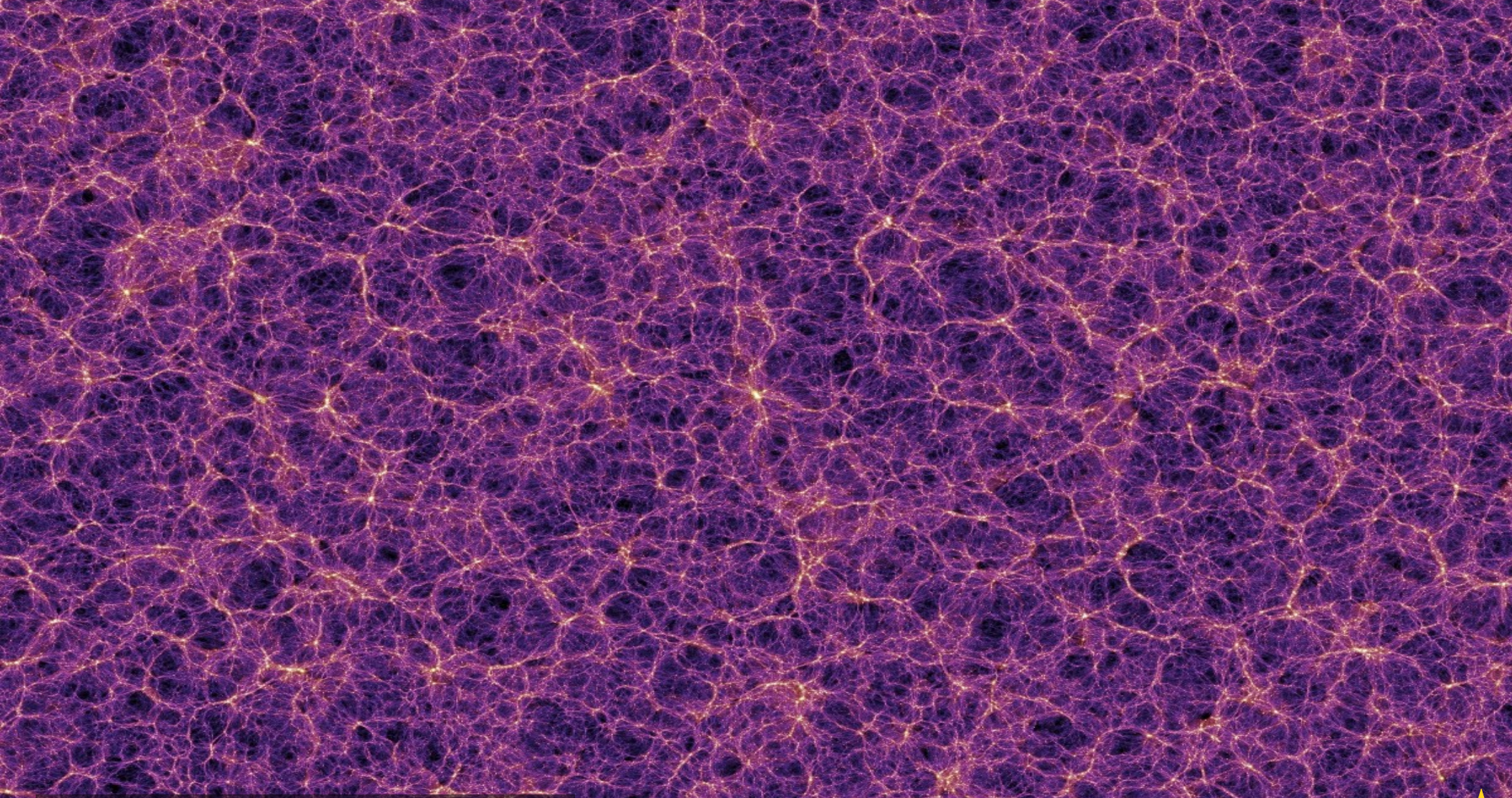


Solar system

Materia oscura

Disco galattico





Millenium simulation © Max Plank



INFLAZIONE

RADIAZIONE COSMOLOGICA DI FONDO

ESPANSIONE ACCELERATA
DALLA ENERGIA OSCURA

UNIVERSO BUIO
PRIME STELLE

BIG BANG

FORMAZIONE GALASSIE,
STELLE, PIANETI ECC.

