hi

Day 26, 04.23.2019

Particle Physics 3

4 days until our daughter’s 33rd birthday

Marcus Miller week

April 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
31	1	2 lecture	3	4 lecture	5 HW9 due	6 HW10
7	8	9 lecture	10	11 lecture	12 project day 2 HW10 due	13 HW11
14	15	16 lecture	17	18 lecture	19	20 HW12 MA & paper (look in notes for MA set)
21 HW11 due	22	23 lecture	24	25 lecture	26 Honors data upload HW12 MA due	27 2nd Midterm ...
28 2nd Midterm (incl early universe) Friday midnight through Monday midnight ...	29	30	1	2	3 FINAL EXAM 07:30 HW12 paper due	4

Week 15 last, Higgs Boson, the Big Bang is properly named, and the Flatness of the world

TUESDAY, April 23	**Higgs Boson and mass**
Required Readings:	Chapter 12 in PCC
	TOE chapter 9
	Chapter 17 in PCC
Recommended Readings:	
Additional content:	primitiveDiagrams_0 (13m), primitiveDiagrams_1 (4m), primitiveDiagram_2 (9m) in:
Tasks:	3 movies on how to make Feynman Diagrams
Homework available:	
Homework due:	
anything posted?	slides
THURSDAY, April 25	**The Big Bang, for real and the geometry of the universe**
Required Readings:	CP Section 22.1-22.4, 23.1-23.4
Recommended Readings:	
Additional content:	
Tasks:	
Homework available:	Midterm 2: **available Friday, April 26 midnight and closes Monday, April 29 midnight**
Homework due:	HW12: Friday, April 26, the MasteringAstronomy part
	MW12: Friday, May 3, the paper part
anything posted?	slides

housekeeping 1/3

I believe that all LON-CAPA inputs are now done.

Final Exam Day (May 3, 0730, here):

Poster session: I'll bring bagels and cream cheese

- *poster proponents get points for their work product*
- *viewers get points for asking good questions*

Feynman Diagram Project: read the packet!

You'll turn in a bunch of stuff:

- *HW12 paper*
- *FD project results*
- *Course review*
- *Honors Project paper*

housekeeping 2/3

8 posters, right?

1. *We are **Mark Bassett and David Weinstein**, and we will make a poster on the discovery of Helium.*
2. *We are **Jiaxuan Xiong and Yifei Zhang**, and we will make a poster on the first observation of a Black Hole in Cygnus X.*
3. *I am **Alayna Farrell** and I will make a poster on The Invention of the Cyclotron by Lawrence.*
4. *We are **Kayla Wells and Clea Derozier**, and we will make a poster on the discovery of Cosmic Rays by Hess.*
5. *We are **Monica Judd and Brendan Jenkins** and we will be making a poster on the discovery of the Neutron by Chadwick*
6. *We are **Lauren Chapman and Madison Crosser**, and we will make a poster on The Discovery of a Neutrino by Reines and Cowan.*
7. *I am **Myrna Kada**, and I will make a poster on The Discovery of the Weak Neutral Currents at CERN.*
8. *We are **Evan Smith and Charles Keranen**, and we will make a display about The Discovery of the Longest Redshift Object, GRB 090423.*

housekeeping 3/3

you know the drill:

To: RAYMOND L BROCK

From: sirs@msu.edu

Student Instruction Rating System (SIRS Online) collects student feedback on courses and instruction at MSU. Student Instructional Rating System (SIRS Online) forms will be available for your students to submit feedback during the dates indicated:

ISP 220 001: 4/15/2019 - 5/15/2019
ISP 220 002: 4/15/2019 - 5/15/2019

Direct students to https://sirsonline.msu.edu.

Students are required to complete the SIRS Online form OR indicate within that form that they decline to participate. Otherwise, final grades (for courses using SIRS Online) will be sequestered for seven days following the course grade submission deadline for this semester.

SIRS Online rating summaries are available to instructors and department chairs after 5/15/2019 at https://sirsonline.msu.edu. Instructors should provide copies of the rating summaries to graduate assistants who assisted in teaching their course(s). Rating information collected by SIRS Online is reported in summary form only and cannot be linked to individual student responses. Student anonymity is carefully protected.

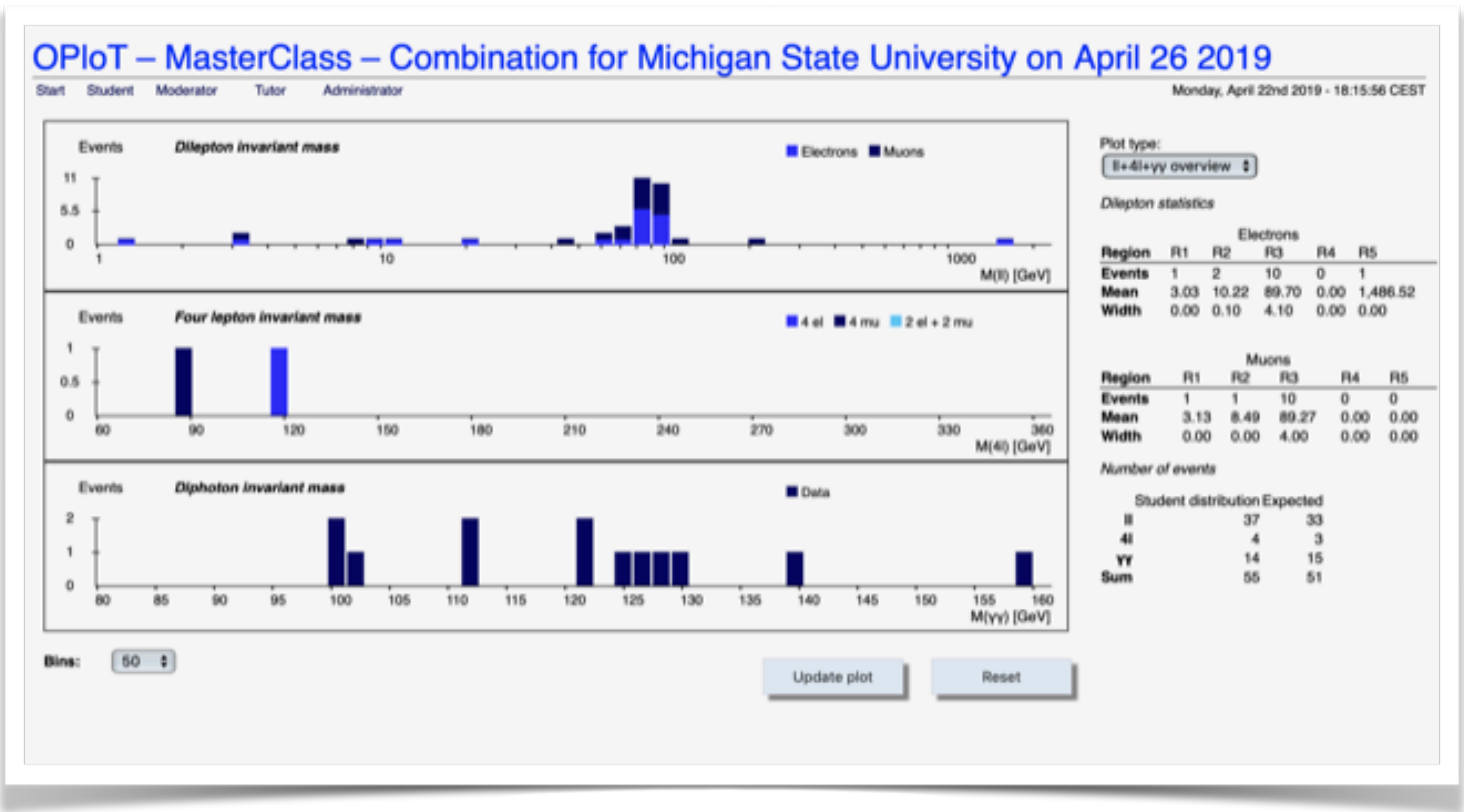
If you have any questions, please contact Michelle Carlson, (mcarlson@msu.edu, (517)432-5936).

I had a section 2

Thanks, Benjamin!

Benjamin got uploading Hypatia data to work fine.

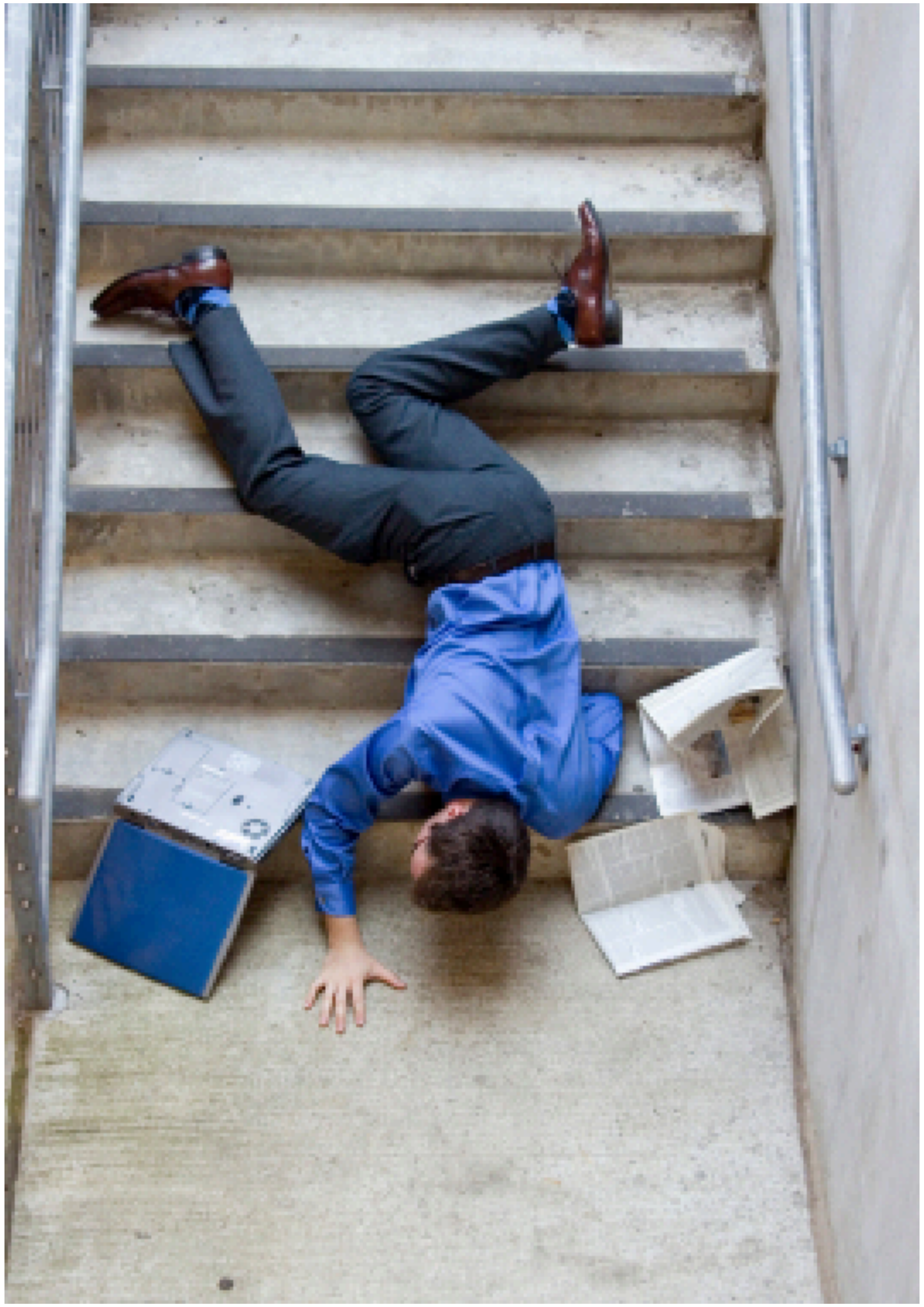
Thanks!



go there

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework_Projects/honors_project_2019/UploadInstructions/


Bilbao
MADRID
ANDORRA
CUENCA
CAMPO DE CRIPTANA
BURGOS
SANTIAGO
León
SIGÜENZA
TORO
New York
Asturias
Lerma
Barcelona
TRANSILVANIA
DRACULA'S CASTLE
Venezia
ROMA
GIBRALTAR



KEEP
CALM
AND
LET'S
REVIEW

the weak interactions

still operate with the increased doublet sets

The complete (circa 2000) particle doublets:

Q			
+2/3 -1/3	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

the modern picture

of the elementary particle patterns

circa 2000

and still current

the lepton families...lepton "doublets"

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

and their interactions: ✗ no, ✓ yes.

leptons	ν_e	e	ν_μ	μ	ν_τ	τ
strong g	✗	✗	✗	✗	✗	✗
electromagnetic γ	✗	✓	✗	✓	✗	✓
weak W	✓	✓	✓	✓	✓	✓
gravitational	✓	✓	✓	✓	✓	✓

the modern picture

of the elementary particle patterns

circa 2000

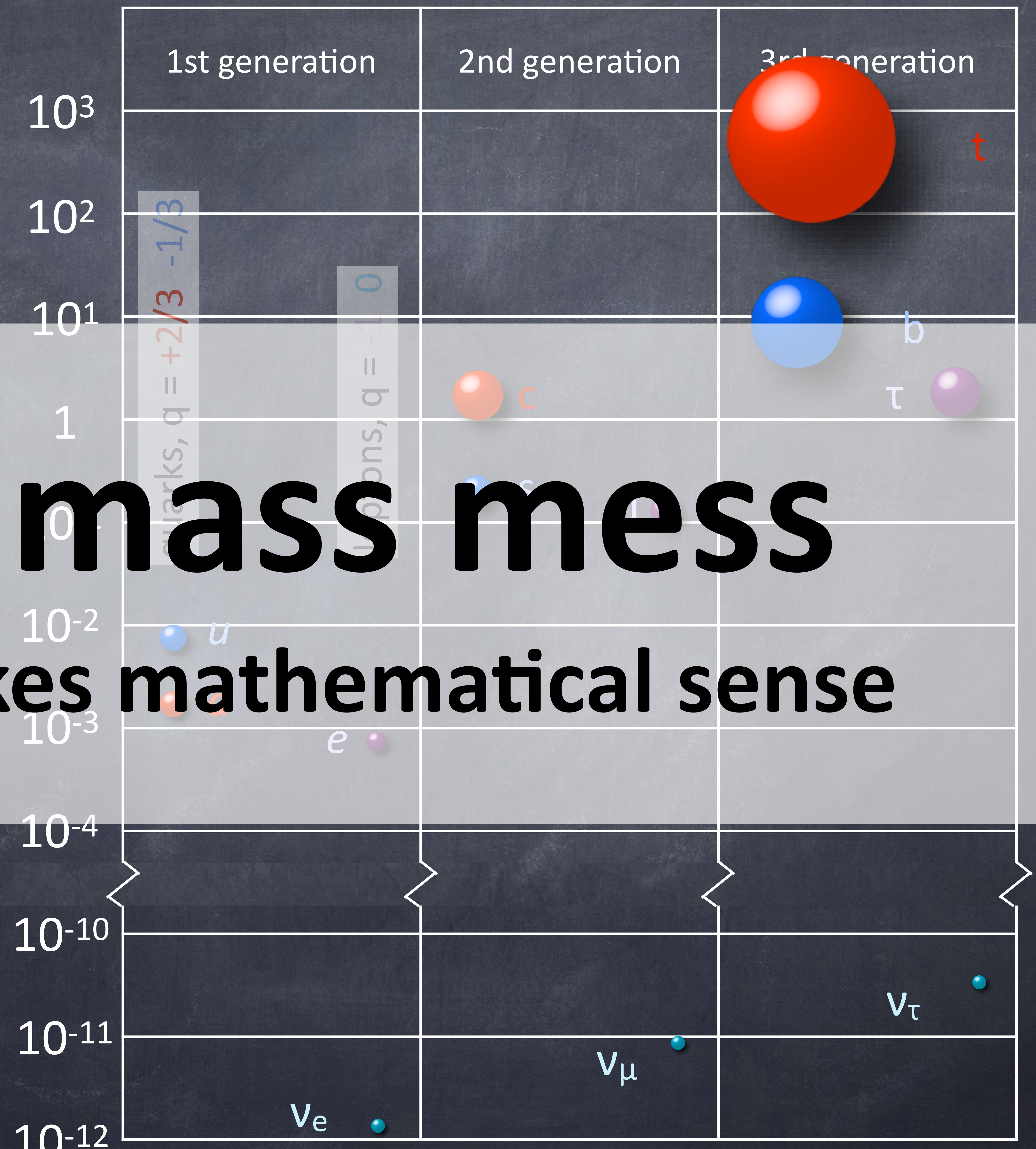
the quark families...quark "doublets"

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

and their interactions: ✘ no, ✔ yes.

quarks	u	d	c	s	t	b
strong g	✔	✔	✔	✔	✔	✔
electromagnetic γ	✔	✔	✔	✔	✔	✔
weak W	✔	✔	✔	✔	✔	✔
gravitational	✔	✔	✔	✔	✔	✔

quarks & leptons



this mass mess

$m = 0$ makes mathematical sense

shifting gears

the weak and electromagnetic forces are one.

why

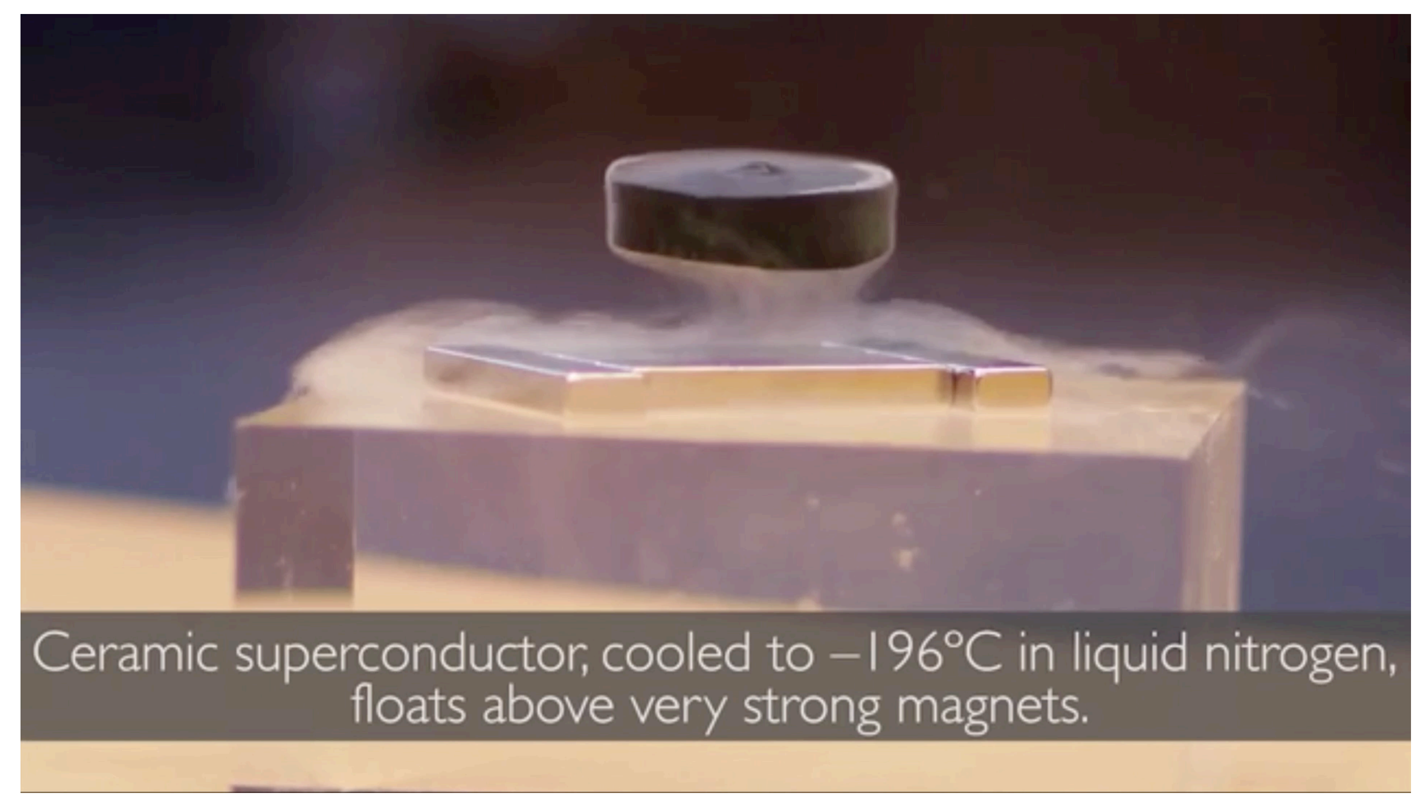
is he talking about phase transitions you're asking yourself?

Superconductivity

room temperature, insulator

below 1.9 K - superconducting

LHC magnets, NSCL cyclotron



Superfluidity

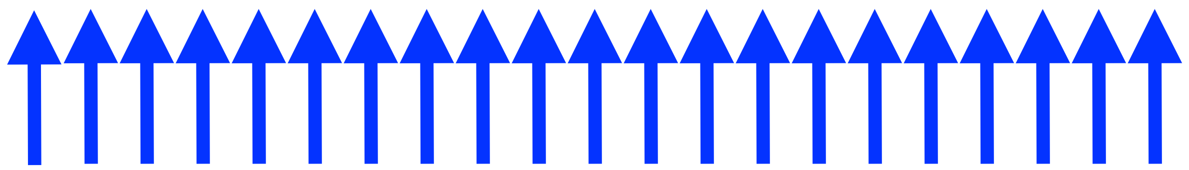
4.2 K - liquifies

2.17 K - superfluid

a little model of an *ideal* ferromagnet

in one - dimension

At a low temperature – like room temperature:



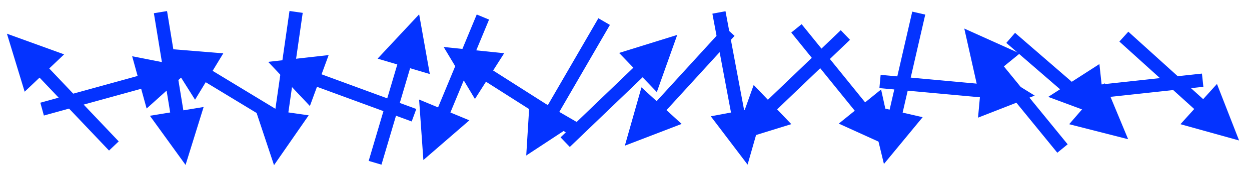
M is maximum

M, "magnetization": a measure of how magnetized

"ground state" – state of lowest energy –

when all electron-spin magnets are aligned

At 1043 K – the "Curie Point":



the "ground state" – state of lowest energy –

when all electronic magnets are random

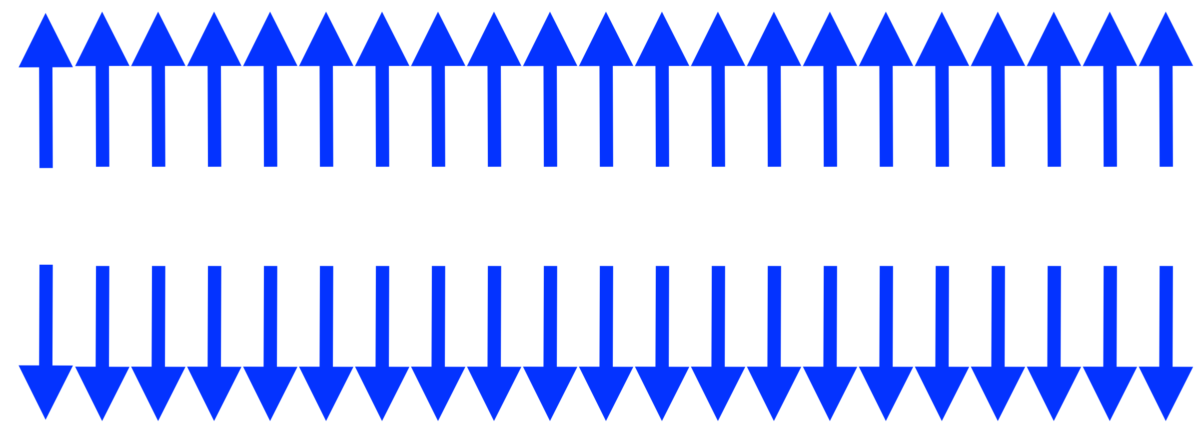
M becomes zero

an important difference

between these two situations

H  M = 0

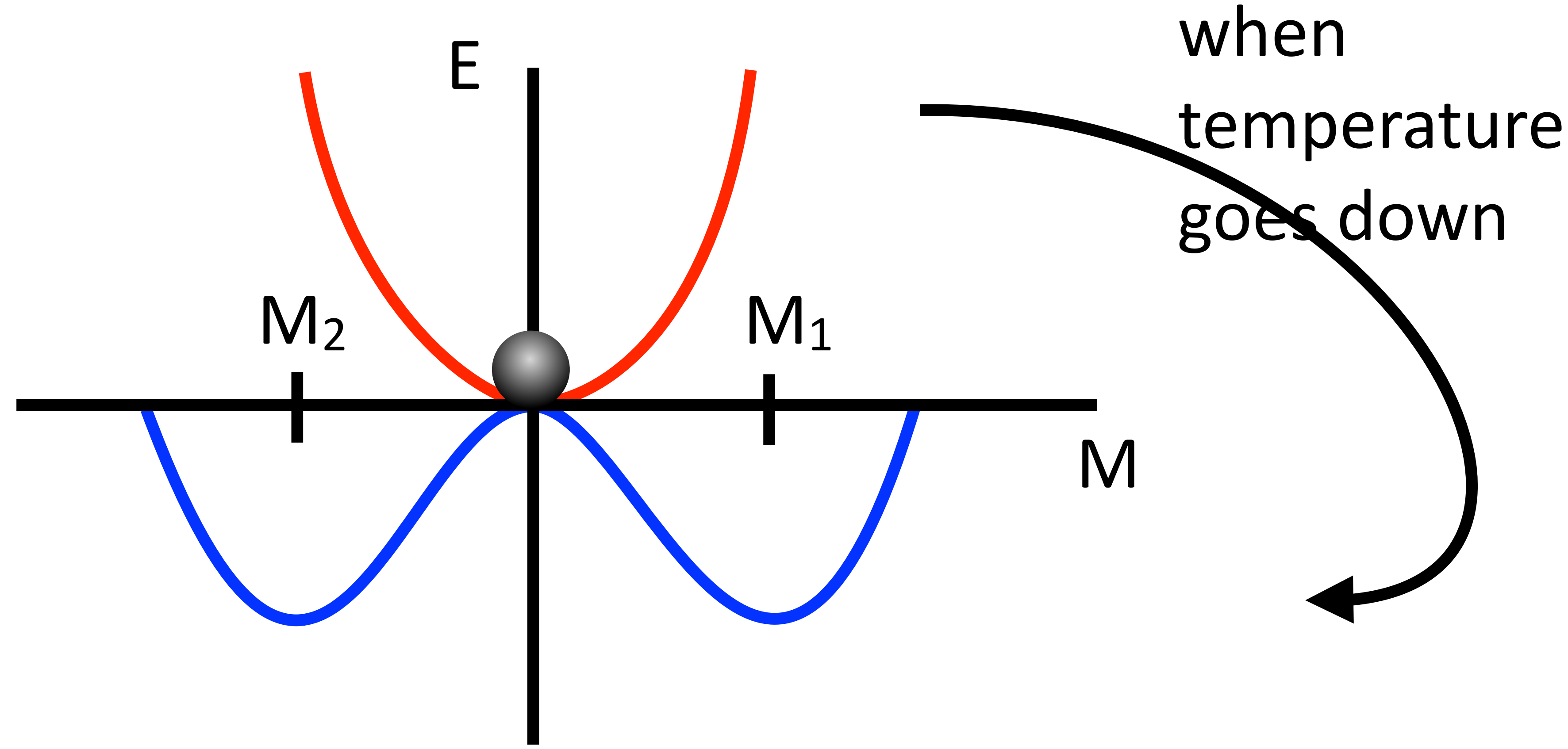
temperature cools...magnet goes to one of two states:

C 

$M_1 \neq 0$

$M_2 \neq 0$

we say that the symmetry is “broken”: it’s reduced



the energy level of the **hot ground state** is higher than the energy level of the **cold ground state**

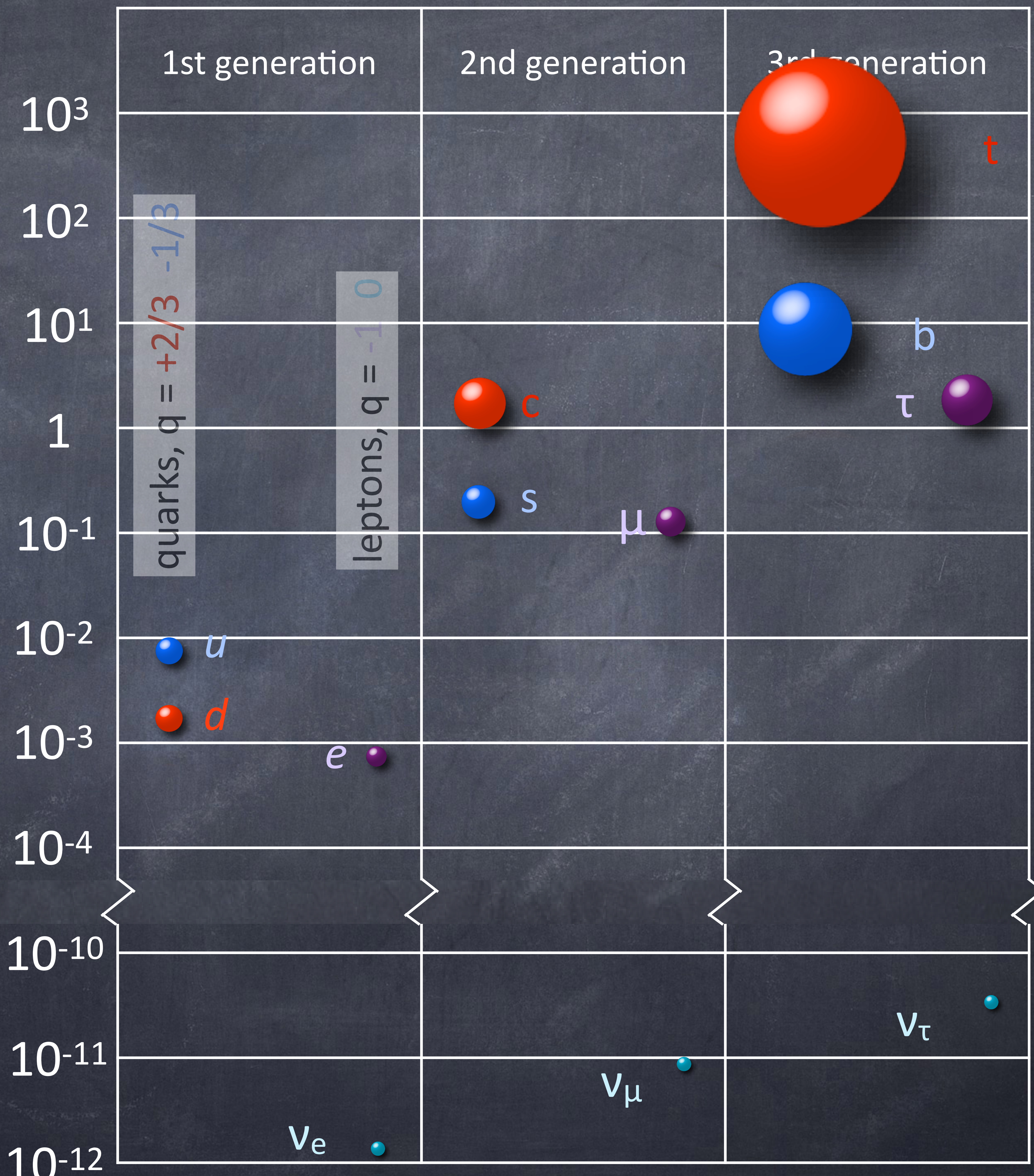
when the iron is hot, there is no “concept” of magnetization

