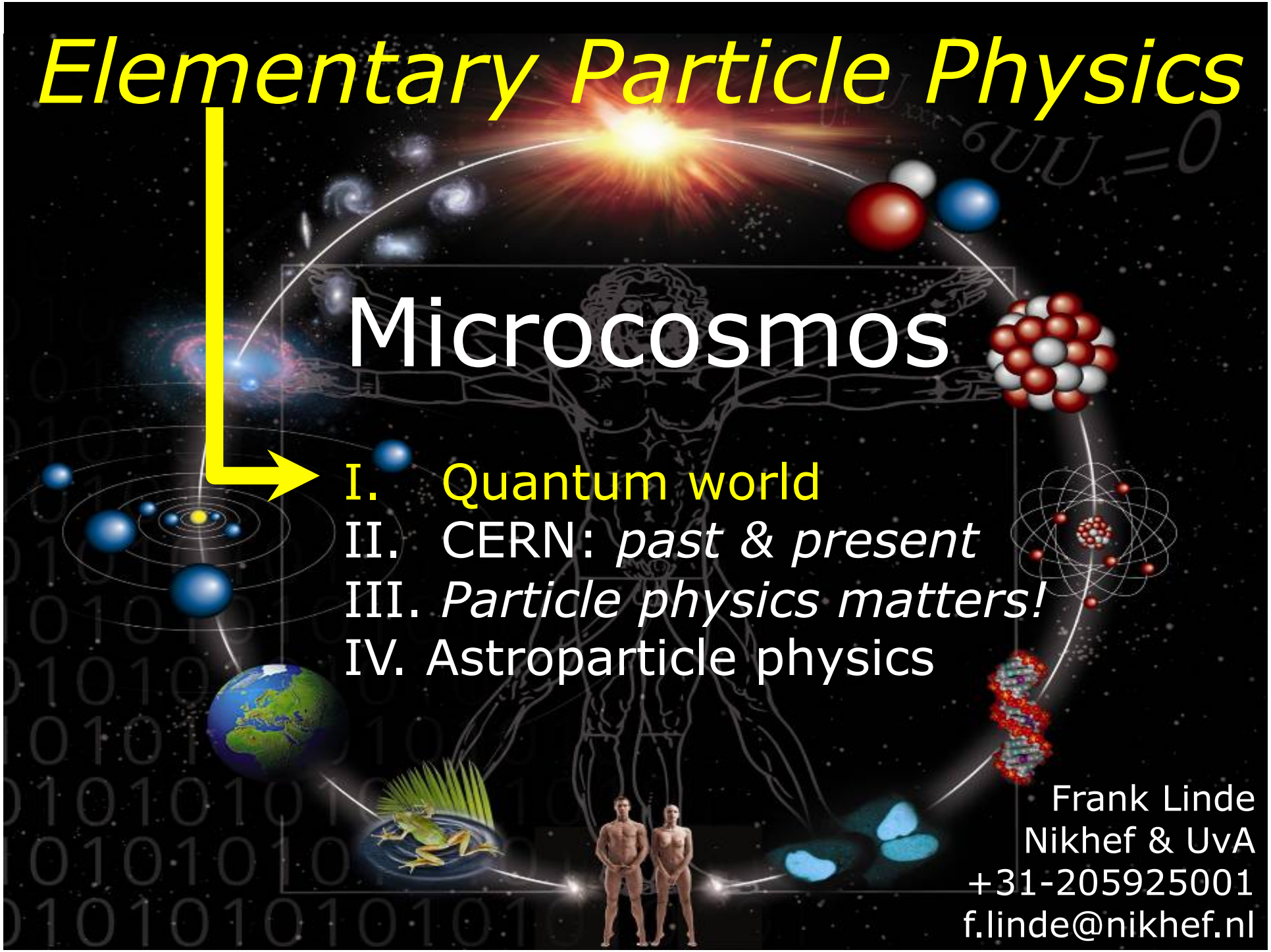
Elementary Particle Physics



Microcosmos

I. Quantum world
II. CERN: *past & present*
III. *Particle physics matters!*
IV. Astroparticle physics

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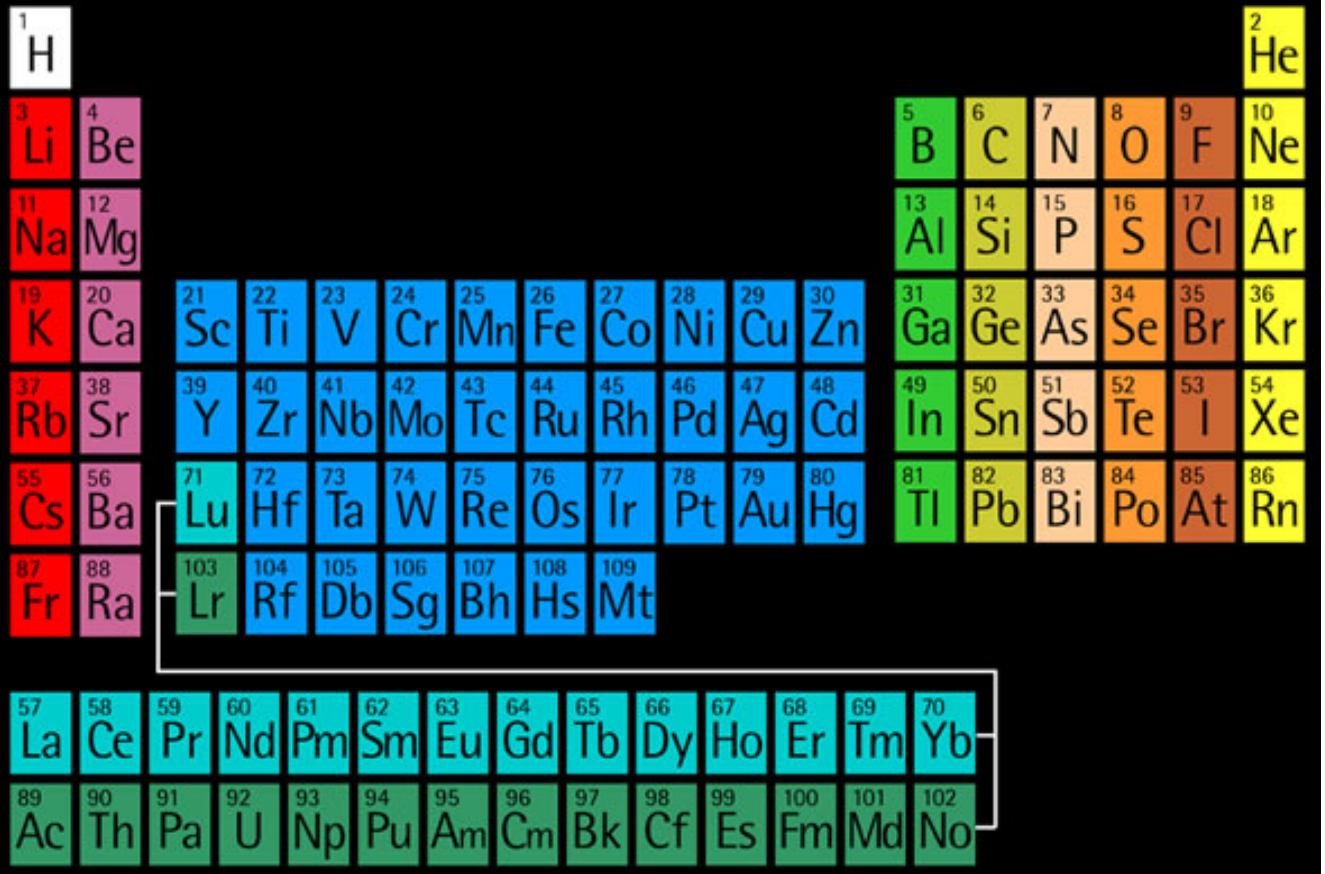
Dark ages


1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca
21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn
31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr
39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd
49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba
71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg
81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra
103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No

Long ago ...

Empedocles

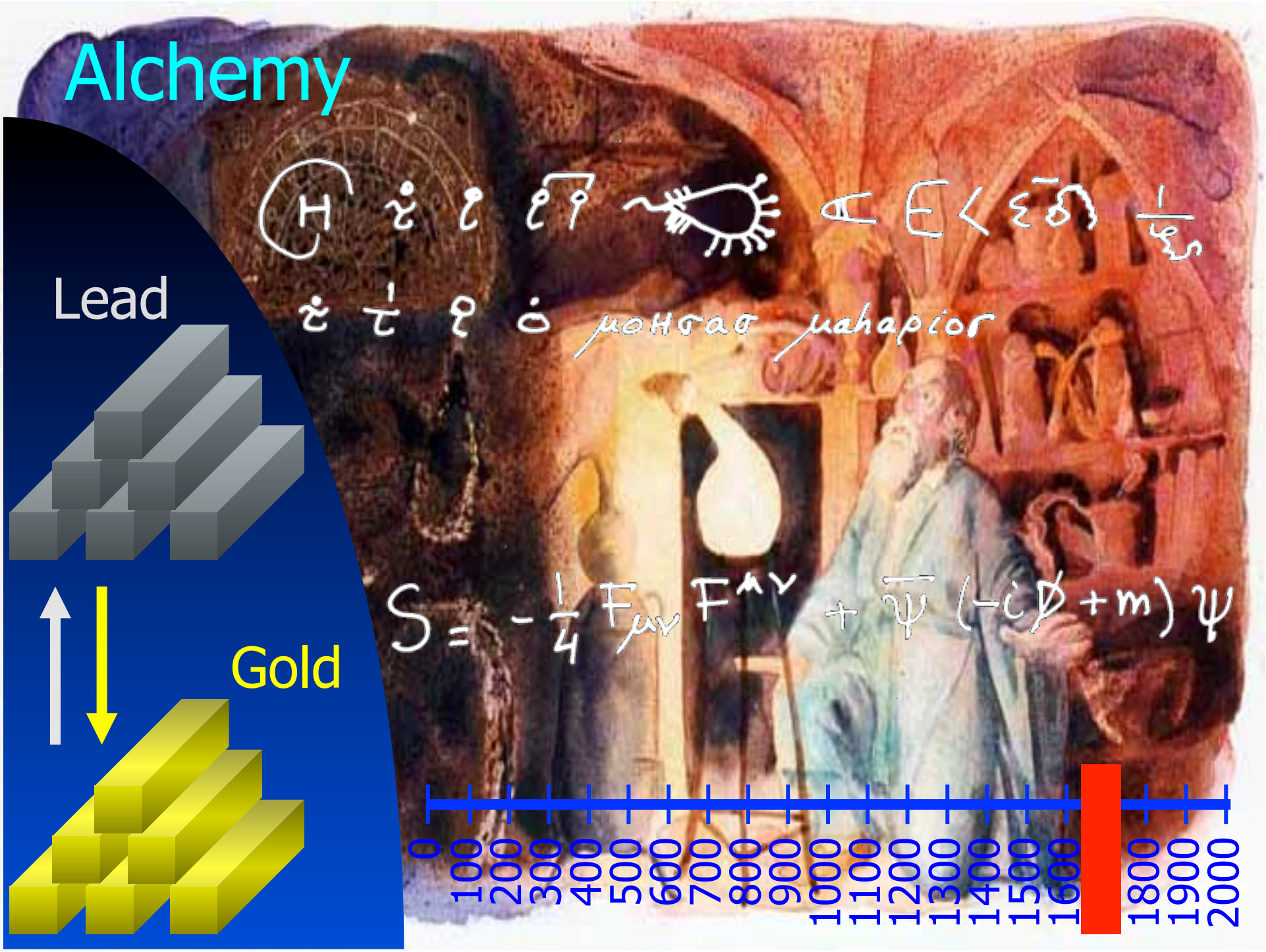
Plato

Aristoteles

Leucippus

Democritus

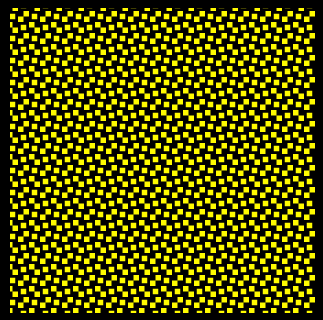
Air
Wate
Fire
Earth


Alchemy
Lead
Gold
$S = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} (-i\not{\partial} + m) \psi$
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1800
1900
2000

Water electrolysis

Number of atoms per volume independent of atom type! (Avogadro)

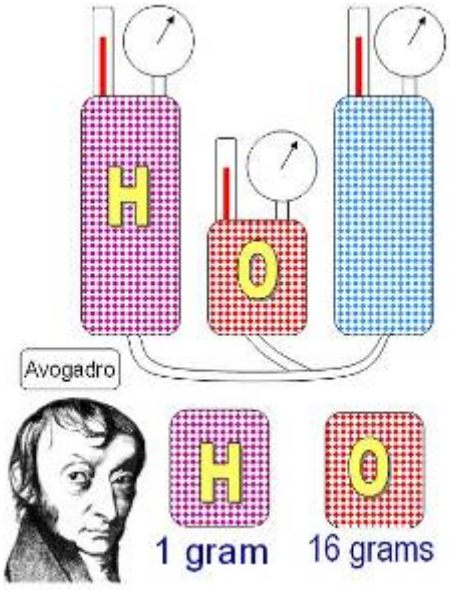
N_A atoms = 1 Mole



22.4 liters

Atoms

$N_A = 6.0221420 \times 10^{23}/\text{Mol}$



How large? 30-300×10^{-12} meters

How heavy? 2-450×10^{-25} kilograms

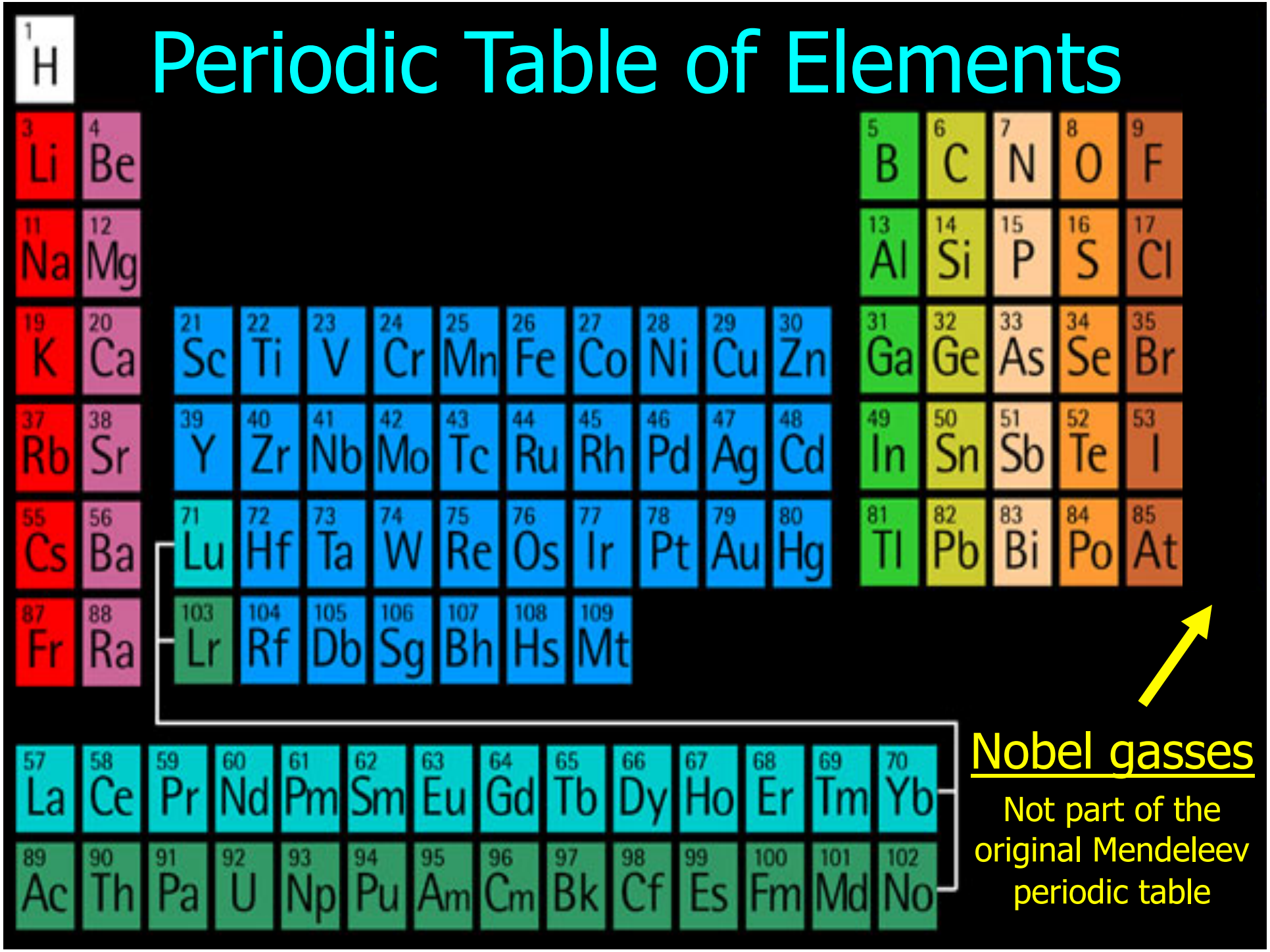
How many? 3×10^{23}/gram hydrogen

Question

How many atoms of Ceasar's last blast do you think you inhale whenever you take in air?

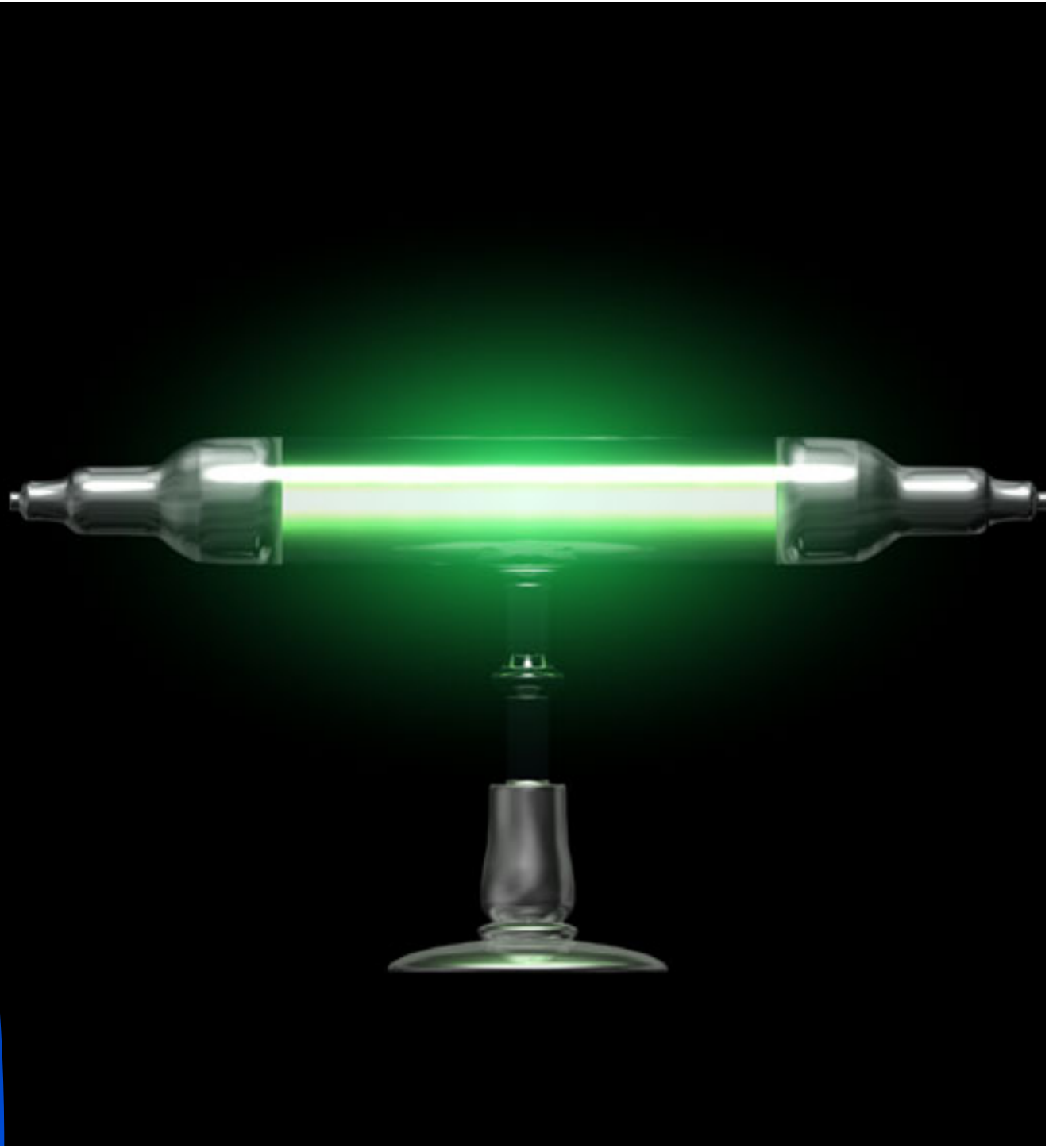
A. between 0.001 and 1000
B. less than 0.001
C. more than 1000