materia oscura

materia ordinaria

Storia dell'universo

380.000 anni
dopo il Big Bang

420 milioni di anni
dopo il Big Bang

9 miliardi di anni
dopo il Big Bang

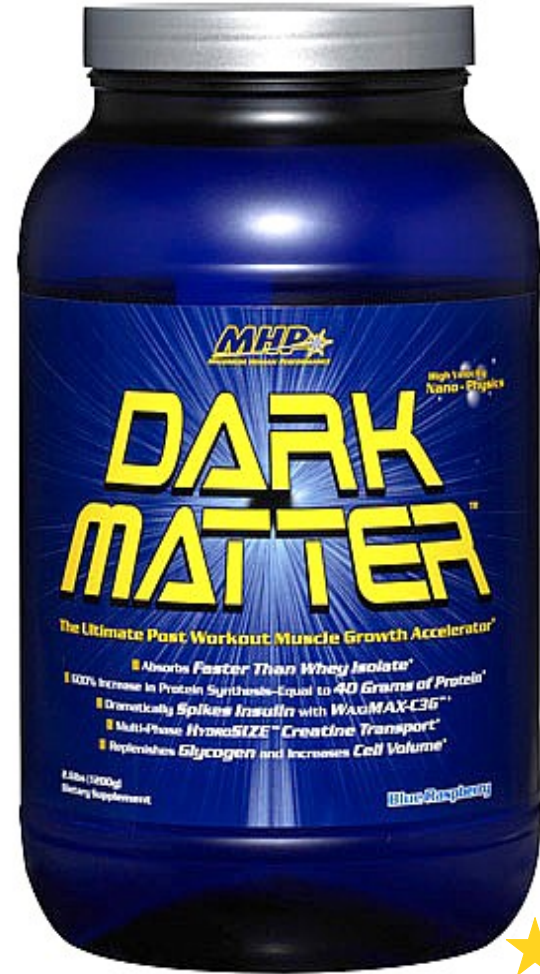
13,7 miliardi di anni
dopo il Big Bang

OGGI

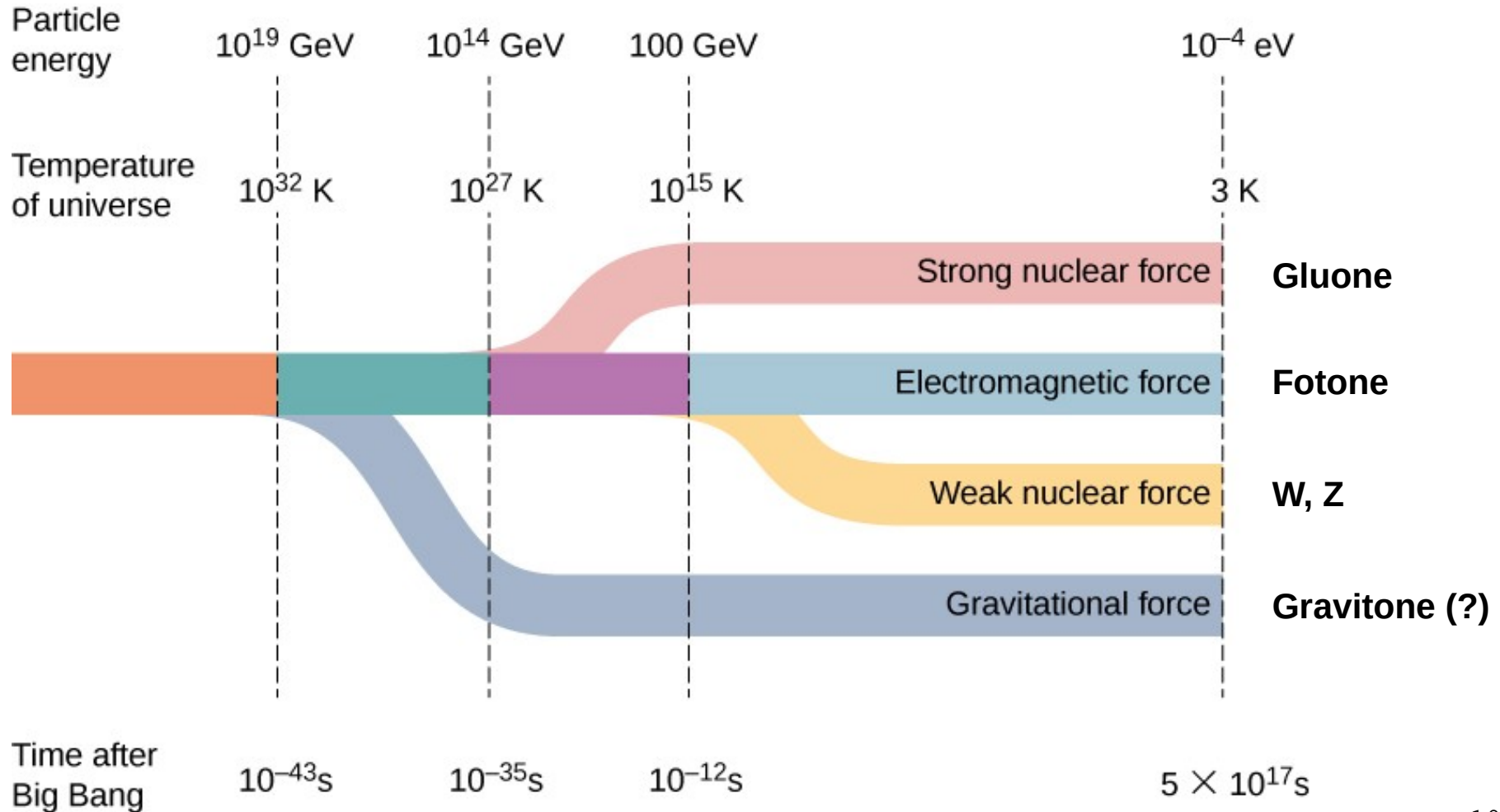


