Modern Physics

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Lesson XIII
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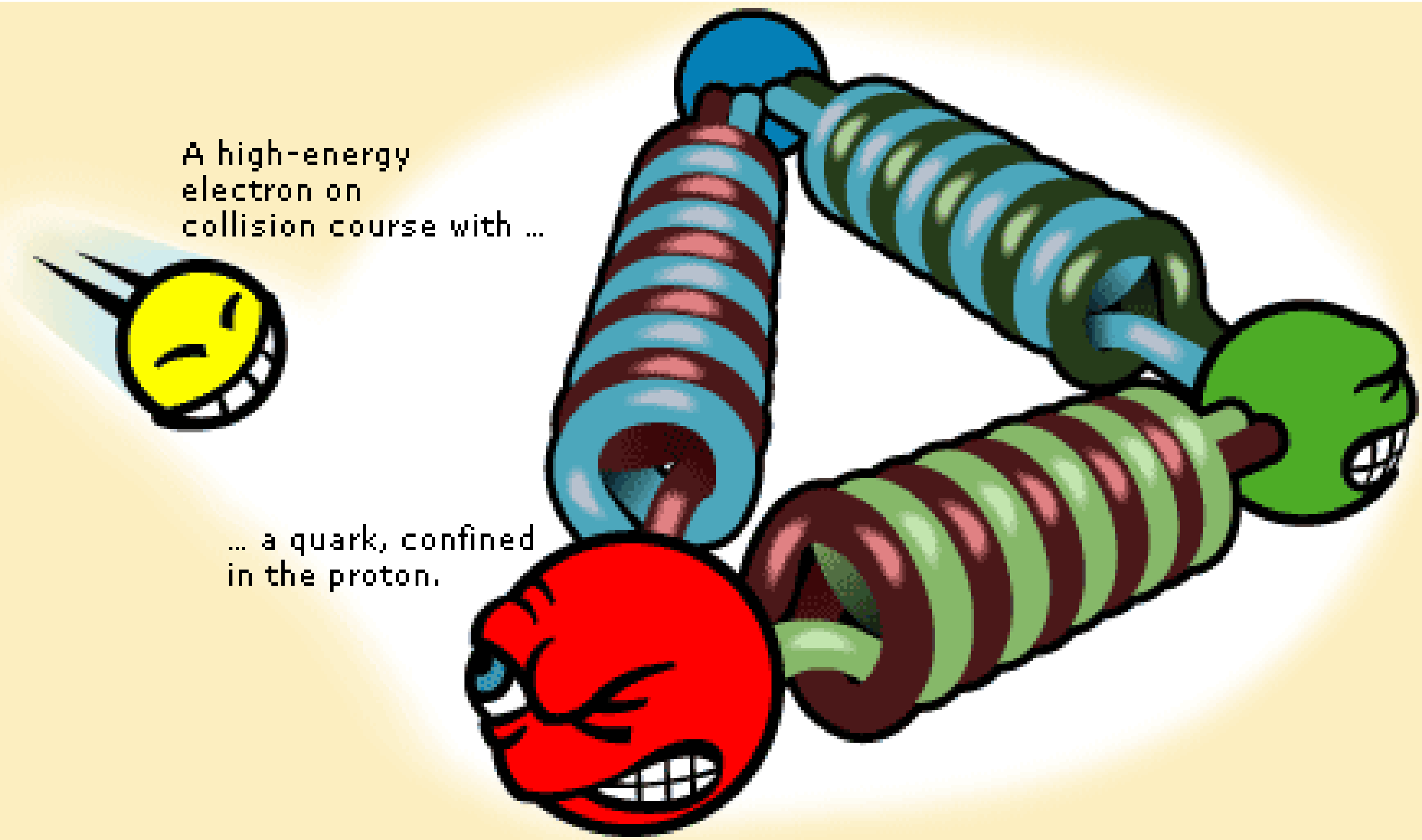
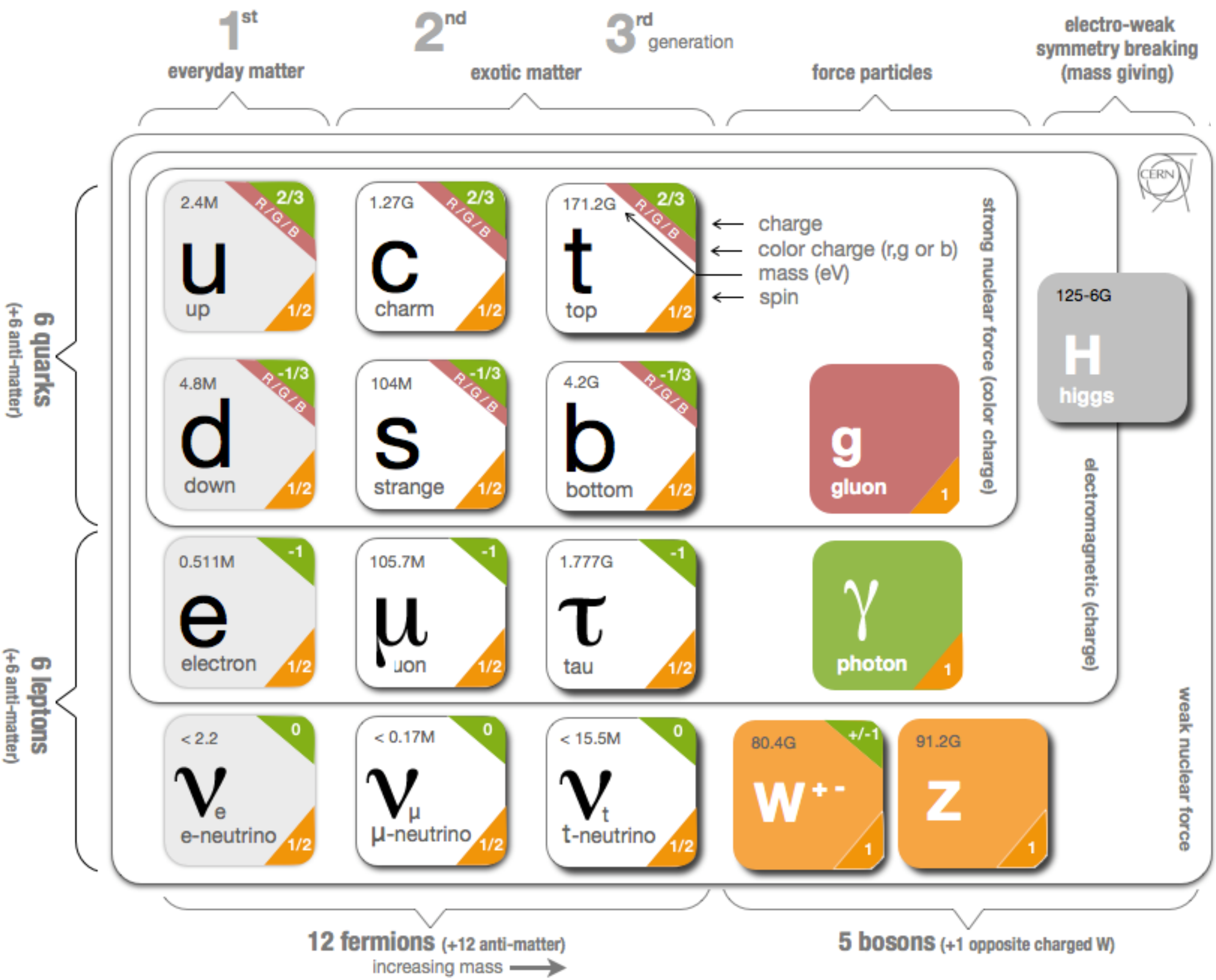

A high-energy
electron on
collision course with ...
... a quark, confined
in the proton.

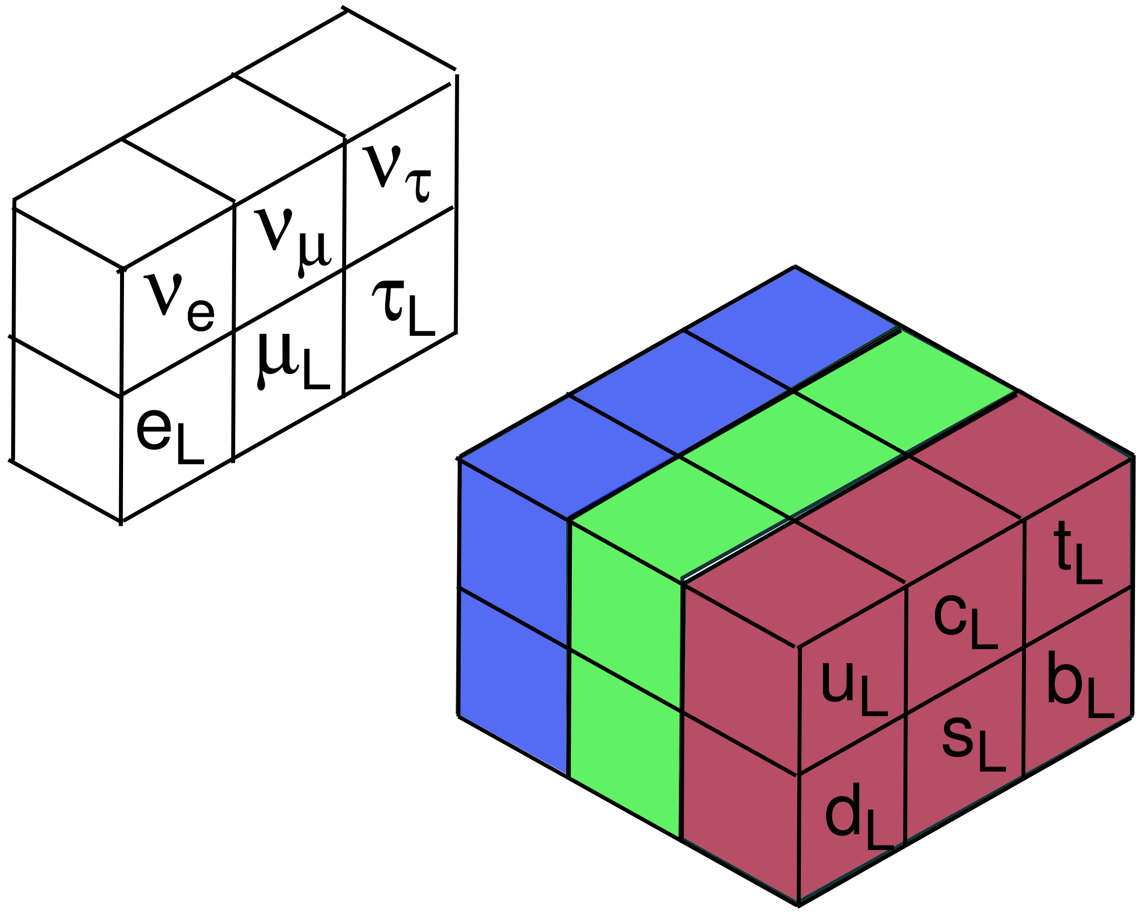
The Standard Model



Electroweak Theory

takes three crucial clues from experiment

➢ The existence of left-handed weak-isospin doublets



➢ The universal strength of the weak interactions

➢ The idealization that neutrinos are massless

Electroweak Theory

To incorporate electromagnetism into theory

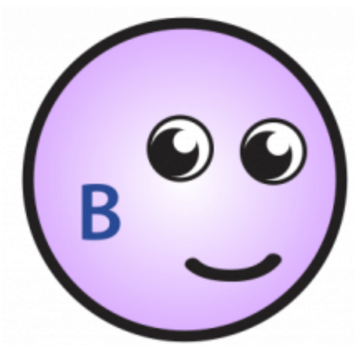
we add to the weak-isospin family symmetry

a weak-hypercharge phase symmetry

The electroweak theory then implies two sets of gauge bosons

a weak isovector ☛

a weak isoscalar ☛

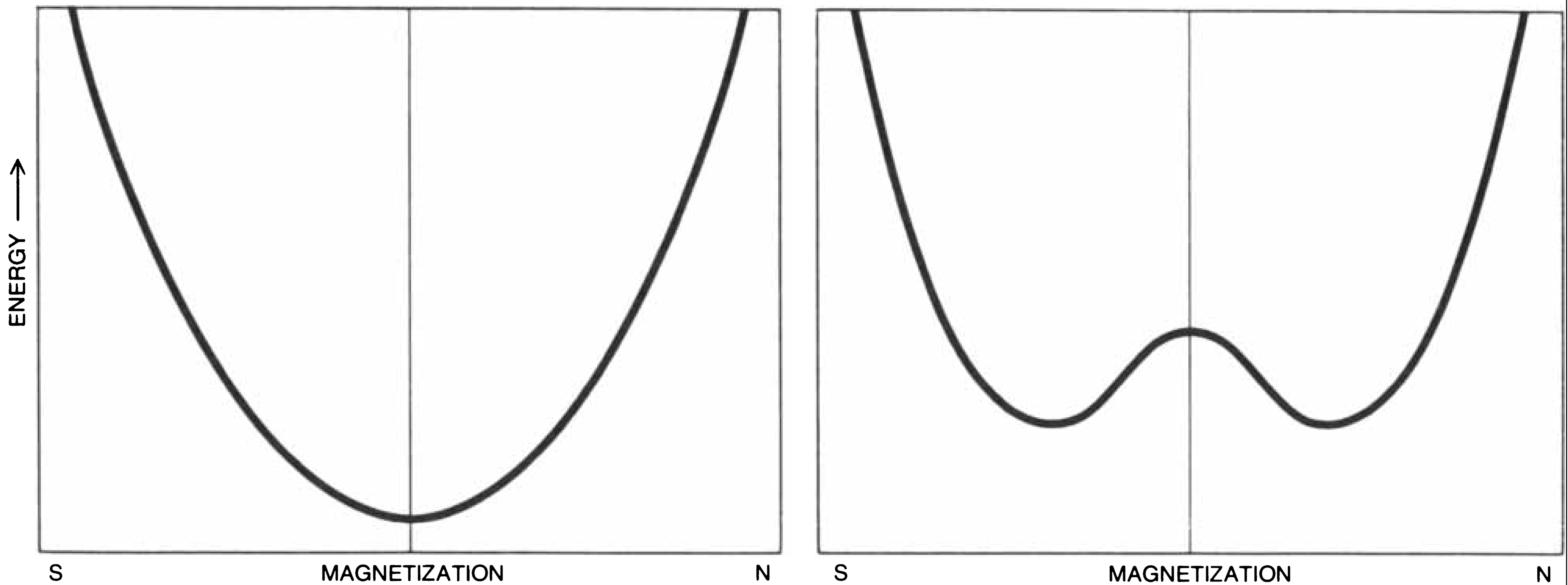


Symmetry Breaking

The free energy of a ferromagnet is related to its magnetization M

$$G = \alpha M^2 + \beta M^4$$

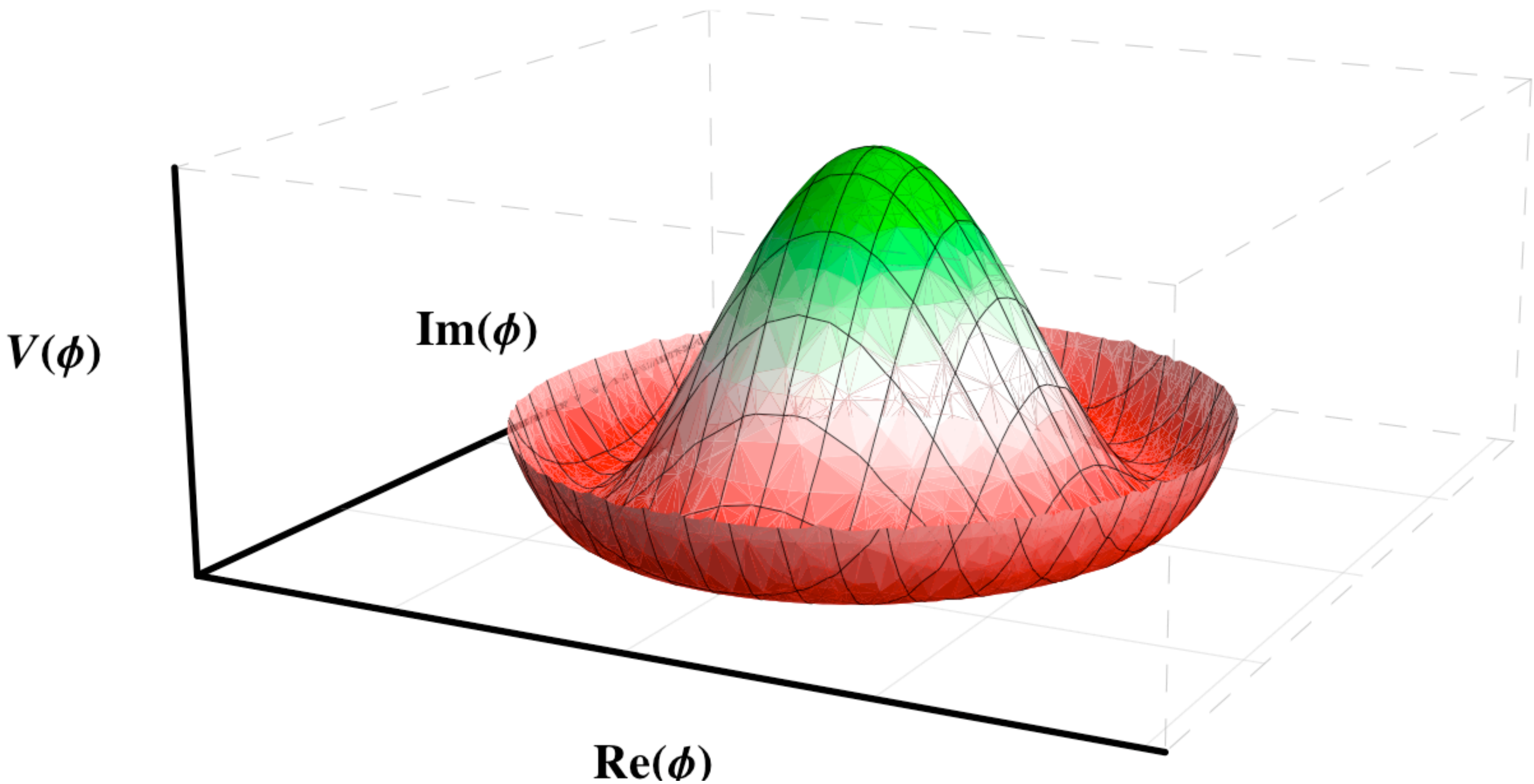
The free energy is symmetric under rotation in space



