



# Introduction to Particle Physics

(for non physics students)

## 4. UNIFIED UNIVERSE

(no strings attached)



*PROFESSOR FRANK CLOSE*  
*EXETER COLLEGE*  
*UNIVERSITY OF OXFORD*



# FORCES Summary

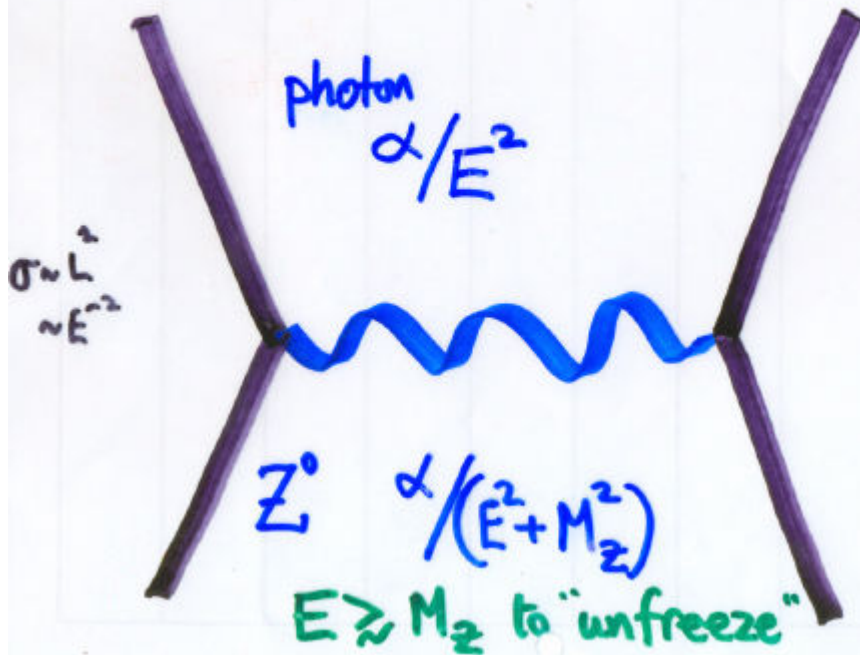
(remember that waves  $\leftrightarrow$  particles)

NAME	action	CARRIER
Gravity	keeps us on ground	graviton ?
Electromagnetic	electrons in atoms solids stops us falling to centre of Earth	photon ( $\gamma$ )
Weak	$\beta$ -radioactivity $p \rightarrow He$ in Sun	$W^+$ $W^-$ $Z^0$
Strong	quarks glued inside $p, n \dots$ $p, n$ in nuclei	gluons ( $g$ ) 8 different

Only the weak force carriers have MASSES

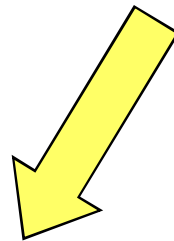
$$M_W \sim 80 \text{ GeV}/c^2$$

$$M_Z \sim 91 \text{ GeV}/c^2$$



Feynman rules:

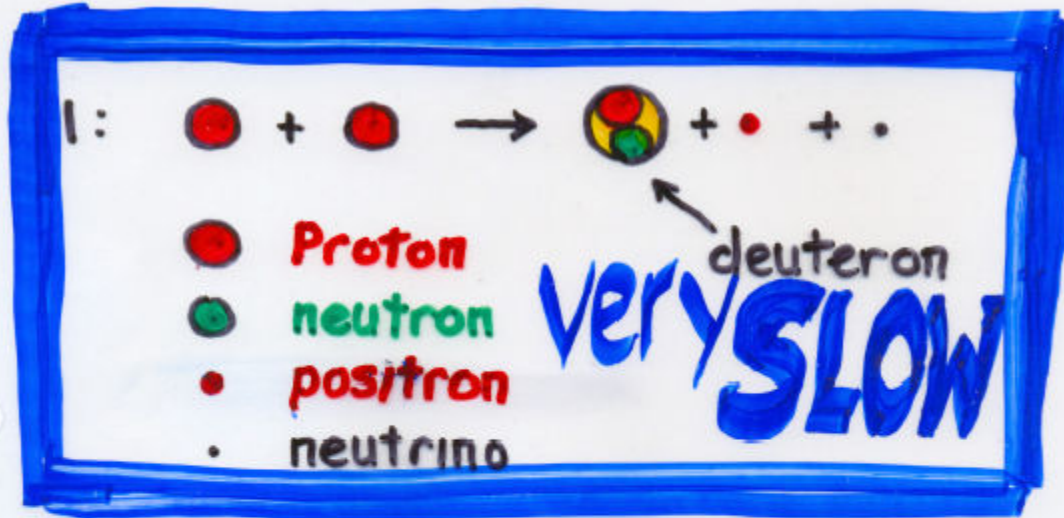
If energy  $E$  flows through  
 the transmitted "virtual"  
 particle (photon;  $Z$ )  
 it costs  $1/(E^2 + M^2)$



If  $E \gg M$  the cost is  $1/E^2$ ....like the case of the photon

Only appears weak at low energy. Unified at high energy

# At the heart of the Sun:

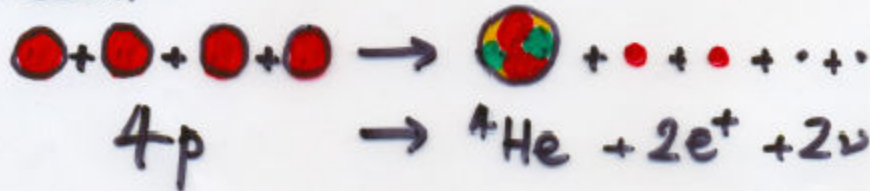


**WEAK**



**STRONG**

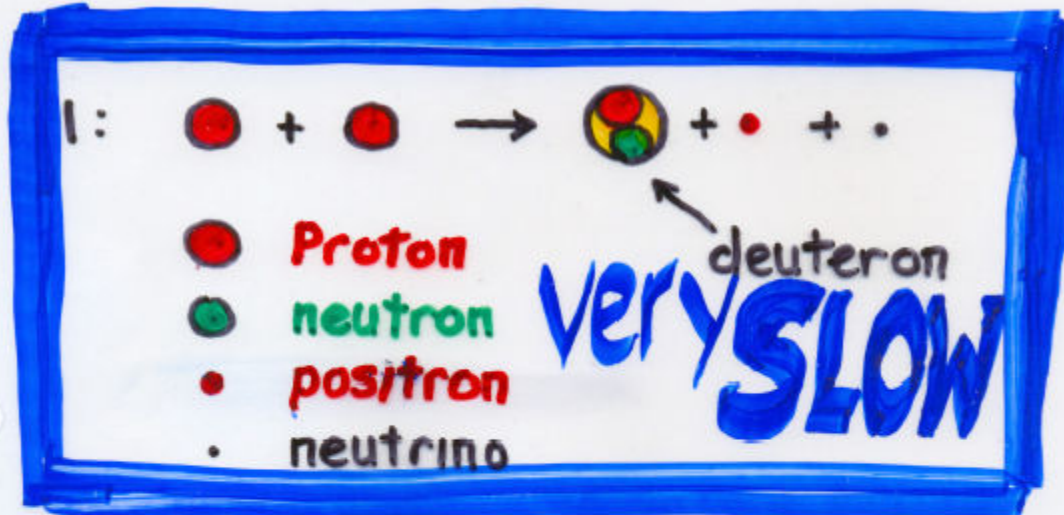
Net result:



$\Delta E = \Delta M c^2: \quad ^4\text{He} + 4p \approx 28\text{MeV}$



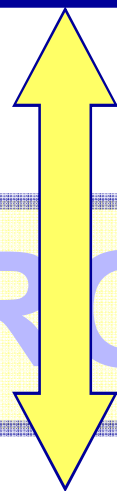
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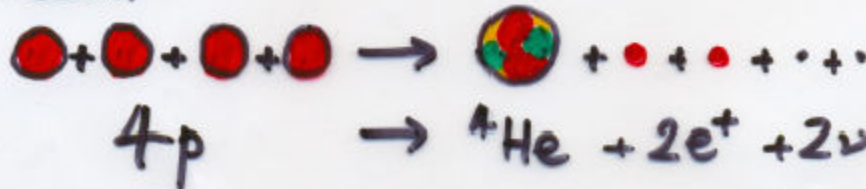
**WEAK**



**STRONG**



Net result:



$\Delta E = \Delta M c^2: {}^4\text{He} + 4p \approx 28\text{MeV}$

→ why sun has shone for 5 Byr...  
→ Intelligent life developed

**The weak force is feeble in the Sun ..**

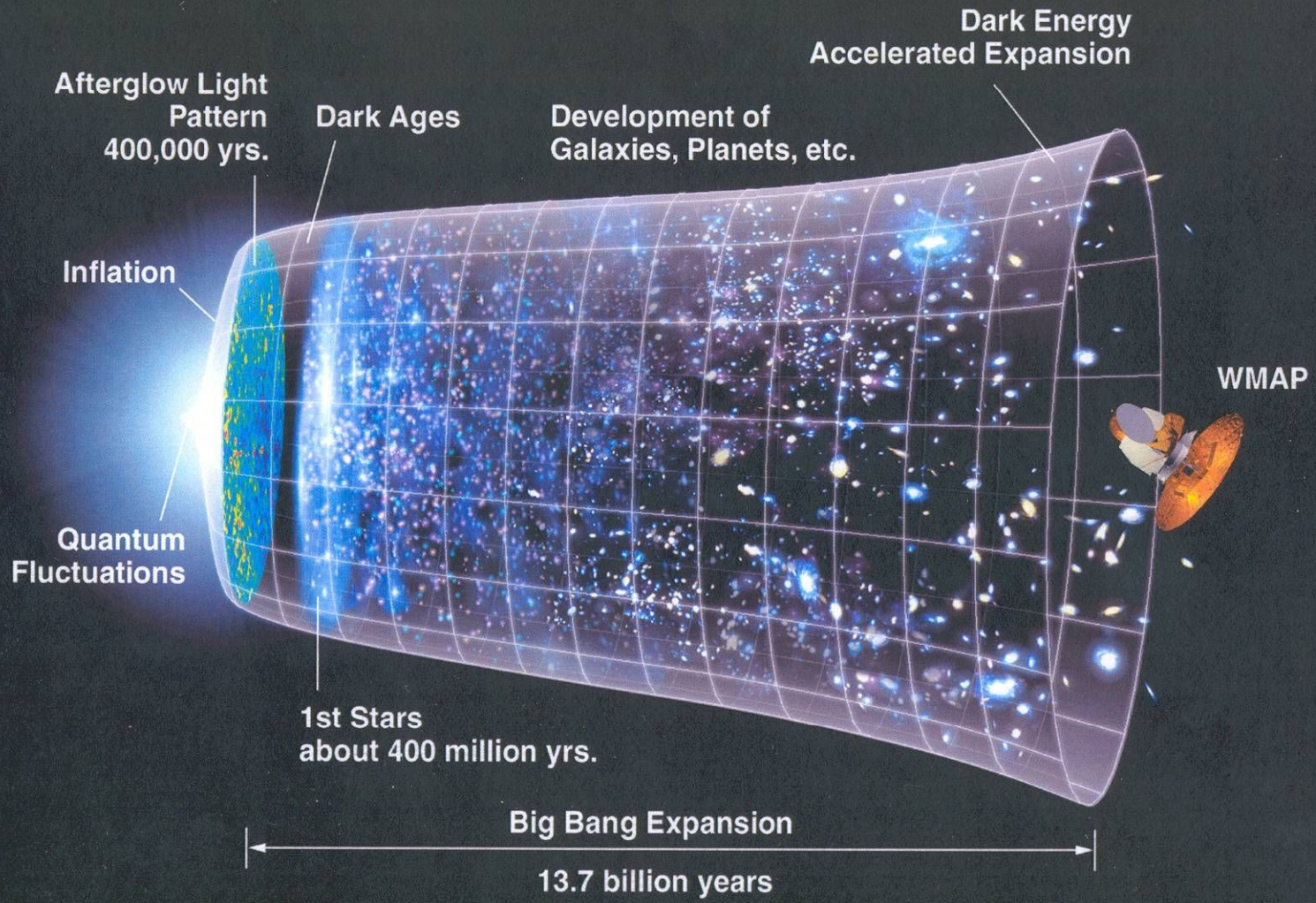
**..because  $10,000,000\text{K} \sim 1 \text{ keV} \ll 80 \text{ GeV}$**