this often-told magnet story

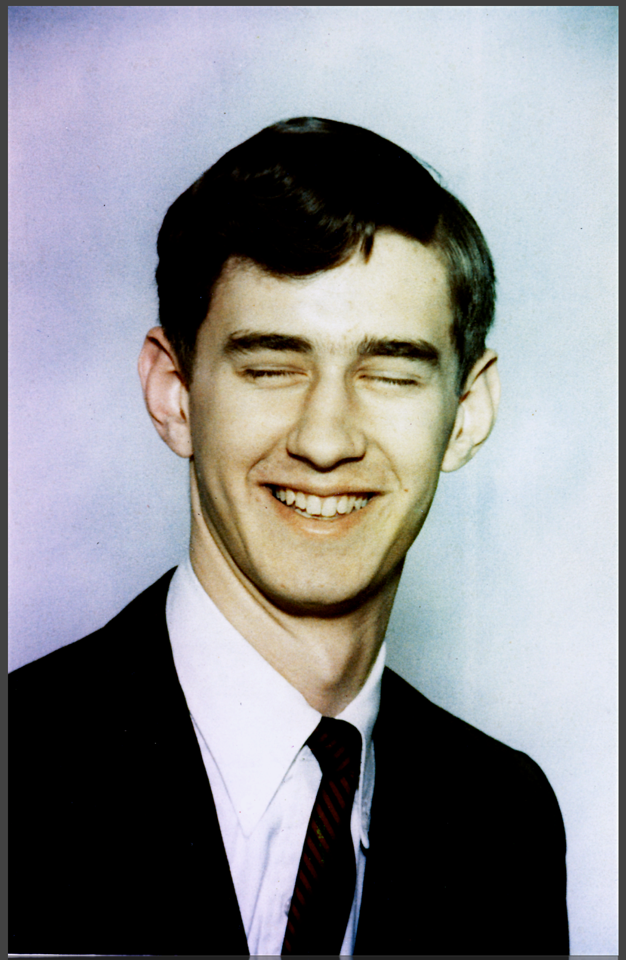
evolves into the new story of MASS

quarks & leptons

proton masses



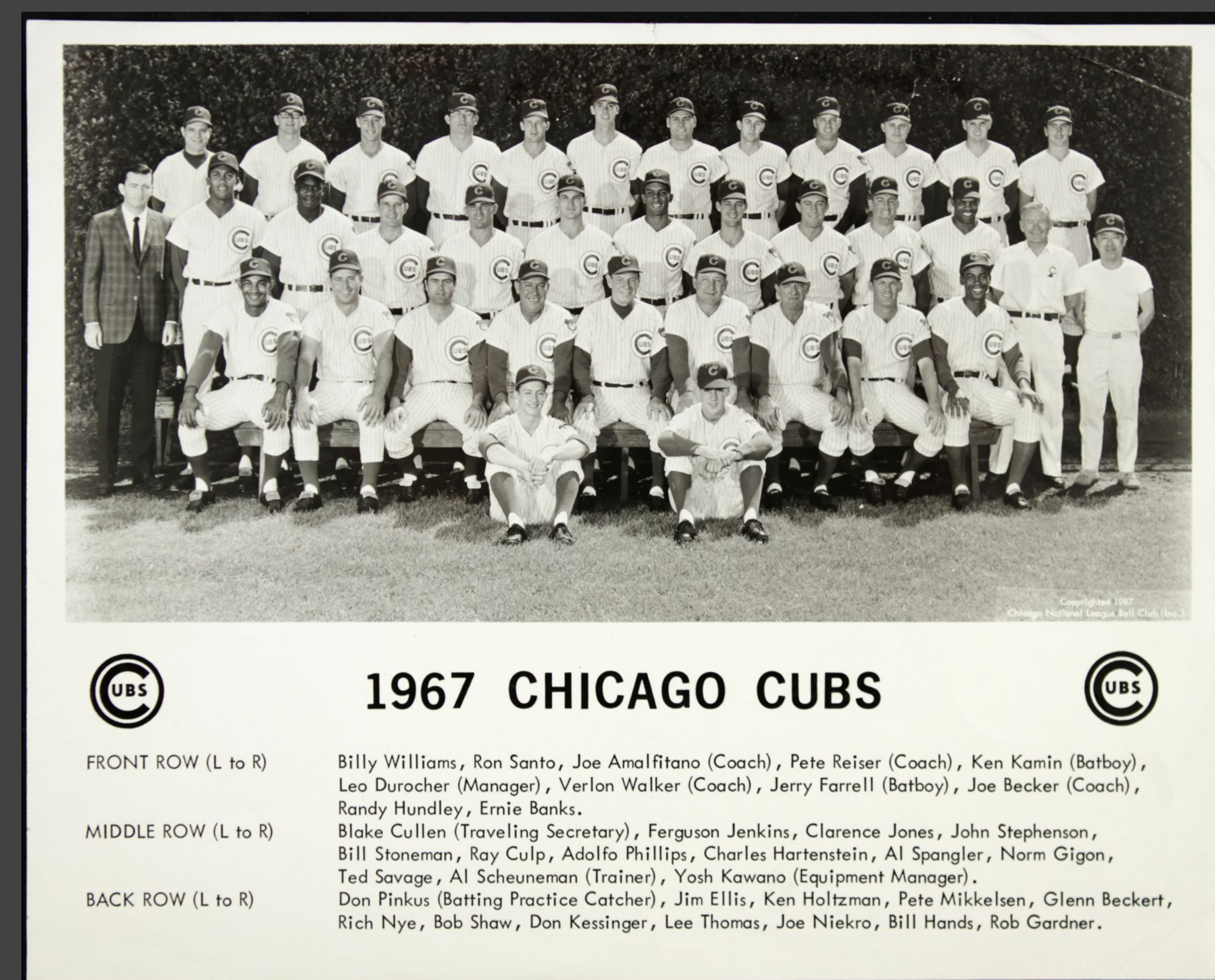
1967



1967

http://www.mustangdreams.com/mdfastback.htm

1967



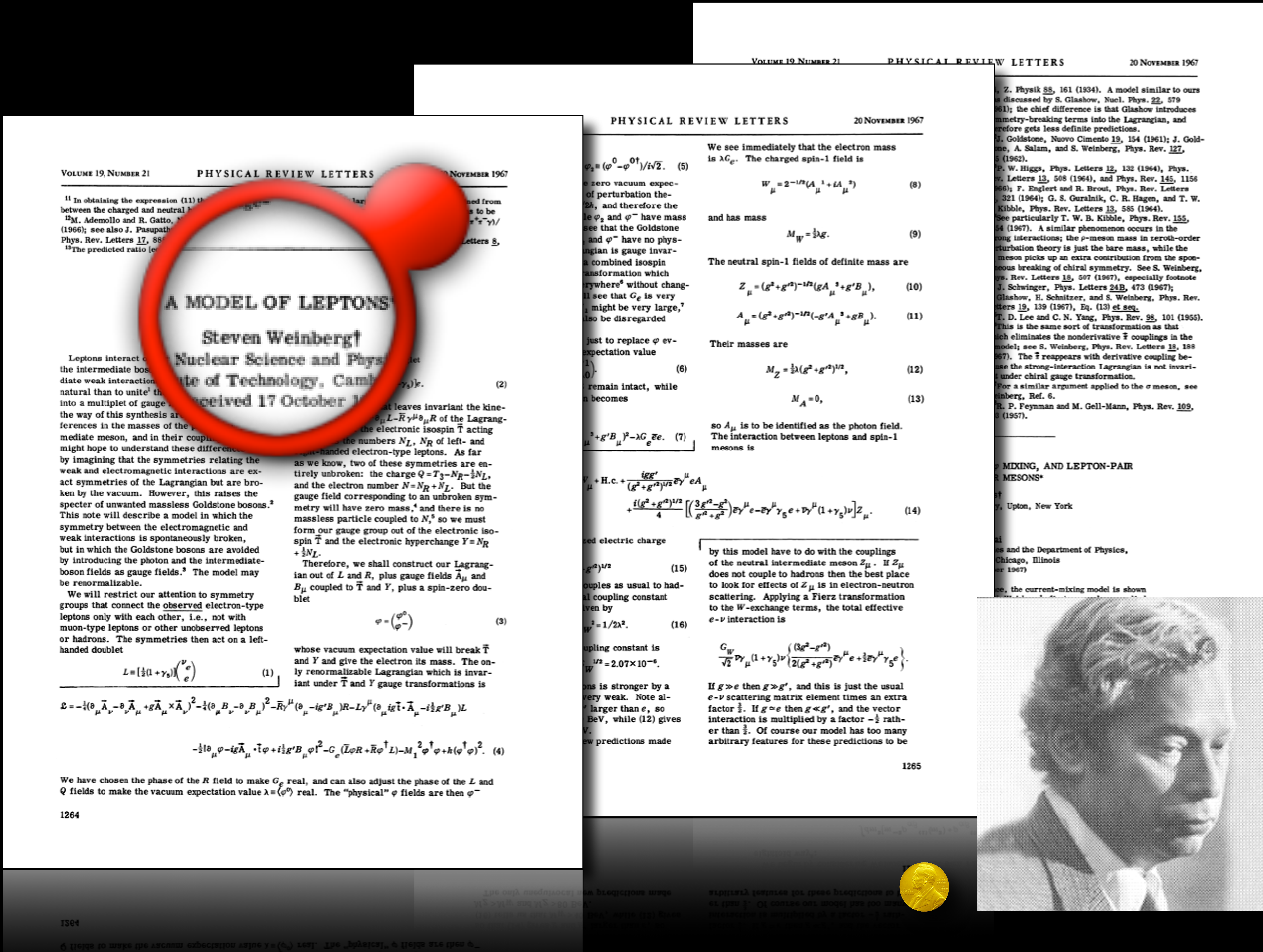
http://www.mustangdreams.com/mdfastback.htm

1967

http://www.mustangdreams.com/mdfastback.htm

http://nobelprize.org/nobel_prizes/physics/laureates/1979/weinberg-autobio.html

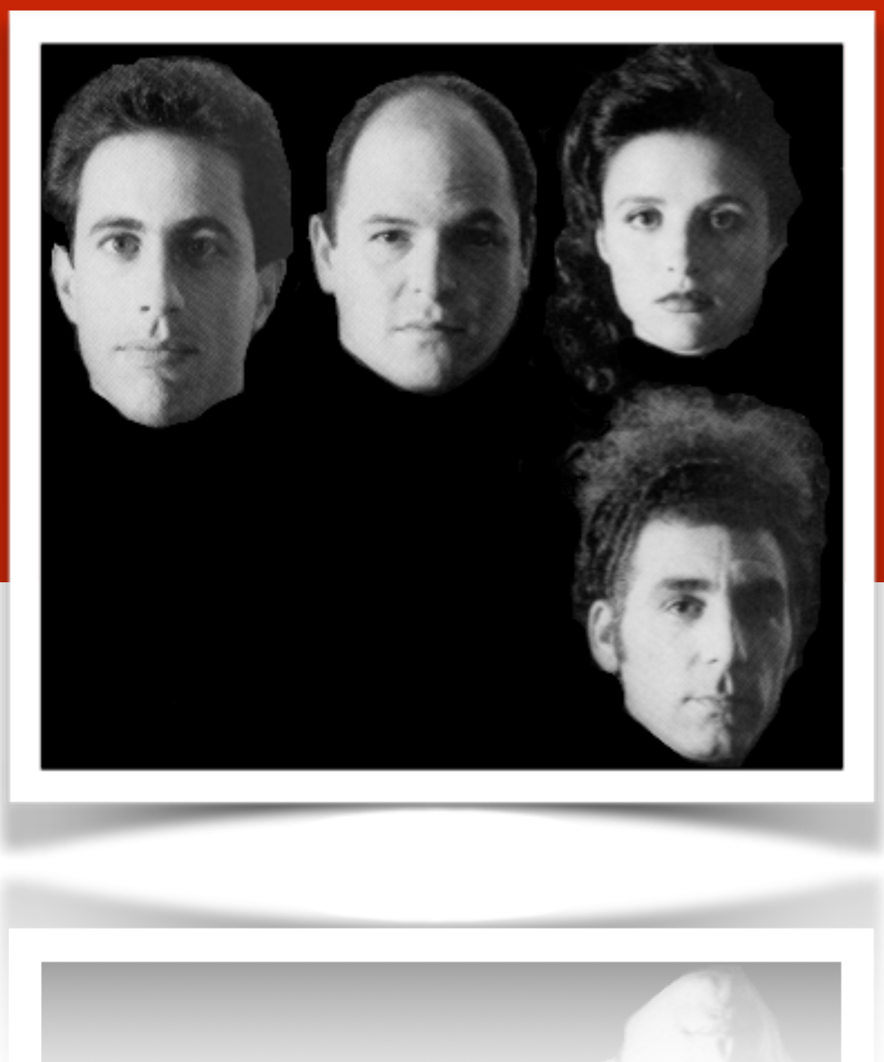
http://hacks.mit.edu/Hacks/by_year/2006

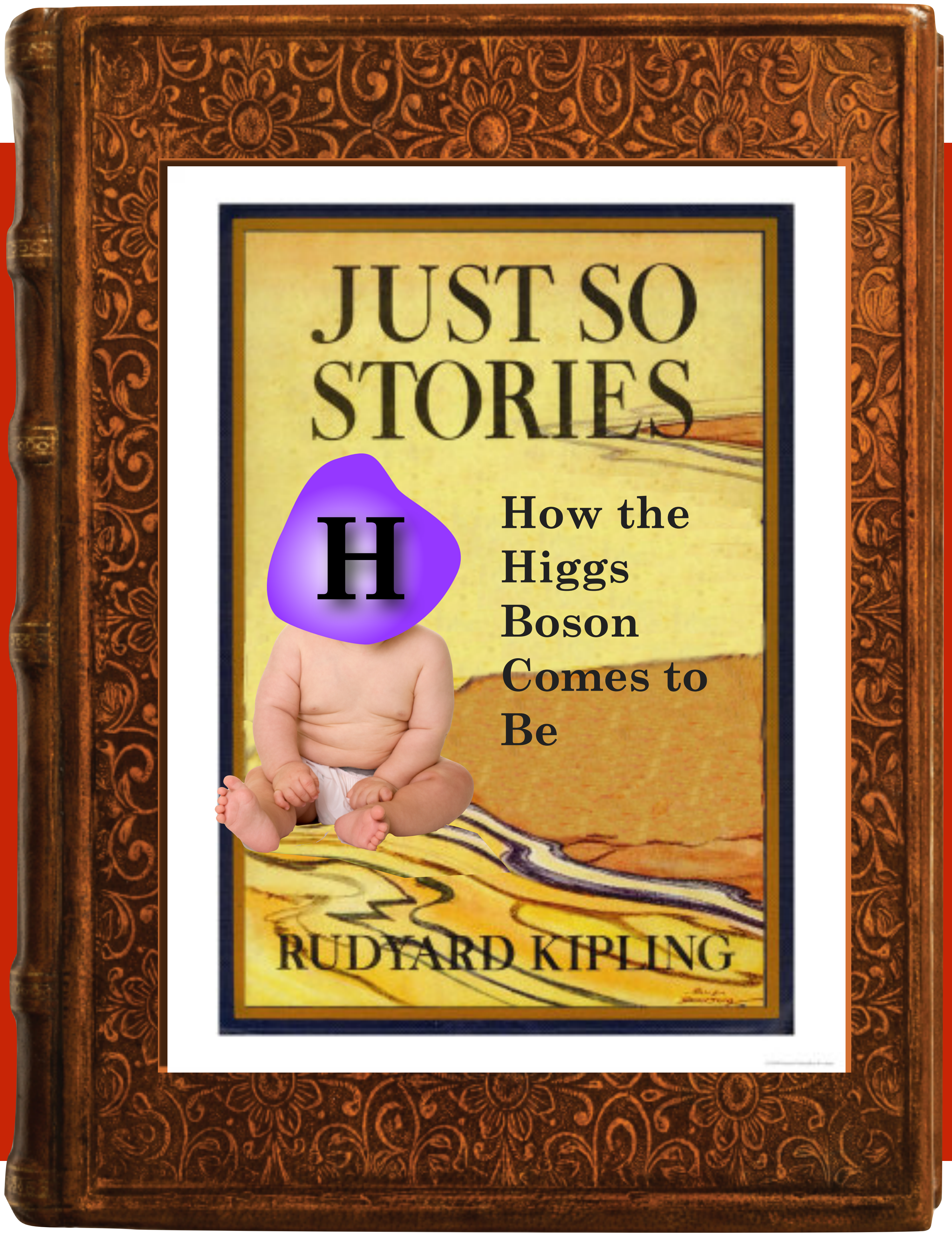

VOLUME 19, NUMBER 21
PHYSICAL REVIEW LETTERS
20 NOVEMBER 1967
A MODEL OF LEPTONS
Steven Weinberg†
1264
1265

of particle physics

the story of the Higgs Boson

a story about nothing.





This quickly became a story

of a particular epoch in the early Universe

which itself underwent a phase transition

Not in your average hunk of iron

the “system”?

that’s right. the whole enchilada

the entire Universe

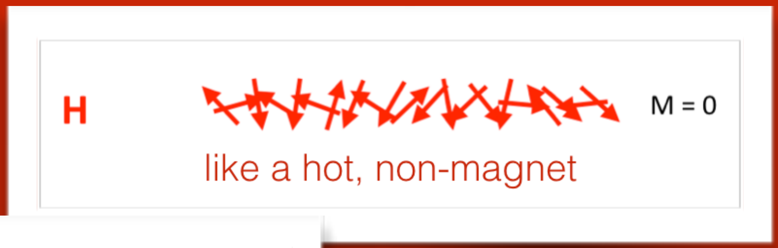
the phase transition?

everywhere in the Universe

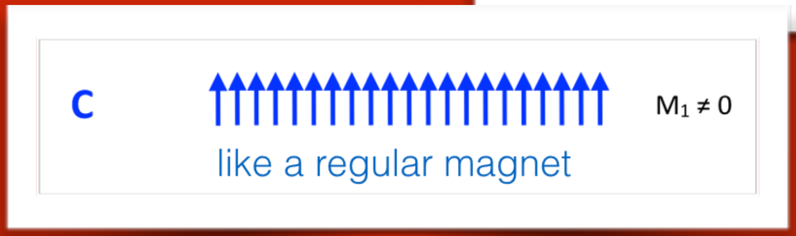
a phase change in all of space

at temperature at about 1 picosecond after the big bang

there were PRIMORDIAL fields and particles before (**hot**)



and different fields and particles after (**cold**)

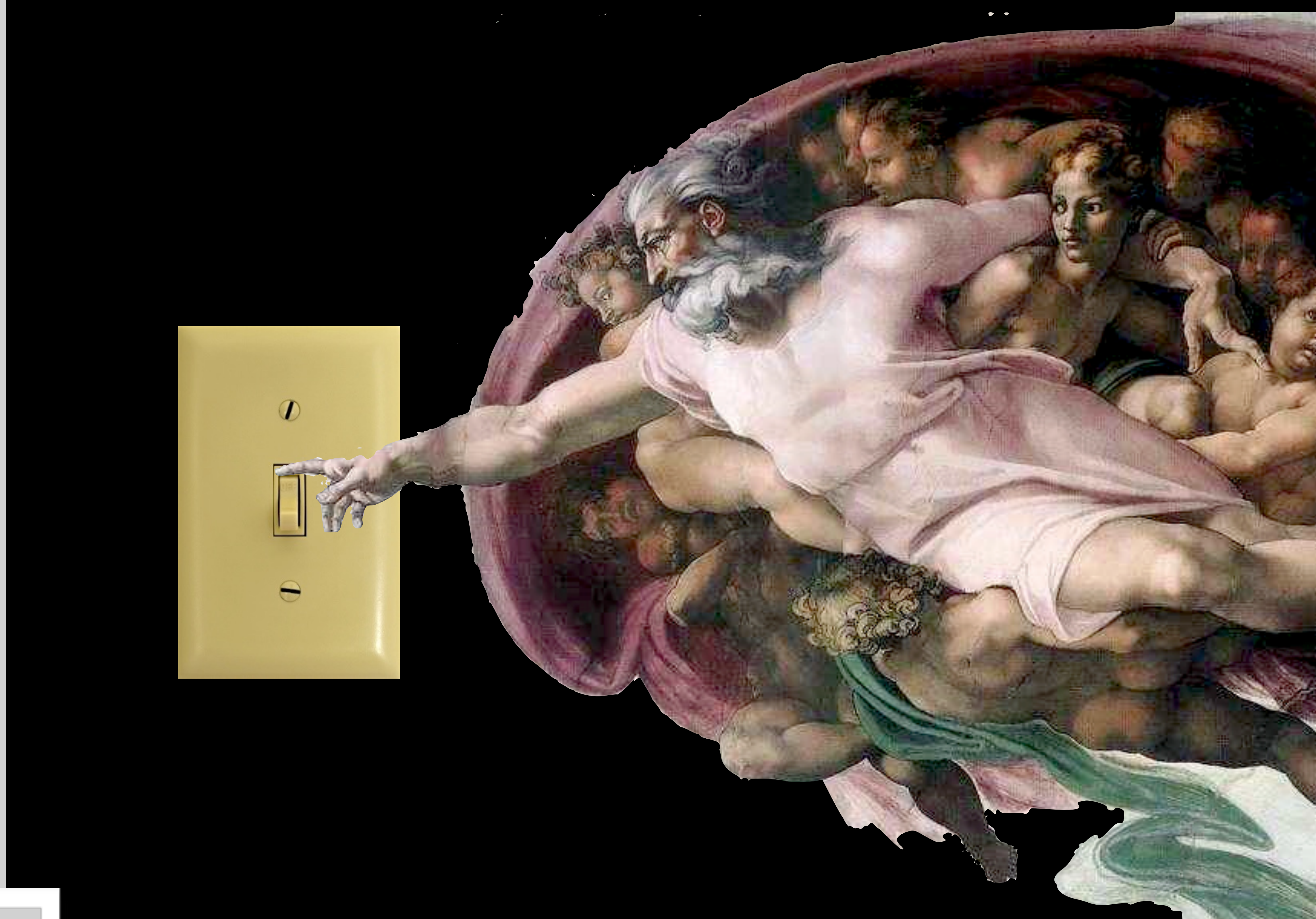


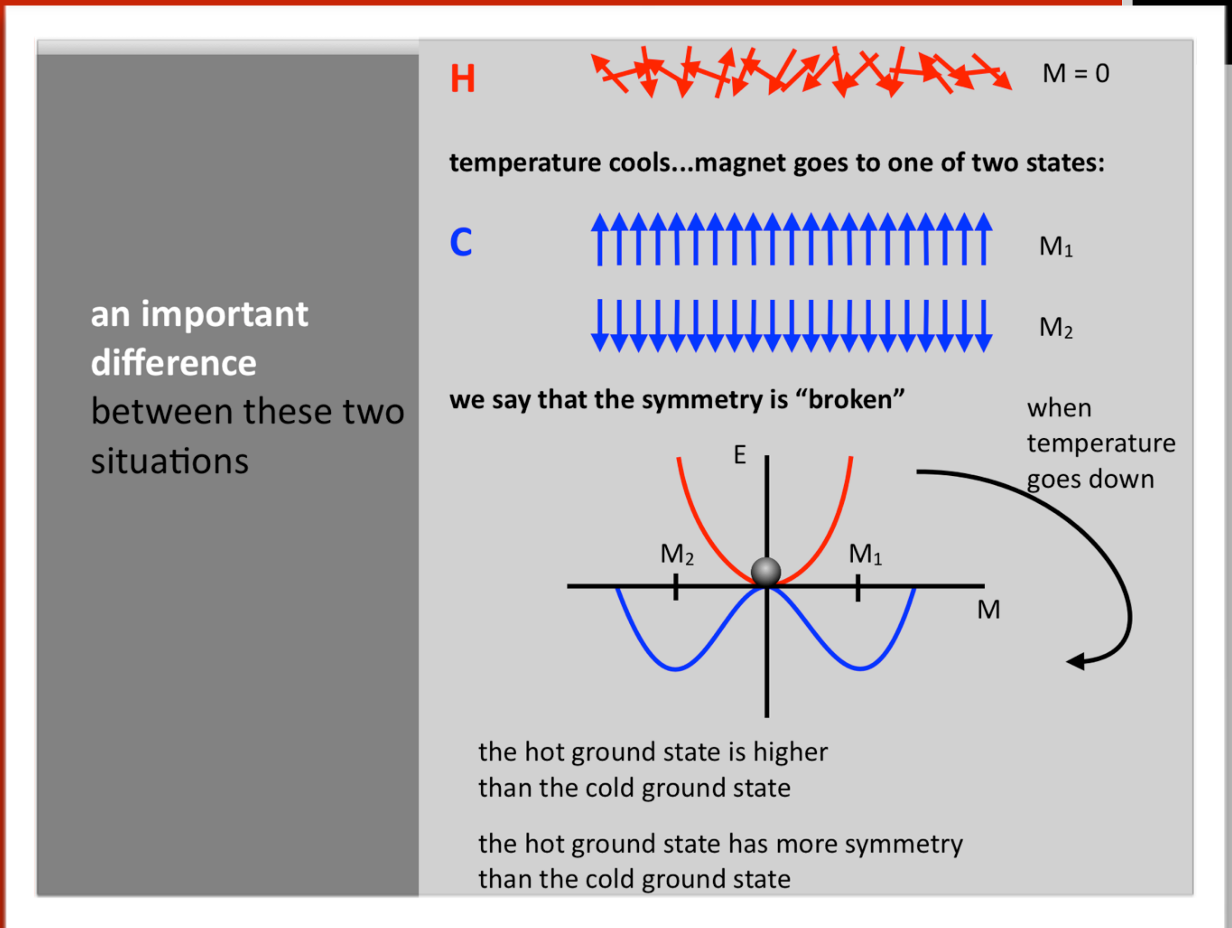
we live in the resulting "cold" universe

