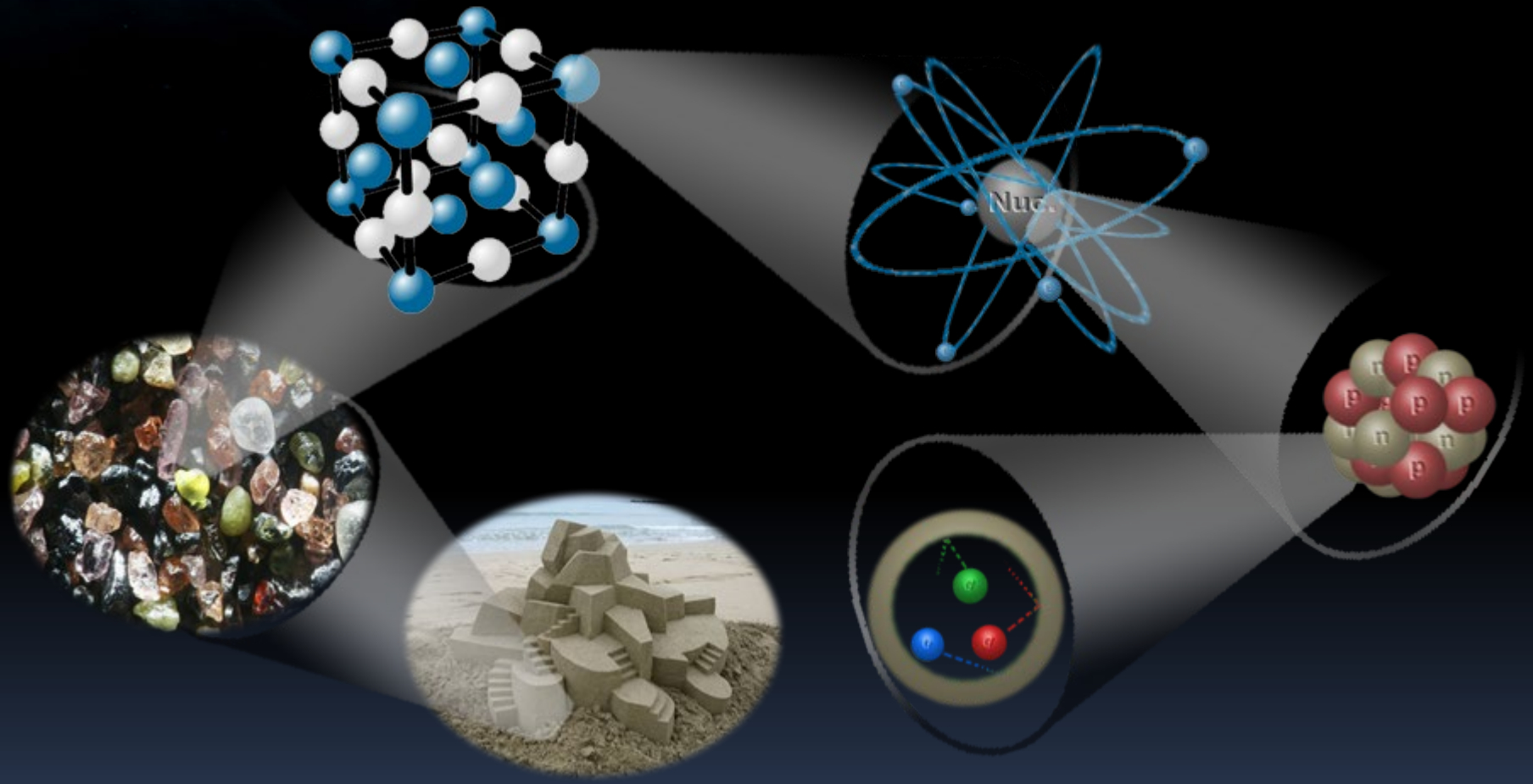
INFIERI 2023

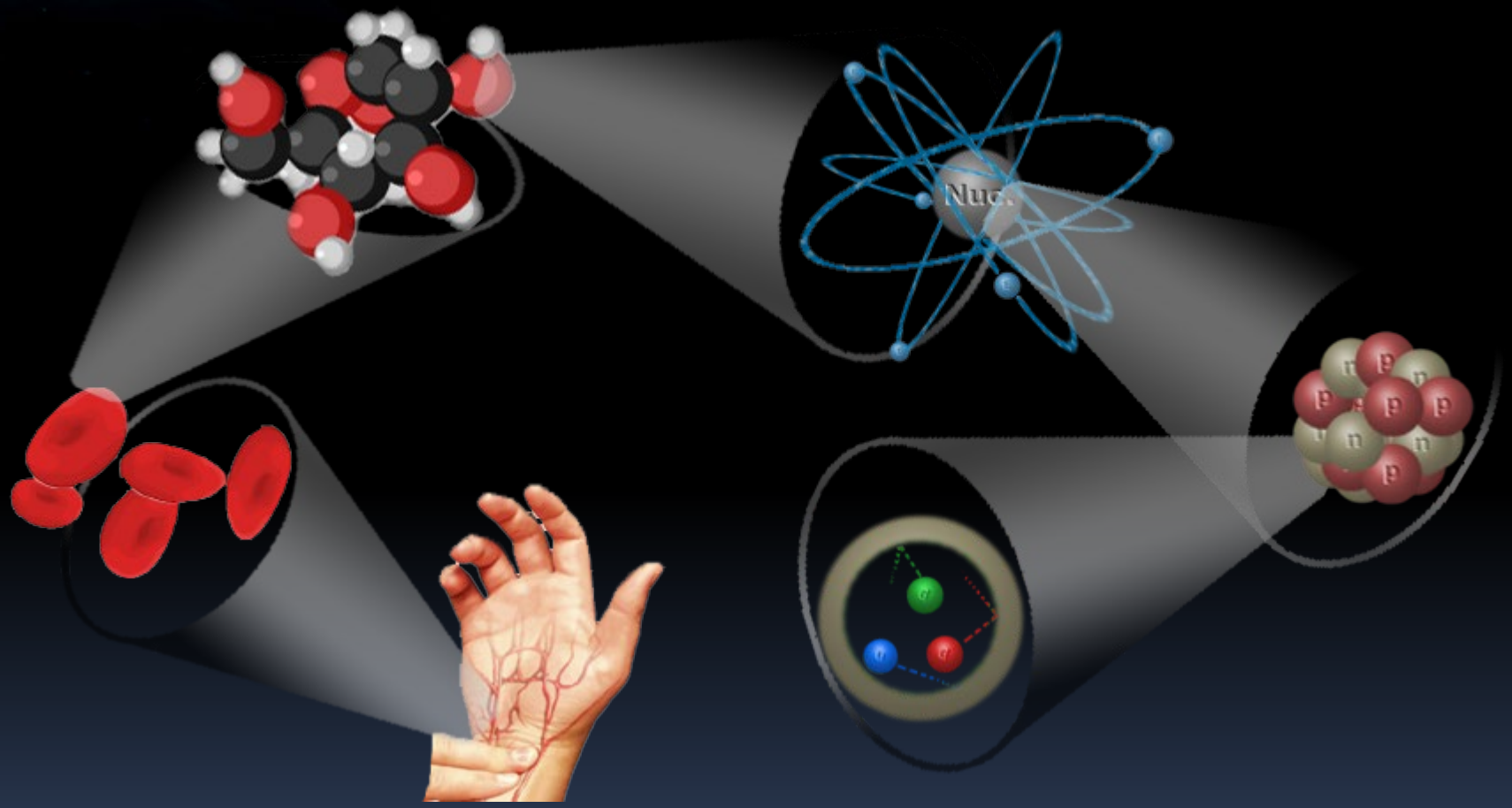
Masterclass: Particle Physics

Ricardo D’Elia Matheus

What do we want from Particle Physics?

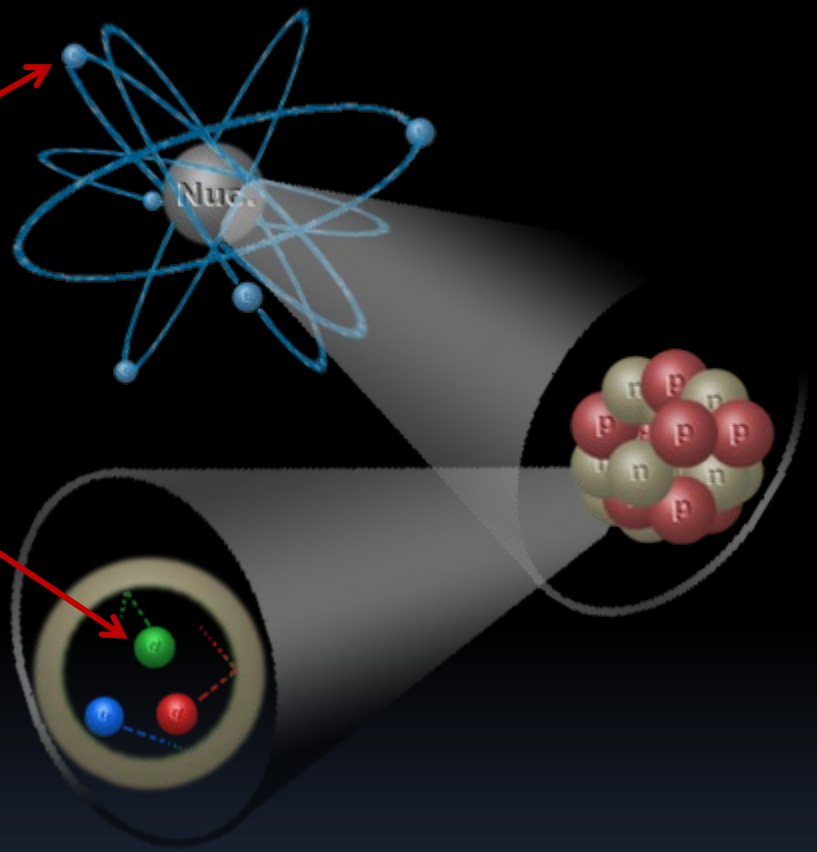


What do we want from Particle Physics?



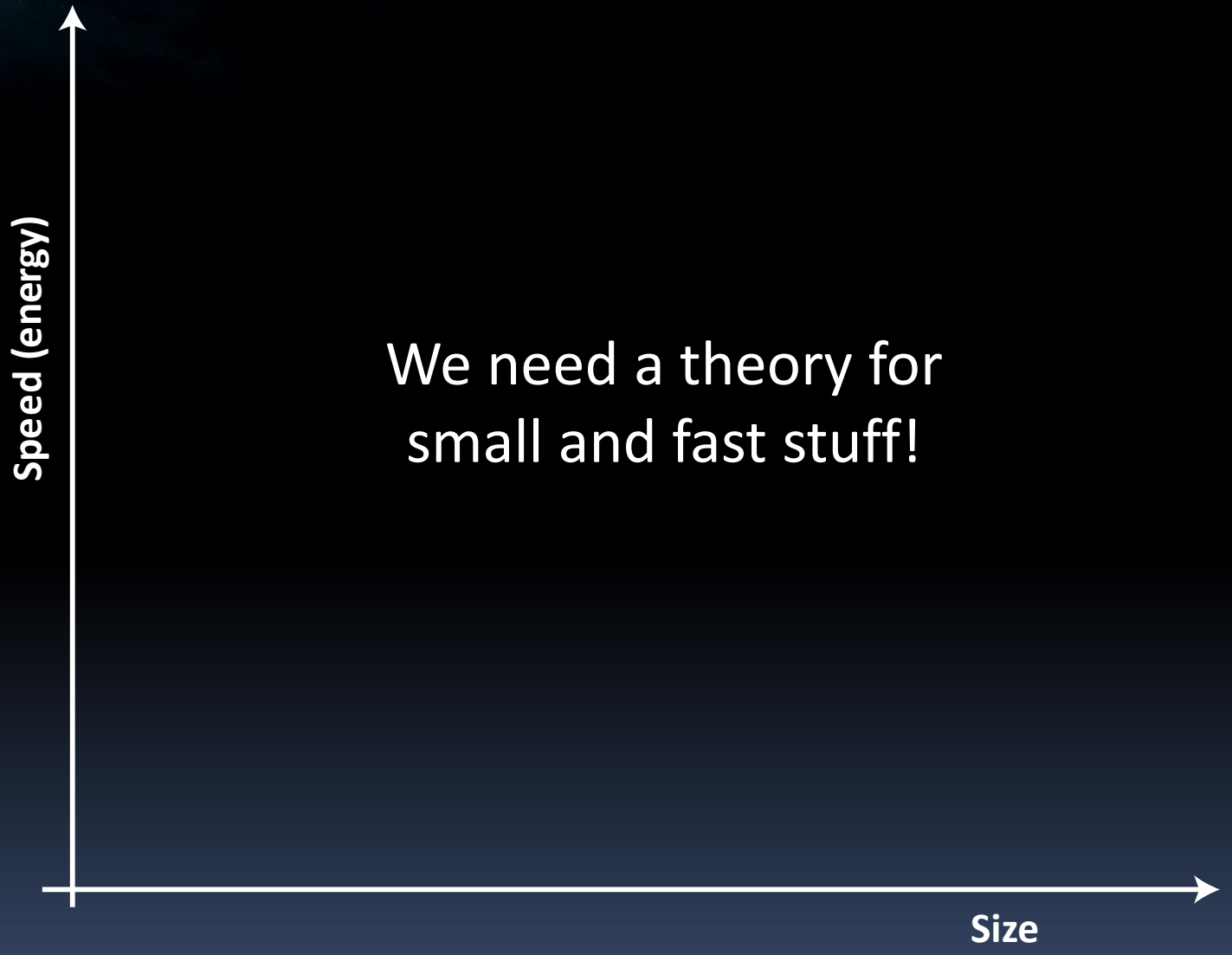
What do we want from Particle Physics?

Well, but do “particles” can really be treated as “billiard balls”?



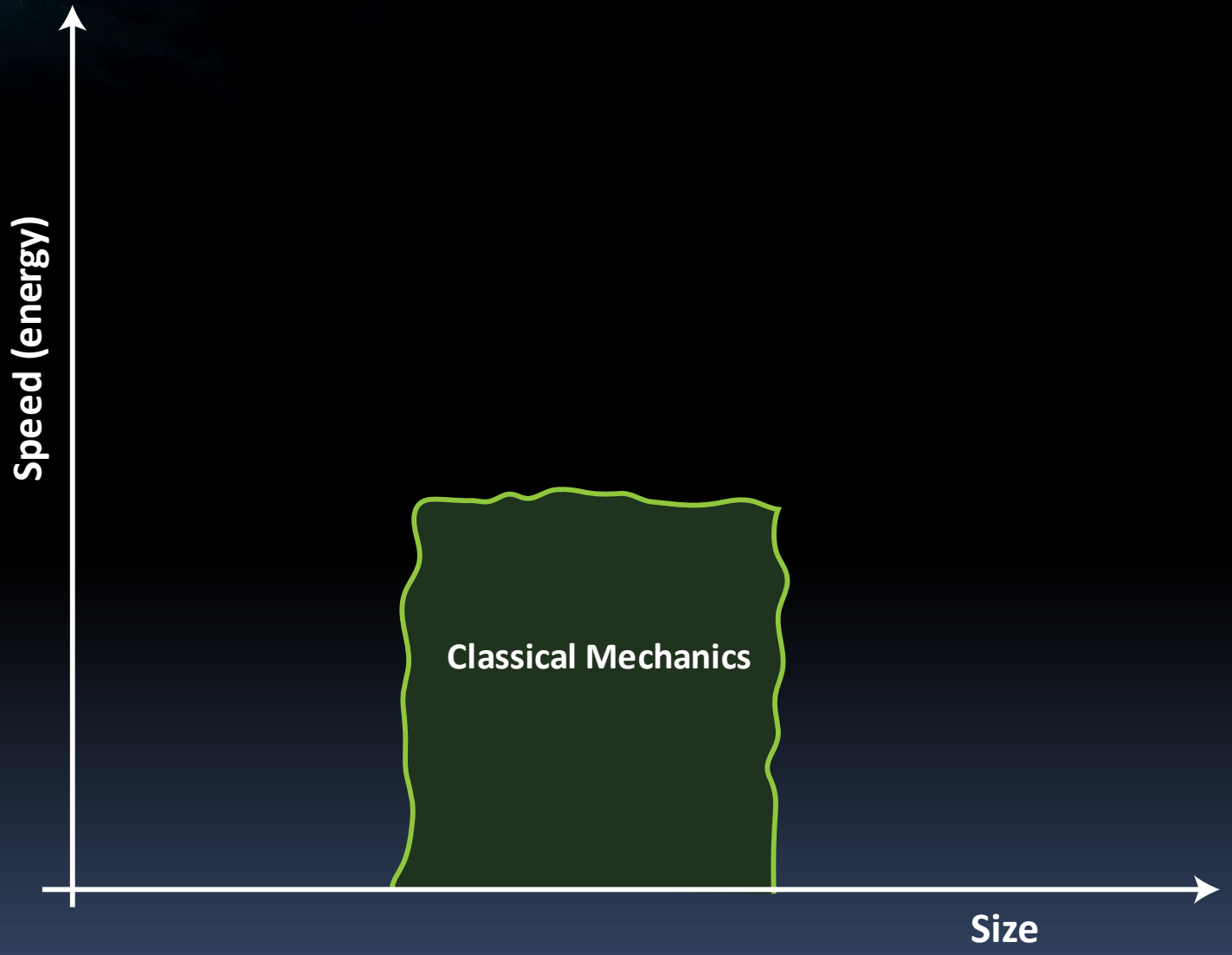
What is the appropriate mathematical description for these objects?

Particles: Small and Fast!



We need a theory for
small and fast stuff!

Particles: Small and Fast!



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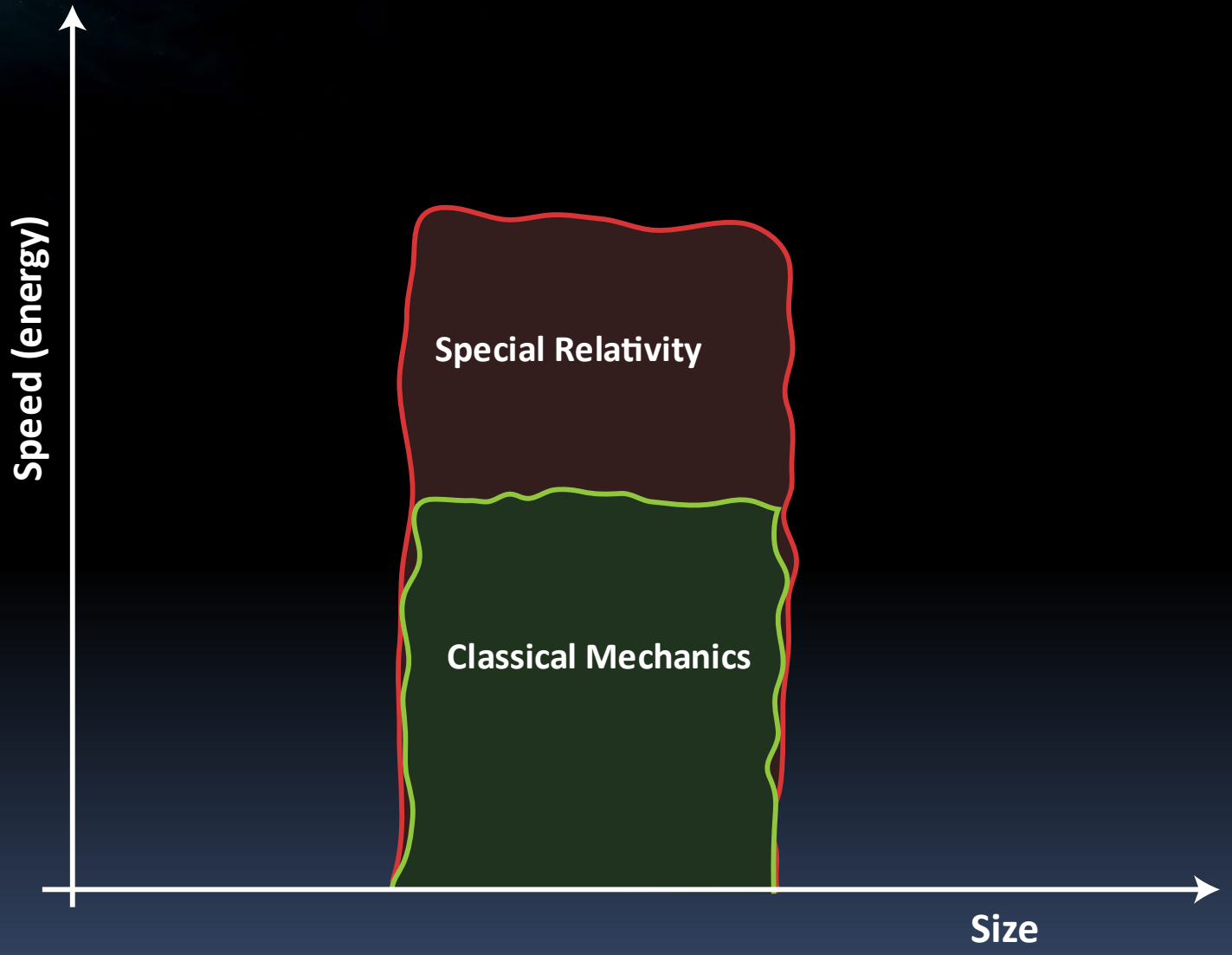

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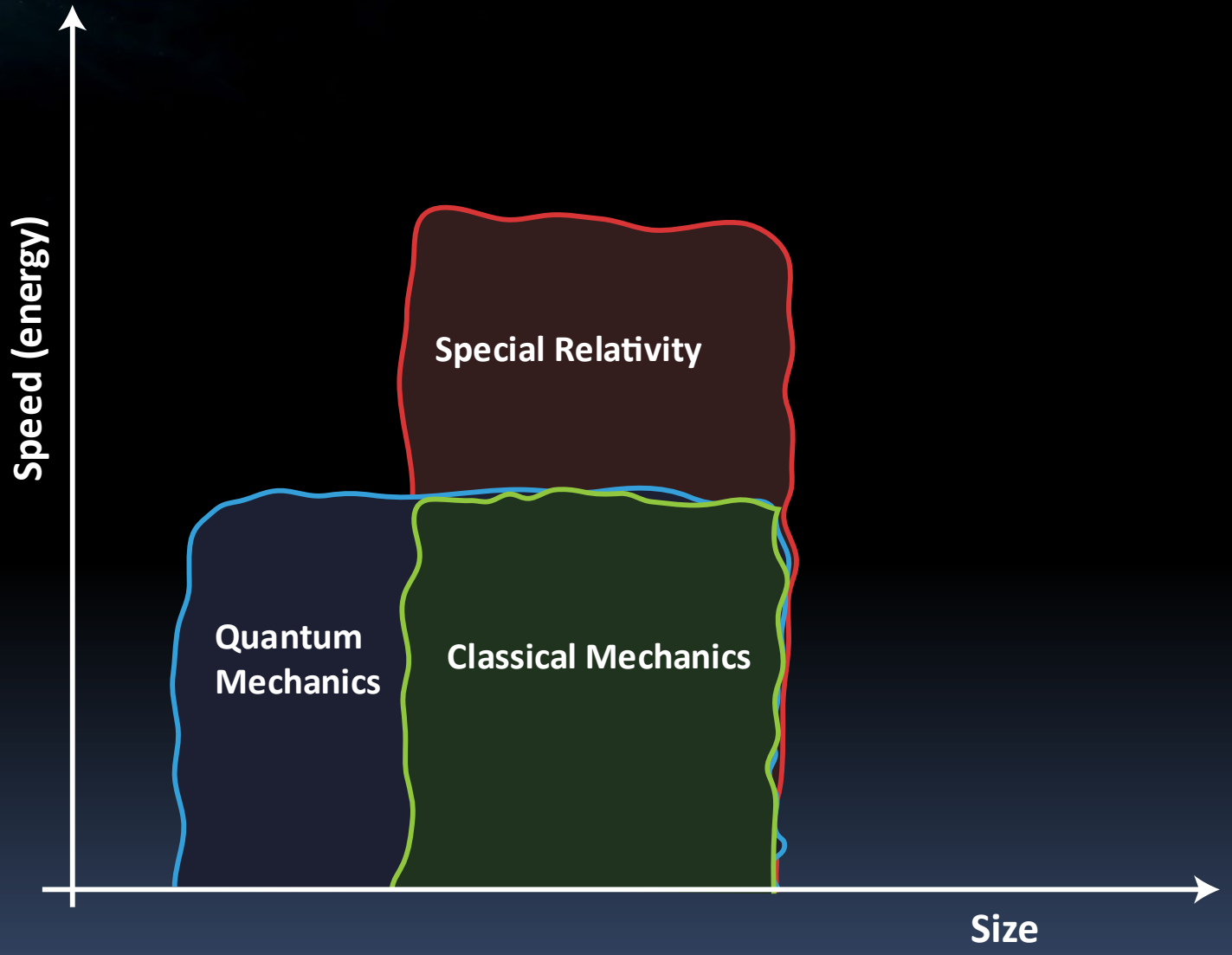