**...this is why the sun has stayed active long enough for us to have evolved and be having this conversation.**

**→ We exist because  $m(W)$  is not zero**

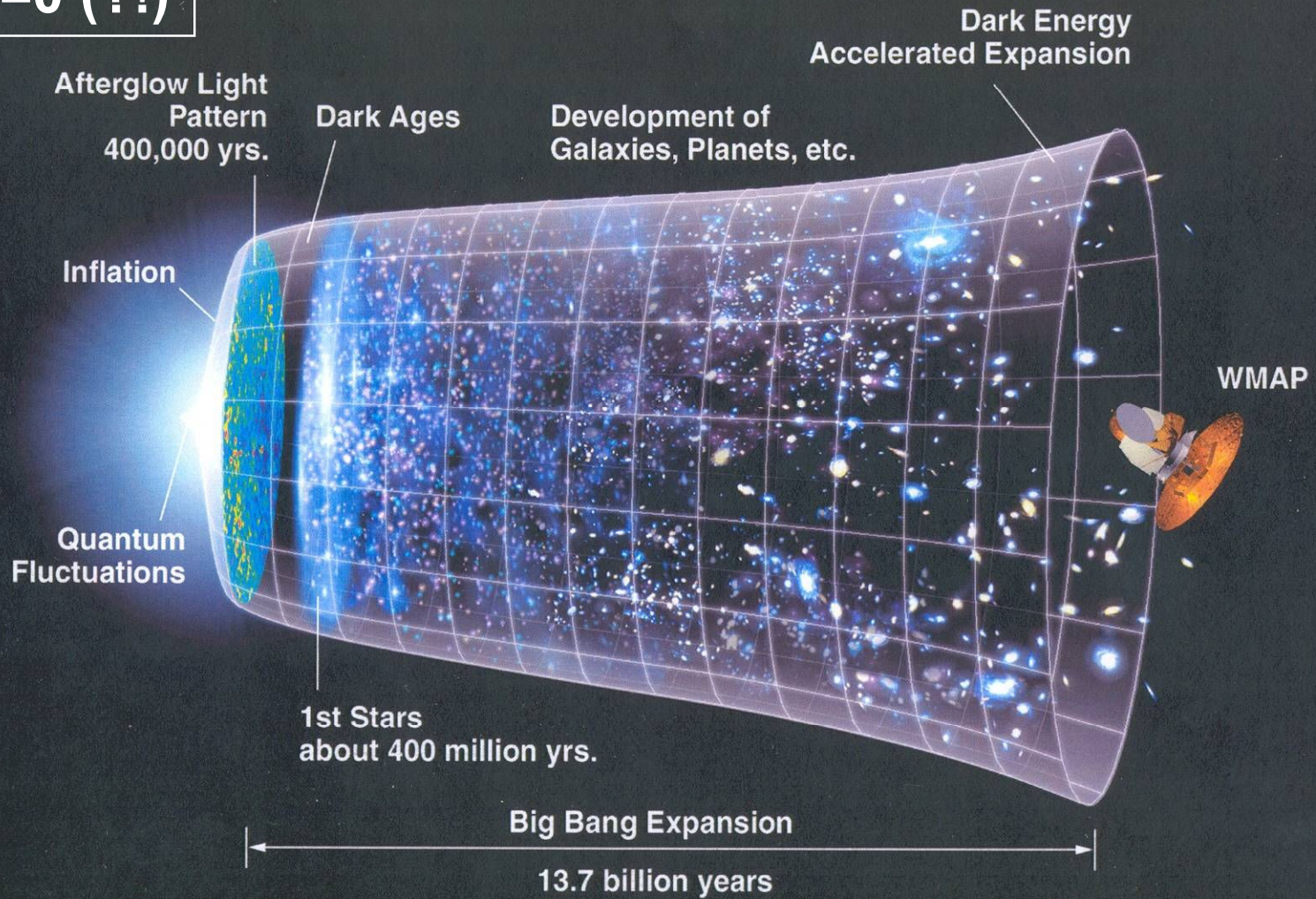
**→ Mass matters**





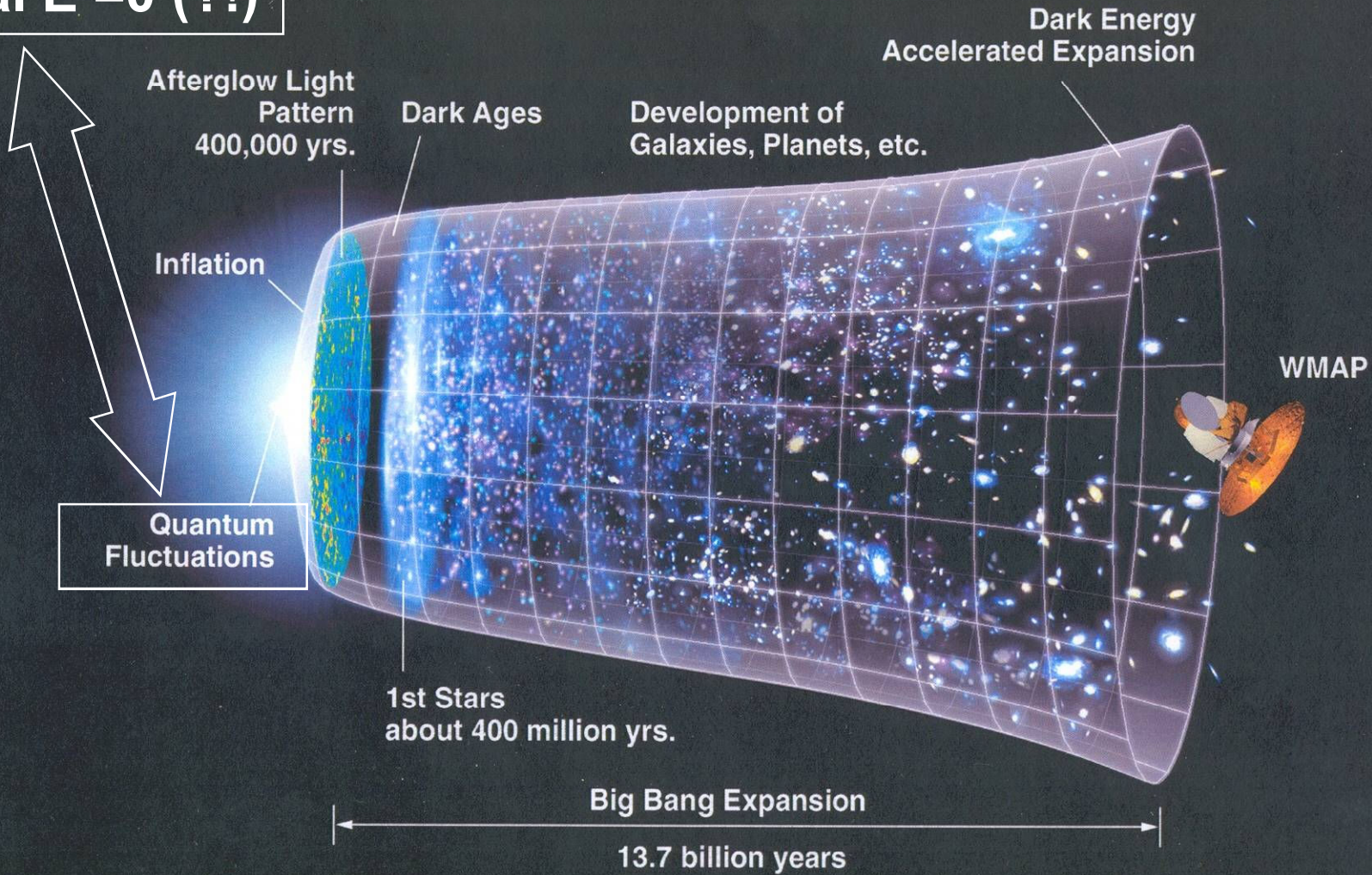


$\rho c^2 > 0$   
Gravity PE  $< 0$   
Total E = 0 (?!)





$\rho c^2 > 0$   
Gravity PE  $< 0$   
Total E = 0 (?!)





$Mc^2 > 0$   
Gravity PE  $< 0$   
Total E = 0 (?!)

Afterglow Light  
Pattern  
400,000 yrs.

Dark Ages

Development of  
Galaxies, Planets, etc.

Dark Energy  
Accelerated Expansion

Inflation

Quantum  
Fluctuations

WMAP

1st Stars  
about 400 million yrs.

Big Bang Expansion

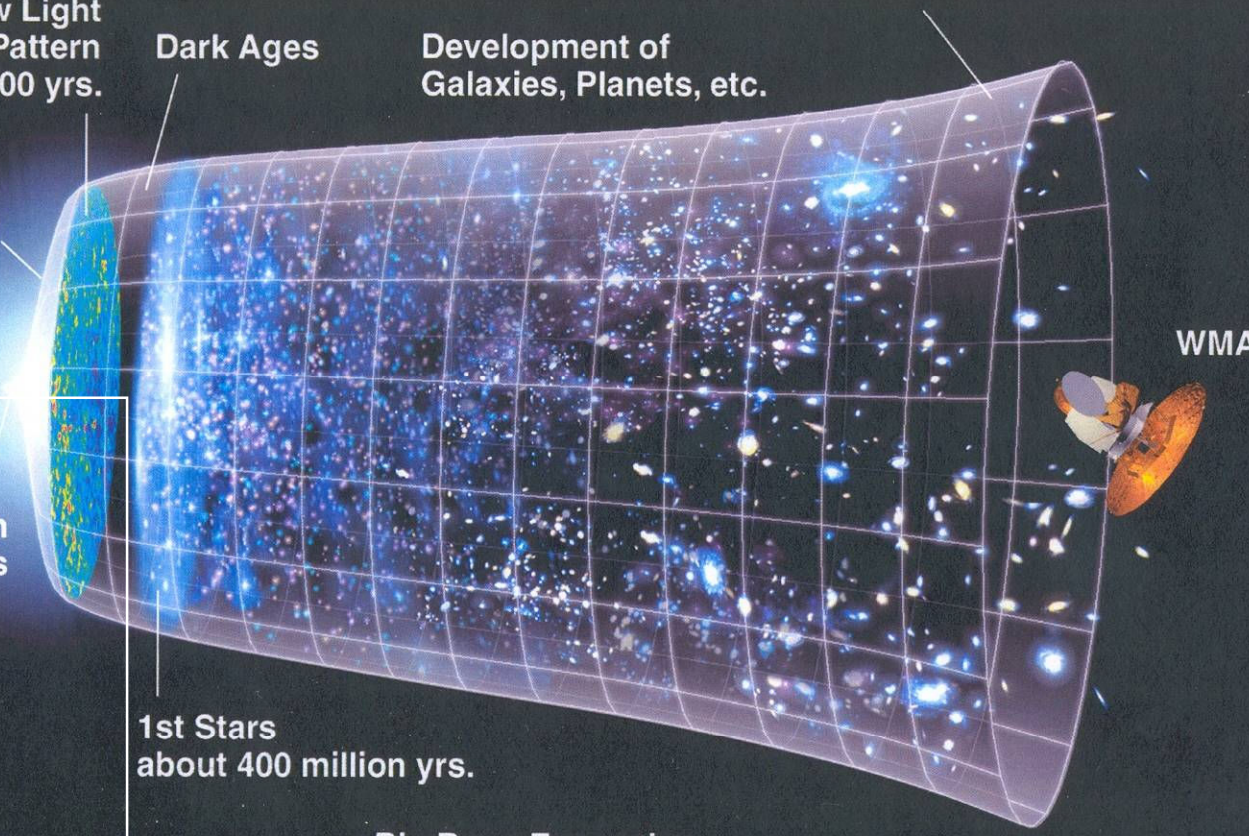
13.7 billion years

Heisenberg:

$E \rightarrow 0$   
 $t \rightarrow \text{infinity}$

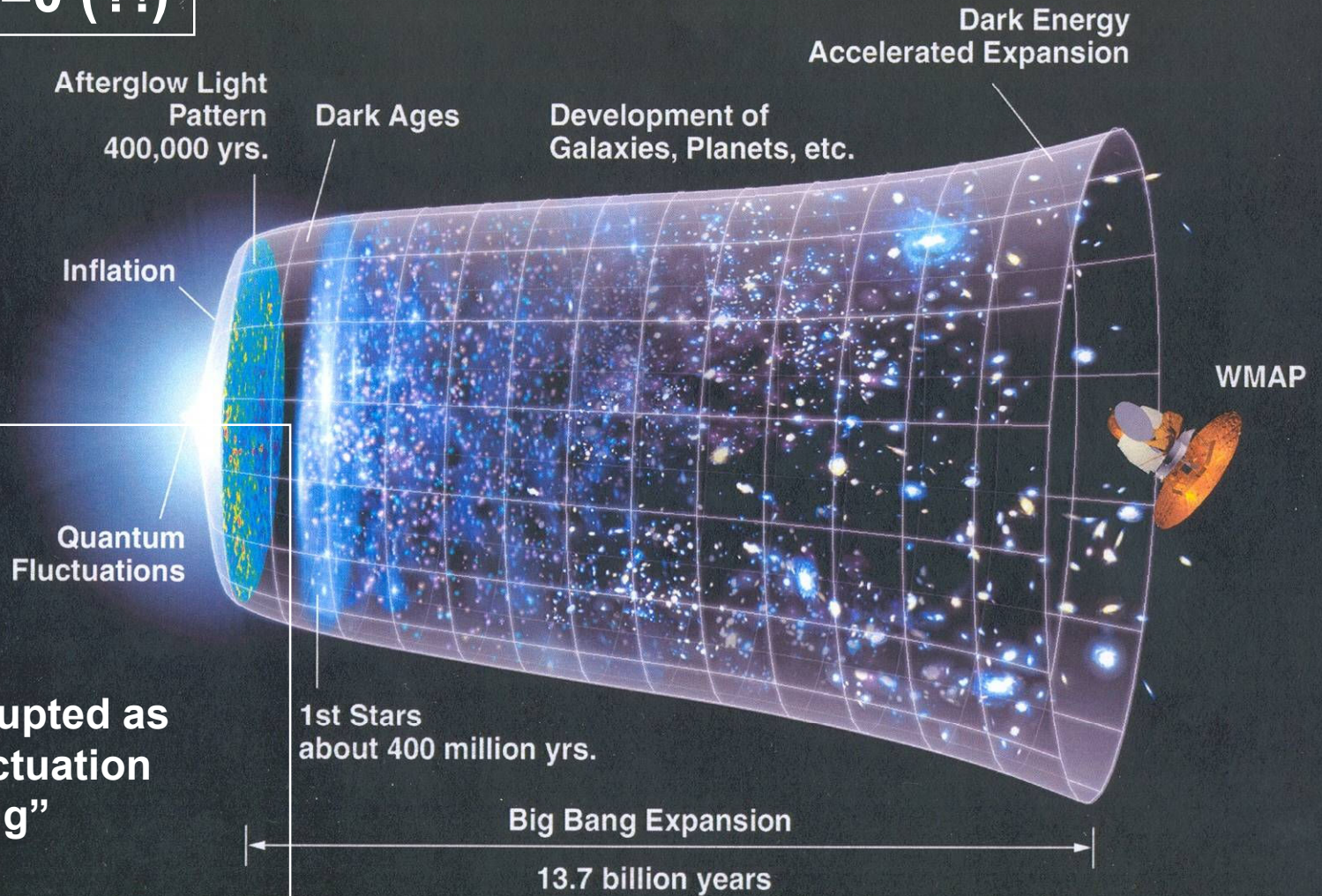
“Universe erupted as  
quantum fluctuation  
out of nothing”

How did it start?  
How did it begin?





$Mc^2 > 0$   
Gravity PE  $< 0$   
Total E = 0 (?!)



**Heisenberg:**

$E \rightarrow 0$   
 $t \rightarrow \text{infinity}$

“Universe erupted as quantum fluctuation out of nothing”

(what/where/how encoded Heisenberg in “nothing”?)





TeV  $10^{16}$  K

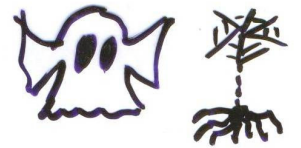
LHC

LEP



early univ.

$< 10^{-9}$  sec.



GeV

MeV

100 sec.

keV  $10^7$  K



eV  $10^4$  K

300 K yrs.

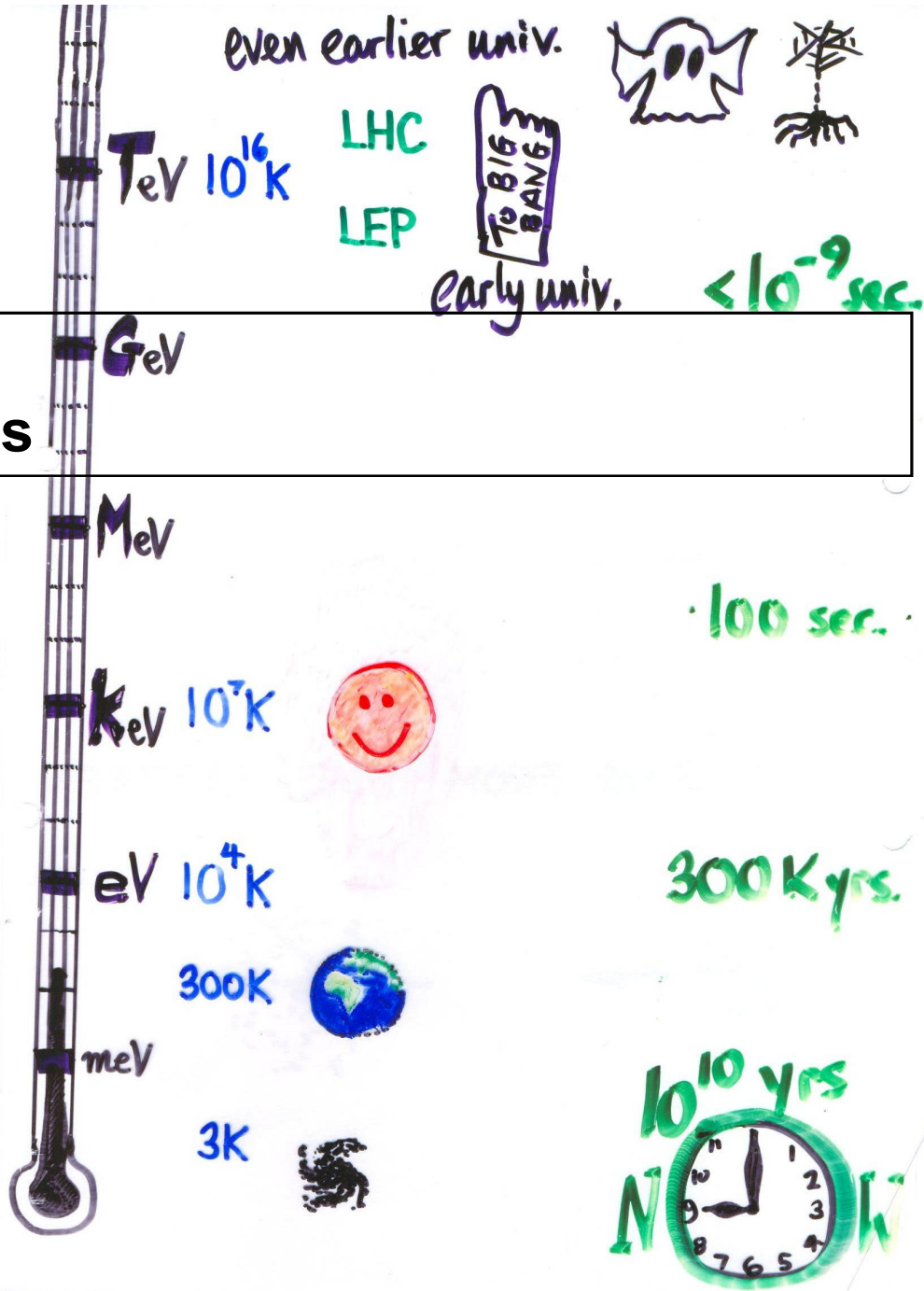
300K



meV

3K





Quarks "freeze" into protons/neutrons

# Big Bang $\rightarrow$ $e + p$

Thermal Equilibrium:



Temperature (energy) drops  $\rightarrow$   
After 1  $\mu$ sec  $\rightarrow$  one way only:



But at the same time:



then like processes 2 and 3 in the Sun\* until all the **neutrons** have gone

\* MAKING  
**Helium**

or

particles so far apart in the expanding universe that they no longer interact



$T = 1 \mu\text{sec}$  after BIG BANG

neutrinos are free  
( "the first fossils in the Universe)

move at high speed  
and if they have mass they  
start clustering together  
→ contribute to formation of galaxies

Billion  $\nu$  per atom  
⇒ if  $m(\nu) > m(\text{proton})/10^9 \approx 1 \text{ eV}$   
they will dominate mass  
density of the Universe

⇒  $m_\nu$  big question  
for future of universe  
and its formation

Universe expands - and cools  
expansion rate



Rate depends on pressure  
which depends on the  
temperature in the gas and  
the number of neutrinos inside  
the gas volume (density)  
and this # depends on  
number of neutrino species

$T = 3$  minutes after BIG BANG

75% protons

24% Helium Nuclei

+ small amount of deuterons

+ free electrons.