$\alpha > 0 \ \& \ \beta > 0$ $\alpha < 0 \ \& \ \beta > 0$

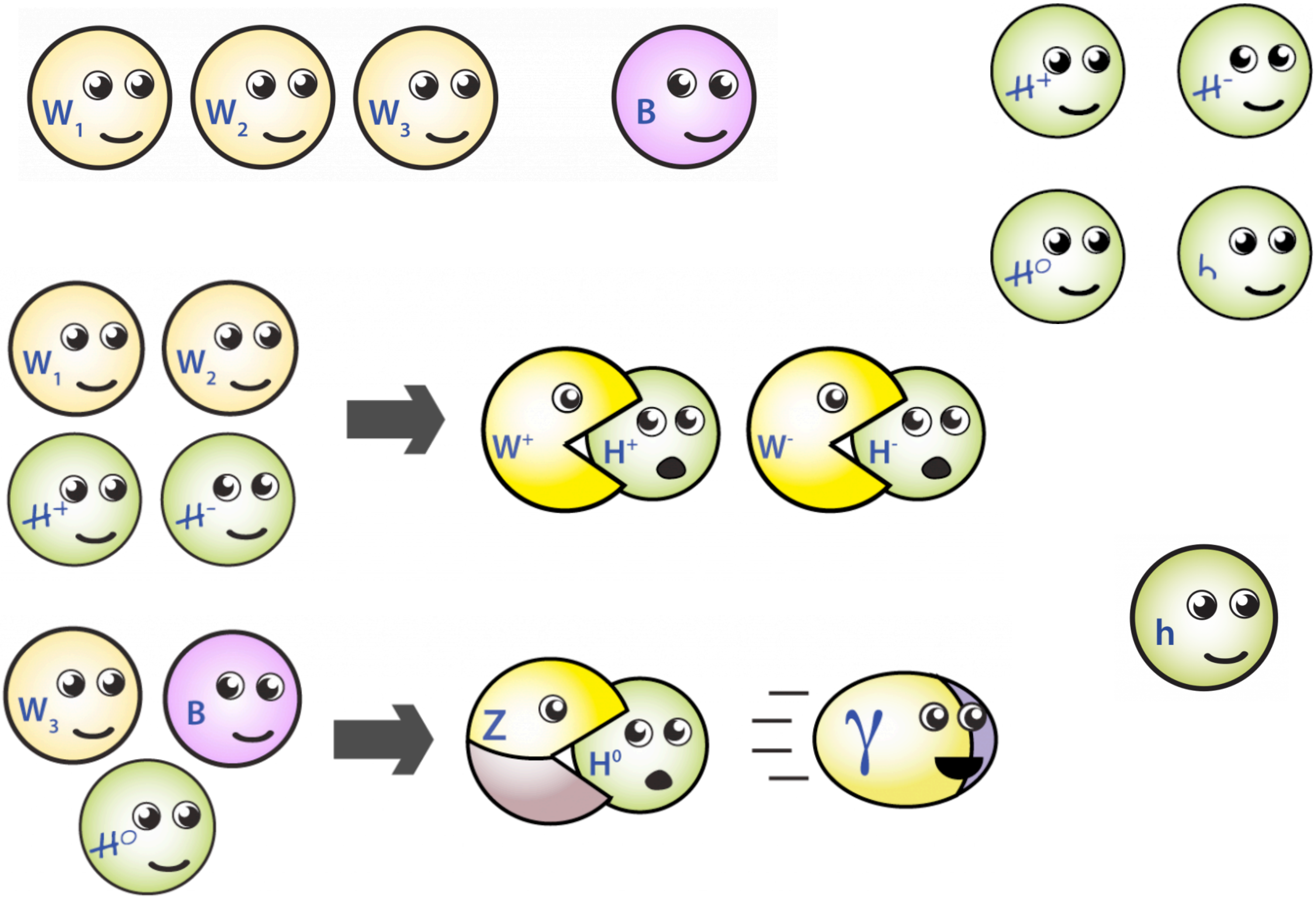
Mexican Hat Potential

$$V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2 \qquad \mu^2 < 0 \ \& \ \lambda > 0$$

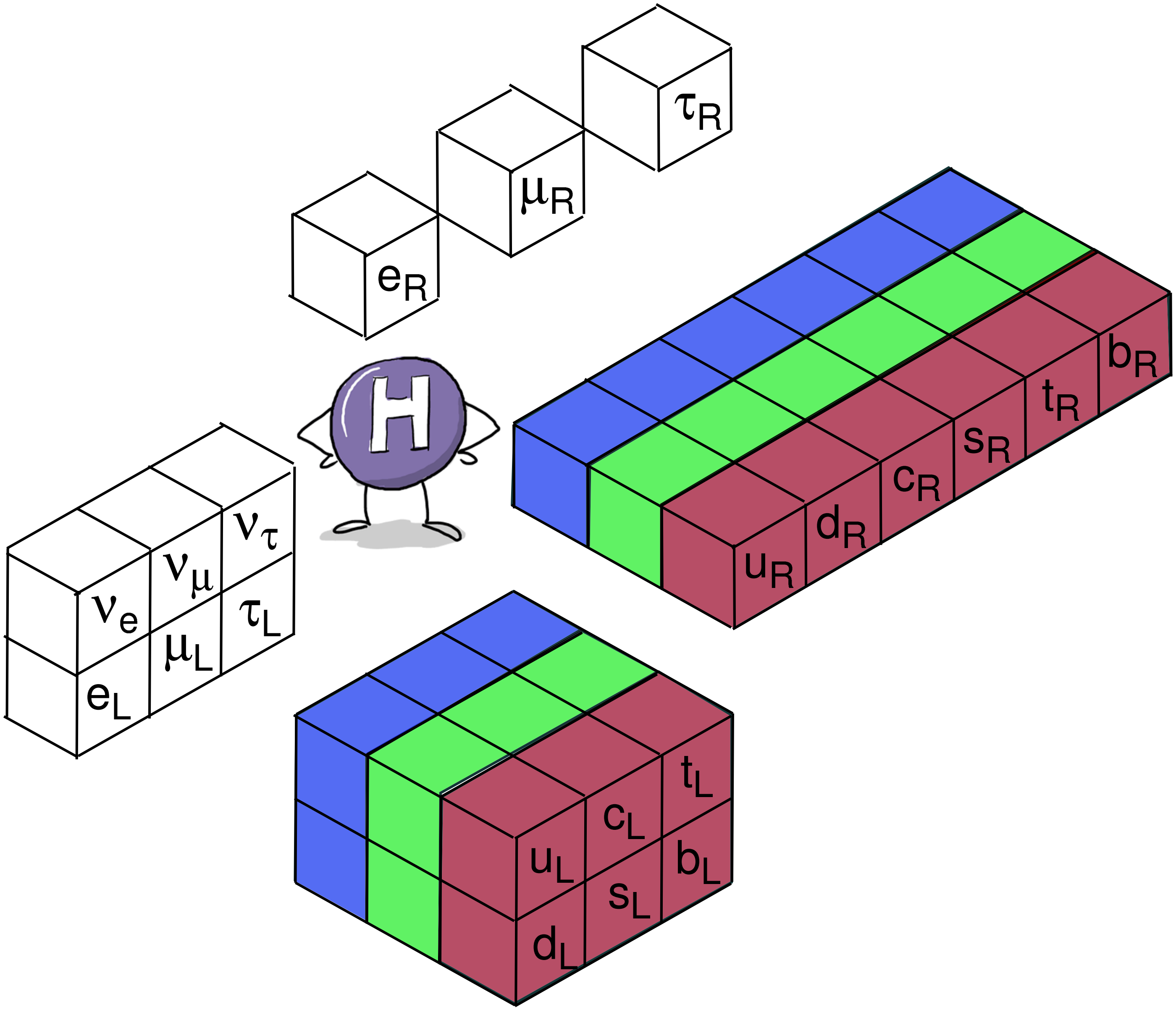


is symmetric under rotations in ϕ space

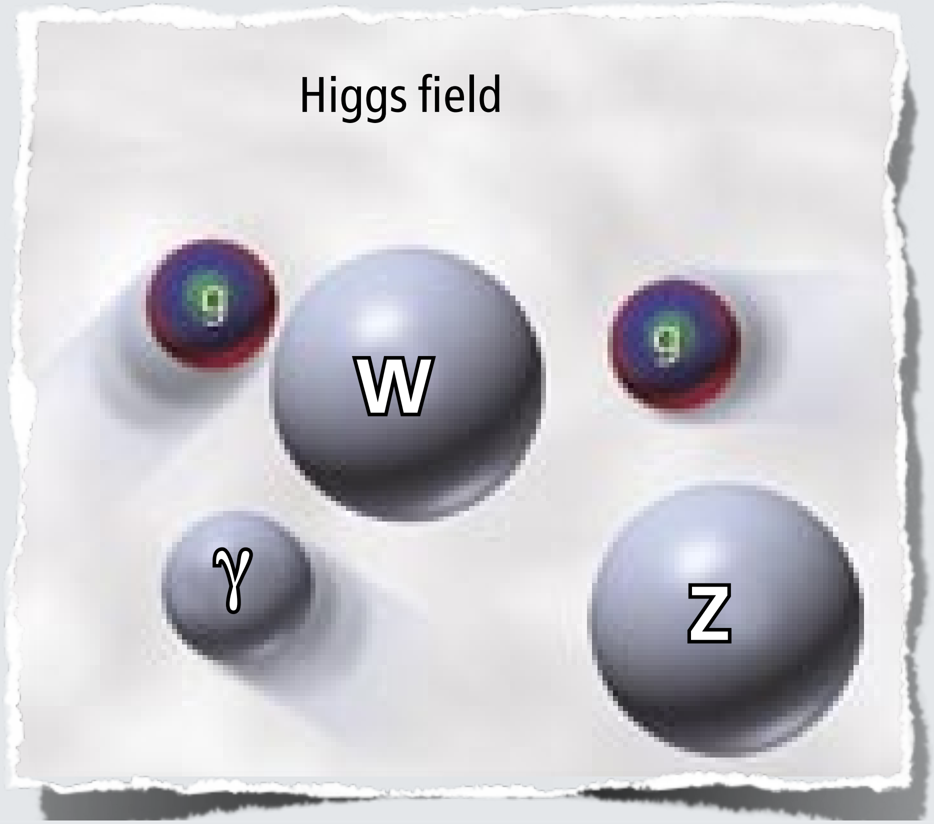
Electroweak Symmetry Breaking



Yukawa Interactions



Electroweak Symmetry



Beware of quantum ducks: quark, quark, quark...

- Development of successful gauge theory of strong interaction
  which is unique to hadrons
  cannot not be undertaken
  until inherent property about the hadrons is understood:
  they are not elementary particles

- Hadron ☞ made up of quarks according to two archetypes
  - Binding together three quarks leads to a baryon
    class of hadrons that includes neutron and proton
  - Combining one quark and one antiquark makes a meson
    class typified by pions

- Keystone of any theory of strong interactions
  explain peculiar rules for building hadrons out of quarks

Baryons and Mesons

- Structure of meson is not so hard to account for:
  since meson is made out of quark and antiquark
  assume quarks carry some property analogous to electric charge
- Binding of quark and antiquark
  explained on principle that opposite charges attract
  just as they do in electromagnetism
- Structure of baryons is far profound enigma
- To describe how three quarks can produce bound state
  we must assume that three like charges attract

Color

- Analogue of electric charge is property called color
- Rules for forming hadrons
  require combinations of quarks to be "white" or colorless
- Quarks are assigned the primary colors ☞ red, green, and blue
- Antiquarks have complementary "anticolors"
  cyan, magenta and yellow
- Each of the quark flavors comes in all three colors
  introduction of color charge triples number of distinct quarks

QCD

- Non-Abelian gauge theory responsible for strong interactions
- Gauge symmetry:
  invariance with respect to local transformations of quark color
- Easy to imagine global color symmetry
  - Quark colors ☞ like isotopic-spin states of hadrons
    indicated by arrow orientation in some imaginary internal space
  - Successive rotations of $\frac{1}{3}$ of turn
    would change quark from red to green to blue and back to red again
  - Baryon ☞ 3 arrows with 1 arrow set to each of 3 colors
  - Global symmetry transformation ☞ by definition
    must affect all 3 arrows in same way and at same time
  - E.g. ☞ all 3 arrows might rotate clockwise $\frac{1}{3}$ of turn
  - Result of transformation ☞ all 3 quarks would change color
    but all observable properties of the hadron would remain as before
  - Particularly ☞ there would still be one quark of each color
    and so baryon would remain colorless

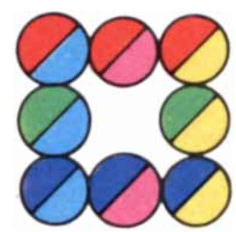
Local symmetry

- QCD requires that invariance be retained
  even when symmetry transformation is local
- In absence of forces or interactions invariance is obviously lost
- Local transformation can change color of one quark
  but leave other quarks unaltered
  which would give hadron a net color
- As in other gauge theories
  way to restore invariance wrt local symmetry operations
  ☞ introduce new fields
- In QCD fields needed are analogous to electromagnetic field
  but are much more complicated
  have 8 times as many components as electromagnetic field has
- It is these fields that give rise to the strong force

Gluons

- Quanta of color fields are called gluons
  (because they glue the quarks together)
- There are 8 of them: they are all massless
  they have a spin angular momentum 1
  they are massless vector bosons like the photon
- Also like photons ☞ gluons are electrically neutral
  but they are not color-neutral
- Each gluon carries one color and one anticolor
- There are nine possible combinations of a color and an anticolor but one of them is equivalent to white and is excluded
  leaving eight distinct gluon fields

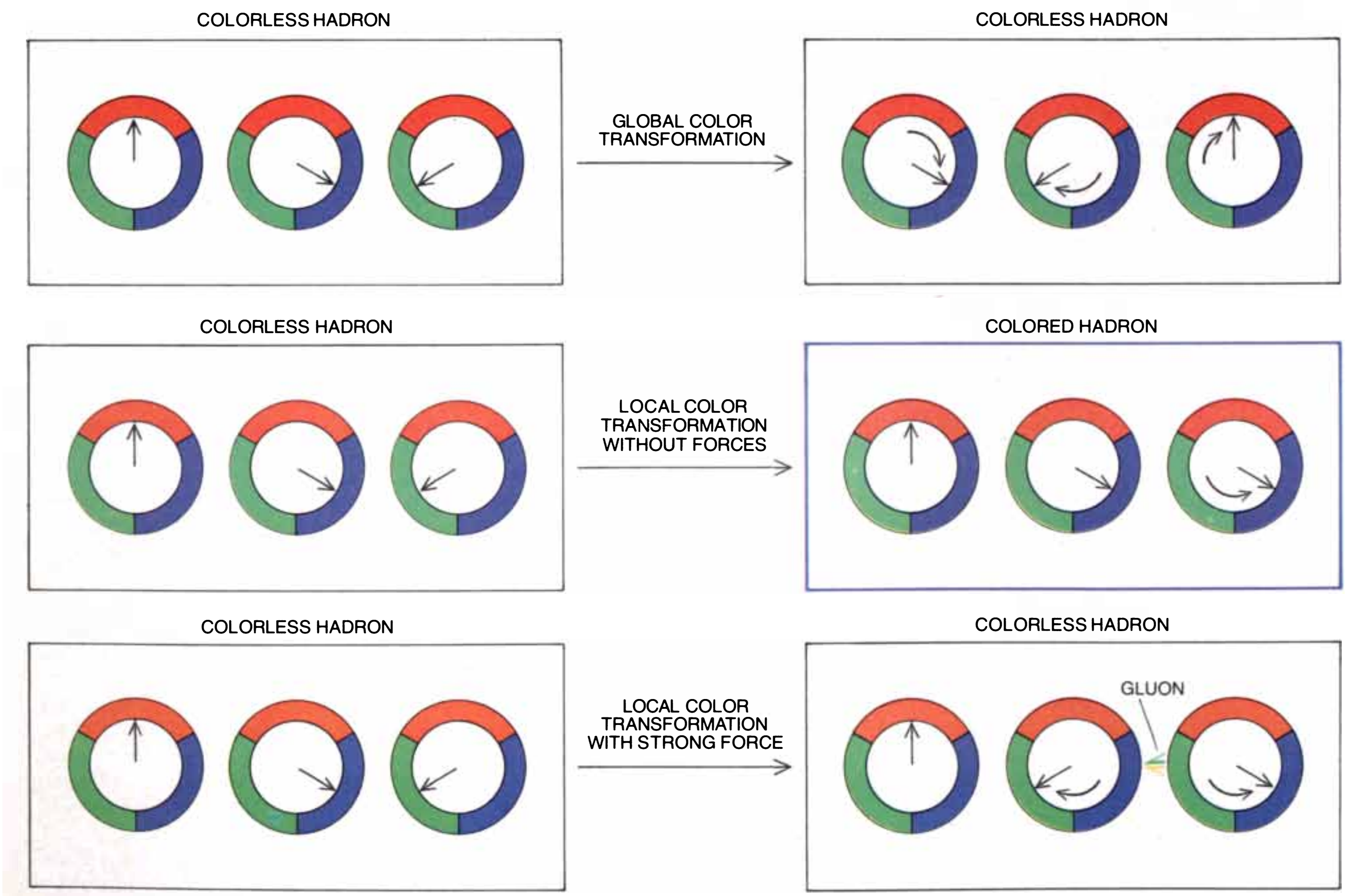
x8 combinations



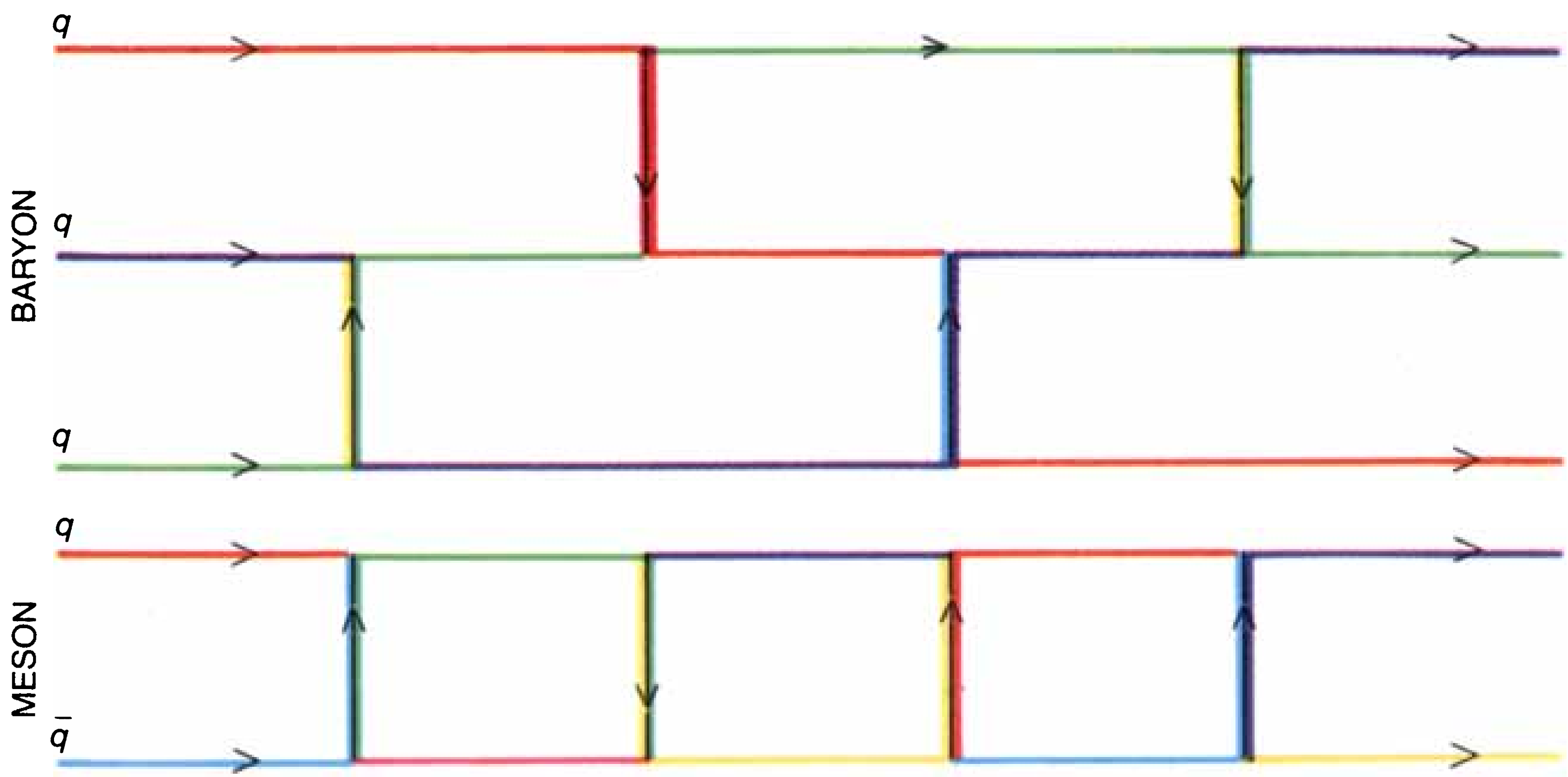
Gluons preserve local color symmetry in following way...