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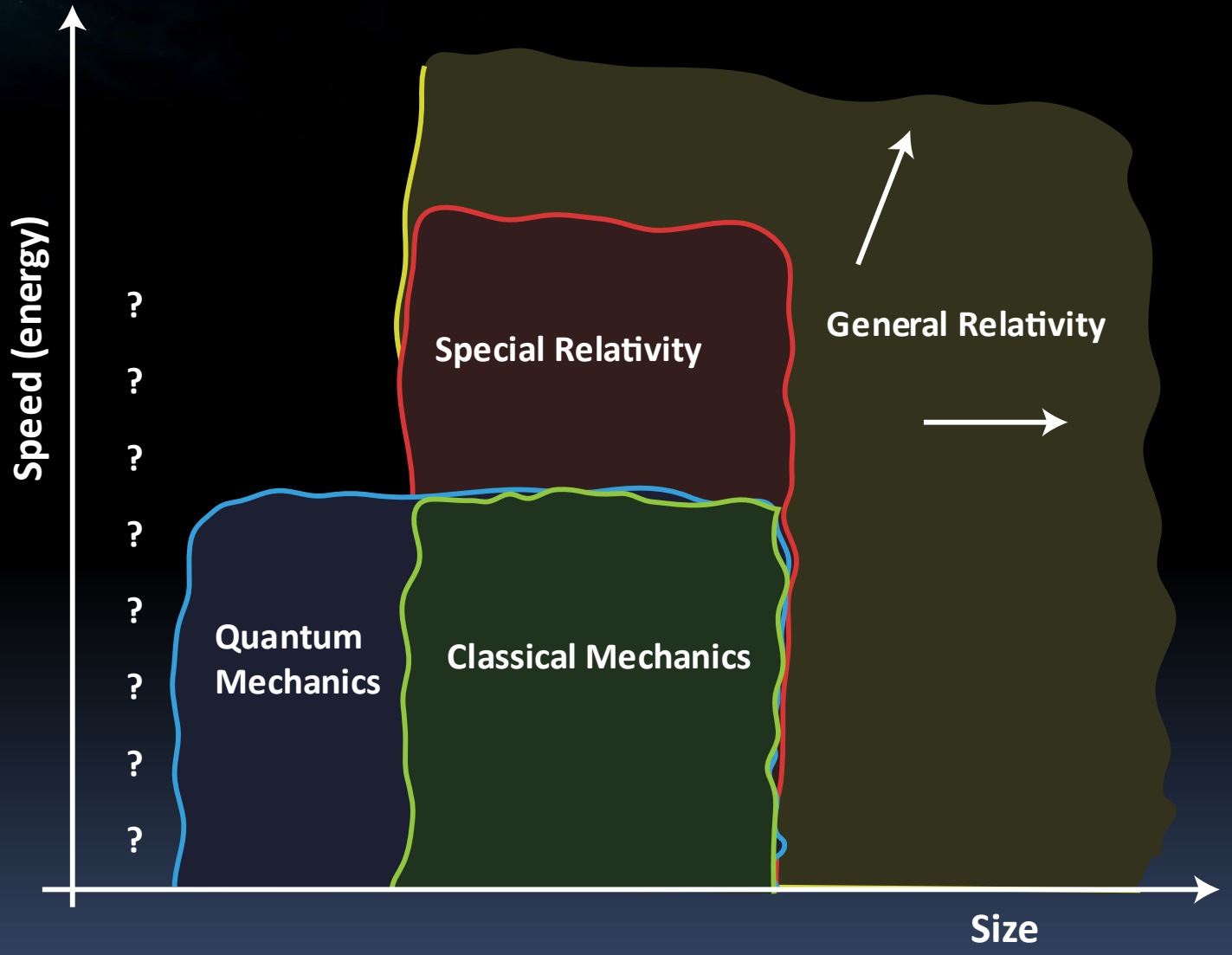

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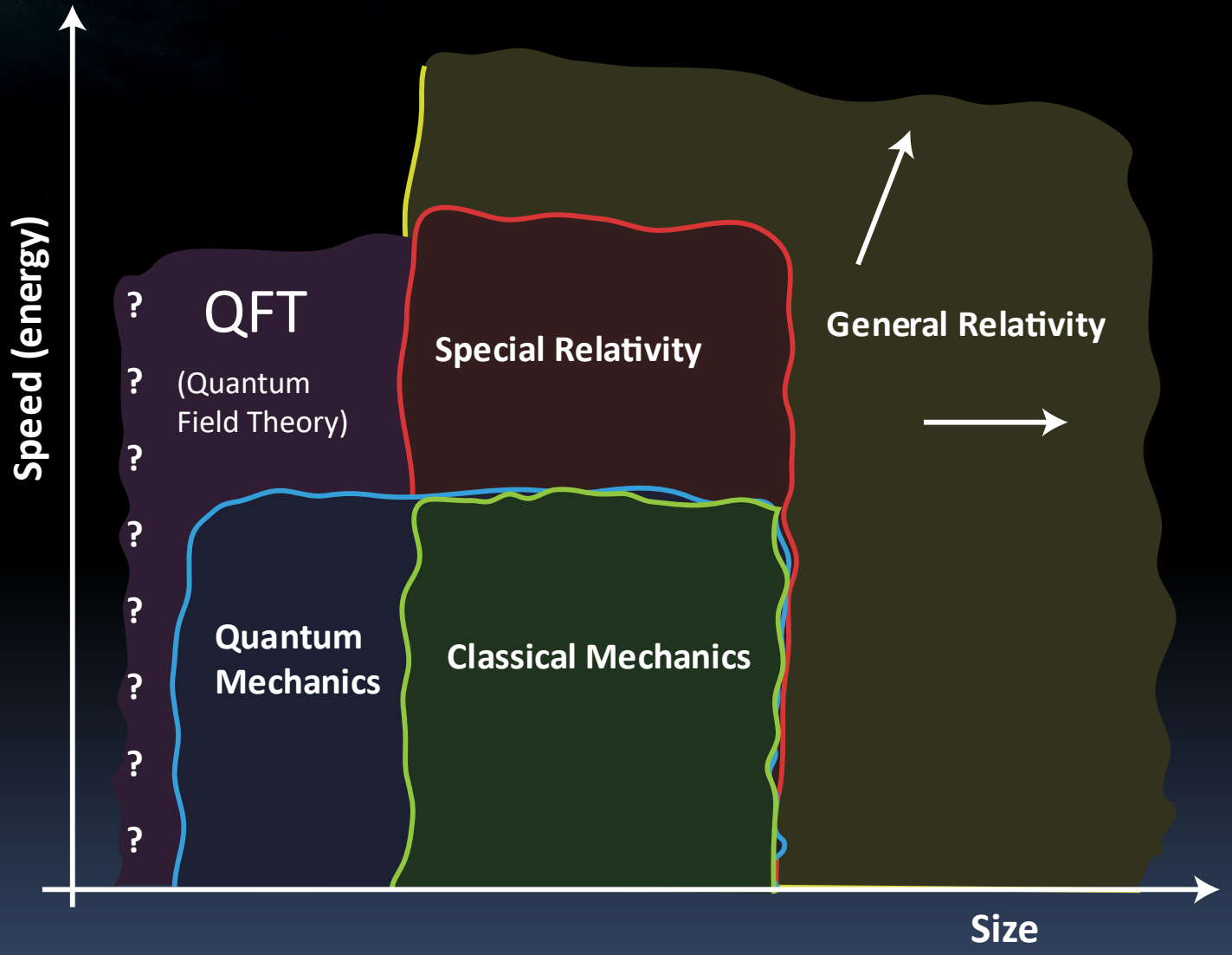
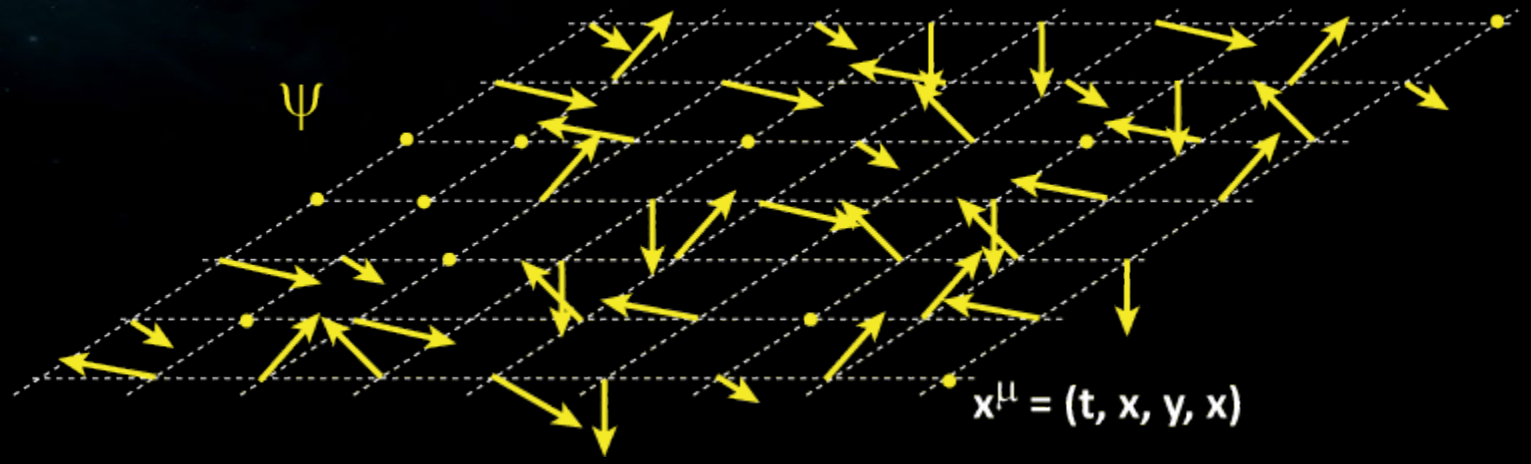


Fields

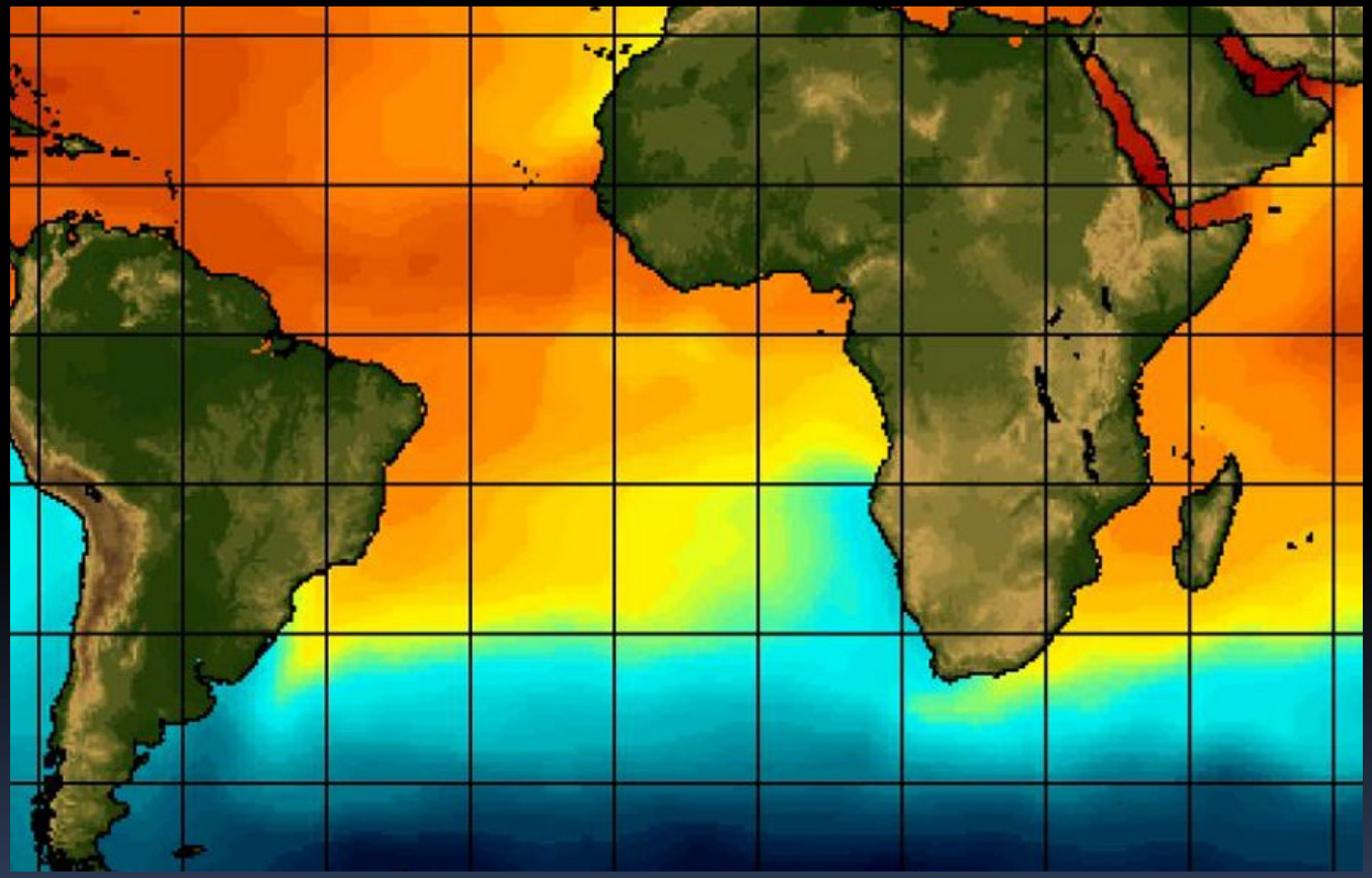


Many types of Fields are possible:

- Scalar. Ex: Temperature, Energy
- Vector. Ex: Electric, Velocities in some fluid or gas
- and more...

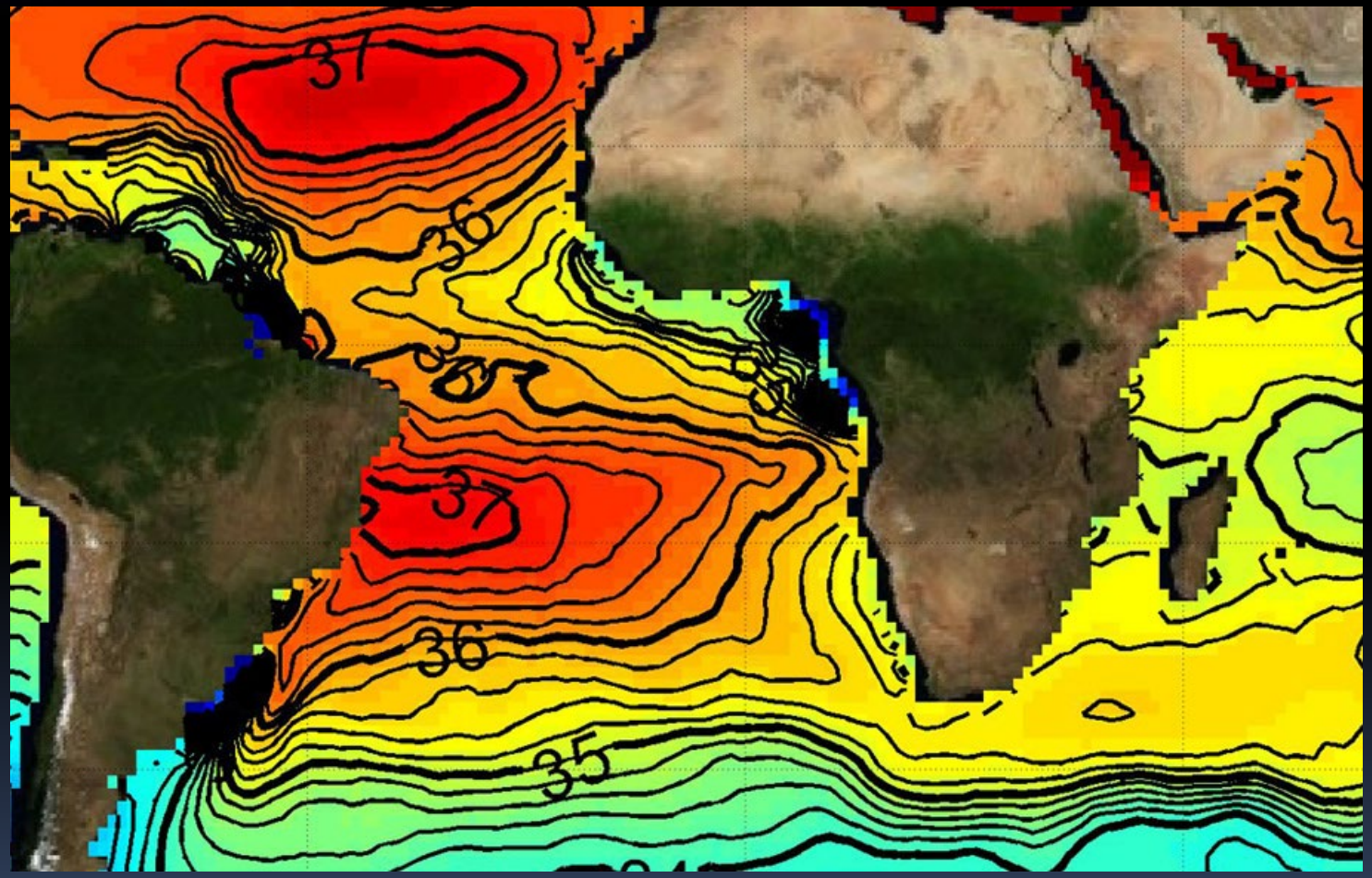
Fields

Example: temperature of oceans (scalar field)



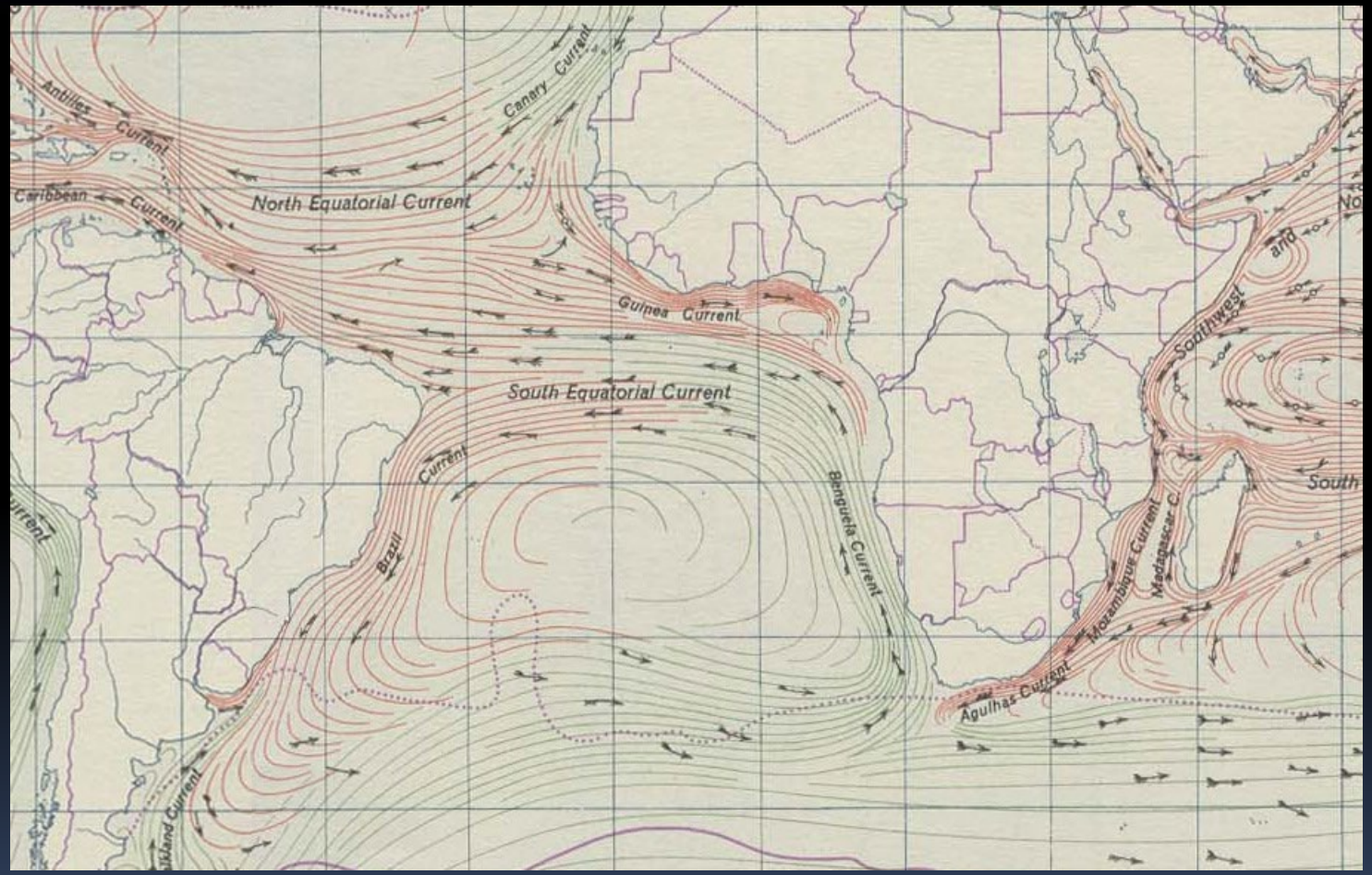
Fields

Example: salinity of oceans (scalar field)



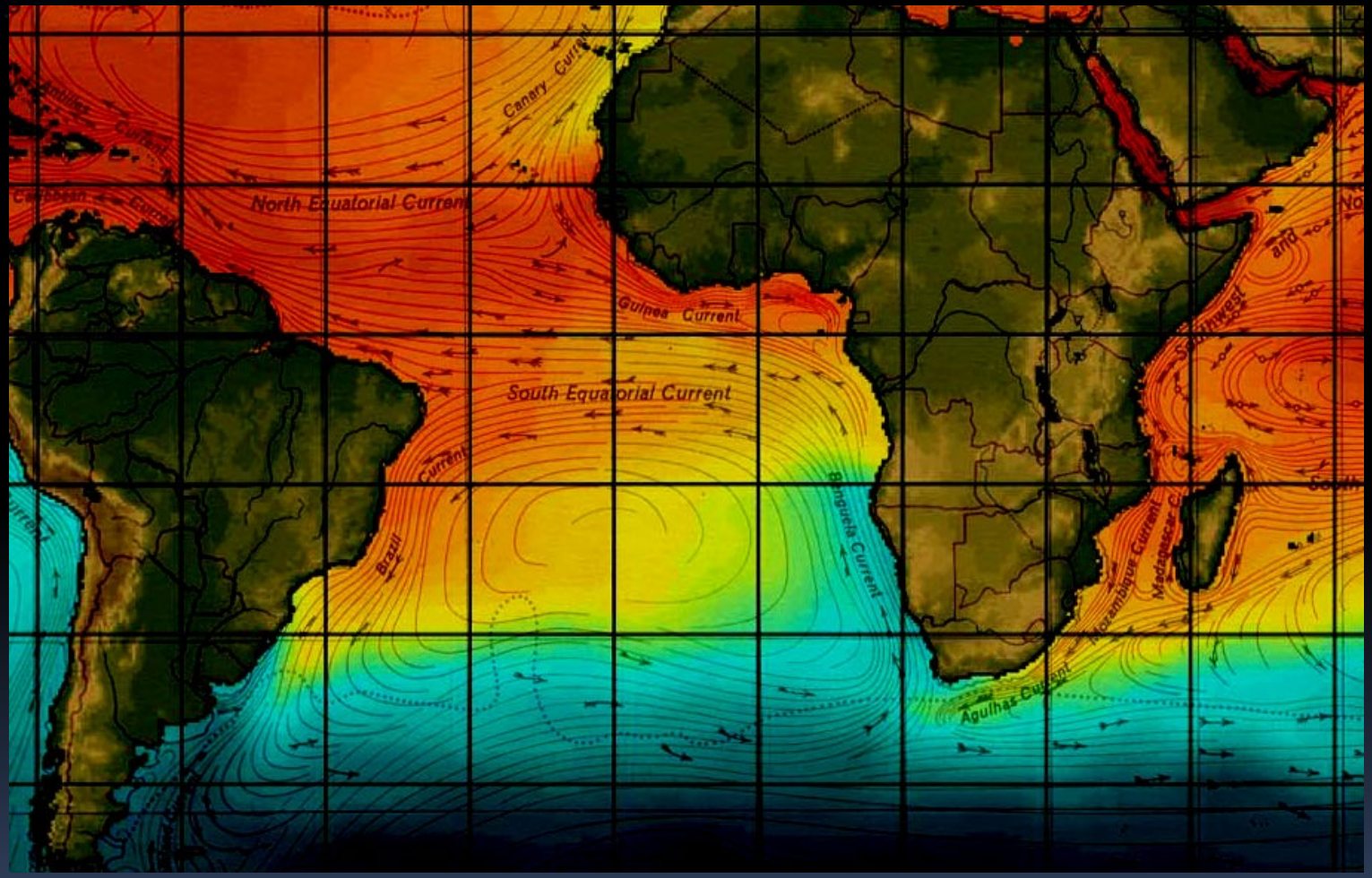
Fields

Example: ocean currents (vector field)

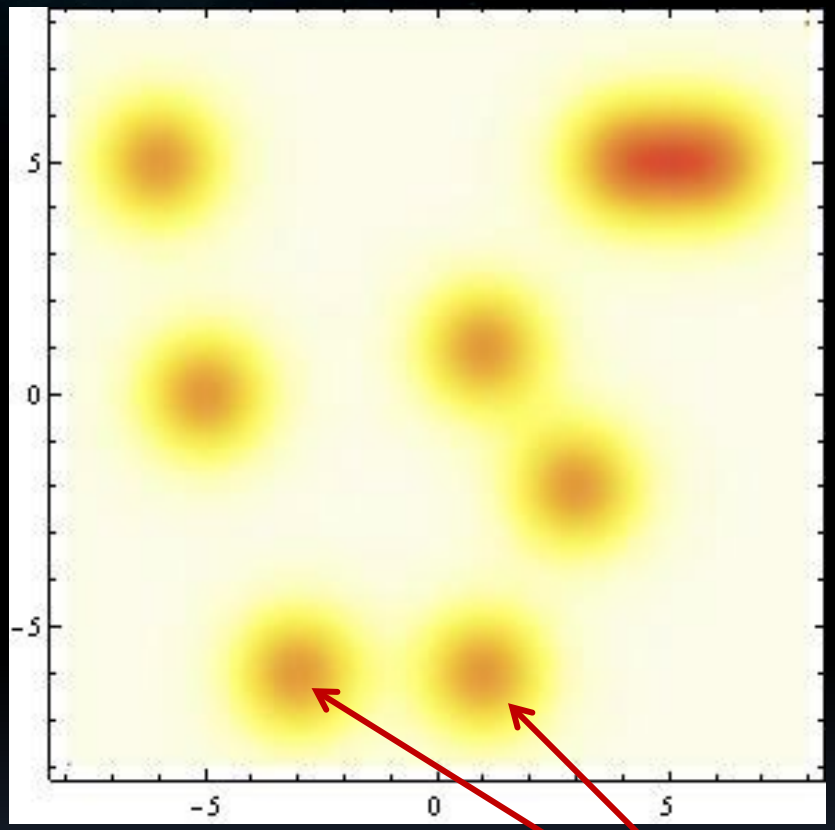


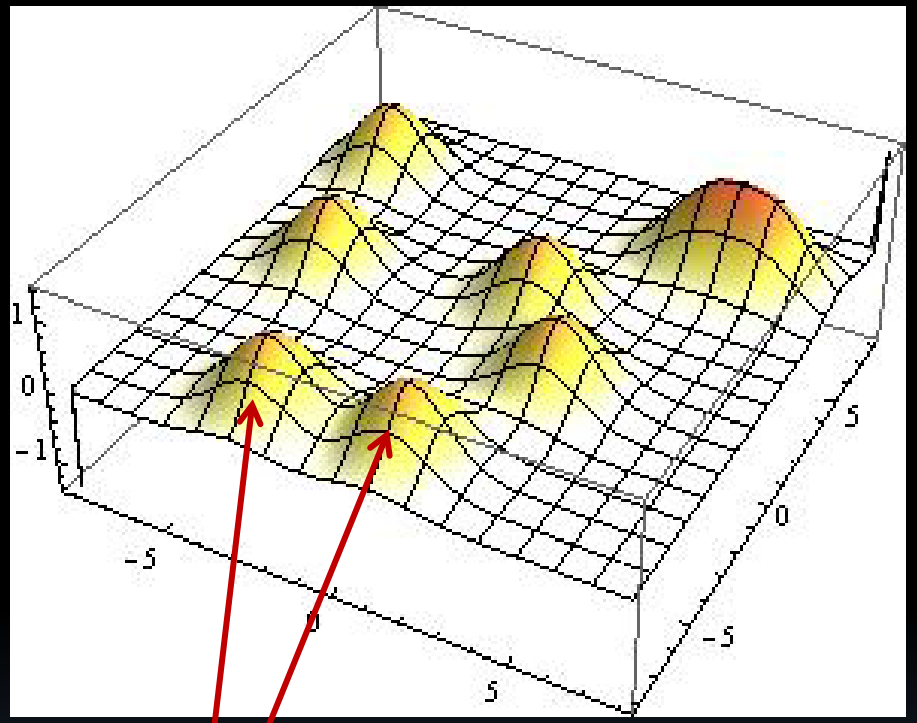
Fields

Can we build a combined field that encapsulates every oceanic property?