Periodic Table of Elements

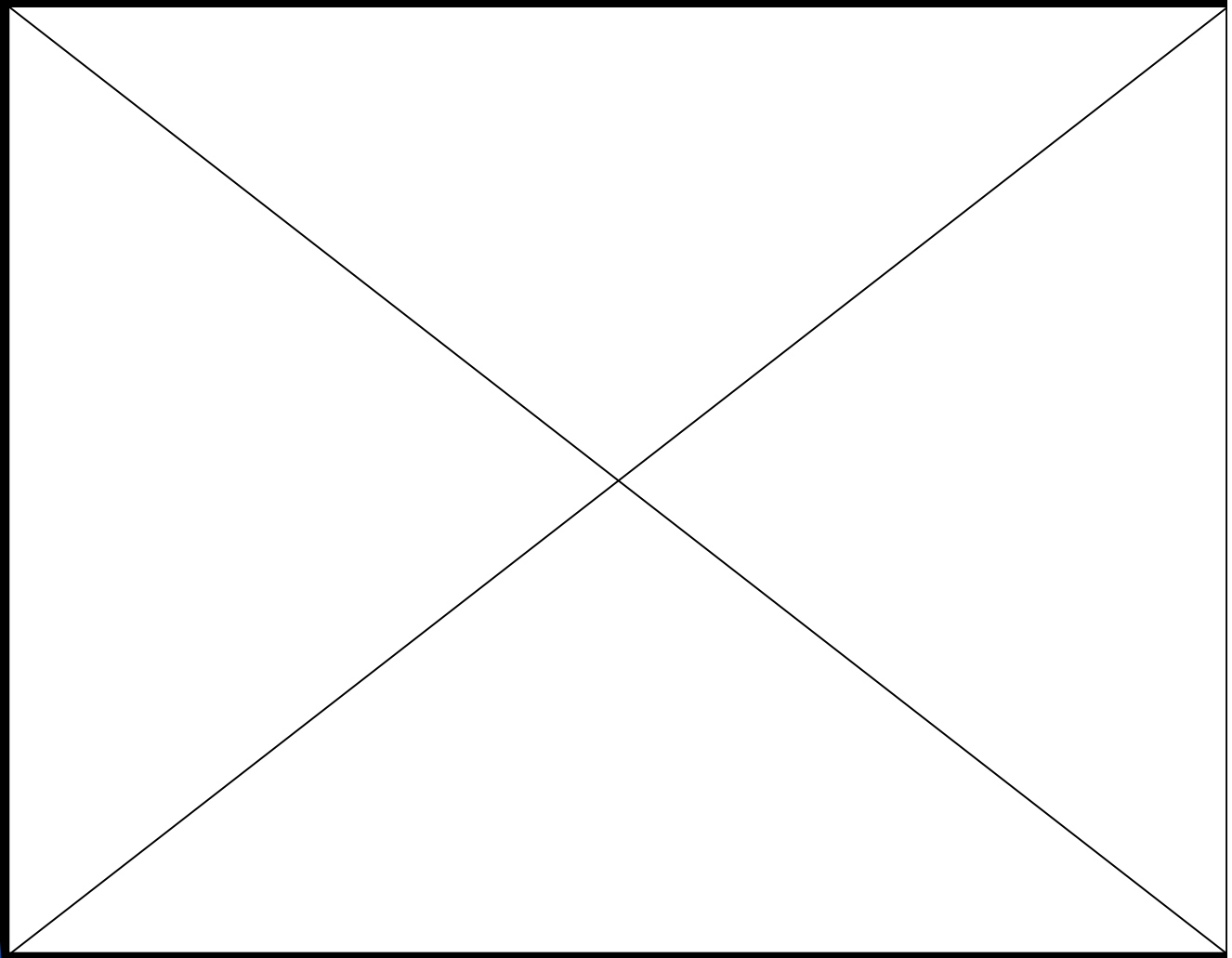


The atom

Thomson
1897



$e/m = -1.76 \times 10^{11}$ C/kg

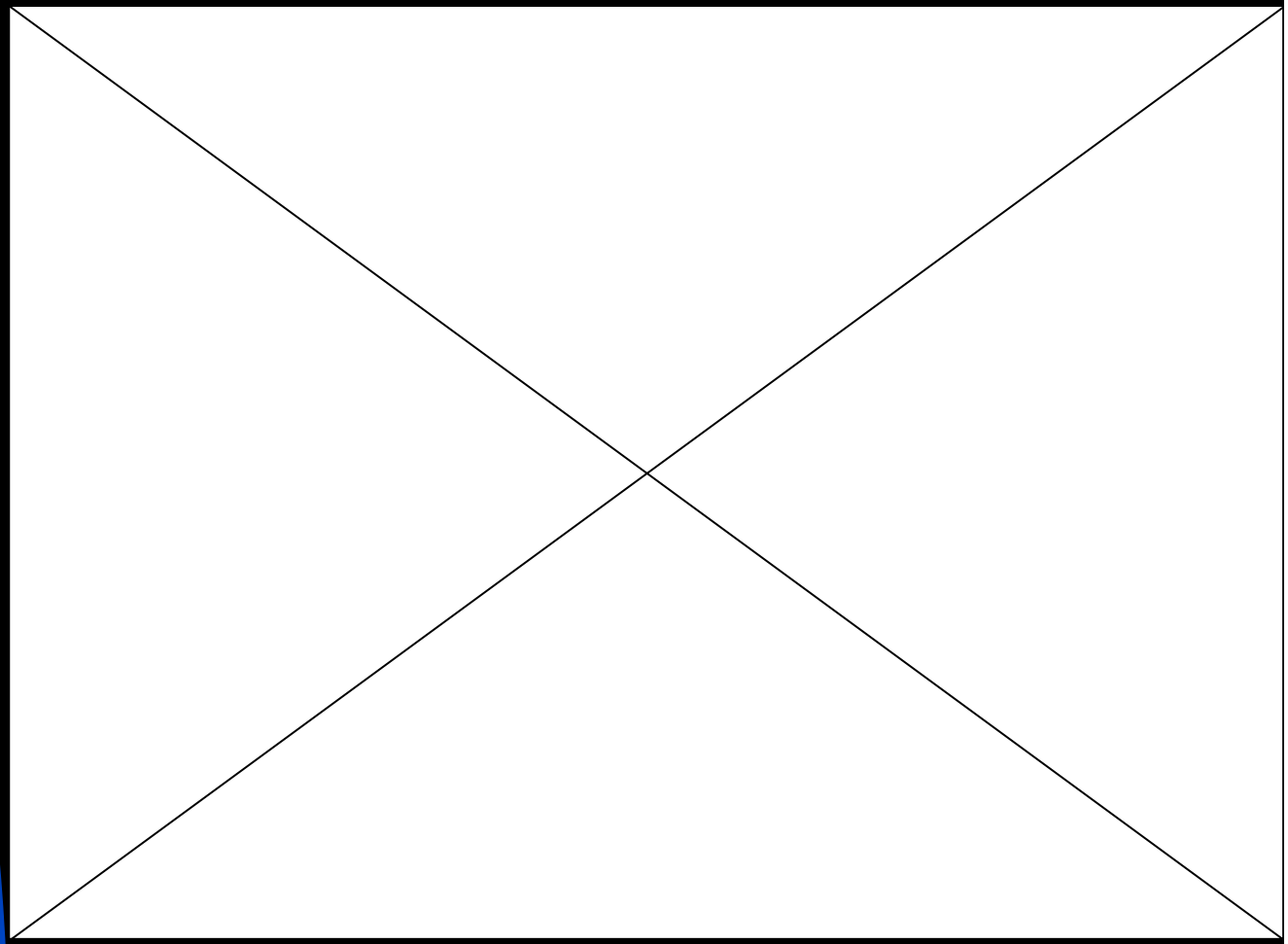


Thomson

1897

$q_e = -1.60217646 \times 10^{-19}$ C

$m_e = 9.1093819 \times 10^{-31}$ kg



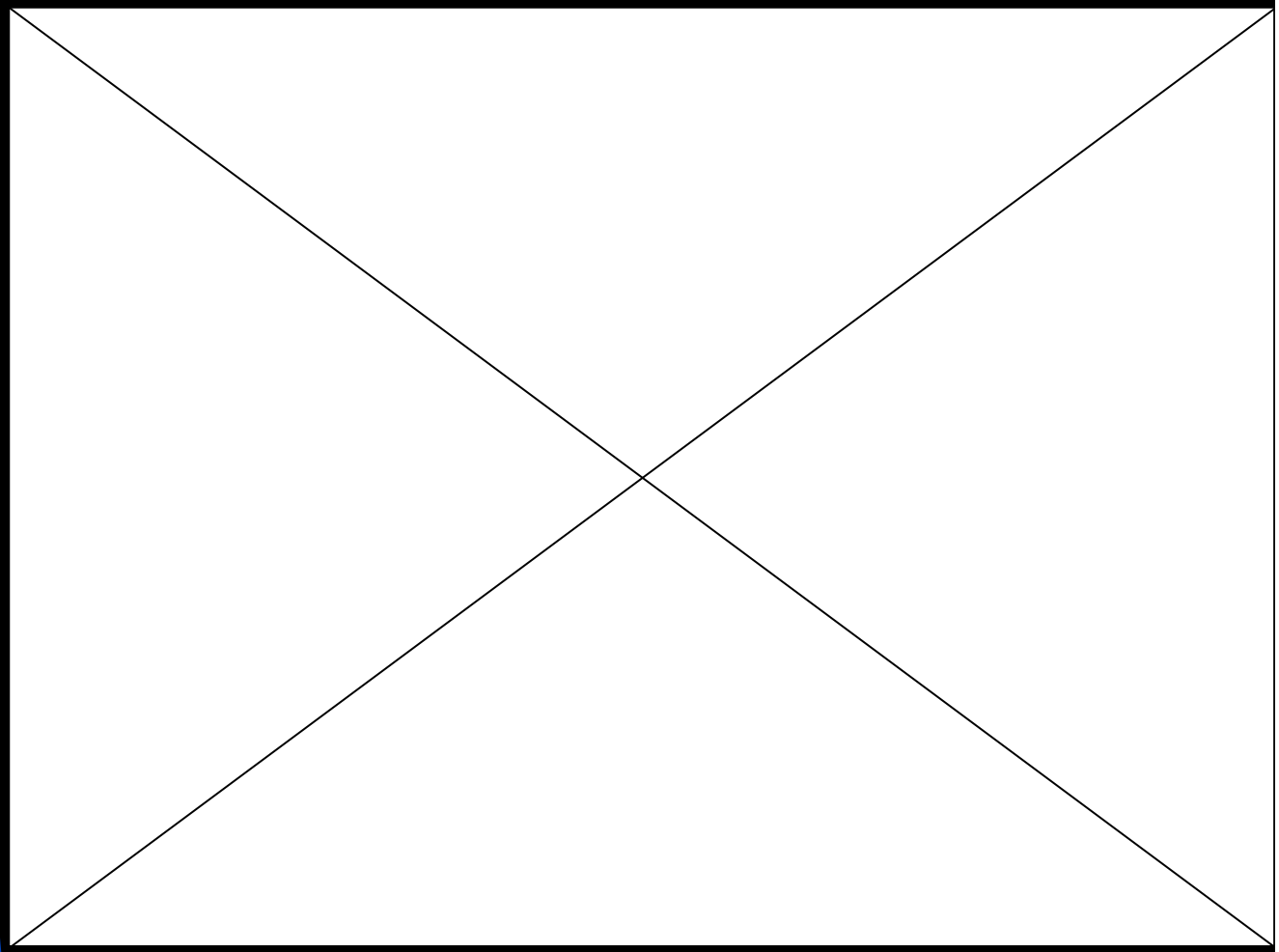
Millikan

1900

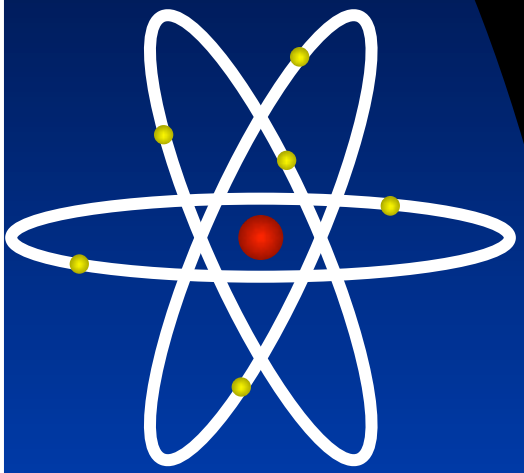
electron

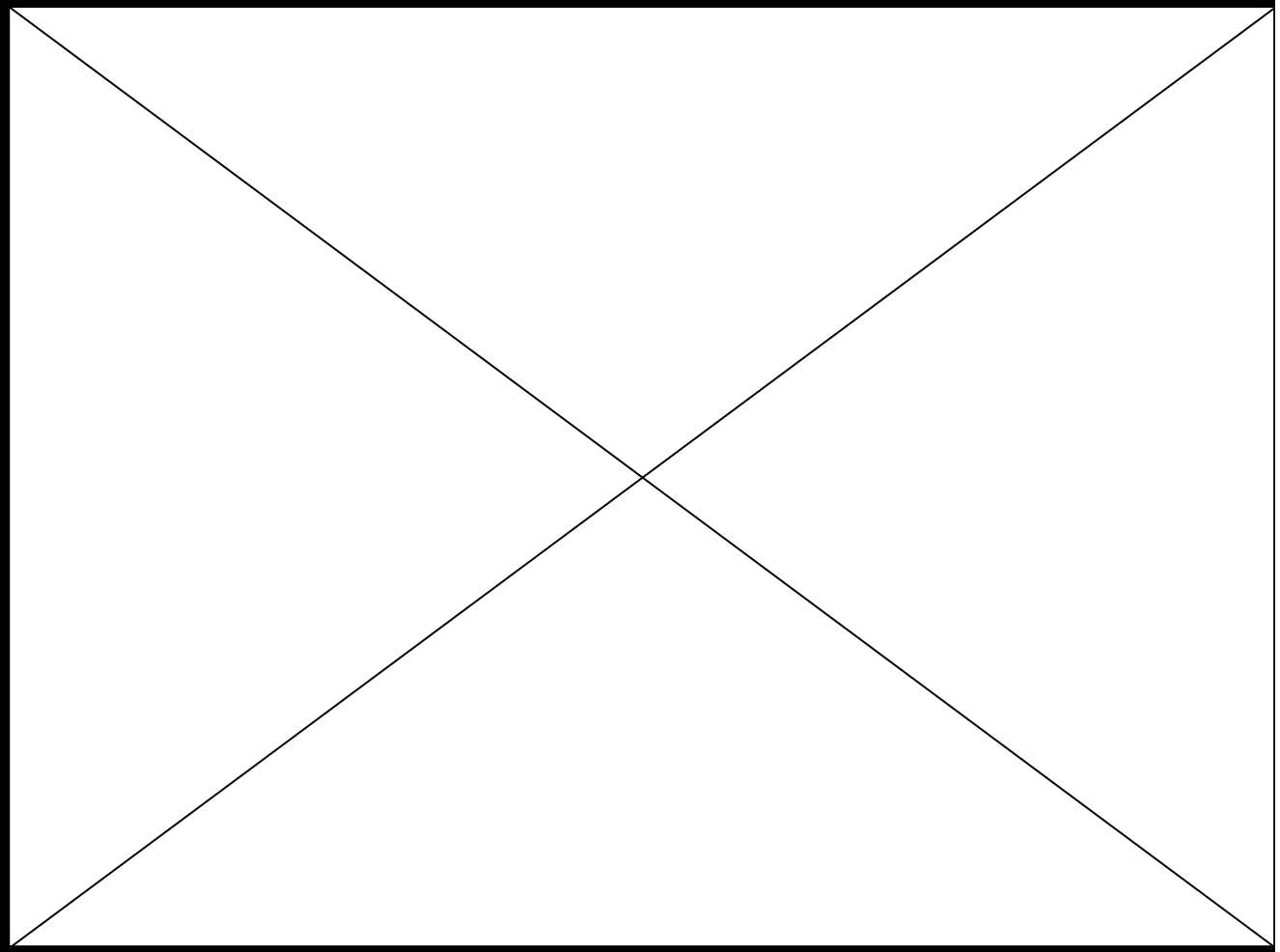

ELECTRON
e–
The ELECTRON is a fundamental subatomic particle carrying a negative charge. Its mass is 1/1000 that of the smallest atom. It participates in electromagnetic interactions, and is typically found orbiting the nucleus of an atom.
Fleece with poly fill for minimum mass.
$9.75 PLUS SHIPPING
MADE IN CHINA.
AGE 3 AND UP.
BACK
LIGHT
HEAVY
electron
The PARTICLE ZOO

Atoms: *Thomson's view*



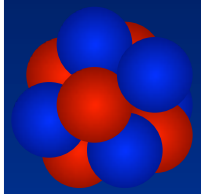
Atoms: *Rutherford's view*





Elementary particles (1932):
Electron, Proton & Neutron

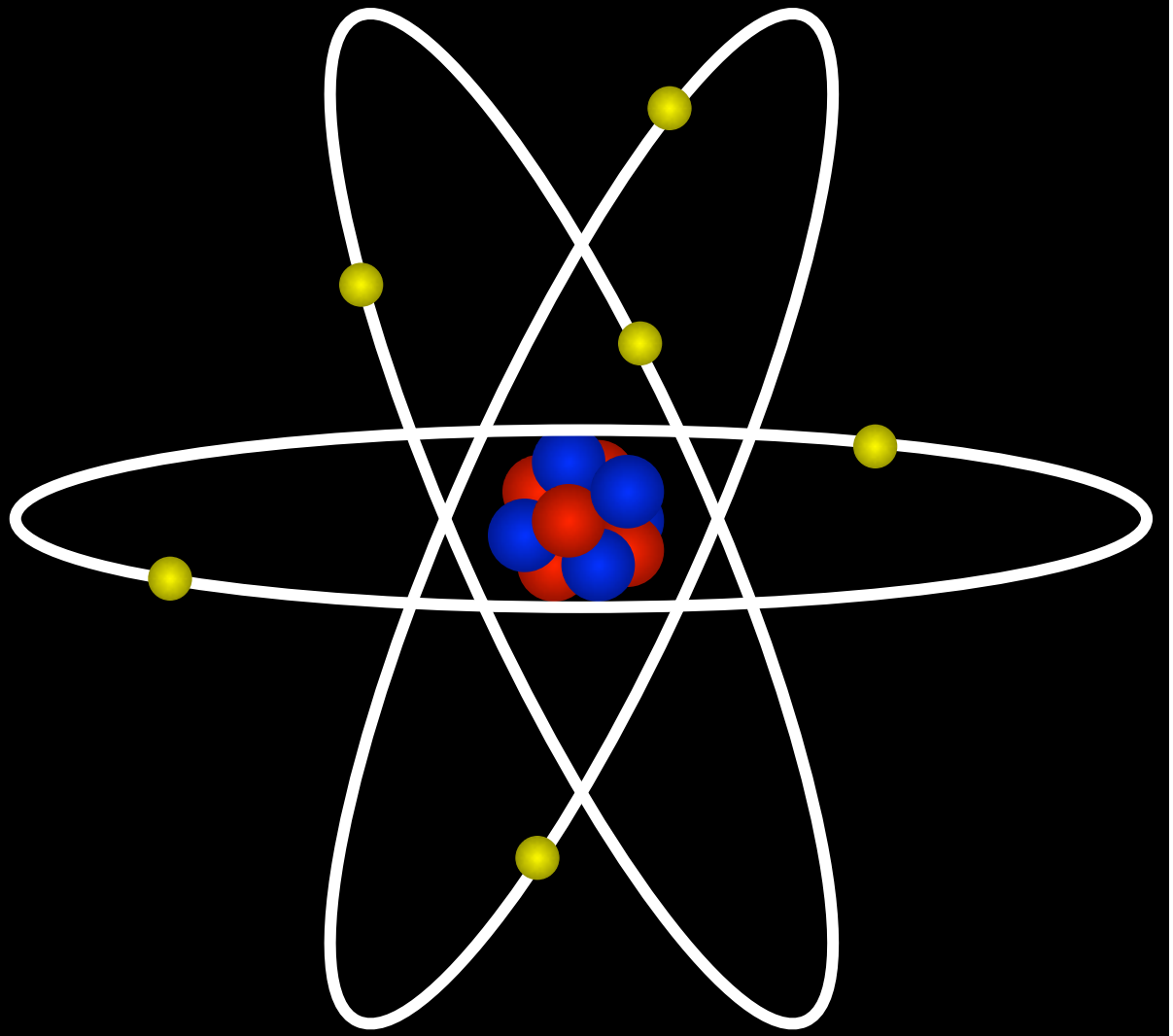
1897
electron
Thomson



1911
nucleus
Rutherford

1911
proton
Rutherford

1932
neutron
Chadwick



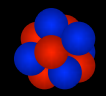
Physics just before 1900

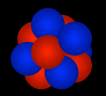
??????? all ok ???????

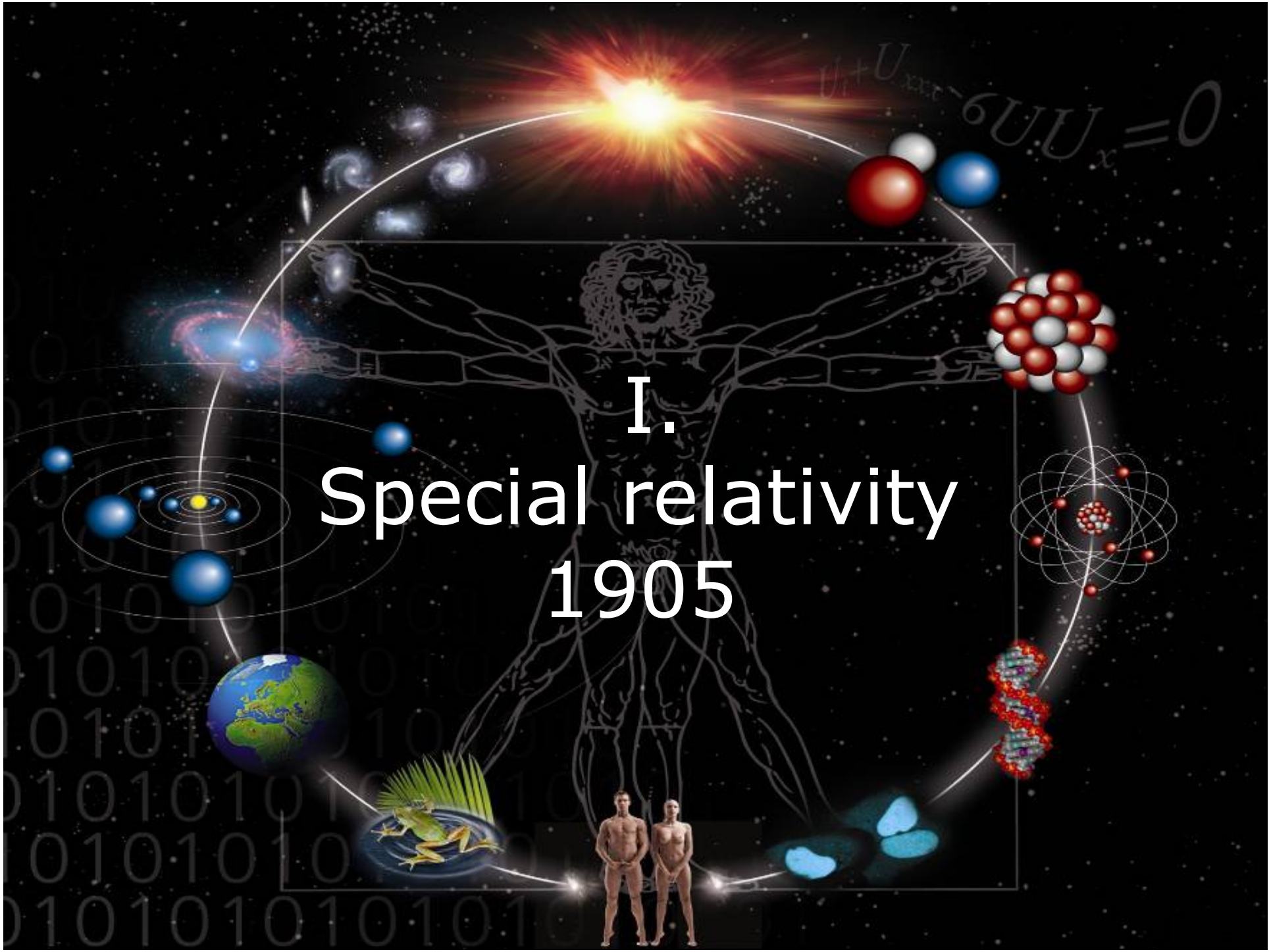
No: *few "minor" problems:*

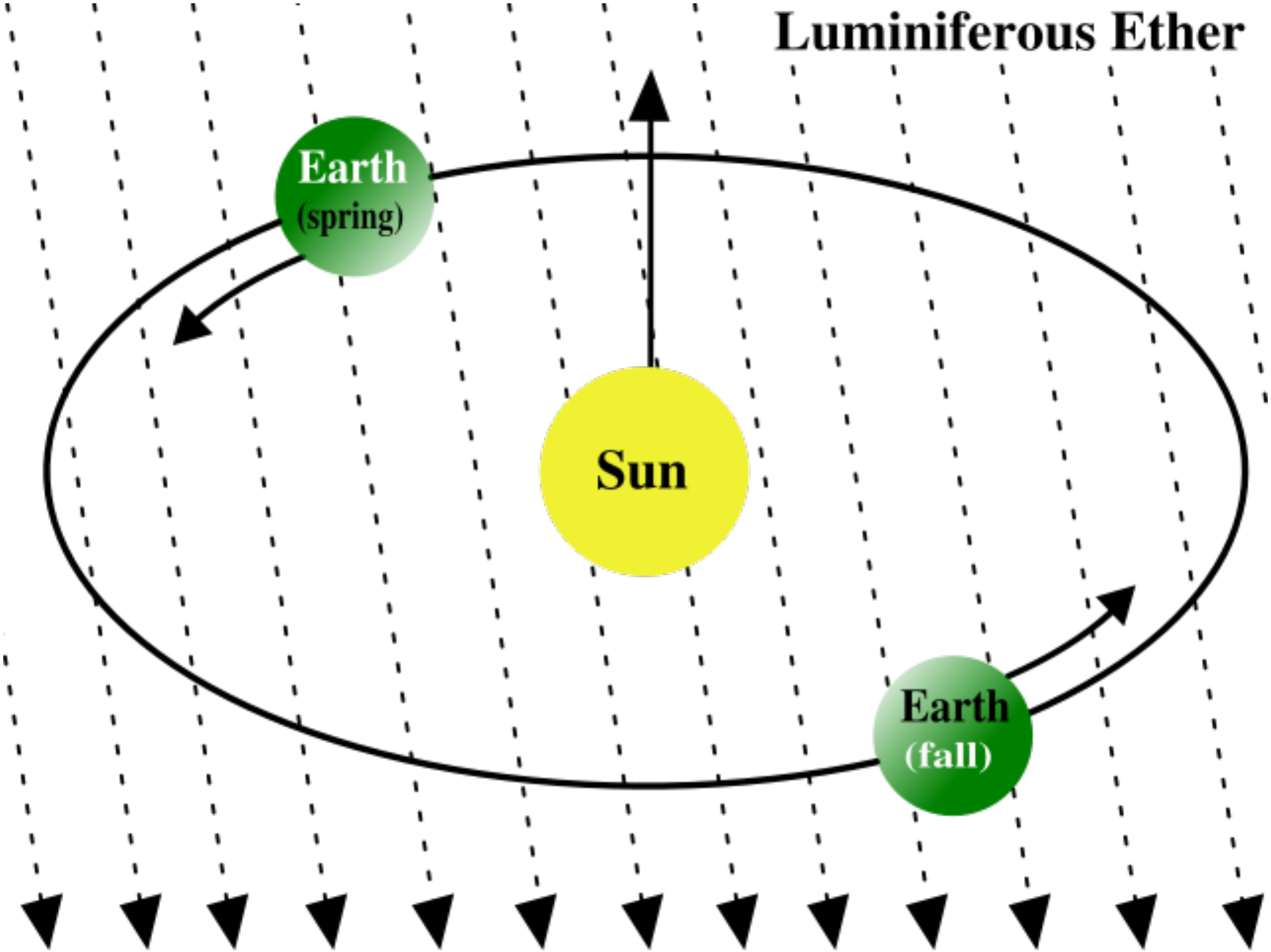
- *"black body" radiation*
- *no eather?*
- *natural radioactivity (Curie et al.)*
- *stability of the Rutherford atom*

Done?

