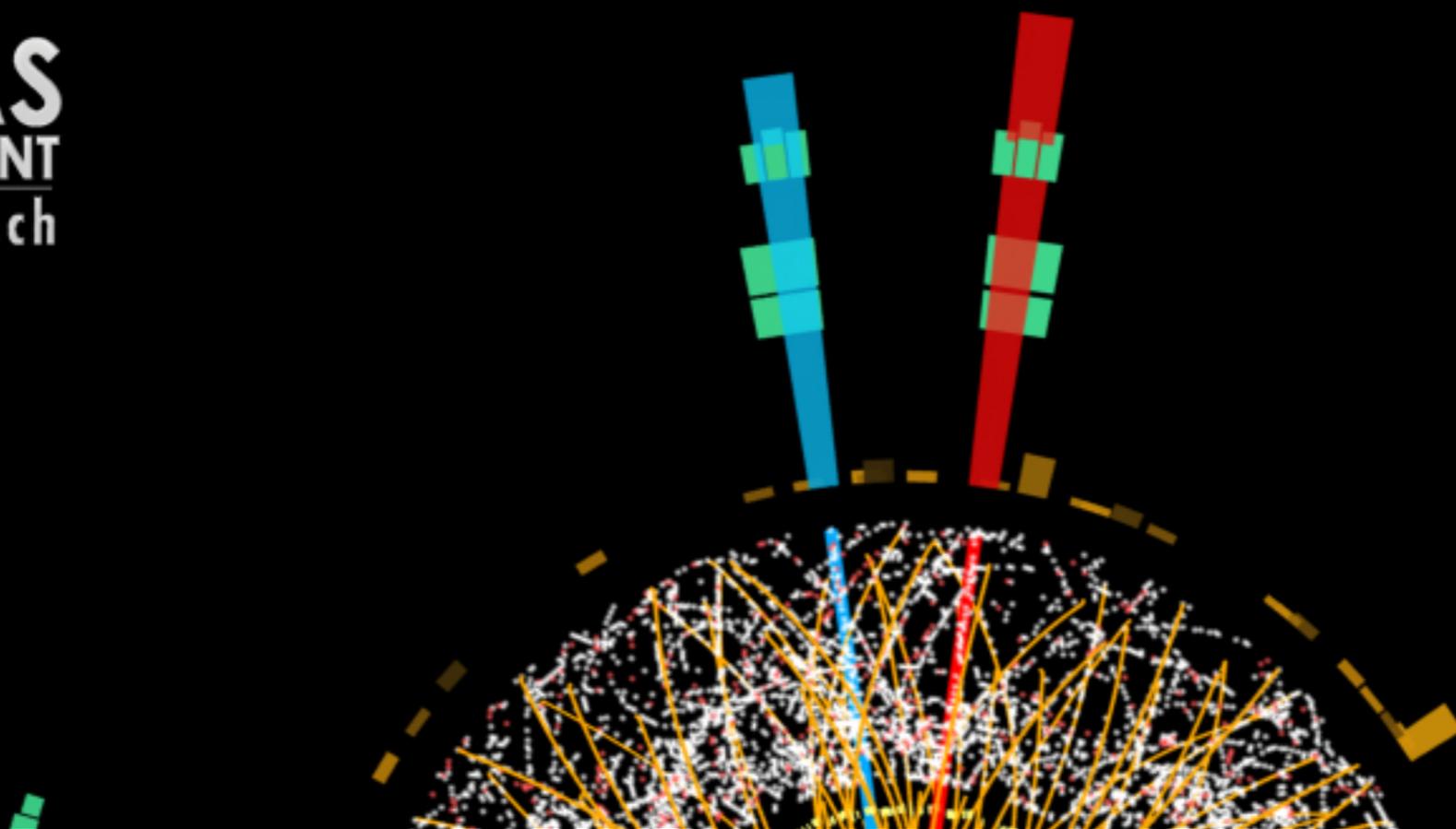


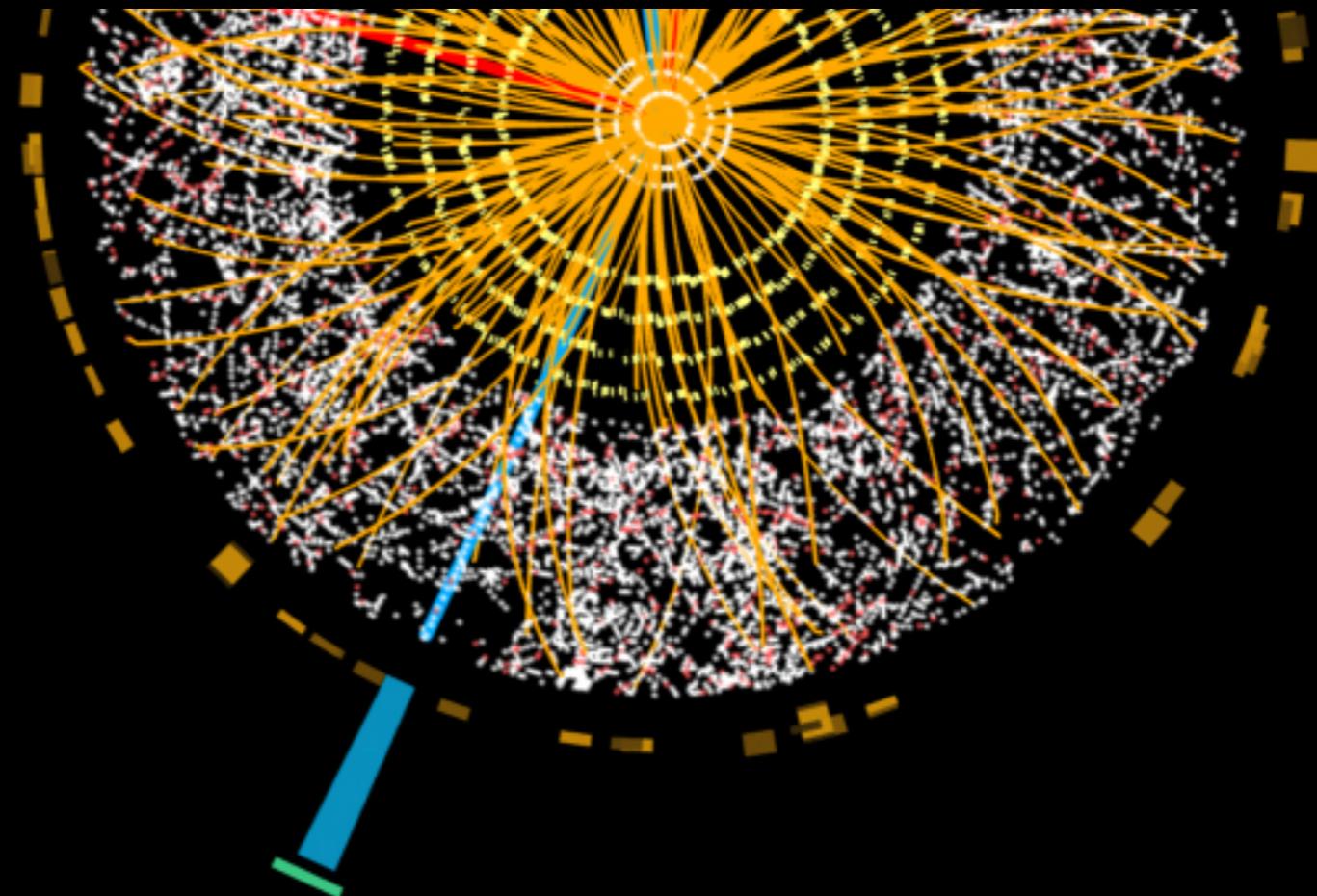
Introduzione alla fisica delle particelle e al Modello Standard

Paolo Francavilla
INFN Sezione di Pisa
Pisa, 11/3/2021

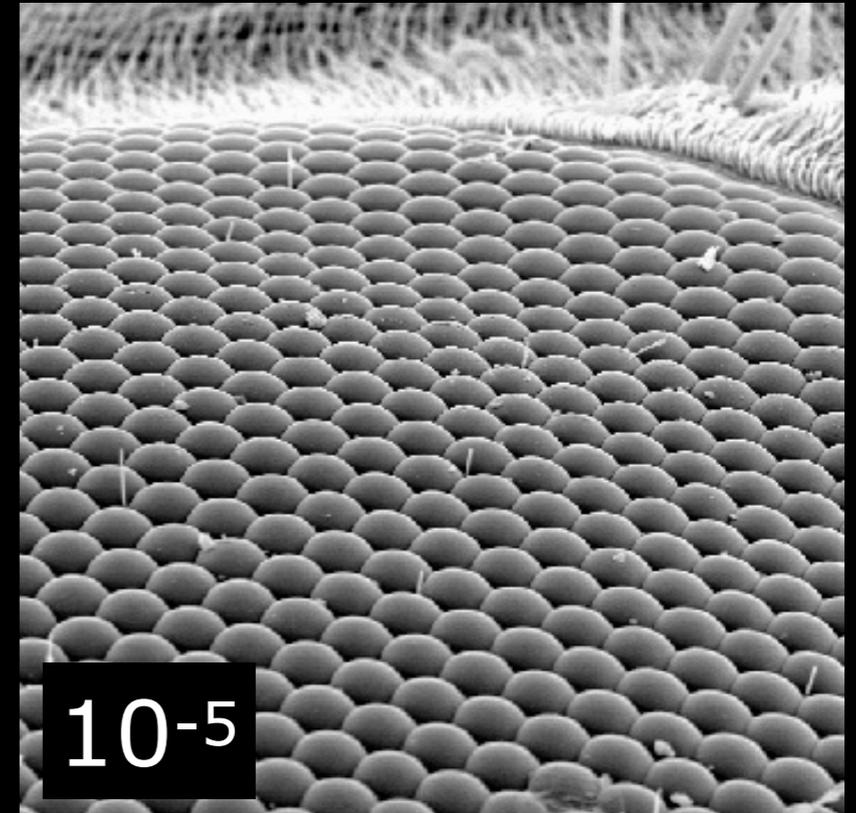
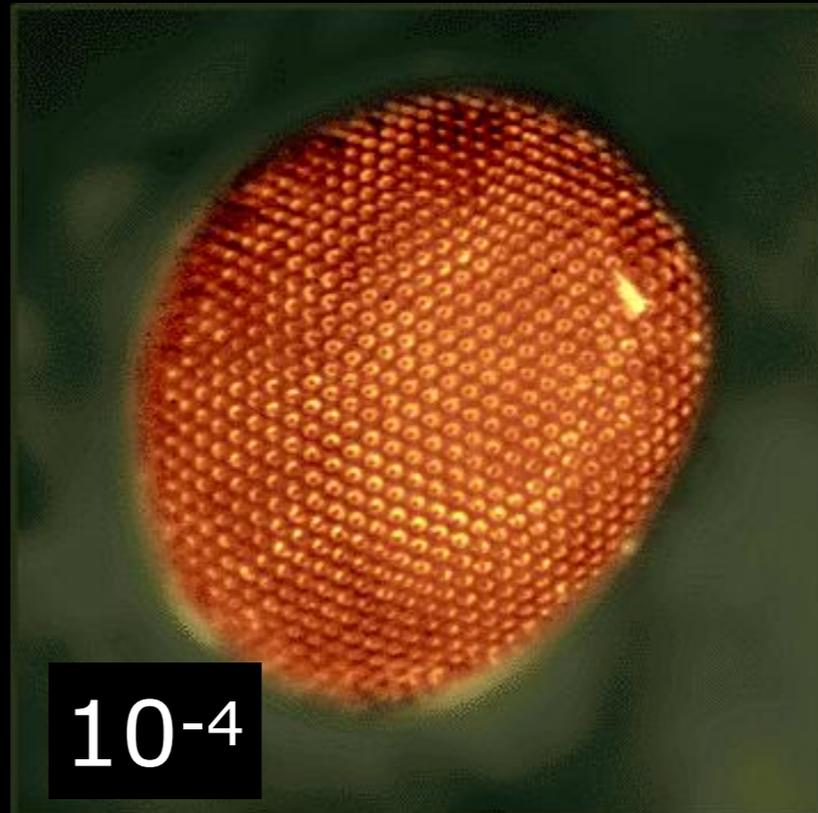
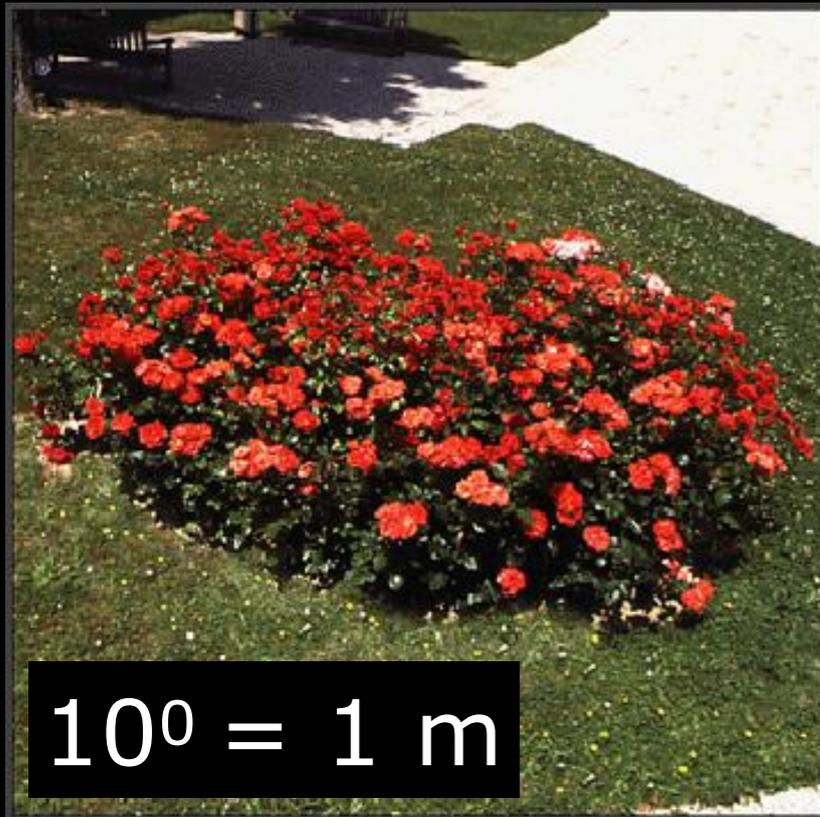




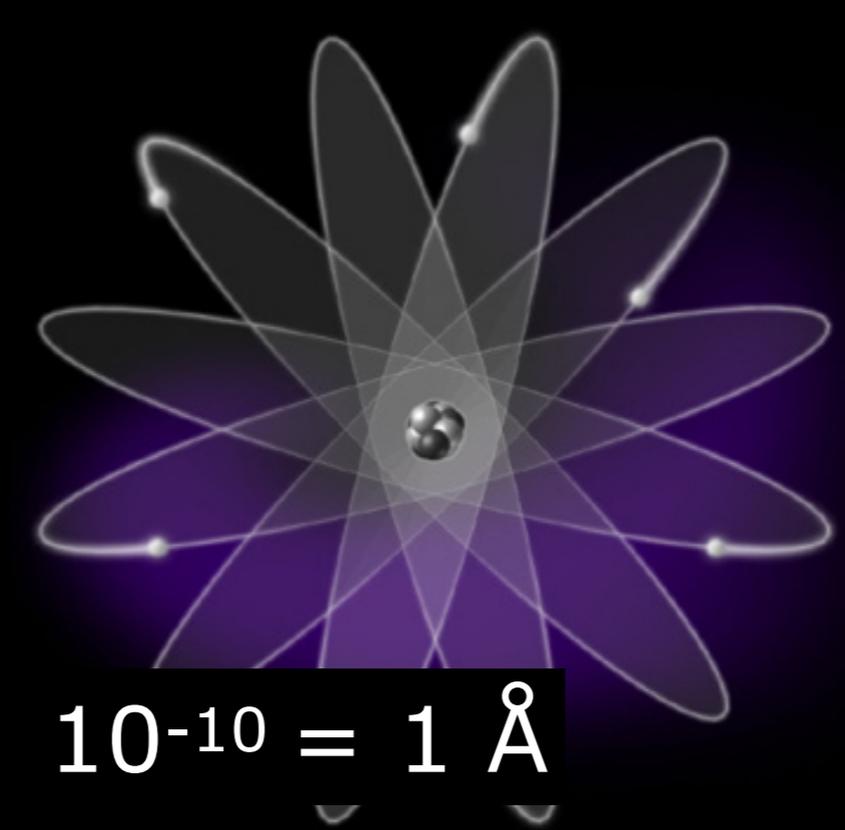
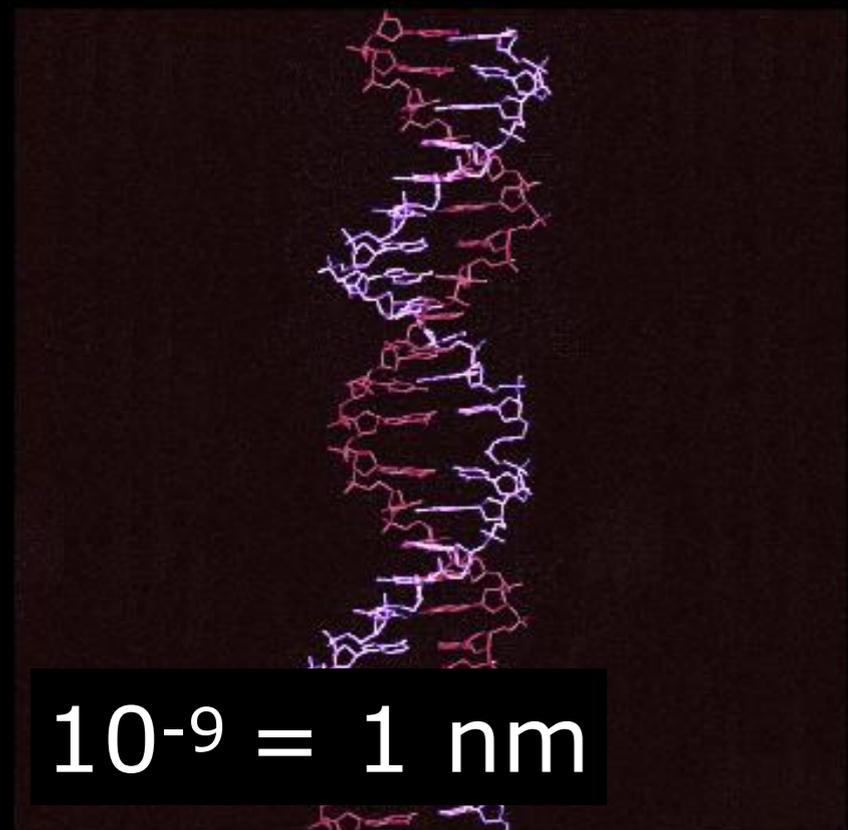
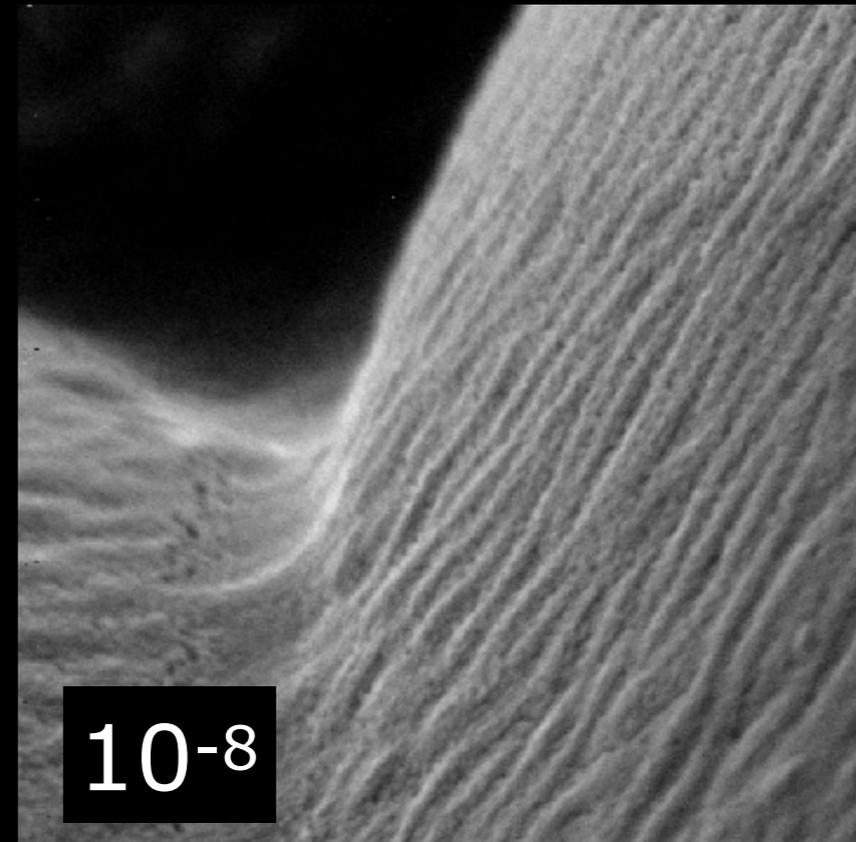
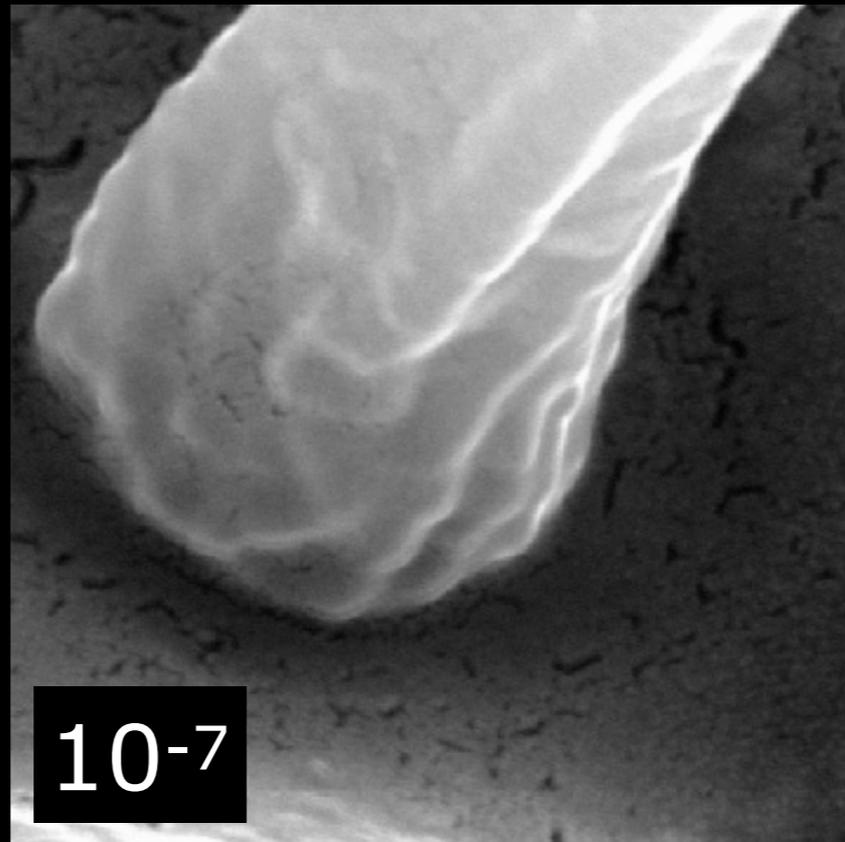
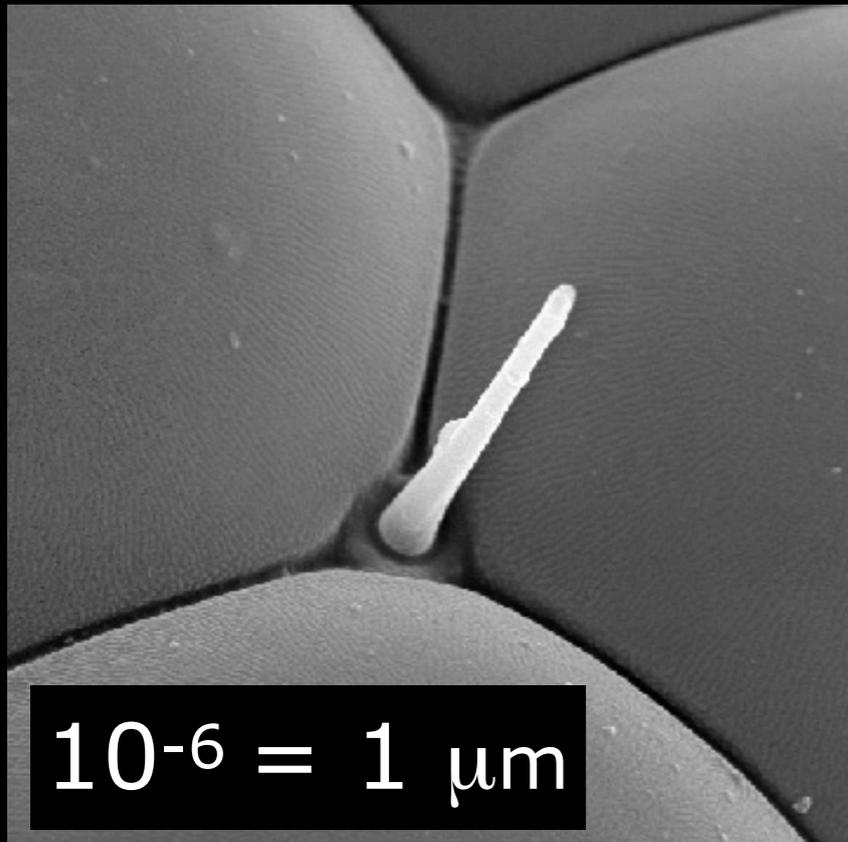
Materia



Verso l'infinitamente piccolo...



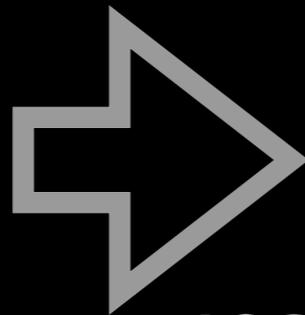
Verso l'infinitamente piccolo...



L'atomo non é poi così indivisibile....



~400 AC: Democrito
Ipotesi che la materia
sia fatta da costituenti
indivisibili
**Nascita dell'idea di
atomo**



1869: Mendeleev
Tavola periodica degli
elementi

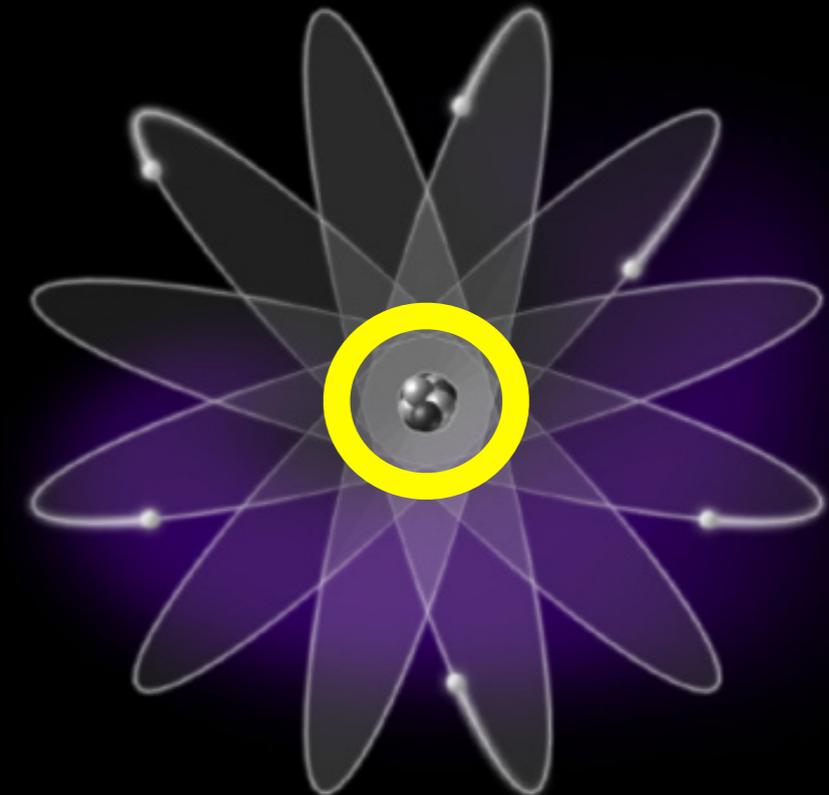
Periodic Table of the Elements																						
1	2											10	11	12								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18					
H	He											Ne										
Li	Be											B	C	N	O	F	Ne					
Na	Mg											Al	Si	P	S	Cl	Ar					
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr					
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe					
Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn					
Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110	111	112											

Naming conventions of new elements

* Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
+ Actinide Series	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



1911: Rutherford
Scoperta del nucleo

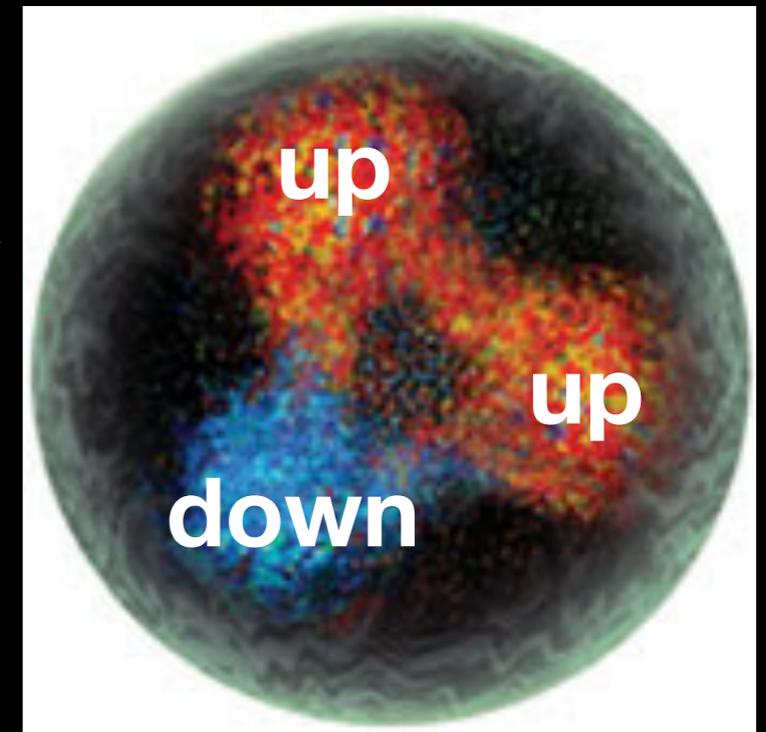
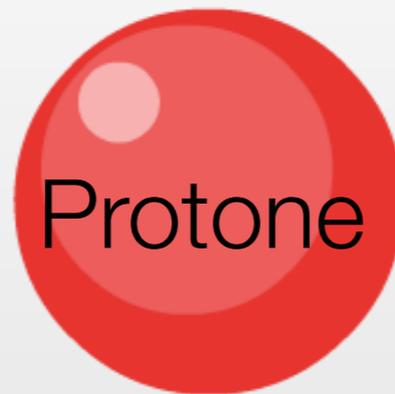
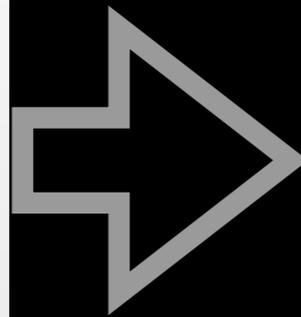


e il nucleo? (in meno di 100 anni)

nucleo

nucleoni

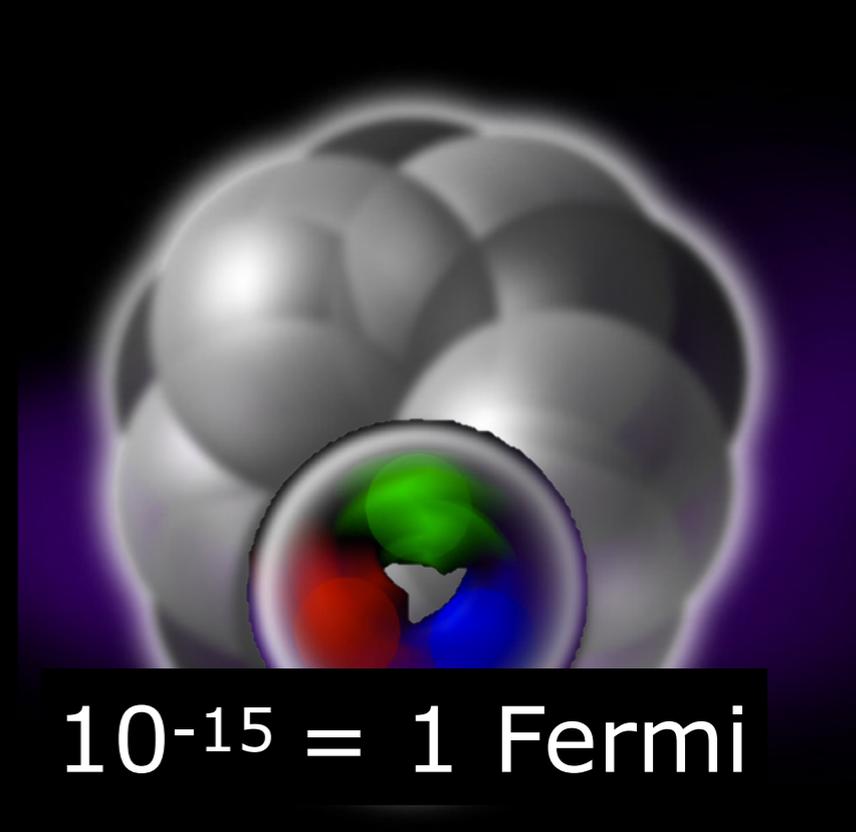
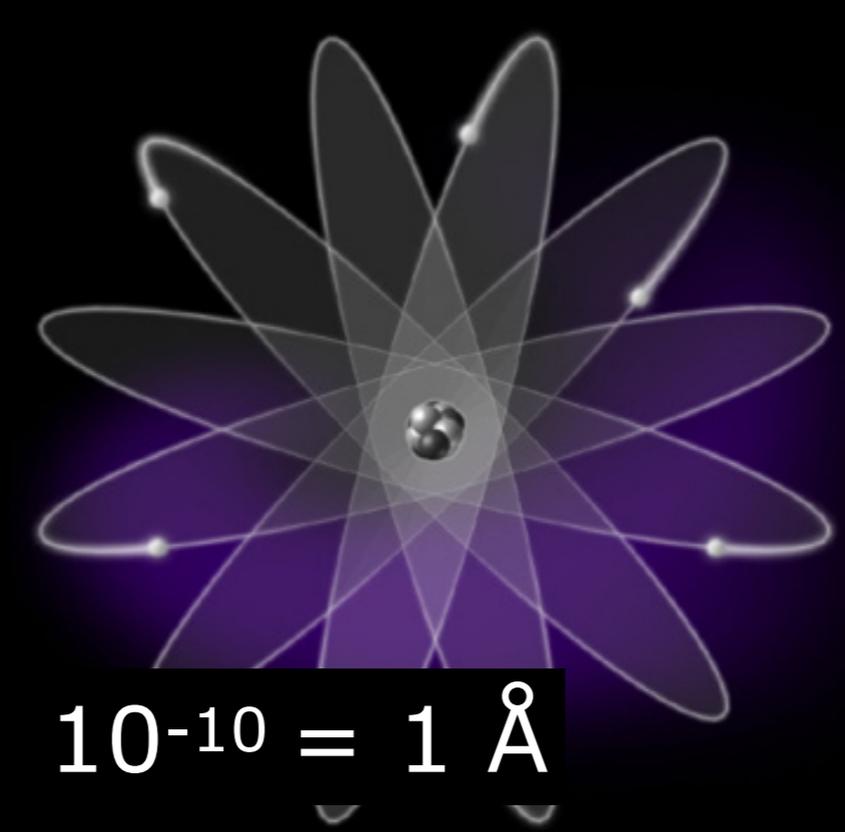
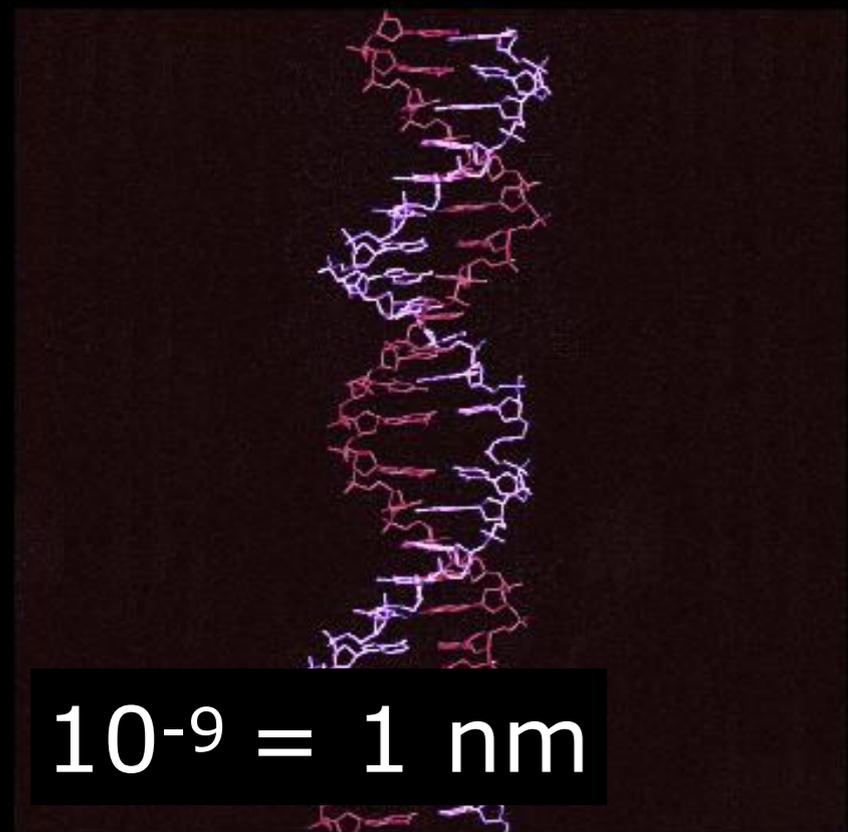
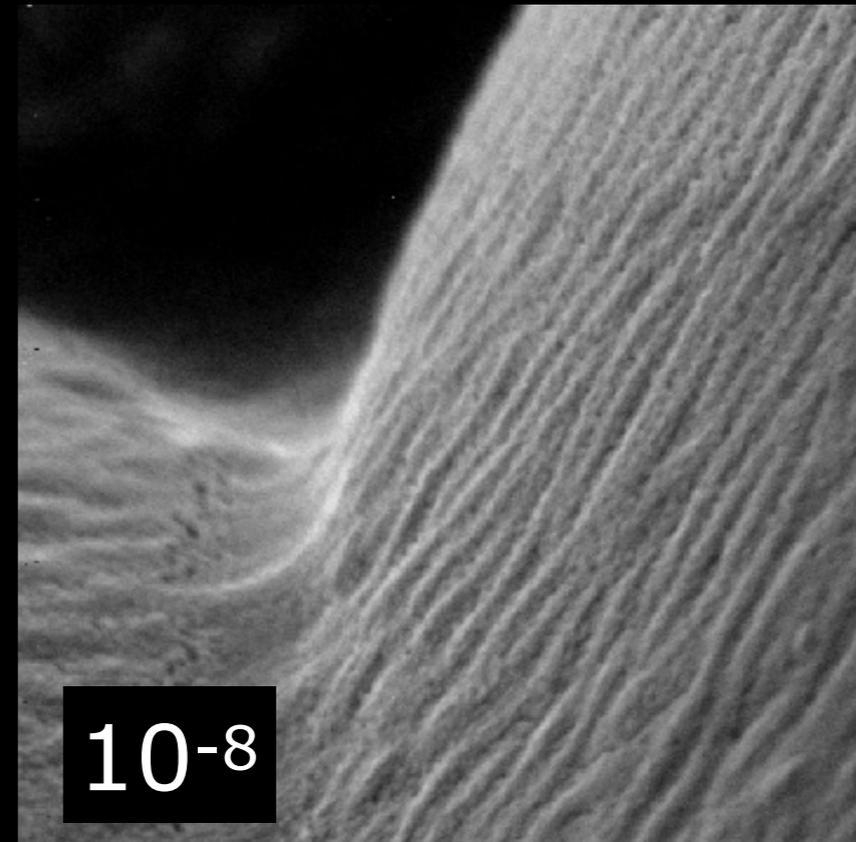
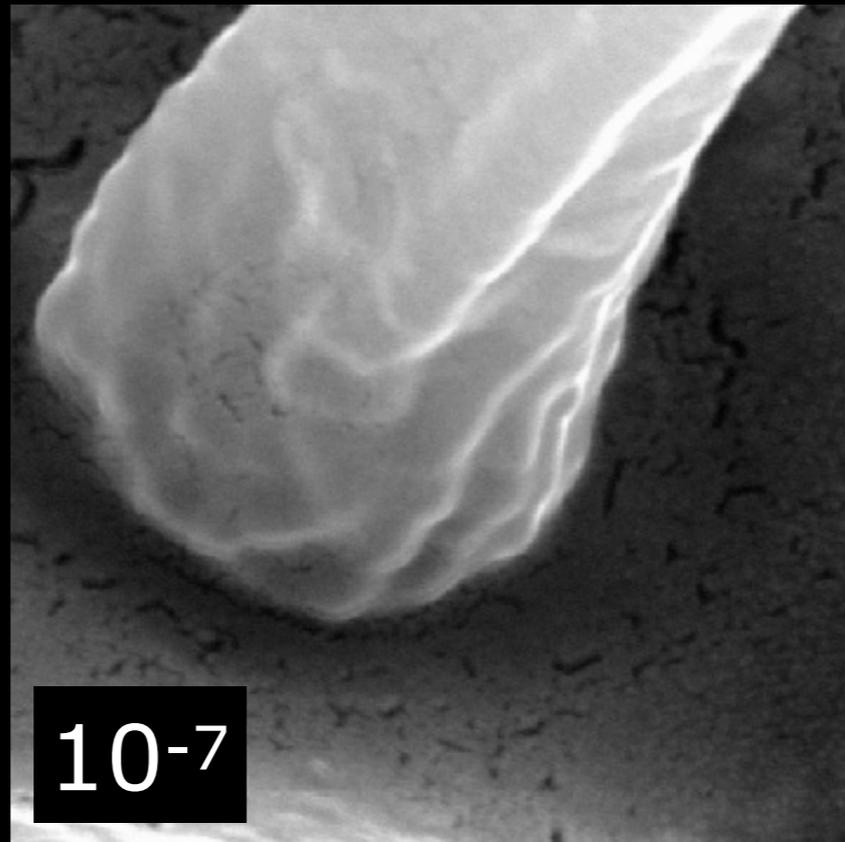
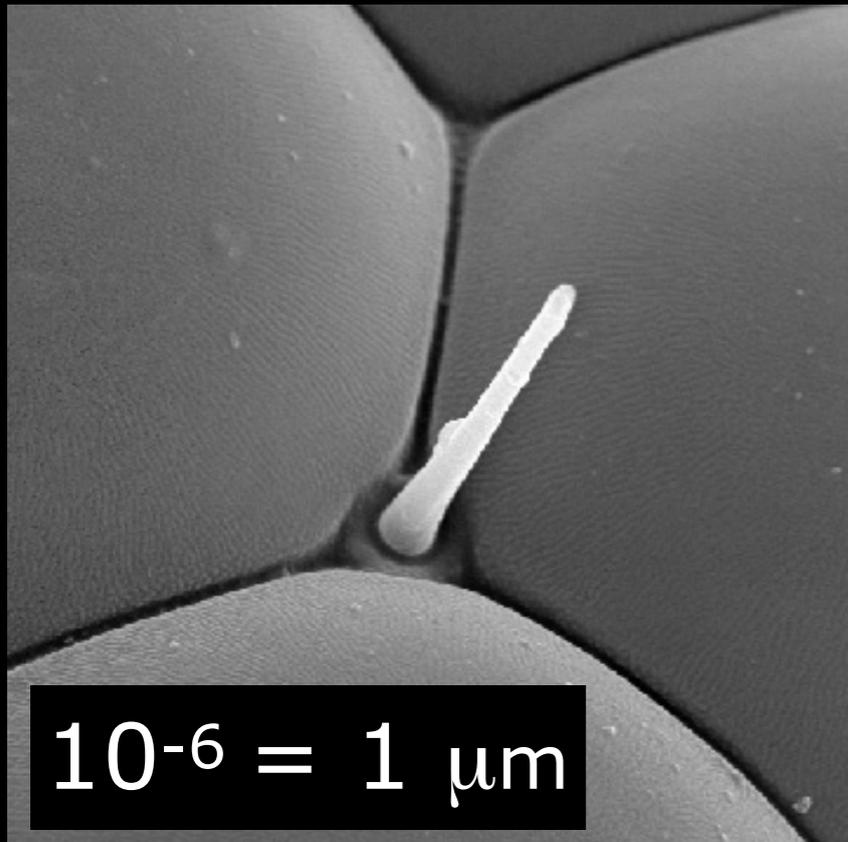
quarks