We did it for particles!





Particles

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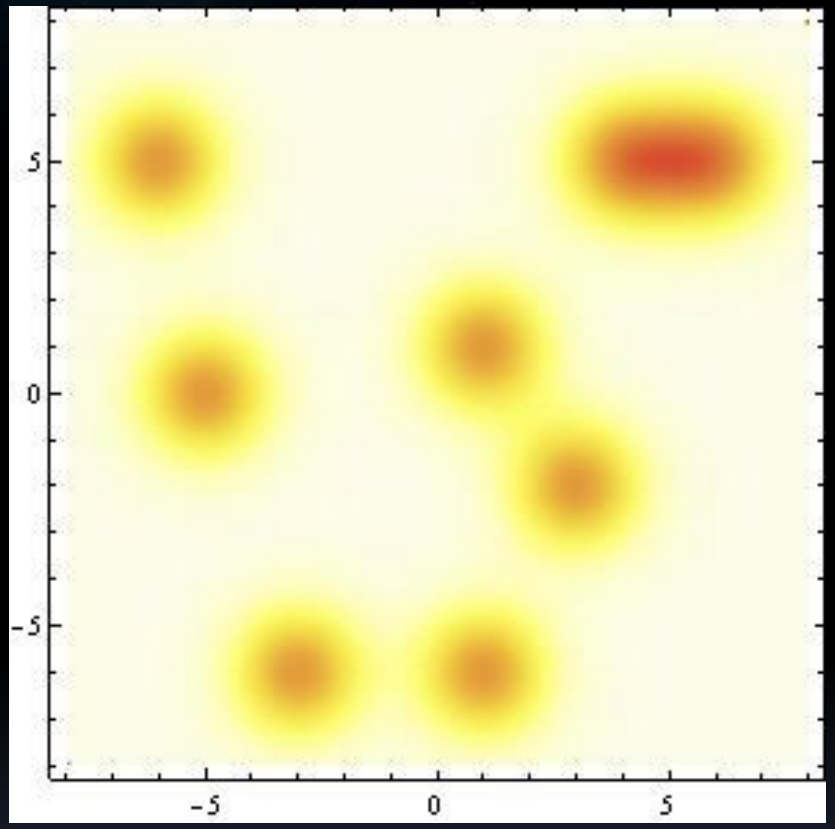
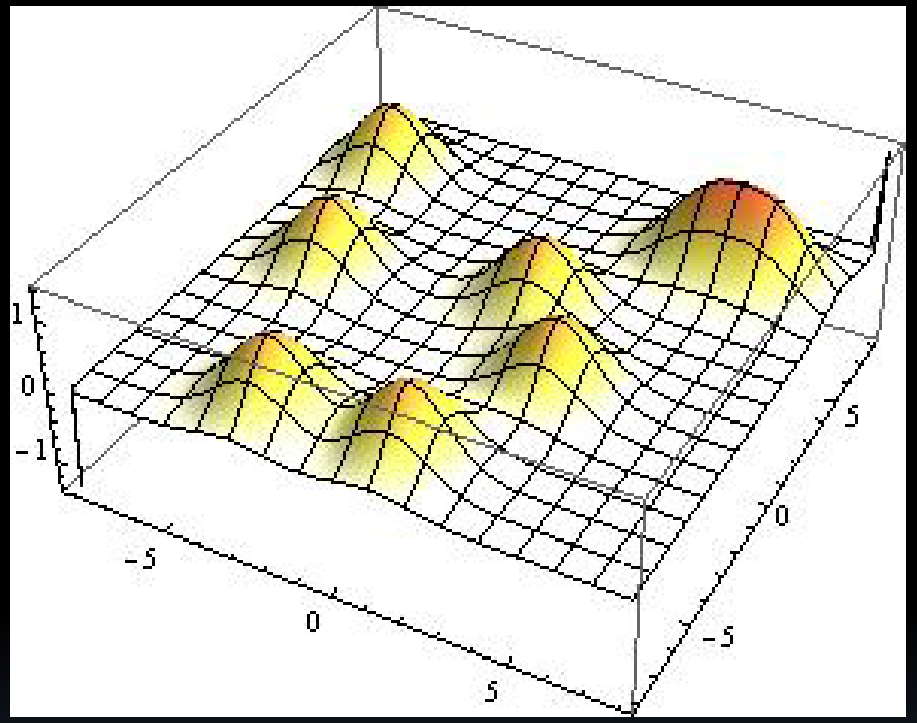




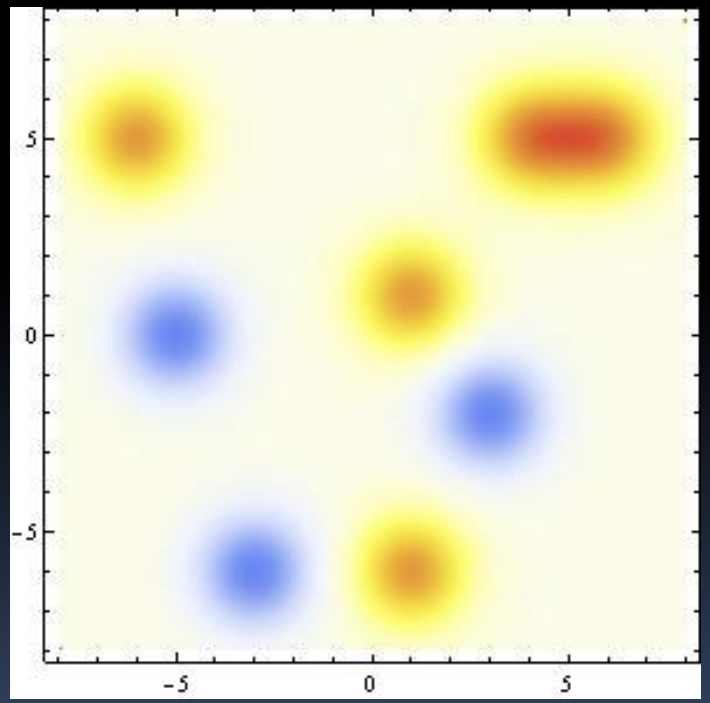
These fields encode not only the probabilities of finding particles in a region of space-time, but also information on velocity, spin, and other quantum numbers.

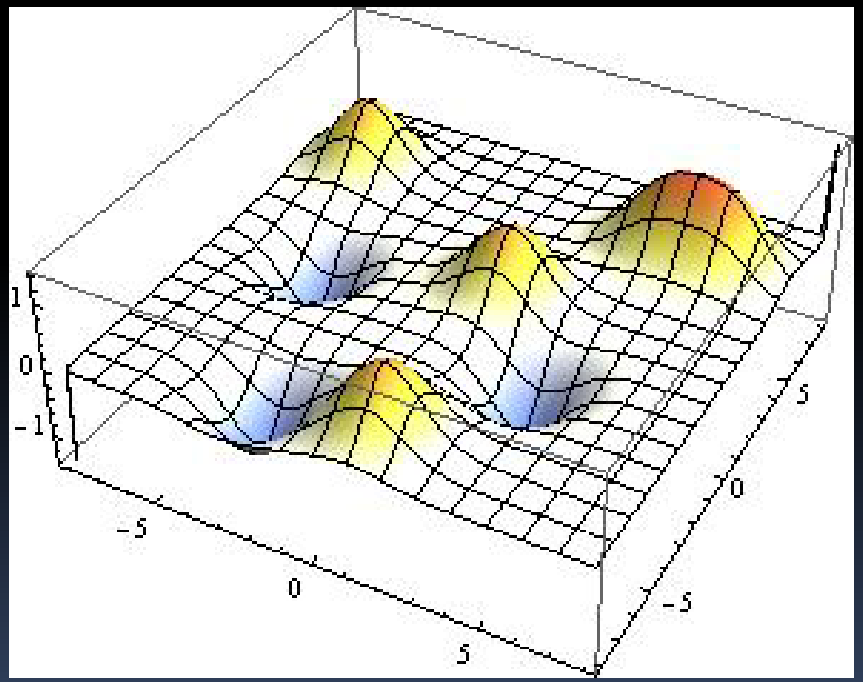
The simplest consistent Quantum & Relativistic description we know!

Relativistic & Quantum Fields

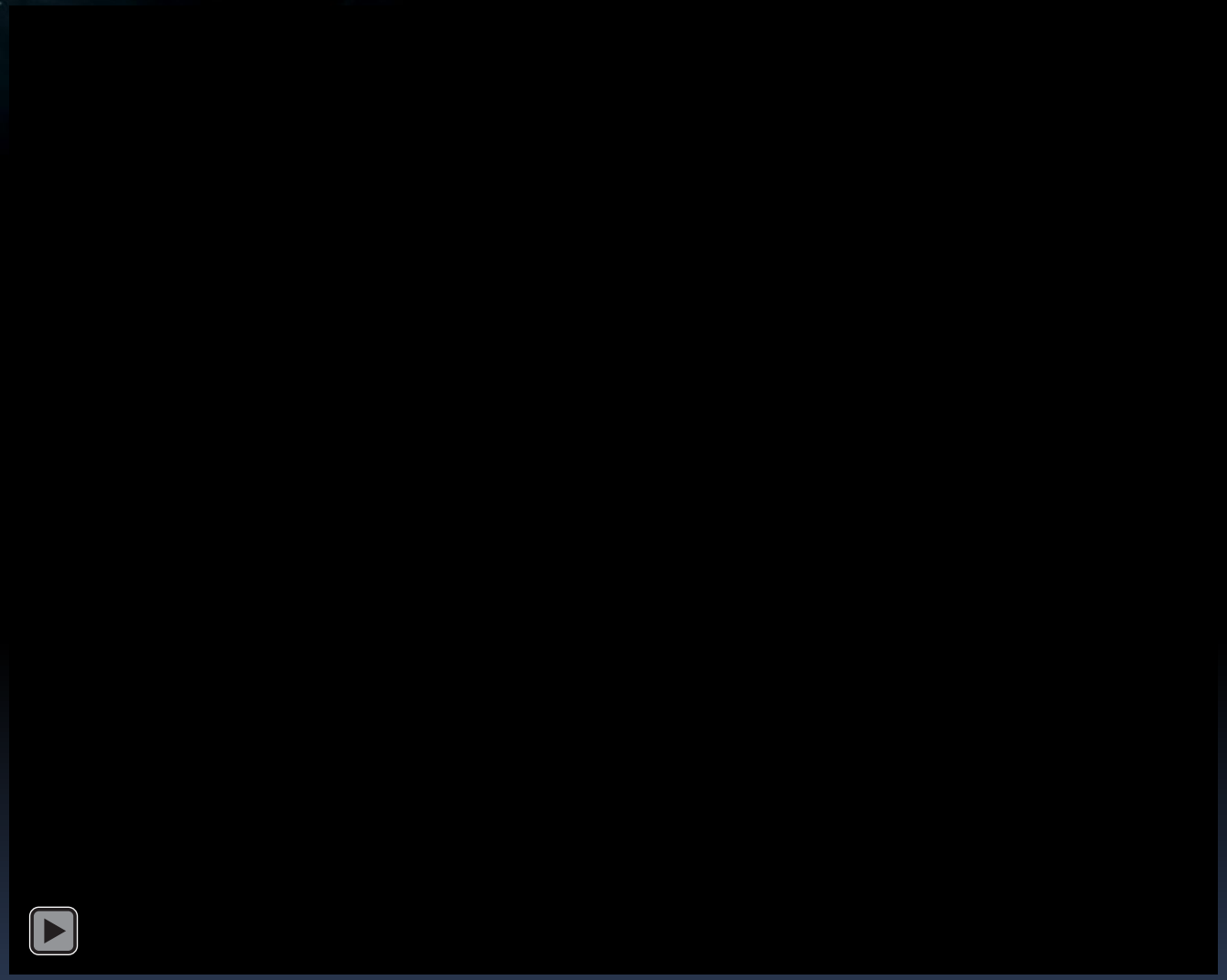
We get interesting effects both from the quantum side and the relativistic side. A couple of examples:

- Quantized excitations with a relativistic dispersion relation (particles!)
- Anti-particles are obligatory! Total number of particles change with time!





Relativistic & Quantum Fields



(note what happens when these excitations cross each other)

Relativistic & Quantum Fields

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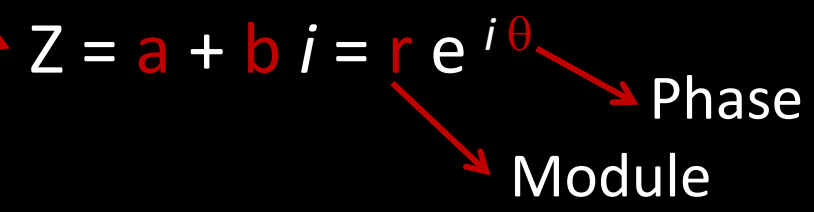
- Complex Fields



Relativistic & Quantum Fields

We get interesting effects both from the quantum side and the relativistic side. A couple of examples:

- Complex Fields

$$Z = a + b\,i = r\,e^{i\theta}$$

Phase

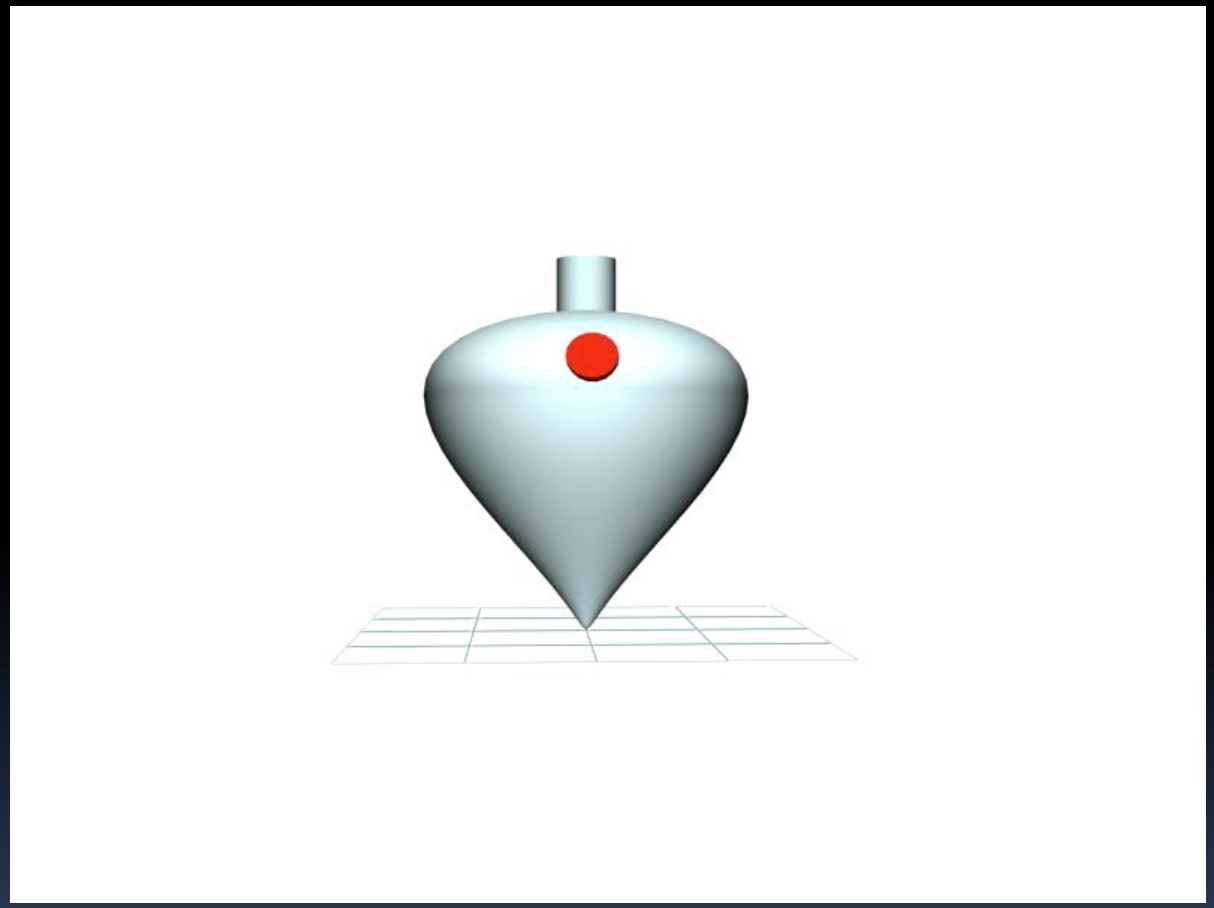
Module

However, our observations are REAL, and do not depend on this phase

Symmetry!!

Role of Symmetries in Physics

What is a symmetry?



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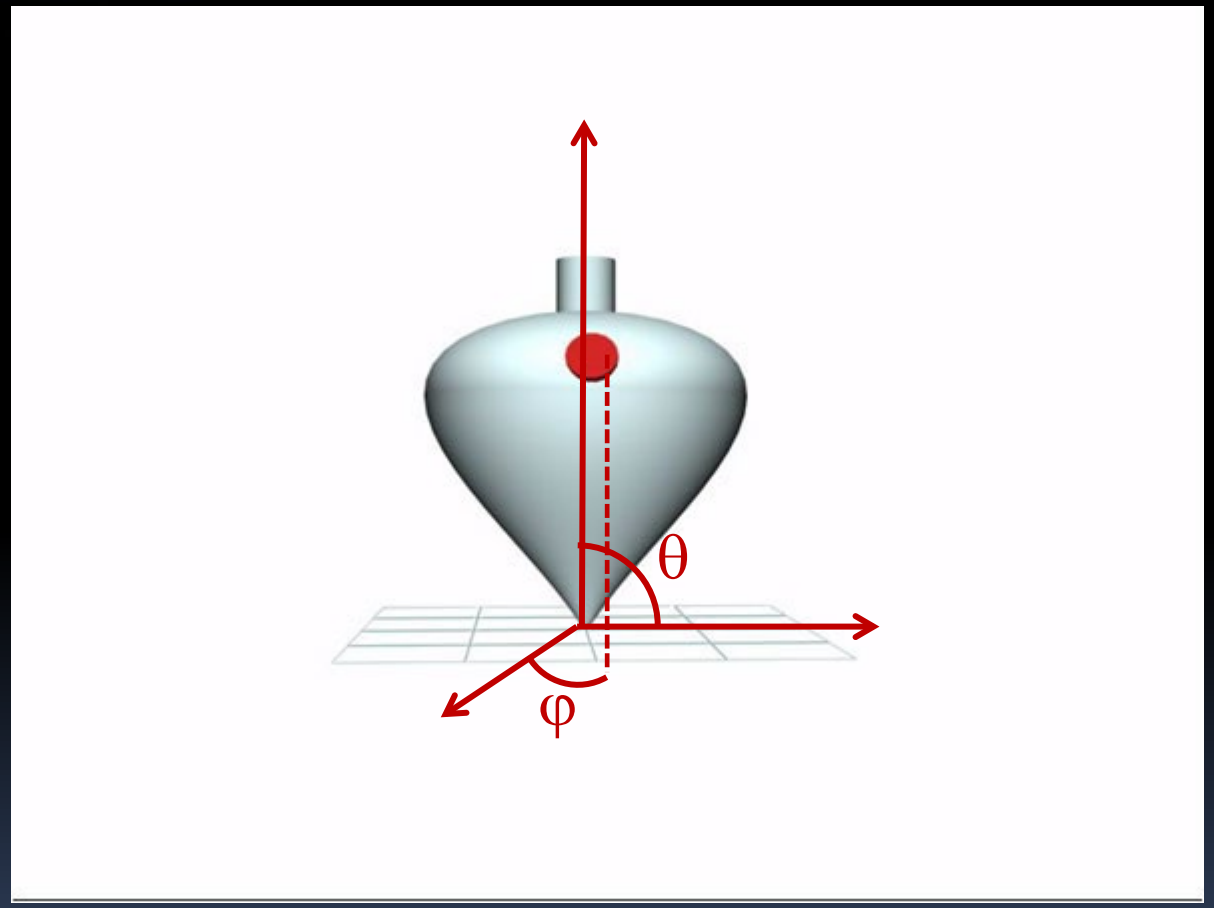

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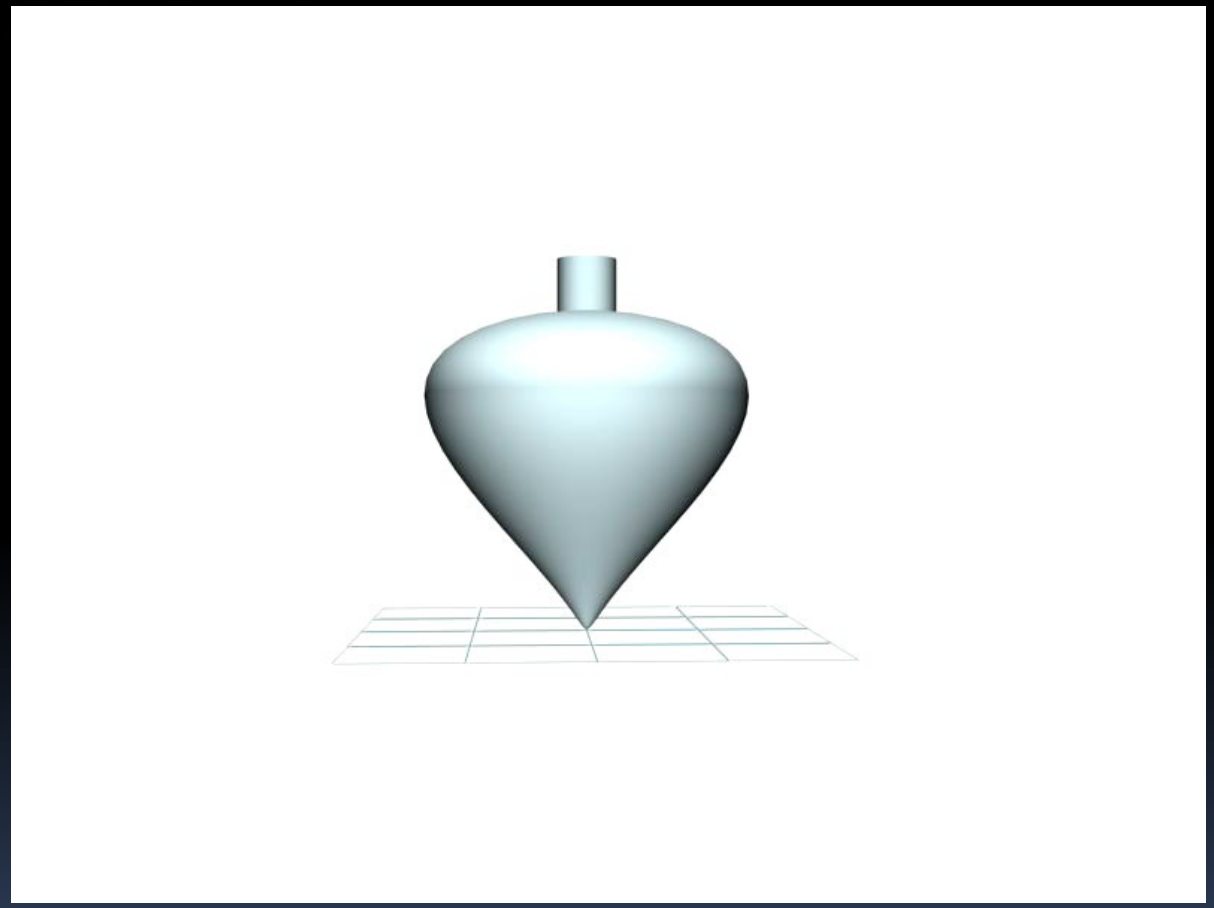


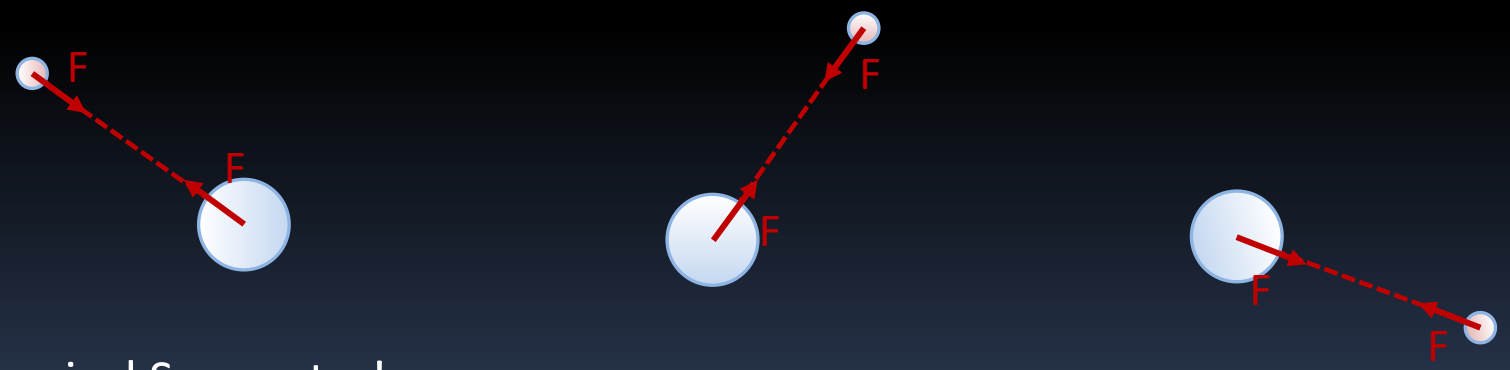
Role of Symmetries in Physics

Before the XX century:

Laws of Nature → Symmetries → Simplification
(sometime essential for a solution)

Example: Newton's Gravitation

...force is proportional to the masses and inversely proportional do the square of the distance between bodies

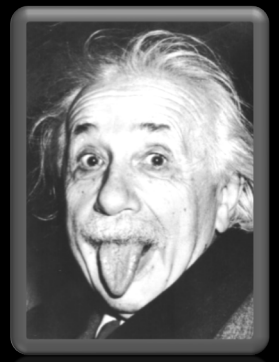


Spherical Symmetry!

