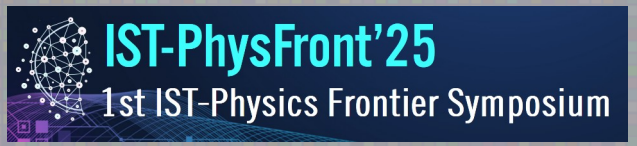
Quantum information theory of Higgs couplings and Flavor

Andreas Trautner



Técnico Innovation Center (TIC)

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de Desenvolvimento Regional

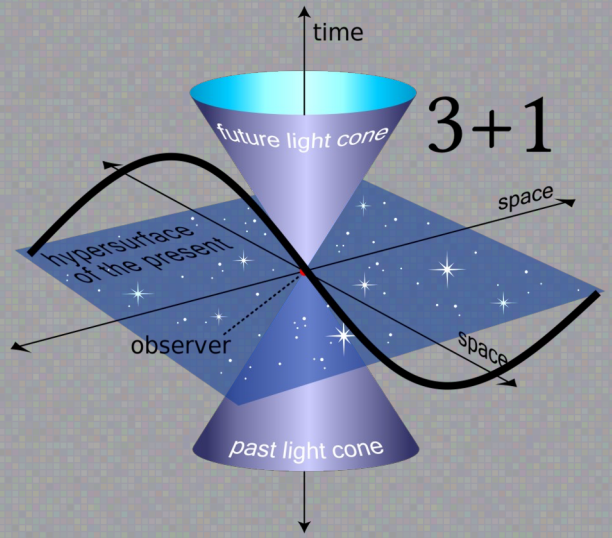
Supported by grants 2023.06787.CEECIND, 2024.01362.CERN, UIDP/00777/2020, UIDB/00777/2020

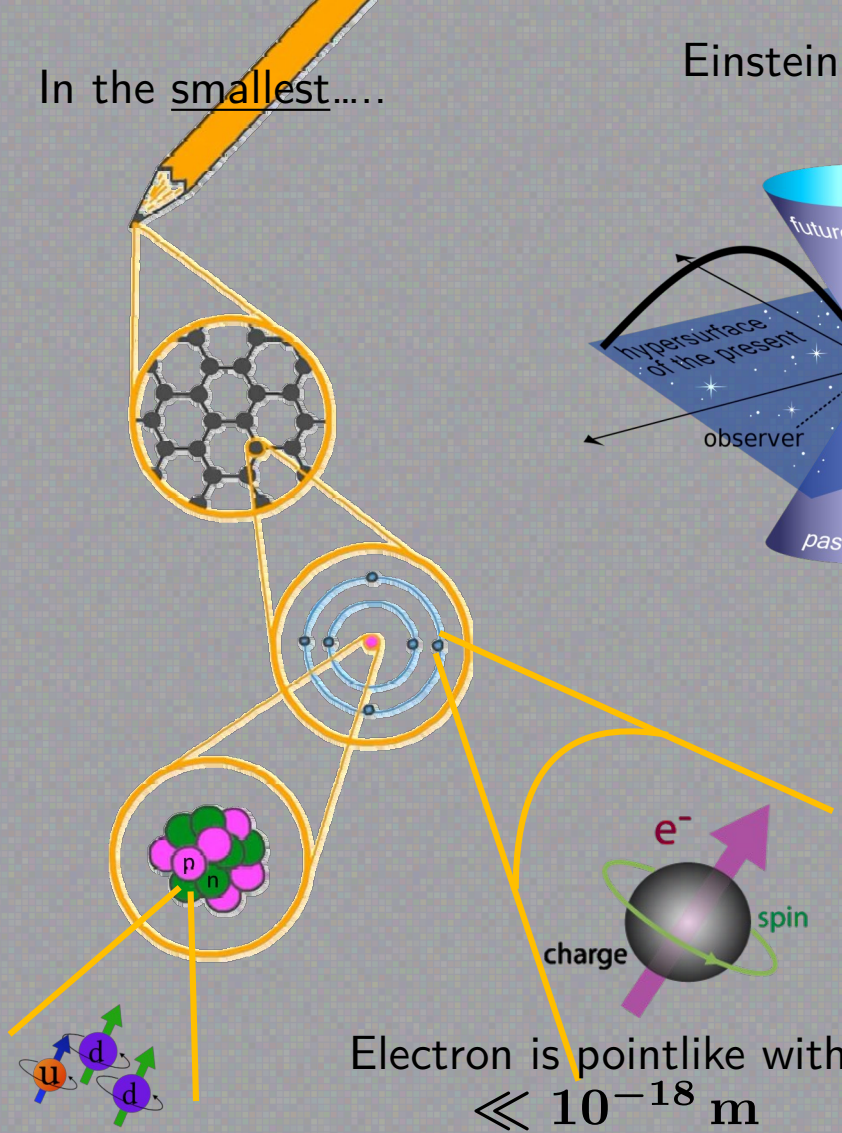
Most people have little to no idea,

how well we understand Nature...

In the smallest.....

Einstein's Special Relativity + known **forces** of Nature:





Electron is pointlike with size

$$\ll 10^{-18}\,\mathrm{m}$$

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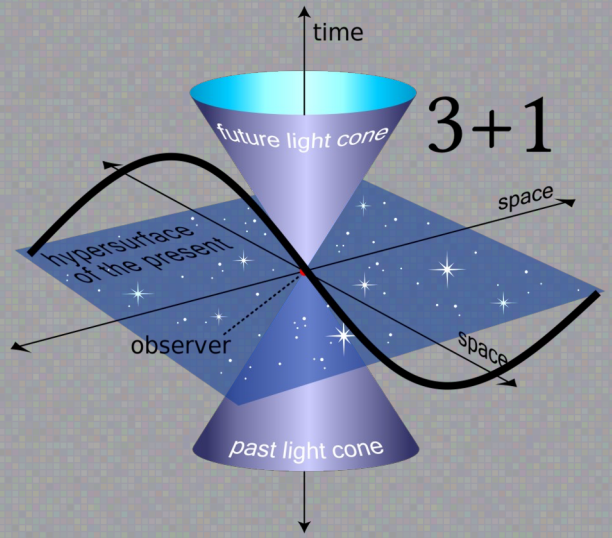

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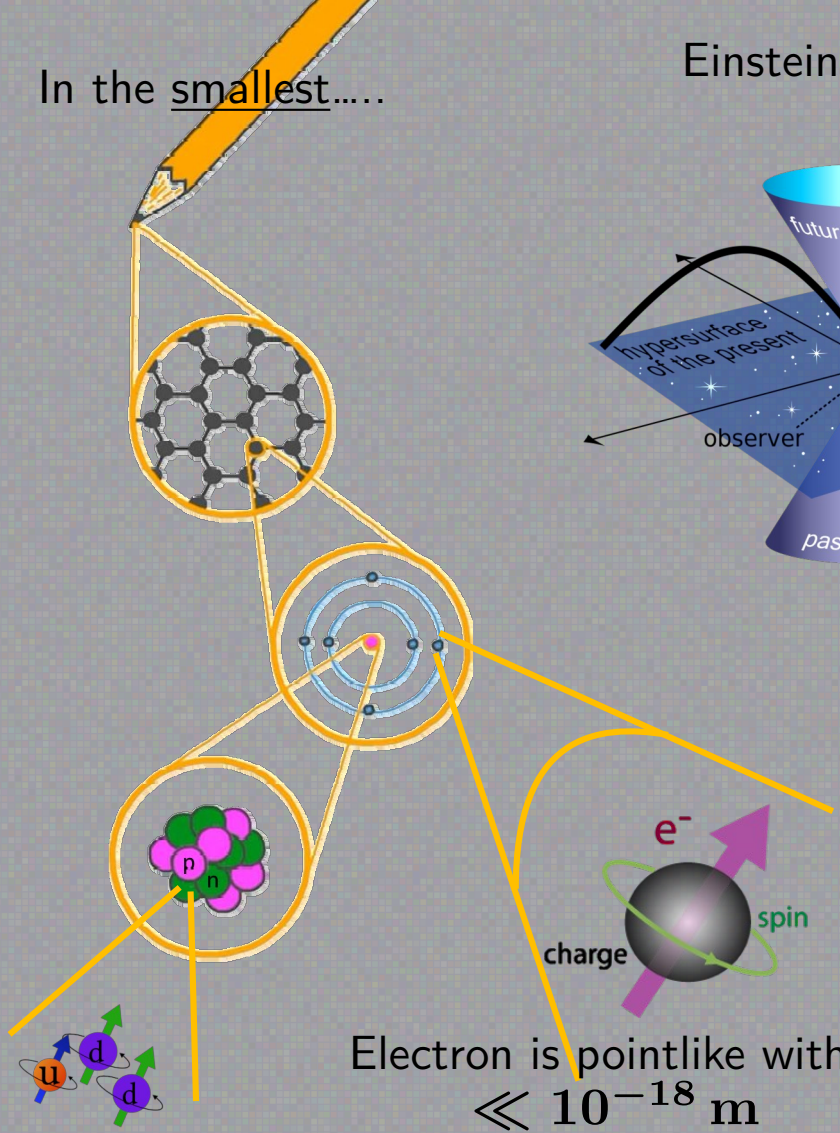

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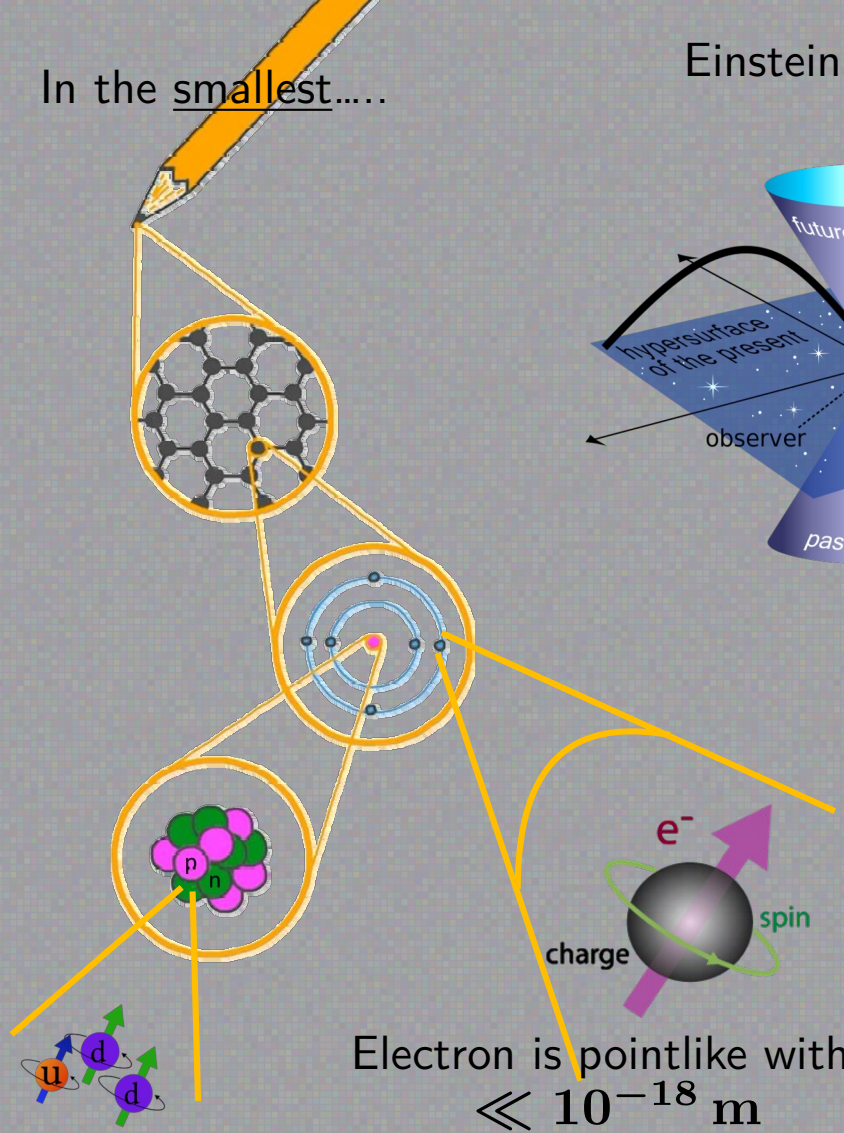

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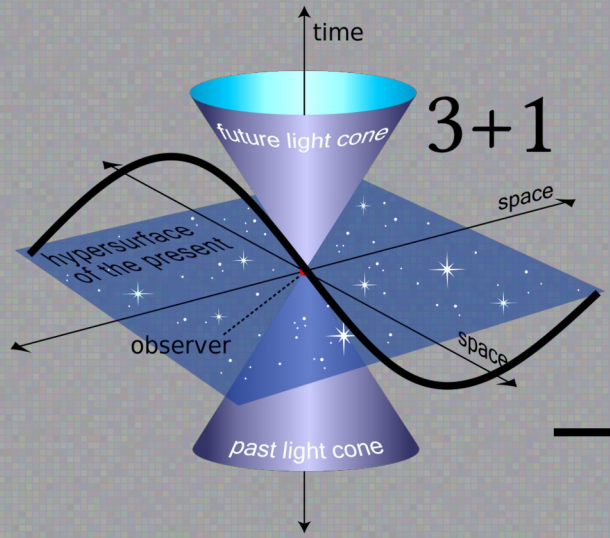


+

Electron and Positron anomalous magnetic moments

$$a_e^{\text{theo.}} = 0.001\,159\,652\,182\,04(72)$$

$$a_{e^-}^{\text{expt.}} = 0.001\,159\,652\,180\,59(13)$$

$$a_{e^+}^{\text{expt.}} = 0.001\,159\,652\,187\,90(430)$$

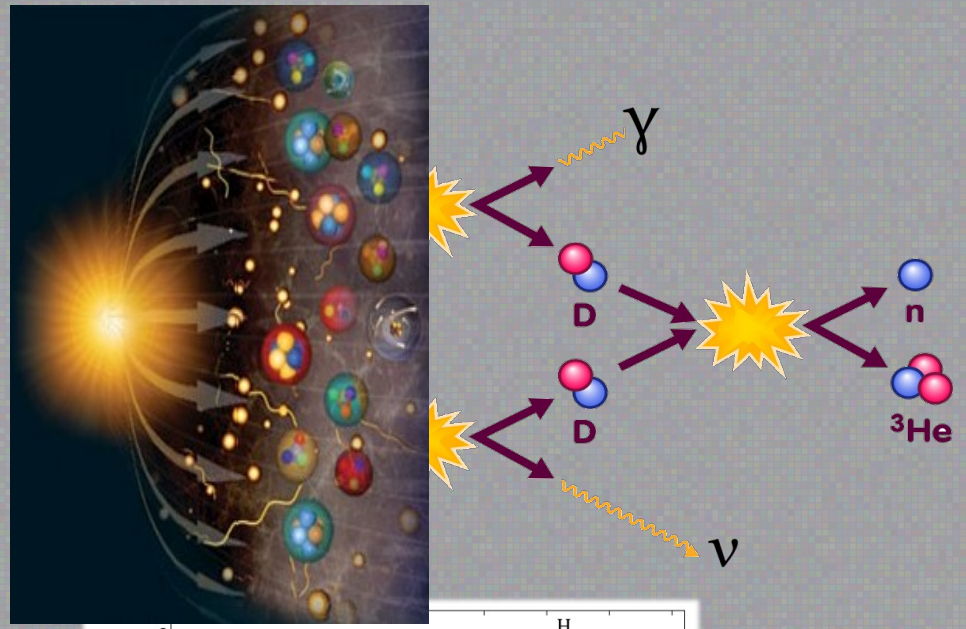
Gabrielse et al, PRL 130 (2023)

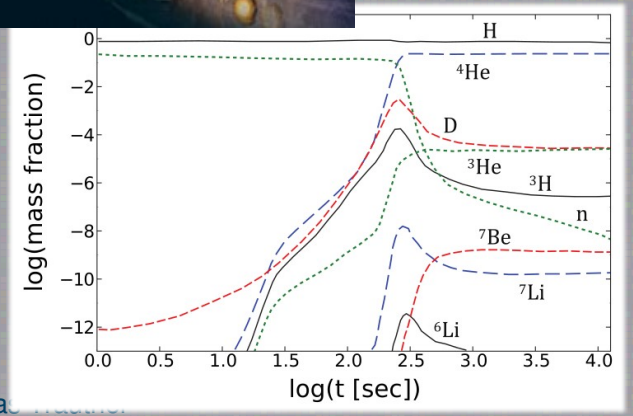
Most precise quantity we can predict and measure.