Helium abundance<sup>\*</sup>; +traces of other light elements

depends on expansion rate of the Universe which depends on number of neutrino species

Deuterium abundance

depends on density of "ordinary matter" in the Universe.



$T = 3$  minutes after BIG BANG

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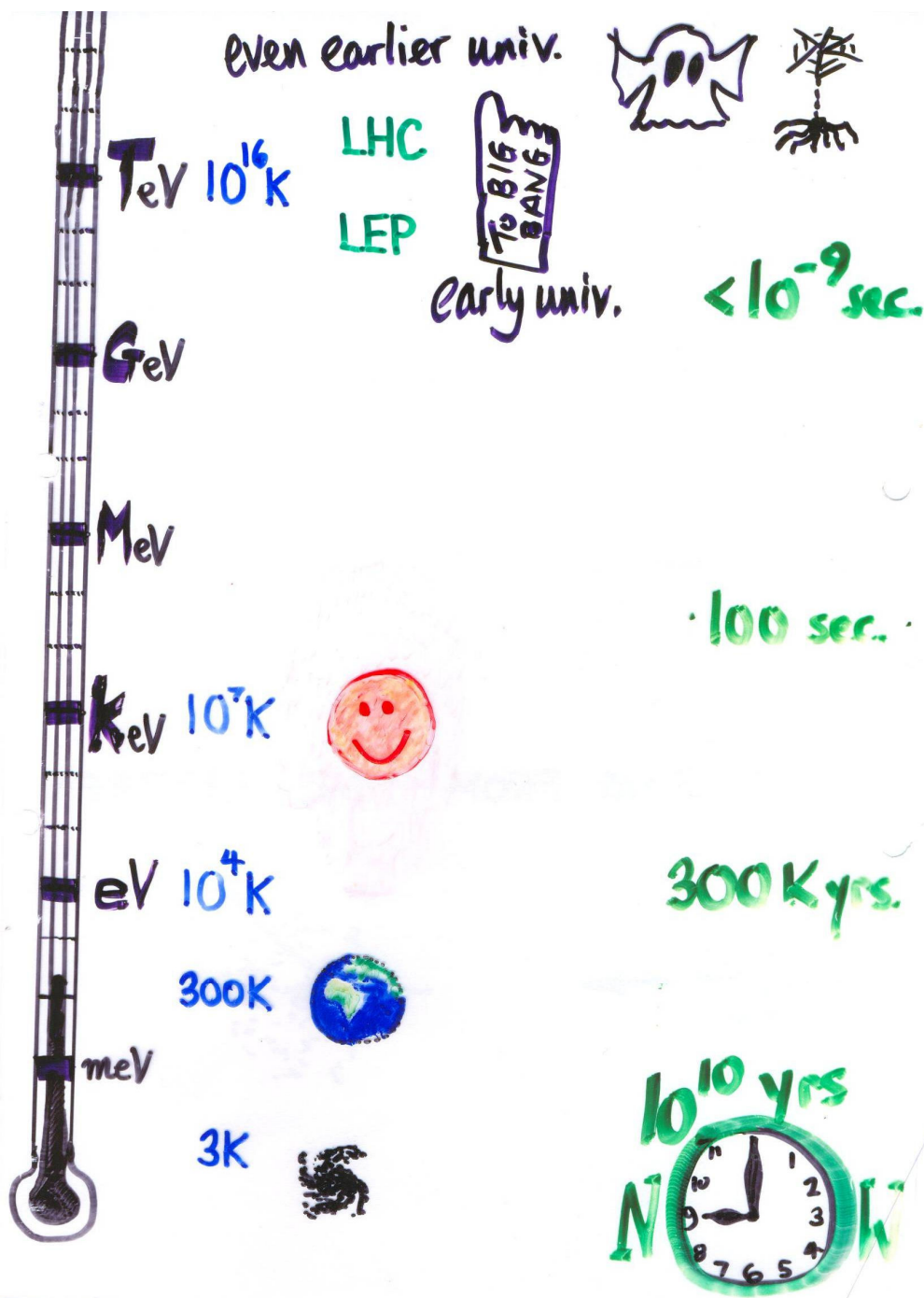
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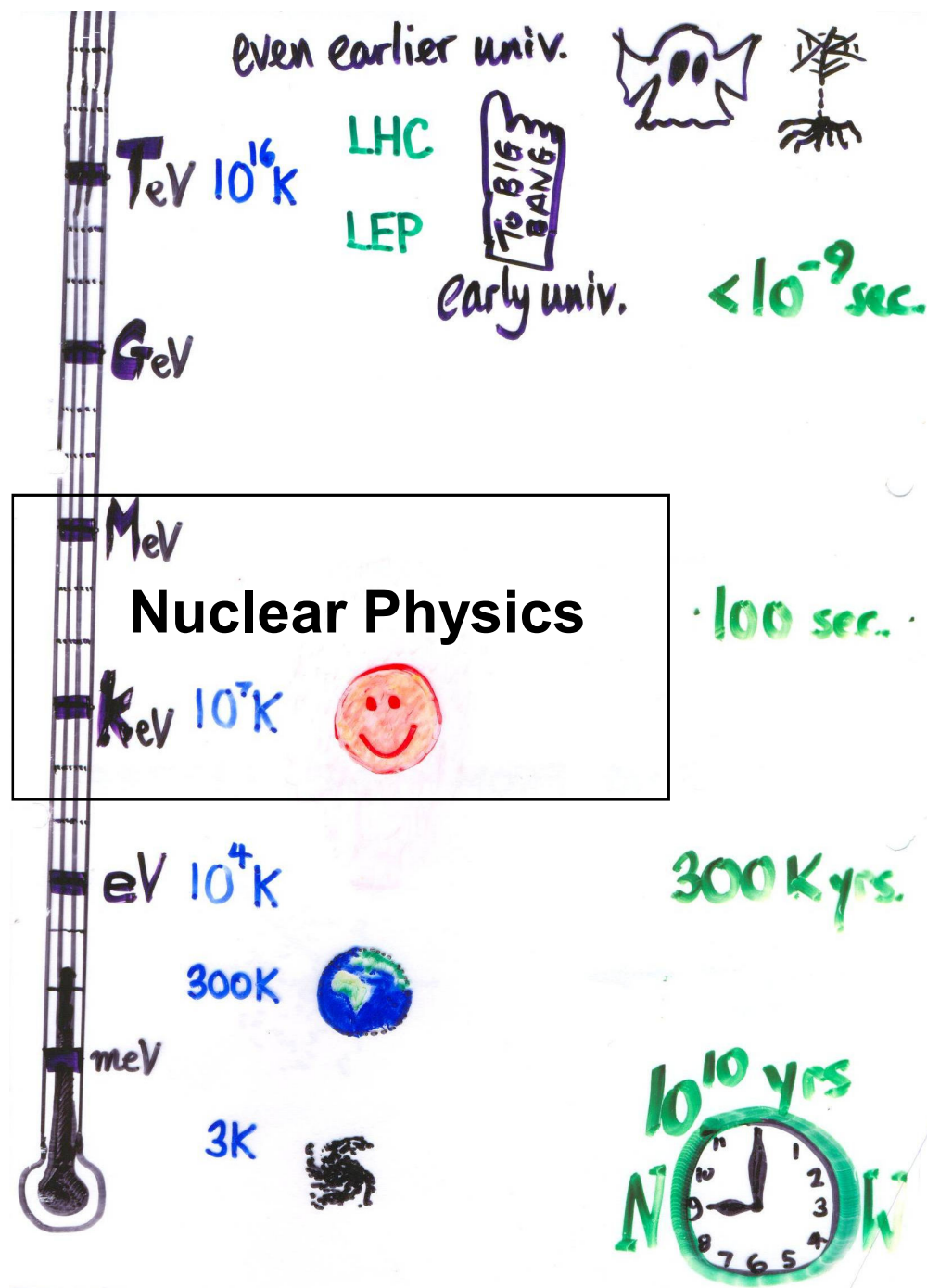
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if 3  $\nu$  species  
Helium abundance\*  
\* +traces of other light elements

depends on expansion rate of the Universe which depends on number of neutrino species

Deuterium abundance

depends on density of "ordinary matter" in the Universe.

IF density of ordinary matter  $\ll$  total in universe  
 $\Rightarrow$  part of DARK MATTER puzzle



Time Passes. Temp drops

300,000 years later  $E < 10\text{eV}$   
 $T < 10^4\text{K}$

electrons combine with nuclei  
and make neutral atoms



electromagnetic radiation was set free

Universe becomes transparent

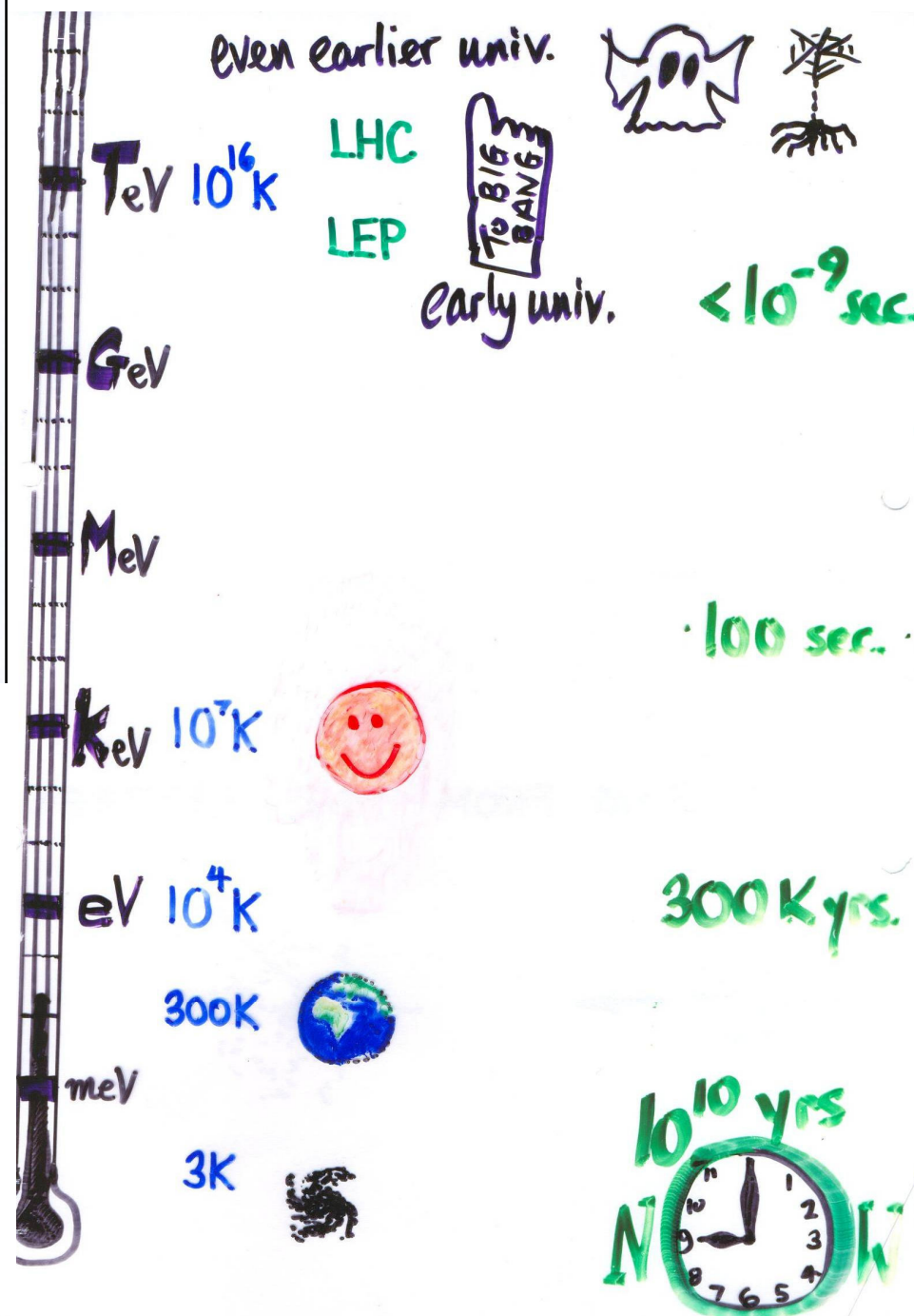
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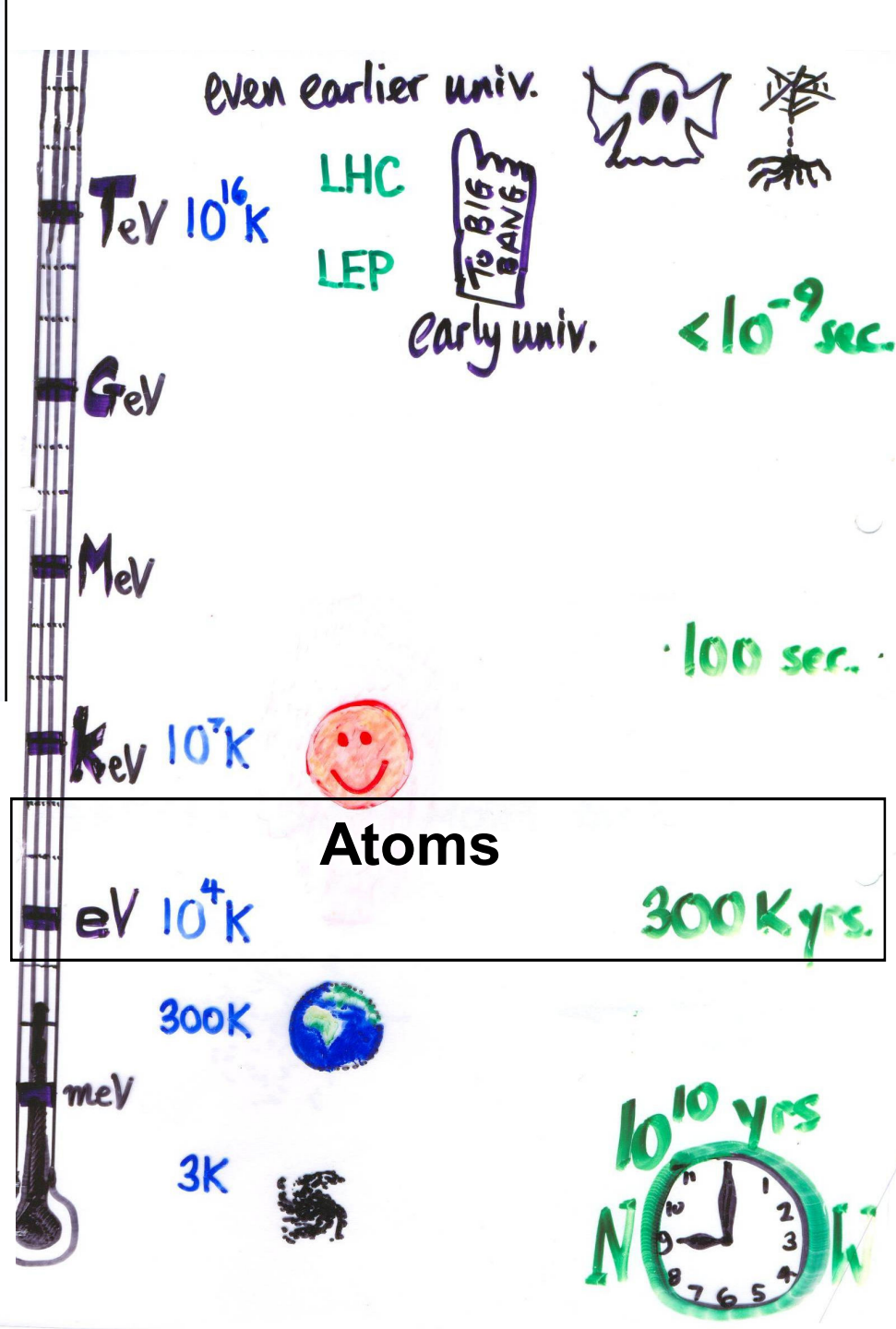
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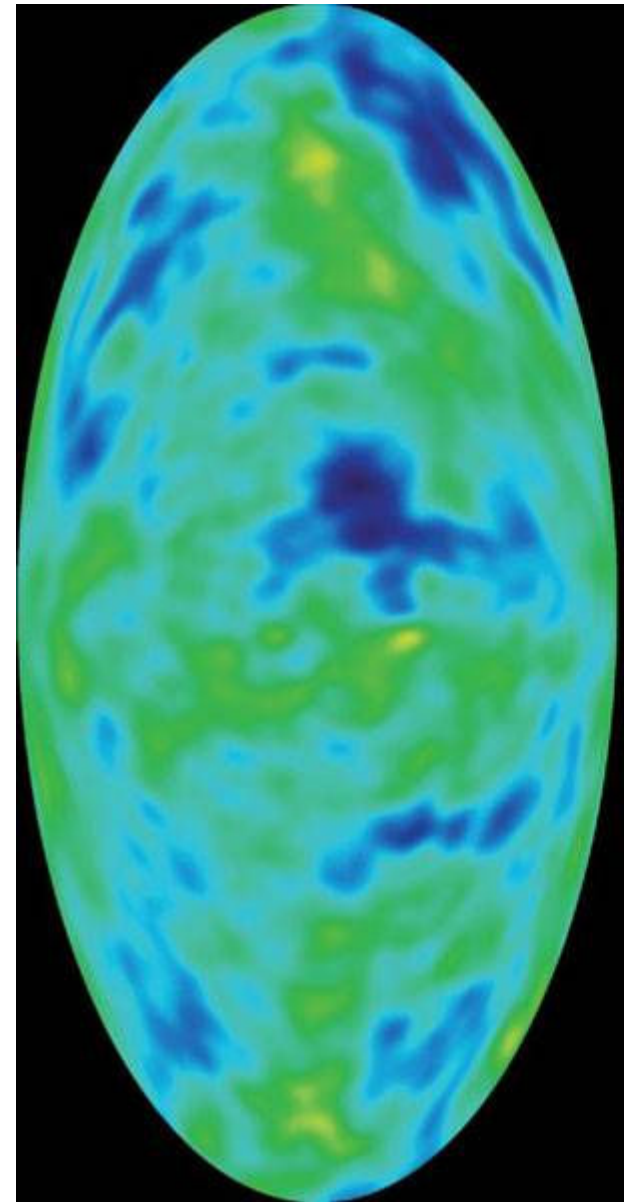