Materia oscura

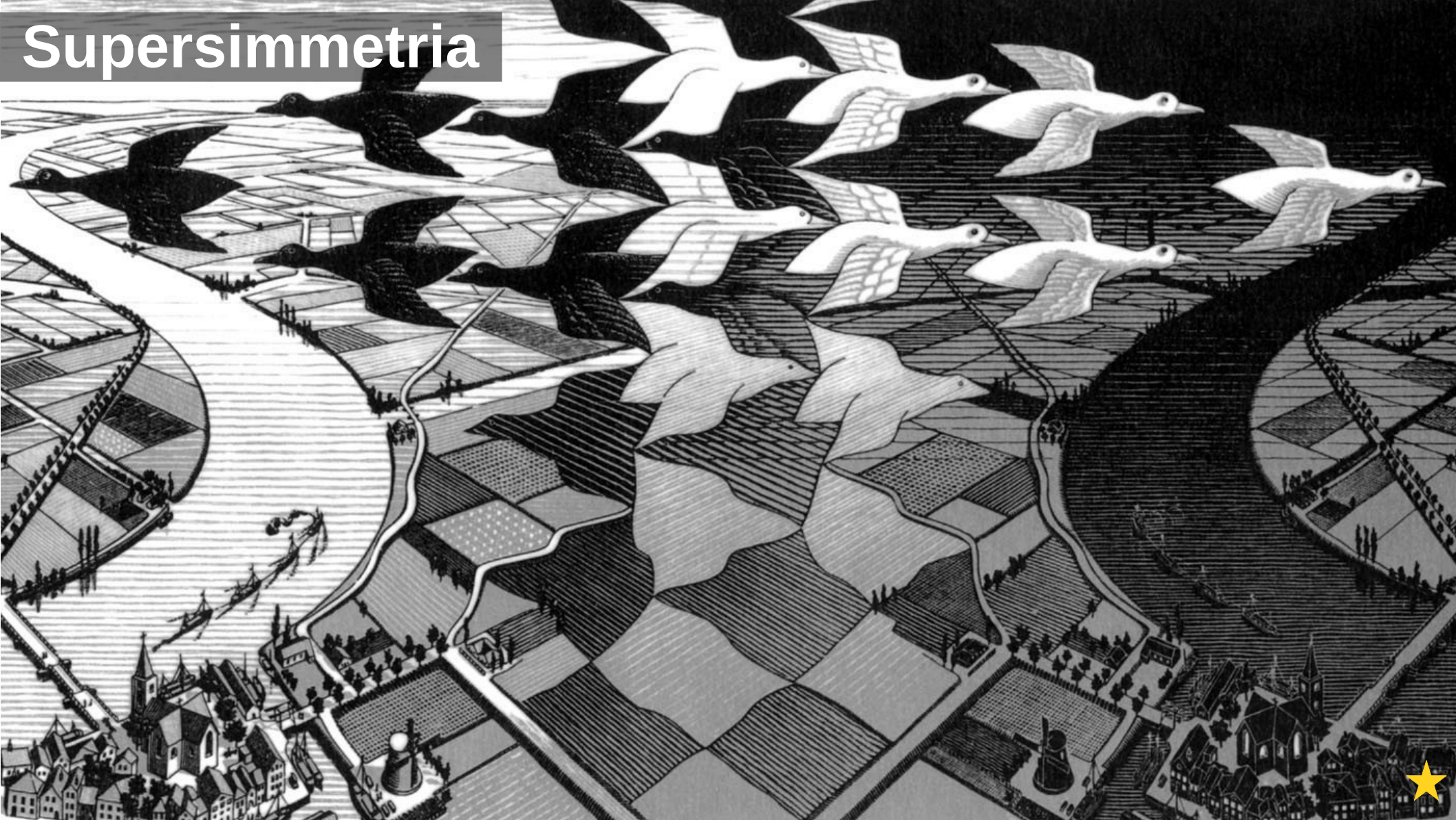
- **Permea** lo spazio
- Interagisce solo **gravitazionalmente**
- Seme per formazione **galassie**
- **Non compatibile** con il modello standard delle particelle elementari
 - Possibili spiegazioni nelle teorie di unificazione delle forze



