

THE PHYSICAL SCIENCES

MOST OF THE EXAMPLES I HAVE GIVEN ARE FROM PHYSICS — THAT'S WHAT THIS COURSE IS ABOUT.

DEMARCATIION BETWEEN PHYSICAL SCIENCE

AND OTHER SCIENCES IS NOT OBVIOUS

ARE OTHER SCIENCES JUST PHYSICS?

CAN DIVIDE SCIENCES BY DISTANCE
SCALE

← COMPLEXITY →

FIELDS ARRANGED BY PURITY

← MORE PURE →

REAL WORLD

SOCIOLOGY IS JUST APPLIED PSYCHOLOGY

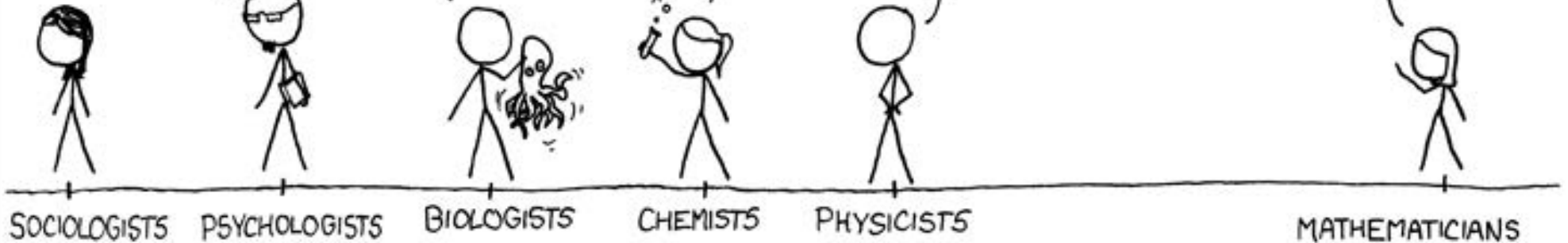
PSYCHOLOGY IS JUST APPLIED BIOLOGY.

BIOLOGY IS JUST APPLIED CHEMISTRY

WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.

???

OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.



THE HUMAN BRAIN → MOST COMPLEX SYSTEM WE KNOW OF

CONSCIOUSNESS

ZOOLOGY — DOESN'T DEPEND ON QUARKS
AND LEPTONS. SURELY DOES
DEPEND ON CHEMISTRY — QUANTUM

MECHANICS
WHAT IS LIFE? → — STABILITY
SCHRÖDINGER 1944 OF DNA

GEOLOGY
G EOPHYSICS
ATMOSPHERIC
PHYSICS

CLASSICAL MECHANICS
PHYSICS OF CONTINUOUS MEDIA
THERMODYNAMICS

↳ · NO DEPENDENCE ON
ATOMIC NATURE

· QUANTUM MECHANICS

CHEMISTRY

— MODERN CHEMISTRY IS
ESSENTIALLY NON-RELATIVISTIC
QUANTUM MECHANICS

— DEPENDS ON PERIODIC TABLE
→ NUCLEI
→ QUANTUM MECHANICS

CONDENSED MATTER

→ QUANTUM MECHANIC

QUANTUM OPTICS

ALL OF THESE SCIENCES "DISCONNECTED"
FROM ULTIMATE DISTANCE SCALE

→ QUARKS & LEPTONS

COSMOLOGY

ASTRONOMY

ELEMENTARY
PARTICLE
PHYSICS

ADVENT OF BIG BANG
COSMOLOGY — UNIVERSE
WAS ONCE VERY SMALL

— LARGE SCALE STRUCTURE
OF THE UNIVERSE
DEPENDS ON BIG BANG

— PARTICLE PHYSICS

AT EACH OF THESE DISTANCE SCALES
PHYSICS PROVIDES THE UNDERPINNING
OF OUR UNDERSTANDING.

AT NO DISTANCE SCALE DO WE SEE
PHENOMENA REQUIRING SOMETHING } OUTSIDE
PHYSICS

PHYSICAL SCIENCE — UNDERPINS TECHNOLOGY

MOST MEDIA CONFUSE

SCIENCE ↔ TECHNOLOGY

UNDERSTANDABLE

SCIENCE → TECHNOLOGY → EVERYDAY LIFE

CLASSICAL MECHANICS

FLUID MECHANICS

CONTINUOUS MEDIA

BRIDGES

AIRCRAFT

AUTOMOBILES

QUANTUM MECHANICS

ELECTRO MAGNETISM

CONDENSED MATTER

CHEMISTRY

PHARMACEUTICALS

HEALTH

CONSUMER ELECTRONICS

INFORMATICS

NUCLEAR PHYSICS

POWER GENERATION

HEALTH SCIENCE

WEAPONS

SCIENCE ↔ TECHNOLOGY

- IMPORTANT THAT SOCIETY / GOVERNMENT UNDERSTANDS THIS DISTINCTION
- SCIENCE PUBLICLY FUNDED
TENDANCY TO FUND APPLICATIONS

FUNDAMENTAL SCIENCE — BIG
COSTLY
LONG TERM
GOVERNMENTS MUST UNDERSTAND

FUNDAMENTAL SCIENCE ⇒ NEW PRINCIPLES ⇒ TECHNOLOGY

PHYSICS \Leftrightarrow EXPERIMENT

ETHICS \rightarrow MAJOR CONSTRAINT IN MANY SCIENCES

PHYSICS \rightarrow ONLY CONSTRAINTS ARE FINANCIAL AND TECHNOLOGICAL

LHC + EXPERIMENTS \sim \$15 BILLION

- CANNOT AFFORD TO GO MUCH BEYOND LHC IN ENERGY

- NO TECHNOLOGY TO INVESTIGATE PLANK SCALE

- CREATE A UNIVERSE IN THE LAB

GREENE CHAPTER #10

PHYSICS & PRECISION

OTHER SCIENCES DO NOT ASPIRE TO THE
EXTRAORDINARY AGREEMENT THEORY \leftrightarrow EXPERIMENT
SEEN IN PHYSICS

QUOTATION (DISPUTED) FROM LORD KELVIN ~ 1894?

THERE IS NOTHING NEW TO BE DISCOVERED
IN PHYSICS NOW. ALL THAT REMAINS IS MORE
& MORE PRECISE MEASUREMENT

— JUST BEFORE — RELATIVITY

QUANTUM MECHANICS
EXPANSION OF UNIVERSE

ATOMIC PHYSICS

NUCLEAR PHYSICS

PRECISION MEASUREMENTS SEARCH FOR NEW PHENOMENA

FRANKLIN GIVES HISTORICAL EXAMPLE:

DISCOVERY OF ARGON BY RAYLEIGH

TWO WAYS OF MAKING NITROGEN

- 1) FROM AIR - REMOVE OXYGEN ETC.
- 2) DECOMPOSE AMMONIA

→ PRECISE DENSITY MEASUREMENT
SHOWED 1 PART IN 10^3 DISCREPANCY

→ ACCOUNTED FOR BY HITHERTO
UNKNOWN NOBEL GAS

PROTON DECAY

MOST SCIENCE ASSUMES PROTON STABLE
IN PRESENT EPOCH 4 FORCES

GRAVITY

WEAK FORCE

ELECTRO MAGNETISM

STRONG FORCE

} UNIFIED AS
ASPECTS OF
SAME FORCE

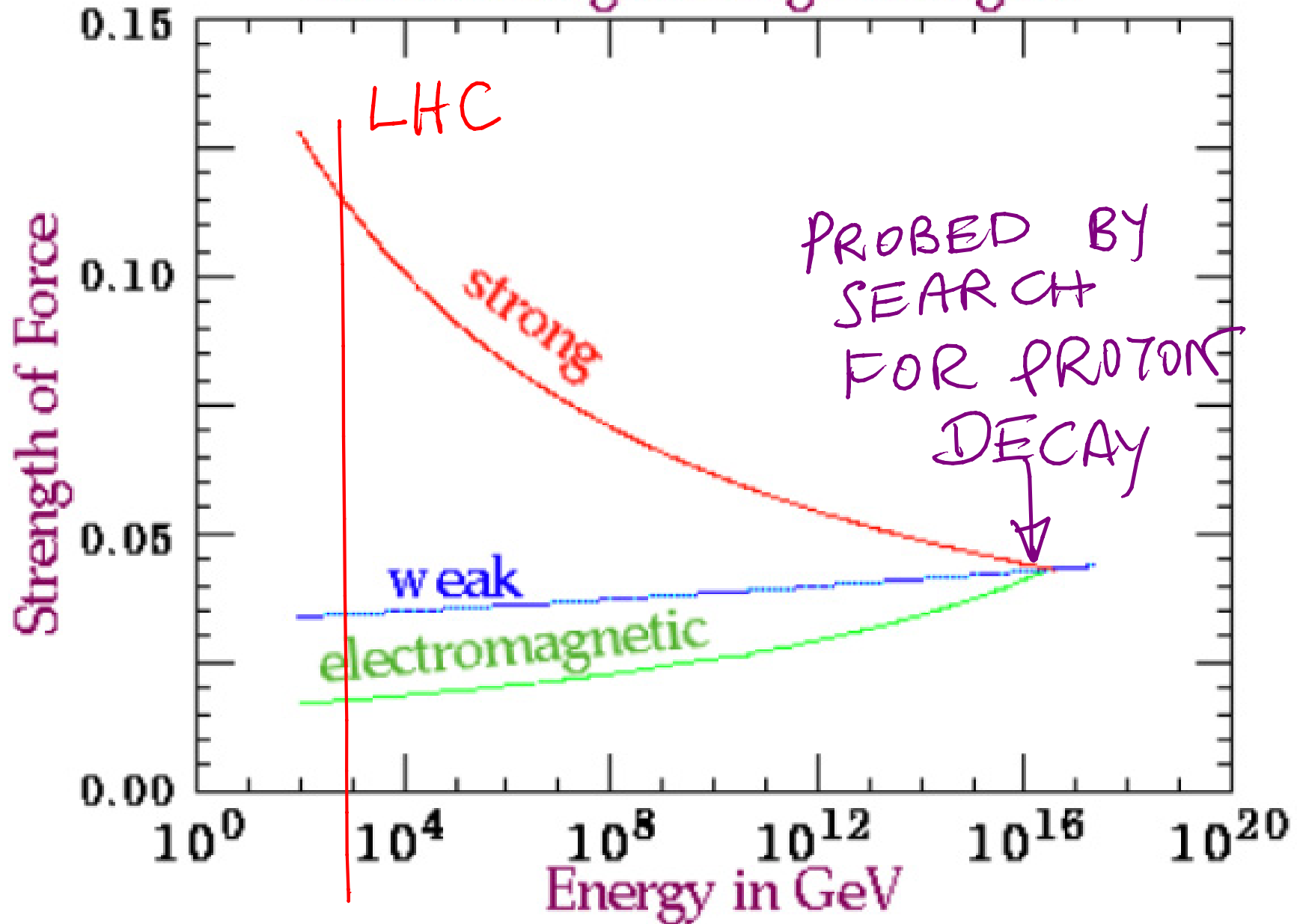
} UNIFY?

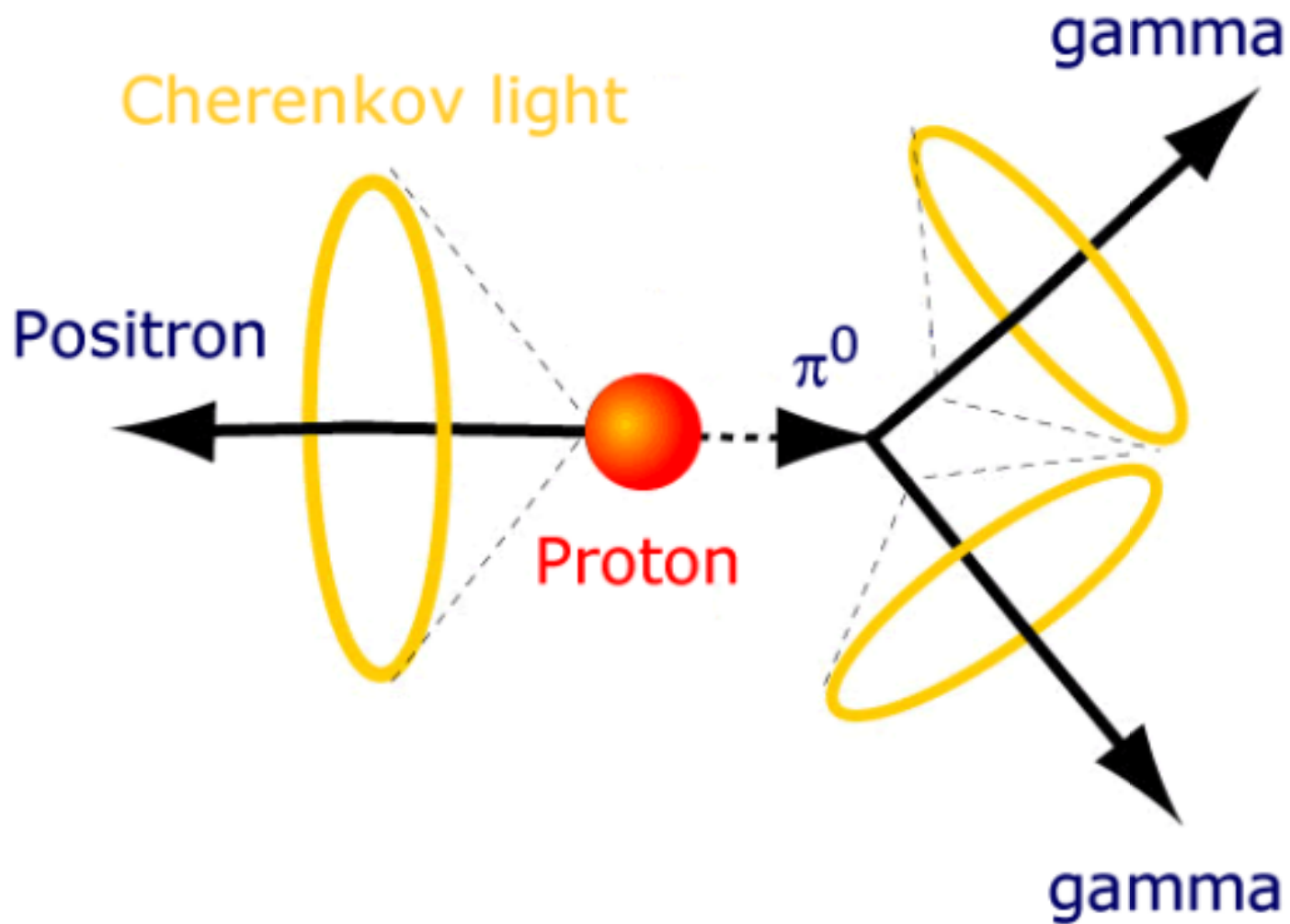
GRAND UNIFIED THEORIES (GUTS)