Electron is pointlike with size $\ll 10^{-18}\,\mathrm{m}$

In the largest... and earliest... ...and the whole Universe:

O(seconds) after Big Bang: "Big Bang Nucleosynthesis"





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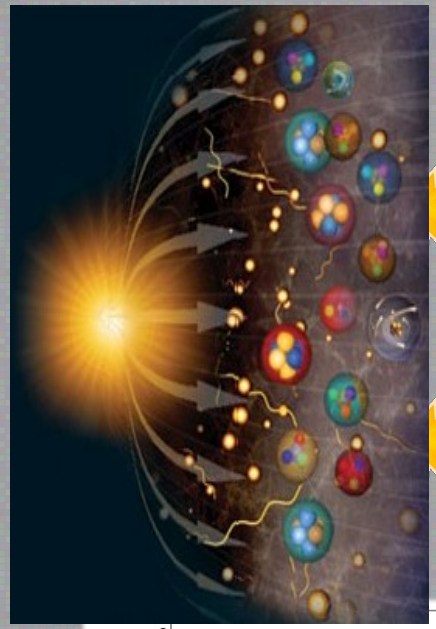

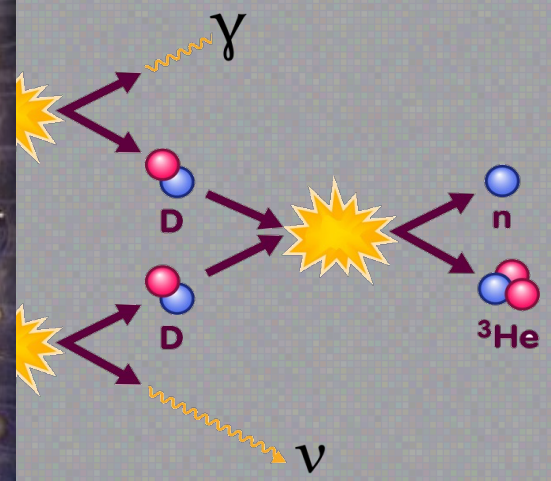

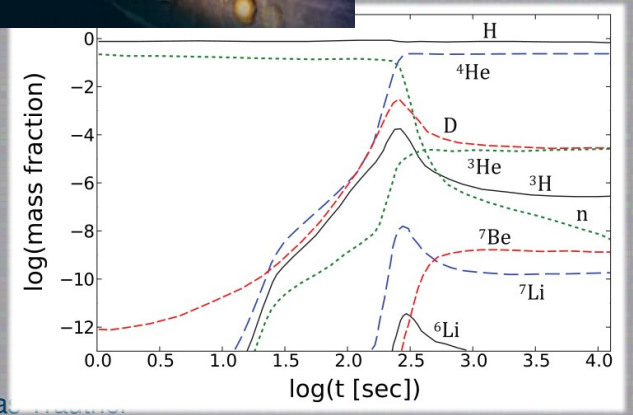

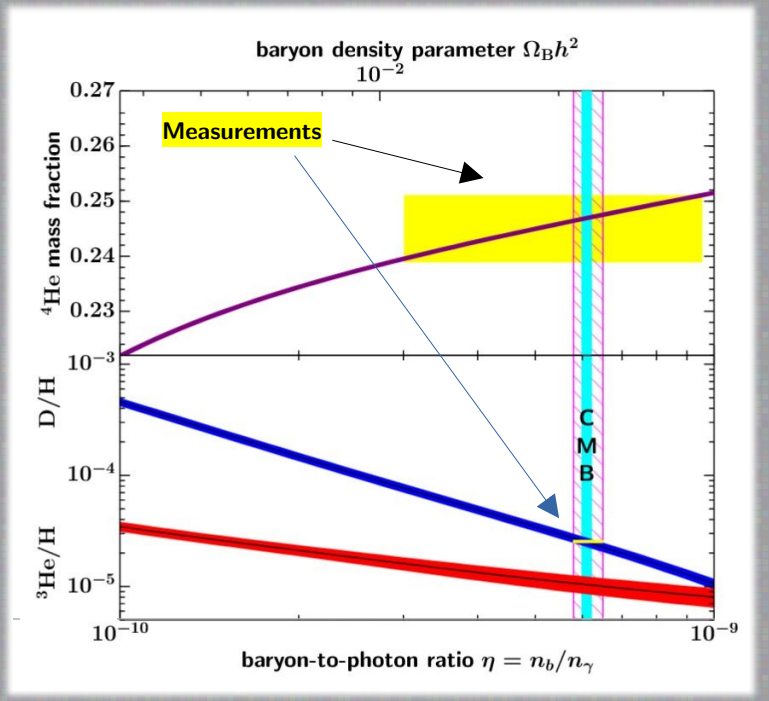

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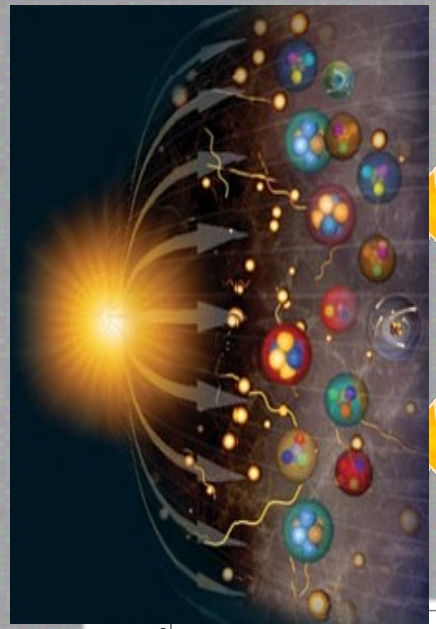
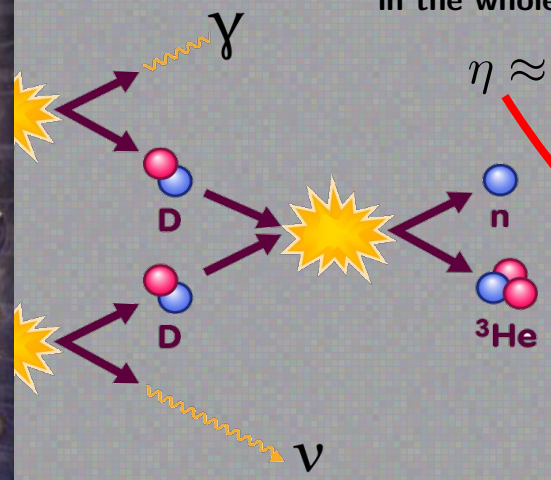
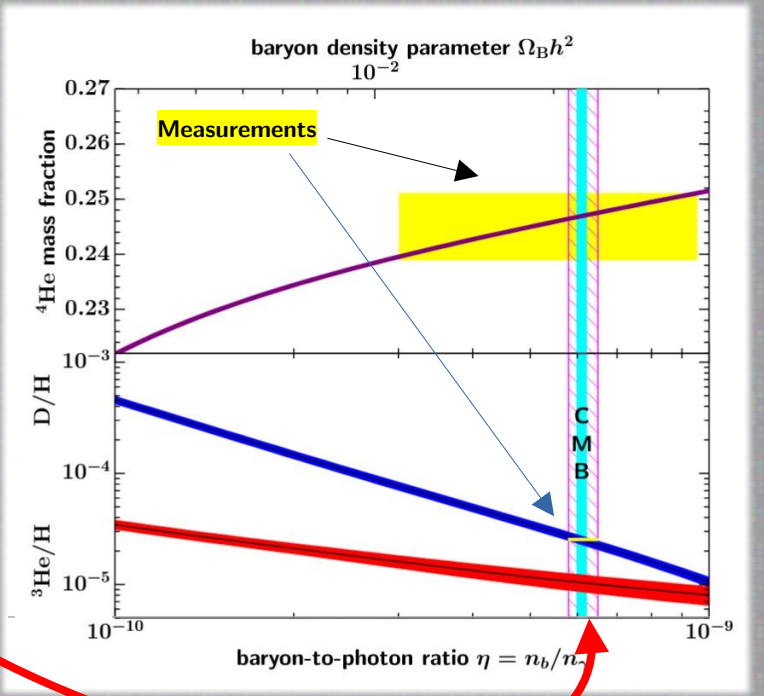


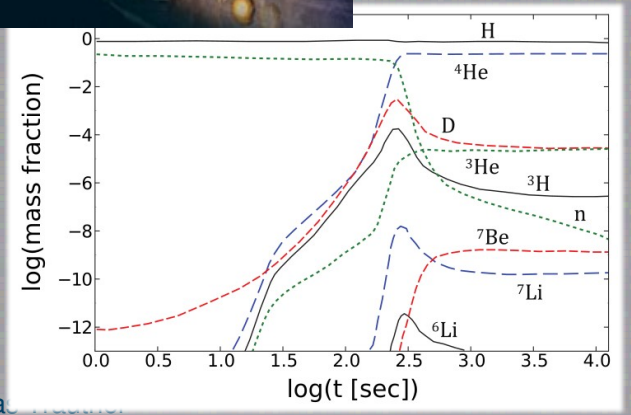


This measures:

Ratio of matter (baryons) to anti-matter in the whole Universe!

$$\eta \approx 6 \times 10^{-10}$$





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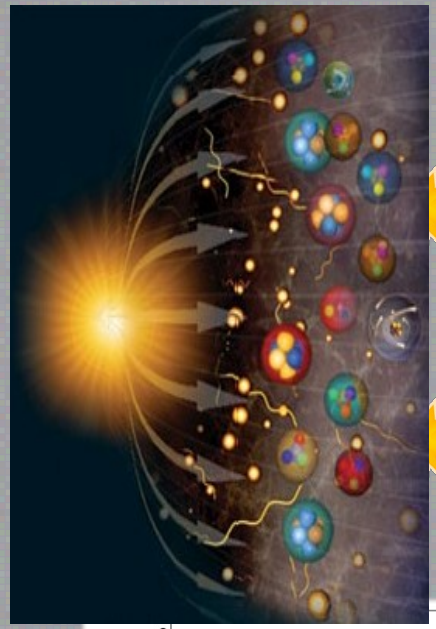

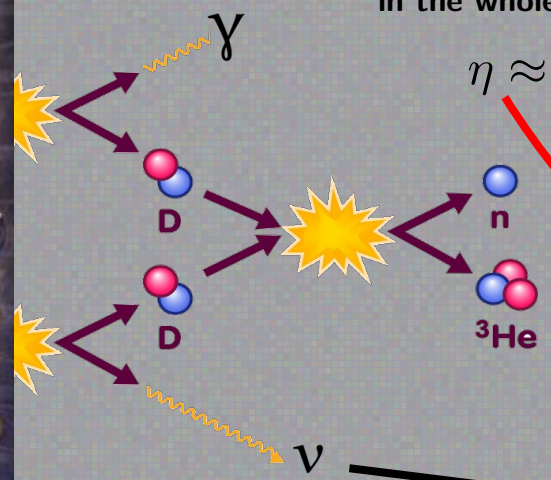

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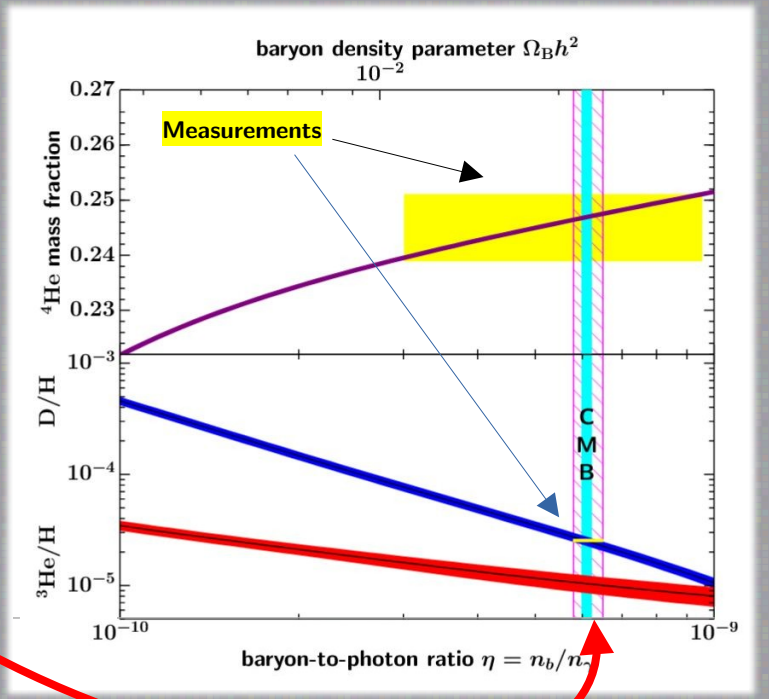
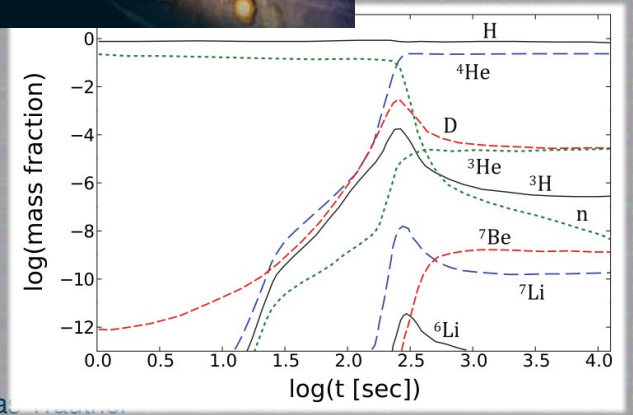
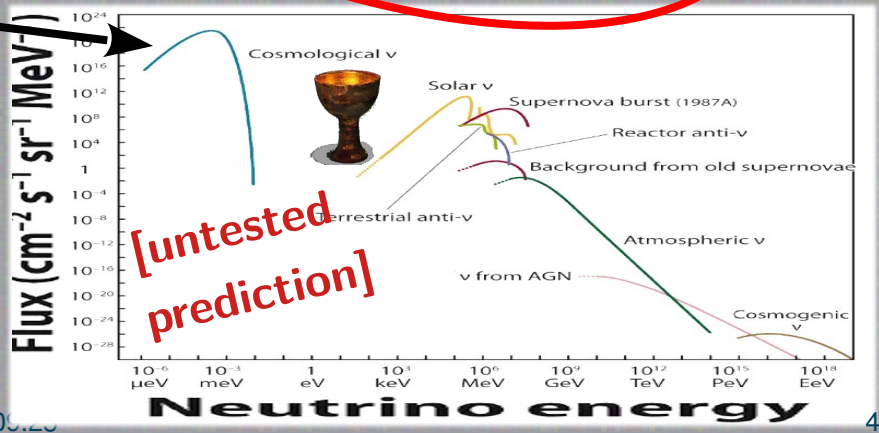