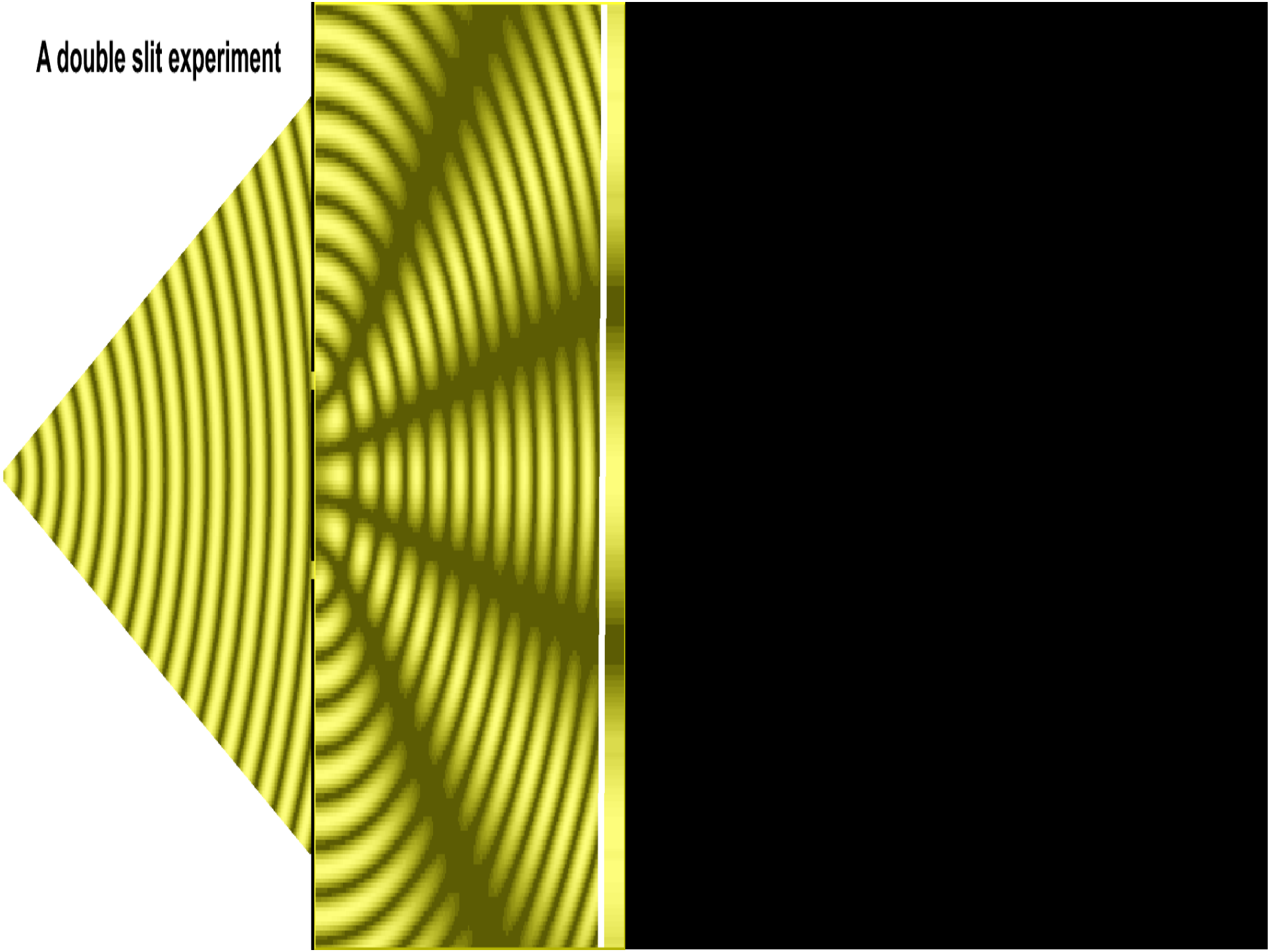




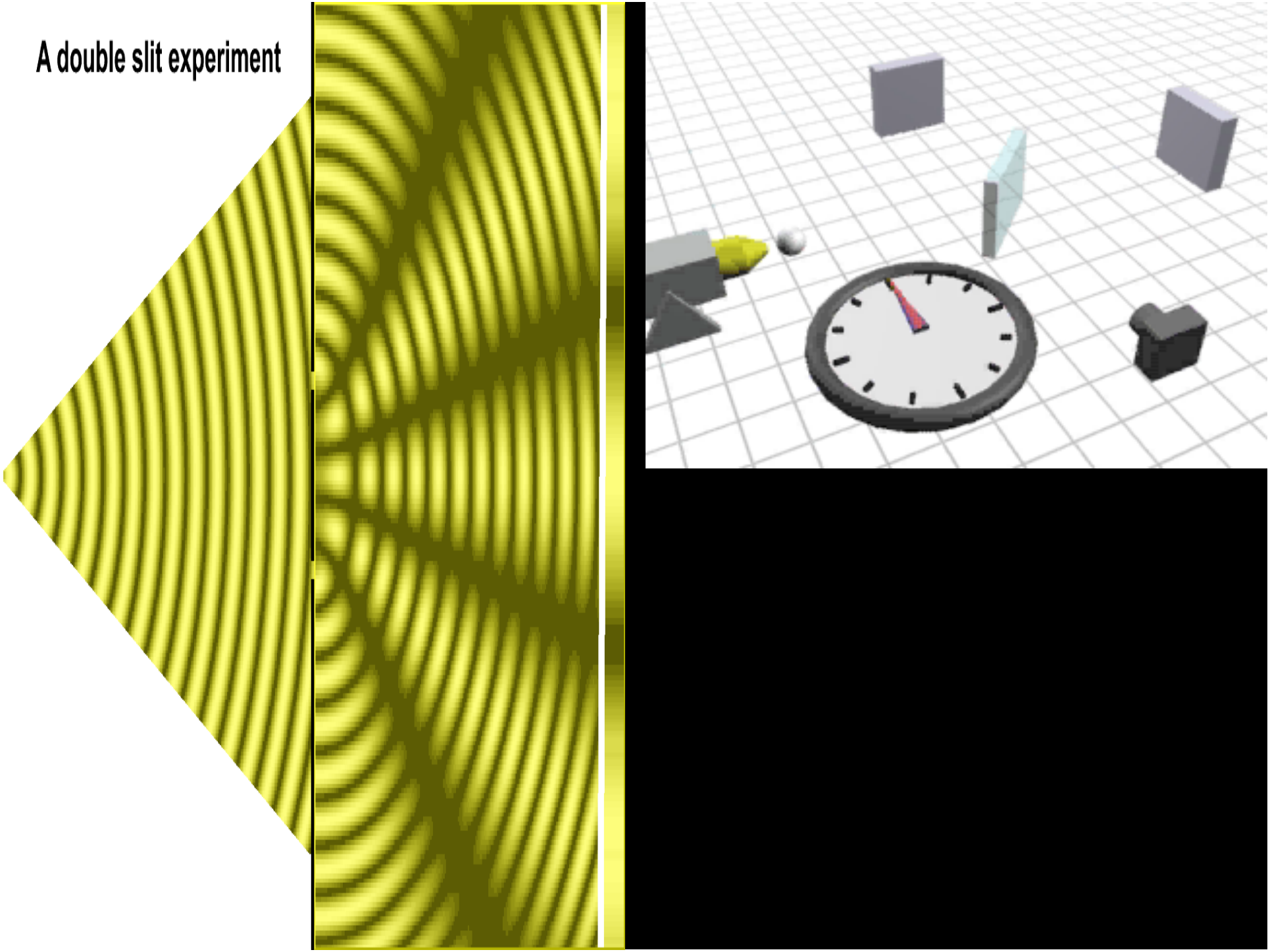

I.
Special relativity
1905


Luminiferous Ether
Earth
(spring)
Sun
Earth
(fall)

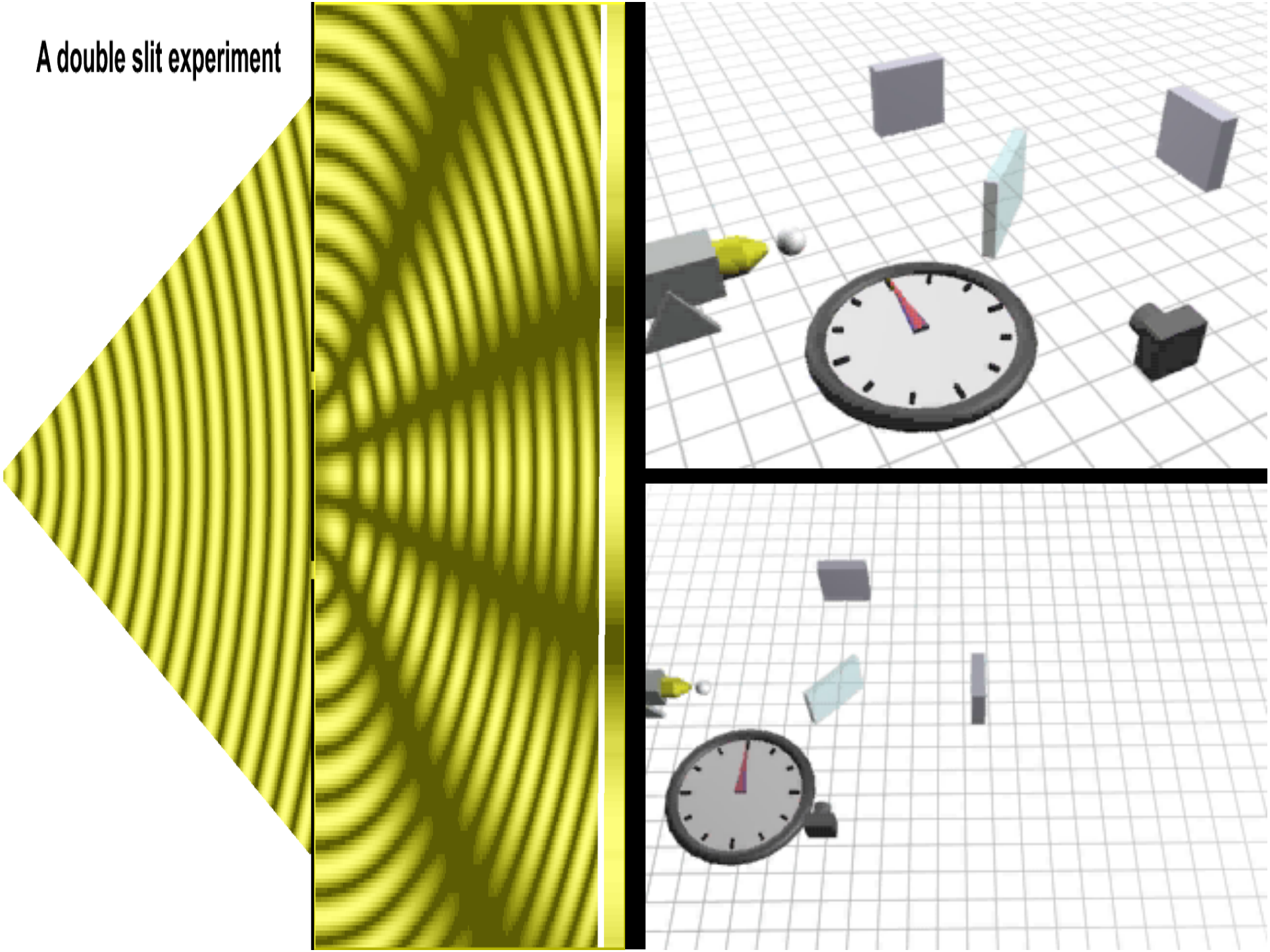
A double slit experiment



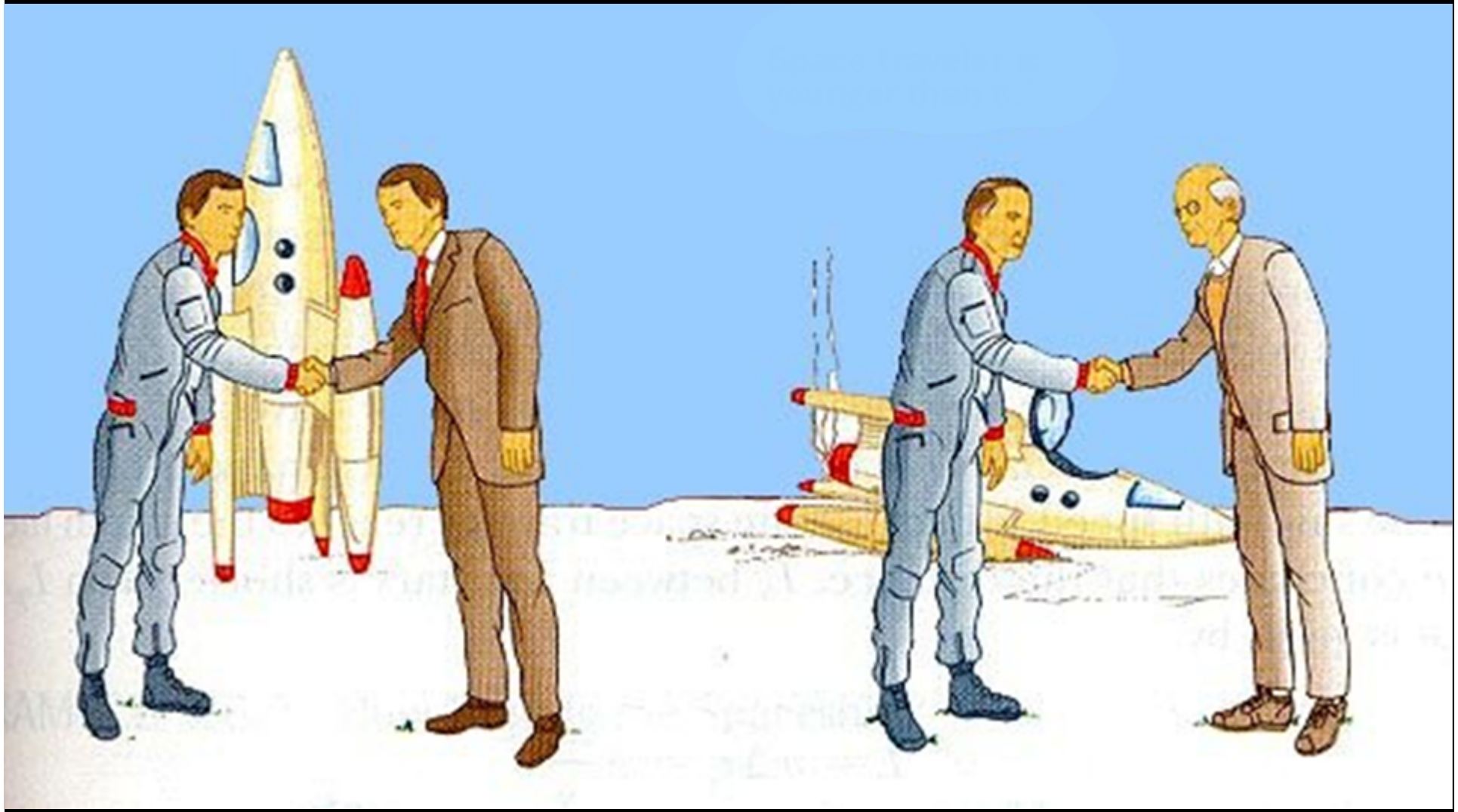
A double slit experiment



A double slit experiment

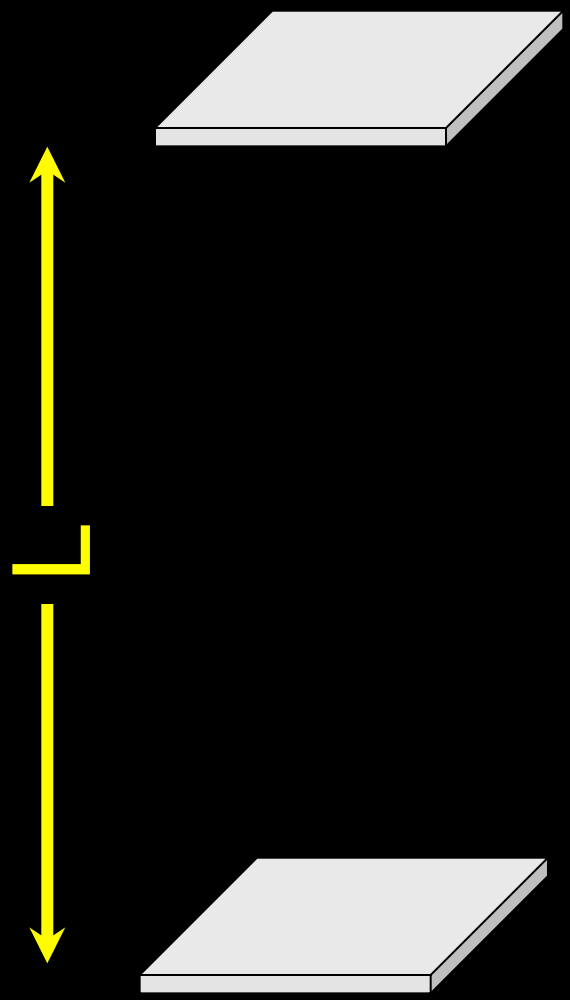


Intermezzo: ***Einstein*** *& relativity*



Time travel becomes a reality!

‘click’ of the light clock *at rest*: t



‘hence-and-forward’
light flash period t:

$$t = \frac{2L}{c}$$

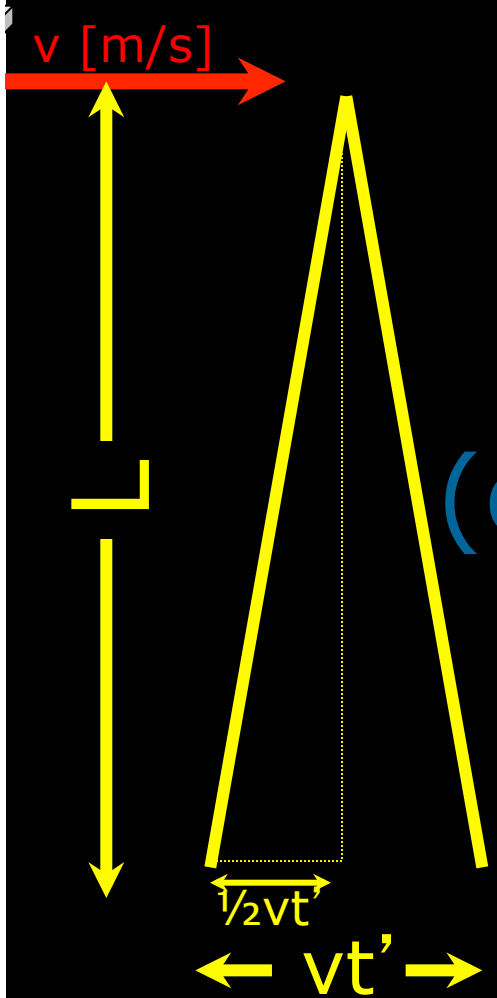
c=299792458 m/s (exact)

observer at rest

c=299792458 m/s (exact)

'click' of the *moving* light clock: t'

'hence-and-forward' light flash period: t'



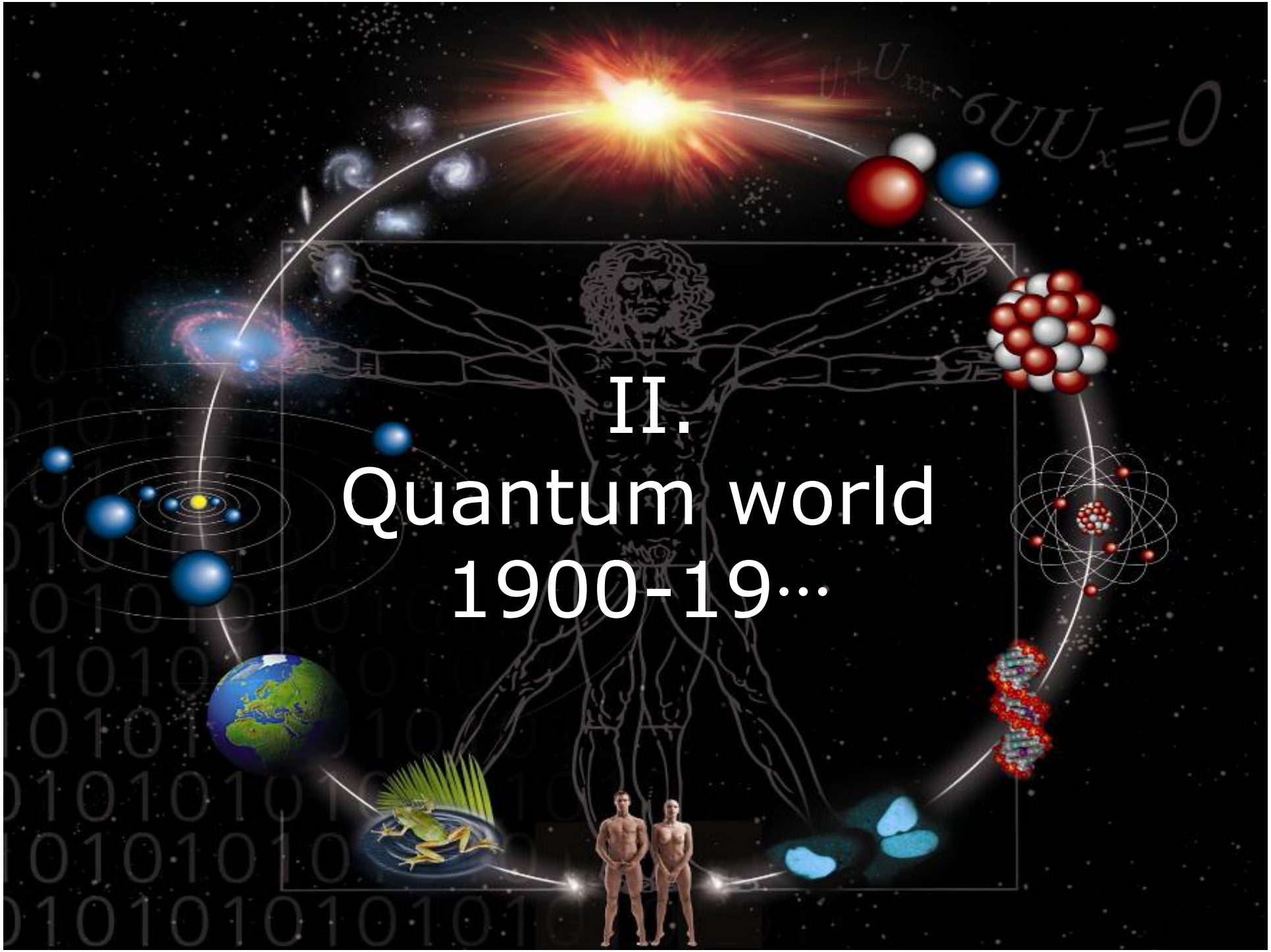
$$t' = \frac{2\sqrt{L^2+(\tfrac{1}{2}vt')^2}}{c}$$

$$(ct')^2 = 4L^2+(vt')^2$$

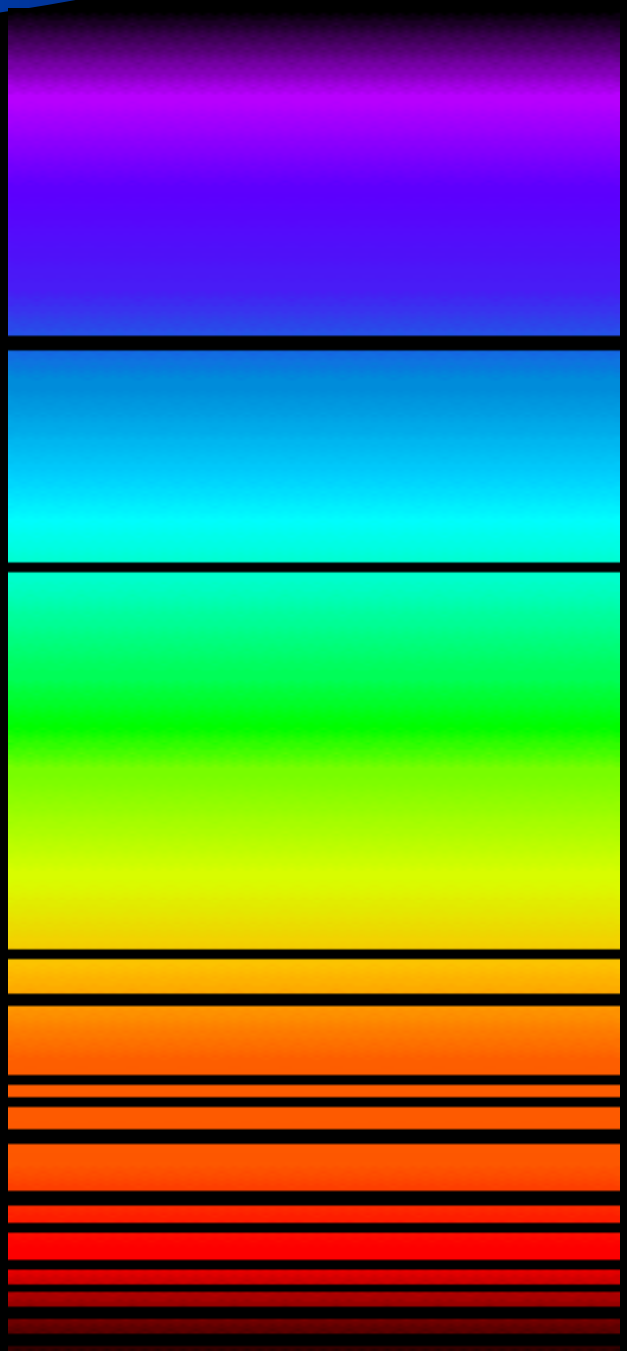
$$t' = \frac{2L}{\sqrt{c^2-v^2}} = \frac{t}{\sqrt{1-v^2/c^2}} \geq t$$

Moving clock 'clicks' slower!

observer moving with velocity v

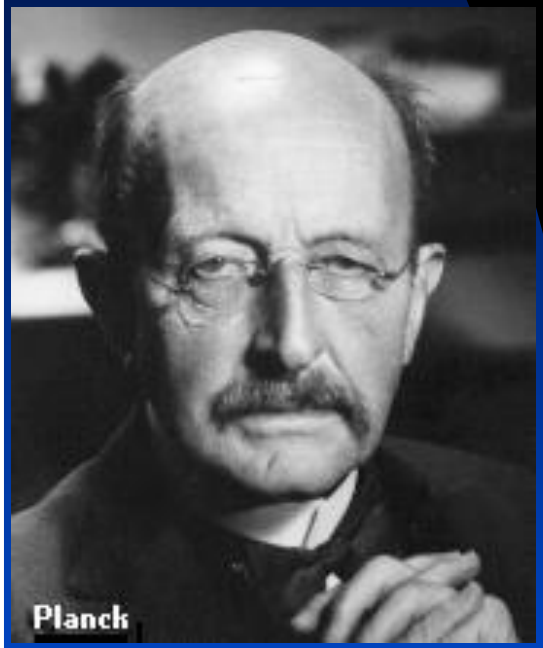

II.
Quantum world
1900-19…

Imagination



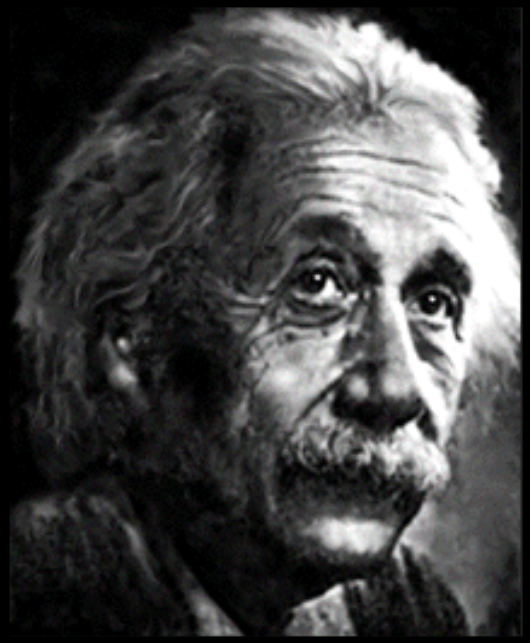
Light: *quantum effects*

Planck
1900



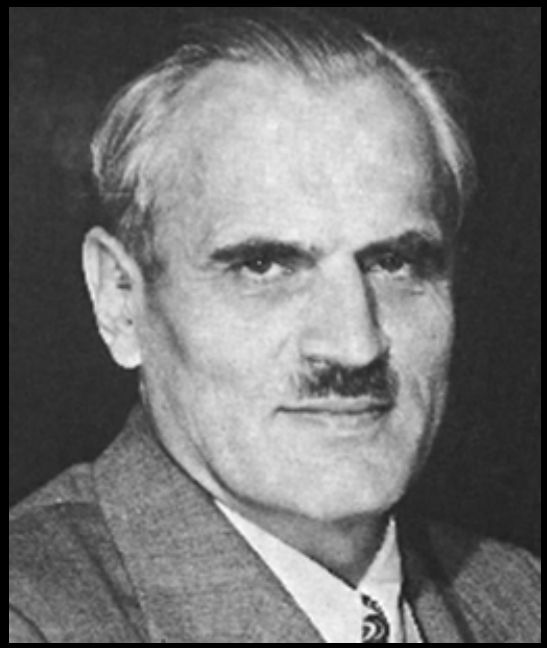
Planck (1858-1947)