PREDICT PROTON DECAY

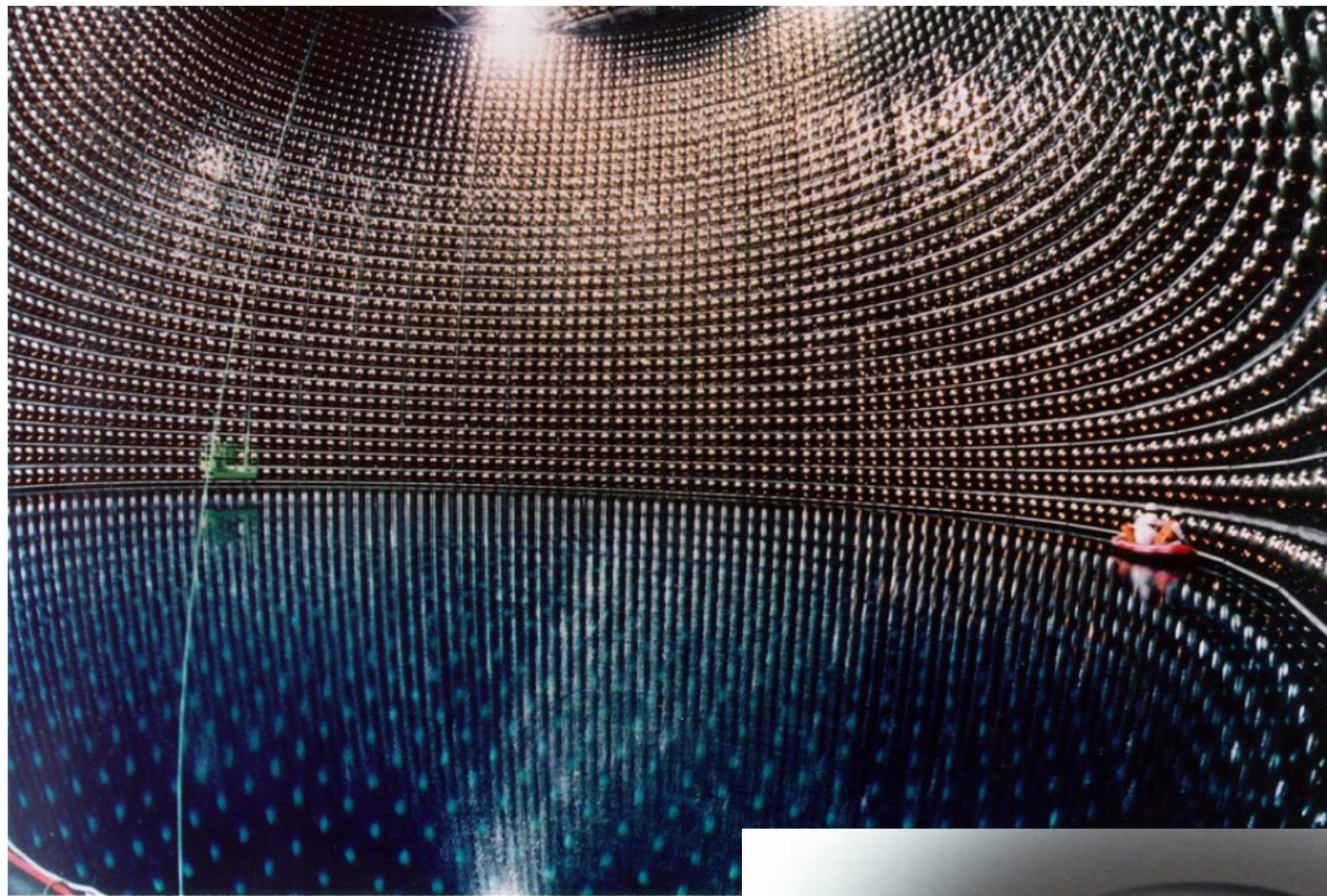
WITH MEAN LIFETIME $\sim 10^{33}$ YEARS

Forces Merge at High Energies





10^{33} YEARS IS A LONG TIME TO WAIT
IF HAVE $>10^{33}$ PROTONS, SEVERAL DECAYS
PER YEAR.

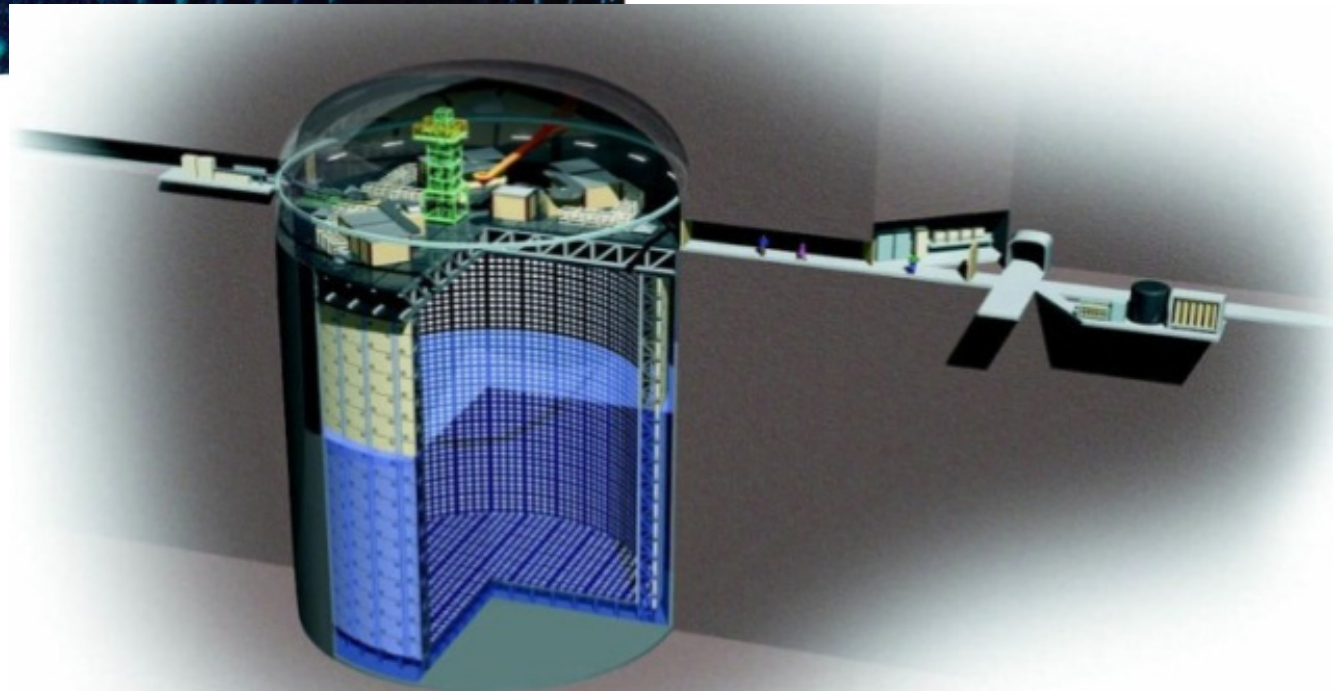


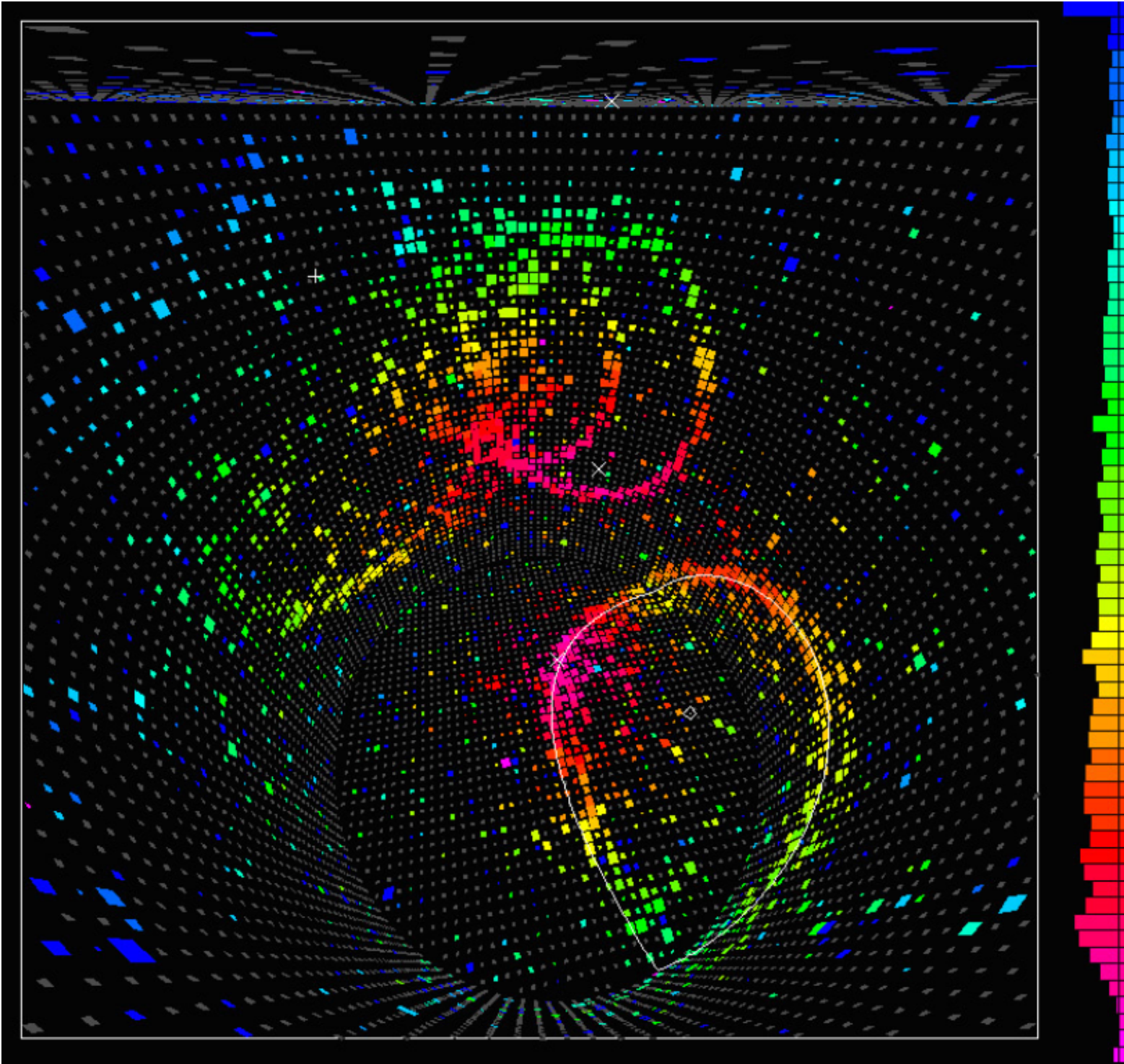
SUPERKAMIOKANDE

50,000 tons H_2O

12 000
PHOTOMULTIPLIERS

日本





ELECTRONS
PRODUCED
BY
COSMIC RAY
NEUTRINOS

RESULT IS THE PROTON LIFETIME $> 10^{34}$ YEARS

DUE TO THE FACT THAT NO DECAYS HAVE BEEN OBSERVED.