Cosmic Neutrino Background



Big Bang

galaxies

Most universal

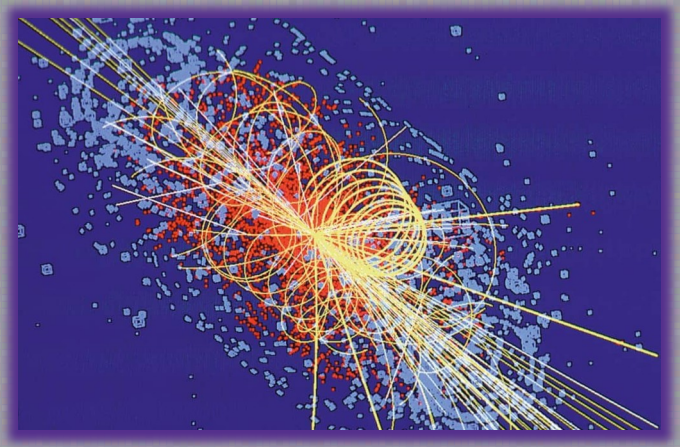
stellar

stuff

molecules

atoms

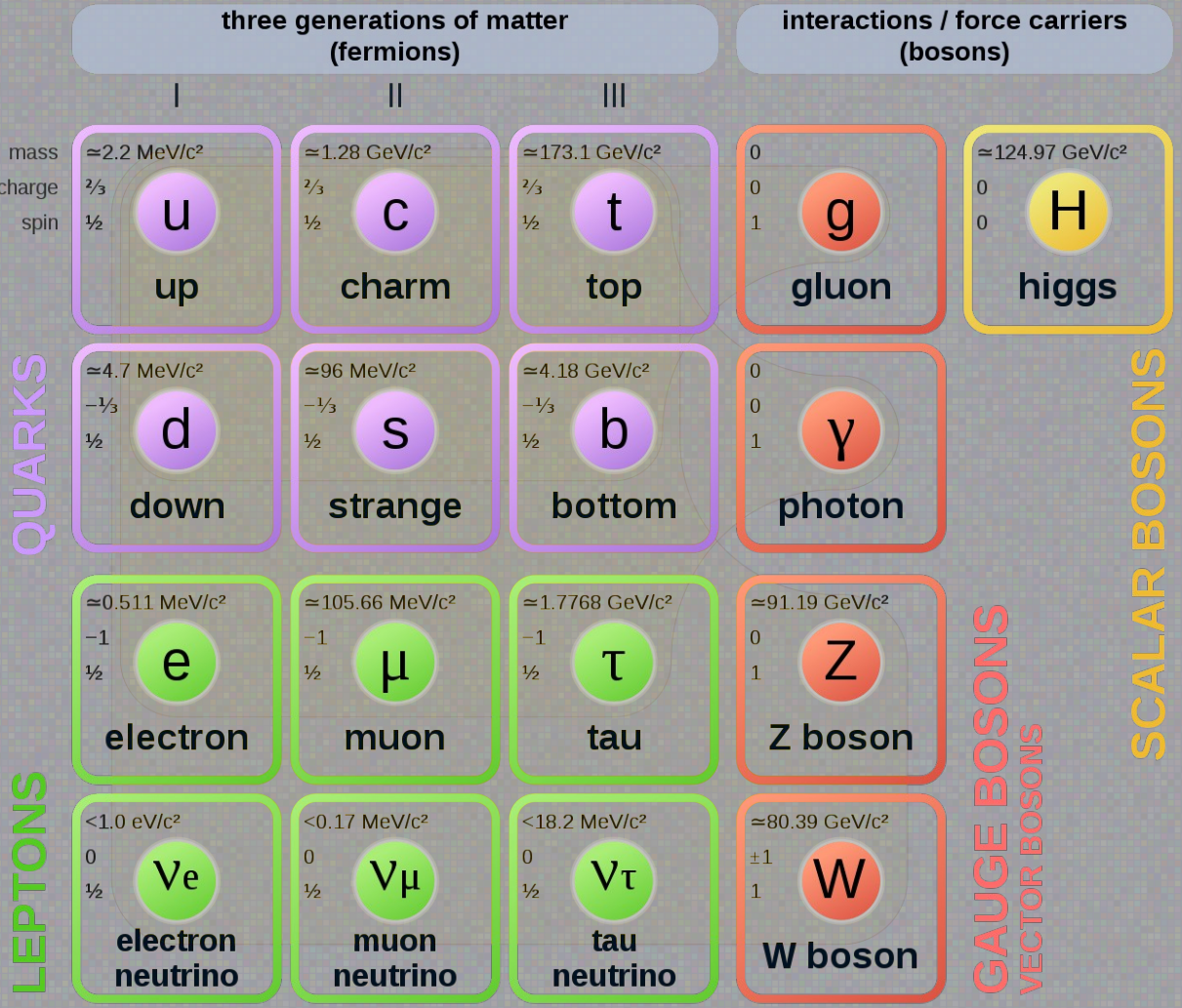
particles



Most precise

All of this* is governed by...

Standard Model of Elementary Particles



Most successfull model **ever**

More than two dozens Nobel prices

Requires (min.) **27 parameters**

"constants of Nature"

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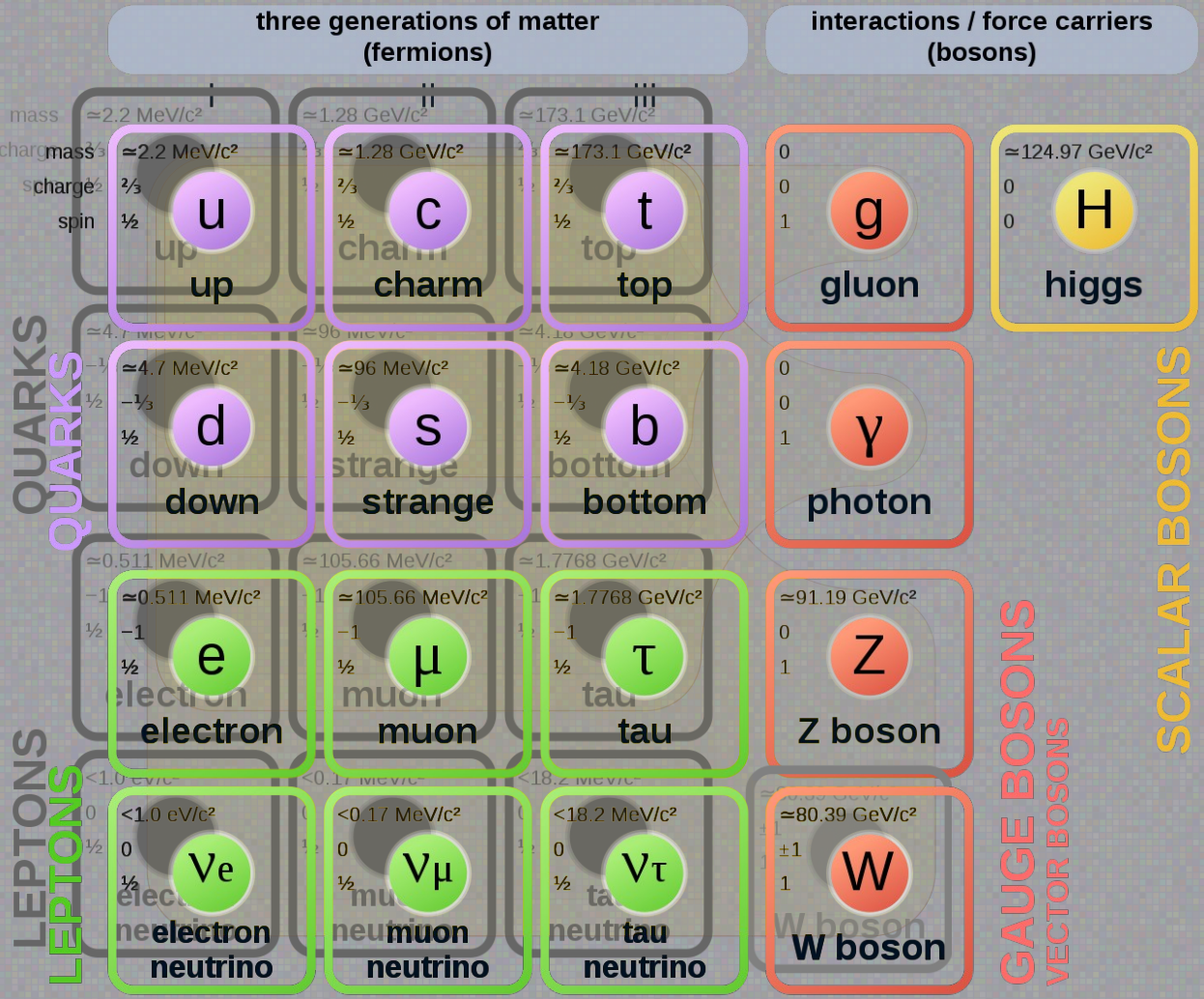

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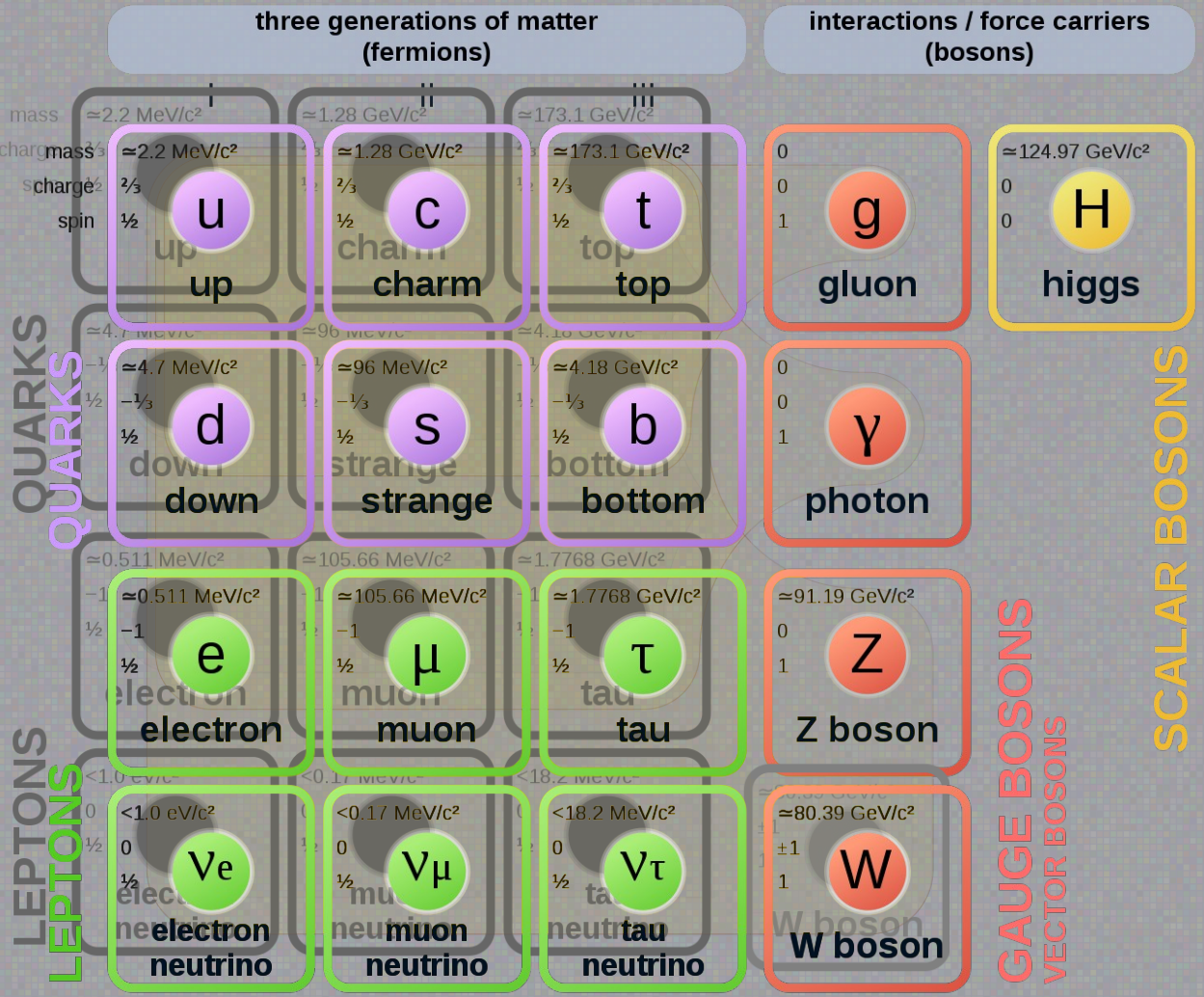

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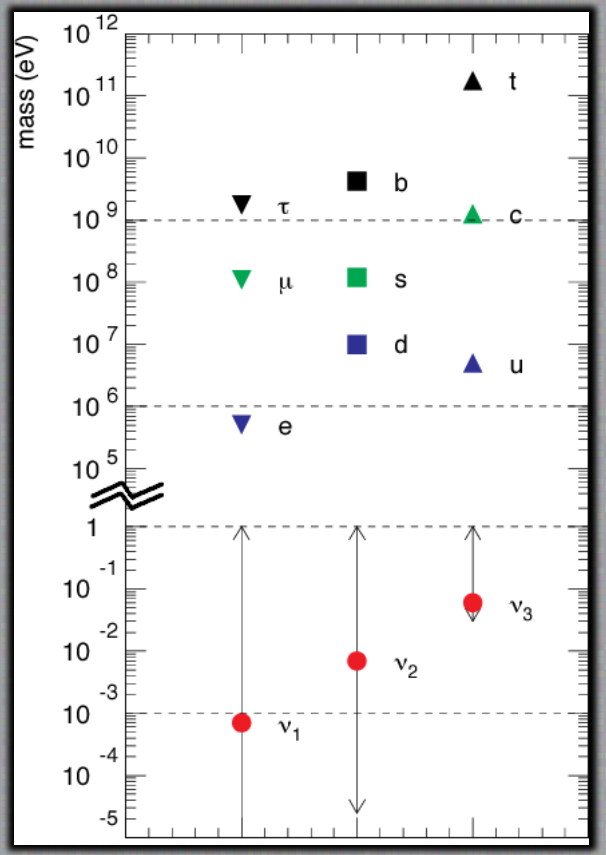
Incl. (min.) **1** known parameter for Matter-Antimatter Symmetry Violation ("CP Violation")

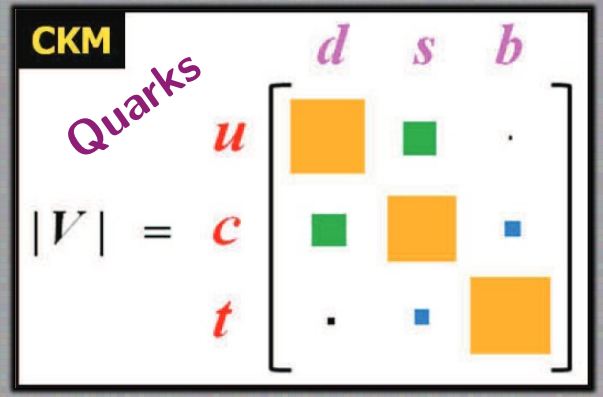
22 out of 27 required parameters correspond to couplings of the Higgs field!