Einstein
1905



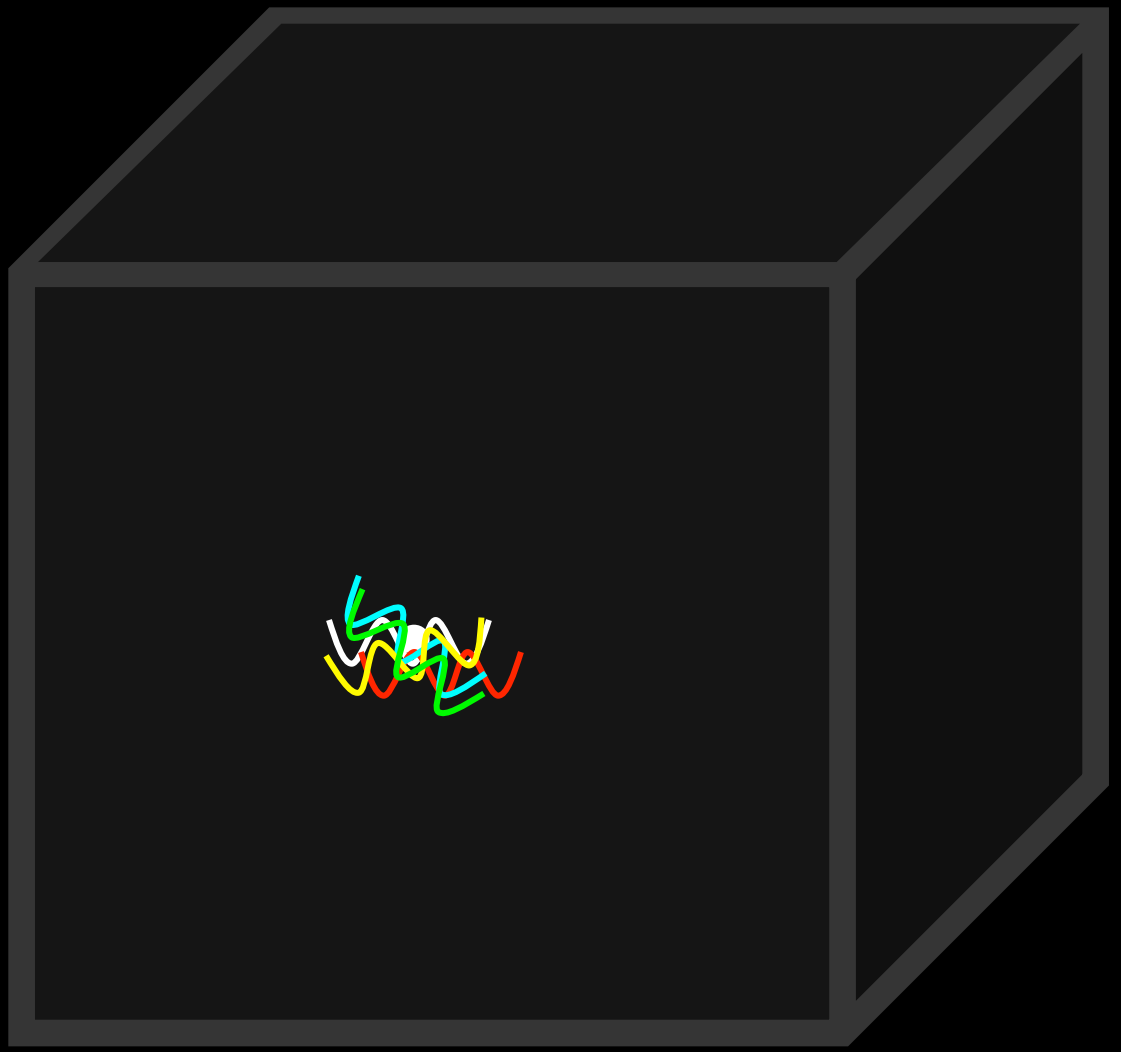
Einstein (1879-1955)

Compton
1922



Compton (1892-1962)

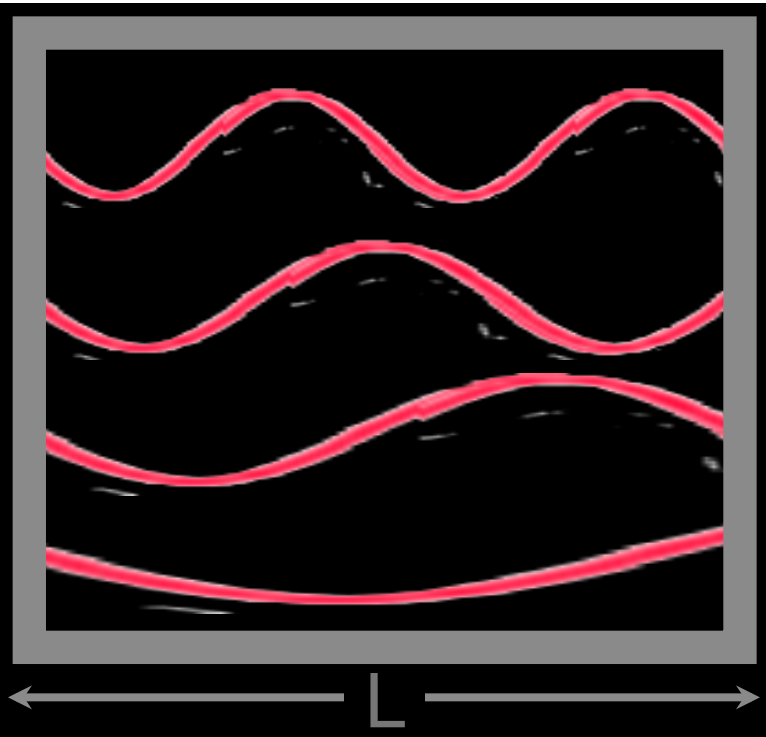
I. *Black body radiation*



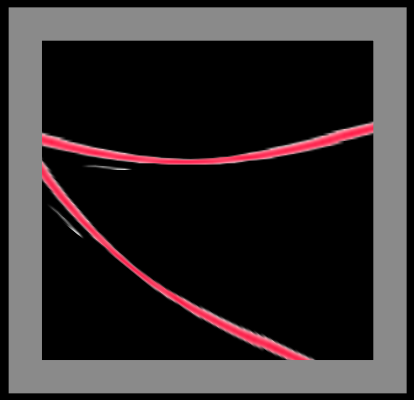
Planck 1900

Stacking waves!

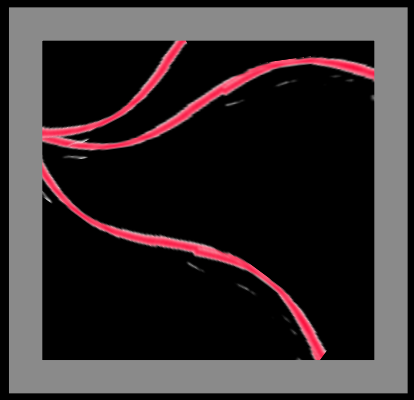
Fit ½, 1, 1½, 2, etc. wavelengths in box such that amplitude=0 on walls



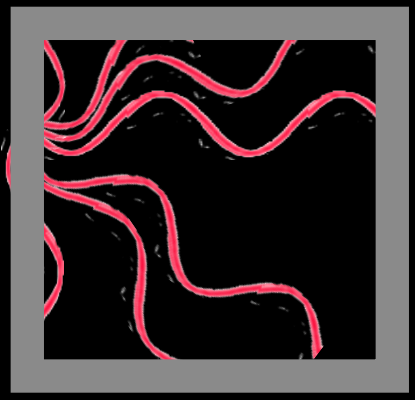
Easier to fit short wavelengths!



$\lambda = 2 \times L$

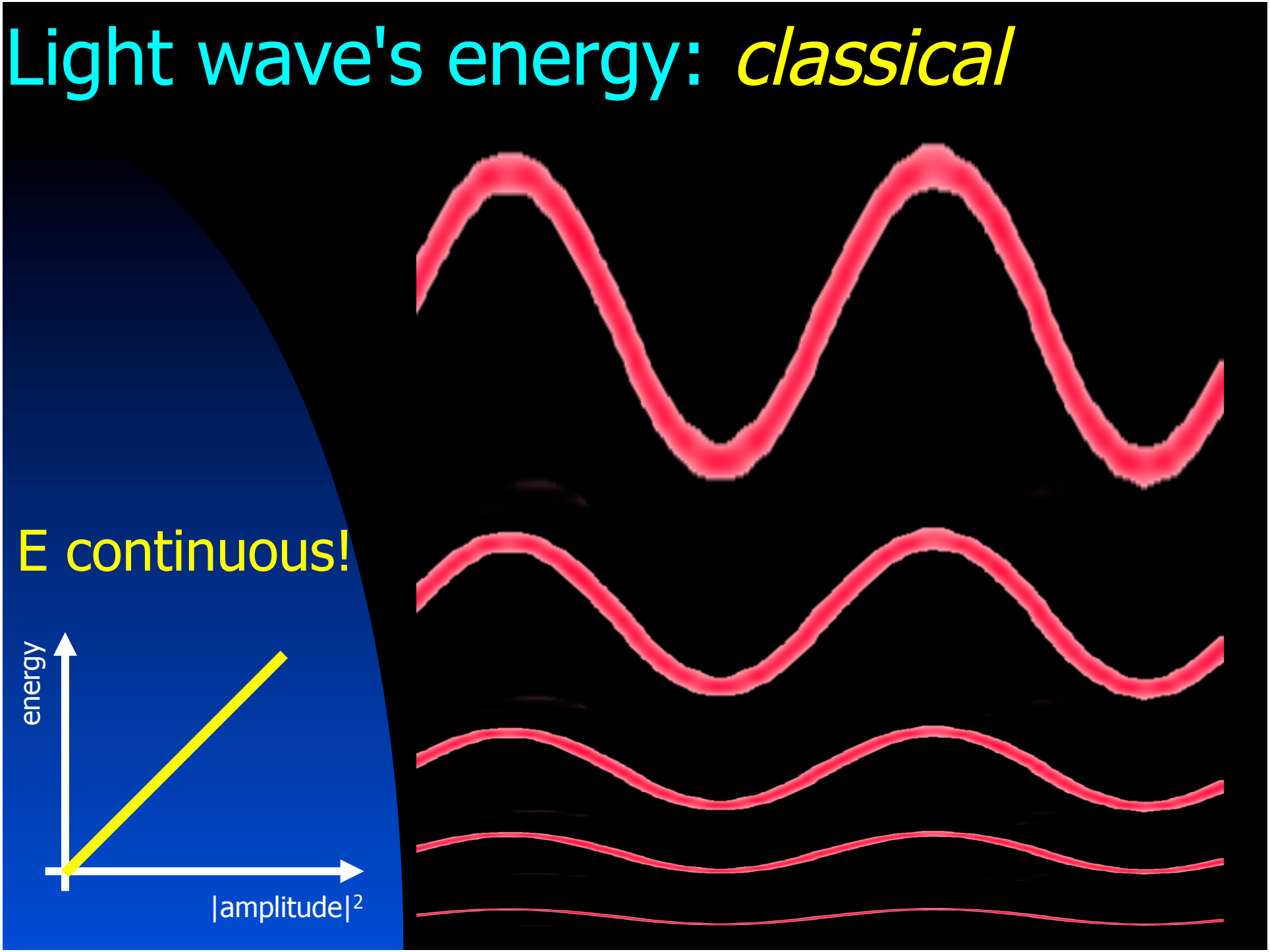


$\lambda = 1 \times L$

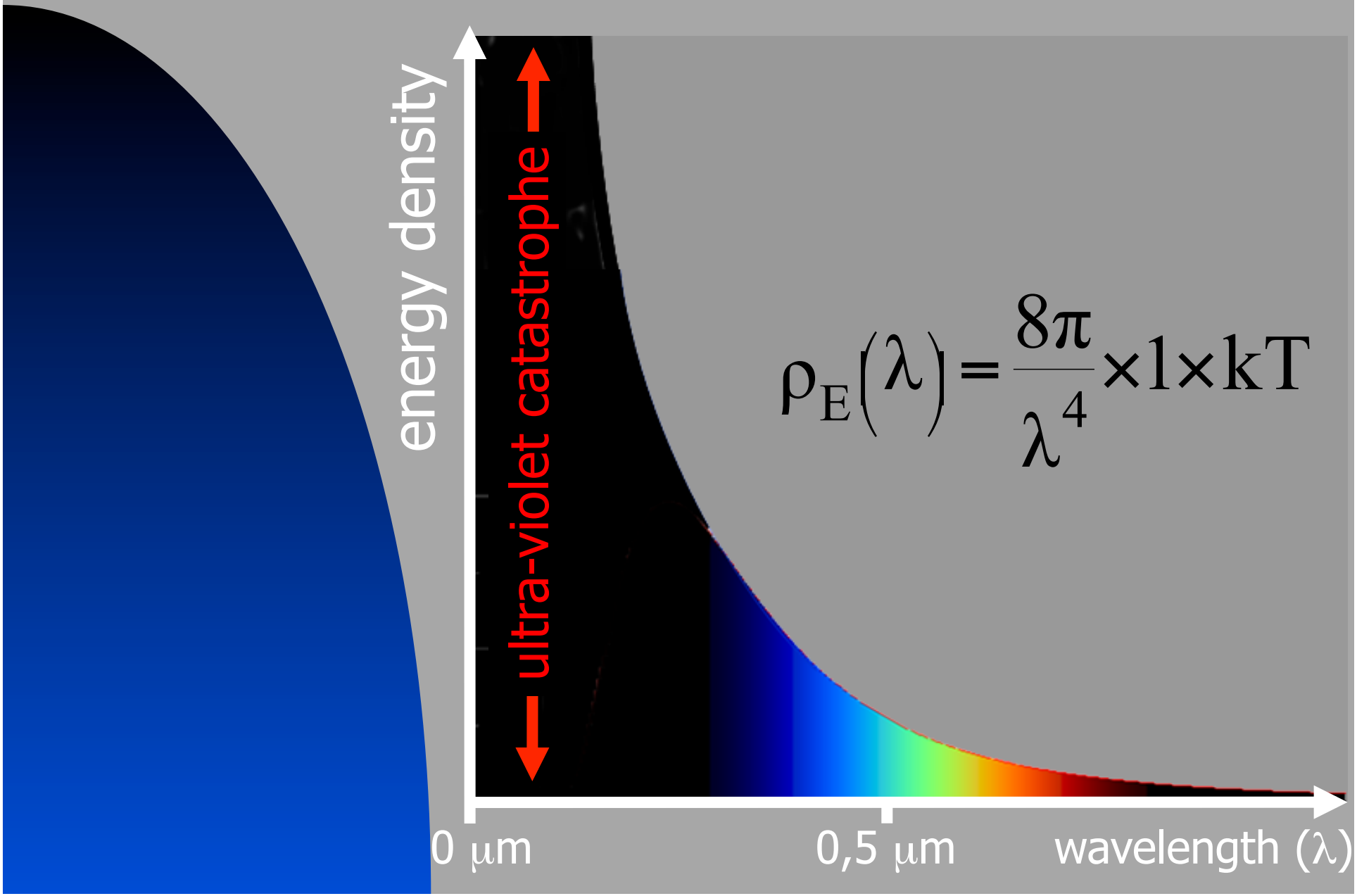


$\lambda = \frac{1}{2} \times L$

Light wave's energy: *classical*



Radiated energie spectrum: *classical*

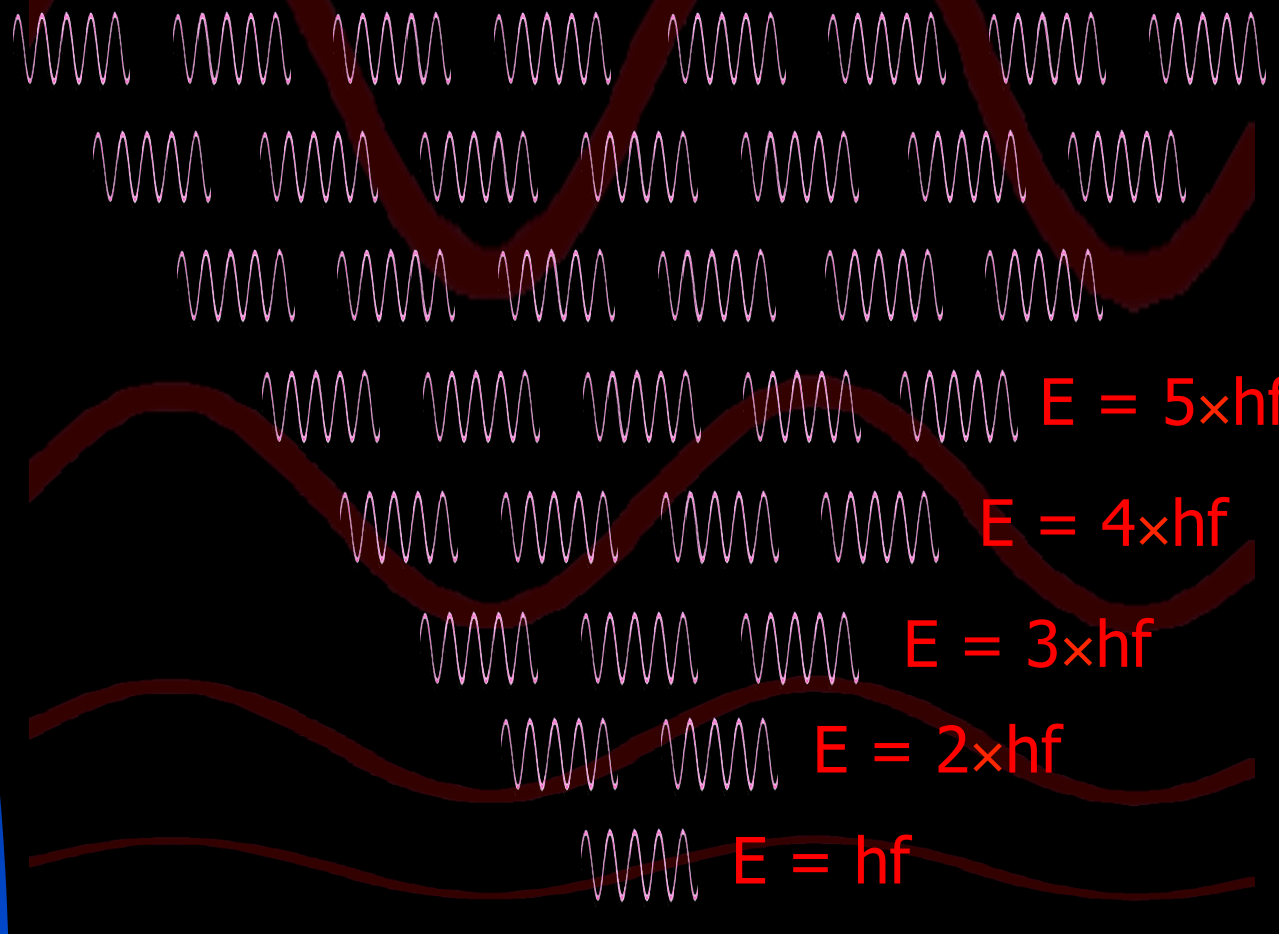


Light wave's energy: *quantum*

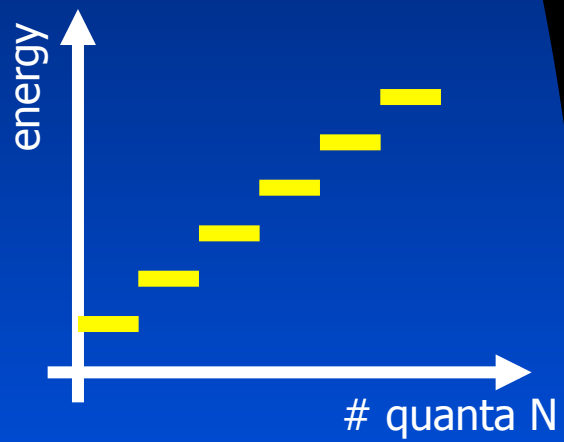
$E = N \times hf$

Planck's constant

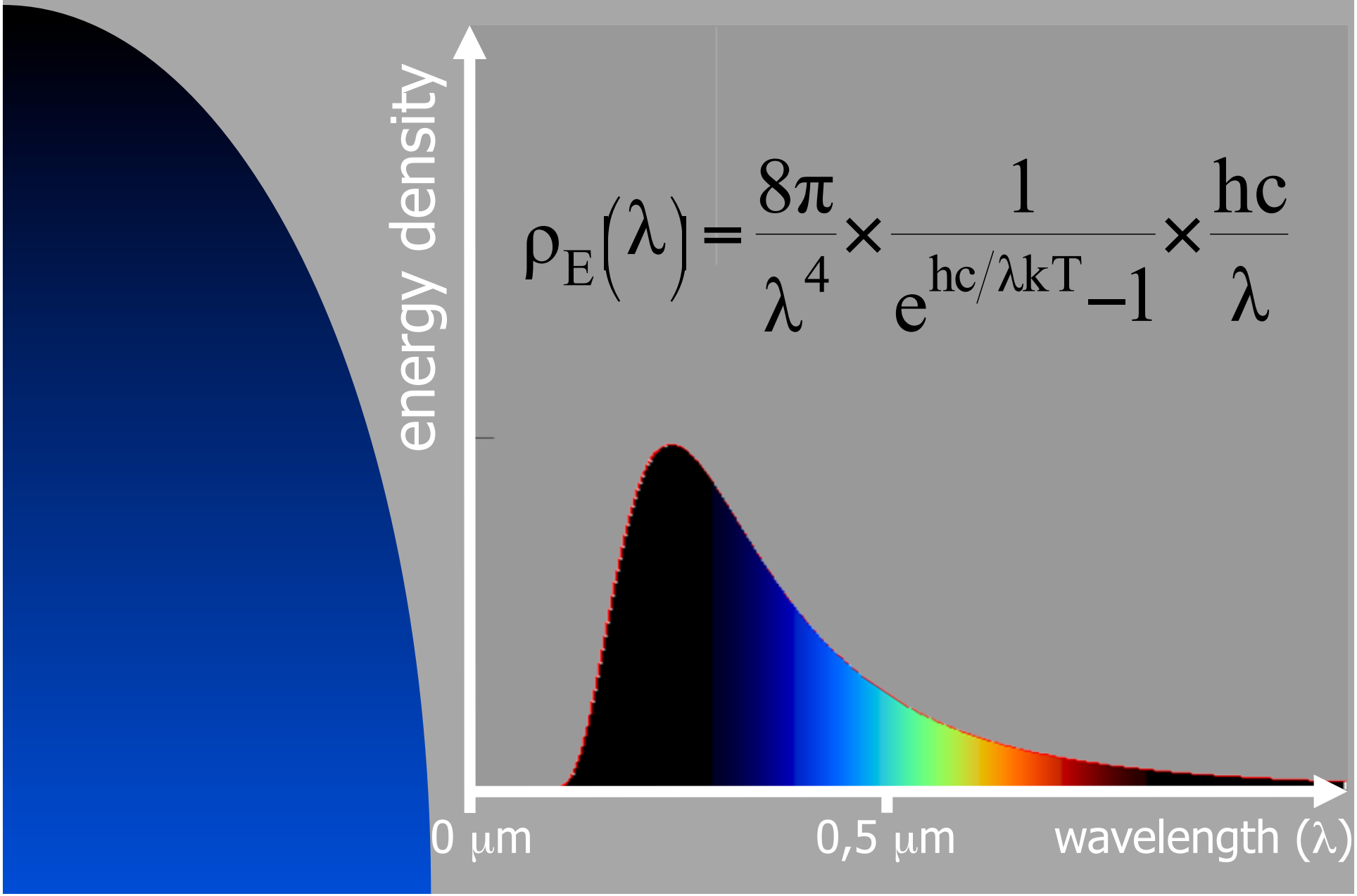
$h = 6.6260688 \times 10^{-34}$ J/s



E discrete!