DESPITE POPPER THIS DOES NOT EXCLUDE PROTON DECAY & GRAND UNIFICATION

MORE COMPLICATED THEORIES

NO COMPELLING REASON WHY PROTON SHOULD NOT DECAY

AFFORDABLE WAY TO PROBE ENORMOUS ENERGY SCALE

ELECTRON MAGNETIC DIPOLE MOMENT

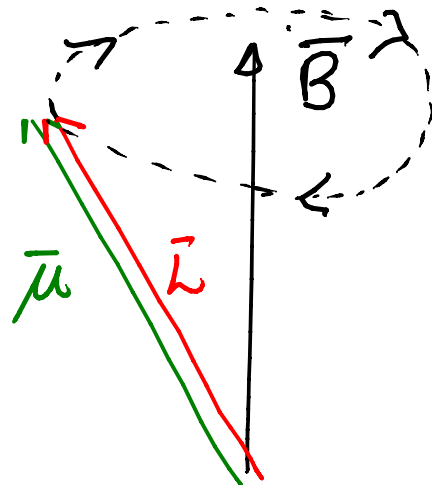
A CLASSICAL, ELECTRICALLY CHARGED PARTICLE
ROTATING ON ITS AXIS

$$\vec{\mu} = \frac{e}{2me} \vec{L}$$

MAGNETIC MOMENT

ANGULAR
MOMENTUM

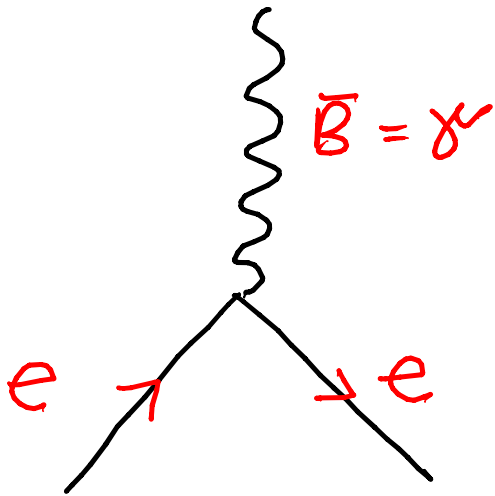
IN A MAGNETIC FIELD $\vec{\mu}$ AND \vec{L}
PRECESS WITH SAME FREQUENCY



IN QUANTUM ELECTRODYNAMICS

$$\vec{\mu} = g \frac{e}{2m\hbar} \vec{L}$$

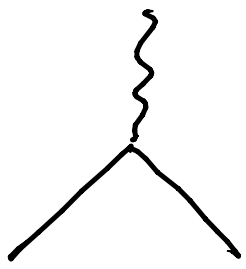
HOW DO YOU CALCULATE g ?



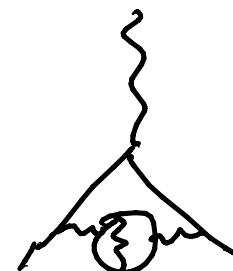
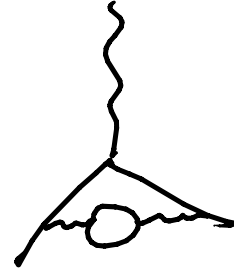
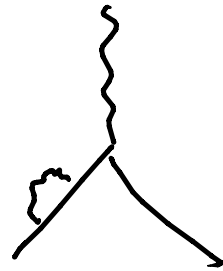
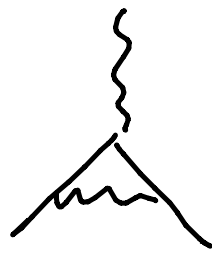
GRAPHICAL
REPRESENTATION
OF QUANTUM
AMPLITUDE

ELECTRON
INTERACTS
WITH MAGNETIC
FIELD

$g=2$
MAGNETIC MOMENT
PRECESSES AT
TWICE FREQUENCY
OF ANGULAR
MOMENTUM



IS ONLY FIRST TERM IN AN ∞ PERTURBATION SERIES

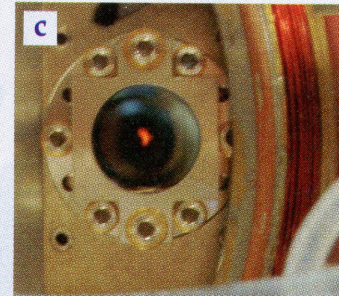
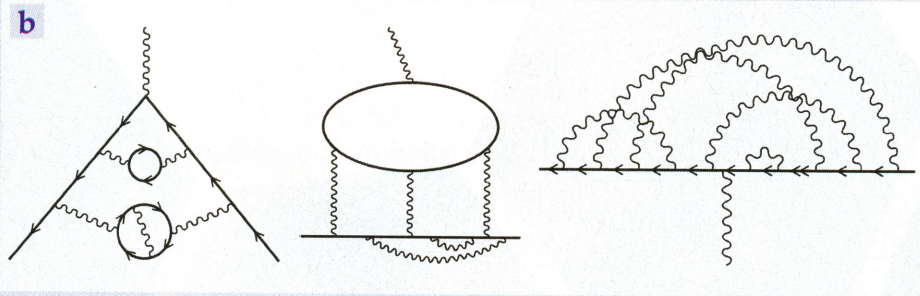


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THIS IS A CONVERGENT SERIES BECAUSE
THE ELECTROMAGNETIC FORCE IS WEAK
EACH SUCCESSIVE TERM IS A SMALL
CORRECTION

QUANTUM ELECTRODYNAMICS CAN
CALCULATE g TO ARBITRARY
ACCURACY

SO FAR AGREES WITH EXPERIMENT
TO 1 PART IN 10^{13}



FRANÇOIS BIRABEN

d Predicted: $\mu/\mu_B = -1.001\,159\,652\,181\,78$ (77)
 Measured: $\mu/\mu_B = -1.001\,159\,652\,180\,73$ (28)

Unprecedented confrontation of theory and experiment. **(a)** Our Penning trap shown here suspended a single electron for the months it took to measure its magnetic moment μ —the

most precisely measured property of an elementary particle. **(b)** The magnetic moment is also the quantity most precisely predicted by the standard model of particle physics. The prediction requires the calculation of nearly 14 000 integrals. These Feynman diagrams represent three of those. **(c)** Fluorescing rubidium atoms are used to measure the fine-structure constant α , which gives the strength of the electromagnetic interaction. The measured α and the standard-model calculation are the essential inputs for the precise prediction. **(d)** The predicted and measured values of μ agree to an astounding part per trillion. Both values shown here are divided by the Bohr magneton μ_B defined in the text. Parentheses denote uncertainties in the rightmost two digits.

The C_n are calculated by evaluating Feynman diagrams with more spin flips taking place as the drive frequency approaches ω_s .

The spin frequency is proportional to B , which must then be measured to extract μ . Fortunately, the cyclotron frequency, $\omega_c = eB/m$ for an electron with charge $-e$ and mass m , is also proportional to B , so it can be used as an internal magnetometer. The electron is kept cold—with a temperature less than 0.1 degree above absolute zero—to keep the cyclotron motion in its quantum ground state. As with spin flips, a measurable one-quantum excitation of the cyclotron motion, which increases the energy by $\hbar\omega_c$, requires an appropriate driving force. Excitations take place more frequently as the drive frequency approaches ω_c .

Eliminating B from $\hbar\omega_s = -2\mu B$ and $\omega_c = eB/m$ gives the magnetic moment as a ratio of the two measurable frequencies, $\mu/\mu_B = -\omega_s/\omega_c$. The Bohr magneton $\mu_B = e\hbar/(2m)$ is the magnetic moment for circular electron motion with angular momentum \hbar . The magnetic moment μ is negative—

A two parts per trillion contribution, a_{hadronic} , comes from the electron's interaction with hadron-antihadron pairs. (Hadrons are heavy particles whose internal structure would need to be known here if the correction weren't so small.) The standard-model weak-interaction contribution to the electron moment, a_{weak} , is smaller than the measurement precision.

Quantum electrodynamics gives a_{QED} as a power series in the fine-structure constant, $\alpha \equiv e^2/(4\pi\epsilon_0\hbar c) \approx 1/137$, which is a measure of the strength of the electromagnetic interaction in the low-energy limit. Specifically,

$$a_{\text{QED}}(\alpha) = C_2 \left(\frac{\alpha}{\pi}\right) + C_4 \left(\frac{\alpha}{\pi}\right)^2 + C_6 \left(\frac{\alpha}{\pi}\right)^3 + C_8 \left(\frac{\alpha}{\pi}\right)^4 + C_{10} \left(\frac{\alpha}{\pi}\right)^5 + \dots$$

Each of the five displayed terms is much smaller than the previous one, but all are needed to achieve the measurement precision of the magnetic moment.

THIS ENORMOUS PRECISION IN THE AGREEMENT

EXPERIMENT  THEORY

PERSUASIVE ARGUMENT FOR

- EXISTENCE OF EXTERNAL OBJECTIVE REALITY
- THAT PHYSICAL THEORIES DESCRIBE IT
- ALLOW US TO KNOW NEW THINGS ABOUT IT.

