

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

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

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

# 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](mailto: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](mailto:mcarlson@msu.edu), (517)432-5936).





# I had a section 2

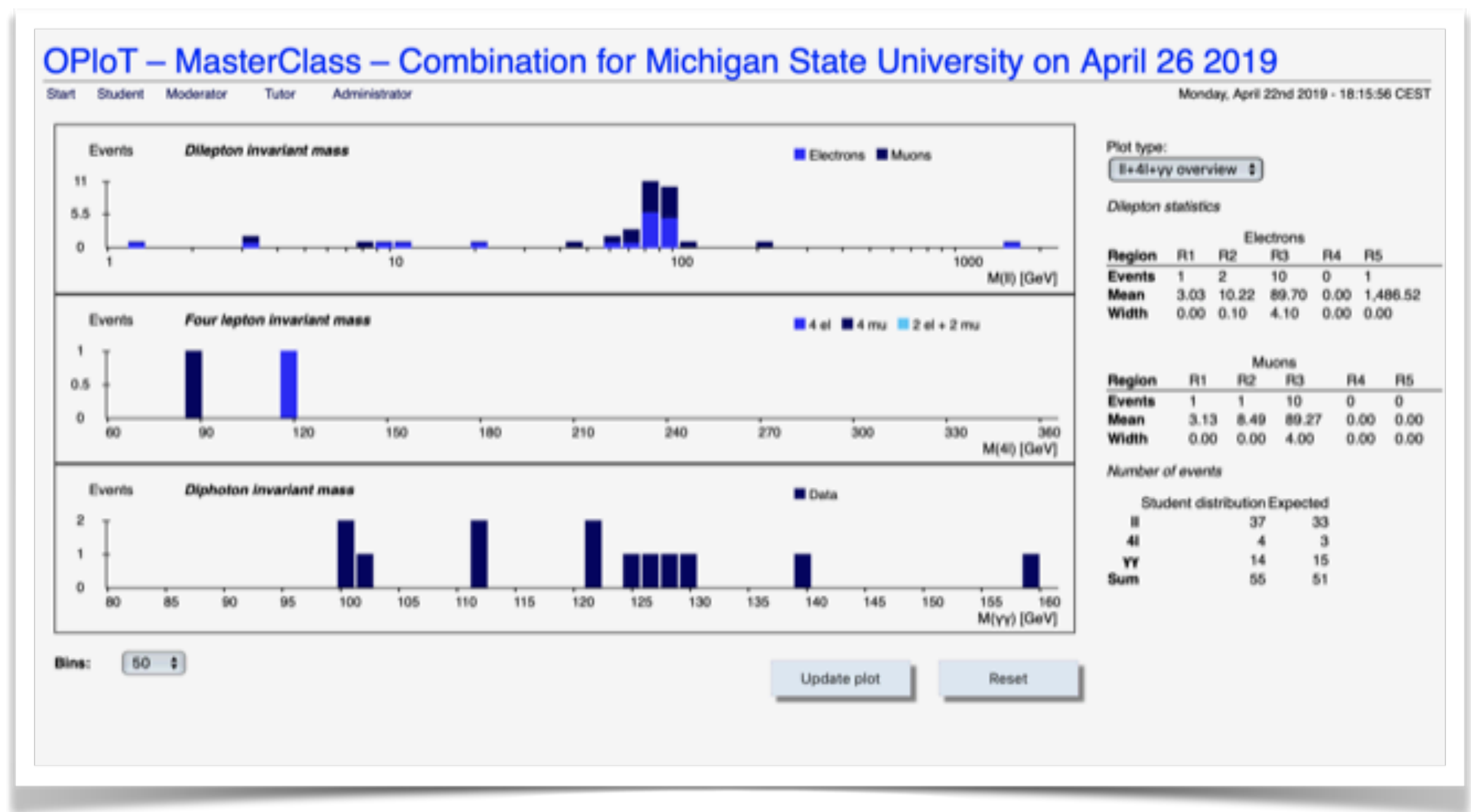
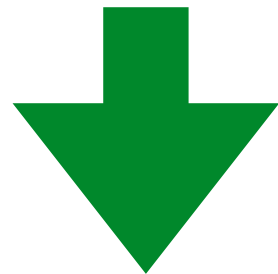
Thanks, Benjamin!



Benjamin got uploading Hypatia data to work fine.

Thanks!

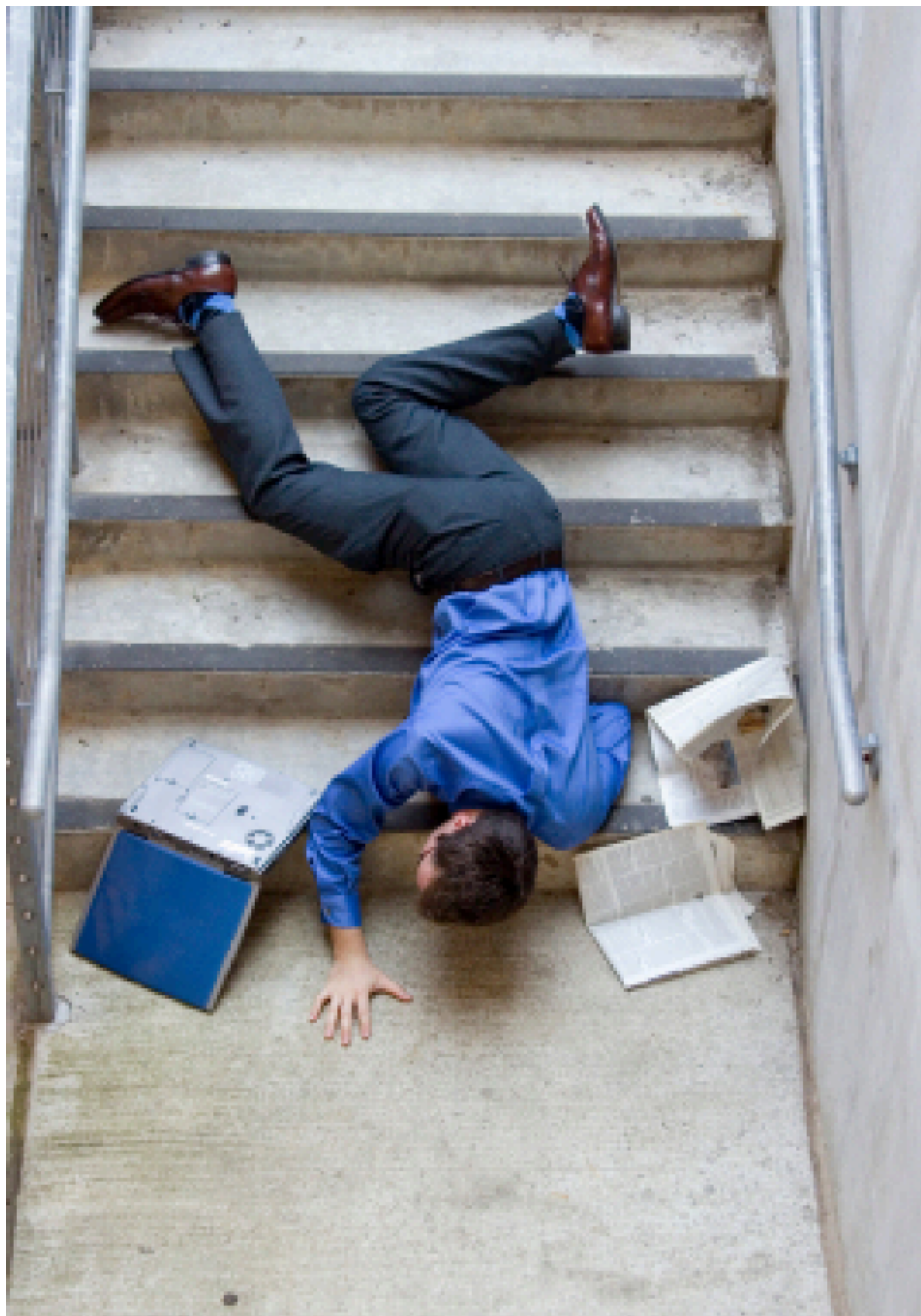
go there















**KEEP  
CALM  
AND  
LET'S  
REVIEW**

# the weak interactions

still operate with  
the increased  
doublet sets

The complete (circa 2000) particle doublets:

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

# 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                                                                                                              | $\nu_e$                                  | $e$                                 | $\nu_\mu$                                | $\mu$                               | $\nu_\tau$                               | $\tau$                              |
|----------------------------------------------------------------------------------------------------------------------|------------------------------------------|-------------------------------------|------------------------------------------|-------------------------------------|------------------------------------------|-------------------------------------|
| strong<br><br>$g$               | <span style="color: red;">✗</span>       | <span style="color: red;">✗</span>  | <span style="color: red;">✗</span>       | <span style="color: red;">✗</span>  | <span style="color: red;">✗</span>       | <span style="color: red;">✗</span>  |
| electromagnetic<br><br>$\gamma$ | <span style="color: red;">✗</span>       | <span style="color: blue;">✓</span> | <span style="color: red;">✗</span>       | <span style="color: blue;">✓</span> | <span style="color: red;">✗</span>       | <span style="color: blue;">✓</span> |
| weak<br><br>$W$                 | <span style="color: blue;">✓</span>      | <span style="color: blue;">✓</span> | <span style="color: blue;">✓</span>      | <span style="color: blue;">✓</span> | <span style="color: blue;">✓</span>      | <span style="color: blue;">✓</span> |
| gravitational                                                                                                        | <span style="color: lightblue;">✓</span> | <span style="color: blue;">✓</span> | <span style="color: lightblue;">✓</span> | <span style="color: blue;">✓</span> | <span style="color: lightblue;">✓</span> | <span style="color: blue;">✓</span> |



# 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<br> $g$               | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| electromagnetic<br> $\gamma$ | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| weak<br> $W$                 | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| gravitational                                                                                                     | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |

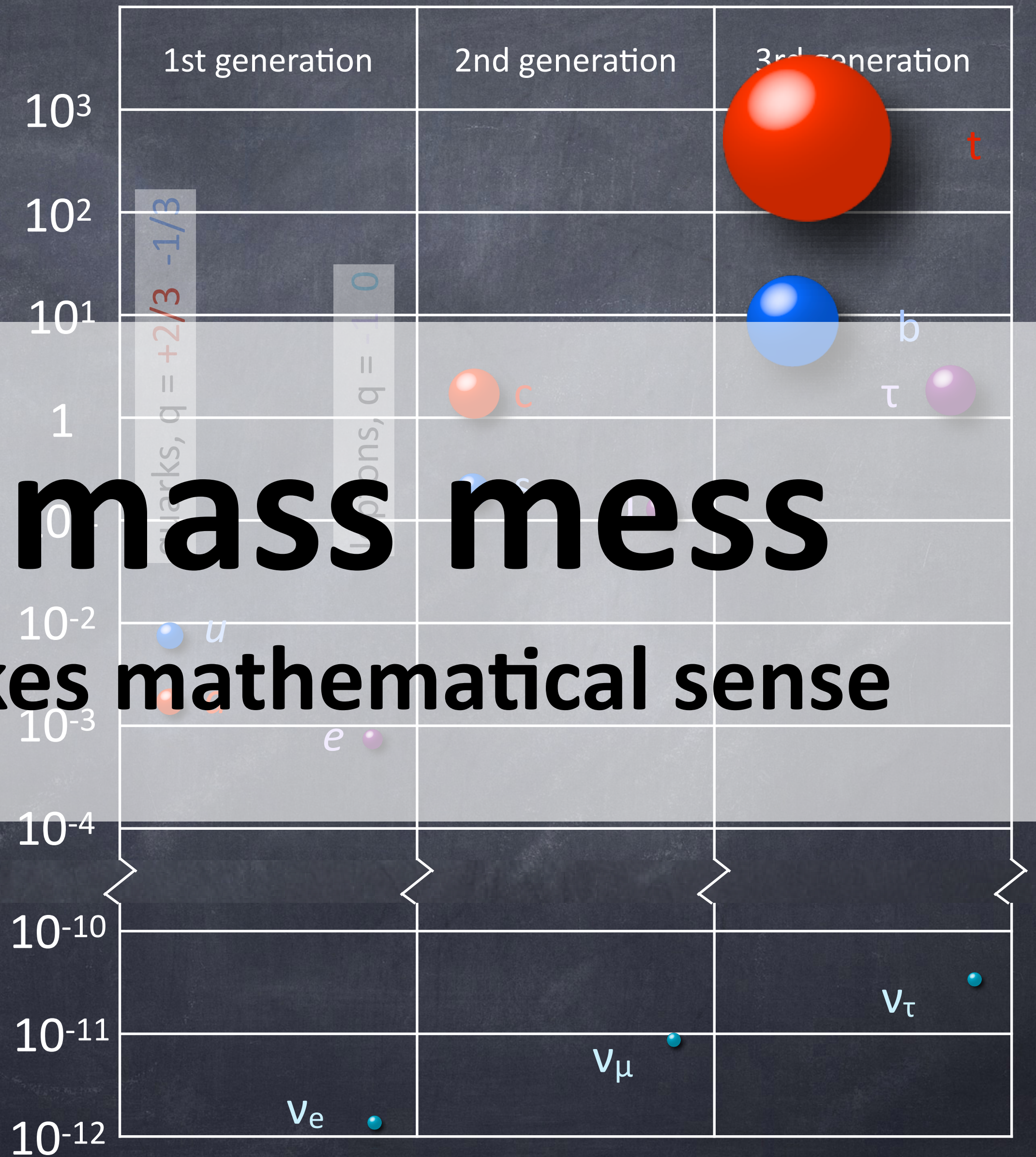


# quarks & leptons

proton masses

# this mass mess

$m=0$  makes mathematical sense





# shifting gears

the weak and electromagnetic forces are one.



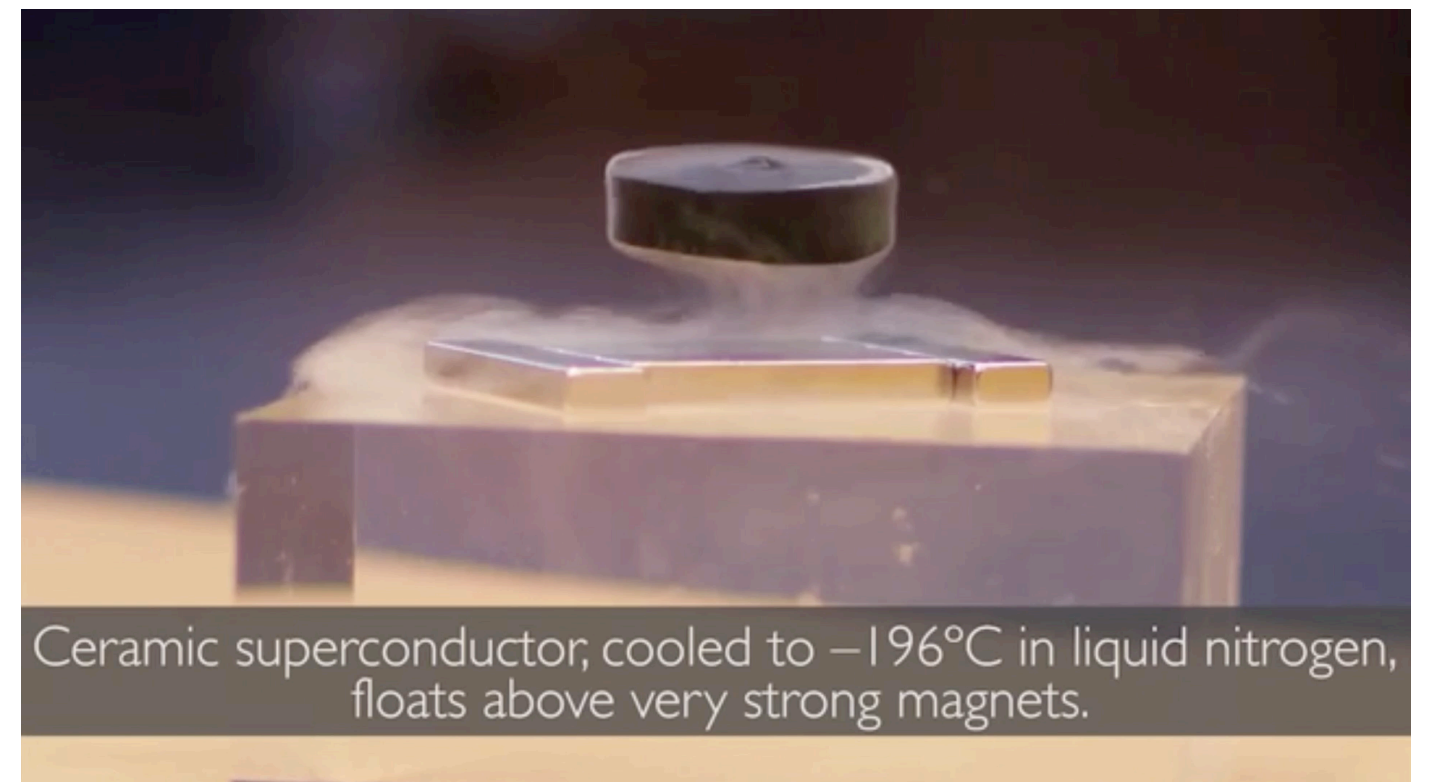


# why

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



Superconductivity  
room temperature, insulator  
below 1.9 K - superconducting  
LHC magnets, NSCL cyclotron



Superfluidity

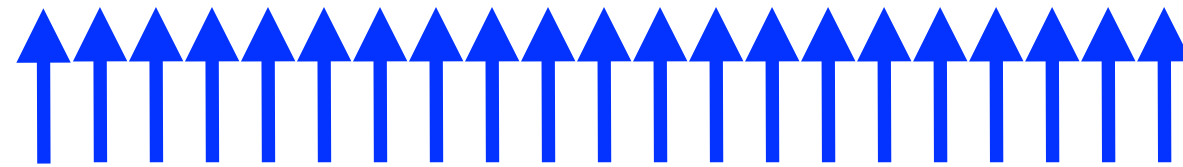
4.2 K - liquifies

2.17 K - superfluid

a little  
model of an  
*ideal*  
ferromagnet

in one -  
dimension

At a low temperature – like room temperature:

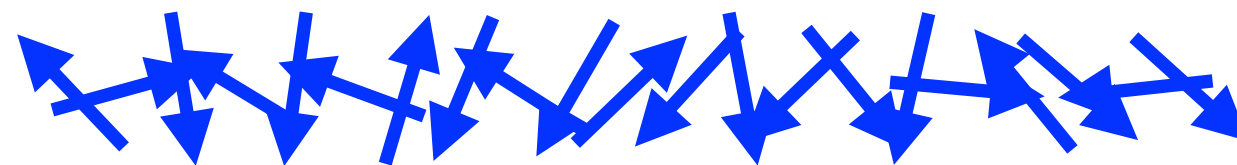


**M** is maximum

**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

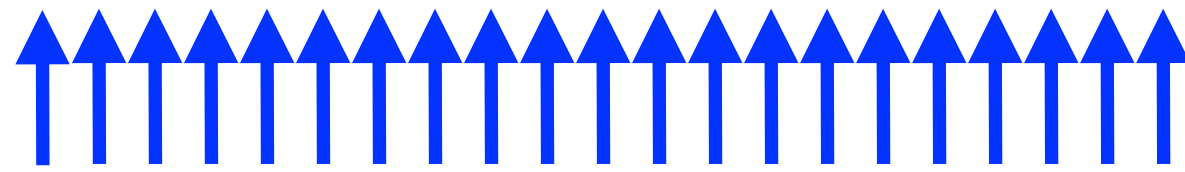
H



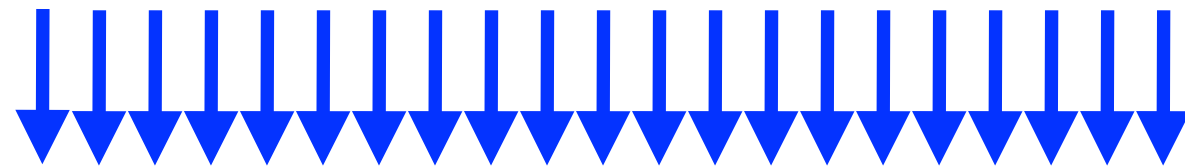
$$M = 0$$

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

C

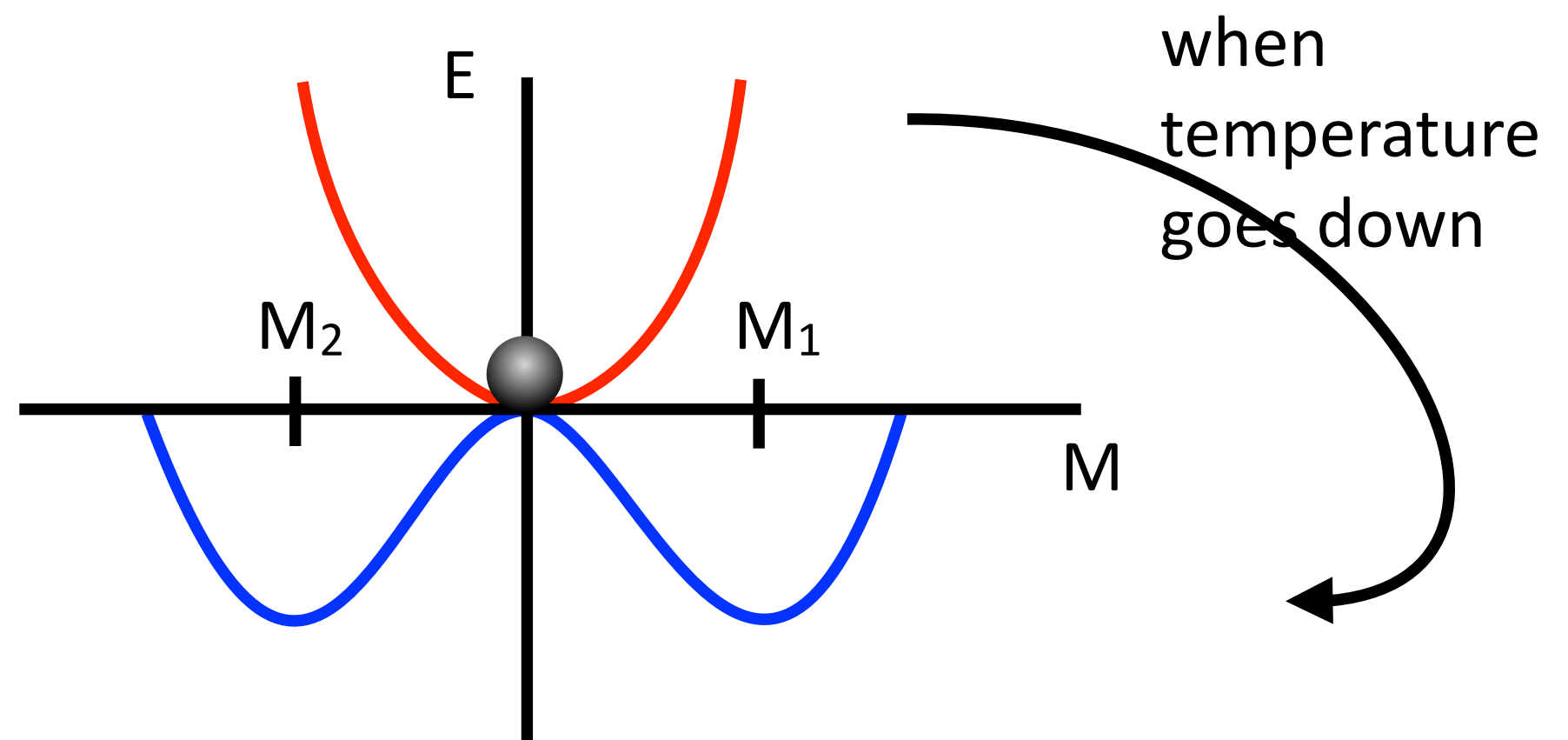


$$M_1 \neq 0$$



$$M_2 \neq 0$$

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



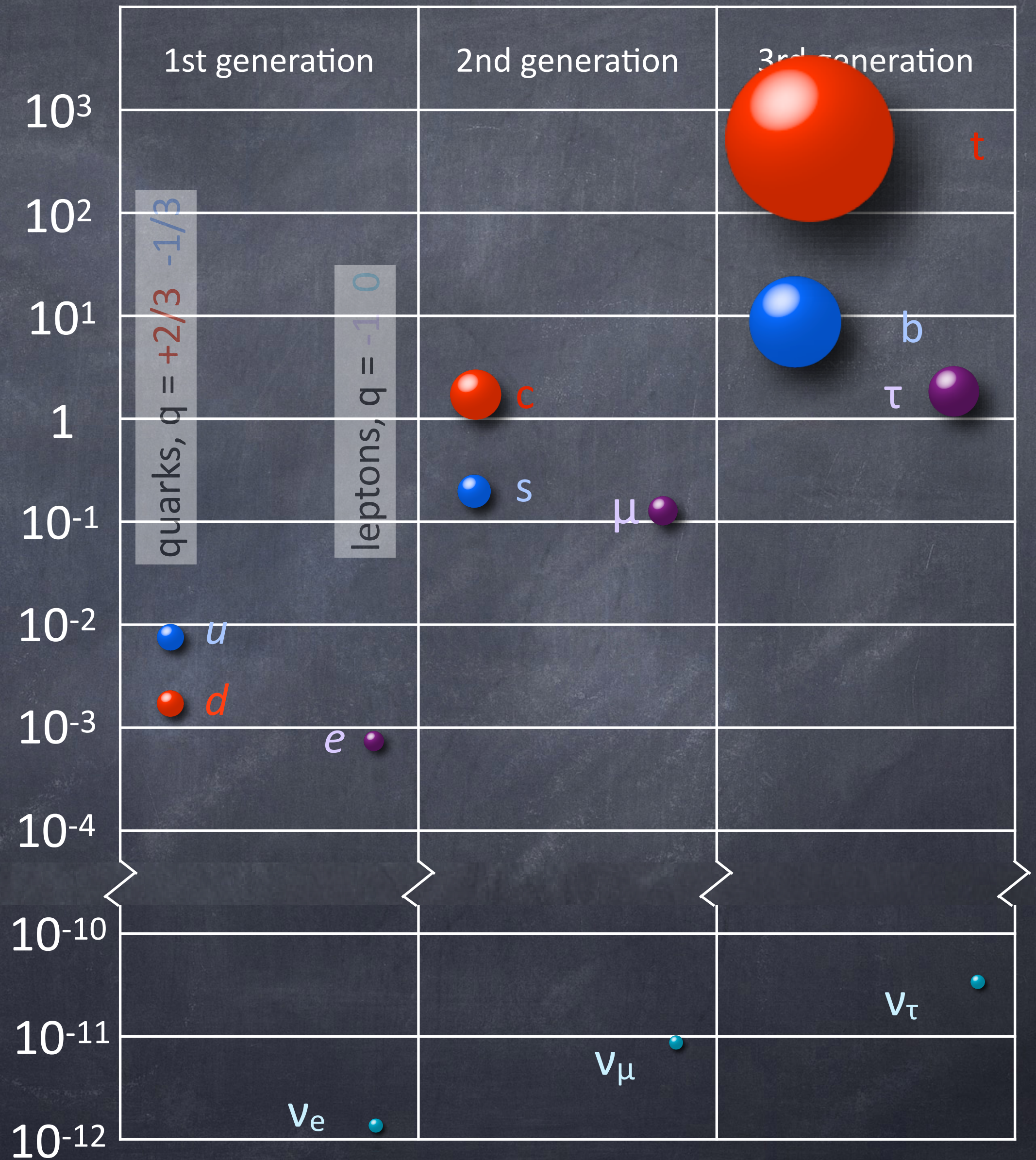
this often-told magnet story

evolves into the new story of MASS



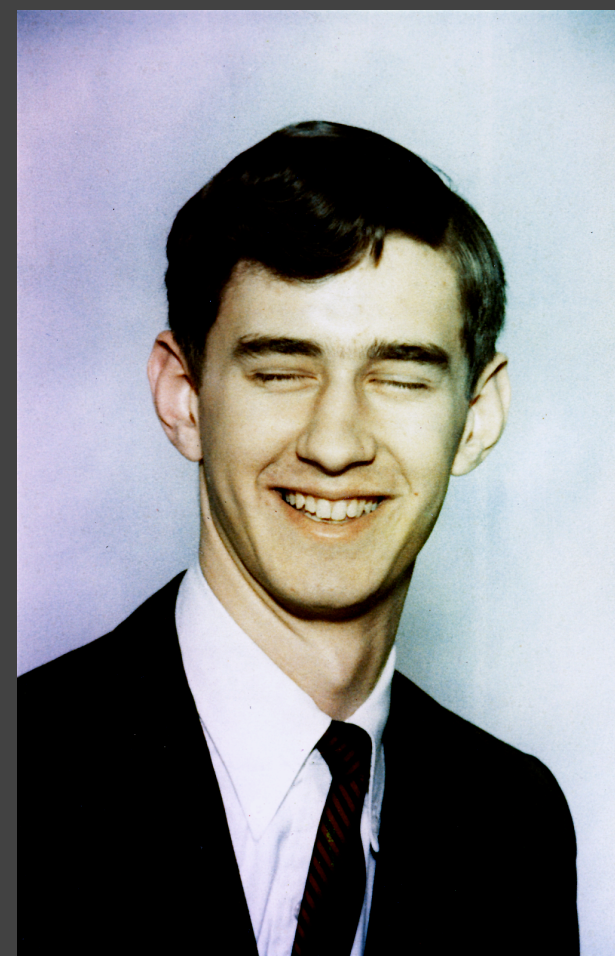
# quarks & leptons

proton masses





1967

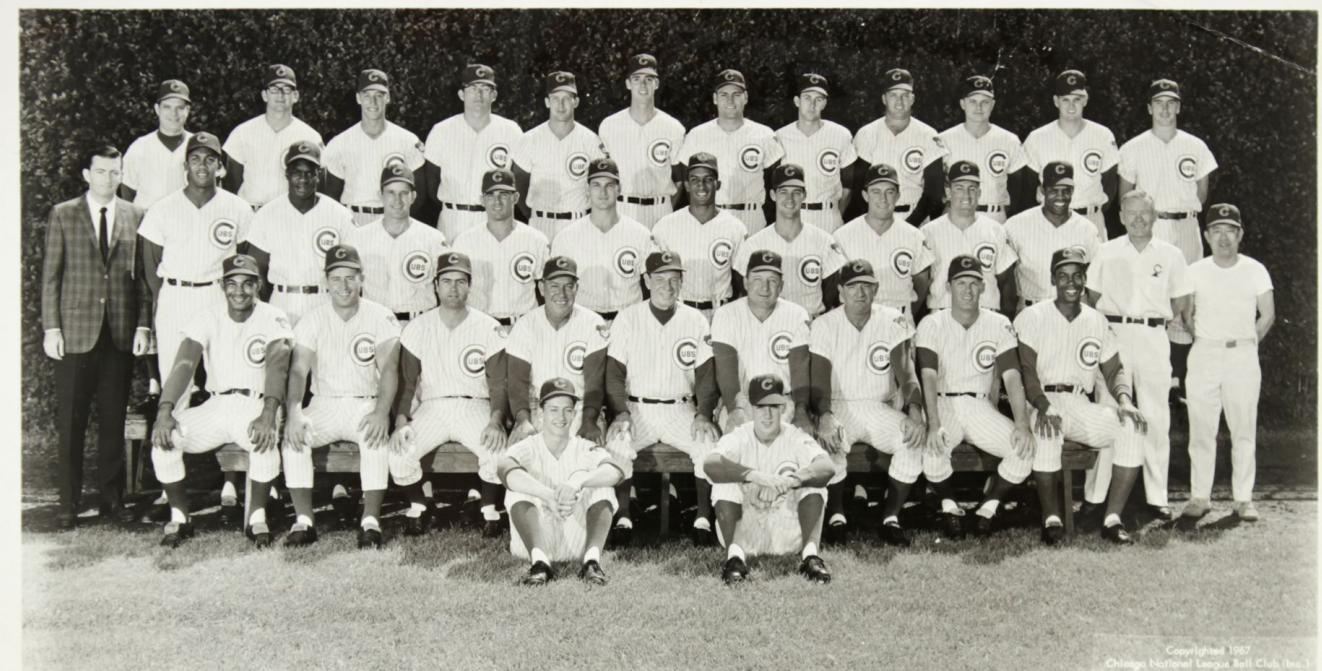




# 1967



# 1967



## 1967 CHICAGO CUBS



FRONT ROW (L to R)

MIDDLE ROW (L to R)

BACK ROW (L to R)

Billy Williams, Ron Santo, Joe Amalfitano (Coach), Pete Reiser (Coach), Ken Kamin (Batboy), Leo Durocher (Manager), Verlon Walker (Coach), Jerry Farrell (Batboy), Joe Becker (Coach), Randy Hundley, Ernie Banks.  
Blake Cullen (Traveling Secretary), Ferguson Jenkins, Clarence Jones, John Stephenson, Bill Stoneman, Ray Culp, Adolfo Phillips, Charles Hartenstein, Al Spangler, Norm Gigon, Ted Savage, Al Scheuneman (Trainer), Yosh Kawano (Equipment Manager).  
Don Pinkus (Batting Practice Catcher), Jim Ellis, Ken Holtzman, Pete Mikkelsen, Glenn Beckert, Rich Nye, Bob Shaw, Don Kessinger, Lee Thomas, Joe Niekro, Bill Hands, Rob Gardner.