Radiated energy spectrum: *quantum*



Color

the sun

T=2,500 °C

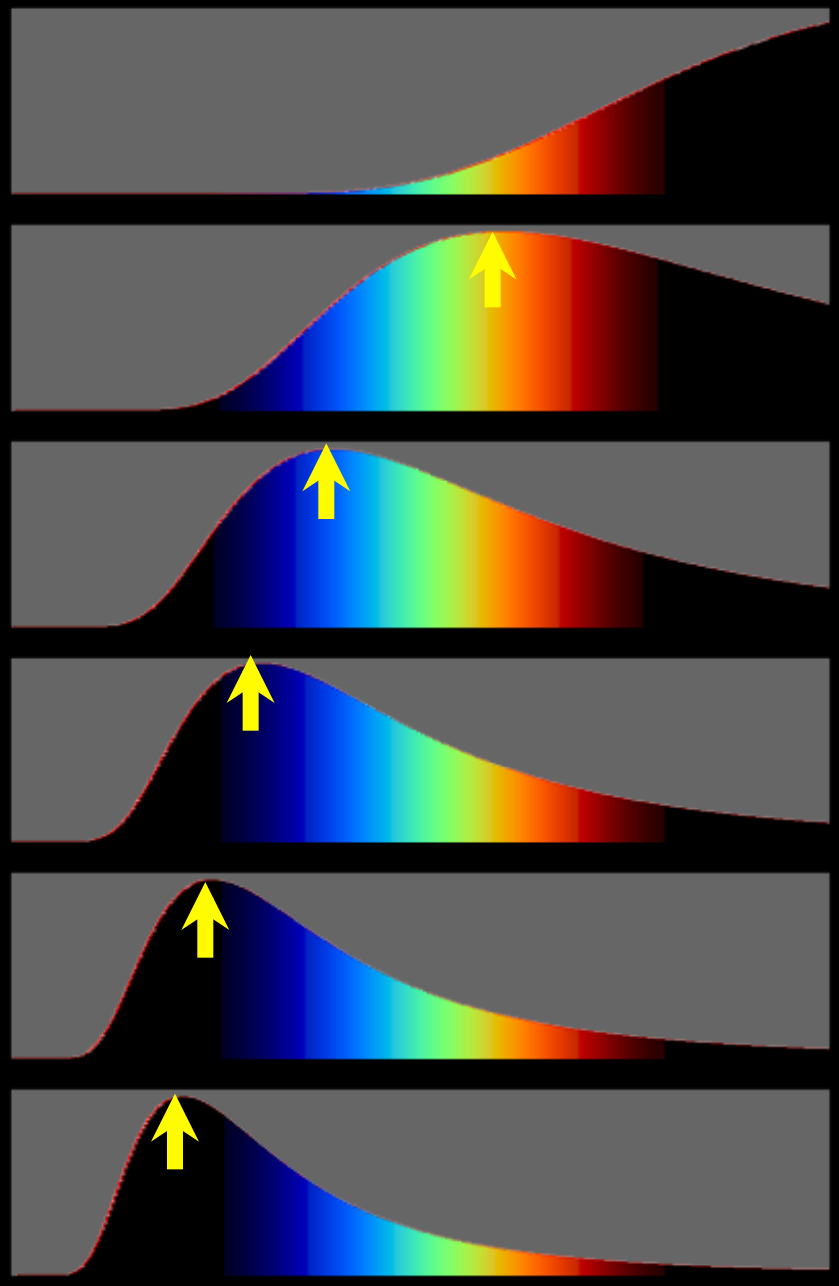
T=5,000 °C

T=7,500 °C

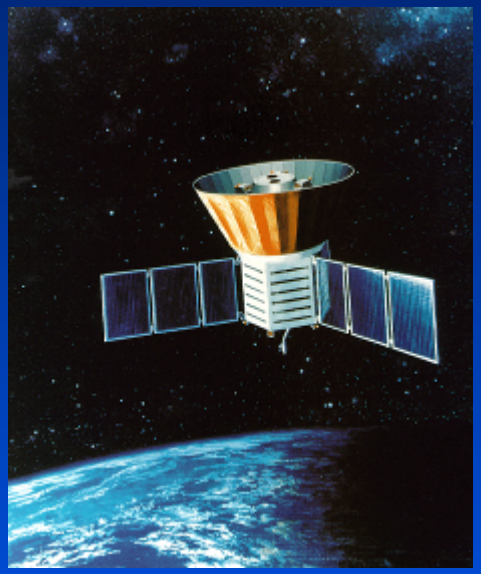
T=10,000 °C

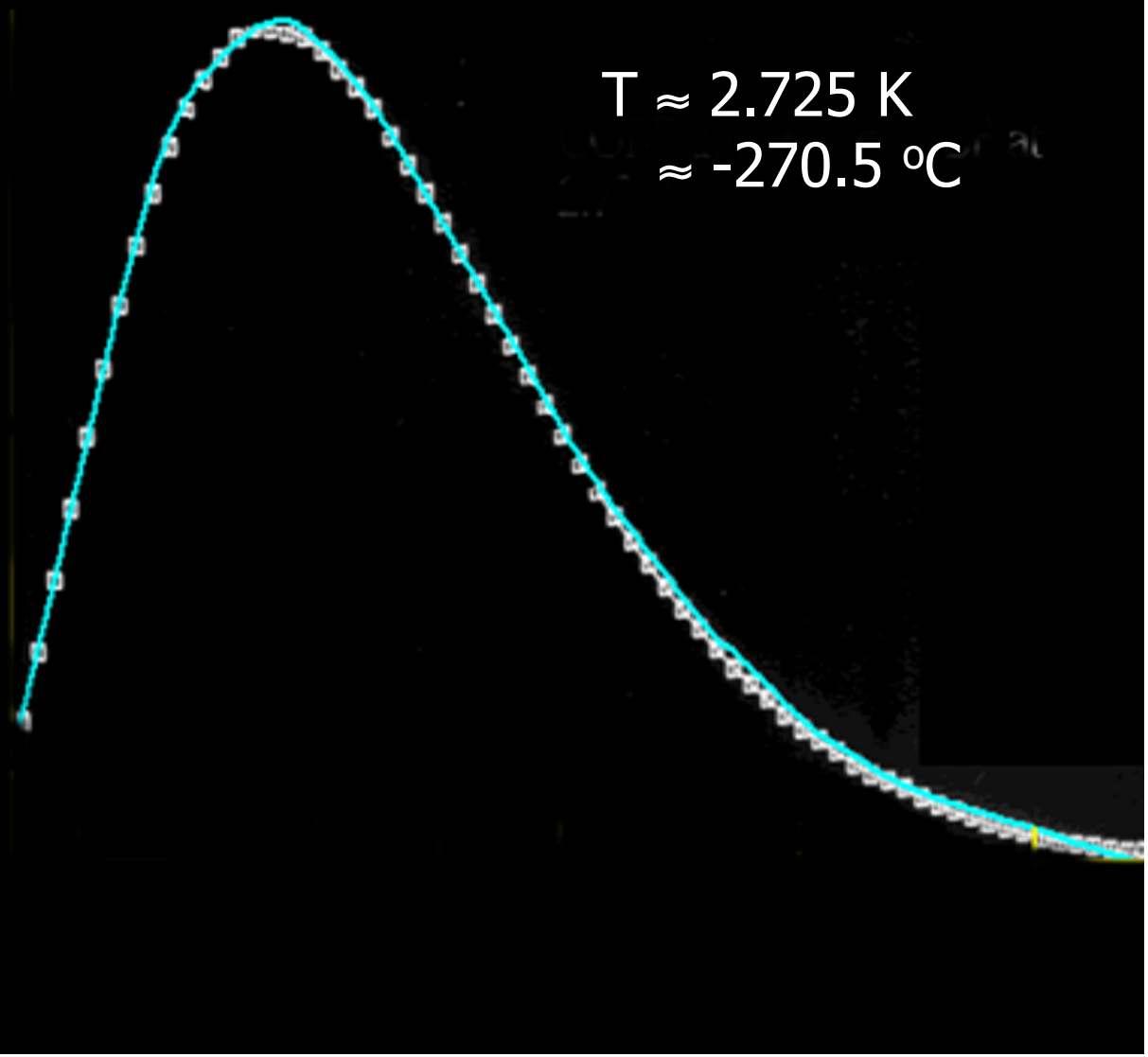
T=12,500 °C

T=15,000 °C

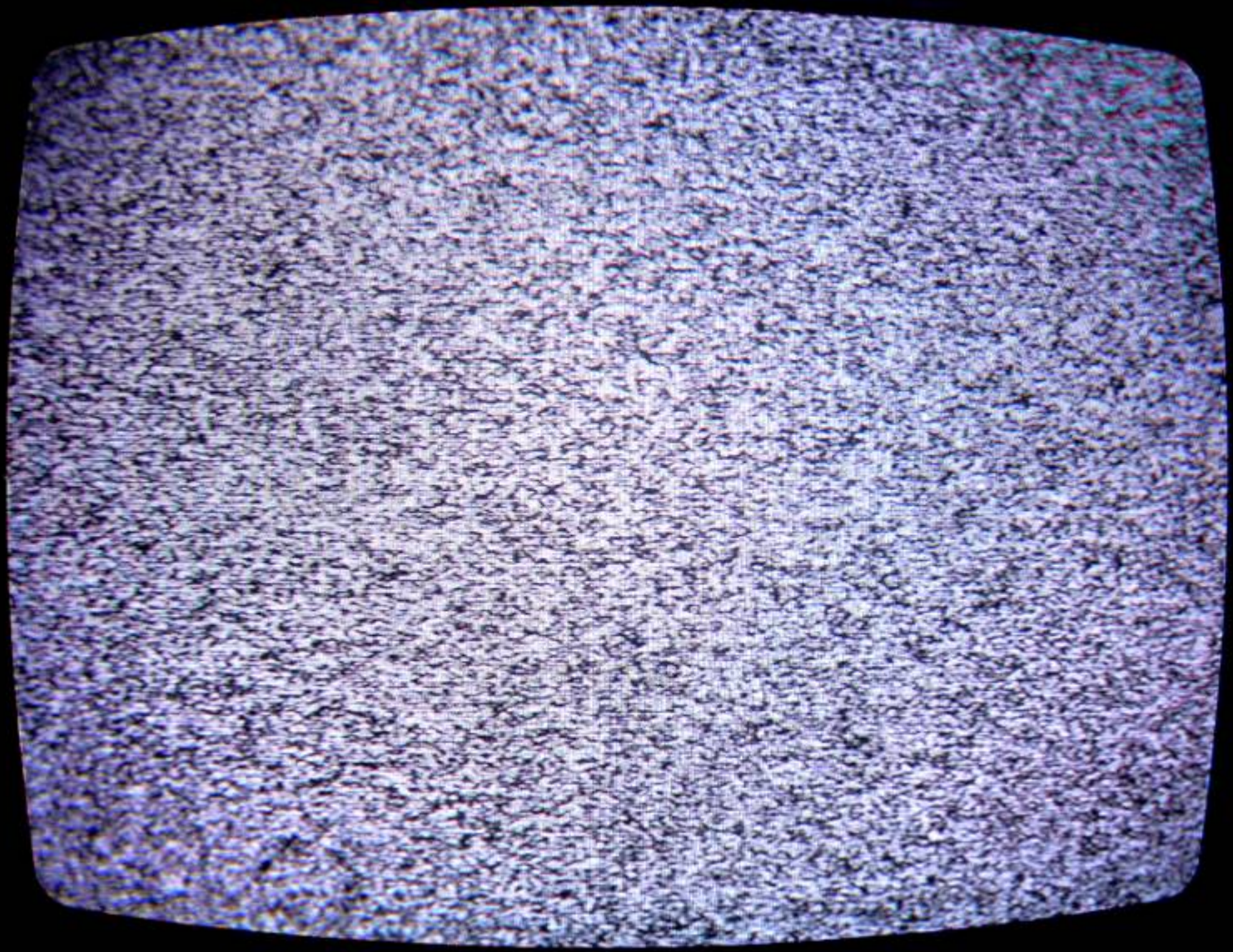


Universe as black body radiator

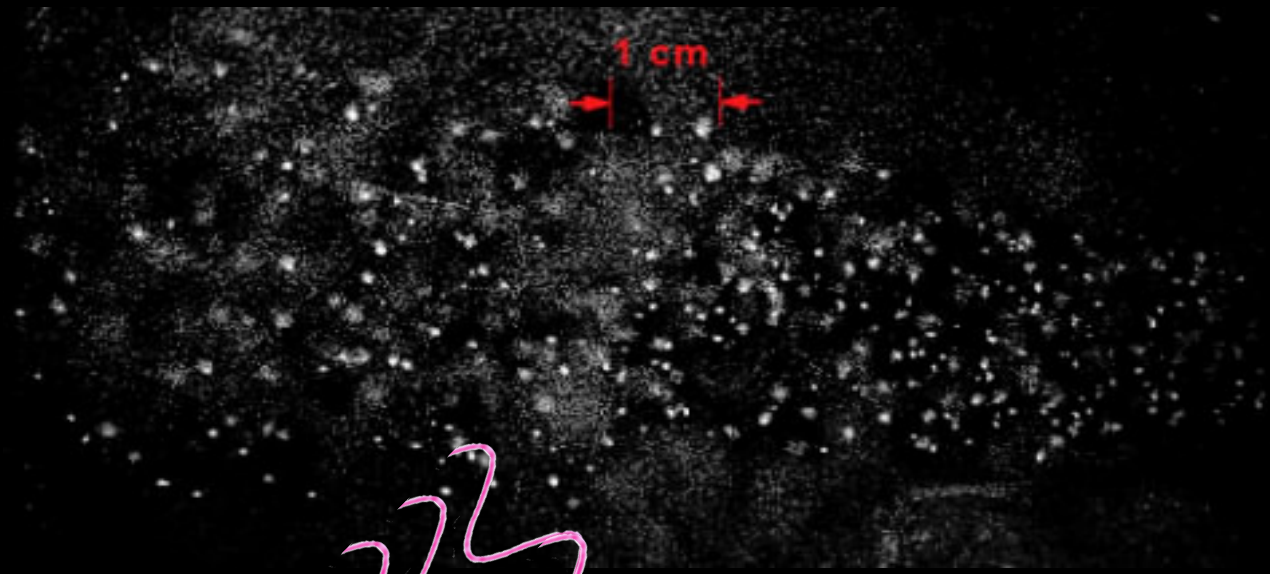


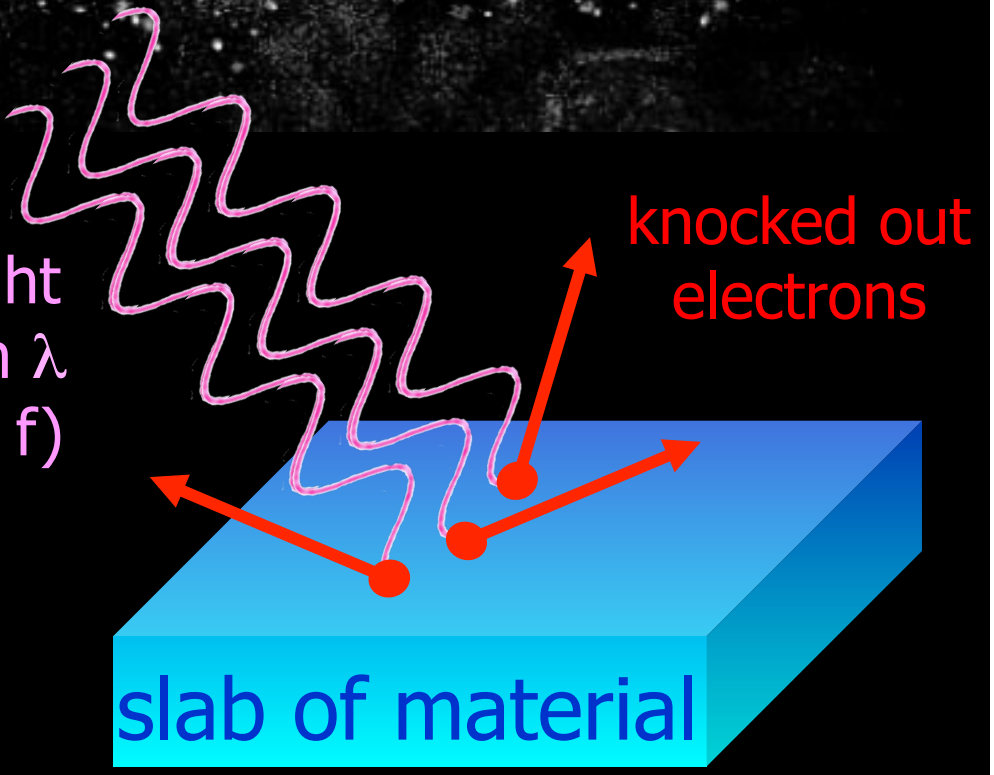


Big Bang's afterglow *on your TV*



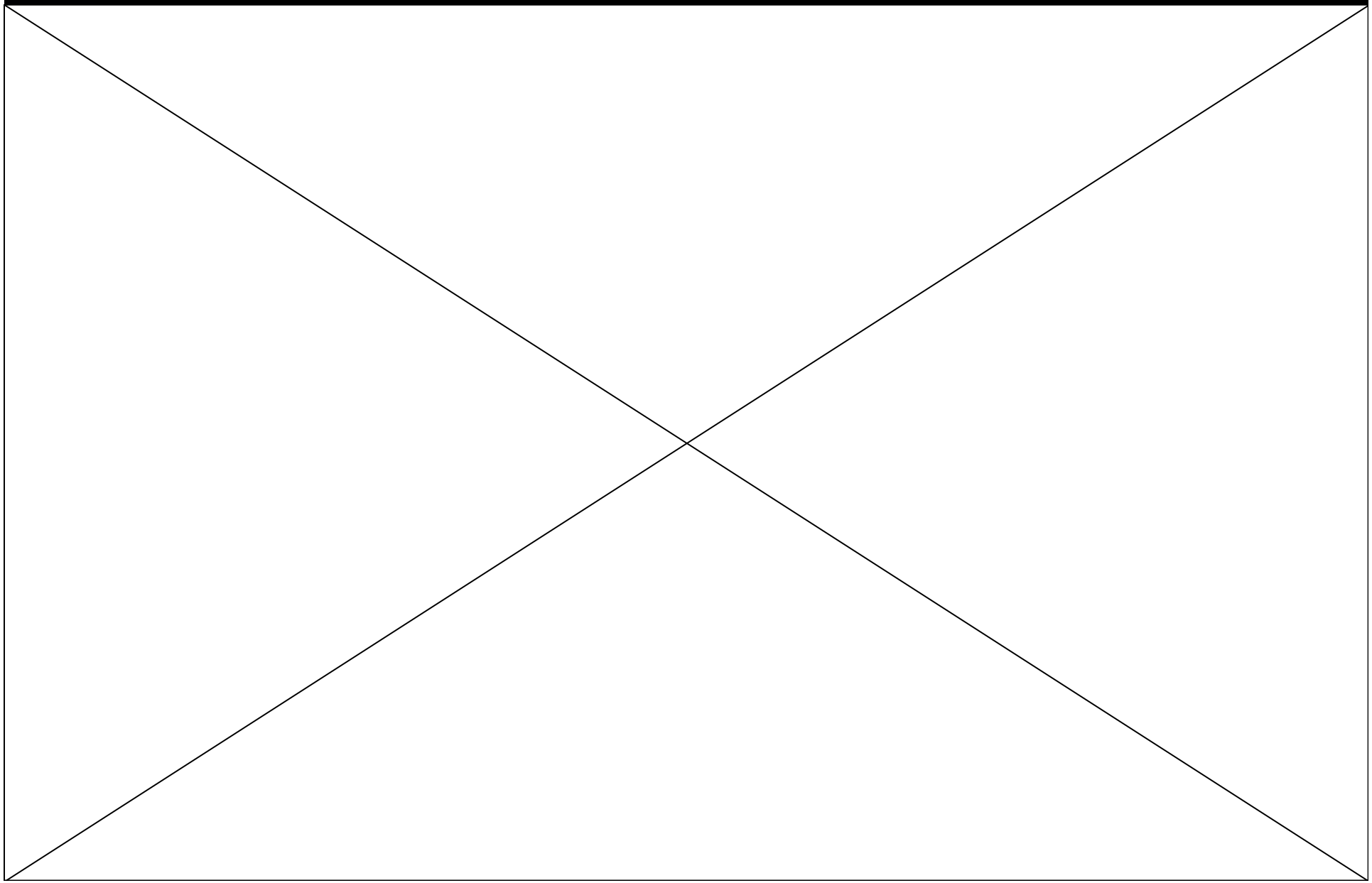
II. *Photo electric effect*



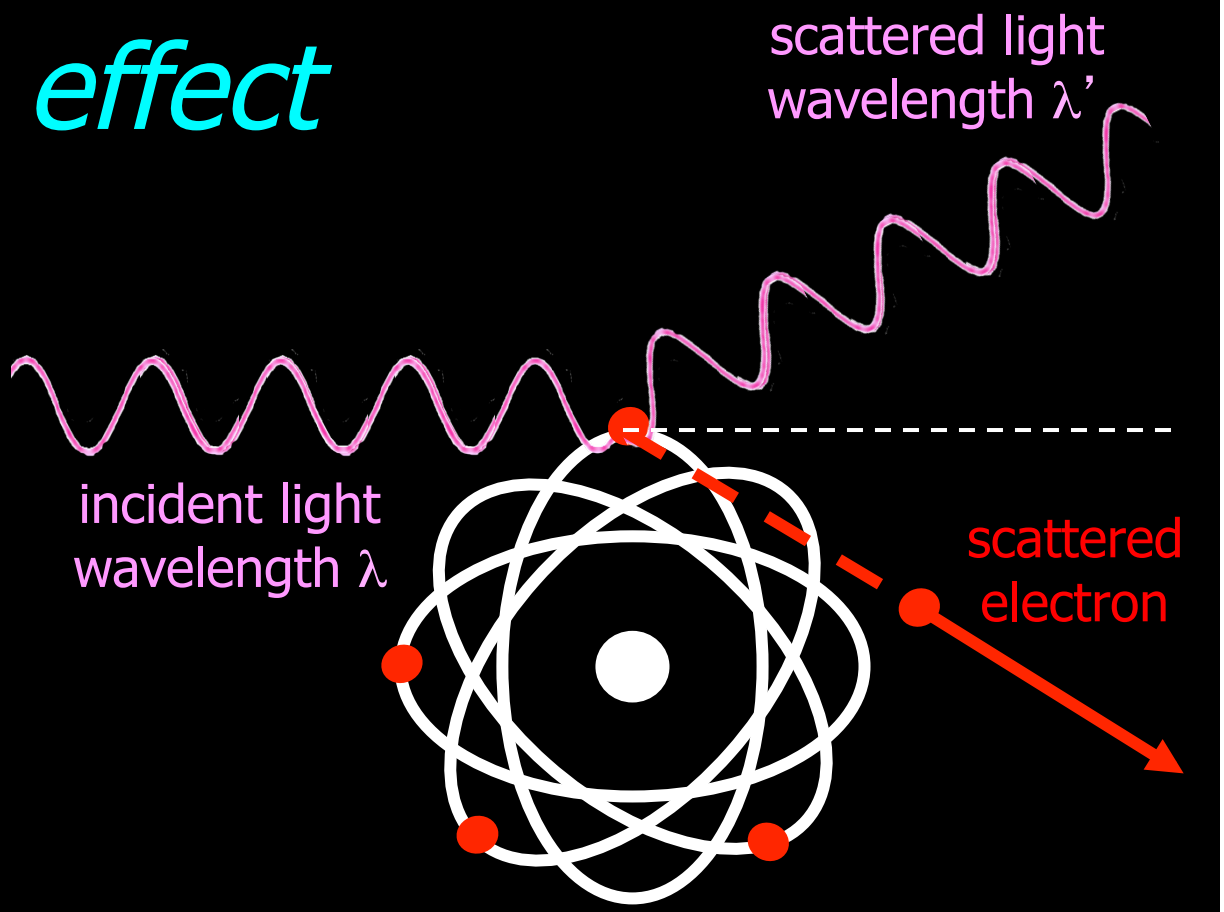


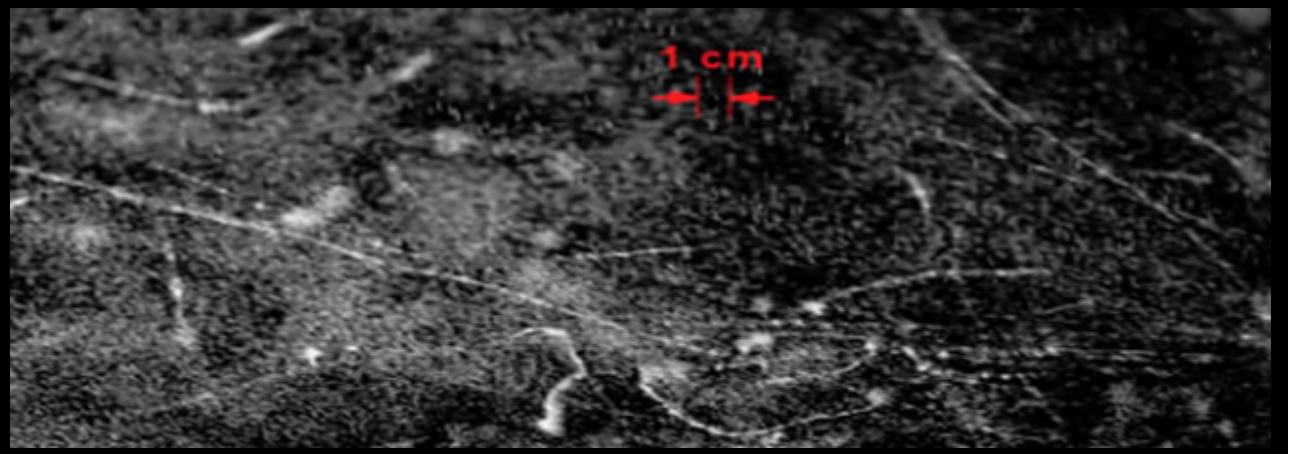
Einstein 1905

Photo-electric effect



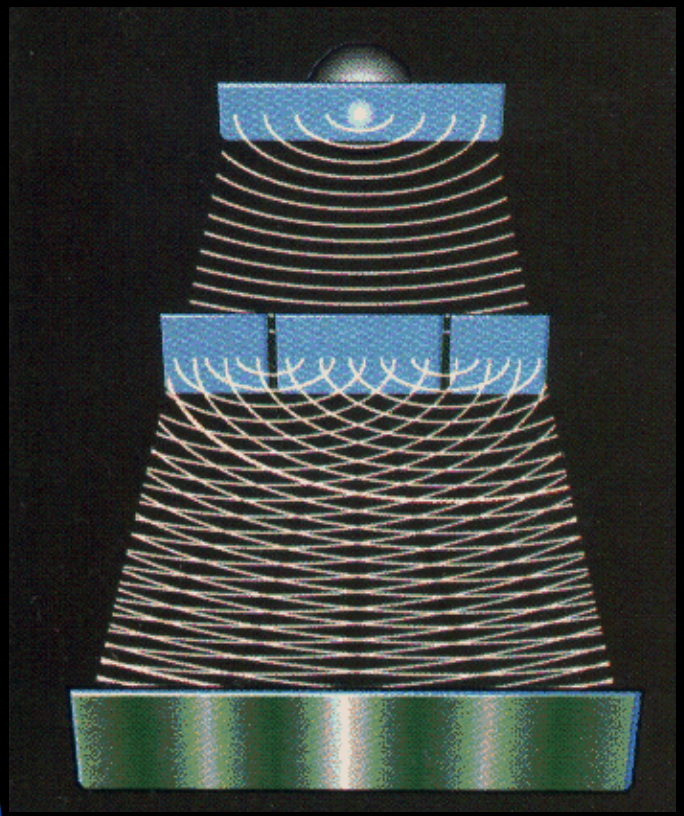
III. *Compton effect*

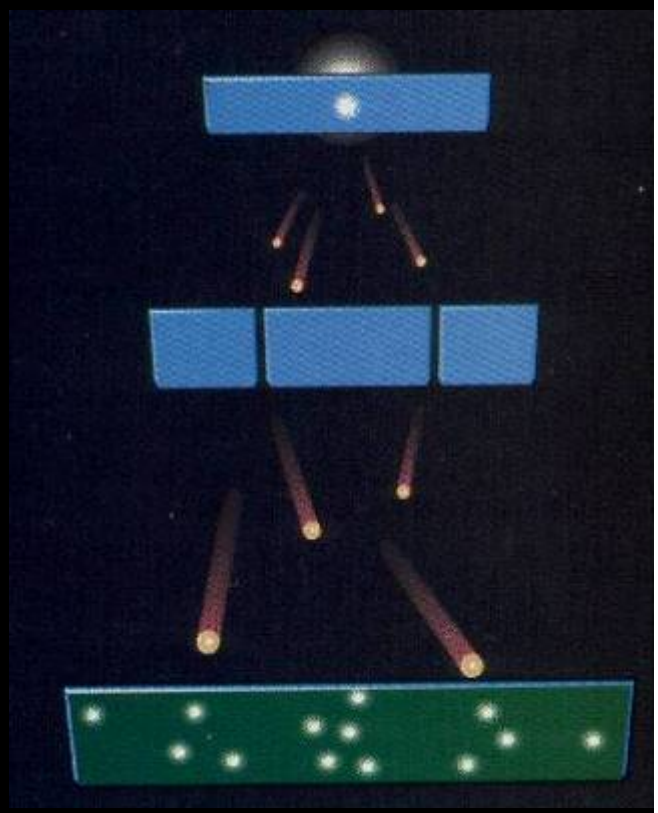




Compton 1922

Duality: *wave & particle characteristics*





It is safe to say that nobody understands quantum mechanics. R.P. Feynman

Quantum mechanics is magic.
Daniel Greenberger.