- Quark is free to change its color
  and can do so independently of all other quarks
  but every color transformation
  must be accompanied by gluon emission
  just as electron can shift its phase only by emitting a photon
- Gluon propagating at speed of light
  is then absorbed by another quark
  which will have its color shifted
  in exactly the way needed to compensate for the original change
- Assume red quark changes its color to green and
  in the process emits gluon that bears colors red and antigreen
- Gluon is absorbed by green quark and in the ensuing reaction
  green of quark and antigreen of gluon annihilate each other
  leaving second quark with a net color of red
- In final state as in initial state
  there is one red quark and one green quark

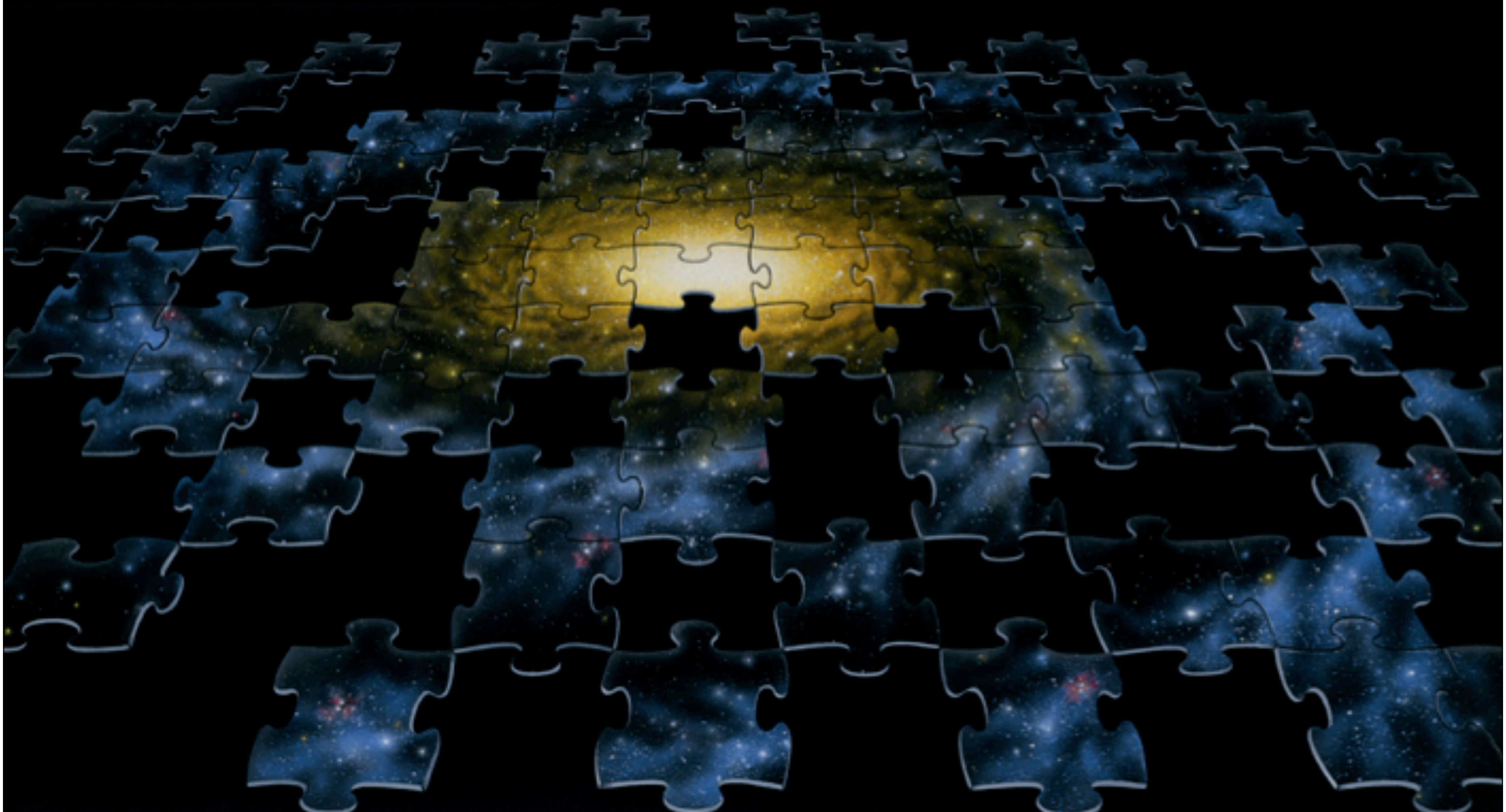
- Because of the continual arbitration of the gluons there can be no net change in the color of a hadron even though quark colors vary freely from point to point
- All hadrons remain white and the strong force is nothing more than the system of interactions needed to maintain that condition



Gluon exchange

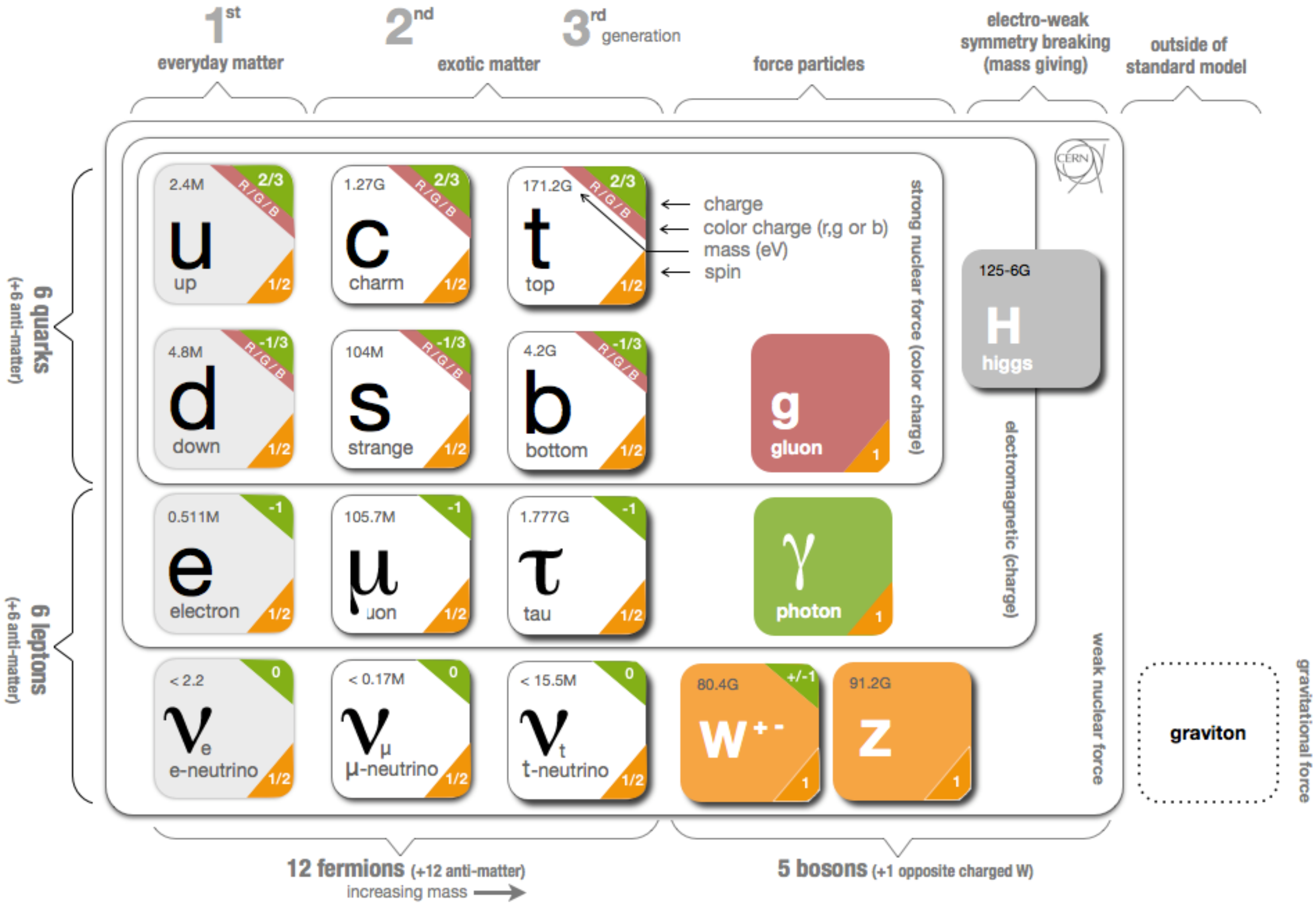


Despite the resilience of the Standard Model



it seems clear that there is more to the story...

The Standard Model is not enough



Hierarchy Problem

Relative strength of the 4 forces for two protons inside a nucleus

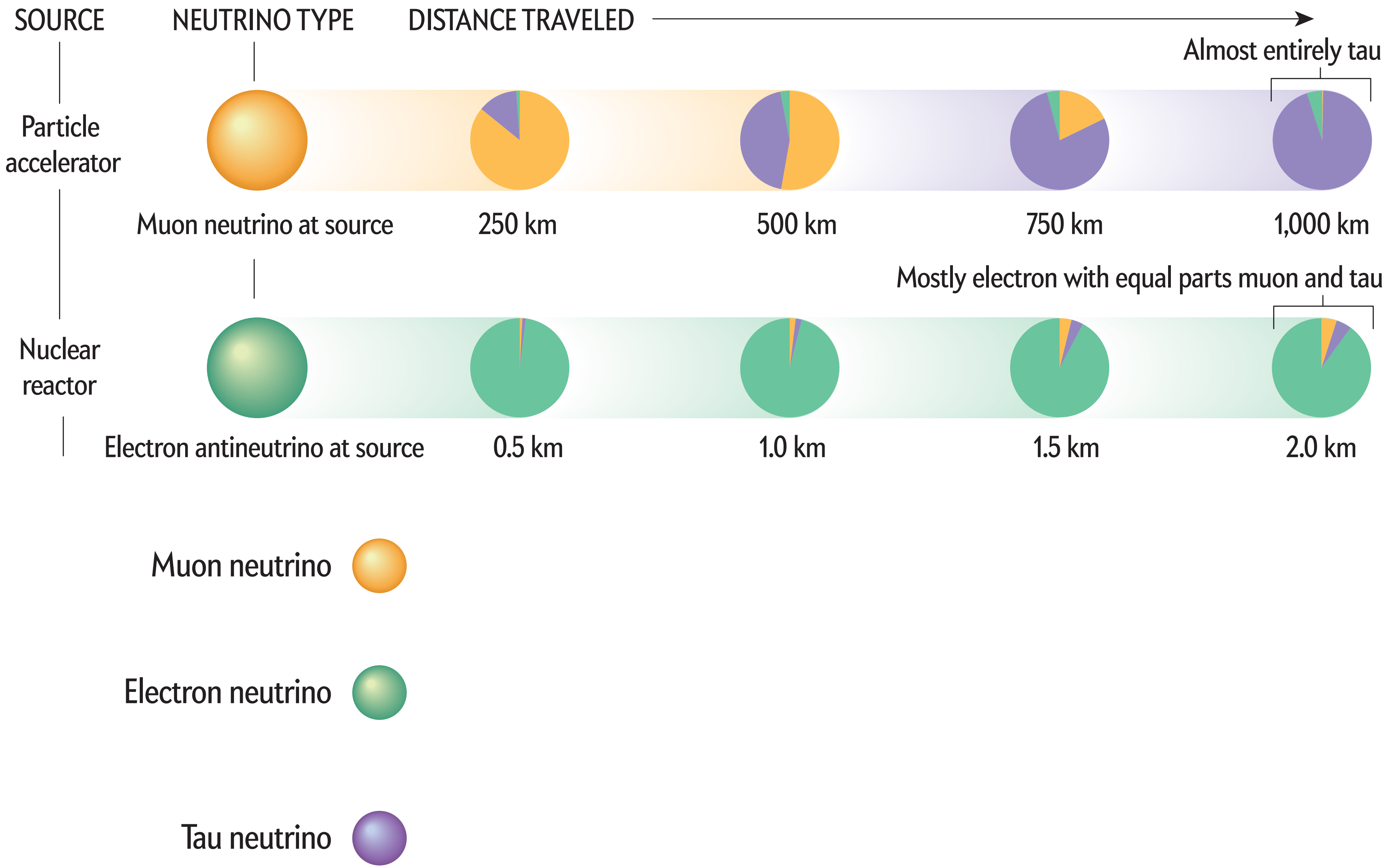
Type	Relative Strength	Field Particle
Strong	1	gluons
Electromagnetic	10^{-2}	photon
Weak	10^{-6}	$W^{\pm}$ and Z
Gravitational	10^{-38}	graviton

Why is the weak force 10^{32} times stronger than gravity?

Planck scale $E = GM_{\rm Pl}^2/r = \hbar c/r$

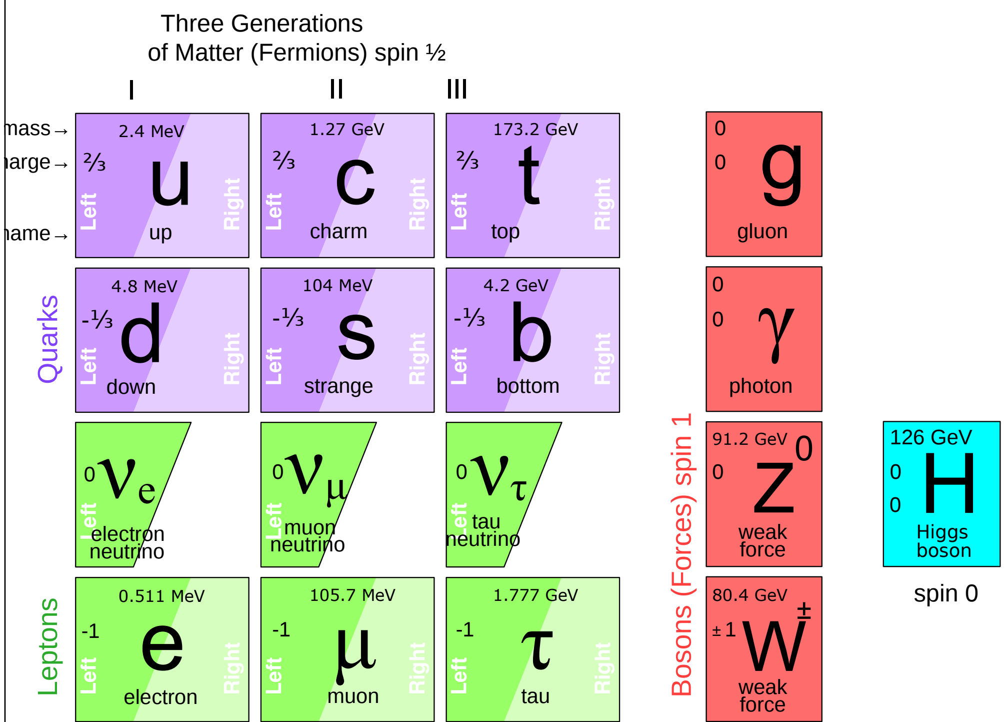
$$M_{\rm Pl} \sim 10^{19}\ \mathrm{GeV}$$