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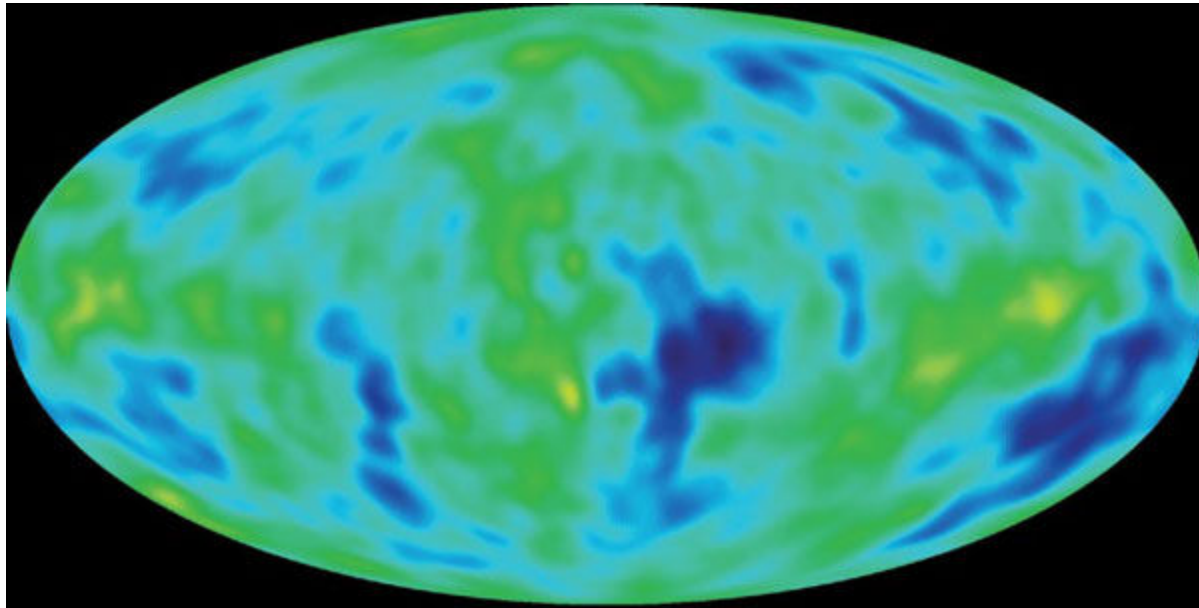
$10^{10}$  years later

$E_{\text{mag}} \lambda$  stretched : Microwave Regd.  
Black body background 3K

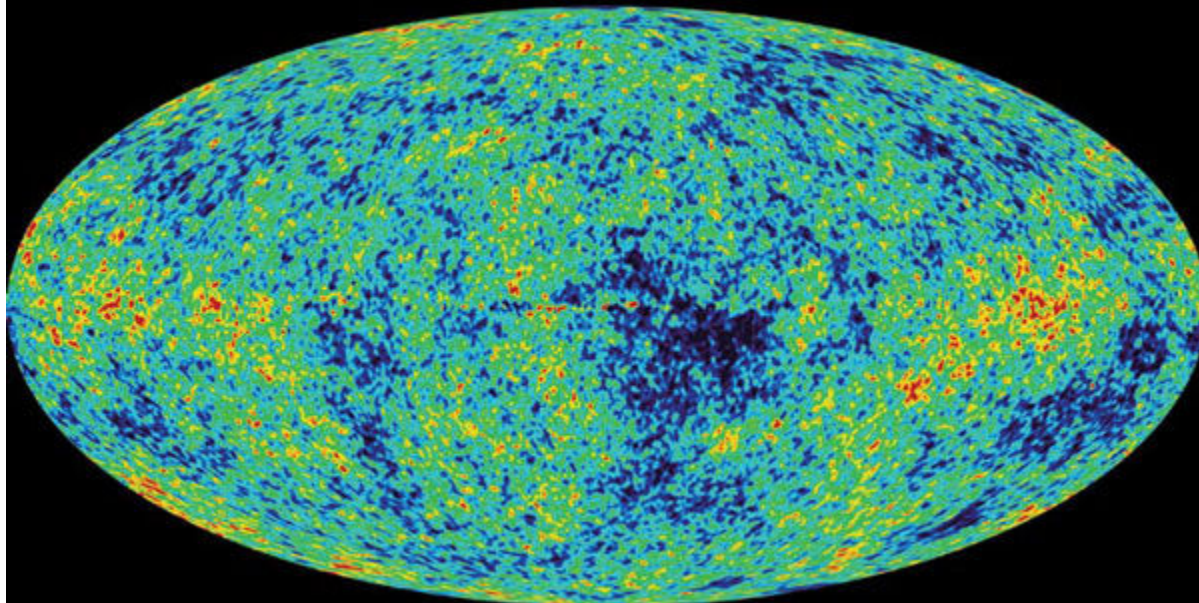
(small fluctuations in Microwave rad  
= hints of proto structures, galaxies  
in early universe)



# 3K microwave bgnd now seen to have structure



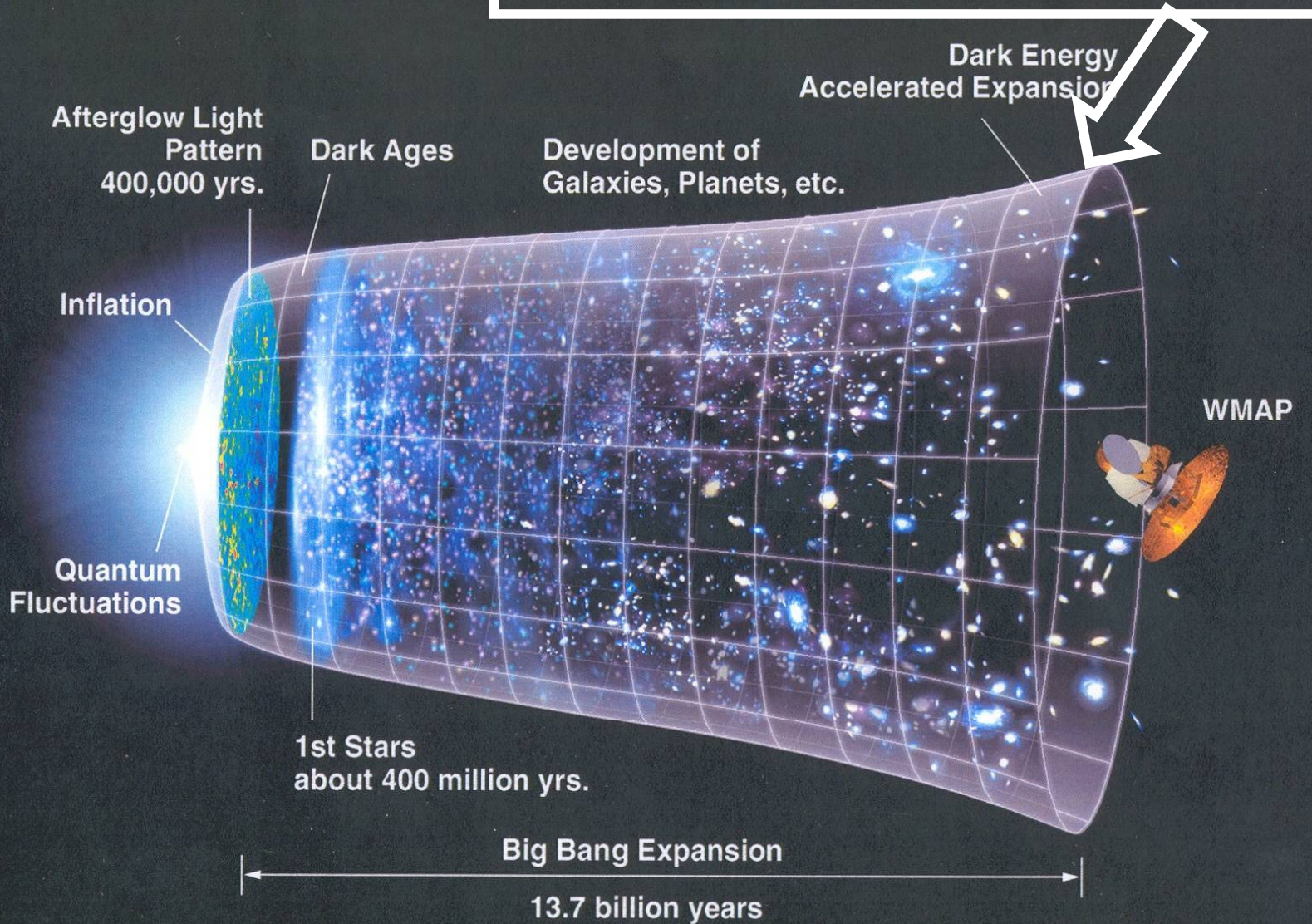
**COBE 2000**



**WMAP 2003**

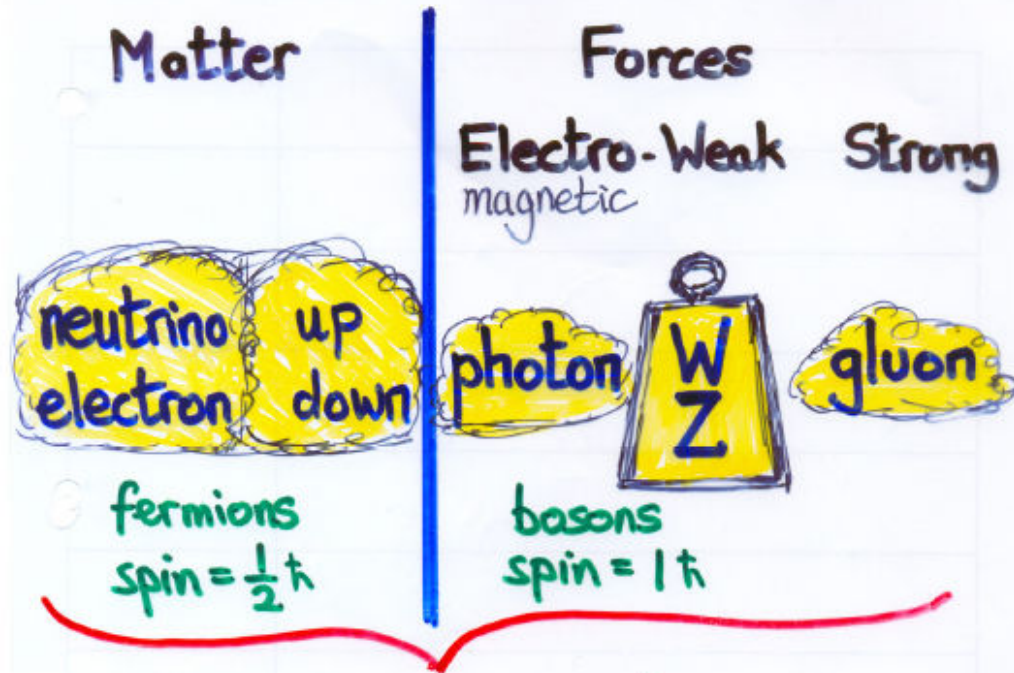


# 5byr ago accelerated expansion = Dark Energy. What? Why?.....





# One further symmetry??



**Supersymmetry "SUSY"**

Dark Matter?

(LHC energies)  $T > 10^{16}$  K

Matter

Forces

Electro-Weak  
magnetic      Strong

neutrino  
electron      up  
down

photon

W  
Z

gluon

fermions  
spin =  $\frac{1}{2} \hbar$

bosons  
spin =  $1 \hbar$

Supersymmetry "SUSY"

David Maltoni

(LHC energies)  $T > 10^{16}$  K

bosons

fermions

sneutrino sup  
selectron sdown

photino

Wino  
Zino

gluino

Massive.  
Mass breaks SUSY

Lightest - non E.M.  
DARK ??

Whole new families  
to be found

# Particle Physics @ CERN.

## Standard Model of Matter + Forces.

- Quarks + Leptons. Spin  $\frac{1}{2}$  fermions
- $\gamma$   $W^\pm$   $Z$  gluons Spin 1 gauge bosons
- Higgs Spin 0 boson

High Energy  $\longleftrightarrow$  Early Universe


Origins of matter.

