

Theoretische Teilchenphysik

Robert Harlander

RWTH Aachen University

28 August 2025

jDPG Exkursion

Aachen

Quantenfeldtheorie

Quantenfeldtheorie

Quantenfeldtheorie

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \\ & + \bar{\psi}(x) i \not{D} \psi(x) + h.c. \\ & + \bar{\psi}(x) \gamma \psi(x) \phi(x) \\ & + |D_\mu \phi(x)|^2 - V(\phi(x))\end{aligned}$$

Quantenfeldtheorie

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \\ & + \bar{\psi}(x) i \not{D} \psi(x) + h.c. \\ & + \bar{\psi}(x) \gamma \psi(x) \phi(x) \\ & + |D_\mu \phi(x)|^2 - V(\phi(x))\end{aligned}$$

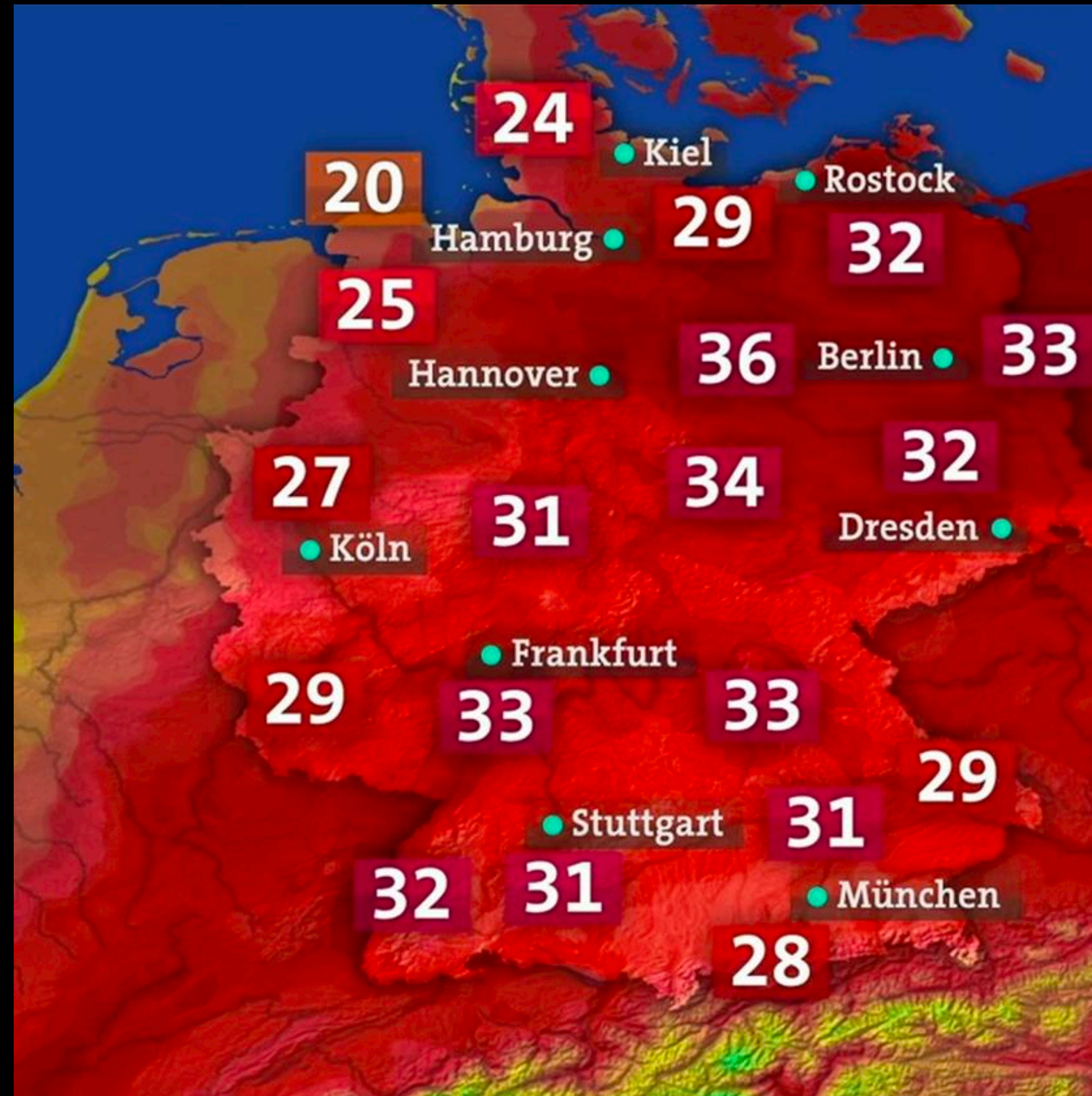
Quantenfeldtheorie

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \\ & + \bar{\psi}(x) i \not{D} \psi(x) + h.c. \\ & + \bar{\psi}(x) \gamma \psi(x) \phi(x) \\ & + |D_\mu \phi(x)|^2 - V(\phi(x))\end{aligned}$$