Role of Symmetries in Physics

Start of XX century: roles start to change

Symmetry → Laws of Nature



A. Einstein – 1905 ~ 1915

Relativity (Special and General) is derived for symmetry principles (laws should be reference frame independent)

Restricts possible “laws”

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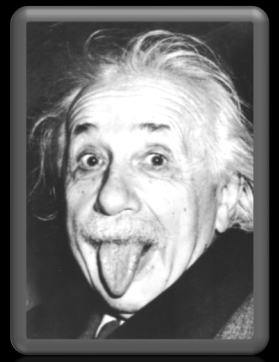

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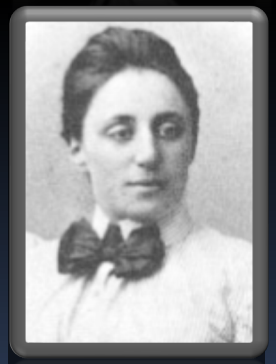


A.E. Noether- 1918

Symmetries imply conservation law

Invariance under:

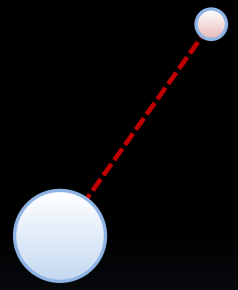
- Translations in space → Momentum conservation
- Translations in time → Energy conservation
- Rotations in 3D → Angular momentum conservation

Role of Symmetries in Physics

Start of XX century: roles start to change

Symmetry → Laws of Nature

Example: Newton's Gravitation

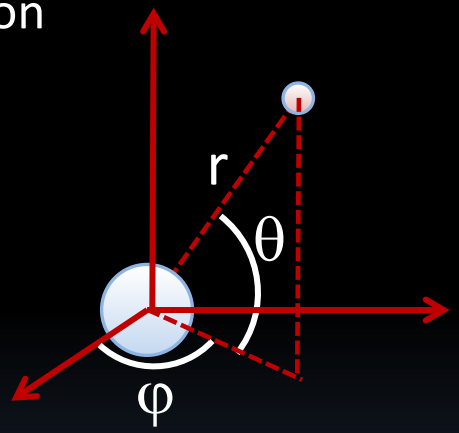


Role of Symmetries in Physics

Start of XX century: roles start to change

Symmetry ⟶ Laws of Nature

Example: Newton's Gravitation

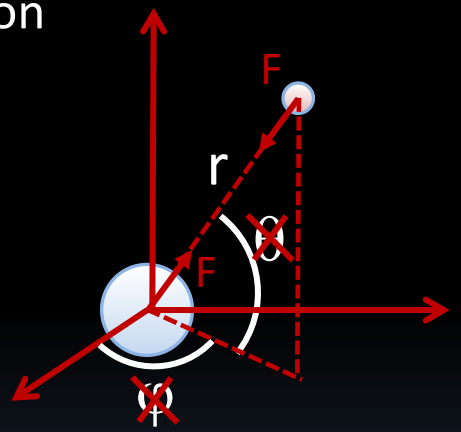


Role of Symmetries in Physics

Start of XX century: roles start to change

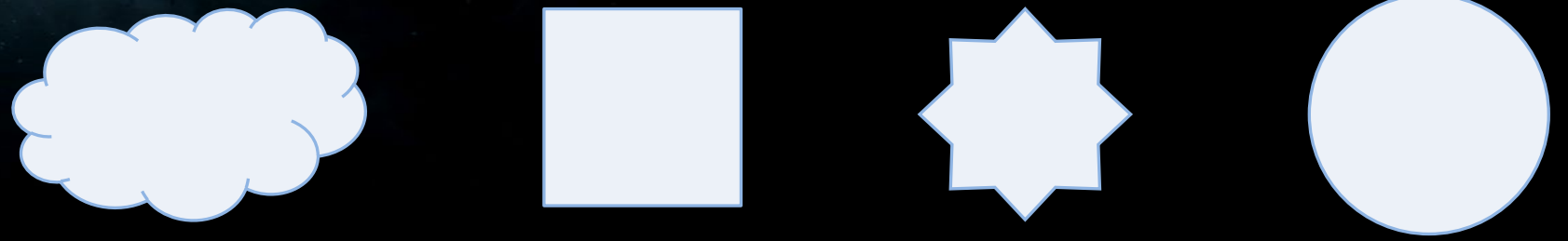
Symmetry → Laws of Nature

Example: Newton's Gravitation



Spherical Symmetry → Force depends only on distance

Symmetries → Restrictions



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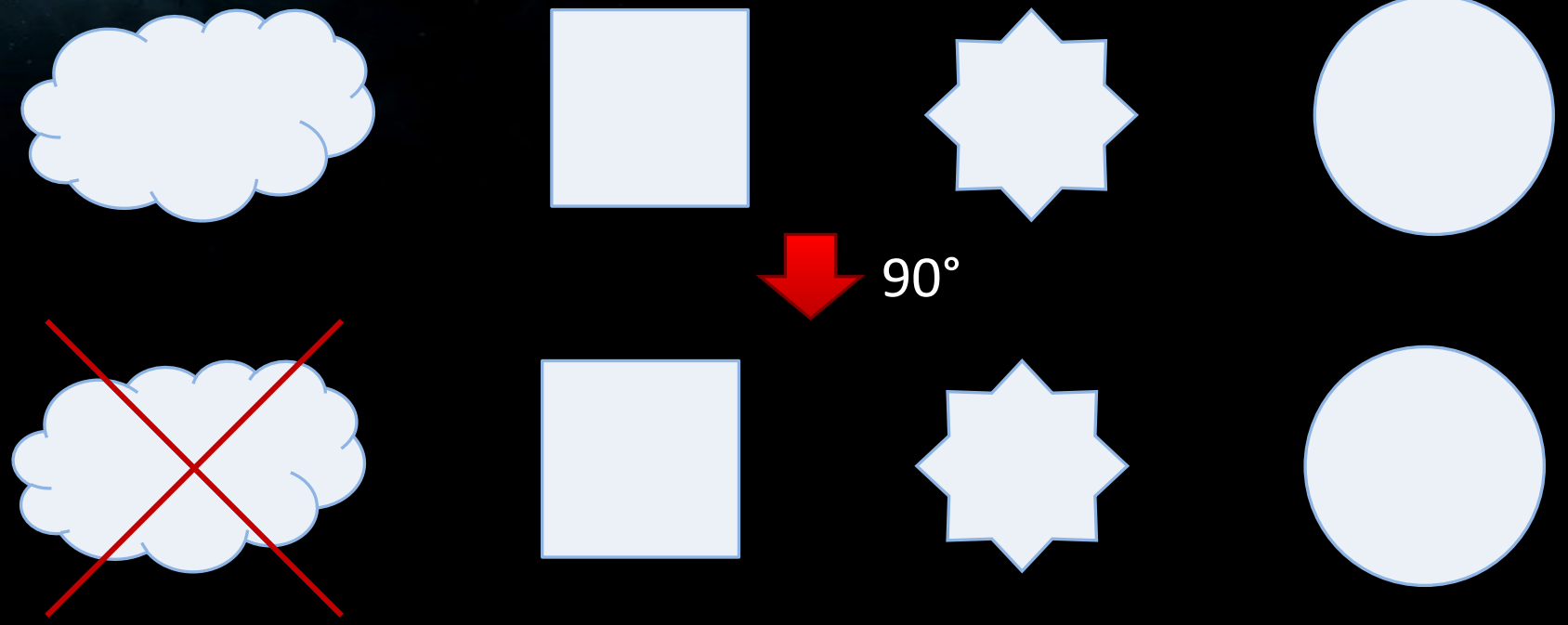

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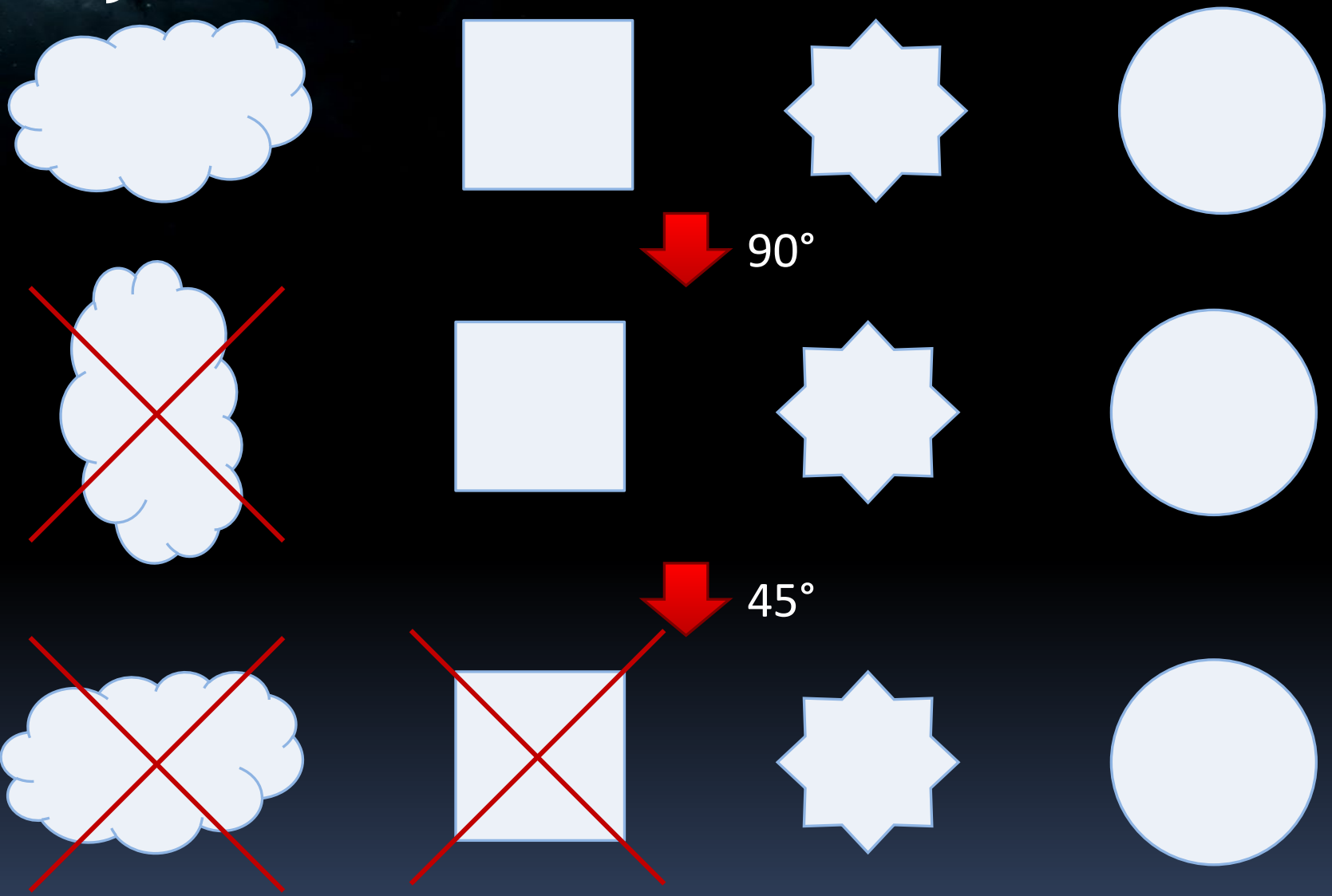

Role of Symmetries in Physics

Complex Field: $Z = a + b\,i = r\,e^{i\theta}$ → Theory must be symmetric phase

Noether: Symmetry → Conserved Quantity

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Conservation of ELECTRIC CHARGE

Role of Symmetries in Physics

Complex Field: $Z = a + b\,i = r\,e^{i\theta}$ → Theory must be symmetric phase

Noether: Symmetry → Conserved Quantity

Conservation of ELECTRIC CHARGE

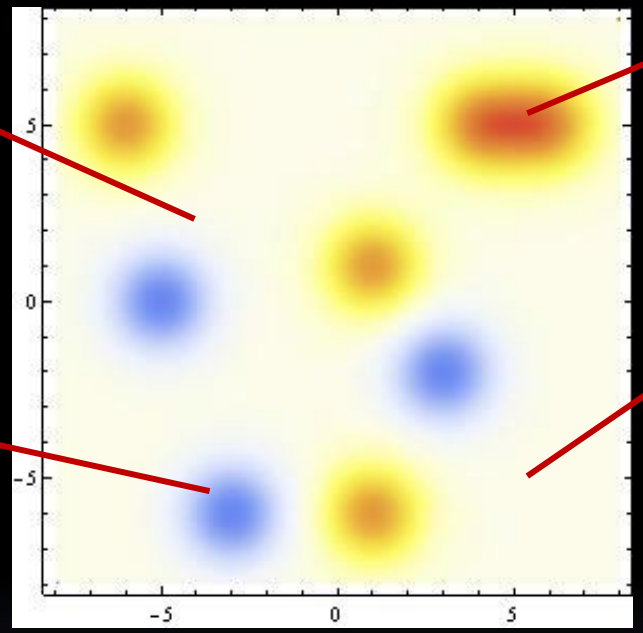
Complex fields describe charged particles!

(the electron field also describes spin ½ particles, fields of this type are called spinor fields, and are different from vector or scalar fields)

Global vs Local Symmetries

$Z_1 = r_1 e^{i(\theta_1)}$

$Z_2 = r_2 e^{i(\theta_2)}$



$Z_3 = r_3 e^{i(\theta_3)}$

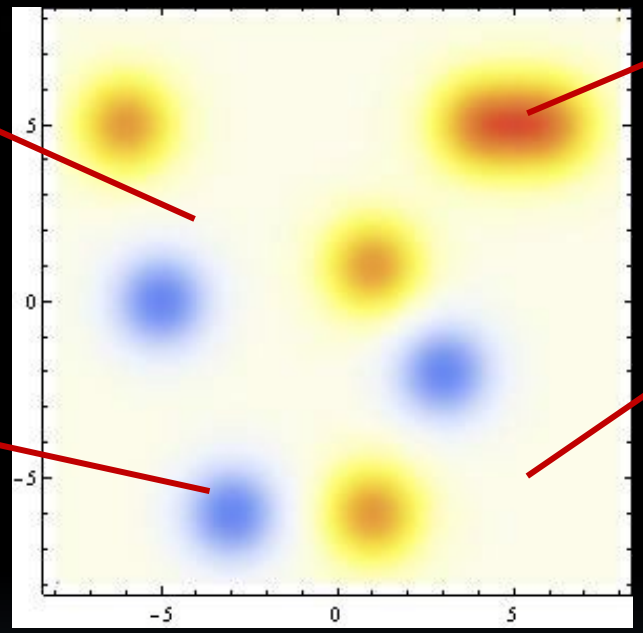
$Z_4 = r_4 e^{i(\theta_4)}$

Global Transformation

Global vs Local Symmetries

$Z_1 = r_1 e^{i(\theta_1 + \alpha)}$

$Z_2 = r_2 e^{i(\theta_2 + \alpha)}$



$Z_3 = r_3 e^{i(\theta_3 + \alpha)}$

$Z_4 = r_4 e^{i(\theta_4 + \alpha)}$

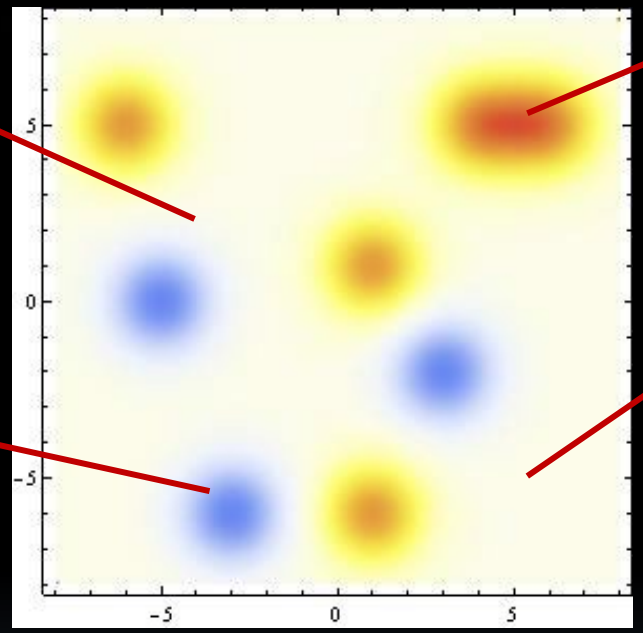
Global Transformation

Conservation of ELECTRIC CHARGE

Global vs Local Symmetries

$Z_1 = r_1 e^{i(\theta_1 + \alpha)}$

$Z_2 = r_2 e^{i(\theta_2 + \beta)}$



$Z_3 = r_3 e^{i(\theta_3 + \gamma)}$

$Z_4 = r_4 e^{i(\theta_4 + \delta)}$

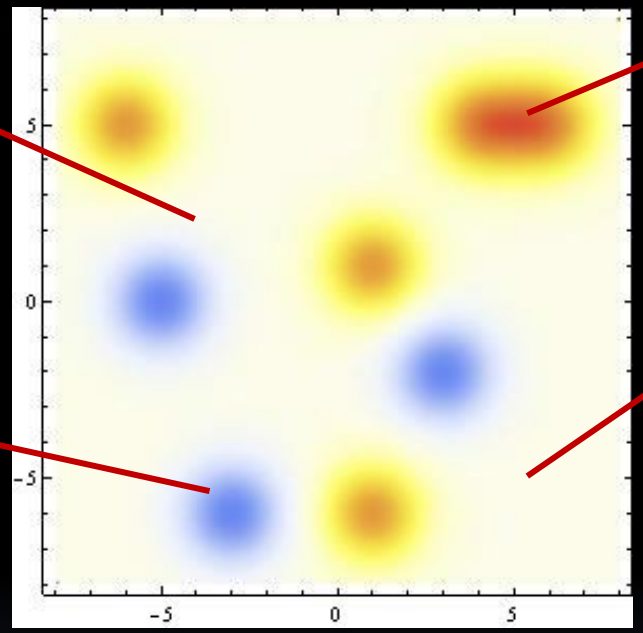
Local Transformation

???

Global vs Local Symmetries

$Z_1 = r_1 e^{i(\theta_1 + \alpha)}$

$Z_2 = r_2 e^{i(\theta_2 + \beta)}$



$Z_3 = r_3 e^{i(\theta_3 + \gamma)}$

$Z_4 = r_4 e^{i(\theta_4 + \delta)}$

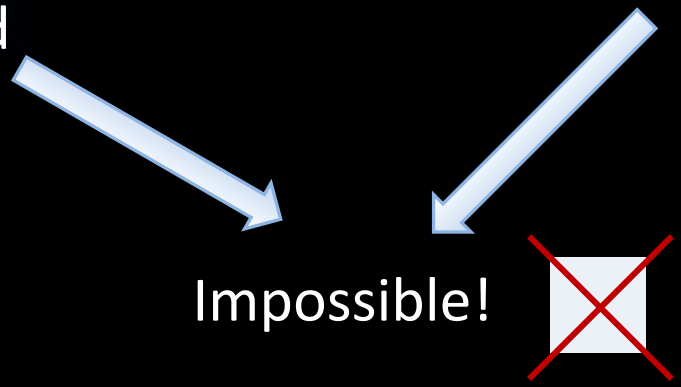
Local Transformation

INTERACTIONS!!

Local Symmetries and Gauge Bosons

Complex Field

Local Phase transformation

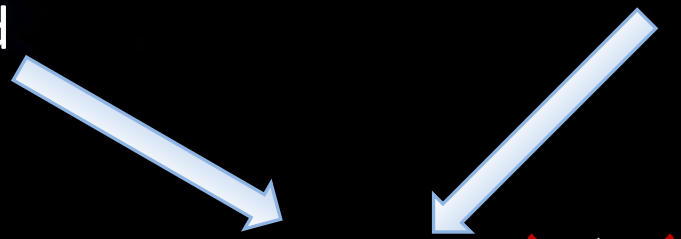


Impossible!

Local Symmetries and Gauge Bosons

Complex Field

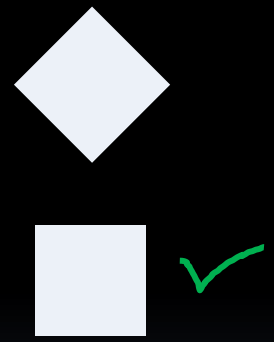
Local Phase transformation



Impossible!

New field must be introduced!

The theory with these two fields is symmetric



Local Symmetries and Gauge Bosons

Complex Field

Local Phase transformation

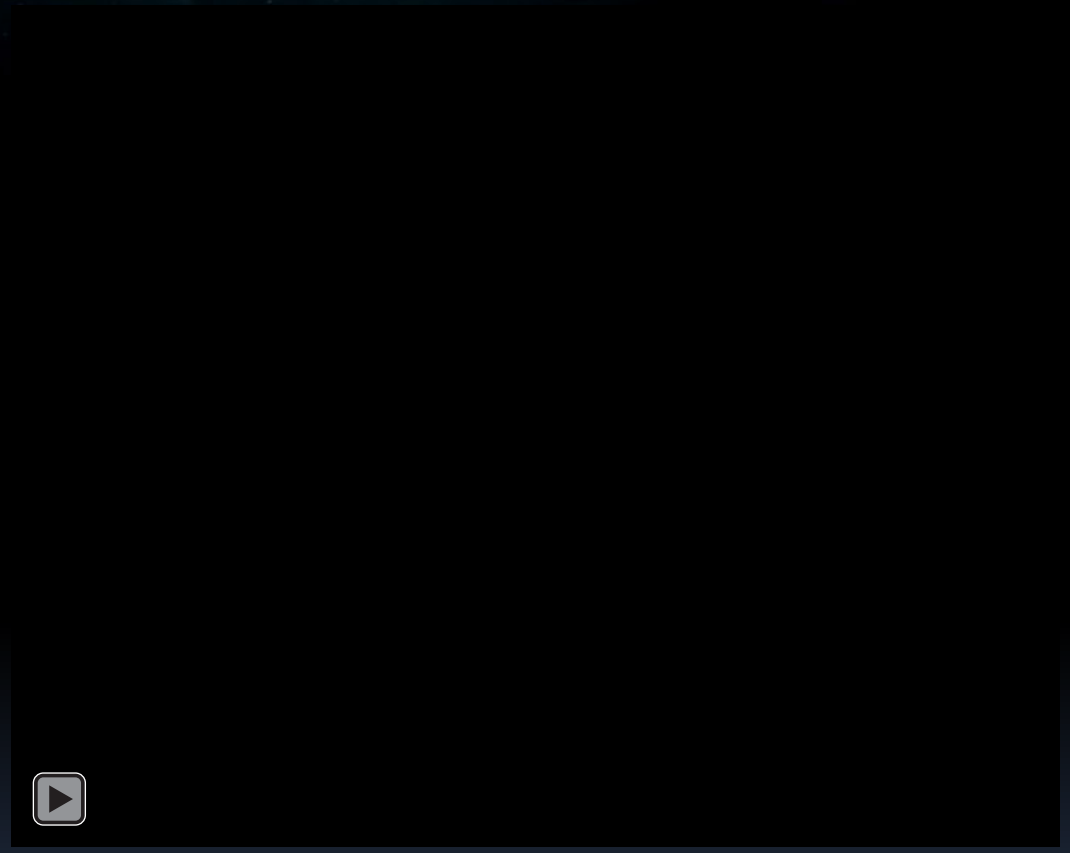
Impossible!