[ Structures + patterns at  $E \lesssim 1 \text{ TeV}$

[ Symmetry revealed at  $E \gtrsim 10 \text{ (TeV)}$

Forces (and particles) unified - SUSY.

Some current big puzzles.

- Dark Matter, Solar  $\nu$ , massive  $\nu$ ?  
(all the same?)
- Why 3 generations  
What is difference between  $M$  and  $\bar{M}$ ? } the same?
- ?  The Fifth Dimension



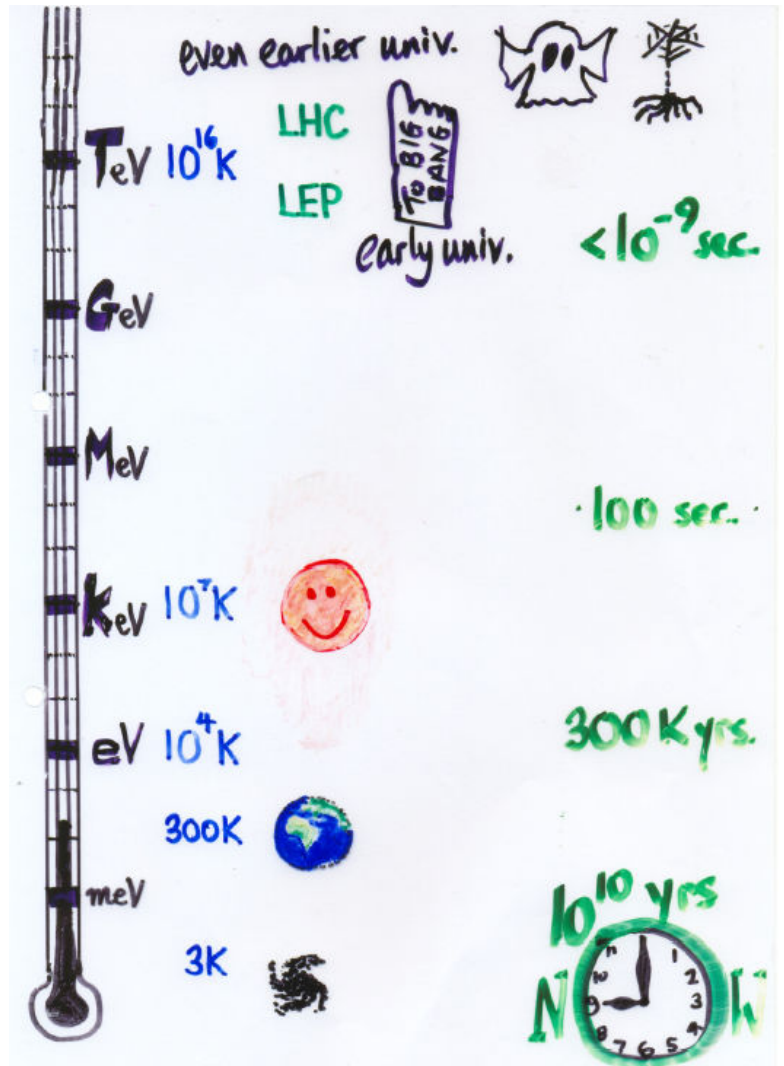
# Finale: A glimpse of the future

recall from lecture 1.....

## The Universe

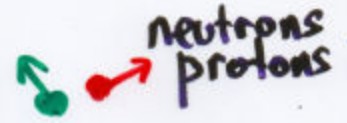
in

Temperature  
Energy and  
Time



...and the nature of matter

QG Plasma



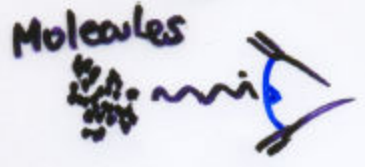
Nuclei melt  
↓ exist



H melt: plasma  
↓ exist



Ice melt  
↓ exist



TeV  $10^{16}$  K

GeV

MeV

KeV  $10^7$  K

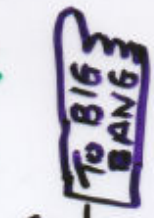
eV  $10^4$  K

300K

meV

even earlier univ.

LHC  
LEP



early univ.



$< 10^{-9}$  sec

100 sec.



300K yrs



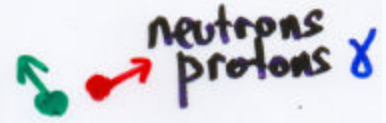
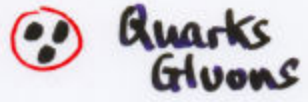
3K





...and patterns (that change)

QG Plasma



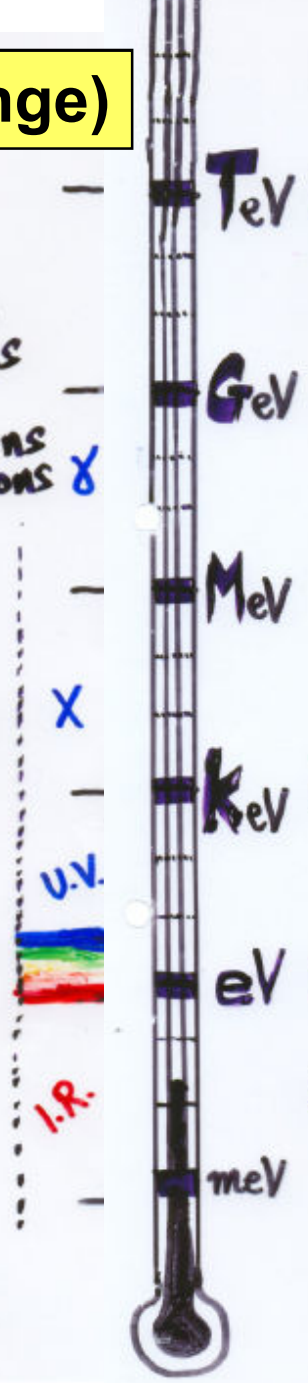
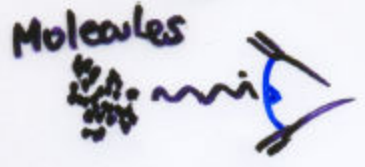
Nuclei melt  
↓ exist



H melt: plasma  
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Ice melt  
↓ exist



No mass. Unified Theory

Standard Model  
MASS

t	b	$\tau$	$\nu$	W
c	s	$\mu$	$\nu$	Z
u	d	e	$\nu$	$\gamma$

Nuclear Isotopes



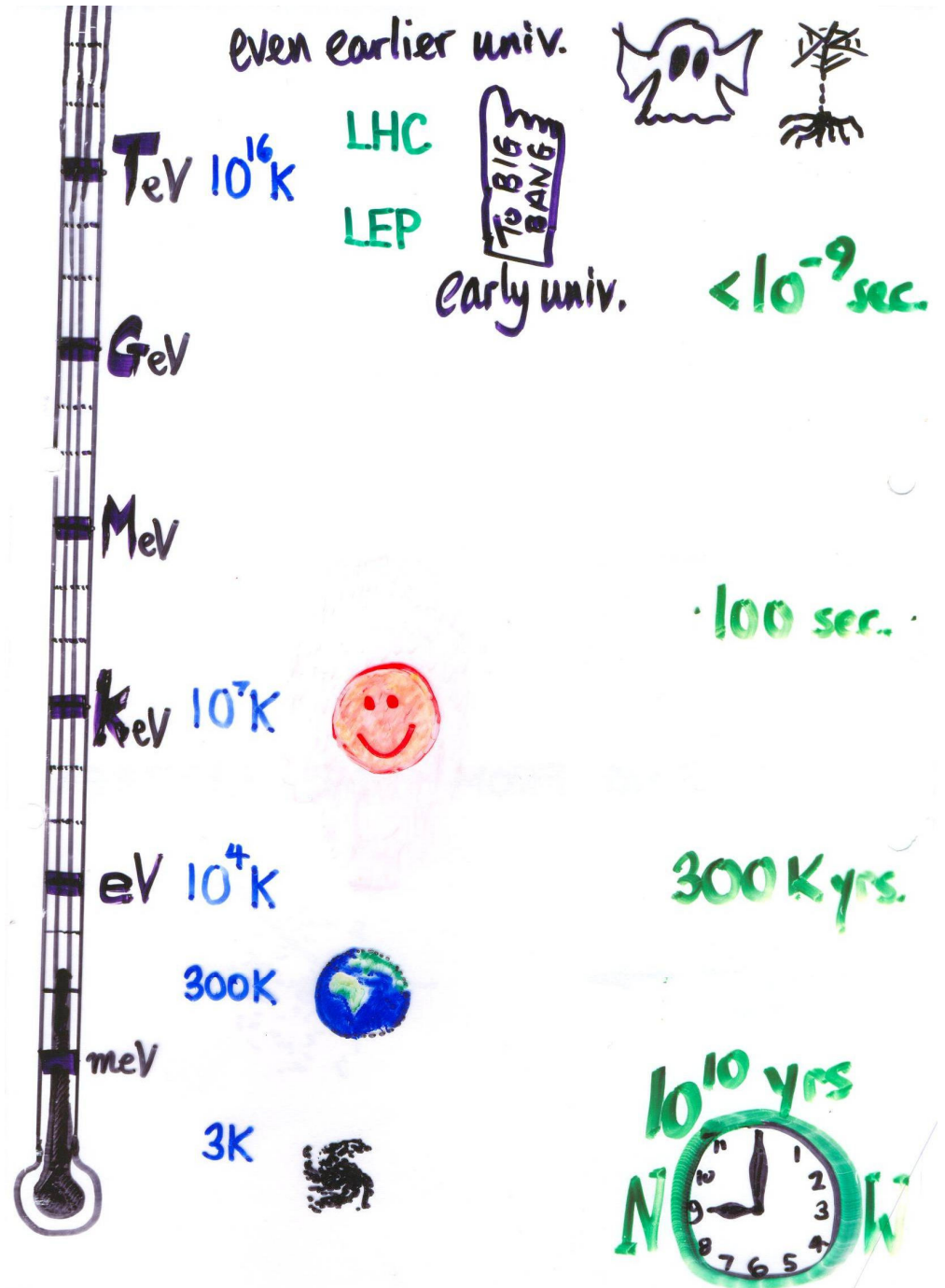
Mendeleev



Snowflake pattern



# Temperature and symmetry in the universe

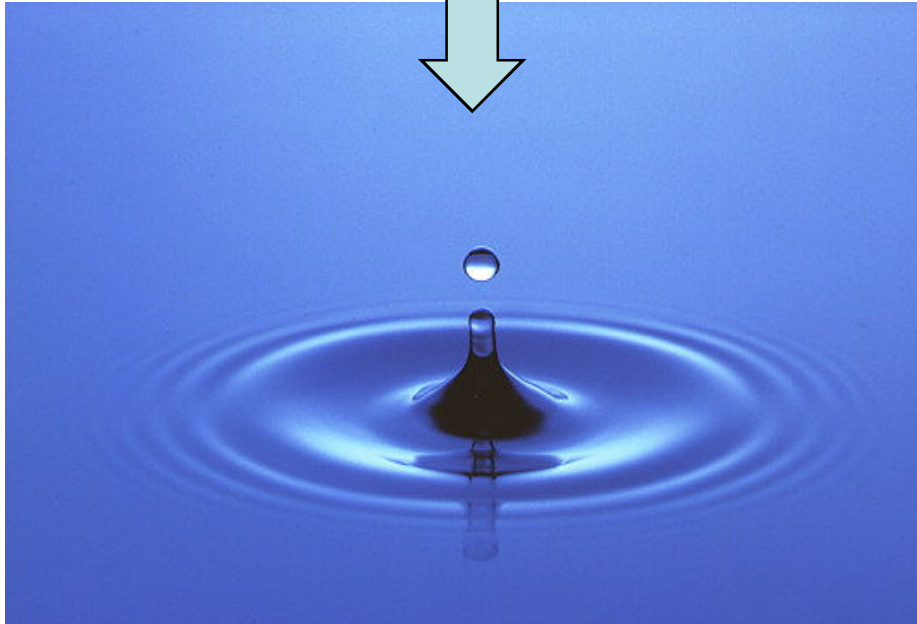
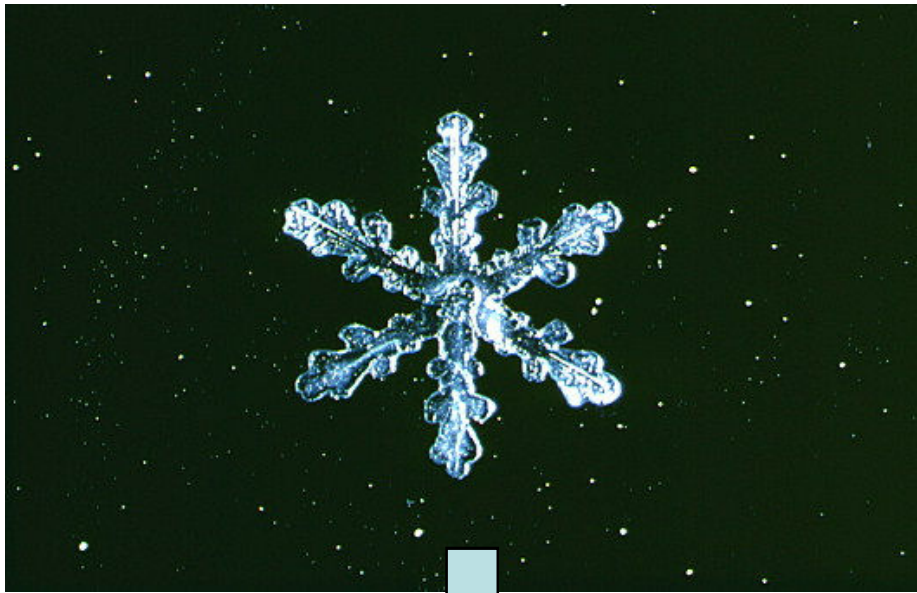




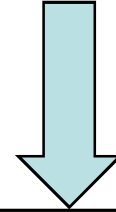
# The Idea



**(I will tell you when to be cautious about inhaling)**



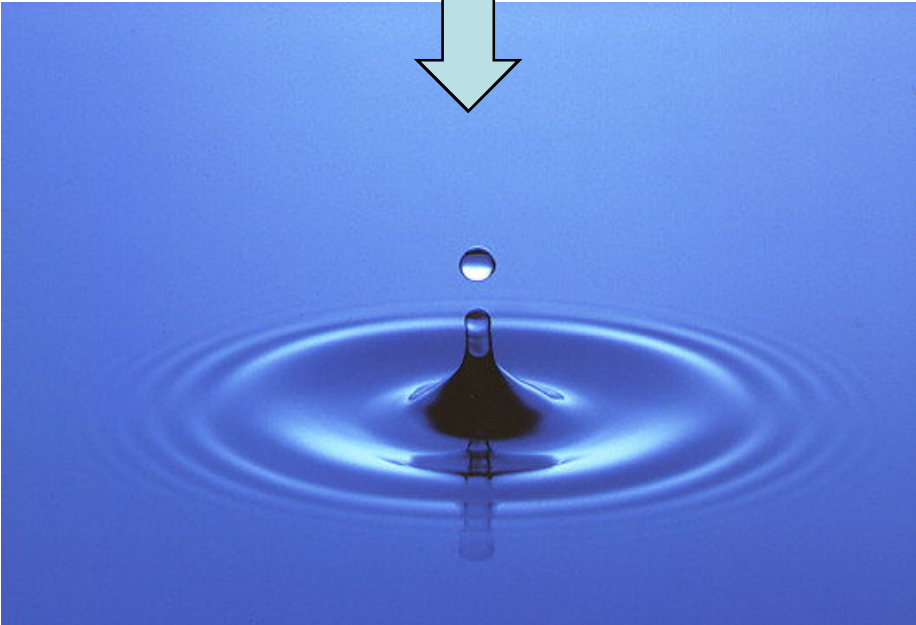
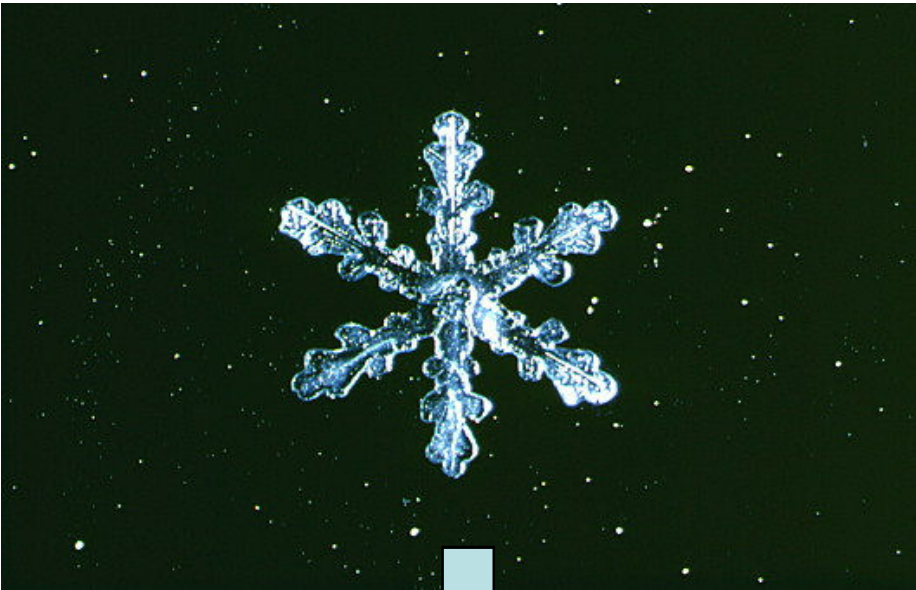
**patterns  
and structures  
when cold  
(low energy)**