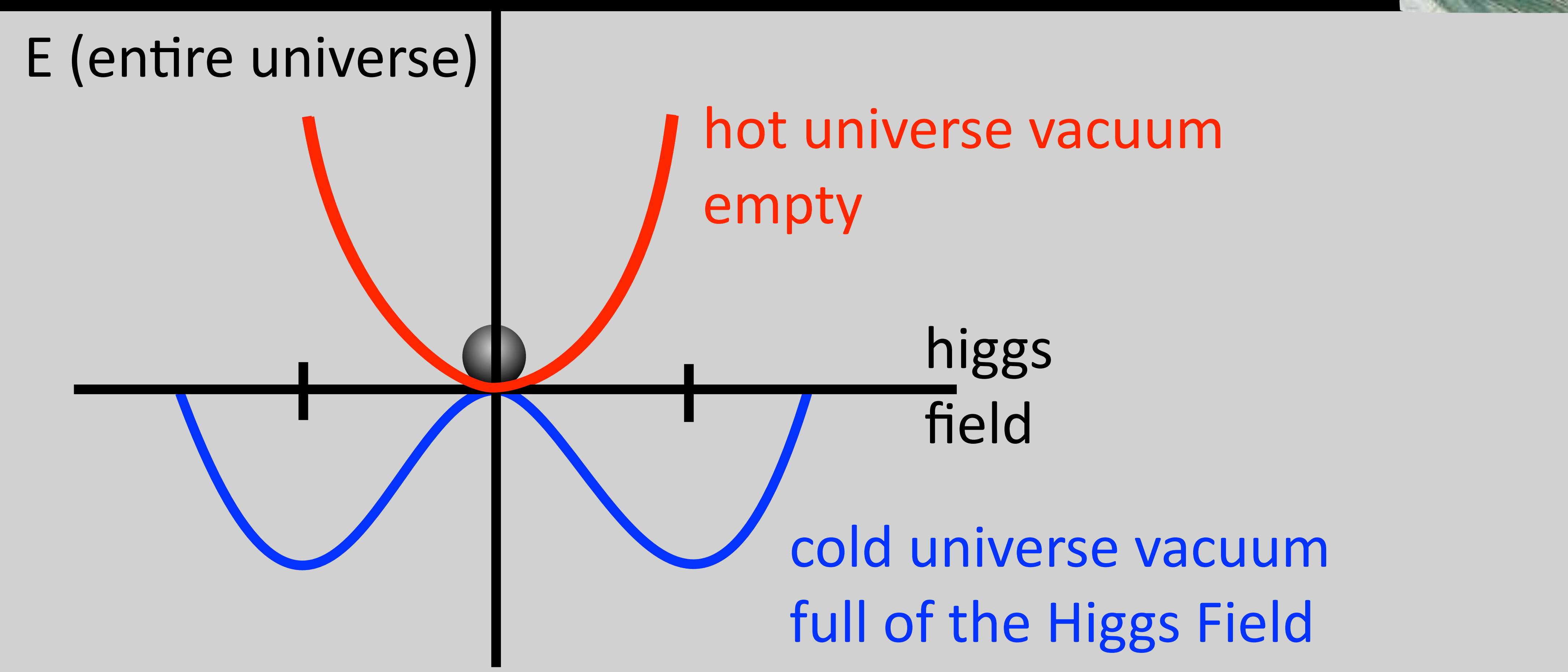
from a hot phase in the universe

cool it all at once

@ 10^{-12} seconds after the BB

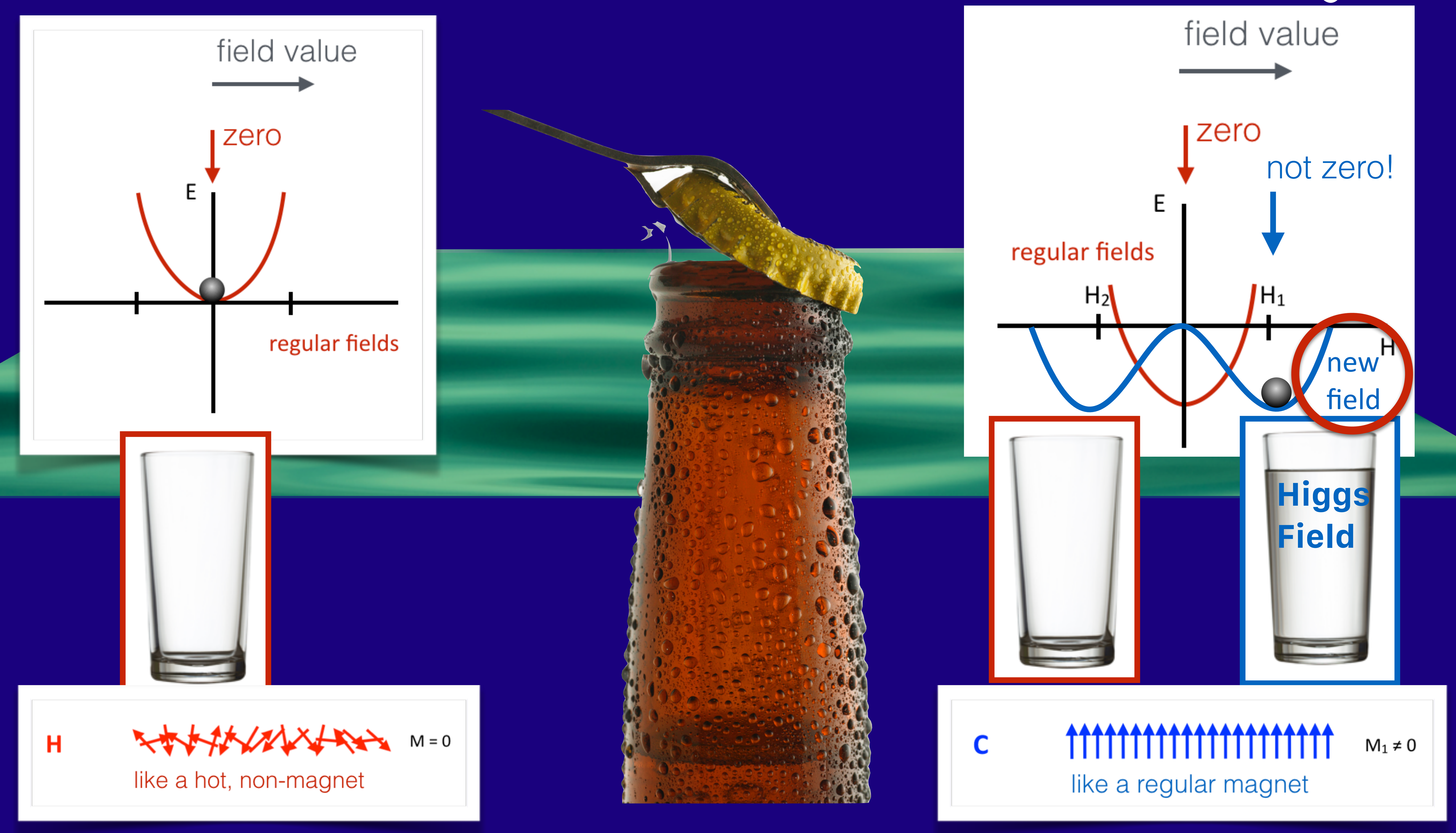




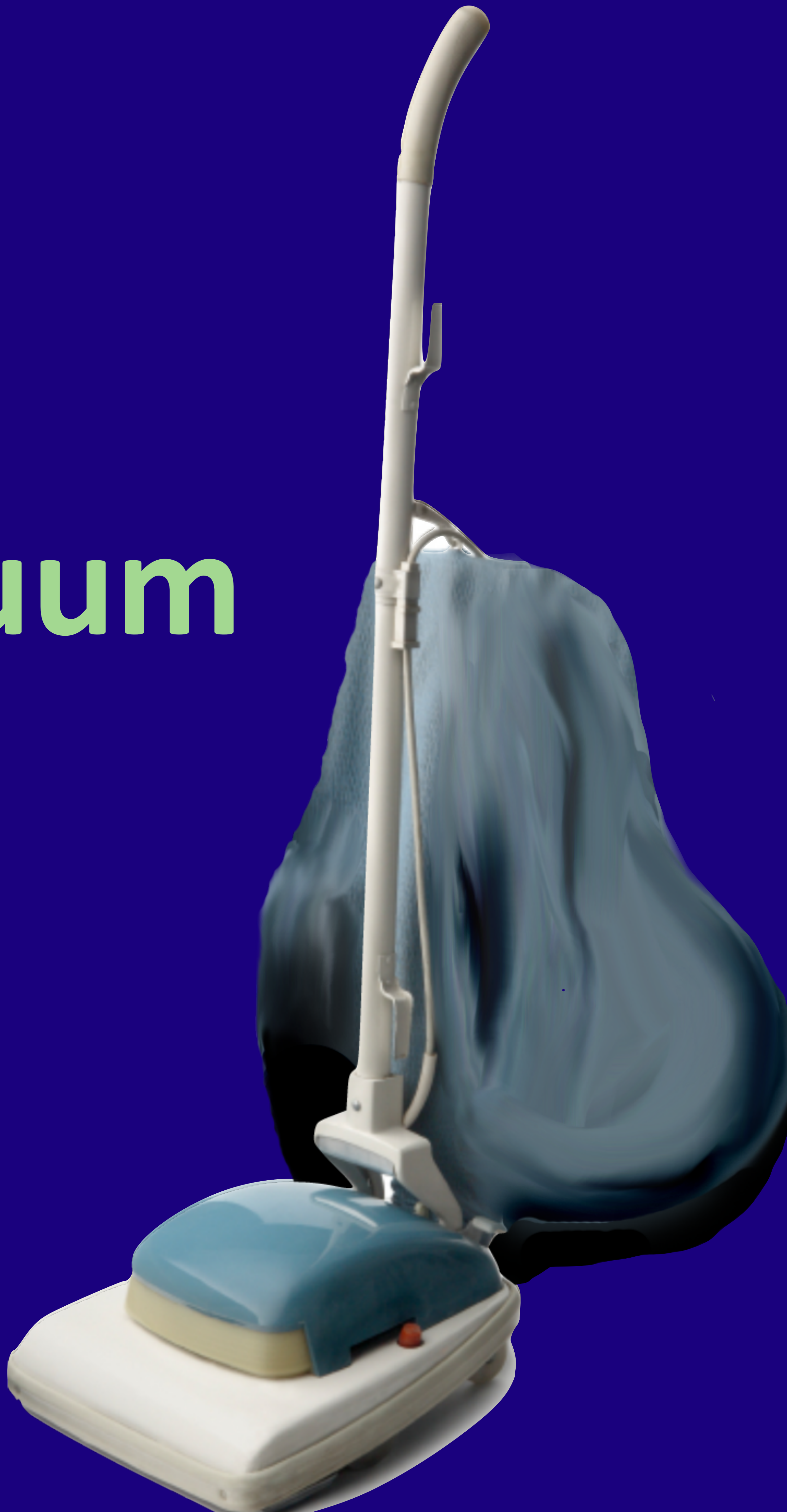


10^{-12}s after the big bang

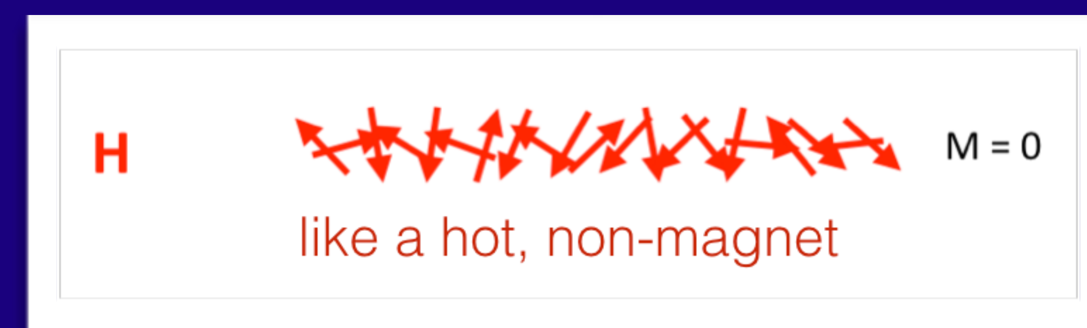
universe condensed: a phase change



vacuum



had only zero-average-value fields

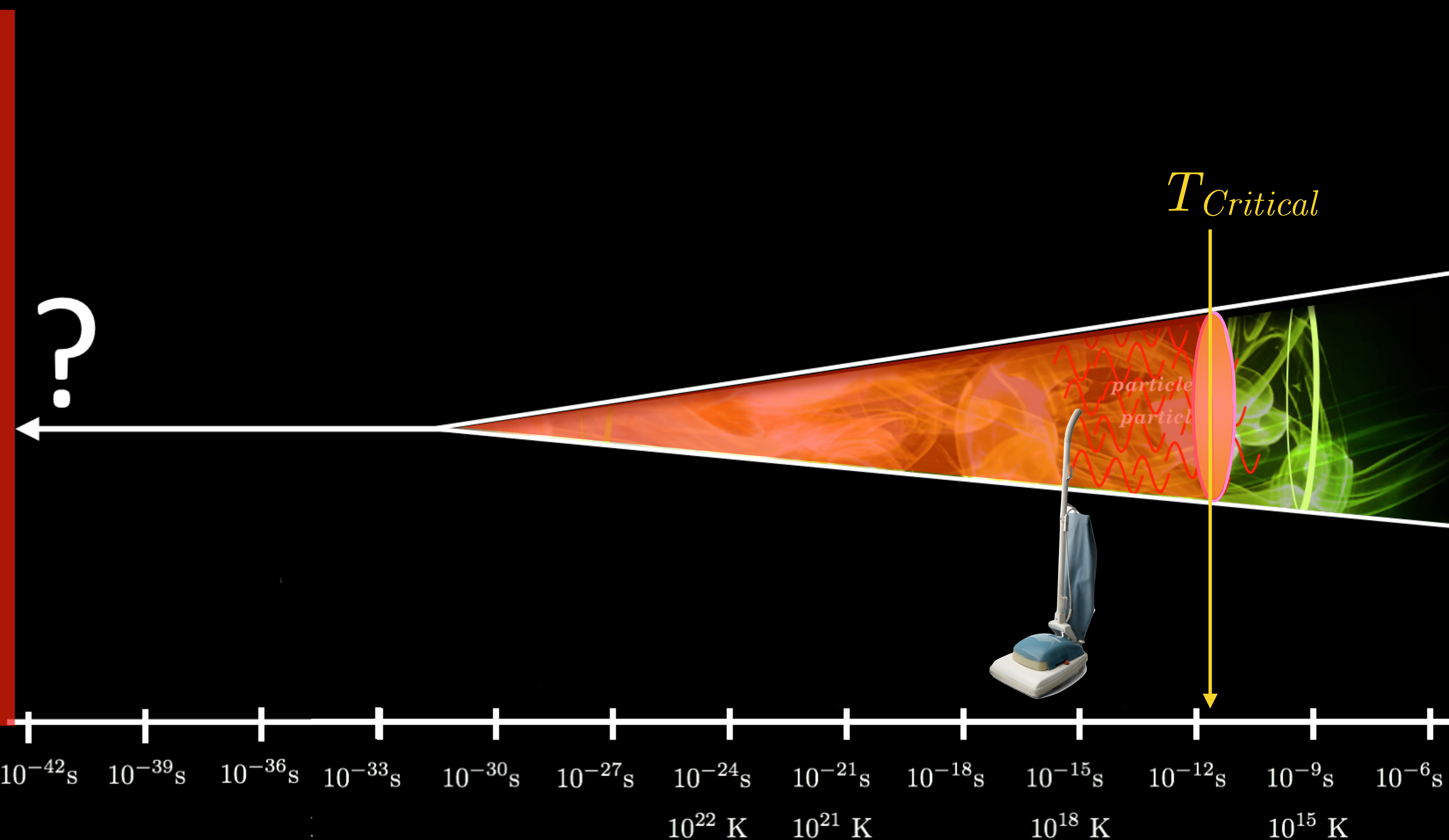


now it's full of a finite average value Higgs Field

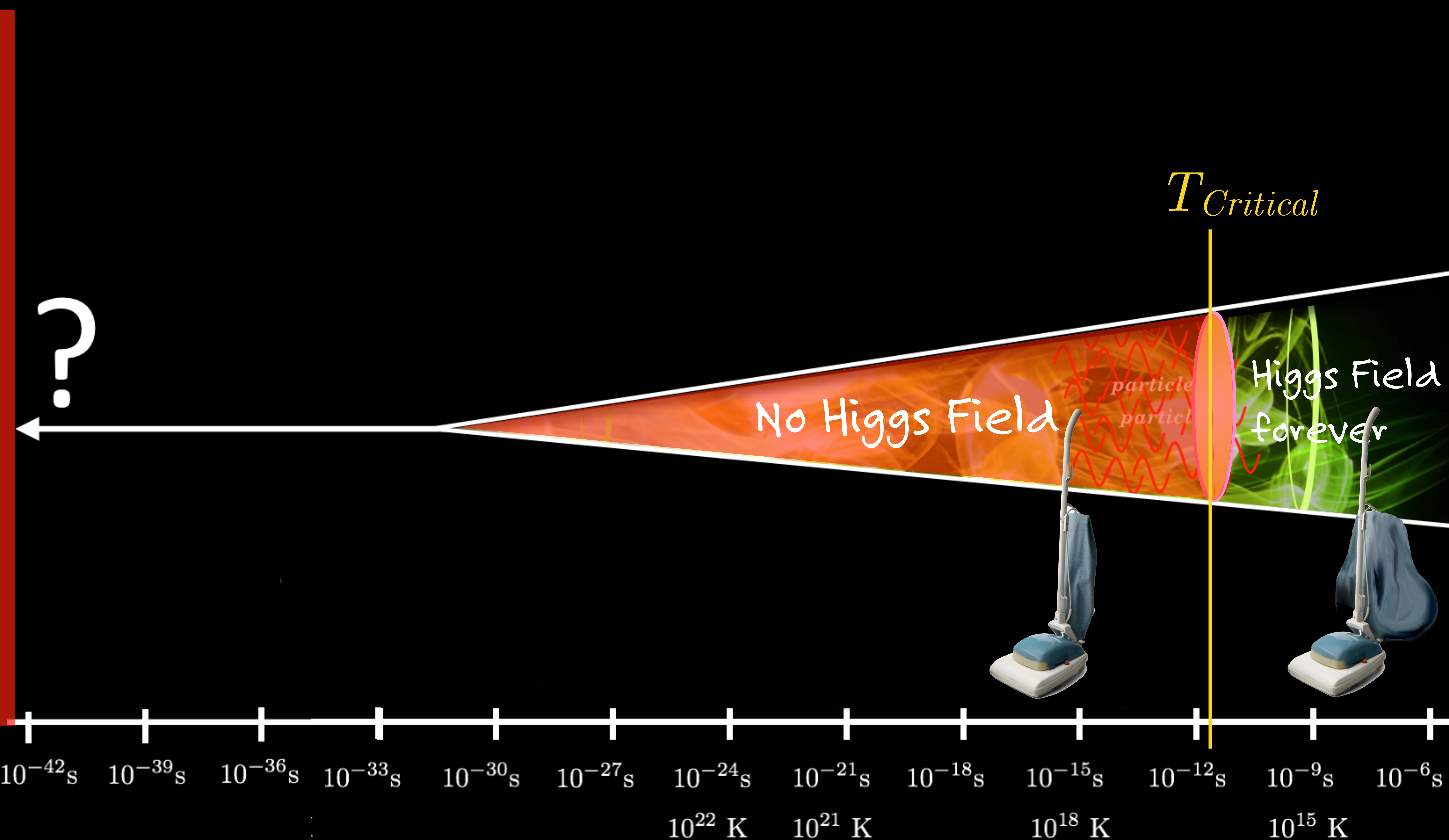
the big story of the Standard Model

is the story of mass.

elementary particle epoch

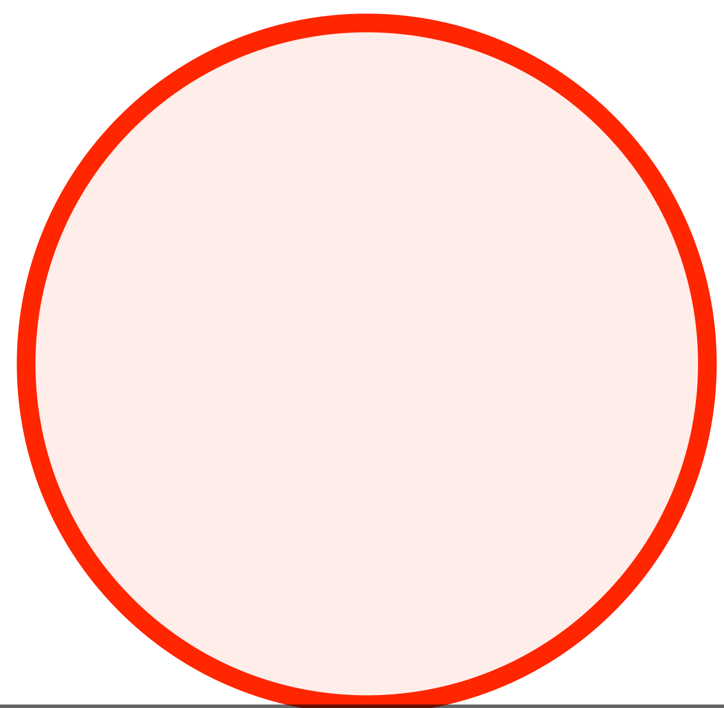


elementary particle epoch



a Higgs metaphor

(after David Miller)

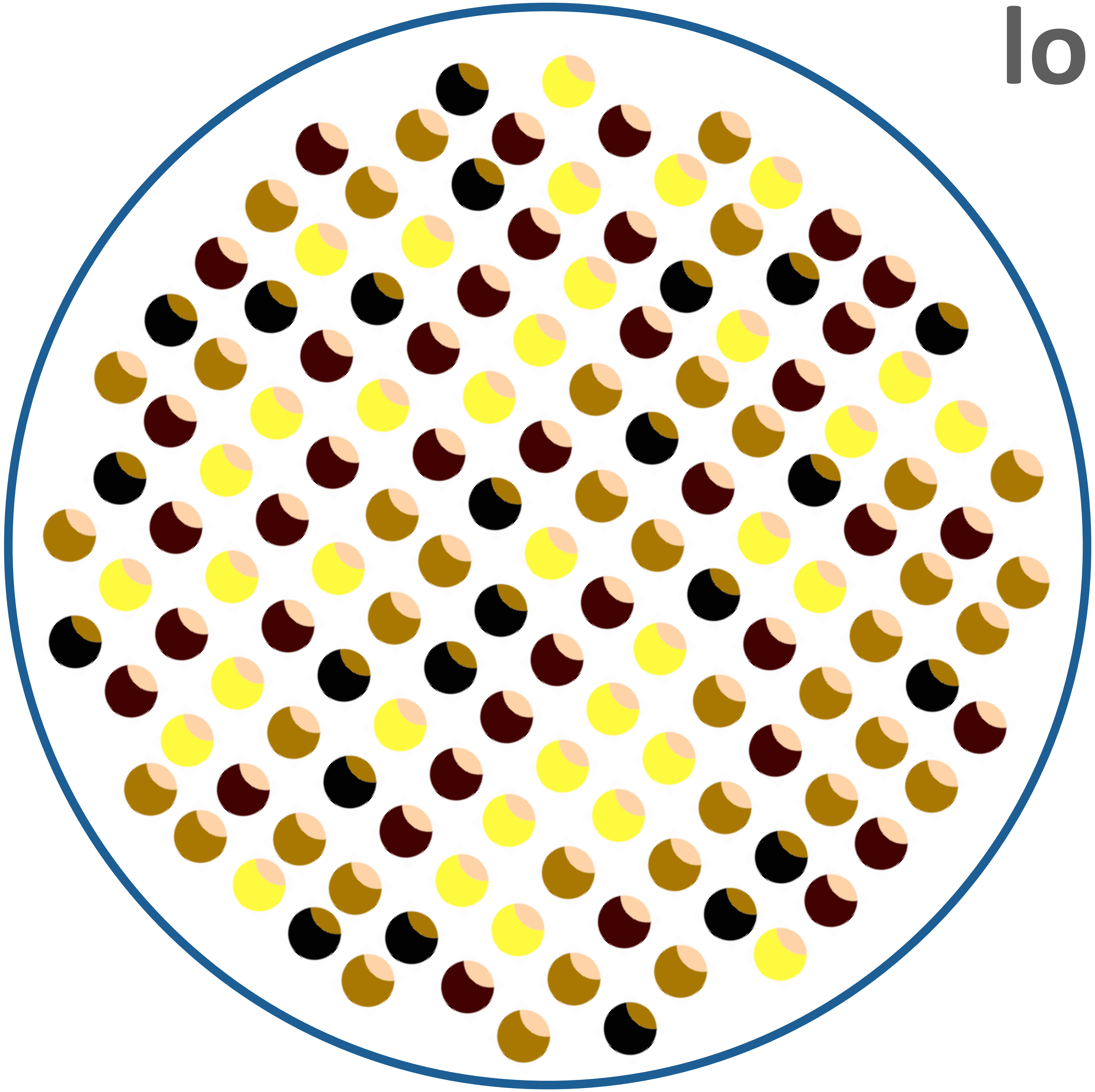


the hot universe: no Higgs Field

(after David Miller)

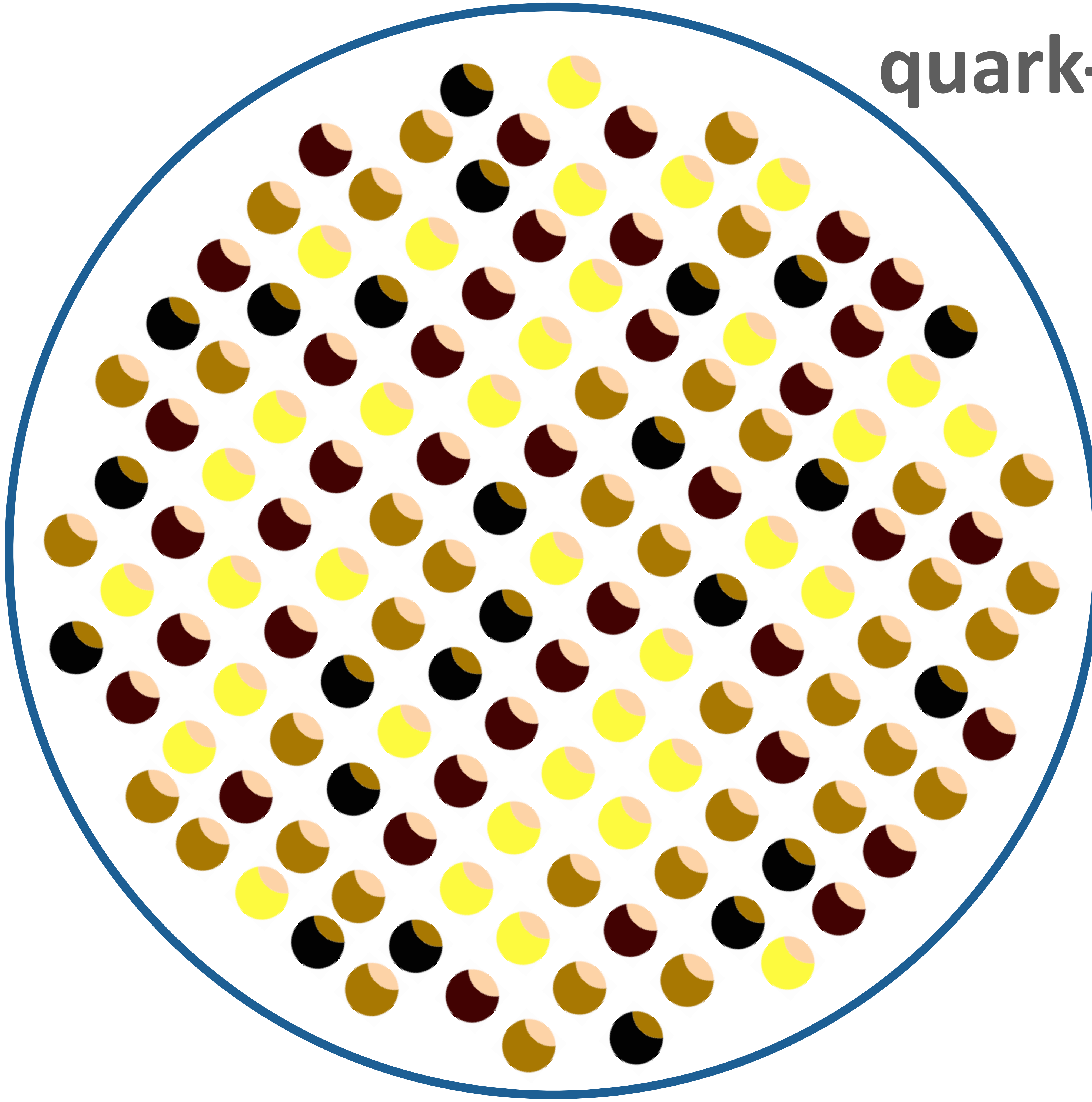
a cooled universe: Higgs Field

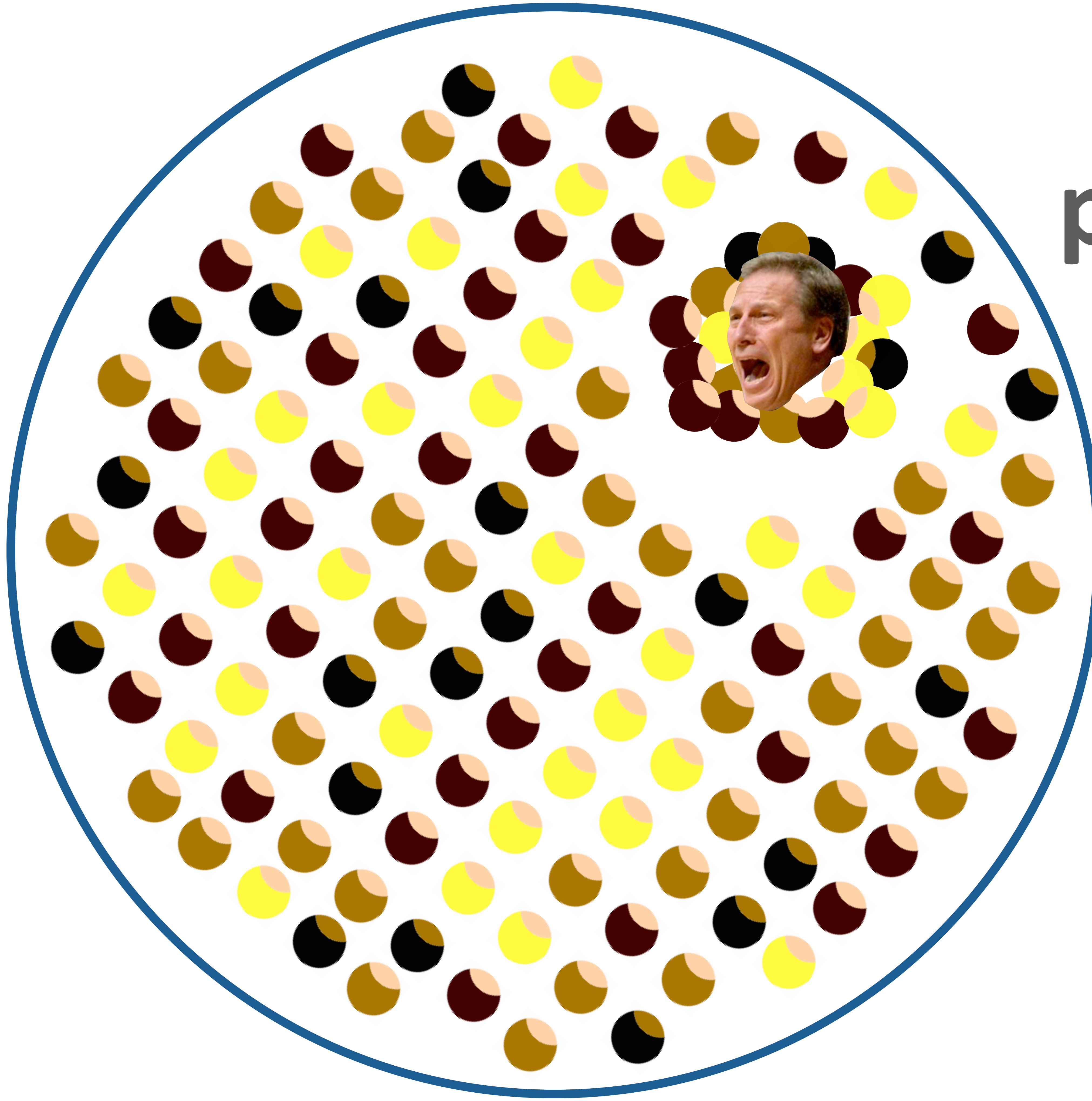
(after David Miller)



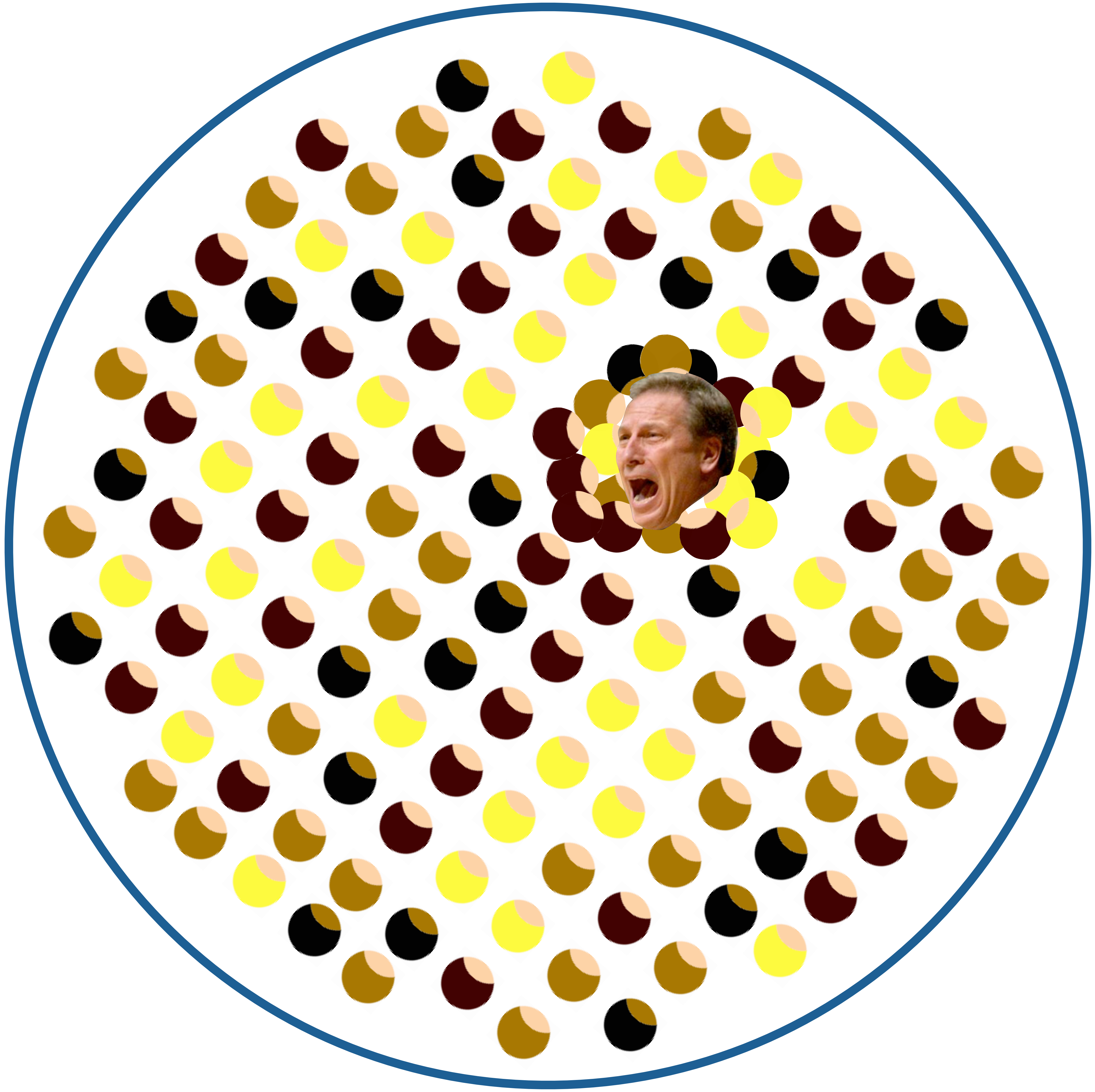
loud

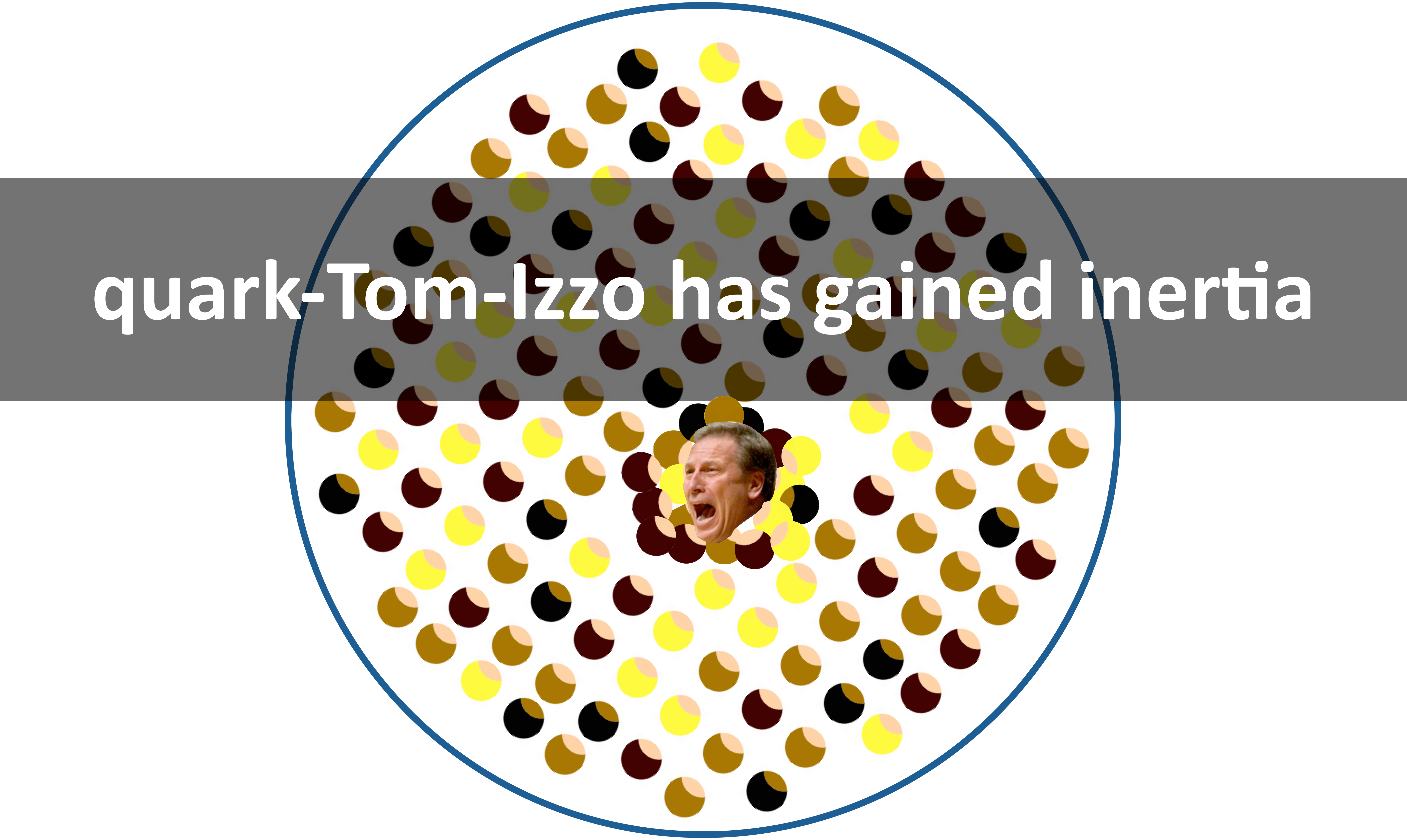
quark-Tom-Izzo



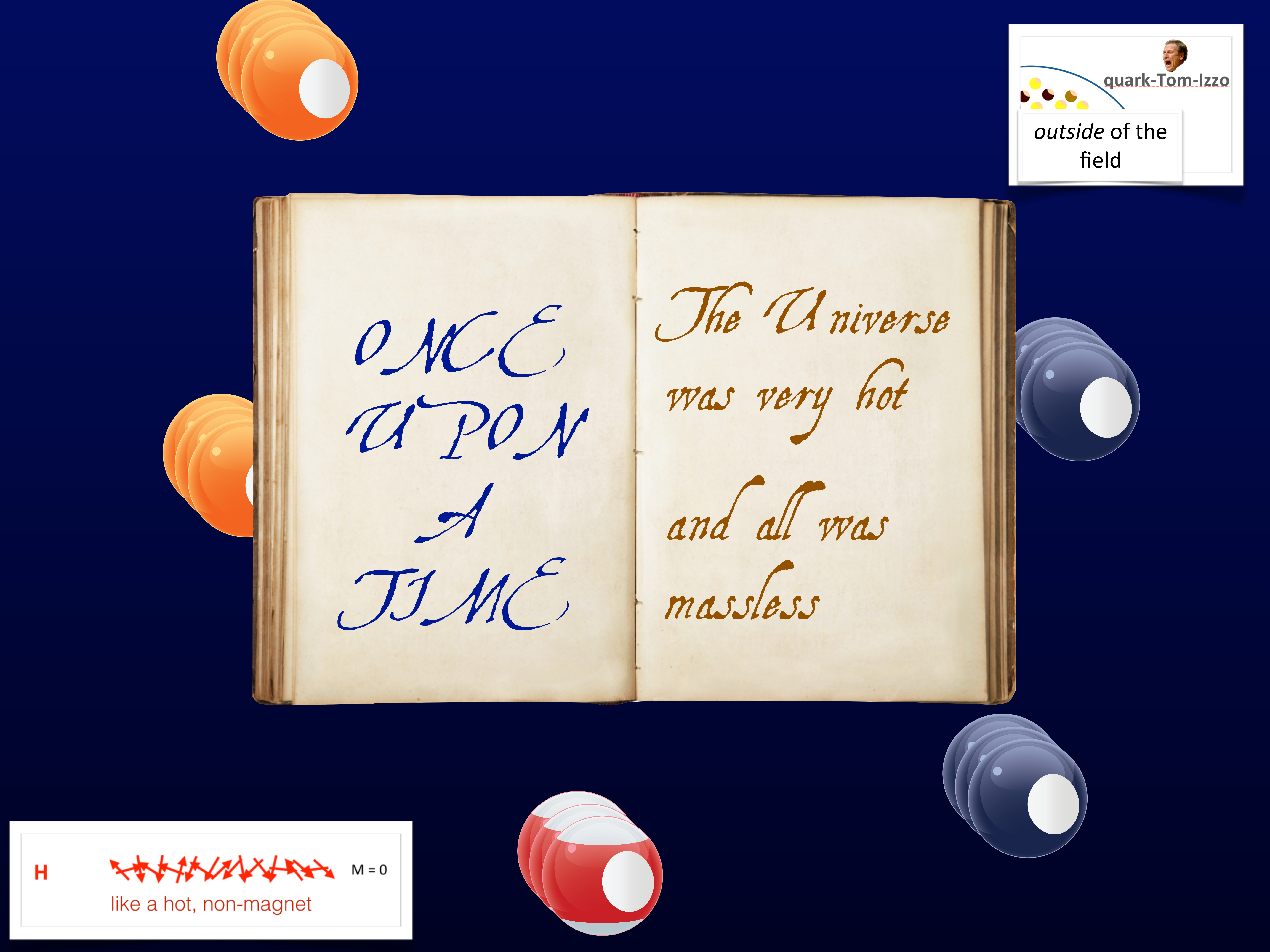


popular




quark-Tom-Izzo has gained inertia

quark-Tom-Izzo has mass.