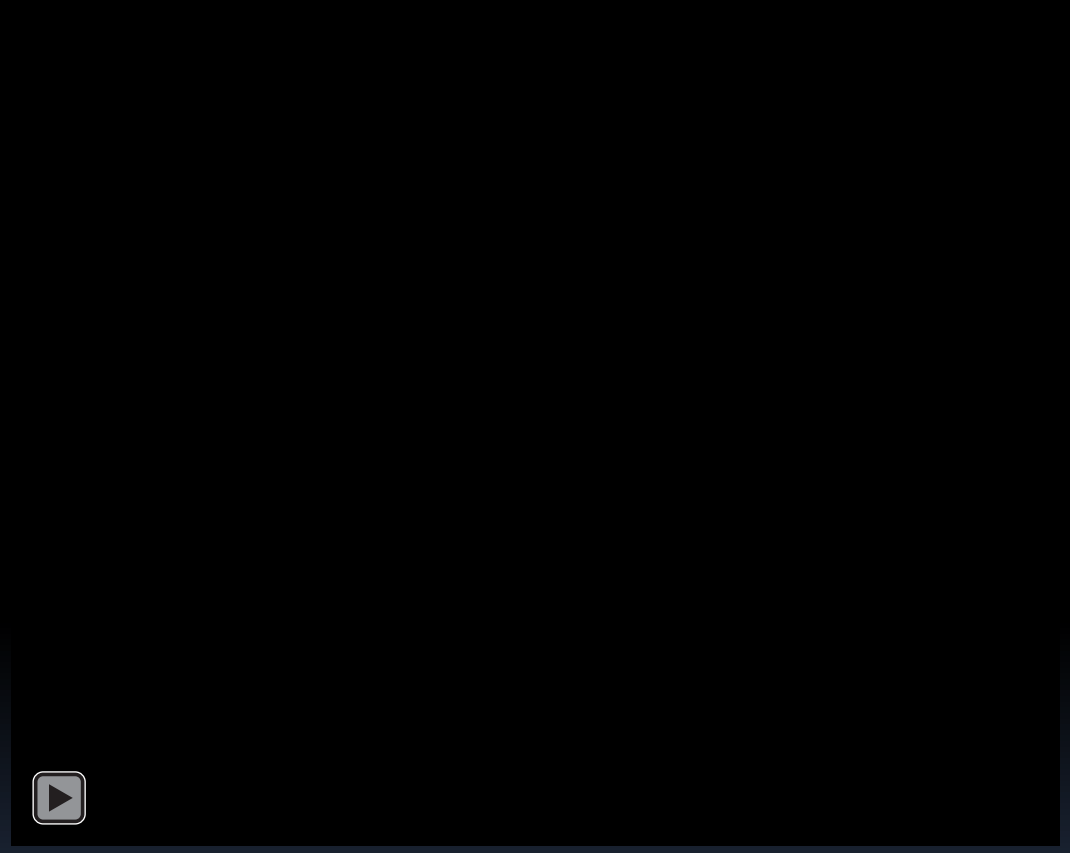
New field must be introduced!

The theory with these two fields is symmetric

- Vector Field
- Field excitations HAVE NO MASS
- Interaction is closely related to the conserved charge and gauge coupling

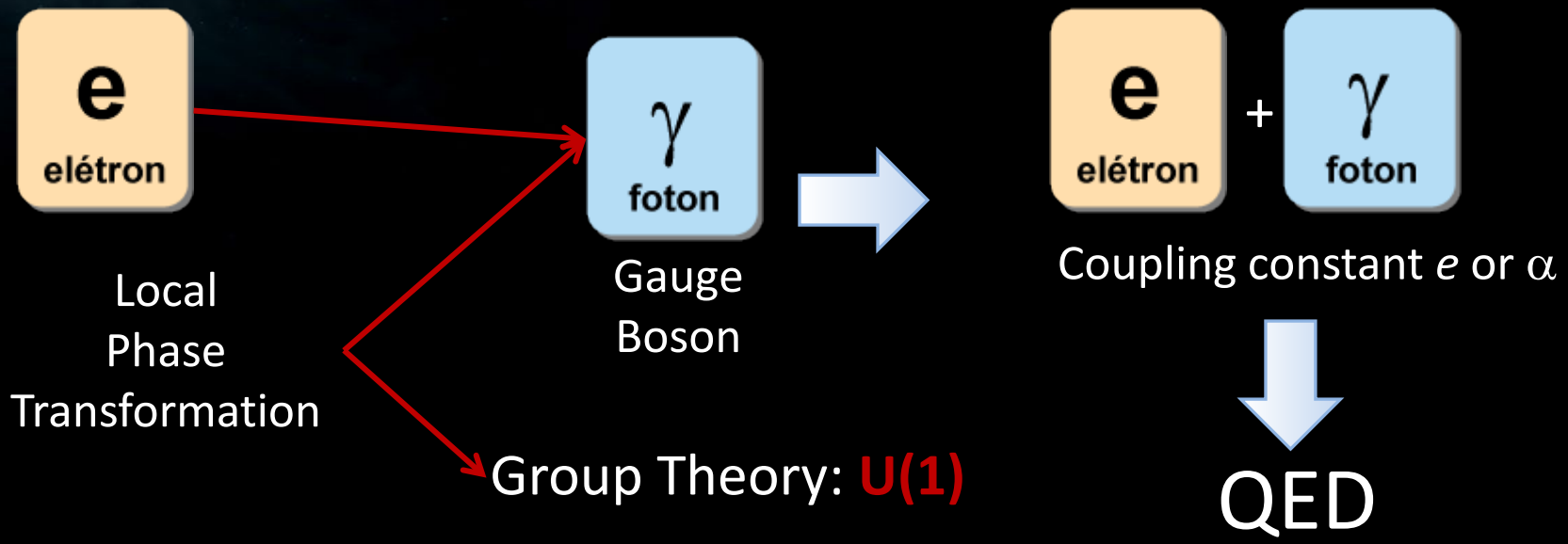
Local Symmetries and Gauge Bosons





Vocabulary: Gauge Symmetries, Gauge Fields and Gauge Couplings

Quantum Electrodynamics (QED)



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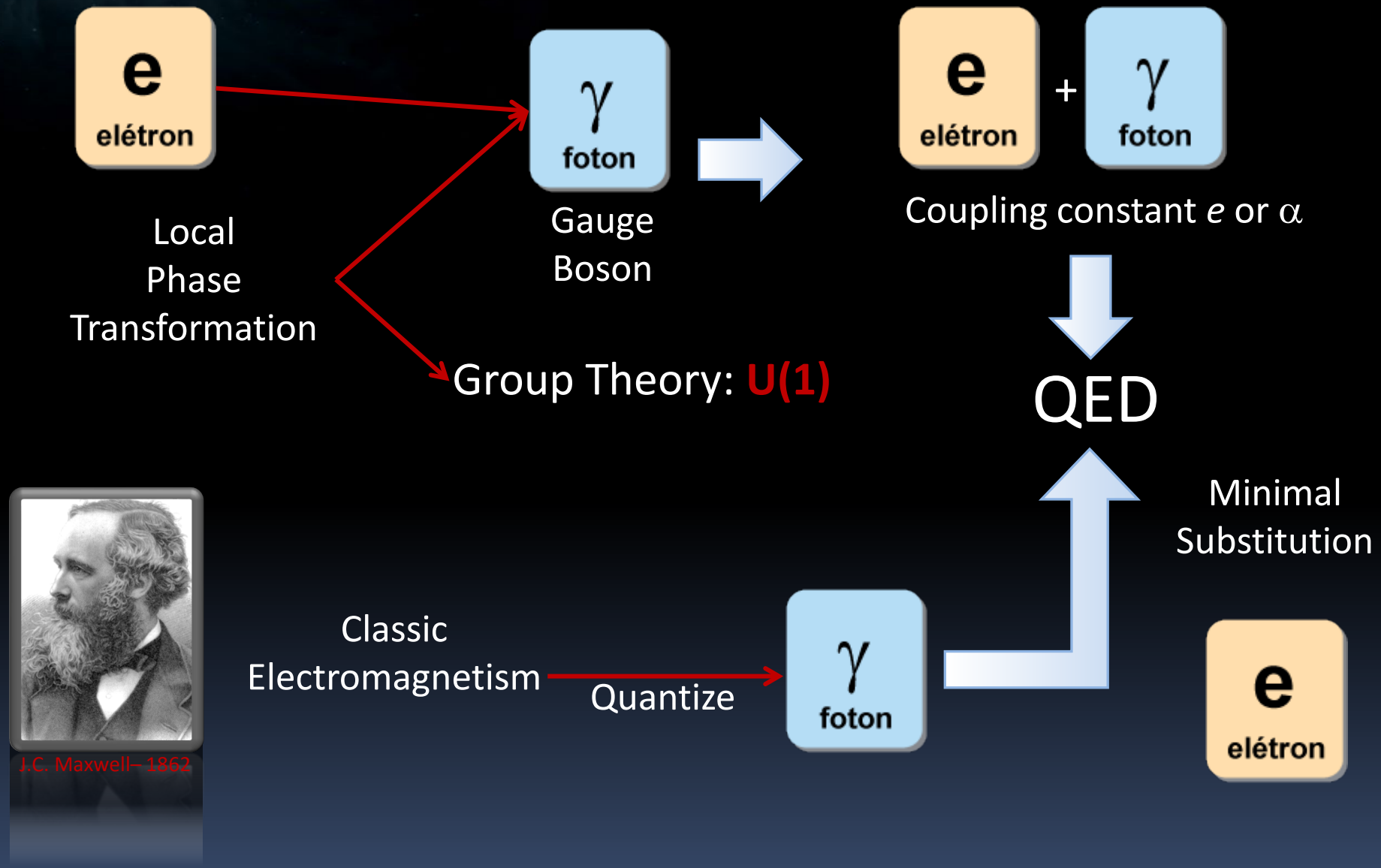
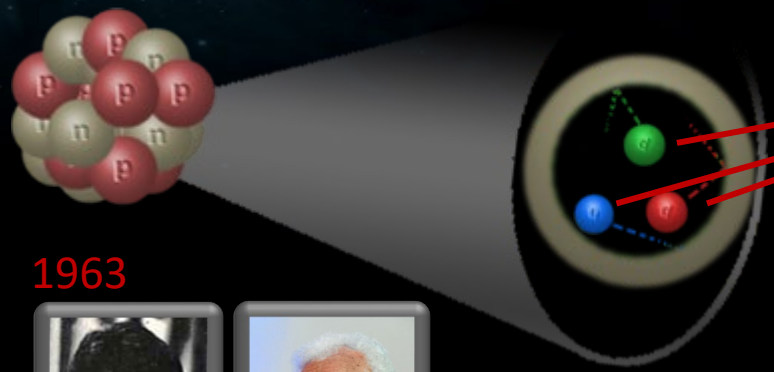


Quantum Chromodynamics (QCD)



Quarks

What holds the quarks together?

1963

G. Zweig M. Gell-Mann

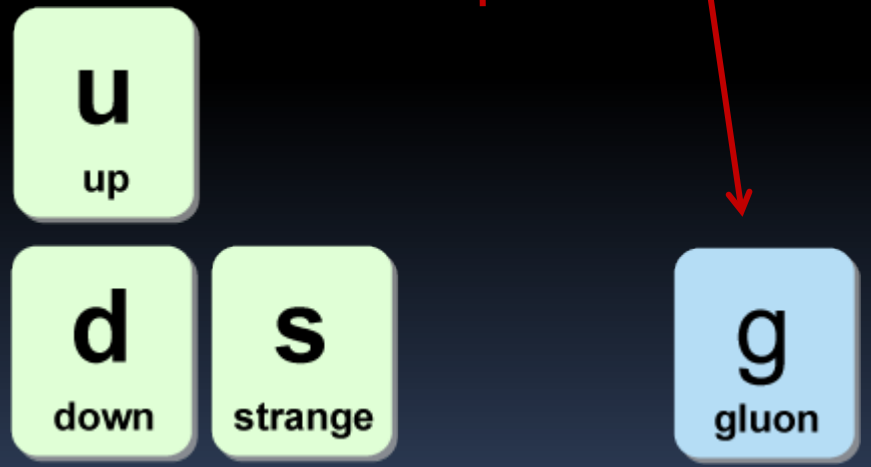
Local Symmetry: **SU(3)**

1965

Y. Nambu M-Y Han O.W. Greenberg

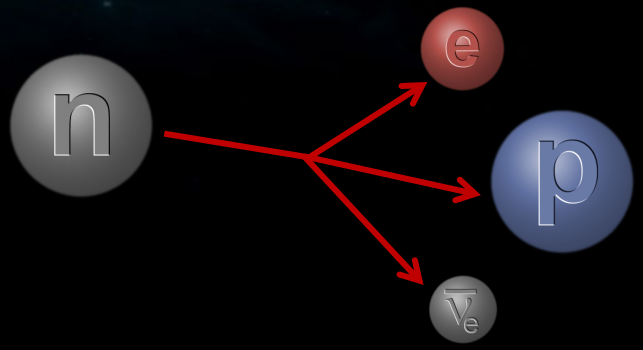
SU(3) charged

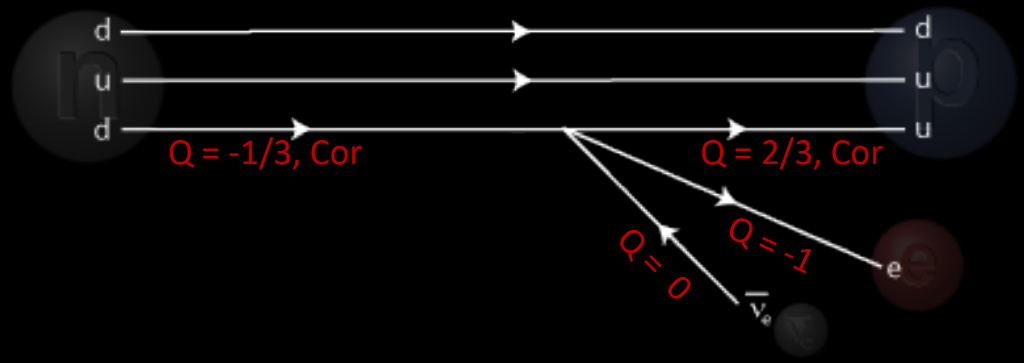
SU(3) Gauge Boson

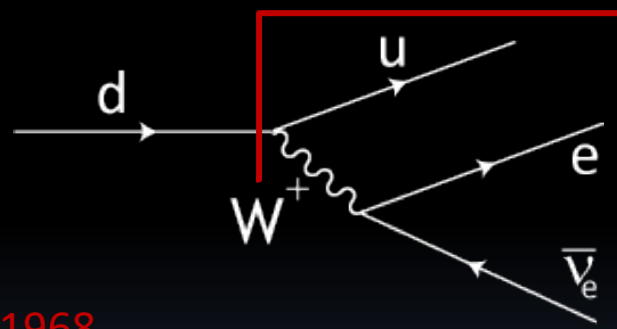


Electroweak Model (GWS)

Decaimento Beta:







Simetria Local: **$SU(2)_L$ x $U(1)_y$**

Bósons de Gauge de **$SU(2)_L$ x $U(1)_y$**

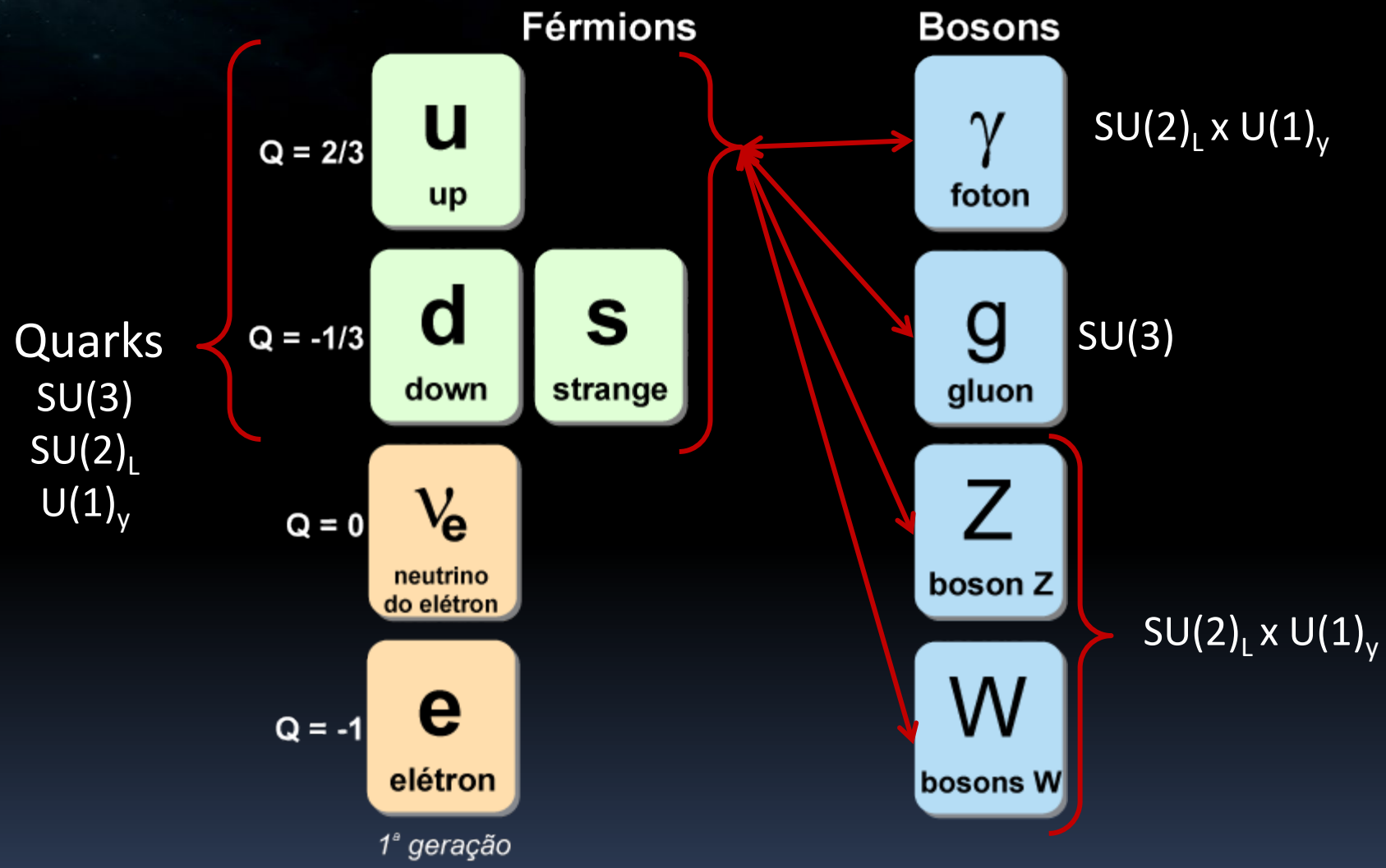
- Z — boson Z
- γ — foton
- W — bosons W

1968

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

The Standard Model (SM)



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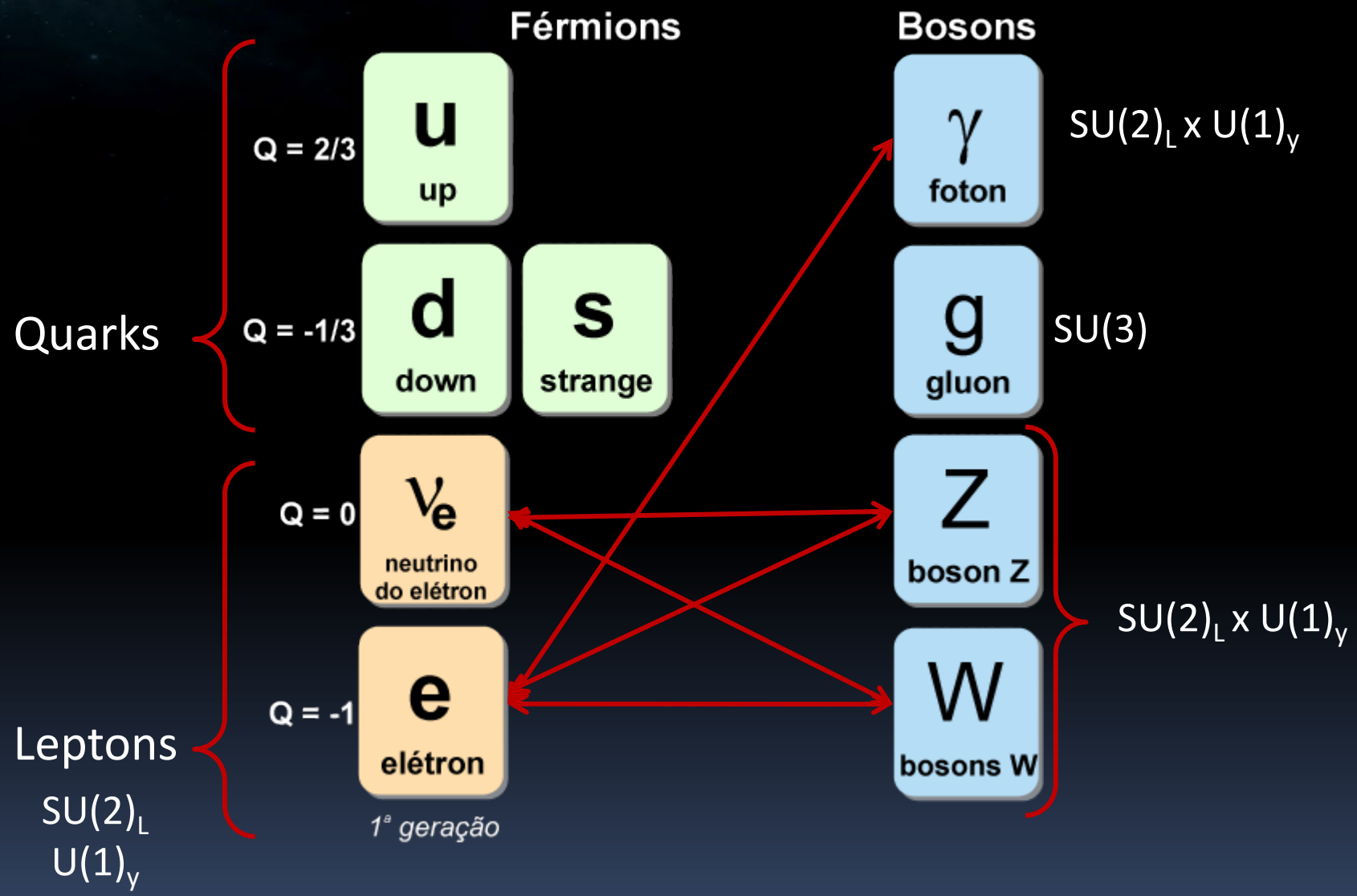

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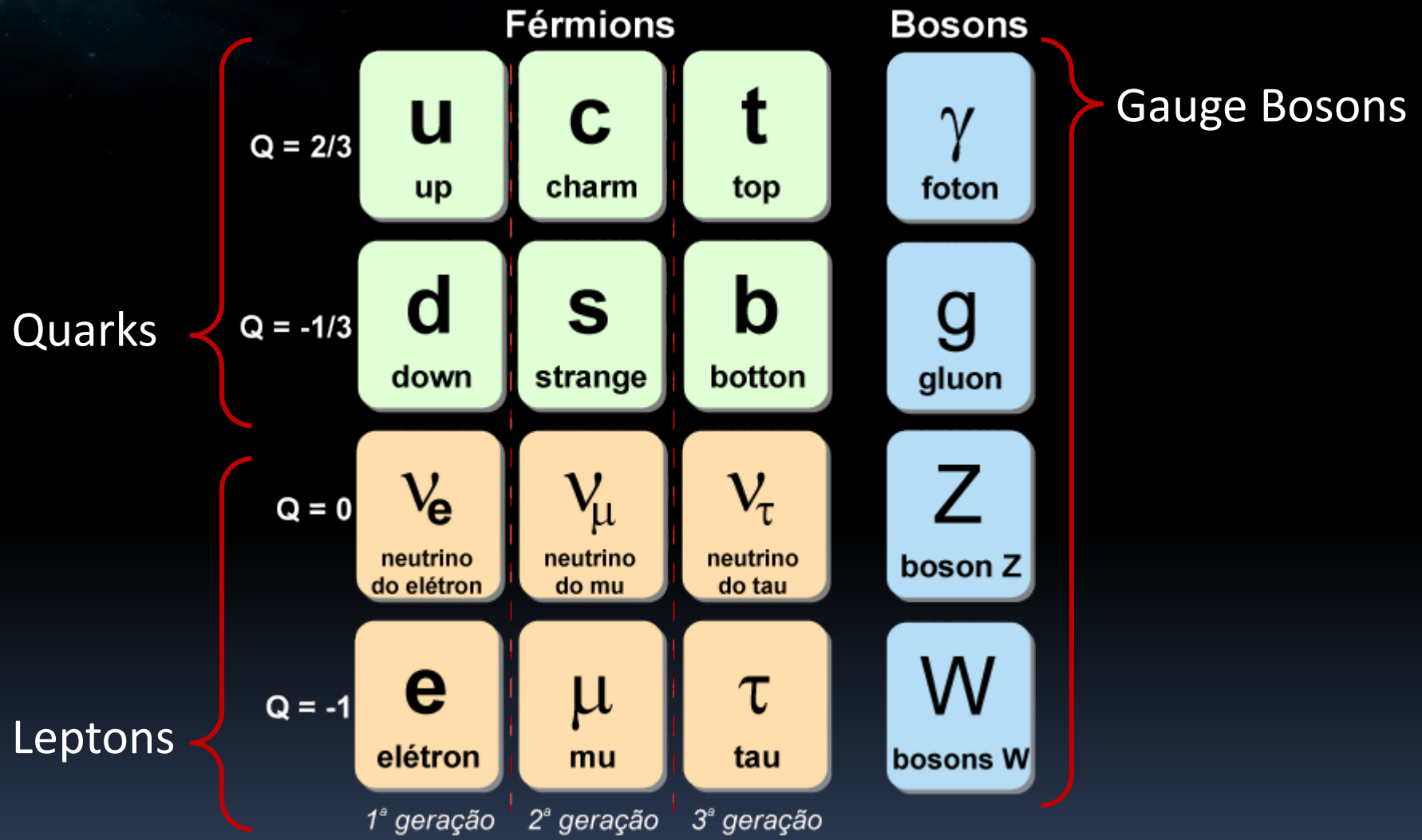


The Standard Model (SM)

Is that all? Can we go home?