# 1967











## A MODEL OF LEPTONS

Steven Weinberg†

Nuclear Science and Physics Department

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received 17 October 1967

<sup>1</sup>In obtaining the expression (11) the vacuum expectation value of the charged and neutral Goldstone bosons is taken to be  $\langle \phi^\pm \rangle = \lambda G_e$  and  $\langle \phi^0 \rangle = \lambda G_e / \sqrt{2}$ , respectively. See also J. Pasupathy, Phys. Rev. Letters **17**, 885 (1966).  
<sup>2</sup>The predicted ratio [eq. (12)] is  $M_W/M_Z = 1/\sqrt{2}$ . See also S. Weinberg, Phys. Rev. Letters **8**, 579 (1962).

Leptons interact only through the intermediate bosons of the weak interaction. It is natural to unite the leptons into a multiplet of gauge fields in the way of this synthesis and to leave invariant the kinetic terms of the Lagrangian. The intermediate meson, and in their coupling to the leptons, might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.<sup>2</sup> This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.<sup>3</sup> The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad (1)$$

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \bar{L} - \partial_\mu L + g \bar{L} \times L)^2 - \frac{1}{2}(\partial_\mu \bar{e} - \partial_\mu e + g' \bar{e} \gamma_5 e)^2 - \bar{L} \gamma^\mu (\partial_\mu - ig' B_\mu) L - \bar{e} \gamma^\mu (\partial_\mu - ig' B_\mu) e - \frac{1}{2}(\partial_\mu \bar{\phi} - \partial_\mu \phi + g' \bar{\phi} \gamma_5 \phi)^2 - G_e (\bar{L} \phi R + \bar{R} \phi^\dagger L) - M_1^2 \phi^\dagger \phi + h(\phi^\dagger \phi)^2. \quad (4)$$

We have chosen the phase of the  $R$  field to make  $G_e$  real, and can also adjust the phase of the  $L$  and  $Q$  fields to make the vacuum expectation value  $\lambda = \langle \phi^0 \rangle$  real. The "physical"  $\phi$  fields are then  $\phi^\pm$

$$\phi^\pm = (\phi^0 - \phi^\pm)/i\sqrt{2}. \quad (5)$$

The zero vacuum expectation value of perturbation theory, and therefore the  $\phi^\pm$  and  $\phi^0$  have mass  $2\lambda$ , and see that the Goldstone bosons, and  $\phi^\pm$  have no physical mass. The Lagrangian is gauge invariant under a combined isospin transformation which leaves invariant the kinetic terms. We see that  $G_e$  is very small, might be very large,<sup>7</sup> and also be disregarded.

$$\text{just to replace } \phi \text{ by } \langle \phi \rangle = \lambda G_e. \quad (6)$$

The intermediate bosons remain intact, while the photon becomes

$$A_\mu = (g' B_\mu - g B_\mu)/\sqrt{g'^2 + g^2}. \quad (7)$$

$$\mathcal{L} = \text{H.c.} + \frac{ig'g}{(g'^2 + g^2)^{1/2}} \bar{e} \gamma^\mu e A_\mu + \frac{i(g'^2 + g^2)^{1/2}}{4} \left[ \left( \frac{3g'^2 - g^2}{g'^2 + g^2} \right) \bar{e} \gamma^\mu e - \bar{e} \gamma^\mu \gamma_5 e + \nu \gamma^\mu (1 + \gamma_5) \nu \right] Z_\mu. \quad (14)$$

$$\text{electric charge} \quad (15)$$

$$g_W^2 = 1/2\lambda^2. \quad (16)$$

$$\text{coupling constant is } g_W^2 = 2.07 \times 10^{-6}.$$

The interaction is stronger by a factor  $1/\sqrt{2}$  than  $e$ , so  $g_W \approx 10^{-3}$  BeV, while (12) gives  $M_W/M_Z = 1/\sqrt{2}$ . The predictions made

We see immediately that the electron mass is  $\lambda G_e$ . The charged spin-1 field is

$$W_\mu^\pm = 2^{-1/2}(A_\mu^\pm + iA_\mu^0) \quad (8)$$

and has mass

$$M_W = \frac{1}{2}\lambda g. \quad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu^0 + g'B_\mu), \quad (10)$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu^0 + gB_\mu). \quad (11)$$

Their masses are

$$M_Z = \frac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \quad (12)$$

$$M_A = 0, \quad (13)$$

so  $A_\mu$  is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

by this model have to do with the couplings of the neutral intermediate meson  $Z_\mu$ . If  $Z_\mu$  does not couple to hadrons then the best place to look for effects of  $Z_\mu$  is in electron-neutron scattering. Applying a Fierz transformation to the  $W$ -exchange terms, the total effective  $e-\nu$  interaction is

$$\frac{G_W}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 + \gamma_5) \nu \left\{ \frac{(3g^2 - g'^2)}{2(g^2 + g'^2)} \bar{e} \gamma^\mu e + \frac{1}{2} \bar{e} \gamma^\mu \gamma_5 e \right\}.$$

If  $g \gg e$  then  $g \gg g'$ , and this is just the usual  $e-\nu$  scattering matrix element times an extra factor  $1/2$ . If  $g \approx e$  then  $g \approx g'$ , and the vector interaction is multiplied by a factor  $-1/2$  rather than  $1/2$ . Of course our model has too many arbitrary features for these predictions to be

Z. Physik **88**, 161 (1934). A model similar to ours is discussed by S. Glashow, Nucl. Phys. **22**, 579 (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions.

J. Goldstone, Nuovo Cimento **19**, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. **127**, 965 (1962).

P. W. Higgs, Phys. Letters **12**, 132 (1964), Phys. Rev. Letters **13**, 508 (1964), and Phys. Rev. **145**, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters **17**, 321 (1966); G. S. Guralnik, C. R. Hagen, and T. W. Kibble, Phys. Rev. Letters **13**, 585 (1964).

See particularly T. W. B. Kibble, Phys. Rev. **155**, 1554 (1967). A similar phenomenon occurs in the strong interactions; the  $\rho$ -meson mass in zeroth-order perturbation theory is just the bare mass, while the  $\rho$ -meson picks up an extra contribution from the spontaneous breaking of chiral symmetry. See S. Weinberg, Phys. Rev. Letters **18**, 507 (1967), especially footnote 1. J. Schwinger, Phys. Letters **24B**, 473 (1967); Glashow, H. Schnitzer, and S. Weinberg, Phys. Rev. Letters **19**, 139 (1967), Eq. (13) et seq.

T. D. Lee and C. N. Yang, Phys. Rev. **98**, 101 (1955). This is the same sort of transformation as that which eliminates the nonderivative  $\bar{\psi}\psi$  couplings in the model; see S. Weinberg, Phys. Rev. Letters **18**, 188 (1967). The  $\bar{\psi}\psi$  reappears with derivative coupling because the strong-interaction Lagrangian is not invariant under chiral gauge transformation.

For a similar argument applied to the  $\sigma$  meson, see Weinberg, Ref. 6.

R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1957).

## LEPTON MIXING, AND LEPTON-PAIR MESONS\*

†Upton, New York

†Department of Physics, University of Chicago, Illinois 60637 (1967)

†The current-mixing model is shown







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 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**)



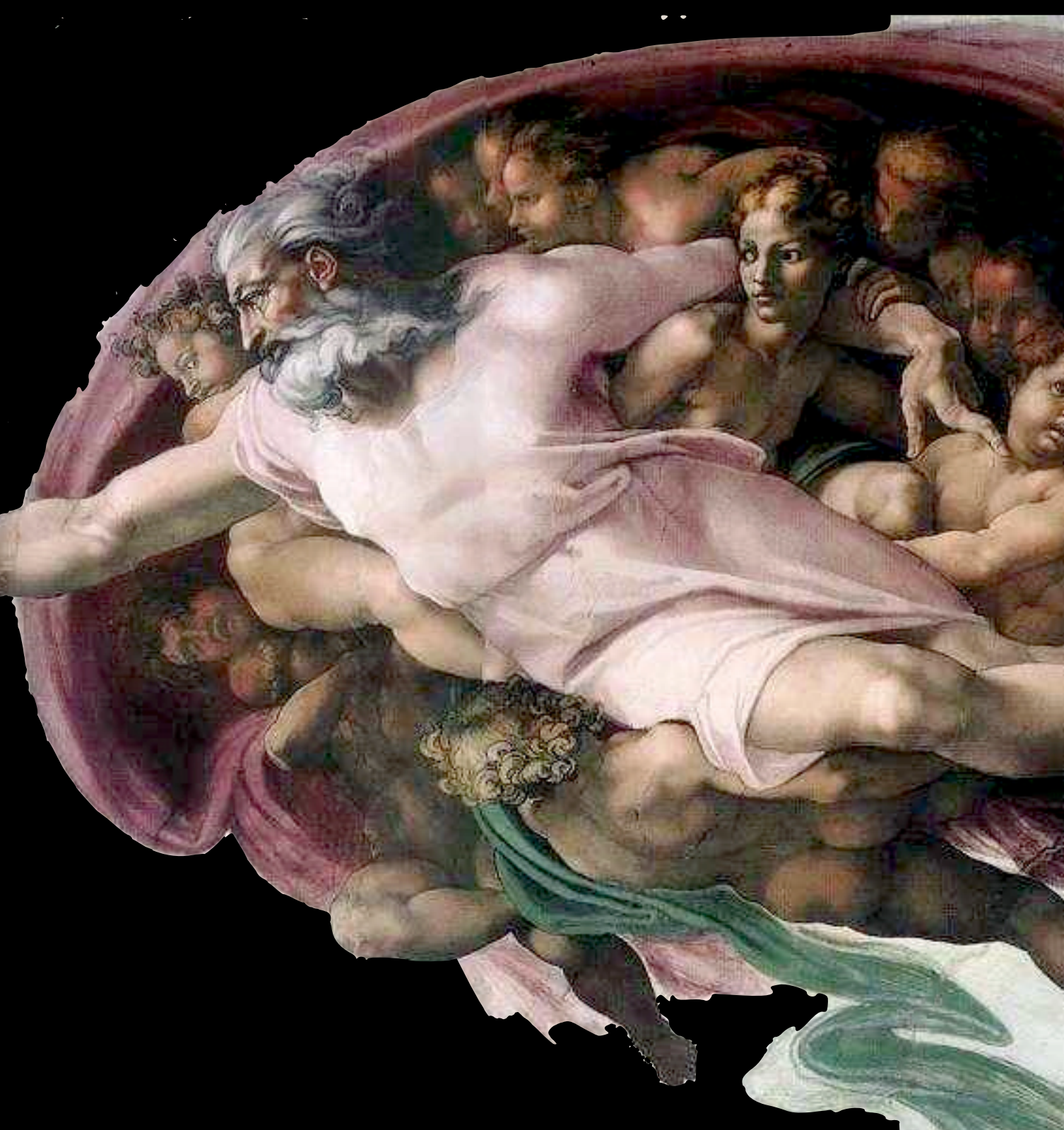
*we live in the resulting "cold" universe*



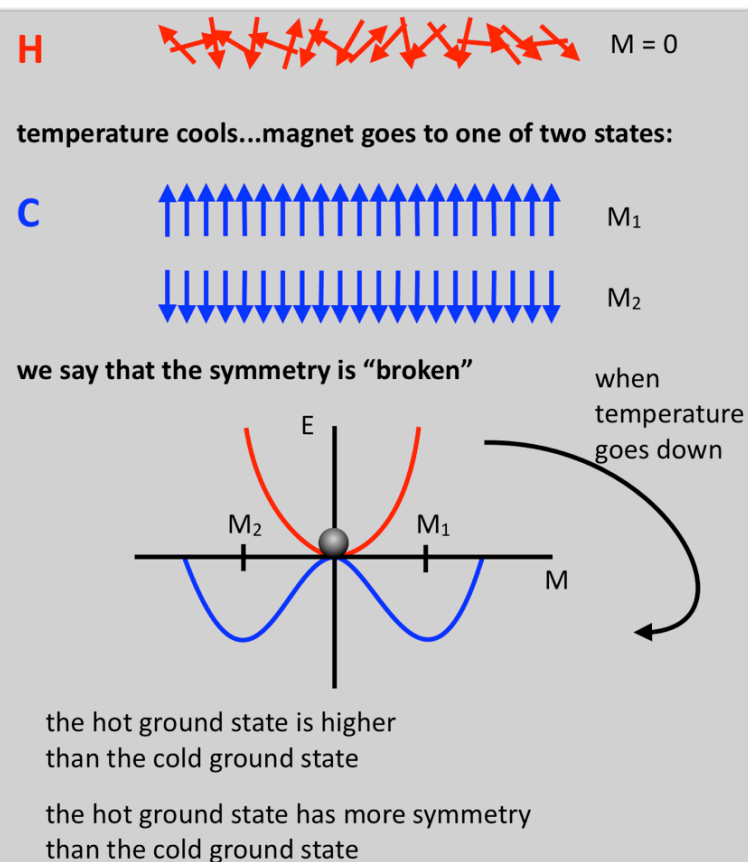
from a  
hot phase  
in the  
universe

cool it all at once

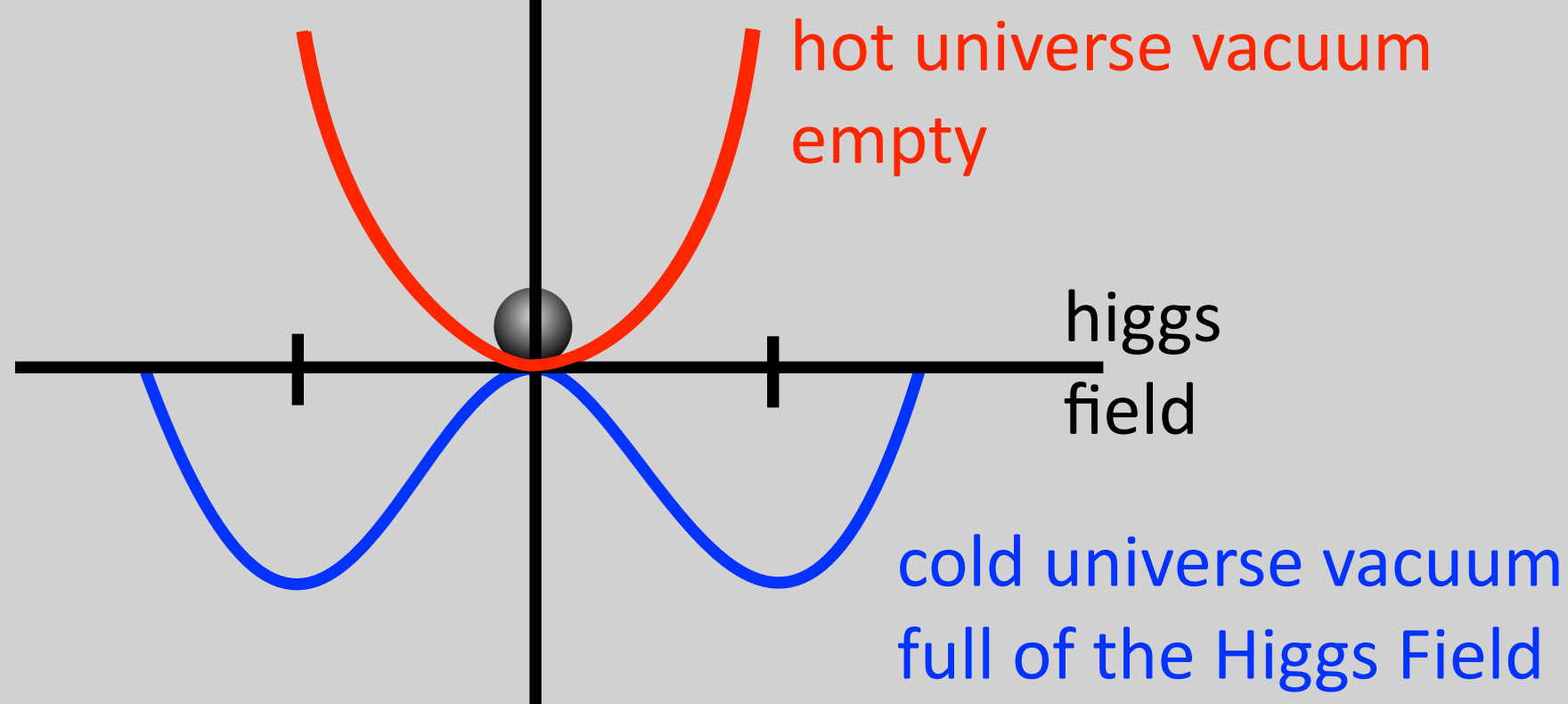
@  $10^{-12}$  seconds after  
the BB



an important  
difference  
between these two  
situations



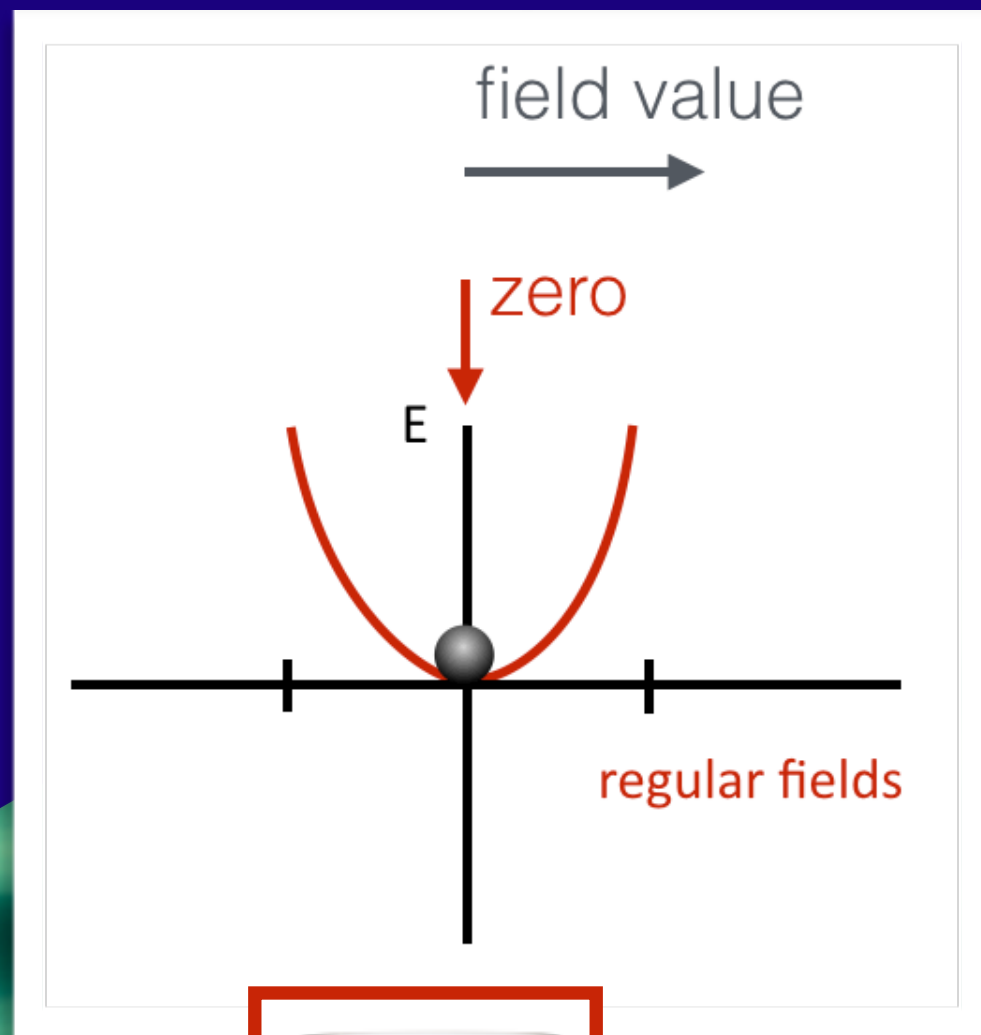
E (entire universe)