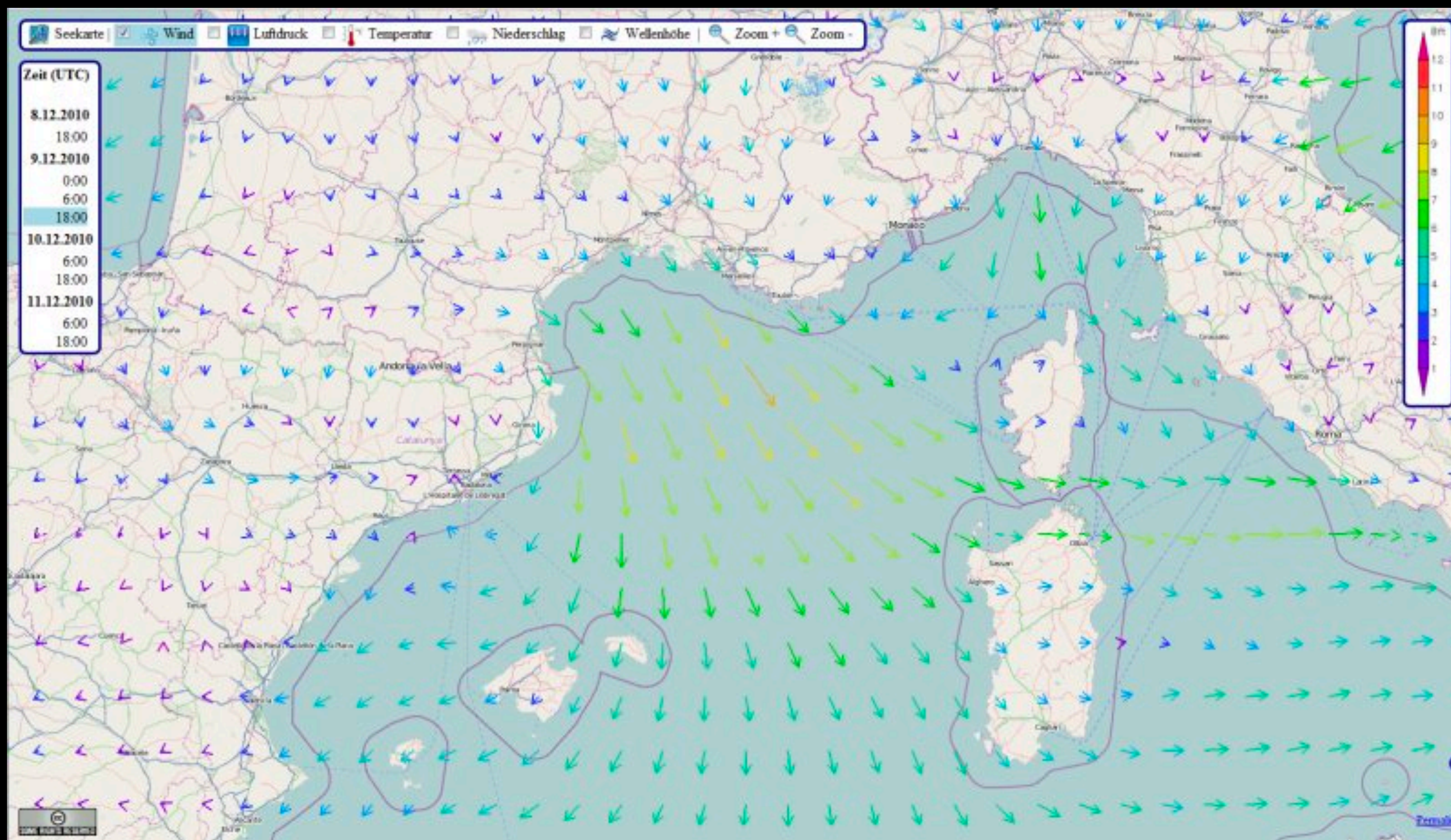
$$\not{D} = D_\mu \gamma^\mu$$

Quantenfeldtheorie

$$\psi(x)$$



$\psi(x)$



$\psi(x)$



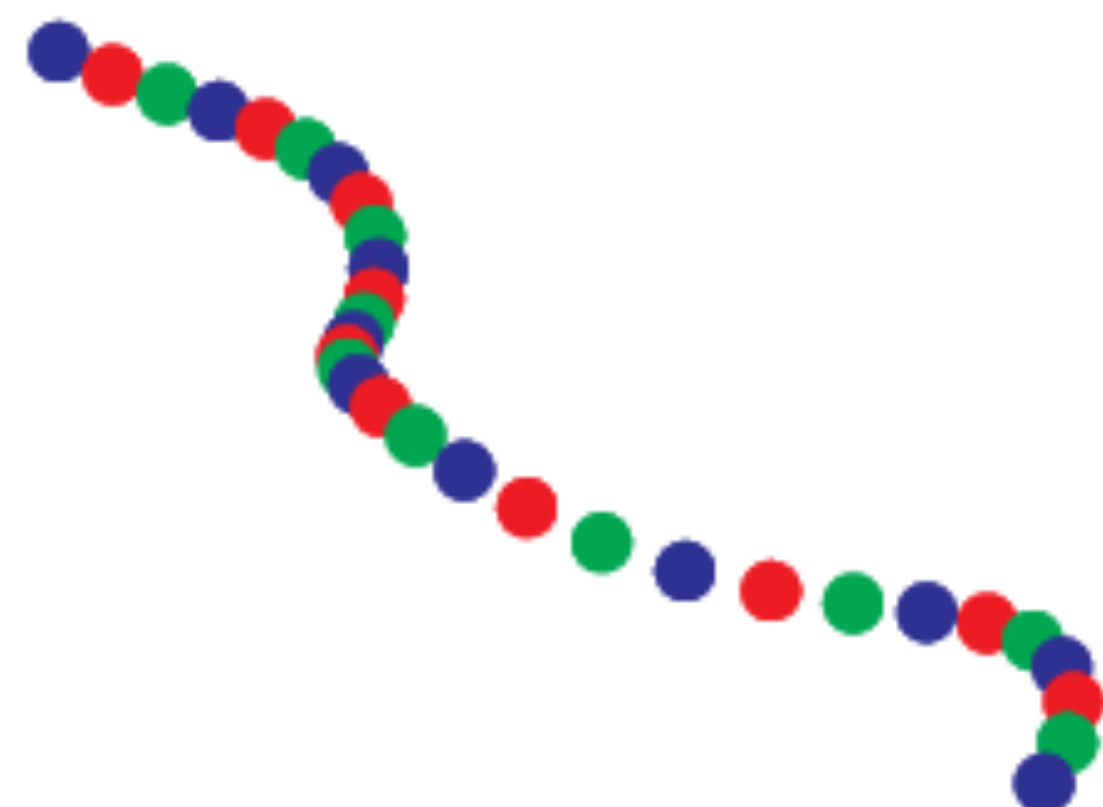
$$\psi(x)$$

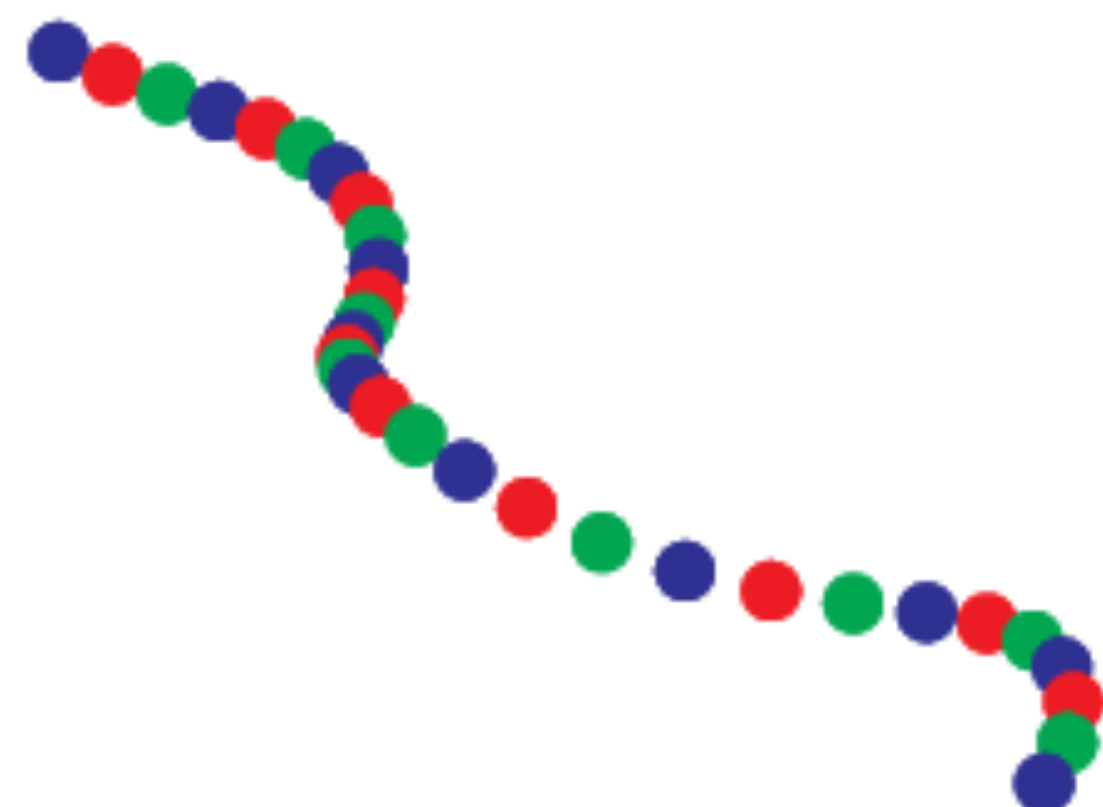