Matter particle (Fermion) masses

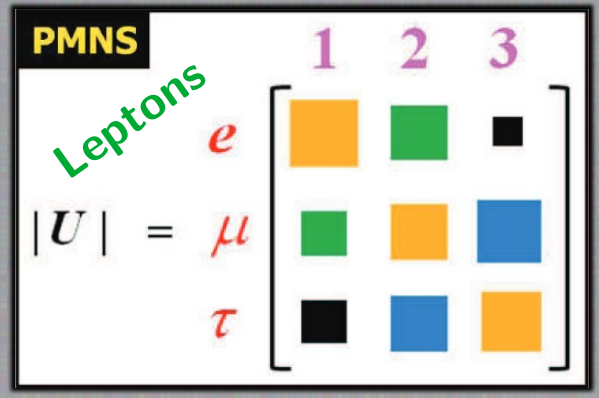
including

Matter particle (Fermion) "mixings"





known
10 of 10
parameters
for Quarks



known
8 of 10..12?
parameters
for Leptons

The Flavor Puzzle

- Why **exactly three** generations of Fermions (matter)?
- What explains their pattern of **hierarchical** masses and mixings?
- Understanding = Need fewer parameters $\Longrightarrow$ Testable predictions.

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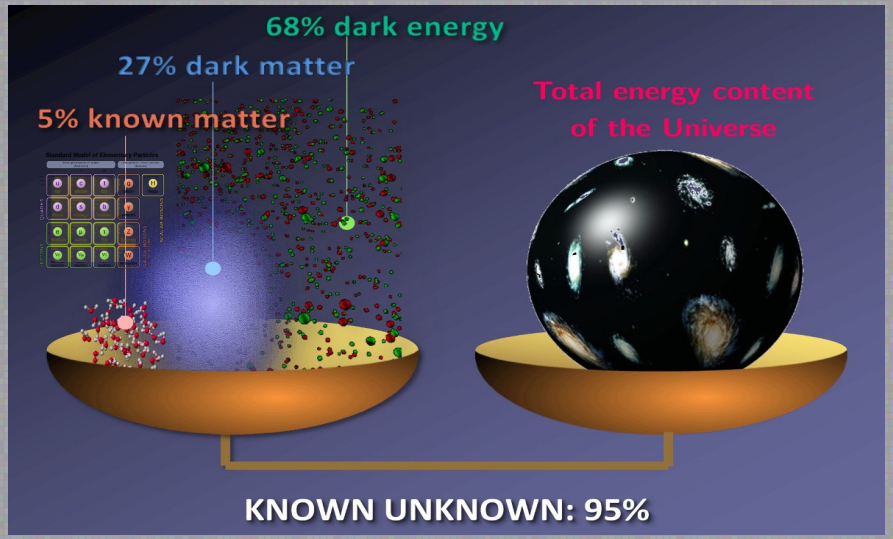
- What makes up Dark Energy?



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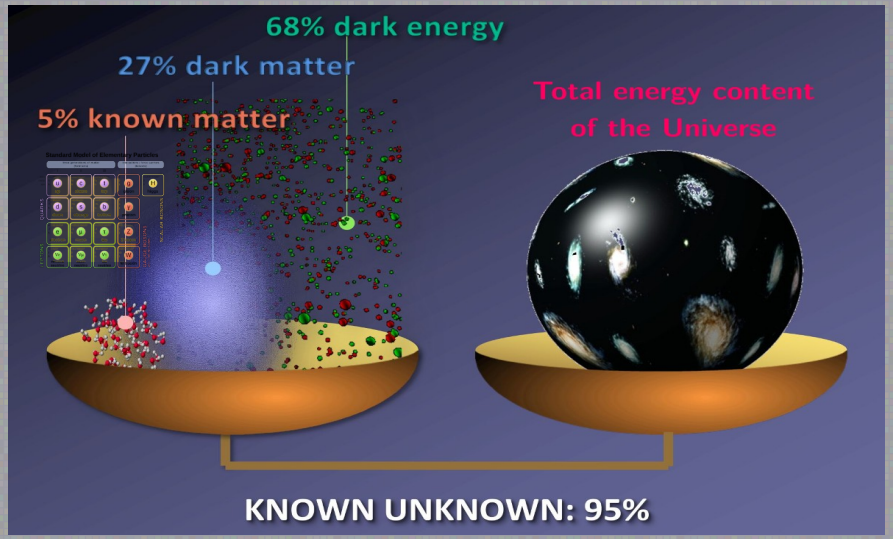

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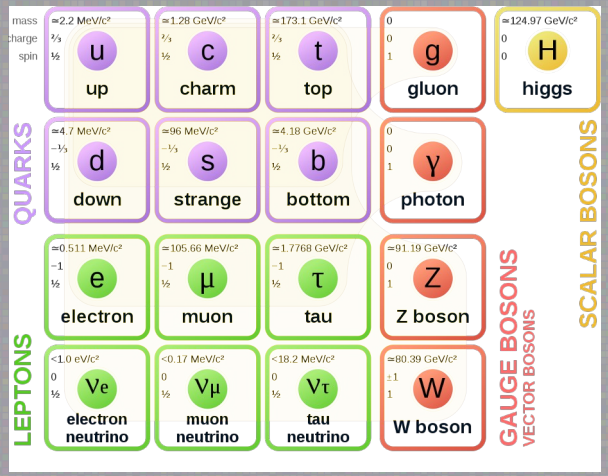

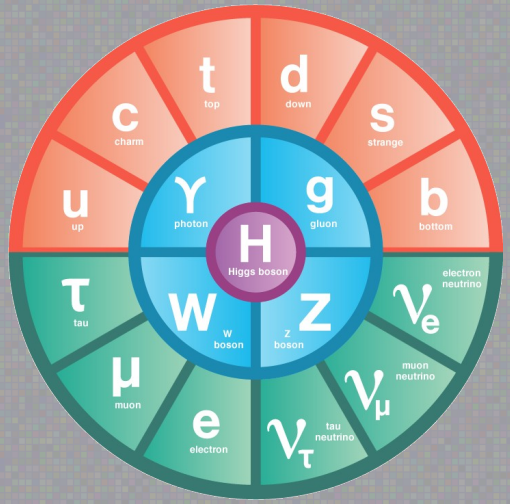

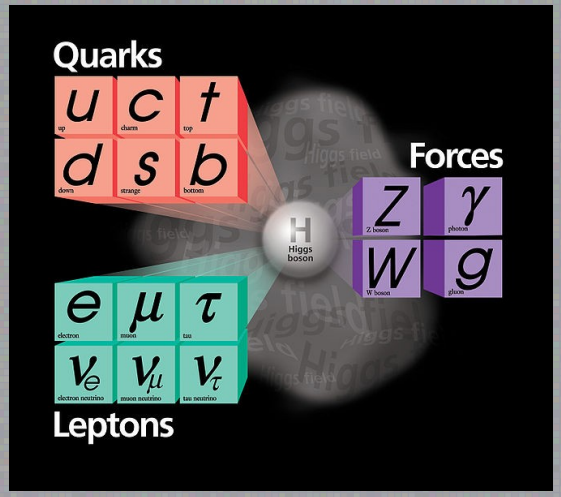

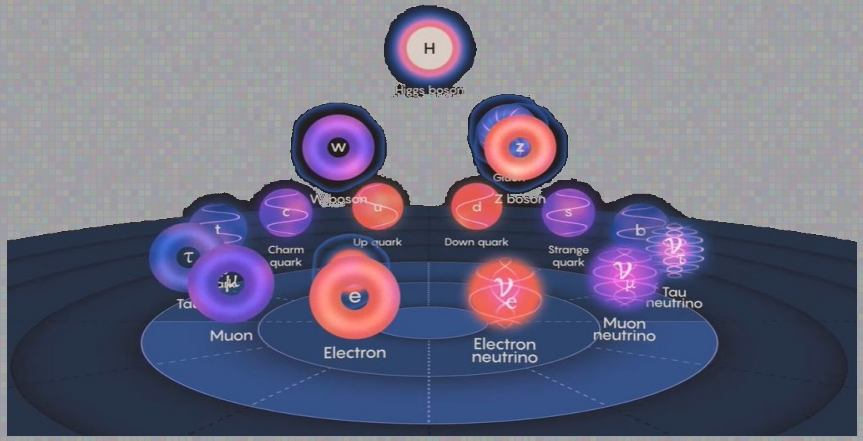

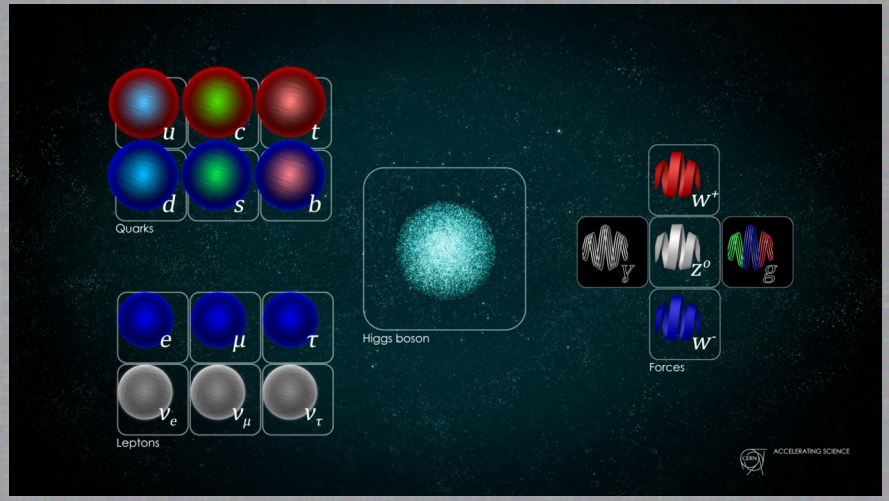

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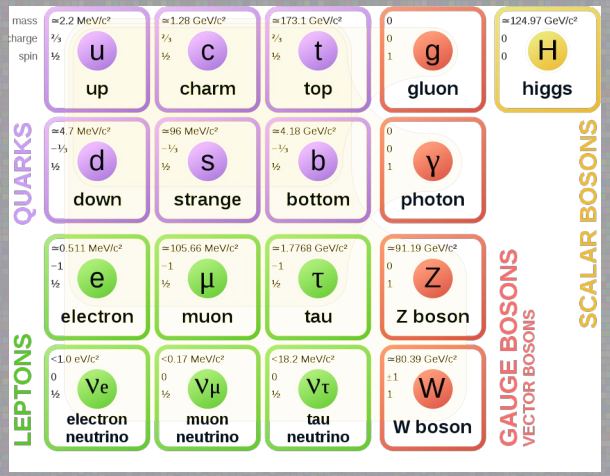
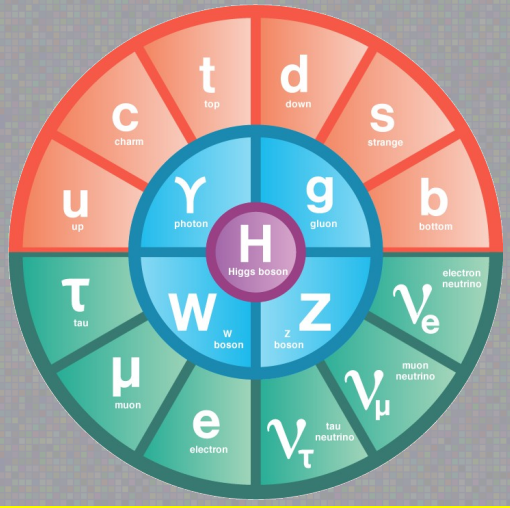
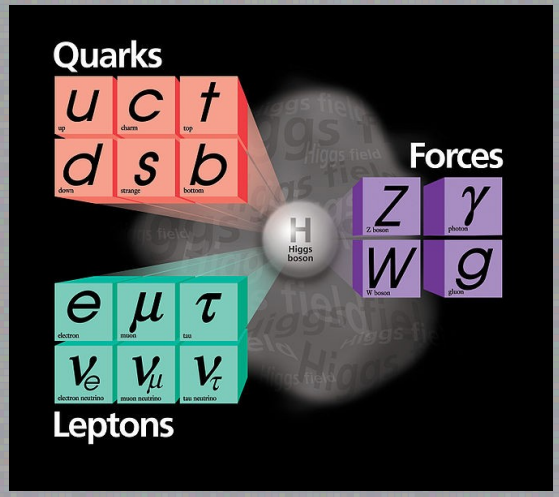
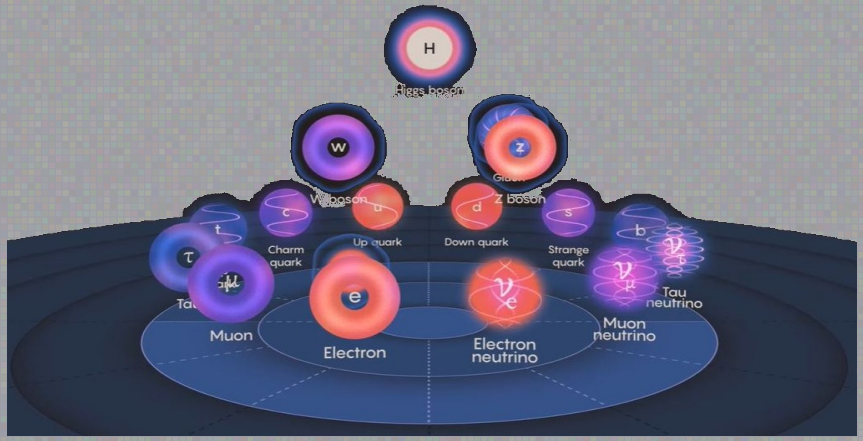
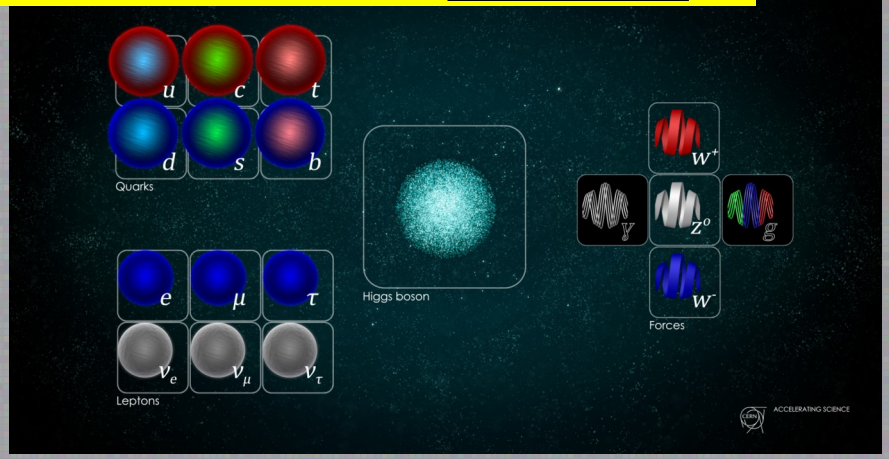






We can *describe* this structure of Nature, but we do not *understand* it!