# 10<sup>-12</sup>s after the big bang

## universe condensed: a phase change

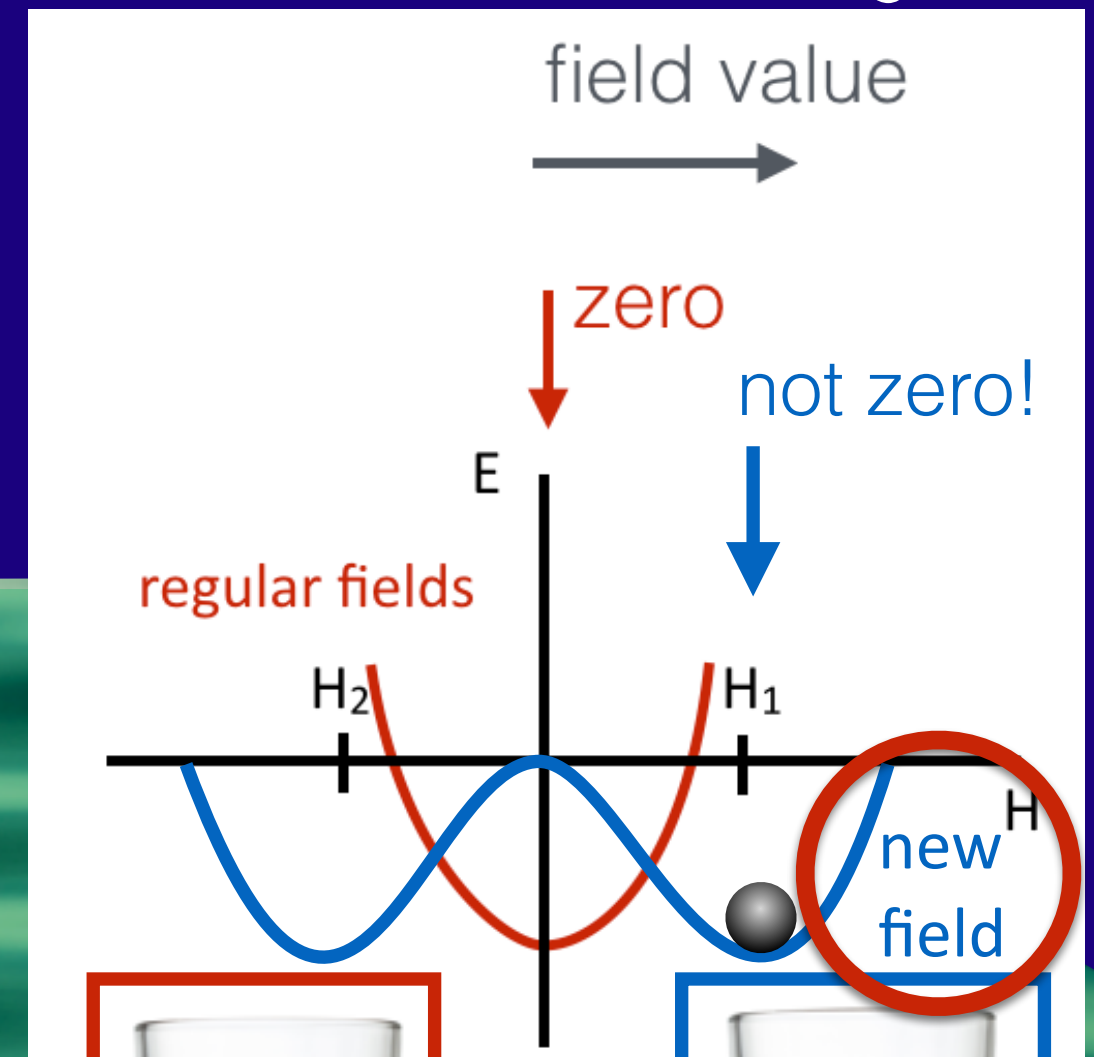


H



$M = 0$

like a hot, non-magnet



Higgs  
Field

C

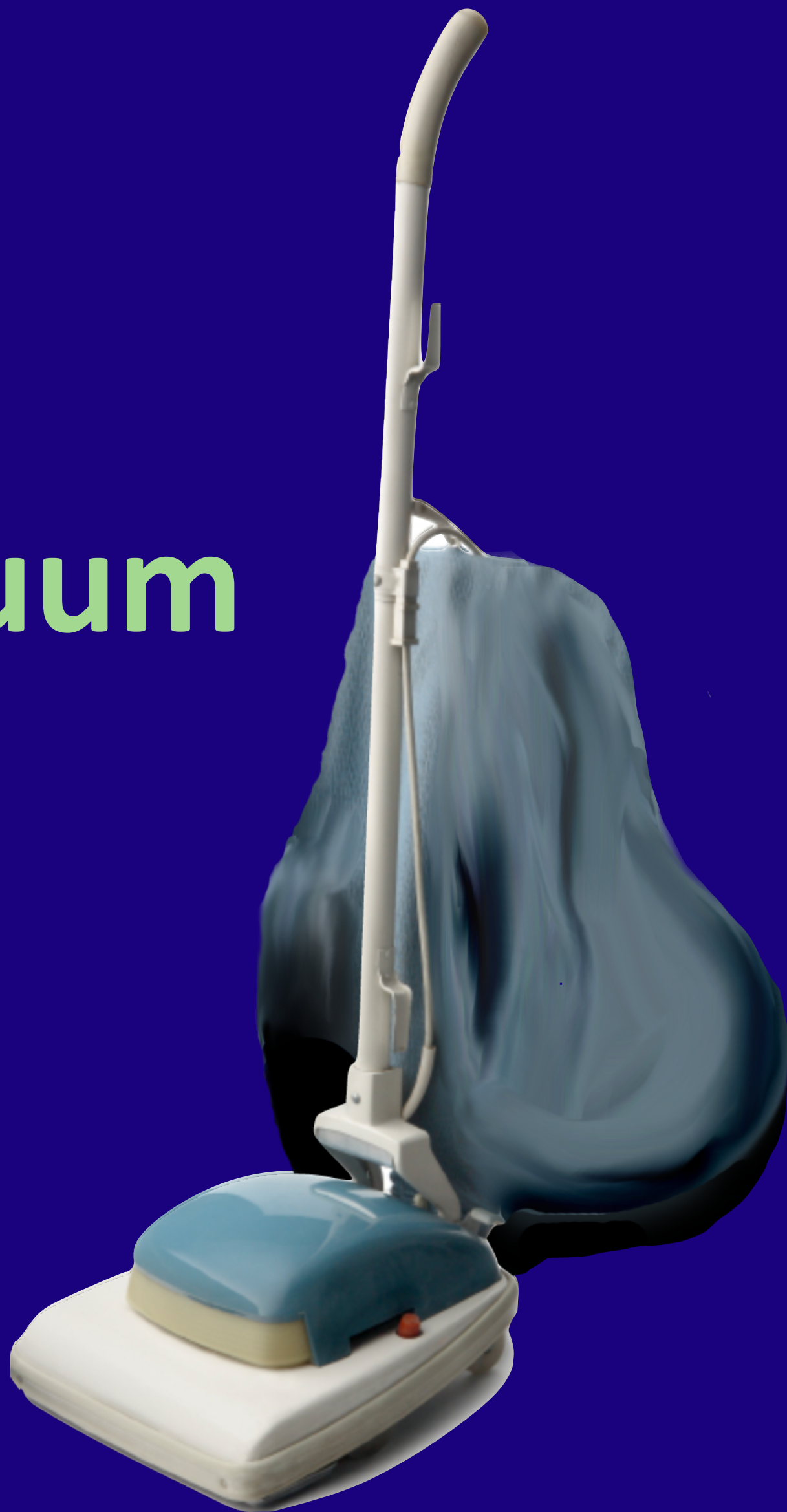


$M_1 \neq 0$

like a regular magnet



vacuum



had only zero-  
average-value  
fields

**H**   $M = 0$   
like a hot, non-magnet

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

**C**   $M_1 \neq 0$   
like a regular magnet

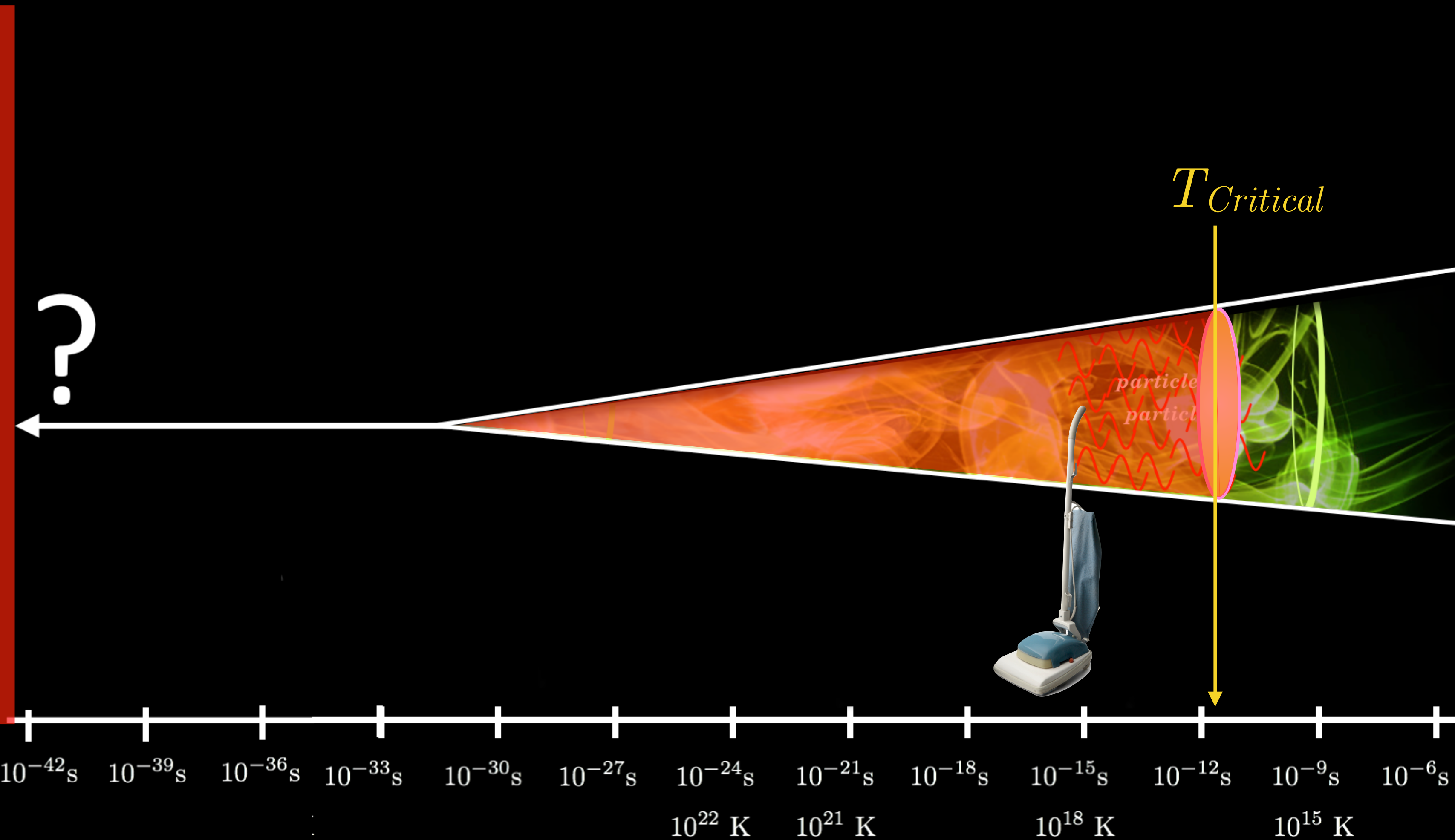
the big story of the  
Standard Model

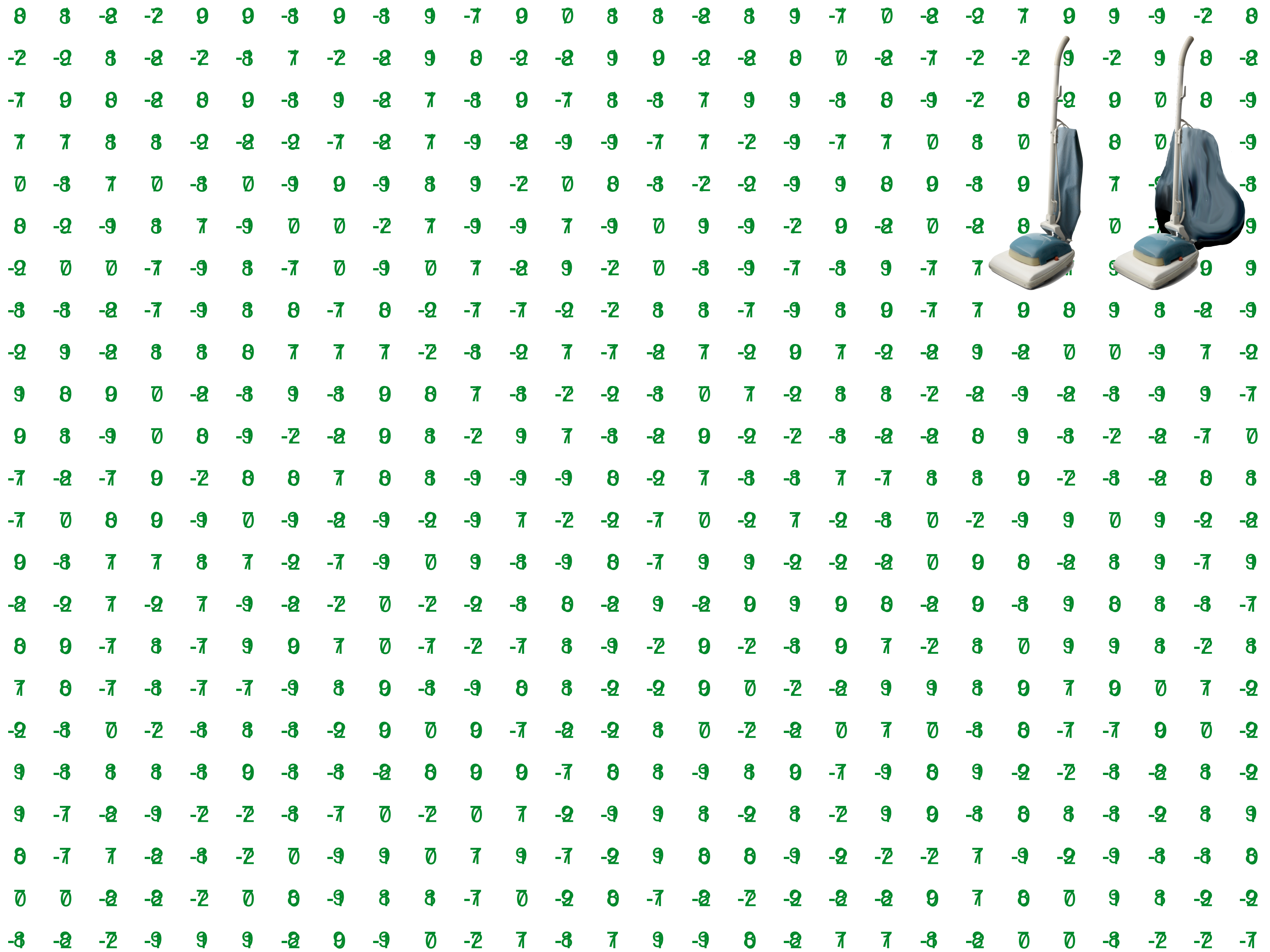
is the story of mass.