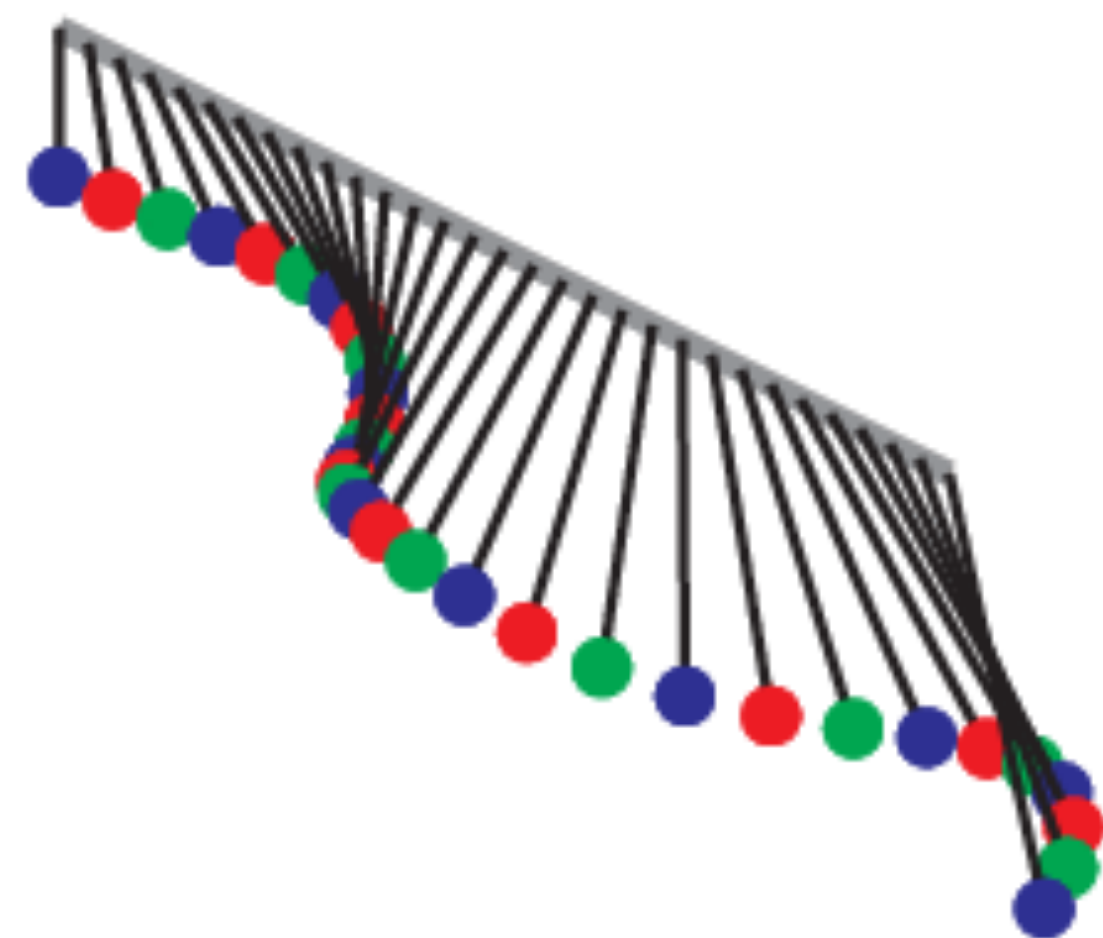
$\psi(x)$

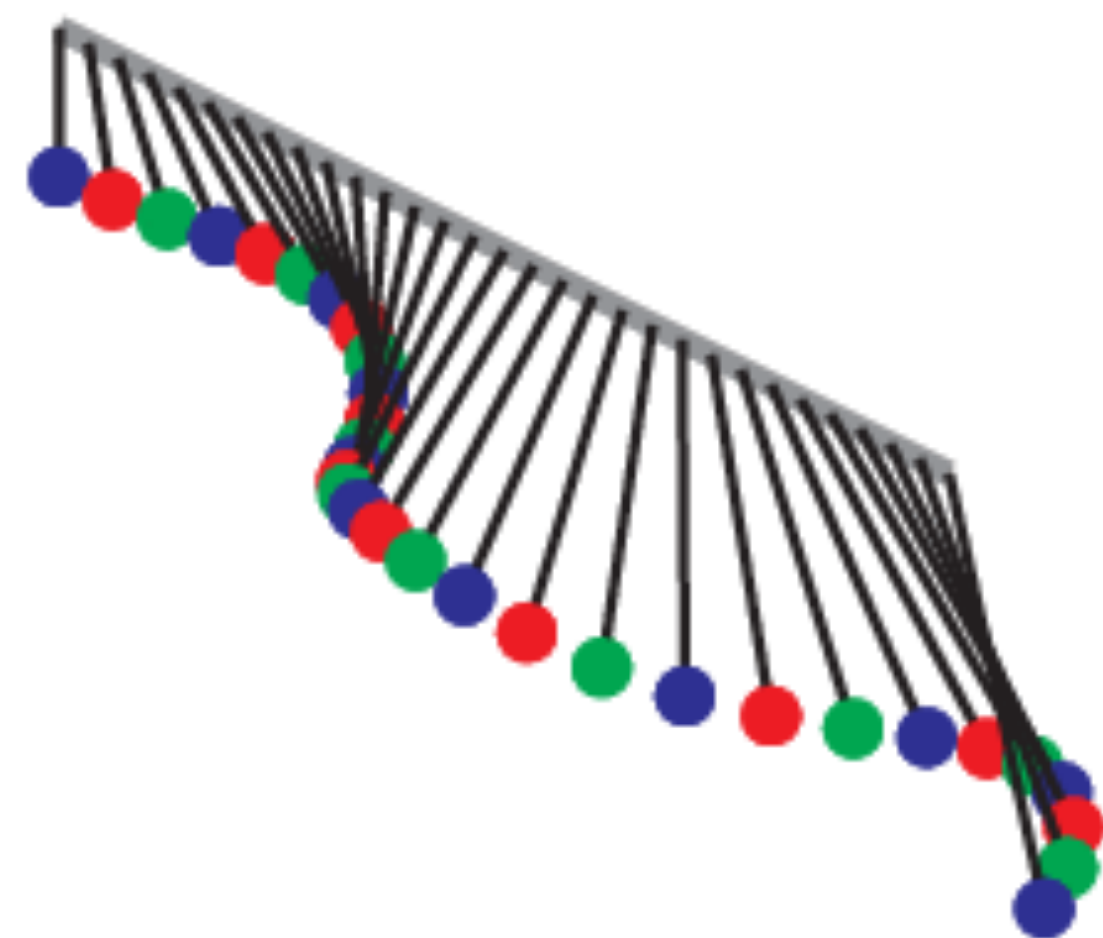




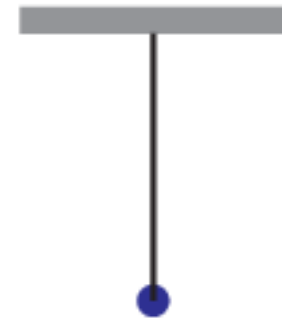




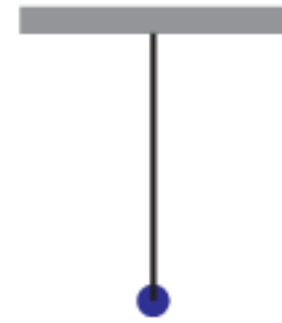