**Symmetry  
when warm  
(high  
energy)**



**FORCES 1955-2005**



**COLD**

**Electromagnetic  
Weak  
Strong**

**WARM**

**ElectroWeak  
Strong (QCD)**

**HOT**

**GrandUnified  
Force**



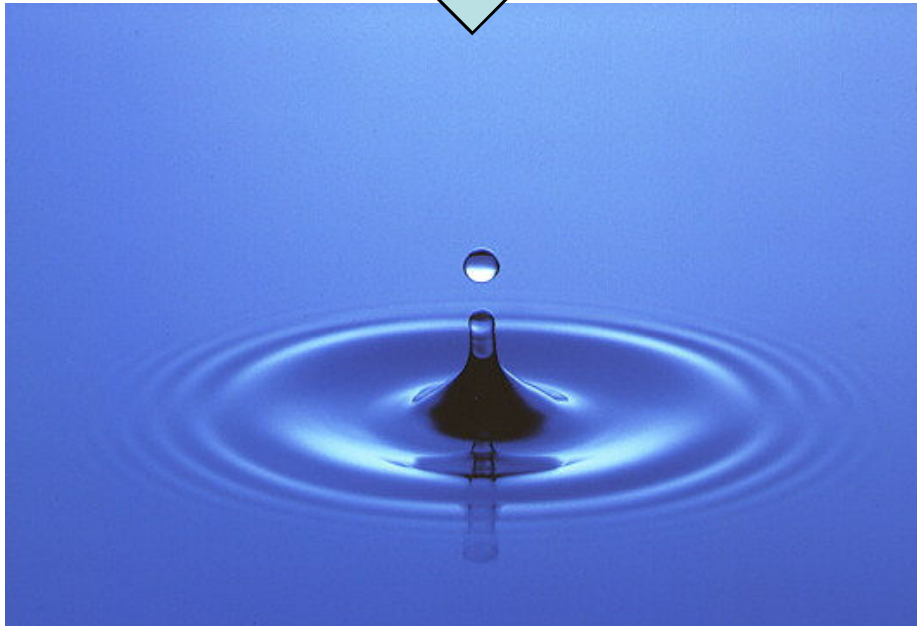
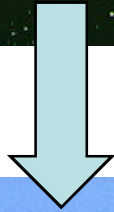
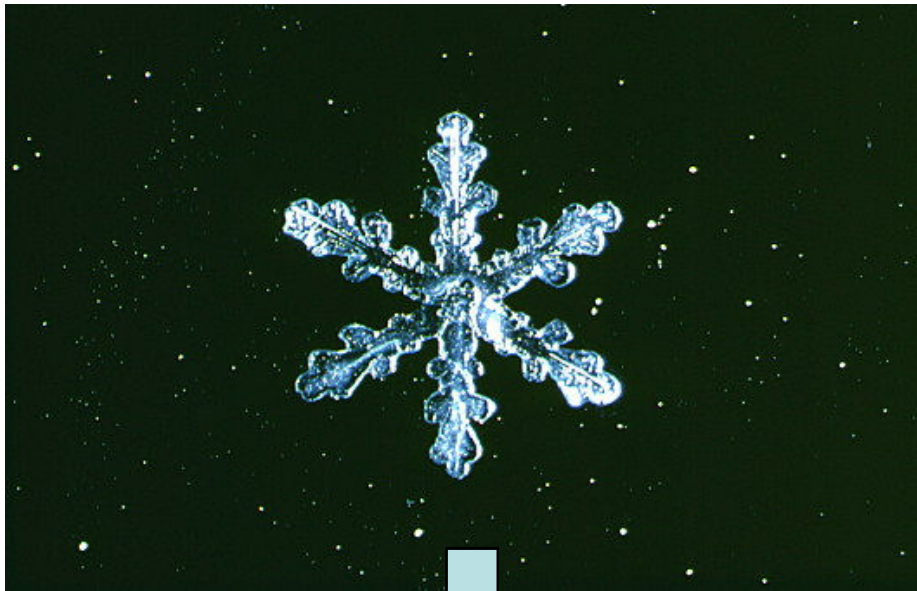
## Standard Model of Quarks Leptons and forces

= **pattern** based on **mass**

“**cold**” = “low” energy

= **below 1 TeV**





## Standard Model of Quarks Leptons and forces

= pattern based on **mass**

“cold” = “low” energy

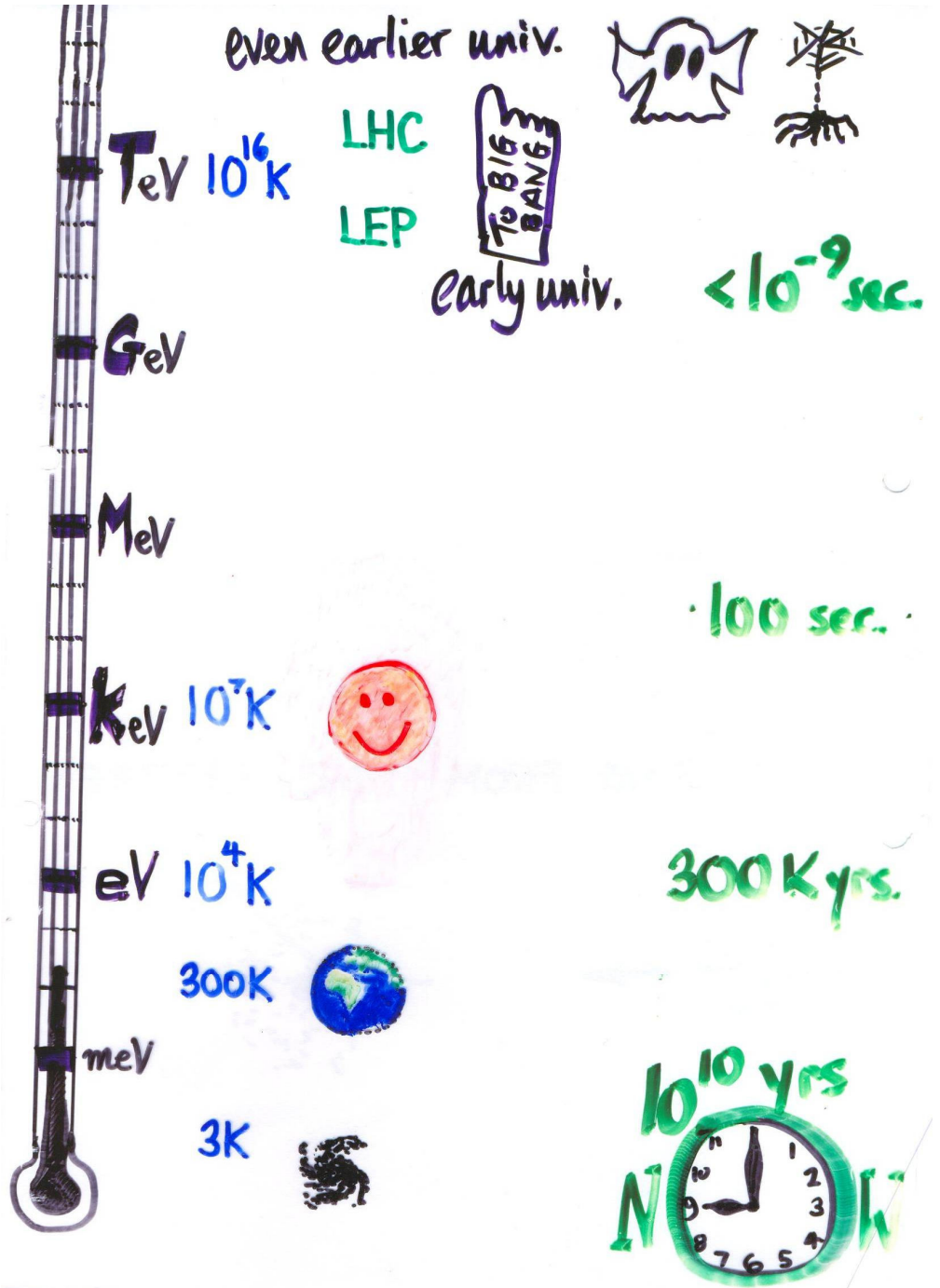
= below 1 TeV



super**Symmetry**  
when “warm”

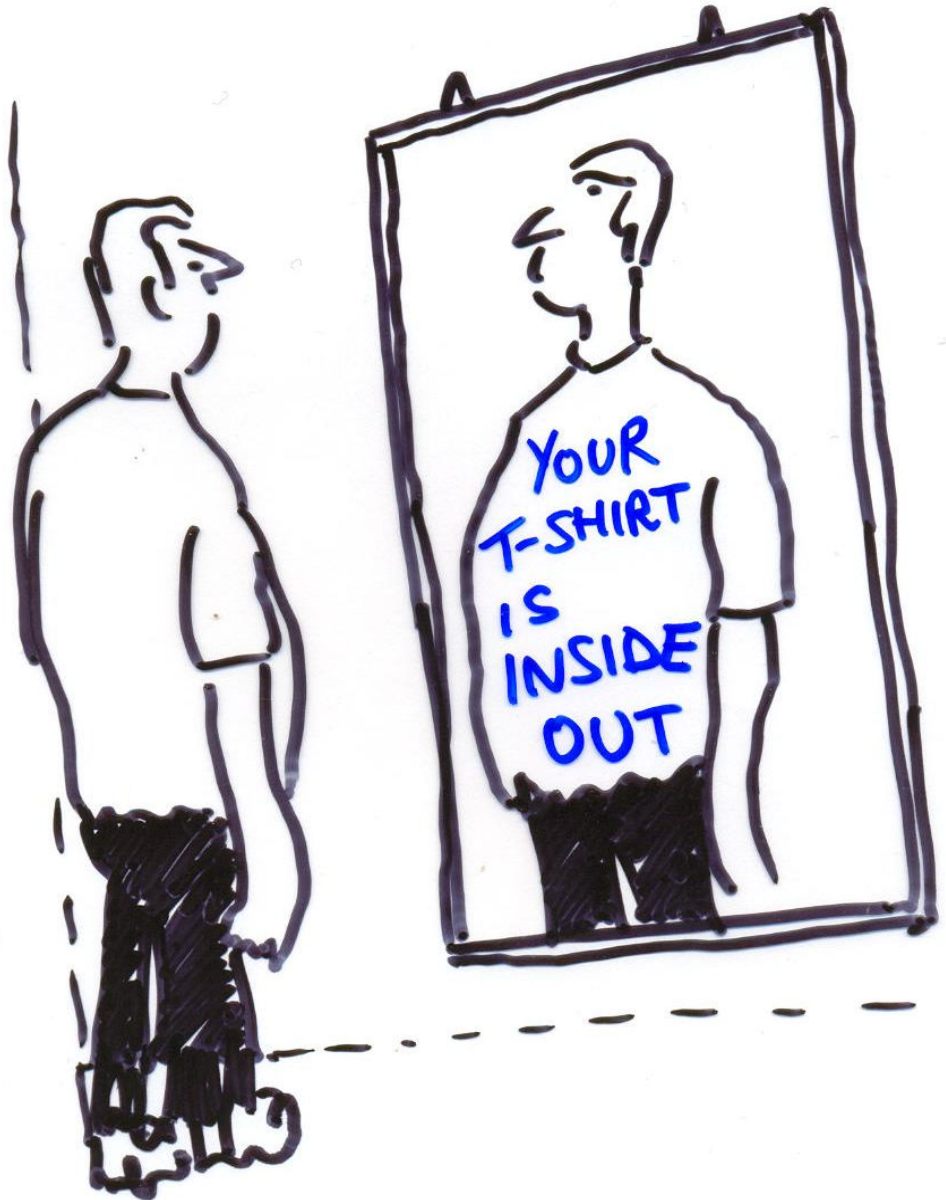
(= high energy  $> 1\text{TeV}$ )