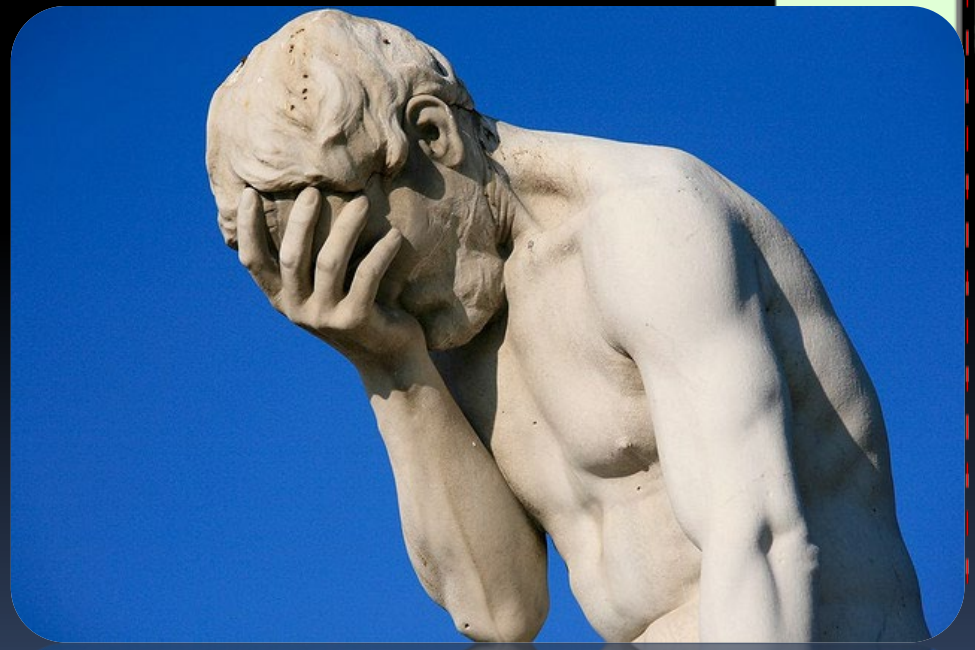
Well, time to recall some facts:

"Gauge Bosons HAVE NO MASS"

... let's take a look.

The Standard Model (SM)

	Férmions			Bosons	
Q = 2/3	u up	c charm	t top	γ foton	m =0 ✓
Q = -1/3	d	s strange	b botton	g gluon	m =0 ✓
	ν_μ neutrino do mu	ν_τ neutrino do tau		Z boson Z	m = 92 GeV ✗
	μ mu	τ tau		W bosons W	m = 80 GeV ✗
	2ª geração	3ª geração			



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W and Z bosons have all the symmetries predicted by $SU(2)_L$ x $U(1)_y$, but they have MASS

The Standard Model (SM)

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Well, time to recall some facts:

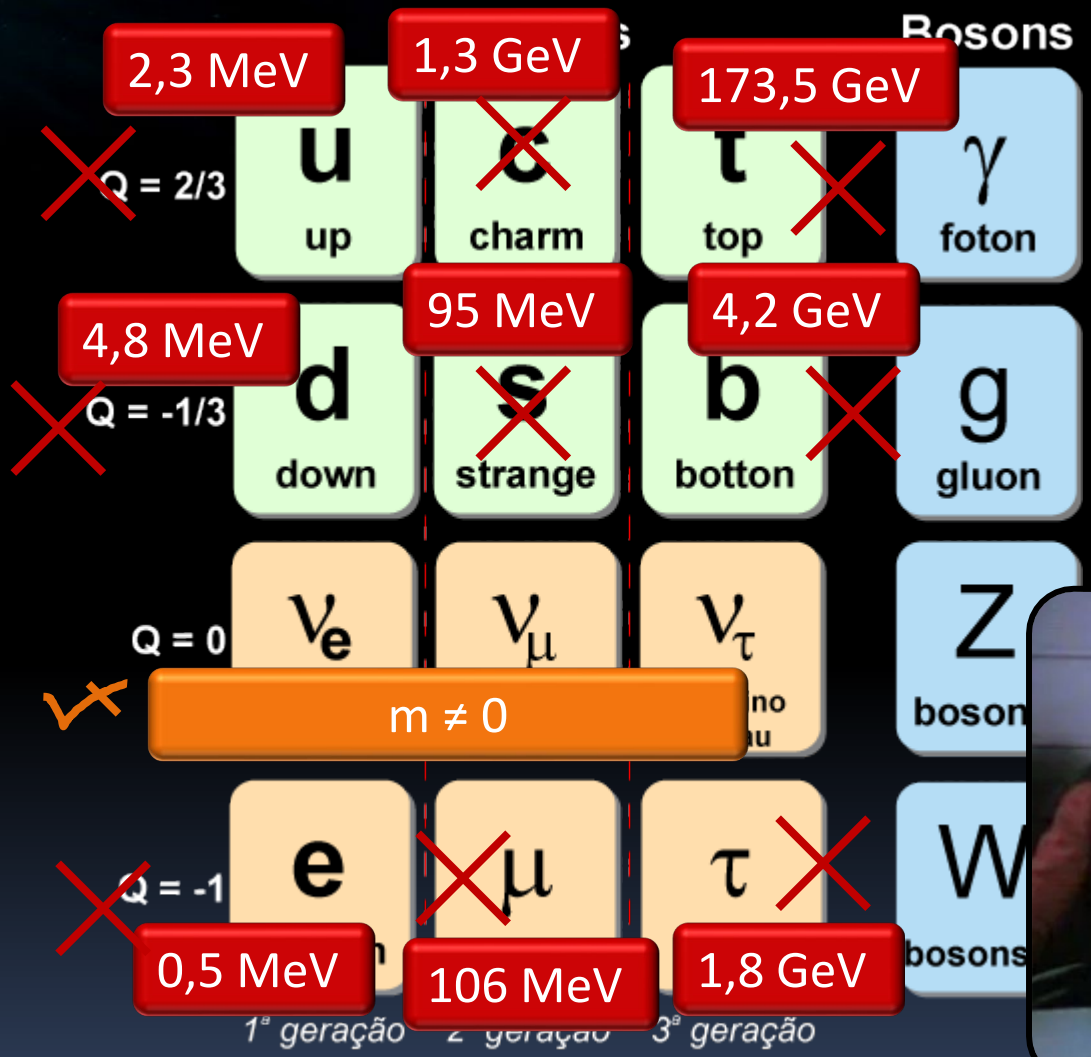
"Gauge Bosons HAVE NO MASS"

... let's take a look.

W and Z bosons have all the symmetries predicted by $SU(2)_L$ x $U(1)_y$, but they have MASS

That is not all: the $SU(2)_L$ symmetry forbids **fermion** masses too! Let's see...

The Standard Model (SM)



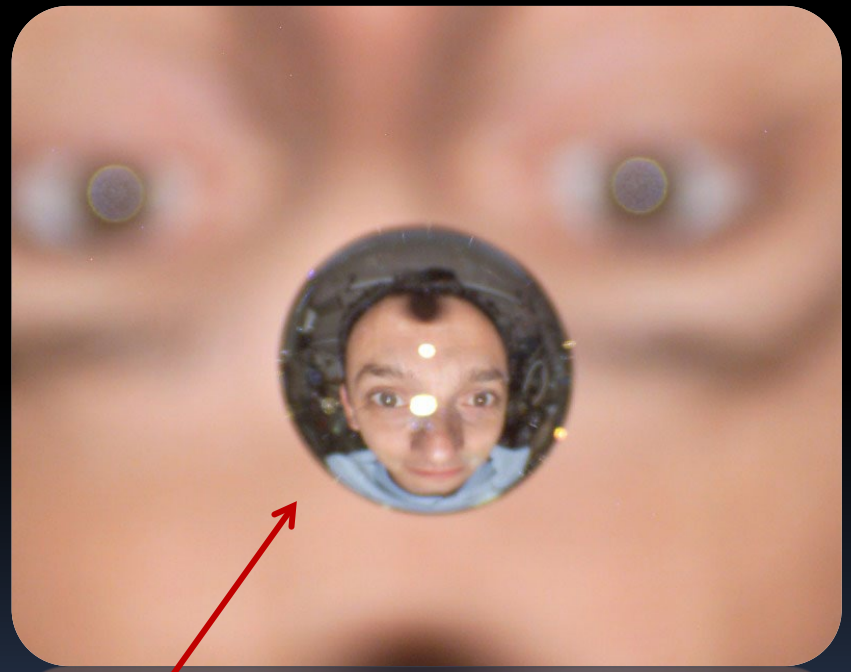
The Higgs Boson

Dilemma: Symmetries work! **VS** Masses are forbidden!

The Higgs Boson

Dilemma: Symmetries work! **VS** Masses are forbidden!

Spontaneous Symmetry Breaking:

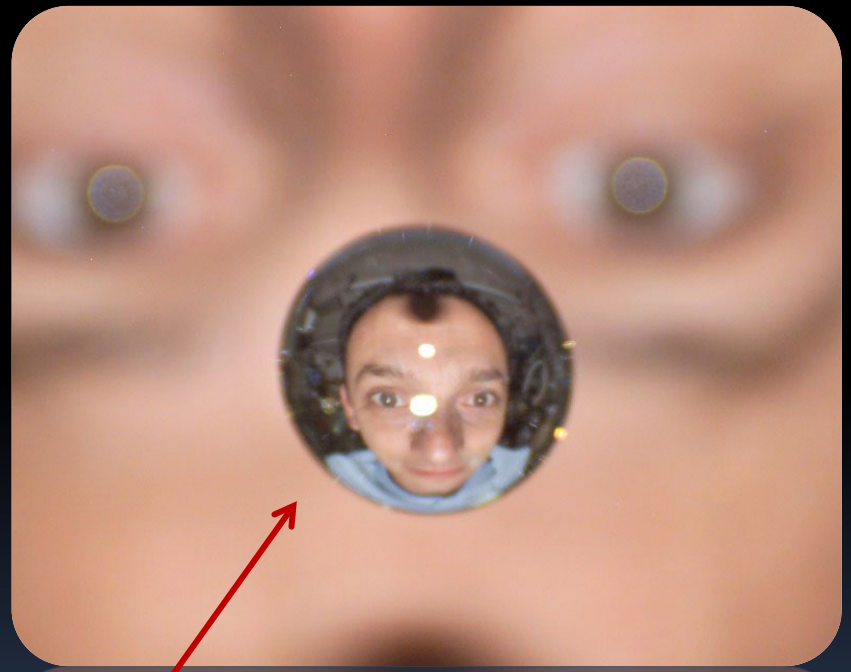


Water droplet (in space)

The Higgs Boson

Dilemma: Symmetries work! **VS** Masses are forbidden!

Spontaneous Symmetry Breaking:



Water droplet (in space)

Cold

(lowest energy state)

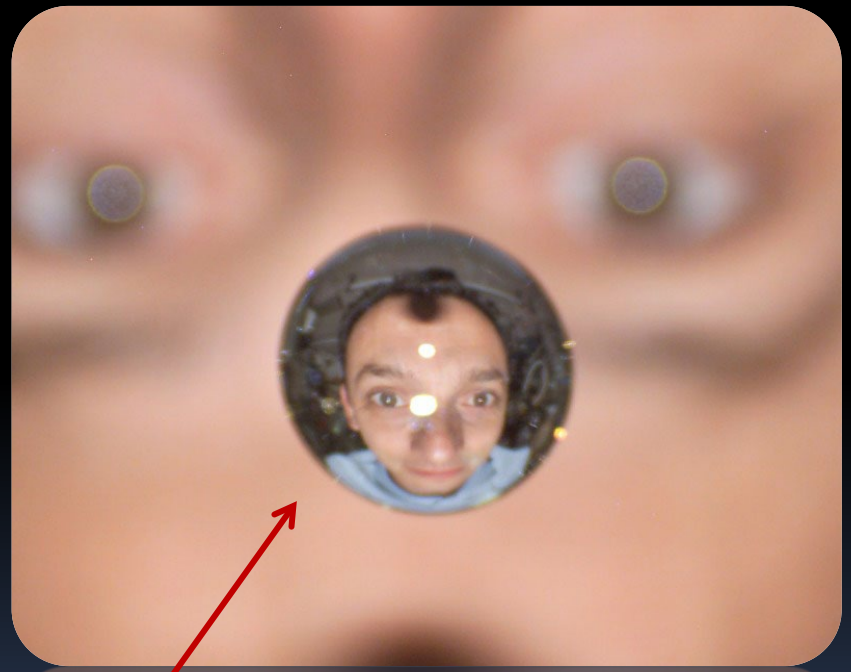
"Smaller" rotational symmetry

But have we really LOST symmetry?

The Higgs Boson

Dilemma: Symmetries work! **VS** Masses are forbidden!

Spontaneous Symmetry Breaking:



Water droplet (in space)

Cold

(lowest energy state)

All possible and equally probable

But have we really LOST symmetry?

NO! It is just manifested in a more subtle way

The Higgs Boson

Englert Brout Higgs Guralnik Hagen Kibble

1964

Scalar Field: H

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

Lowest energy state (Vacuum), does not respect symmetry

The Higgs Boson

Englert Brout Higgs Guralnik Hagen Kibble

1964

Scalar Field: H

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

Lowest energy state (Vacuum), does not respect symmetry

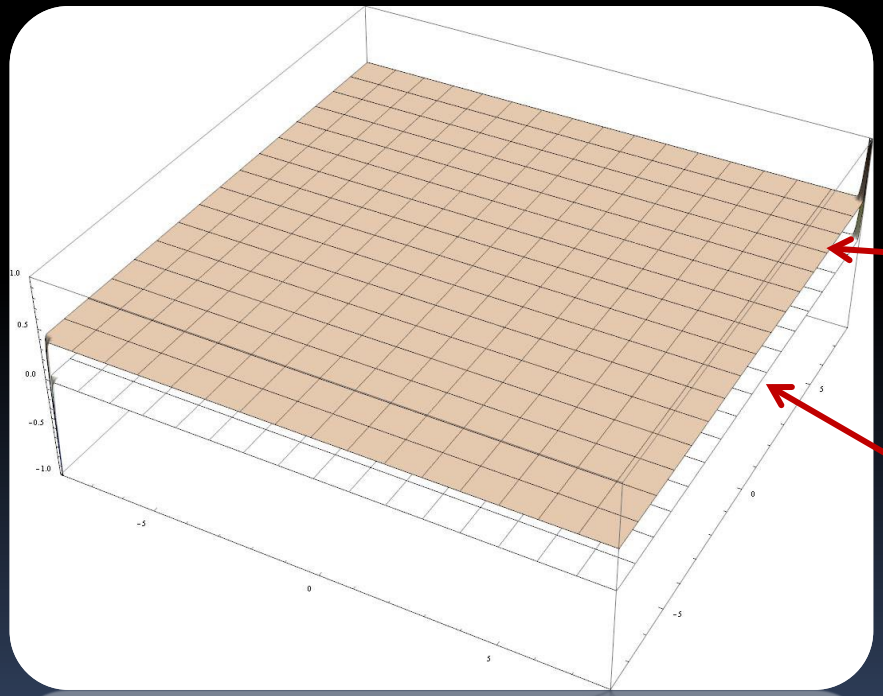
The Higgs Boson

Scalar Field: H

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

Lowest energy state (Vacuum), does not respect symmetry

Effect: Vacuum Expectation Value (VEV)!



No particles here!

Vacuum of the H field
(symmetry breaking)
(246 GeV)

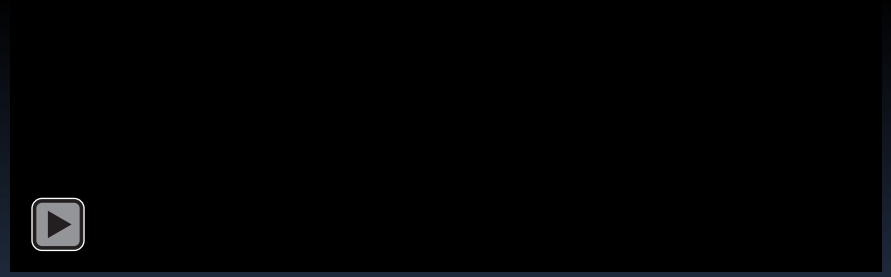
Normal Vacuum

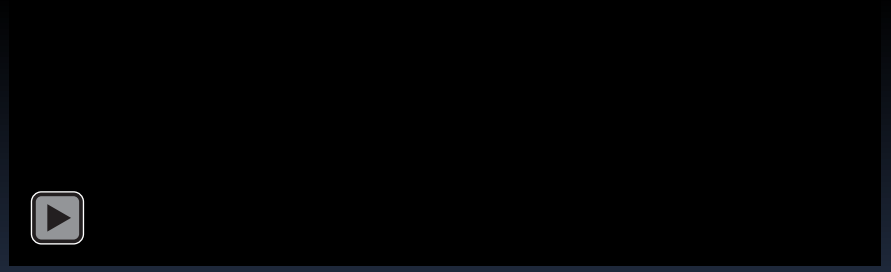
The Higgs Boson

Any field that interacts with H will constantly “feel” this VEV

Non interacting

Low Interaction



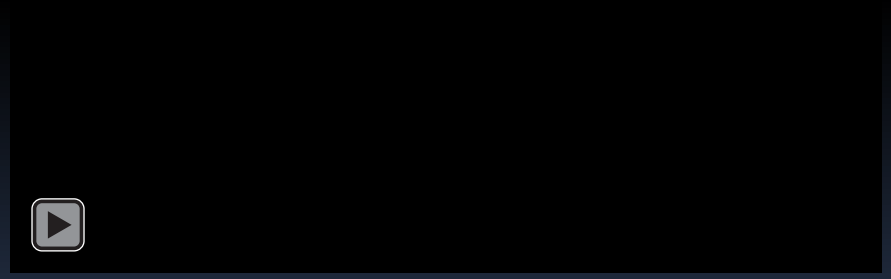


Pictorial “classical” view: even if we allow that “bump” to move at light speed, the effective speed on the interacting case will be smaller than c. Only massive particles can do that.

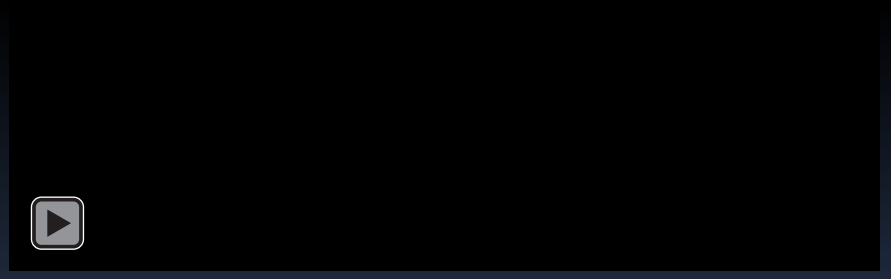
The Higgs Boson

Any field that interacts with H will constantly “feel” this VEV

Low Interaction



High Interaction



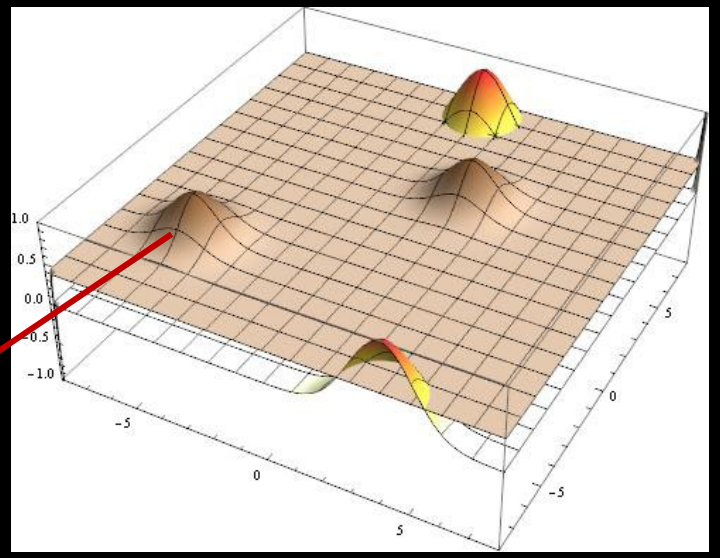
The effect grows with larger interaction (and here the pictorial view fails us).

The Higgs Boson

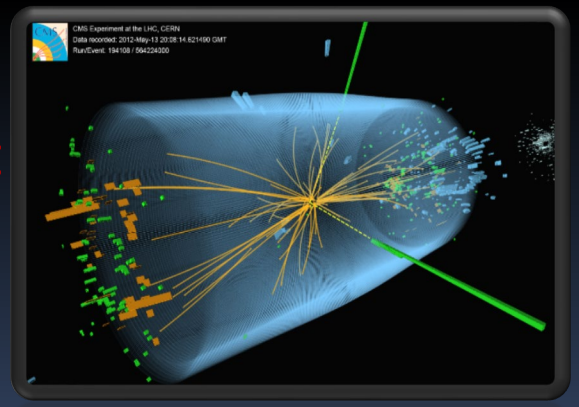
Theory
1968

	Fermions			Bosons
Q = 2/3	u up	c charm	t top	γ foton
Q = -1/3	d down	s strange	b botton	g gluon
Q = 0	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Q = -1	e electron	μ muon	τ tau	W W boson
	1st gen.	*2nd gen.*	*3rd gen.*	

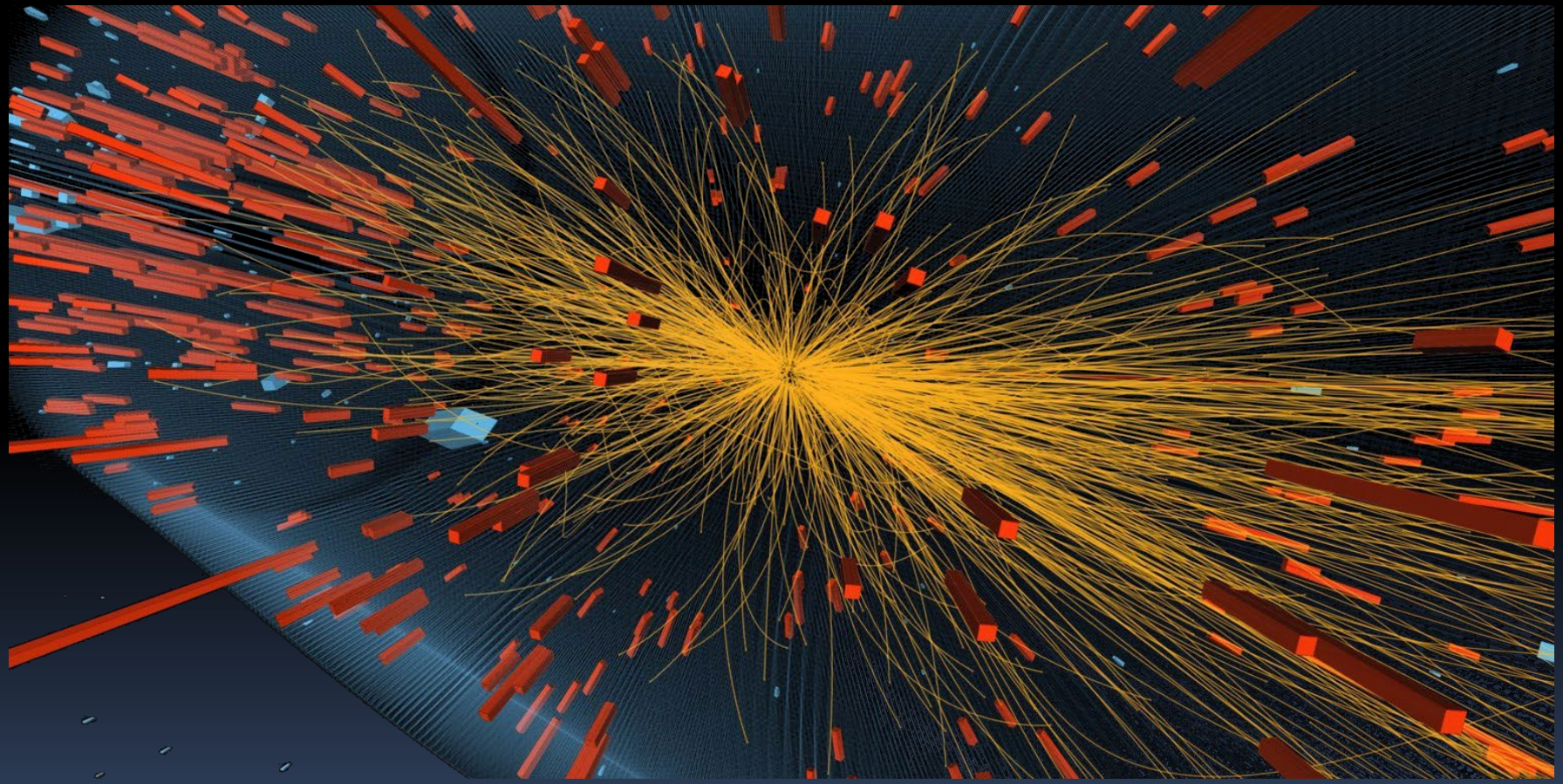
h
Higgs boson



Experiment
2012

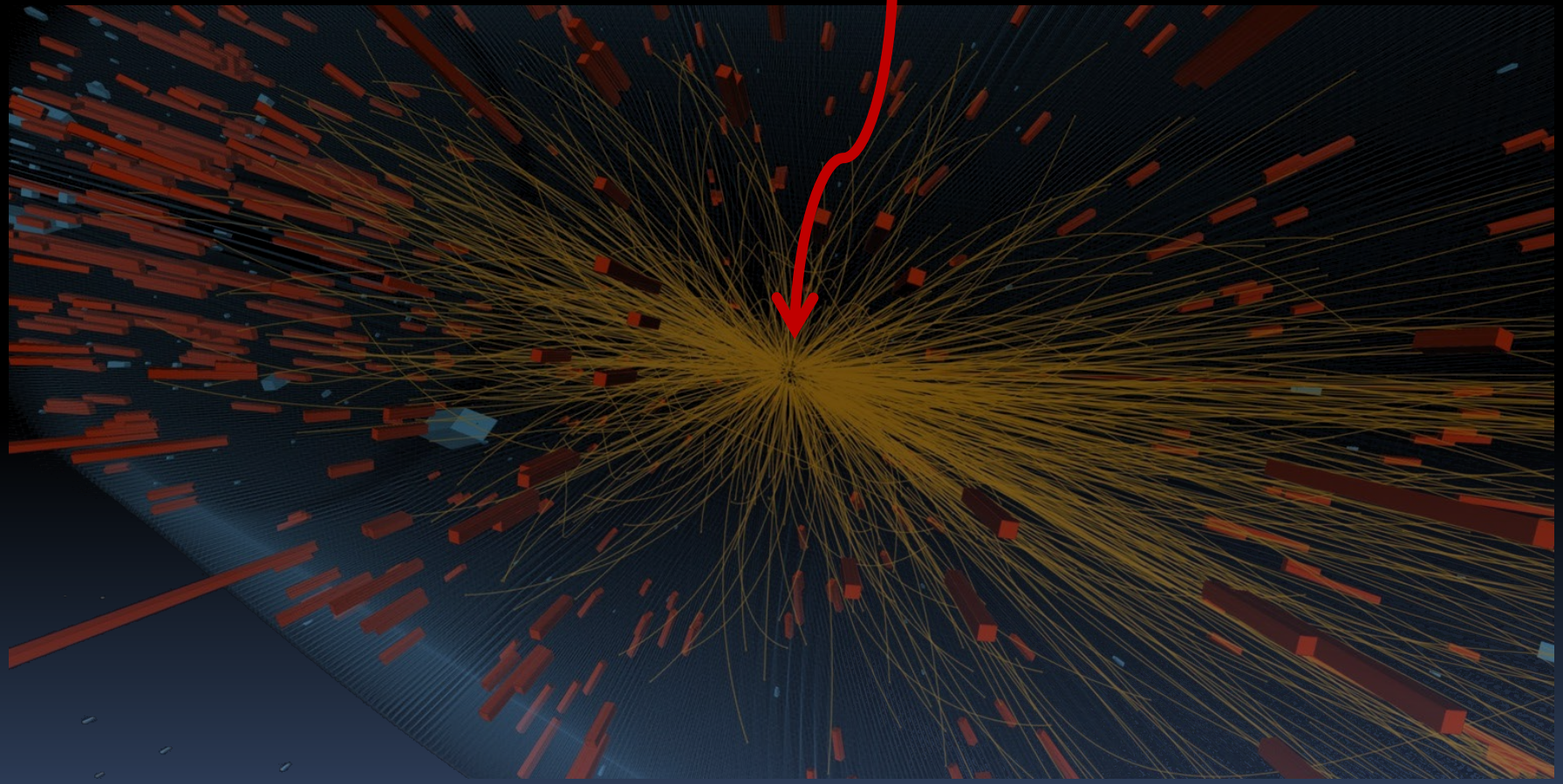


Looking for new particles



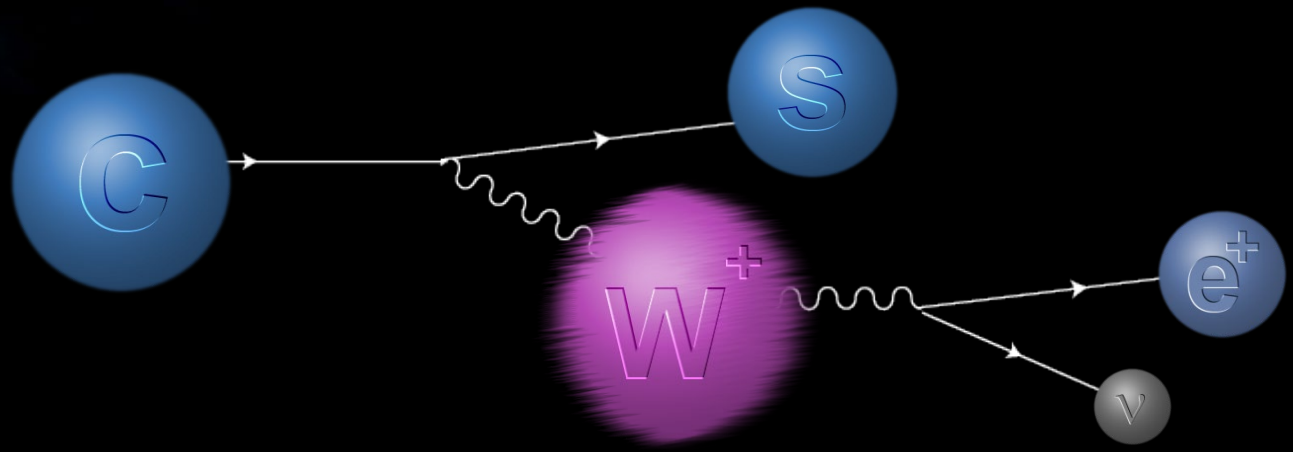
Looking for new particles

How do I know what happened in there?