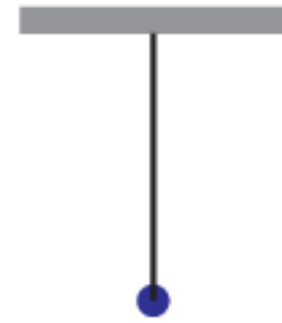
Newton:



Newton:



Newton:



$$E \sim \omega^2 \alpha^2$$

Newton:

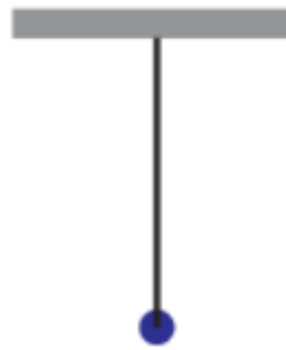
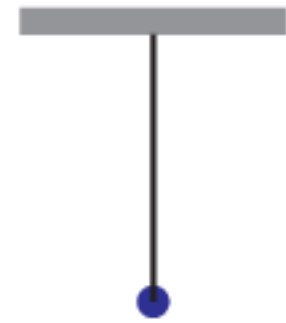
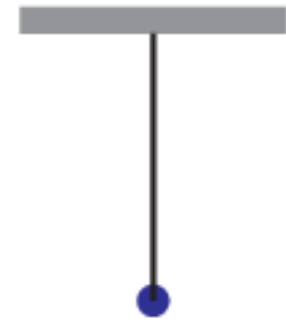