Everything we call real is made of things that cannot be regarded as real.
Niels Bohr.

Those who are not shocked when they first come across quantum theory cannot possibly have understood it.
Niels Bohr.

If you are not confused by quantum mechanics, you do not understand it.
John Wheeler.

If quantum theory is correct, it signifies the end of physics as a science.
Albert Einstein.

I do not like quantum mechanics; I am sorry I ever had anything to do with it.
Erwin Schrödinger.

more quotes

Atom: *quantum effects*

Bohr
1910

Bohr (1885-1962)

Heisenberg
1925

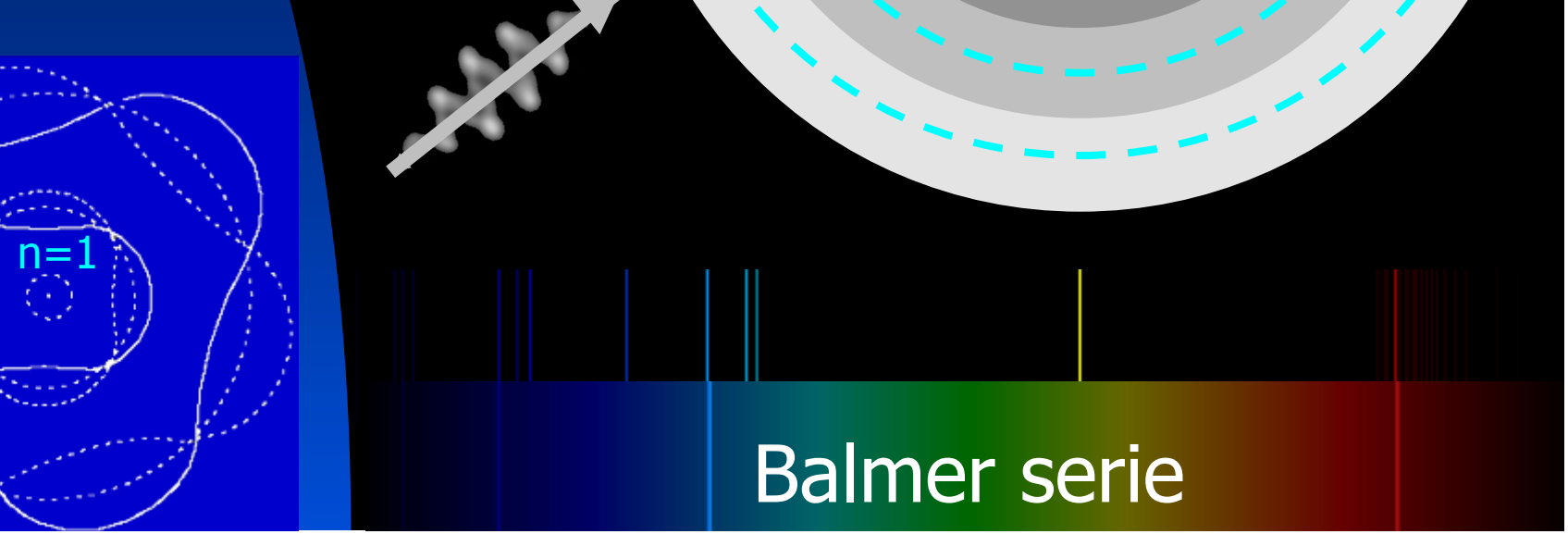
Heisenberg (1901-1976)

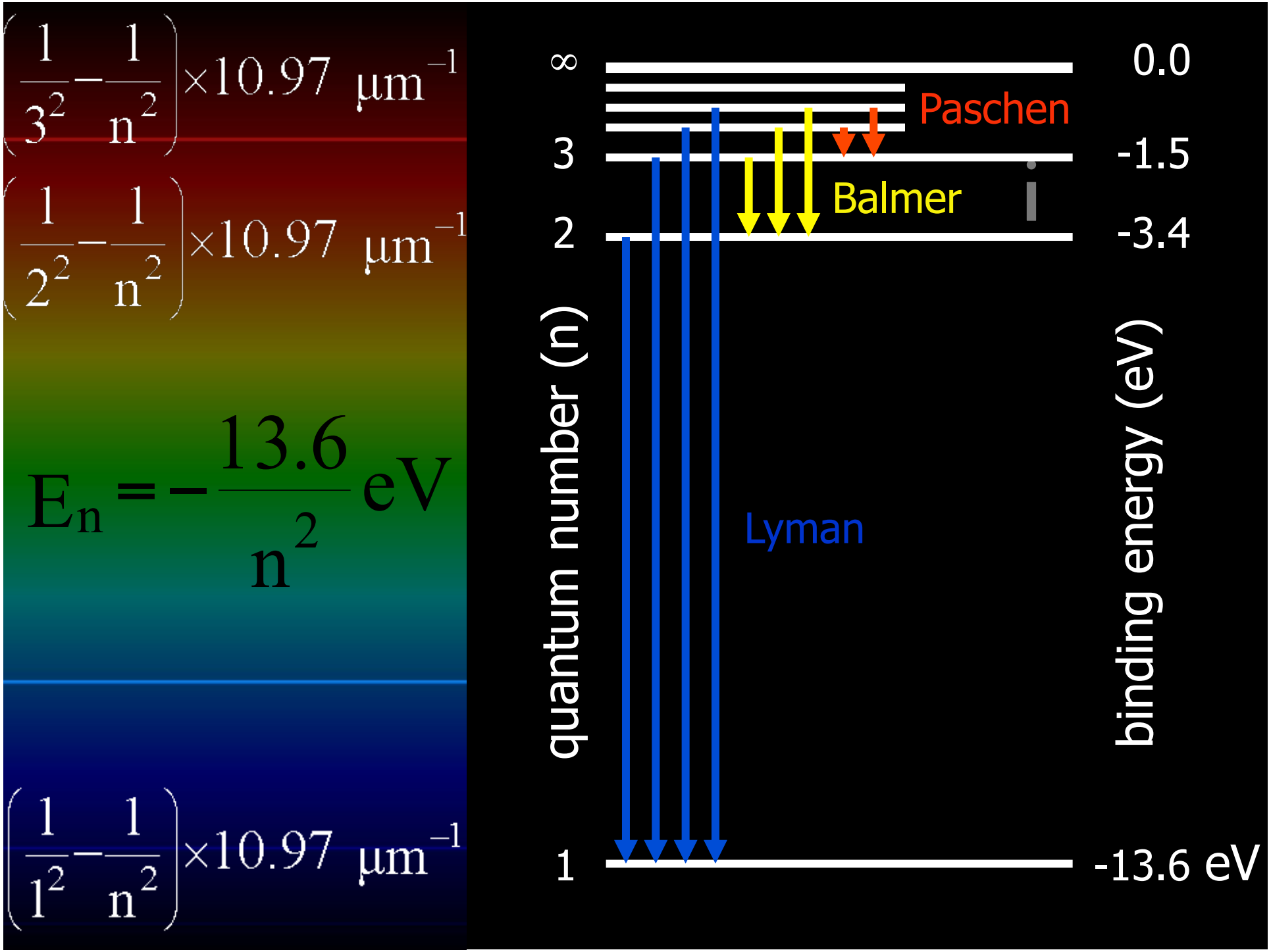
Schrödinger
1927

Schrödinger (1887-1961)

Bohr's *atom model*

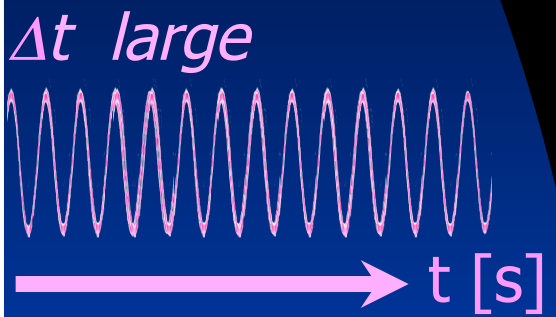
$$E_n = -\frac{13.6}{n^2}\,eV$$

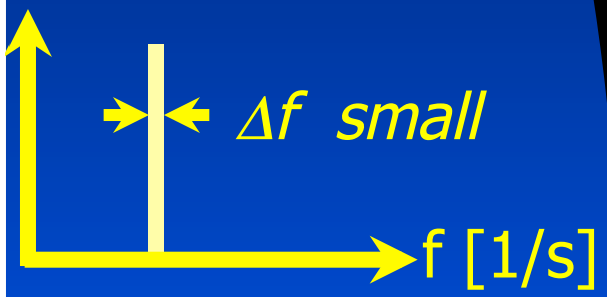


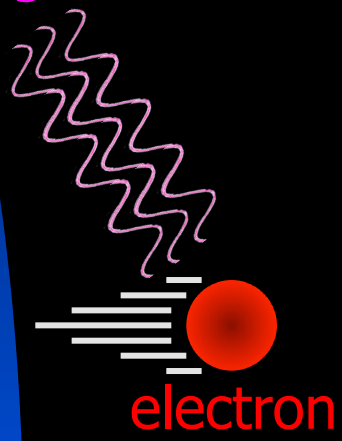

$\left(\frac{1}{3^2}-\frac{1}{n^2}\right)\times 10.97\ \mu m^{-1}$
$\left(\frac{1}{2^2}-\frac{1}{n^2}\right)\times 10.97\ \mu m^{-1}$
$E_n = -\frac{13.6}{n^2}\,eV$
$\left(\frac{1}{1^2}-\frac{1}{n^2}\right)\times 10.97\ \mu m^{-1}$
∞
3
2
1
quantum number (n)
Paschen
Balmer
Lyman
0.0
-1.5
-3.4
-13.6 eV
binding energy (eV)

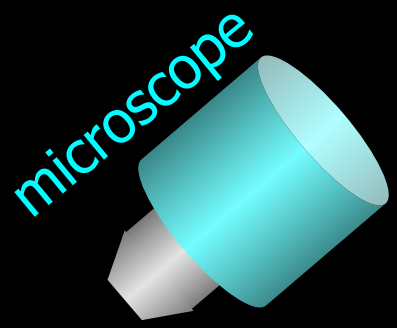
Heisenberg's *uncertainty principle*

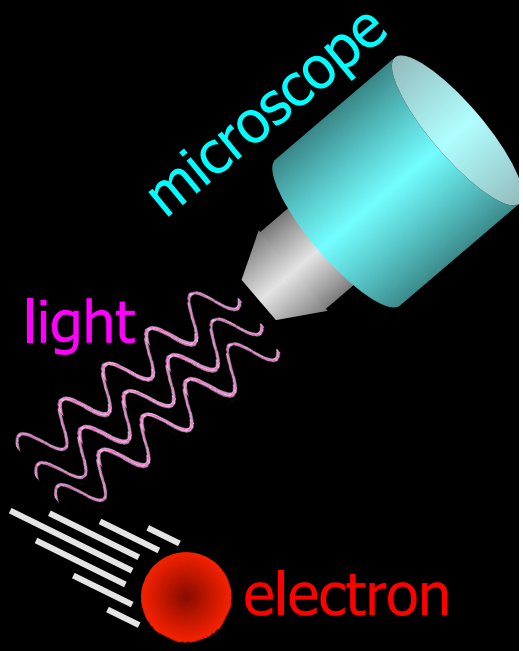
$$\Delta p \times \Delta x \geq \frac{h}{4\pi} \equiv \hbar/2$$







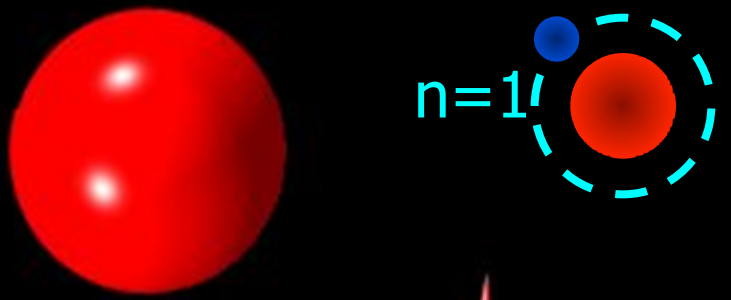


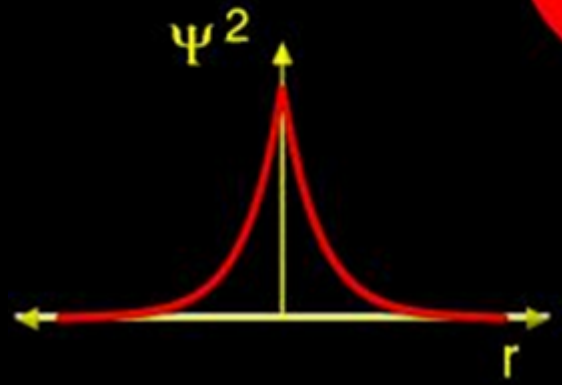


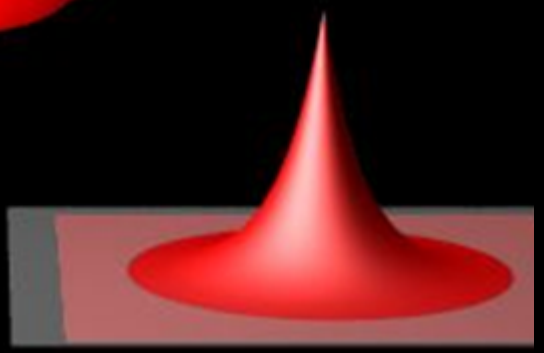
Schrödinger's *wave equation*

$$i\hbar\frac{\partial\Psi}{\partial t}=\frac{-\hbar^2}{2m}\nabla^2\Psi+V\Psi$$

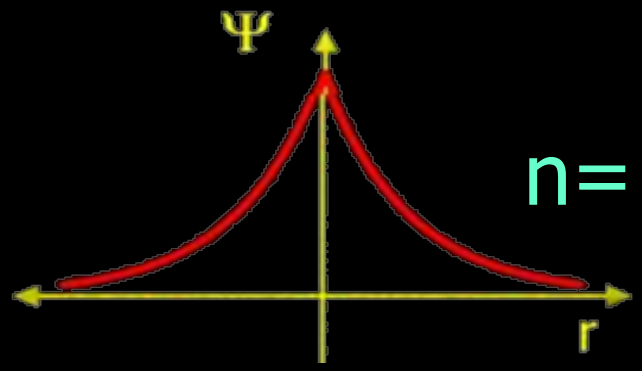
^{1}H ground state



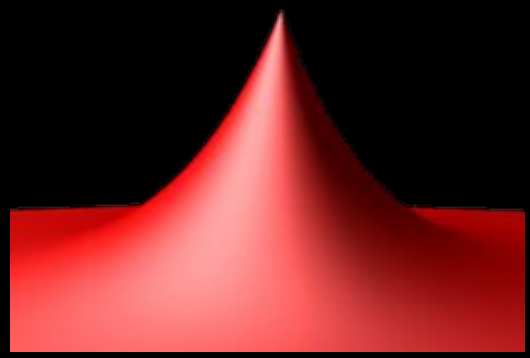


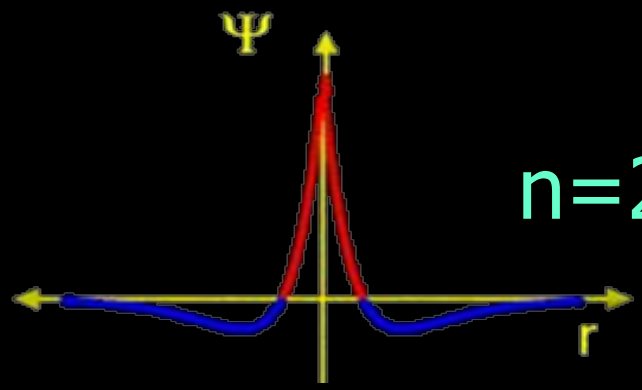


“s” states

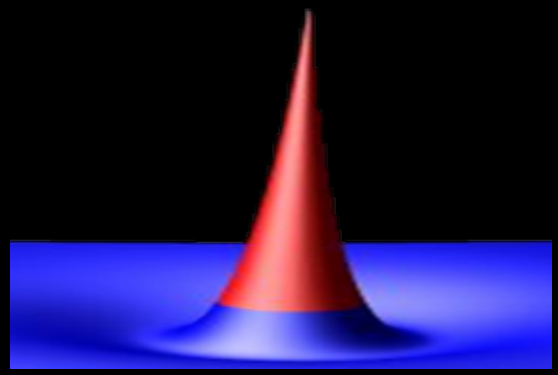


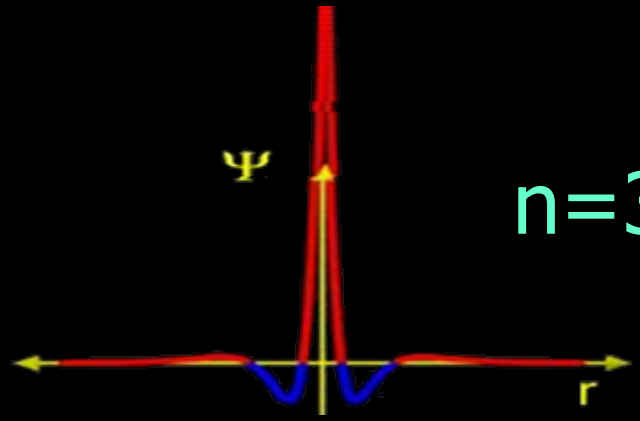
n=1



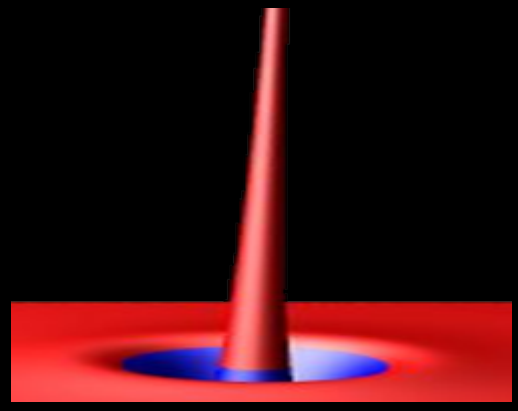


n=2

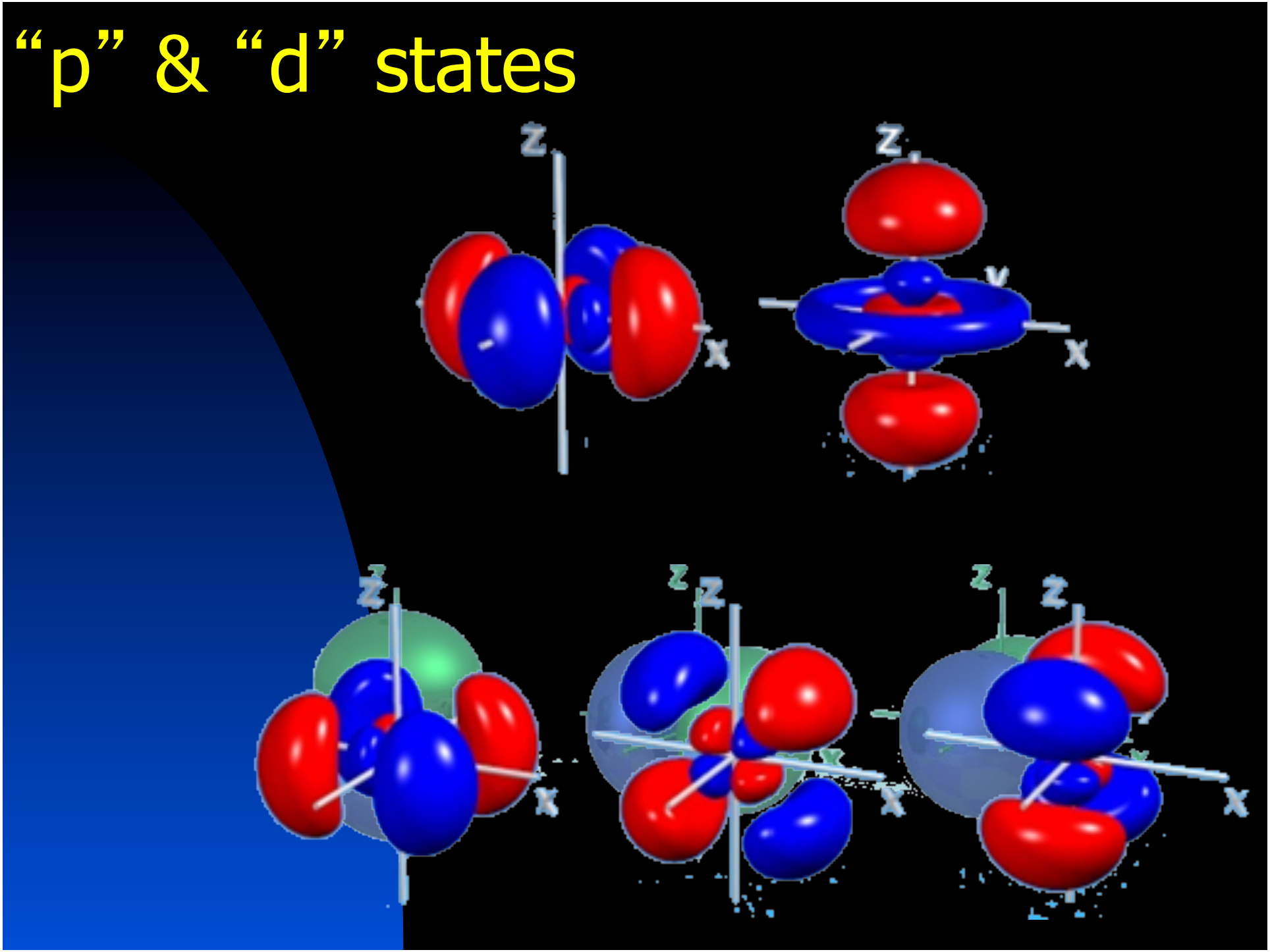


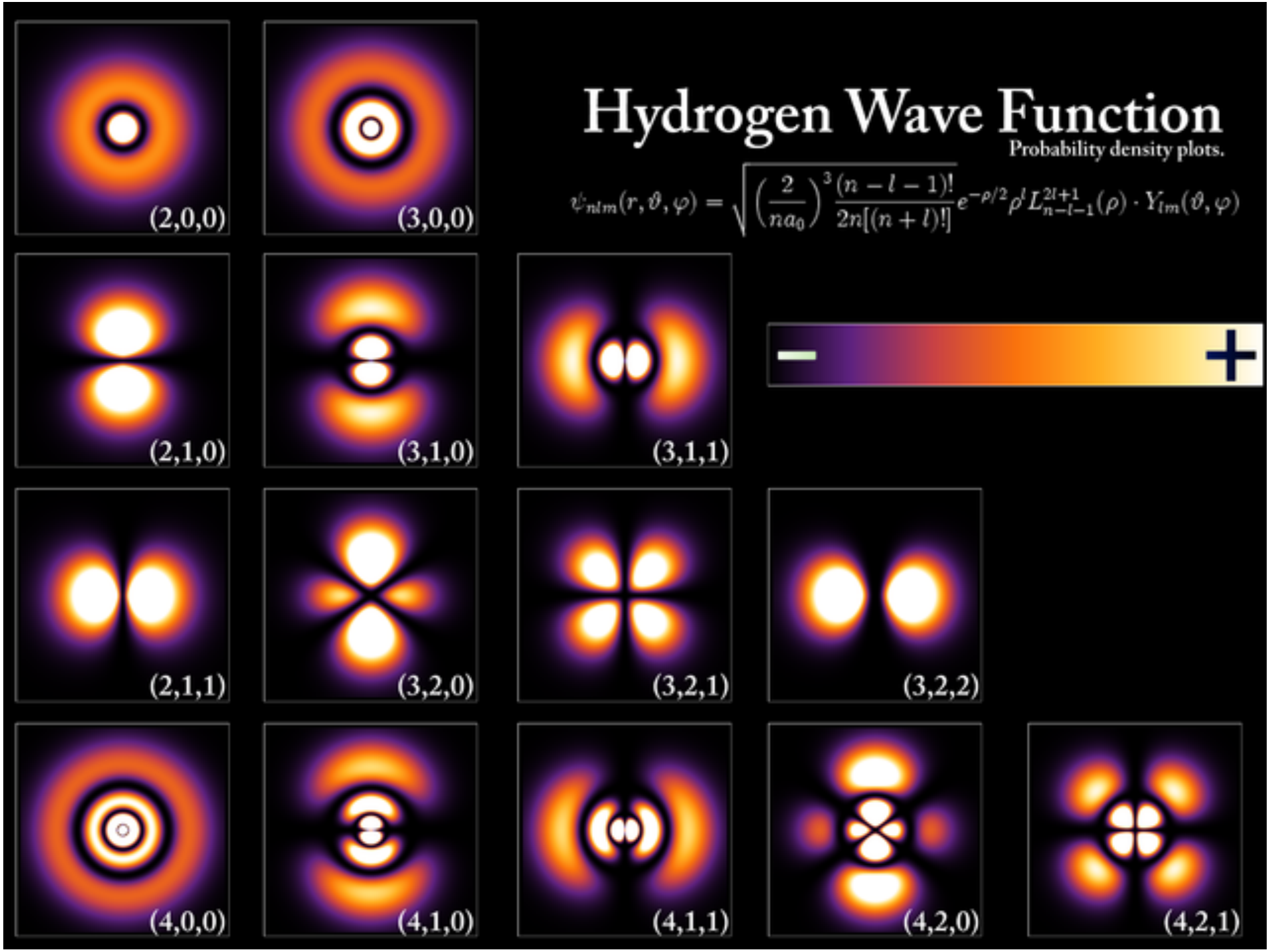


n=3



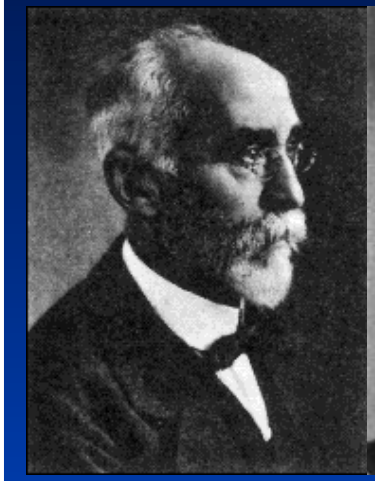
“p” & “d” states




Hydrogen Wave Function
Probability density plots.
$\psi_{nlm}(r,\vartheta,\varphi) = \sqrt{\left(\frac{2}{na_0}\right)^3 \frac{(n-l-1)!}{2n[(n+l)!]}} e^{-\rho/2} \rho^l L_{n-l-1}^{2l+1}(\rho) \cdot Y_{lm}(\vartheta,\varphi)$
(2,0,0)
(3,0,0)
(2,1,0)
(3,1,0)
(3,1,1)
−
+
(2,1,1)
(3,2,0)
(3,2,1)
(3,2,2)
(4,0,0)
(4,1,0)
(4,1,1)
(4,2,0)
(4,2,1)