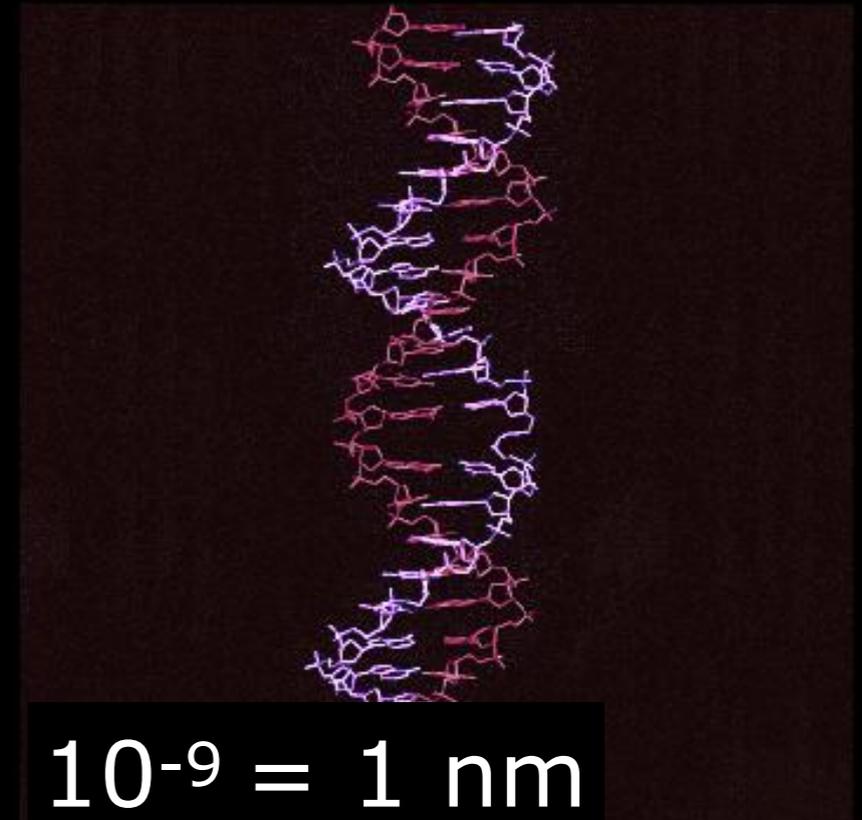
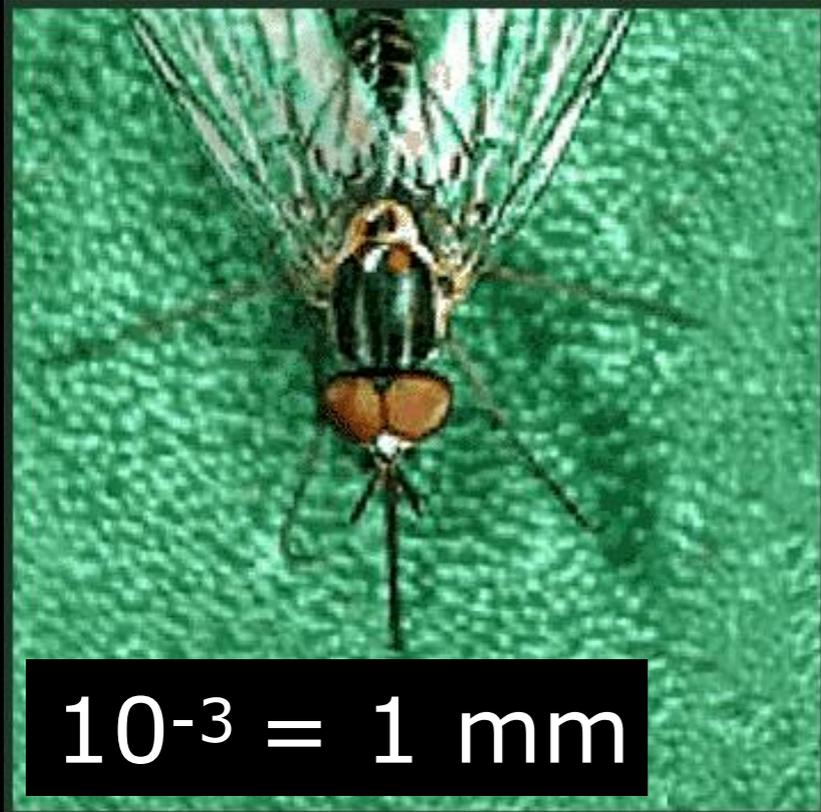
Neutrone

Protone

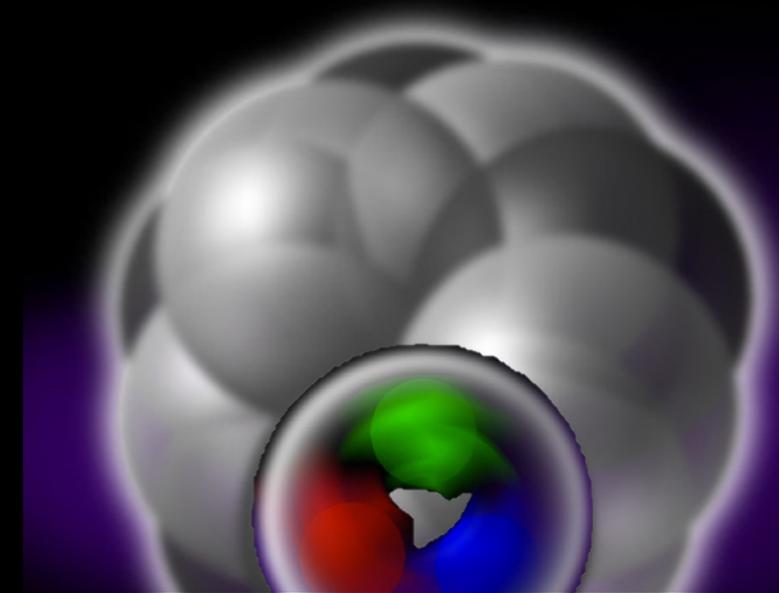
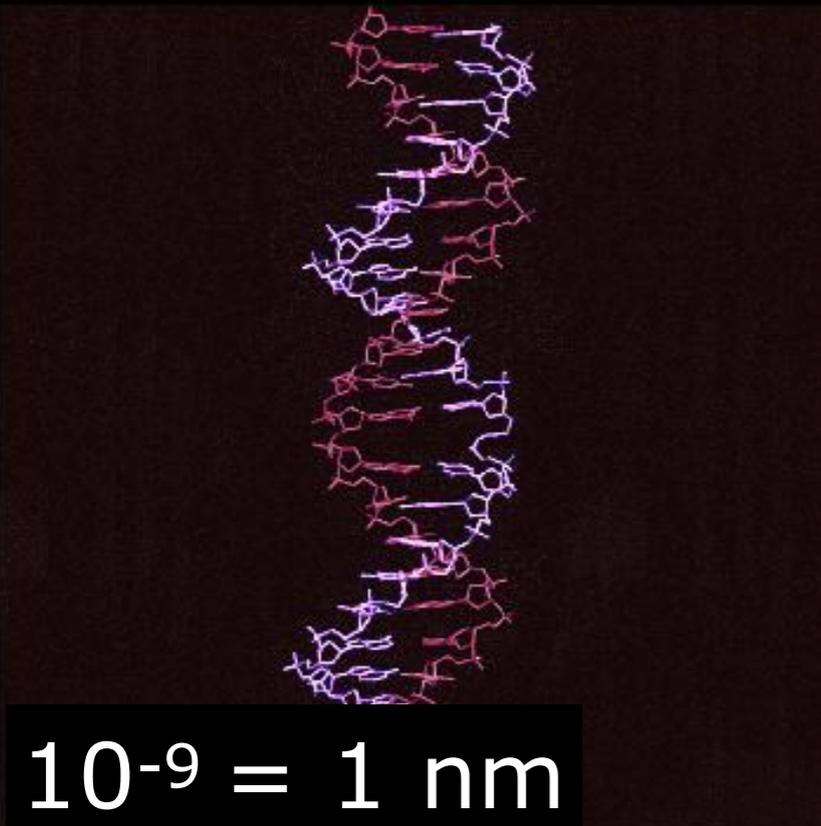
Verso l'infinitamente piccolo...



Zoom: x 1.000.000

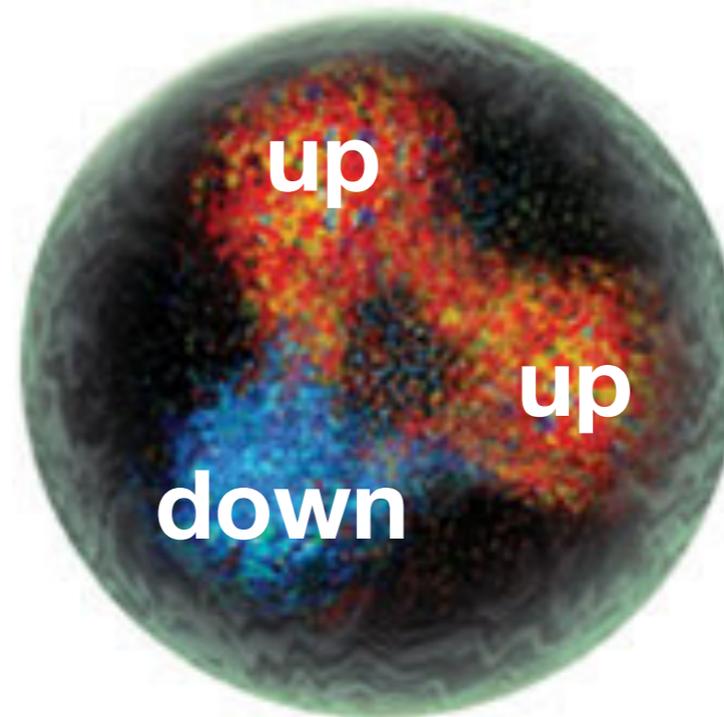
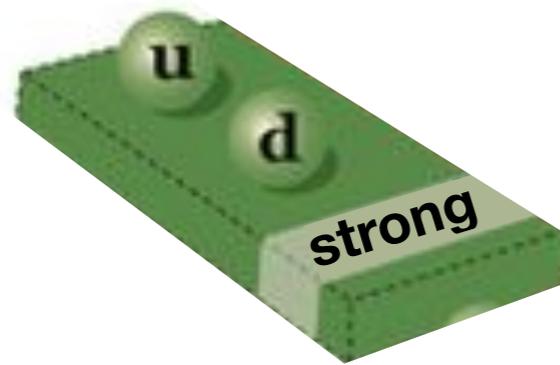


=



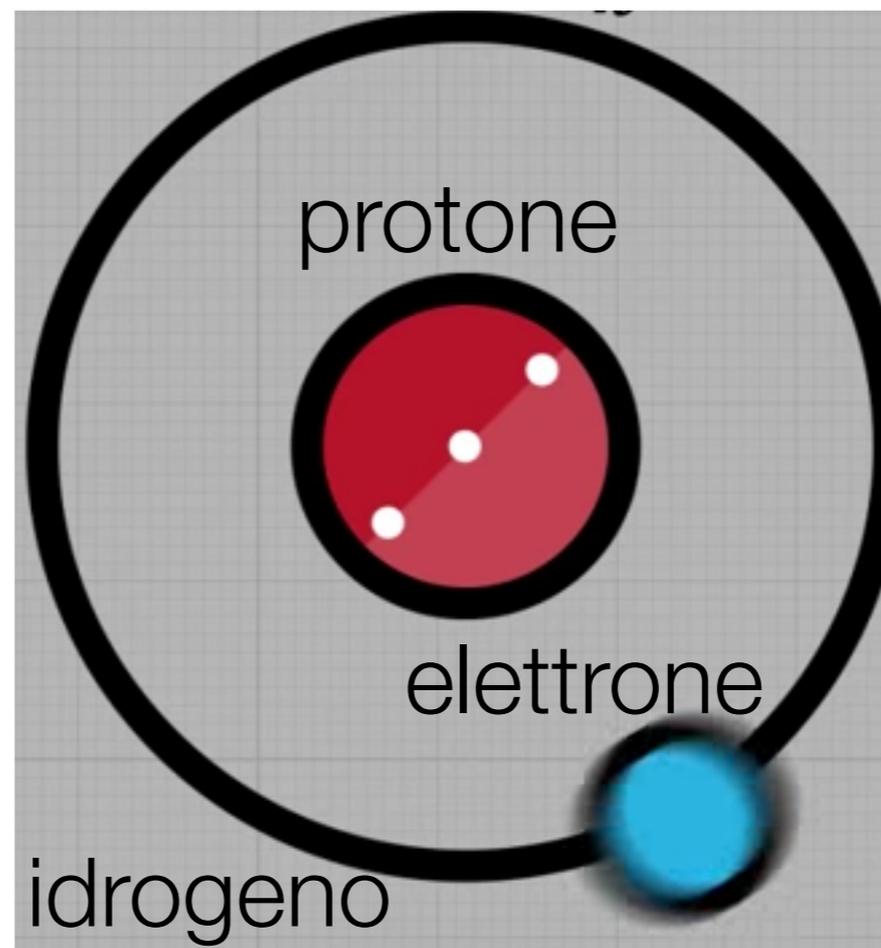
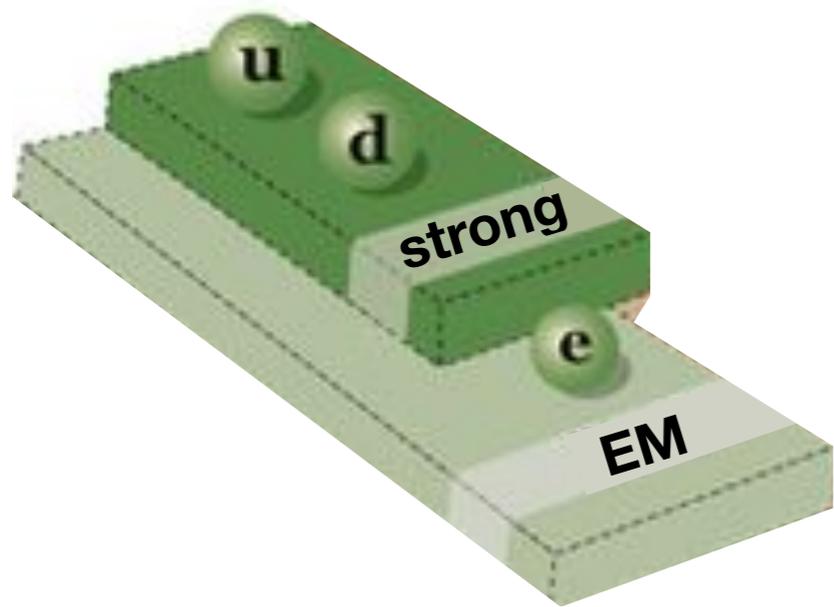
La particelle elementari e le loro interazioni

2 up + 1 down + forza forte (**strong**)
= protone



La particelle elementari e le loro interazioni

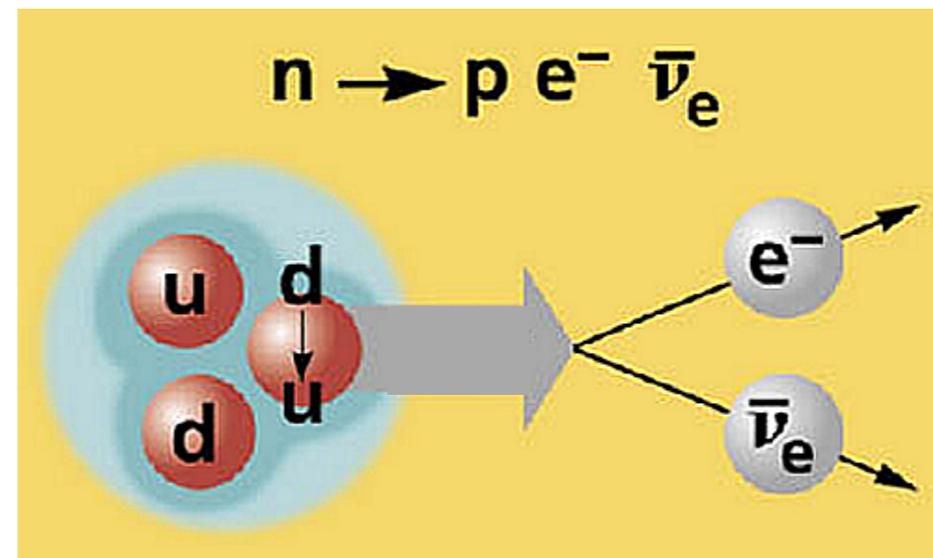
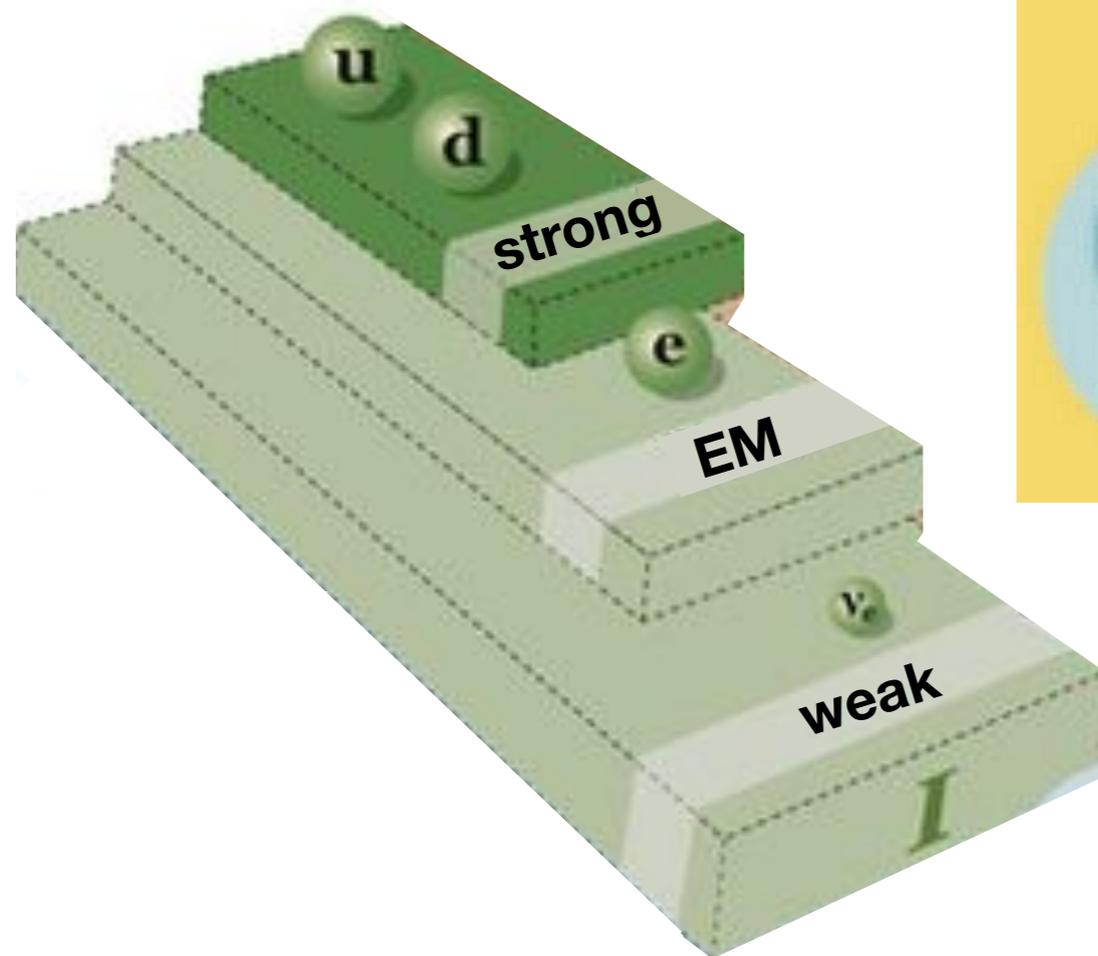
1 protone + 1 elettrone + forza **ElettroMagnetica**
= 1 atomo di idrogeno



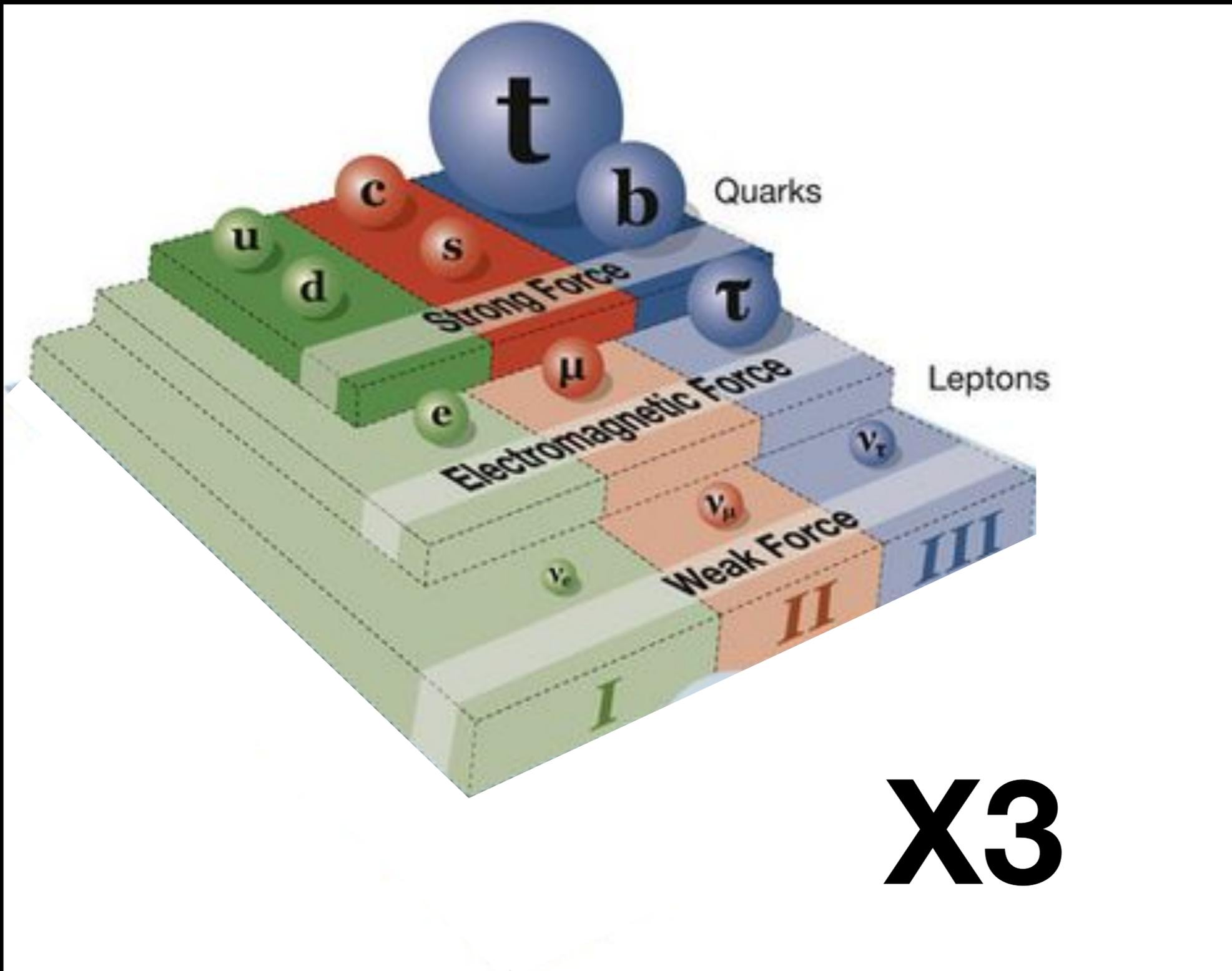
La particelle elementari e le loro interazioni

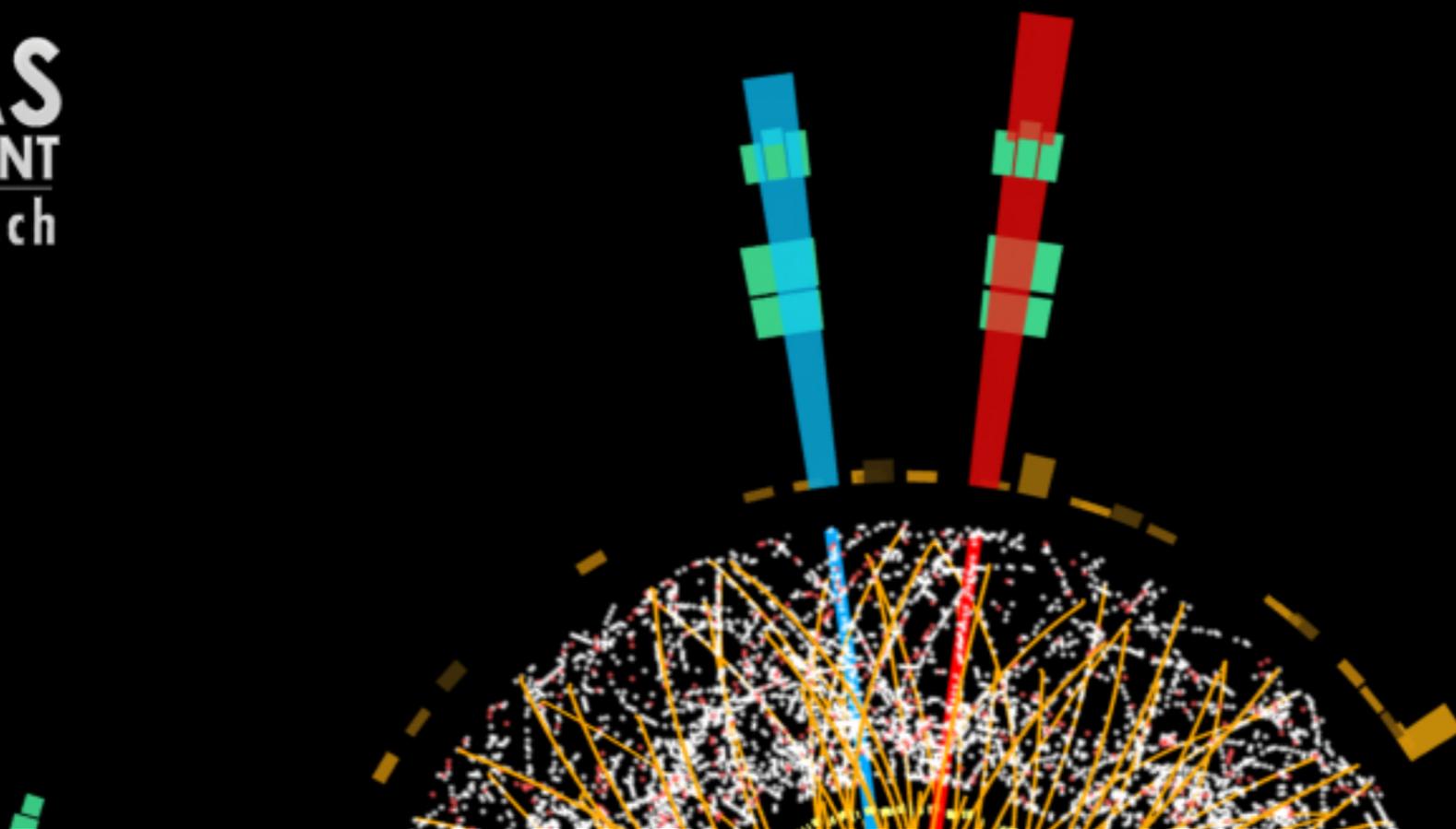
ma i neutroni hanno una vita media di 15 minuti...

⇒ neutrini e forza debole (**weak**)

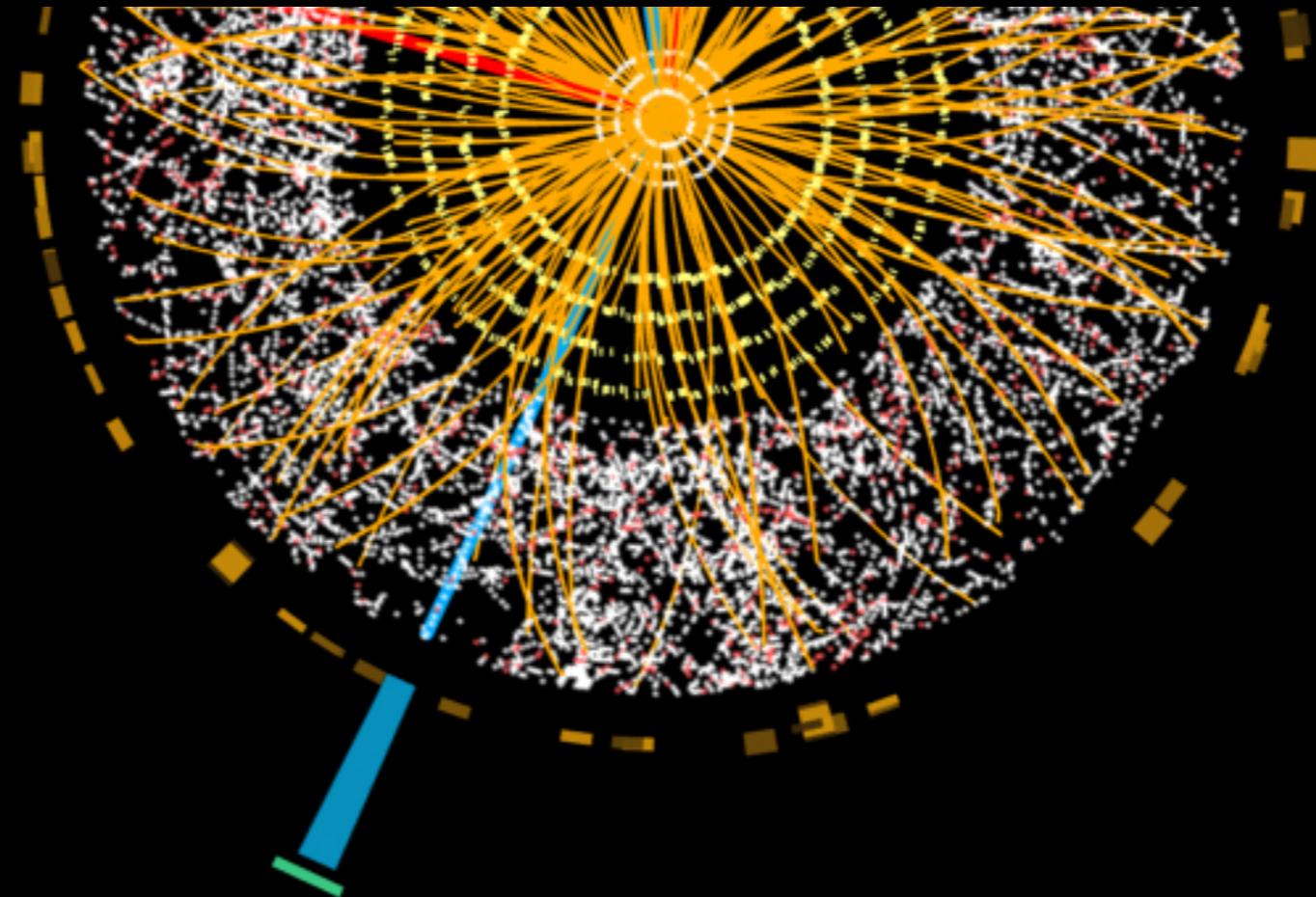


La particelle elementari e le loro interazioni





Interazioni



Interazioni



Forza di Gravità

Interazioni



Forza elettrica



Forza di Gravità



Interazioni



Forza elettrica

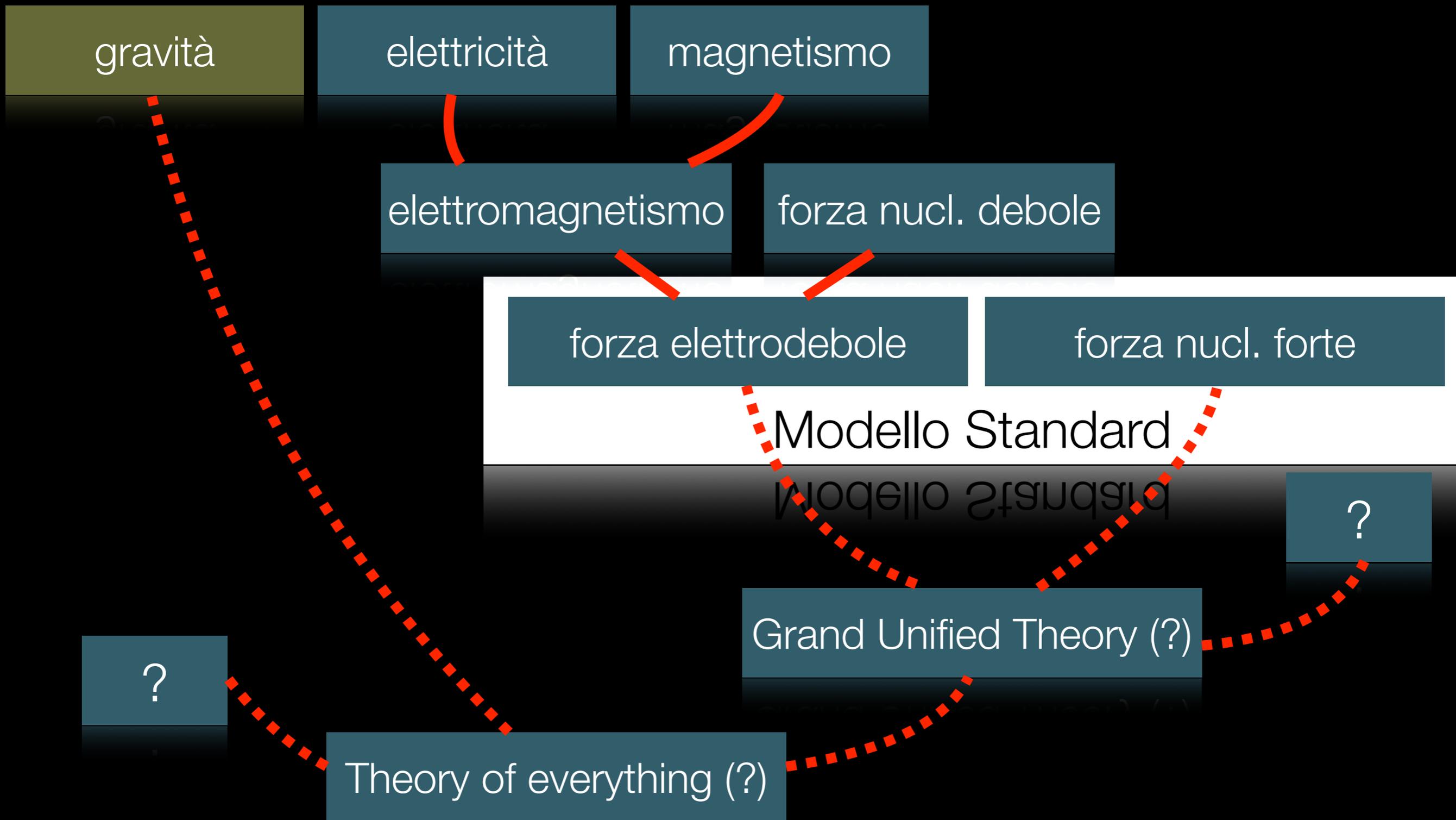


Forza magnetica

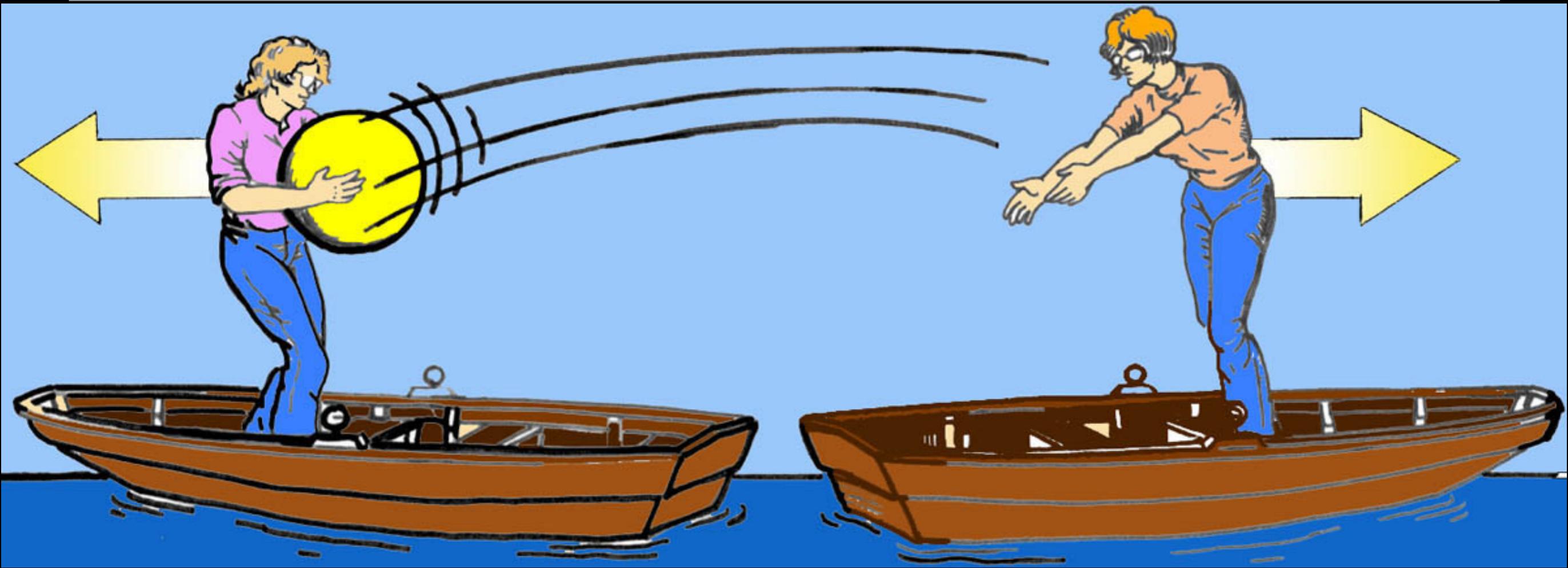


Forza di Gravità

Le interazioni



Interazioni



Tutte le interazioni della natura possono essere descritte come scambio di particelle che trasmettono la forza

La particelle elementari e le loro interazioni

	$2.4 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$1.27 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$171.2 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon	$? \text{ GeV}/c^2$ 0 0 H Higgs boson
Quarks	$4.8 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$104 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$4.2 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon	
	$<2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$<15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$91.2 \text{ GeV}/c^2$ 0 1 Z^0 Z boson	
	$0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$105.7 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$80.4 \text{ GeV}/c^2$ ± 1 1 W^\pm W boson	Gauge boson

- Interazioni fondamentali
- Elettromagnetica
 - Nucleare forte
 - Nucleare debole

$$\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_\nu^0 W_\mu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ 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] - \\
& gM W_\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^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
& m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
& \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \\
& (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
& \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
& \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + \\
& i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \\
& \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \\
& \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
& igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
& igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
& igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
& \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \\
& \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

Il modello standard

- E questa é l'equazione che descrive come queste particelle interagiscono. (non é elfico....)
- Dove sta la bellezza???
- e la semplicità?