THOUGHT EXPERIMENTS (GEDANKENEXPERIMENT)

FRANKLIN THINKS THAT THESE ARE
PECULIAR TO PHYSICS — AND THAT THEY
ARE ENABLED BY A DISTILLATION OF
EXPERIENCE — LOOKING AT THINGS

LOOKING AT THINGS WHICH HAPPENED IN
THE PAST & EXTRAPOLATING

NO PHYSICIST BELIEVES THAT THOUGHT
CAN SUBSTITUTE FOR REAL EXPERIMENTS

BUT VERY INFLUENTIAL IN DEVELOPMENT
OF PHYSICS

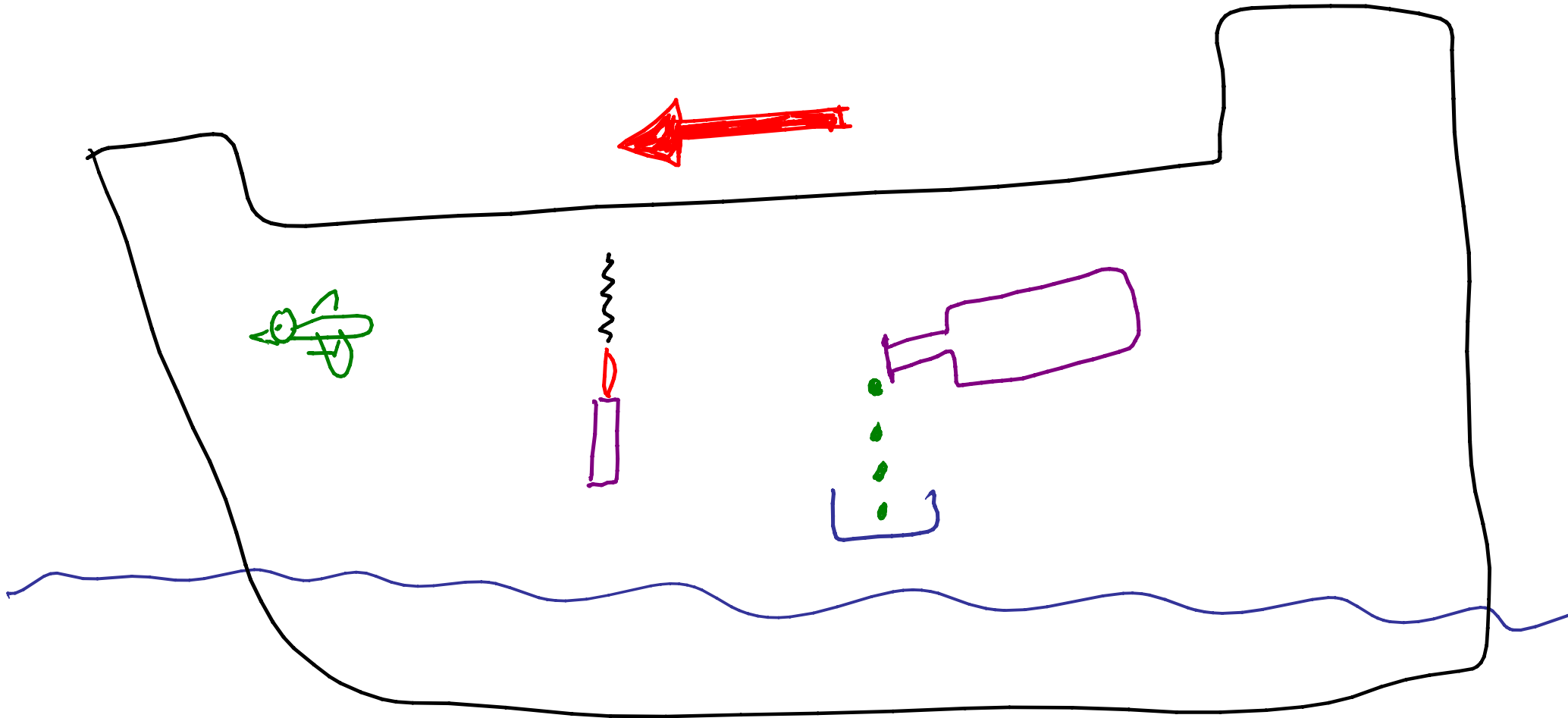
GALILEO

EINSTEIN

SCHRÖDINGER

GALILEO - INERTIA & RELATIVE MOTION

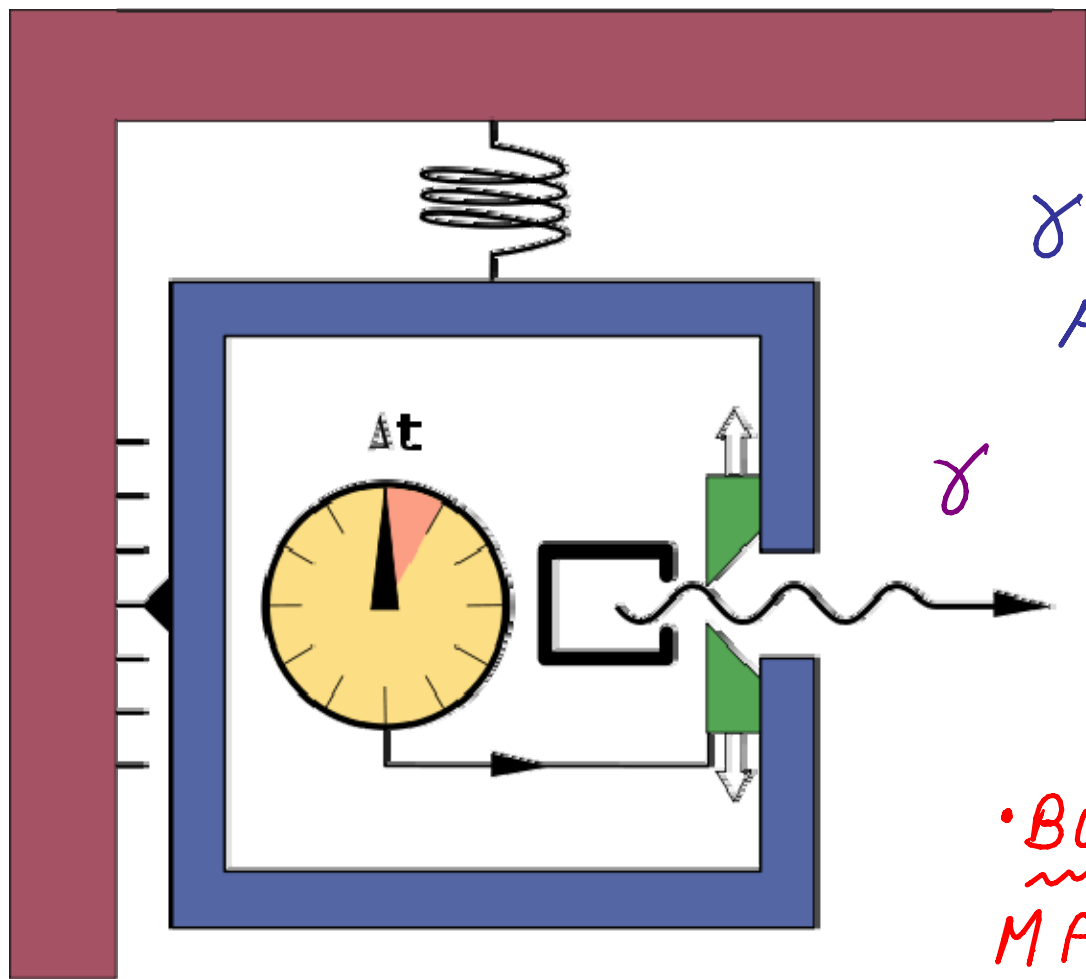
WHY DOES THE EARTH ^{NOT} ROTATE UNDER US
WHEN WE JUMP UP IN THE AIR.?