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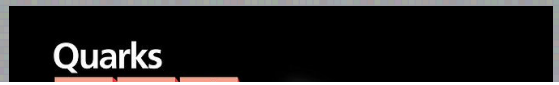
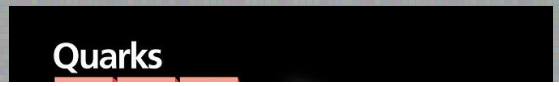


PERIODIC TABLE OF THE ELEMENTS

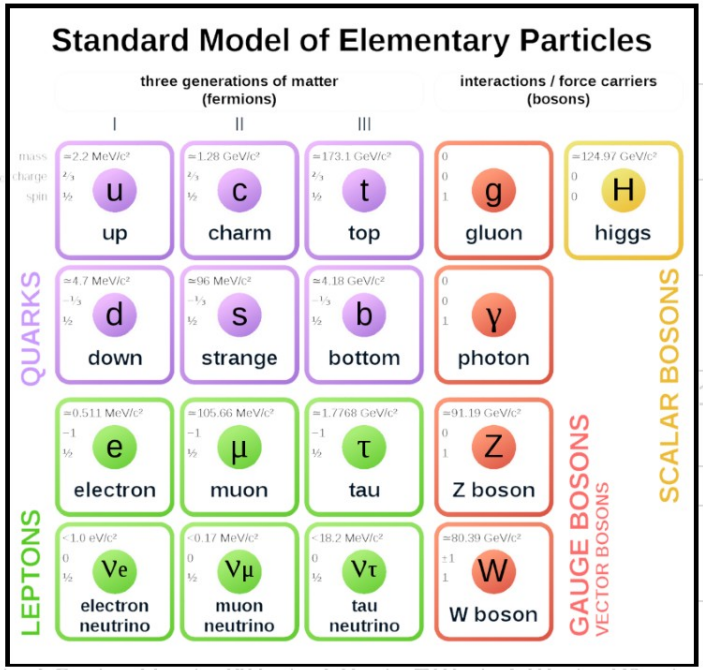
Period	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	†	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

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



NO (known)

PERIODIC TABLE OF THE ELEMENTSARY PARTICLES



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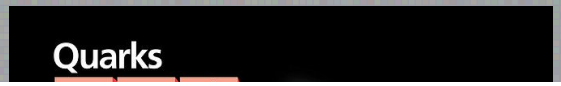

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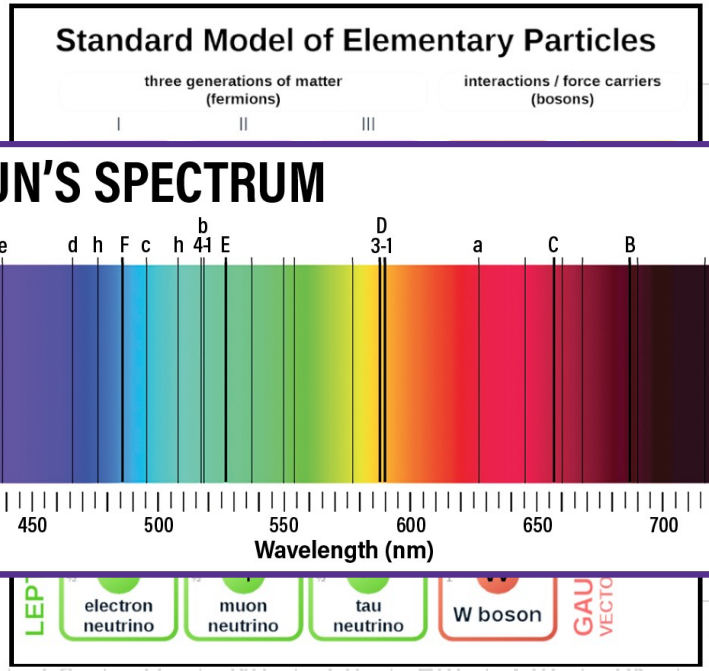
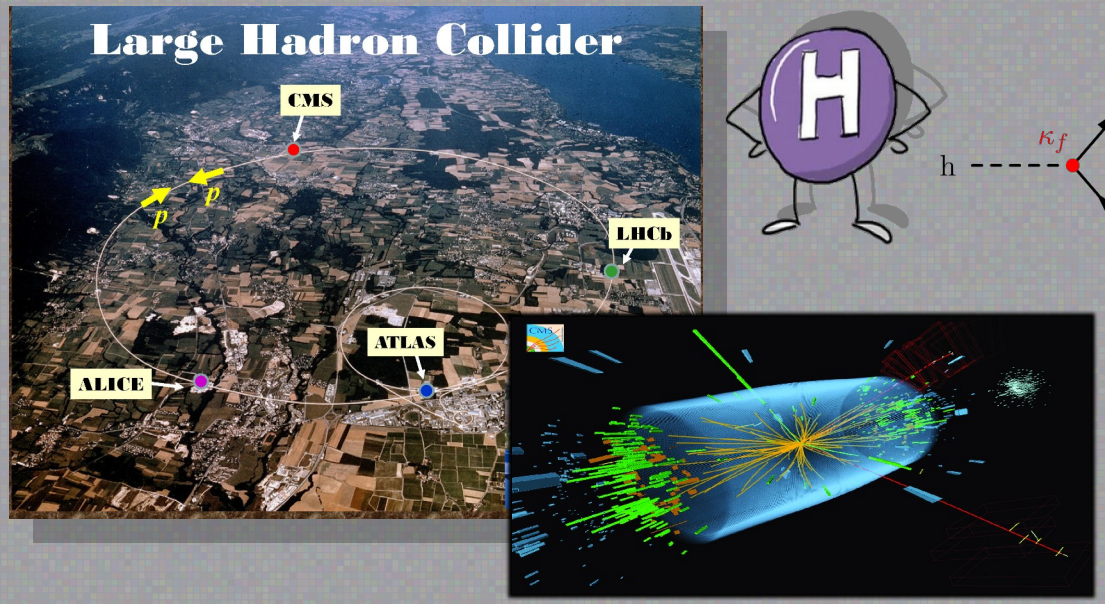
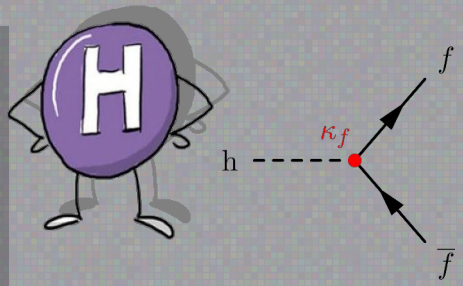
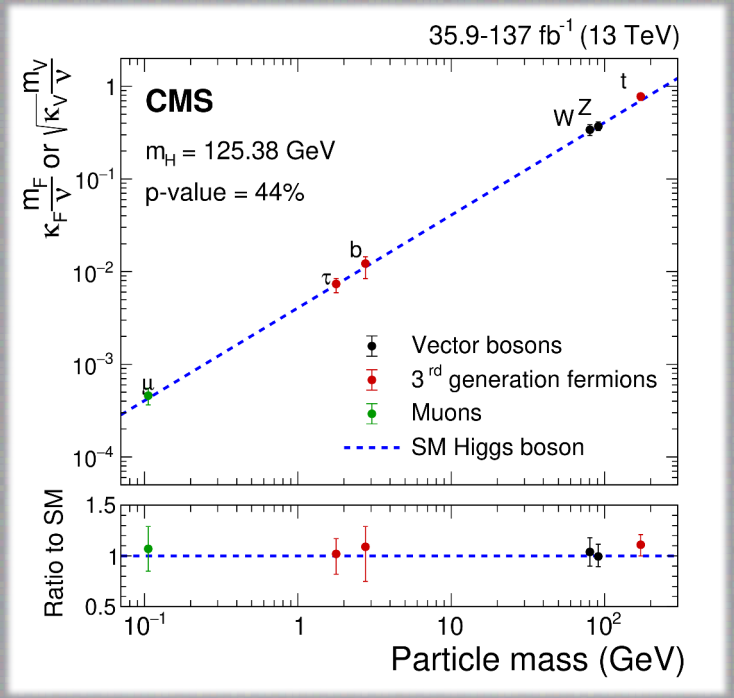


Experimental progress







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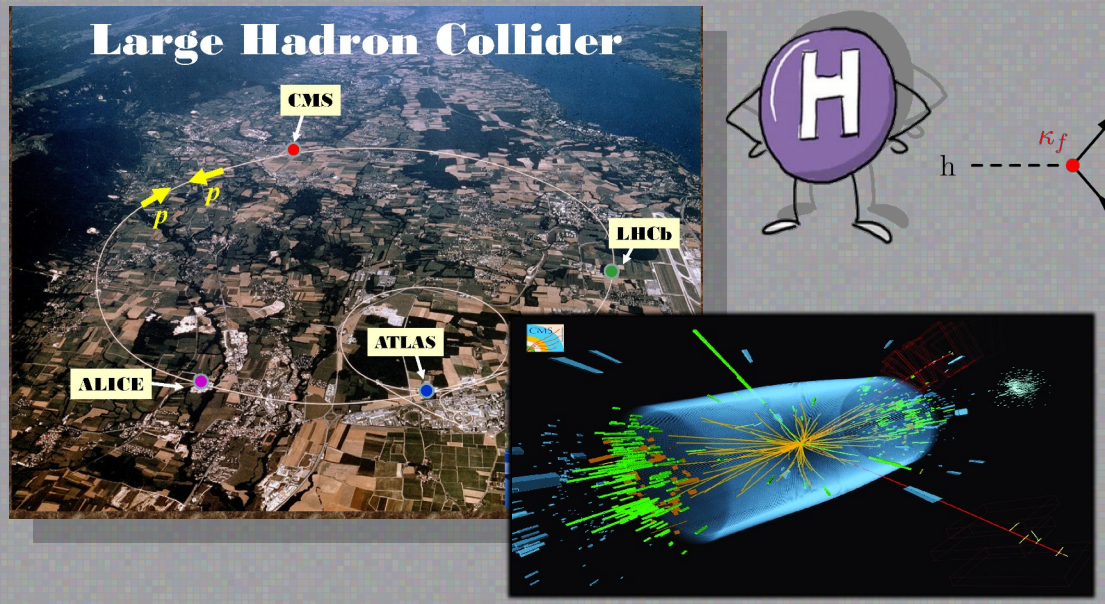
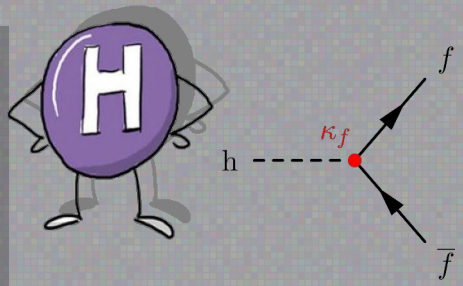
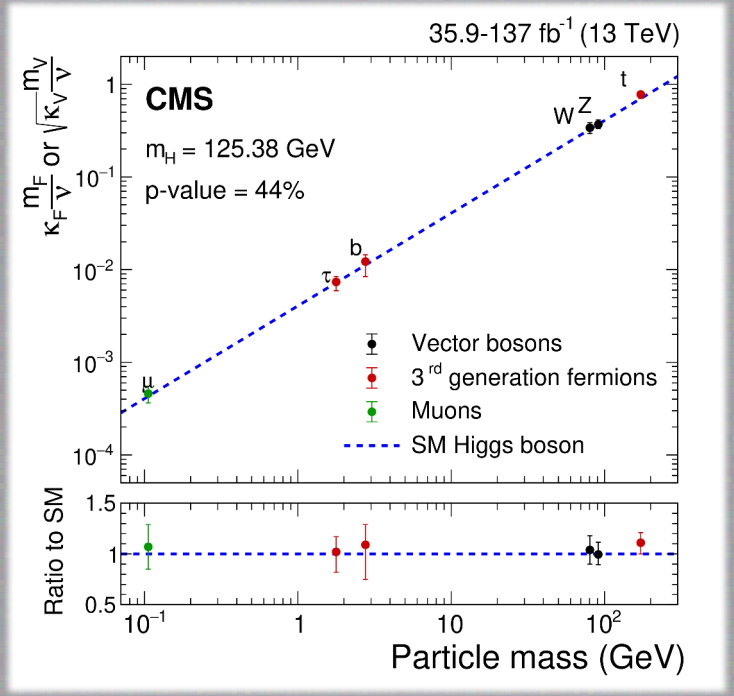
...many equally important epochal discoveries!

Direct measurement of Higgs coupling to t-, b-quark, τ, μ, next: c-quark, ...

Experimental progress







After Higgs discovery 2012...

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Direct measurement of Higgs coupling to t-, b-quark, τ, μ, next: c-quark, ...

All consistent with the SM, re-emphasize the flavor puzzle,

...confirming that we actually address the correct puzzle!

The Flavor Puzzle

Experiments have beautifully delivered, for quarks, all data (10/10) is on the table!

At this point, the flavor puzzle is:

An "open book exam" in pattern recognition!

However, just throwing AI at this ***may*** not help.

What data/models to train the algorithm on?

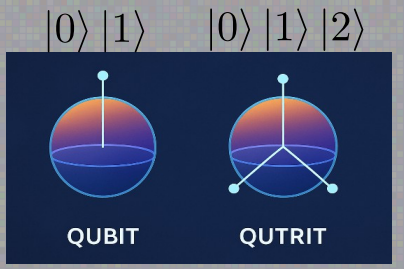
At the boundary of knowledge, there is no training data!

This one may require ***real*** intelligence.

Currently, there is no known model of Flavor that does better than the Standard Model.