Il modello standard

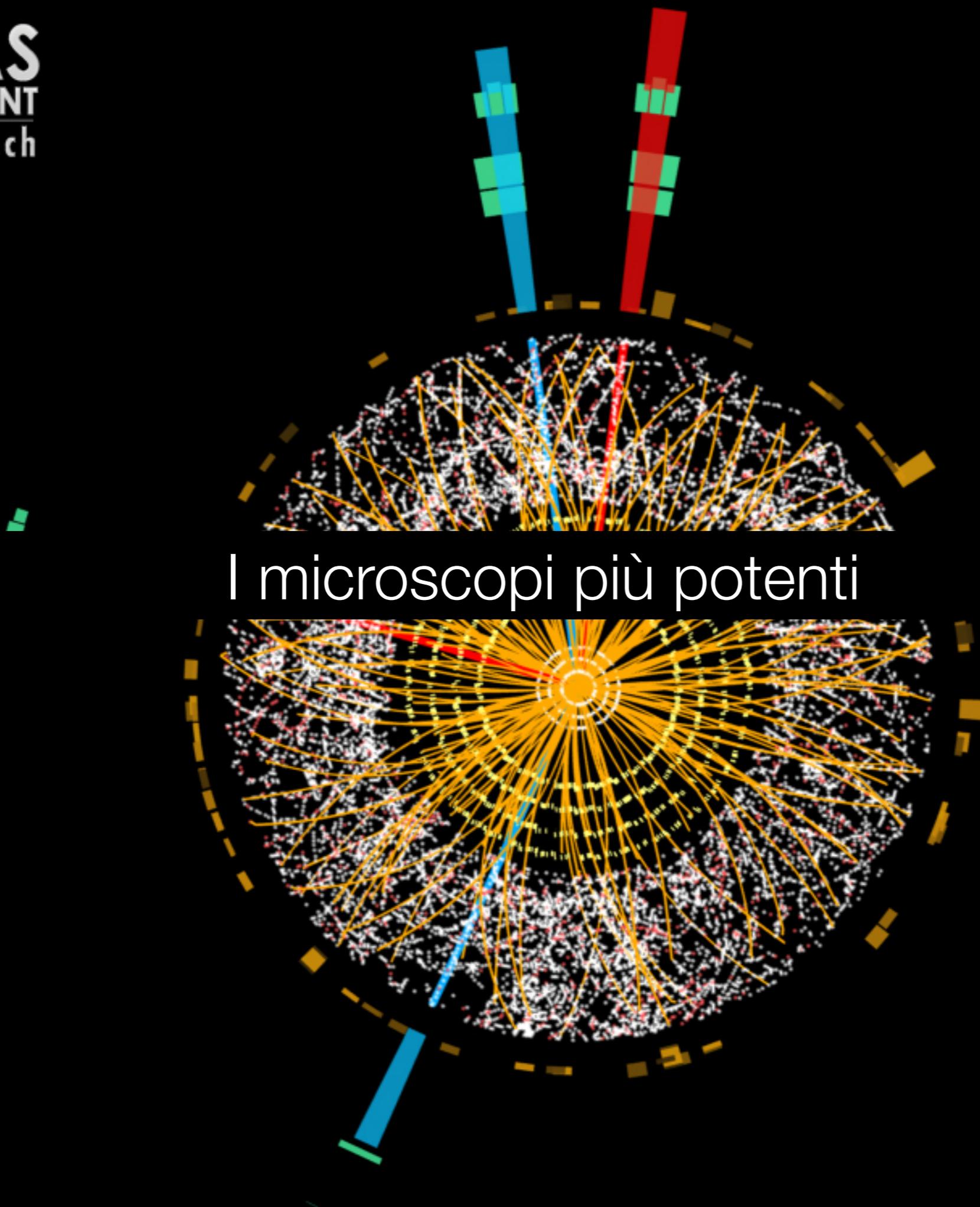
$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\ & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \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_\mu W_\mu^- - \\ & W_\mu^- \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_\mu^- \partial_\nu W_\nu^+)] - \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_\nu^0 W_\mu^+ W_\nu^-) + \\ & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-)] - g_c [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \\ & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + \\ & g M W_\mu^+ W_\mu^- H - \\ & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \\ & \phi^+ \partial_\mu H] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 \\ & igs_w M A_\mu (W_\mu^+ \phi^- - \\ & igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \\ & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + \\ & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu \\ & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \\ & m_d^\lambda d_j^\lambda + igs_w A_\mu [- \\ & \gamma^5) \nu^\lambda] + (\bar{e}^\lambda \gamma^\mu \\ & (d_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \\ & \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} \\ & \frac{ig}{2\sqrt{2}} \frac{m_c^\lambda}{M} [-\phi^+ (\bar{u}^\lambda (1 \\ & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2} \\ & \gamma^5) d_j^\lambda] + \frac{ig}{2M\sqrt{2}} \phi^- \\ & \frac{g m_s^\lambda}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \bar{X}^+ \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \\ & igs_w W_\mu^+ (\partial_\mu \bar{X}^0 X^+ \\ & igs_w W_\mu^- (\partial_\mu \bar{X}^- X^+ \\ & igs_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ \\ & \frac{1}{2}g M [\bar{X}^+ X^+ H + \\ & \bar{X}^- X^0 \phi^-] + \frac{1}{2}ig \\ & \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$



one

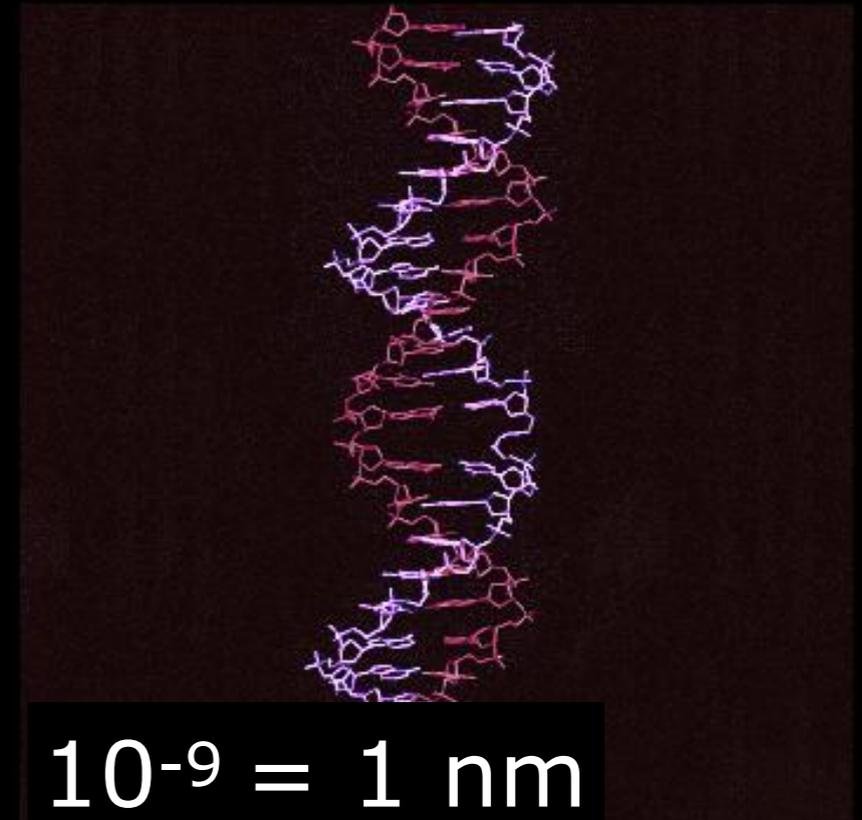
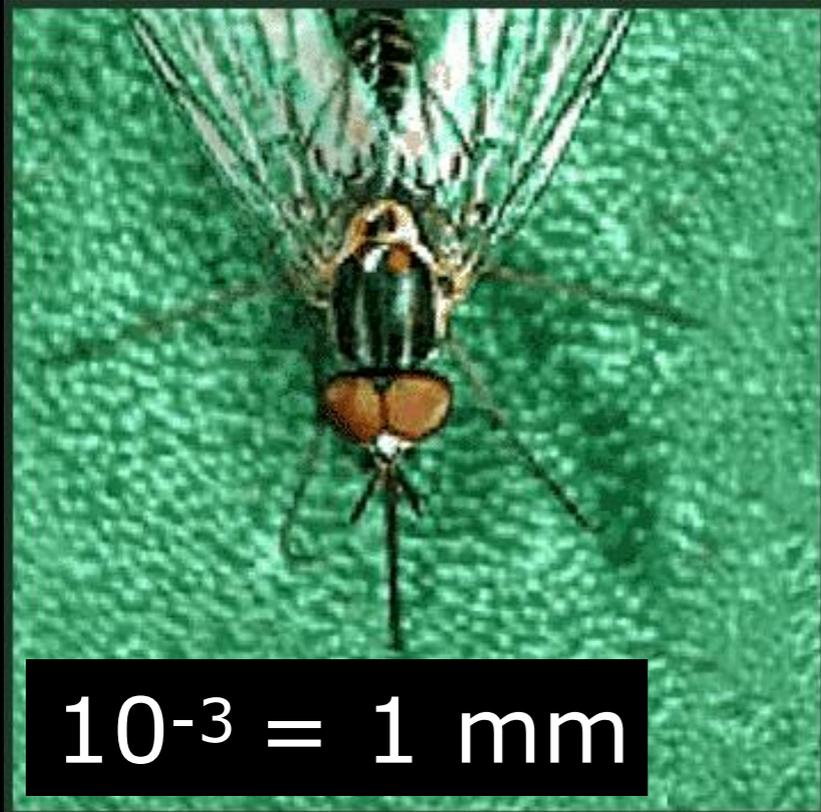
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La versione "compressa"

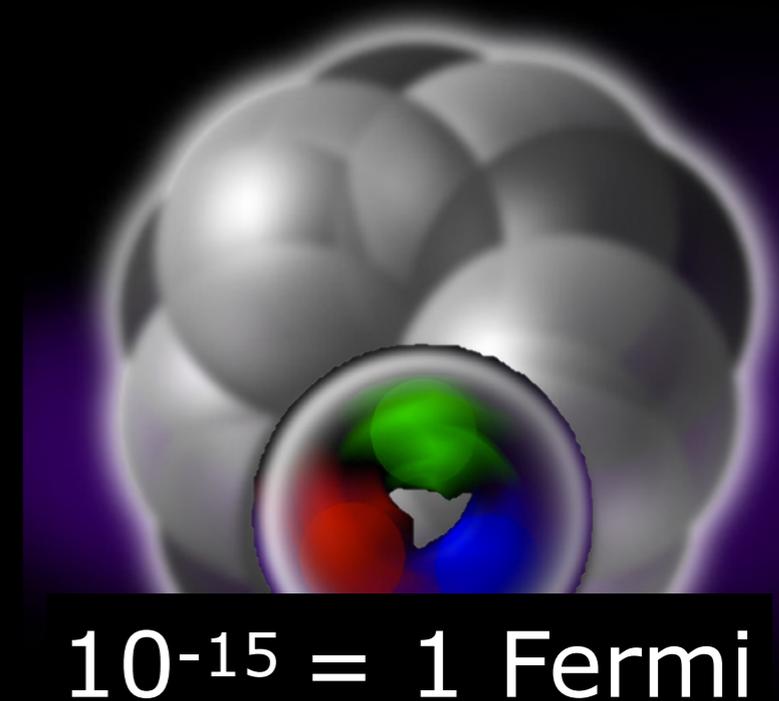
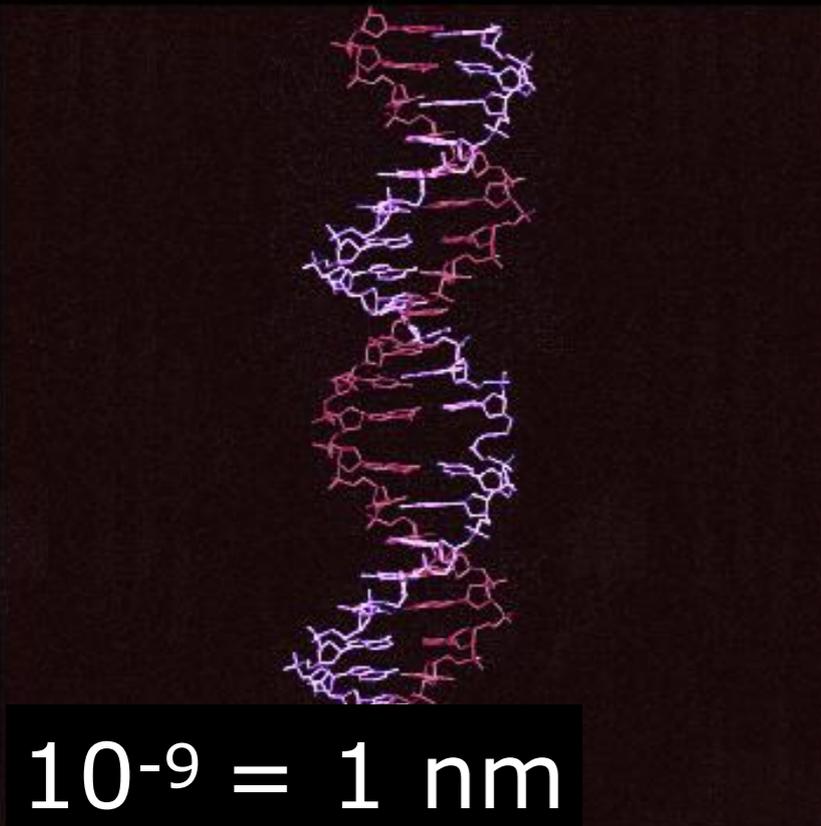


I microscopi più potenti

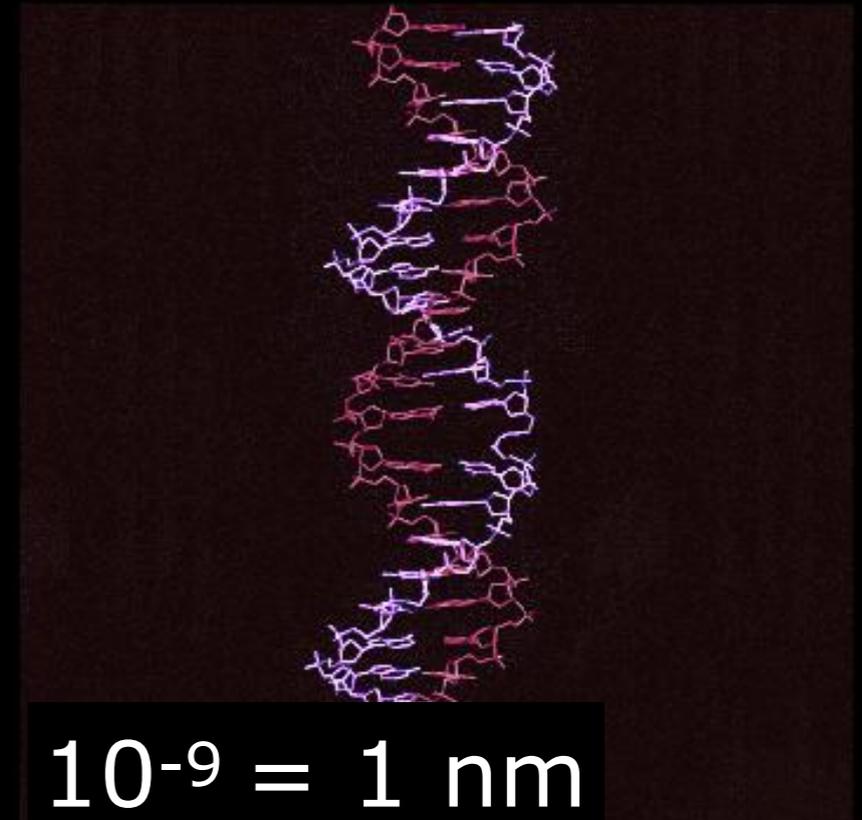
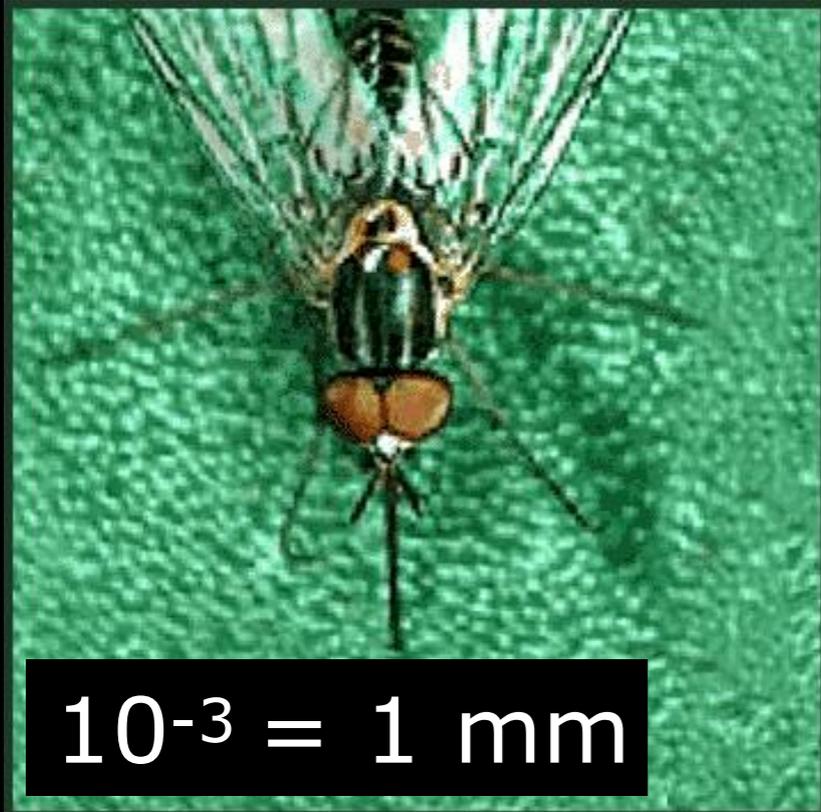
Zoom: x 1.000.000



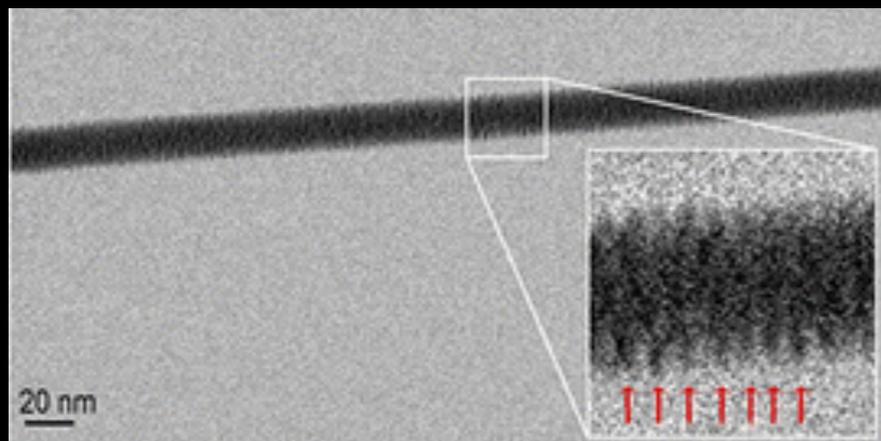
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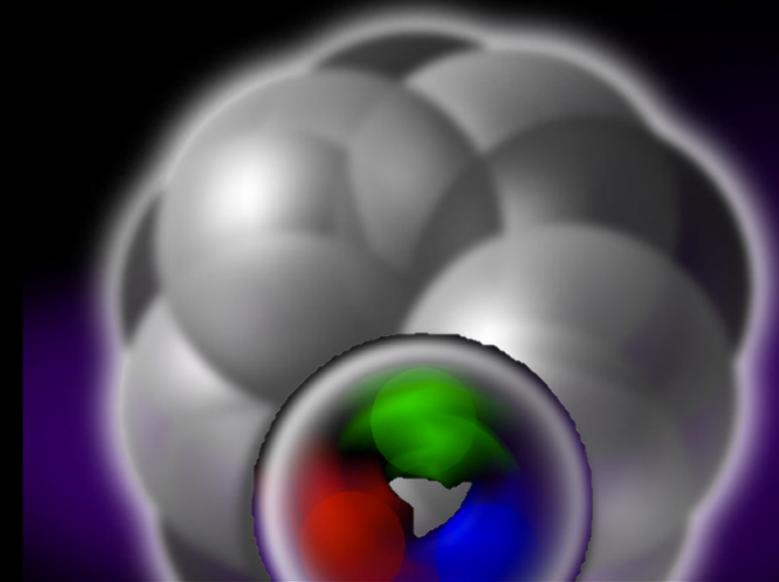
Zoom: x 1.000.000



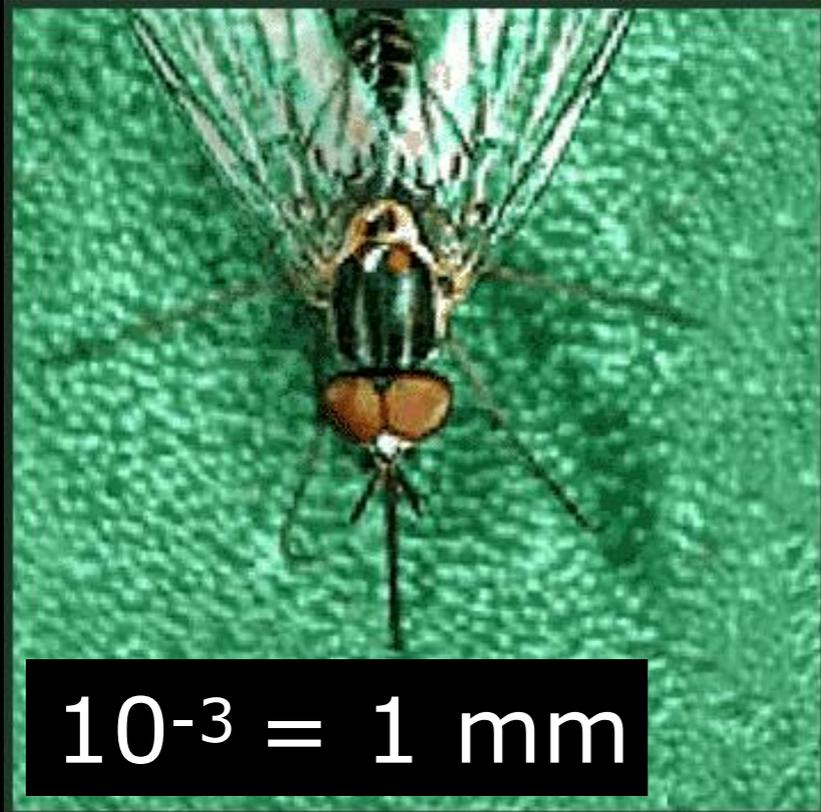
DNA visto
da microscopio elettronico
<http://pubs.acs.org/doi/abs/10.1021/nl3039162>



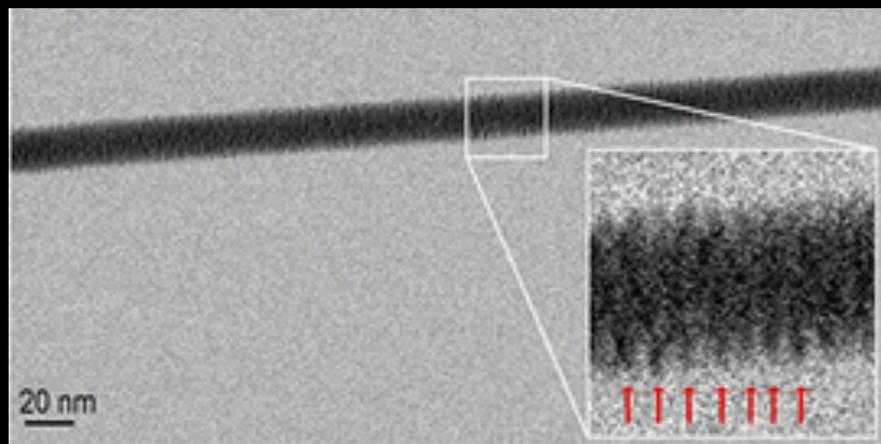
$10^{-9} = 1 \text{ nm}$



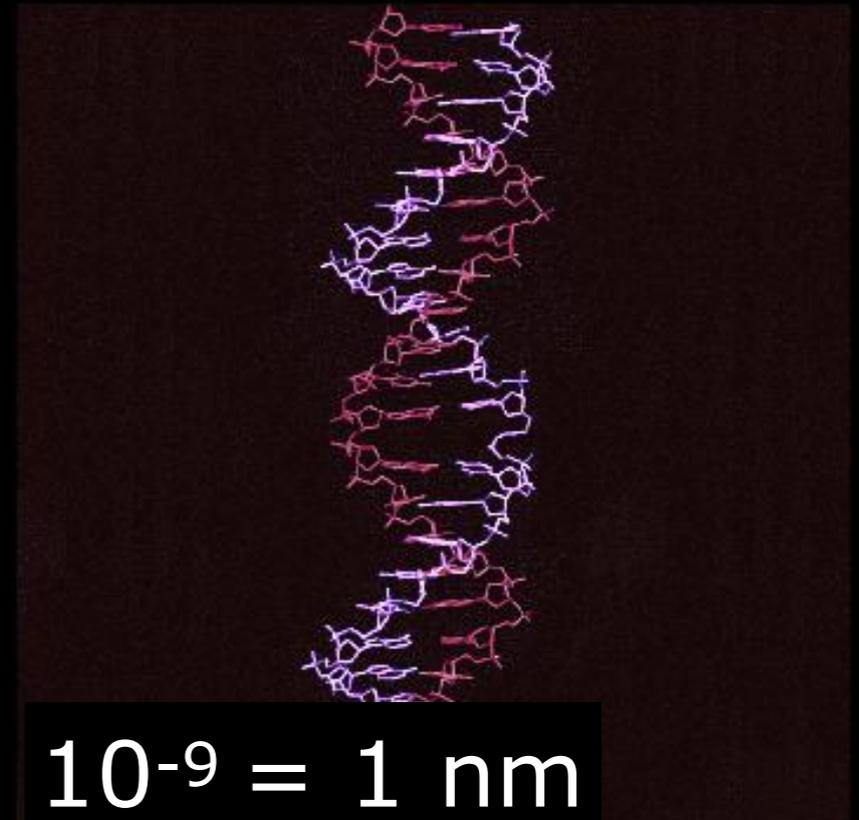
Zoom: x 1.000.000



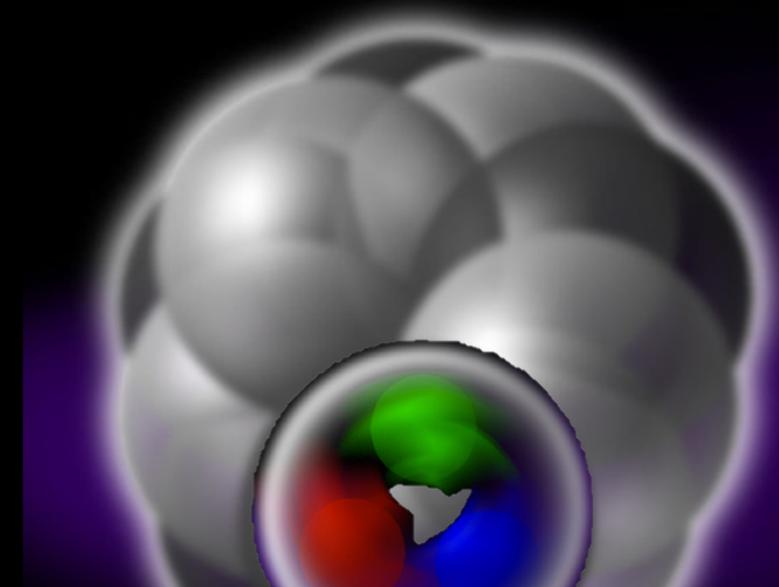
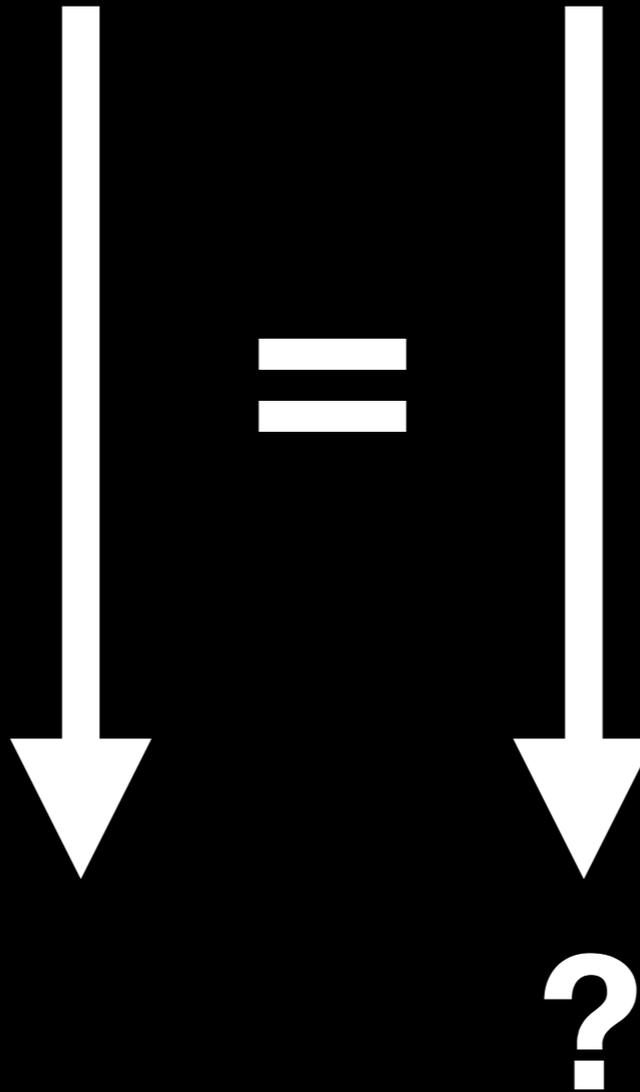
DNA visto
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<http://pubs.acs.org/doi/abs/10.1021/nl3039162>



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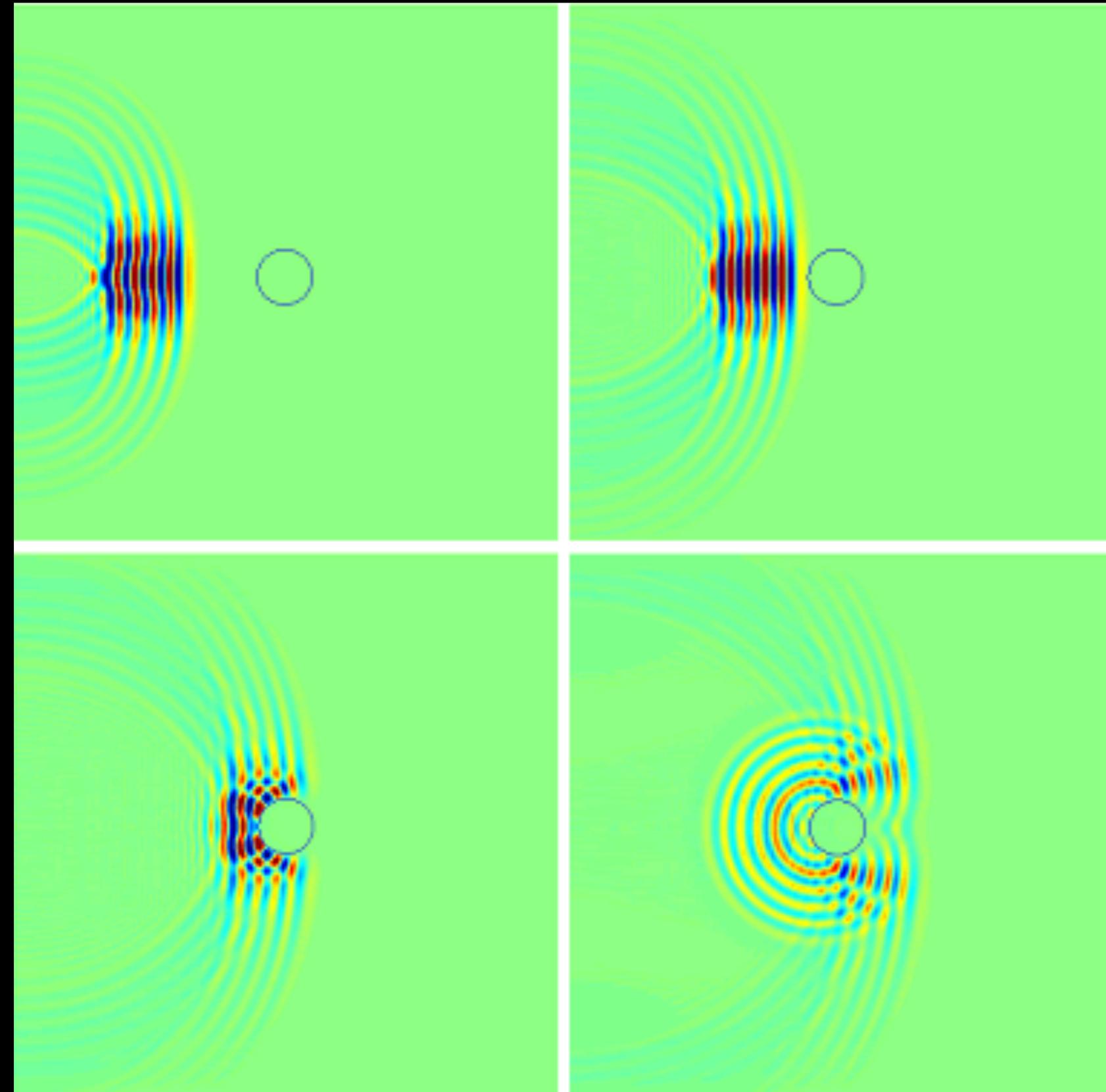


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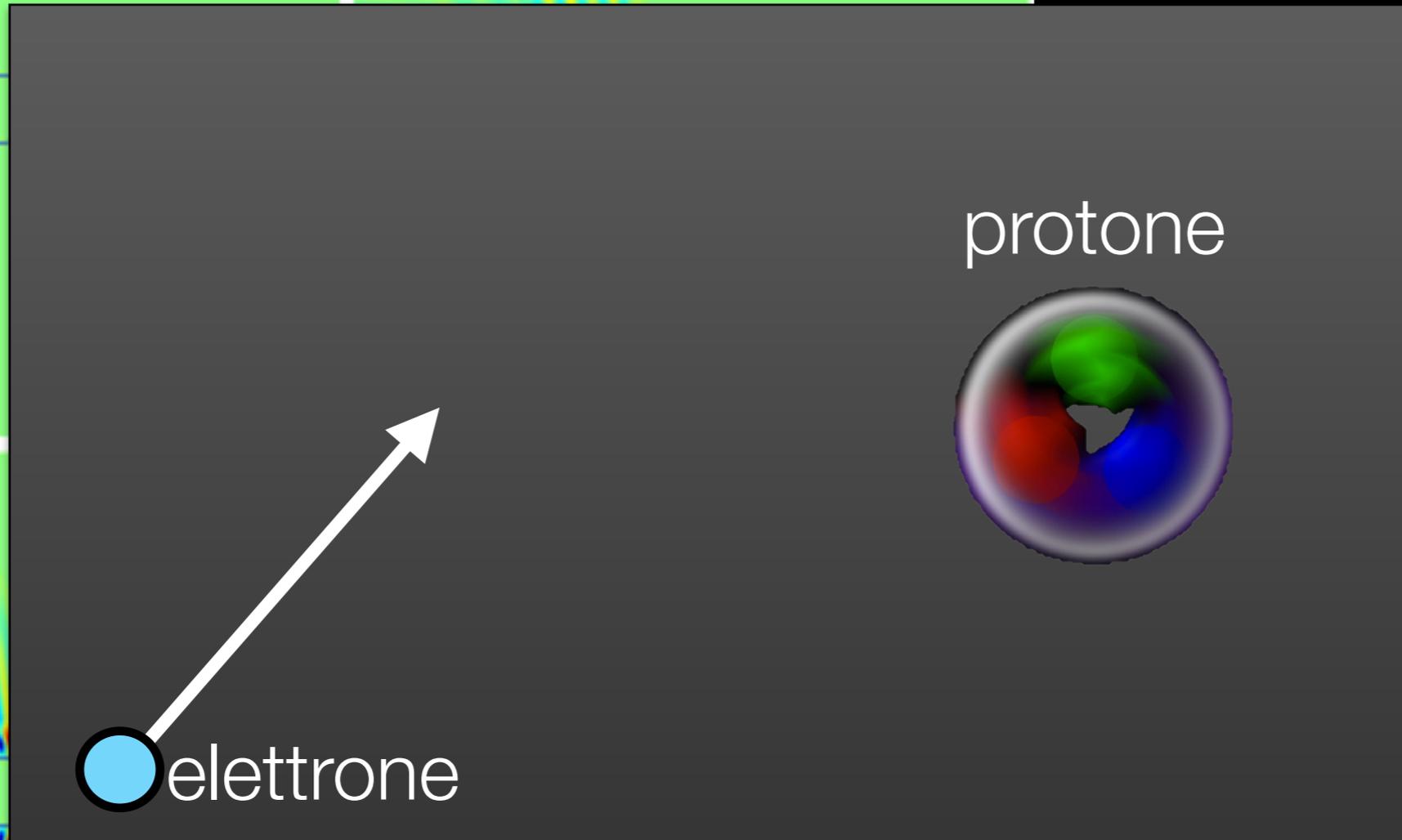
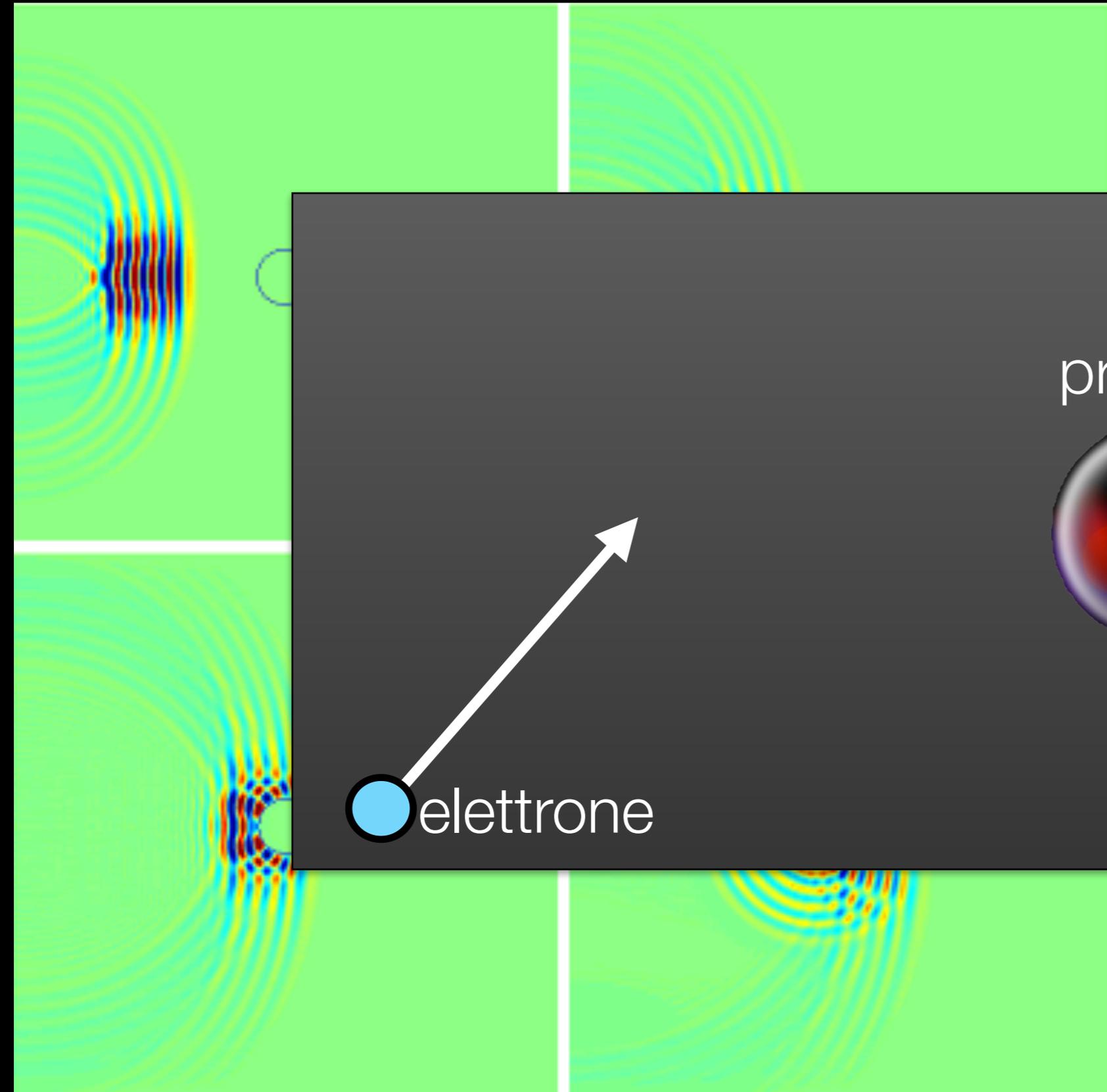