**Higgs Boson**  
**Supersymmetry**  
**Nature of Reality**

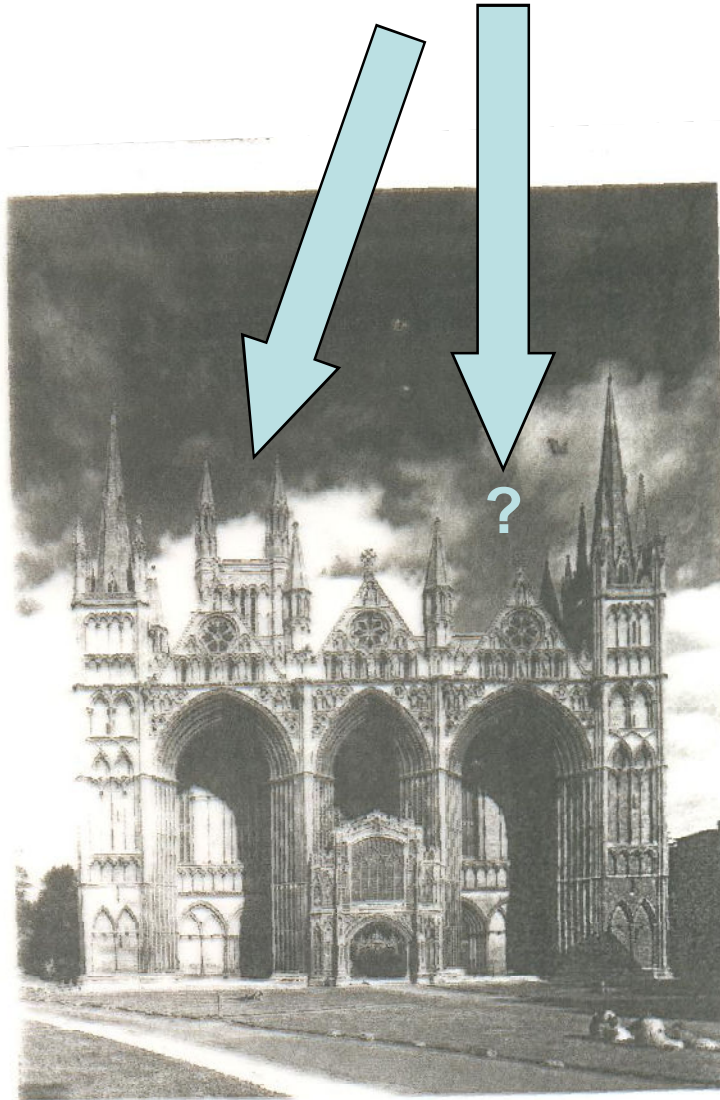




5. symmetries  
can disappear  
or change

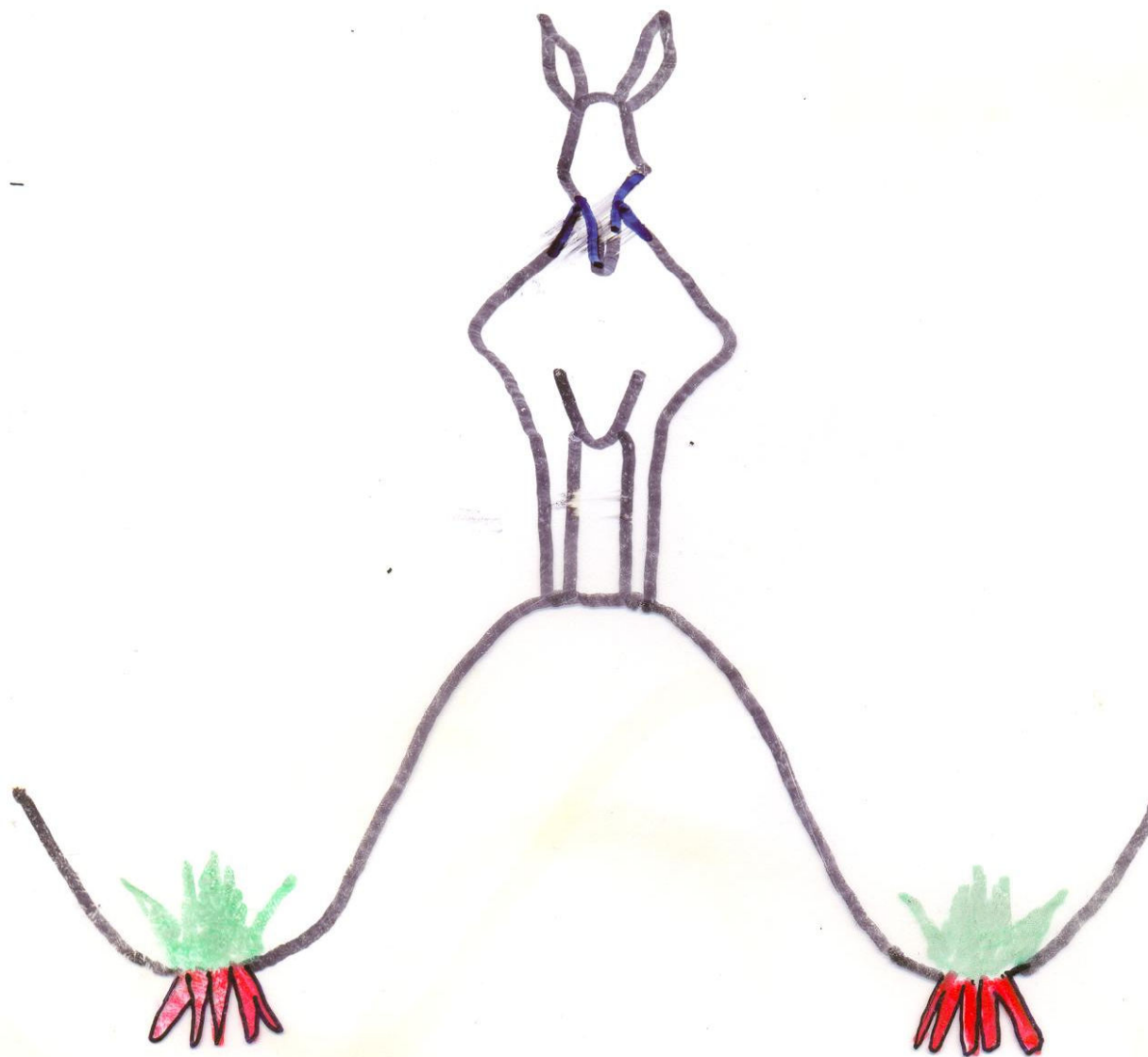


**We like symmetry and when its absent we want to know why**

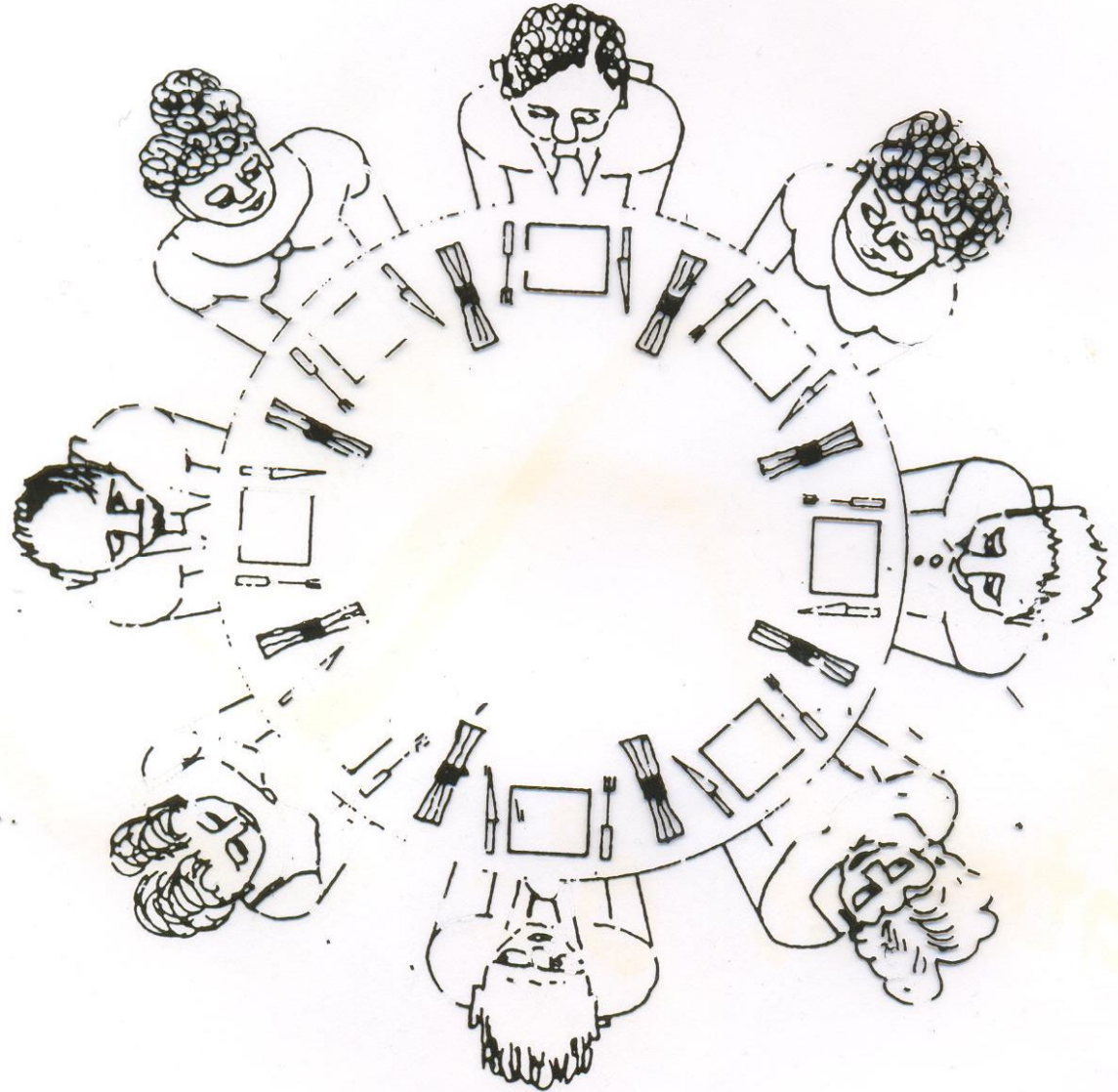




# Buridan's Ass



**The problem of  
the symmetric  
dinner party**



**symmetry**



**Broken symmetry**



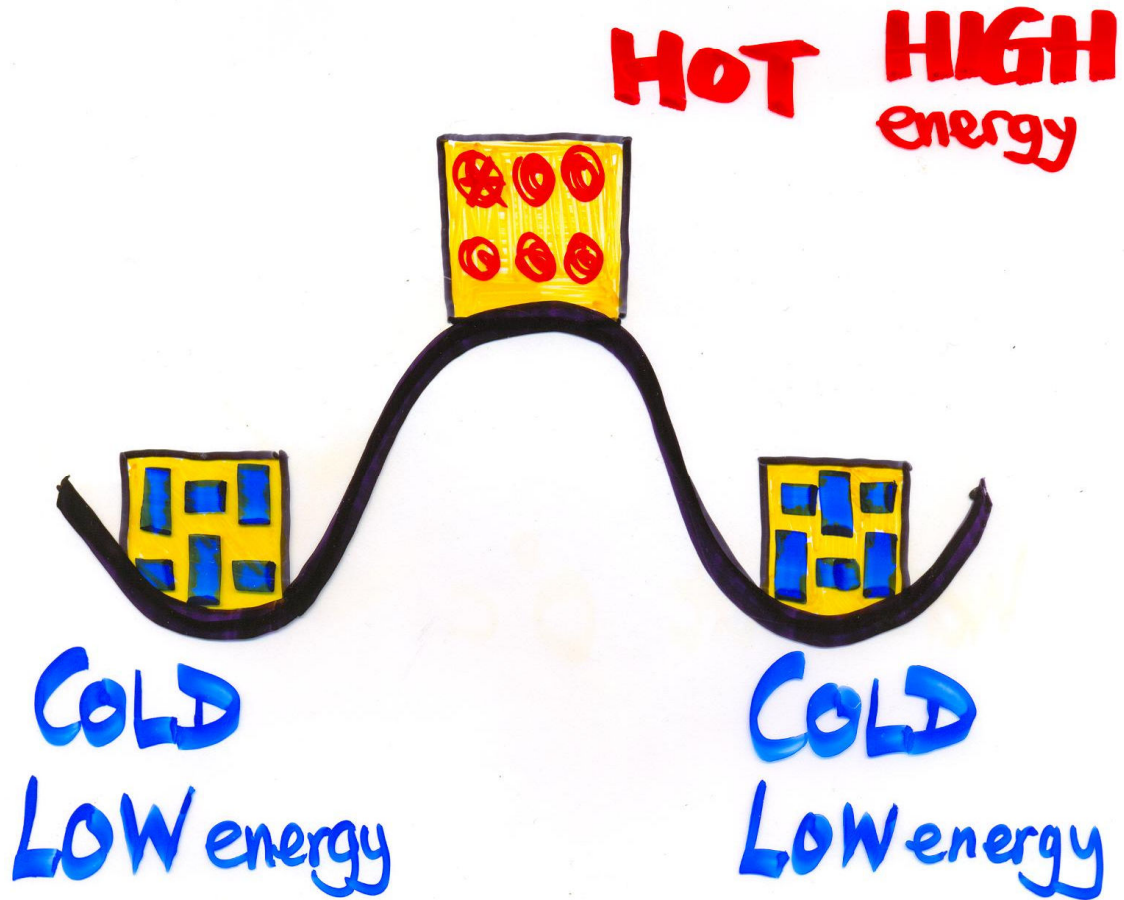
A photograph of sand dunes with a yellow arrow pointing to a peak. The dunes are illuminated from the side, creating a rhythmic pattern of light and shadow. The arrow points to a specific peak on the dune.

**Why is this a peak and not a trough?**

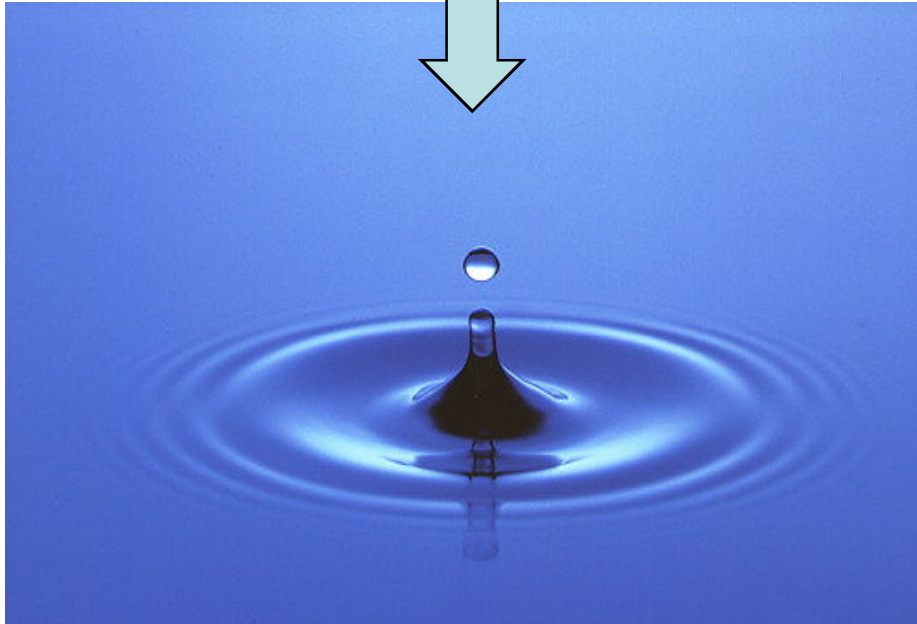
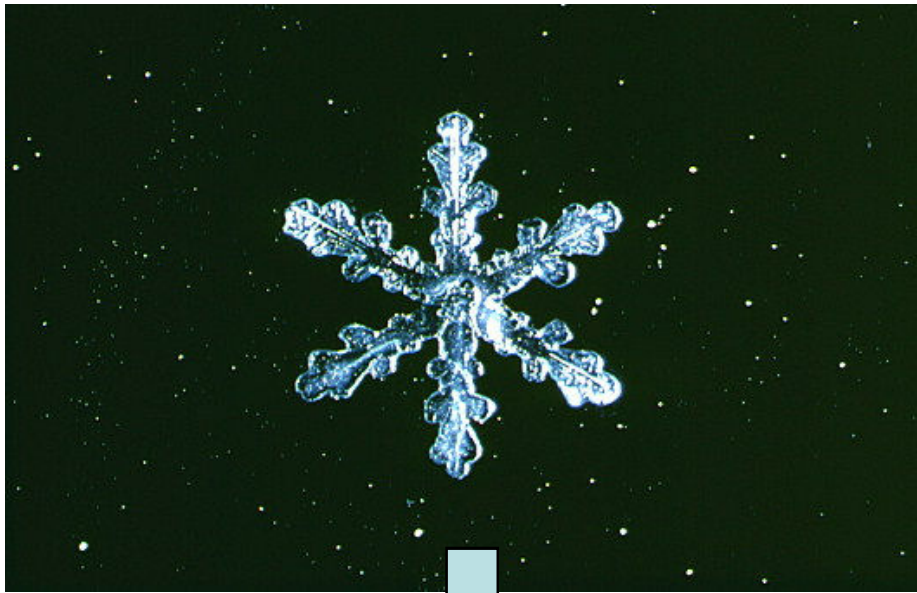
**Answer: random chance  
But given it's a peak here  
it dictates where the other  
peaks are**

**Broken symmetry**

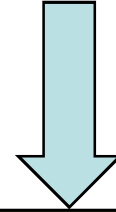
# Magnets







**patterns  
and structures  
when cold  
(low energy)**



**Symmetry  
when warm  
(high  
energy)**



**As the universe cooled after the hot big bang.....  
We think that an elegant symmetry.....**

**... “froze” into structures .... And patterns**

**Such as Atoms ..... Mendeleev’s periodic table,  
And particles .... Quarks, forces and the Standard Model**

**... which is a pattern based on MASS**

**2008: heat up to energies above 1000 GeV = “1 TeV”  
and discover the origin of MASS (= Higgs?)**

No mass. Unified Theory

Next  
....

Standard Model  
MASS

t	b	$\tau$	$\nu$	W
c	s	$\mu$	$\nu$	Z
u	d	e	$\nu$	$\gamma$

even earlier univ.



LHC  
LEP



early univ.