$$x' = x - vt$$

GALILEAN
TRANSFORM

EINSTEIN'S $\Delta x \Delta \phi \sim \Delta E \Delta t \sim \hbar$

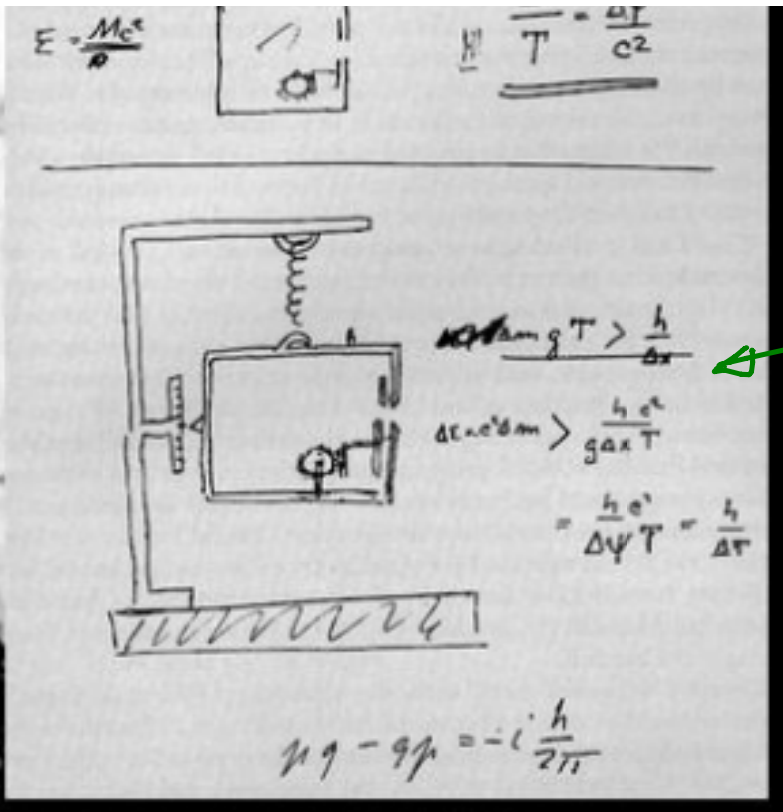


• EMISSION TIME OF γ MEASURED BY VERY ACCURATE CLOCK/SHUTTER

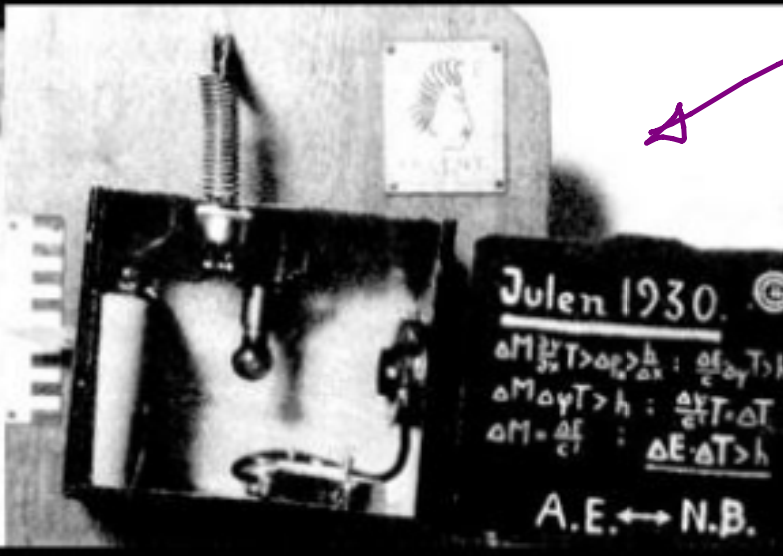
• WEIGH BOX TO GET CHANGE IN MASS = ΔE

• BUT CHANGE IN MASS MAKES CLOCK MOVE

IN GRAVITATIONAL FIELD. SO CLOCK RUNS AT DIFFERENT RATE $\sim \Delta t \Rightarrow \Delta t \Delta E \sim \hbar$

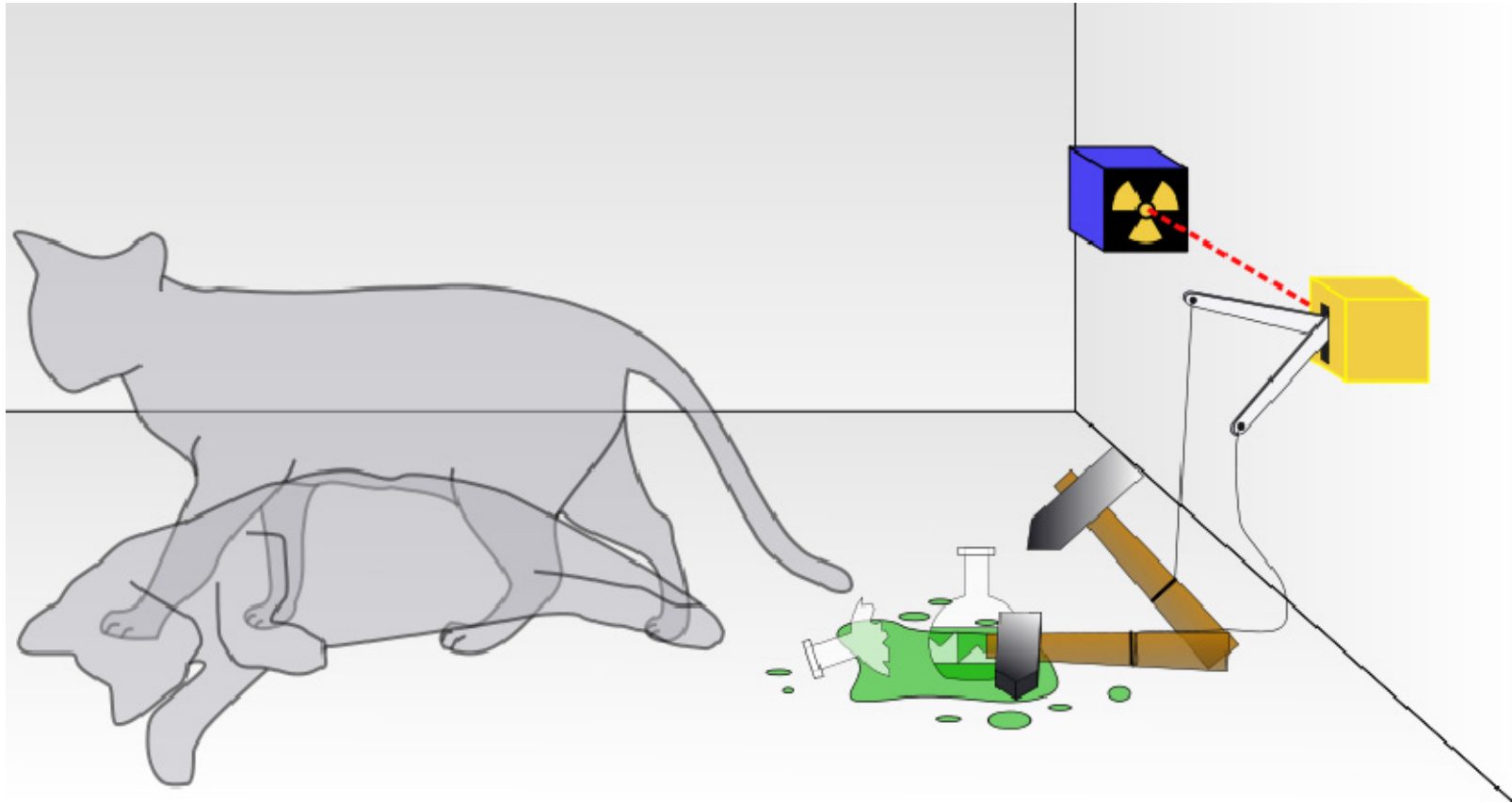


← EINSTEIN



← GEORGE GAMOW SPOOF

SCHRÖDINGER'S CAT



OPENING BOX = MEASUREMENT

BEFORE $\Psi_{\text{NUCLEUS}} = A \Psi_{\text{DECAY}} + B \Psi_{\text{NOTDECAY}}$

$$\Psi_{\text{CAT}} = A \Psi_{\text{DEAD}} + B \Psi_{\text{ALIVE}}$$

AFTER $\Psi_{\text{CAT}} = \Psi_{\text{DEAD}} \text{ OR } \Psi_{\text{ALIVE}}$

UNDERSTANDING QUANTUM MECHANICS
COMES DOWN TO UNDERSTANDING

SCHRÖDINGER EQUATION $\xrightarrow{\text{MEASURE}}$ DEFINITE STATE
DETERMINISTIC STATE

$$\psi = a\psi_a + b\psi_b$$

$$\psi = \psi_a$$

WHERE DOES
THIS GO?