quark-Tom-Izzo
outside of the field
ONCE UPON A TIME
The Universe was very hot
and all was massless
H
M = 0
like a hot, non-magnet

inside of the field

At a Magic Temperature

The Universe expanded and cooled and a

Higgs Field

became manifest and all became heavy

mass

was born

in the Higgs Field

“rumor” travels: Higgs Particle

an excitation of the Higgs Field

So:

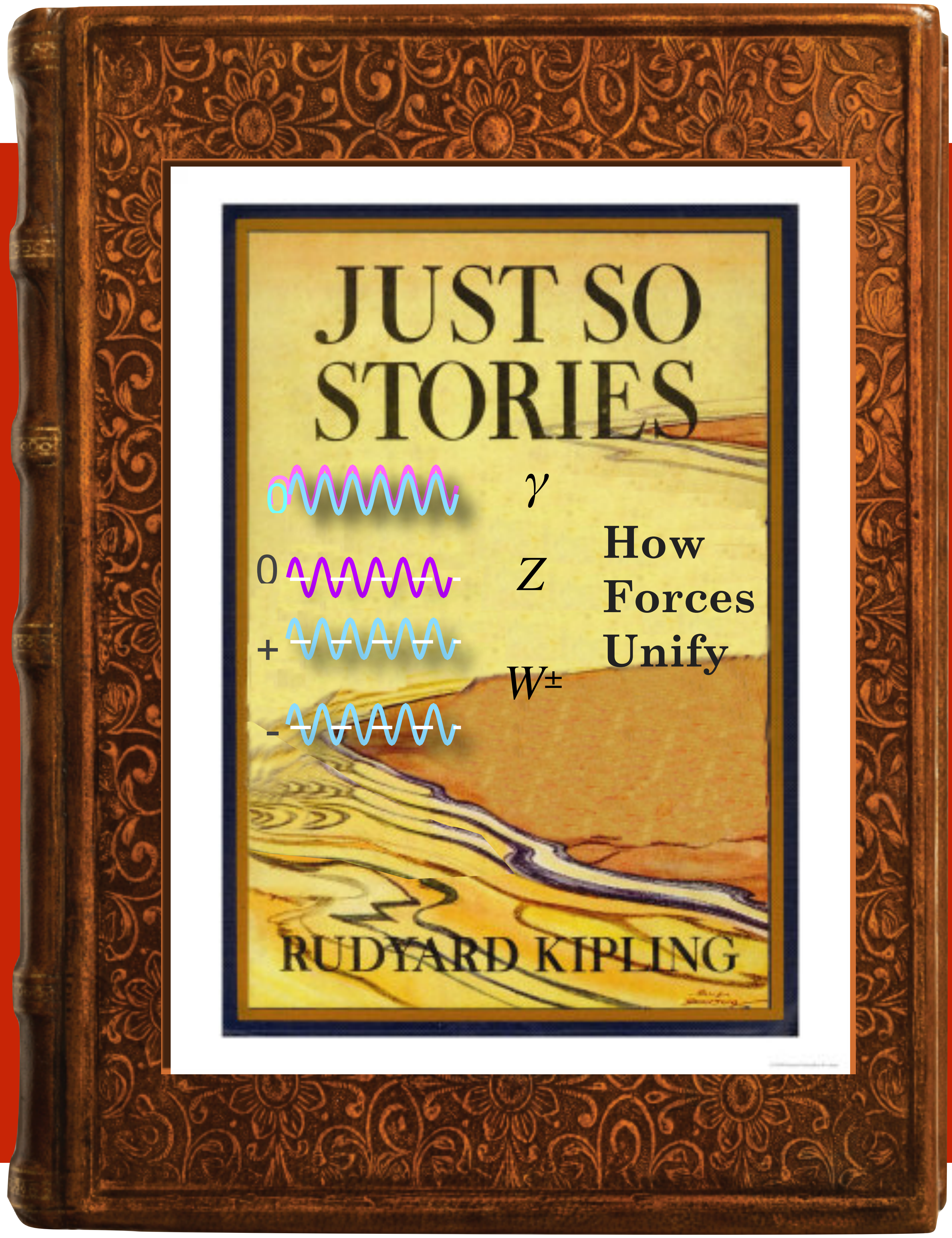
The Higgs Boson is not just another particle.

more details now

what’s really in the model

the story of the Weak and Electromagnetic Fields

the unification of forces



H — M = 0

like a hot, non-magnet

C — $M_1 \neq 0$

like a regular magnet

a^0 0

B^0 0

B^+ +

B^- -

$\phi \begin{pmatrix} + \text{- - - - - - -} \\ 0 \text{- - - - - - -} \end{pmatrix}$

$\phi^* \begin{pmatrix} - \text{- - - - - - -} \\ 0 \text{- - - - - - -} \end{pmatrix}$

γ

Z

$W^\pm$

H^0

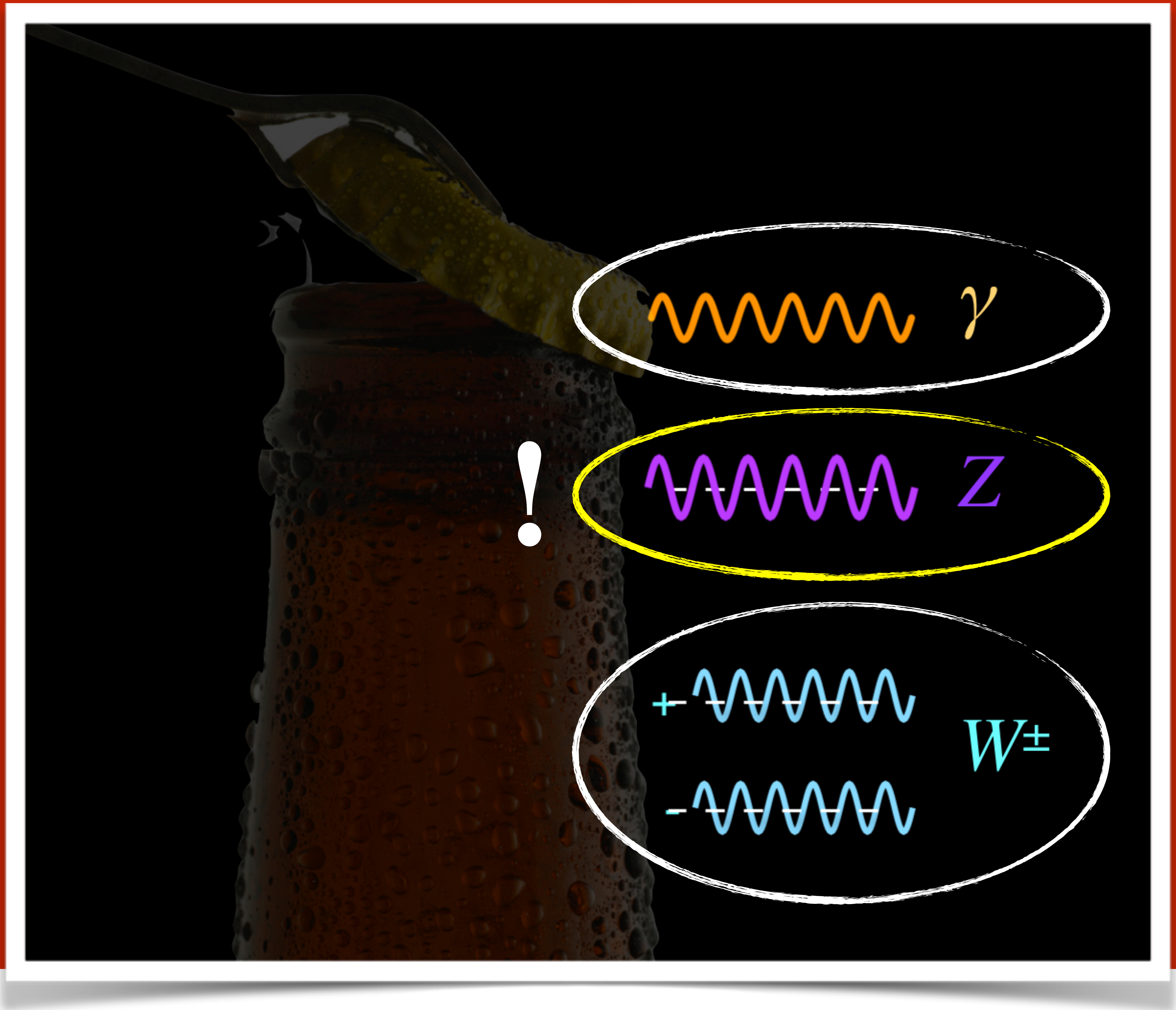
The remaining primordial scalar is the **Higgs Field.**

t = the beginning 0 s — $t = 10^{-12}$ s — $t = 10^{+18}$s

3 of the primordial Higgs fields combine with 2 of the primordial messengers - and that gives them mass in the mathematics

what's this about?

messengers got fat



this is quite remarkable

If the idea is right:

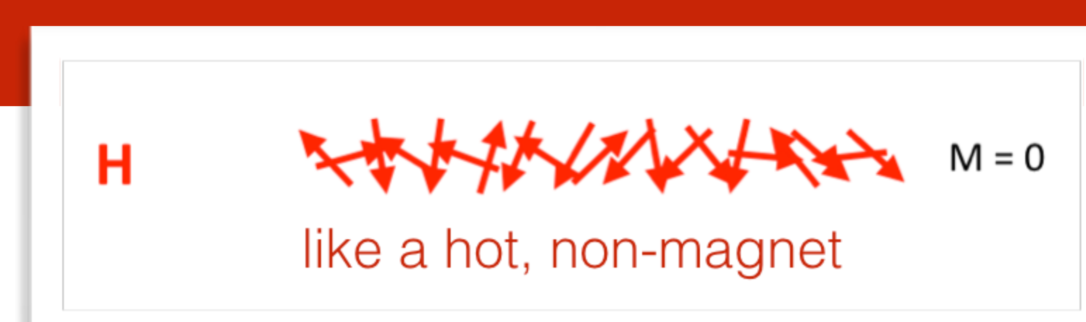
the electromagnetic and weak forces

that are so different today

are actually a "cold-phase" of a single, unified force

"Electroweak Force"

that existed only when the Universe was very, very hot



definite predictions

of Weinberg's model

0. The weak and electromagnetic interactions are two aspects of the same force

1. The *W* Boson should exist

2. An additional "*Z* Boson" should exist

Many physics reactions relate M_W to M_Z

3. This *Z* Boson and the γ are intimately related

any reaction with a photon, must also happen with a Z^0

4. The Higgs Boson should exist

particle:

W Boson

symbol:	W
charge:	$\pm 1e$
mass:	80.399 ± 0.023 GeV/c^2 = 80.4 p
spin:	1
category:	weak Vector Boson

particle: **Z Boson**

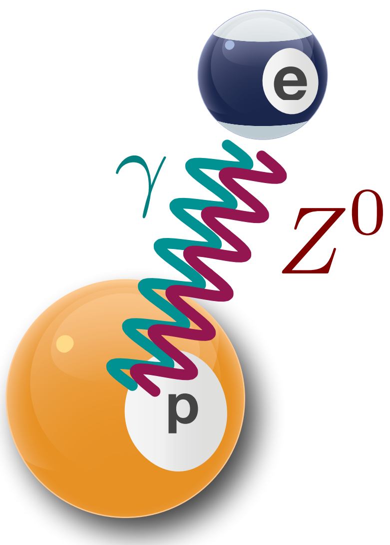
symbol:	Z
charge:	0
mass:	91.1876 ± 0.0021 GeV/c^2 = 91.2 p
spin:	1
category:	weak Vector Boson

Photon and Z always mix

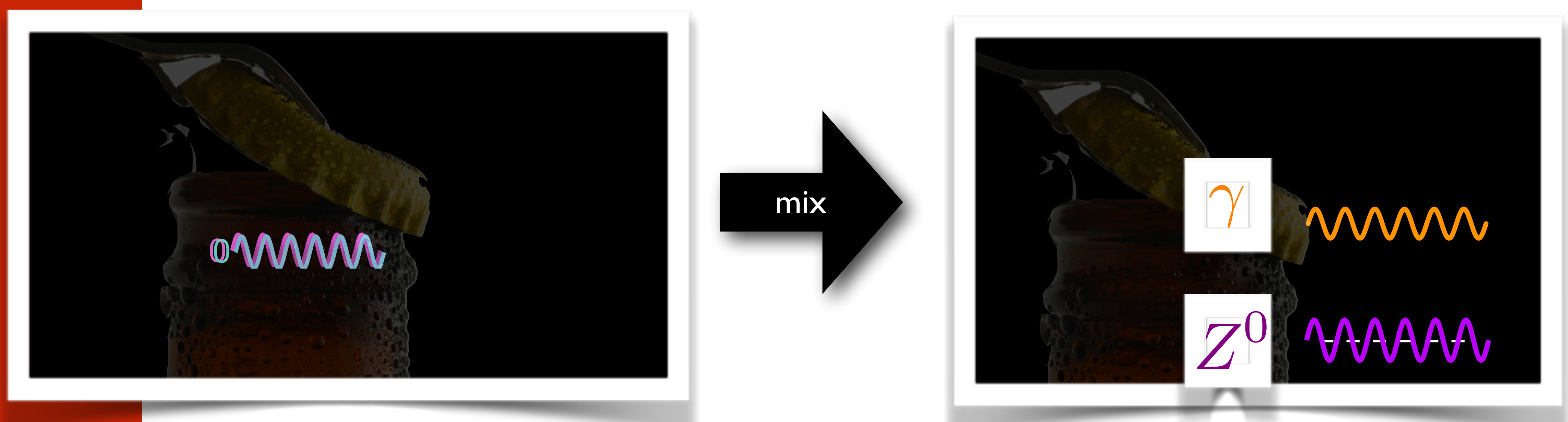
Z, very weakly

3. The Z Boson and the γ are intimately related

any reaction with a photon, must also happen with a Z^0

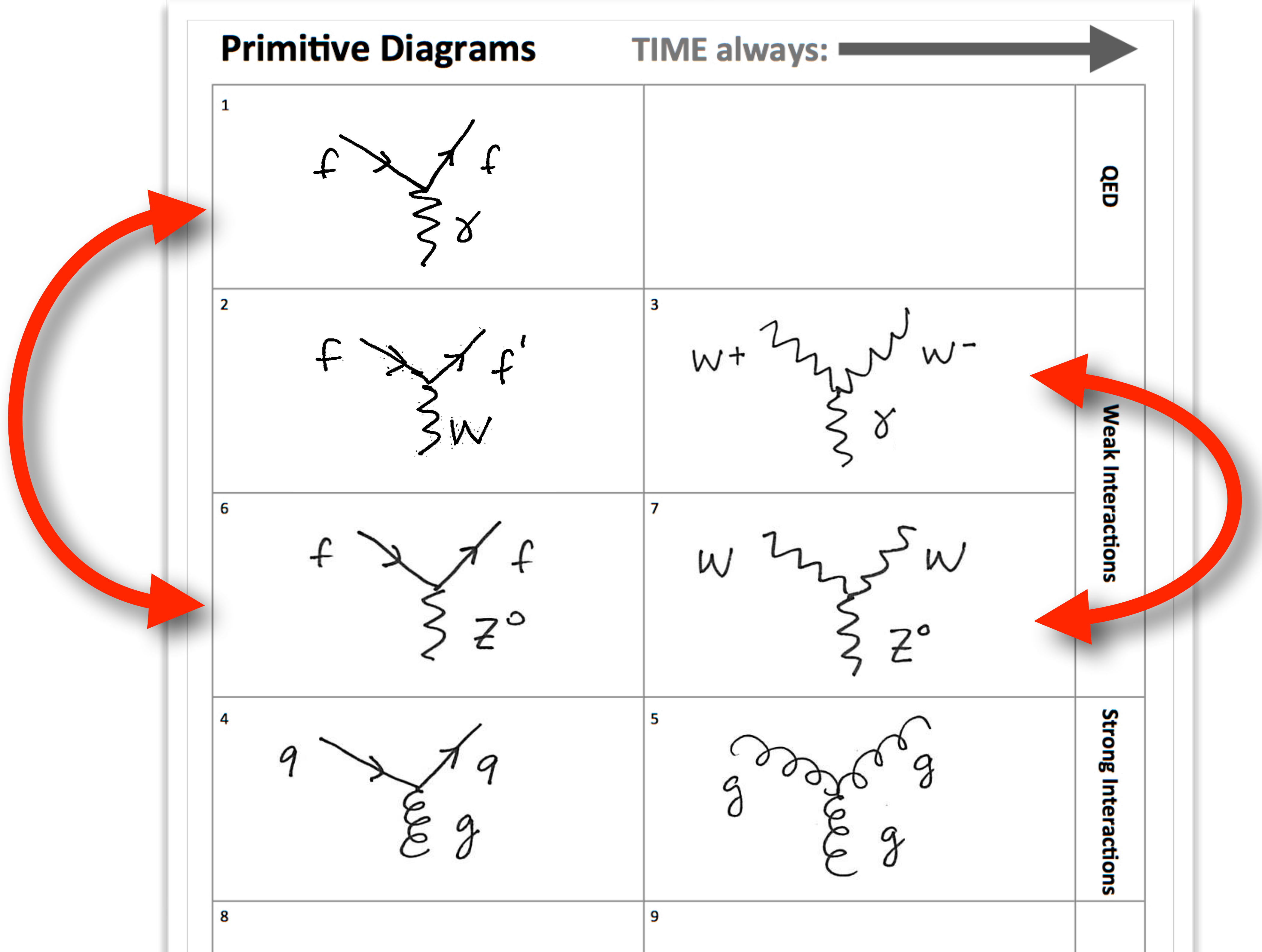


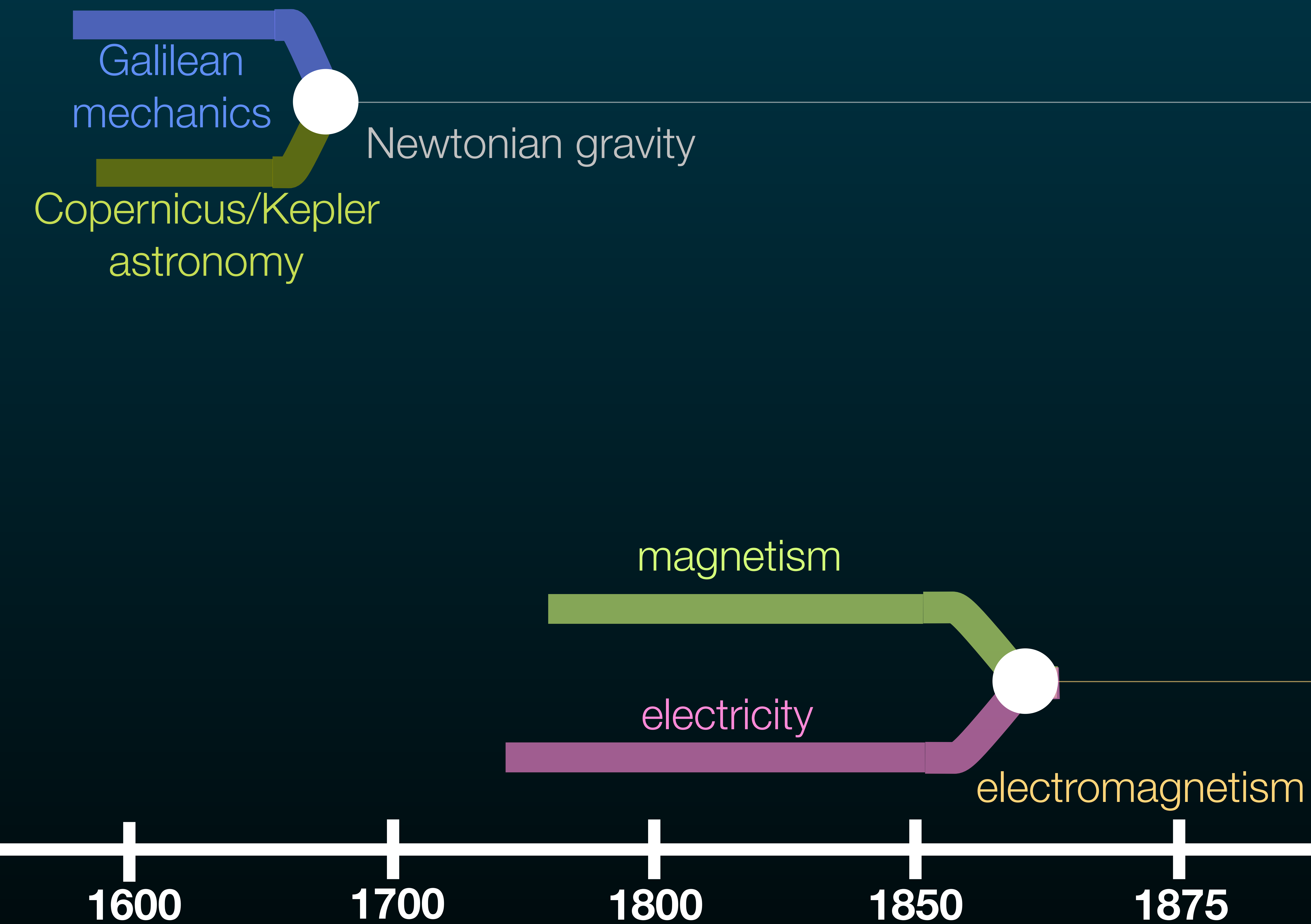
very delicate effects observed in atomic systems due to the Z Boson

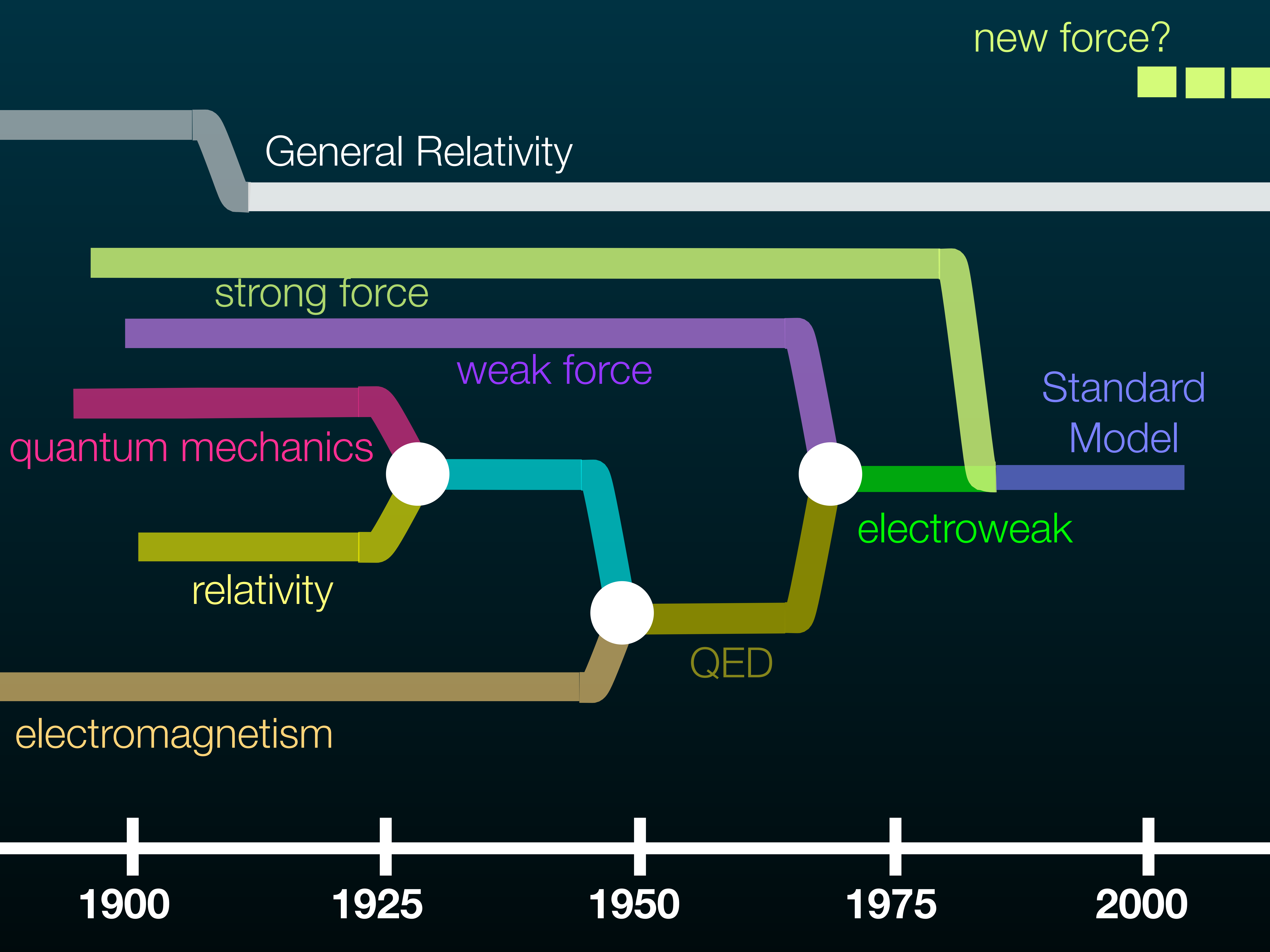


sixth and seventh entries into your

table of primitive diagrams




Galilean mechanics
Copernicus/Kepler astronomy
Newtonian gravity
magnetism
electricity
electromagnetism
1600
1700
1800
1850
1875


new force?
General Relativity
strong force
weak force
Standard
Model
quantum mechanics
electroweak
relativity
QED
electromagnetism
1900
1925
1950
1975
2000

we now think in terms of

epochs in the stages of the early universe

distinguished by phase transitions - stay tuned

‘‘mass generation’’

the holy grail of physics since Newton

what is mass?

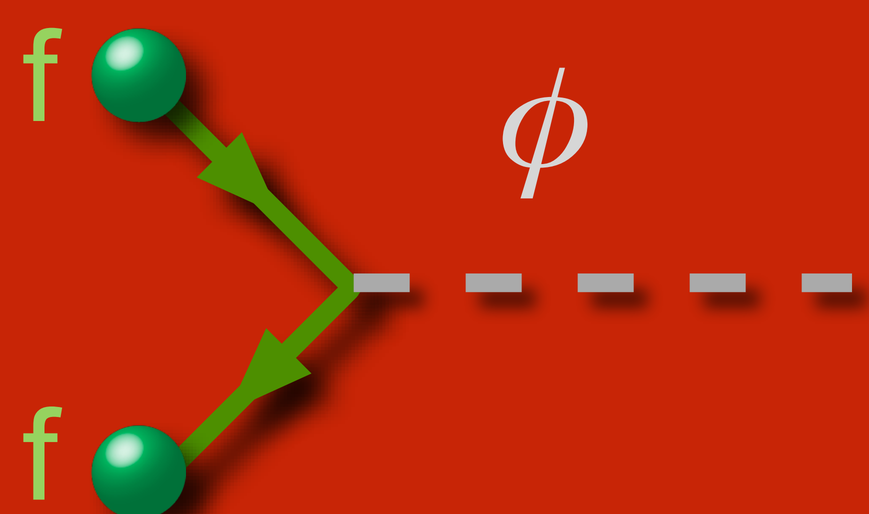
Is “mass” an intrinsic attribute? “nature”?

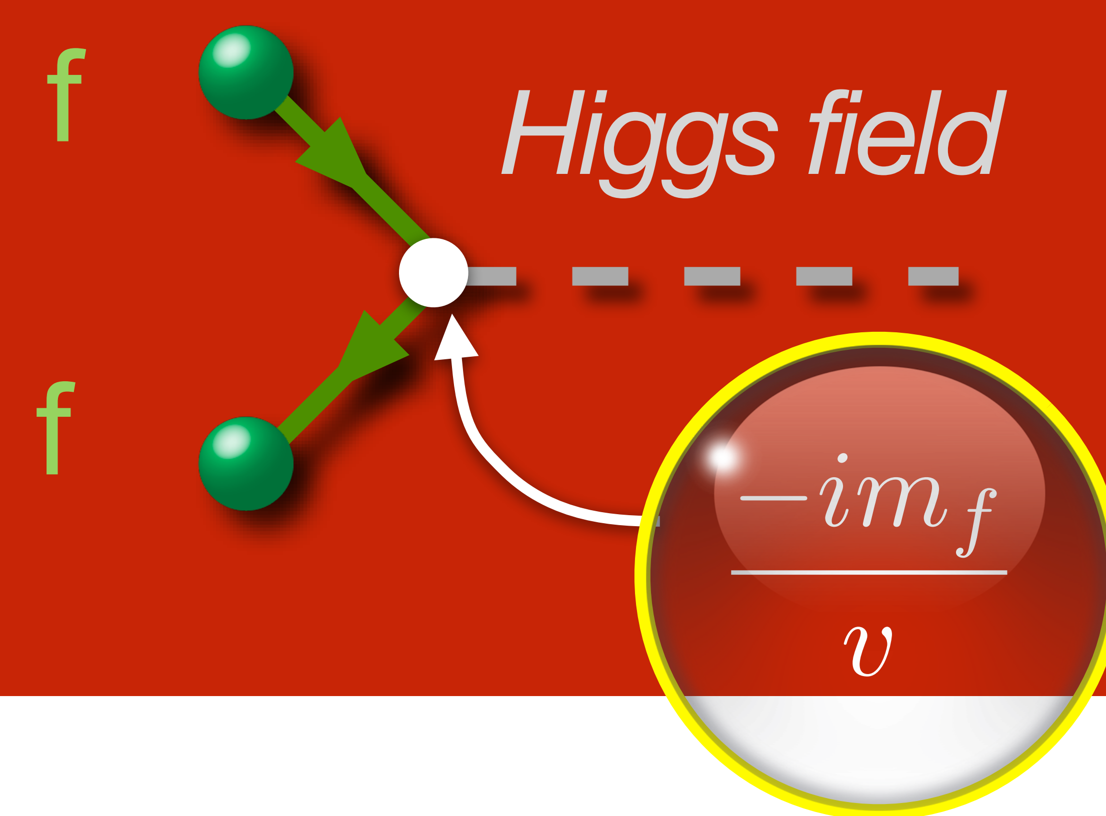
or

Is “mass” an acquired trait? “nurture”?

mass couplings? mass comes from the Higgs FIELD

SM predicts from the hot phase:





find the Higgs particle

confirmation of the process

Big Discovery

July 4, 2012

watch the off-line movie of more details:

https://qstbb.pa.msu.edu/storage/Extras_2017/HiggsDiscovery/

how to find the Higgs?

look for him!


TIME
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Rapid H.I.V. Home Test Wins Federal Approval

By DONALD G. McNEIL Jr.

The OraQuick test, which uses a cheek swab and gives results in 20 to 40 minutes, is the first chance for Americans to learn in the privacy of their own homes whether they are infected.

DEALBOOK

As Bank Frames a Defense, Barclays' C.E.O. Resigns

By BEN PROTESS and MARK SCOTT

Ahead of a British parliamentary hearing, senior Barclays executives said they thought they had implicit approval from regulators to manipulate interest rates.

• A Chief With Flair Falls

Top Judge Helped

Pool photo by Denis Balibouse

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva, could explain the universe's origin.

Fears of Fires Take Fireworks Out of July 4th Celebrations

By DAN FROSCH

Many U.S. cities and towns across the country have decided to scrap their displays, driven by parched

As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles

By AARON EDWARDS

The Fire Department in Narrowsburg, N.Y., canceled its annual display after planned fireworks were said to

OPINION »

EDITORIAL

Too Quiet, Again, on Health Care

The Obama campaign has not forcefully countered Republican misinformation on the reform law.