A route not explored so far:

Quantum Information Theory and the Flavor puzzle



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Quark flavor parameters can be understood as **4 qutrit** states:

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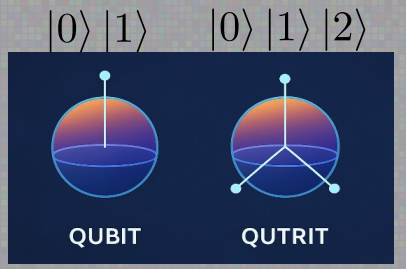

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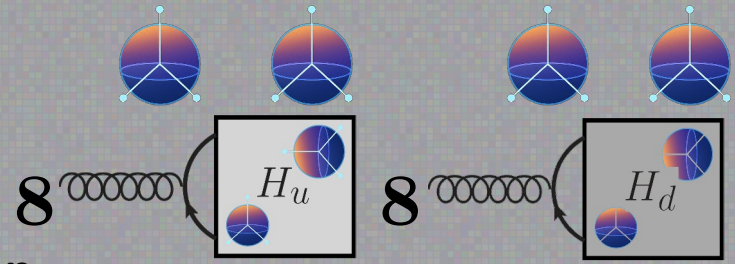

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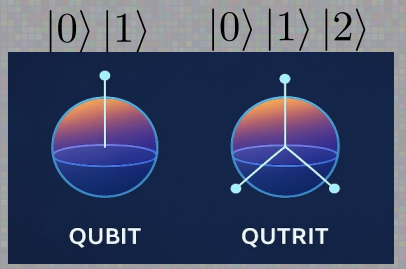

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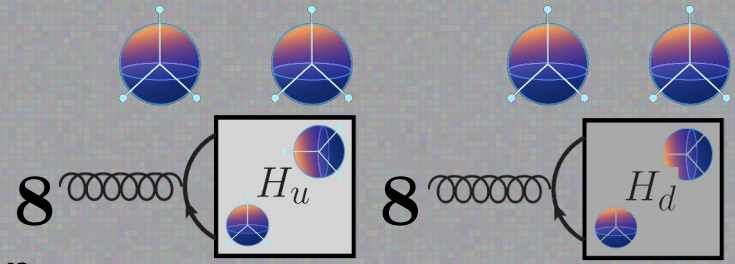

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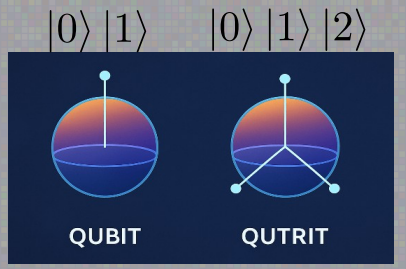

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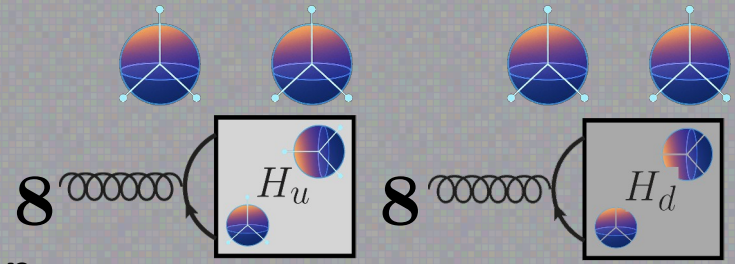

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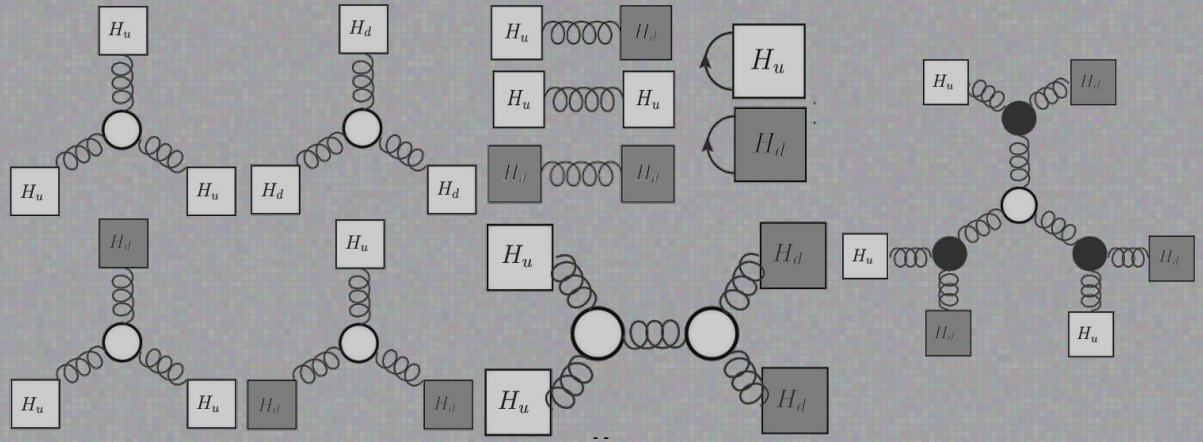

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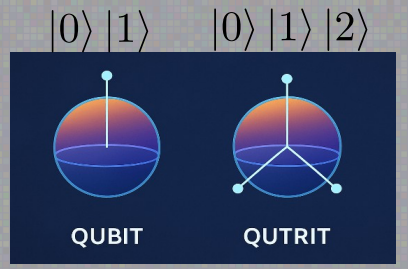

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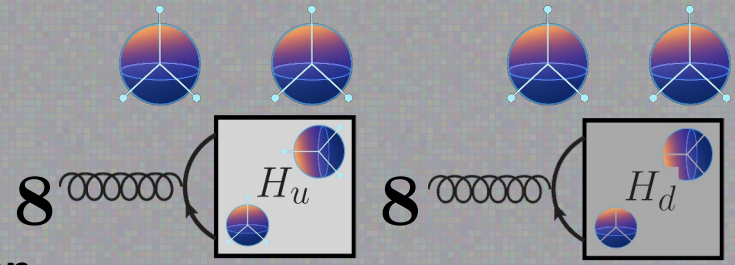

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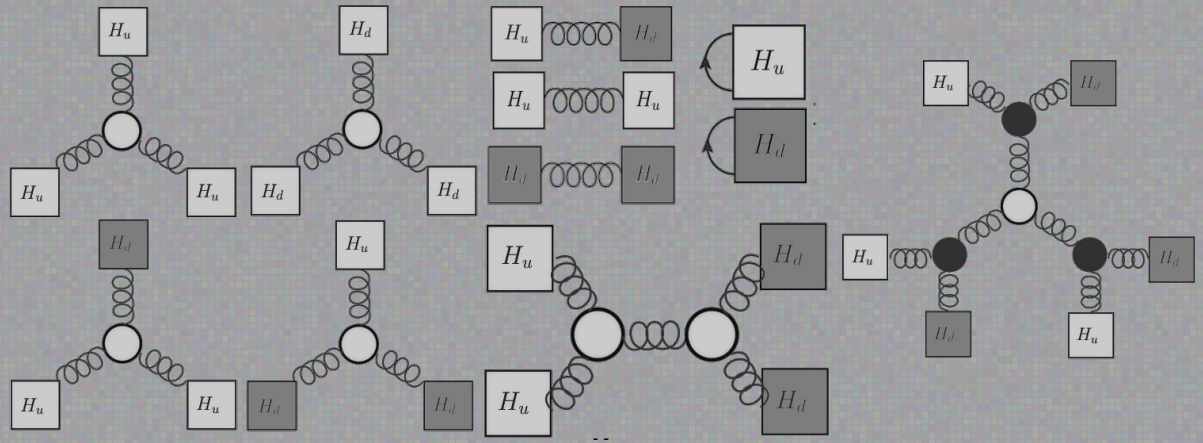

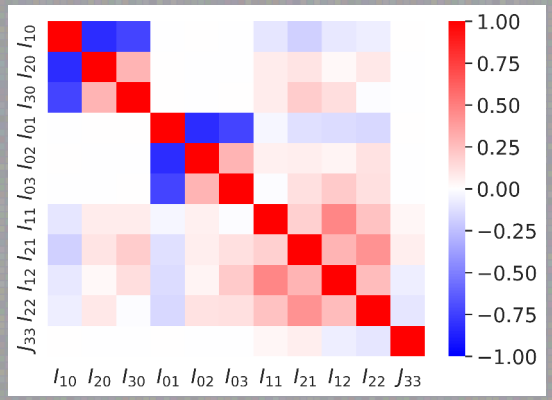

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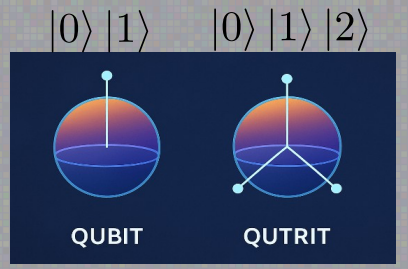

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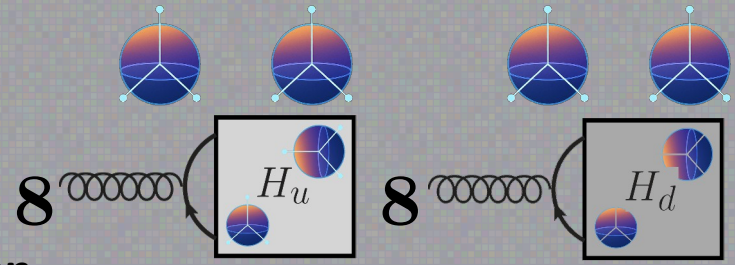

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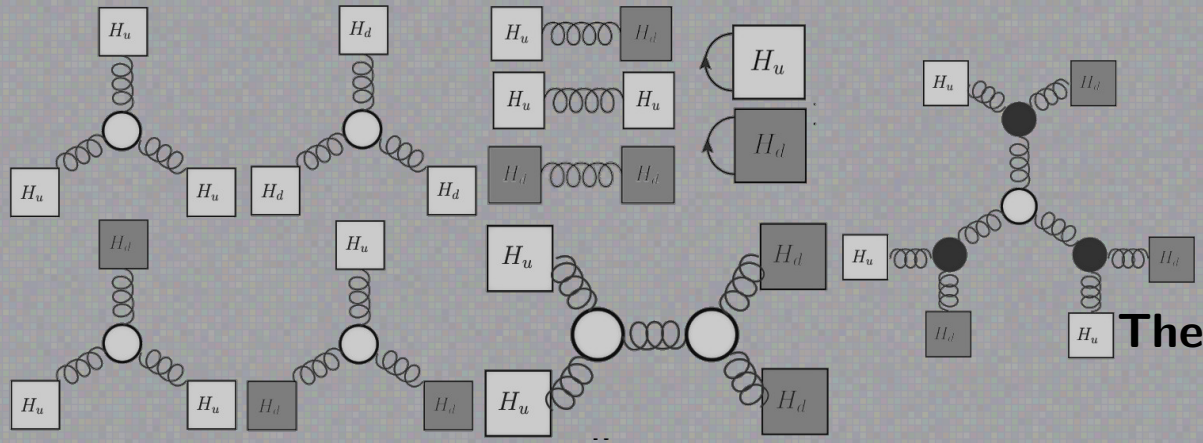

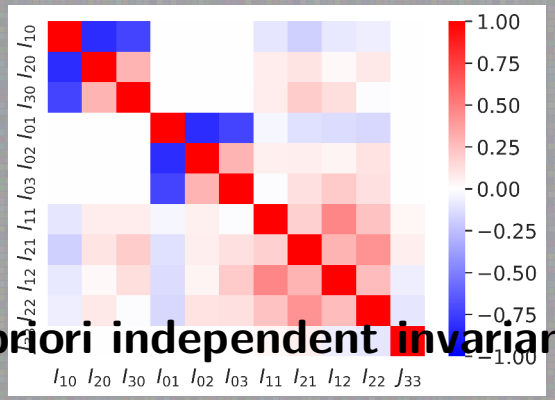

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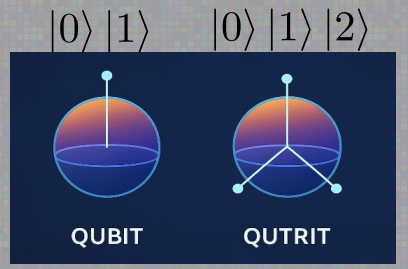

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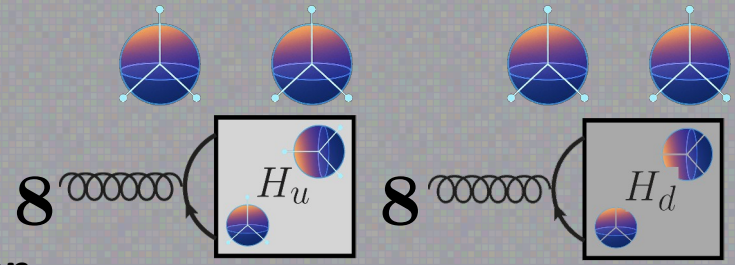

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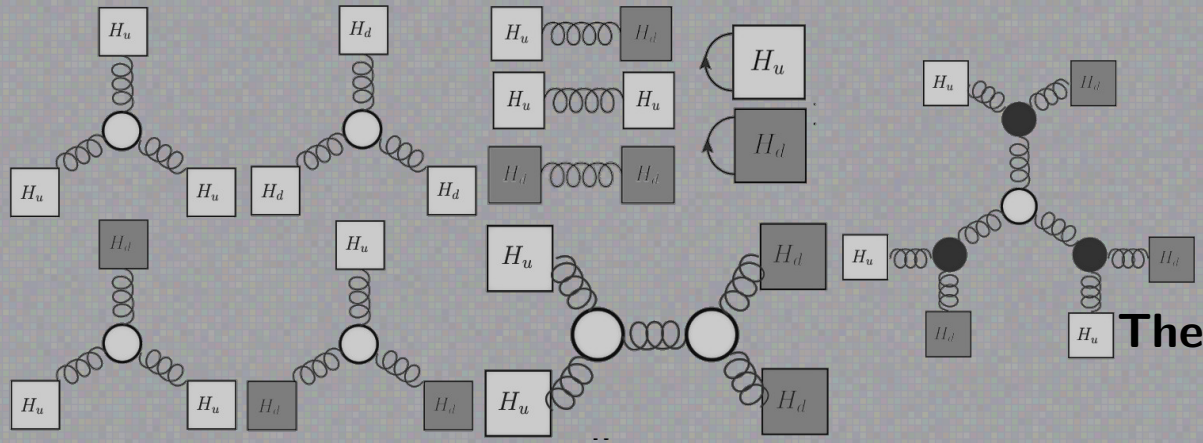

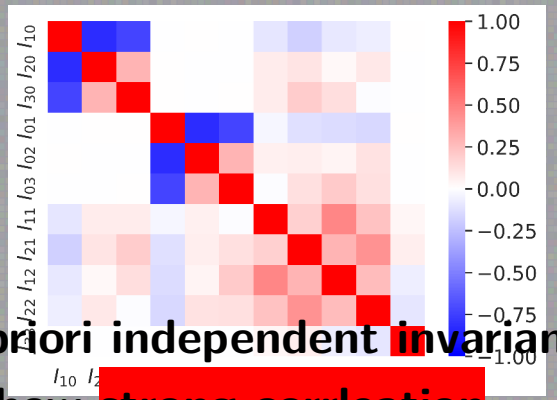

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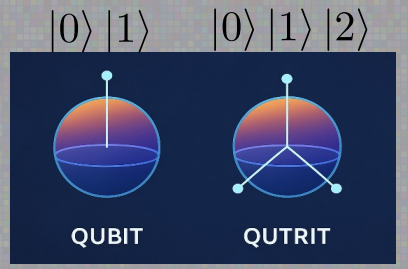

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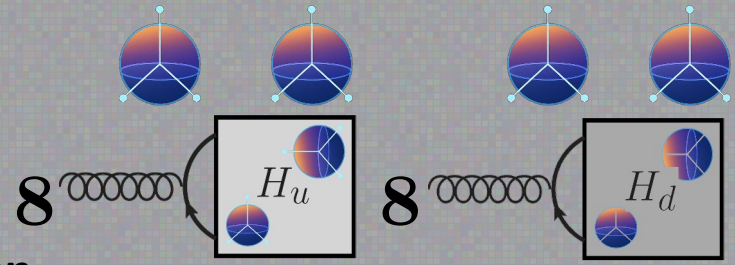