$$E \sim \omega^2 \alpha^2$$



Newton:

$$E \sim \omega^2 \alpha^2$$

$$E = 0$$



Newton:

Quantenmechanik?

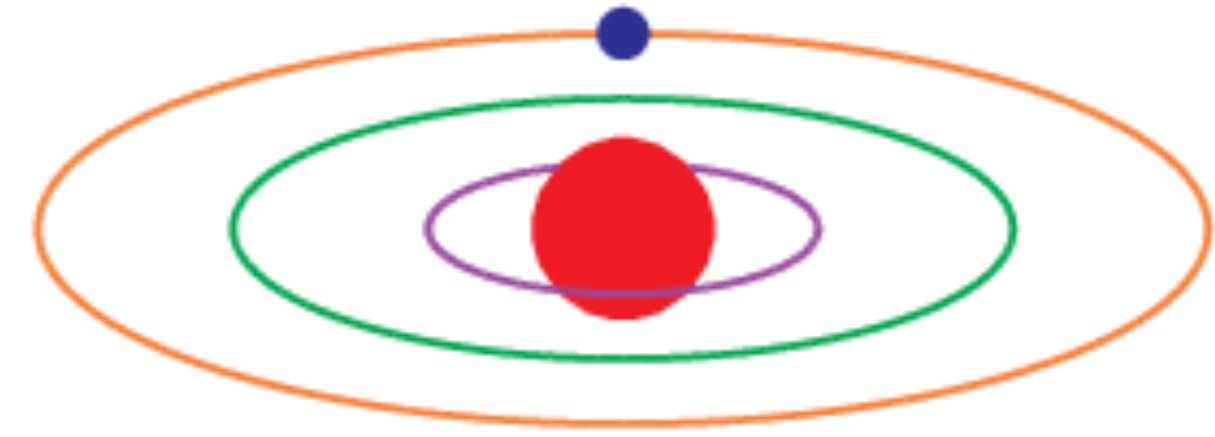
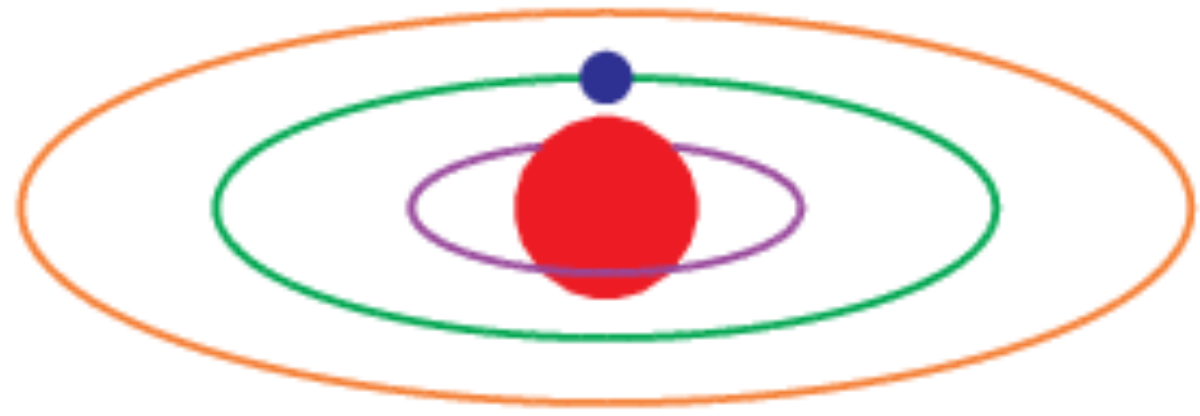
$$E \sim \omega^2 \alpha^2$$