• Dowd: Gaelic Guerrilla
• Friedman: Morsi, Israel
• Douthat: Books for Obama
• Fixes: Rwanda's Miracle
• Kurt Andersen: The Downside of Liberty
• Op-Ed: Anderson Cooper

MARKETS » At 4:02 AM ET

Britain	Germany	France
FTSE 100	DAX	CAC 40
5,673.04	6,553.19	3,248.93
−14.69	−25.02	−22.27
−0.26%	−0.38%	−0.68%

Data delayed at least 15 minutes

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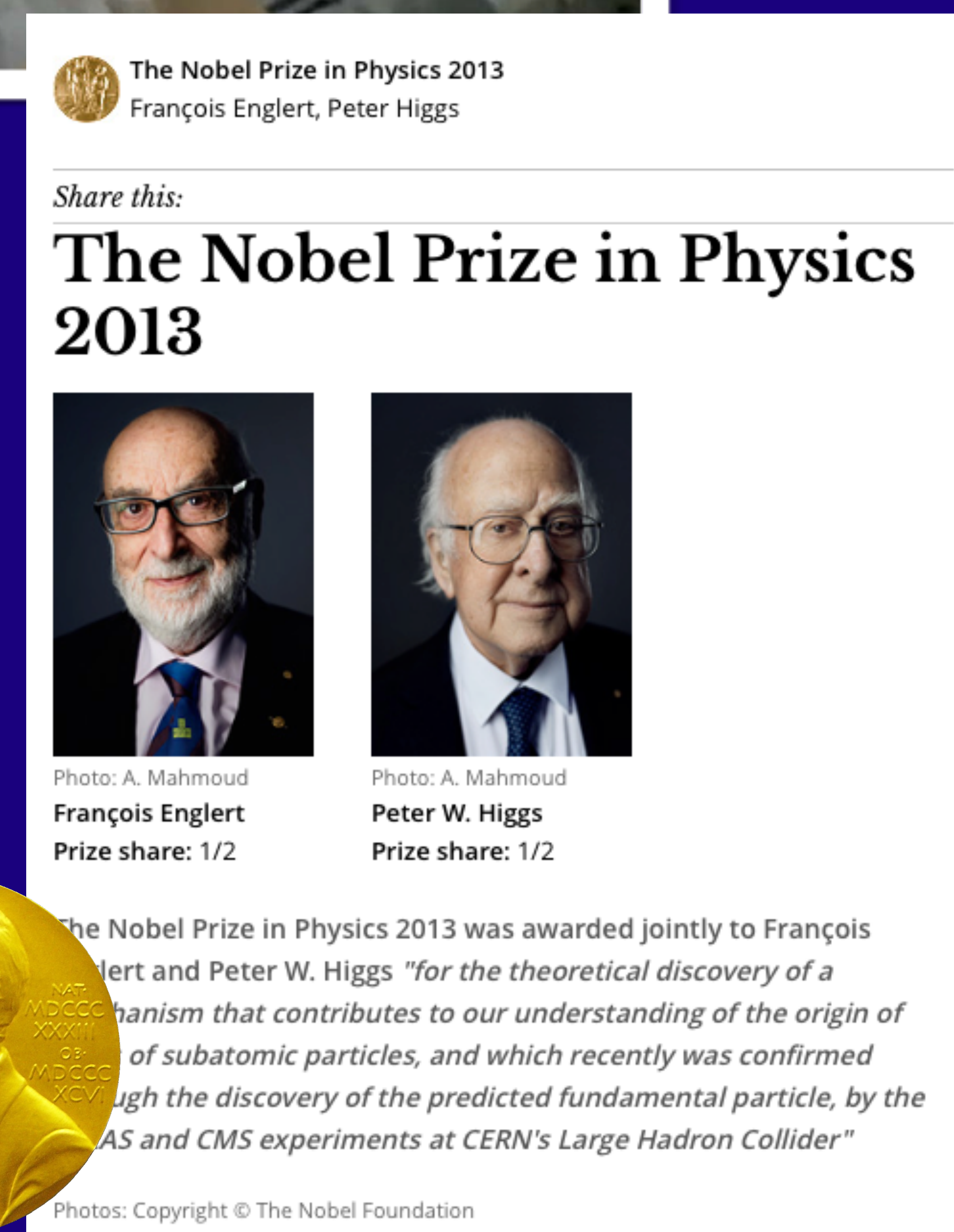
The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a ...hanism that contributes to our understanding of the origin of ... of subatomic particles, and which recently was confirmed ...ugh the discovery of the predicted fundamental particle, by the ...AS and CMS experiments at CERN's Large Hadron Collider"*

of particle physics

definite predictions

of Weinberg's model

0. The weak and electromagnetic interactions are two aspects of the same force

1. The *W* Boson should exist

2. An additional "*Z* Boson" should exist

Many physics reactions relate M_W to M_Z

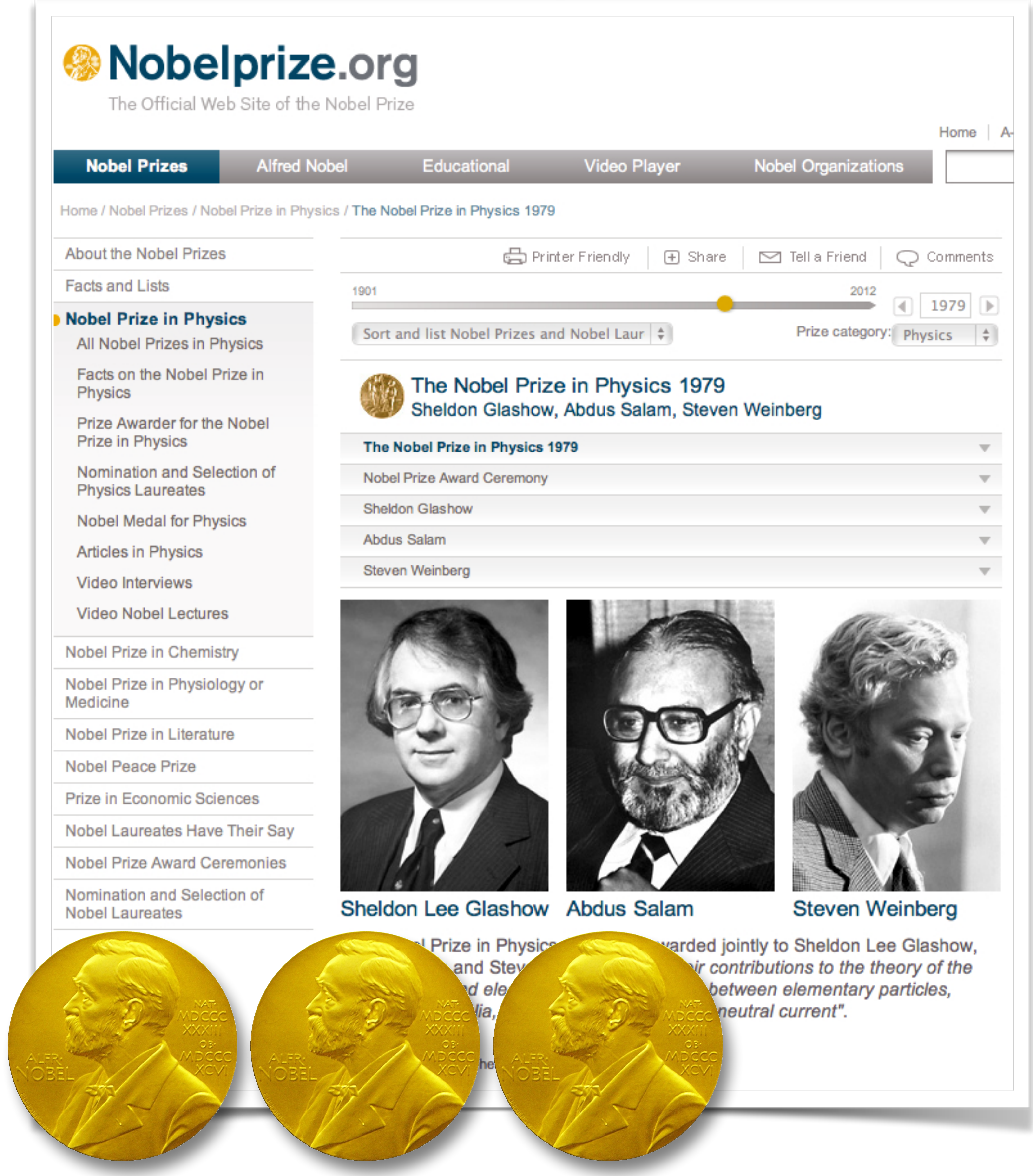
3. This *Z* Boson and the γ are intimately related

any reaction with a photon, must also happen with a Z^0

4. The Higgs Boson should exist

Weinberg, Salam, and Glashow

1979

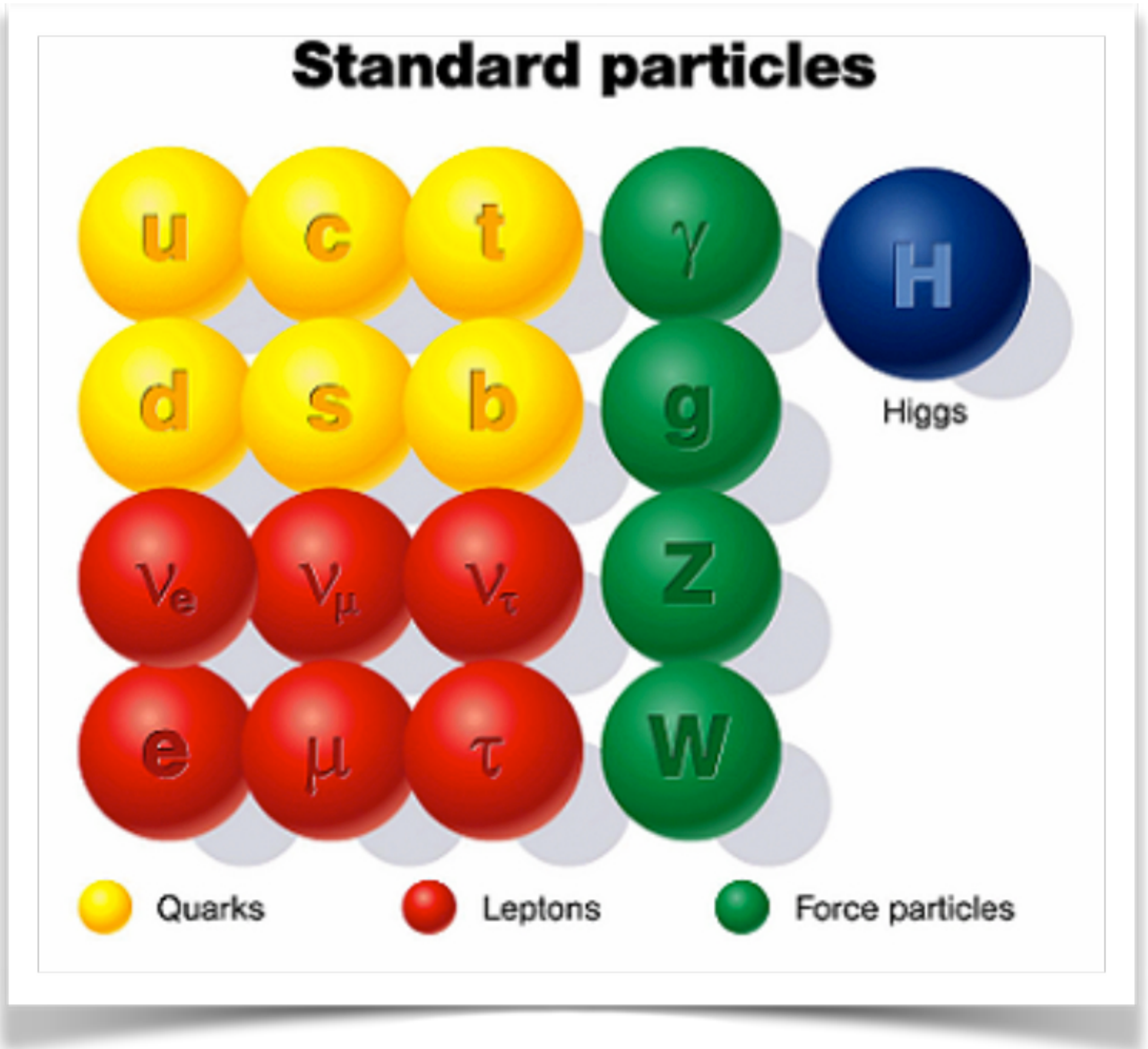


the particle players

and

the "substrate"

Our "Periodic Table"

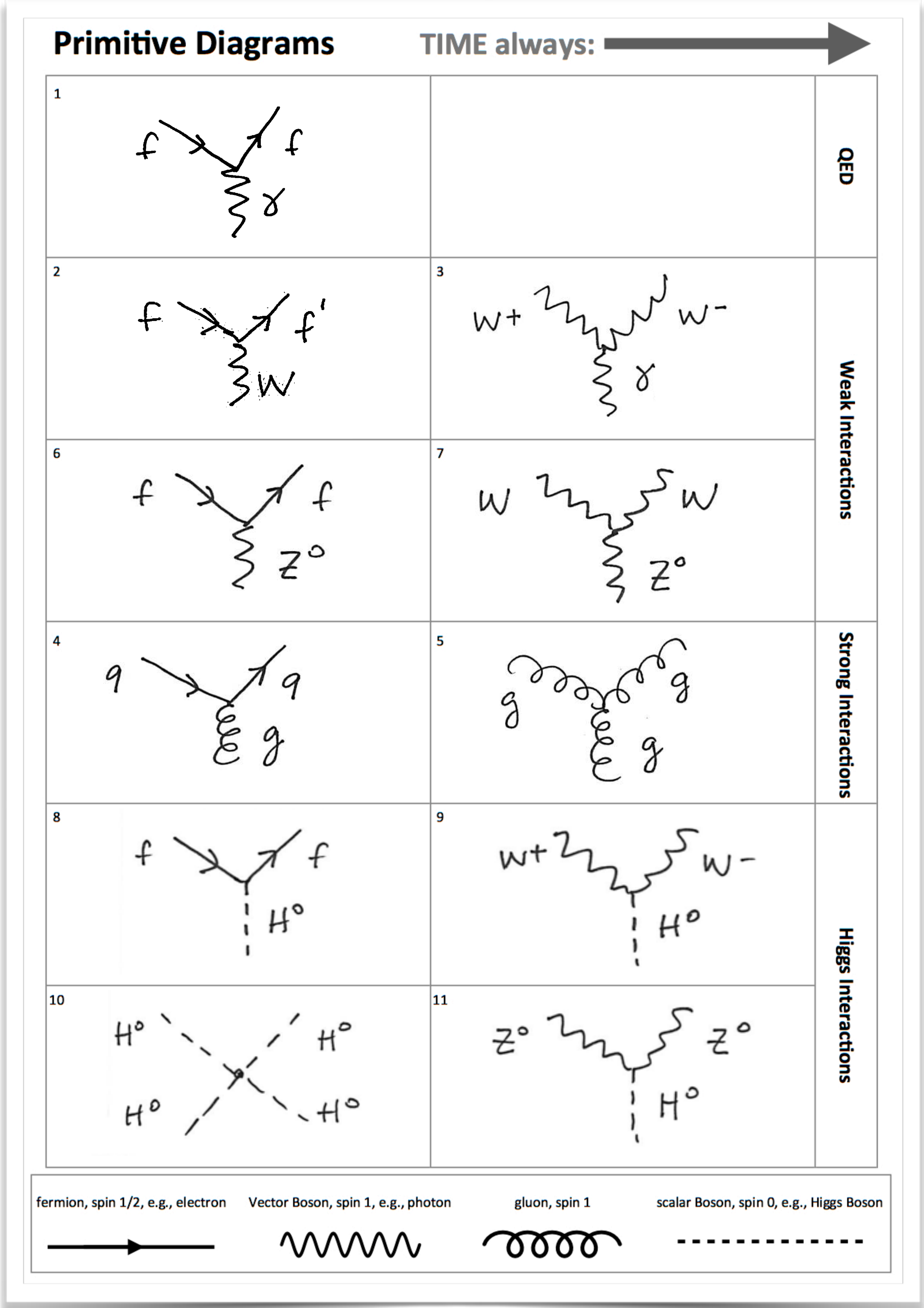


like any particle,

we predict and then search for its manifestation

through its decays

Your final entries into the Primitive Diagram collection



there are two other "issues"

where’s

the antimatter?

what the heck

is dark matter?

watch the off-line movie for more details:

https://qstbb.pa.msu.edu/storage/Extras_2017/DarkMatter/

the more pleasing

extension of the Standard Model

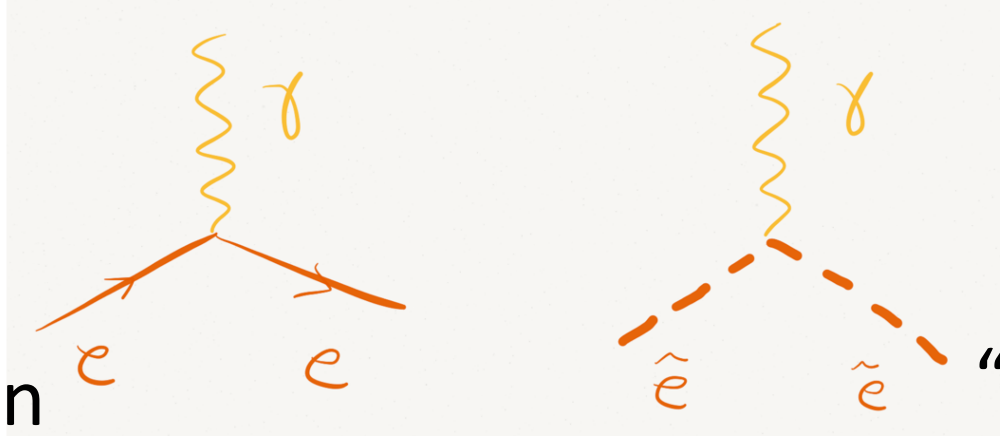
"supersymmetry"

every "Standard Model Particle"

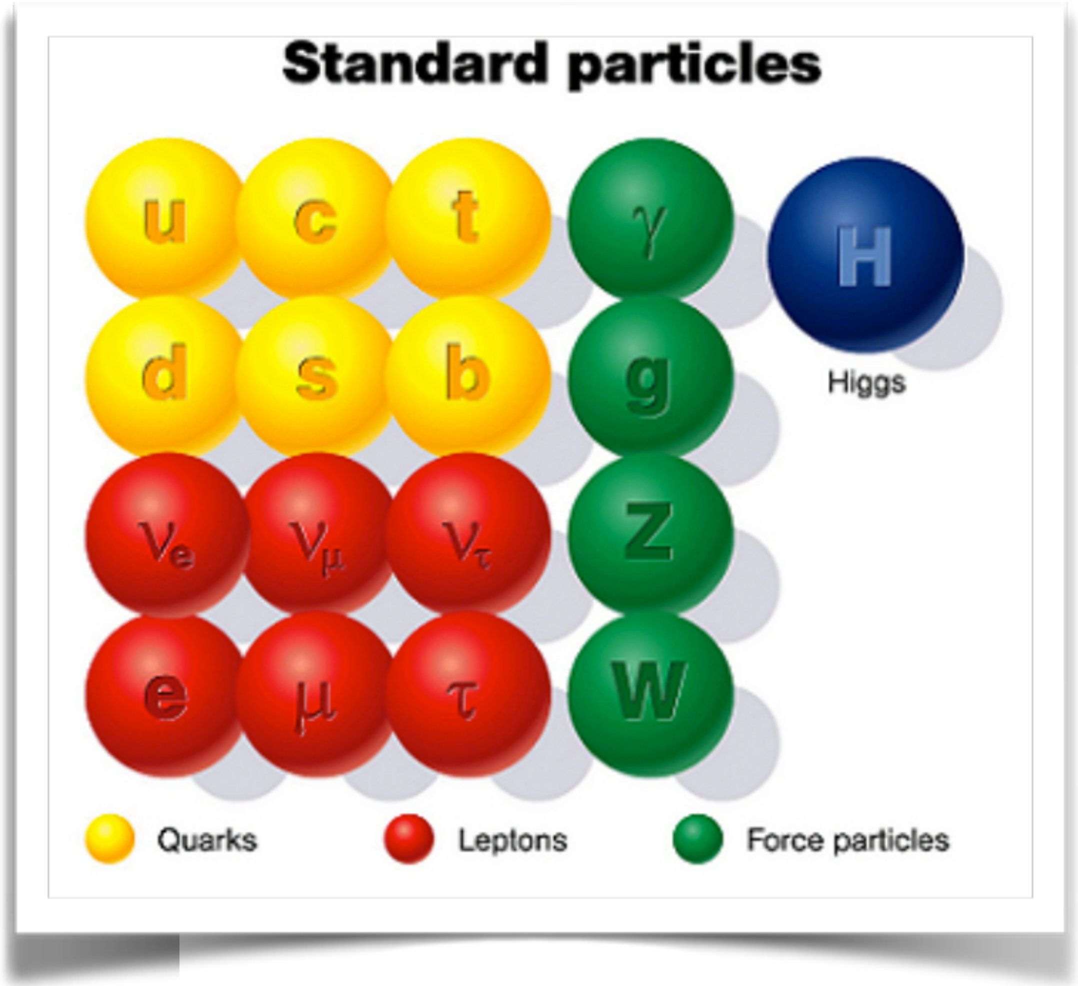
has a super-partner

presumably much heavier

electron



"selectron"



Searching for decades with every incremental increase in energy and luminosity. <u>No evidence so far.</u>

For decades physicists have been working on a beautiful theory that has promised to lead to a deeper understanding of the quantum world. **Now they stand at a crossroads:** prove it right in the next year or confront an epochal paradigm shift

By Joseph Lykken and Maria Spiropulu

PARTICLE PHYSICS

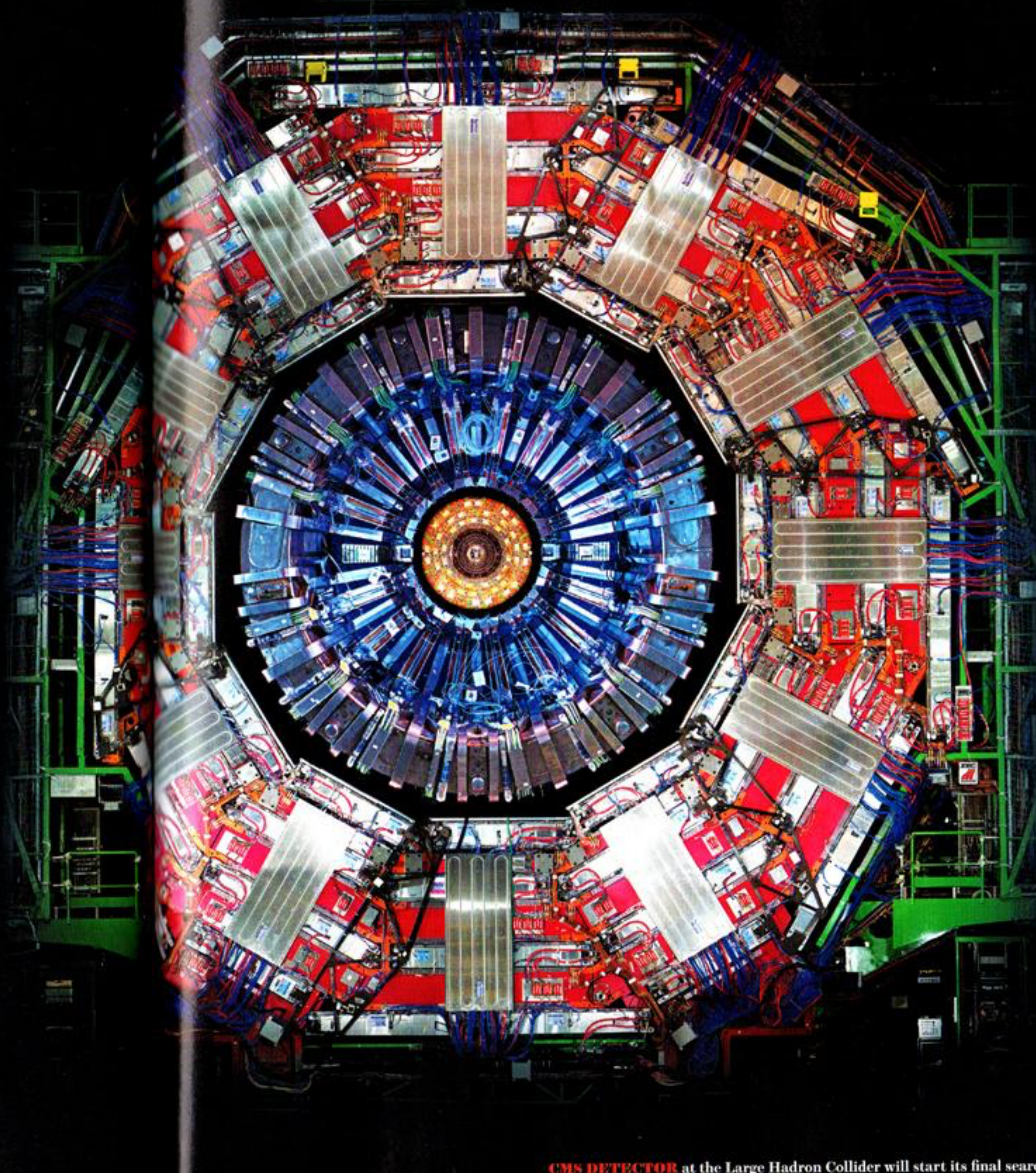
Supersymmetry and the Crisis in Physics

IN BRIEF

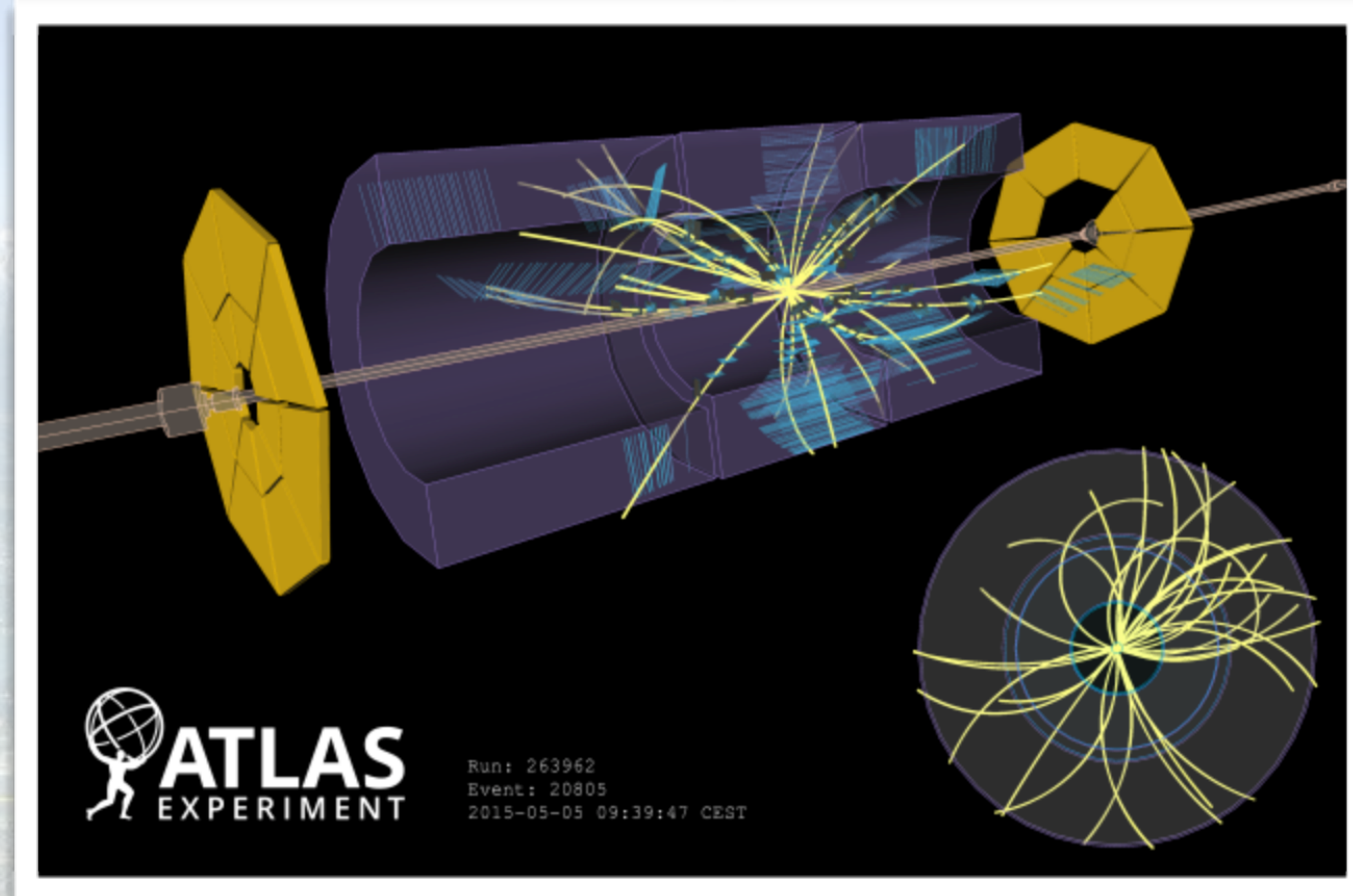
Supersymmetry postulates that every known particle has a hidden superpartner. Physicists love supersymmetry because it solves a number of problems that crop up when they try to extend our understanding of quantum mechanics. It would also potentially solve the mystery of the universe's missing dark matter.

Physicists hoped to find evidence of supersymmetry in experiments at the Large Hadron Collider (LHC). To date, they have not. If no evidence arises in the next run of the LHC, supersymmetry will be in trouble.

The failure to find superpartners is brewing a crisis in physics, forcing researchers to question assumptions from which they have been working for decades.