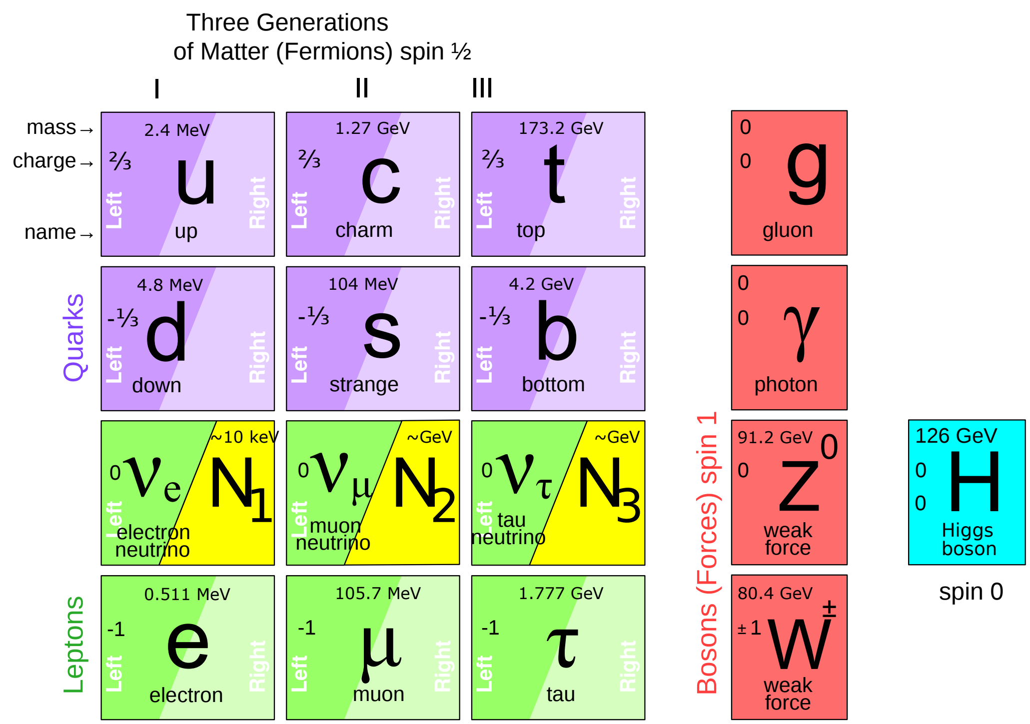
Neutrino Oscillations



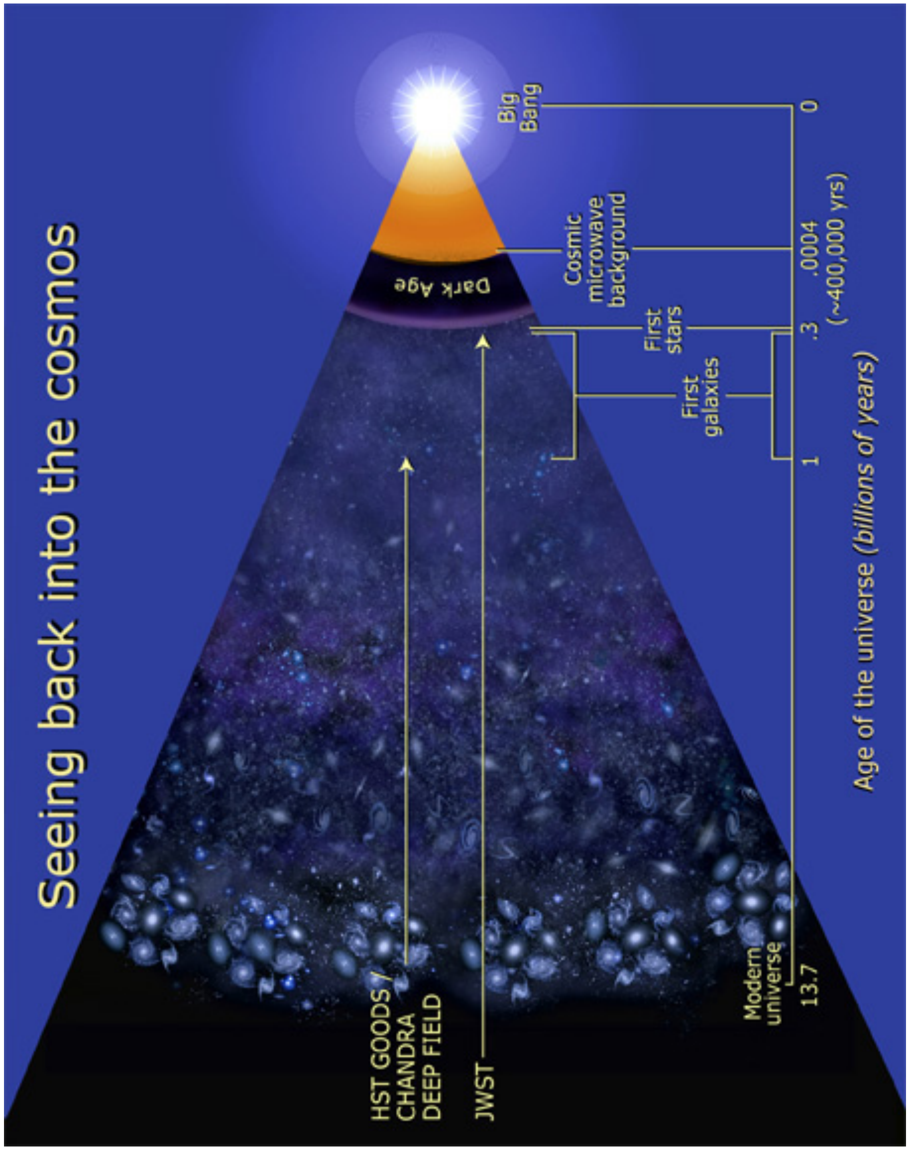
Neutrino Oscillations

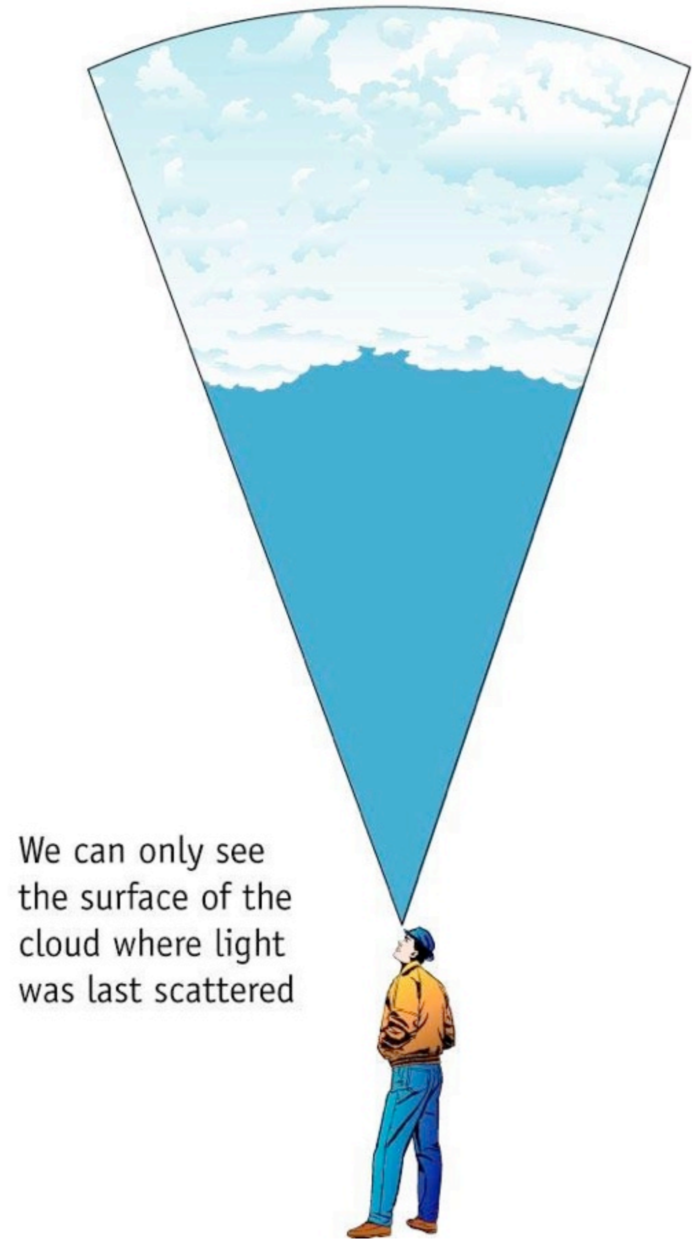
How to kill a vampire





Lookback Time





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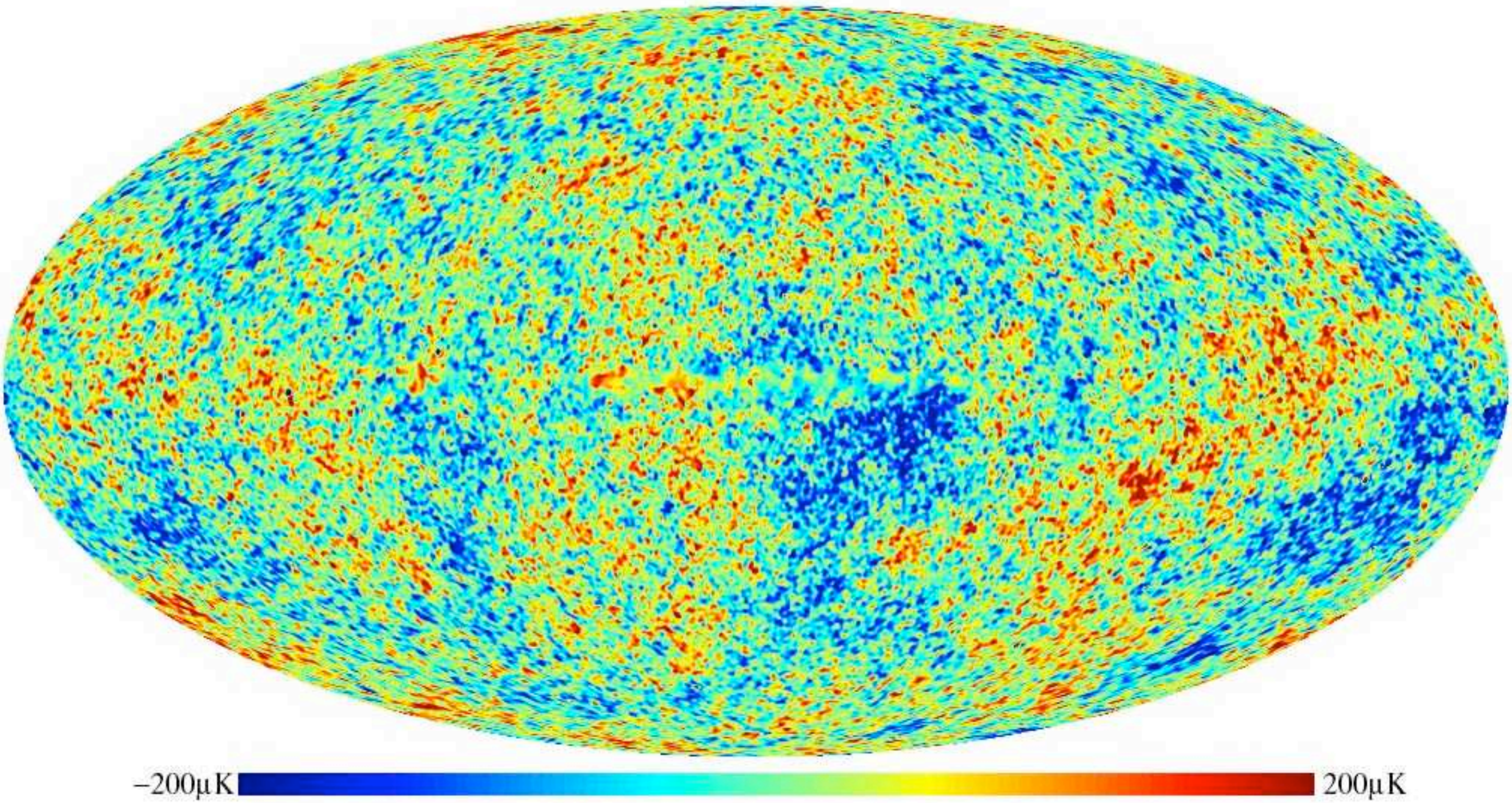

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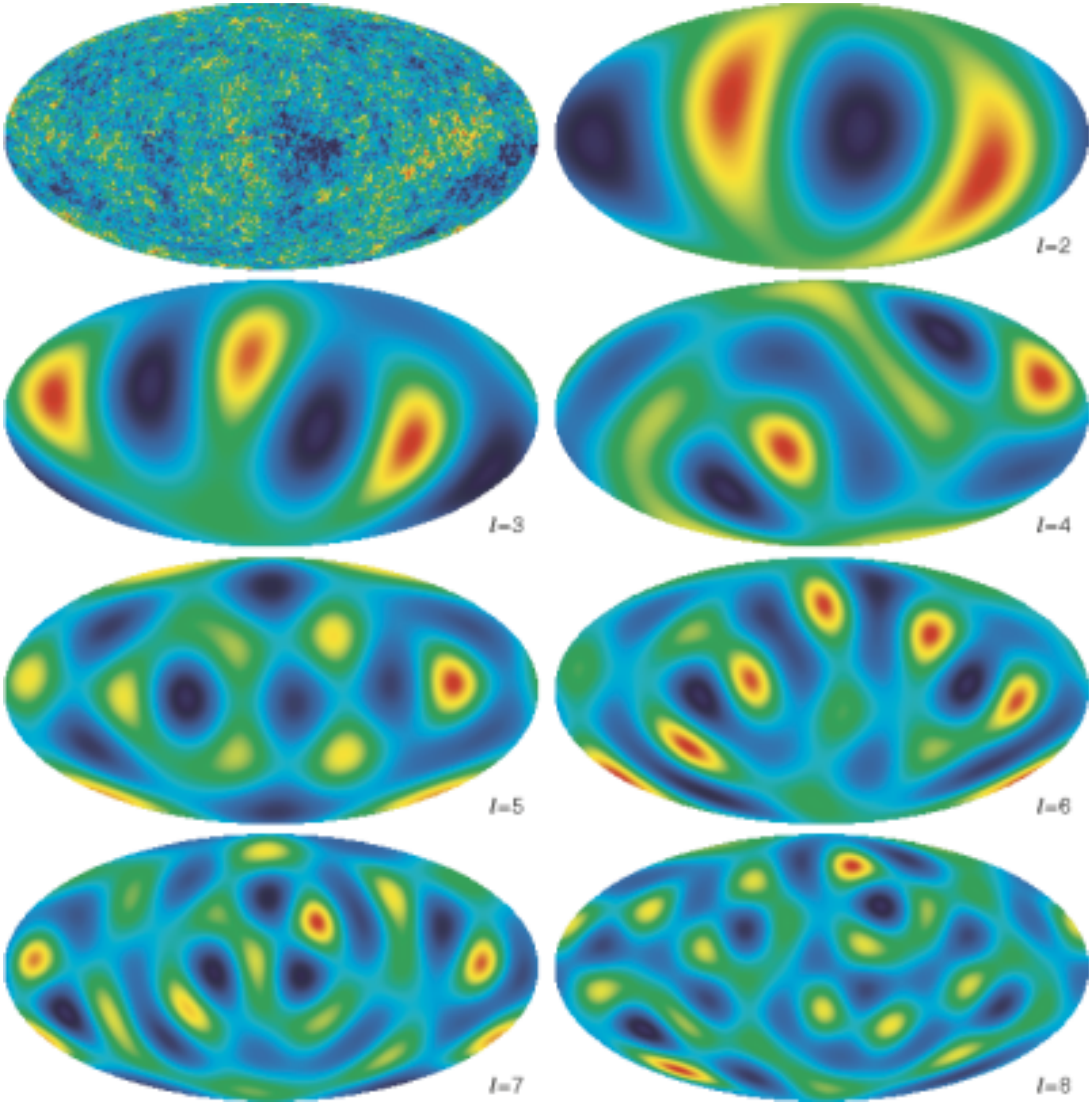
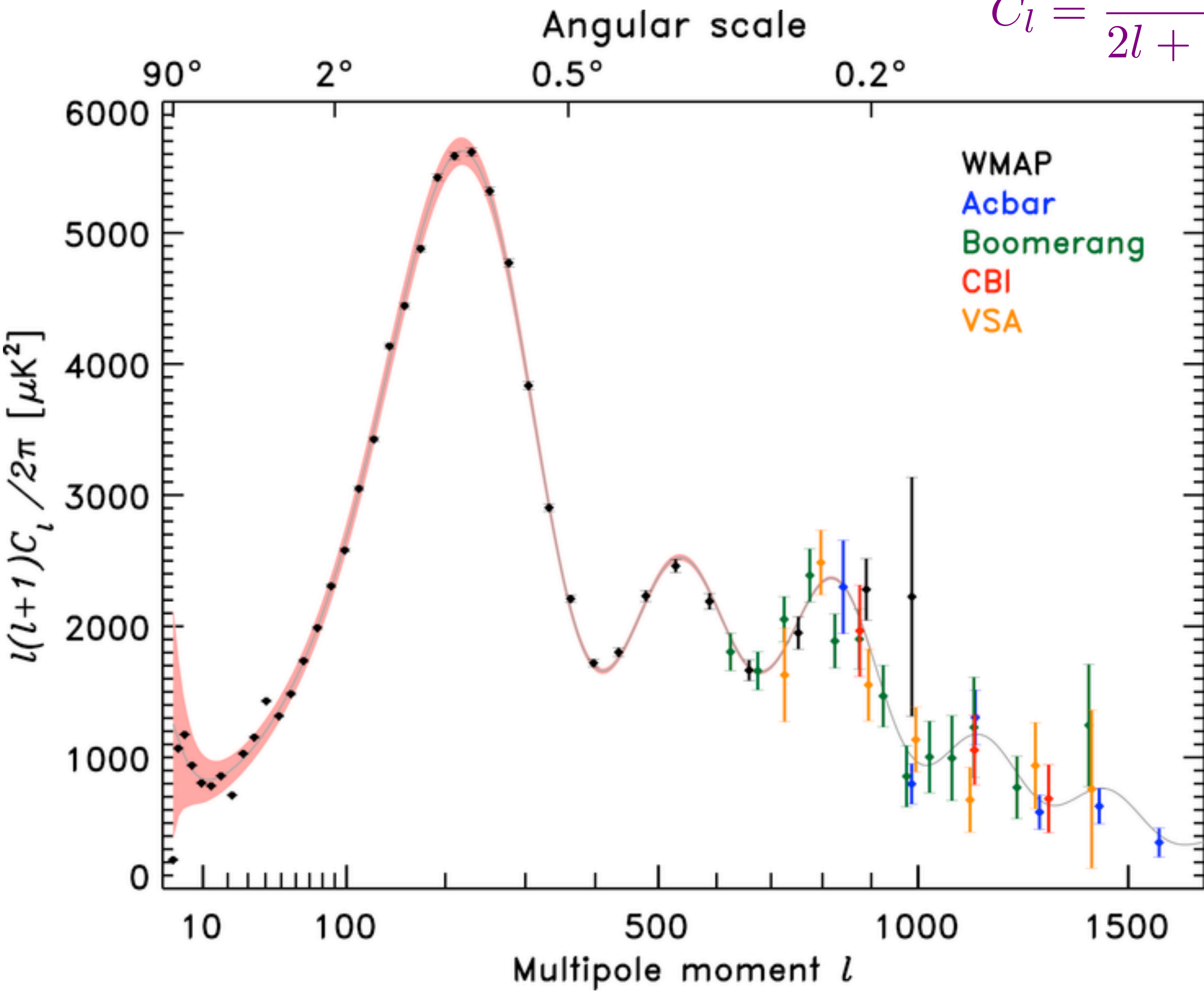


$$\Delta T(\hat{n}) = \sum_{l>0} \sum_{m=-l}^{l} a_{lm} \, Y_{lm}(\hat{n})$$

$$a_{lm} = \int \mathrm{d}\Omega_{\hat{n}} \, \Delta T(\hat{n}) \, Y^*_{lm}(\hat{n})$$