Teorie di unificazione

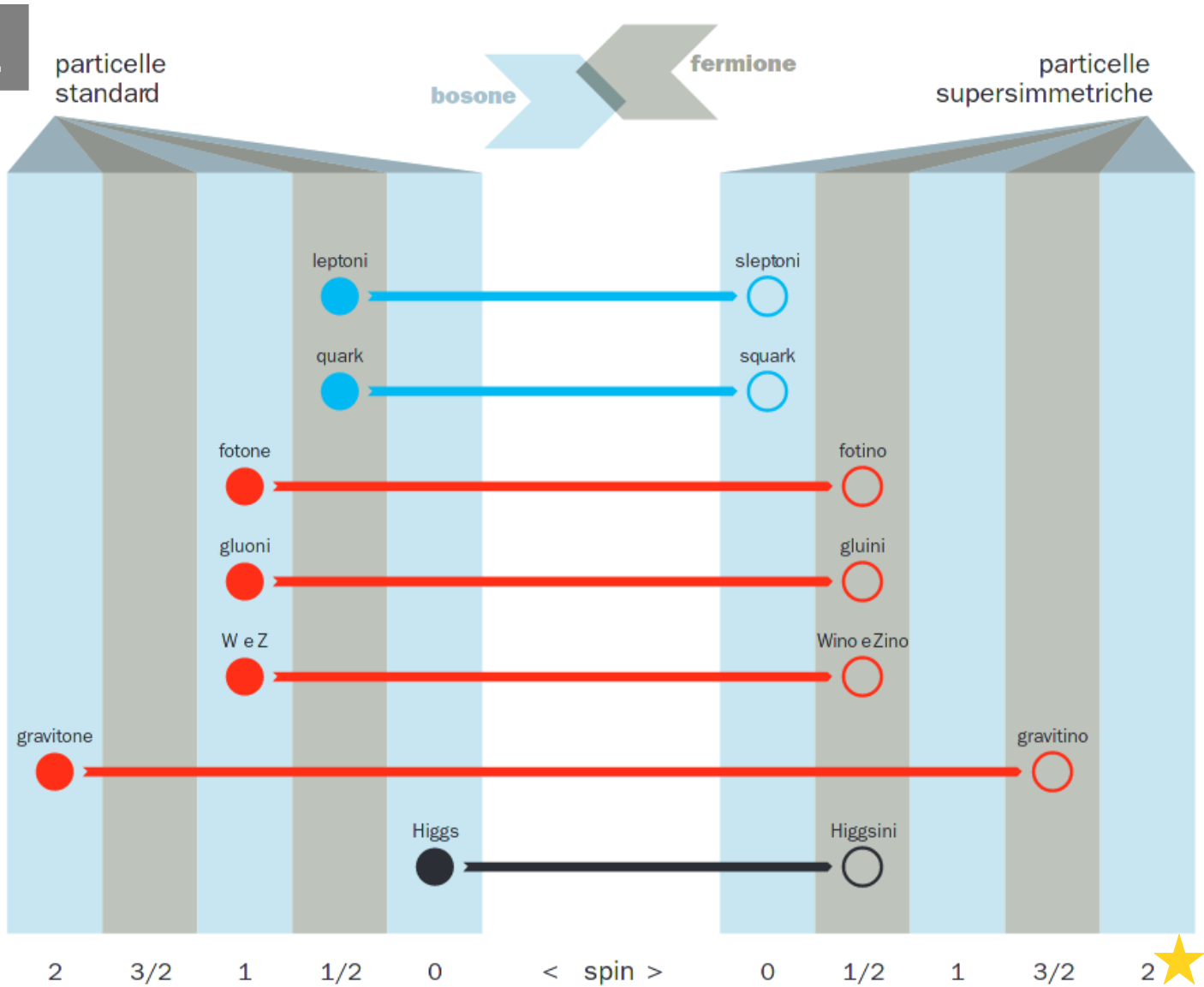


Supersimmetria



Supersimmetria

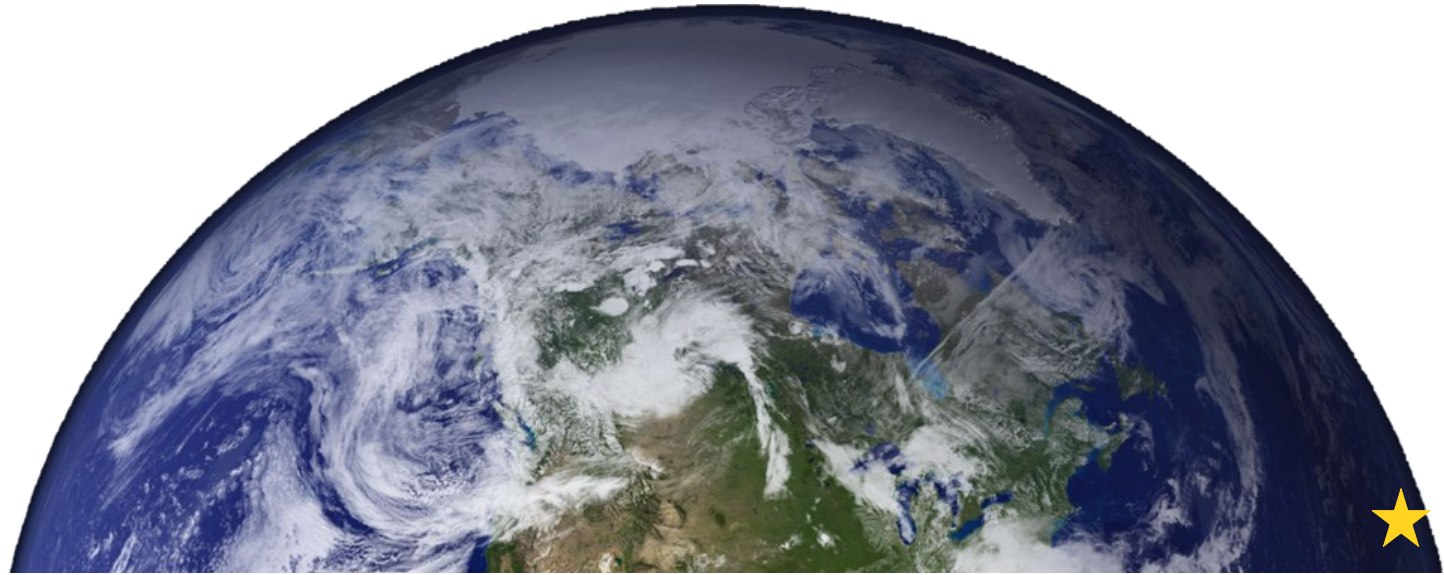
- materia
- mediatori
- massa



La gravità è ?