Heavy Particles Decay

Decay:

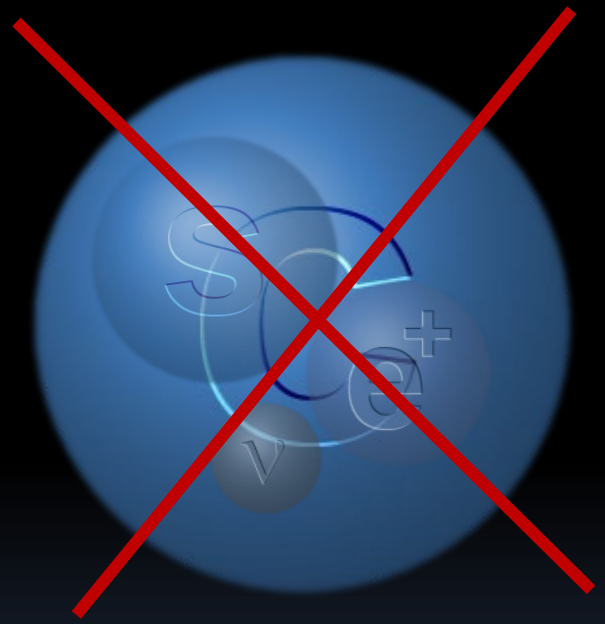


Before

After

Heavy Particles Decay

Be careful!



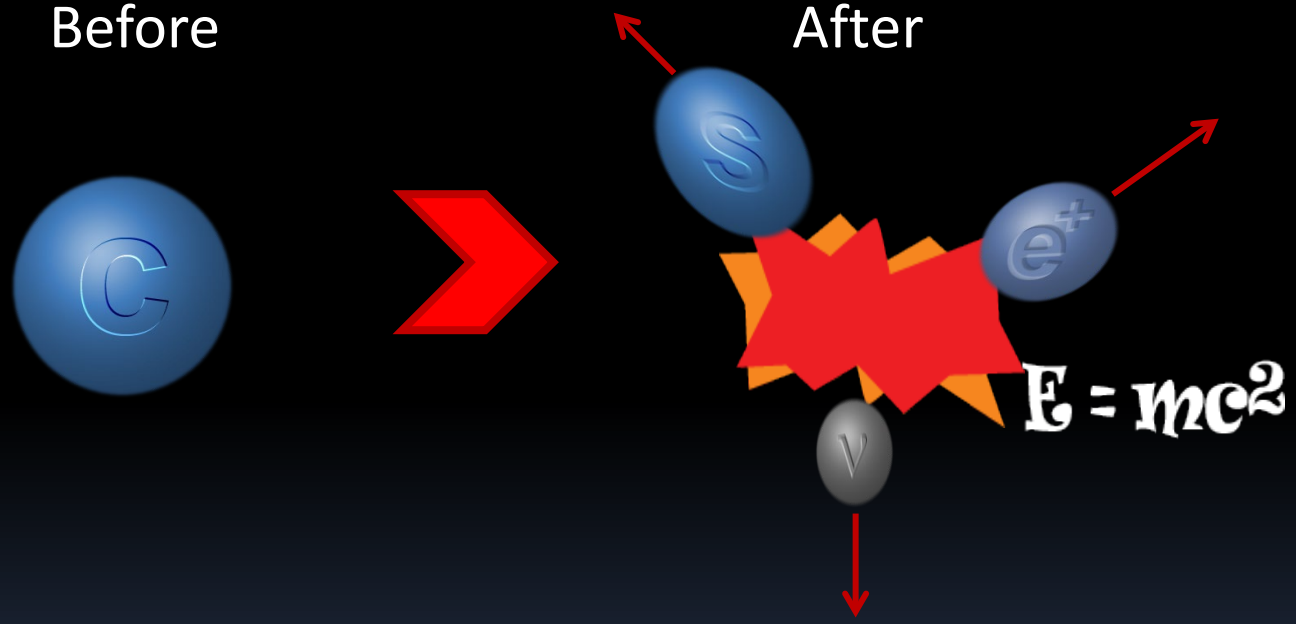
Decay does not imply “composition”!

Heavy Particles Decay

Heavy Particles Decay

This is balanced by kinetic energy for the decay products!

Heavy Particles Decay



If I carefully measure the energy/momentum of the decay products
I can reconstruct the original state

Reconstructing the Higgs

As a example, let's look at one of the simplest Higgs decays:

Reconstructing the Higgs

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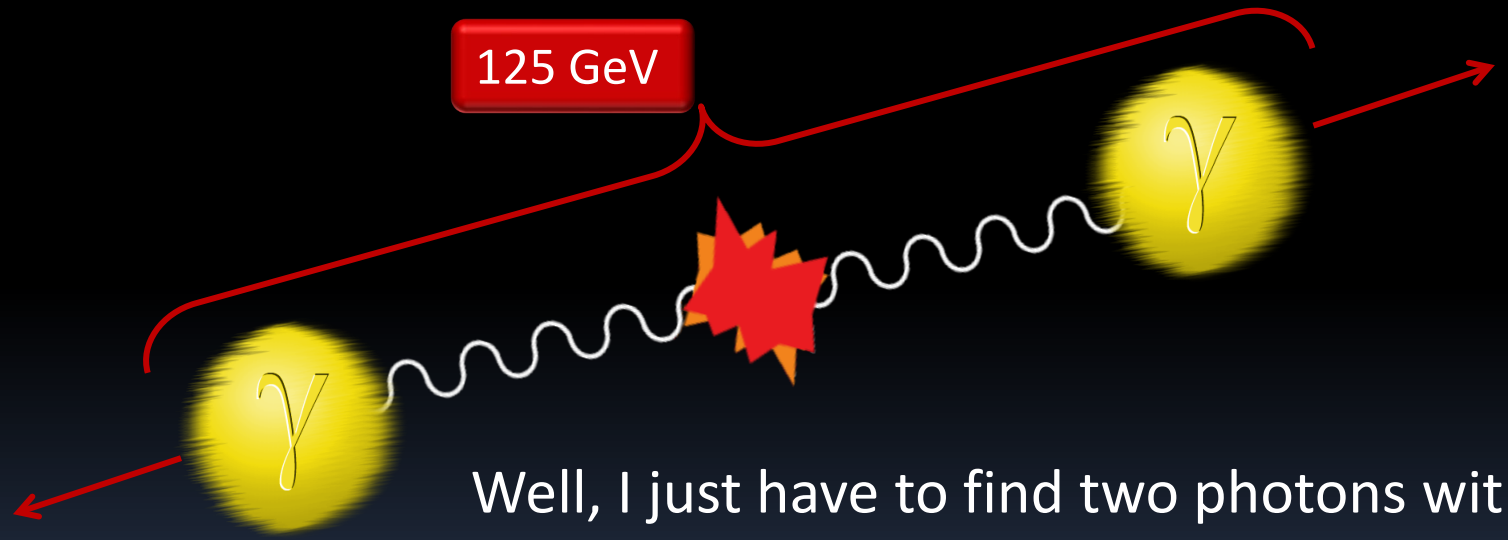
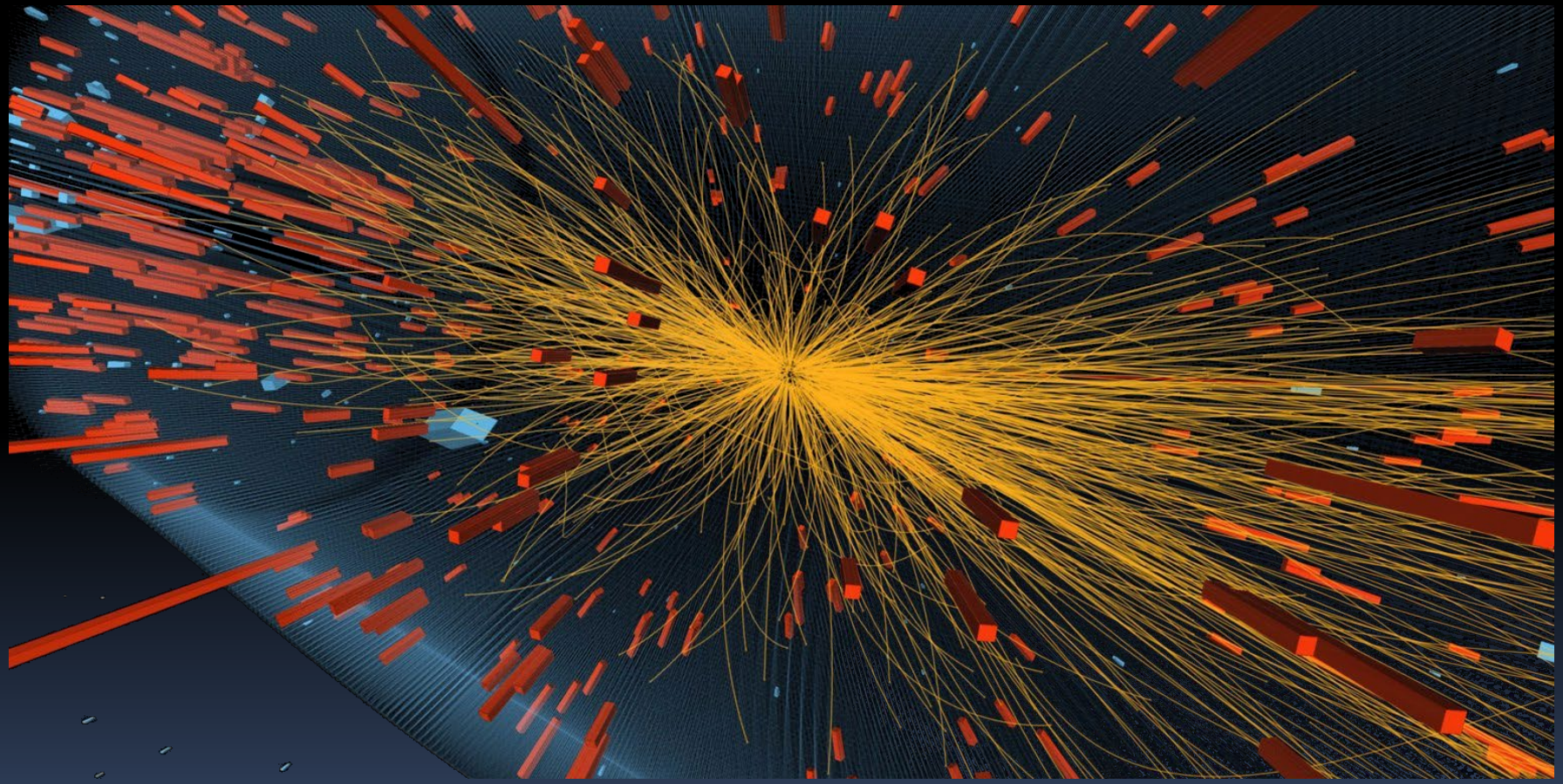


Well, I just have to find two photons with added energy of 125 GeV. Sounds easy, right?

Reconstructing the Higgs

What photons would you choose?

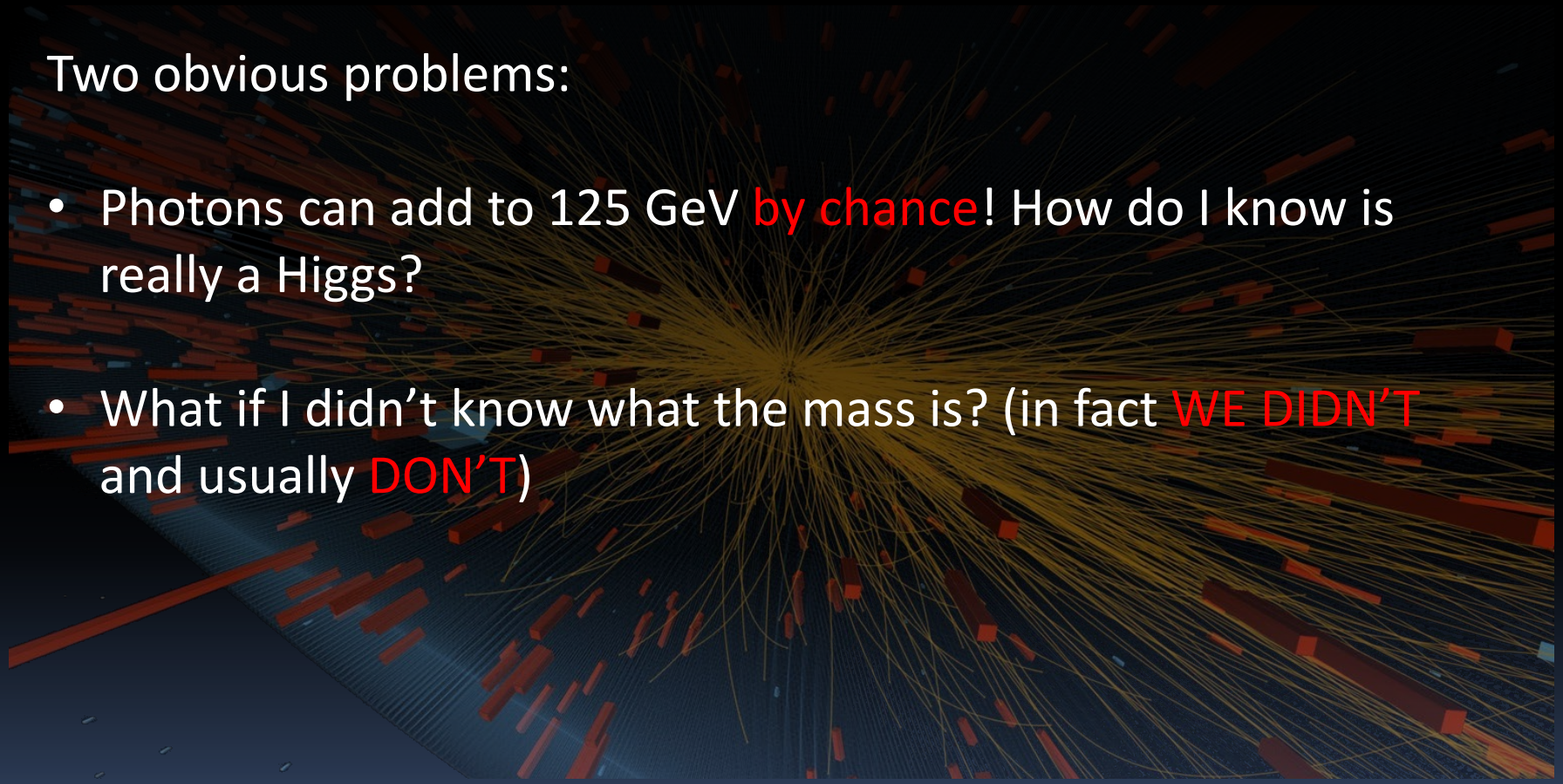


Reconstructing the Higgs

What photons would you choose?

Two obvious problems:

- Photons can add to 125 GeV by chance! How do I know is really a Higgs?
- What if I didn't know what the mass is? (in fact WE DIDN'T and usually DON'T)

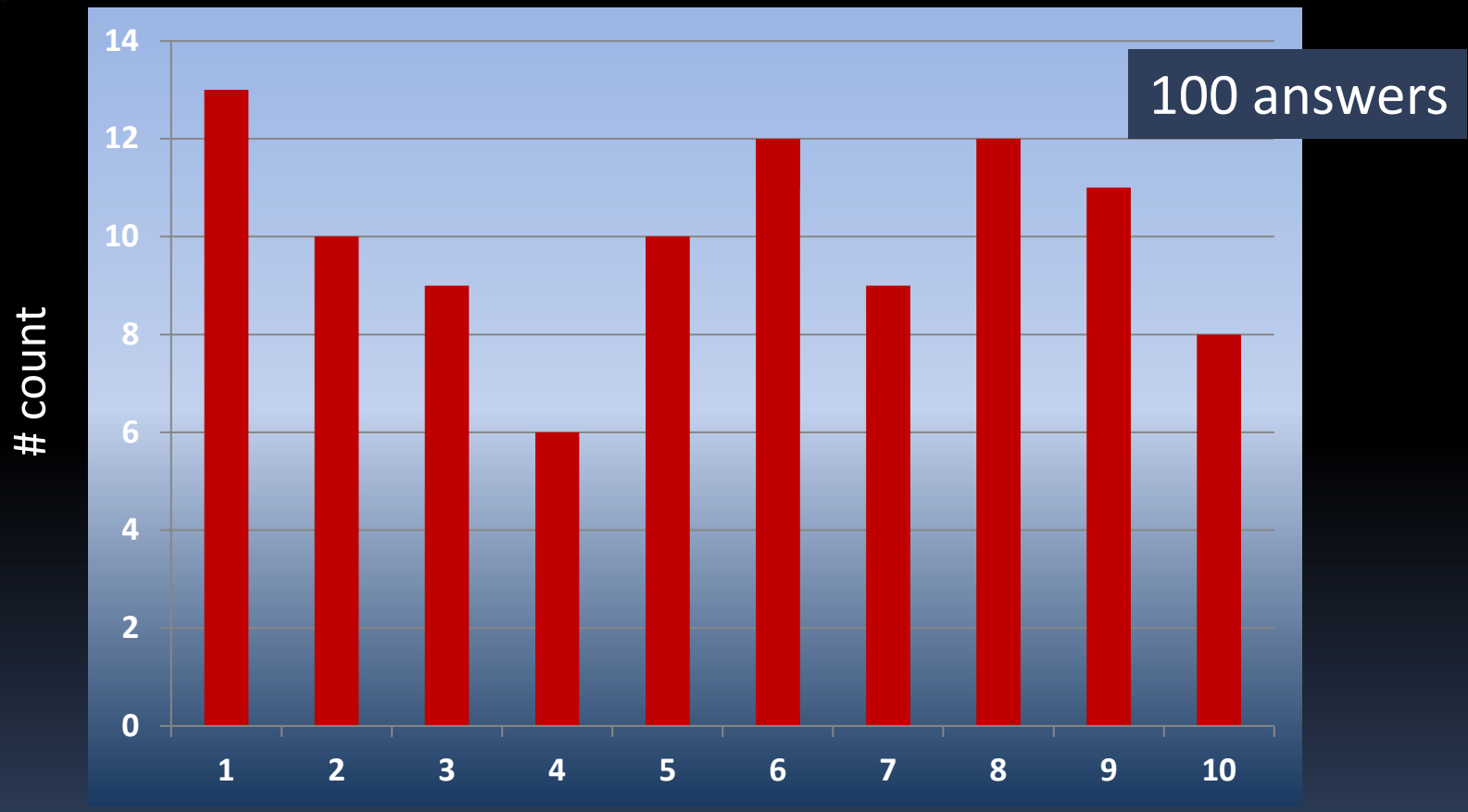


Crazy person game

- 100 people in a room, most are able to choose a random number between 1 and 10
- One of them might be crazy, in the sense the he/she always choose the same number
- The crazy person prefers to remain anonymous (and we don't want to anger a crazy person)
- We ask the whole group to choose number in anonymous way, and only do statistics on the resulting sample

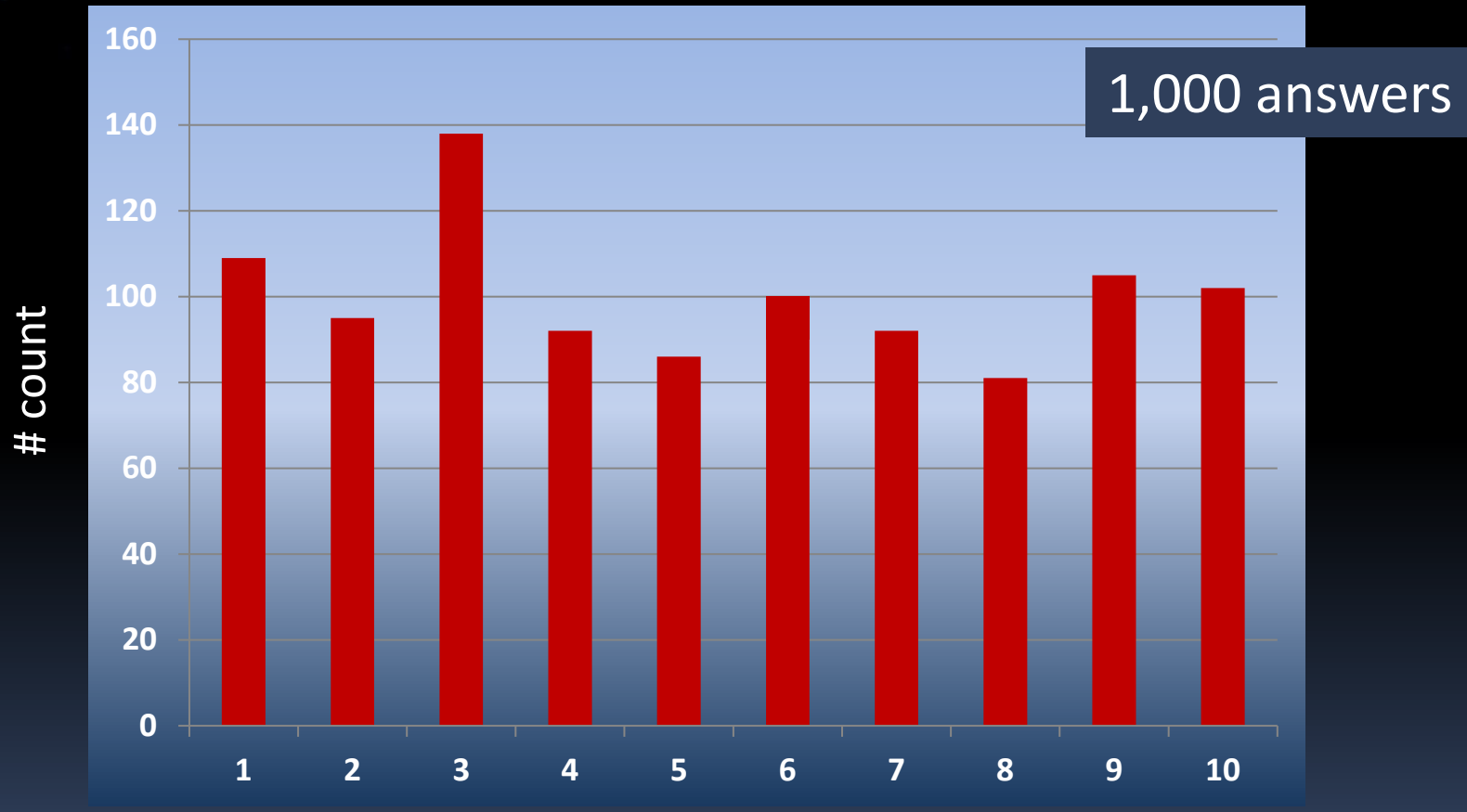
Crazy person game

First sampling (each person deposited one choice):