Lookback Time

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2$$



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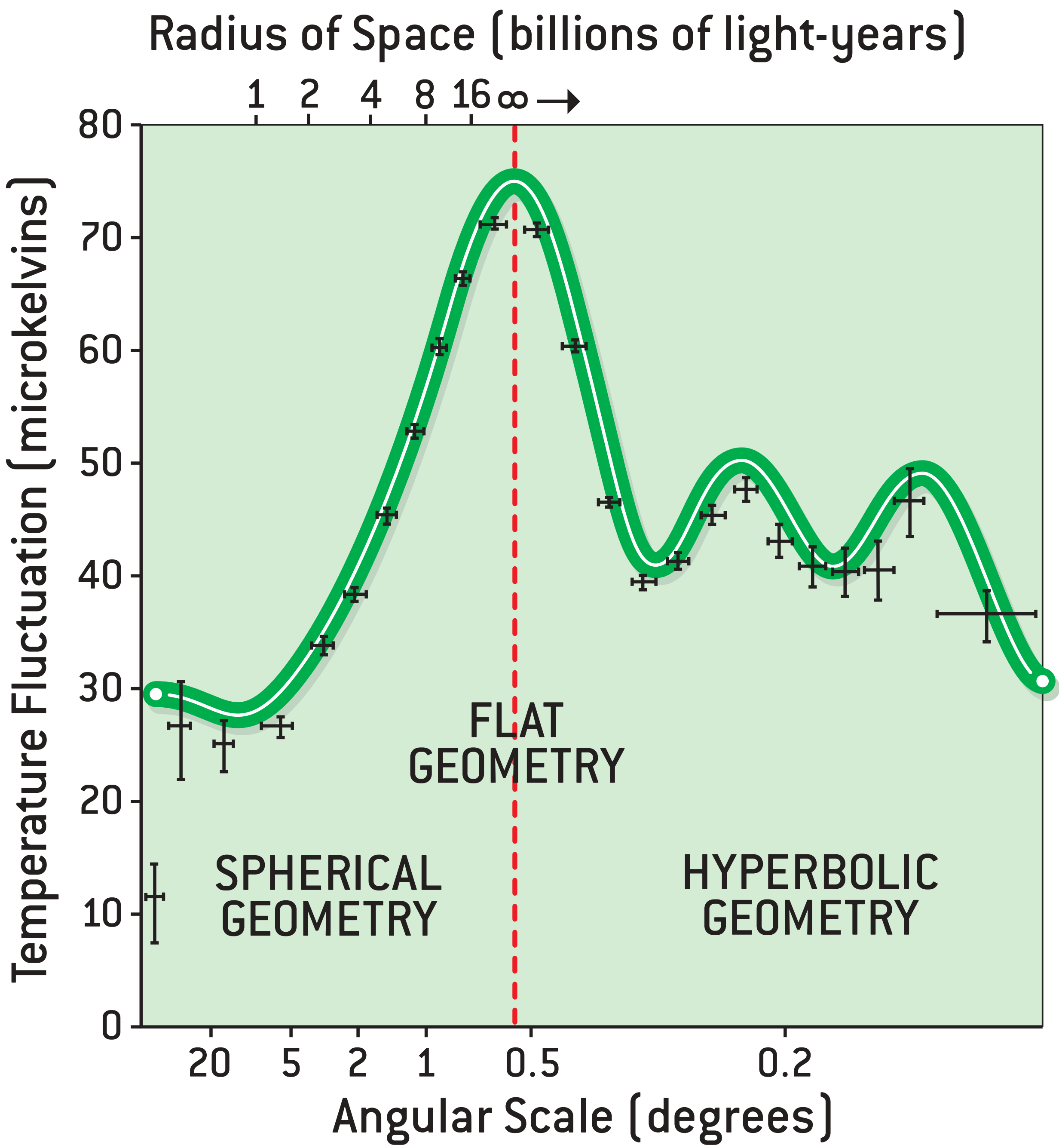
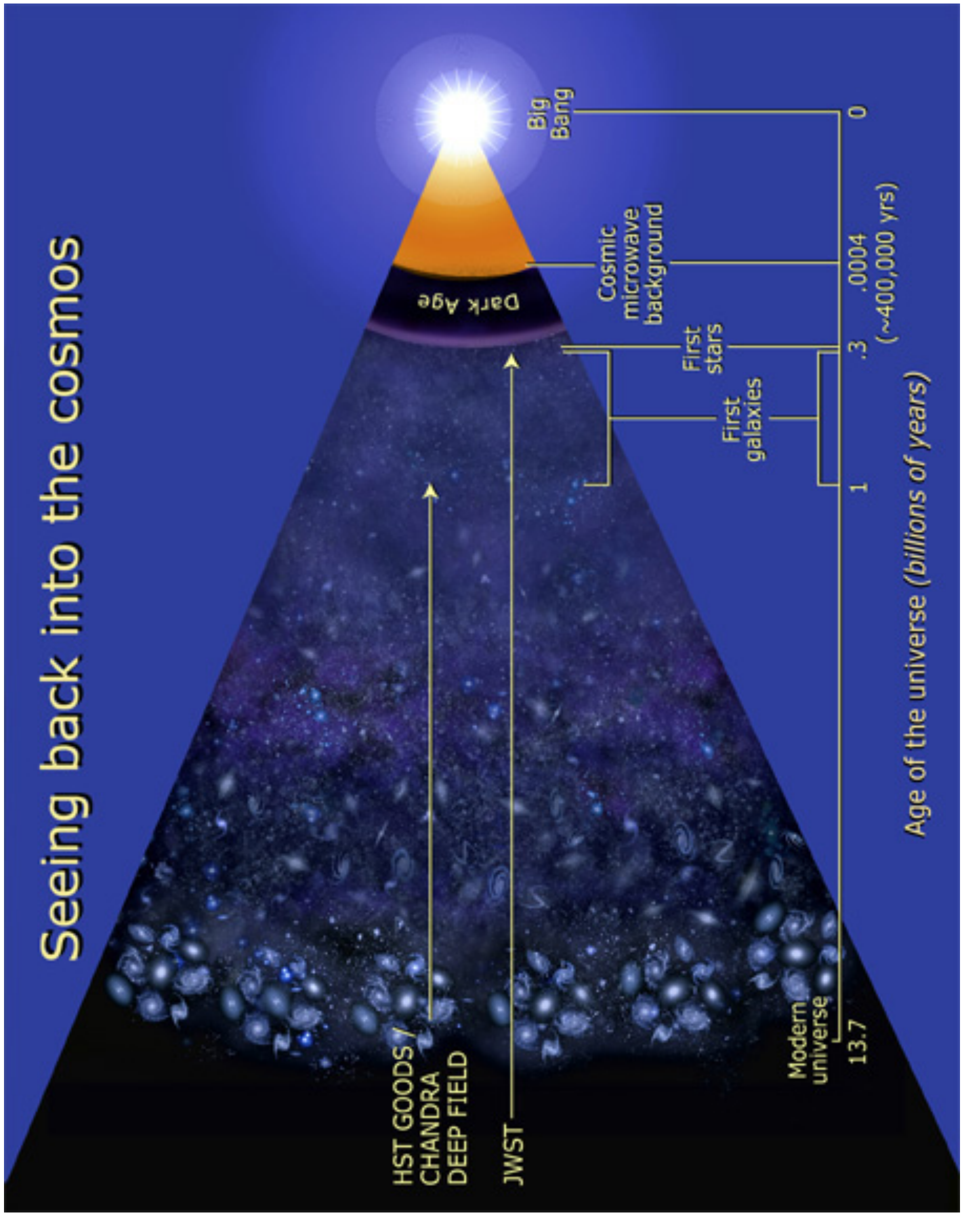
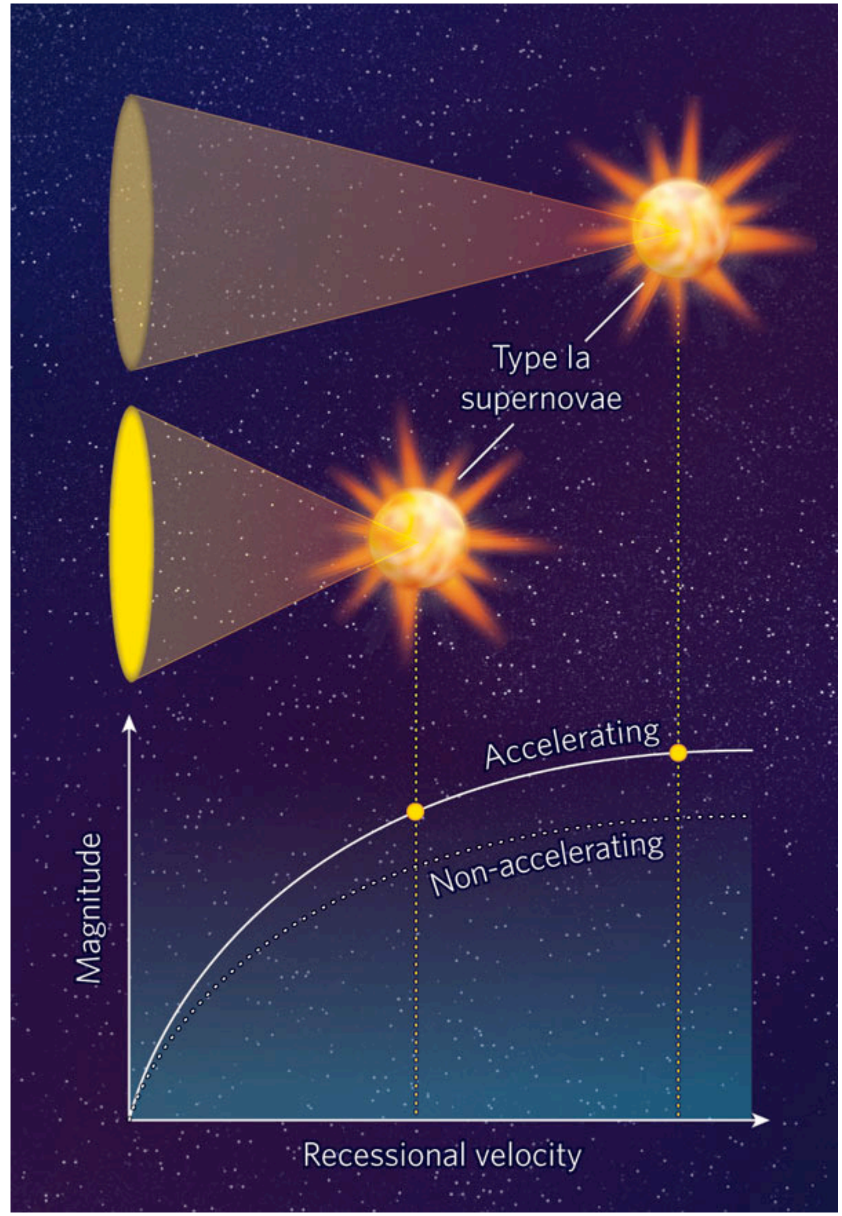
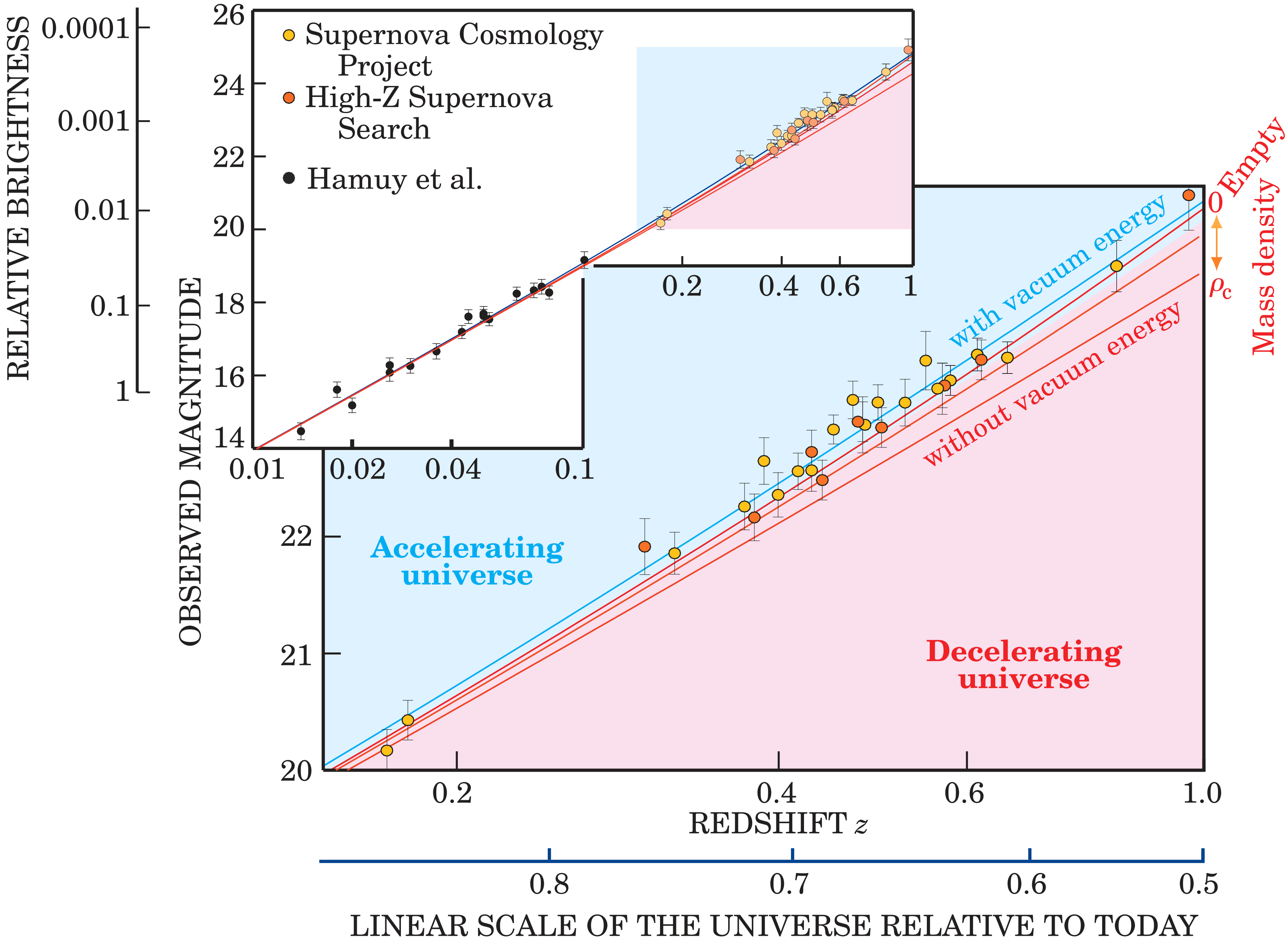