$10^{-15} = 1 \text{ Fermi}$

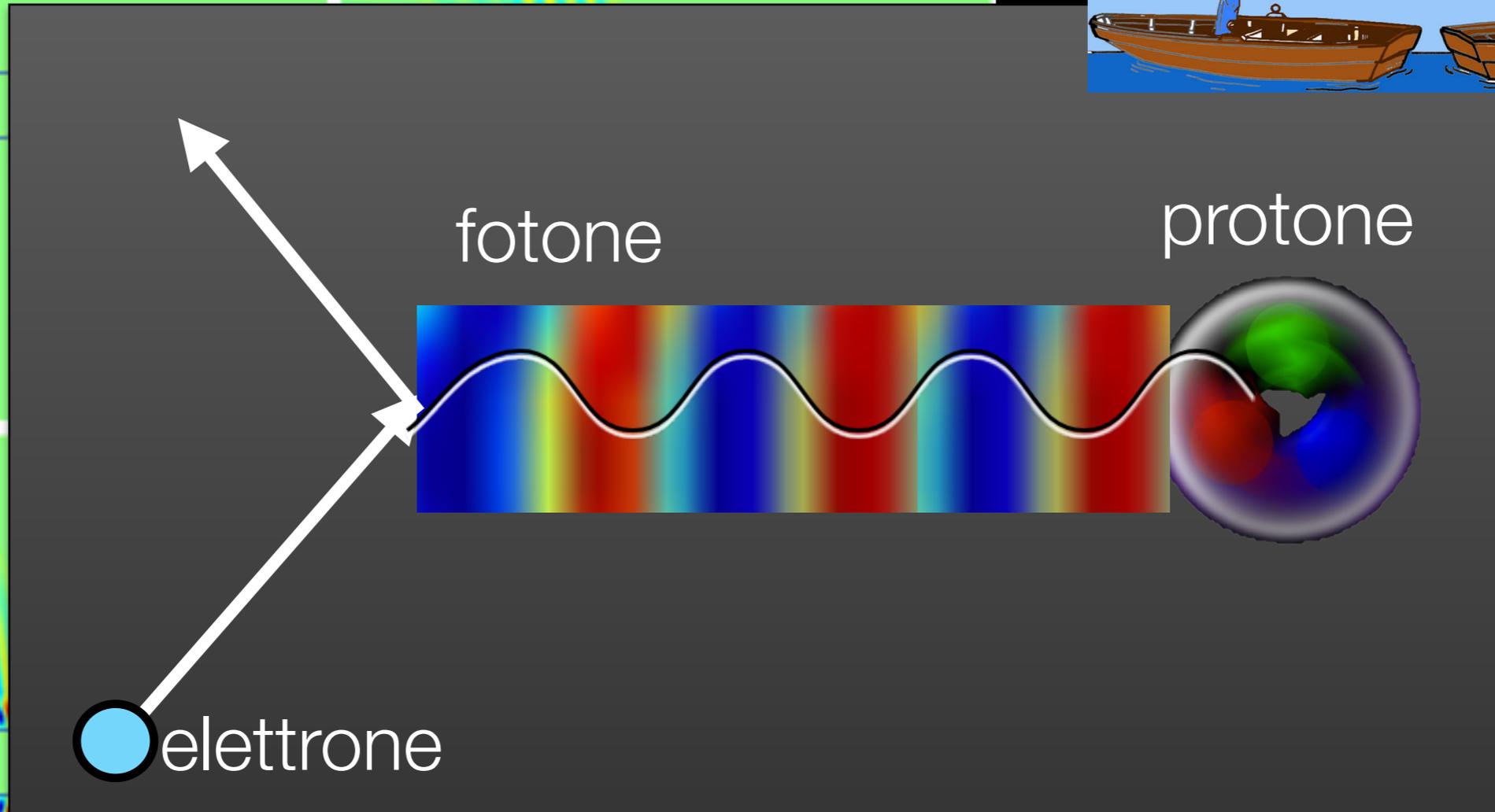
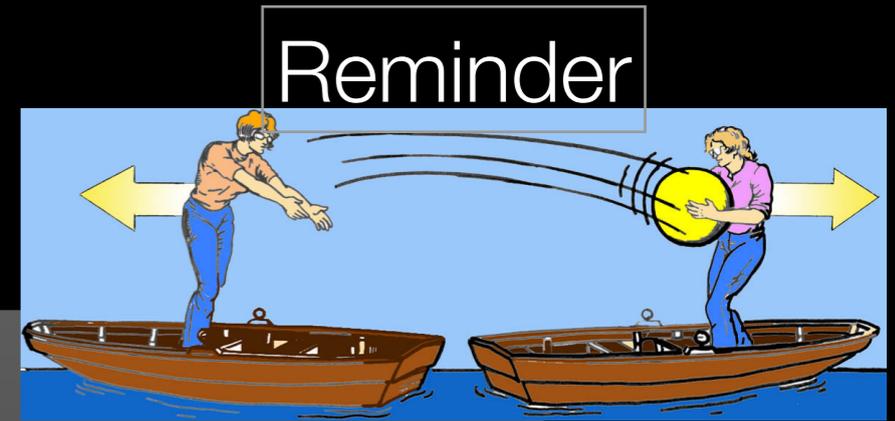
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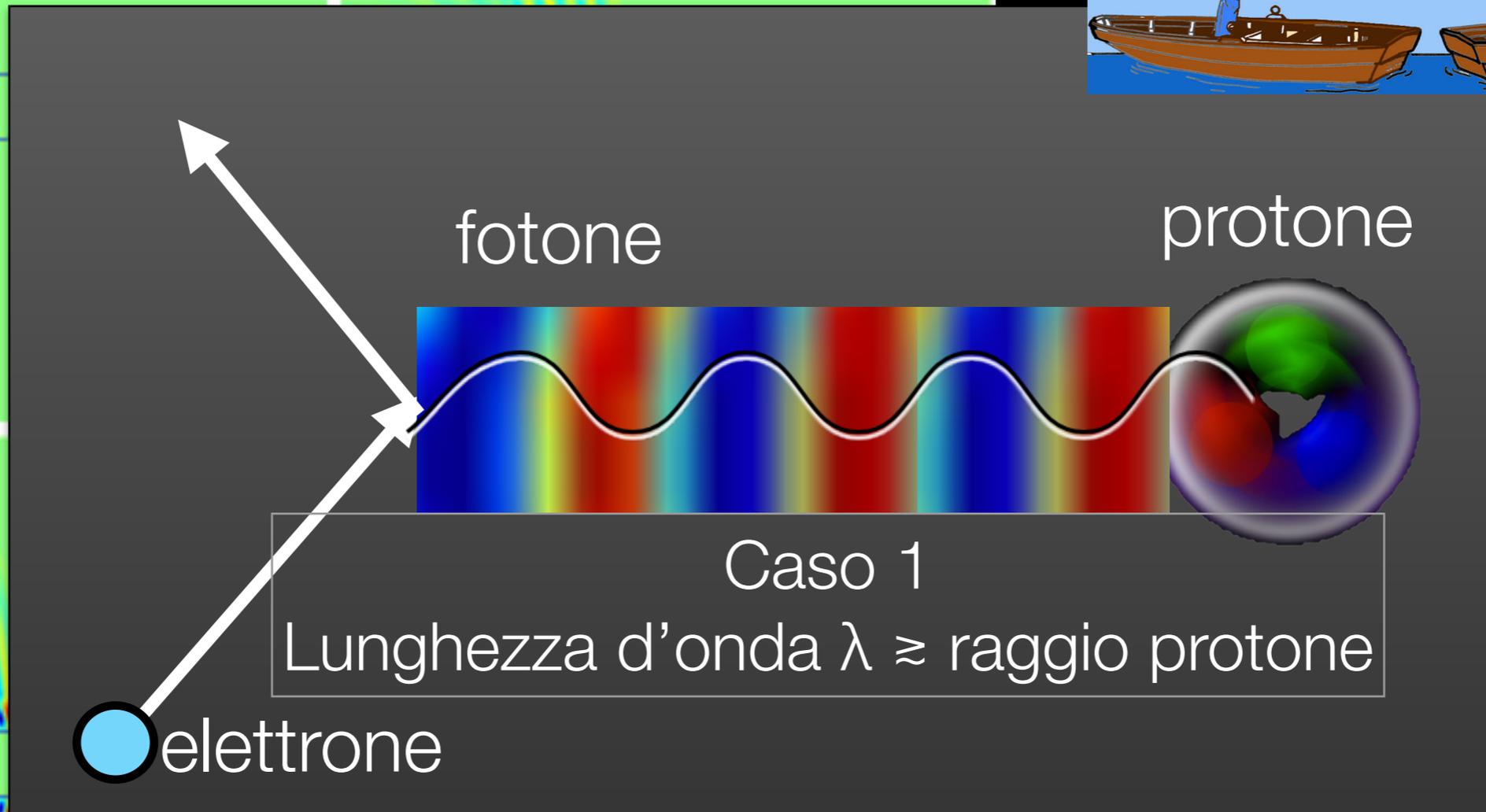
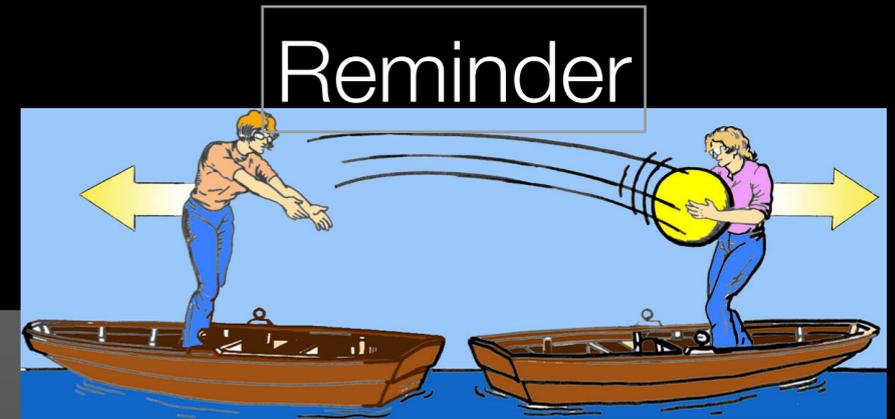


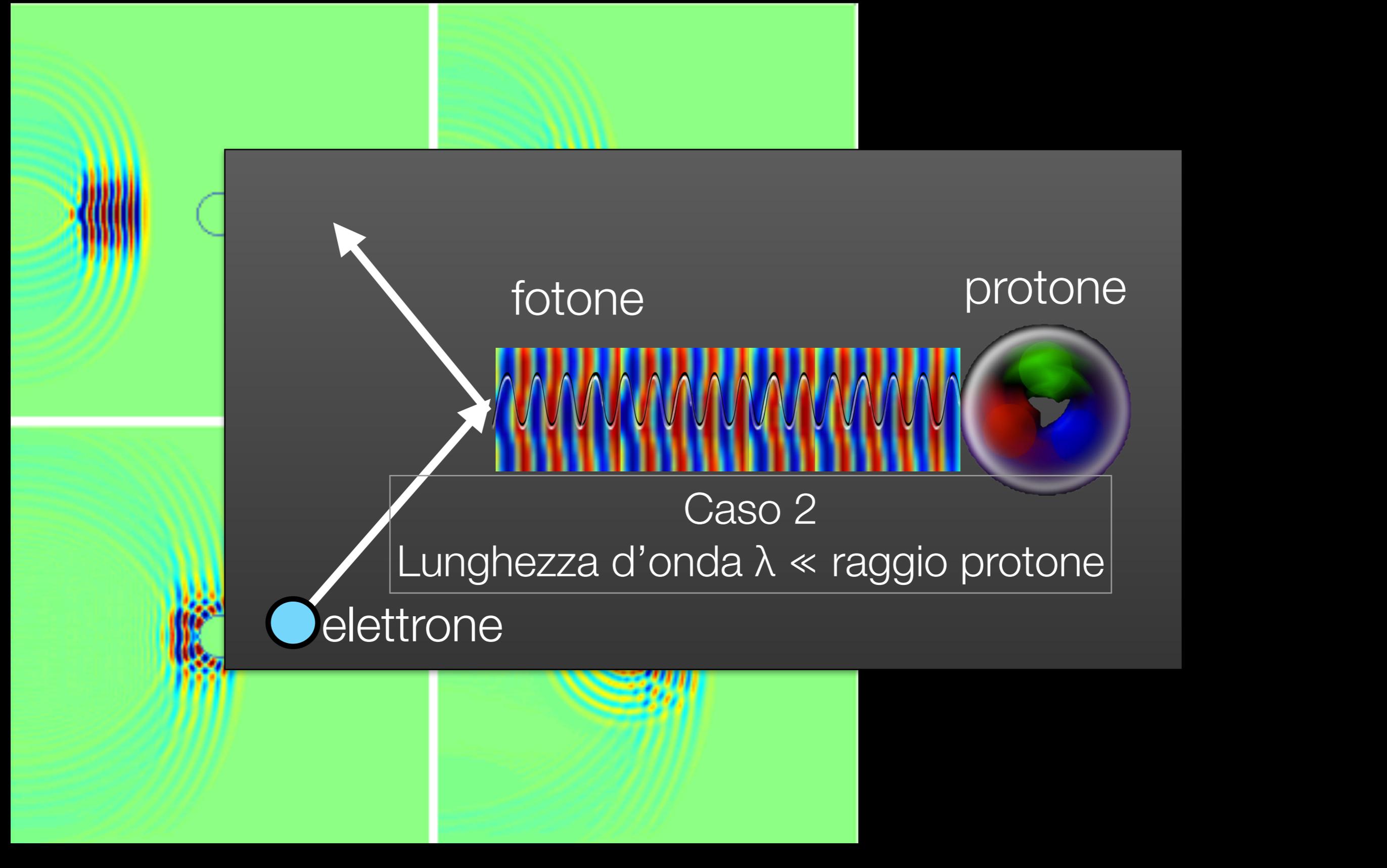
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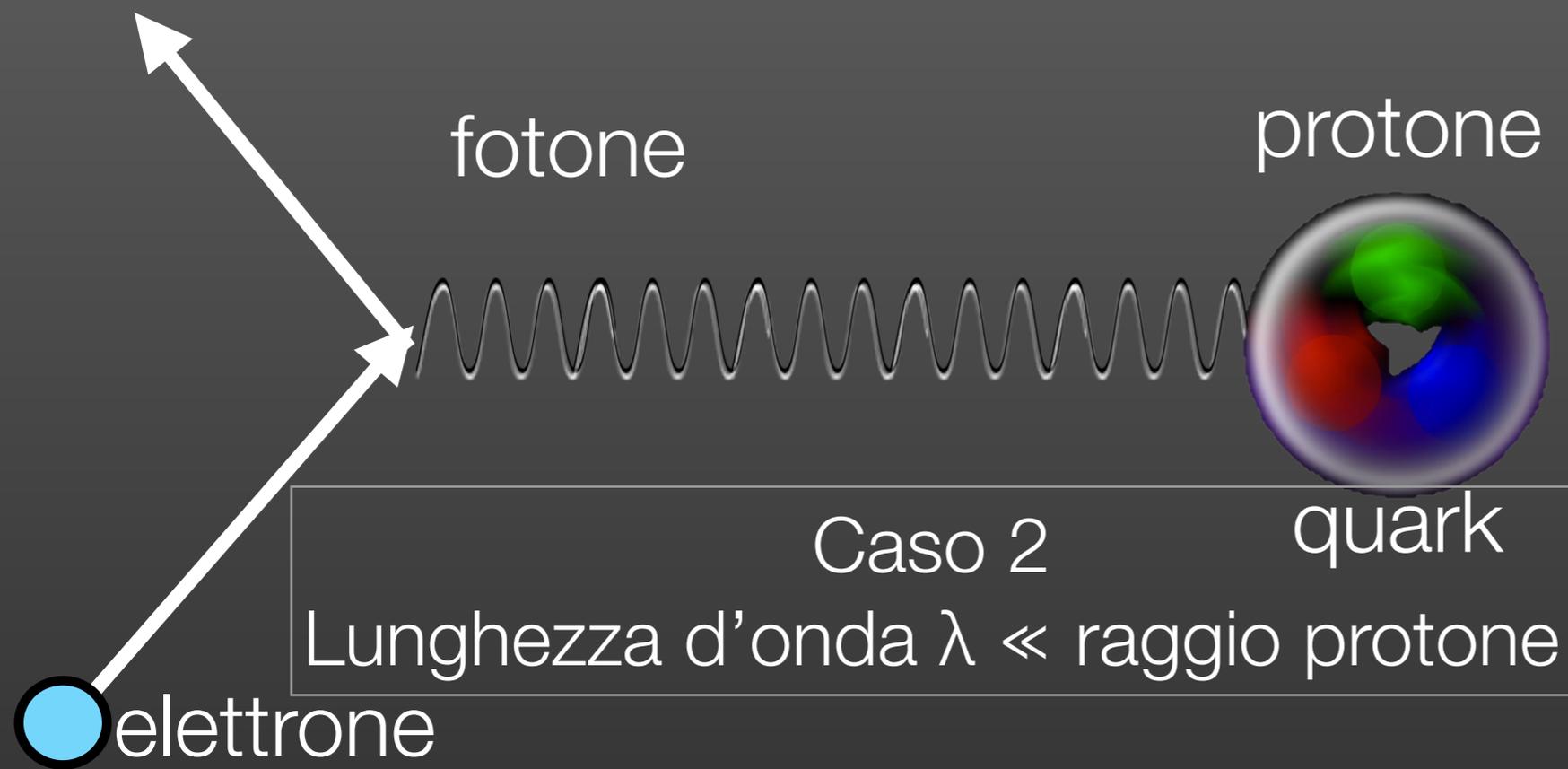
fotone

protone

Caso 2

Lunghezza d'onda $\lambda \ll$ raggio protone

elettrone



$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:
 $\lambda \ll$ 1 fm**

\Rightarrow

$E \gg$ 0.2 GeV

**GeV: 10⁹ eV
1.6 x 10⁻¹⁰ J**

THE THING IS, WE HAVE THIS COLLIDER...

... the quantum magic



THE MAGIC OF A COLLIDER IS THAT YOU CAN MAKE KINDS OF MATTER THAT YOU DON'T HAVE AROUND.

YOU TAKE TWO KINDS OF PARTICLES AND ANNIHILATE THEM...

WHAT COMES OUT DOESN'T HAVE TO BE A RE-ARRANGEMENT OF WHAT WENT IN.



IT'S A KIND OF QUANTUM MAGIC WHERE IT SORT OF DISAPPEARS INTO PURE ENERGY...*

YOU CAN MAKE ANY SORT OF PARTICLE FOR WHICH YOU HAVE ENOUGH ENERGY.

* a force-carrying boson

IT'S LIKE HAVING A MENU...
what can i get in the 500 GeV range?



YOU CAN MAKE ANYTHING THAT COSTS THAT MUCH ENERGY OR LESS.
THAT'S WHY YOU WANT TO HAVE AS MUCH ENERGY AS POSSIBLE.
EVERY TIME YOU CRANK UP THE ENERGY, YOU COULD BE EXPLORING A WHOLE NEW REGIME.

JORGE CHAM © 2012

$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:
 $\lambda \ll 1$ fm**

⇒

E » 0.2 GeV

**GeV: 10⁹ eV
1.6 x 10⁻¹⁰ J**

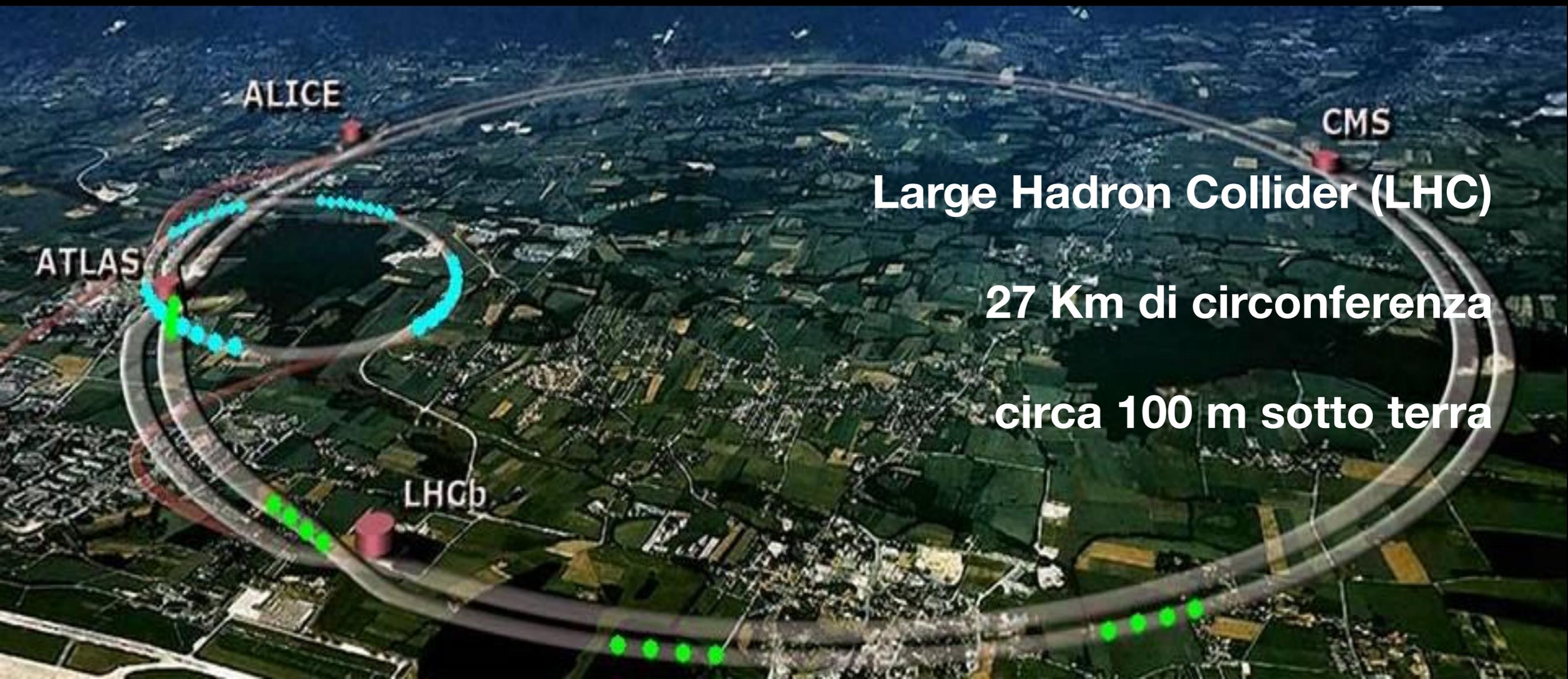
Costruiamo un acceleratore....

Certamente, un gioco da ragazzi se sei un genio, miliardario, playboy, filantropo.

Ma torniamo ai fatti...

A differenza di Toni Stark, nessuno di noi ha un acceleratore di alta energia a casa.

MA, in questo caso, le dimensioni contano!!!



Large Hadron Collider (LHC)

27 Km di circonferenza

circa 100 m sotto terra

Nella realtà non siamo proprio come Tony Stark



Anche se ogni tanto qualcuno



Ma non siamo neanche così:

Anche se ogni tanto qualcuno...



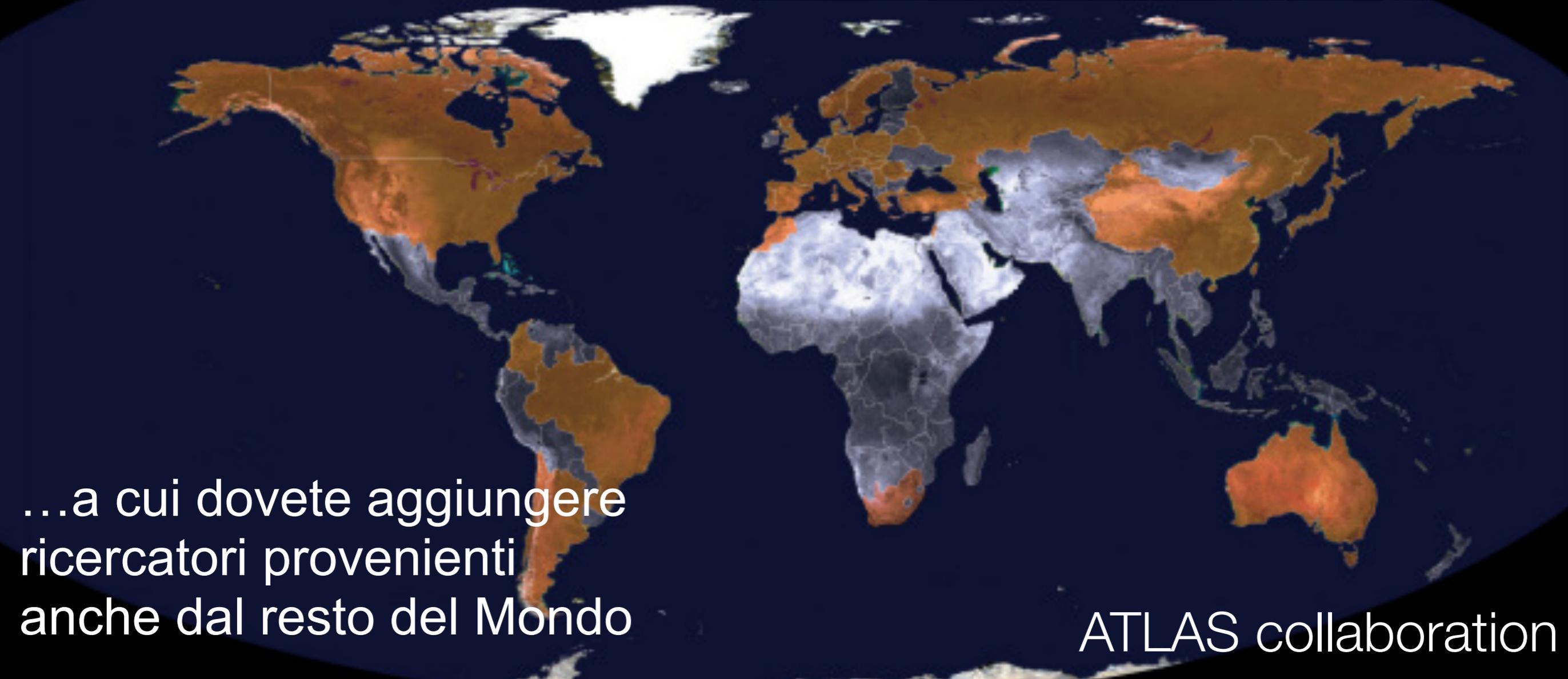
La pulisci tu la lavagna, vero?



Ufficio del gruppo ATLAS di Pisa 2011

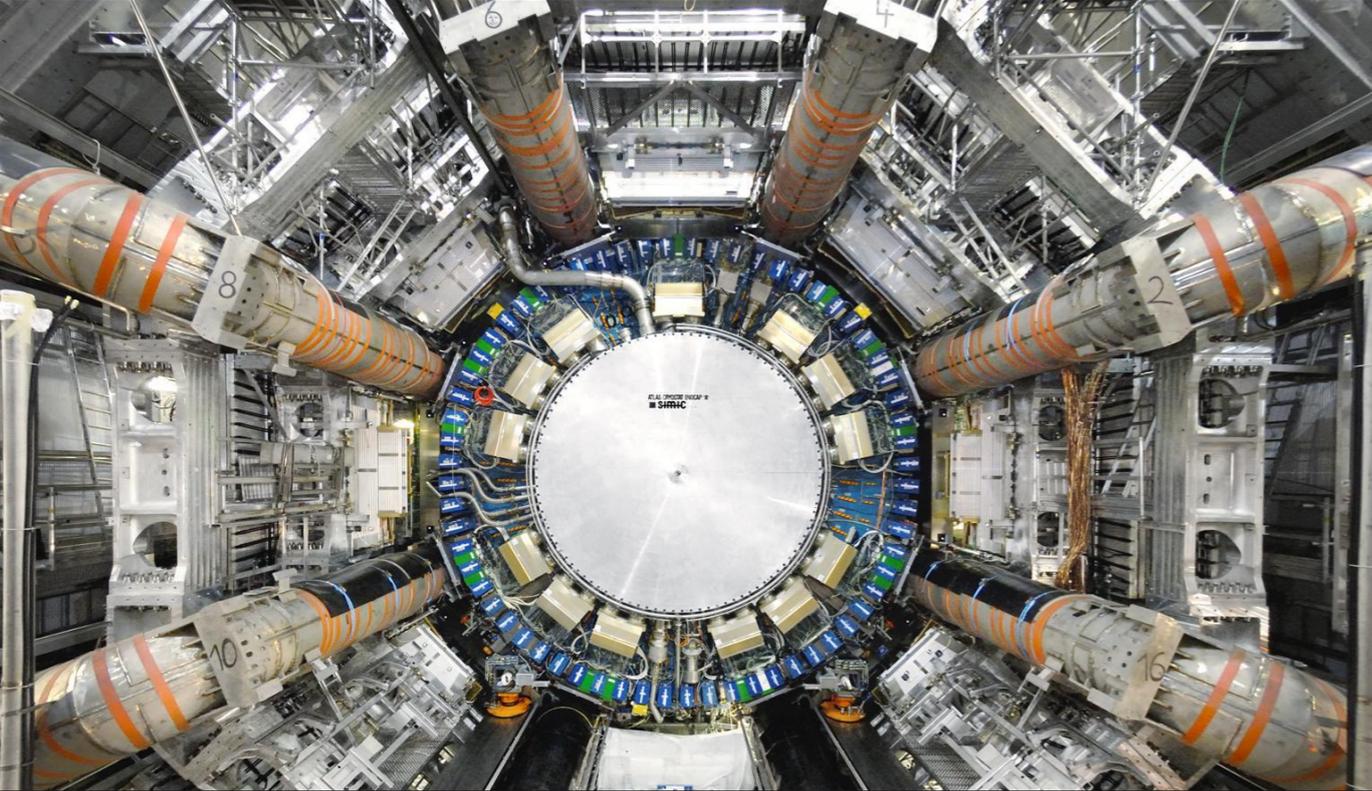
Ma c'è tanta
ricchezza in più

Collaborazioni
internazionali, in alcuni
casi con più di 4000
persone

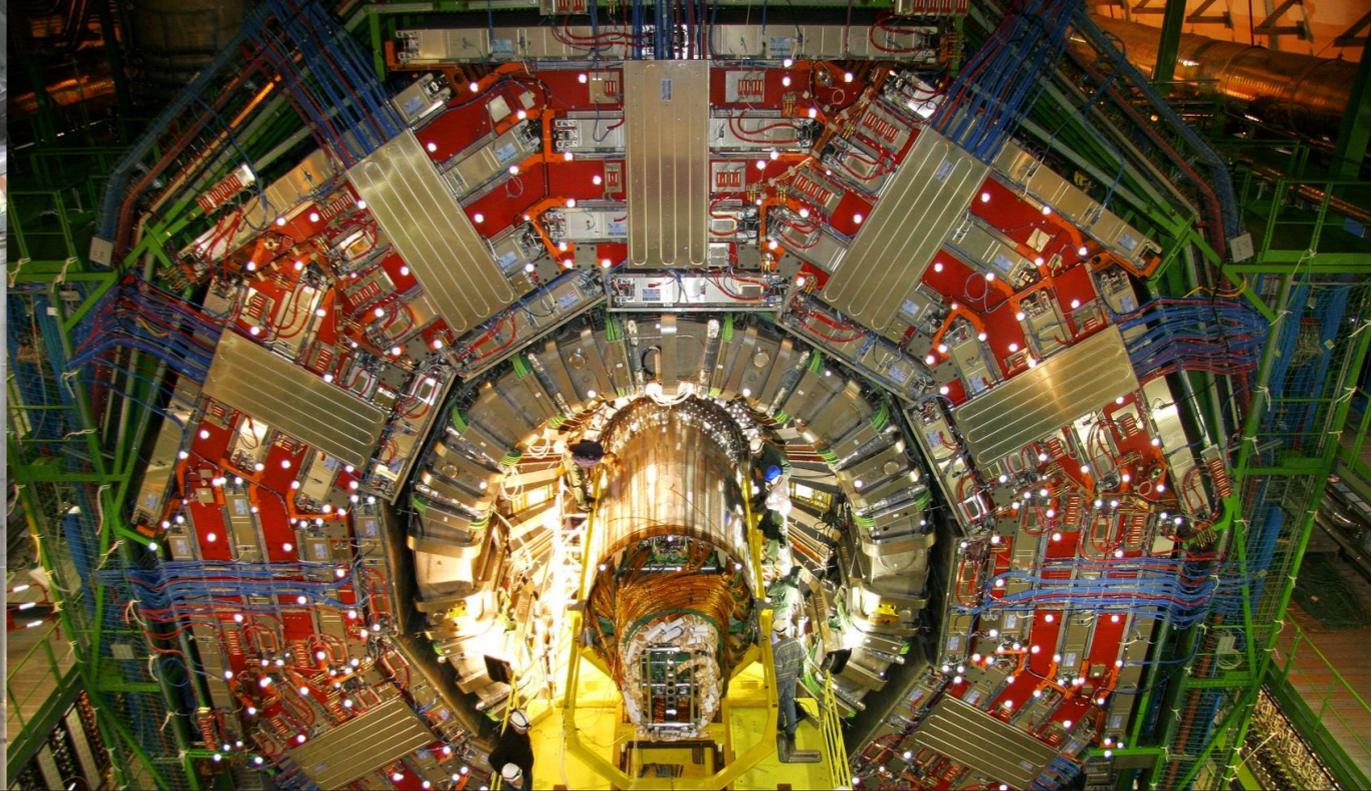


...a cui dovete aggiungere
ricercatori provenienti
anche dal resto del Mondo

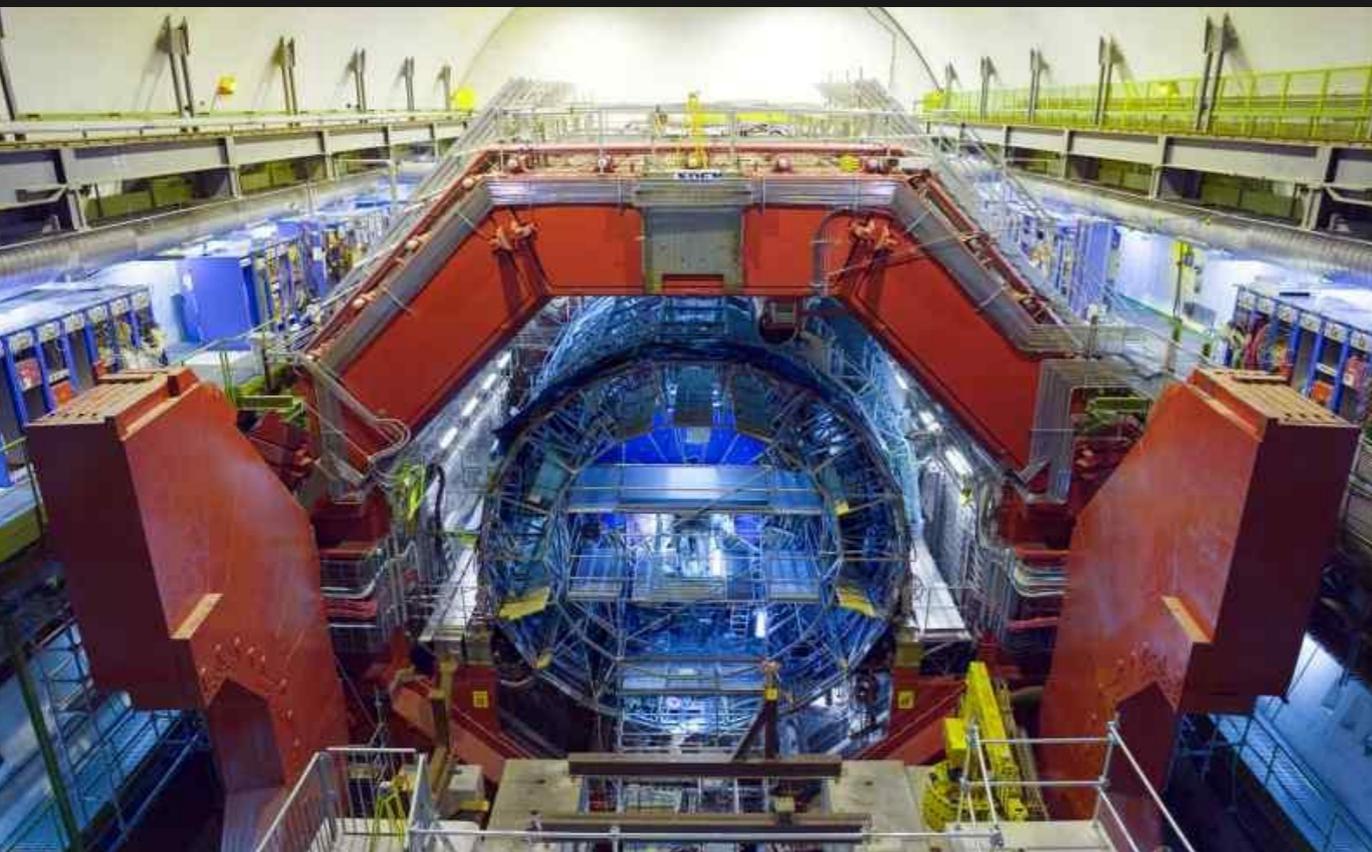
ATLAS collaboration



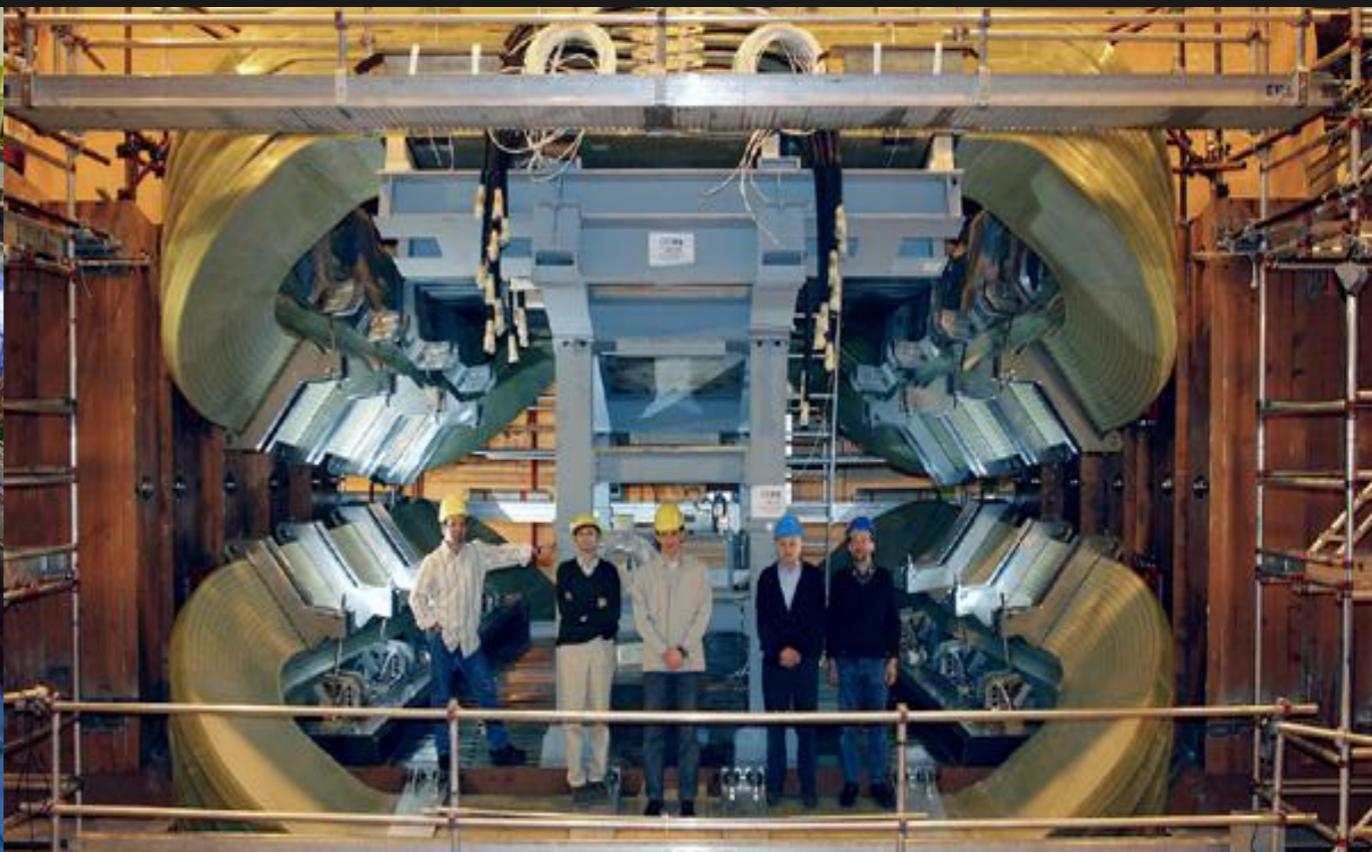
ATLAS



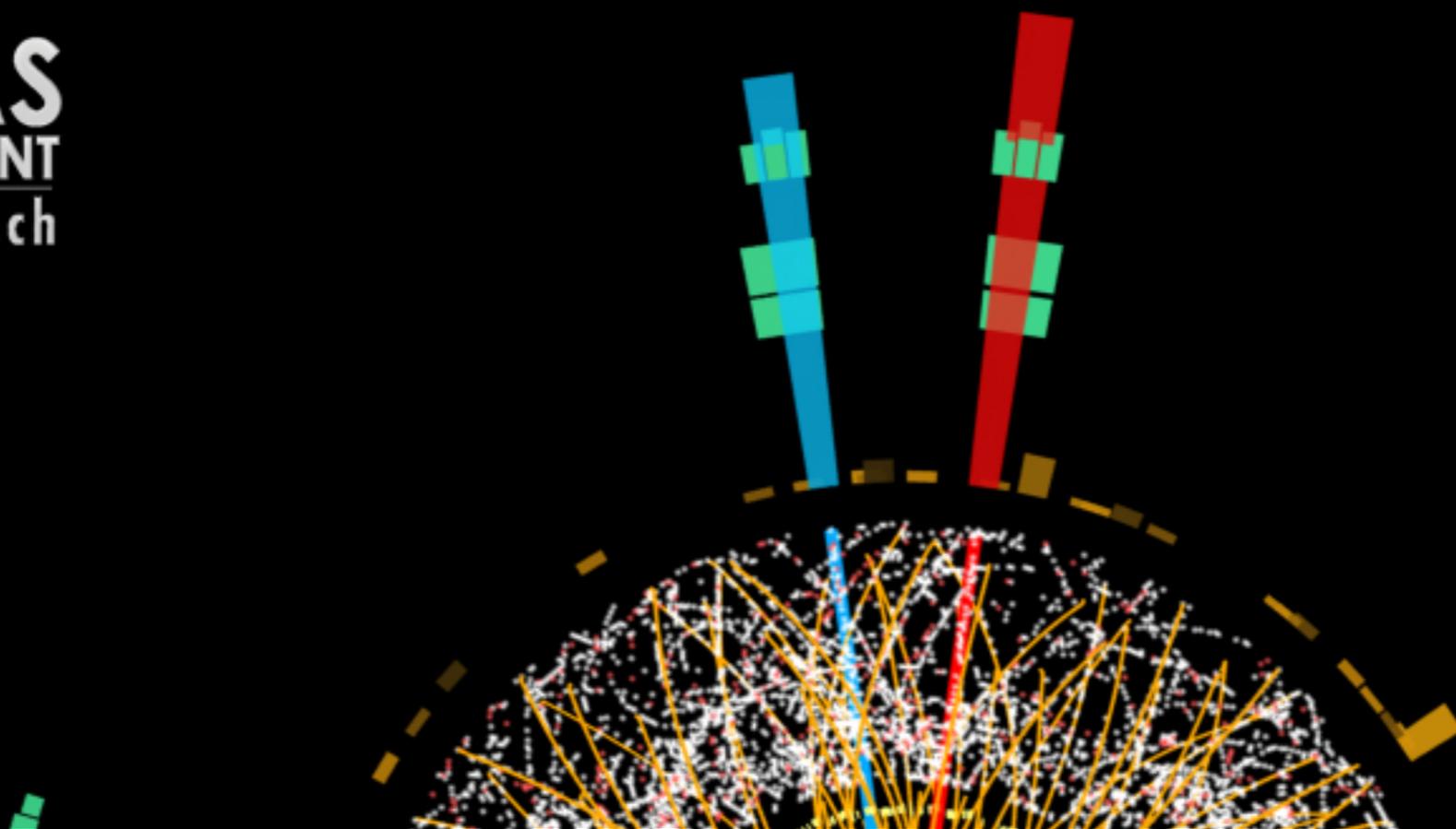
CMS



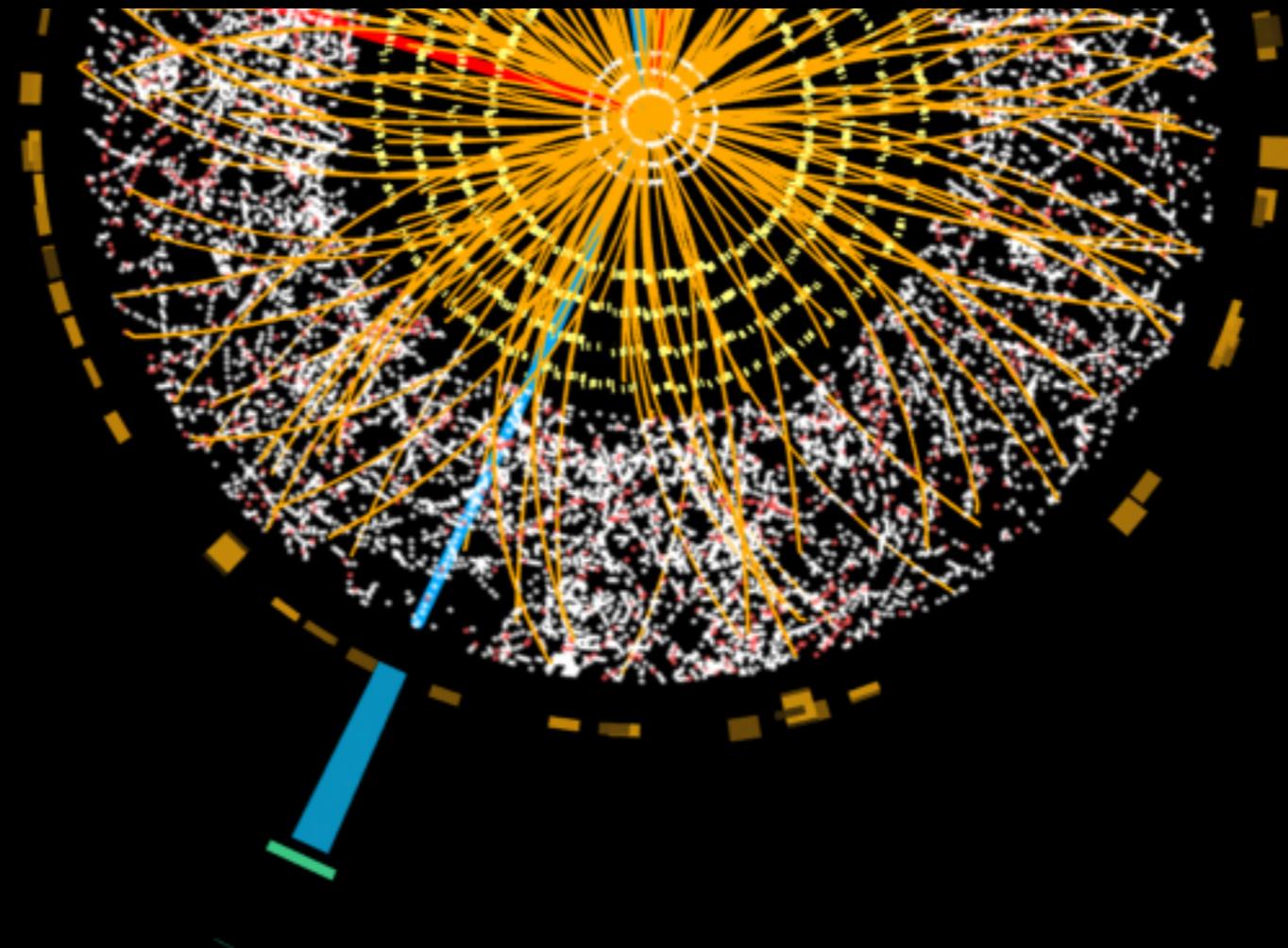
ALICE



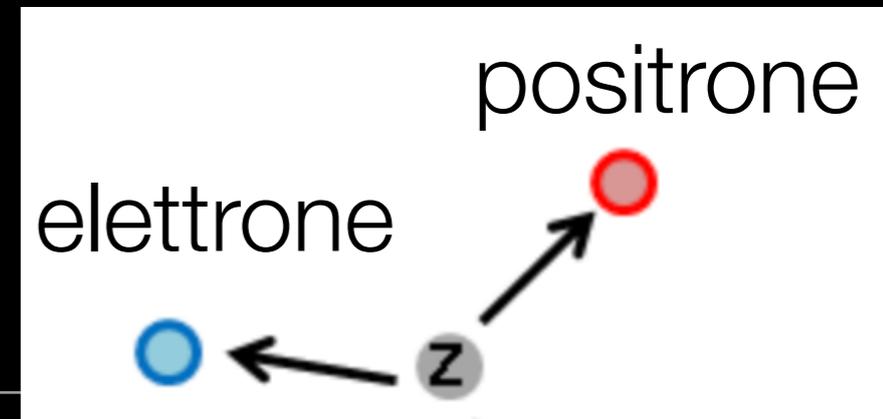
LHCb



Dati e scoperte



Decadimento



Molte delle particelle subatomiche che studiamo sono instabili

Decadono spontaneamente in altre particelle (a loro volta instabili o stabili) dette prodotti del decadimento

È un evento probabilistico che avviene dopo un certo tempo.
Il valor medio di questo tempo si chiama vita media della particella.