Electron: *quantum details*

Lorentz & Zeeman
1896



(1885-1962)
Leiden

(1887-1961)
Amsterdam

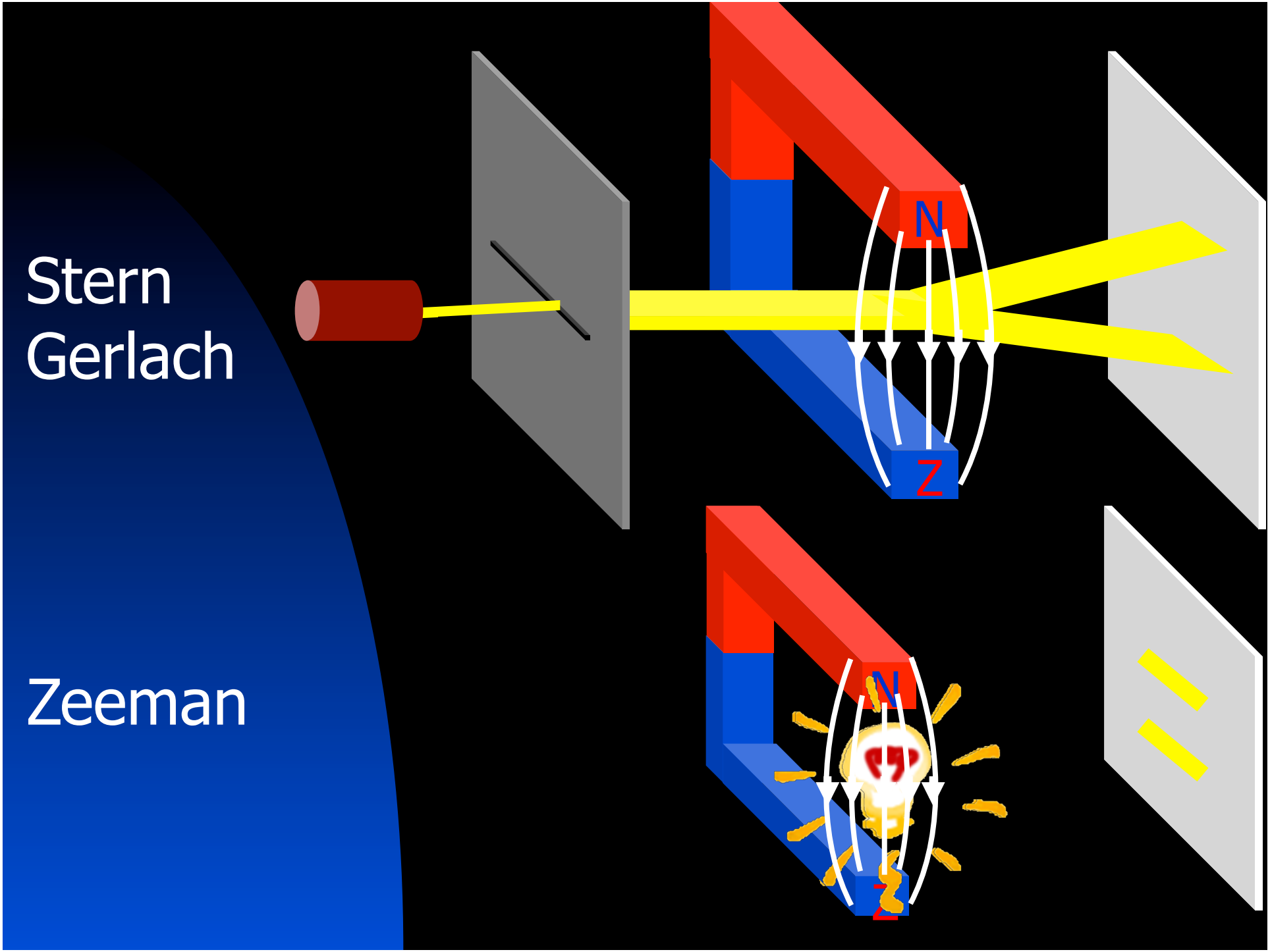
Uhlenbeck & Goudsmit
1925

(1887-1961)
Leiden

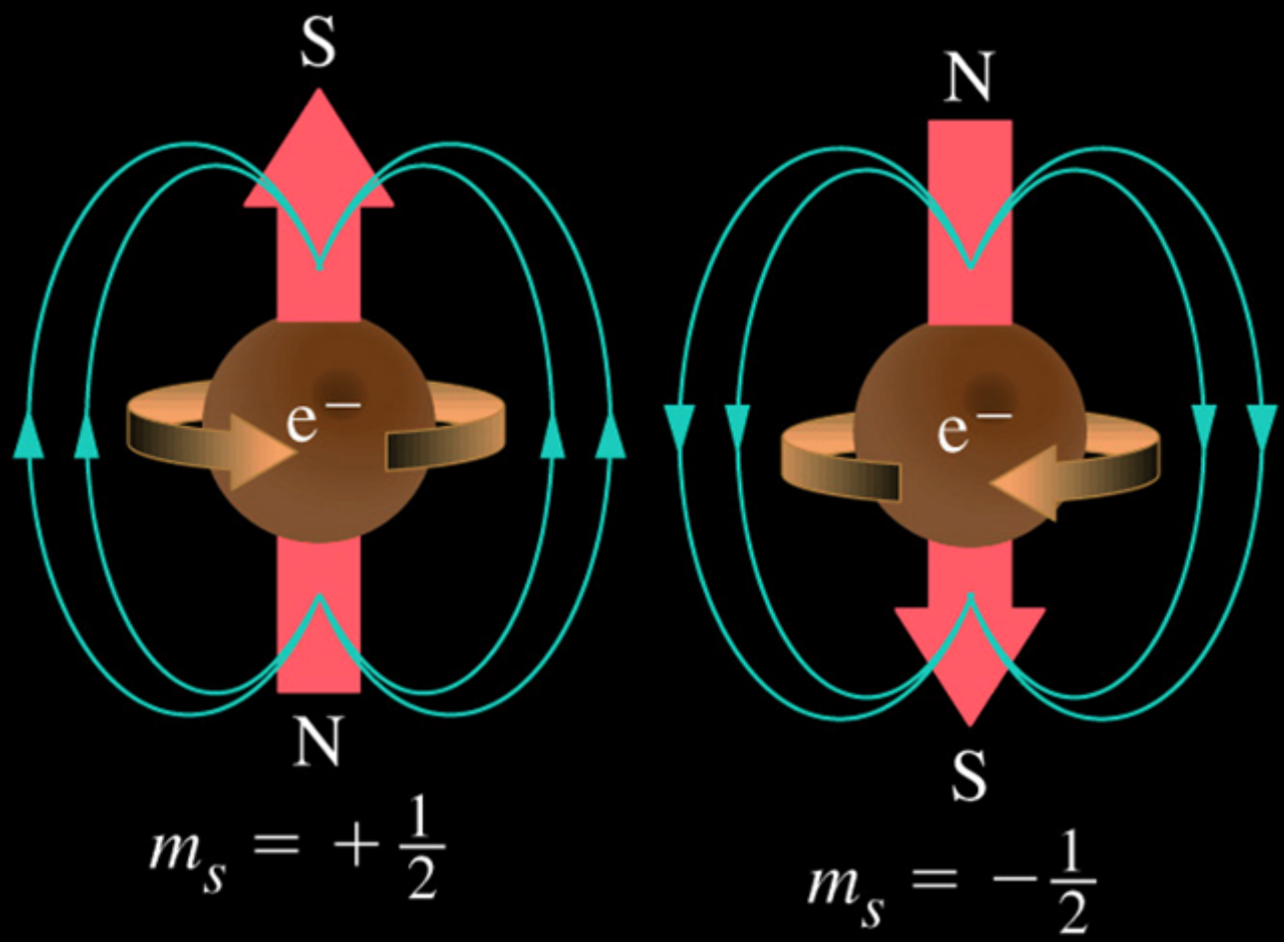
(1901-1976)
Leiden

Pauli
1925

(1900-1958)

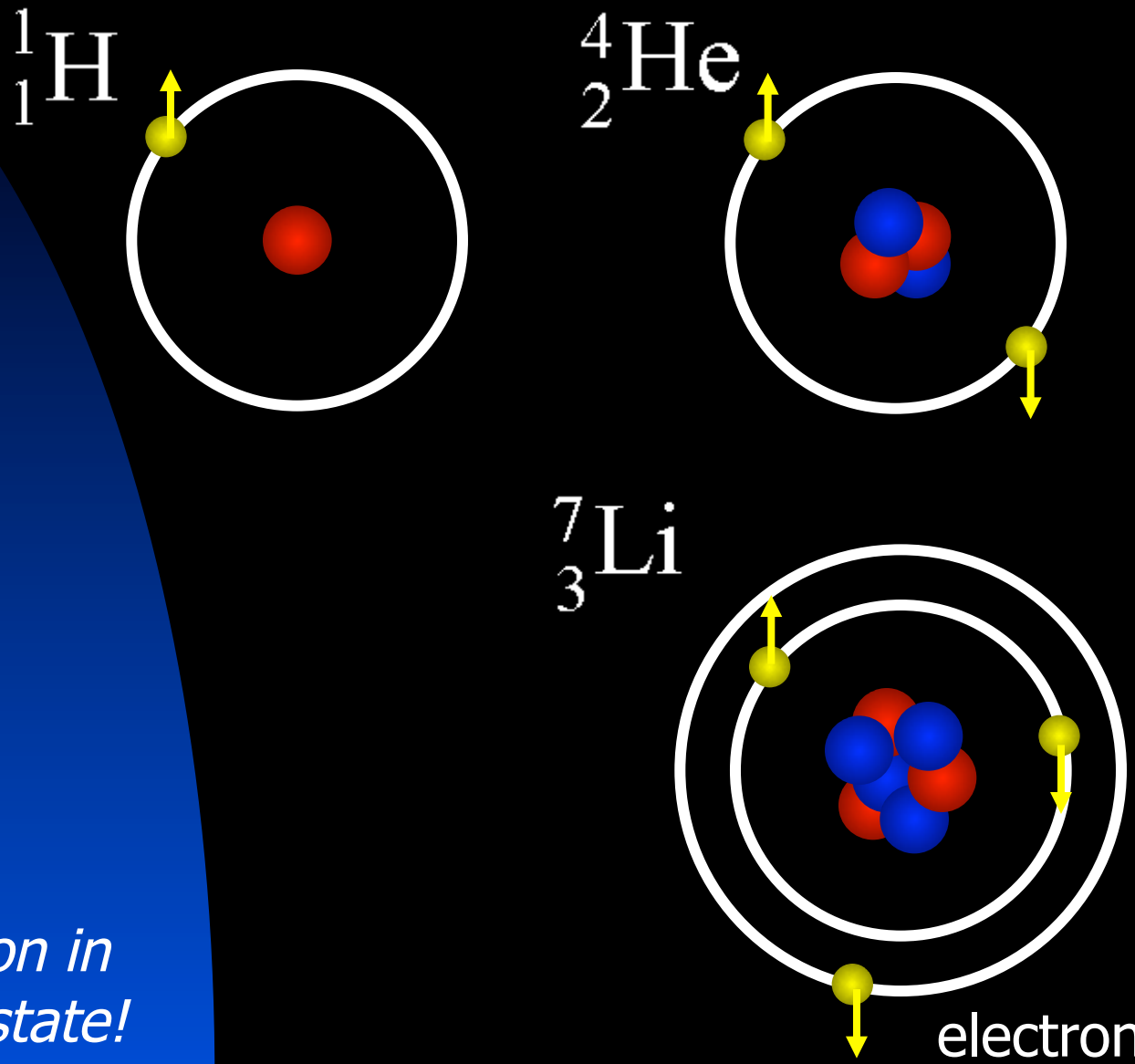

Stern
Gerlach
Zeeman
N
S
N
S

Electron spin!



Uhlenbeck
Goudsmit

Democracy: *all electrons are equal*

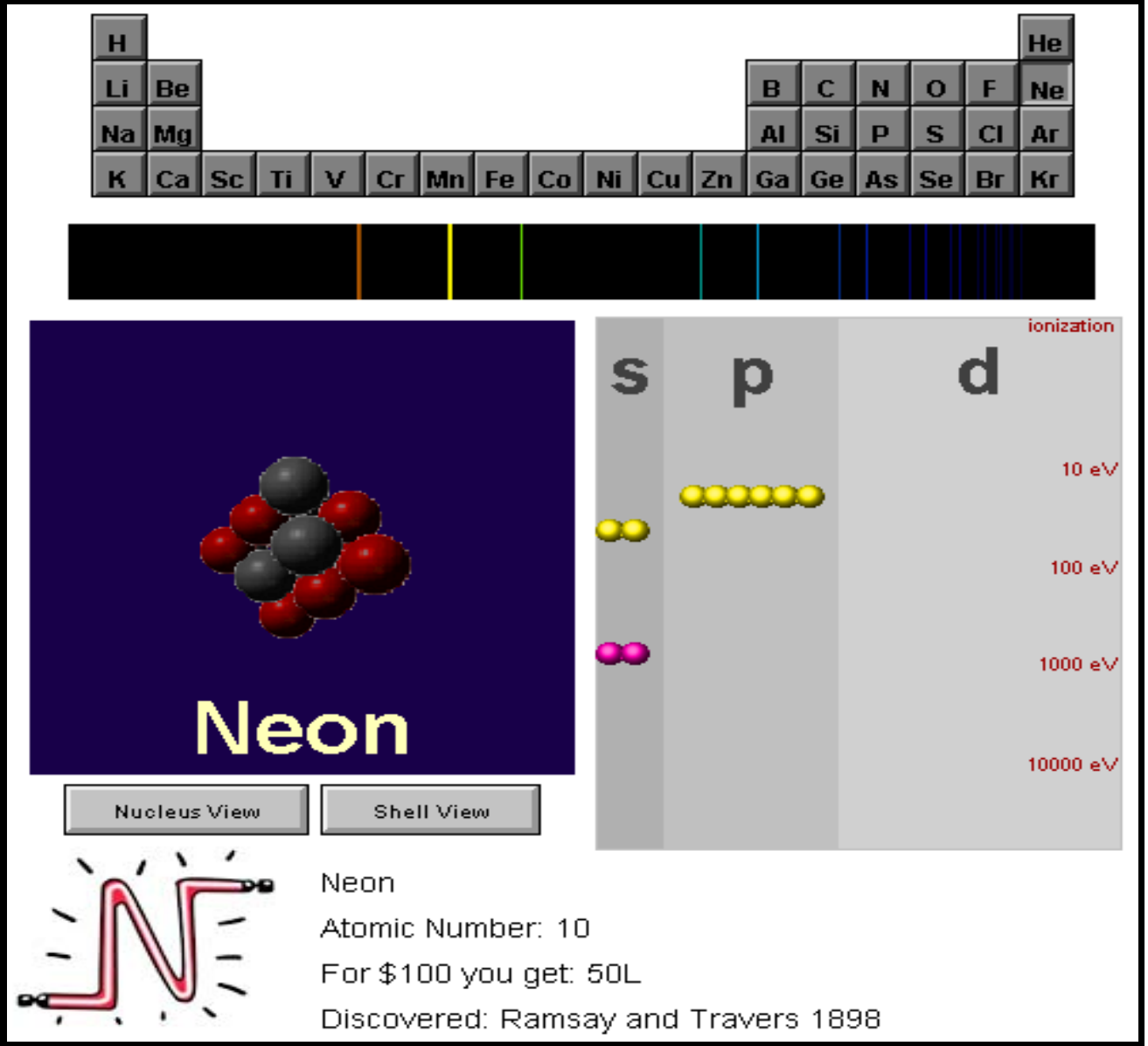


Pauli:

Each electron in a different state!

electron = asocial

Perfect description of atoms!



The electron

Mass:

0.000000000000000000000000000*910938188 gram*

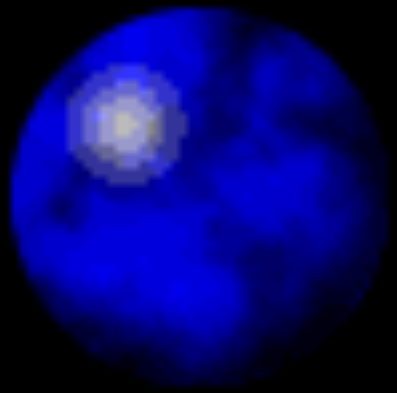
Electric charge:

-0.000000000000000000*16021765 Coulomb*

Mean lifetime:

∝ (infinite) seconds

”Spin”: ½



Relativistic quantum theory

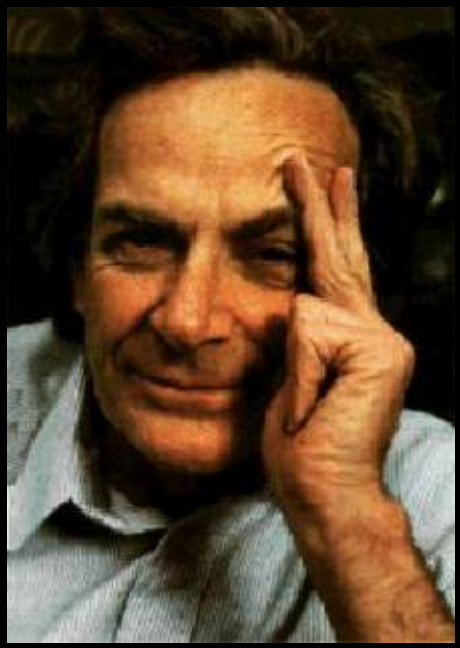
Dirac
1928

Dirac (1902-1984)

Anderson
1932

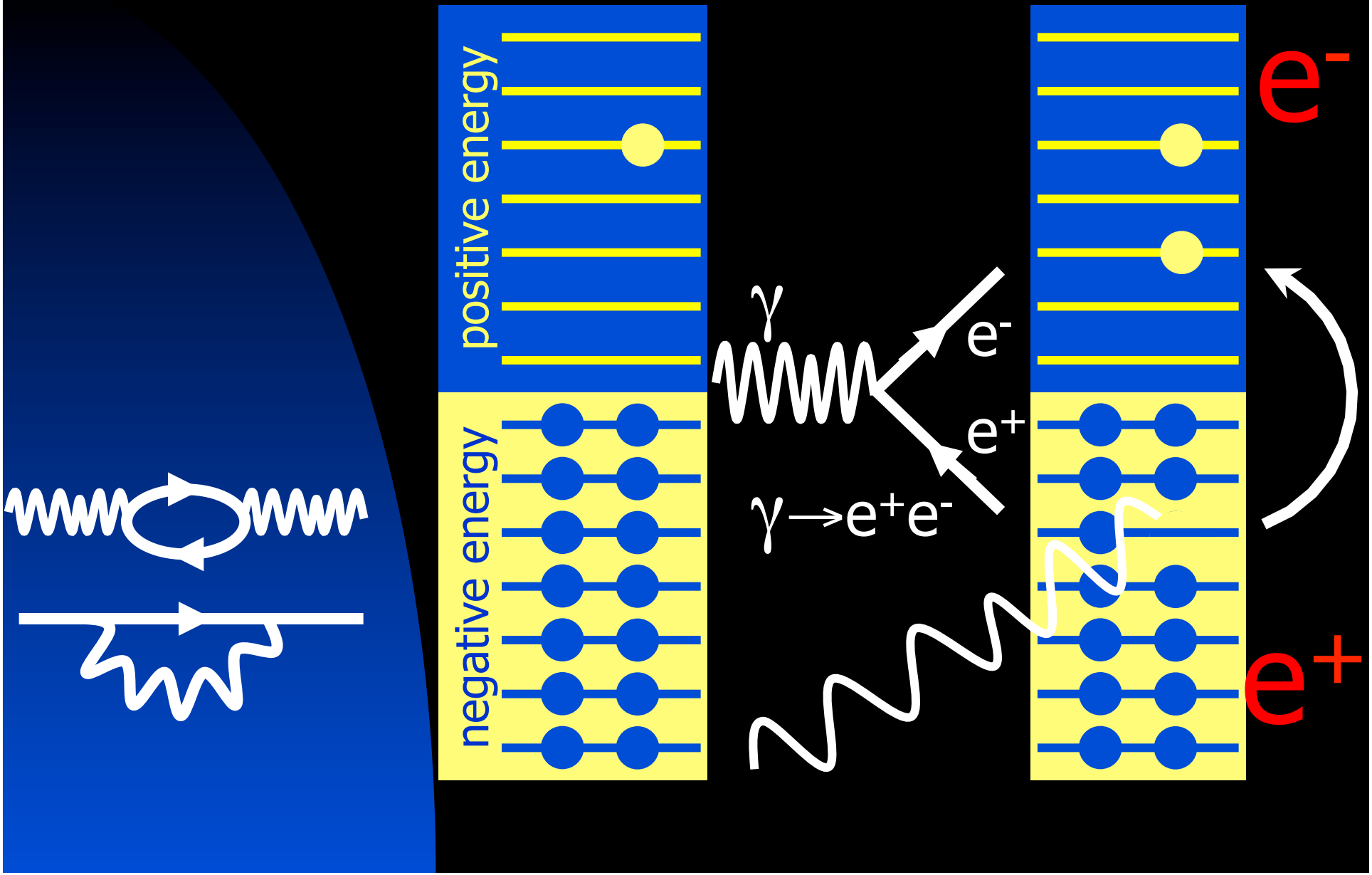
Anderson (1905-1991)

Feynman
1947

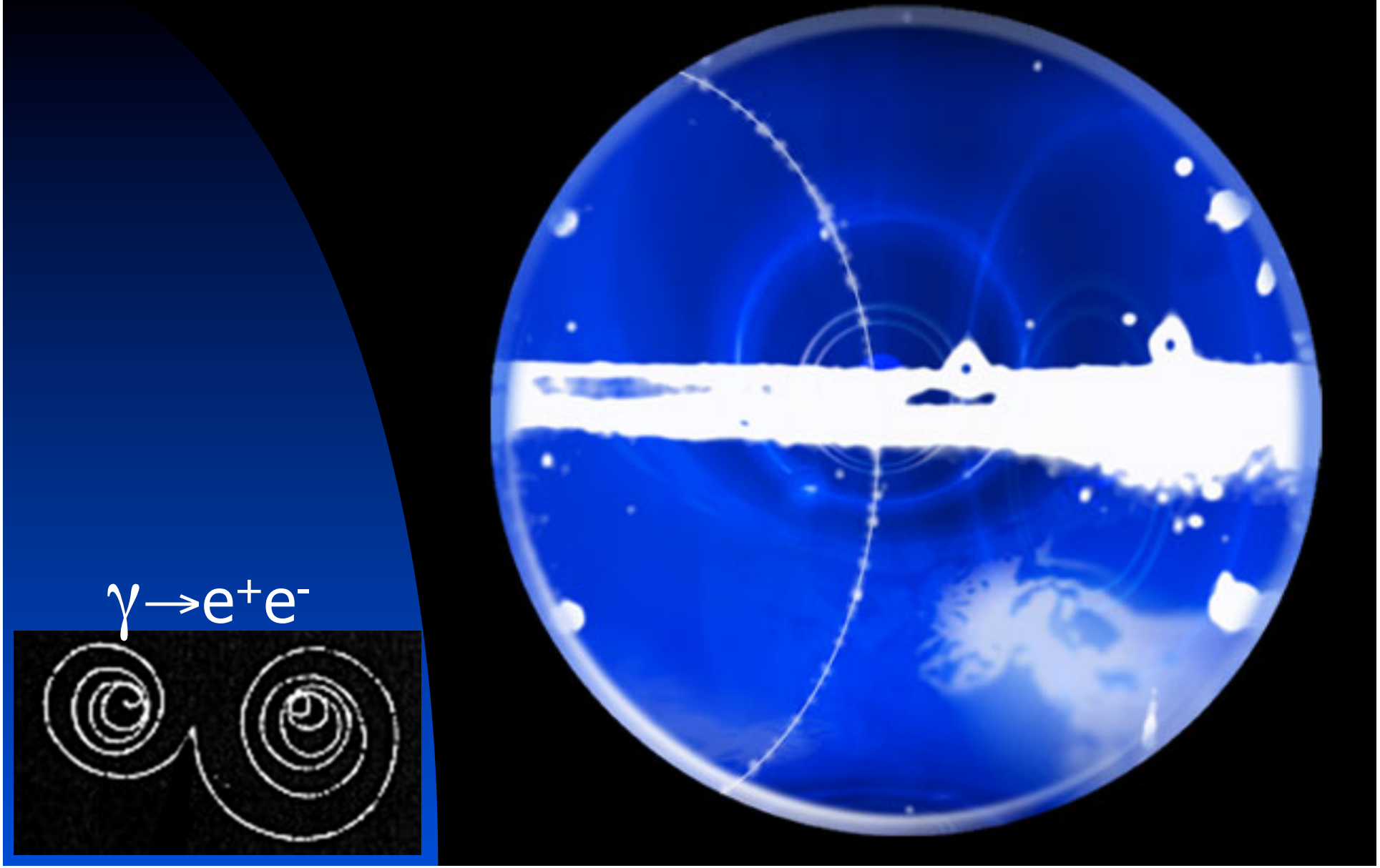


Feynman (1918-1988)