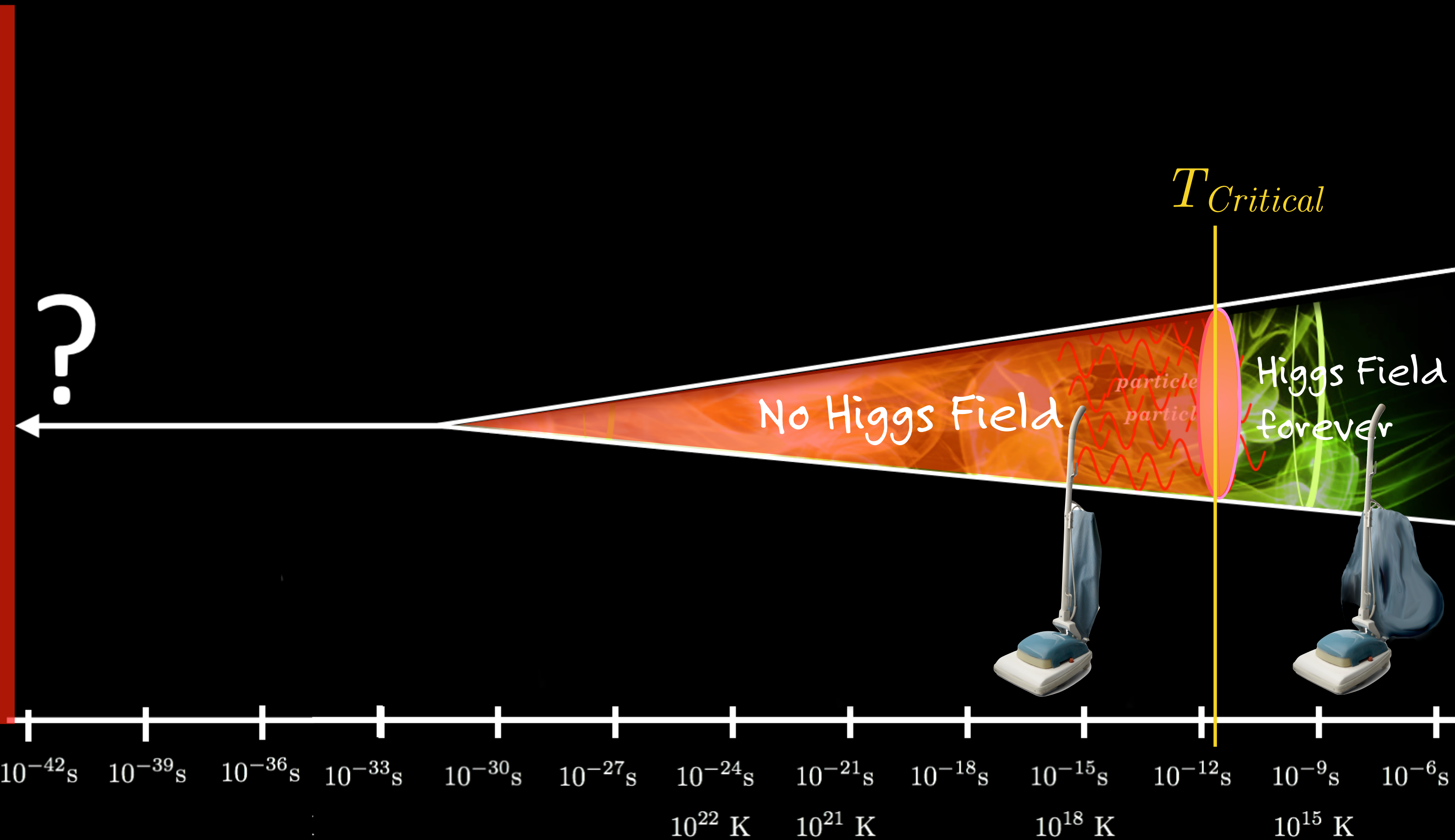
# elementary particle epoch





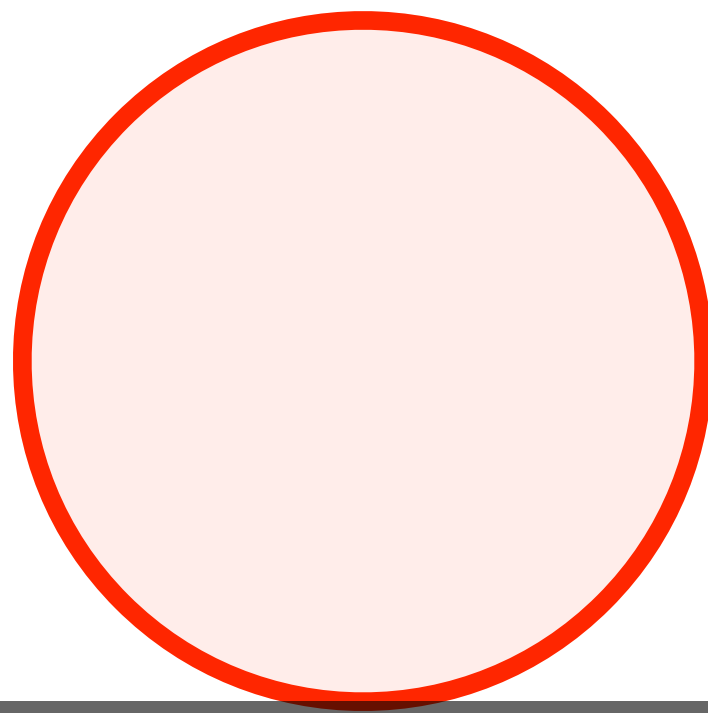


# elementary particle epoch

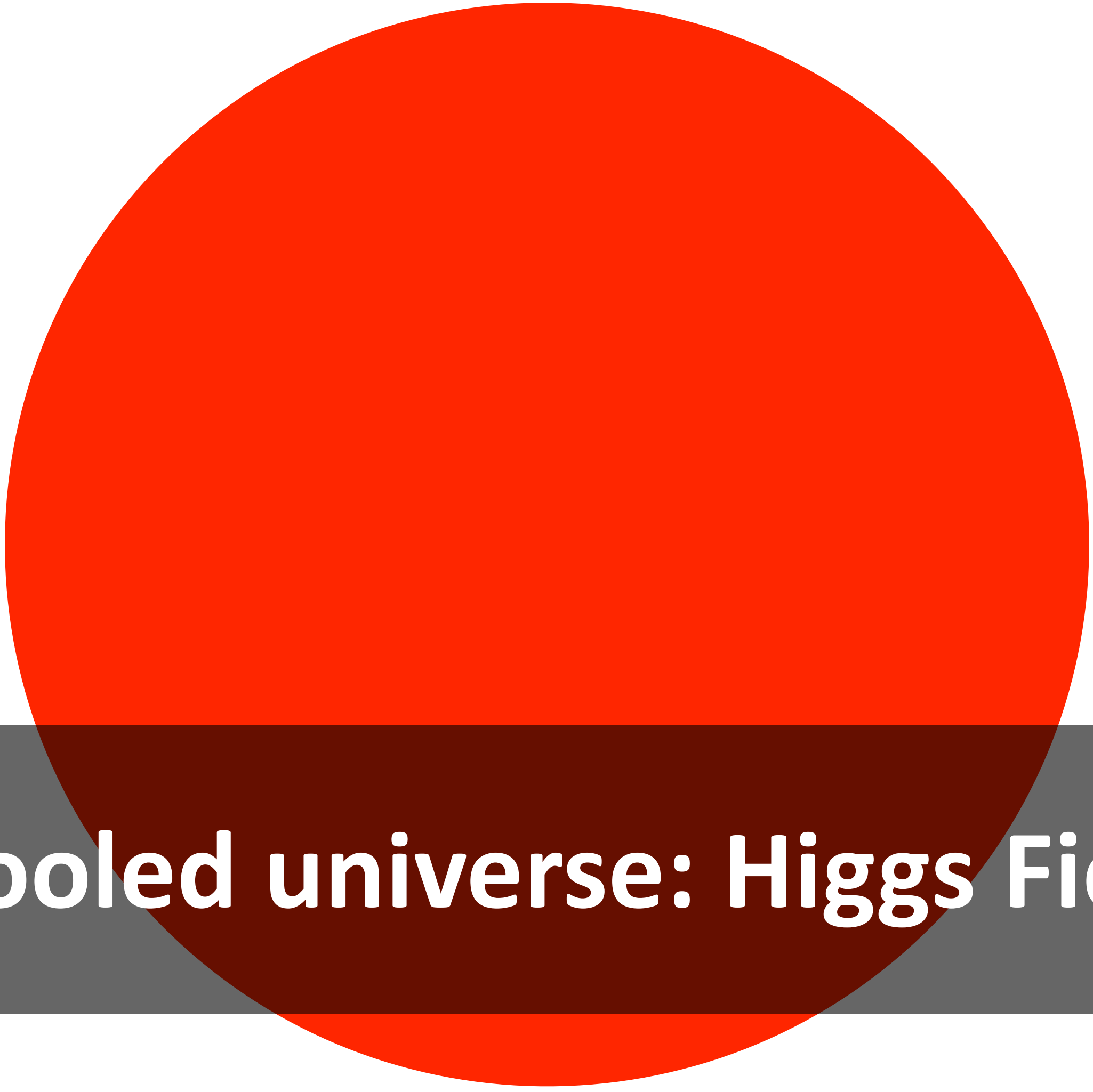








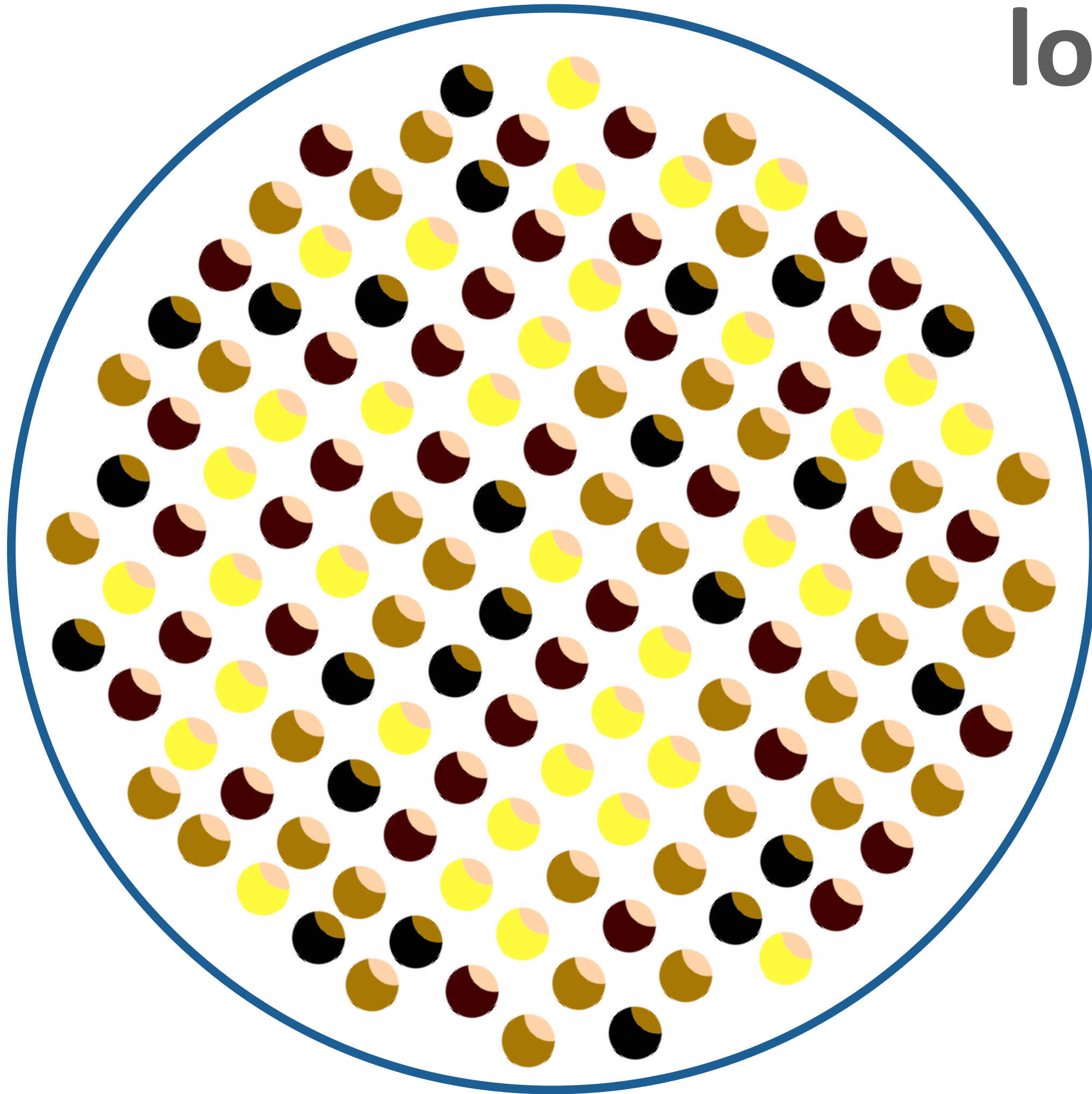
**the hot universe: no Higgs Field**

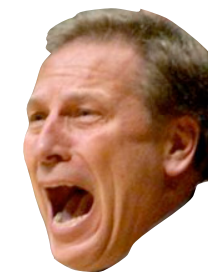


**a cooled universe: Higgs Field**

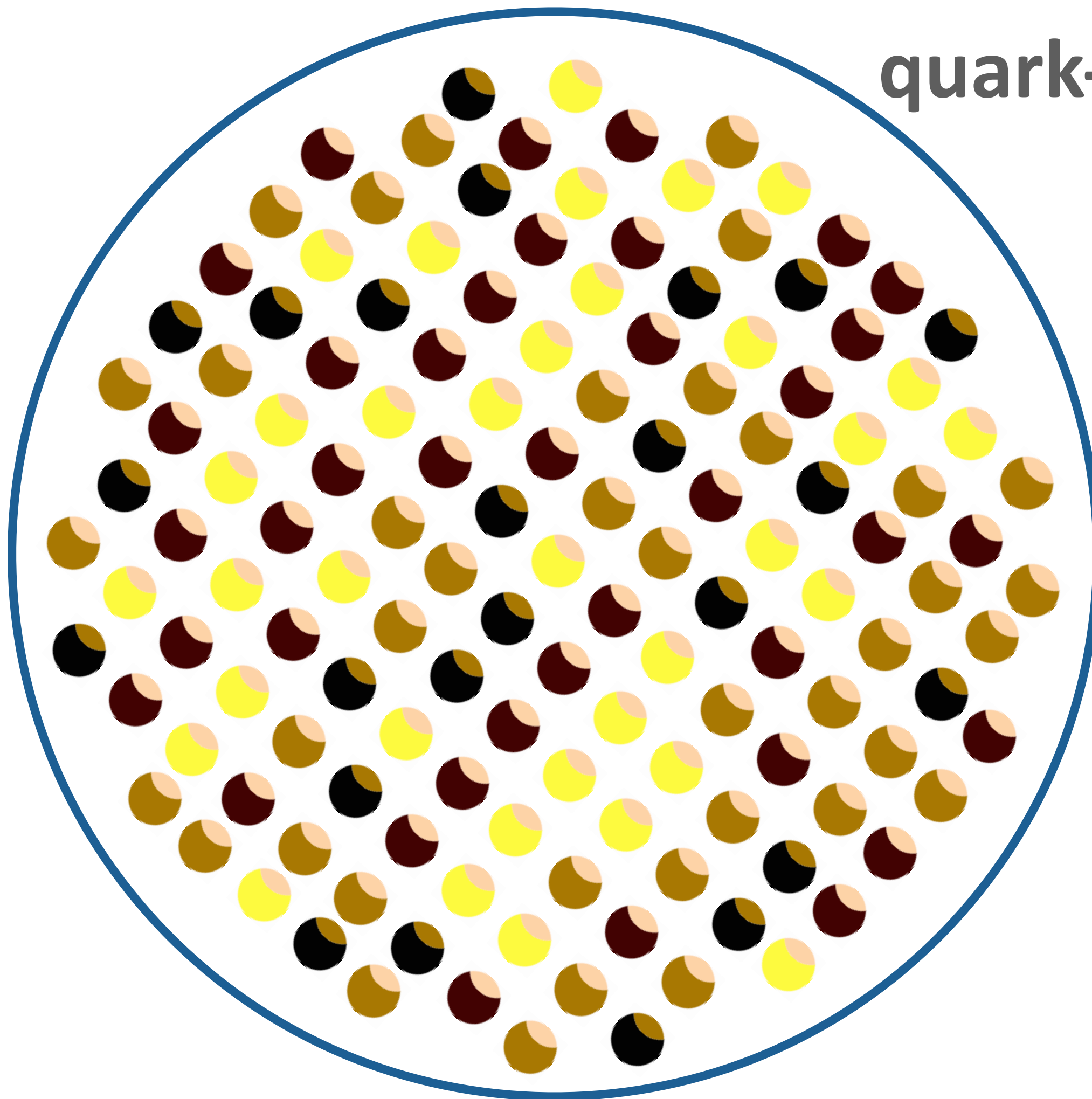


loud

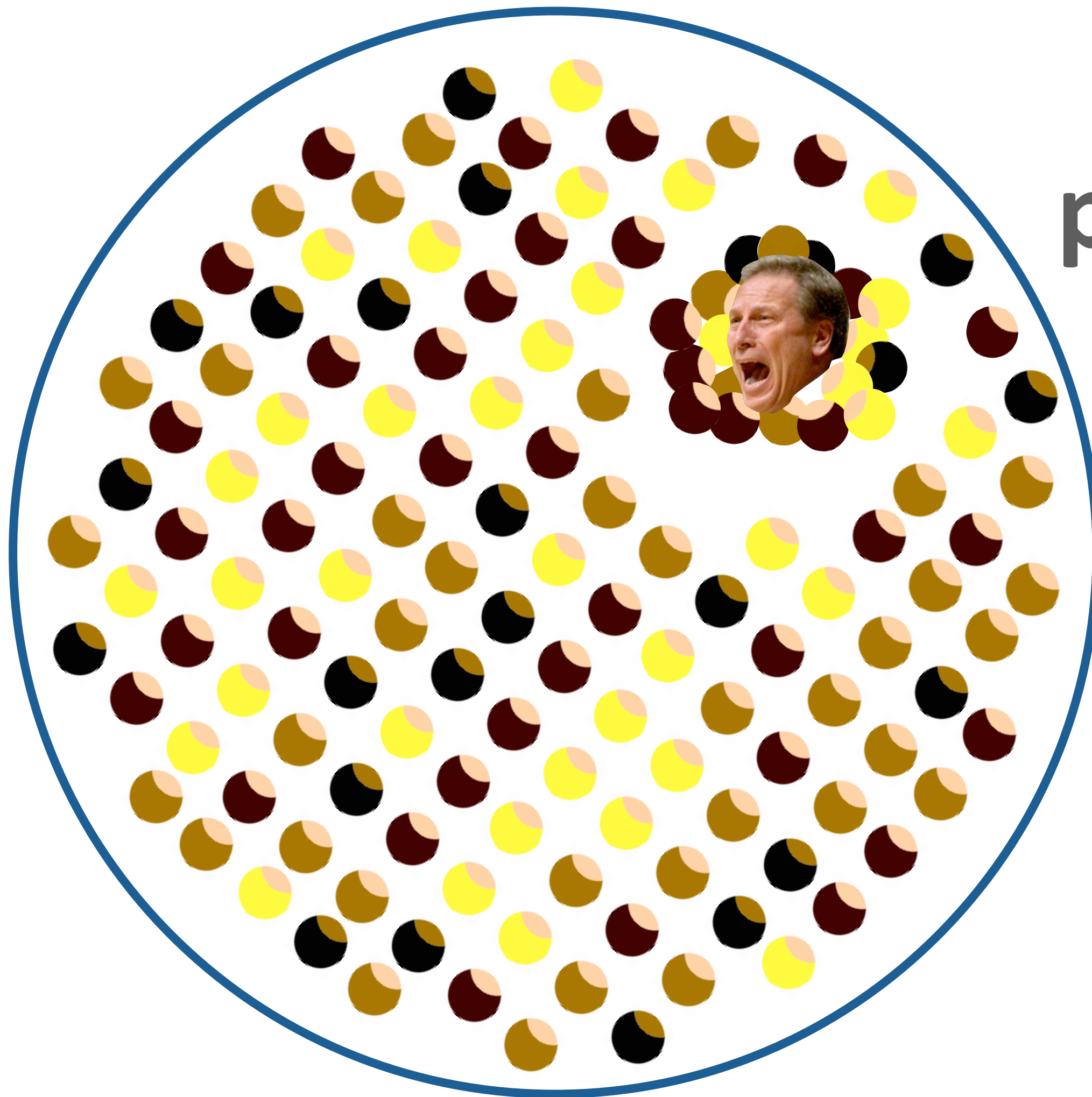




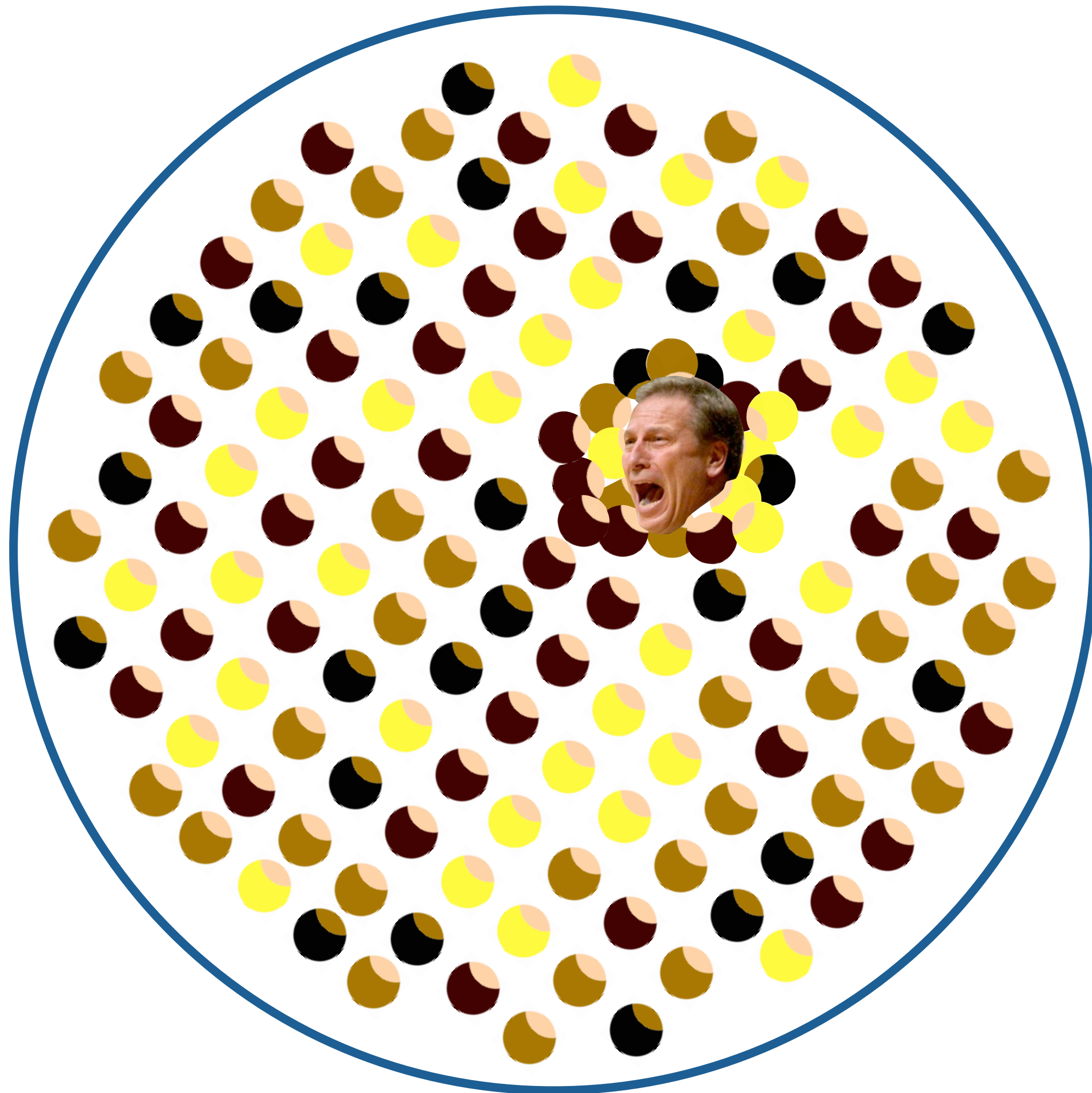
quark-Tom-Izzo



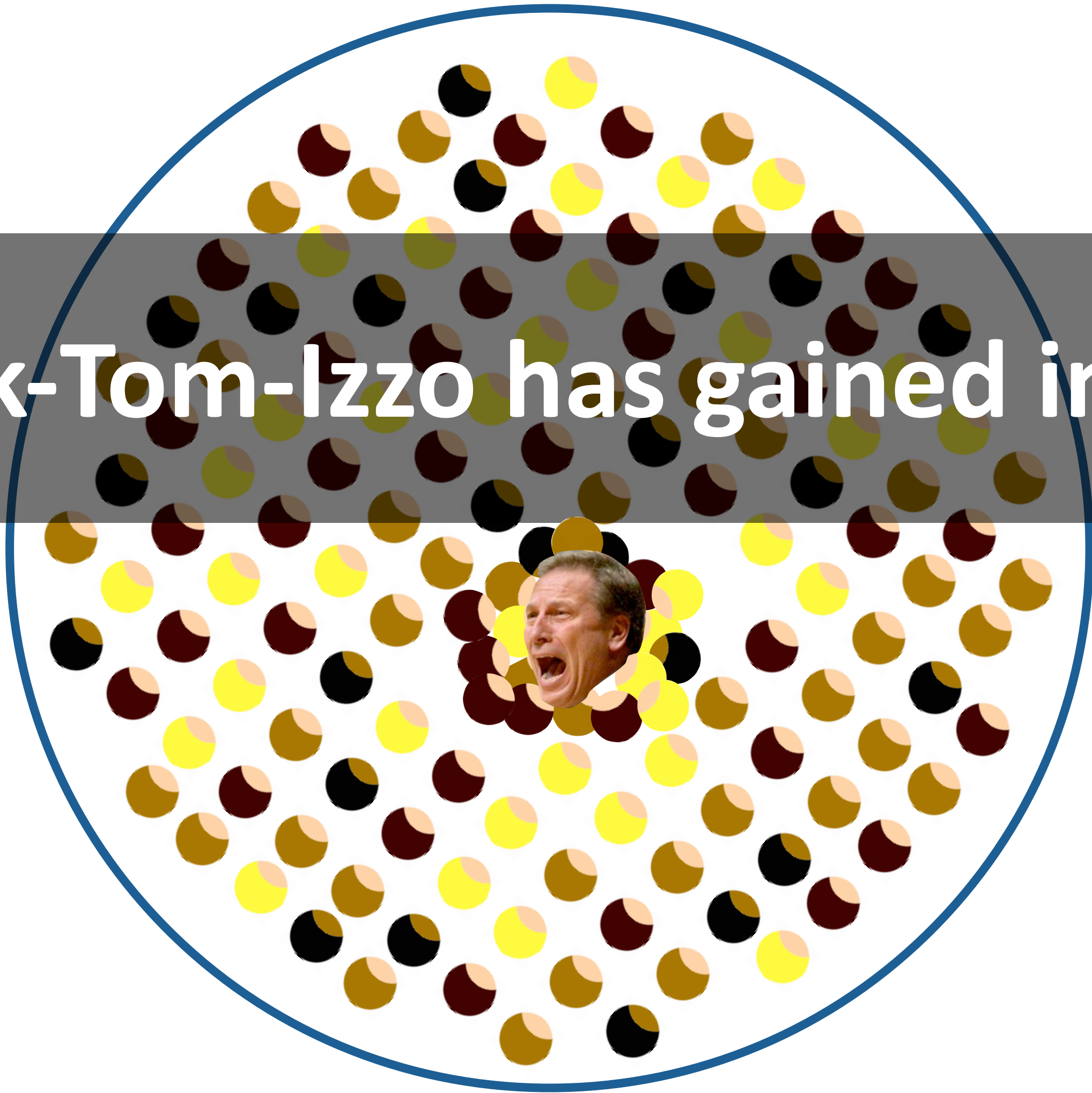




popular



quark-Tom-Izzo has gained inertia





quark-Tom-Izzo has mass.





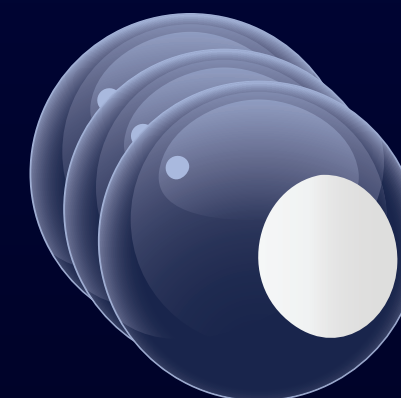
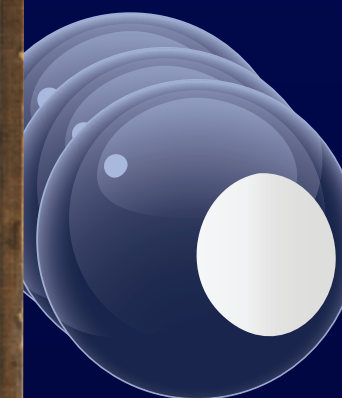
quark-Tom-Izzo

outside of the field

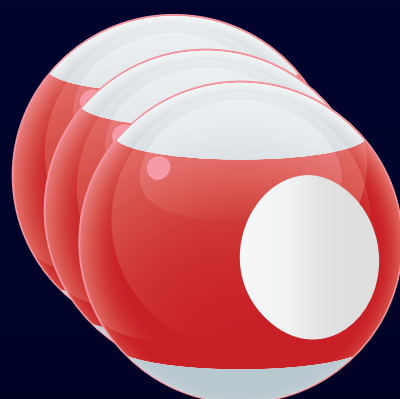


O M C E  
U P O N  
A  
T I M E

The U n i v e r s e  
w a s v e r y h o t  
  
a n d a l l w a s  
m a s s l e s s



H  M = 0  
like a hot, non-magnet







inside of  
the field

*At a Magic  
Temperature*

*Higgs Field*

*The Universe  
expanded and  
cooled and a*

*became manifest  
and all became  
heavy*



**C**



$M_1 \neq 0$

like a regular magnet



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

$\alpha^0$



$B^0$



$B^+$



$B^-$



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

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

$\gamma$

Z

$W^\pm$

$H^0$

The remaining primordial scalar is the Higgs Field.

t = the beginning 0 s

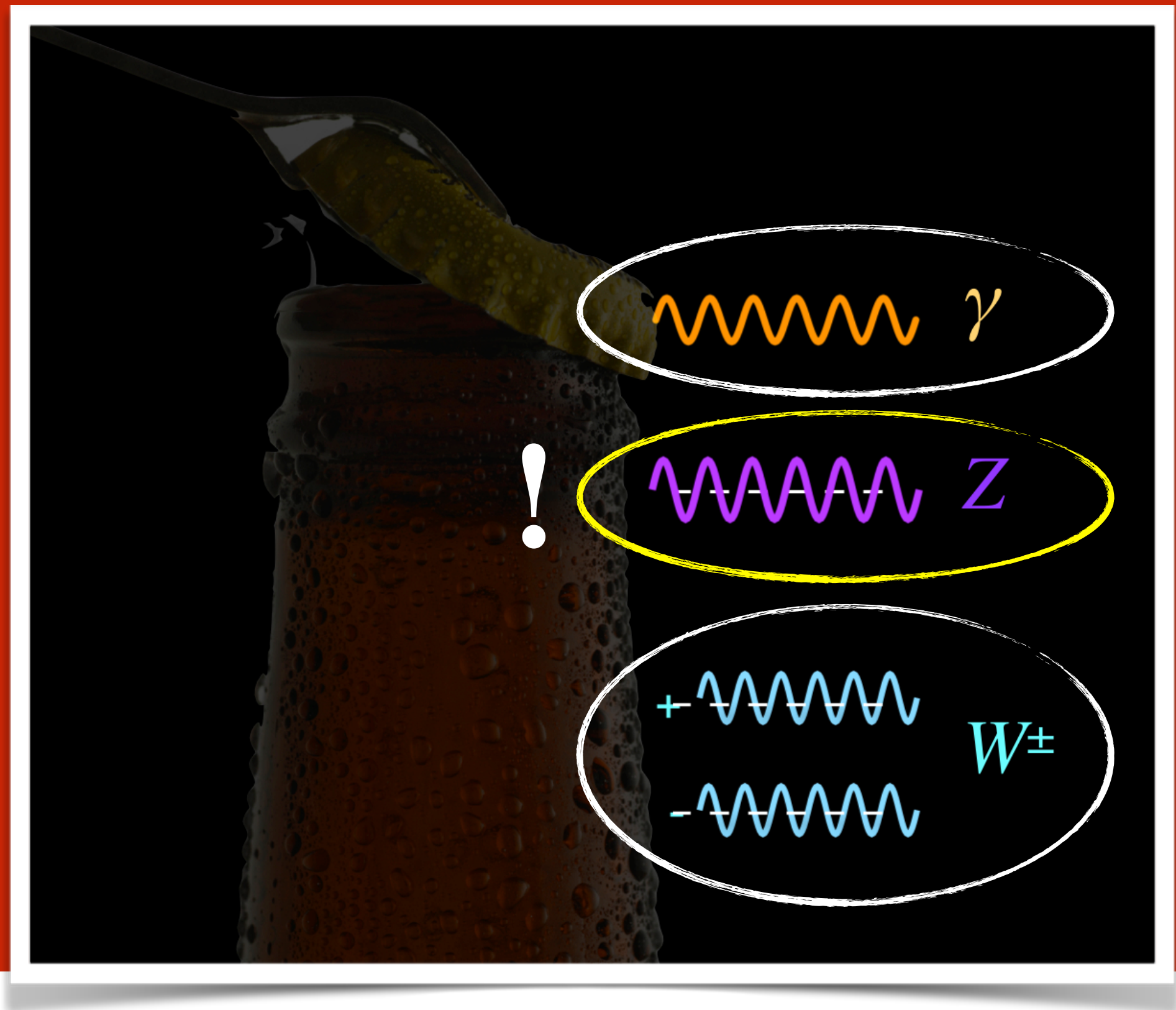
t =  $10^{-12}$  s

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

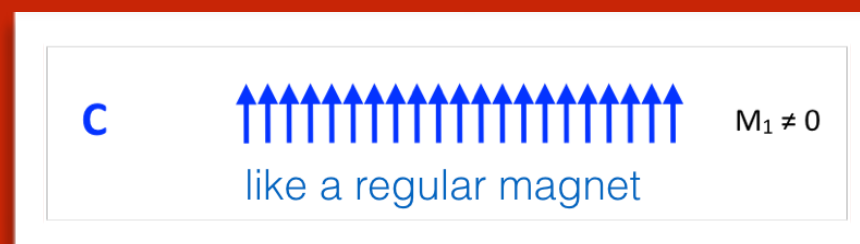
If the idea is right:

the electromagnetic and weak forces

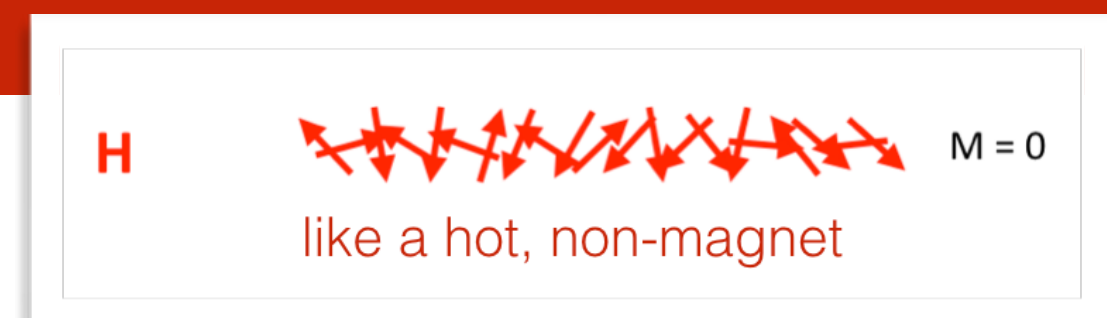
*that are so different today*

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

*that existed only when the Universe was very, very hot*



"Electroweak  
Force"





# 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  $\gamma$  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:

$80.399 \pm 0.023 \text{ GeV}/c^2 = 80.4 \text{ p}$

spin:

1

category:

weak Vector Boson

particle:

## Z Boson

symbol:

Z

charge:

0

mass:

$91.1876 \pm 0.0021 \text{ GeV}/c^2 = 91.2 \text{ p}$

spin:

1

category:

weak Vector Boson

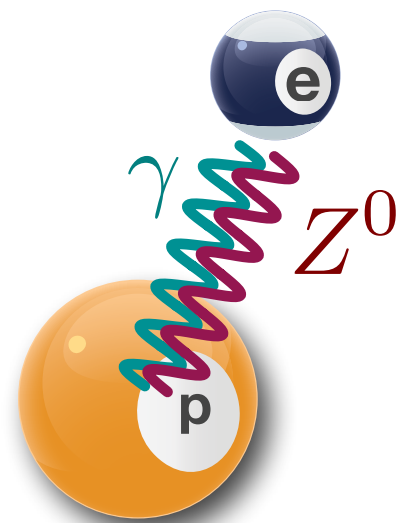


# Photon and Z always mix

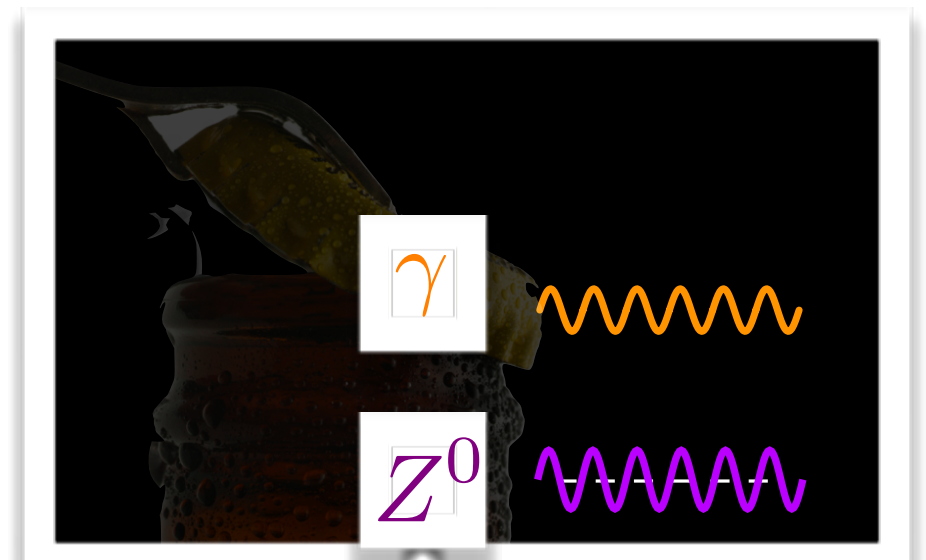
Z, very weakly

3. The Z Boson and the  $\gamma$  are intimately related

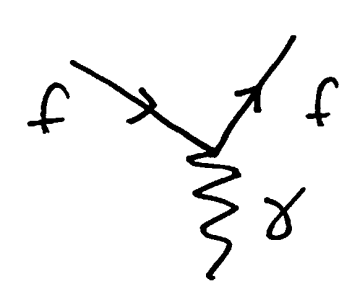
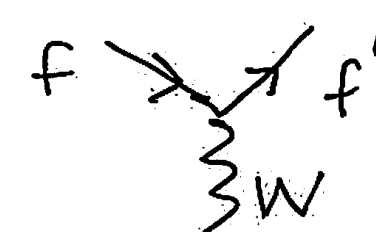
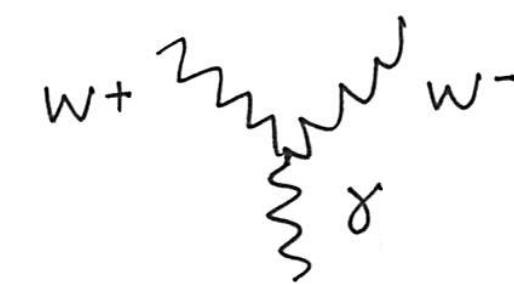
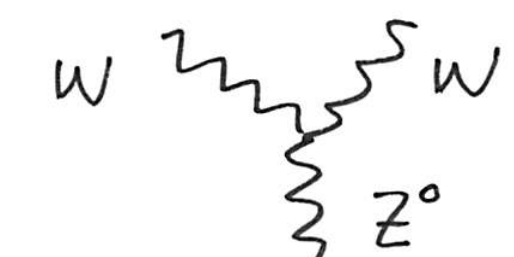
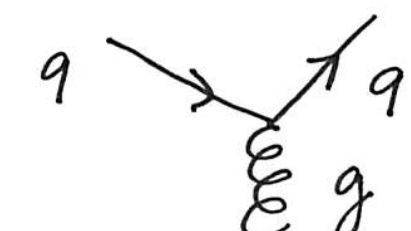
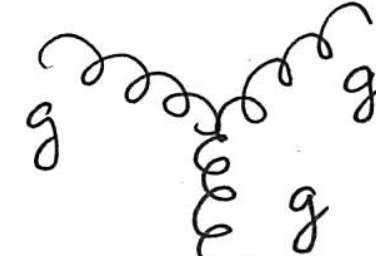
any reaction with a photon, must also happen with a  $Z^0$

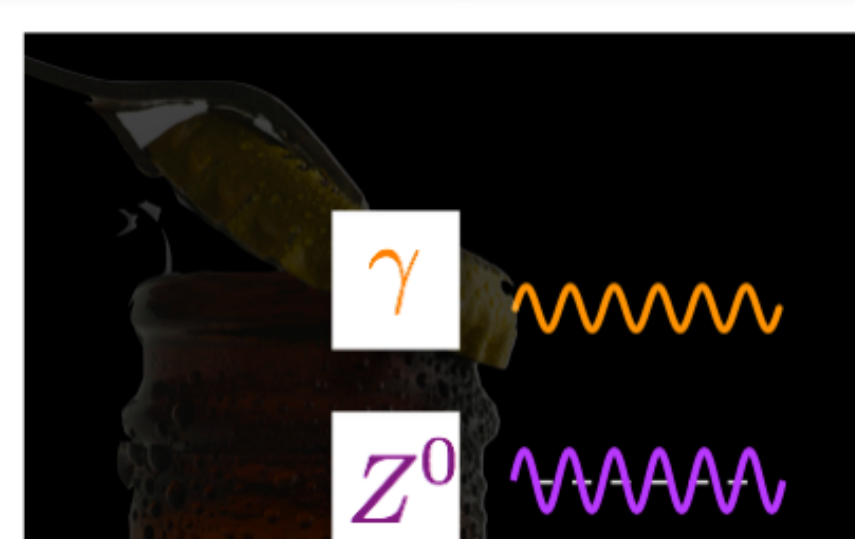


very delicate effects  
observed in atomic systems  
due to the Z Boson



sixth and  
seventh  
entries  
into your  
table of primitive  
diagrams

| Primitive Diagrams                                                                         |                                                                                            | TIME always:  |
|--------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| 1<br>   |                                                                                            | QED                                                                                              |
| 2<br>   | 3<br>   |                                                                                                  |
| 6<br>   | 7<br>  | Weak Interactions                                                                                |
| 4<br> | 5<br> |                                                                                                  |
| 8                                                                                          | 9                                                                                          | Strong Interactions                                                                              |
|                                                                                            |                                                                                            |                                                                                                  |
|                                                                                            |                                                                                            | Higgs Interactions                                                                               |
|                                                                                            |                                                                                            |                                                                                                  |

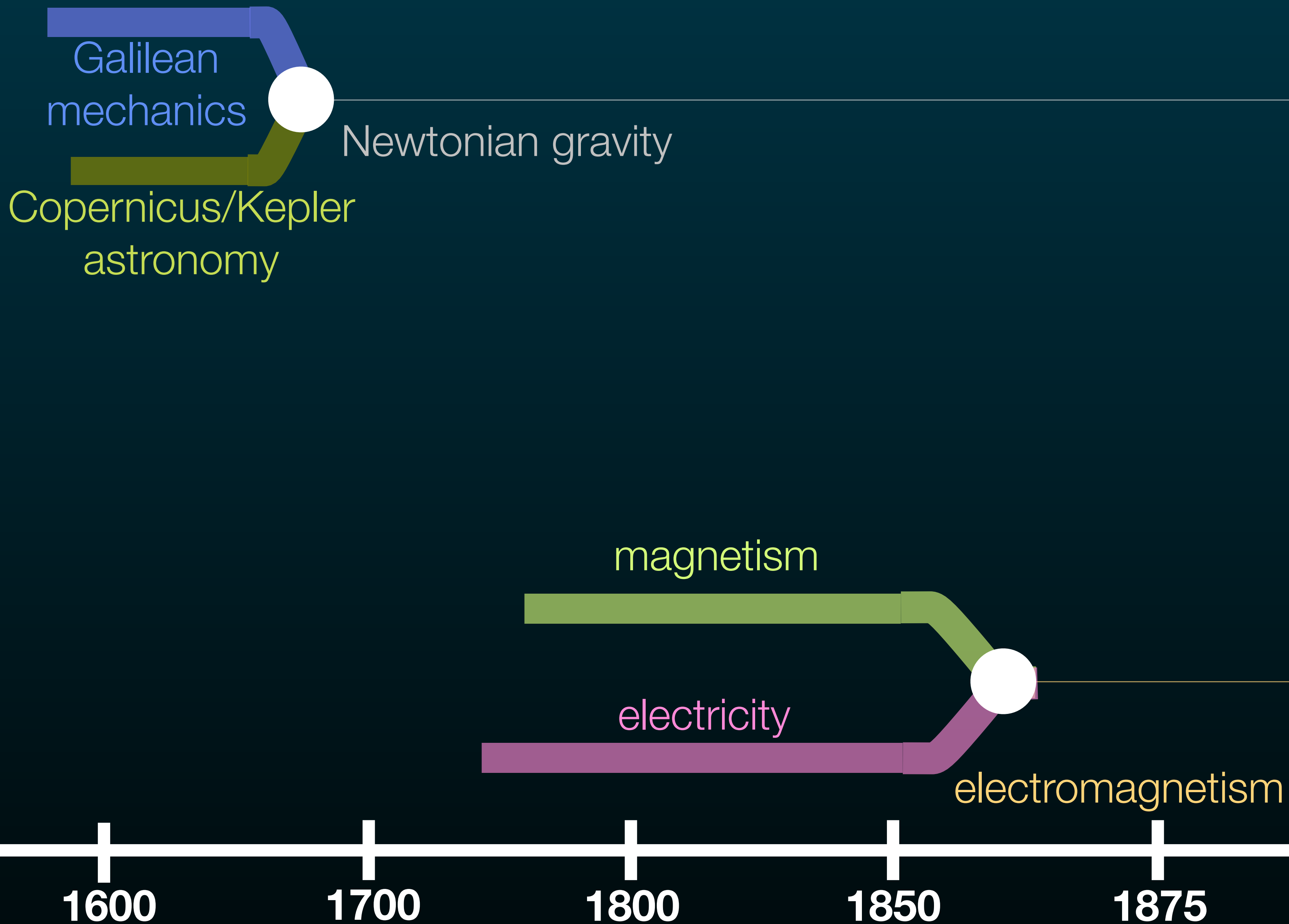
mix

$\gamma$

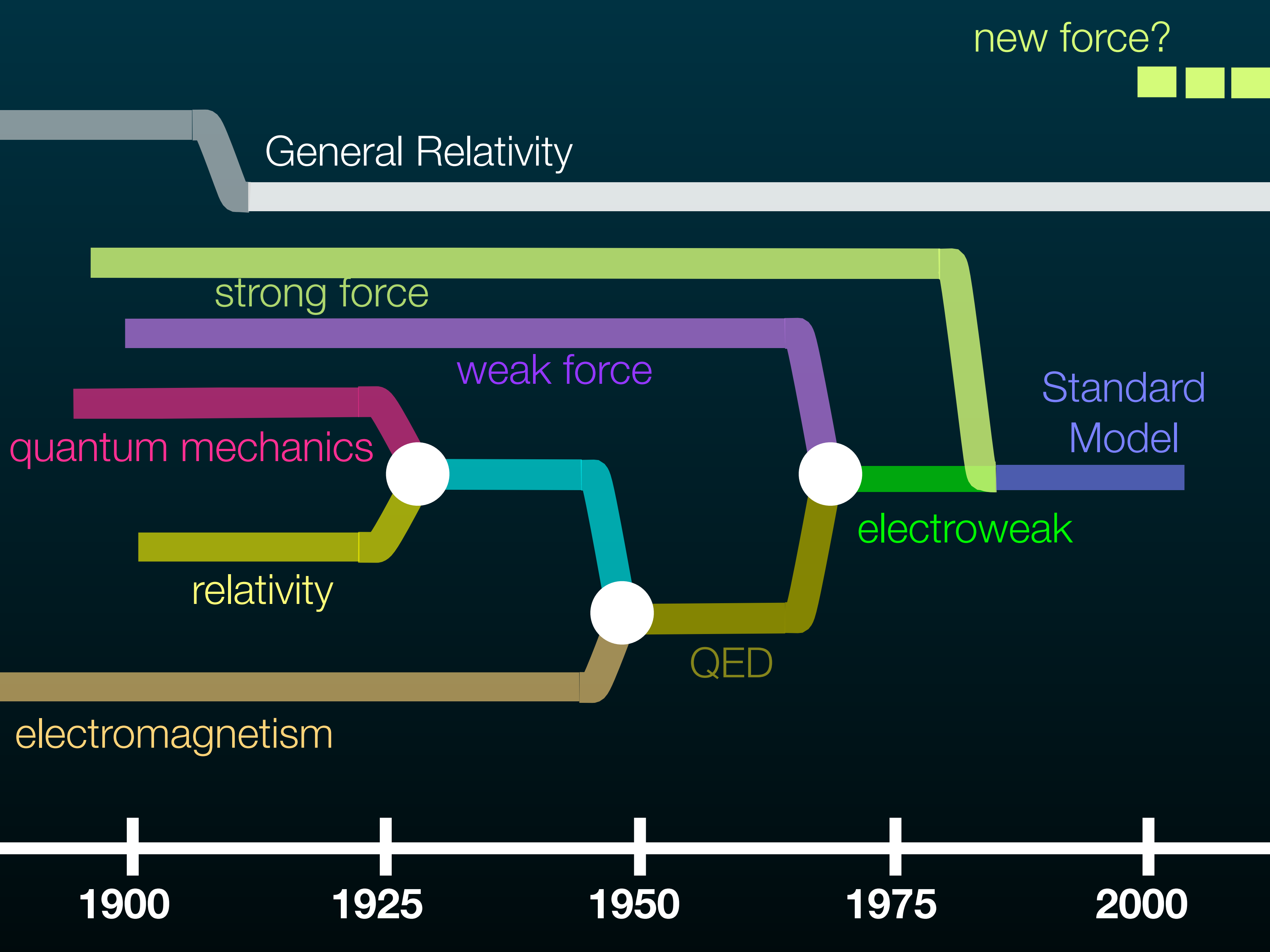
$Z^0$

scalar Boson, spin 0, e.g., Higgs Boson

.....







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”?

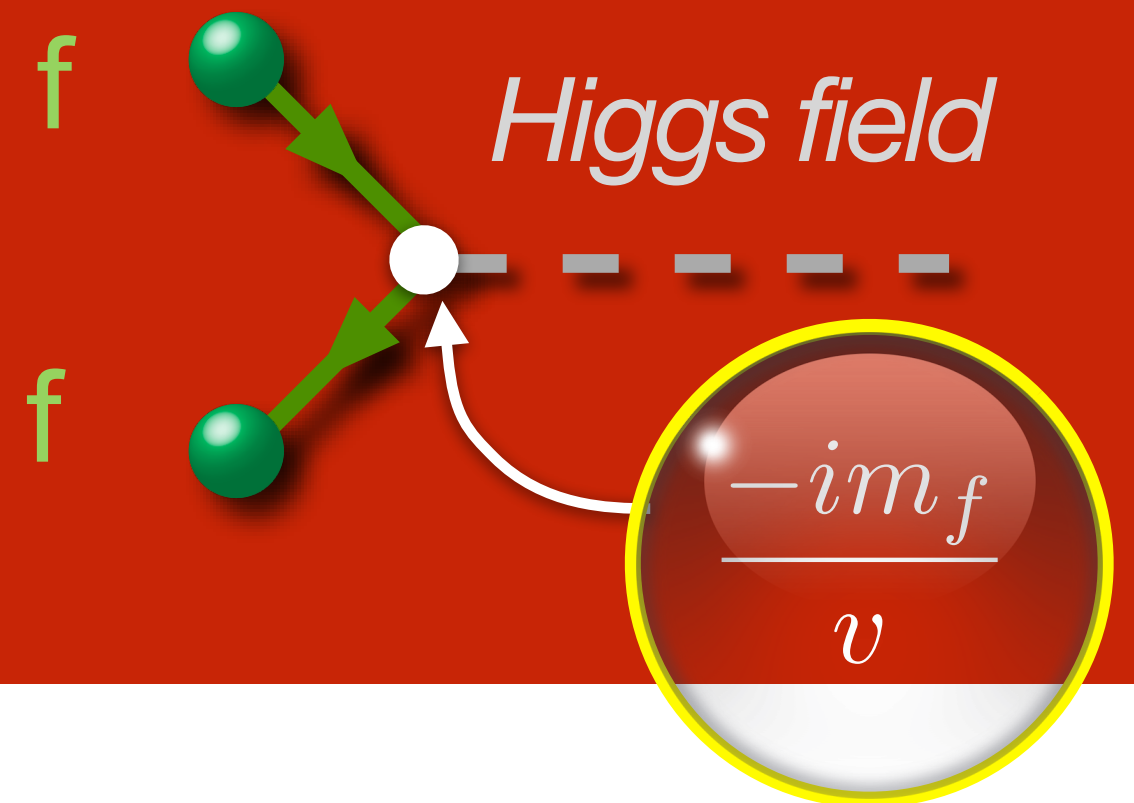
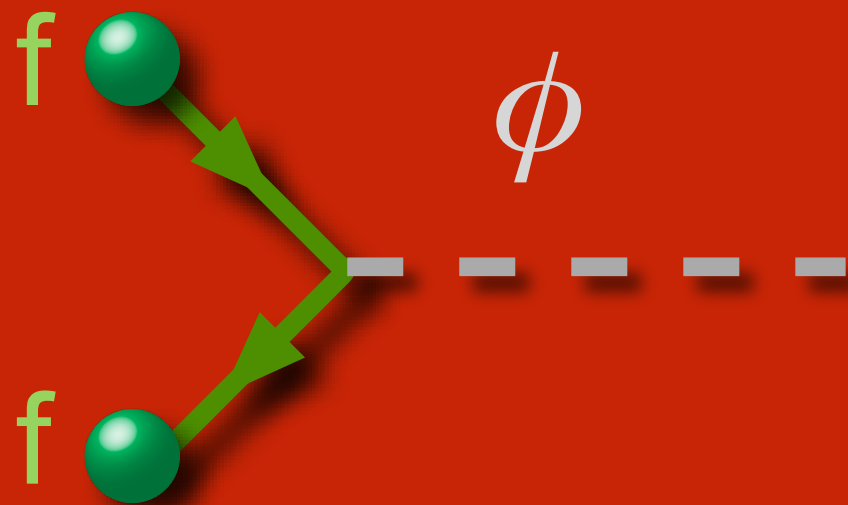
or

**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/](https://qstbb.pa.msu.edu/storage/Extras_2017/HiggsDiscovery/)



how to find the  
Higgs?

look for him!