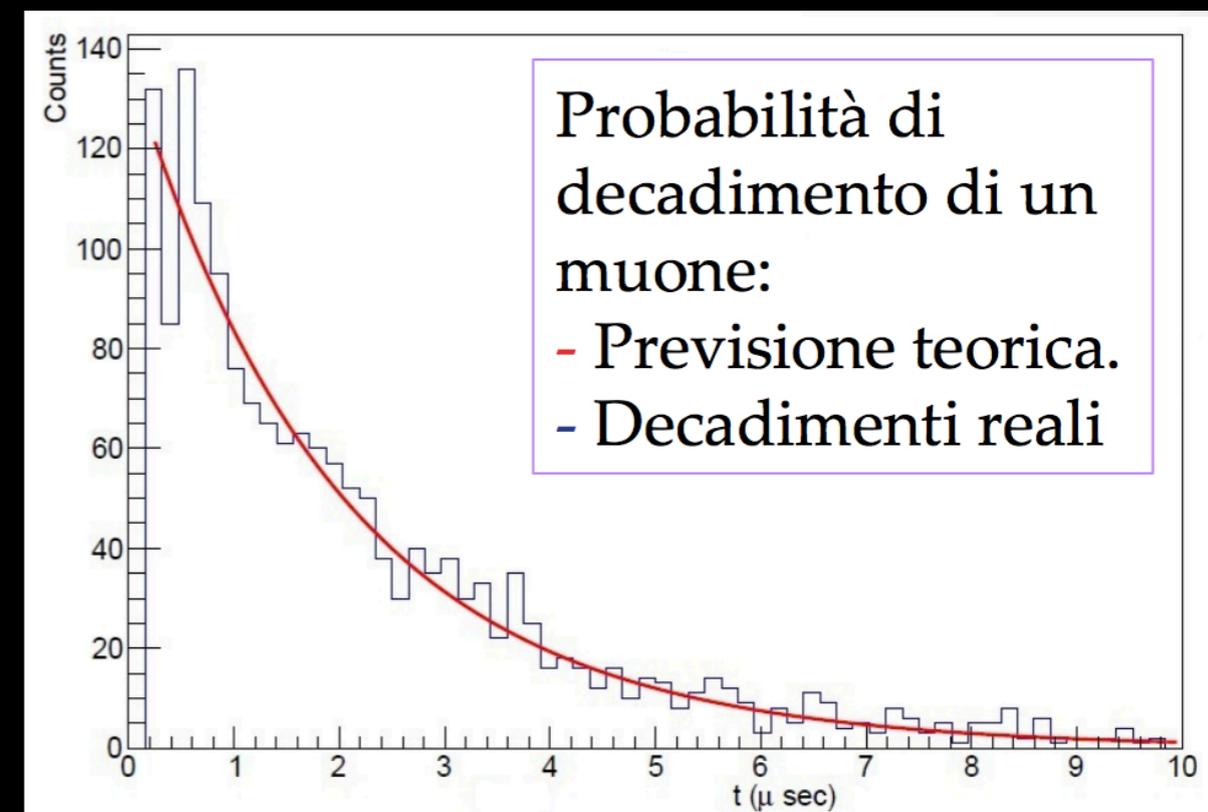
Vita media del bosone Z:

0.2 ys (0.2×10^{-24} s)

Vita media del muone μ :

2.2 μ s (2.2×10^{-6} s)

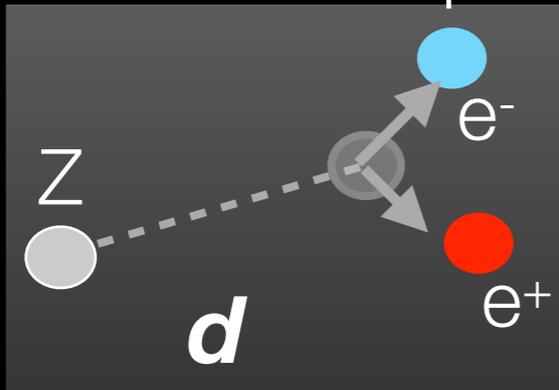
L'andamento temporale è rappresentato da una curva che chiamiamo esponenziale



Vita media della Z: é tanto o poco?

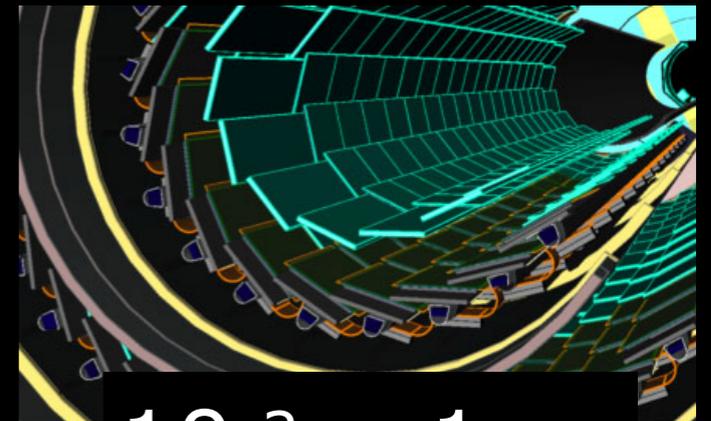
Per una Z con impulso di 1000 GeV la distanza media percorsa prima di decadere ($d = v \times t$) é circa **$d \sim 1 \text{ fm}$ (10^{-15} m)**

I sensori di ATLAS piú vicini al punto di produzione della Z sono a circa **3.3 cm**

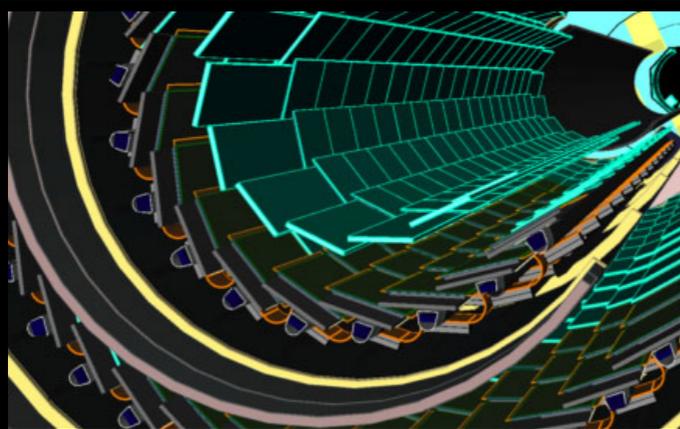


$$10^{-15} = 1 \text{ fm}$$

=



$$10^{-2} = 1 \text{ cm}$$



$$10^{-2} = 1 \text{ cm}$$



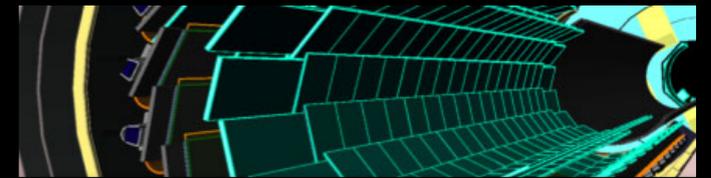
$$10^{11} = 100 \text{ M km}$$

Per un muone da 1000 GeV, $d \sim 6500 \text{ km}$ - é praticam. stabile per ATLAS

Vita media della Z: é tanto o poco?

Per una Z con impulso di 1000 GeV la distanza media percorsa prima di decadere ($d = v \times t$) é circa **$d \sim 1 \text{ fm}$ (10^{-15} m)**

I sensori di ATLAS piú vicini al punto di produzione della Z sono a circa **3.3 cm**



La probabilità che un bosone Z arrivi ad interagire con il rivelatore é praticamente nulla.

Se vogliamo scoprire e studiare il bosone Z, dobbiamo puntare sui suoi prodotti di decadimento.

I prodotti del decadimento, se sono particelle stabili, possono essere misurati e ci raccontano qualcosa delle particelle madri

$$10^{-2} = 1 \text{ cm}$$

$$10^{11} = 100 \text{ M km}$$

Per un muone da 1000 GeV, $d \sim 6500 \text{ km}$ - é praticam. stabile per ATLAS

Massa invariante

Ingredienti:

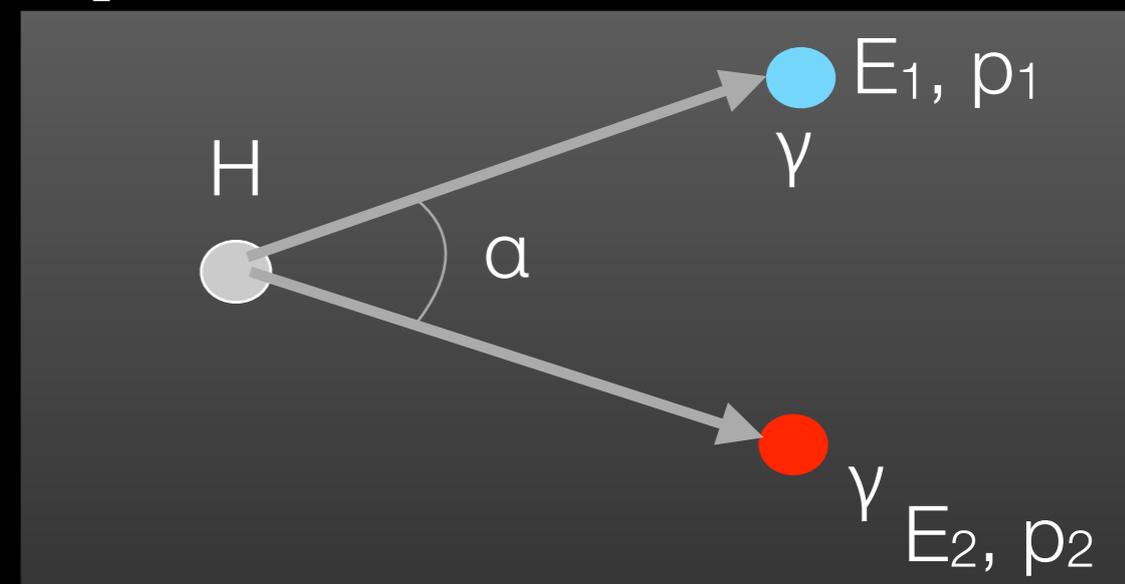
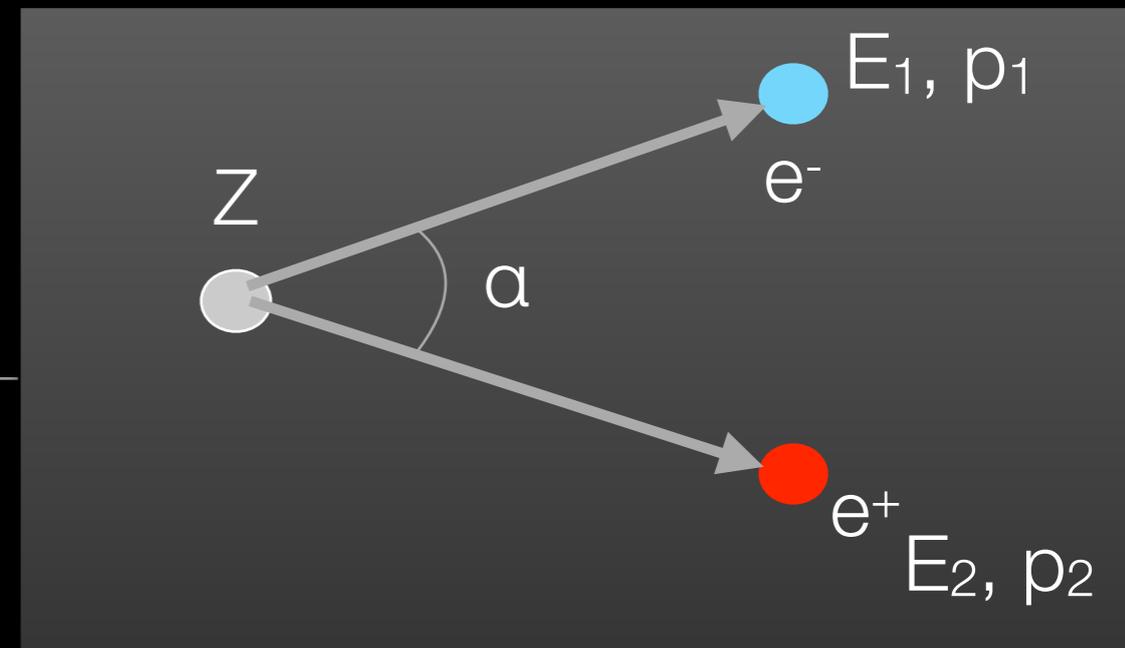
- l'energia E si conserva
- il momento p si conserva
- $E=mc^2$
- un po' di relatività ristretta

Se misuriamo l'energia e l'impulso dei prodotti di decadimento, possiamo calcolare il valore della massa della particella madre nel sistema di riferimento a riposo. **Questa si chiama massa invariante**

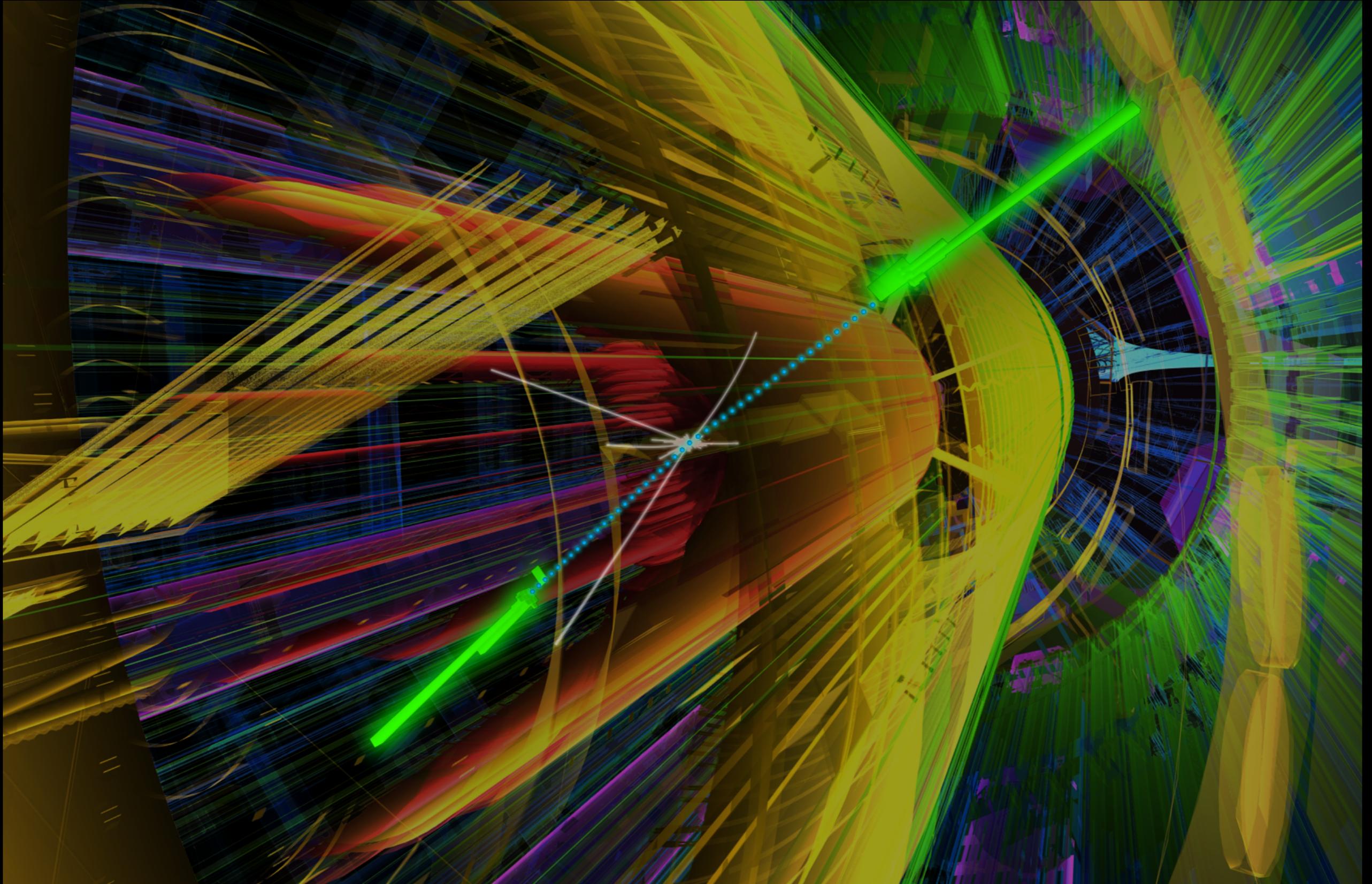
$$M^2_Z = 2 E_1 E_2 - 2 p_1 p_2 \cos \alpha$$

per Z $M_Z \sim 90$ GeV

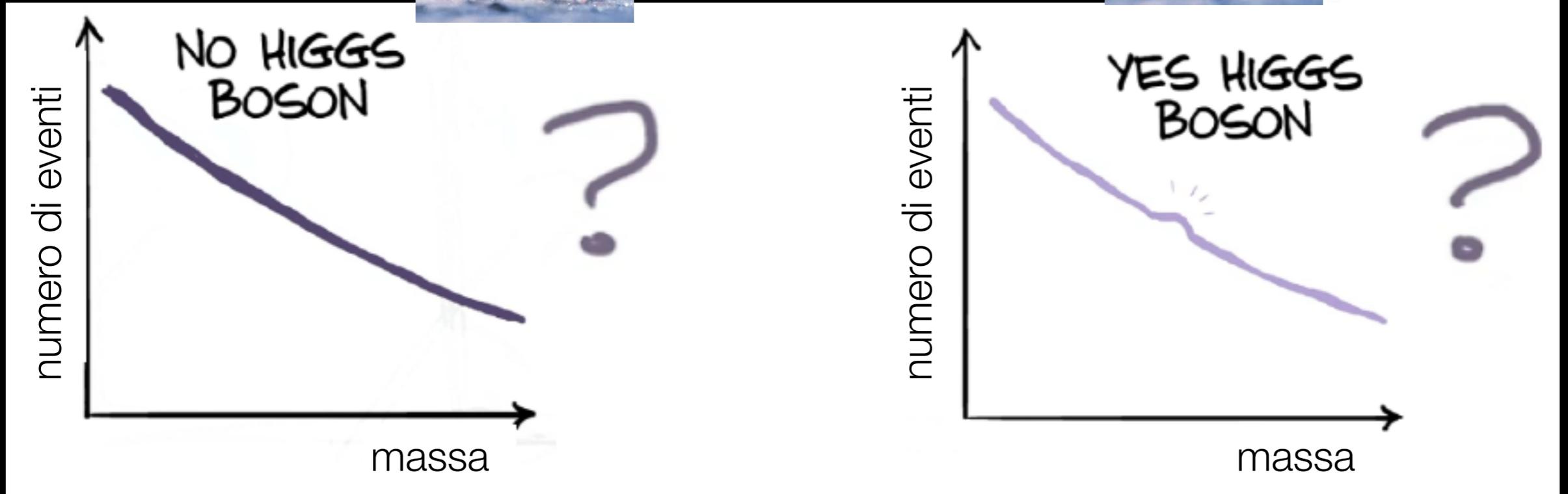
per Higgs boson: $M_H \sim 125$ GeV



Higgs in 2 fotoni



Come stabilire una scoperta

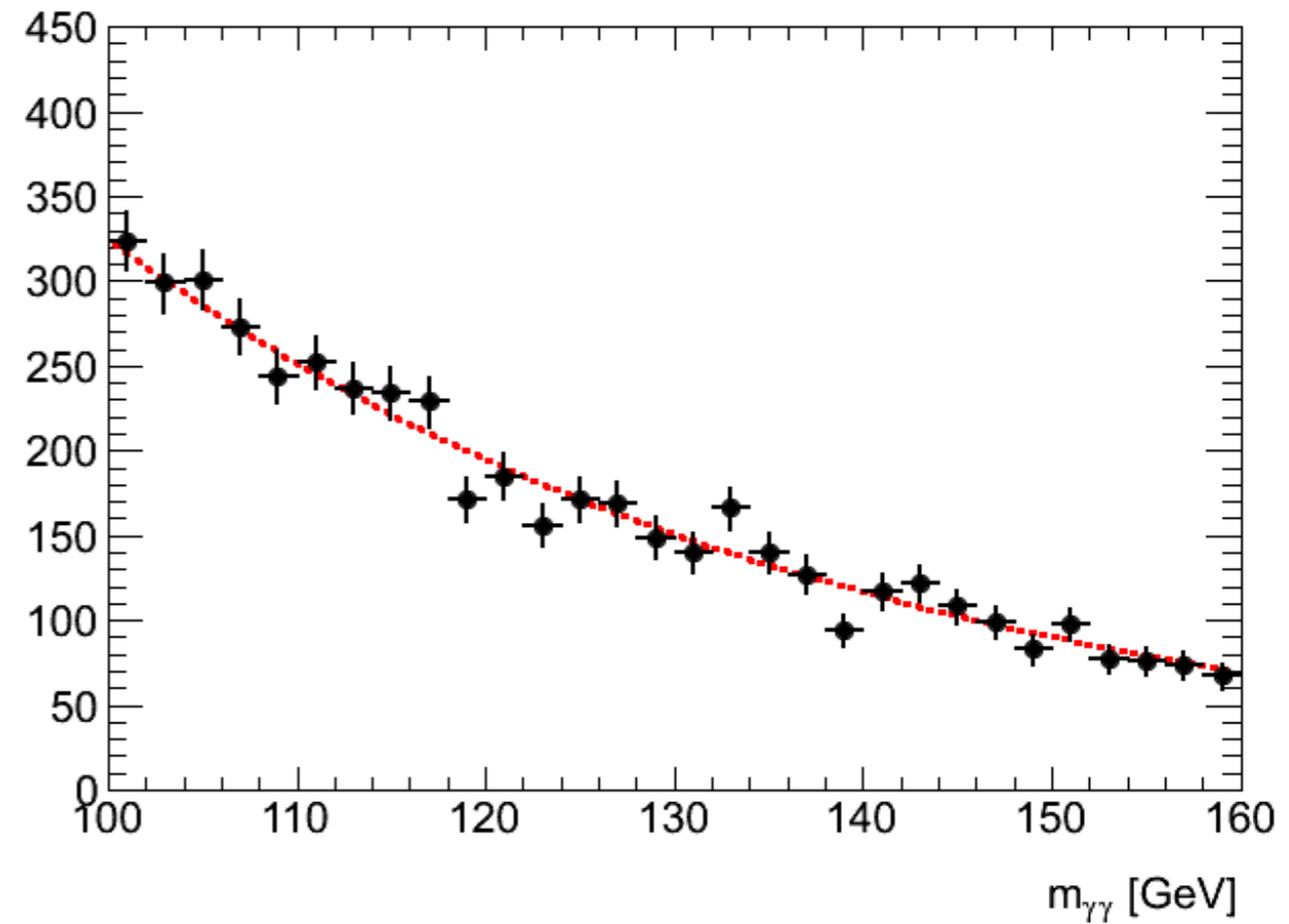
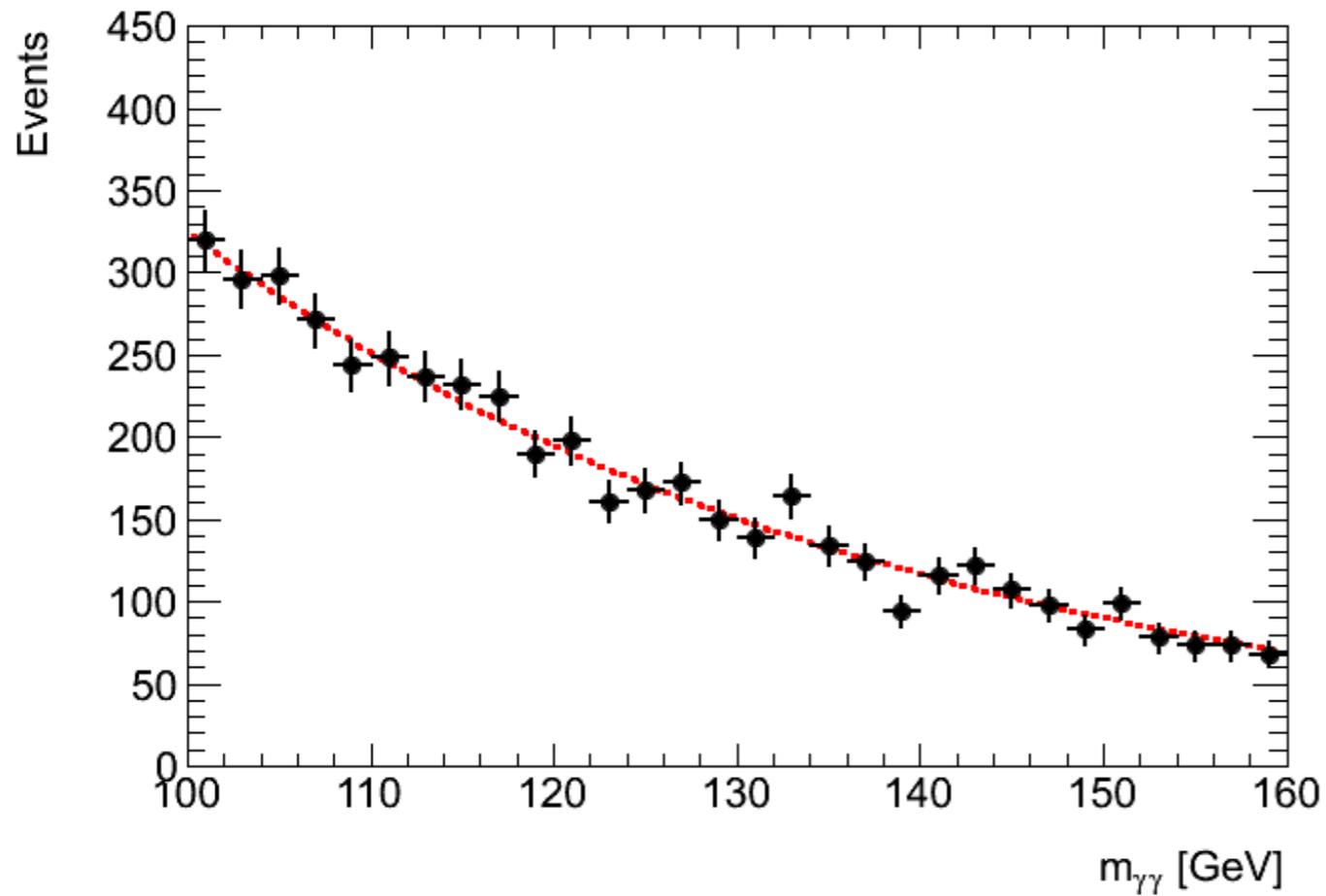


Valutare la probabilità che il fondo possa formare un falso segnale dovuto a fluttuazioni statistiche.

Come dipende questo con il numero di eventi?

Facciamo l'analisi insieme

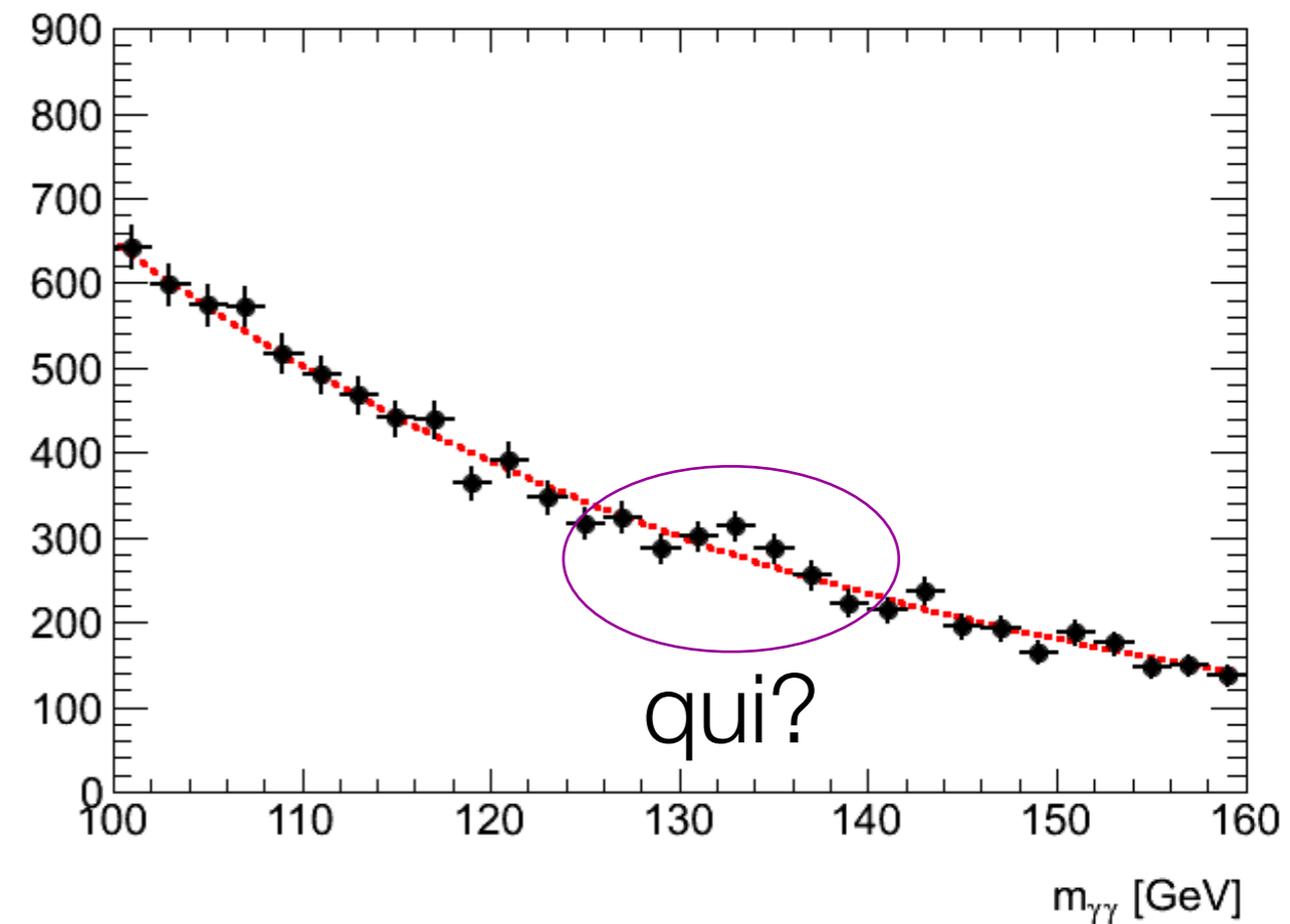
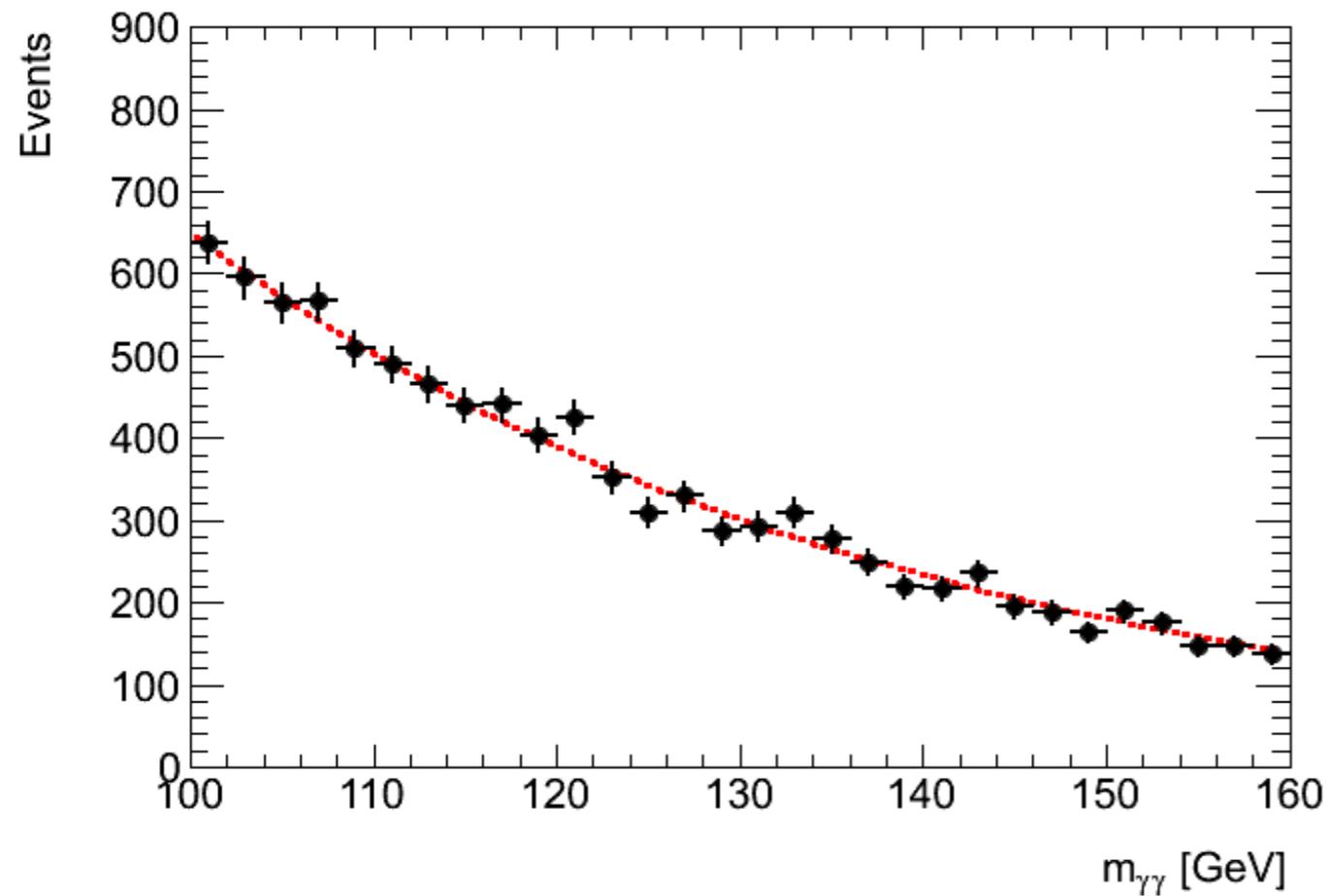
~100 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