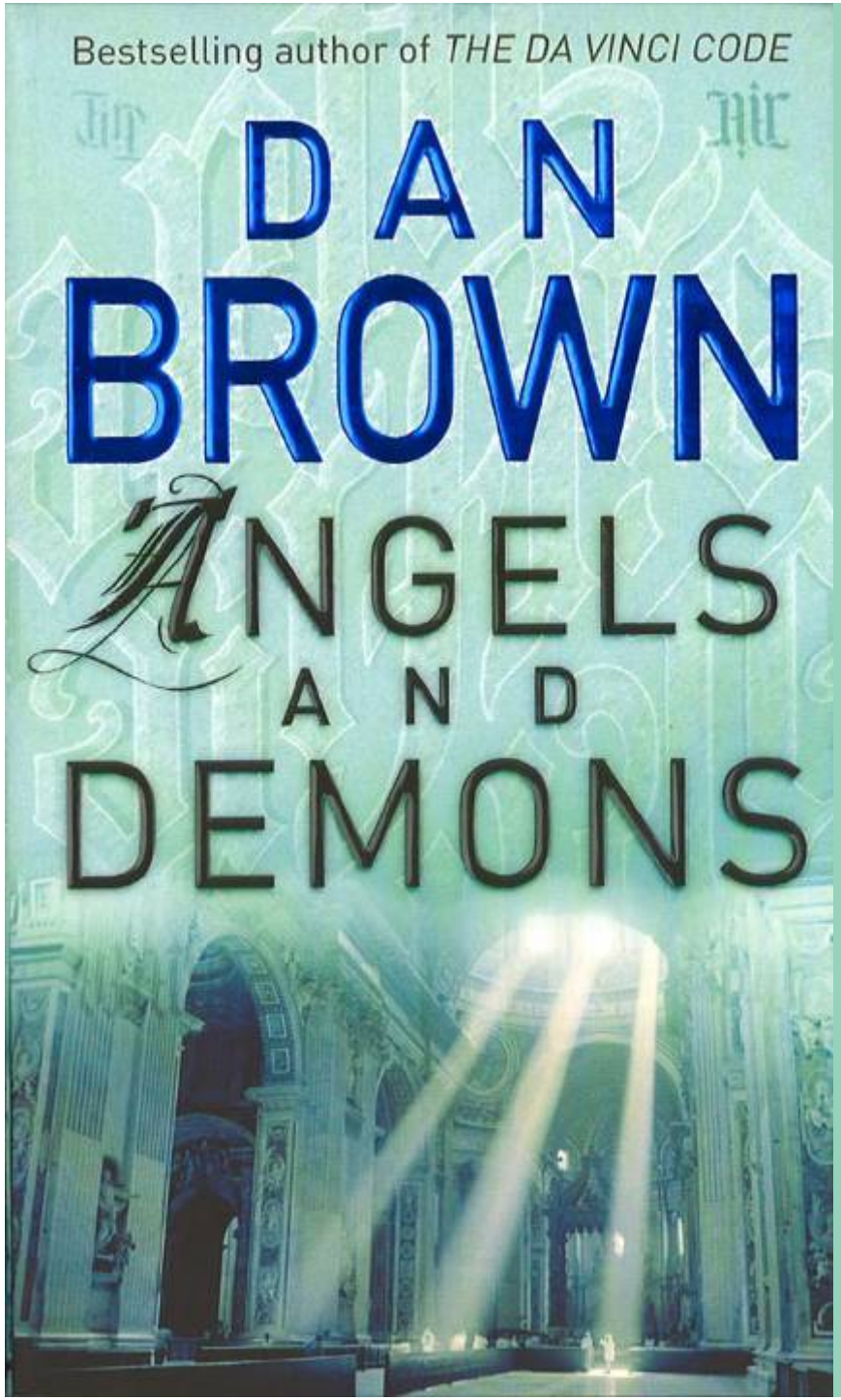
Dirac's *anti-matter* hypothesis



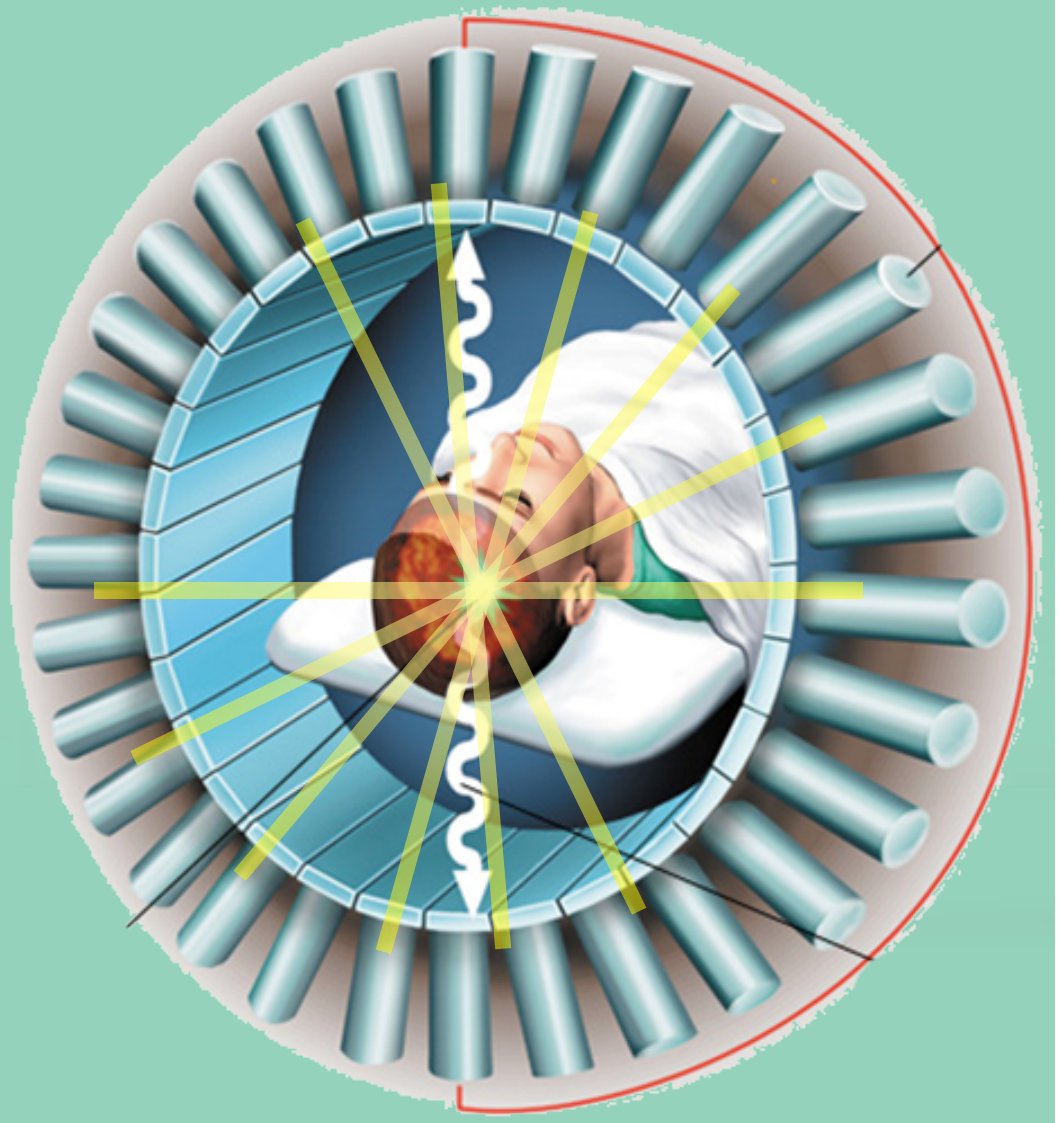
Anderson's *anti-electron* discovery



$\gamma \rightarrow e^+e^-$



Positron Emission Tomograph



Angels & Demons: *the movie*

Feynman: *fabulous accuracy*

Experiment:

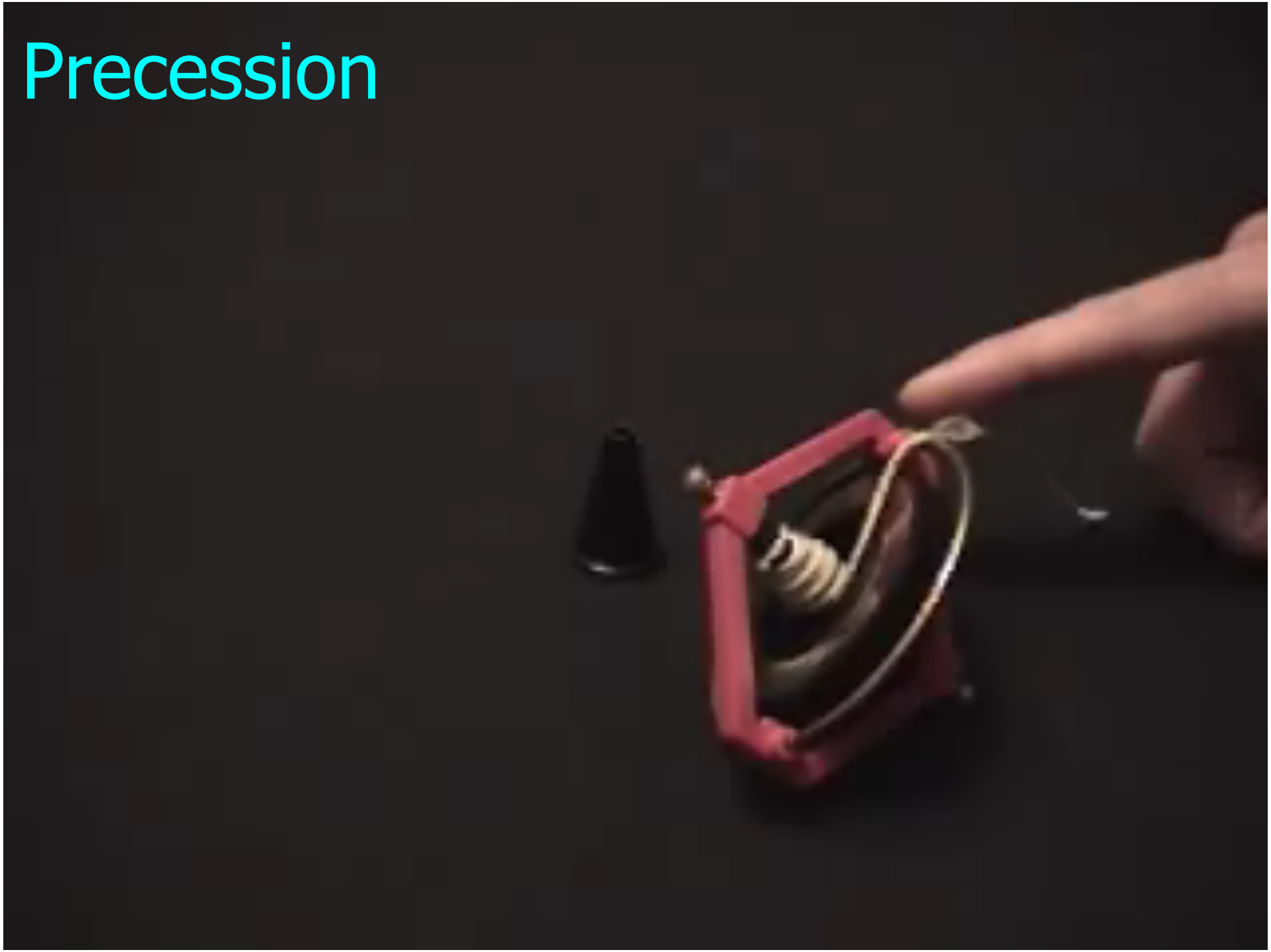
$\mu_e = 1.00115965218\,7 \times eh/(4\pi m_e)$

Theory:

$\mu_e = 1.00115965218\,8 \times eh/(4\pi m_e)$

Feynman 1947

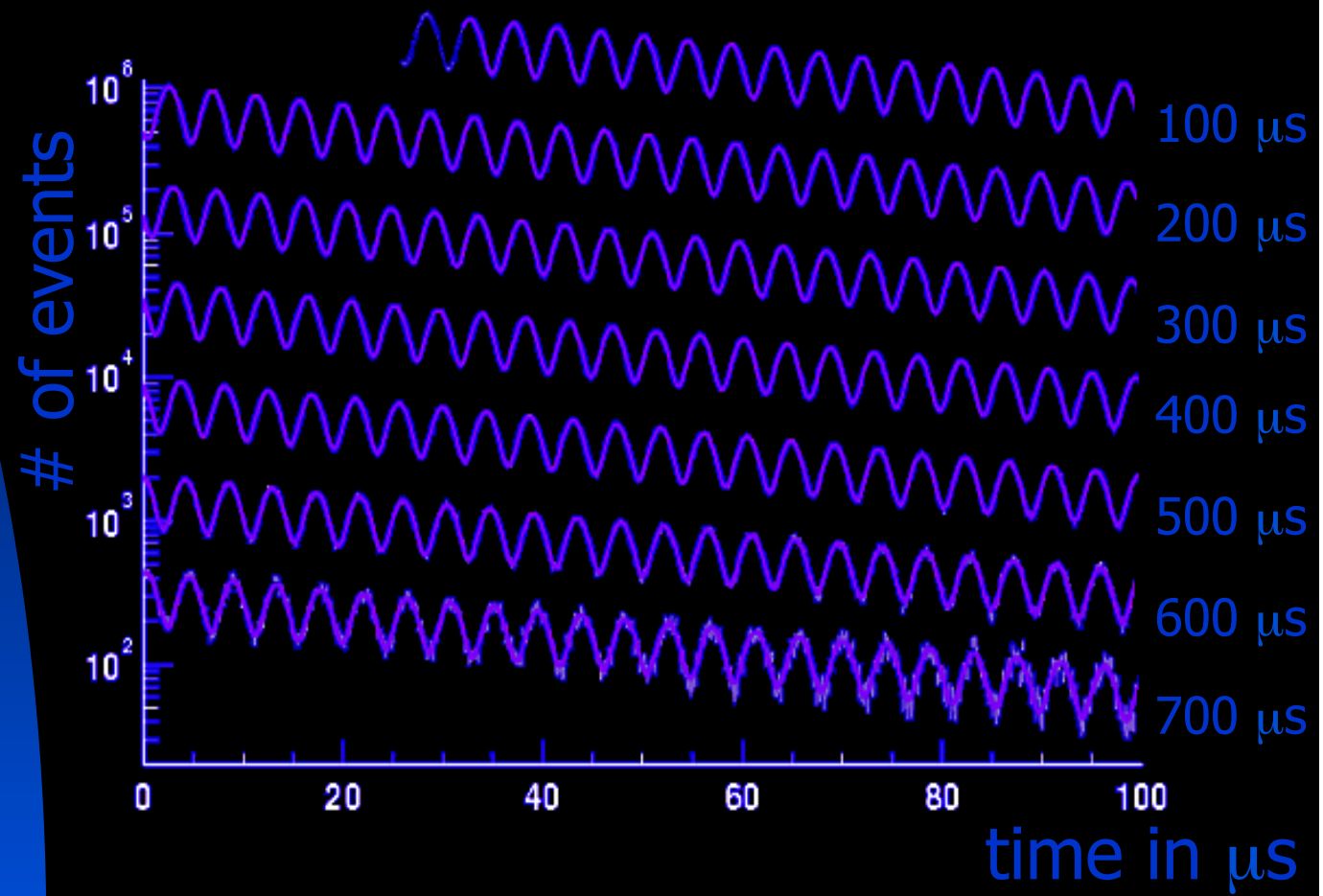
Precession



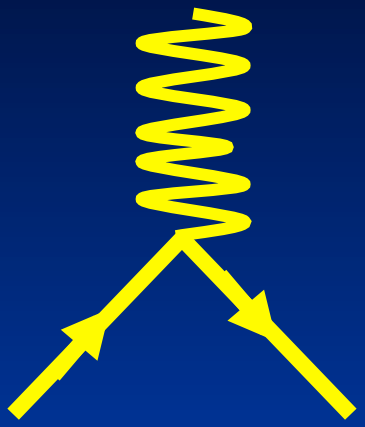
Precession @ home

Precession

$$\mu_\mu = 1.0011659160 \times eh/(4\pi m_\mu)$$



Real fun: *creation & annihilition*



the only interaction

time

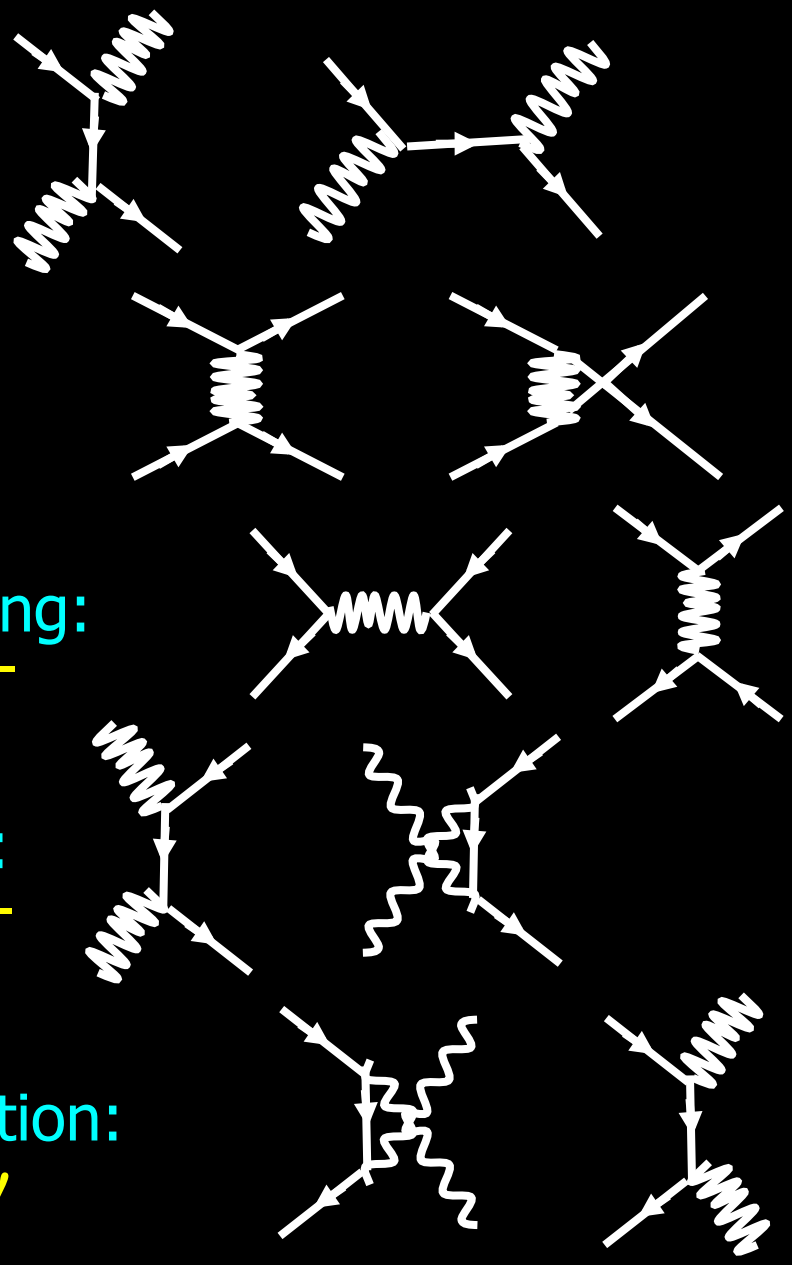
Compton scattering:
$\gamma e^- \rightarrow \gamma e^-$

Möller scattering:
$e^- e^- \rightarrow e^- e^-$

Bhabha scattering:
$e^+ e^- \rightarrow e^+ e^-$

Pair creation:
$\gamma\gamma \rightarrow e^+ e^-$

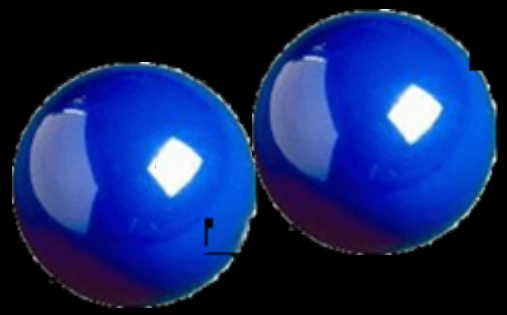
Pair annihilation:
$e^+ e^- \rightarrow \gamma\gamma$



Particle collisions

boring
collisions

exciting collisions



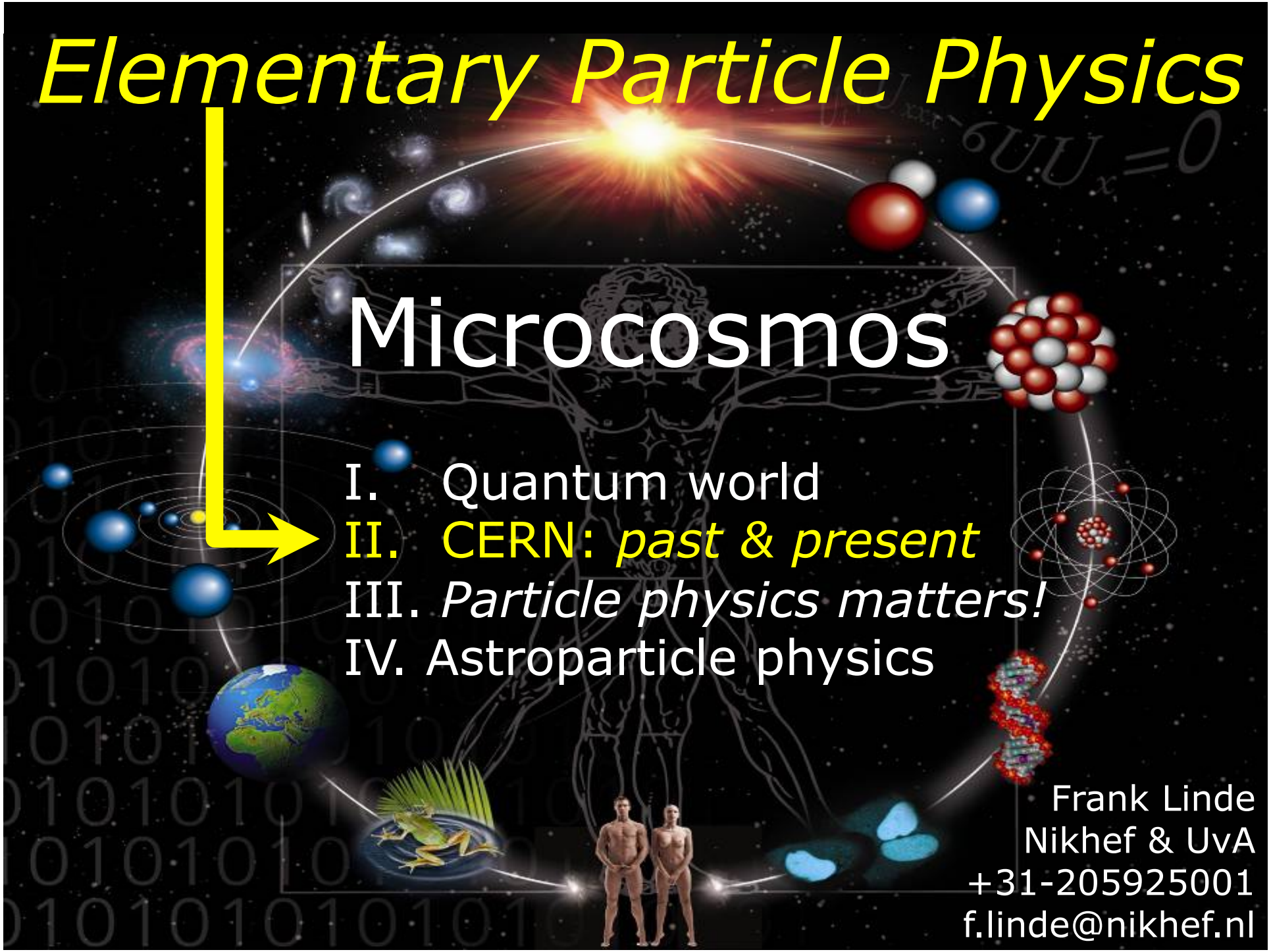
high energy

fun collisions

$E = mc^2$

large mass

Elementary Particle Physics



Microcosmos

I. Quantum world
II. CERN: *past & present*
III. *Particle physics matters!*
IV. Astroparticle physics

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