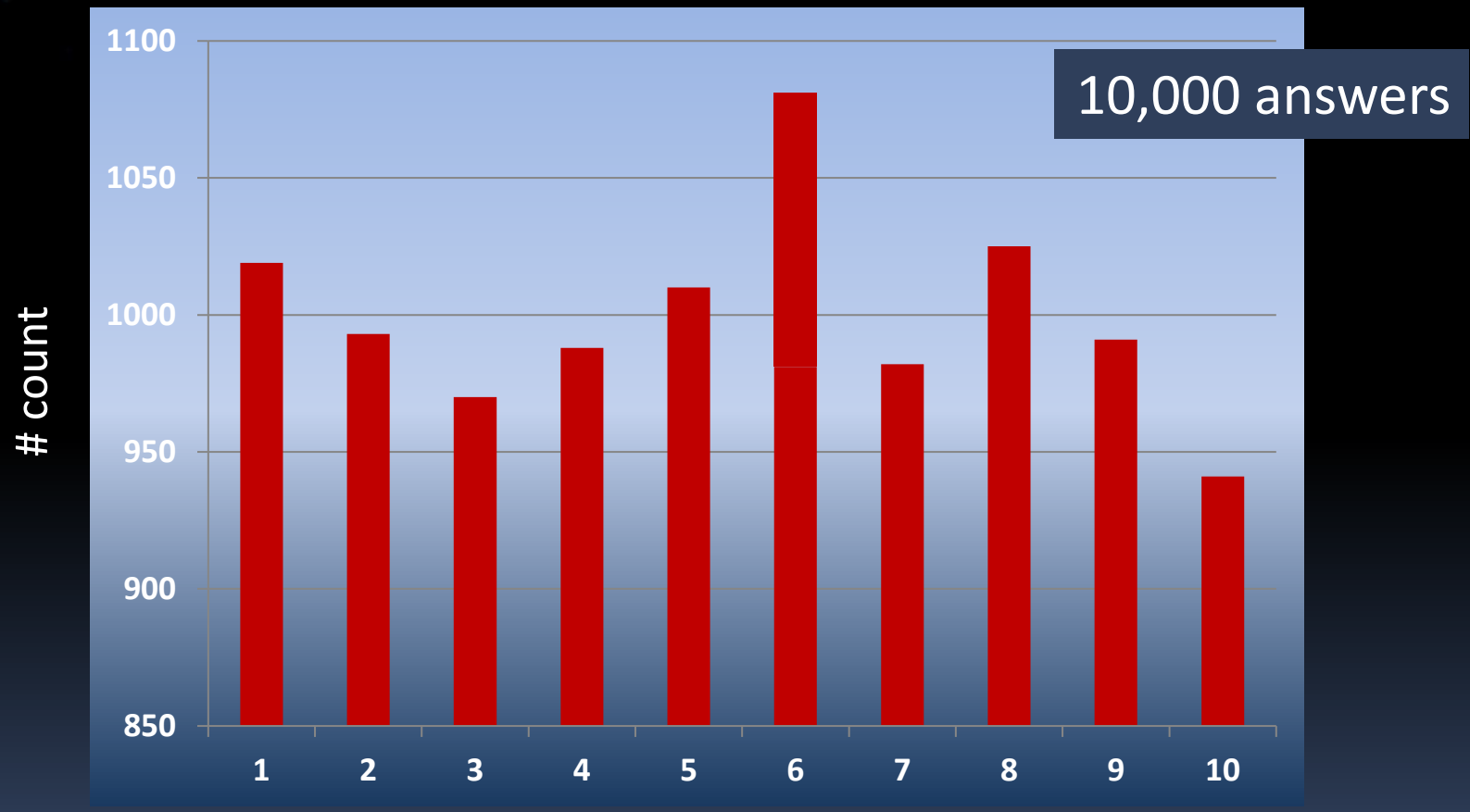
Crazy person game

10 samplings (each person deposited 10 choices):



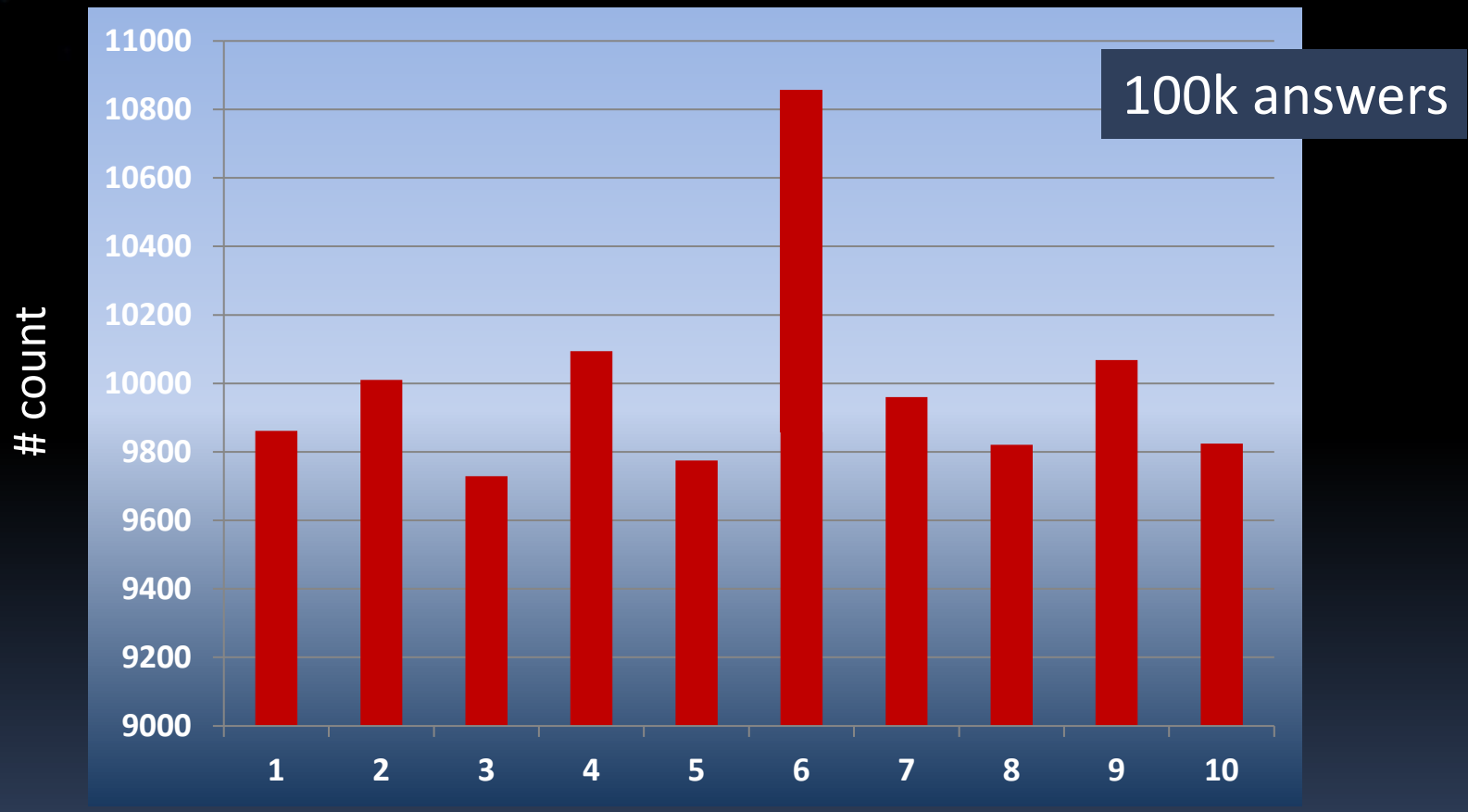
Crazy person game

100 samplings



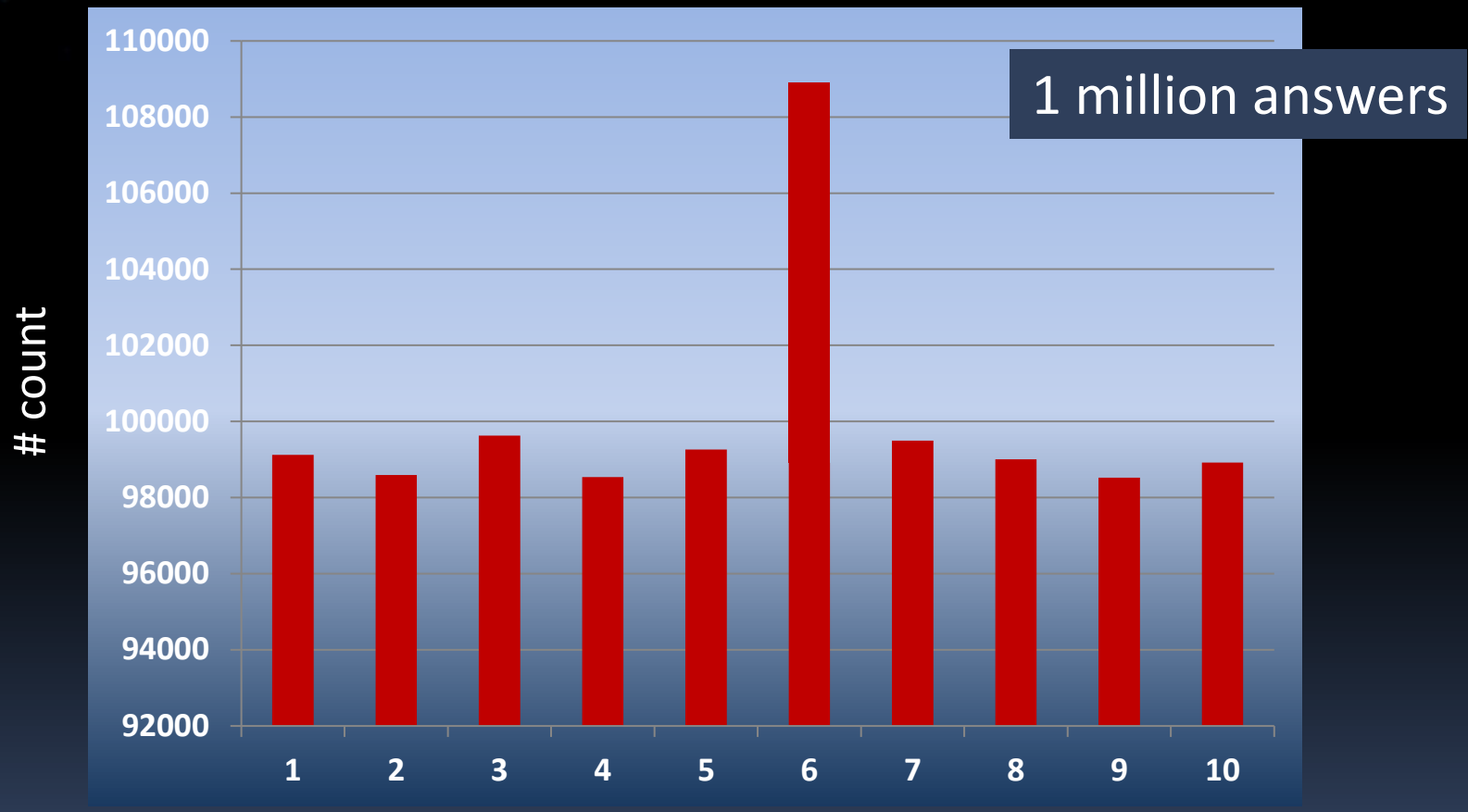
Crazy person game

1,000 samplings



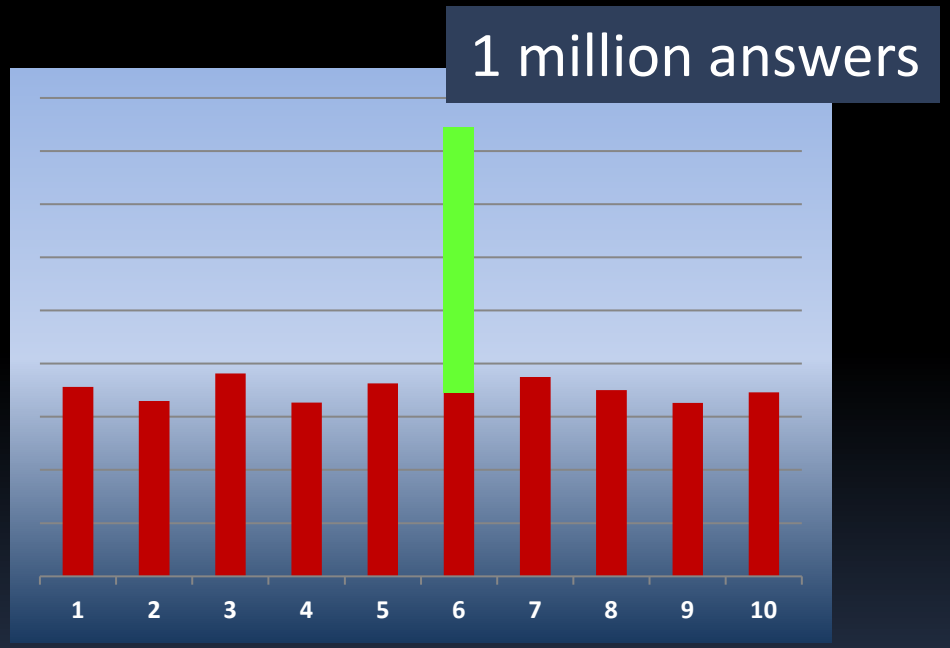
Crazy person game

10,000 samplings

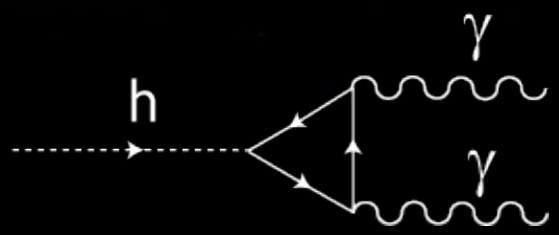


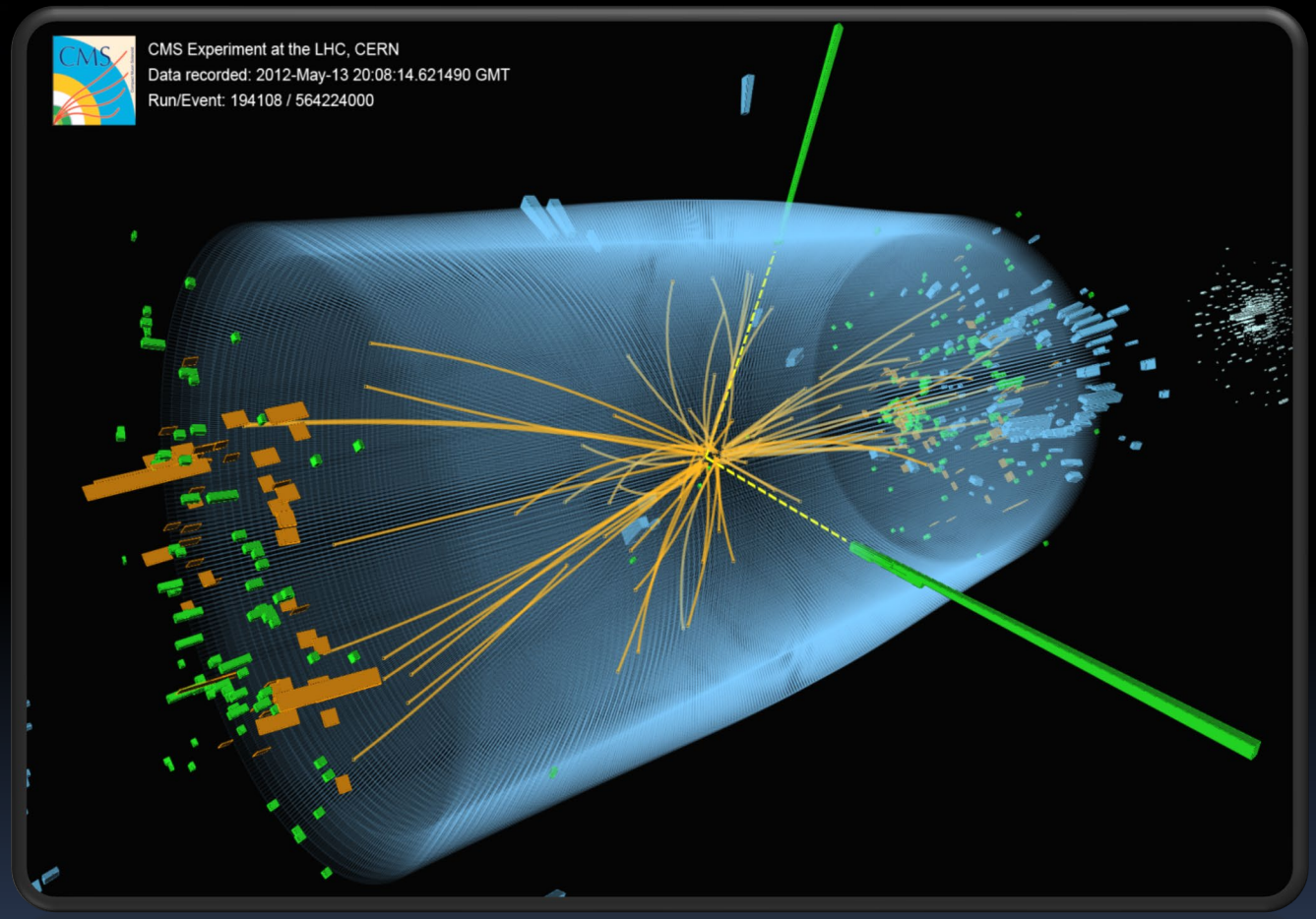
Crazy person game

A loucura fica óbvia depois de um número suficientemente grande de repetições

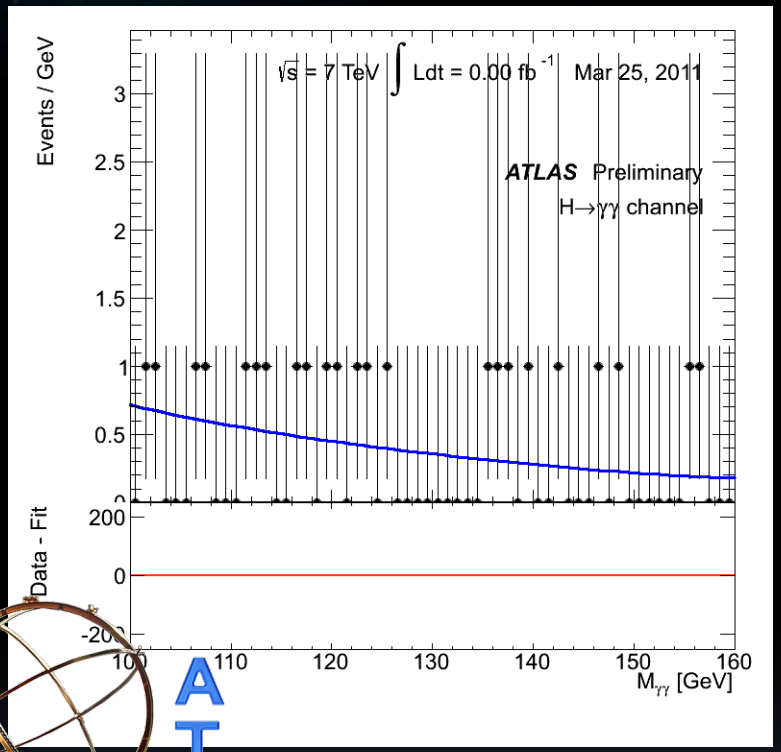


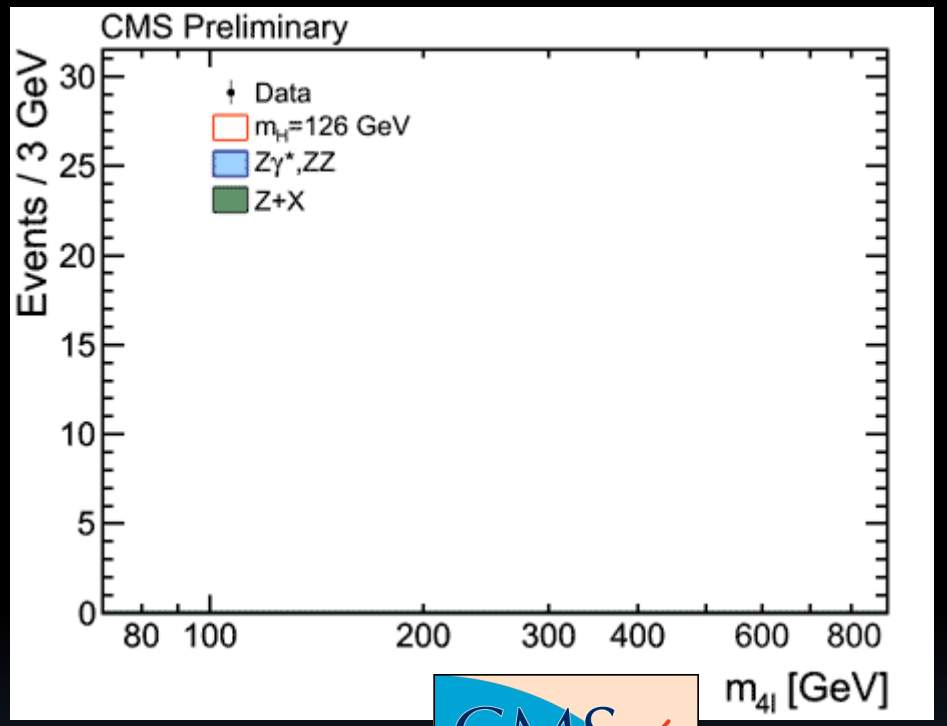
Finding the Higgs Boson





Finding the Higgs Boson



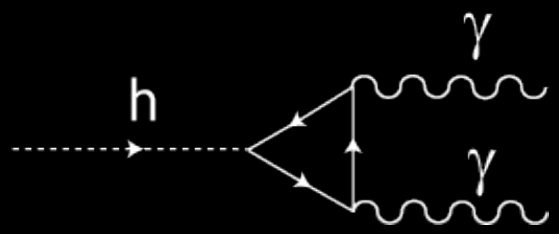


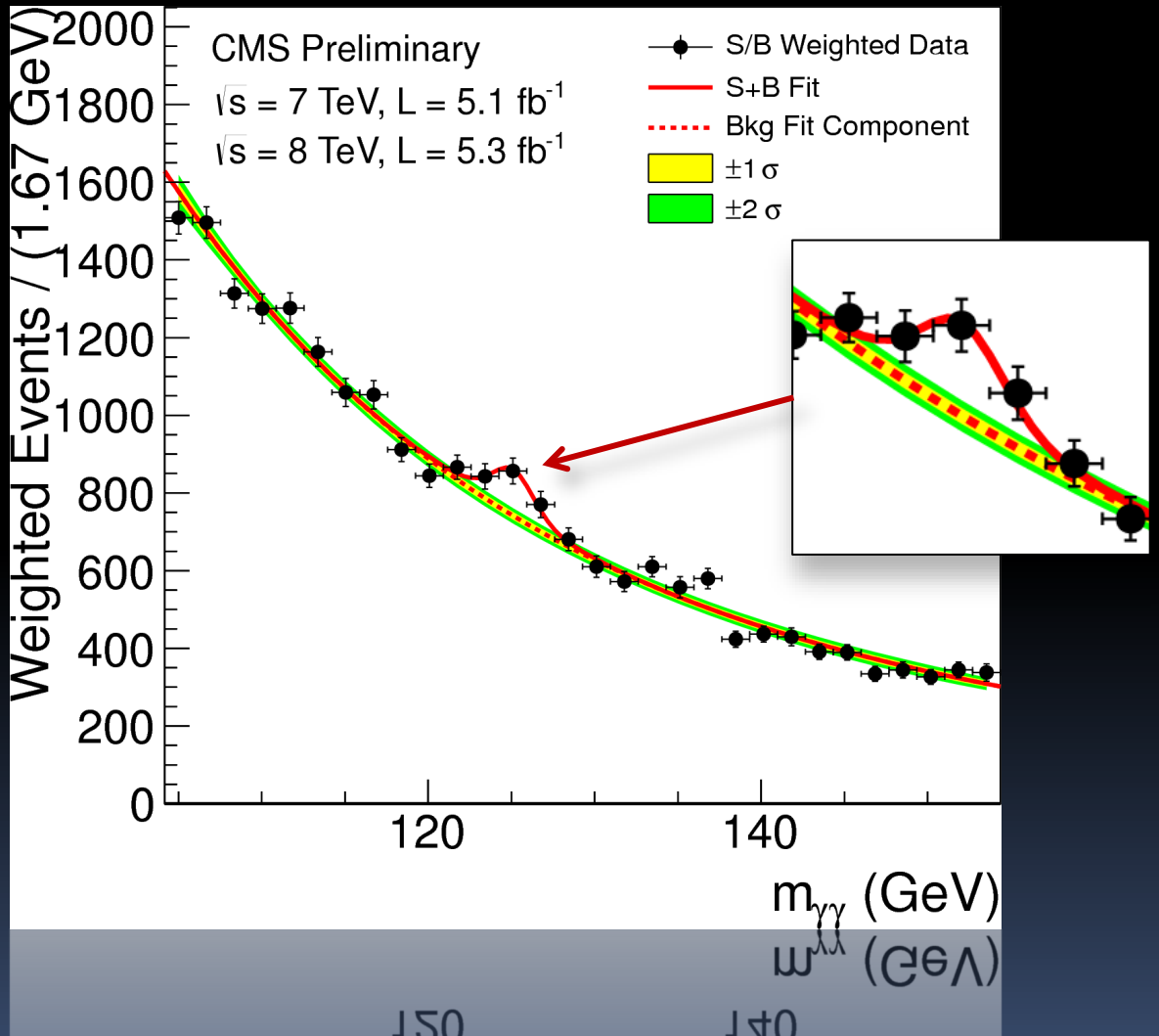
ATLAS

CMS

Finding the Higgs Boson

First signs in Dec/2011, and finally in Jul 4th/2012:





Finding the Higgs Boson

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