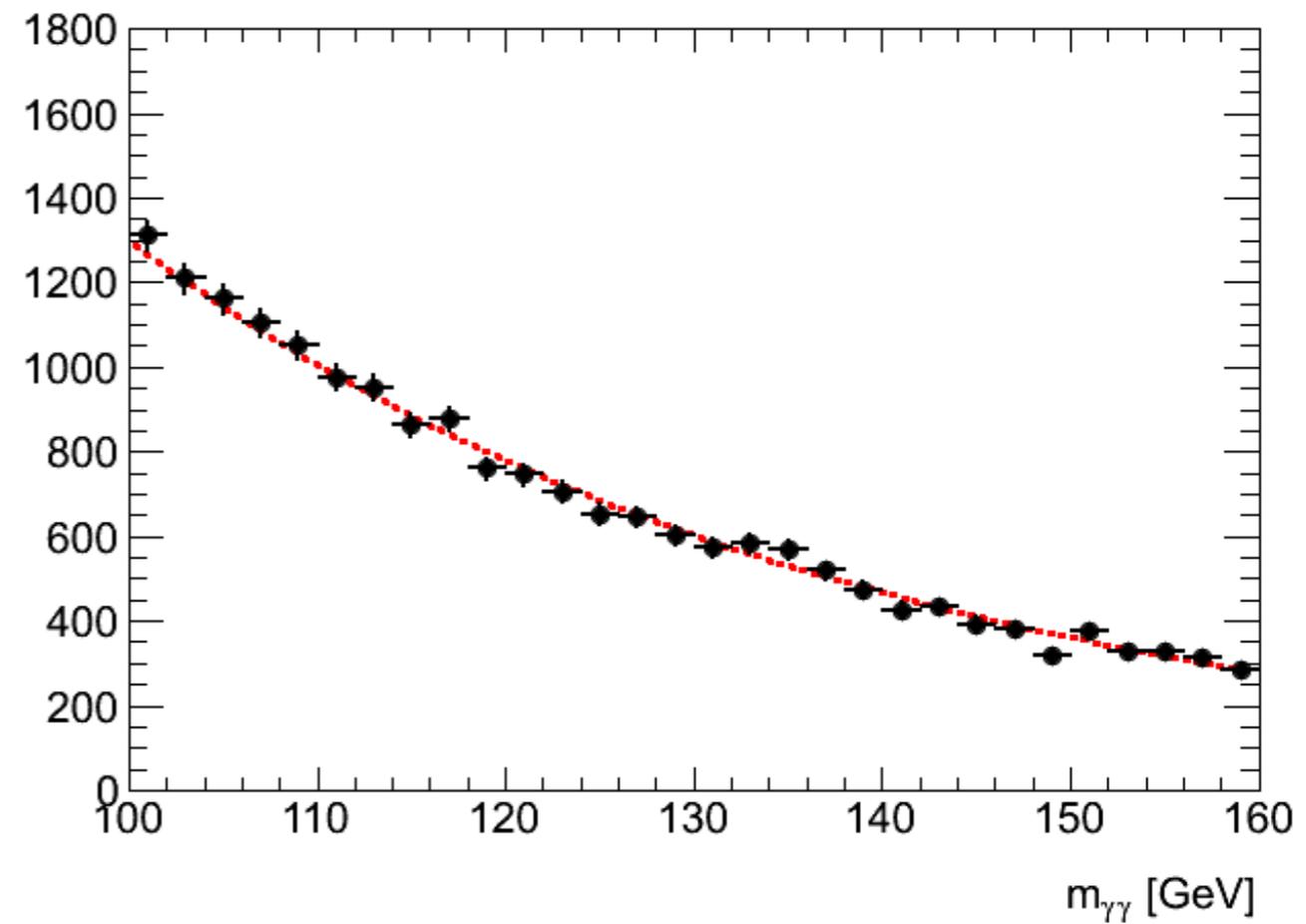
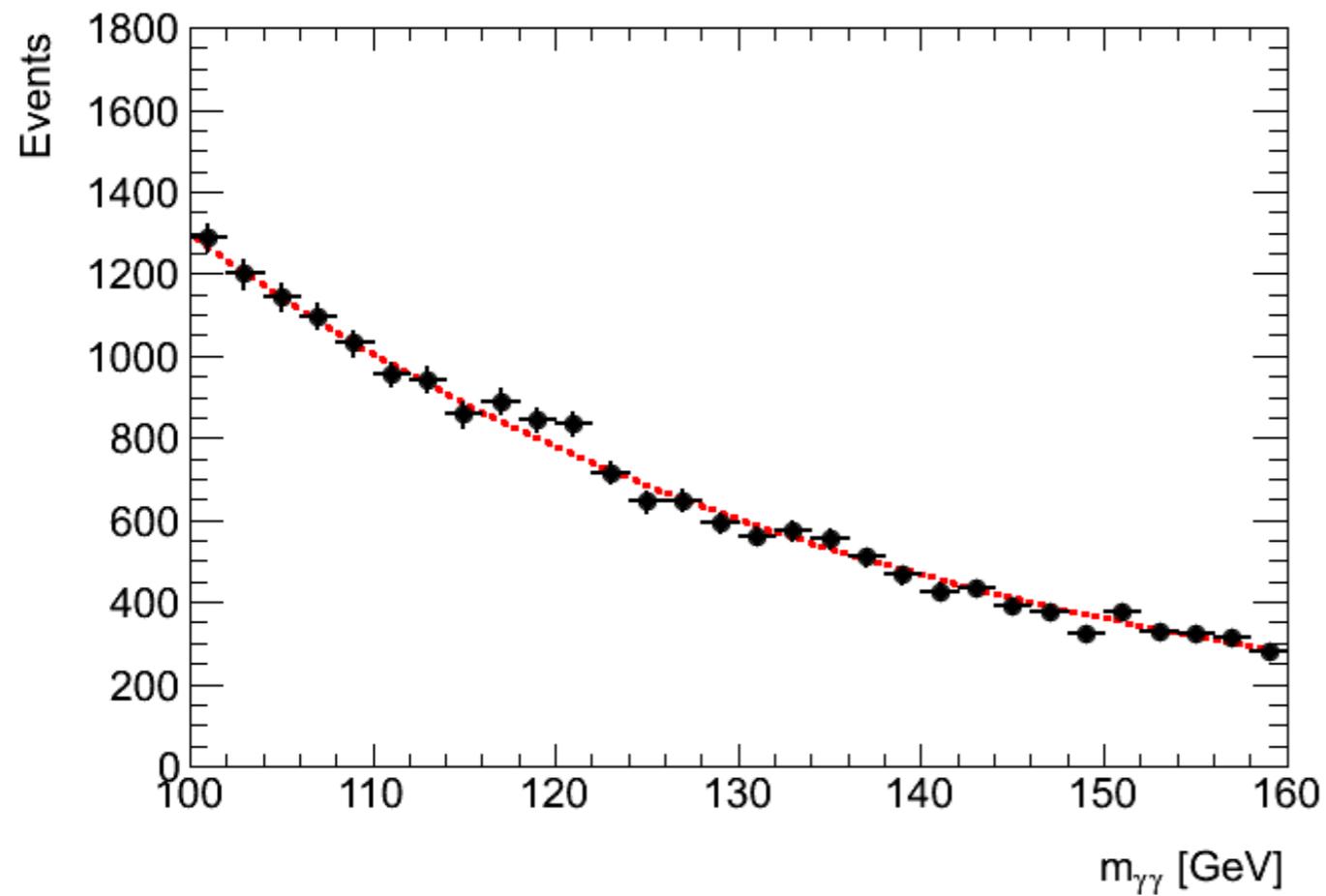
~200 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

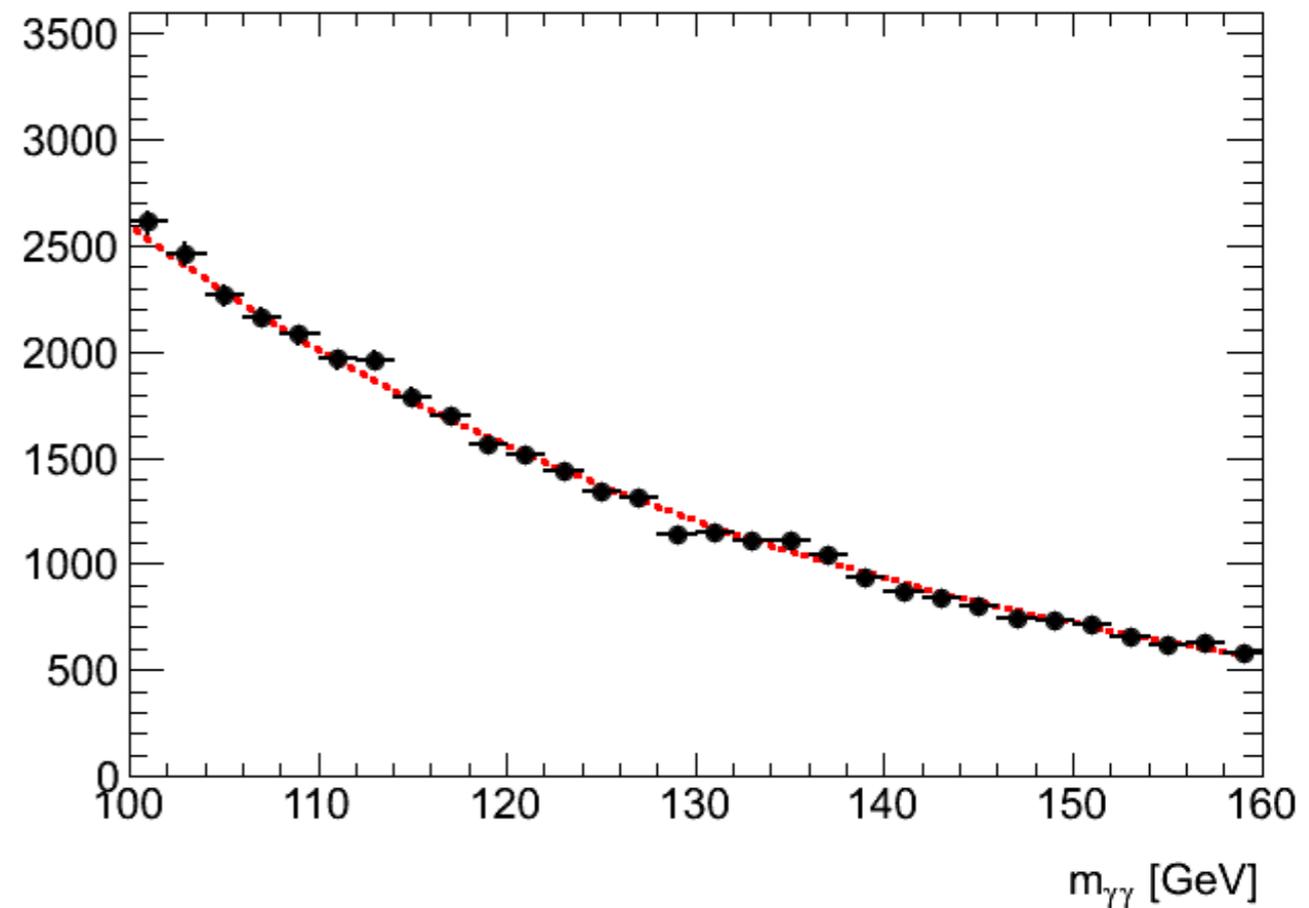
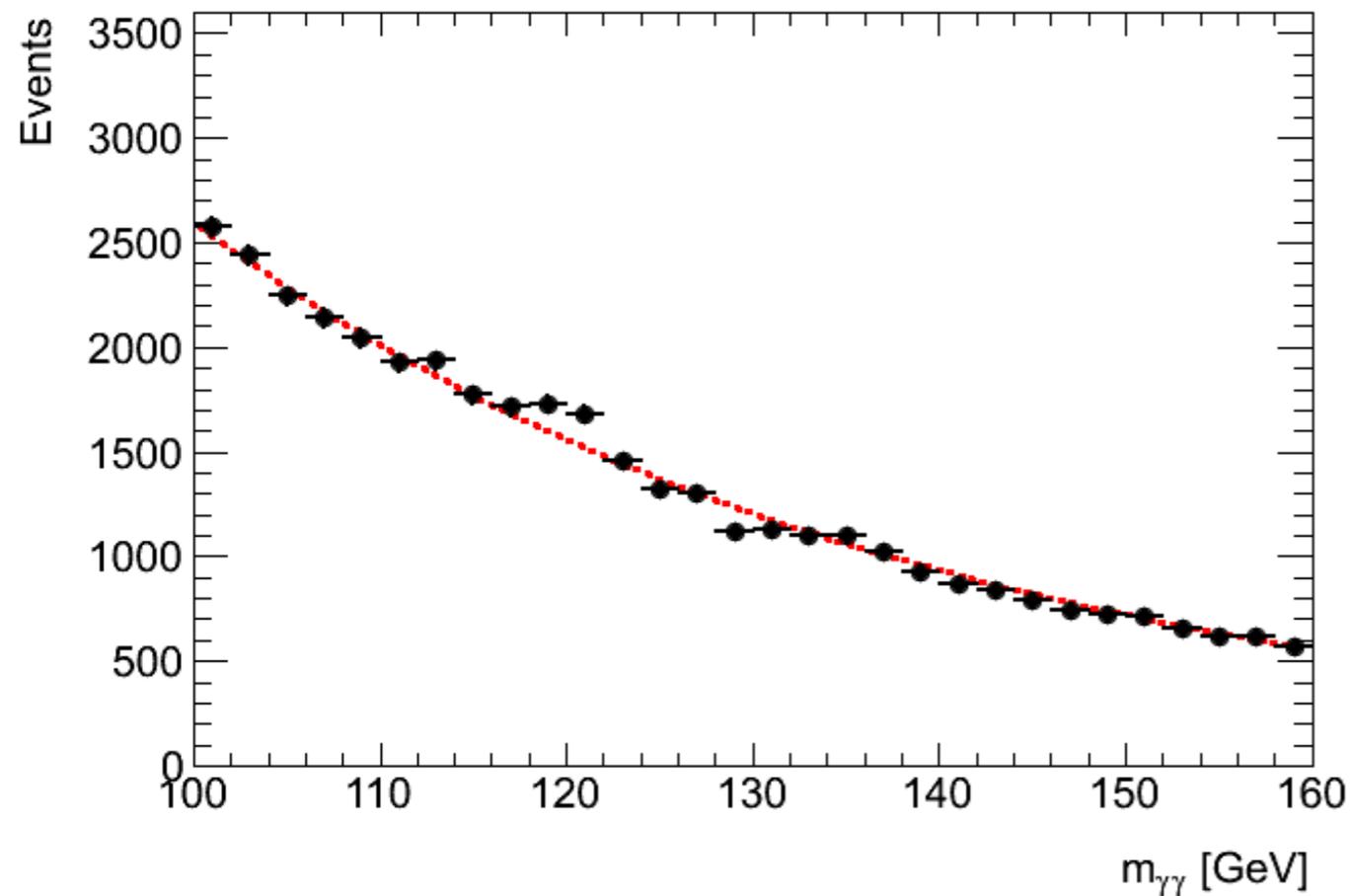
~400 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

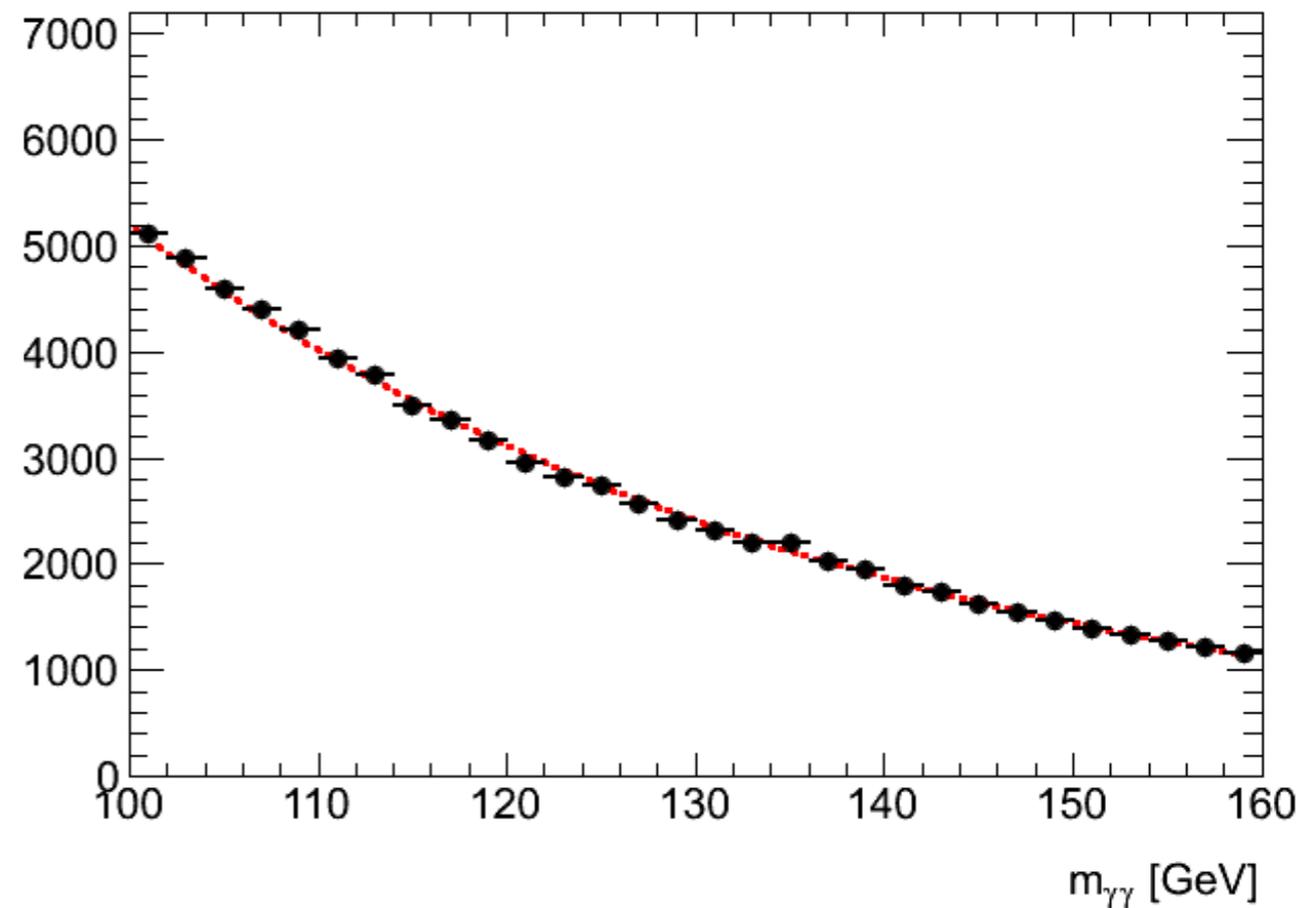
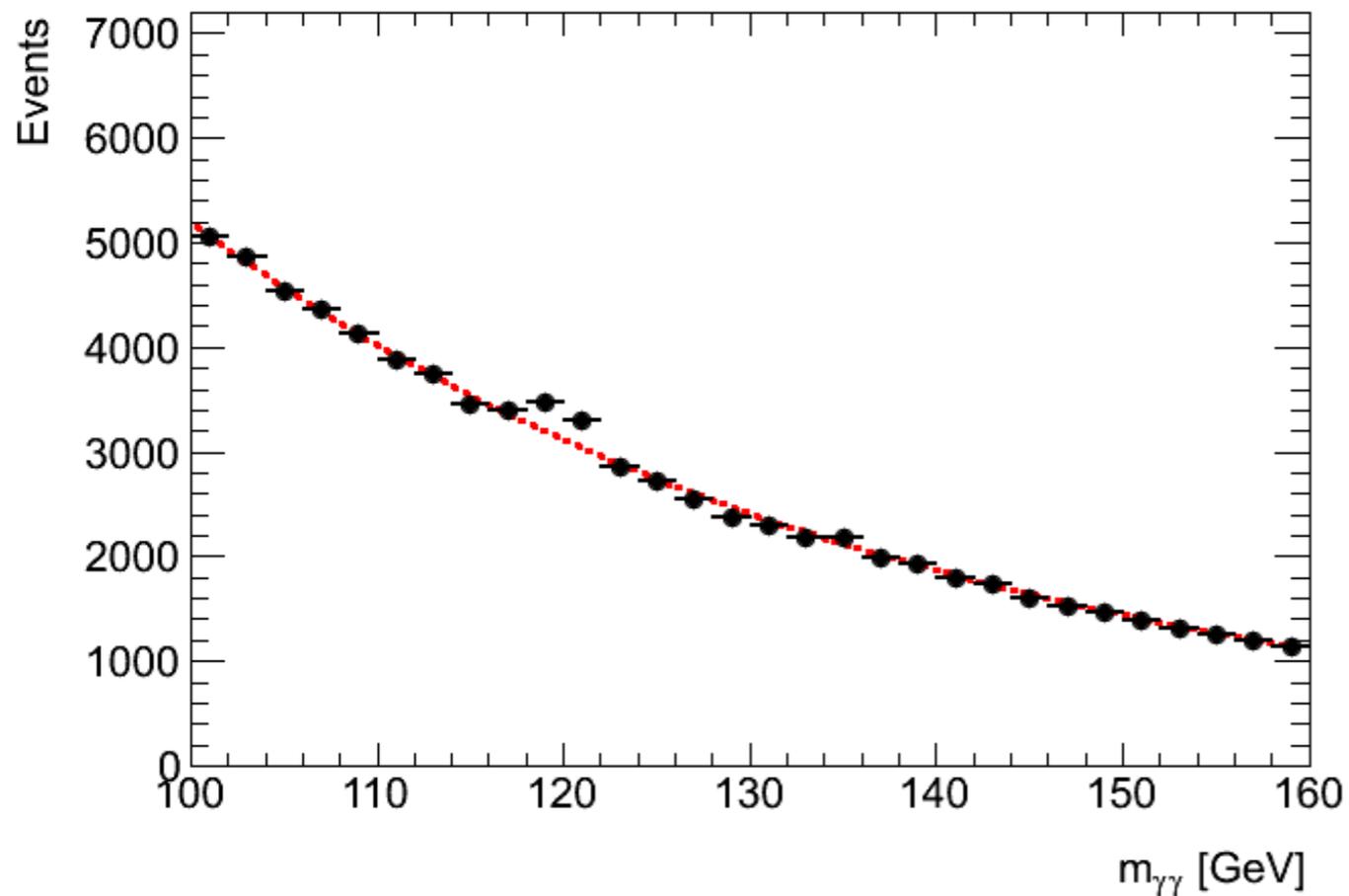
~800 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

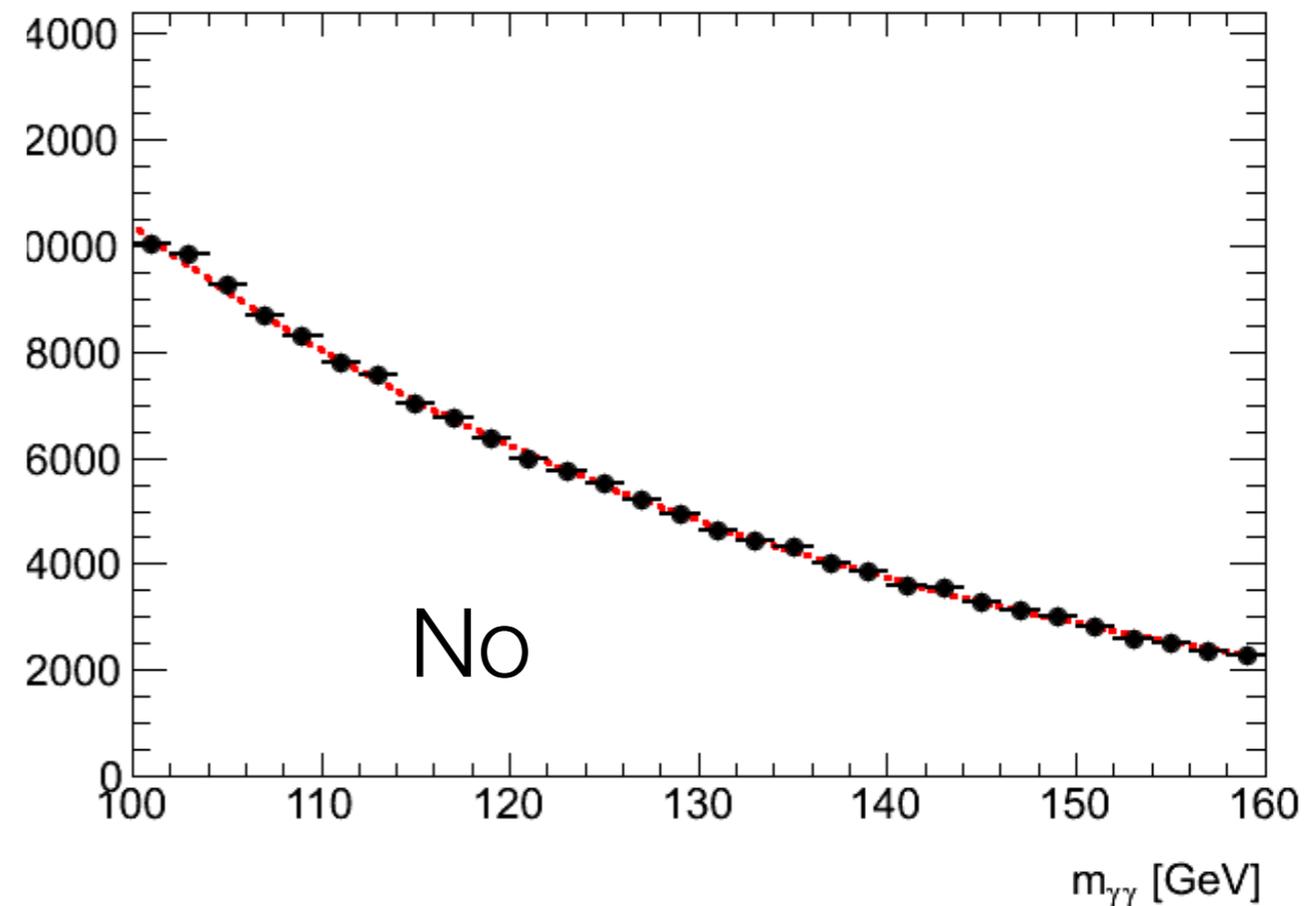
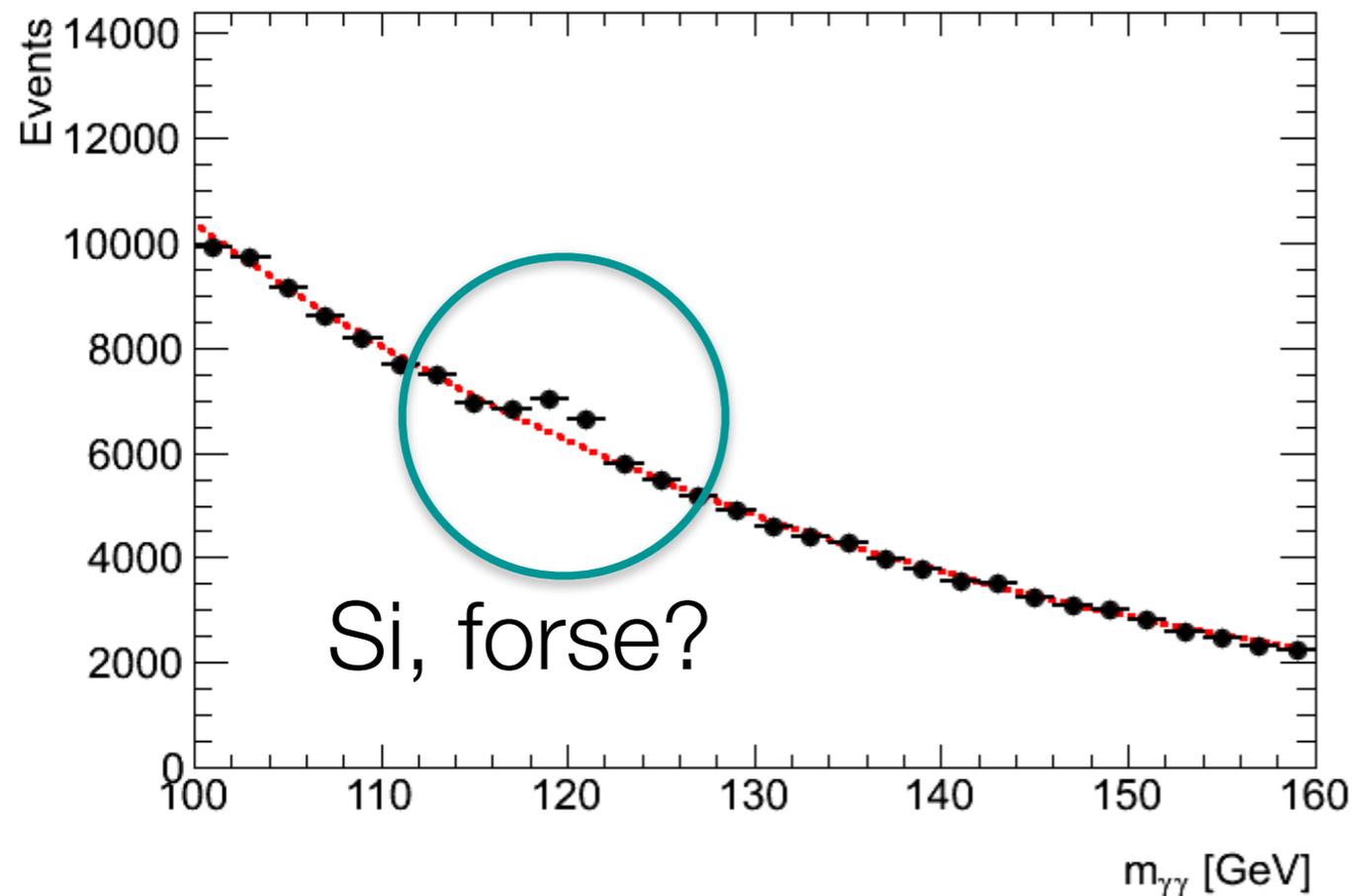
~1600 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

~3200 miliardi di collisioni

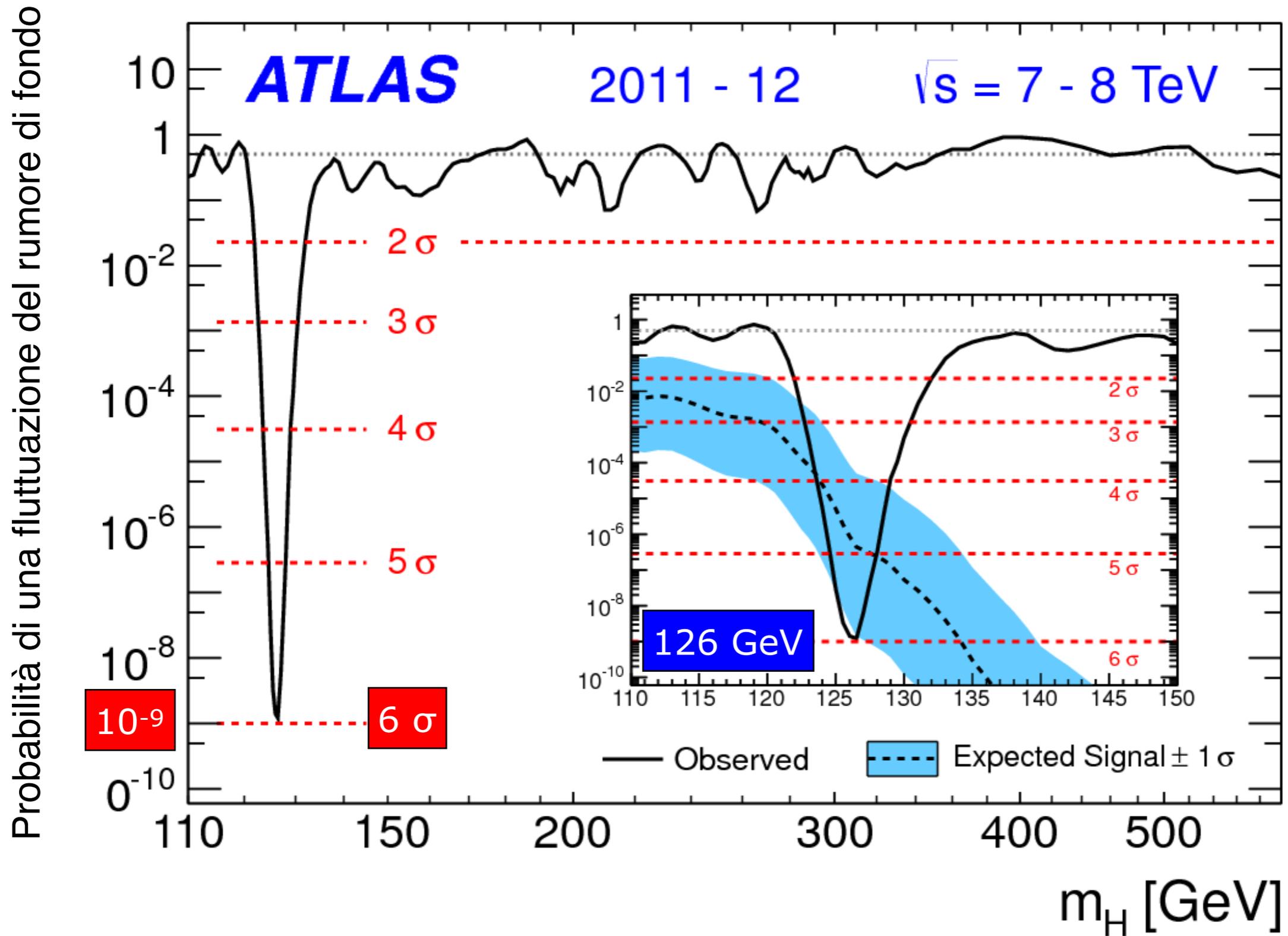


Quanto é "significativo" l'eccesso?

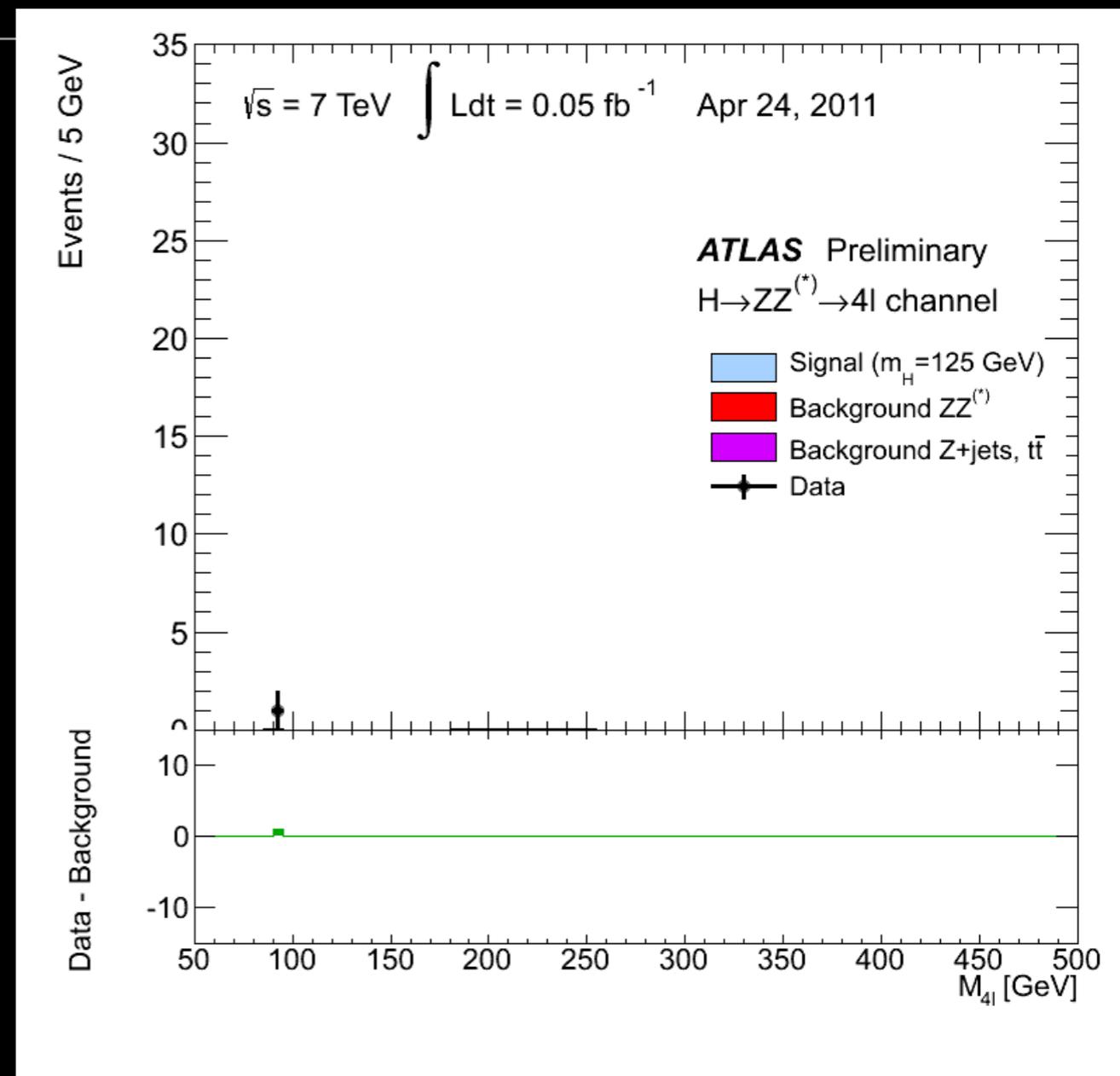
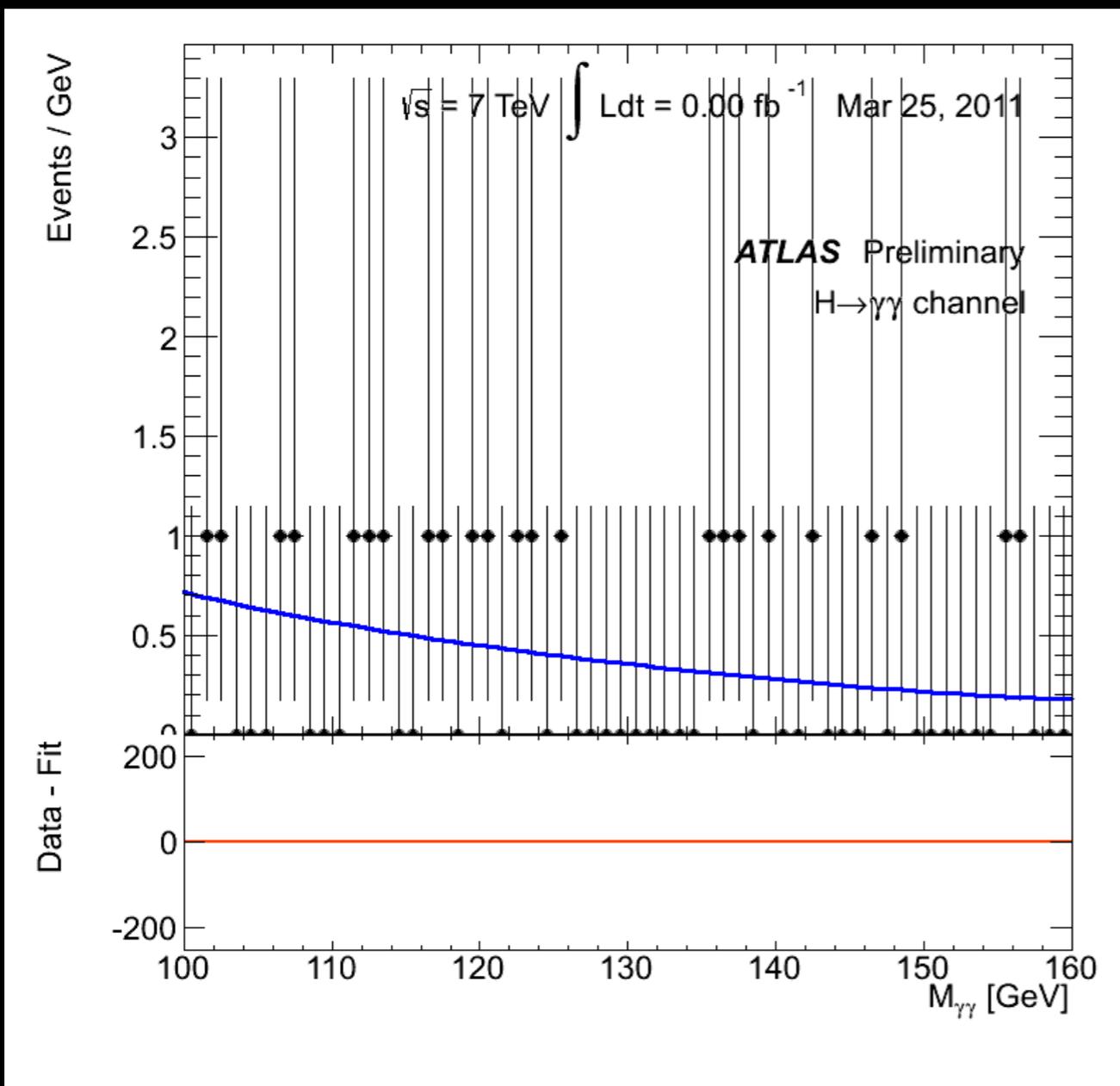
più la probabilità di fluttuazione é piccola, più un eccesso diventa significativo.

Come definiamo una scoperta?

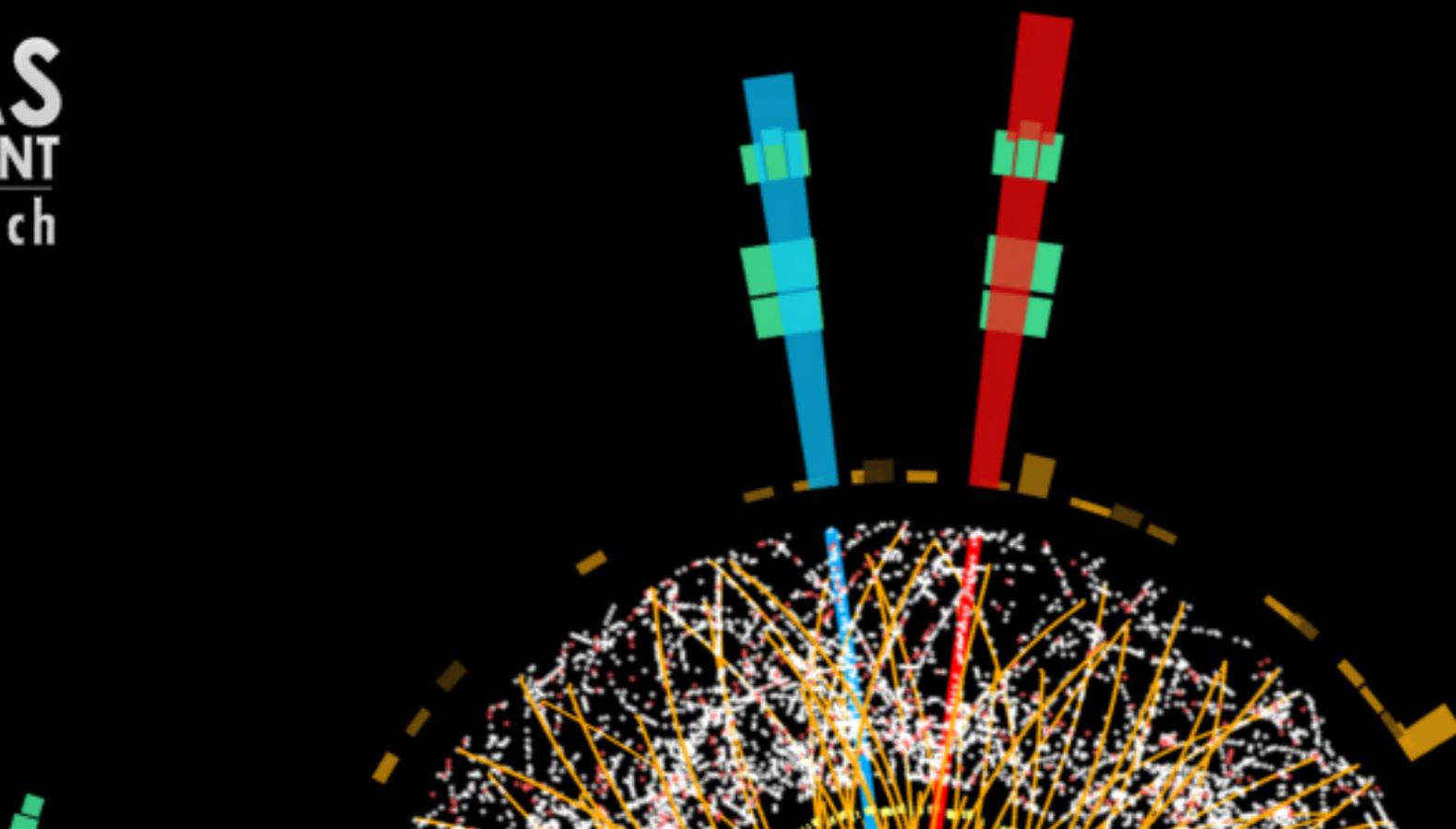
Abbiamo una scoperta?