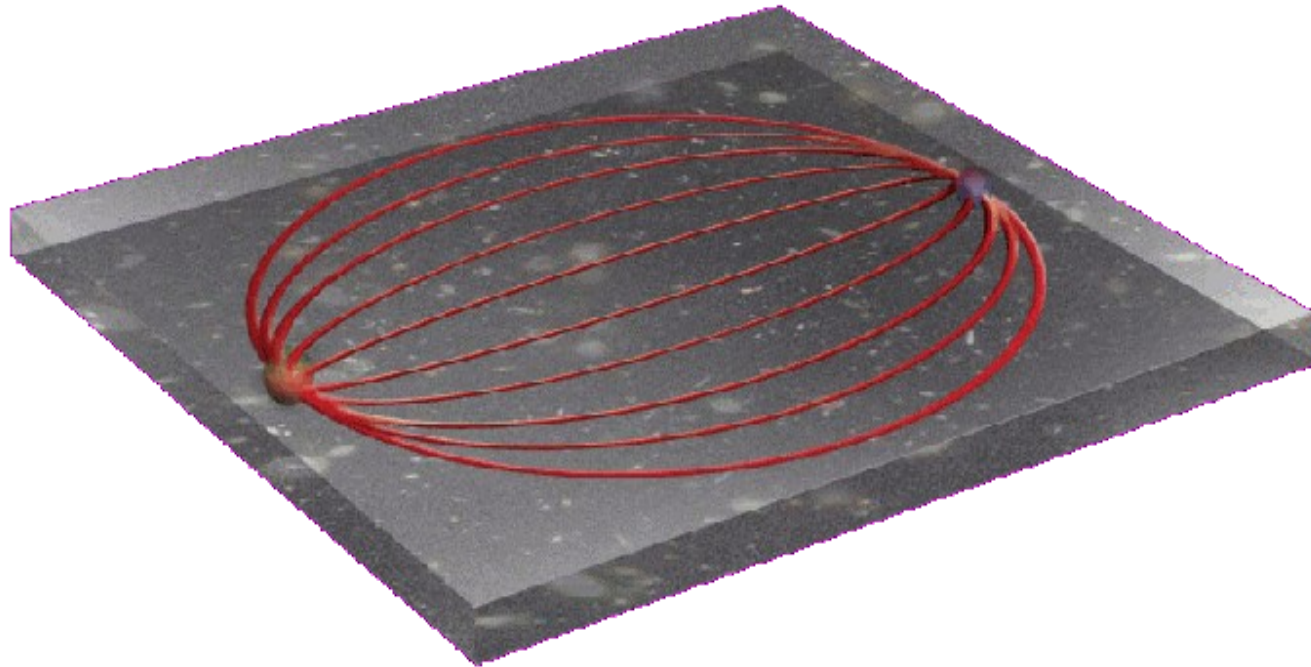
La gravità è **debole!**



Dimensioni aggiuntive?

Potrebbero spiegare debolezza forza gravitazionale

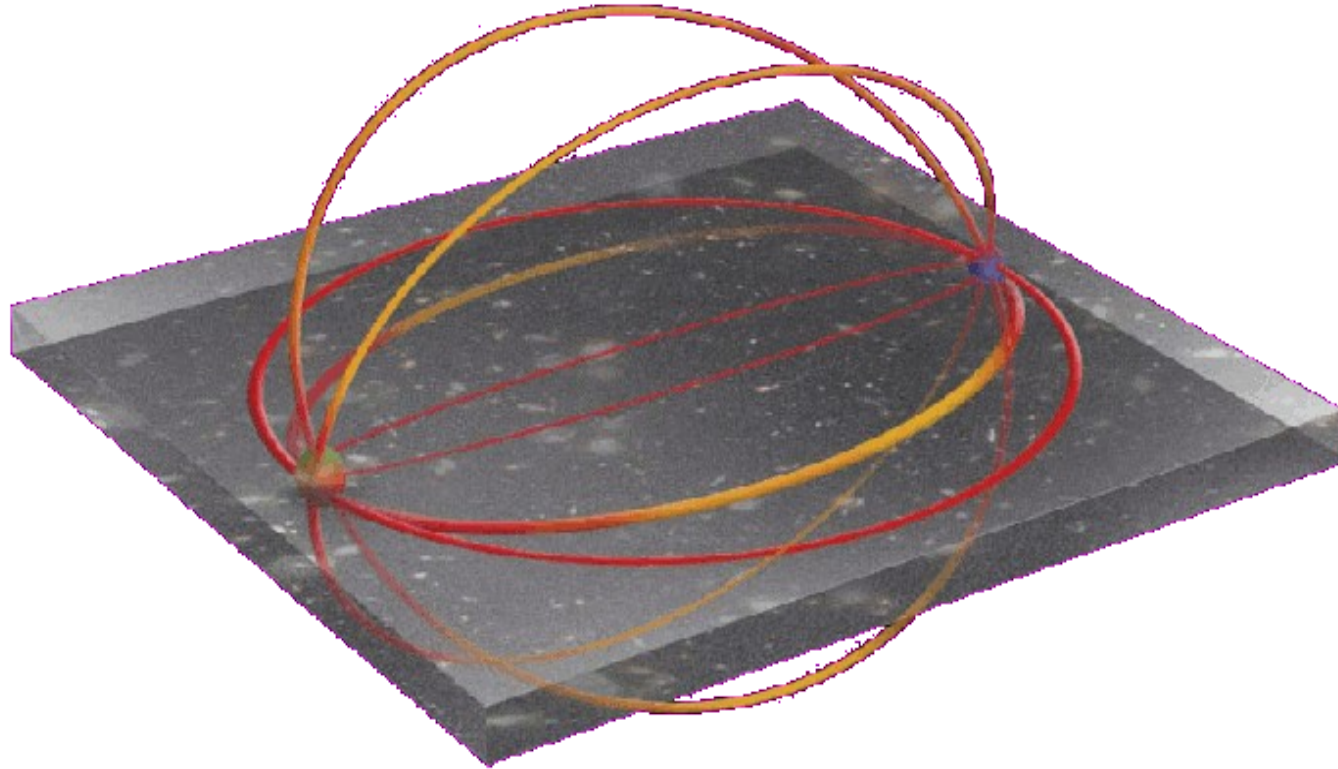
- Le altre forze sono **confinata** in 3D