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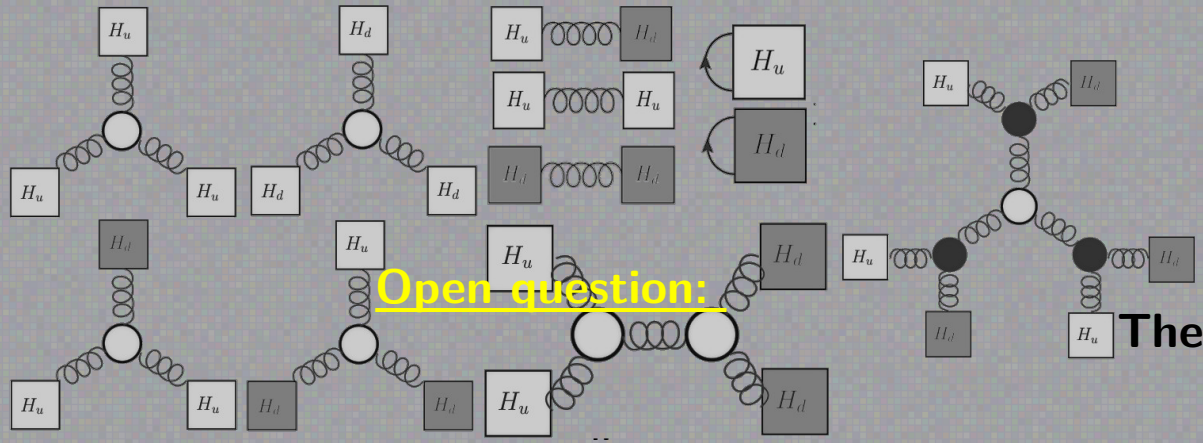

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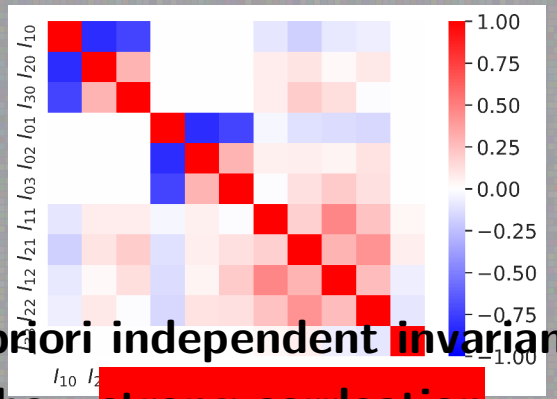

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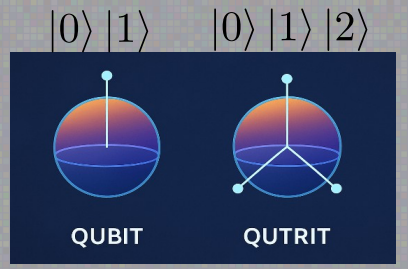

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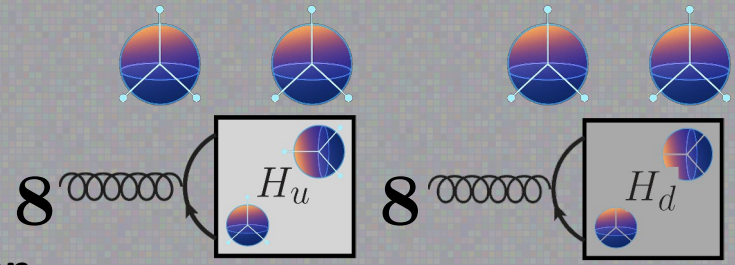

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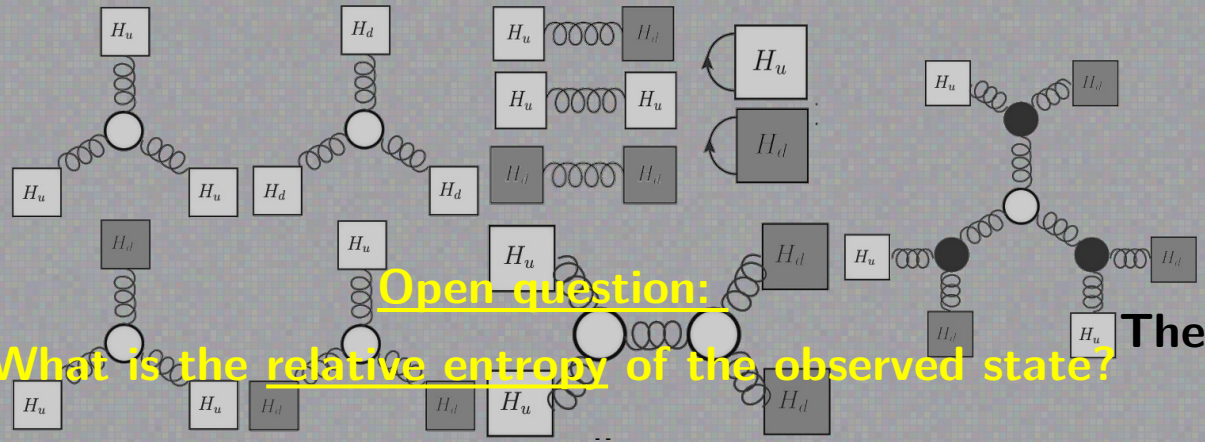

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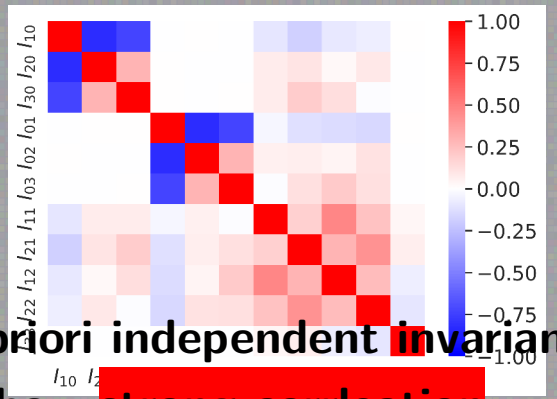

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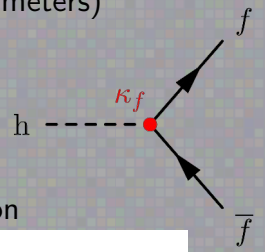
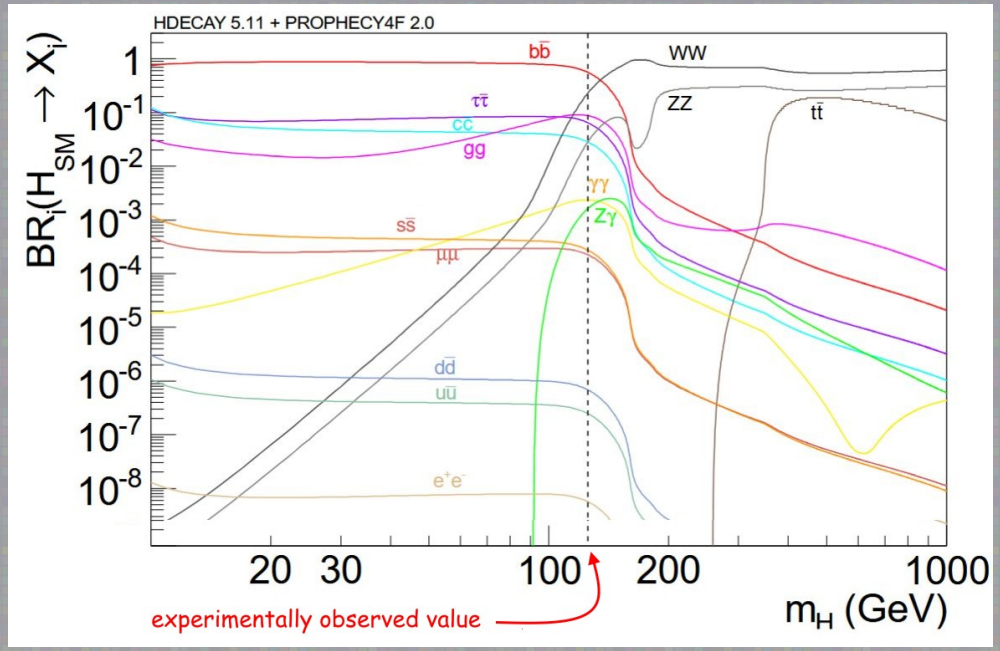
For the Higgs mass (another one of the 27 parameters)
one can play the following game:

$$\mathrm{BR}_i = \mathrm{BR}_{H \to X_i}(m_H)$$



All possible two body decays of the Higgs boson



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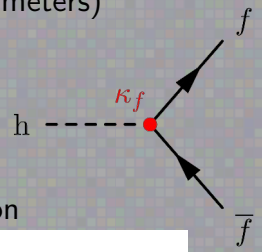

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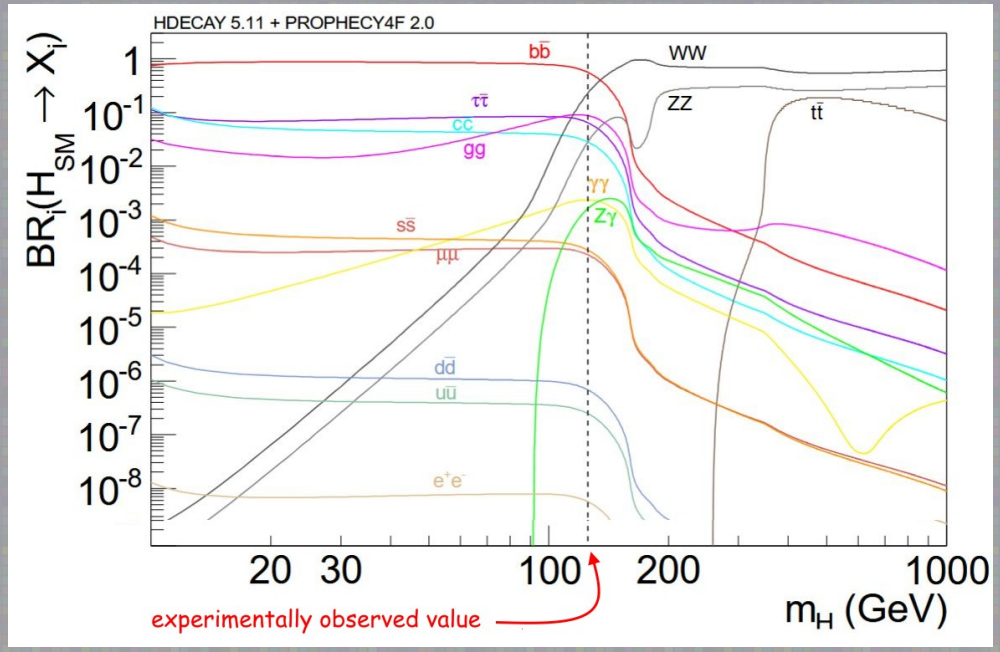

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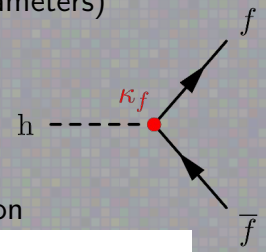

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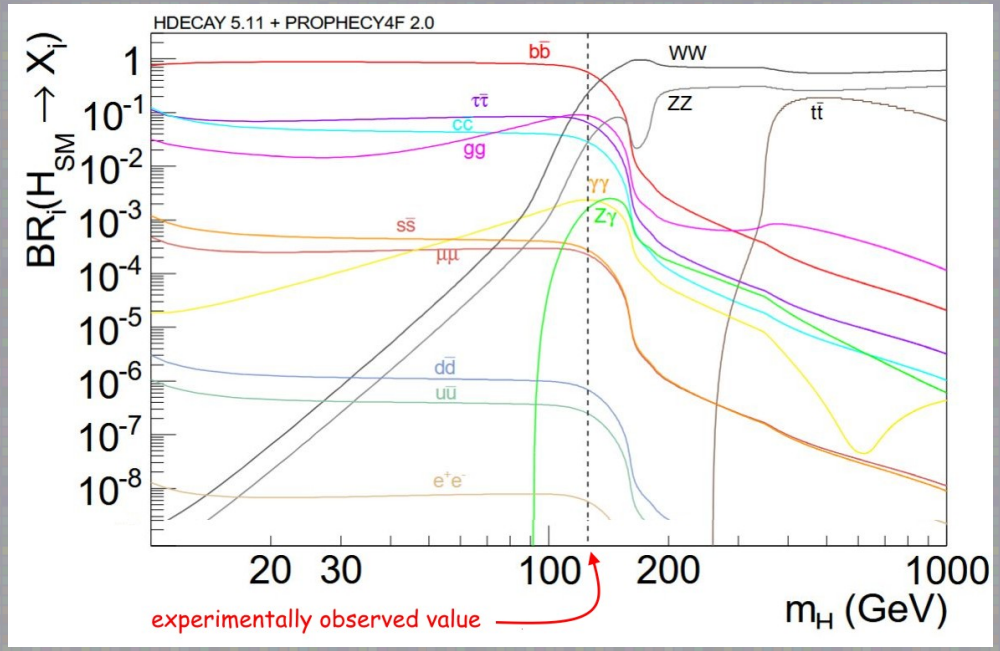

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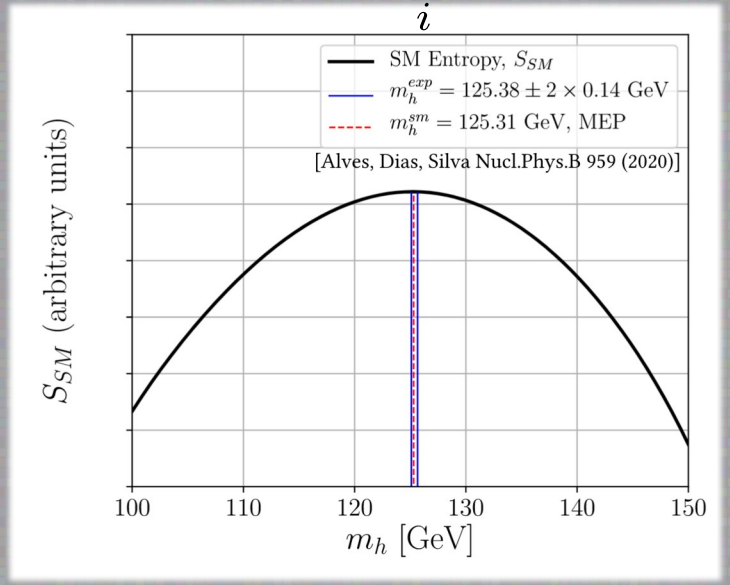

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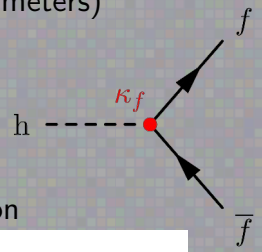