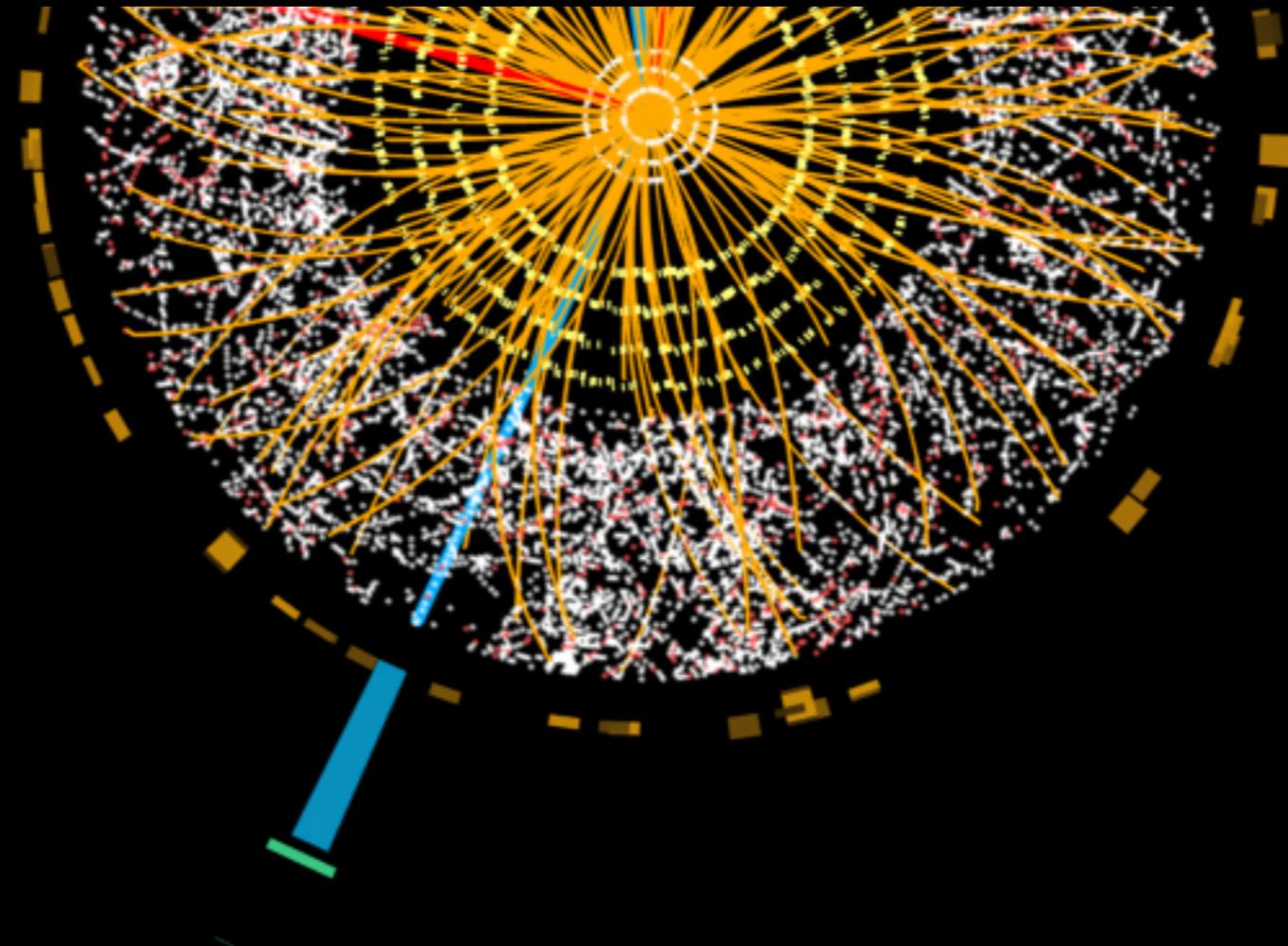
La nascita di una scoperta



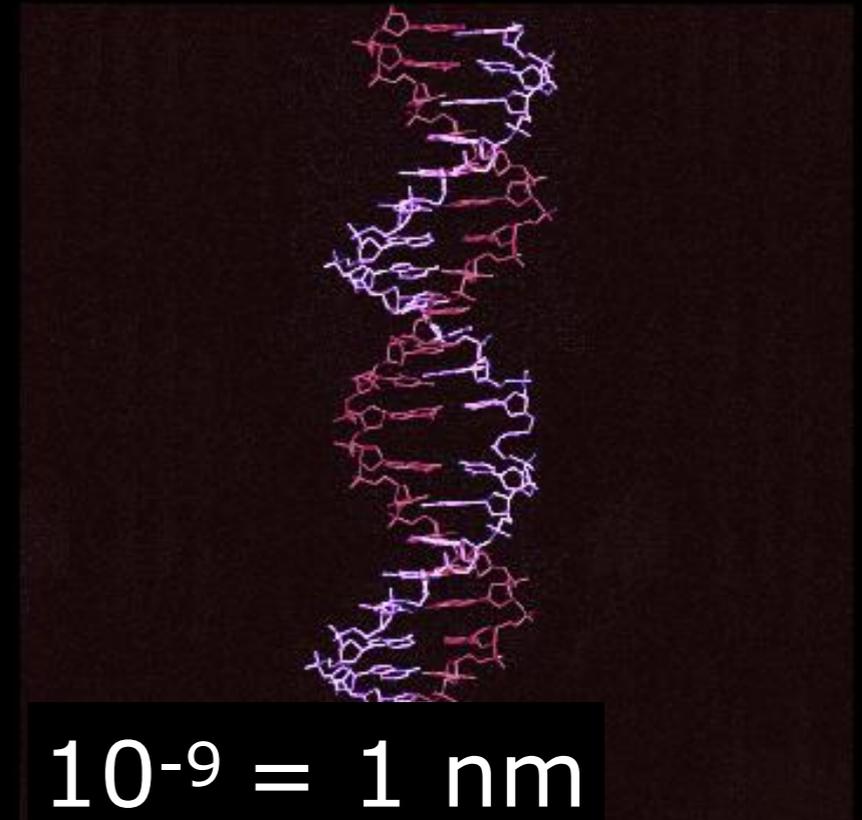
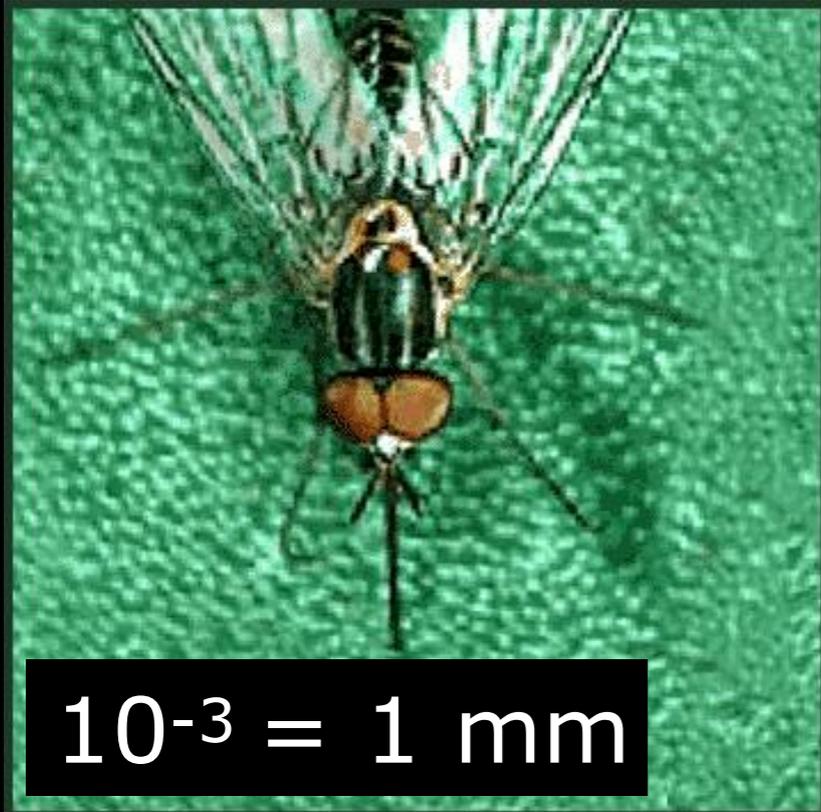
Buona Scoperta!



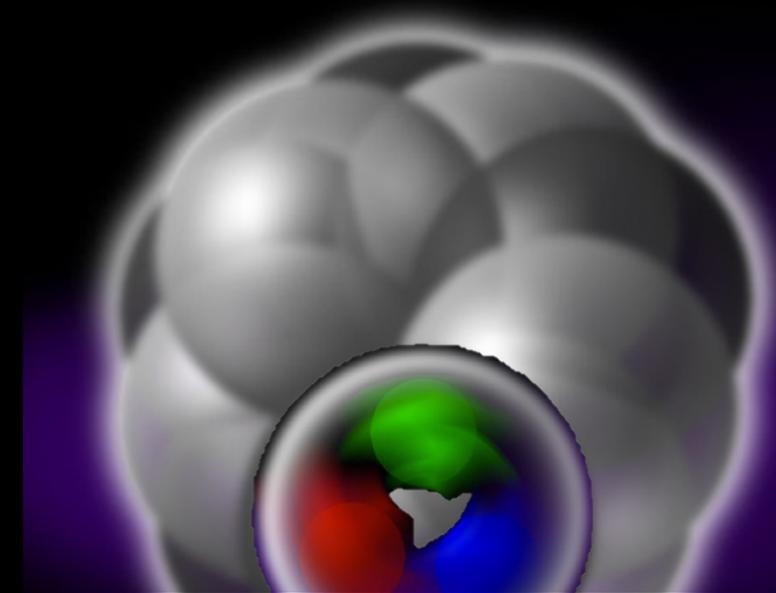
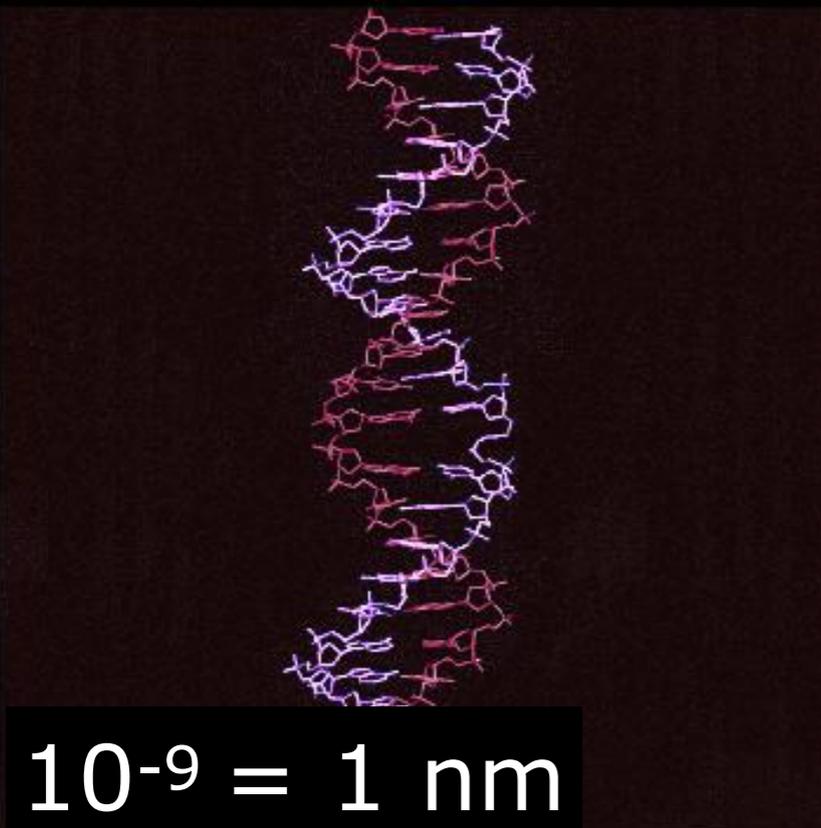
Strumenti e collaborazioni



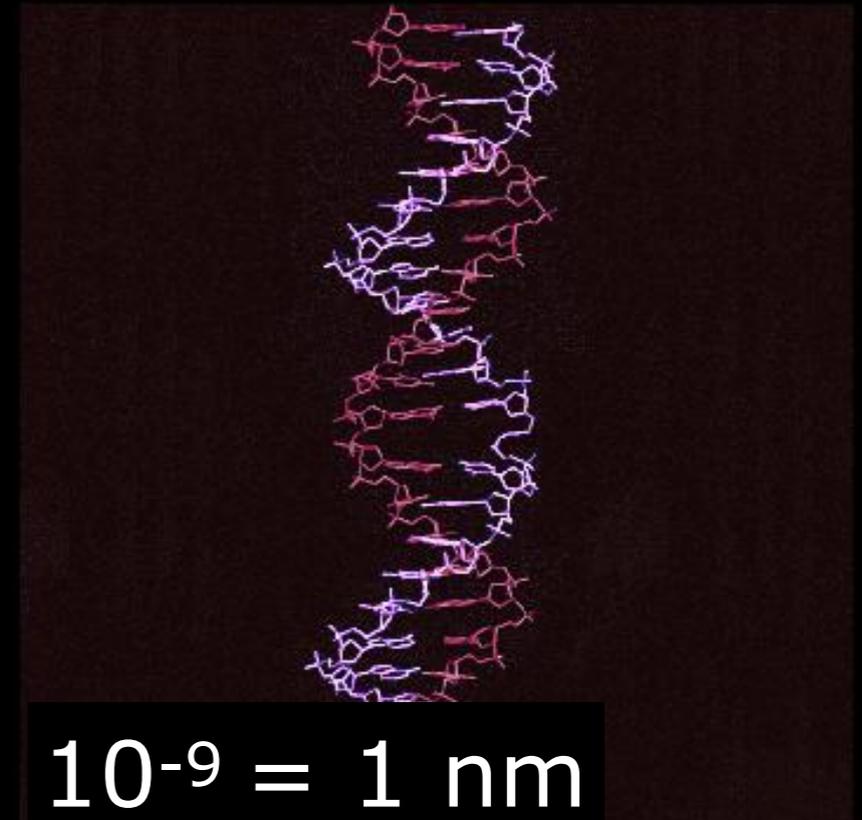
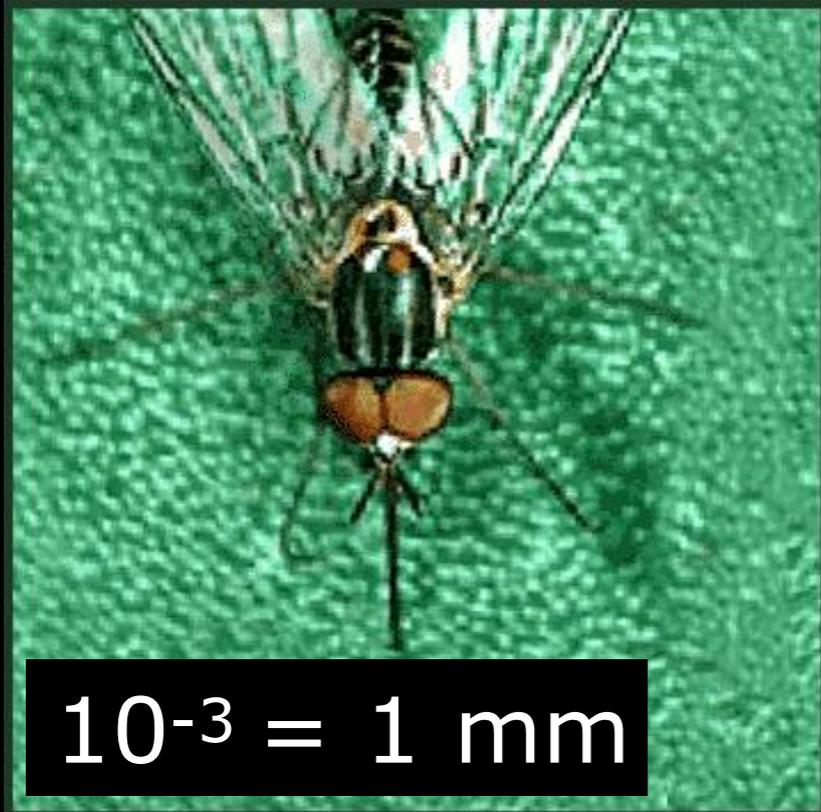
Zoom: x 1.000.000



=

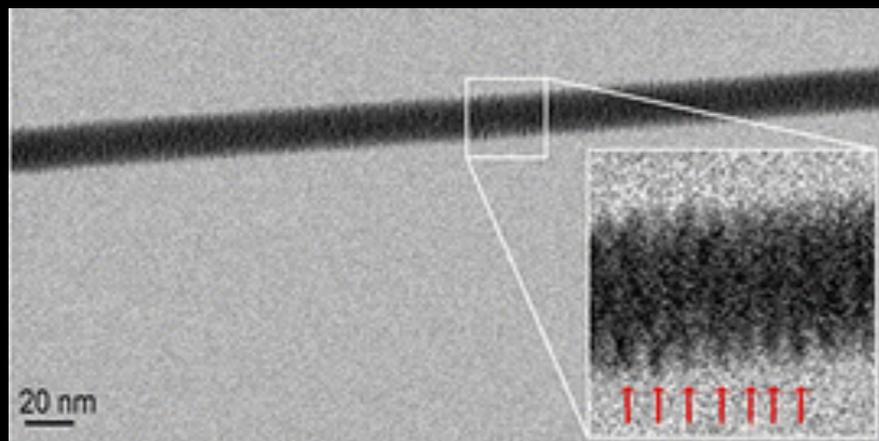


Zoom: x 1.000.000

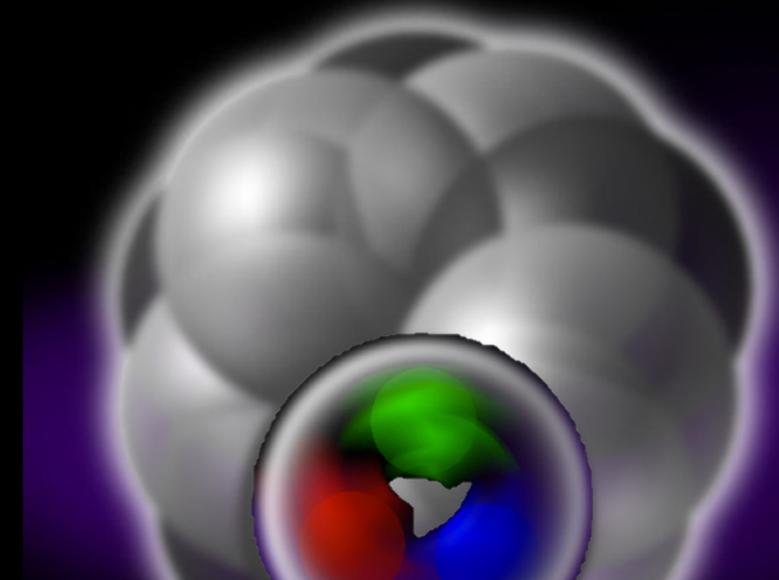


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DNA visto
da microscopio elettronico
<http://pubs.acs.org/doi/abs/10.1021/nl3039162>

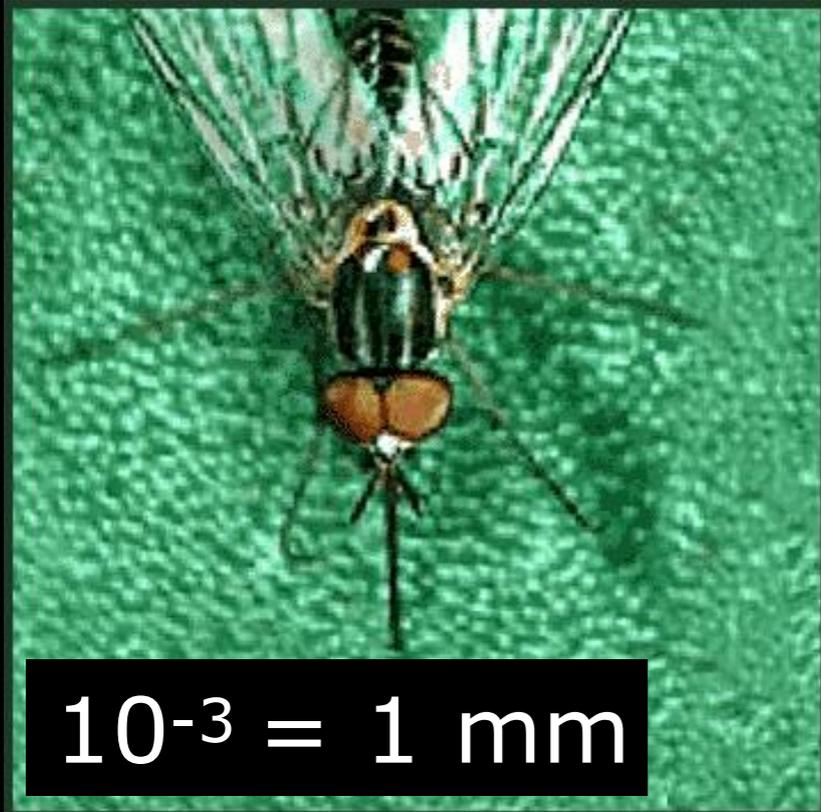


$10^{-9} = 1 \text{ nm}$

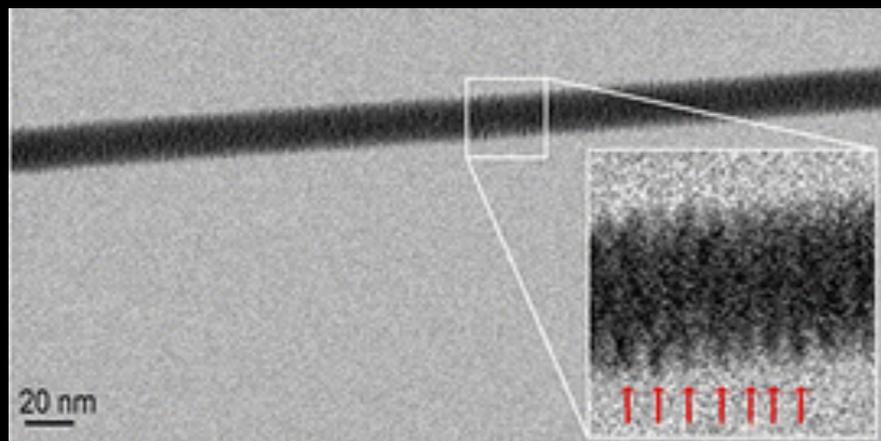


$10^{-15} = 1 \text{ Fermi}$

Zoom: x 1.000.000

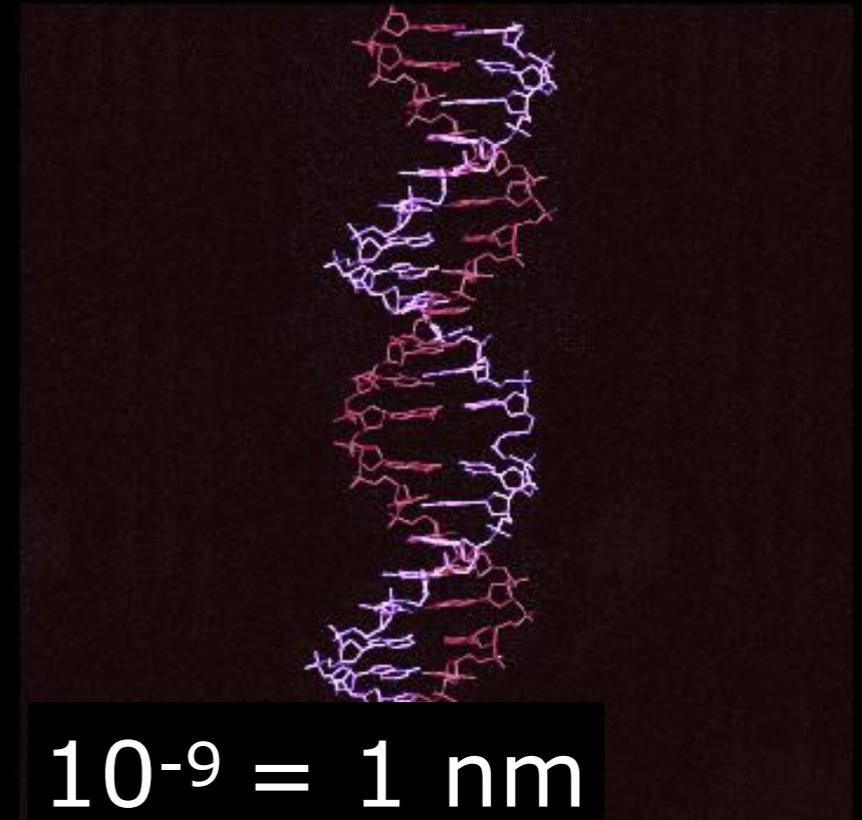


DNA visto
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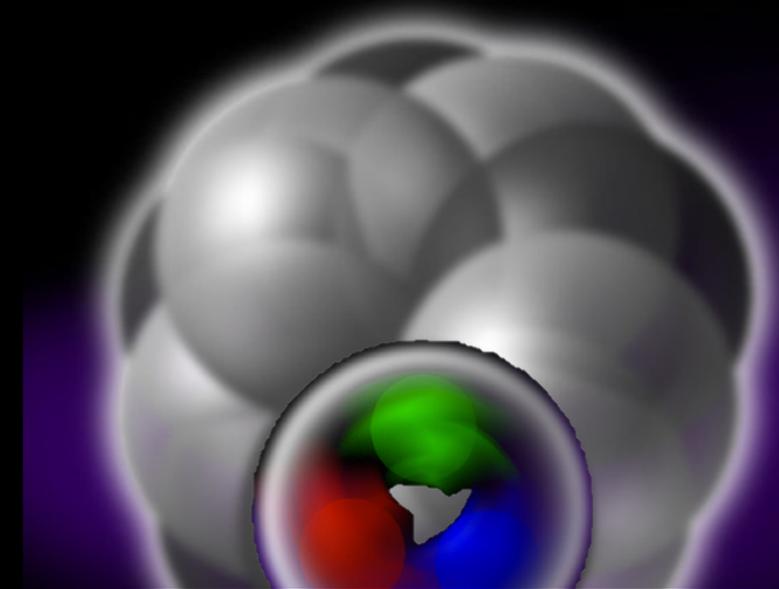


$10^{-9} = 1 \text{ nm}$

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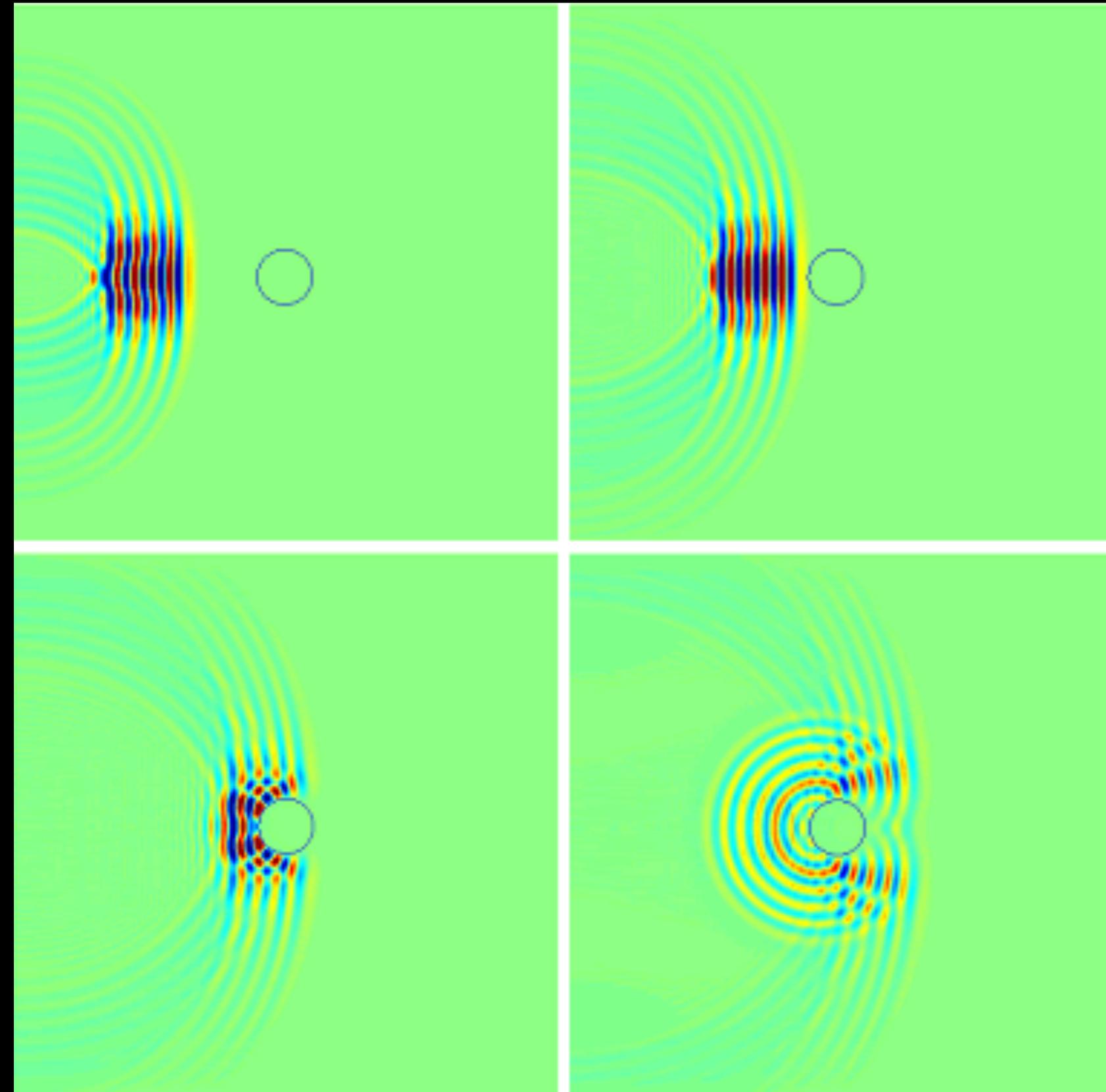


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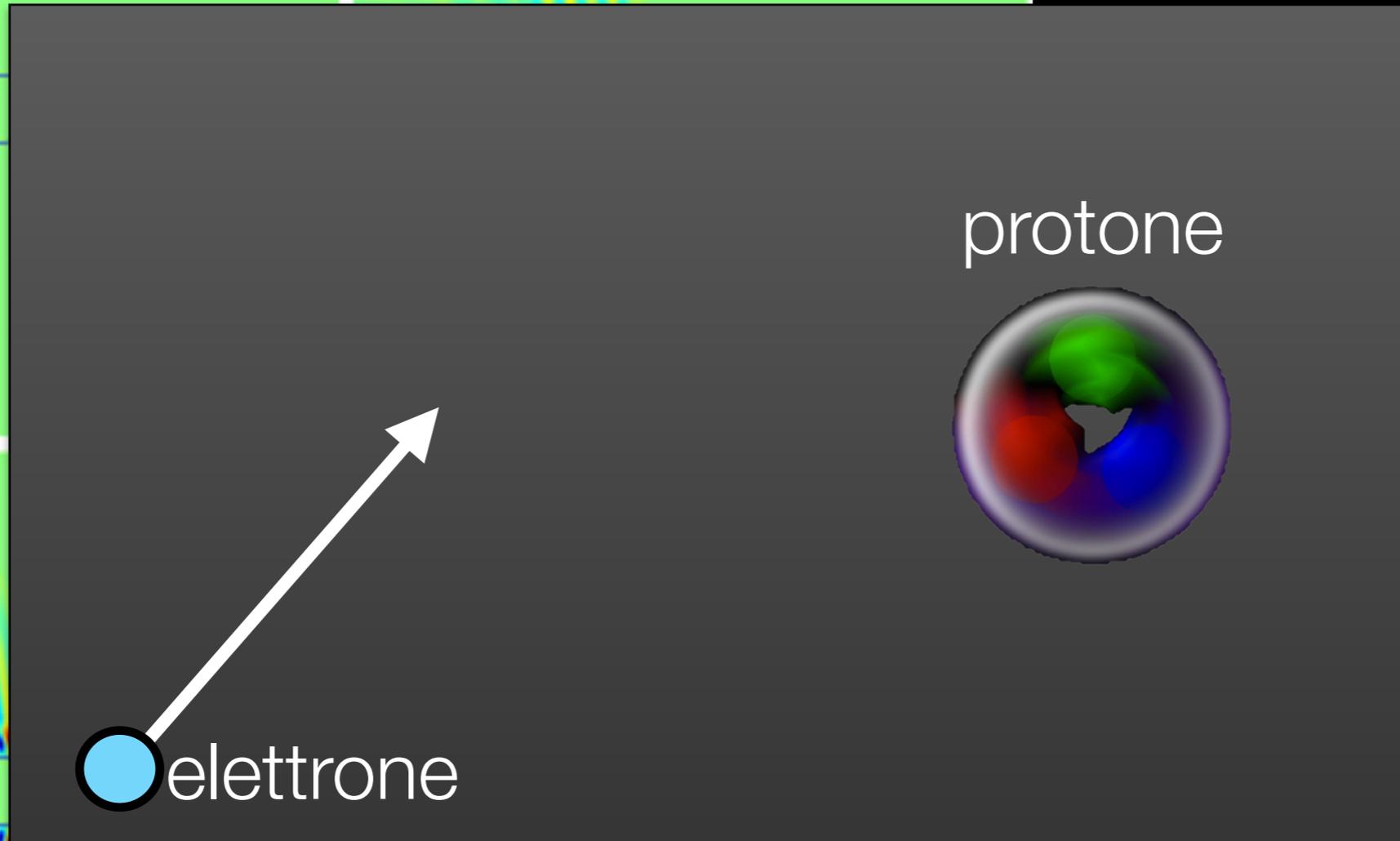
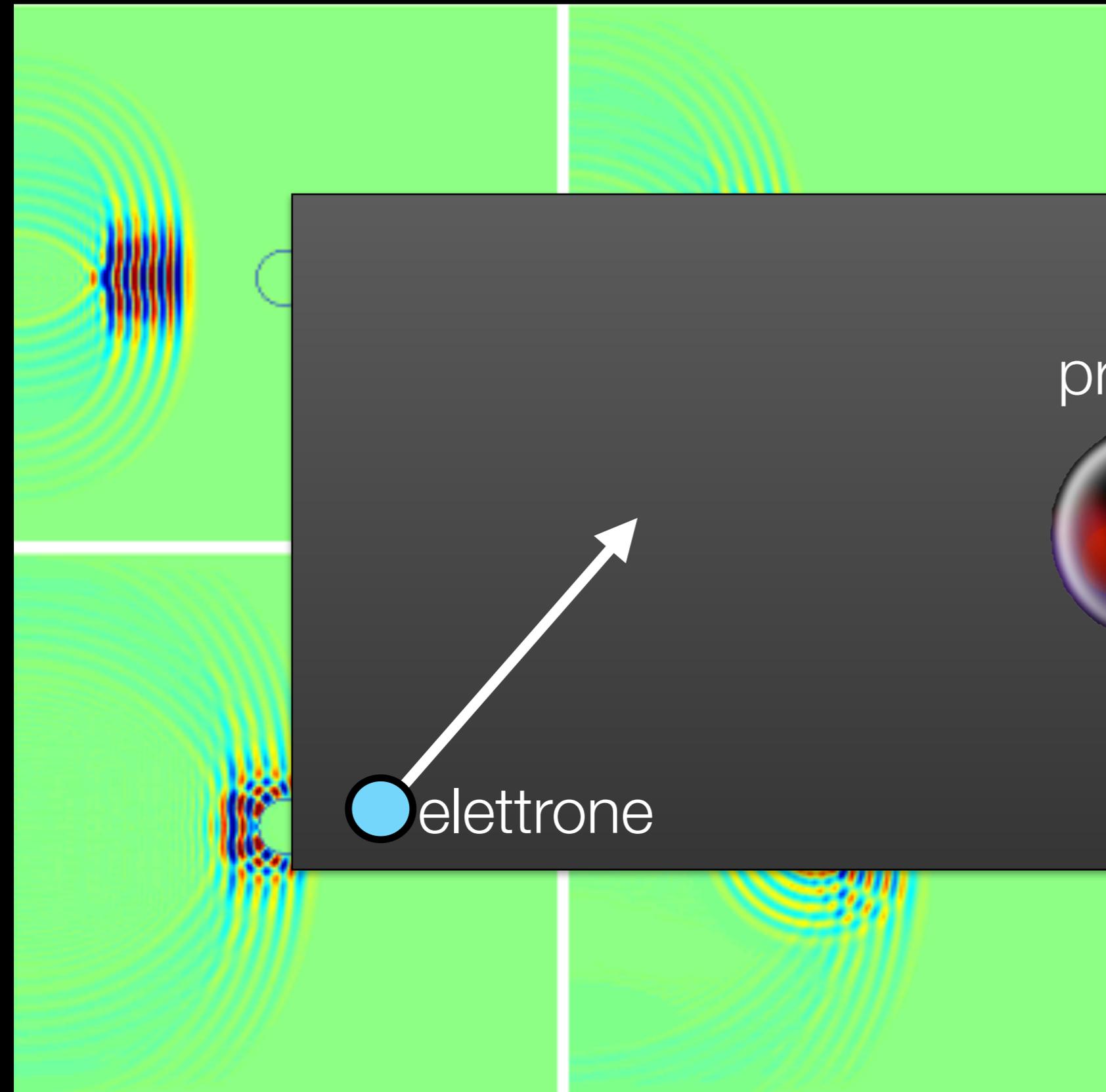


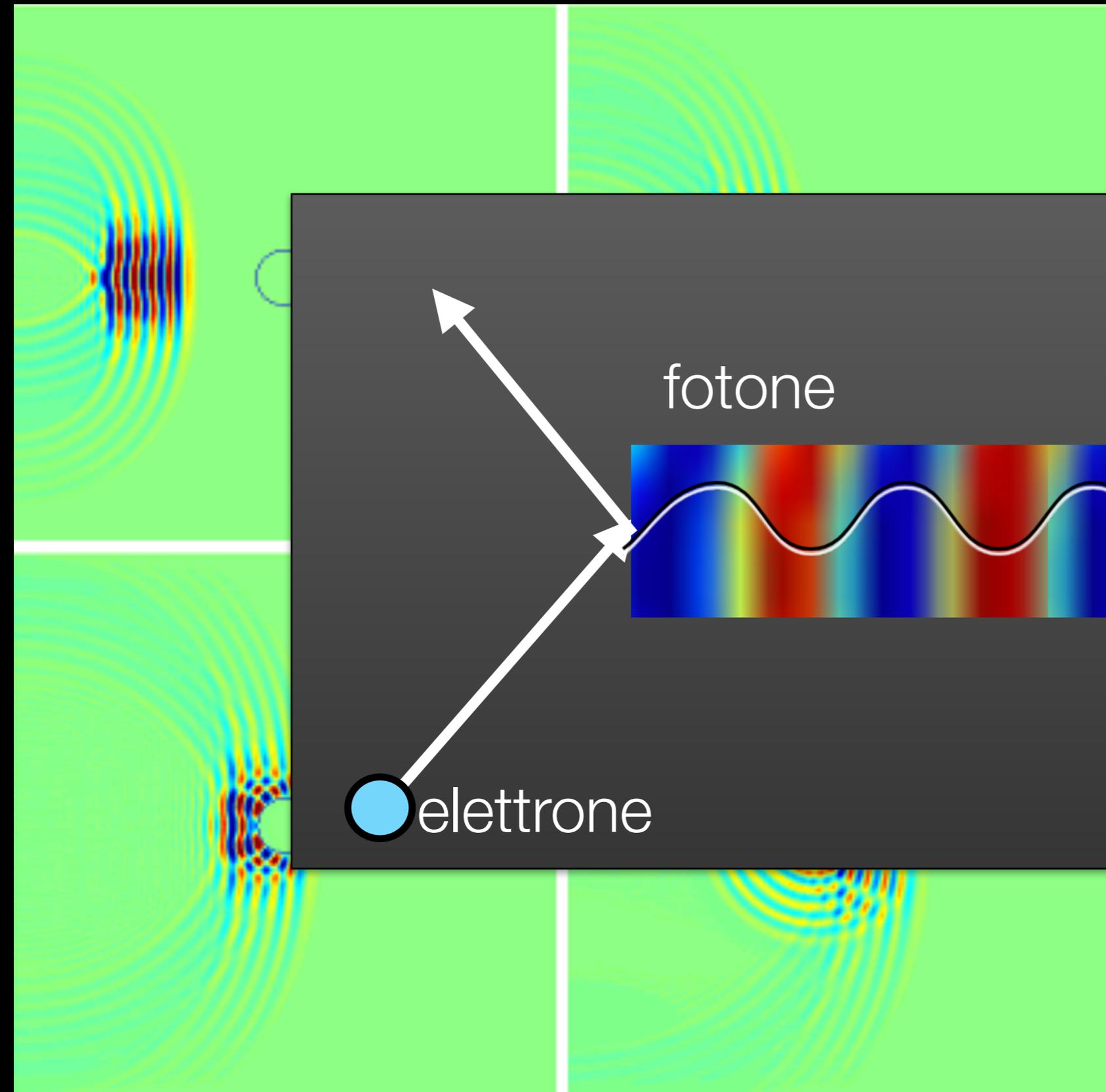
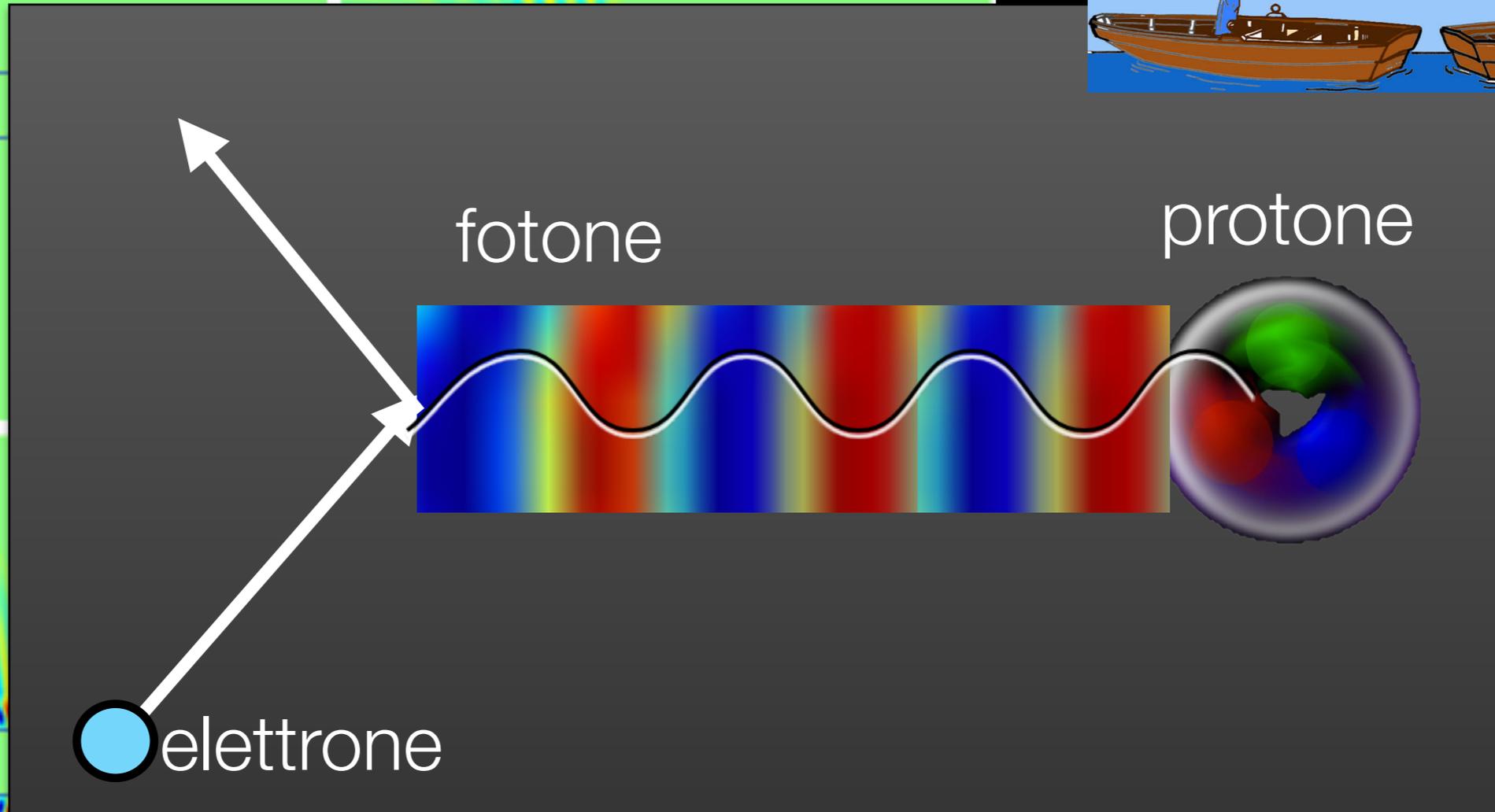
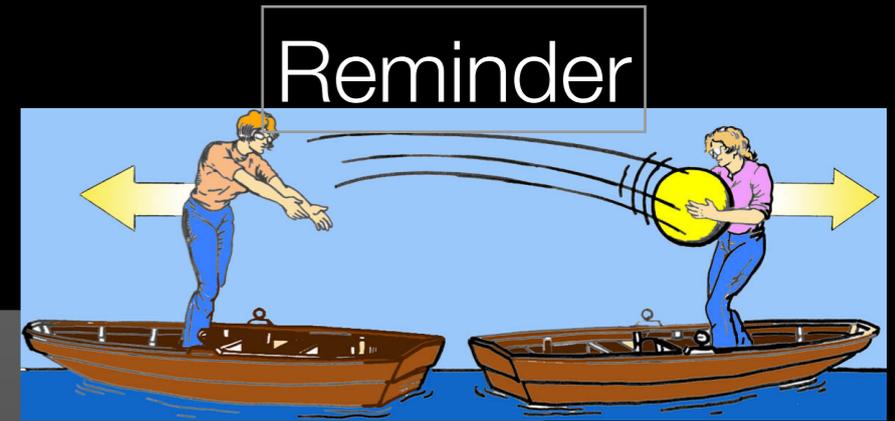
$10^{-15} = 1 \text{ Fermi}$