- COPENHAGEN INTERPRETATION
- SHUT UP & CALCULATE
- MANY WORLDS INTERPRETATION
- DECOHERENCE

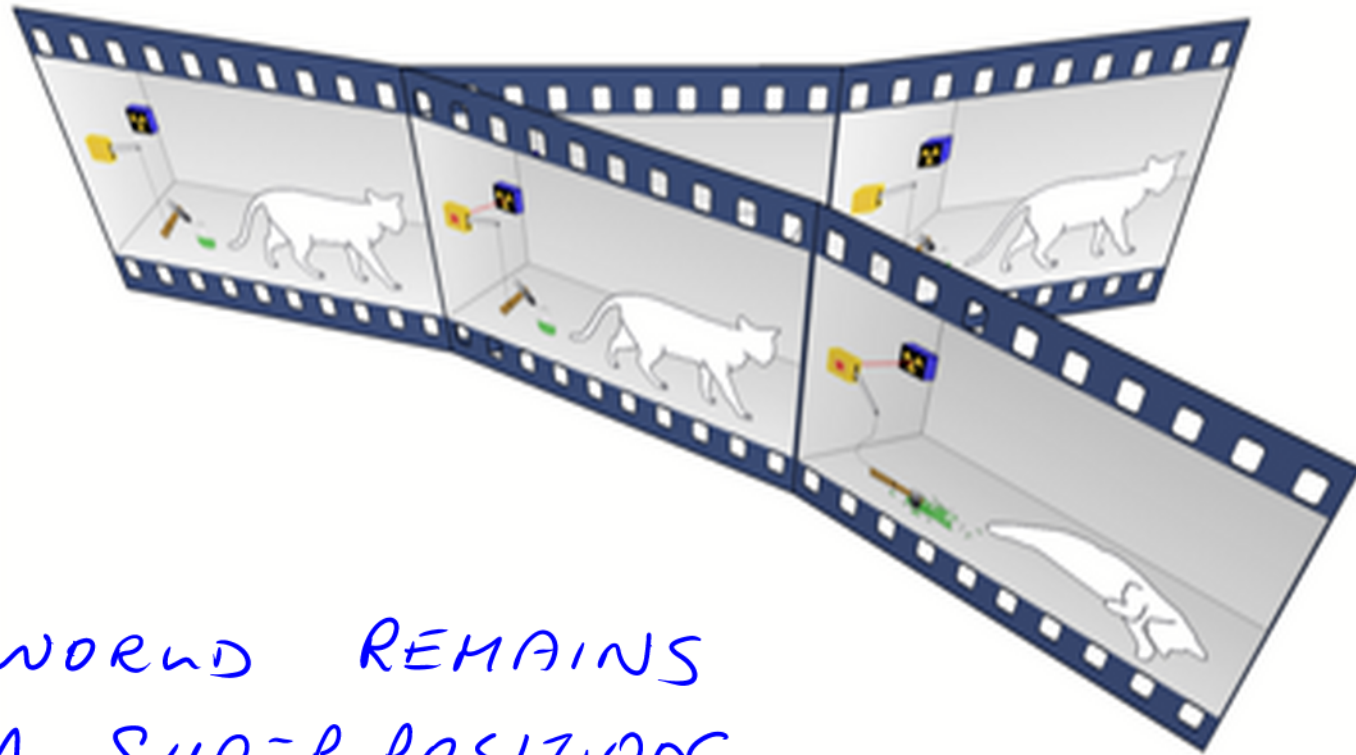
QUANTUM MECHANIC DOES NOT SEEM TO
DESCRIBE THE WORLD WE LIVE IN
SYSTEMS IN A MIXTURE OF STATES
WHICH EVOLVE DETERMINISTICALLY

DECOHERENCE → ANY MACROSCOPIC SYSTEM
INTERACTS WITH ENVIRONMENT
- COHERENCE OF MIXTURE LOST

MANY WORLDS → DIFFERENT PARTS OF
MIXTURE SPLIT OFF
AT MEASUREMENT
→ "REALITY SPLITS"

PLEASE READ GREEN - CHAPTER 8

MANY WORLDS INTERPRETATION OF QM.



THE WORLD REMAINS
IN A SUPERPOSITION

→ AFTER AN OBSERVATION
OUR CONSCIOUSNESS IS IN A

SUPERPOSITION

"THE CONSCIOUS MIND." D. J. CHALMERS

ON THE BOTTOM OF PAGE 87 FRANKLIN

"COMPETING THEORIES ATTEMPTING TO
EXPLAIN THESE FACTS COLORFUL IN
THEIR MUTUAL INCONSISTENCY"

I DO NOT KNOW WHAT HE IS
REFERRING TO:

WE UNDERSTAND PHYSICS FROM

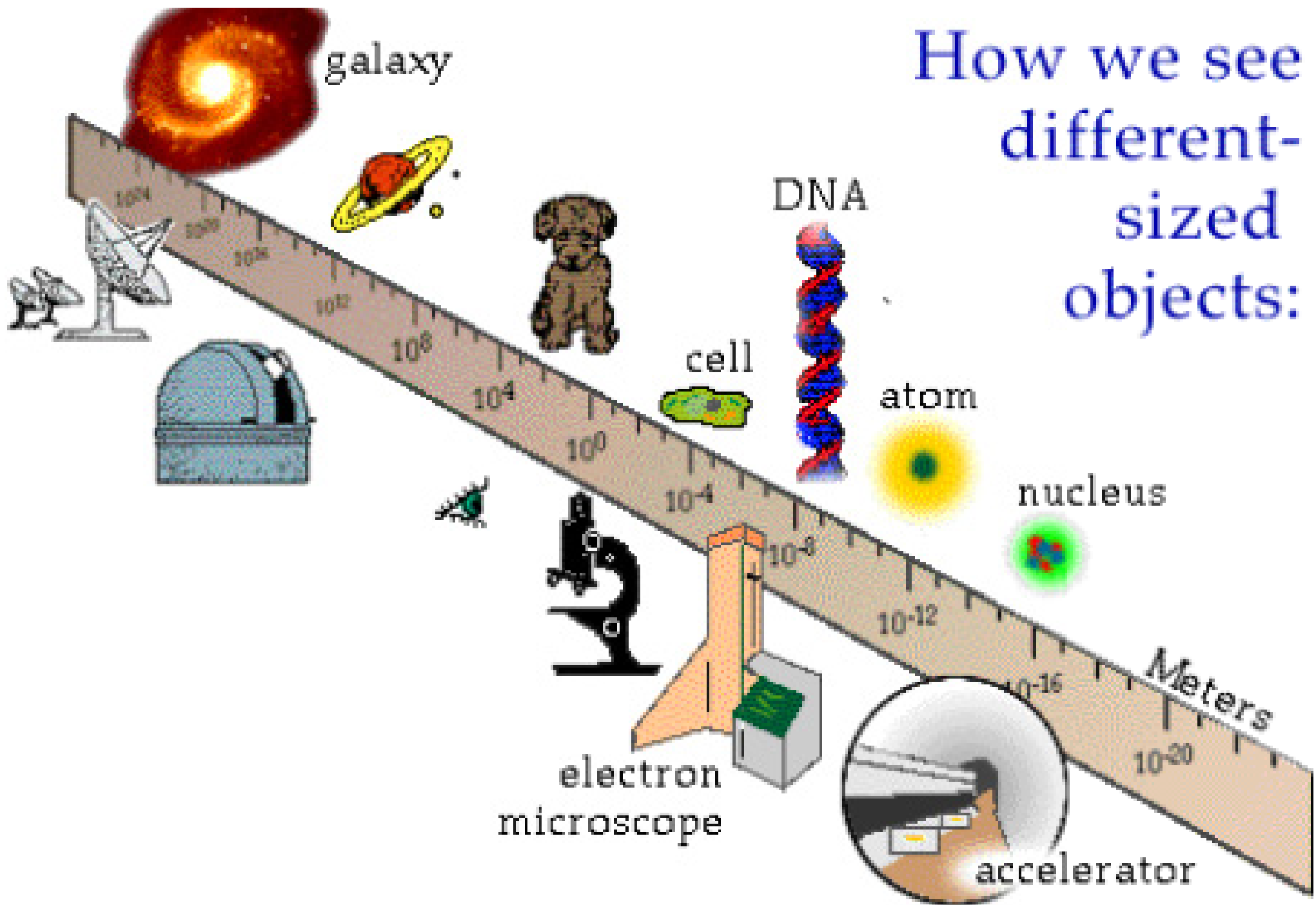
10^{-18} m

QUARKS

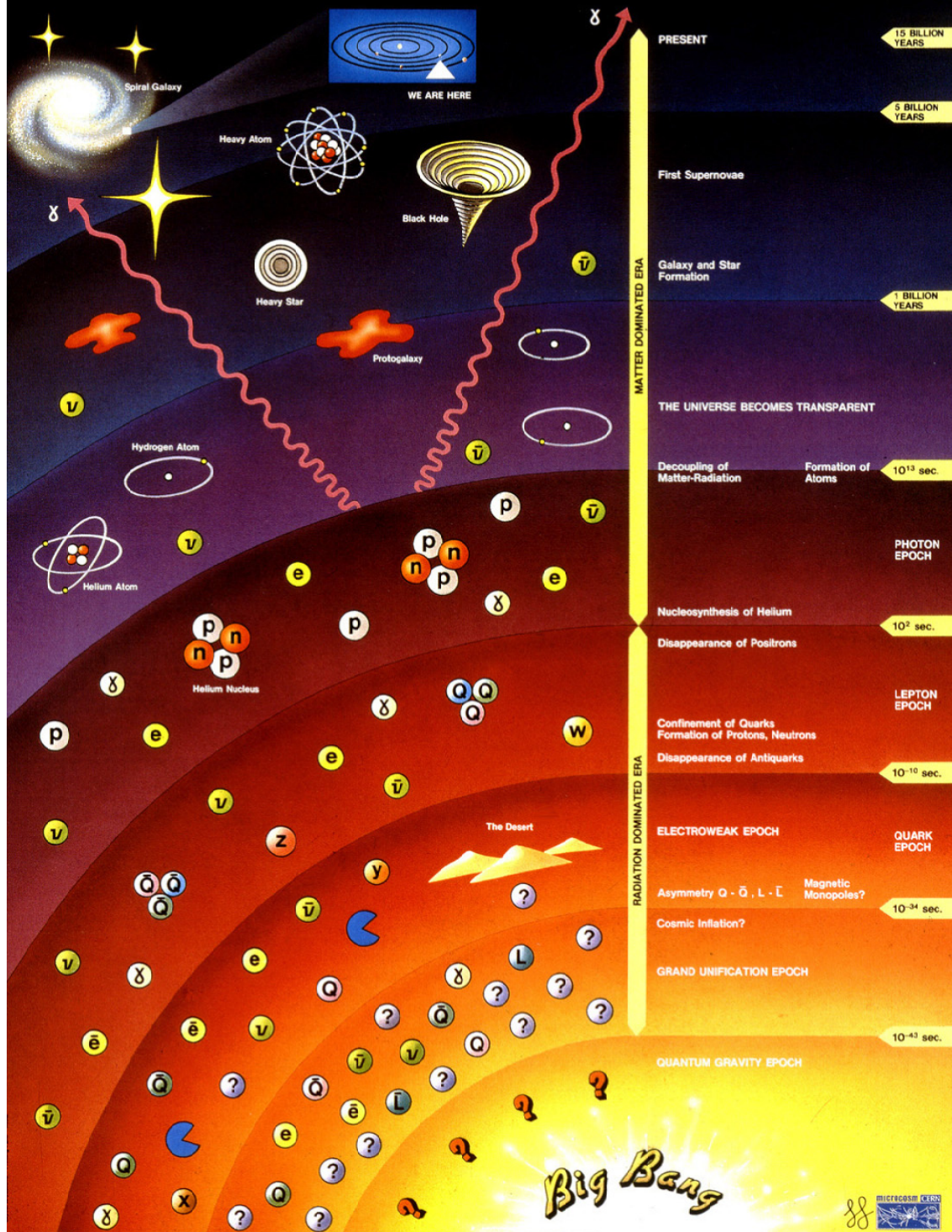
→ 10^{27} m

RADIUS OF
OBSERVABLE
UNIVERSE

How we see different-sized objects:



History of the Universe



2×10^{10} YEARS

10^9 YEARS

10^{13} S

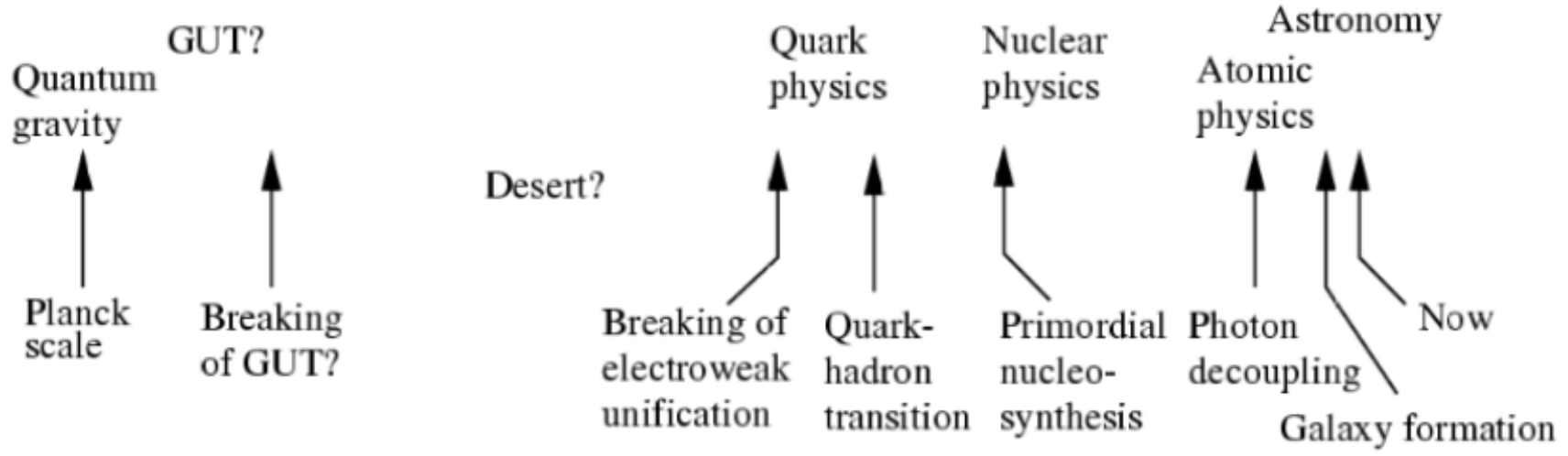
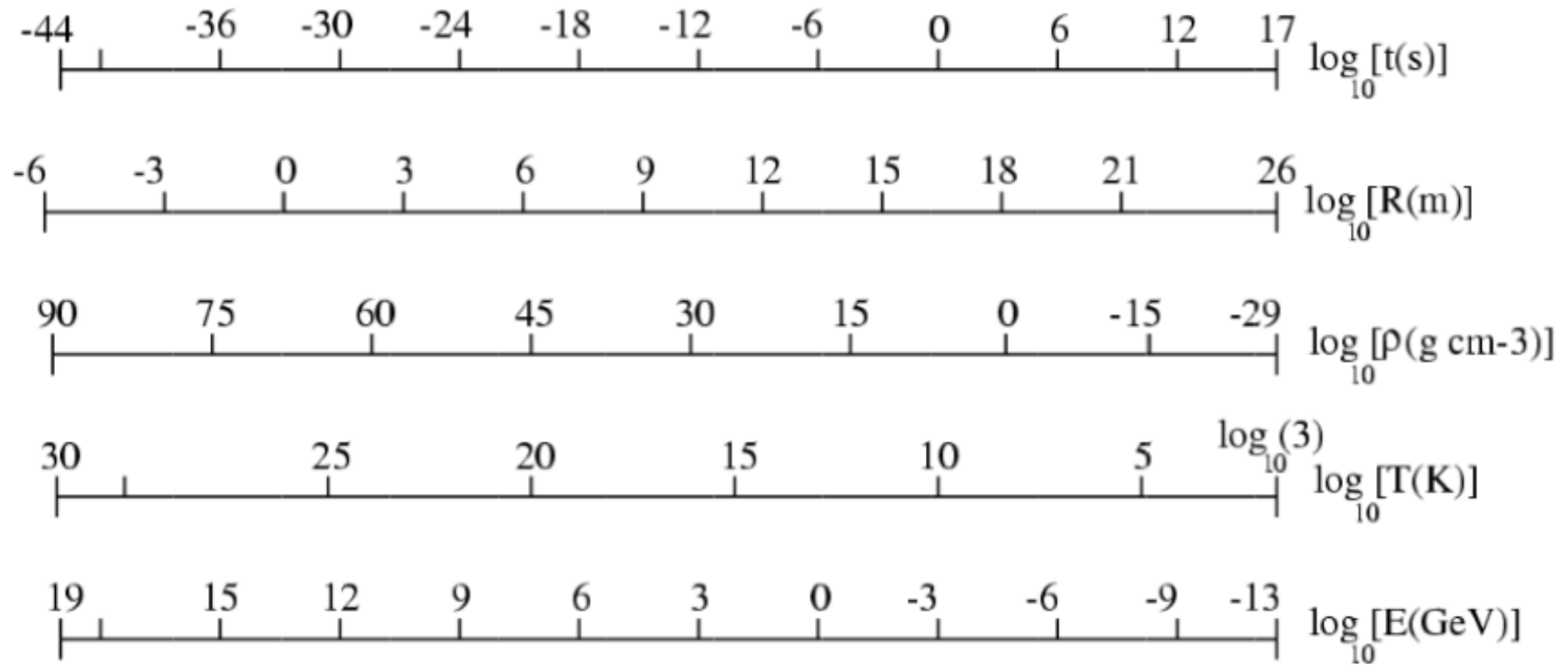
10^2 S

10^{-10} S

10^{-34} S

10^{-43} S

The "History" of the Universe from the Planck time to the present, showing how the size of the presently observable universe R , the average density ρ , the temperature T , and the energy per particle kT , have varied with time t according to the hot big bang model.



PROBLEMS WITH LARGEST SCALES

I'M GOING TO TRY TO TOUCH ON SOME OF THESE ISSUES FROM GREEN'S BOOK

— VAST EXTRAPOLATION OF EVERYDAY KNOWLEDGE

— IS "DARK MATTER / ENERGY" SOME BREAKDOWN OF THIS EXTRAPOLATION?

— MUCH OF PHYSICS MAKES STATISTICAL PREDICTIONS (QM) WHAT DOES IT MEAN WHEN YOU ONLY HAVE ONE UNIVERSE?