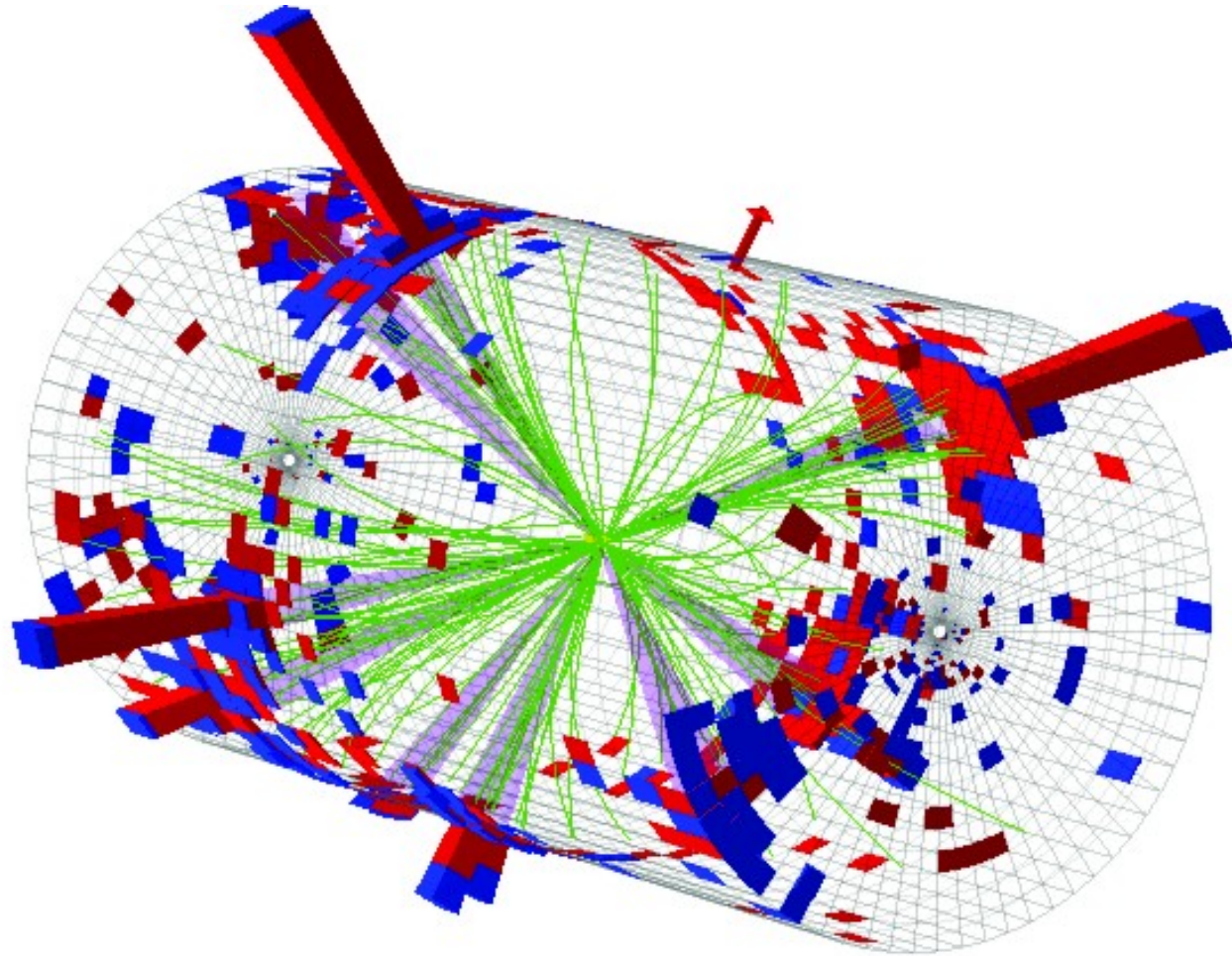
Dimensioni aggiuntive?