$< 10^{-9}$  sec

Nuclear Isotopes



TeV  $10^{16}$  K

GeV

MeV

KeV  $10^7$  K

eV  $10^4$  K

300K

meV

300K

3K



100 sec.

300K yrs

$10^{10}$  yrs  
NOW



Mendeleev



Snowflake pattern

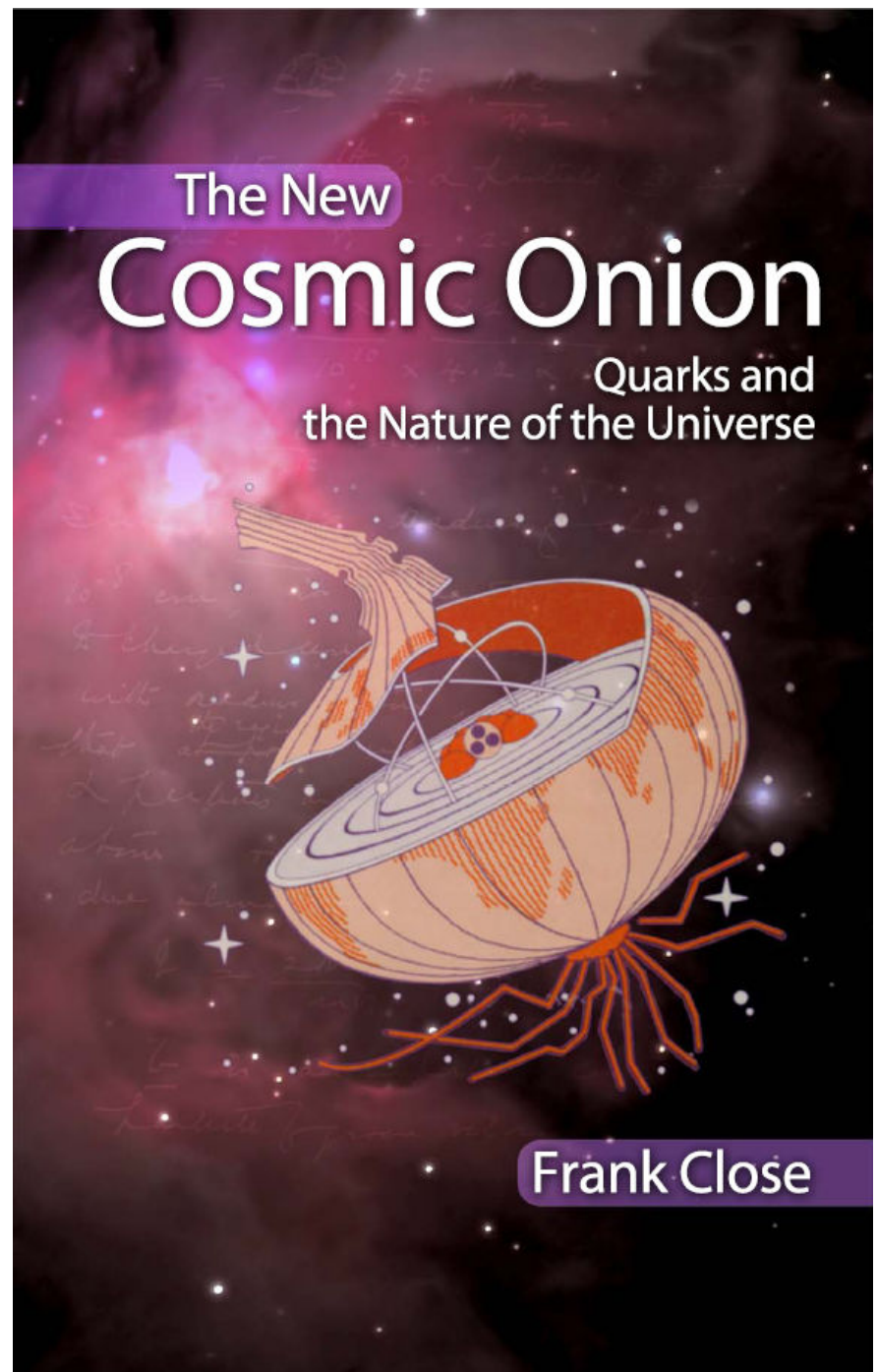
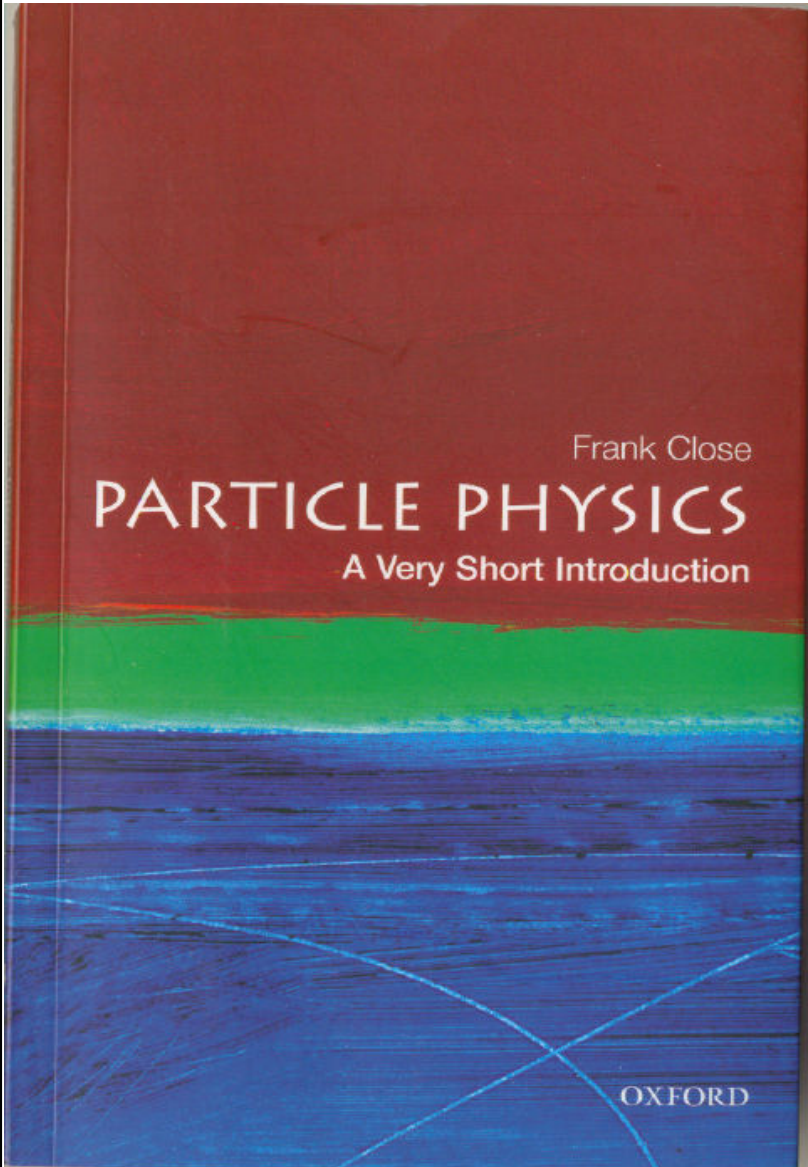




ANTI-MATTER  
FRANK CLOSE

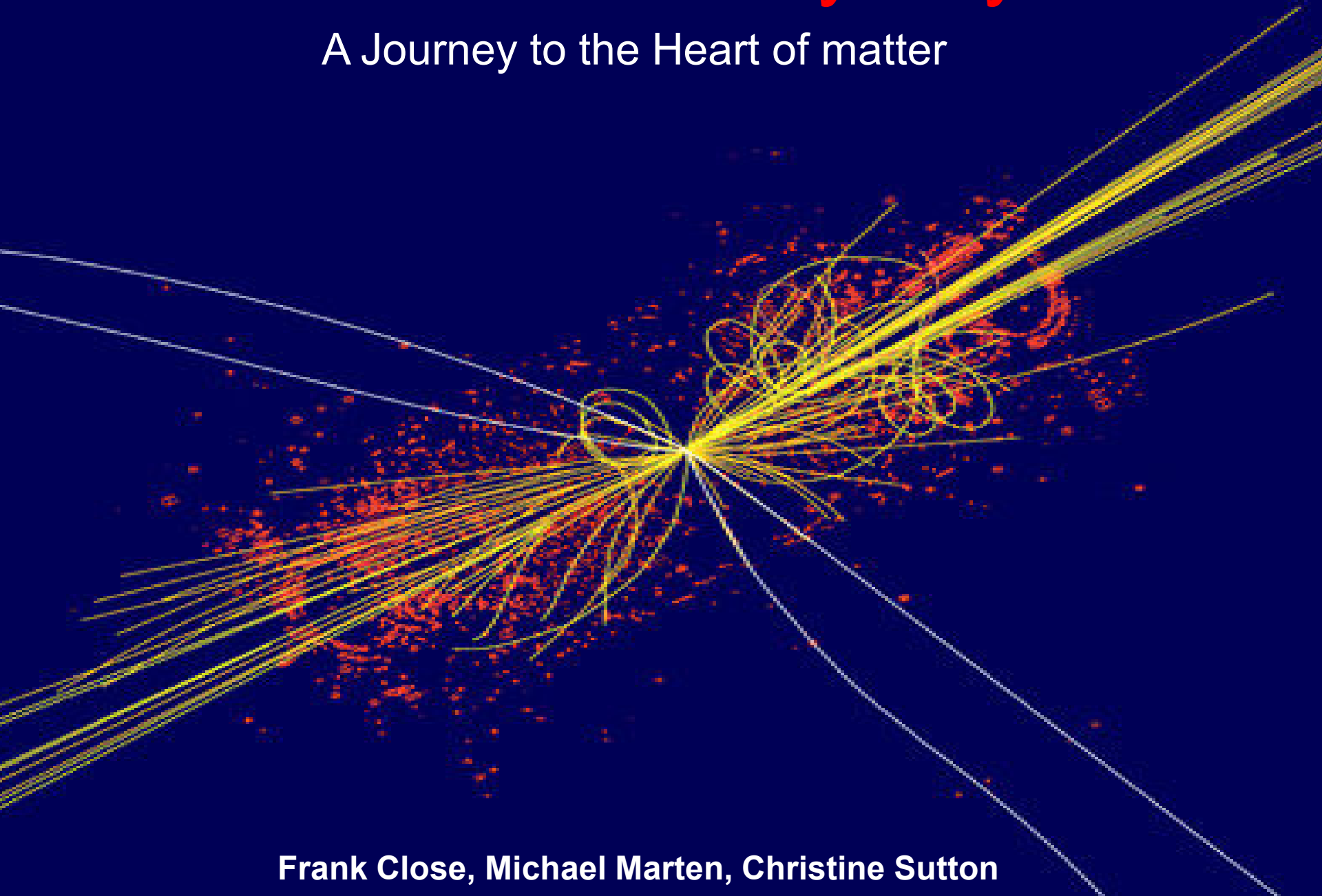


# A Very Short Introduction



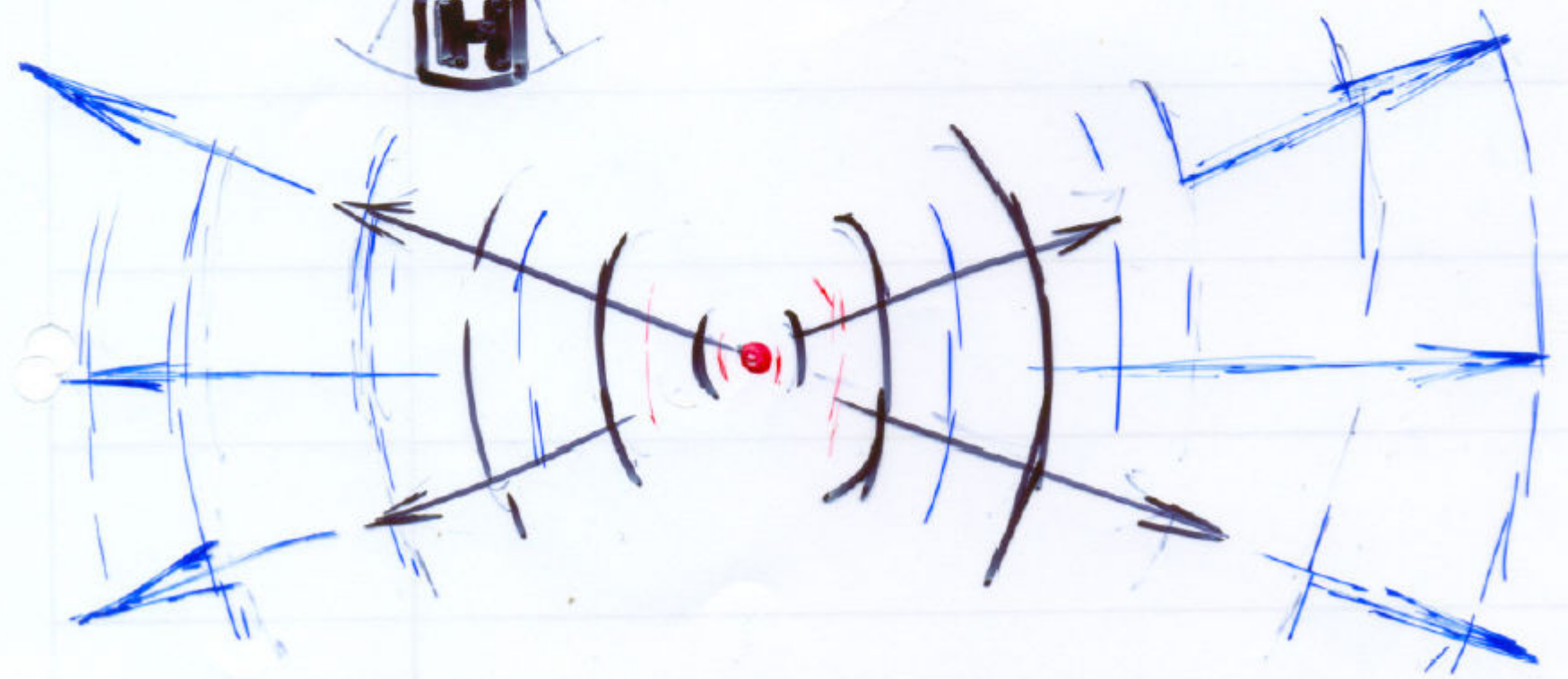
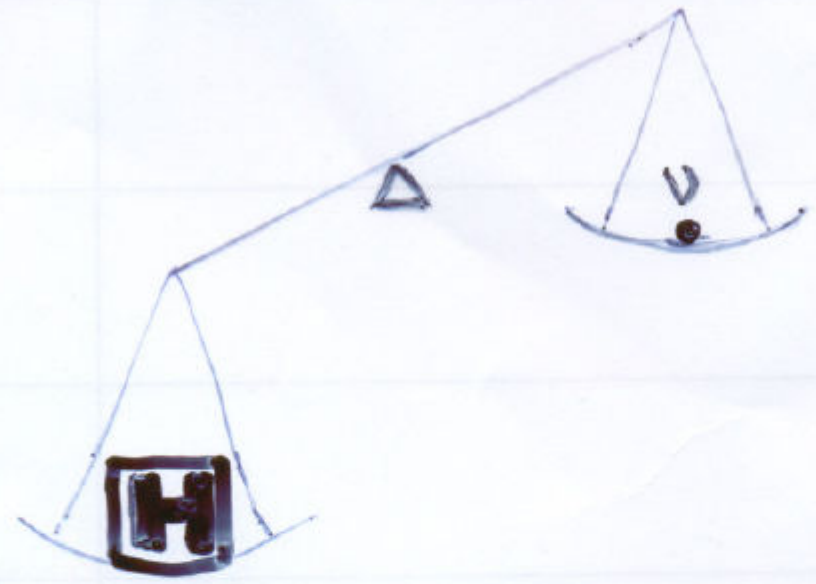
# The Particle Odyssey

A Journey to the Heart of matter



**Frank Close, Michael Marten, Christine Sutton**

either





or