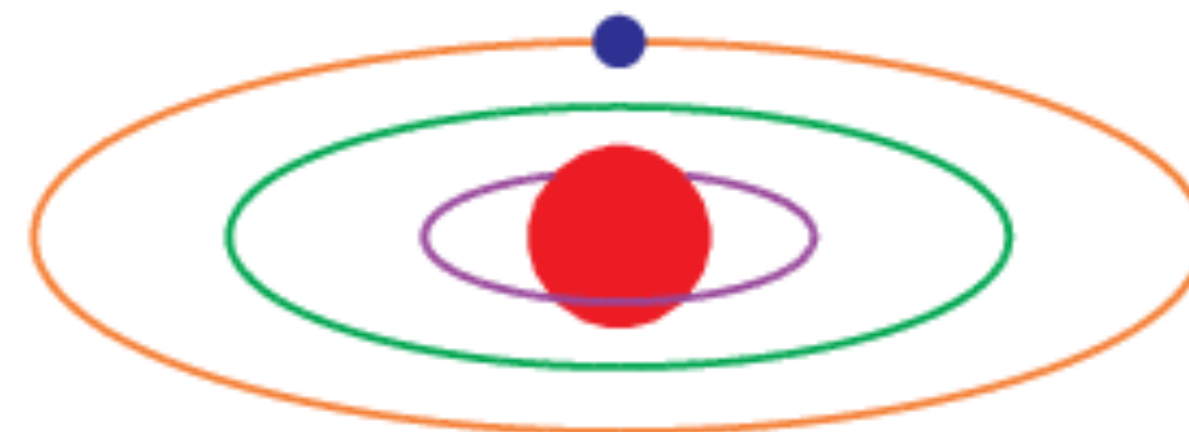
$$E = 0$$

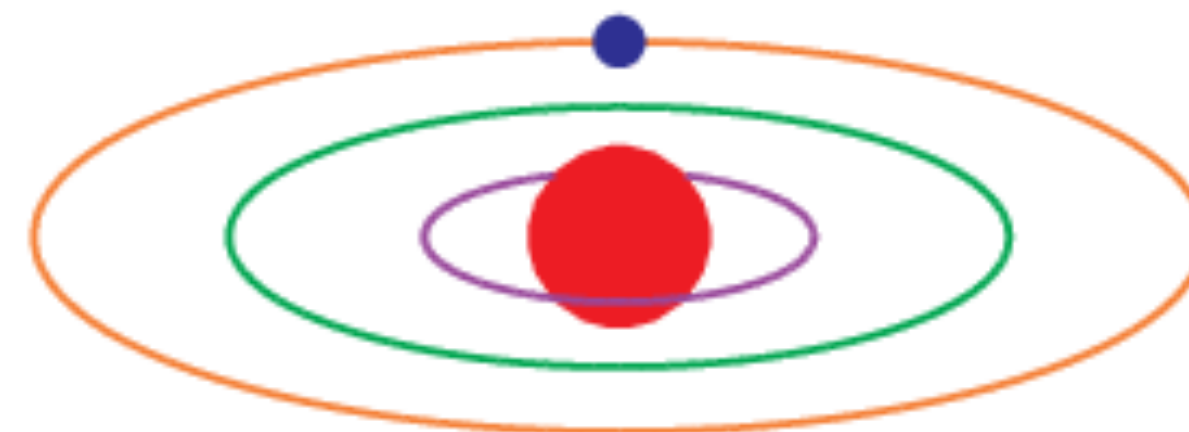