MARCJACOBS.COM

# The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET



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Education  
Event Guide  
Fashion & Style  
Home & Garden  
Jobs  
Magazine  
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Music  
Photo archive

## 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 PROTSESS 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 Barboise

## 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 fireworks displays after a series of fires.

## 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 clash with the town's Hamlet's Bald Eagles.

### 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

GET QUOTES My Portfolios  
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INTRODUCING  
NEW YORK TIMES  
CORPORATE DIGITAL  
SUBSCRIPTIONS.  
From insight comes inspiration.



The Nobel Prize in Physics 2013  
François Englert, Peter Higgs

Share this:

## 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 mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Photos: Copyright © The Nobel Foundation







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  $\gamma$  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

 **Nobelprize.org**  
The Official Web Site of the Nobel Prize

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Home / Nobel Prizes / Nobel Prize in Physics / The Nobel Prize in Physics 1979

About the Nobel Prizes

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1901 2012

Sort and list Nobel Prizes and Nobel Laur Prize category: Physics

 **The Nobel Prize in Physics 1979**  
Sheldon Glashow, Abdus Salam, Steven Weinberg

**The Nobel Prize in Physics 1979**

Nobel Prize Award Ceremony

Sheldon Glashow

Abdus Salam

Steven Weinberg

**Sheldon Lee Glashow Abdus Salam Steven Weinberg**

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam, and Steven Weinberg for their contributions to the theory of the weak interaction between elementary particles, and the prediction of the neutral current.

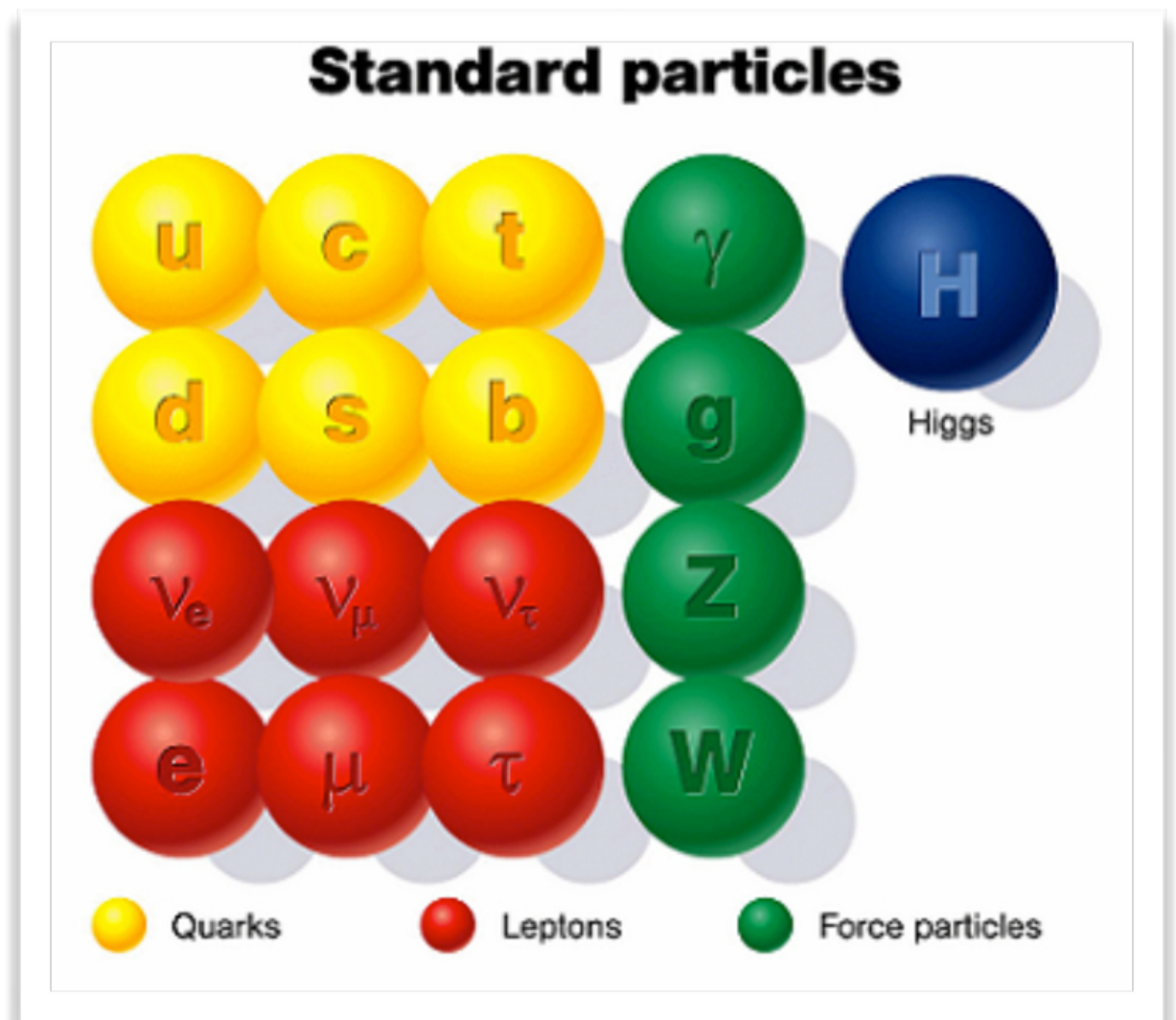
  

the  
particle  
players

and

the "substrate"

Our "Periodic Table"



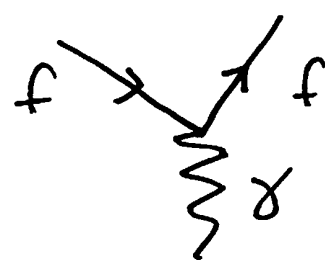
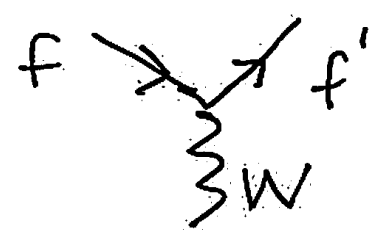
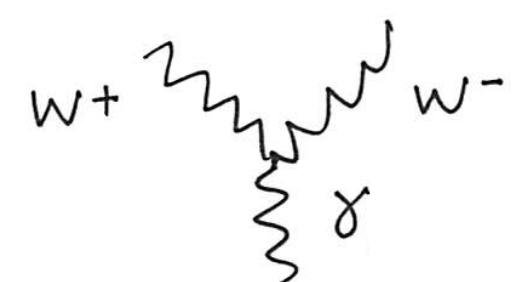
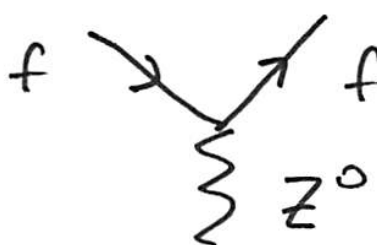
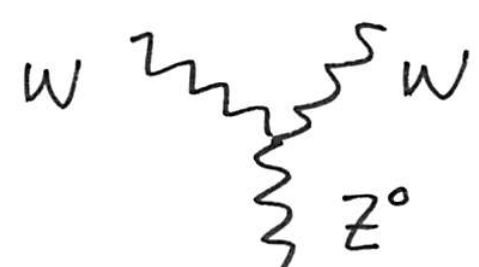
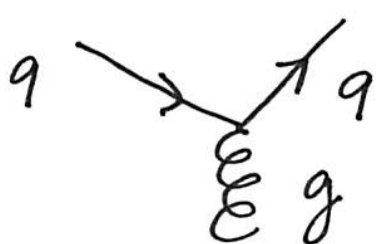
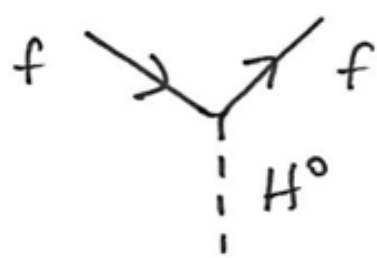
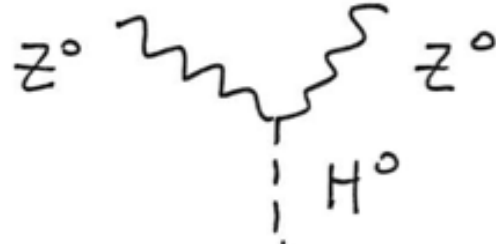


like any  
particle,

we predict and  
then search for its  
manifestation

through its decays

Your final entries  
into the Primitive  
Diagram  
collection

| Primitive Diagrams                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                       | TIME always:  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |    | QED                                                                                              |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |    | Weak Interactions                                                                                |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |    |                                                                                                  |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |   | Strong Interactions                                                                              |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |   |                                                                                                  |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | Higgs Interactions                                                                               |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  |                                                                                                  |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  |                                                                                                  |
| 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | Higgs Interactions                                                                               |
| 10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                                                                                  |
| 11                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                                                                                  |
| <div>fermion, spin 1/2, e.g., electron</div> <div>Vector Boson, spin 1, e.g., photon</div> <div>gluon, spin 1</div> <div>scalar Boson, spin 0, e.g., Higgs Boson</div> <div></div> <div></div> <div></div> <div></div> |                                                                                       |                                                                                                  |





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/](https://qstbb.pa.msu.edu/storage/Extras_2017/DarkMatter/)





the more  
pleasing

extension of the  
Standard Model

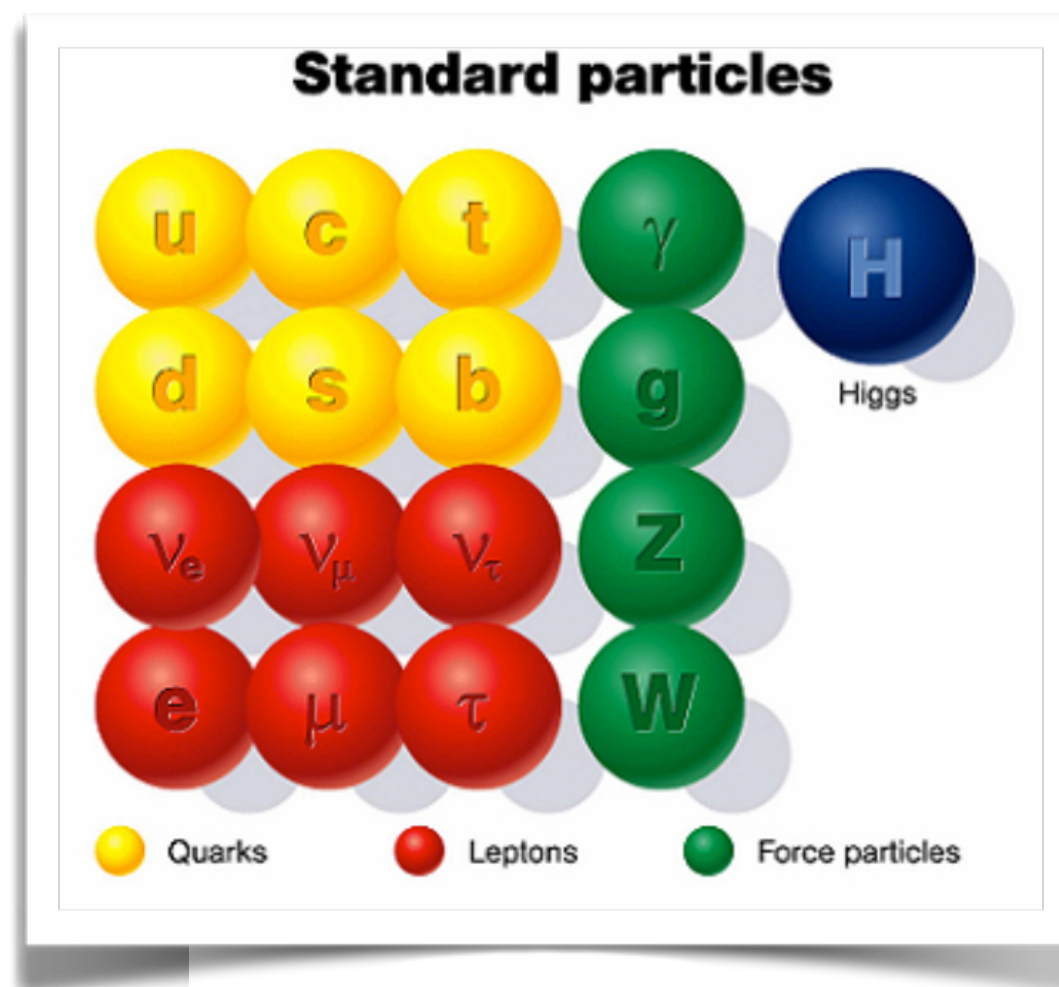
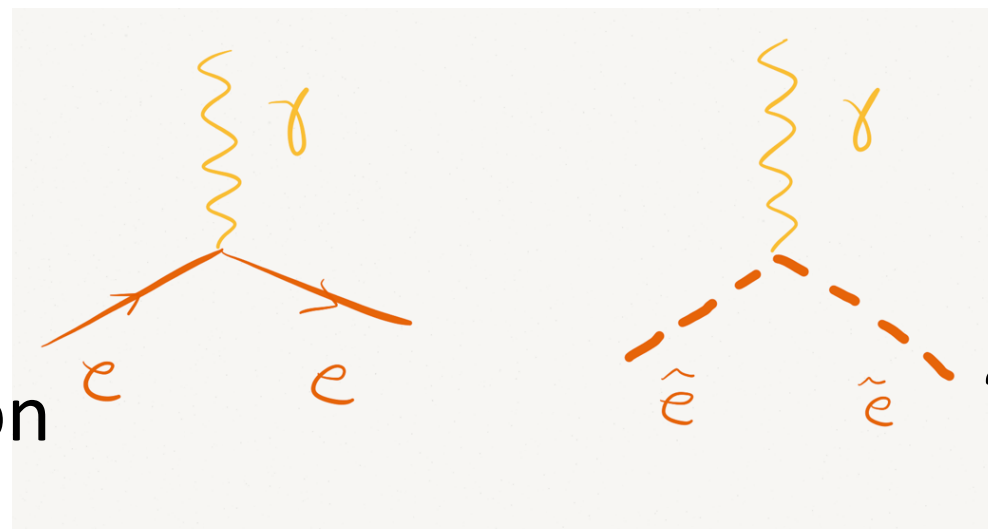
"supersymmetry"

every "Standard  
Model Particle"

has a super-partner

*presumably  
much heavier*

electron



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



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*

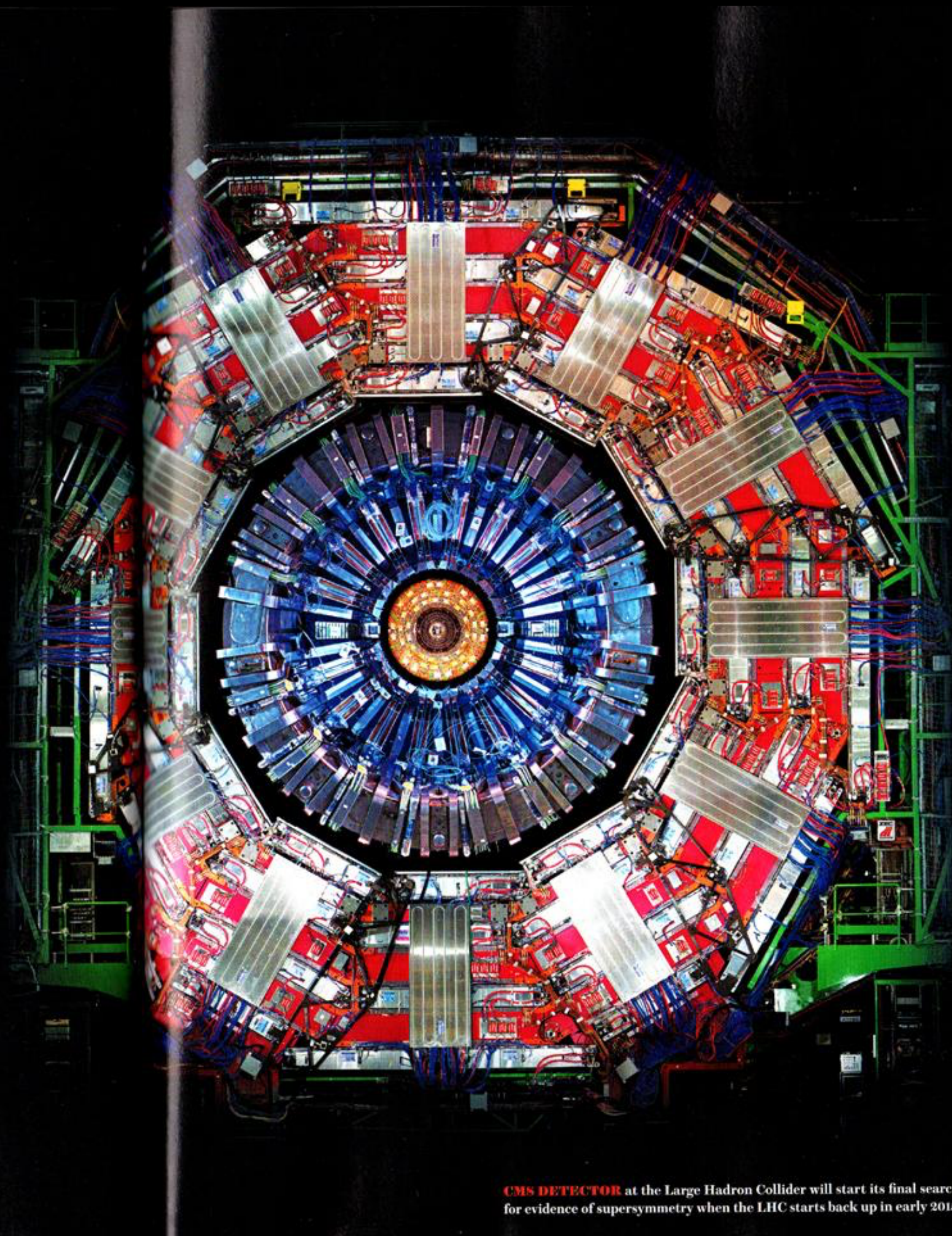
PARTICLE PHYSICS

# Supersymmetry and the Crisis in Physics

## IN BRIEF

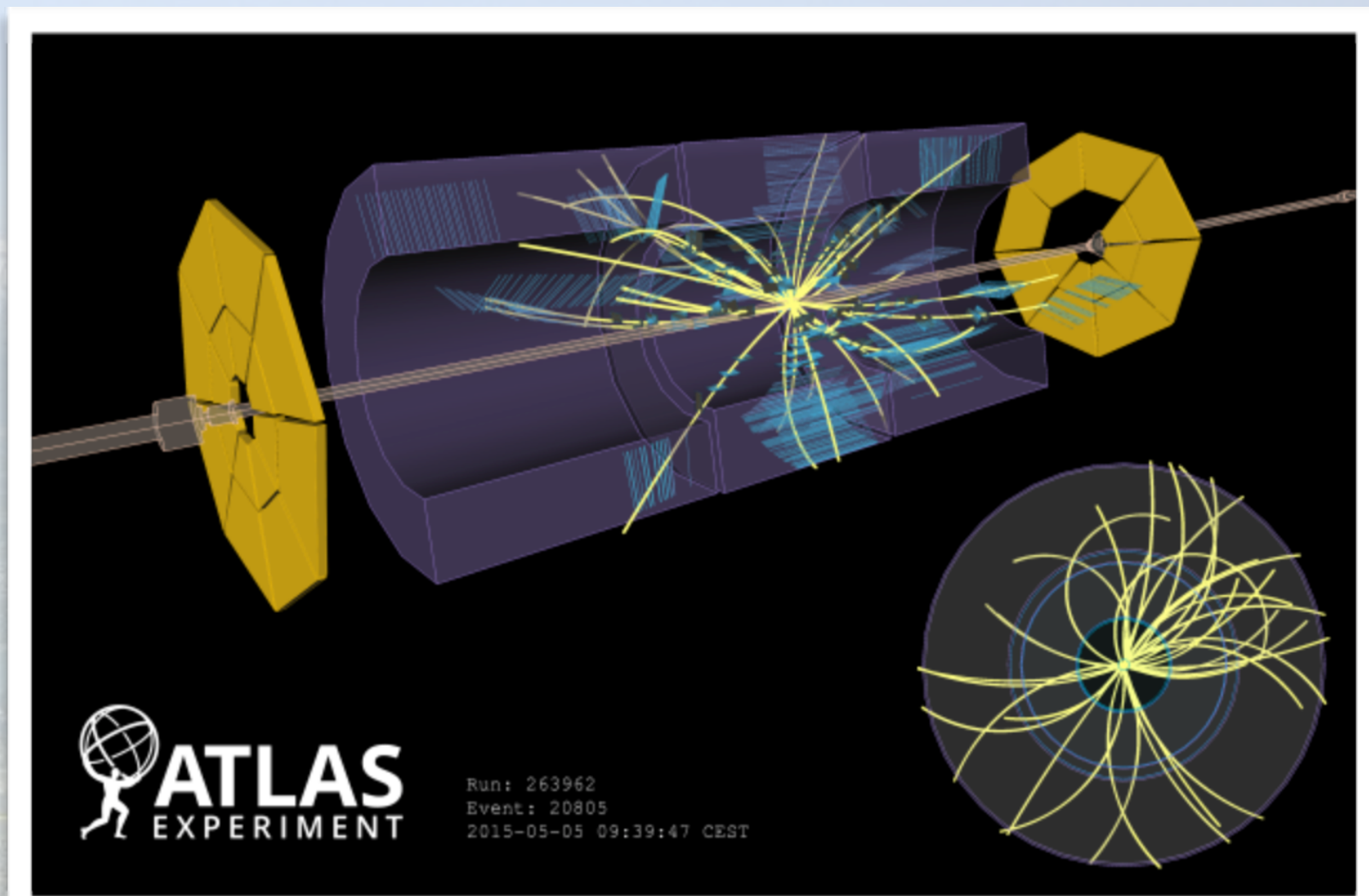
Supersymmetry postulates that every known particle has a hidden superpartner. Physicists love supersymmetry because it solves a number of problems that crop up when they try to extend our understanding of quantum mechanics. It would also potentially solve the mystery of the universe's missing dark matter.

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  
 $0.75 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

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

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

20  $\text{fb}^{-1}$

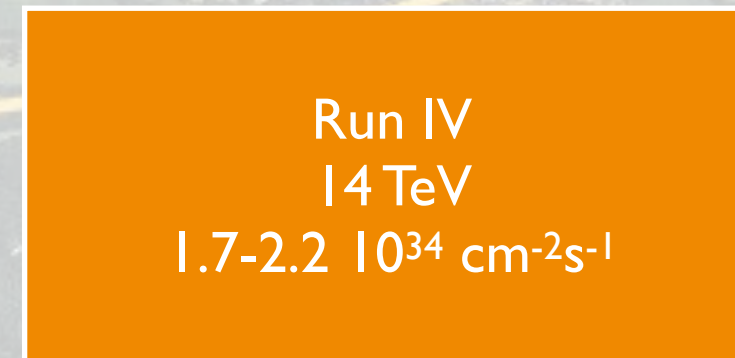
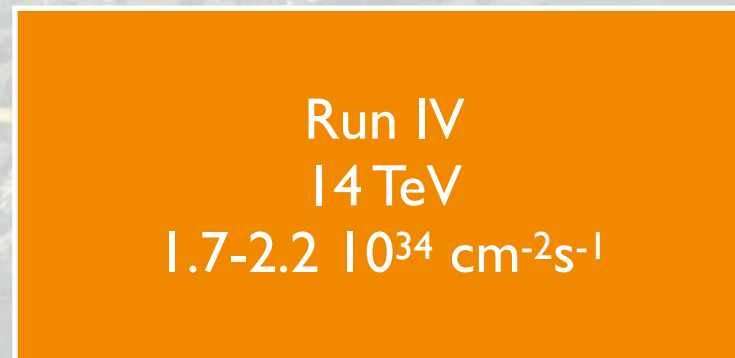
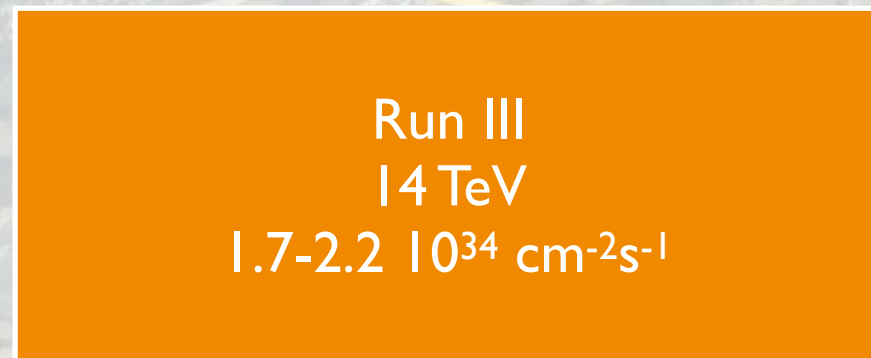
>100  $\text{fb}^{-1}$

300  $\text{fb}^{-1}$



stay buckled in

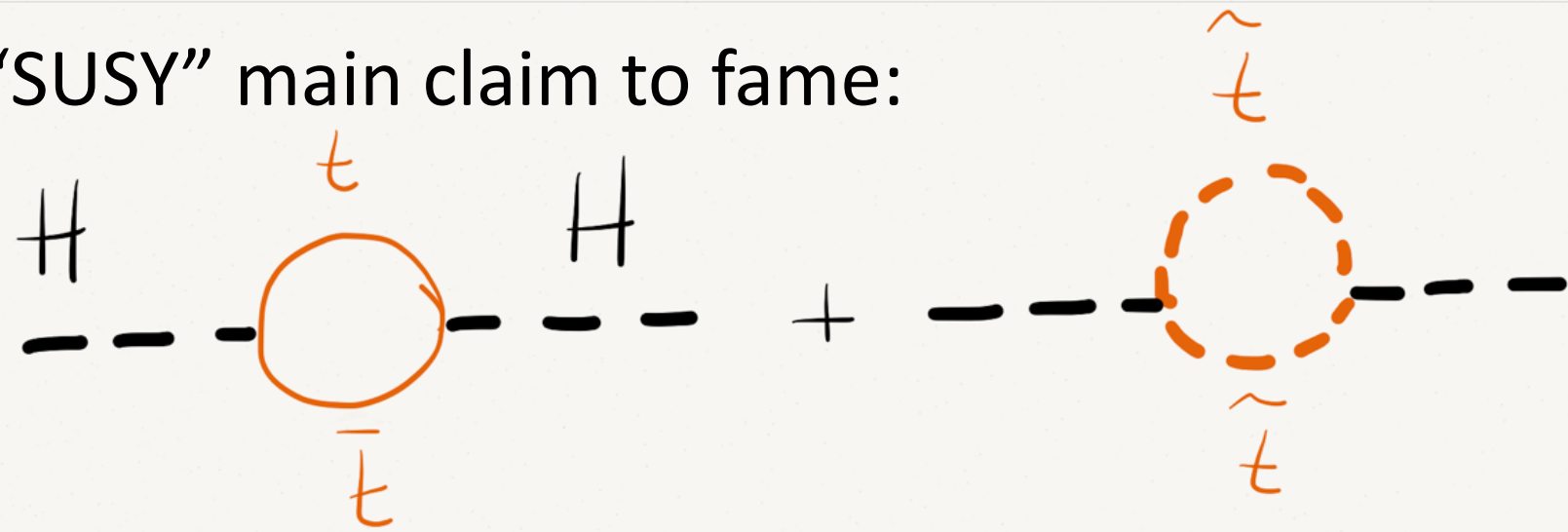
"phase 2 upgrades"



3000 fb<sup>-1</sup>



“SUSY” main claim to fame:



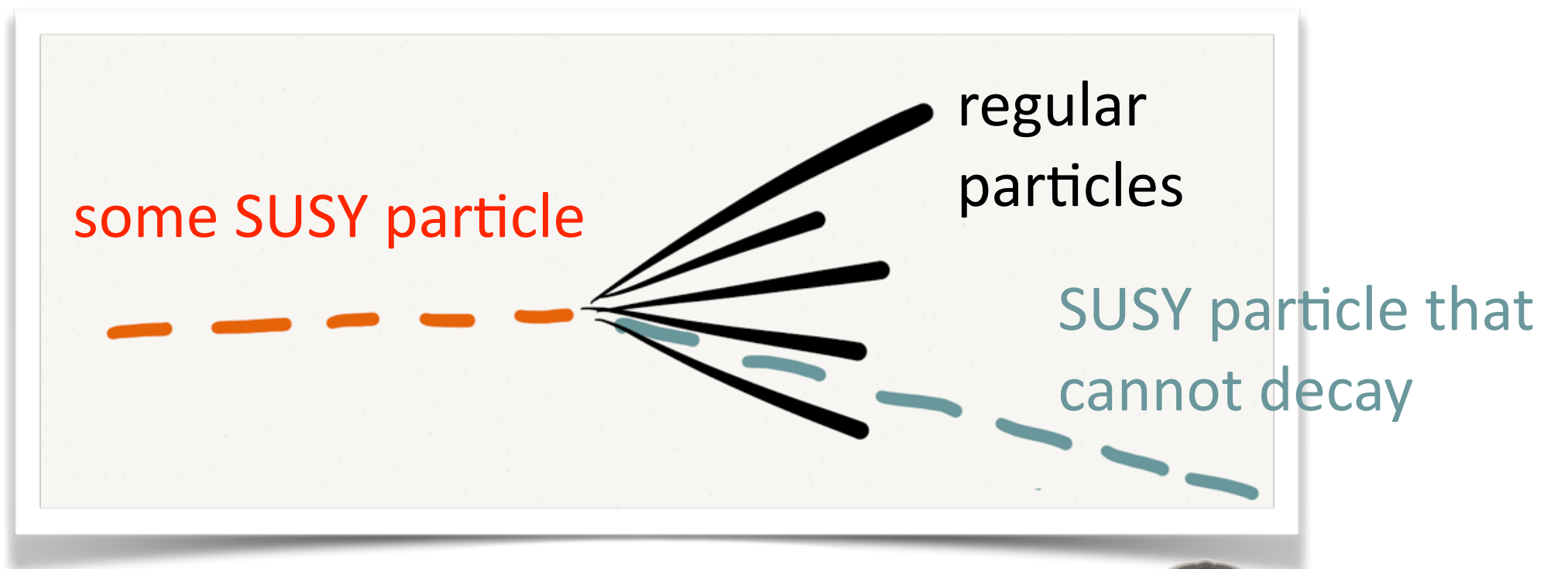
The diagram shows two Feynman diagrams for Higgs mass corrections. The first diagram (left) is a Standard Model loop diagram with a solid orange circle, labeled with  $t$  and  $\bar{t}$ . The second diagram (right) is a SUSY loop diagram with a dashed orange circle, labeled with  $\tilde{t}$  and  $\tilde{t}$ . Both diagrams are connected by a plus sign, and the entire expression is set equal to zero.

$$\text{SM Loop} + \text{SUSY Loop} = 0$$

intriguing

for two big  
reasons

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

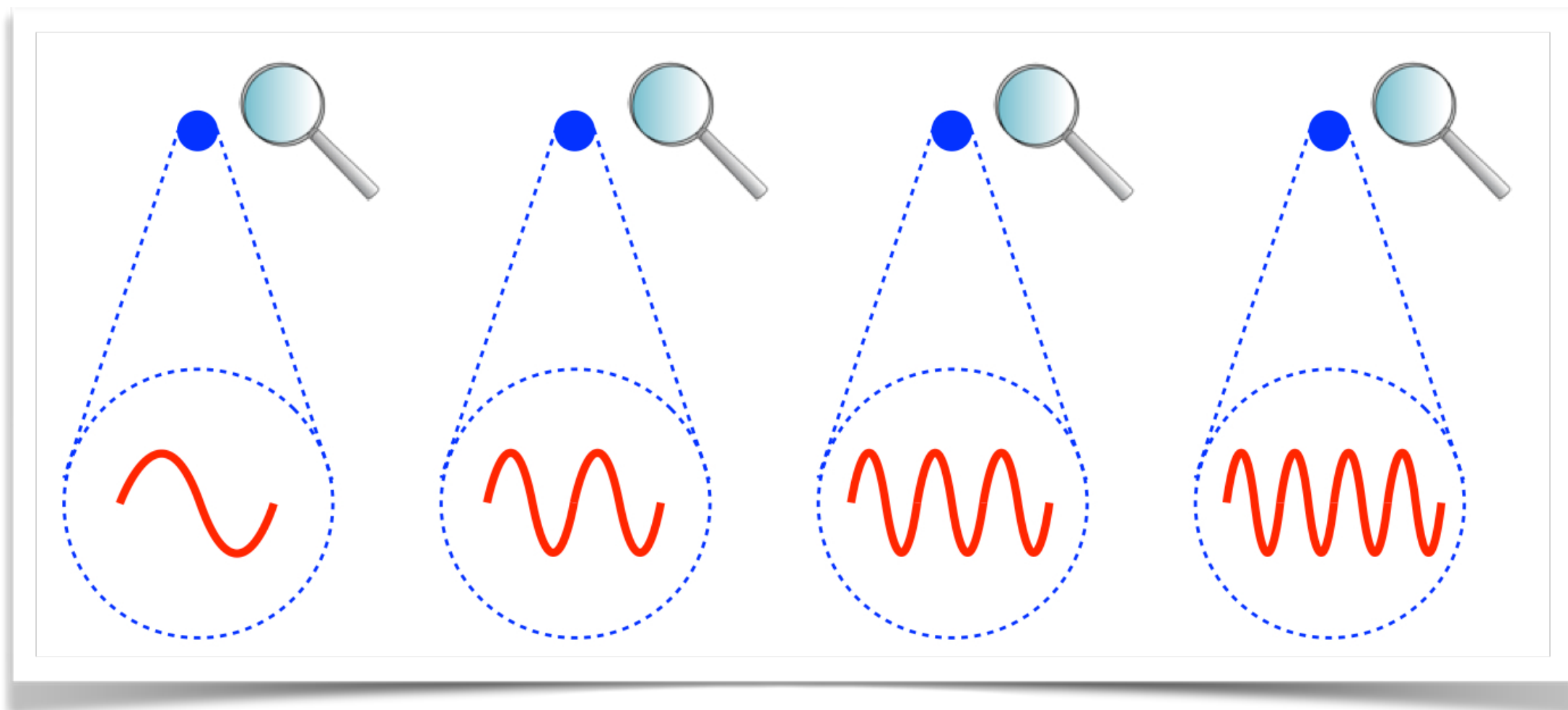
composite Higgs

composite quarks  
and leptons

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

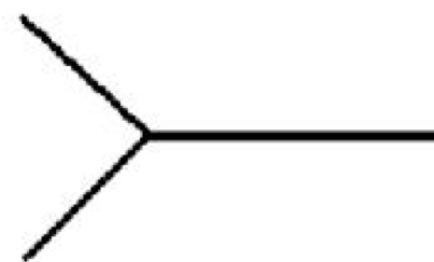
The “infinities” in Relativistic Quantum Field Theory are related to extrapolation in spacetime to zero,  $x, y, z, = 0$

Suppose there is a minimum length in Nature?

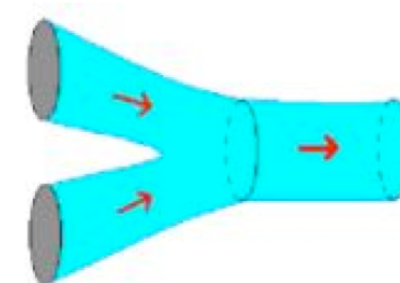


each wavelength...a different – e x t e n d e d – particle.

Plus: get a gravity and the graviton for free!



Point particle interaction

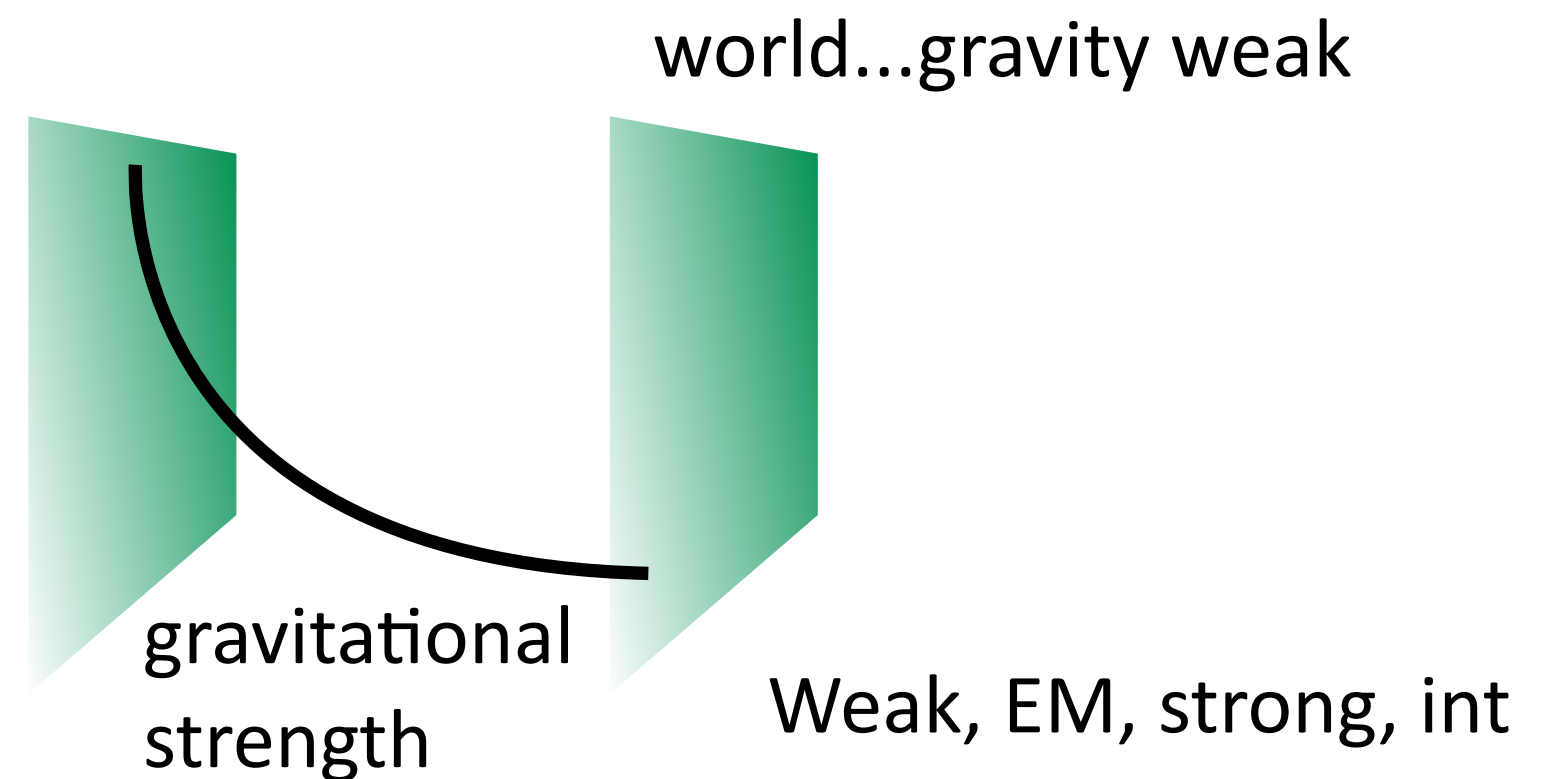


String interaction

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



high energy  
scale  
dimension(s)





pretty:



# hi, again

Day 26, 04.23.2019

Cosmology 5



# FLRW catalogue of Universes

$$\Lambda > 0$$

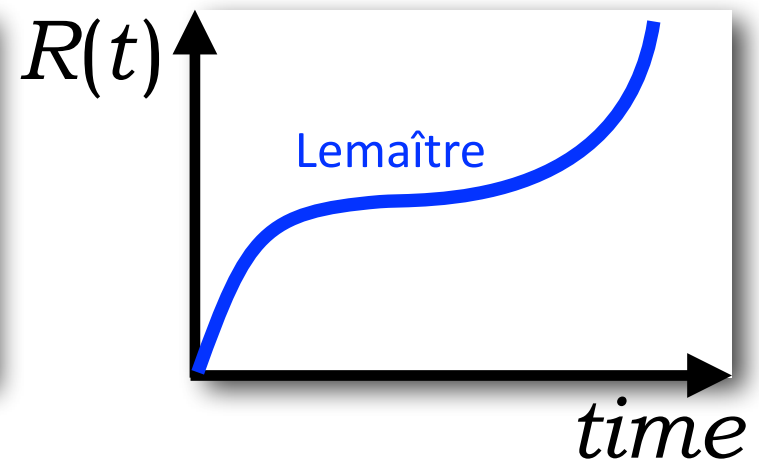
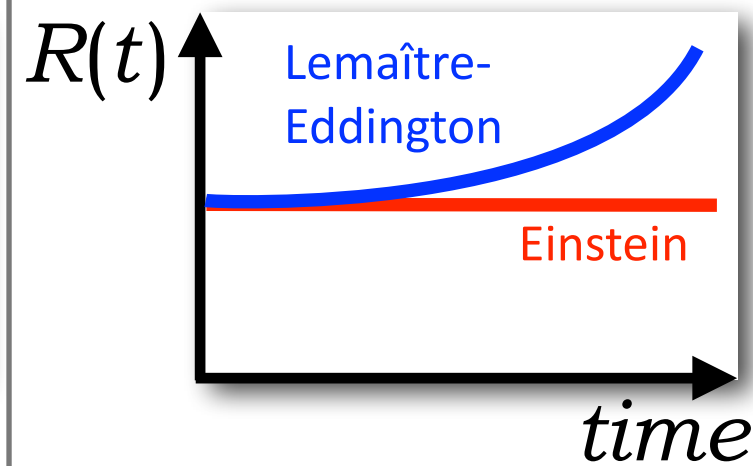
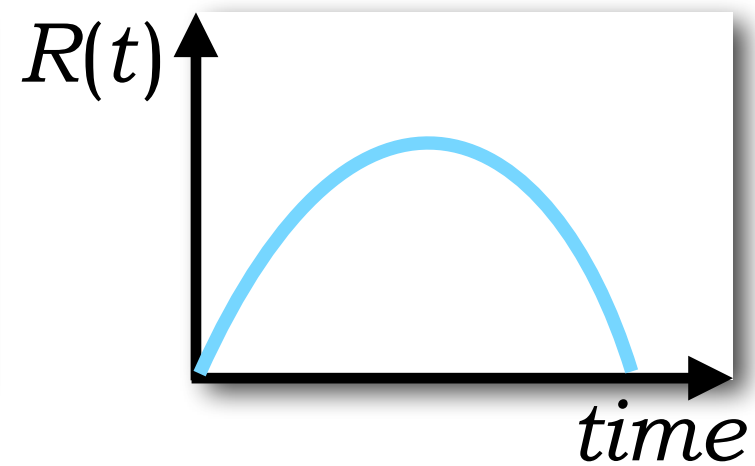
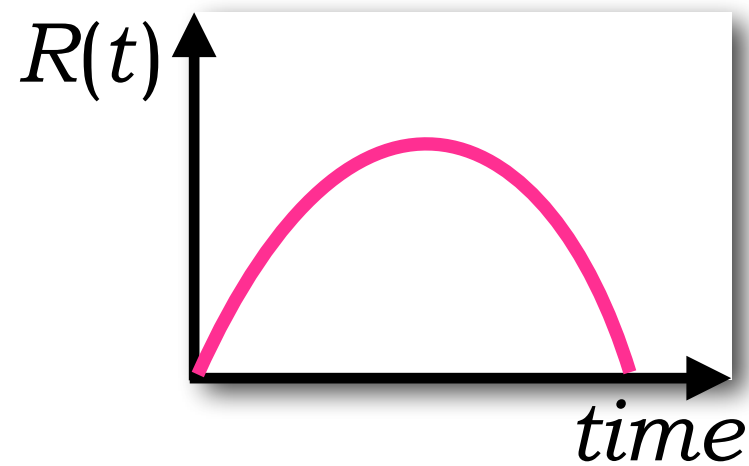
$$\Lambda < 0$$

$$\Lambda = 0$$

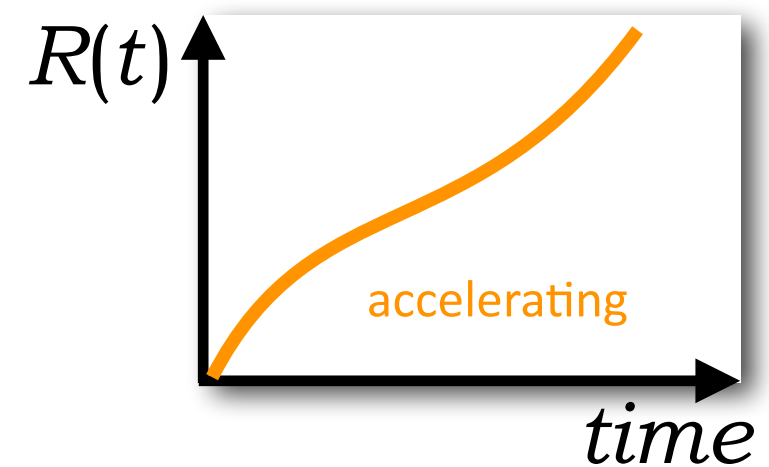
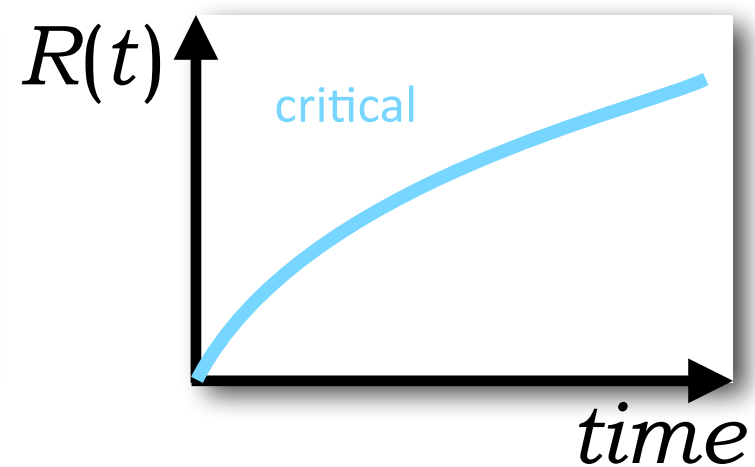
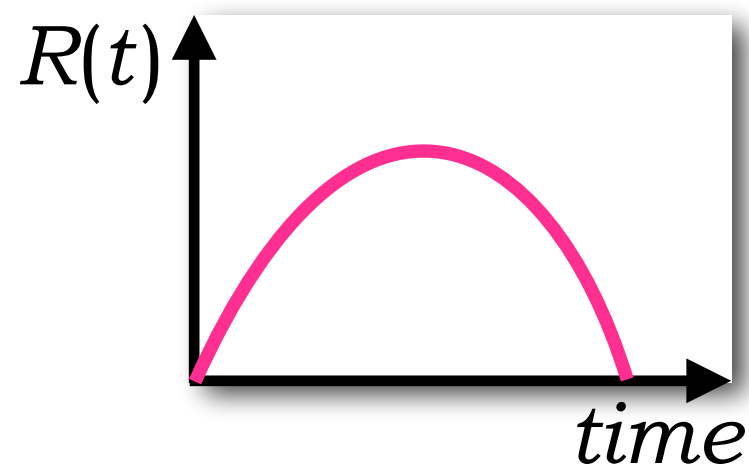
$$\Lambda = \Lambda_E$$

$$\Lambda > \Lambda_E$$

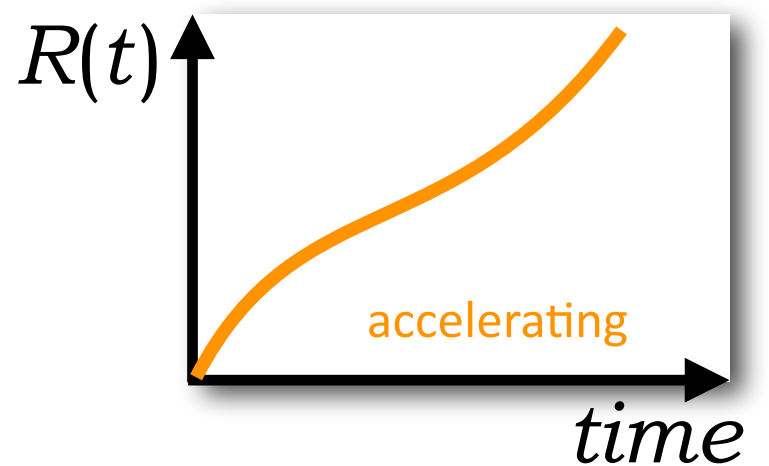
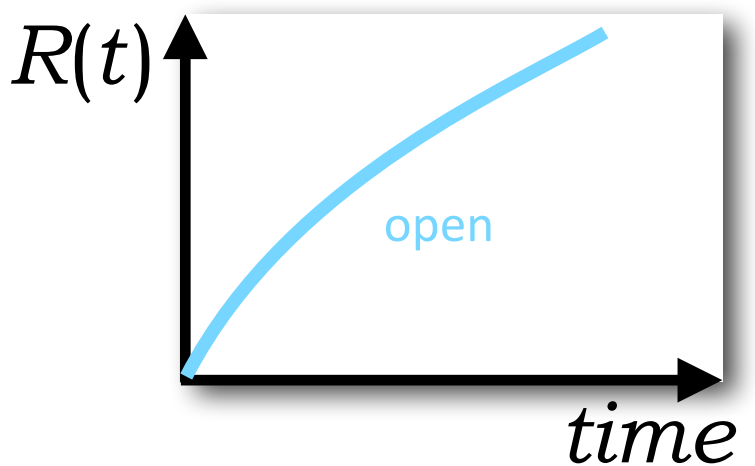
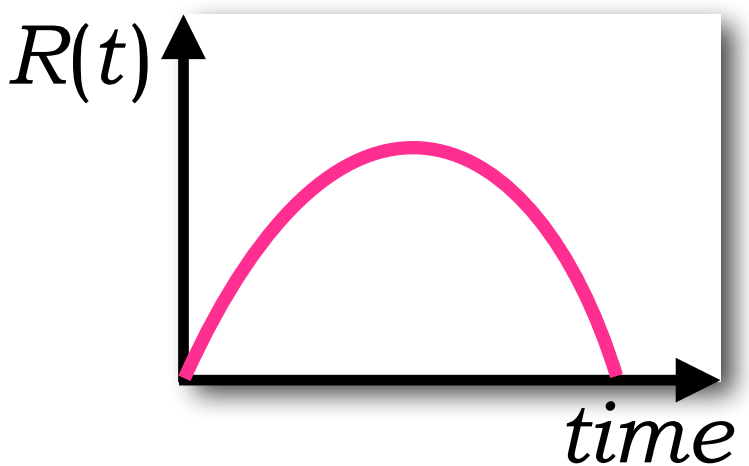
$$k = +1$$



$$k = 0$$



$$k = -1$$



# ~~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 big 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 number of routes, 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 ~~new~~ way I am now going to discuss involves the hypothesis that matter is created continuously.

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 these 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.

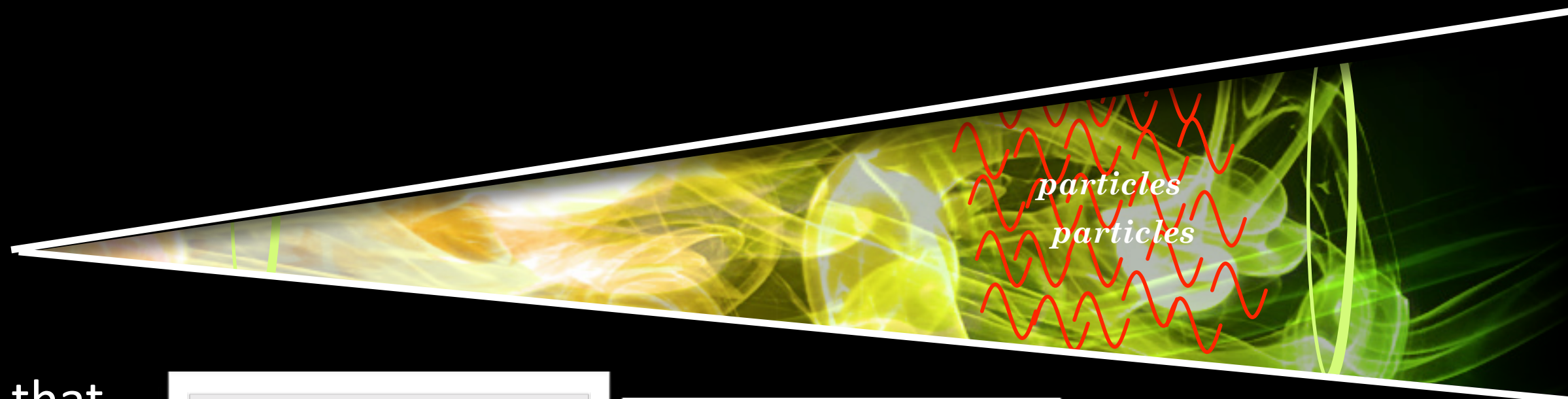
Sorry, Fred.

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

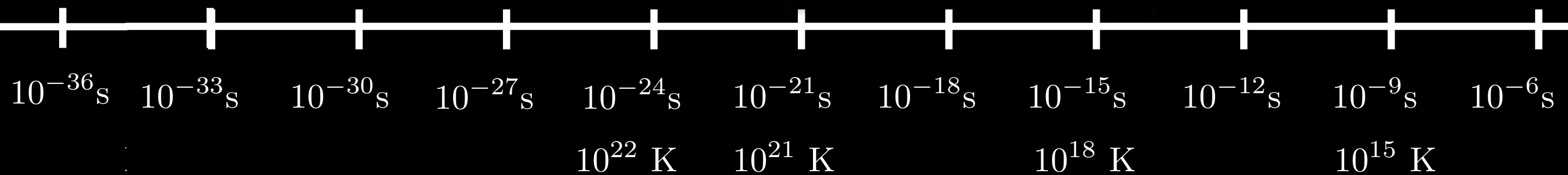
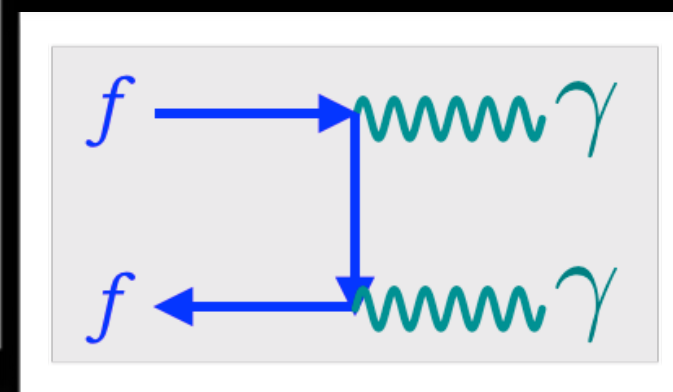
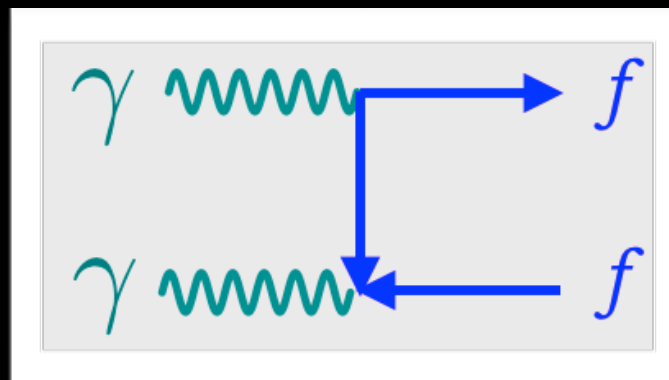
evolving in time and temperature.



# elementary particle epoch



presumed that  
processes are in  
equilibrium



# There is a limit

Beyond which  
there is no  
physics

at the current time

Planck Time =  $5.4 \times 10^{-44}$  s

Planck Length =  $1.6 \times 10^{-35}$  m



need a quantum  
theory of gravity

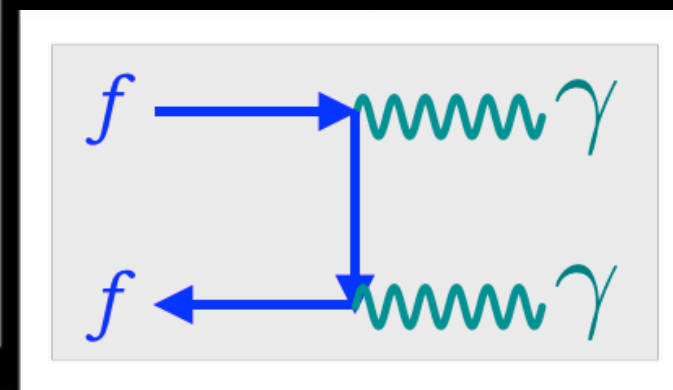
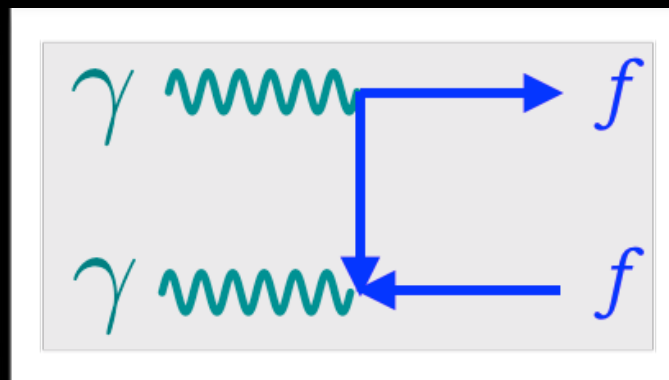
Or a physics with a built-in minimum length in  
Nature...String Theory.