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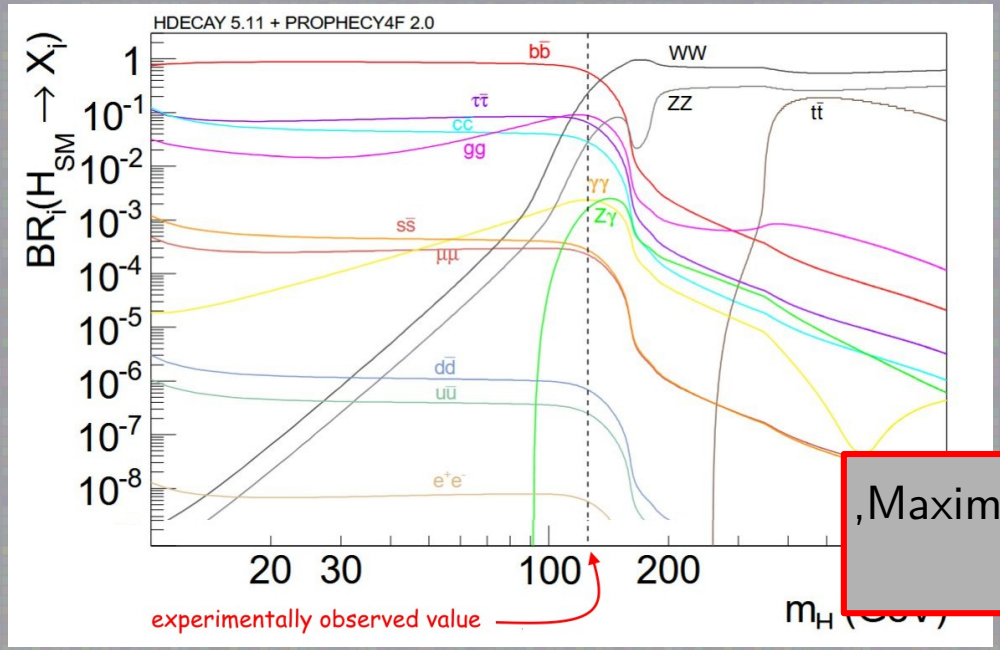

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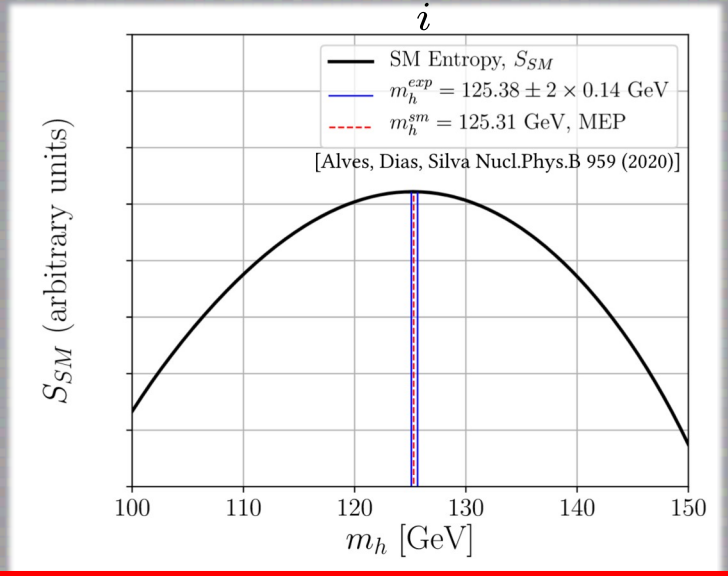

'Maximum Entropy principle': $m_H = 125.25 \pm 0.17\,\mathrm{GeV}$

Latest measurements: $m_H = 125.04 \pm 0.25\,\mathrm{GeV}$

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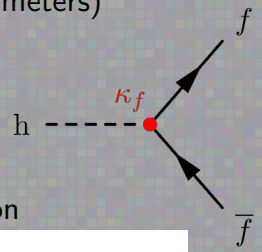

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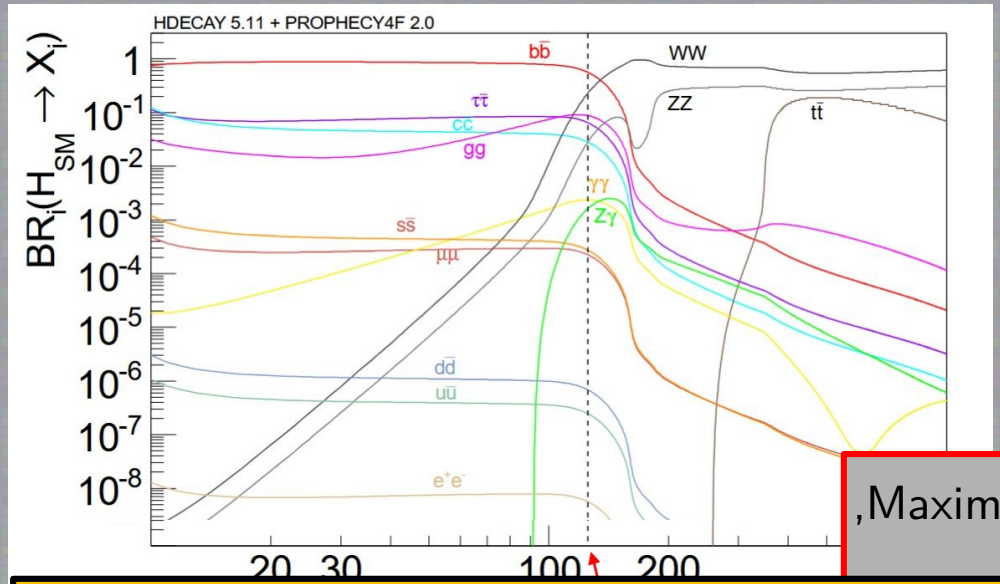

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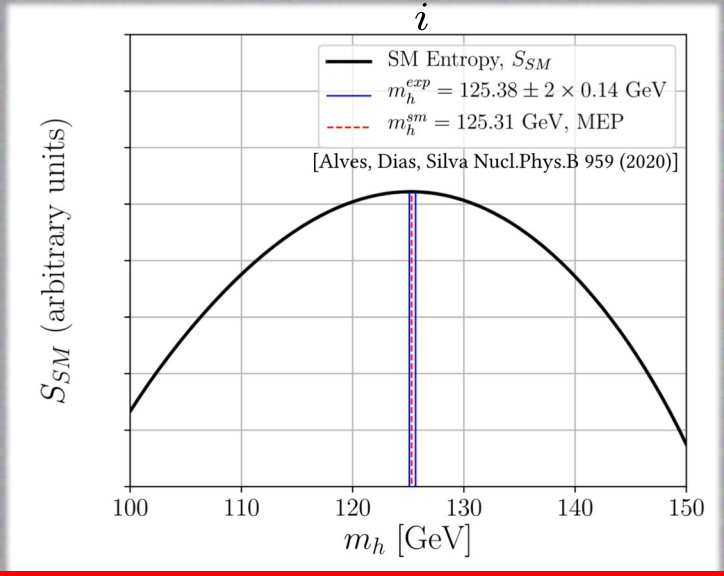
$$S_{\mathrm{SM}}(m_H) = -\sum_i \mathrm{BR}_i \ln[\mathrm{BR}_i]$$



'Maximum Entropy principle': $m_H = 125.25 \pm 0.17\,\mathrm{GeV}$

Latest measurements: $m_H = 125.04 \pm 0.25\,\mathrm{GeV}$

Warning **Presently, this is a "curious observation", not clear what it really means.**

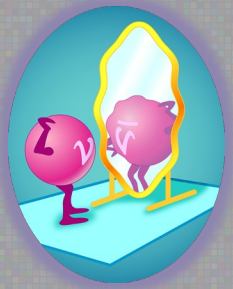
[D. d'Enterria, 1208.1993]

[Alves, Dias, Silva Physica A 420 (2015) & NPB 959 (2020)]

Open questions awaiting experimental results

Future "guaranteed" awaited measurements/discoveries:

- Neutrino masses



- CPV in Leptons

- Nature of neutrinos (Dirac vs. Majorana)

- Cosmic Neutrino Background...

Besides new colliders, "take what Nature gives us":

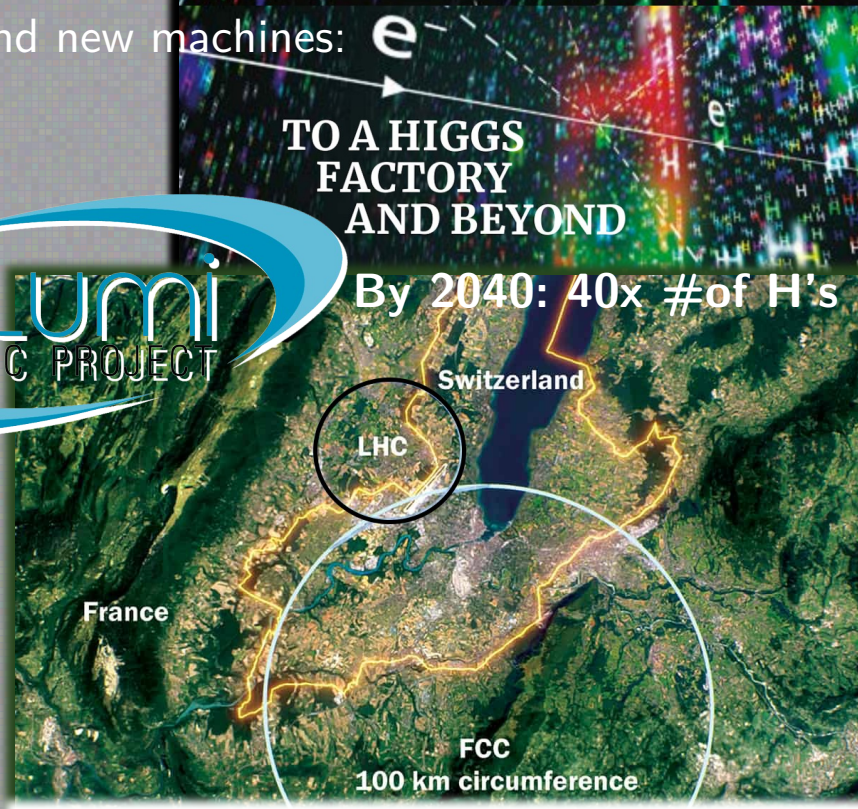
Cosmic rays, Cosmology,

Gravitational waves (BH/NS mergers, phase transitions)

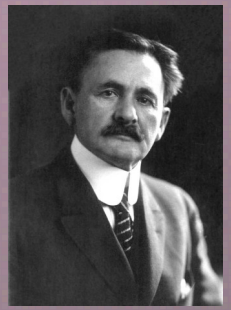
Note: There will not be a single discovery that explains all of our puzzles.

It will require especially theoretical progress!

And new machines:



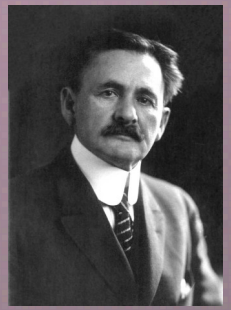
Final remarks



"[...] the grand underlying principles have been firmly established,
[...] the future of physical science are to be looked for in the sixth place of decimals."

Albert A. Michelson, 1894

Final remarks



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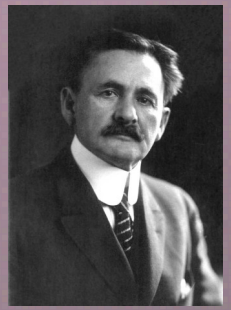
131 years before "100th's anniversay" of Quantum Mechanics `25

Final remarks



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Today again, there might be some double delusion:

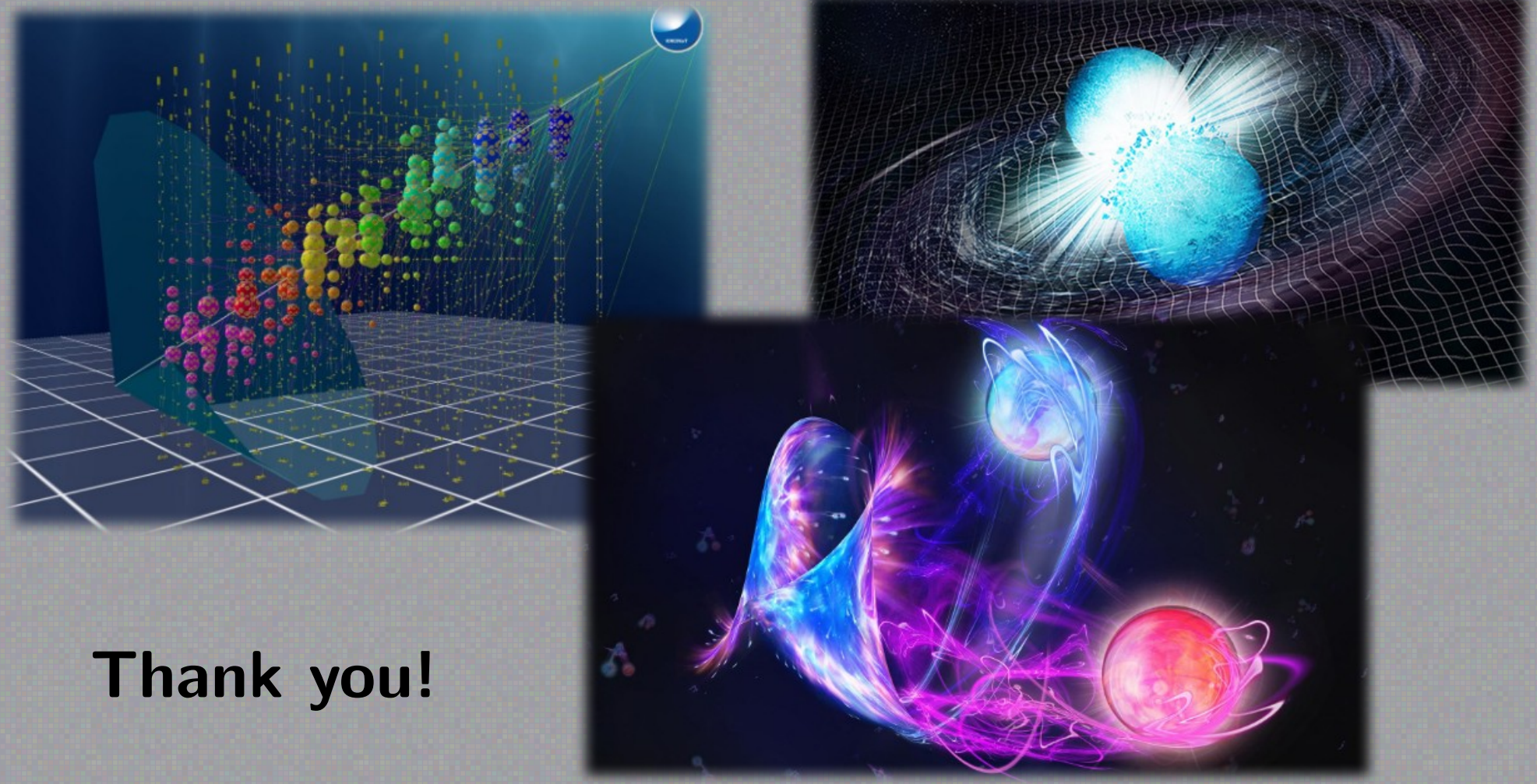
"The more we have measured the more we are done."

"SM is complete in terms of particle content = bad news?"

In my view (and history tells us), exactly the opposite:
The better we understand things, the closer we get to a leap in solving the puzzles we are facing!

All the knowledge gathered allows us ***just now to be sure we adress*** the *"real puzzle"*

You are welcome to join the effort!



Thank you!