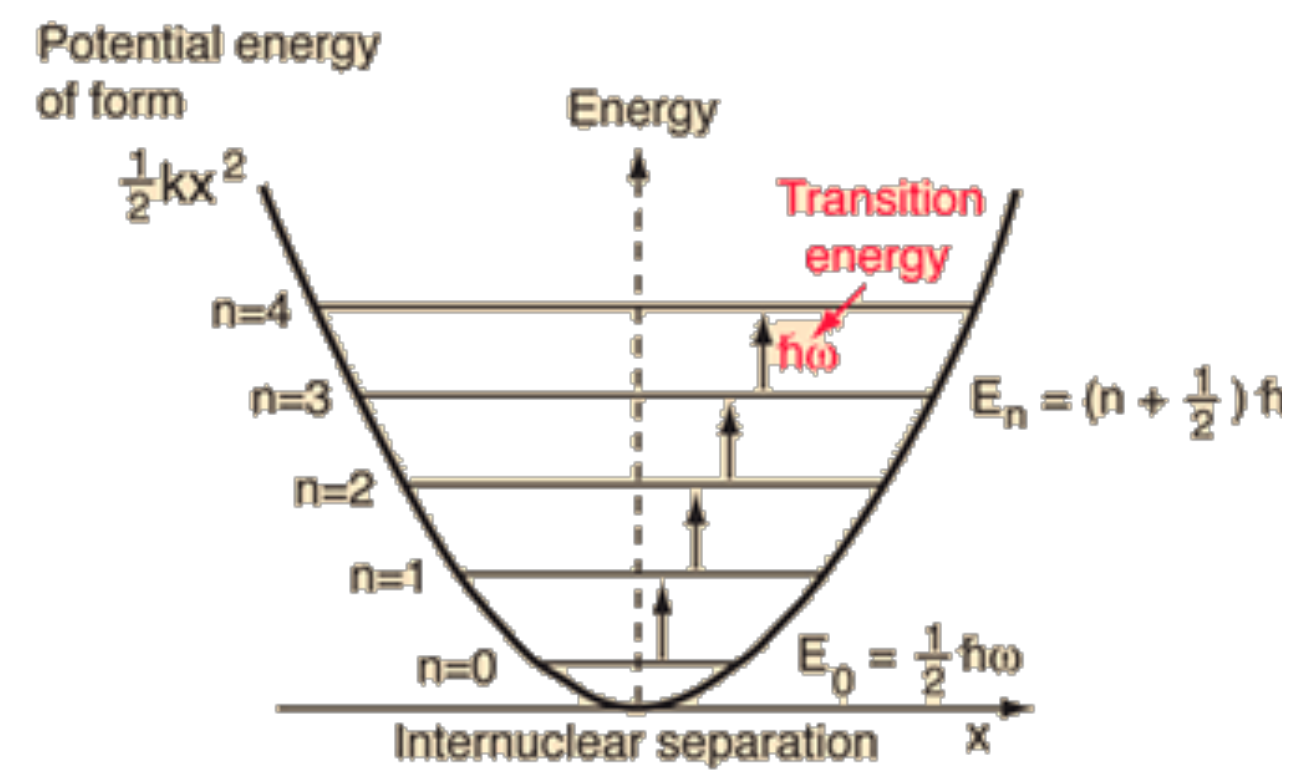
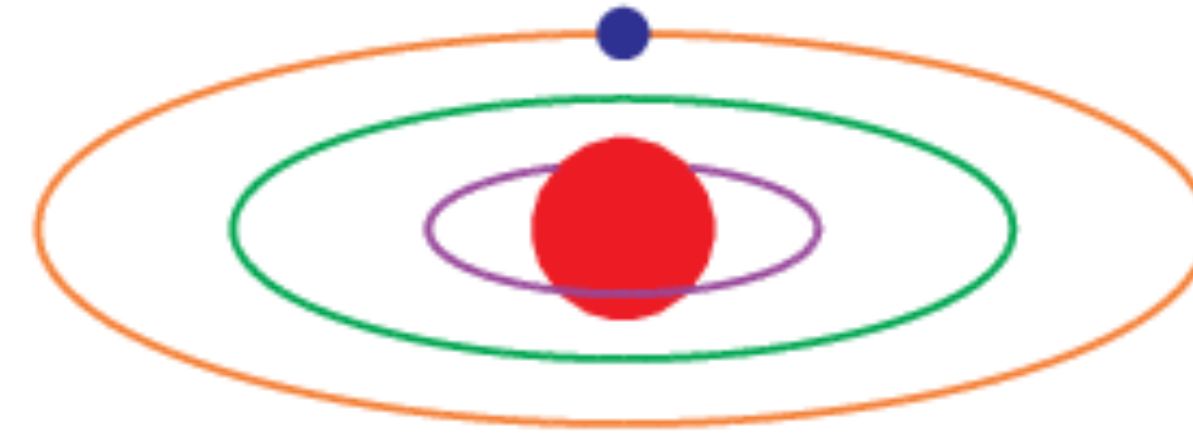
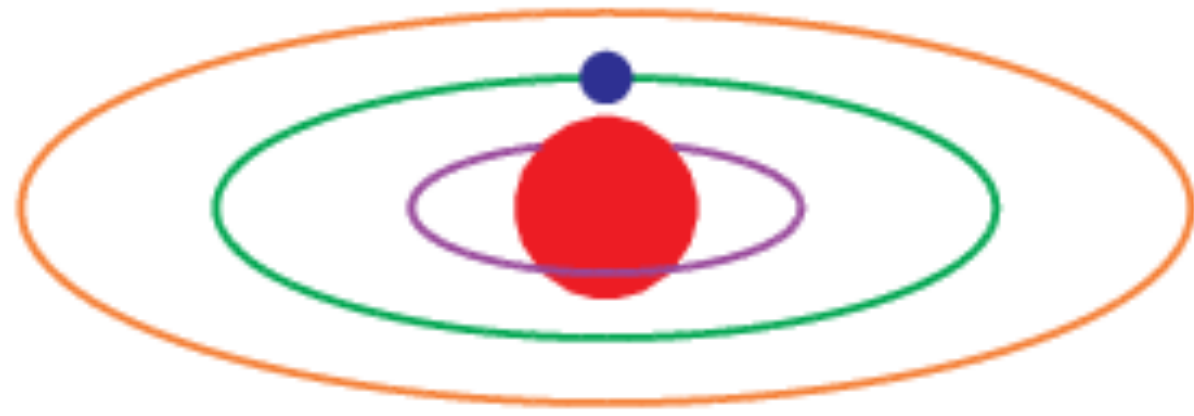