Lookback Time

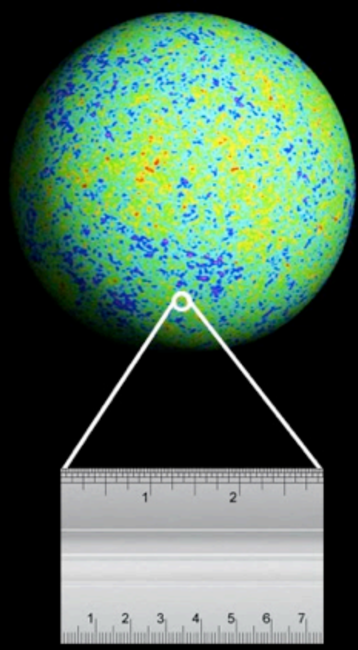


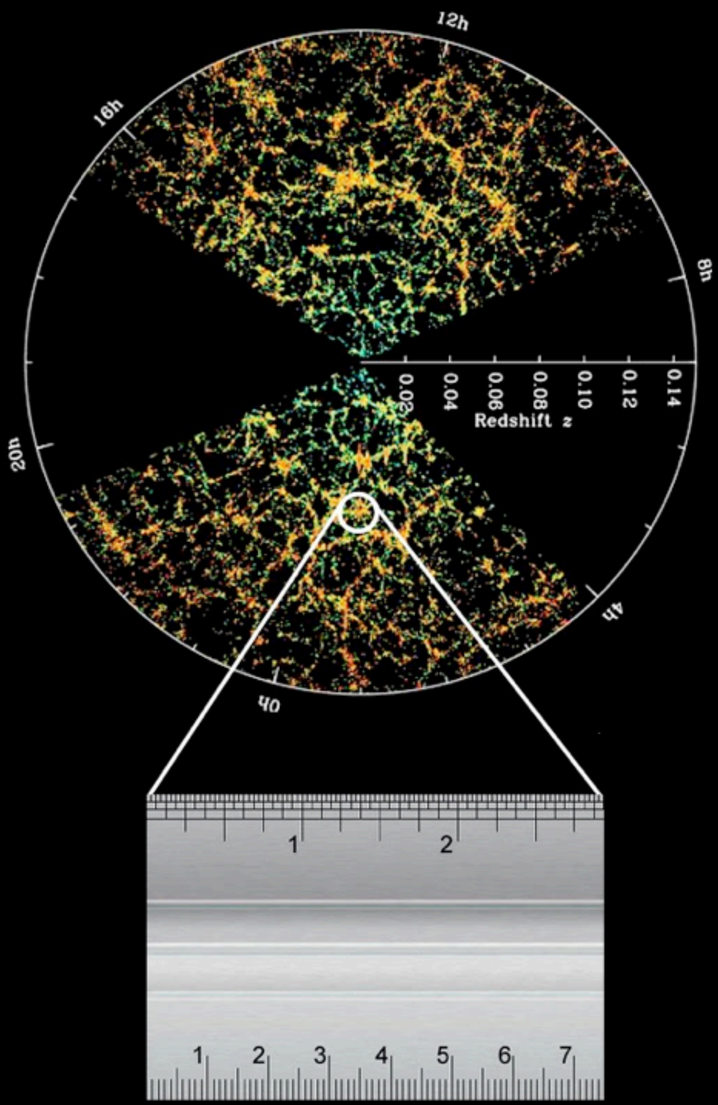


Lookback Time



Lookback Time

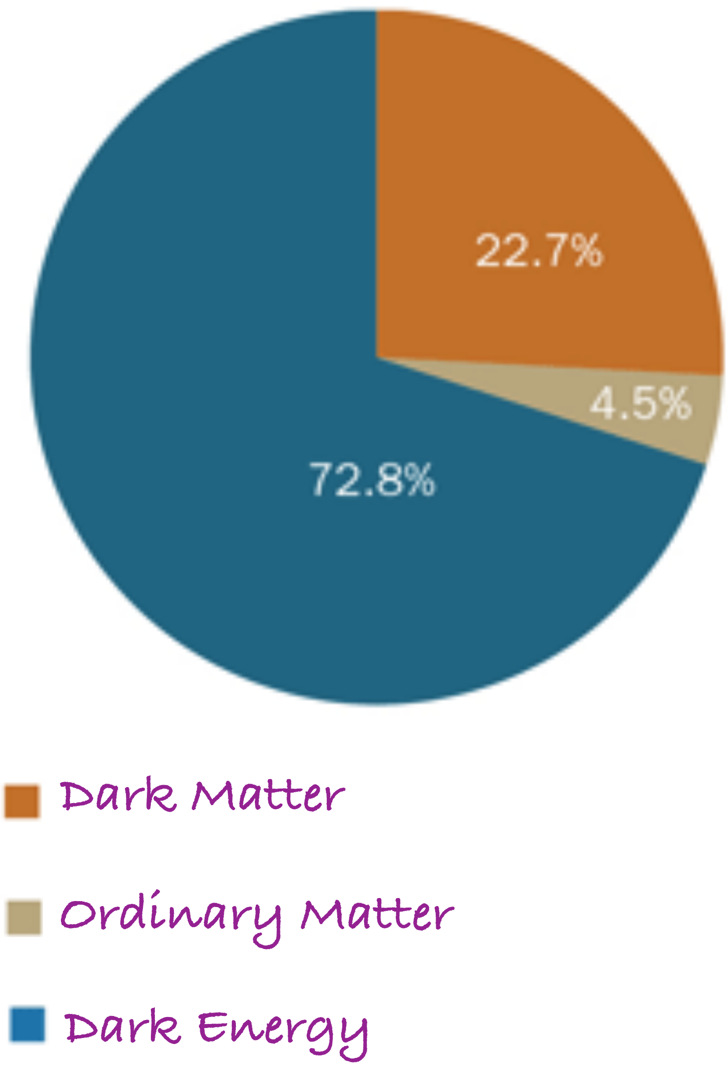


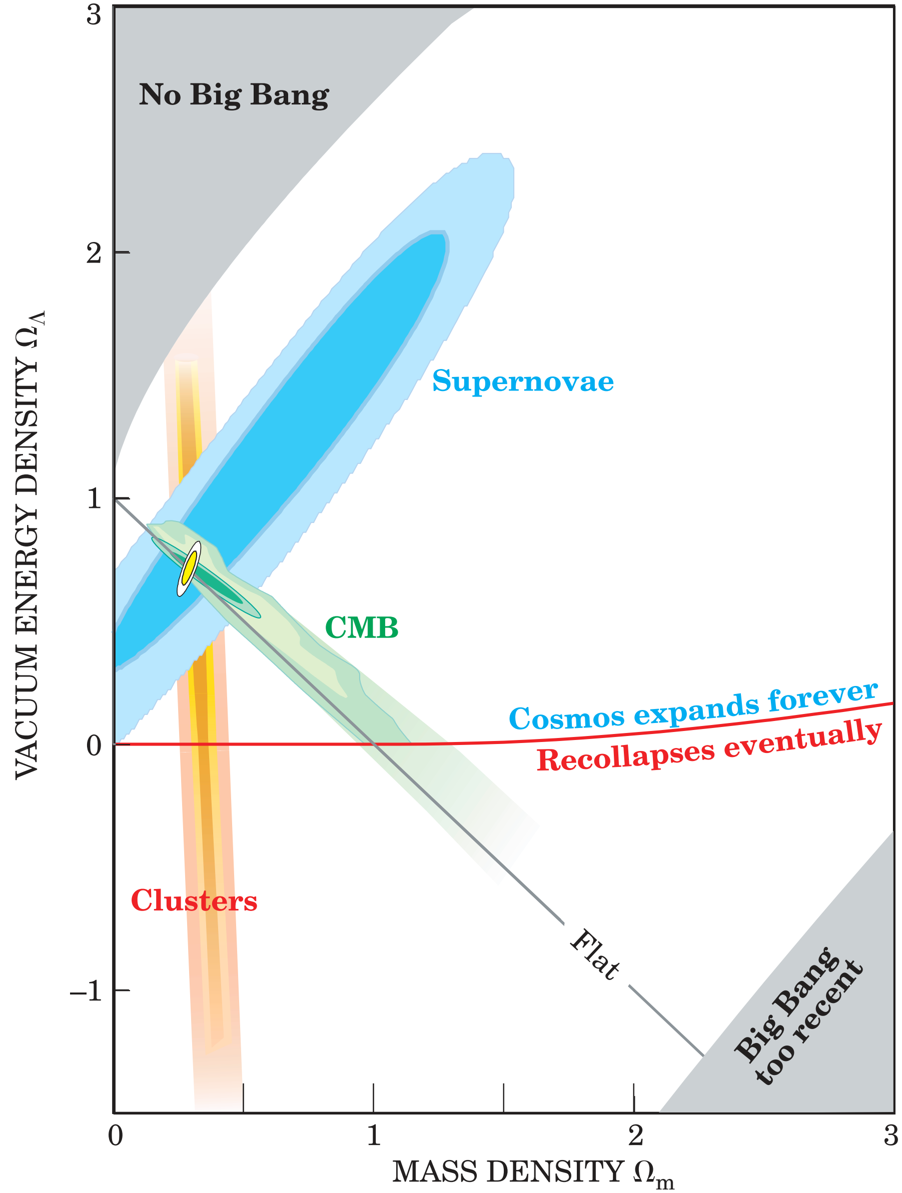


Scale of variations in CMB & in large-scale structure provide ruler to measure Universe's expansion history

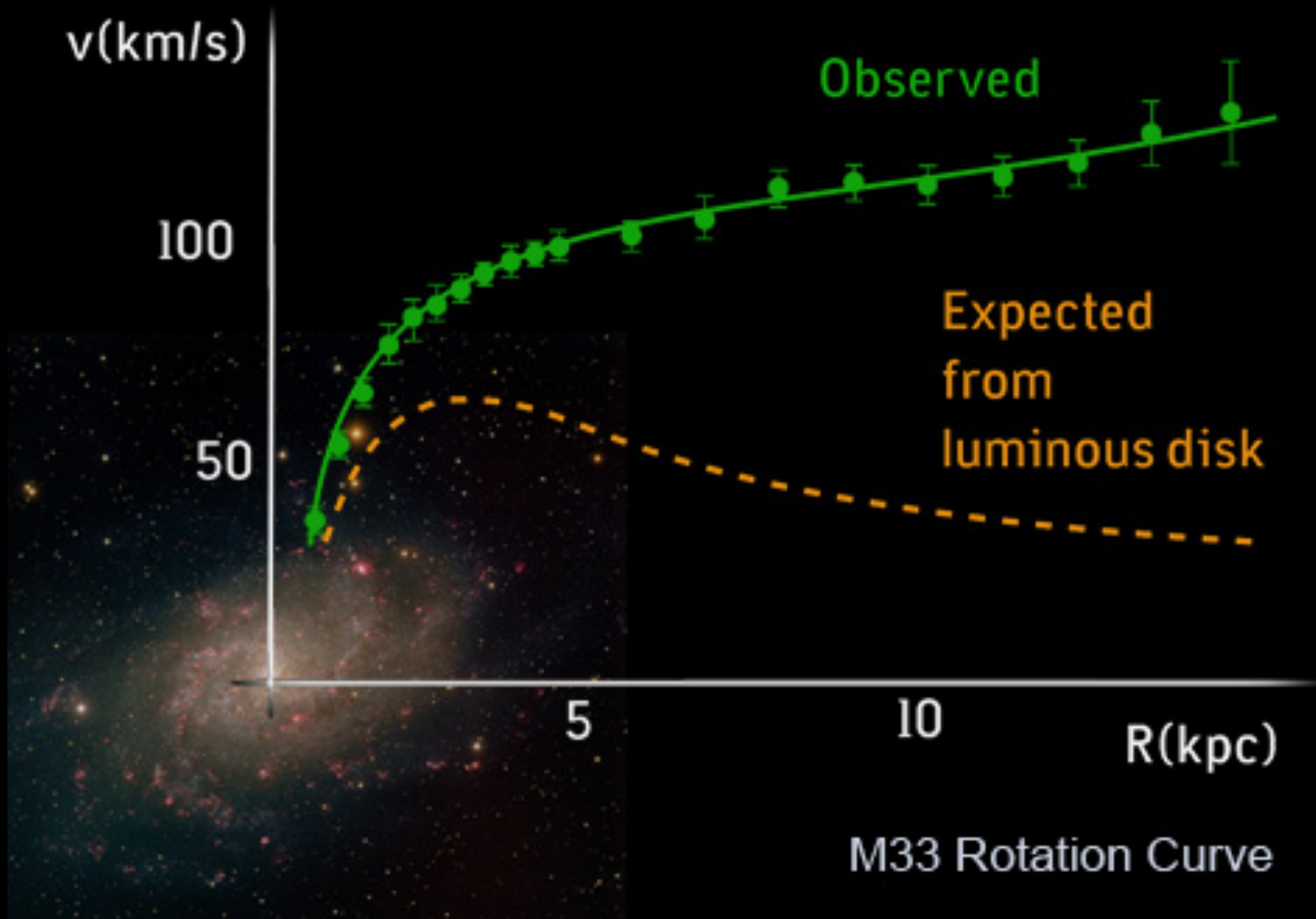
Estimated Composition of the Universe

Supernova Cosmology Project
Supernova Search Team
Hubble Space Telescope
Wilkinson Microwave Anisotropy Probe (WMAP)
Sloan Digital Sky Survey (SDSS)
... have weight the universe





Rotational Velocities of Stars in Spiral Galaxies

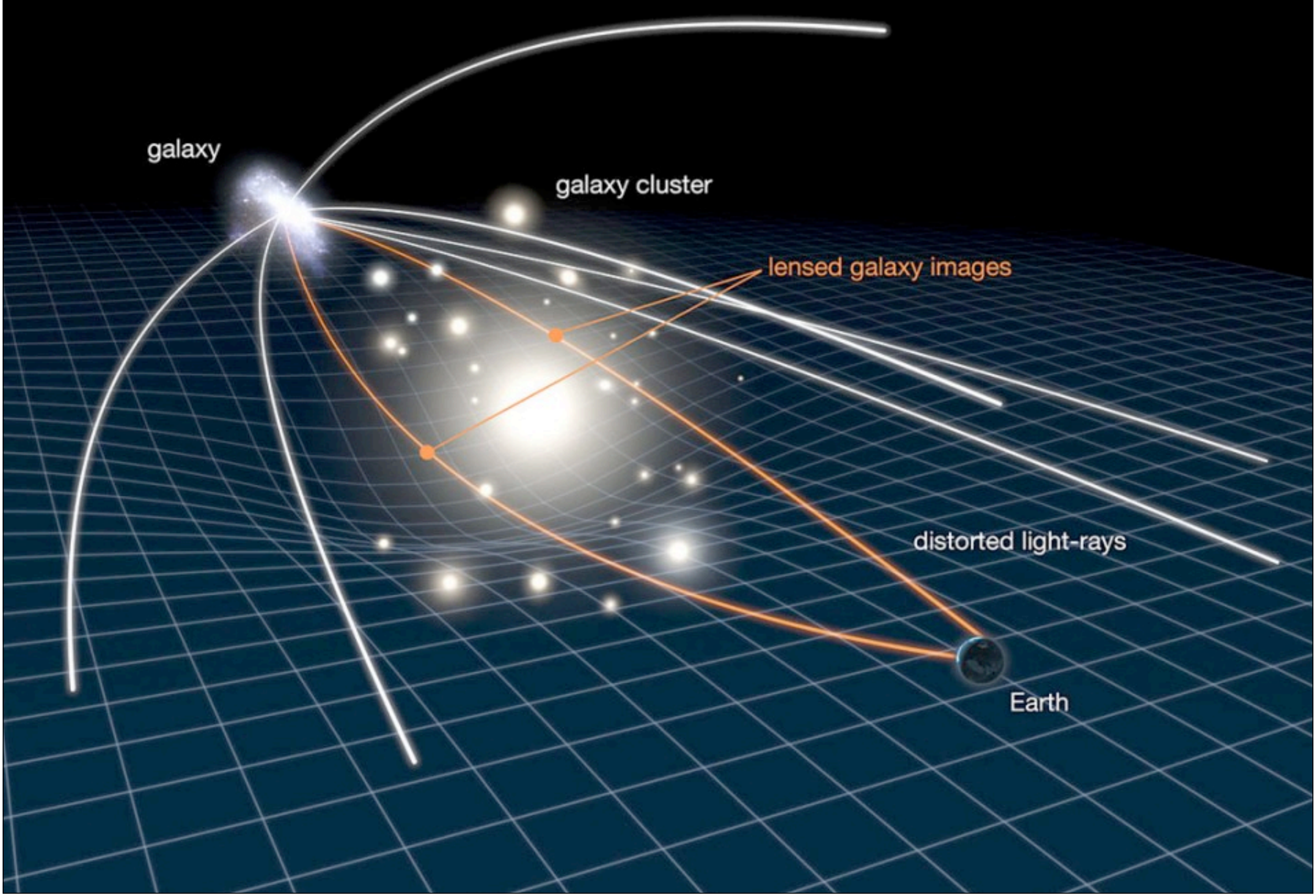


Stars and gas in the disk move in circular orbits

Gravitational field provides inward acceleration

Newtonian approximation ☛ $v^2(R) = G\,M(R)/R$

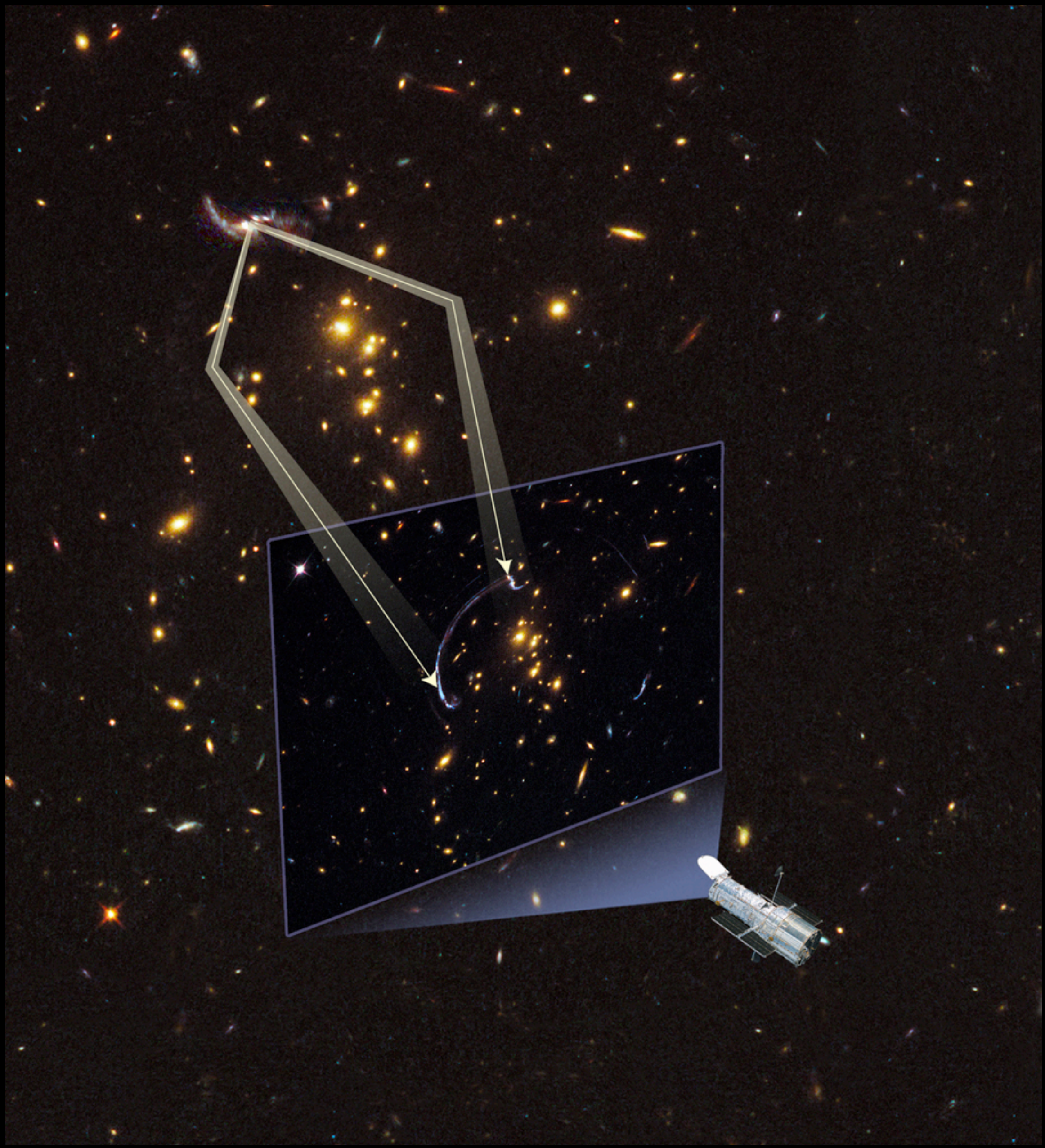
Gravitational Lensing



Gravitational Lensing

RCS2 032727-132623

Gravitational Lensing



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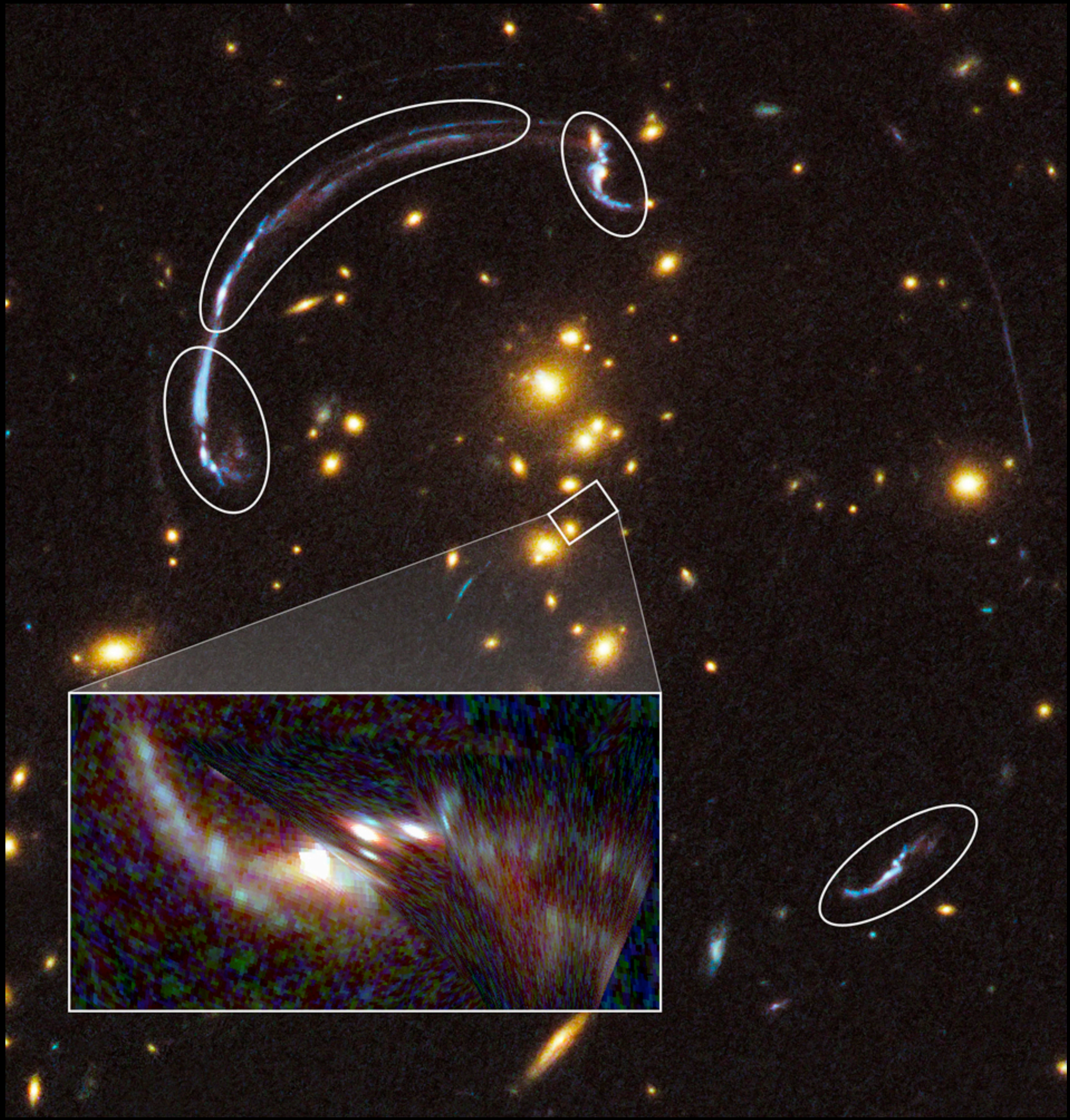
Gravitational Lensing