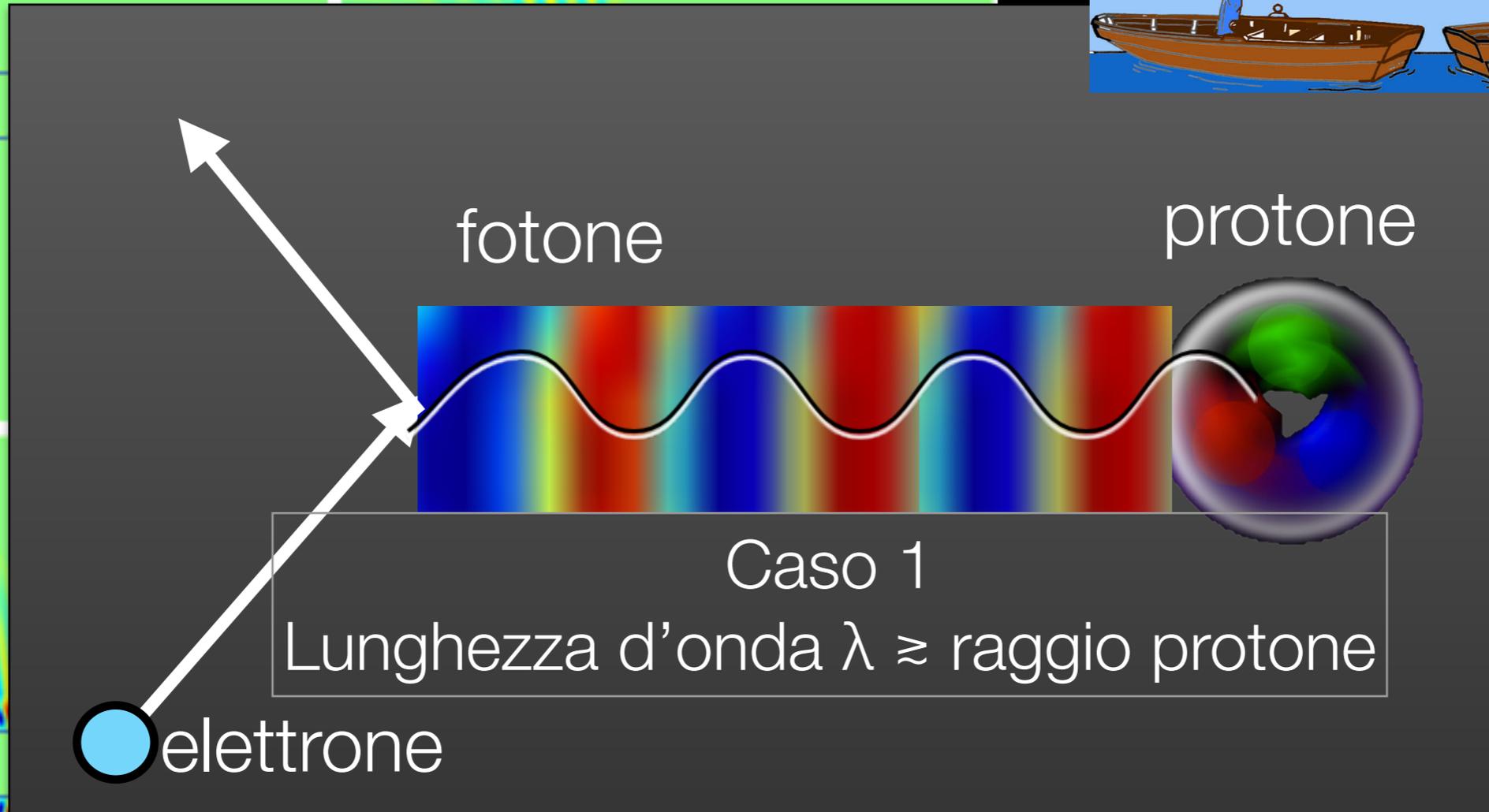
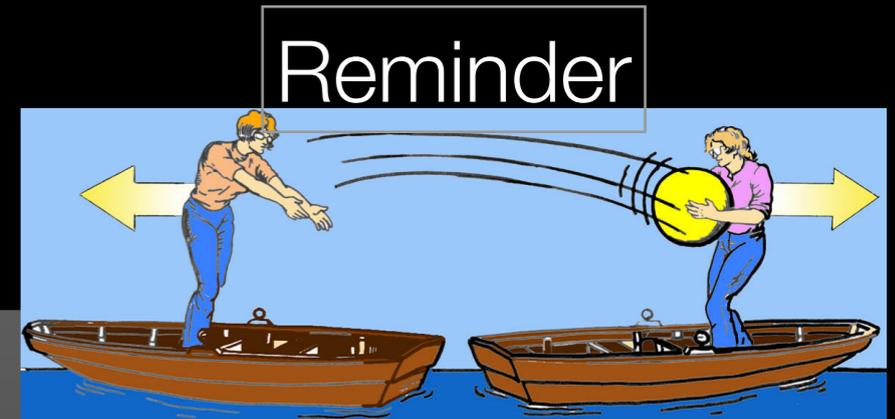
<https://it.mathworks.com/matlabcentral/fileexchange/12097-soundsim-2-5d-acoustic-wave-and-sphere-scattering-simulator?requestedDomain=www.mathworks.com>

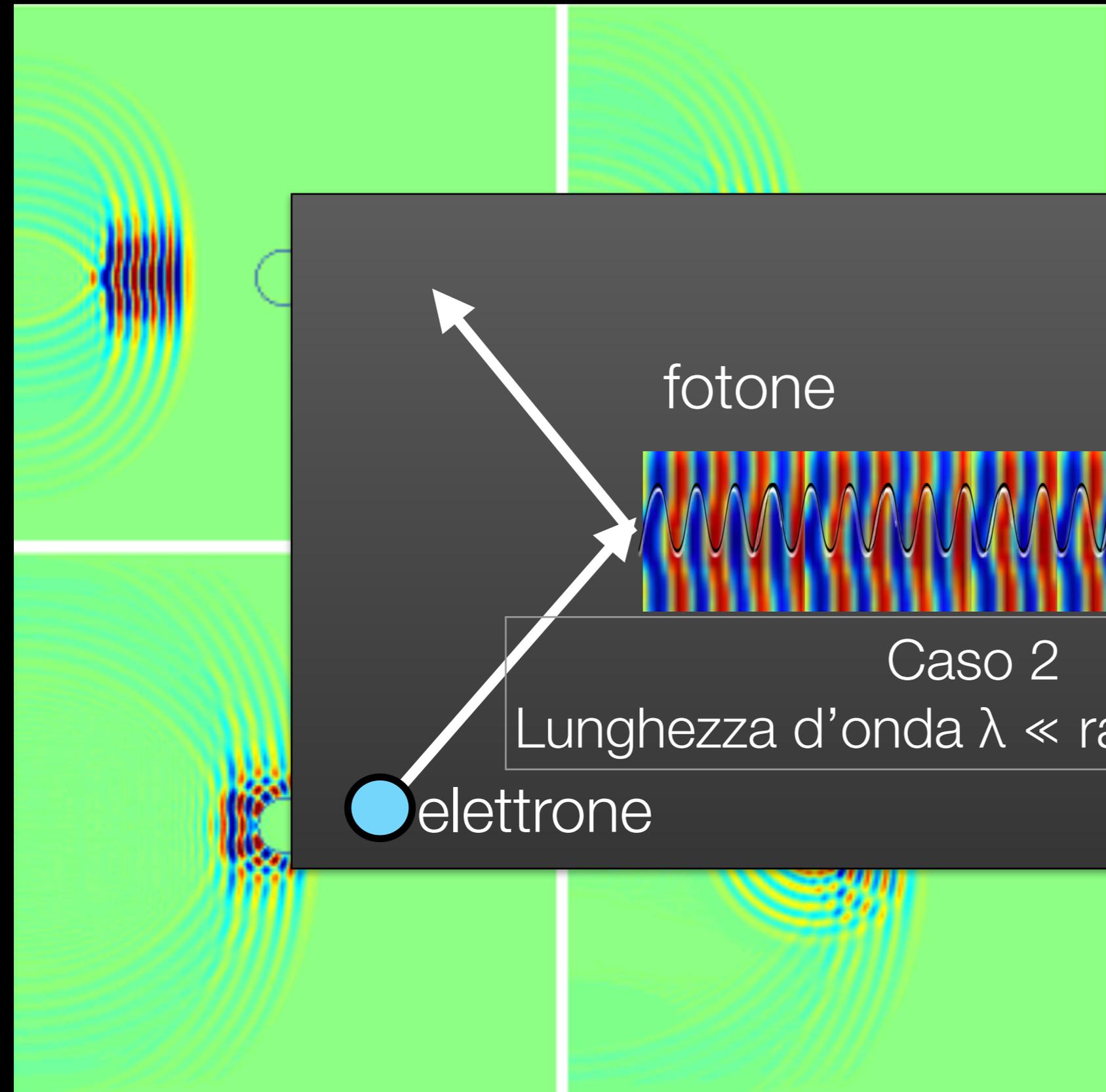


<https://it.mathworks.com/matlabcentral/fileexchange/12097-soundsim-2-5d-acoustic-wave-and-sphere-scattering-simulator?requestedDomain=www.mathworks.com>











$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:
 $\lambda \ll 1$ fm**

\Rightarrow

$E \gg 0.2$ GeV

**GeV: 10⁹ eV
1.6 x 10⁻¹⁰ J**

THE THING IS, WE HAVE THIS COLLIDER...

... the quantum magic



THE MAGIC OF A COLLIDER IS THAT YOU CAN MAKE KINDS OF MATTER THAT YOU DON'T HAVE AROUND.

YOU TAKE TWO KINDS OF PARTICLES AND ANNIHILATE THEM...

WHAT COMES OUT DOESN'T HAVE TO BE A RE-ARRANGEMENT OF WHAT WENT IN.



IT'S A KIND OF QUANTUM MAGIC WHERE IT SORT OF DISAPPEARS INTO PURE ENERGY...*

YOU CAN MAKE ANY SORT OF PARTICLE FOR WHICH YOU HAVE ENOUGH ENERGY.

* a force-carrying boson

IT'S LIKE HAVING A MENU...
what can i get in the 500 GeV range?



YOU CAN MAKE ANYTHING THAT COSTS THAT MUCH ENERGY OR LESS.
THAT'S WHY YOU WANT TO HAVE AS MUCH ENERGY AS POSSIBLE.
EVERY TIME YOU CRANK UP THE ENERGY, YOU COULD BE EXPLORING A WHOLE NEW REGIME.

JORGE CHAM © 2012

$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:
 $\lambda \ll 1$ fm**

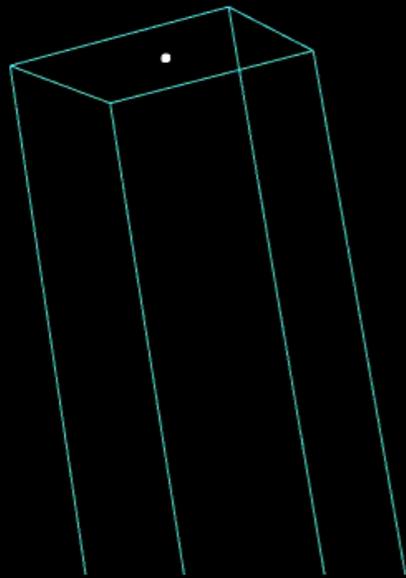
⇒

E » 0.2 GeV

**GeV: 10⁹ eV
1.6 x 10⁻¹⁰ J**

Alte energie: Come?

Protone, 1000 GeV



LHC
CERN
Svizzera

Pierre Auger Observatory
Argentina



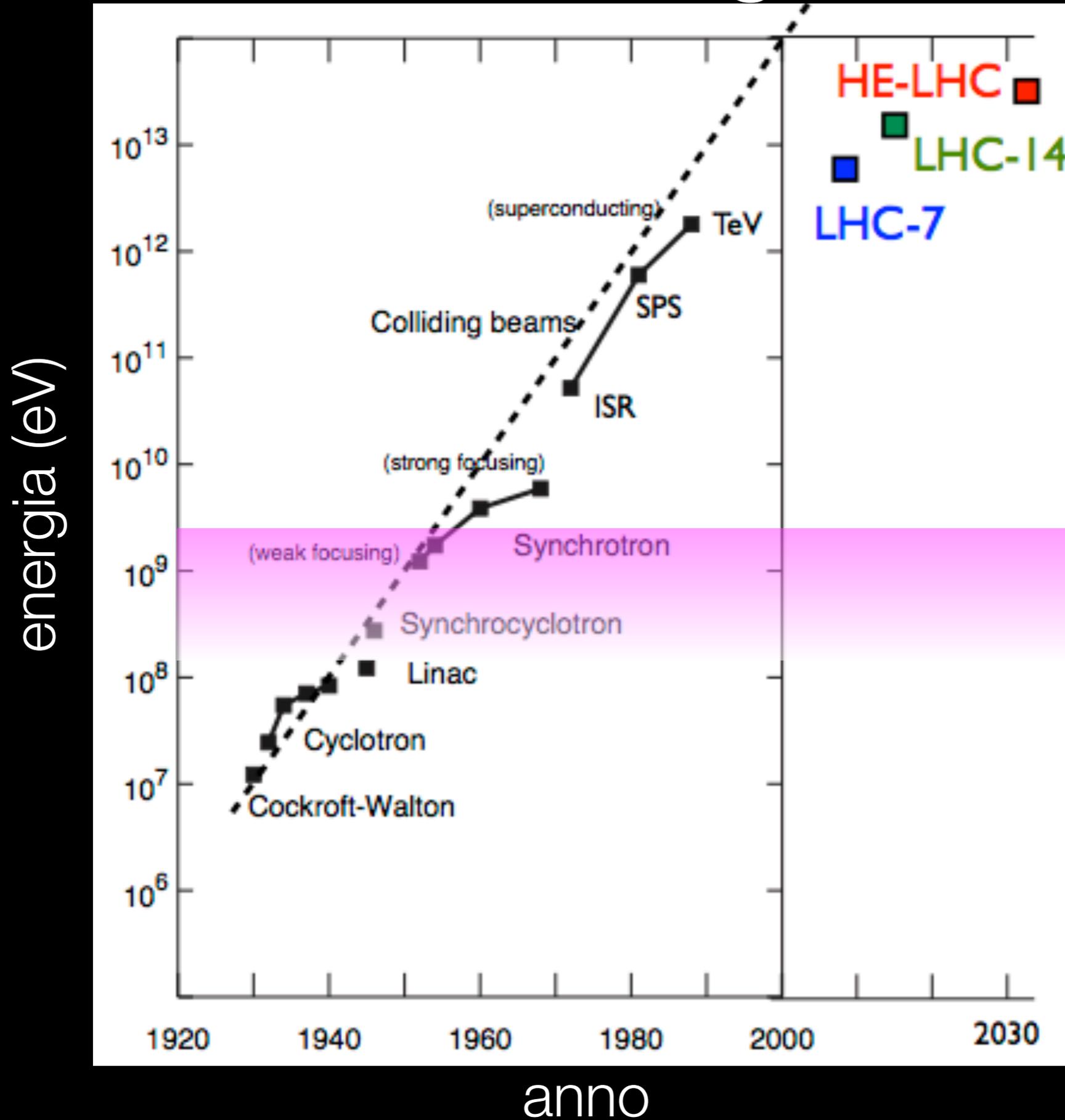
3000 km²

Raggi cosmici,
altissime energie, ma rari



Acceleratori
Energie limitate, ma alte intensità

La corsa agli acceleratori



risolviamo la
struttura del
protone



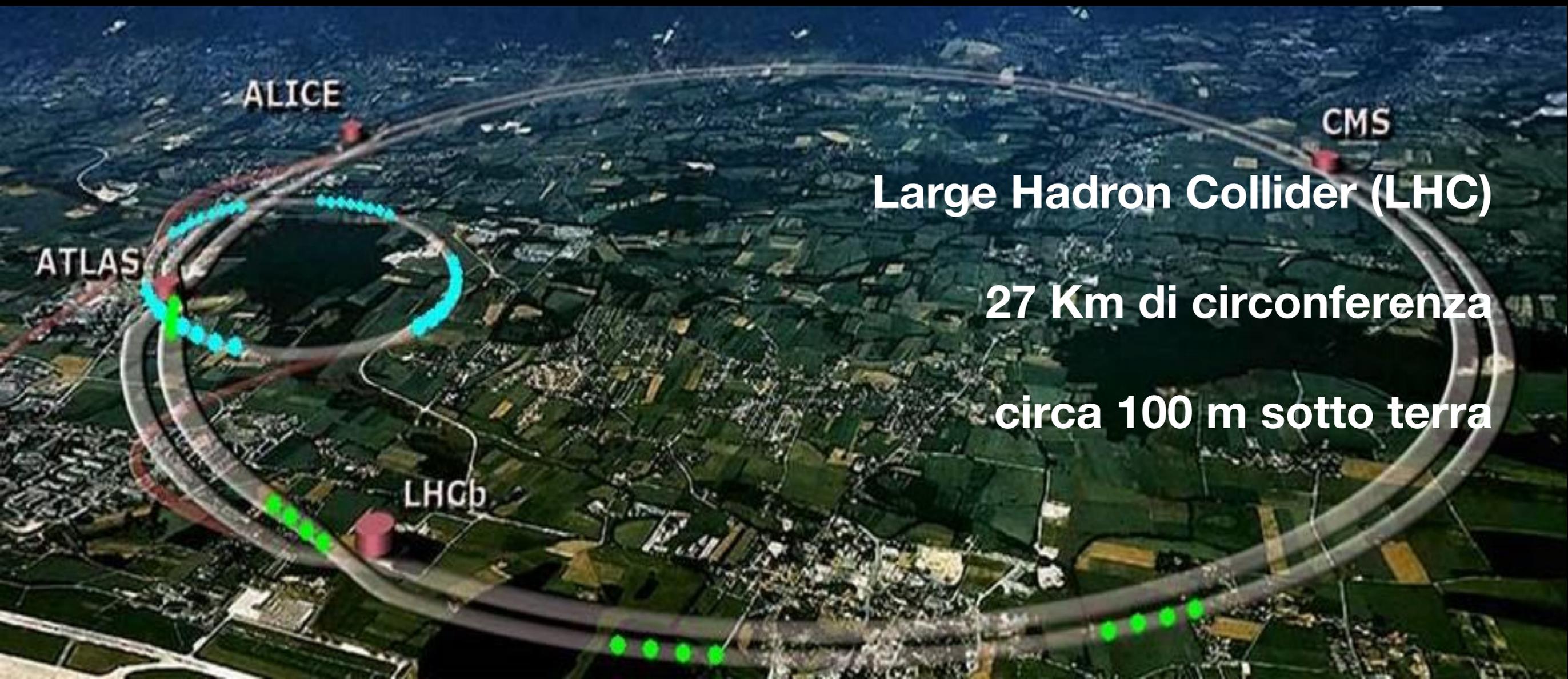
C'è chi ne costruisce uno a casa

Certamente, un gioco da ragazzi se sei un genio, miliardario, playboy, filantropo.

Ma torniamo ai fatti...

A differenza di Toni Stark, nessuno di noi ha un acceleratore di alta energia a casa.

MA, in questo caso, le dimensioni contano!!!



Large Hadron Collider (LHC)

27 Km di circonferenza

circa 100 m sotto terra

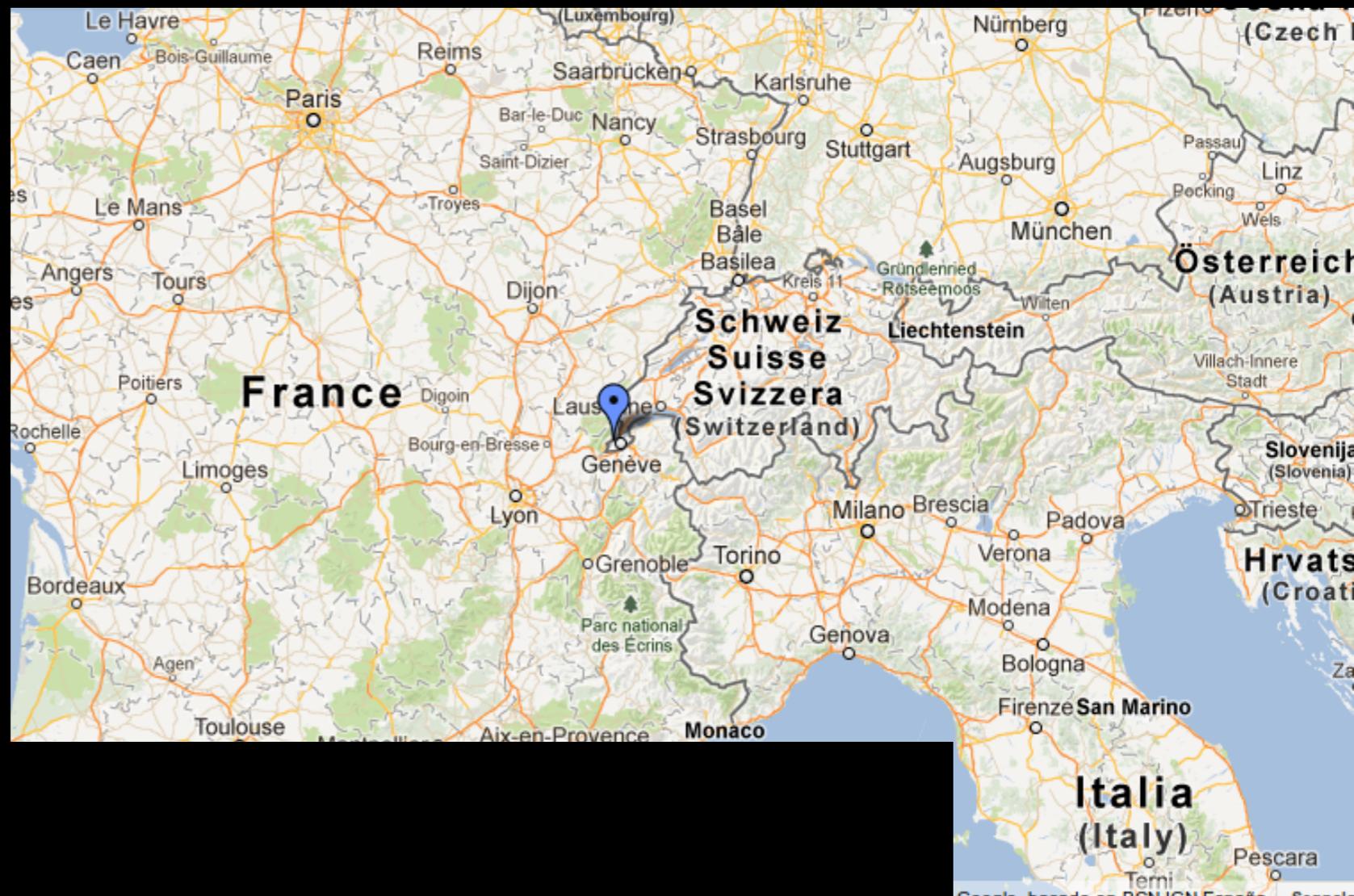
Dove? il CERN !



Il Large Hadron Collider e' il fiore all'occhiello del CERN:
Consiglio Europeo per la Ricerca Nucleare.

Nato negli anni '50,
come centro europeo,
libero e votato alla
collaborazione internazionale.

Tra Svizzera e Francia



Studi di fisica delle **interazioni fondamentali, fisica nucleare,**
fisica medica, fisica degli acceleratori,...

Nella realtà non siamo proprio come Tony Stark



Anche se ogni tanto qualcuno



Ma non siamo neanche così:

Anche se ogni tanto qualcuno...



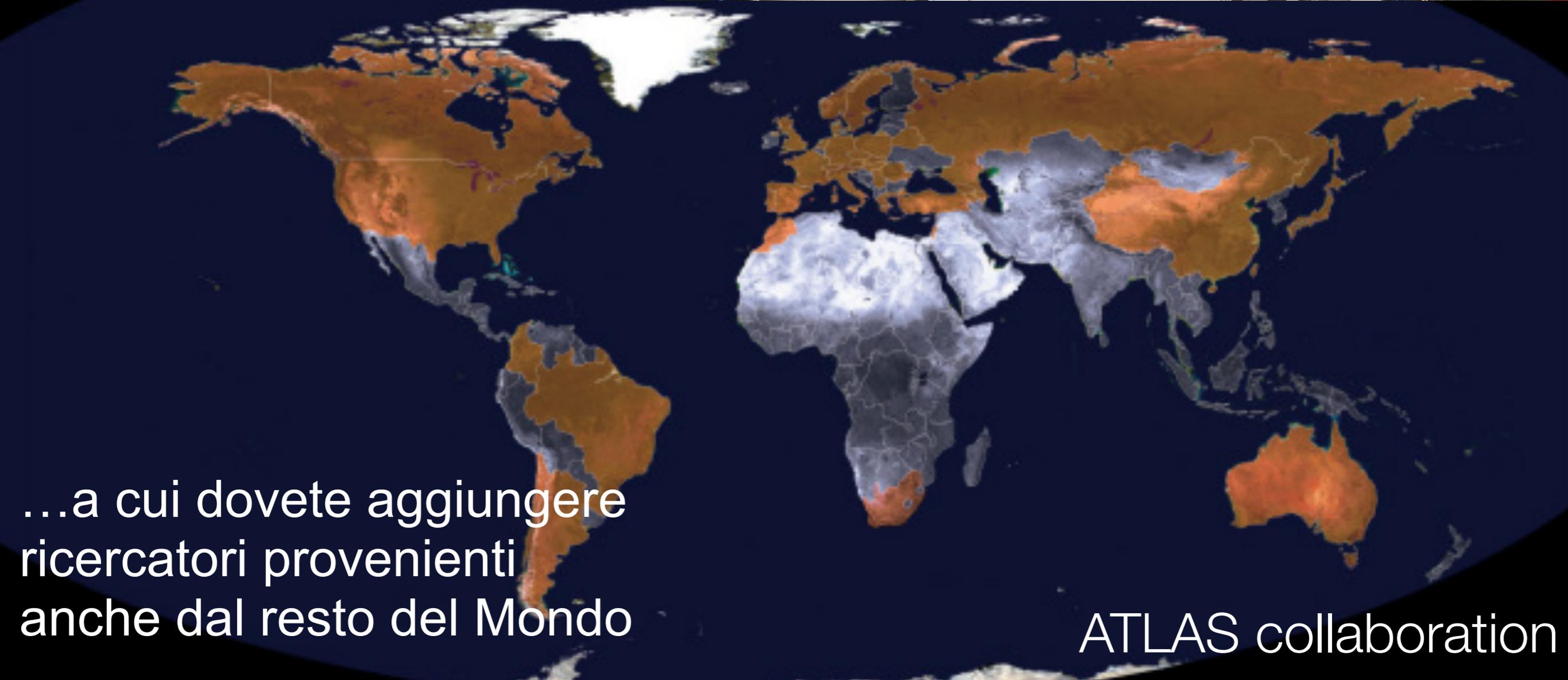
La pulisci tu la lavagna, vero?



Ufficio del gruppo ATLAS di Pisa 2011

Ma c'è tanta
ricchezza in più

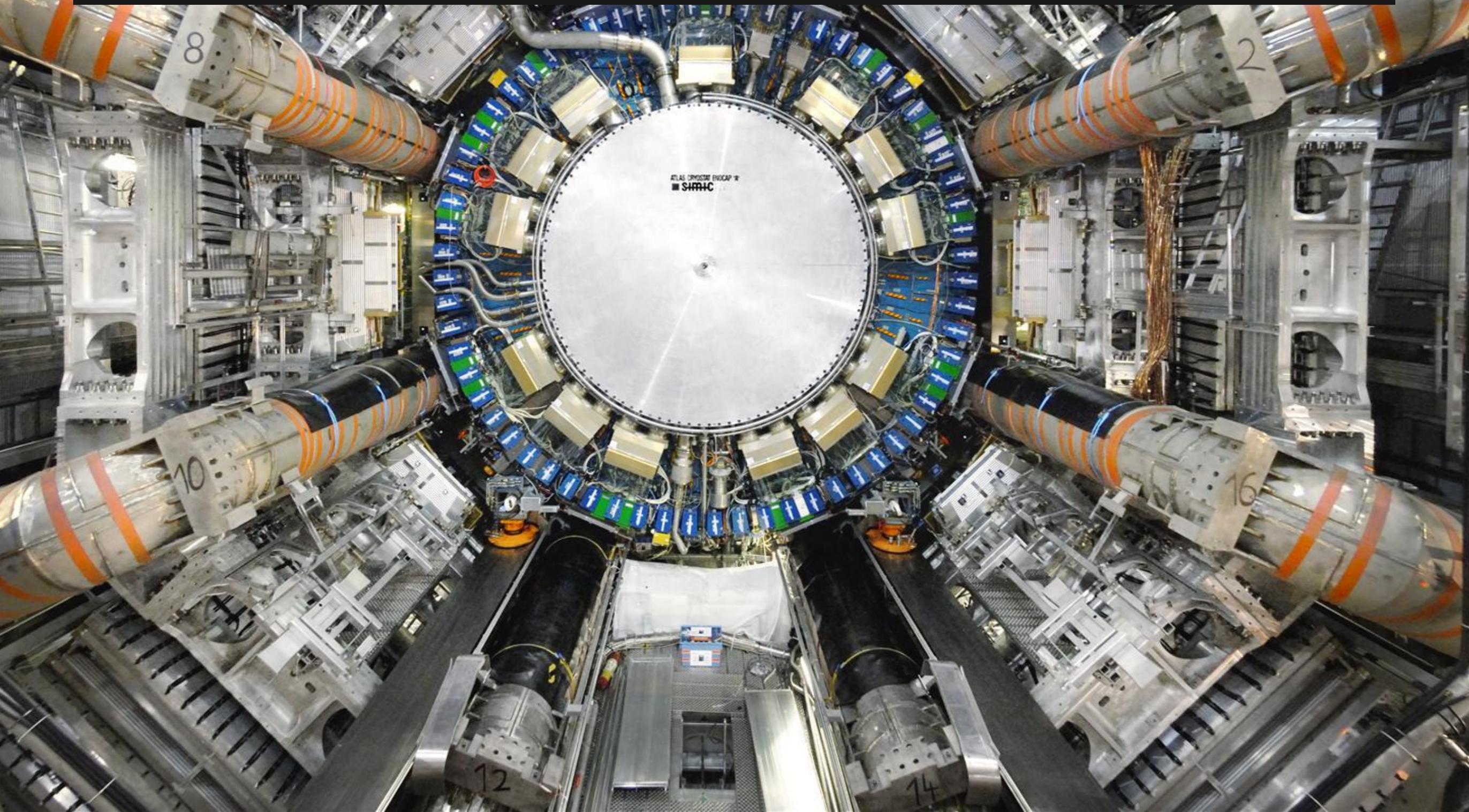
Collaborazioni
internazionali, in alcuni
casi con più di 4000
persone



...a cui dovete aggiungere
ricercatori provenienti
anche dal resto del Mondo

ATLAS collaboration

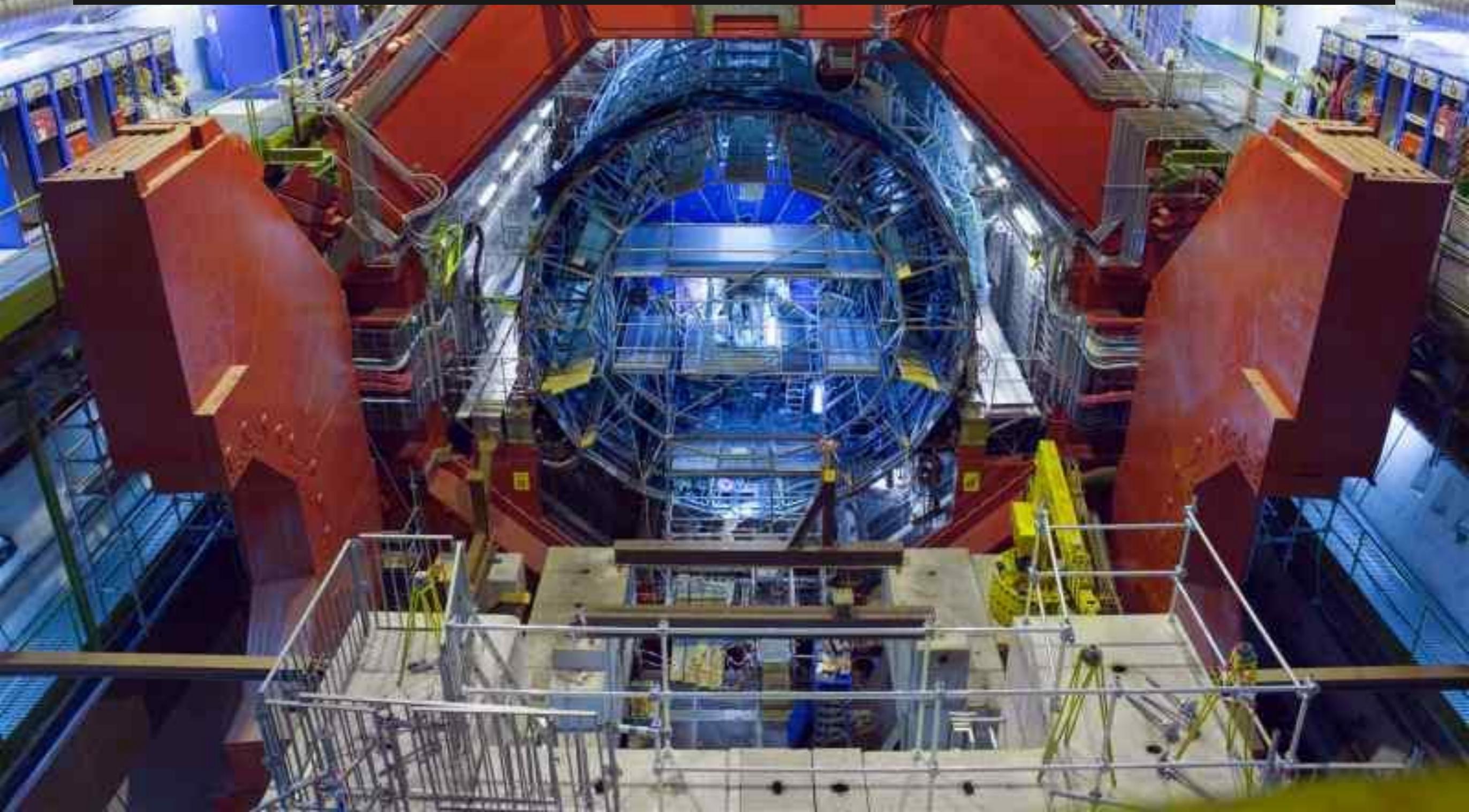
ATLAS



CMS



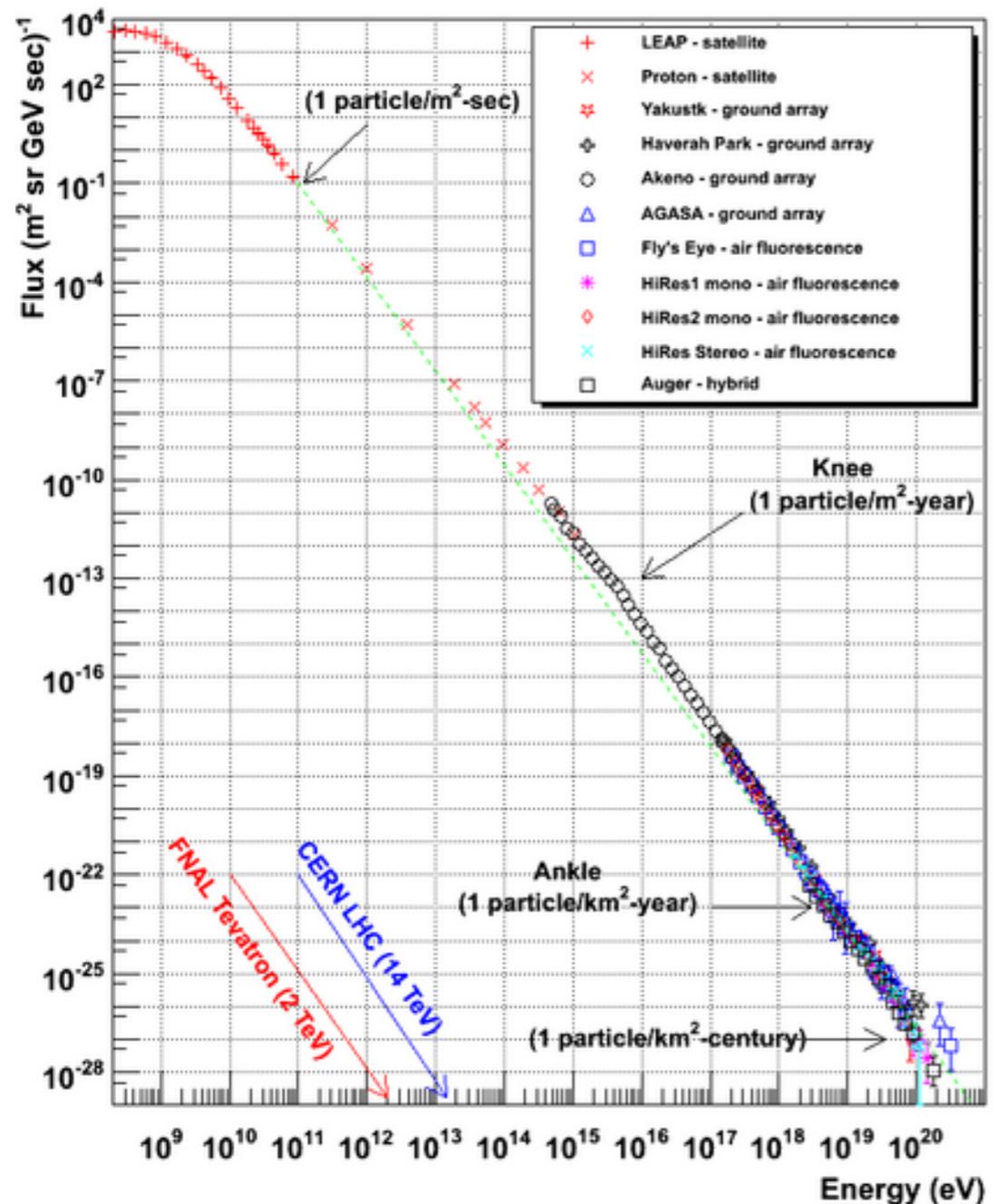
ALICE



LHCB



Cosmic Ray Spectra of Various Experiments



Un vuoto pieno di cose

- Ipotesi: un vuoto pieno di iper**carica** debole dovuta ad un campo che polarizza tutto l'universo
- Questo campo ha una riserva infinita di iper**carica** debole.
 - Donare una ipercarica debole ad una particella, o estrarne una é **gratis**.
- Le particelle sono “bombardate” in continuazione da questa grande generosità di ipercarica debole
 - Sono persuase ad interagire con questo campo, e come effetto emergente, ottengono una massa.
- Più é frequente é l'interazione con questo campo, più alta é la massa