Potrebbero spiegare debolezza forza gravitazionale

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



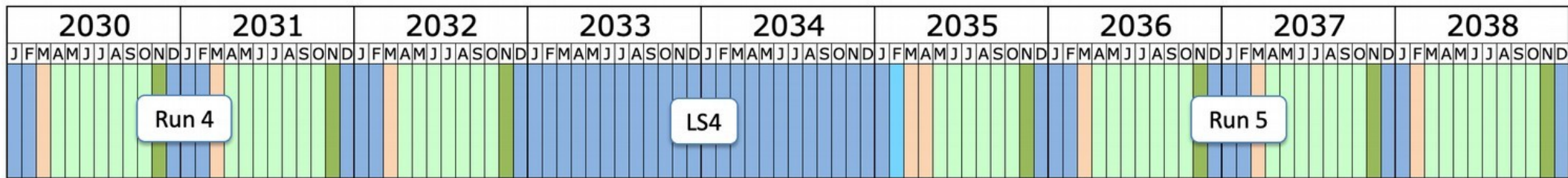
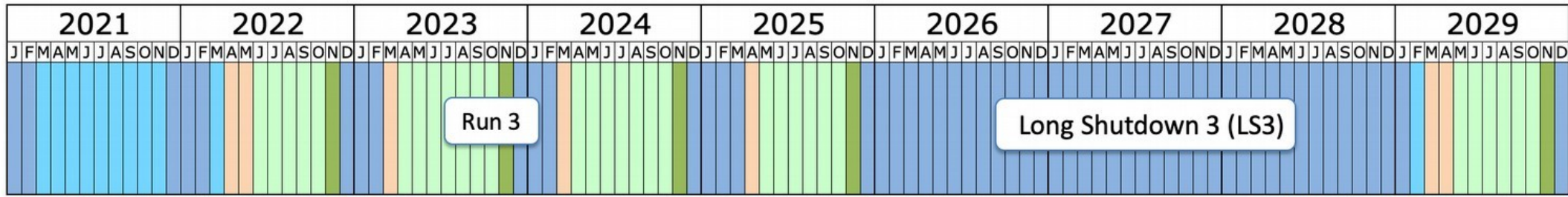
Micro buchi neri