CMS DETECTOR at the Large Hadron Collider will start its final search for evidence of supersymmetry when the LHC starts back up in early 2015.



buckle in

- The LHC running is just beginning

"phase 0 upgrades" "phase 1 upgrades"

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

Run I
8 TeV
0.75 10^{34} $cm^{-2}s^{-1}$

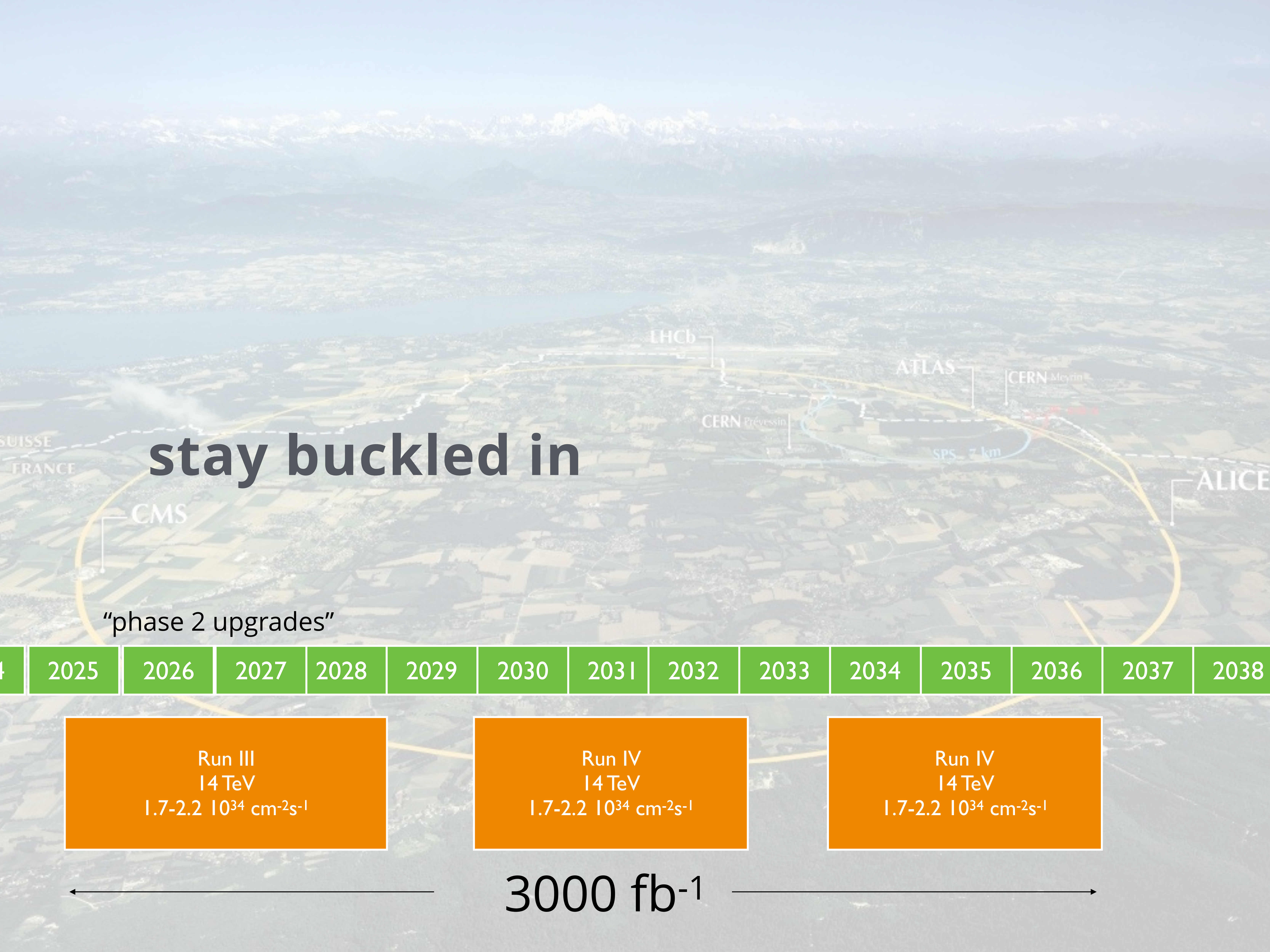
$20\ fb^{-1}$

Run II
13-14 TeV
1.5 10^{34} $cm^{-2}s^{-1}$

$>100\ fb^{-1}$

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

$300\ fb^{-1}$



stay buckled in

"phase 2 upgrades"

4	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

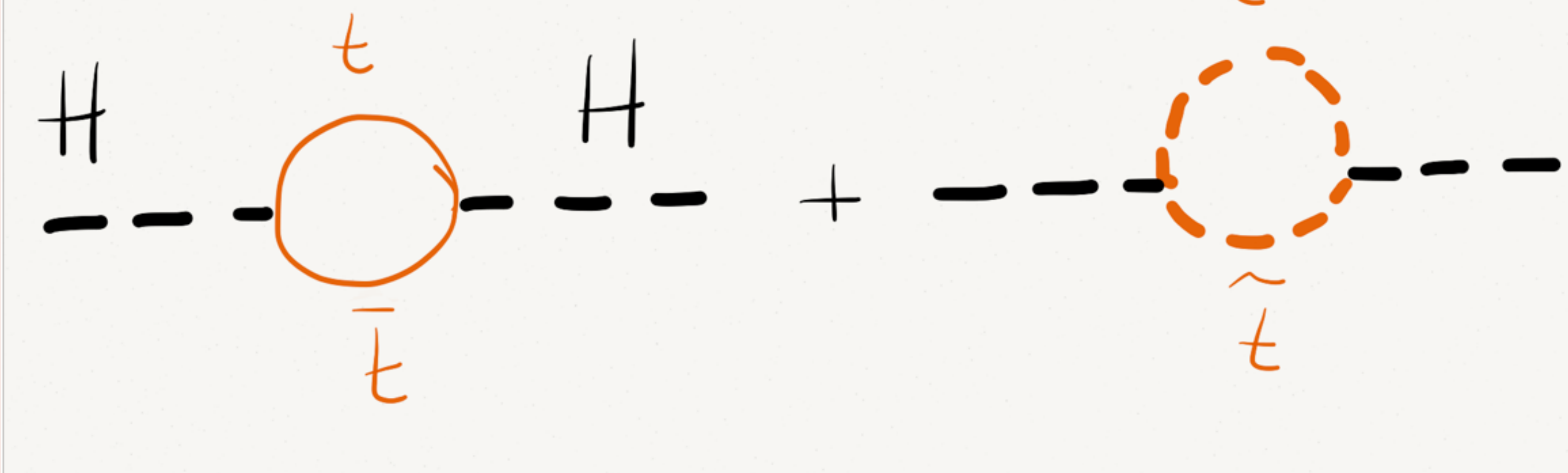
Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

$3000\ fb^{-1}$

intriguing

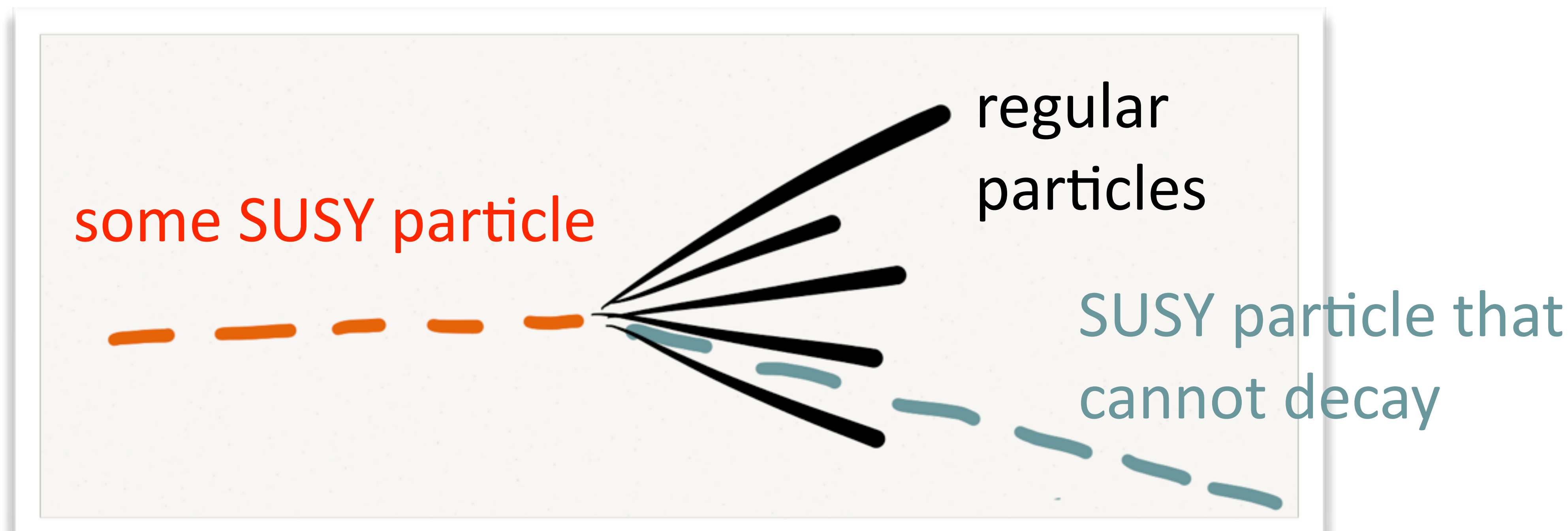
for two big reasons

"SUSY" main claim to fame:



$= 0$

tames a SM Higgs mass problem*, "naturally"



???

*mass should be much higher

many other extensions

which unify forces and fix the infinities

add messenger particles

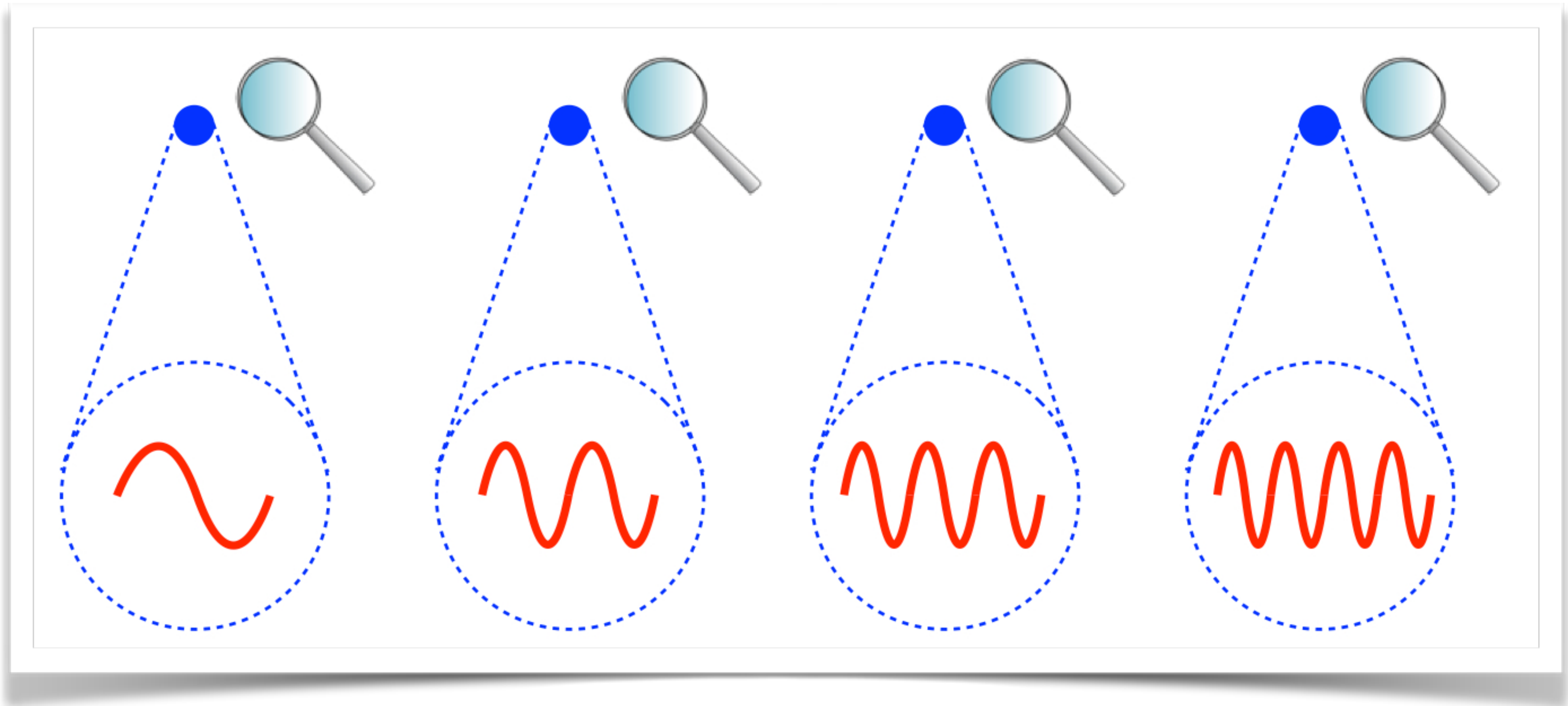
composite Higgs

composite quarks and leptons

“String Theory”...stop and start history in mathematics

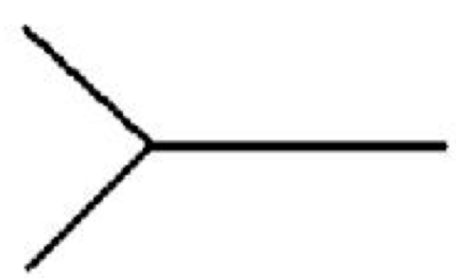
The “infinities” in Relativistic Quantum Field Theory are related to extrapolation in spacetime to zero, x, y, z, = 0

Suppose there is a minimum length in Nature?

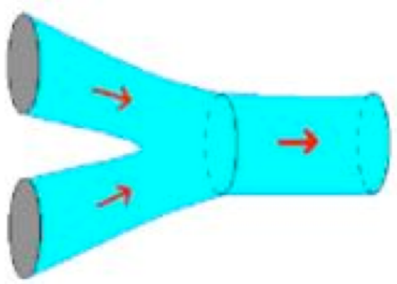


each wavelength...a different – e x t e n d e d – particle.

Plus: get a gravity and the graviton for free!

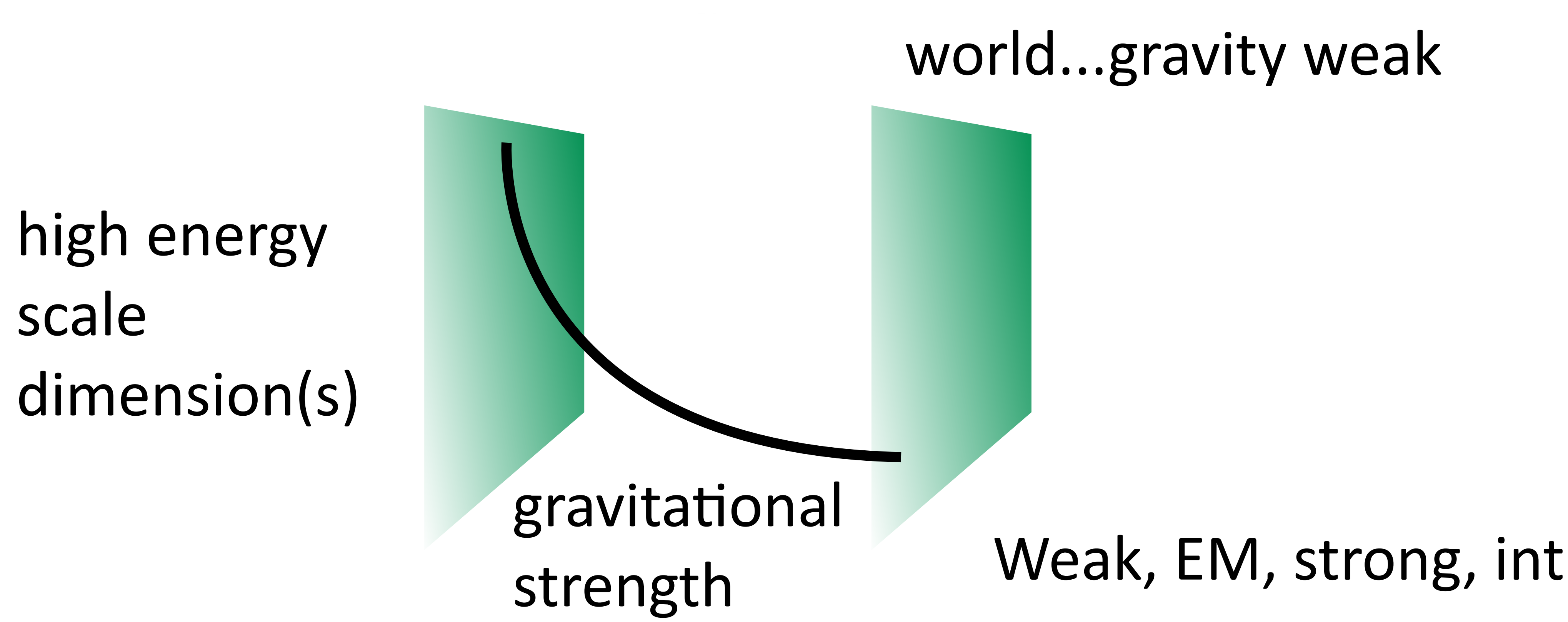


Point particle interaction



String interaction

....up to 10 space and 1 time dimensions.



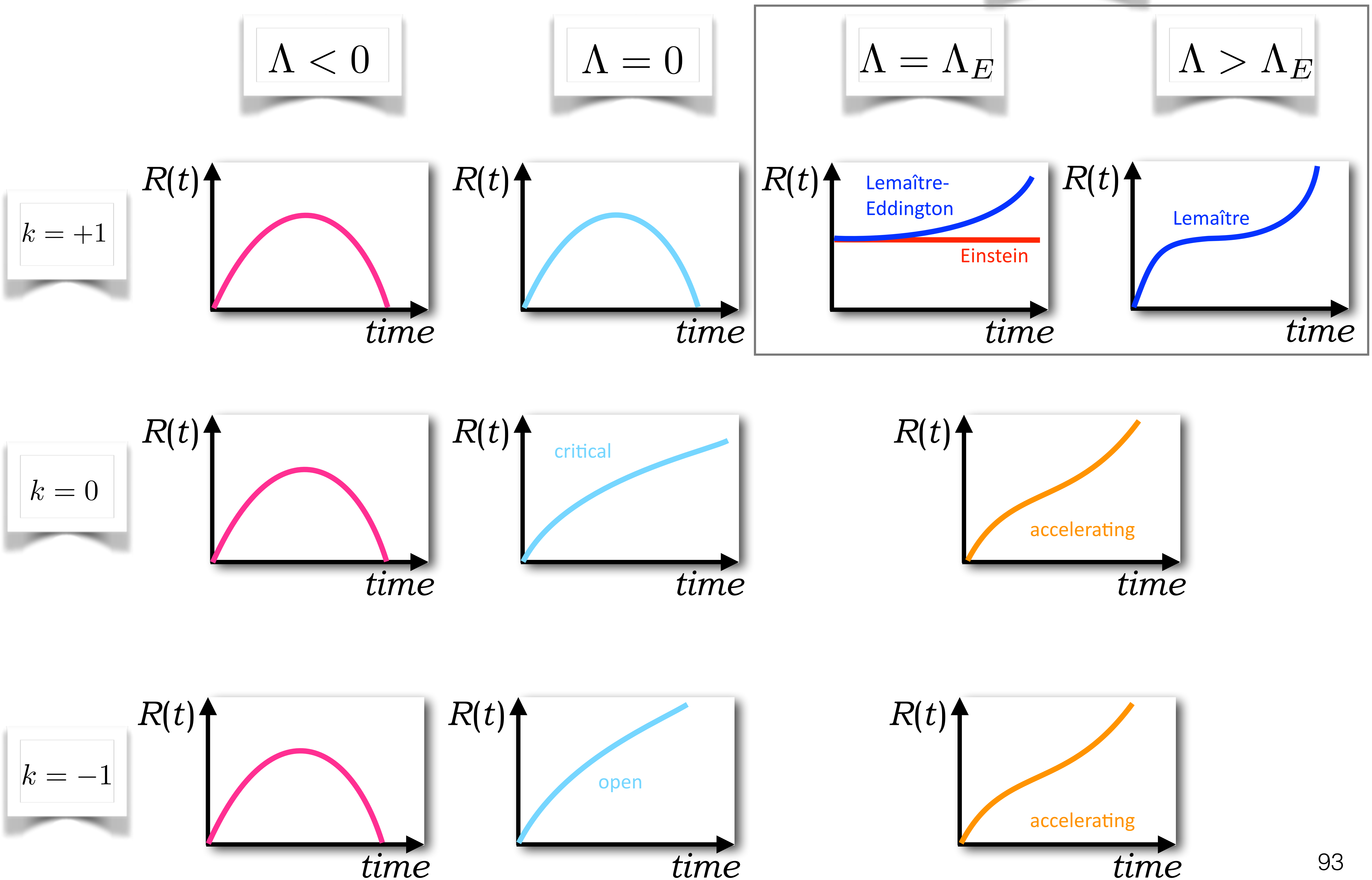
pretty:

hi, again

Day 26, 04.23.2019

Cosmology 5

FLRW catalogue of Universes



three ~~two~~ opposing views

"Steady State Universe"

eternal, matter created out of vacuum to maintain constant energy density...

"Big Bang Universe"

universe began at an instant

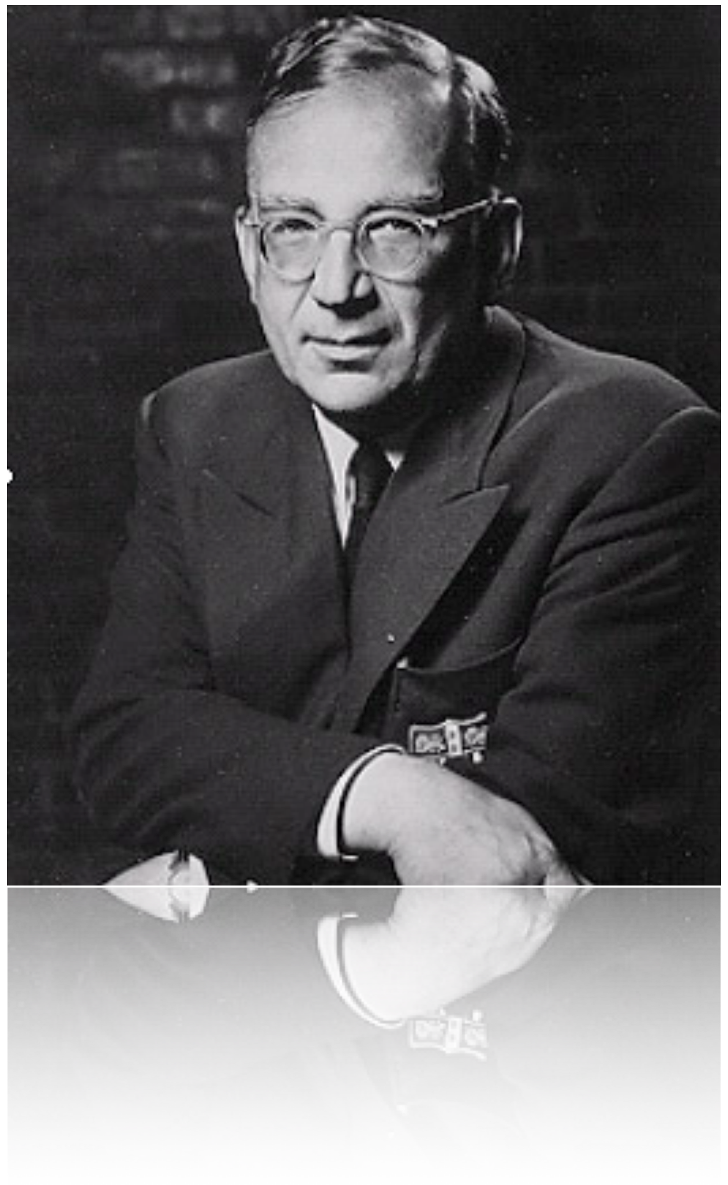
I lied: cyclic universe

over and over...bang and collapse - so eternal and a beginning

George Gamow

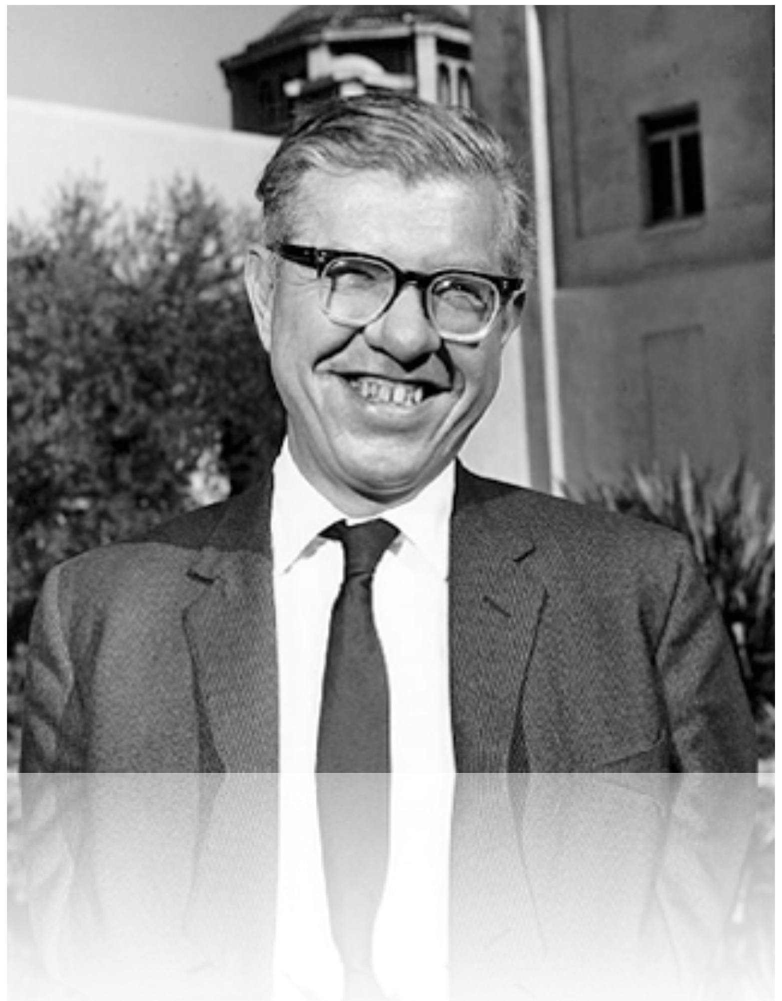
universe born

hot primordial soup



Fred Hoyle

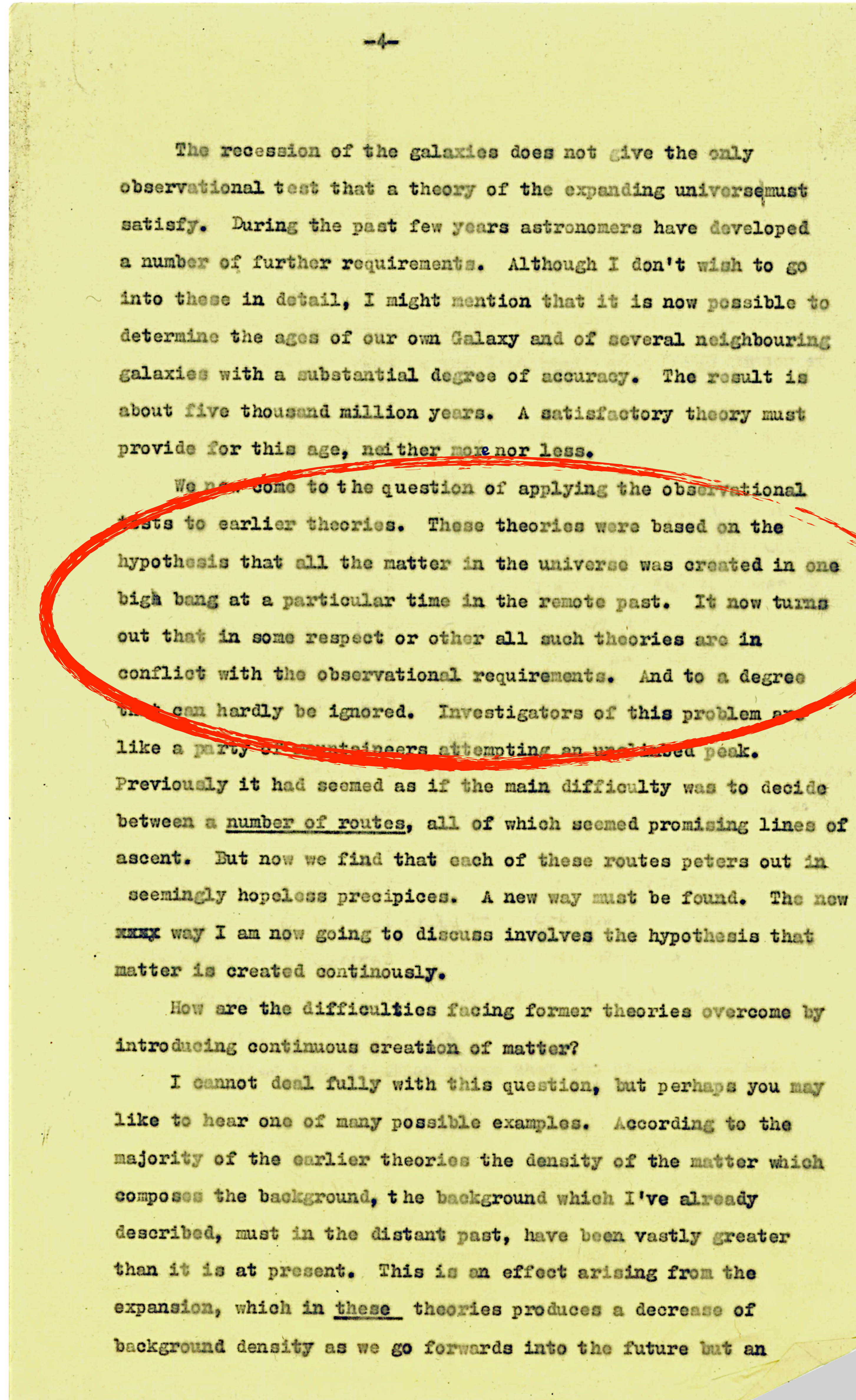
steady state model, continuous creation of matter.



To Hoyle: the Big Bang implied a creator.

‘‘Big Bang’’ was coined by Fred Hoyle in a

BBC radio broadcast for the general public in 1948


-4-

The recession of the galaxies does not give the only observational test that a theory of the expanding universe must satisfy. During the past few years astronomers have developed a number of further requirements. Although I don't wish to go into these in detail, I might mention that it is now possible to determine the ages of our own Galaxy and of several neighbouring galaxies with a substantial degree of accuracy. The result is about five thousand million years. A satisfactory theory must provide for this age, neither more nor less.

We now come to the question of applying the observational tests to earlier theories. These theories were based on the hypothesis that all the matter in the universe was created in one bigh bang at a particular time in the remote past. It now turns out that in some respect or other all such theories are in conflict with the observational requirements. And to a degree that can hardly be ignored. Investigators of this problem are like a party of mountaineers attempting an unclimbed peak. Previously it had seemed as if the main difficulty was to decide between a <u>number of routes</u>, all of which seemed promising lines of ascent. But now we find that each of these routes peters out in seemingly hopeless precipices. A new way must be found. The new ~~xxxx~~ way I am now going to discuss involves the hypothesis that matter is created continously.

How are the difficulties facing former theories overcome by introducing continuous creation of matter?

I cannot deal fully with this question, but perhaps you may like to hear one of many possible examples. According to the majority of the earlier theories the density of the matter which composes the background, the background which I've already described, must in the distant past, have been vastly greater than it is at present. This is an effect arising from the expansion, which in <u>these</u> theories produces a decrease of background density as we go forwards into the future but an

“

Big Bang cosmology is a form of religious fundamentalism ...and this is why these peculiar states of mind have flourished so strongly over the past quarter century. It is the nature of fundamentalism that it should contain a powerful streak of irrationality and that it should not relate, in a verifiable, practical way, to the everyday world. ...it would take an eternity of time to distill even one drop of sense...Big bang cosmology refers to an epoch that cannot be reached from any form of astronomy...

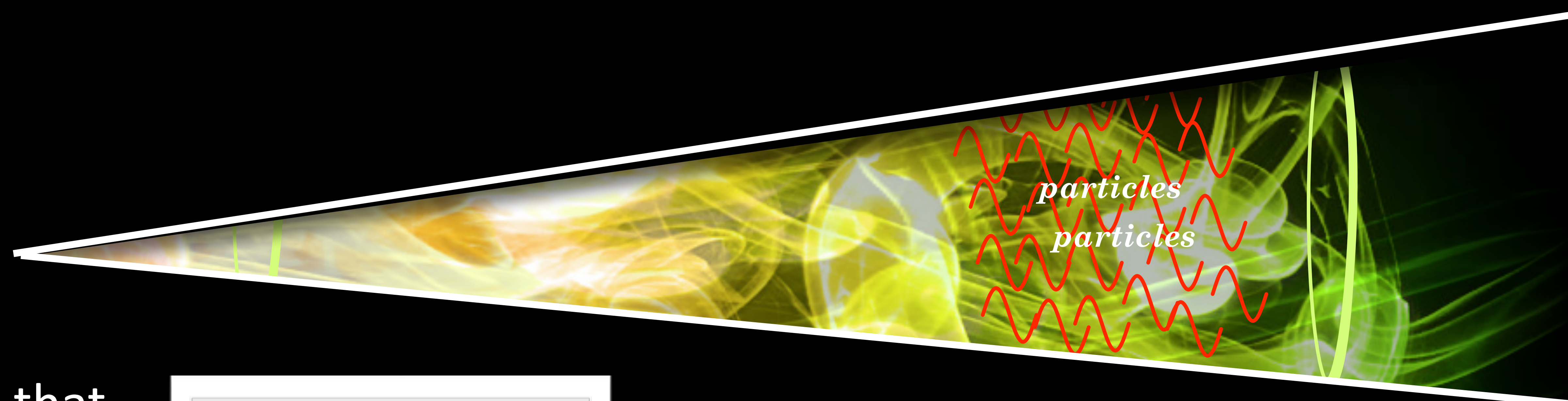
Fred Hoyle
Home is Where the Wind Blows 1994.

Sorry, Fred.

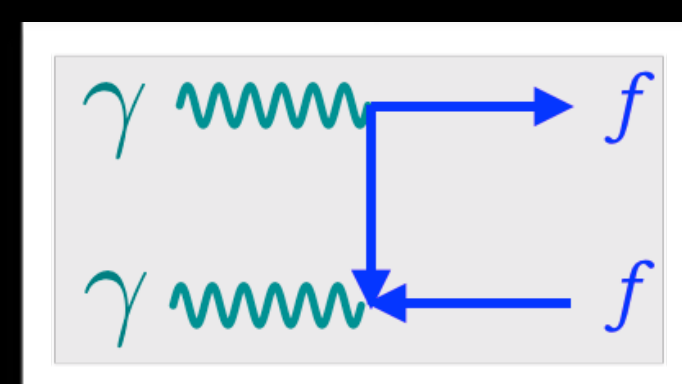
Here's the current understanding of the life of a Universe:

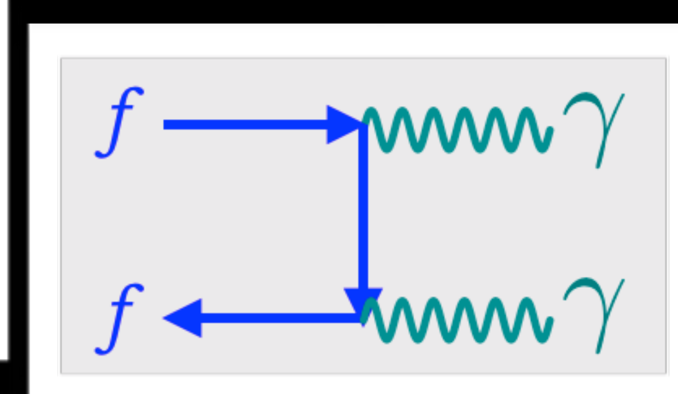
evolving in time and temperature.

elementary particle epoch



presumed that processes are in equilibrium





10^{-36}s 10^{-33}s 10^{-30}s 10^{-27}s 10^{-24}s 10^{-21}s 10^{-18}s 10^{-15}s 10^{-12}s 10^{-9}s 10^{-6}s

10^{22} K 10^{21} K 10^{18} K 10^{15} K

There is a limit

Beyond which there is no physics

at the current time

Planck Time = 5.4×10^{-44} s

Planck Length = 1.6×10^{-35} m

need a quantum theory of gravity

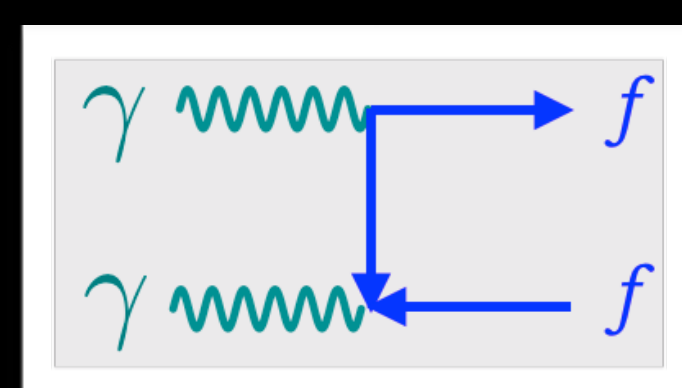
Or a physics with a built-in minimum length in Nature...String Theory.