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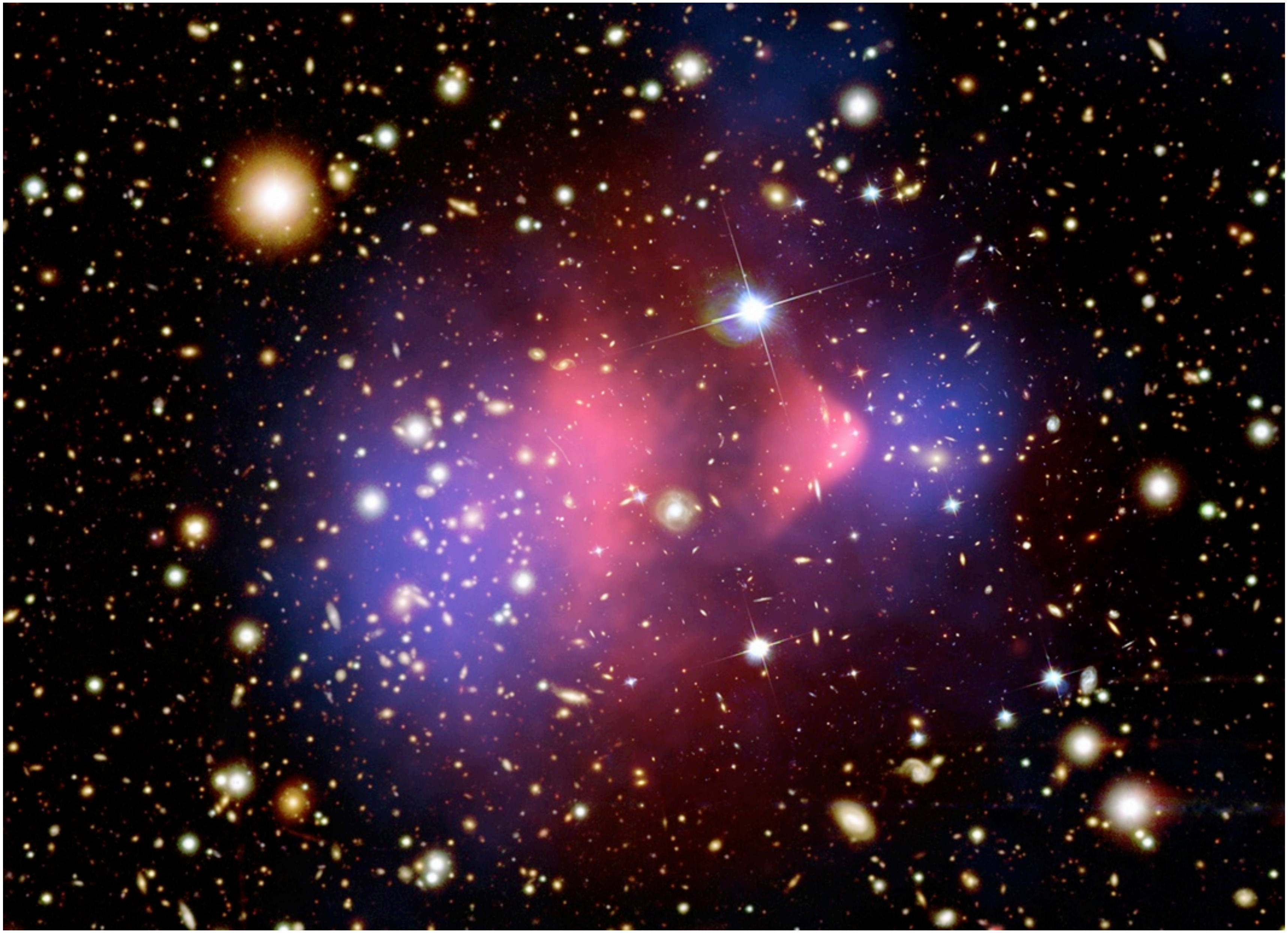
Bullet Cluster



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Bullet Cluster

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Bullet Cluster

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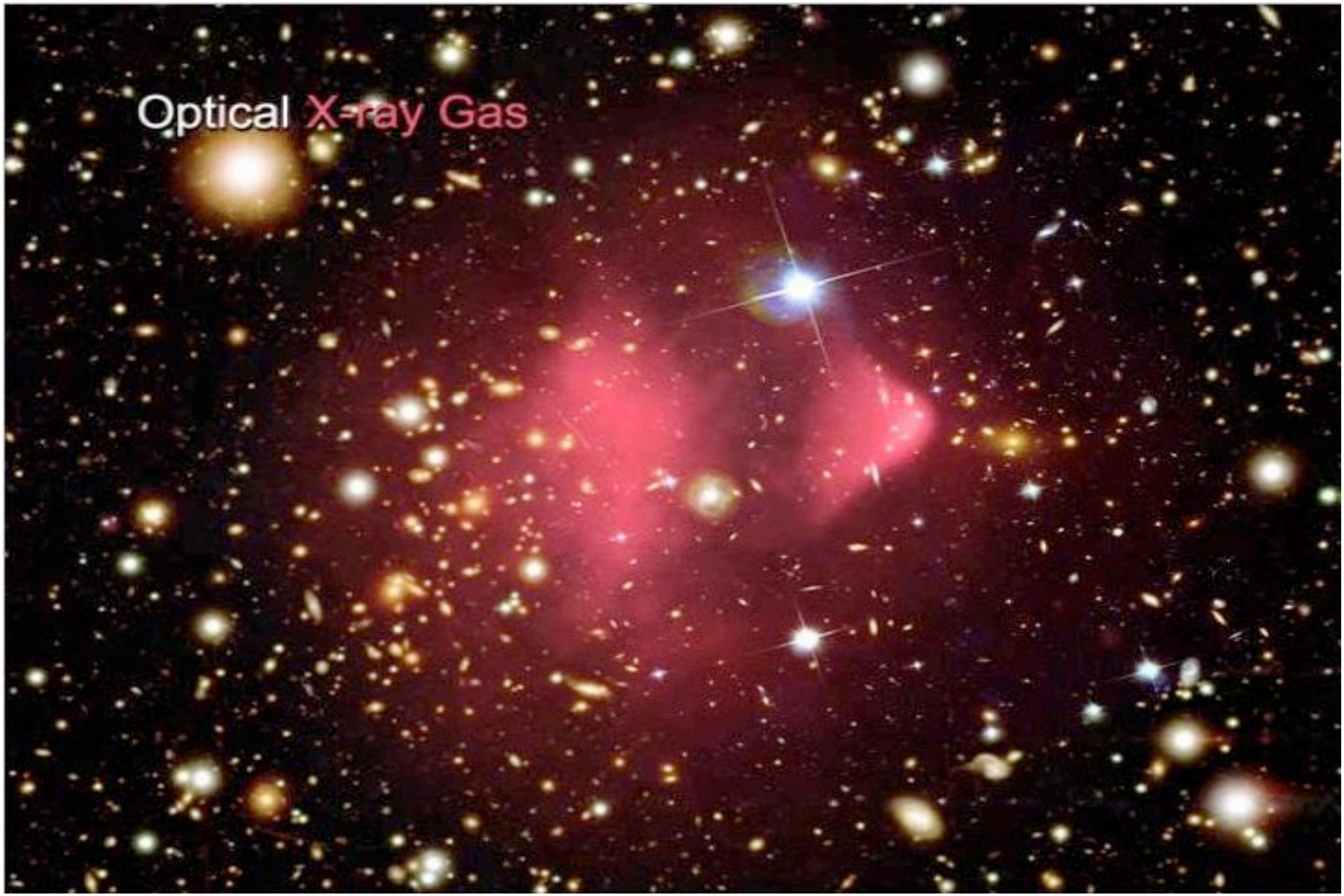
Bullet Cluster



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Bullet Cluster

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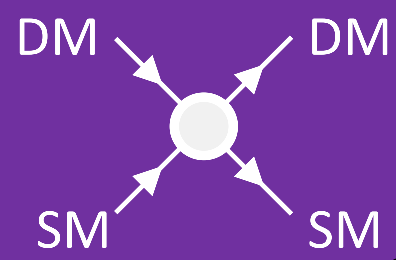
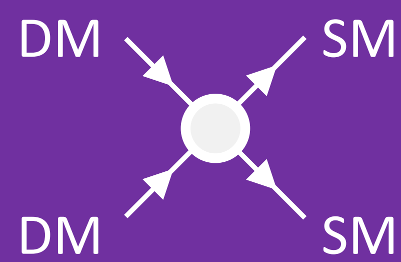
Dark Matter Search Strategies

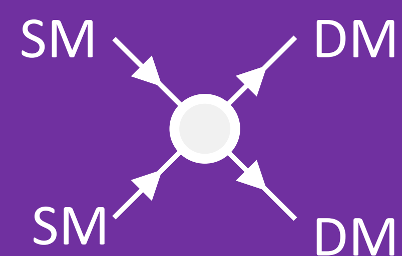
Direct Detection



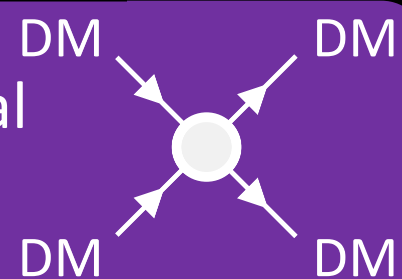
Indirect Detection



Particle Colliders



Astrophysical Probes



The Cosmological Constant Problem

The concordance model of cosmology
with dark energy, DM, baryons, and three flavors of light neutrinos
provides a consistent description of BBN (~ 20 minutes)
the CMB (~ 380 Kyr)
and the galaxy formation epochs of the universe (> 1 Gyr)

$$\Lambda \sim 0.7\,\rho_c \sim 0.7\,\frac{3H_0^2}{8\pi G_N} \sim 10^{-47}\ \mathrm{GeV}^4$$

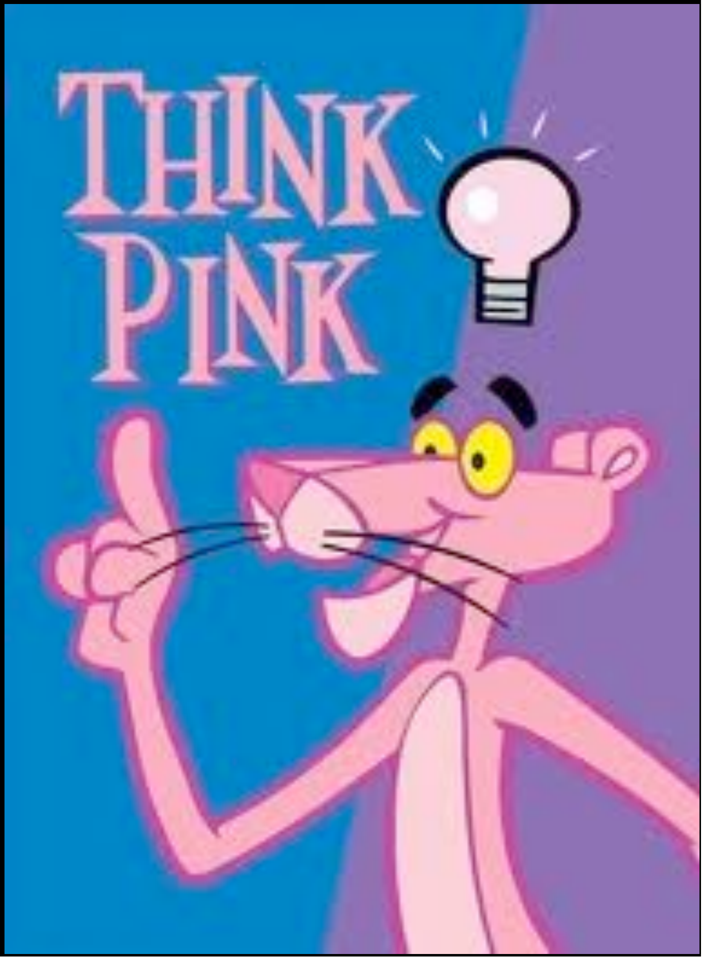
However

if universe is described by effective local QFT down to Planck scale
then the natural value is $\Lambda \sim \mathcal{O}(M_{\rm Pl}^4)$

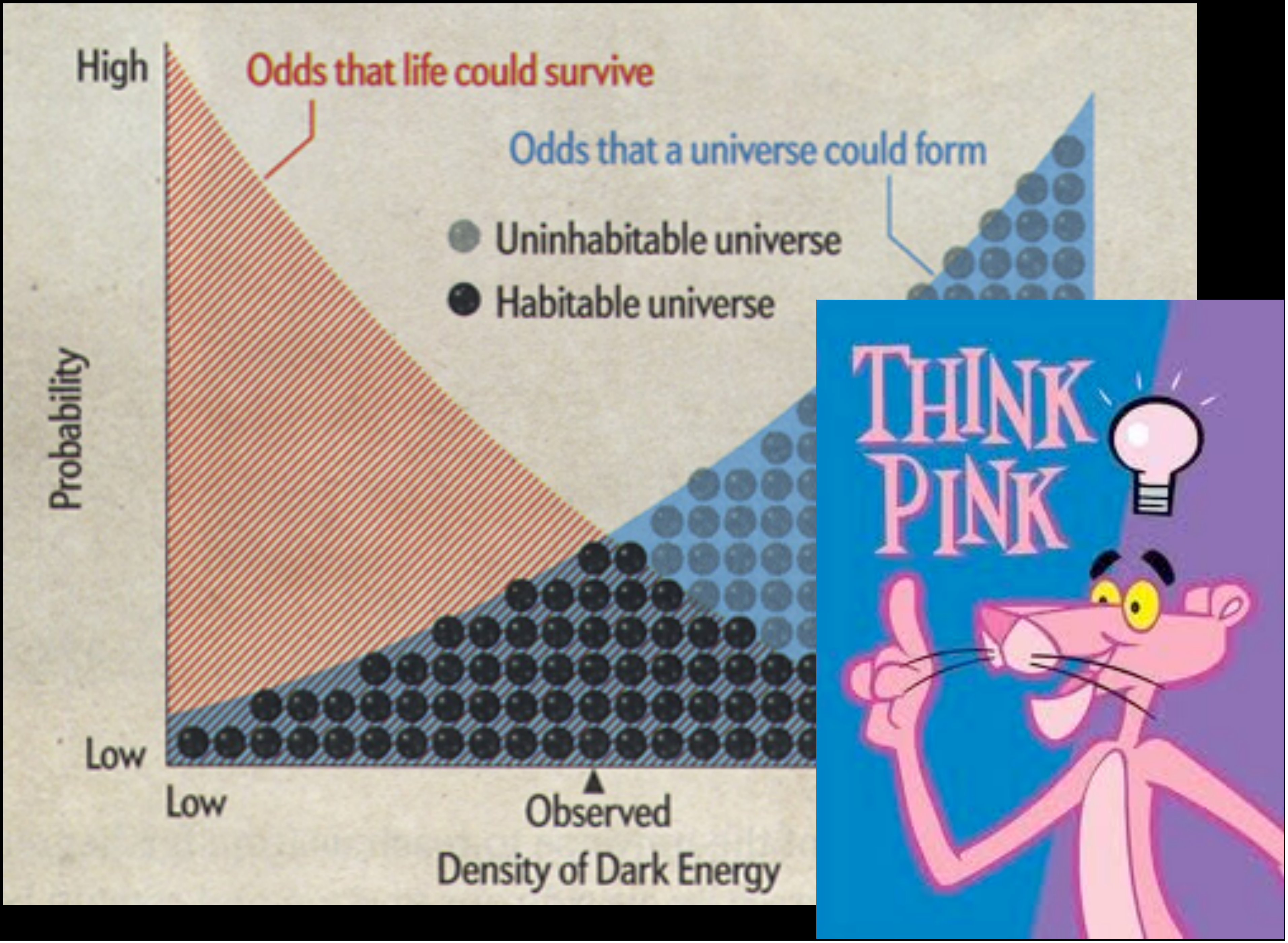
In terms of Planck units and as a natural dimensionless quantity