# elementary particle epoch

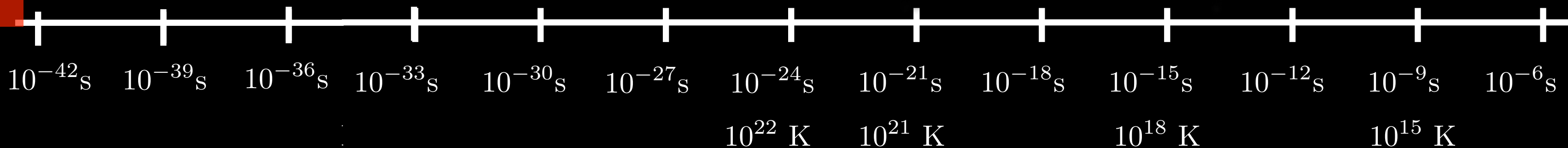
“Quantum Foam”

?

presumed that  
processes are in  
equilibrium



particles  
particles



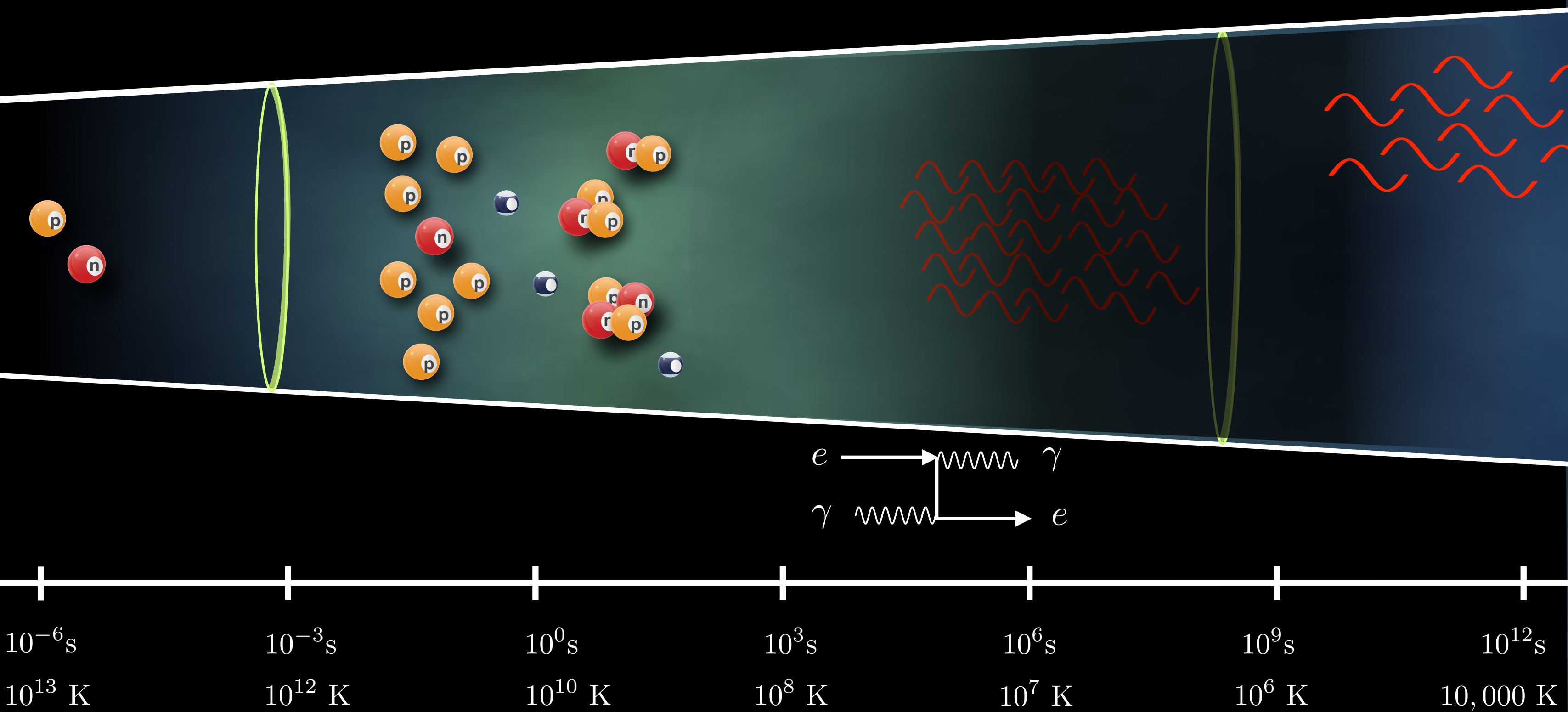


# n u c l e o n   e p o c h

hadron era

nucleosynthesis era

opaque era

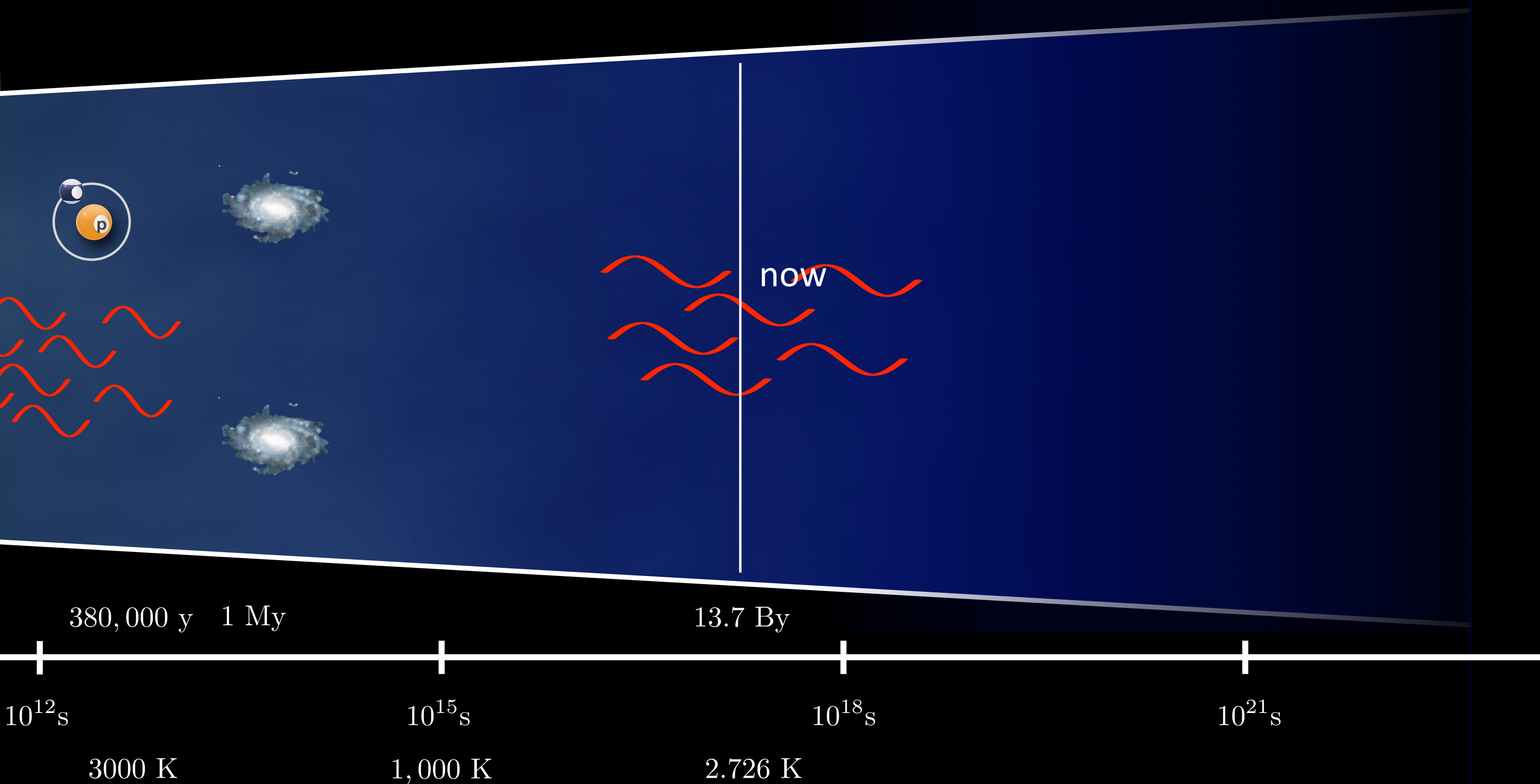


# galactic epoch

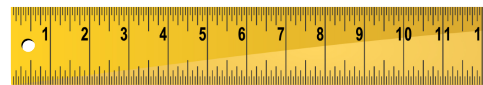
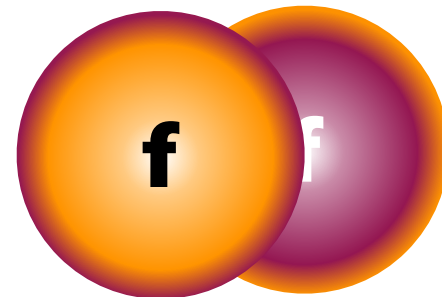
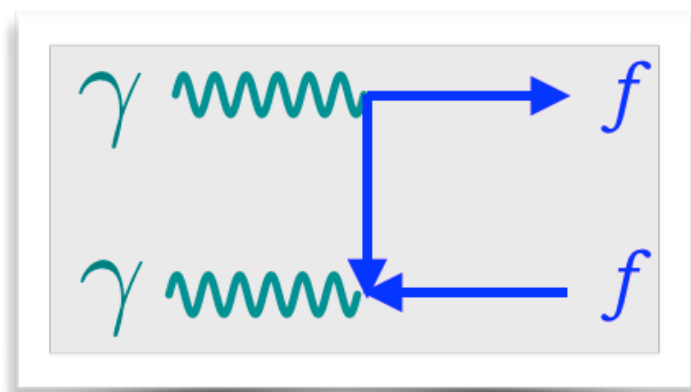
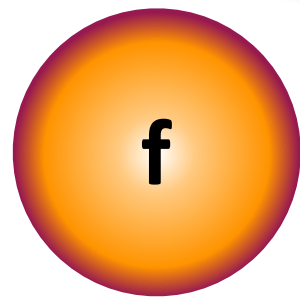
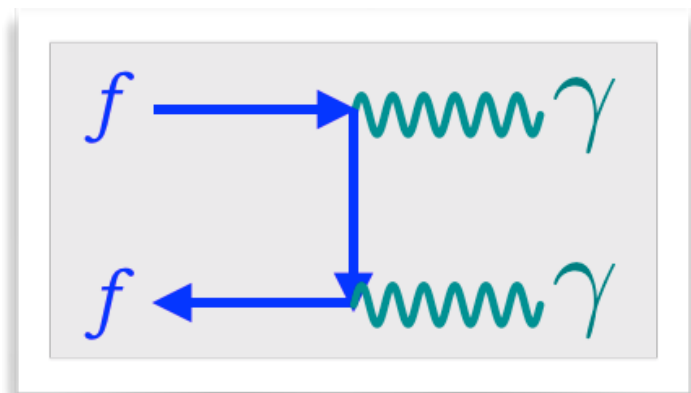
light era

our era

dark era



prior to 3 minutes: balance between radiation and particles.



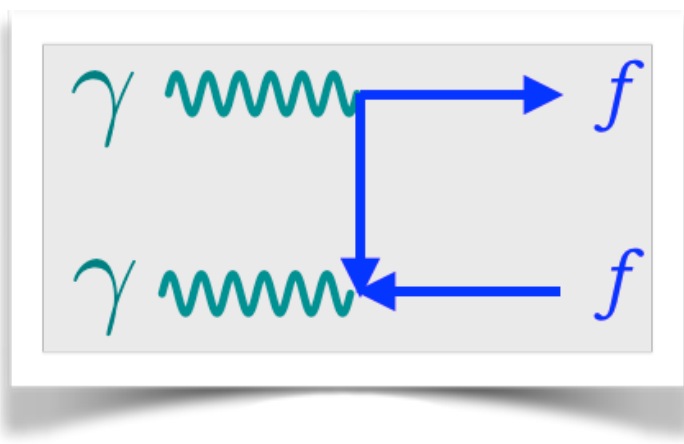
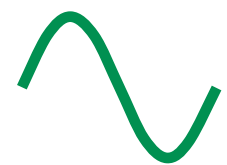
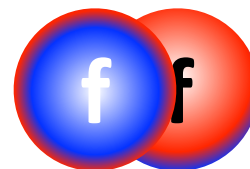
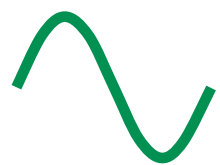
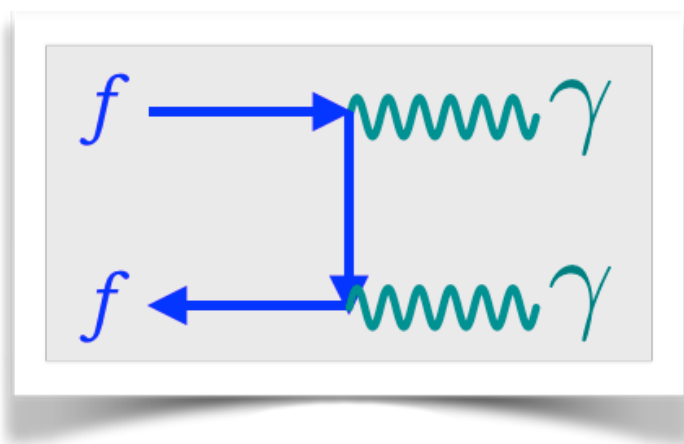
**Early moments:** short wavelength photons = high frequency photons = high energy photons  
lots of  $mc^2$  available—can make heavy particles



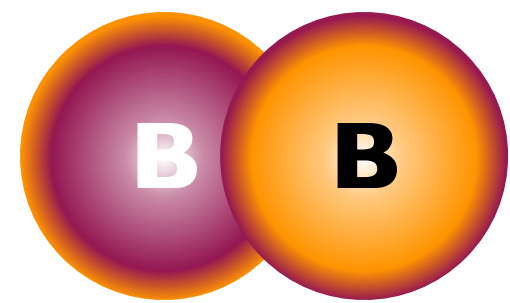
prior to 3 minutes: balance between  
radiation and particles.

spacetime has stretched!

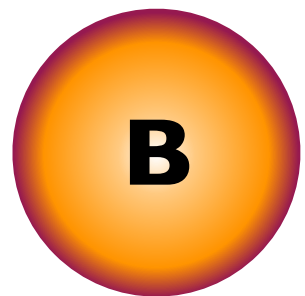
**Later moments:** longer wavelength, lower frequency = less high energy photons  
less  $mc^2$  available—can't make heaviest particles



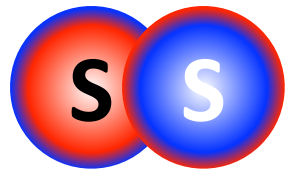
heavy species “freeze out”: pairs cannot be created any more  
energies



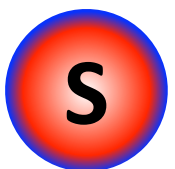
$$2m_{\text{really heavy}}c^2$$



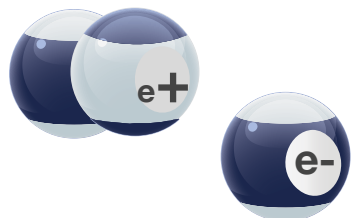
$$m_{\text{really heavy}}c^2$$



$$2m_{\text{heavy}}c^2$$



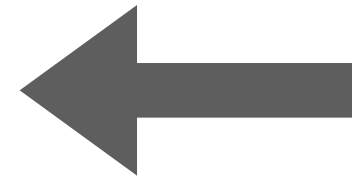
$$m_{\text{heavy}}c^2$$



$$2m_{\text{electron}}c^2$$

$$m_{\text{electron}}c^2$$

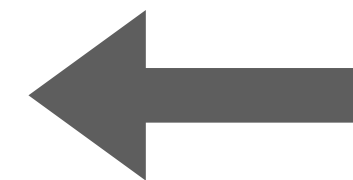
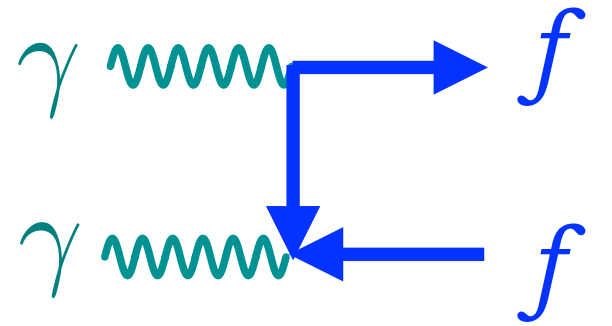
$\gamma + \gamma$



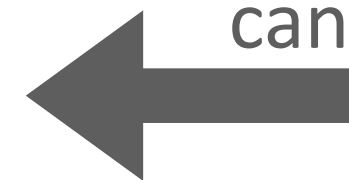
below this point:  
can't make BB

wavelength stretching...  
energy shrinking

from:



below this point:  
can't make SS



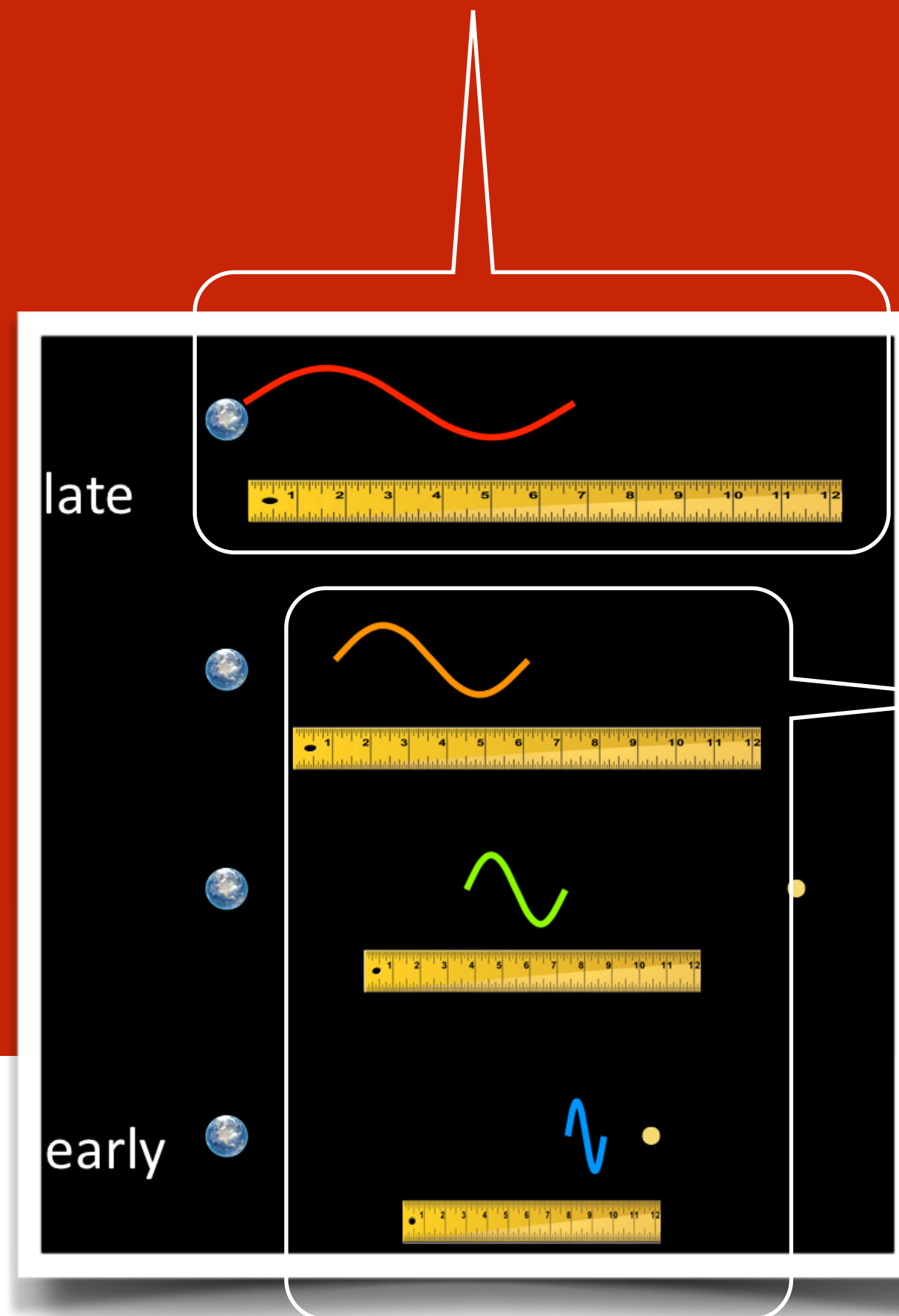
below this point:  
can't make anything!

time →

space stretching →

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



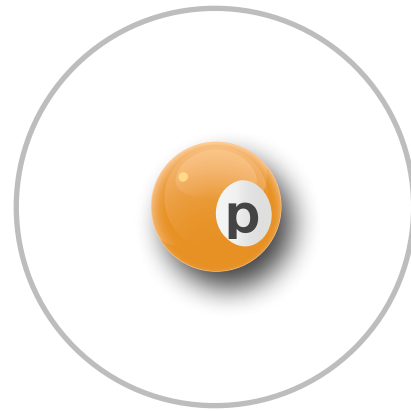
there is  
a magic  
point

at which atoms  
can start to form

"recombination"

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

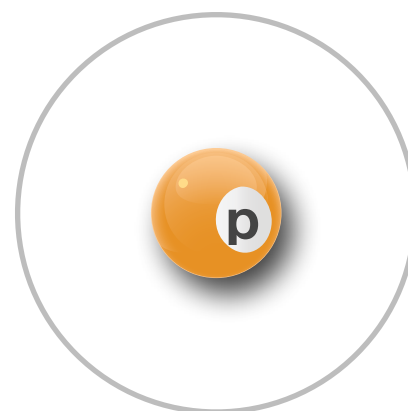
After protons, neutrons, and electrons are stable...



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  $10^{12-13}$  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**

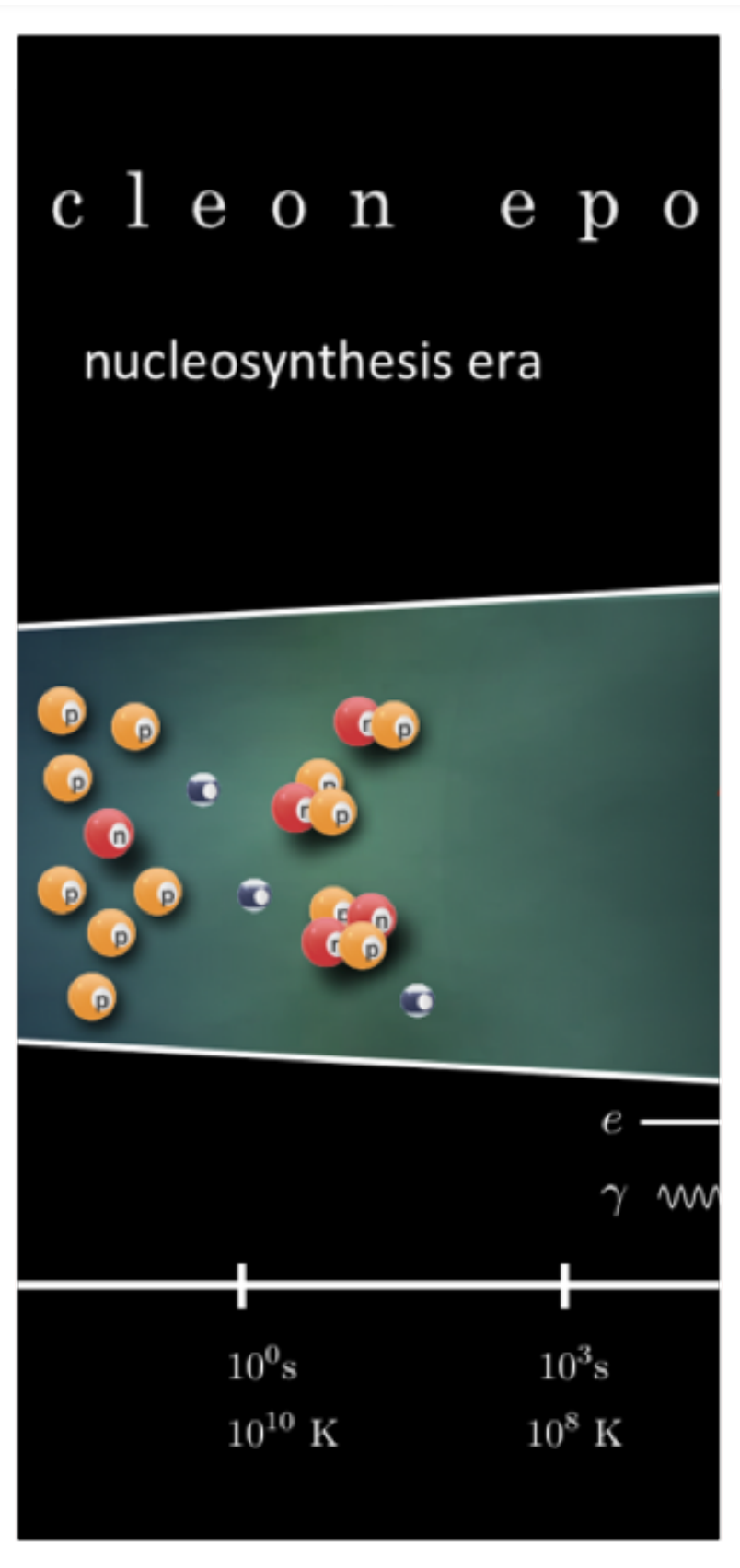
no longer making new matter-antimatter bits

The Cosmic Microwave Background, CMB

There are two critical times  
that confirm the Big Bang





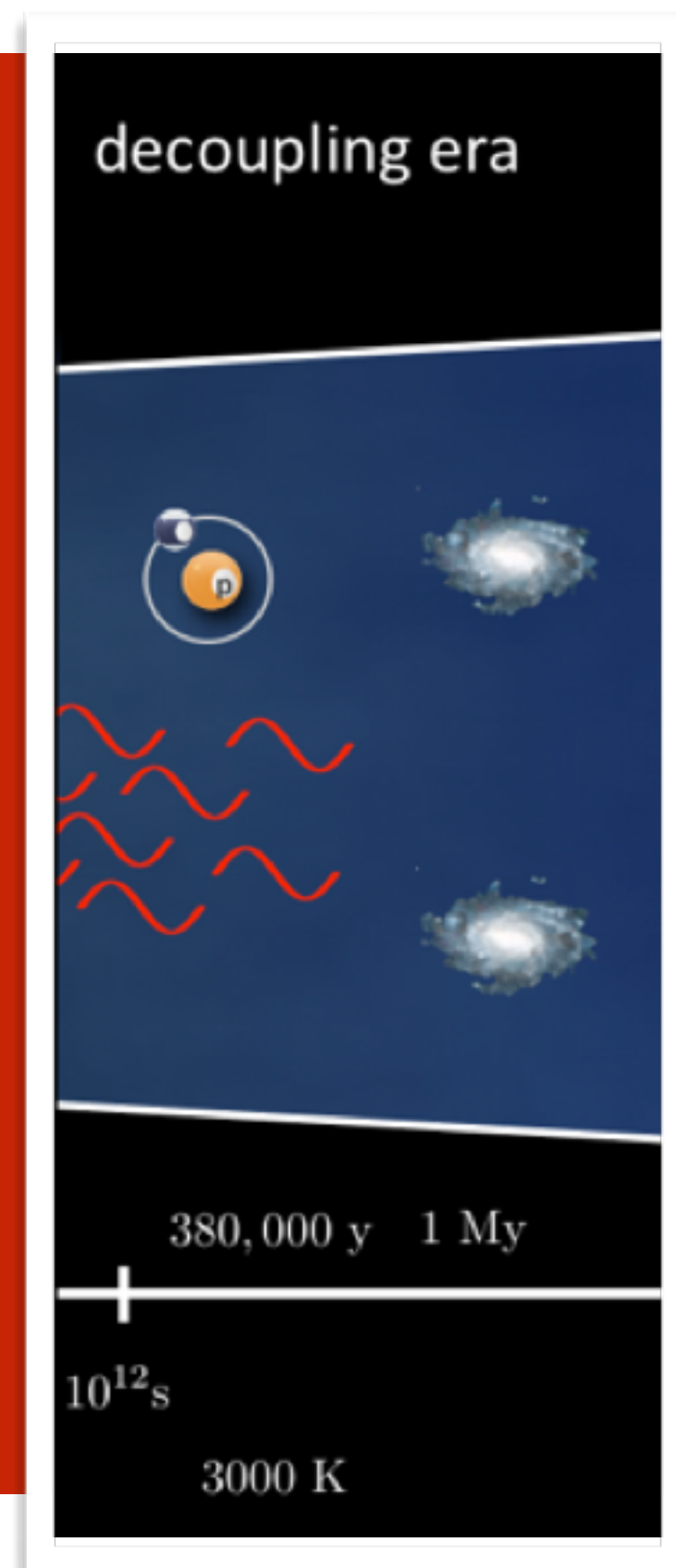


3 minutes



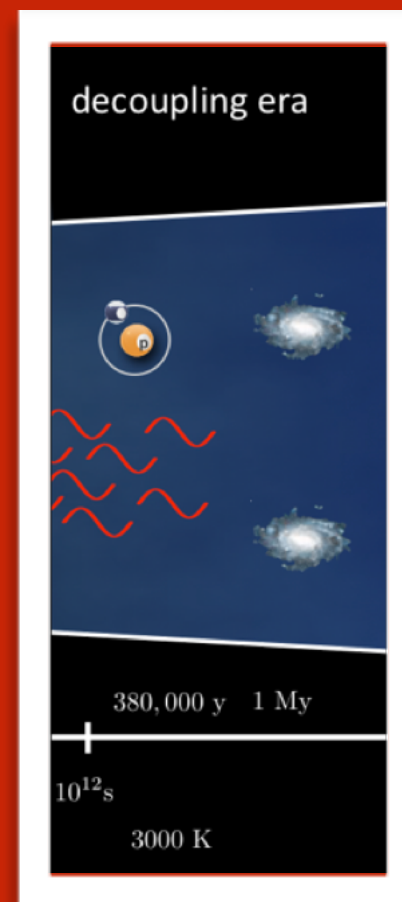
370,000 years

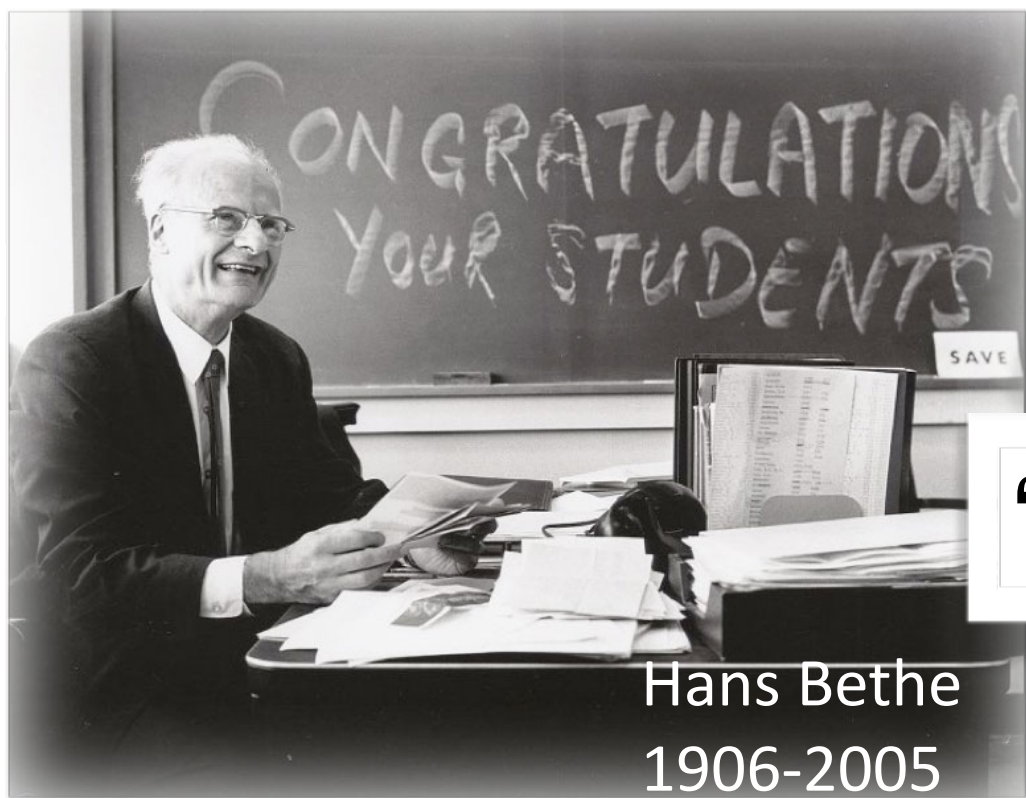
(all within the first 15 fake-minutes on  
my calendar)