LHC fino a 2038





Last updated: January 2022

- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

LHC fino a 2038

Futuri acceleratori



SWITZERLAND

FRANCE

FCC



100 km Circumference



Future Chiara Collider



Al lavoro



UNIVERSITÀ
DI PAVIA



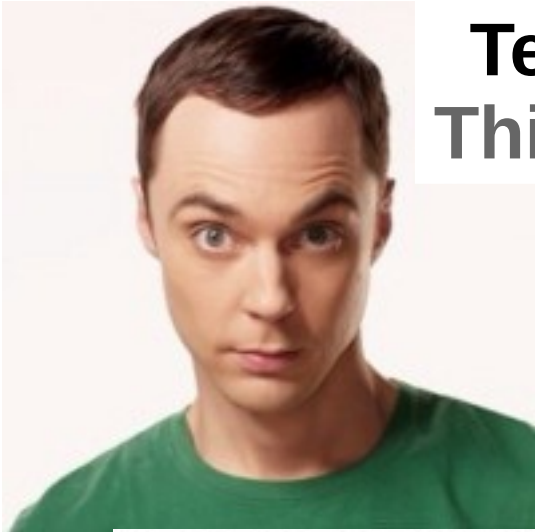
Al lavoro



Al lavoro



Ricadute sulla società

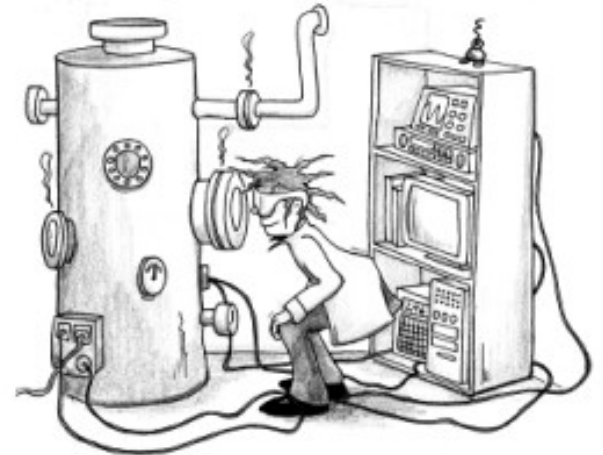


Teorici
Thinkers

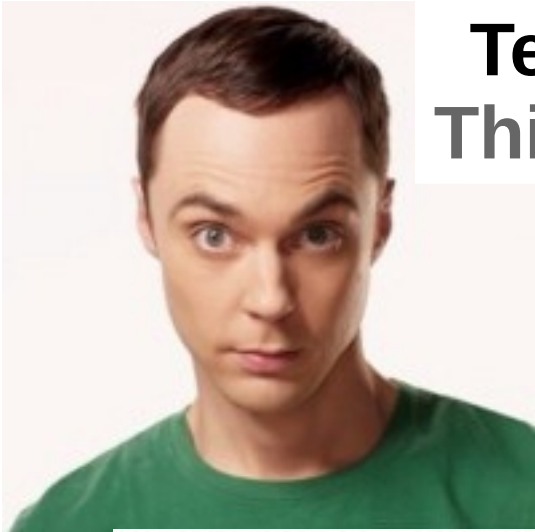
Sperimentali
Makers



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



Ricadute sulla società

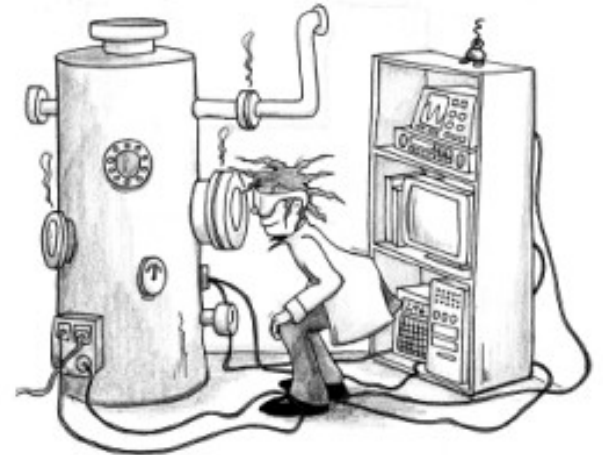


Teorici
Thinkers

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & + \bar{\Psi}_i\gamma_{ij}\Psi_j\Phi + h.c. \\ & + |D_\mu\Phi|^2 - V(\Phi)\end{aligned}$$



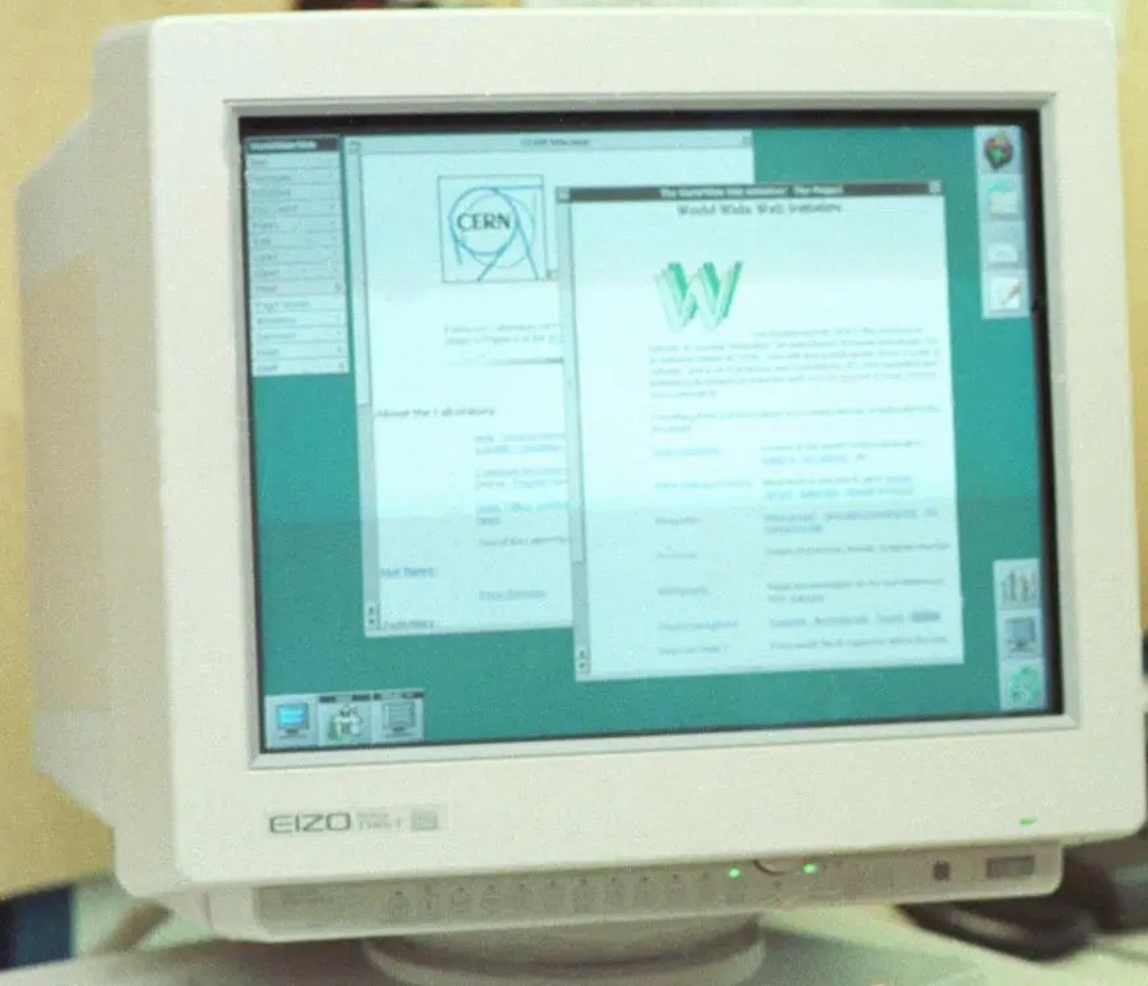
Sperimentali
Makers



Disegnare il futuro



WWW



WWW

Vague but exciting ...

Tim Berners-Lee, CERN/DD

March 1989

Information Management: A Proposal

Abstract



Centro Nazionale Adroterapia Oncologica





Ricerca di base

Non un frutto pronto

A low-angle shot of a massive, ancient tree trunk covered in vibrant green moss. The tree's thick, gnarled branches spread out across the top of the frame, creating a dense canopy of bright green leaves. Sunlight filters through the foliage, creating a soft, ethereal glow and casting long, thin shadows of the surrounding forest onto the ground. The overall atmosphere is one of natural beauty and tranquility.

Ricerca di base

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