$$\Lambda \sim \mathcal{O}(10^{-122})$$

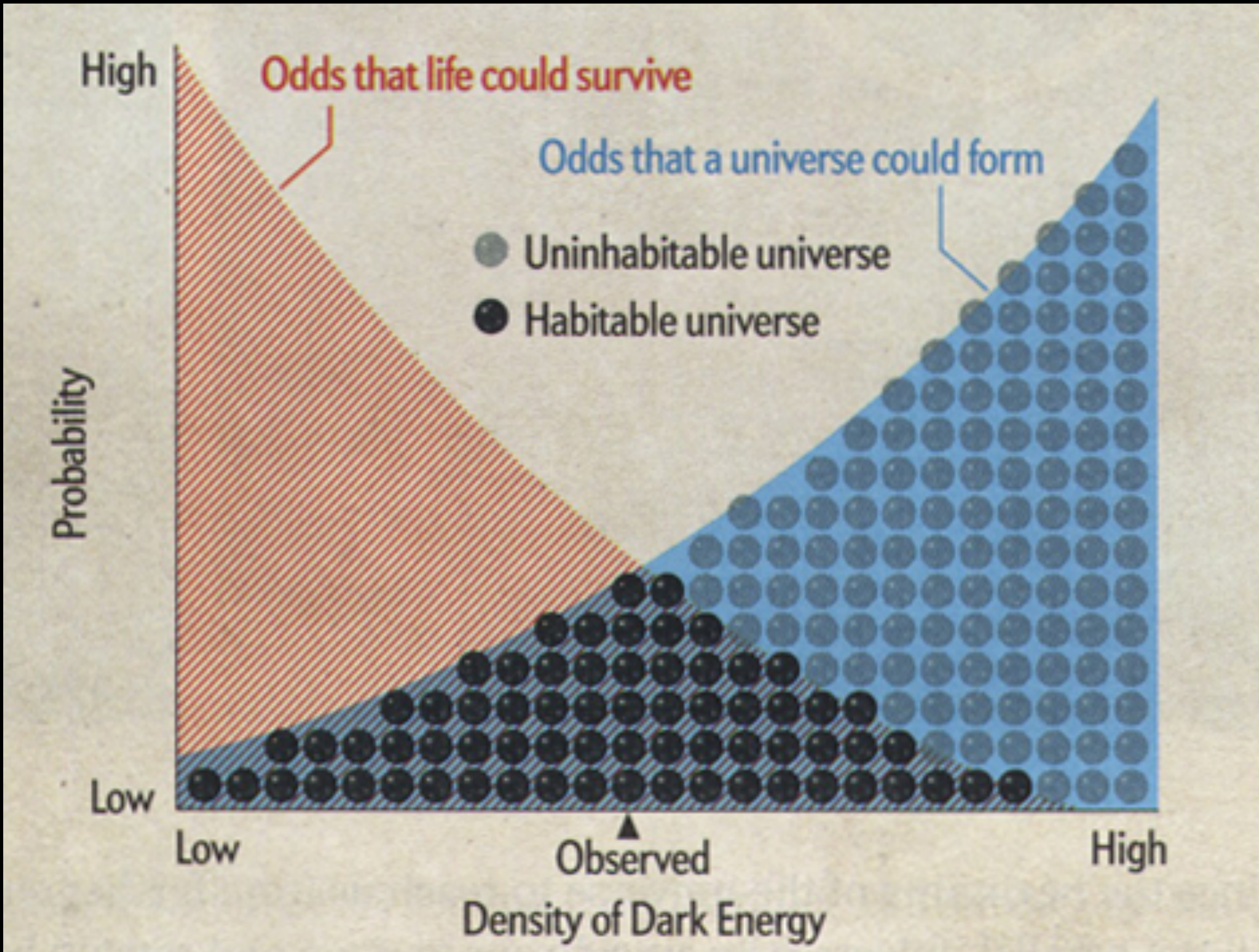
Across the Multiverse

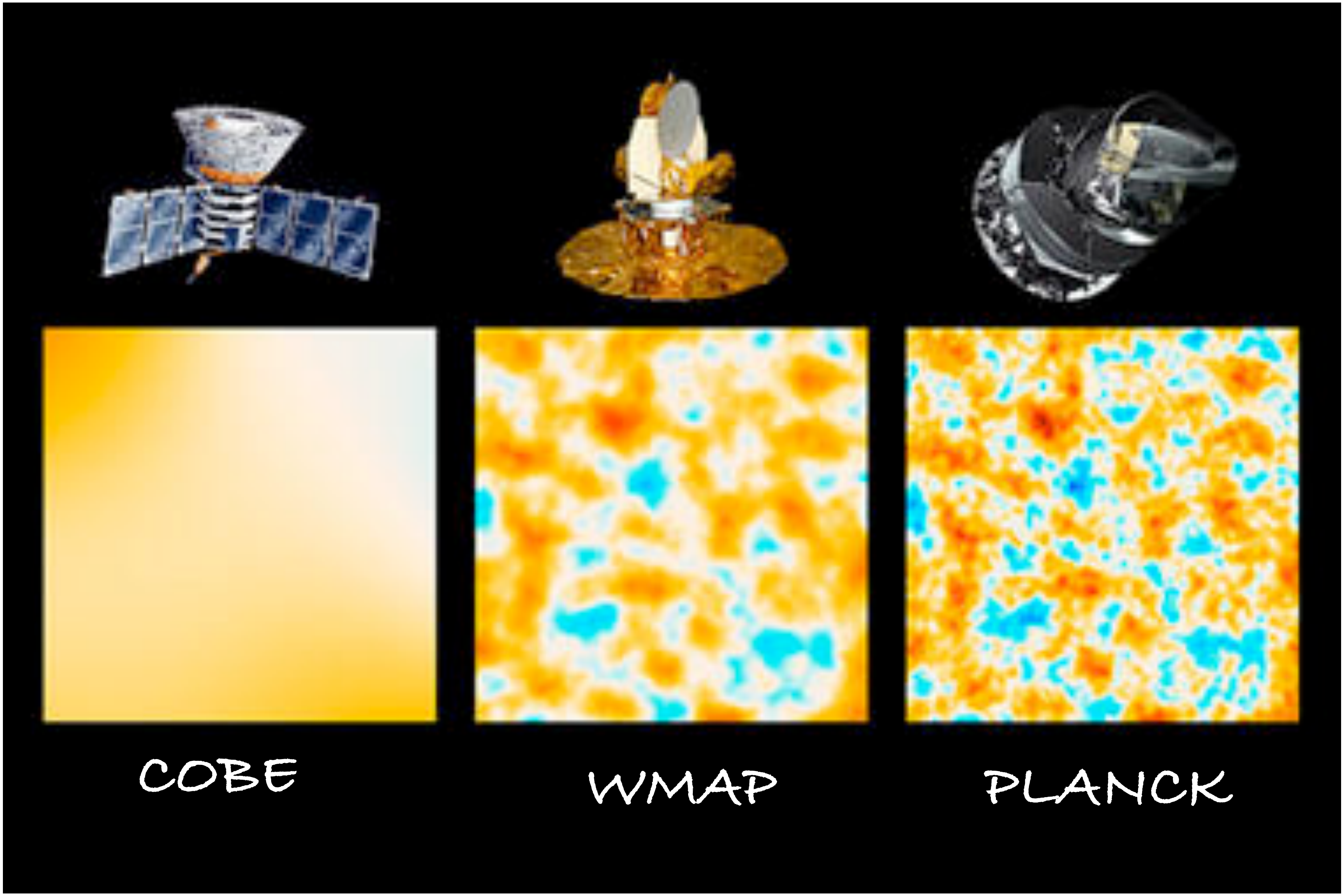


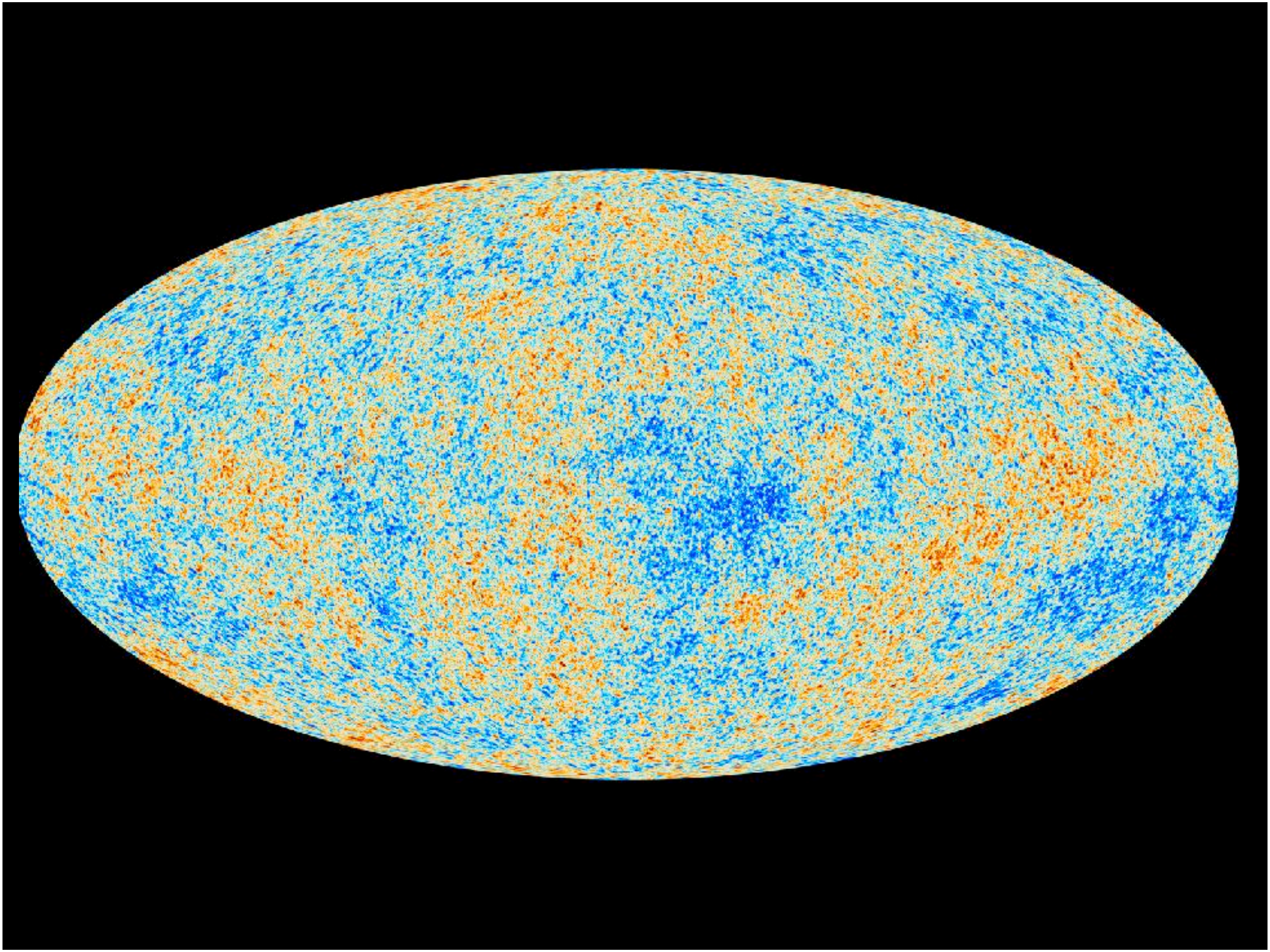
Across the Multiverse



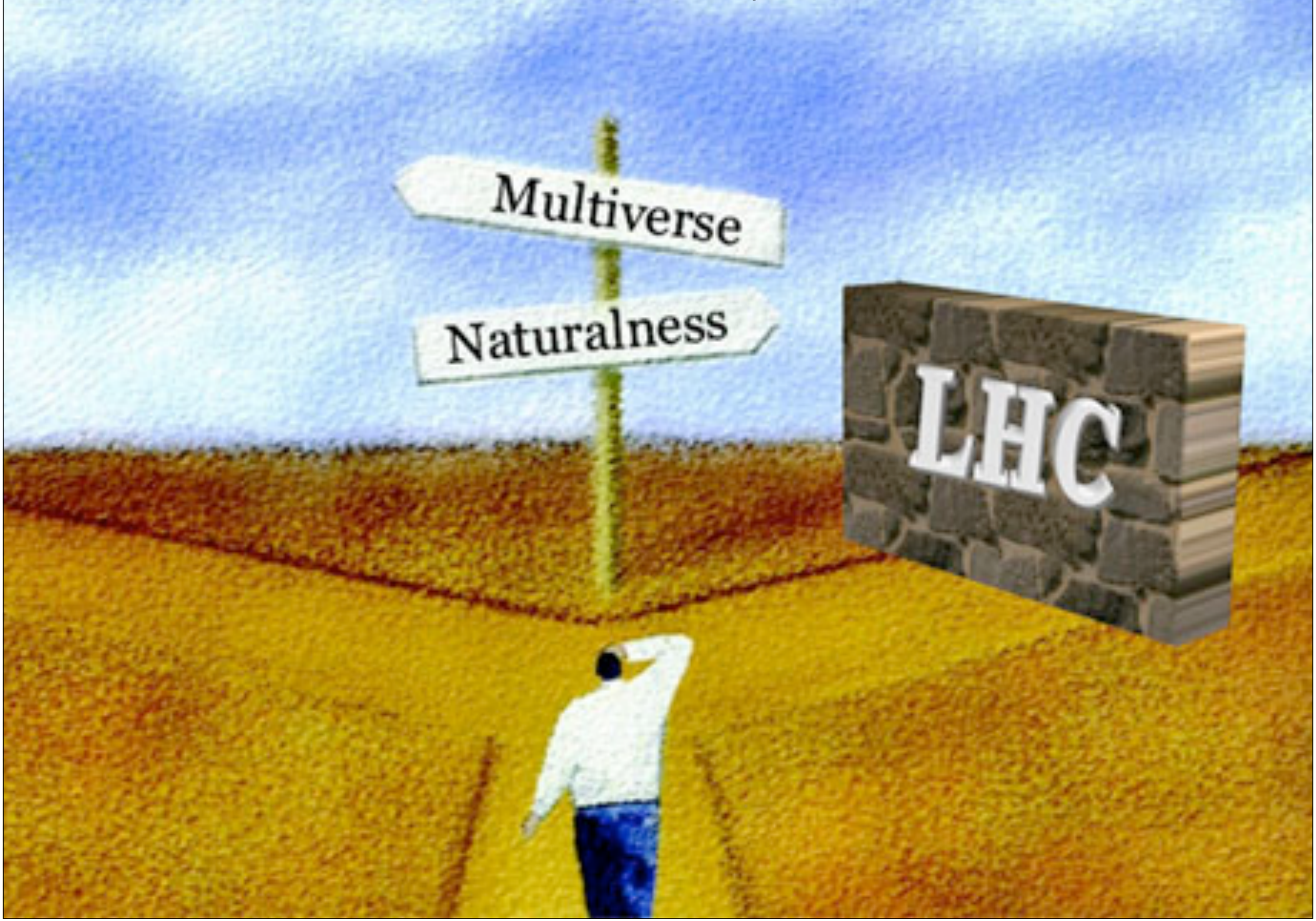
Across the Multiverse



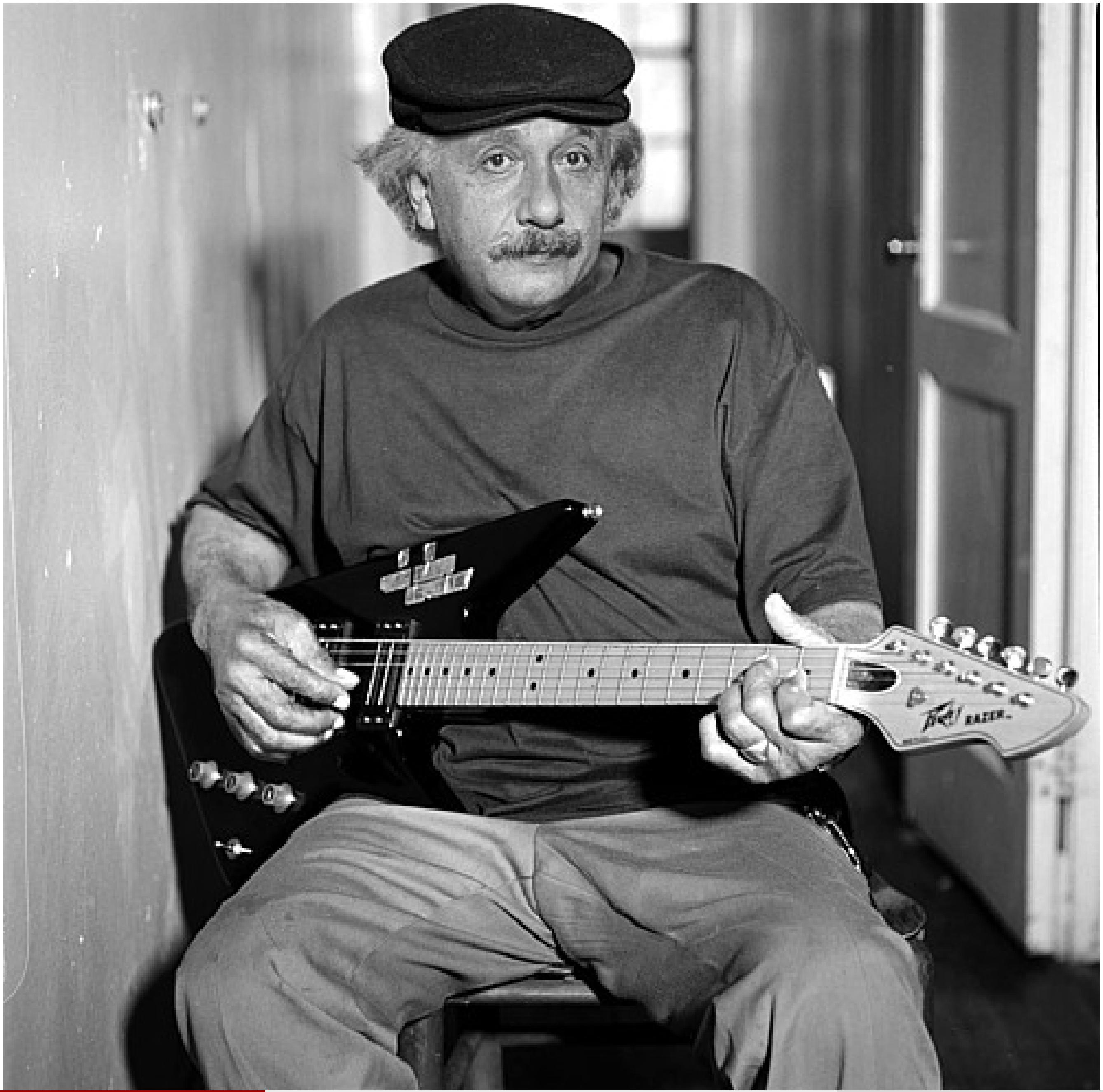

COBE
WMAP
PLANCK



Summary



Good luck on the final...




That's all Folks!