# the Cosmic Microwave Background, CMB

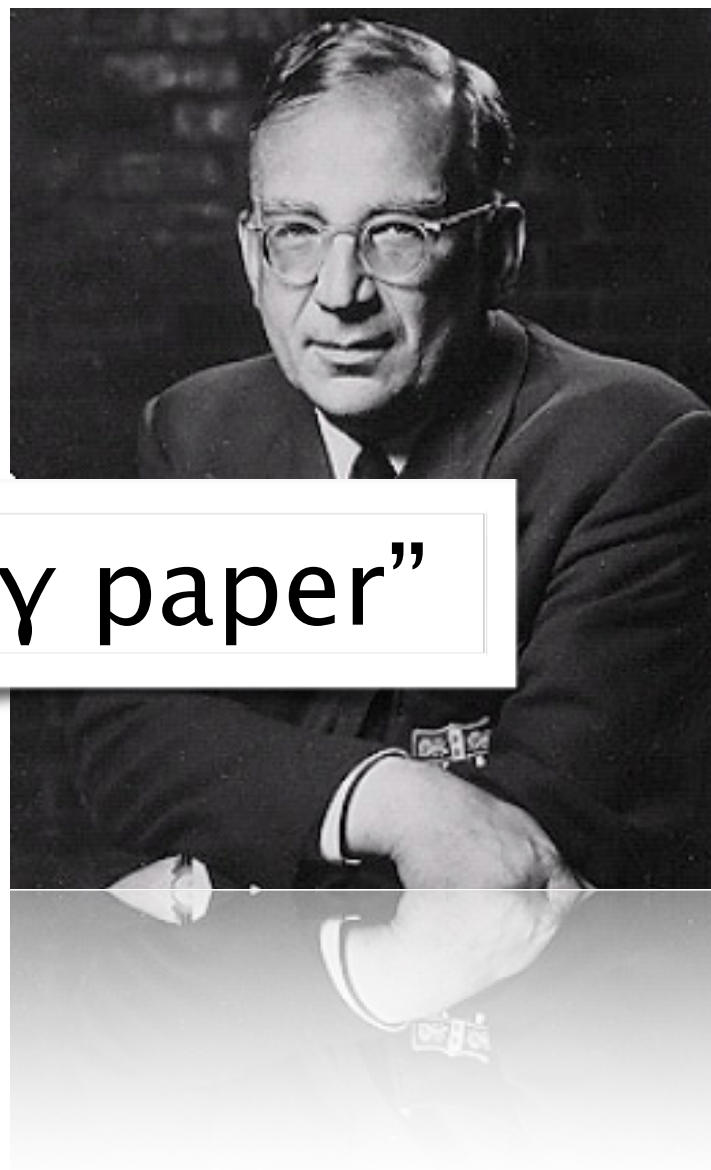
about 370,000 y after BB



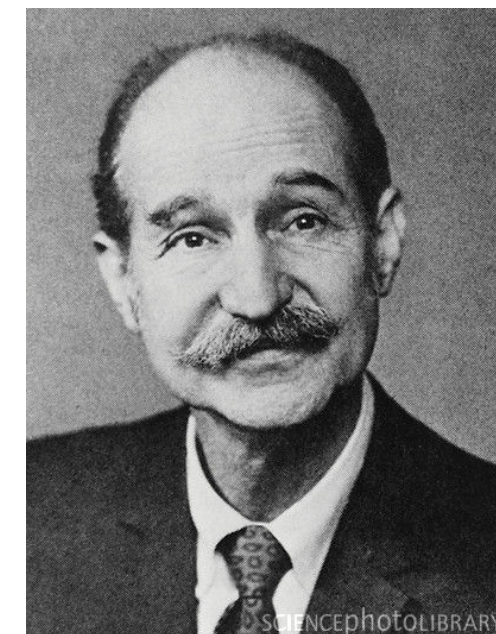


Hans Bethe  
1906-2005

“ $\alpha\beta\gamma$  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

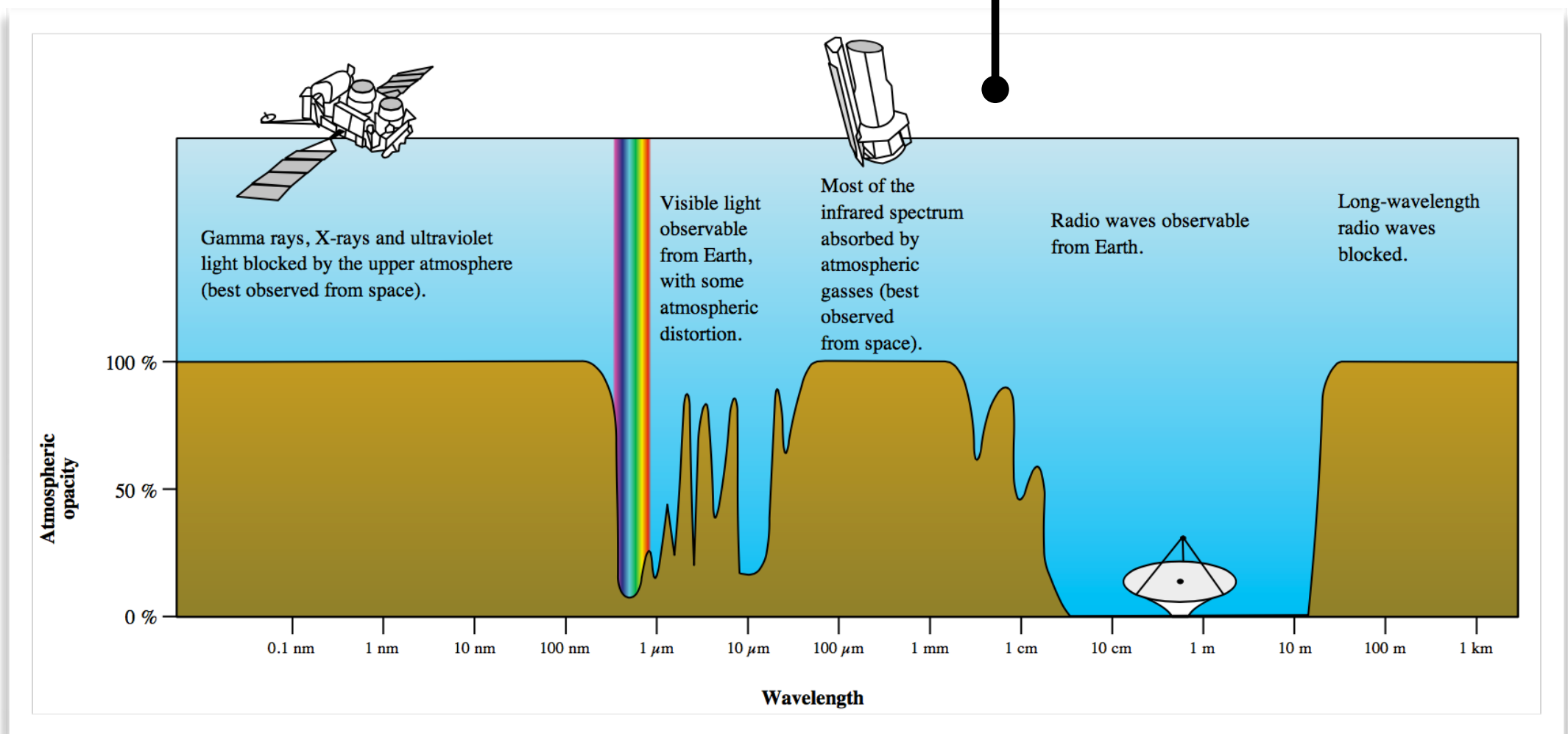
ATT cell phone  
frequencies of

~2 GHz

~15 cm

microwave ovens

where we're going





# the phone company

ATT Labs,  
Crawford Hill, New  
Jersey

1963

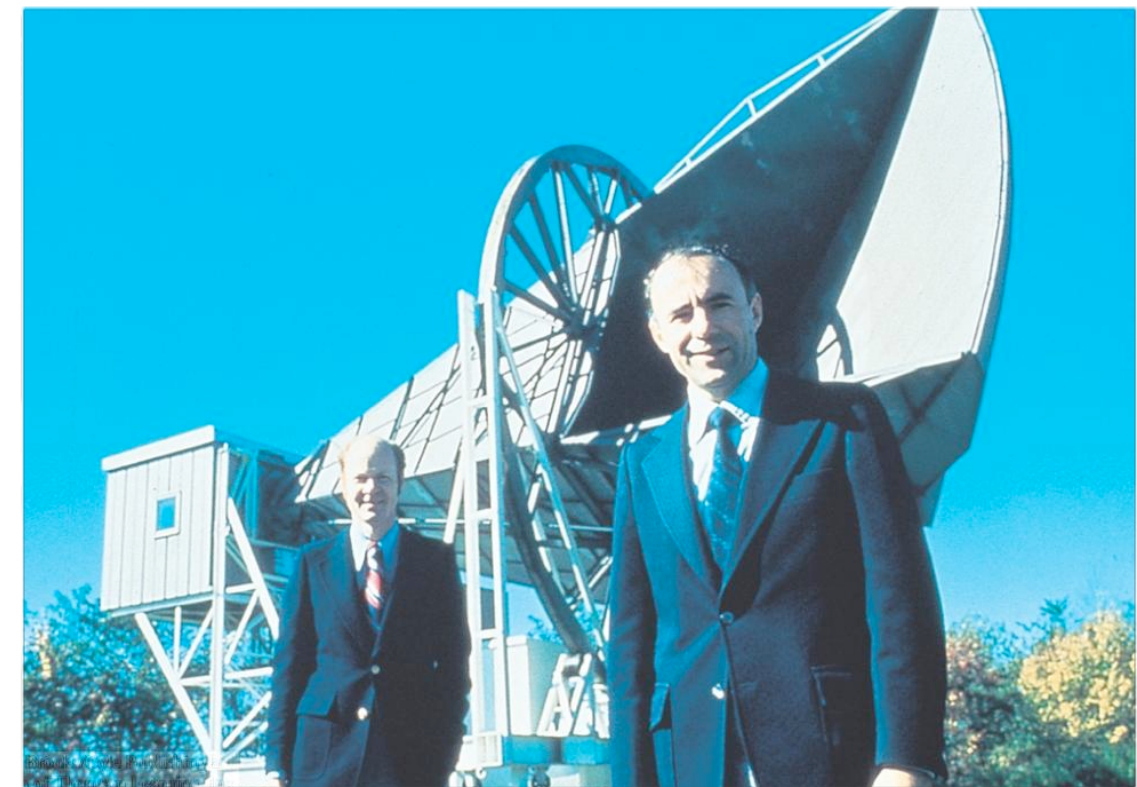
Arno Penzias

Robert Wilson

sensitive to  
wavelengths of  
7.35 cm, 4000MHz



Echo



Giant ultra-sensitive horn-reflector antenna which bounced off the satellite. It is located at Bell Telephone Laboratories, Holmdel, New Jersey.



**BELL TELEPHONE LAB**  
WORLD CENTER OF COMMUNICATIONS RESEARCH



**FIRST PHONE CALL VIA  
MAN-MADE SATELLITE!**

"Project Echo" satellite went into a near-perfect circular orbit 1000 miles high, circling the earth once every two hours. Its orbital path covered all parts of the U. S.

**BELL TELEPHONE LABORATORIES BOUNCES VOICE OFF SPHERE  
PLACED IN ORBIT A THOUSAND MILES ABOVE THE EARTH**

Think of watching a royal wedding in Europe by live TV, or telephoning to Singapore or Calcutta—by way of outer-space satellites! A mere dream a few years ago, this idea is now a giant step closer to reality.

Bell Telephone Laboratories recently took the step by

"Project Echo" foreshadows the day when numerous man-made satellites might be in orbit all around the earth, acting as 24-hour-a-day relay stations for TV programs and phone calls between all nations.

This experiment shows how Bell Laboratories, as part of the Bell System, is working to advance space communi-

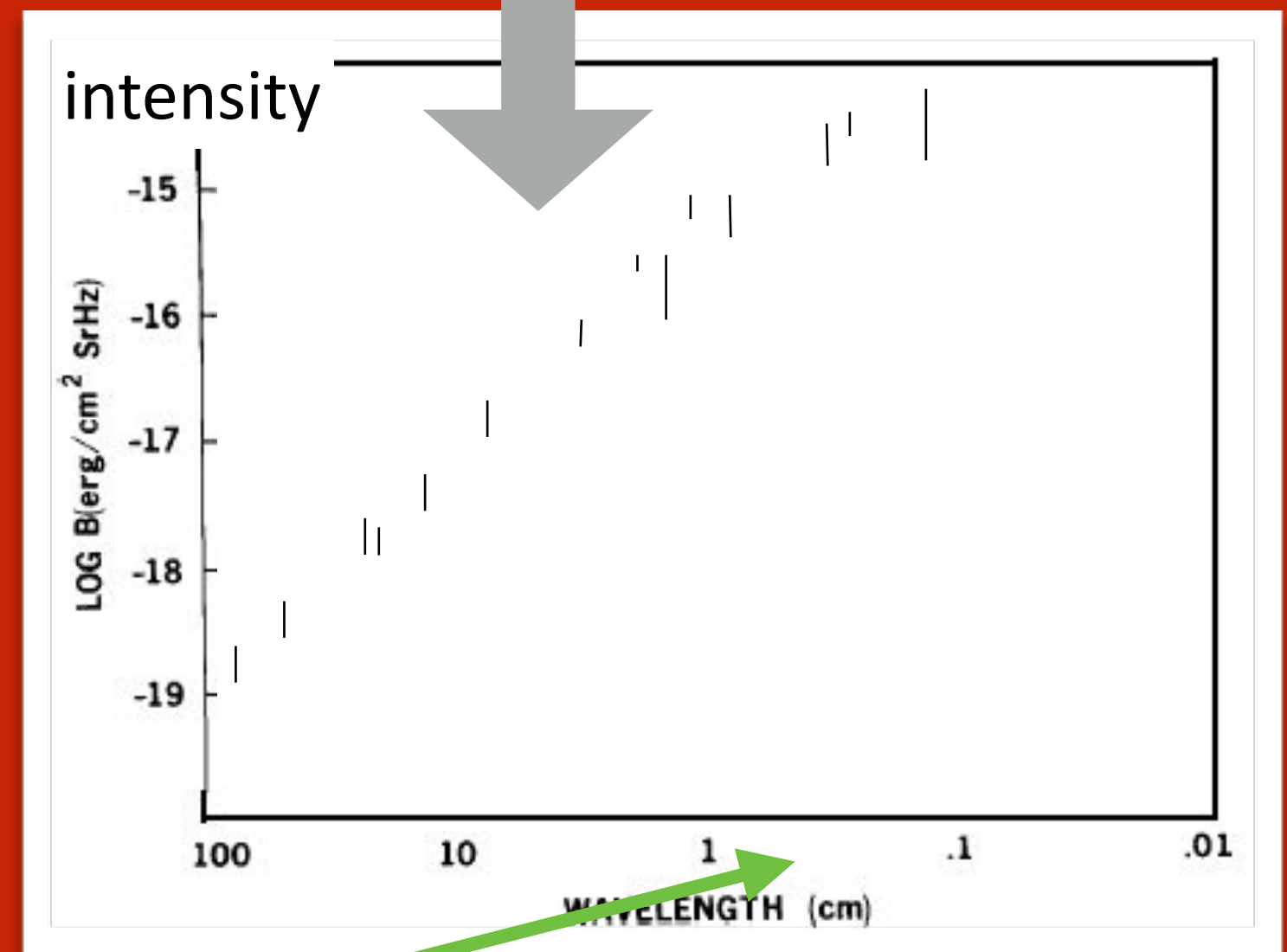
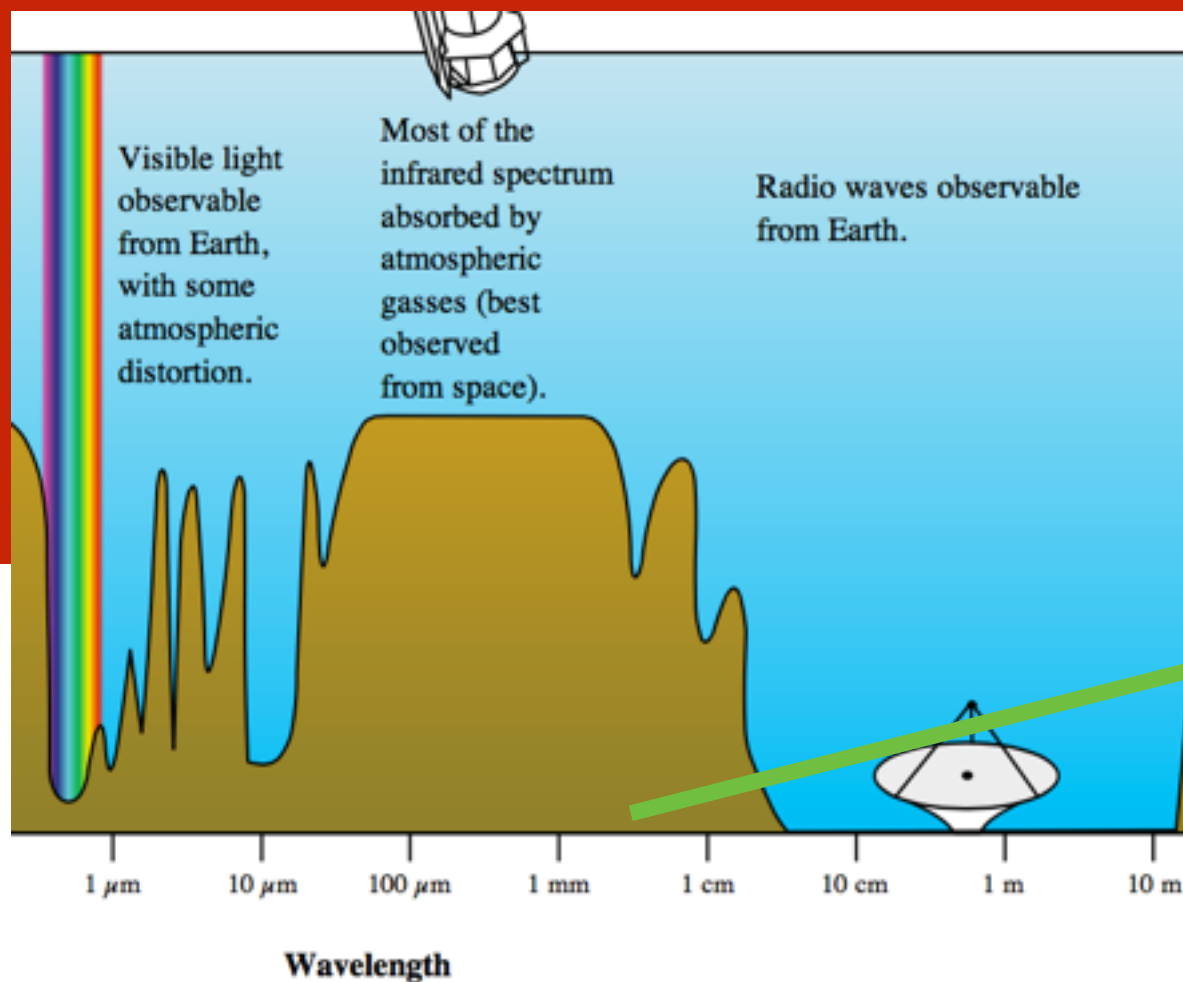


Penzias/Wilson wavelength

microwave hiss

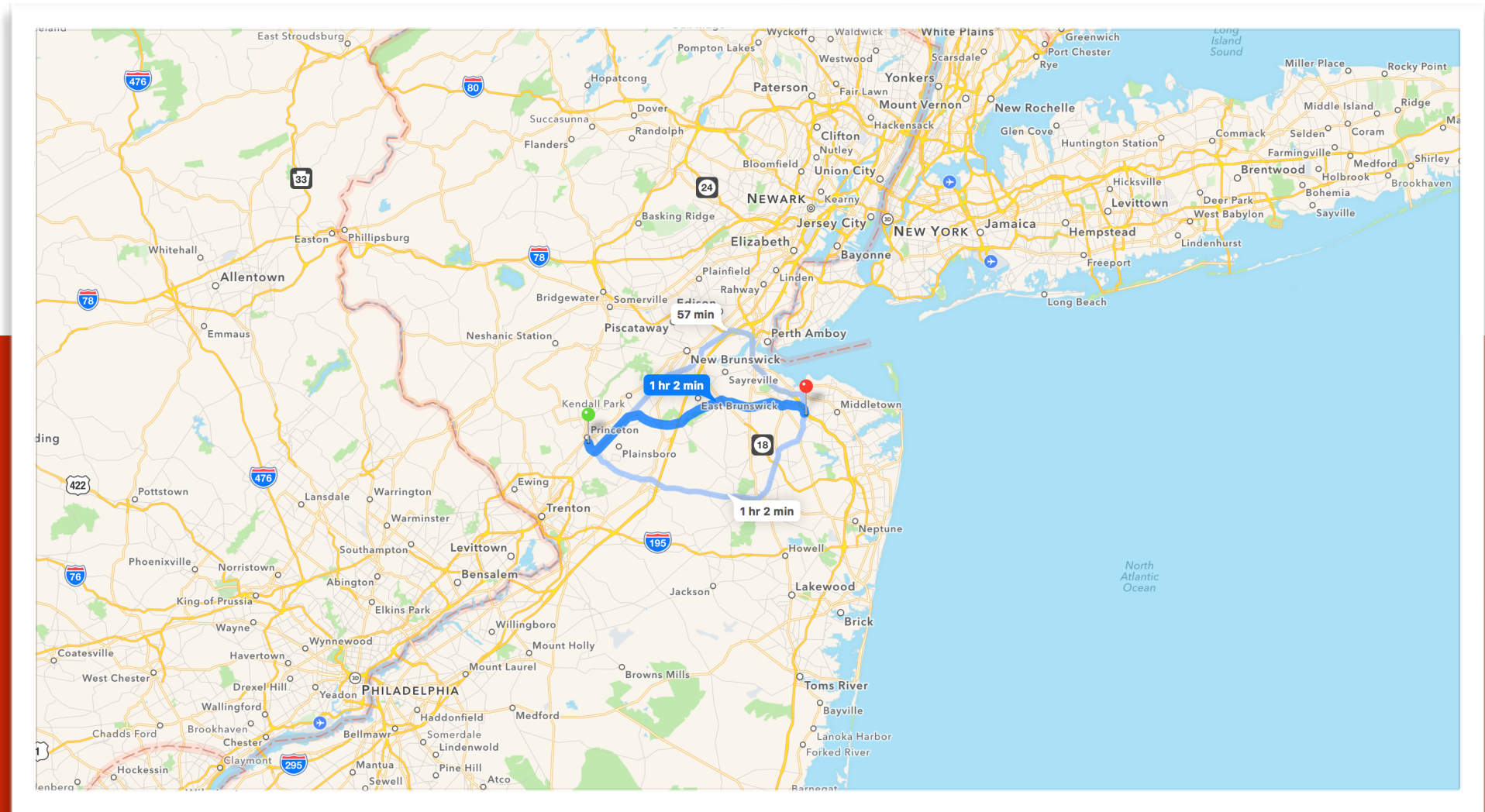
everywhere...

with a special frequency distribution



atmosphere becoming opaque

down the road



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

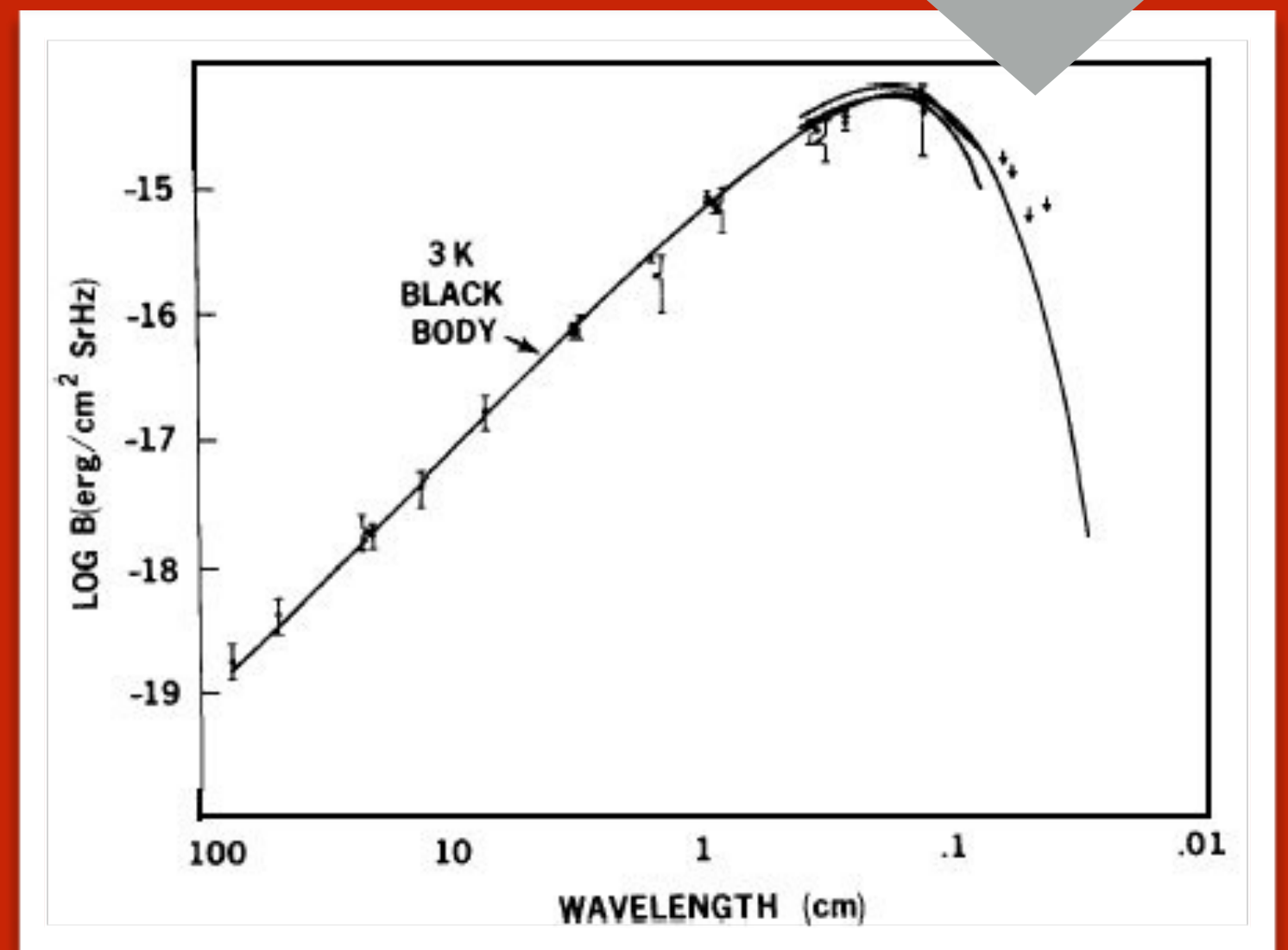
redid Gamow's calculation...forgetting that it had been done!

Robert Dicke was thinking of building a receiver

Penzias called Dicke...

balloons to get above atmosphere to  
measure infrared wavelengths

a blackbody spectrum  
of  $\sim 3\text{K}$  above absolute zero  
the peak is limited by the atmosphere





# Penzias and Wilson 1978

gave credit to the  
deceased George  
Gamow.

 **Nobelprize.org**  
The Official Web Site of the Nobel Prize

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  - Facts on the Nobel Prize in Physics
  - Prize Awarder for the Nobel Prize in Physics
  - Nomination and Selection of Physics Laureates
  - Nobel Medal for Physics
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  - Video Interviews
  - Video Nobel Lectures
- Nobel Prize in Chemistry
- Nobel Prize in Physiology or Medicine
- Nobel Prize in Literature
- Nobel Peace Prize
- Prize in Economic Sciences
- Nobel Laureates Have Their Say
- Nobel Prize Award Ceremonies
- Nomination and Selection of Nobel Laureates

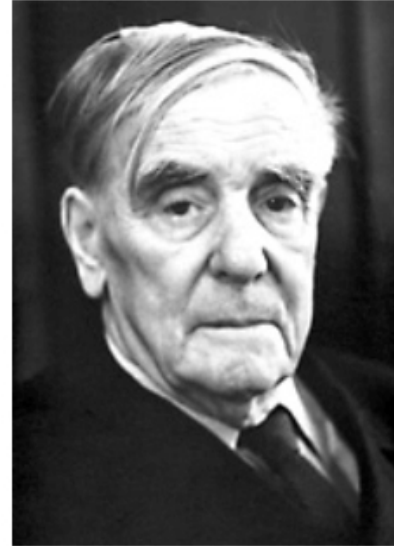
1901 2012 1978

Sort and list Nobel Prizes and Nobel Laureates Prize category: Physics

 **The Nobel Prize in Physics 1978**  
Pyotr Kapitsa, Arno Penzias, Robert Woodrow Wilson

**The Nobel Prize in Physics 1978**

- Nobel Prize Award Ceremony
- Pyotr Kapitsa
- Arno Penzias
- Robert Woodrow Wilson

 **Pyotr Leonidovich Kapitsa**

 **Arno Allan Penzias**

 **Robert Woodrow Wilson**

The Nobel Prize in Physics 1978 was divided, one half awarded to Pyotr Leonidovich Kapitsa *"for his basic inventions and discoveries in the area of low-temperature physics"*, the other half jointly to Arno Allan Penzias and Robert Woodrow Wilson *"for their discovery of cosmic microwave background radiation"*.