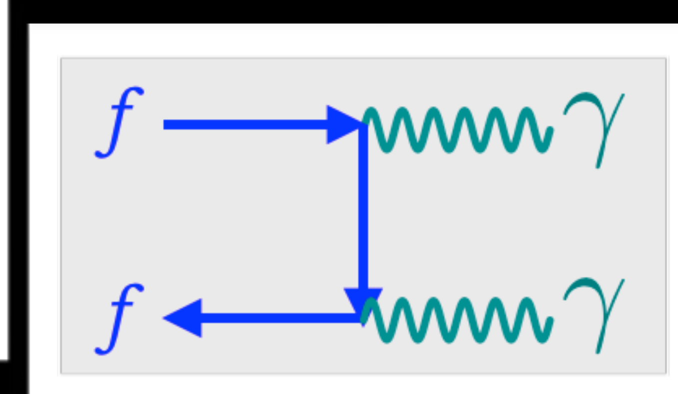
elementary particle epoch

"Quantum Foam"

?

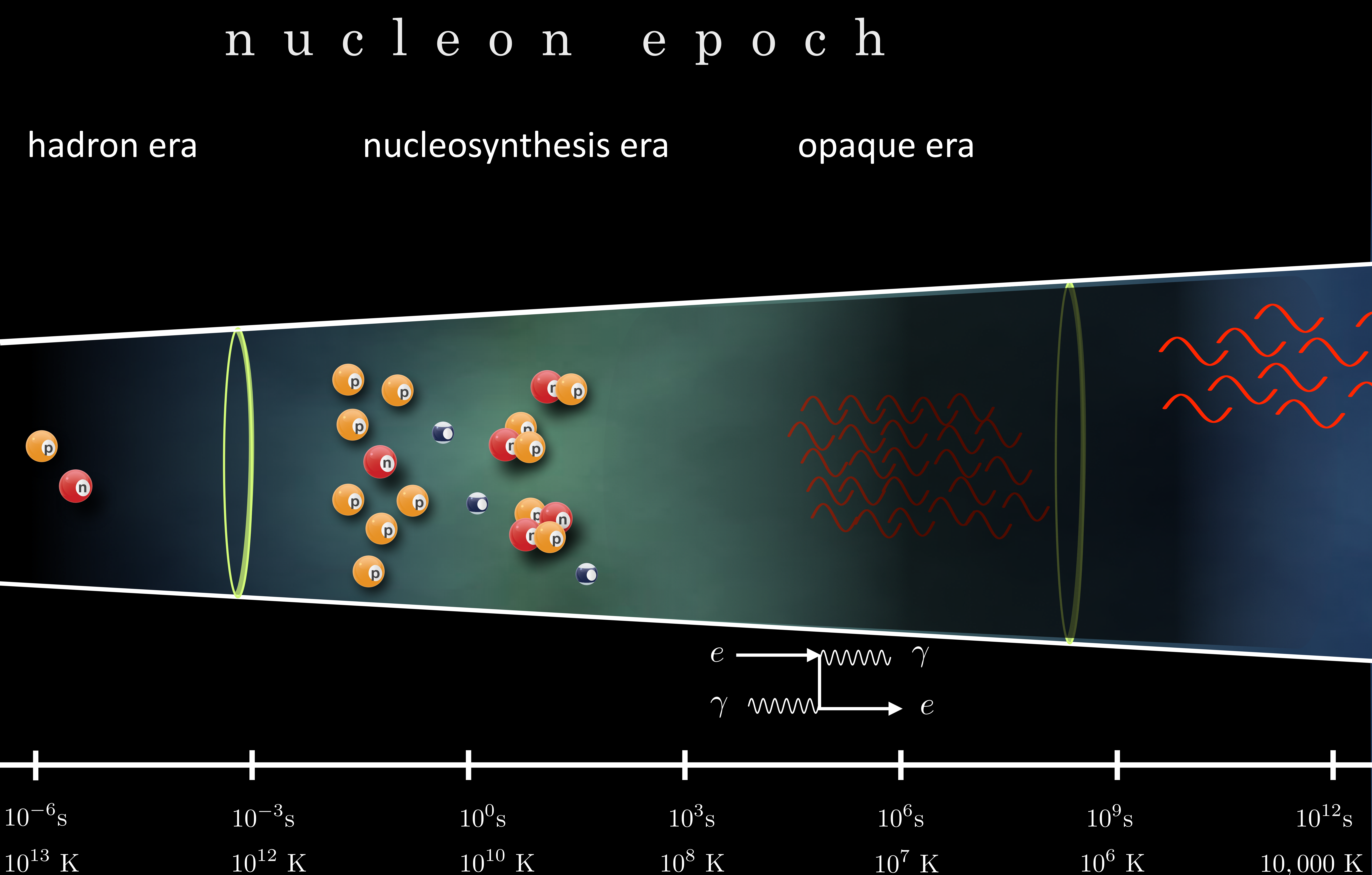
presumed that processes are in equilibrium





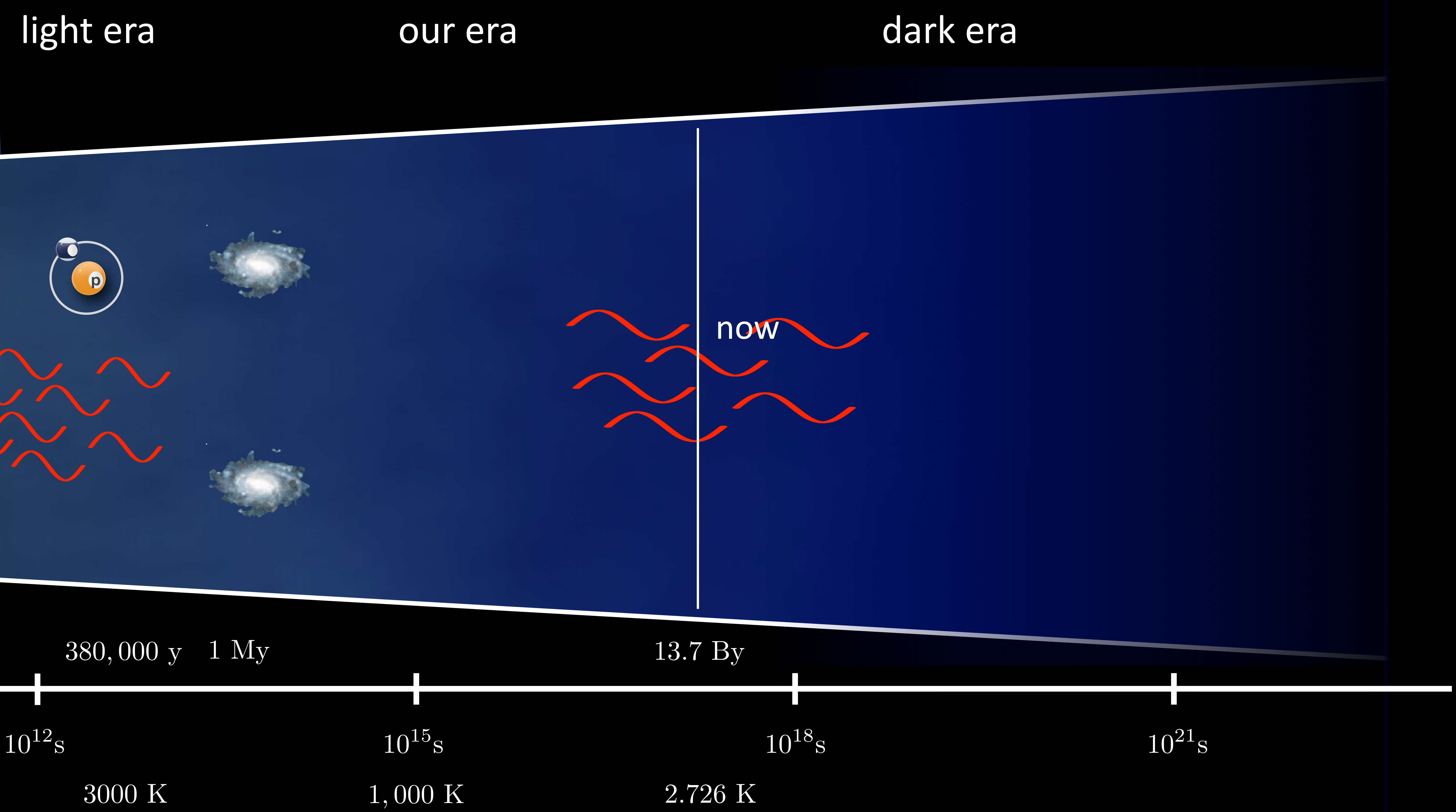
10^{-42}s 10^{-39}s 10^{-36}s 10^{-33}s 10^{-30}s 10^{-27}s 10^{-24}s 10^{-21}s 10^{-18}s 10^{-15}s 10^{-12}s 10^{-9}s 10^{-6}s

10^{22} K 10^{21} K 10^{18} K 10^{15} K

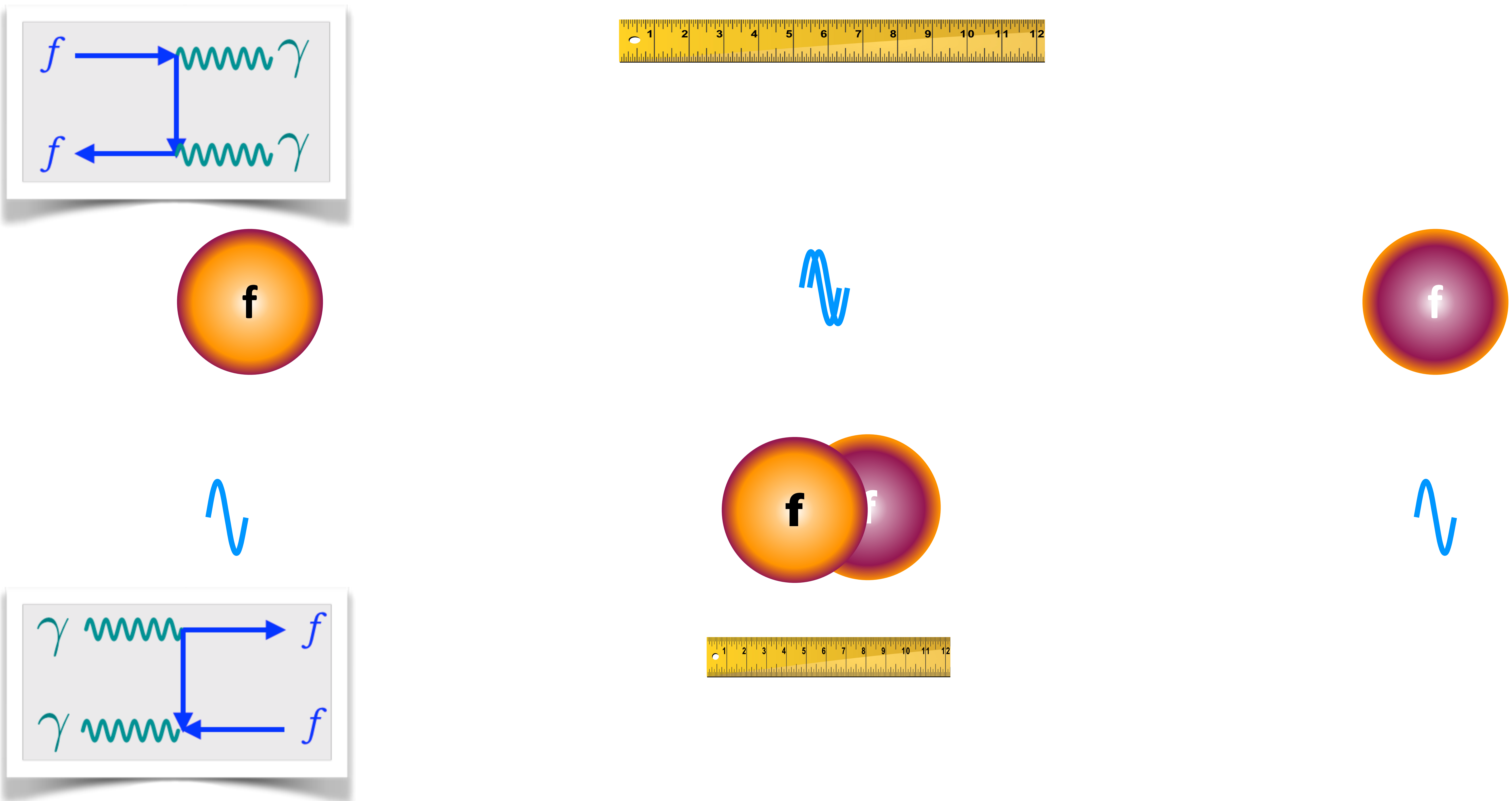


nucleon epoch
hadron era
nucleosynthesis era
opaque era
p
n
e
γ
10^−6 s
10^13 K
10^−3 s
10^12 K
10^0 s
10^10 K
10^3 s
10^8 K
10^6 s
10^7 K
10^9 s
10^6 K
10^12 s
10,000 K

g a l a c t i c   e p o c h



prior to 3 minutes: balance between radiation and particles.



Early moments: short wavelength photons = high frequency photons = high energy photons

lots of mc^2 available–can make heavy particles

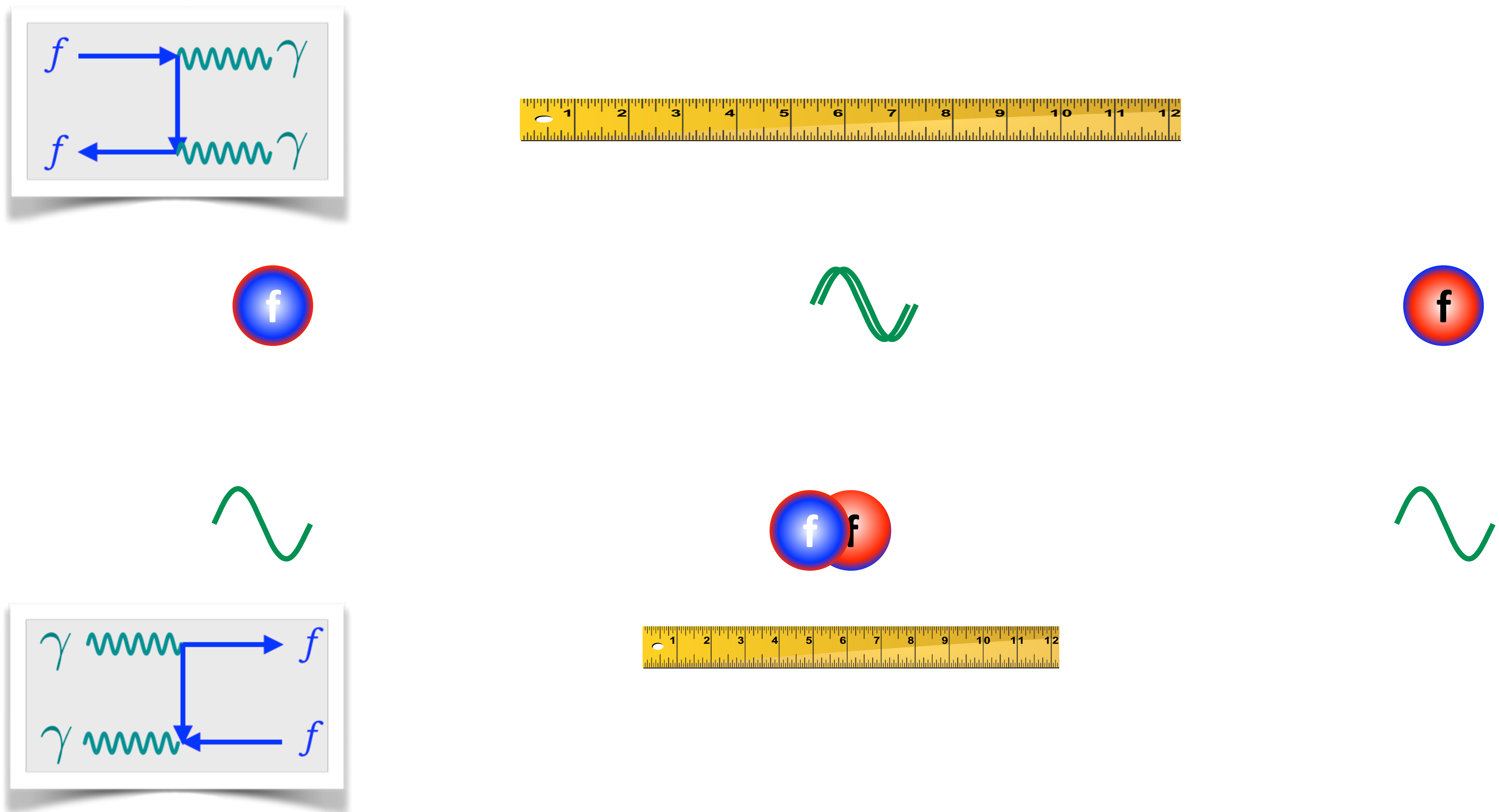
prior to 3 minutes: balance between radiation and particles.

Later moments:

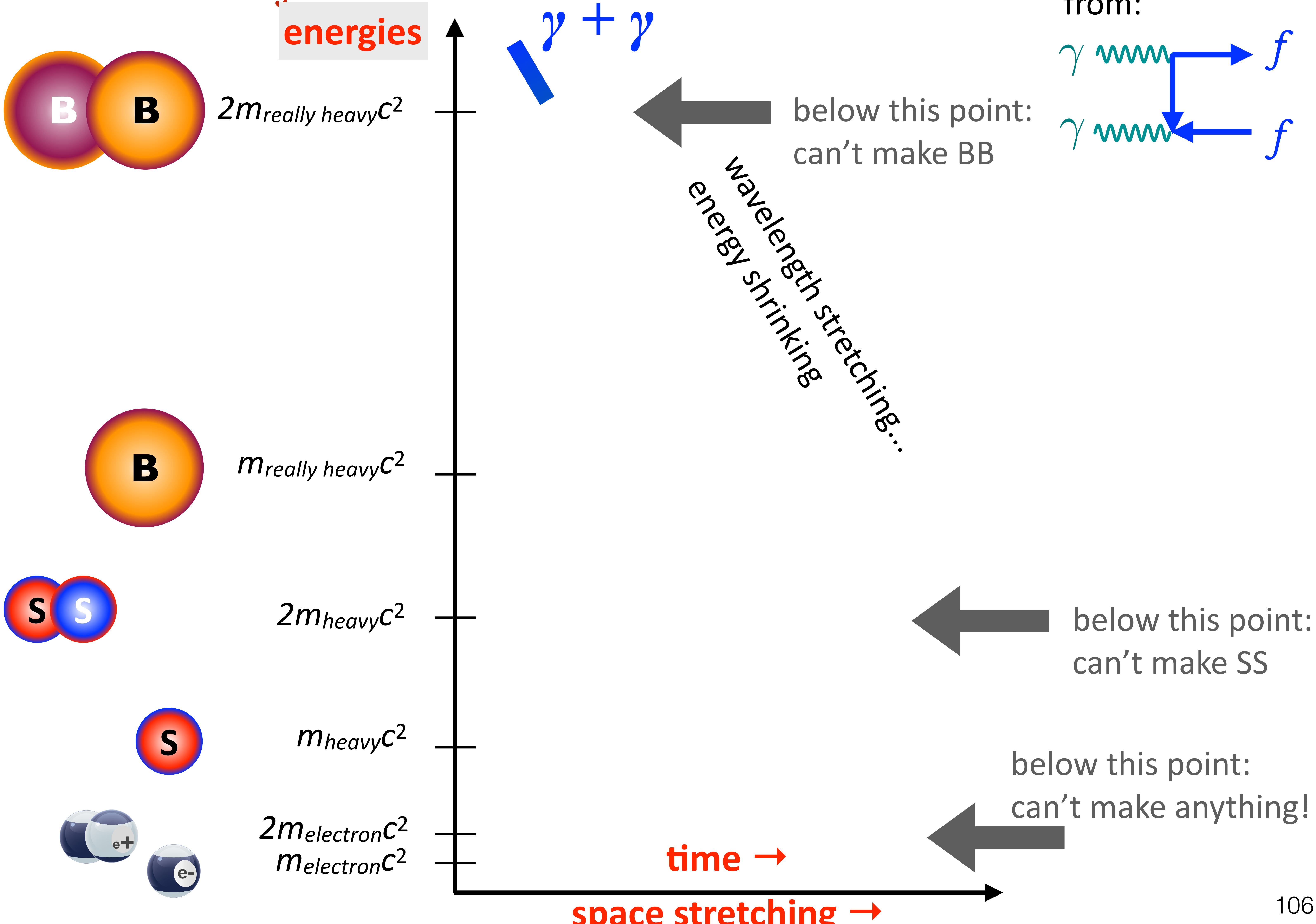
spacetime has stretched!

longer wavelength, lower frequency = less high energy photons

less mc^2 available–can't make heaviest particles

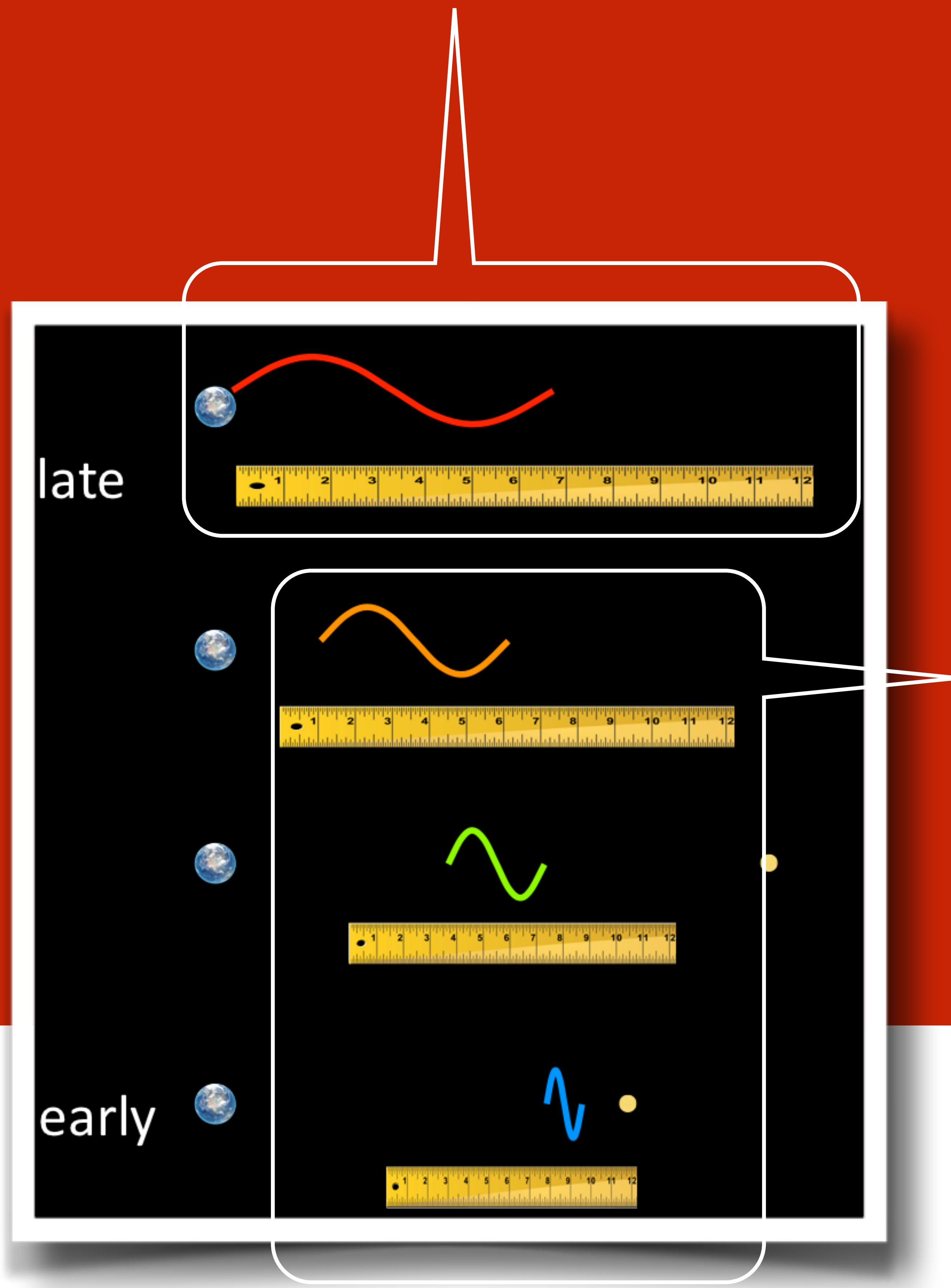


heavy species “freeze out”: pairs cannot be created any more



at some point, they are too low in energy to do anything...they just hang around.
about 70,000 years after BB

remember



many high energy photons: create new particles, ionize atoms, disintegrate nuclei

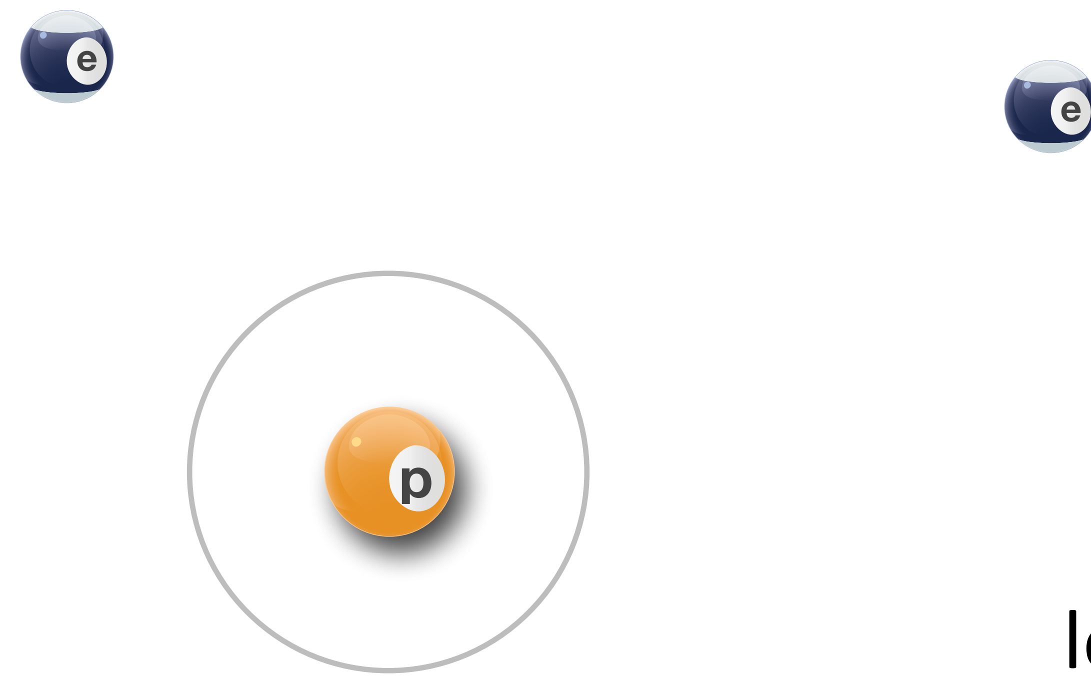
there is a magic point

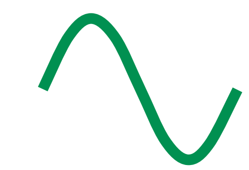
at which atoms can start to form

"recombination"

which is an odd name, since there wasn't a "combination" yet!

After protons, neutrons, and electrons are stable...



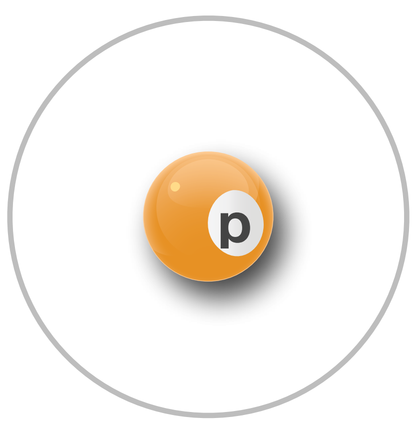


left-over photons ionize the baby Hydrogen atoms

The Universe consists of: a **plasma**...charged particles, unbound...freely moving around. Opaque.

At one point...about $10^{12\text{-}13}$ s - 370,000 y:

the photons don't have 13.6 eV of energy



Bingo.
We have H atoms (and He)

There's nothing else for the photons to do!

The Universe has suddenly become transparent to photons

the photons that are left?

just hanging around

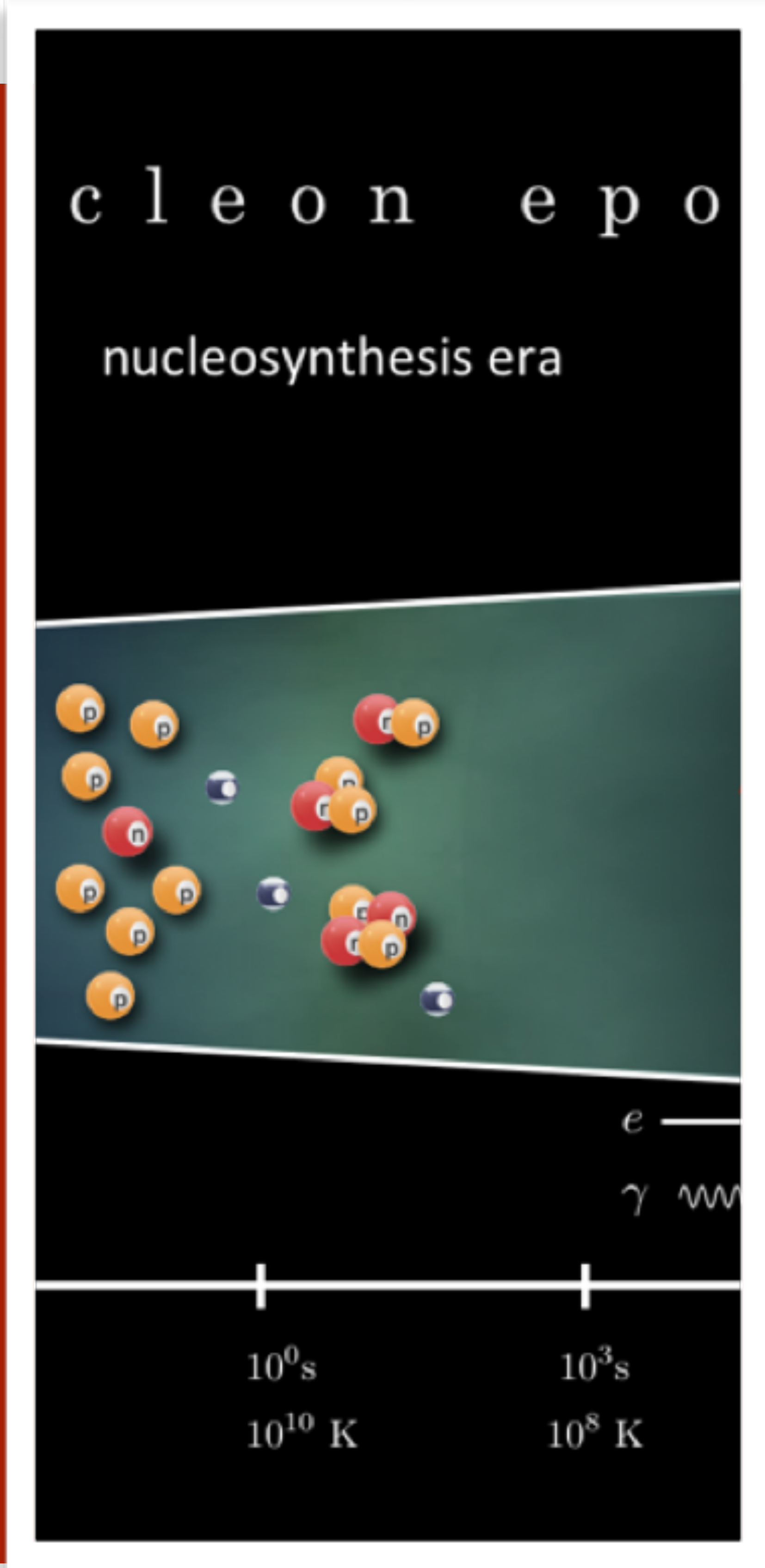
getting "longer," **doing nothing**

no longer making new matter-antimatter bits

The Cosmic Microwave Background, CMB

There are two critical times

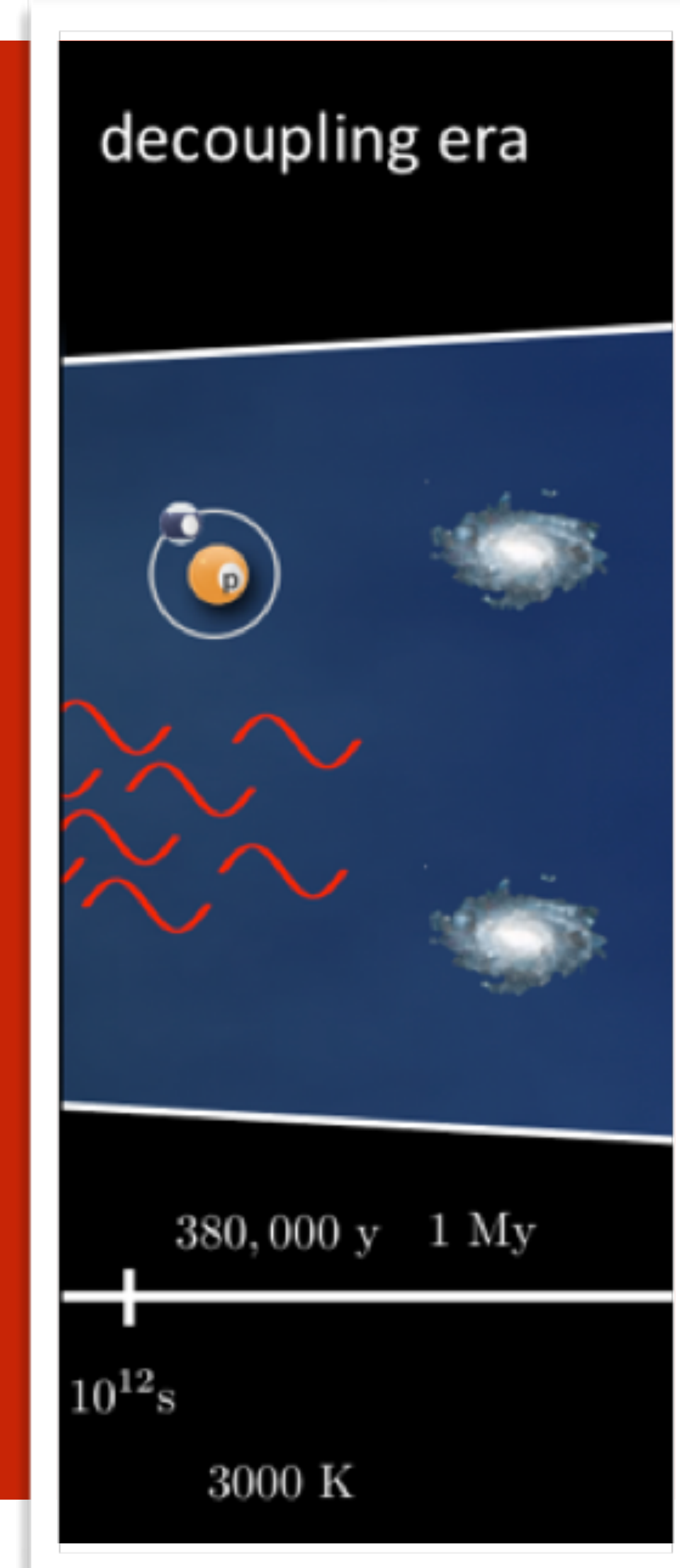
that confirm the Big Bang



3 minutes

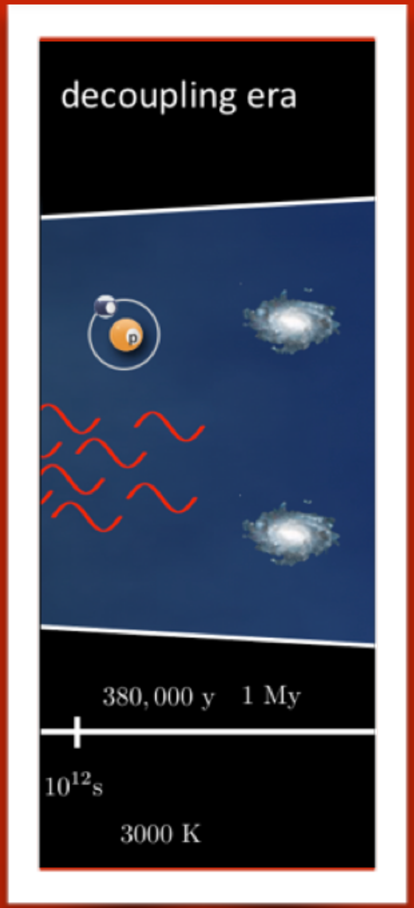
370,000 years

(all within the first 15 fake-minutes on my calendar)



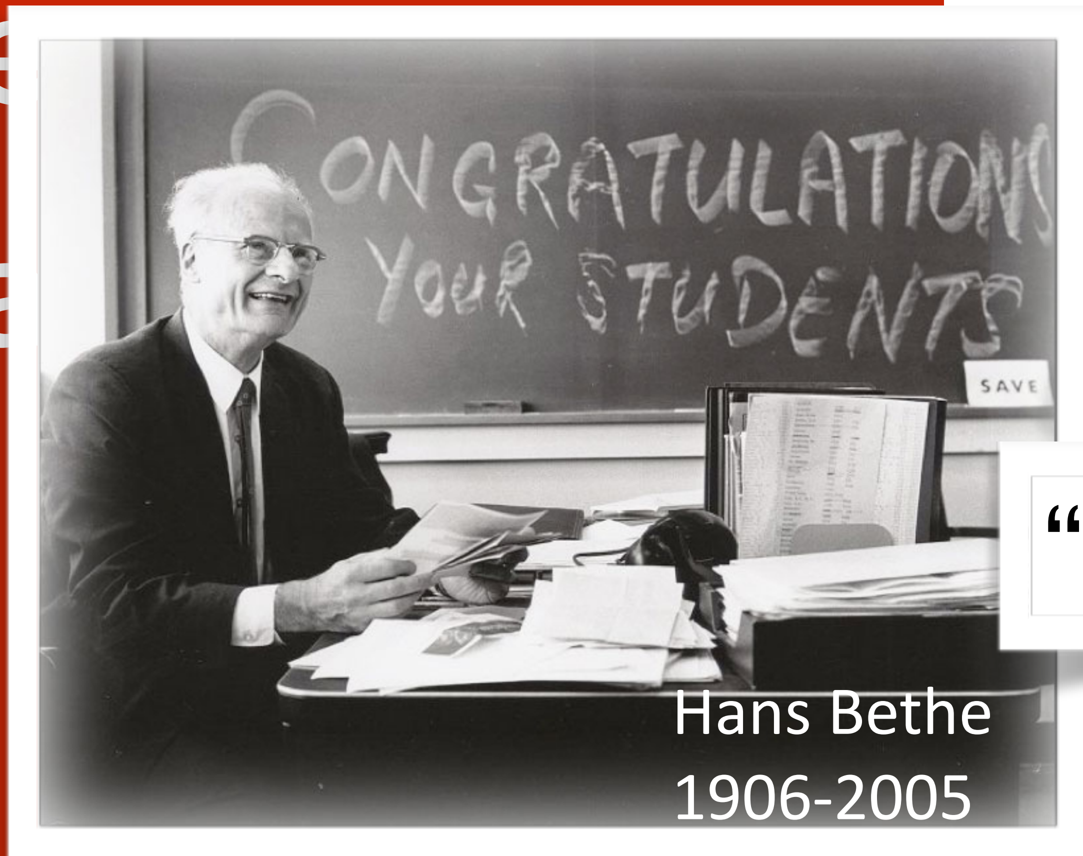
the Cosmic Microwave Background, CMB

about 370,000 y after BB

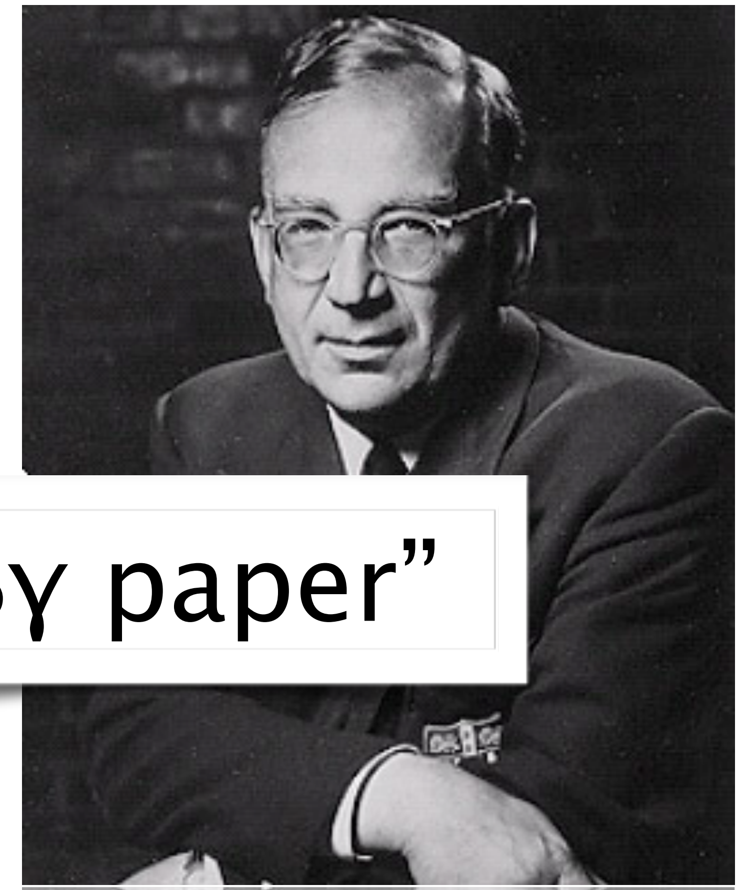


Ge

Ga

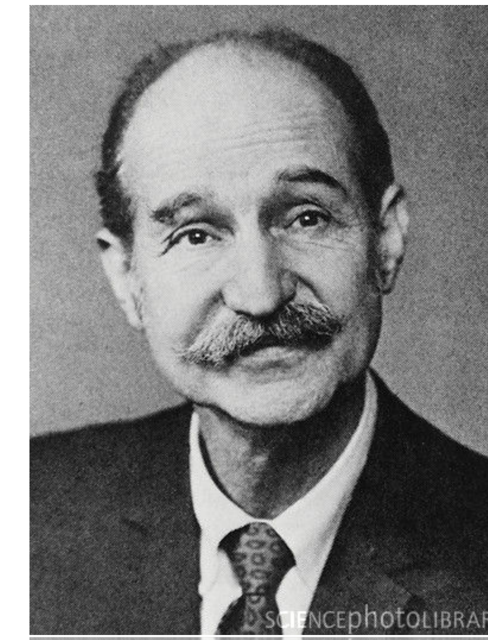


Hans Bethe
1906-2005



"αβγ paper"


Ralph Alpher
1921-2007



Robert Herman
1914 - 1997

predicted this left-over radiation

those left over photons would have started out hot...

but cooled as the Universe expanded

1948 with collaborators Alpher and Herman: predicted a left-over electromagnetic radiation

Alpher and Herman predicted it would be distributed across the Universe in a **Blackbody Spectrum** shape at a temperature of 5^0 K...microwaves

nobody paid attention...or remembered.

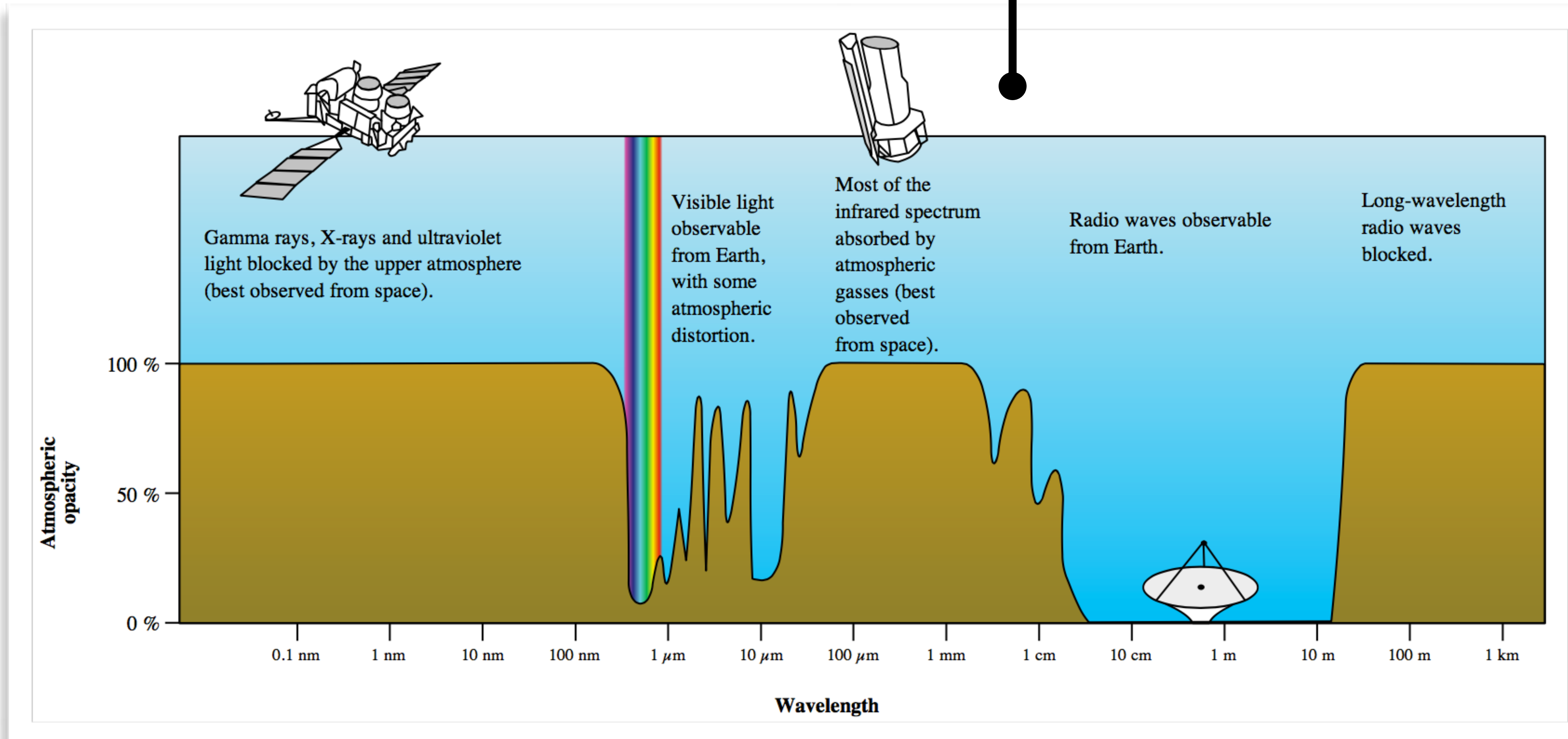
1993, the National Academy of Sciences gave Alpher and Herman the Henry Draper Medal

so, all these cold photons left

the phone company was the hero

satellite communications are usually microwaves

where we're going



ATT cell phone frequencies of

~2 GHz

~15 cm

microwave ovens

the phone company

ATT Labs, Crawford Hill, New Jersey

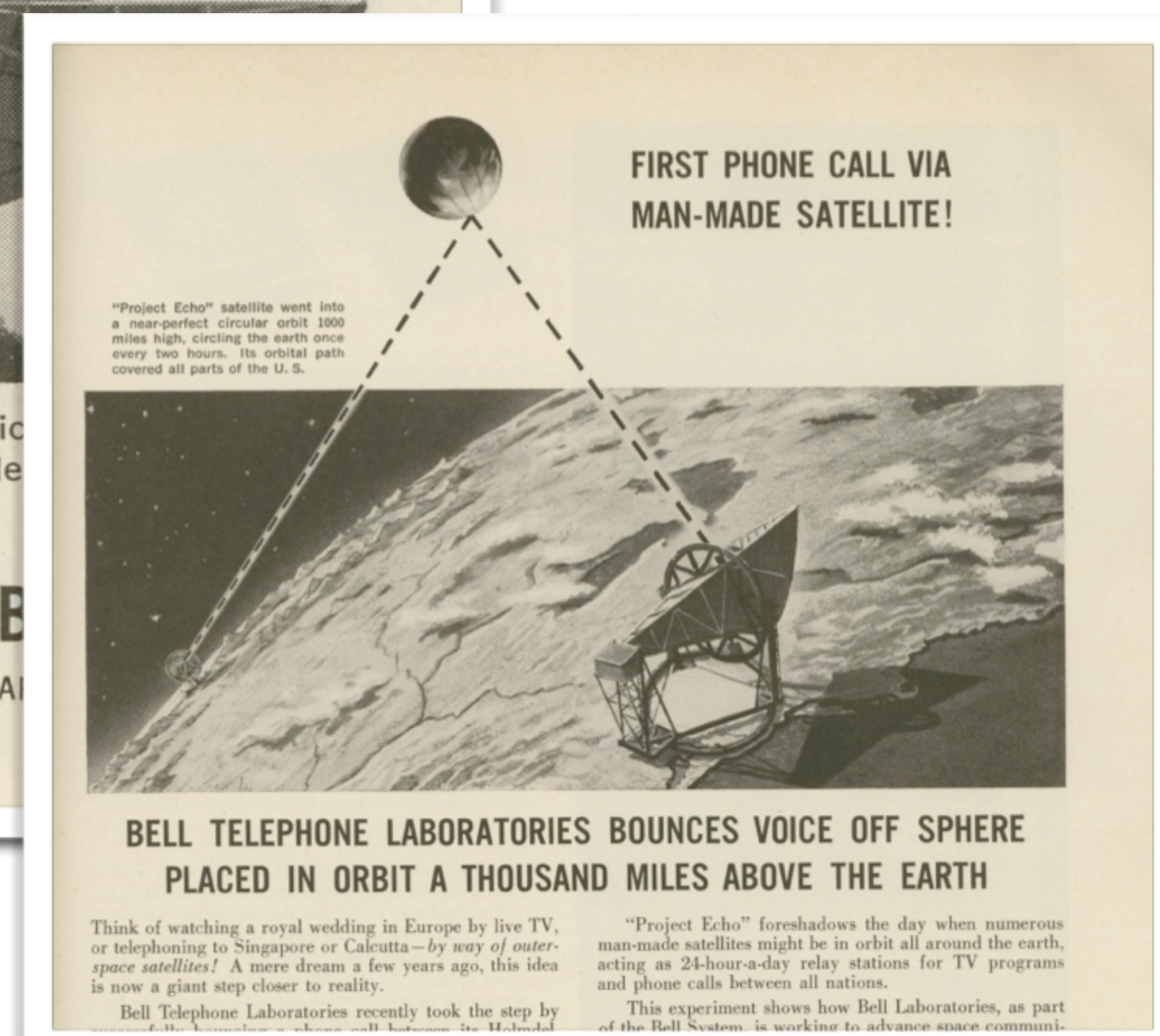
1963

Arno Penzias

Robert Wilson

sensitive to wavelengths of 7.35 cm, 4000MHz

Echo

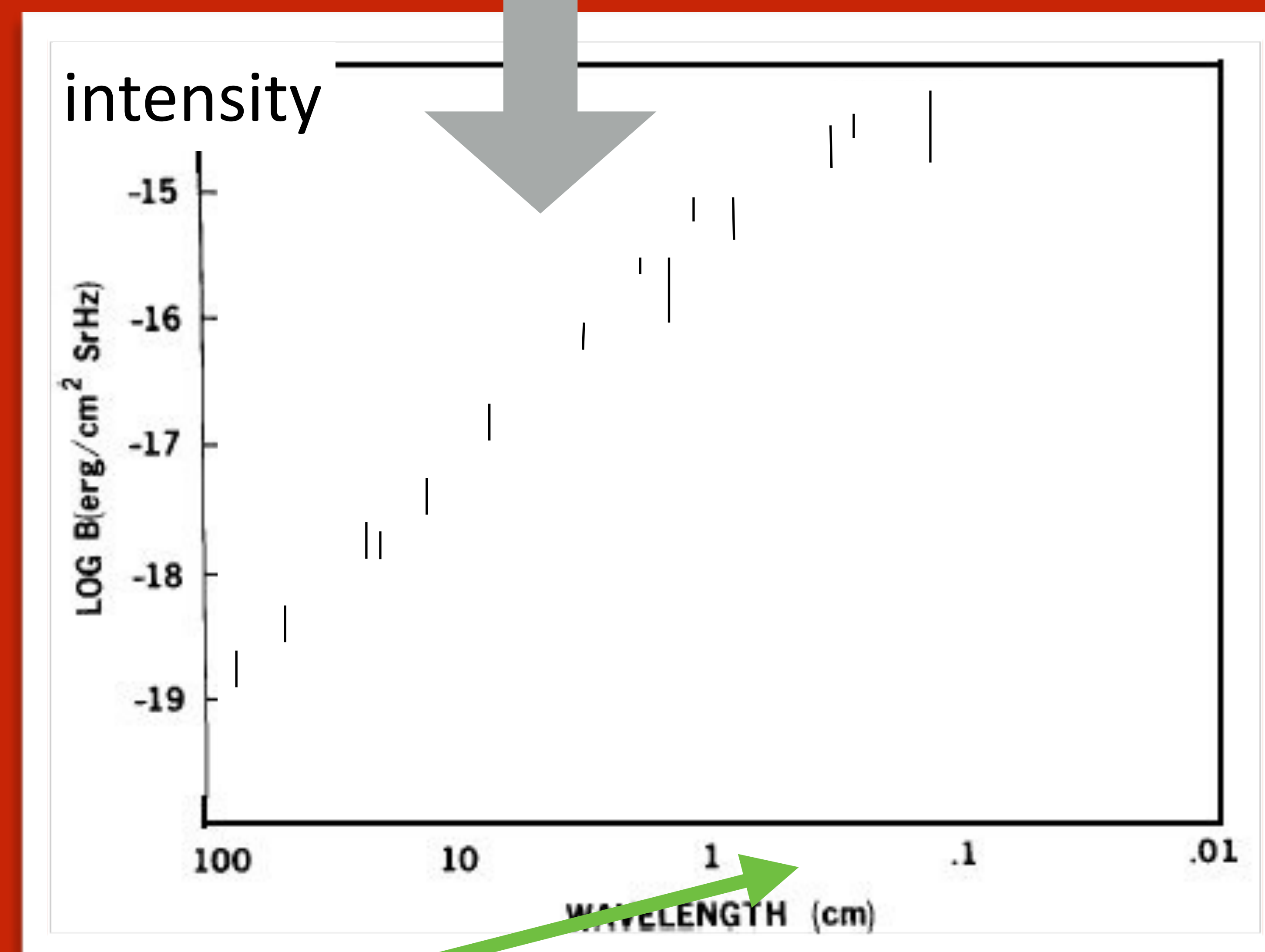


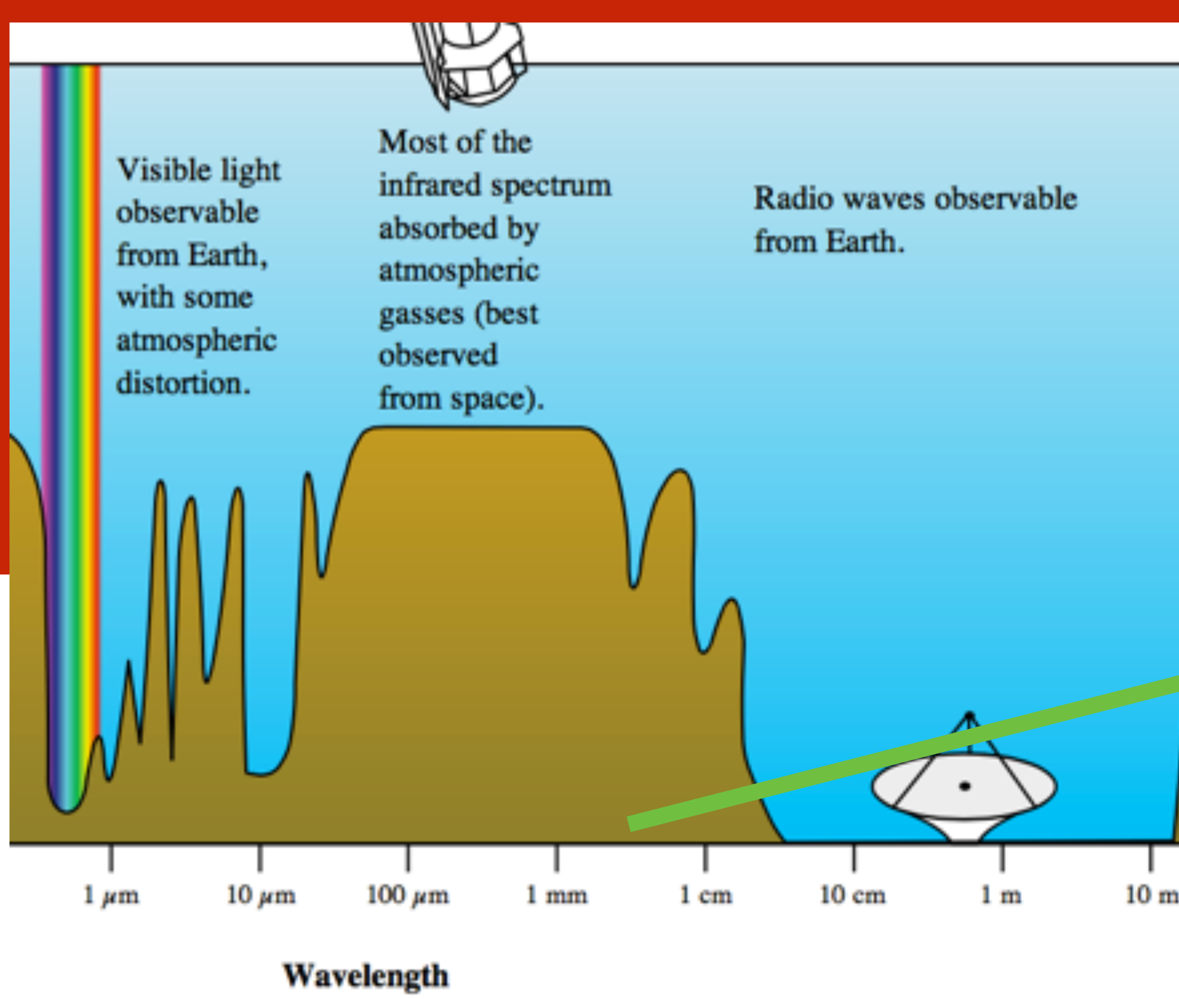
Penzias/Wilson wavelength

microwave hiss

everywhere...

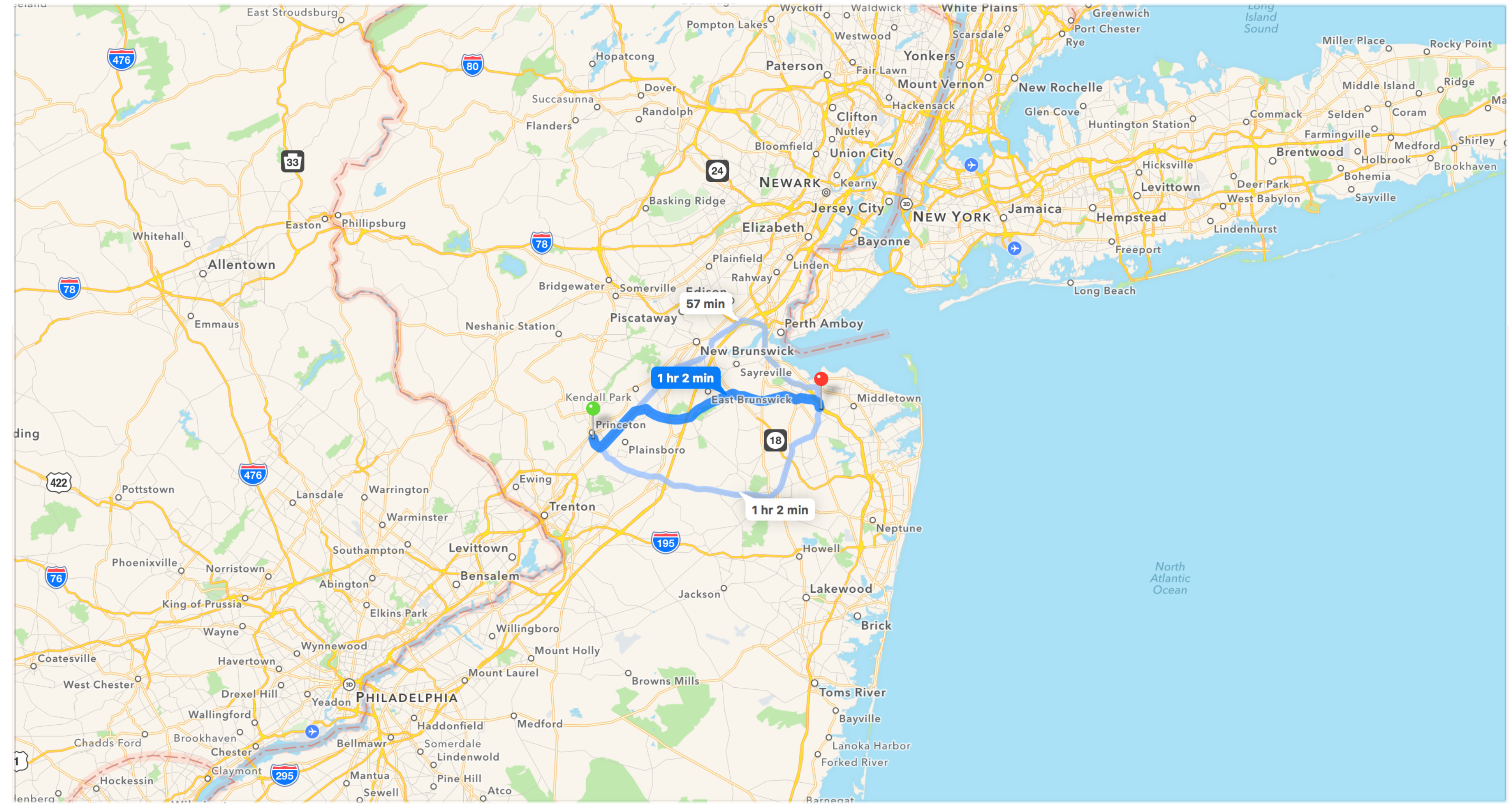
with a special frequency distribution





atmosphere becoming opaque

down the road



Jim Peebles and students, David Todd Wilkinson and Peter G. Roll

redid Gamow's calculation…forgetting that it had been done!

Robert Dicke was thinking of building a receiver

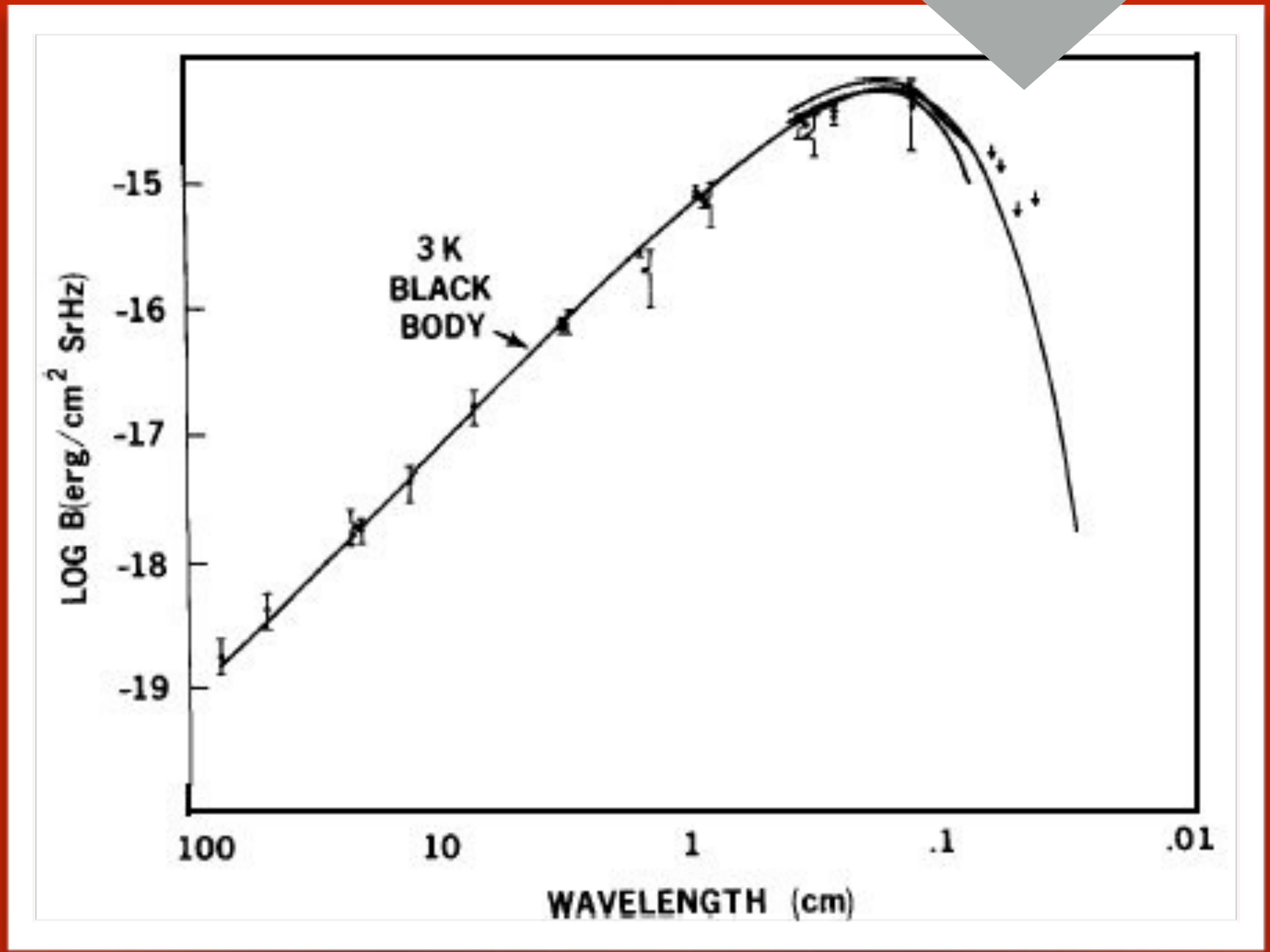
Penzias called Dicke…

balloons to get above atmosphere to measure infrared wavelengths

a blackbody spectrum

of ~3K above absolute zero

the peak is limited by the atmosphere



Penzias and Wilson 1978

gave credit to the deceased George Gamow.