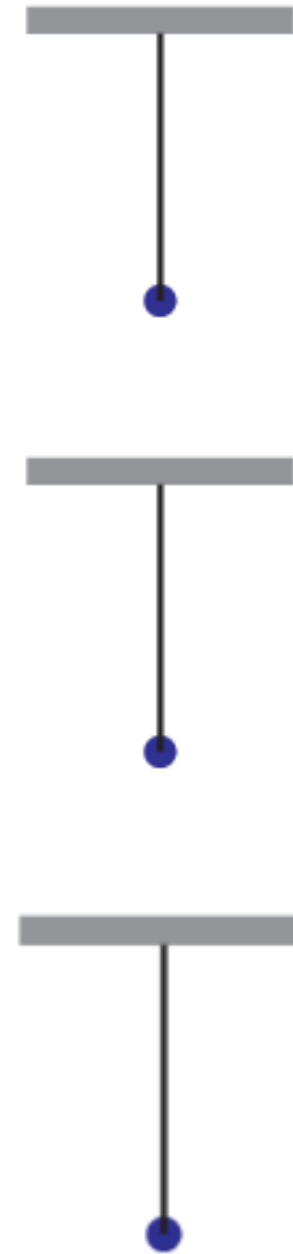




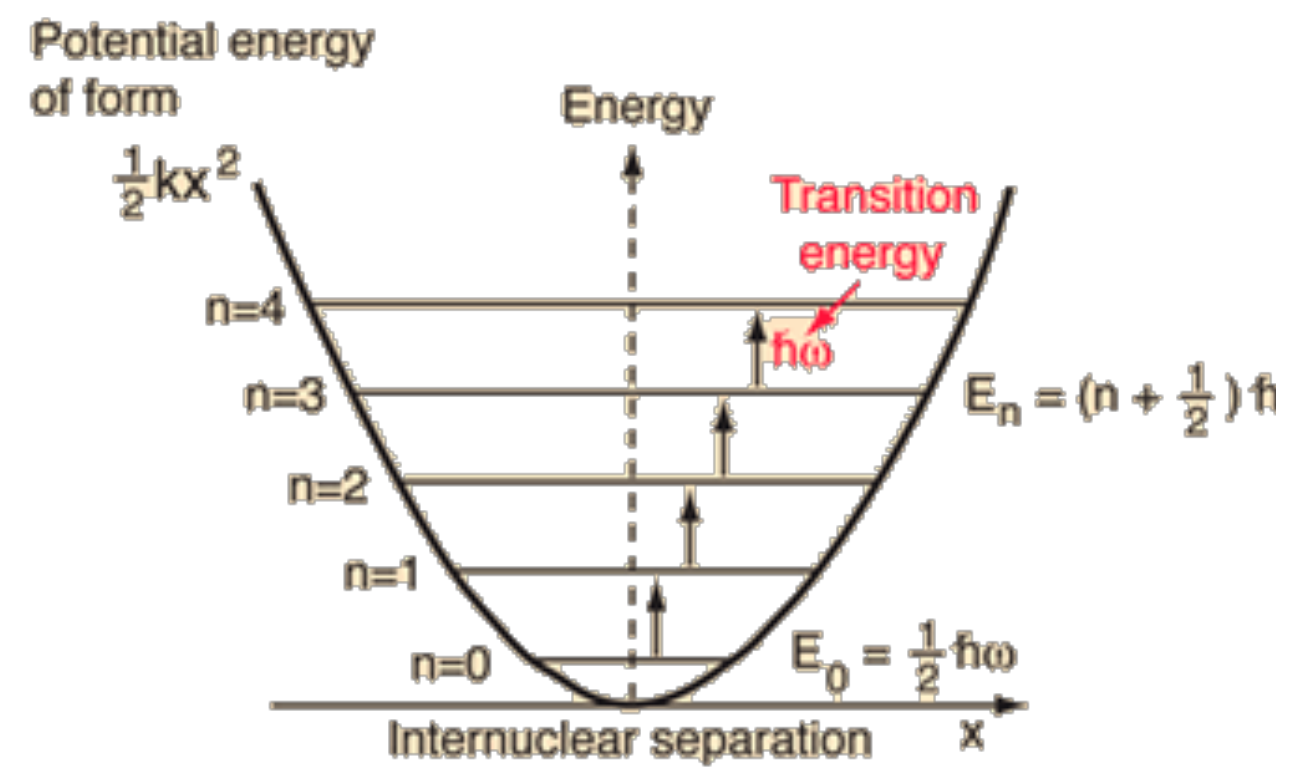
Newton:

$$E \sim \omega^2 \alpha^2$$

$$E = 0$$



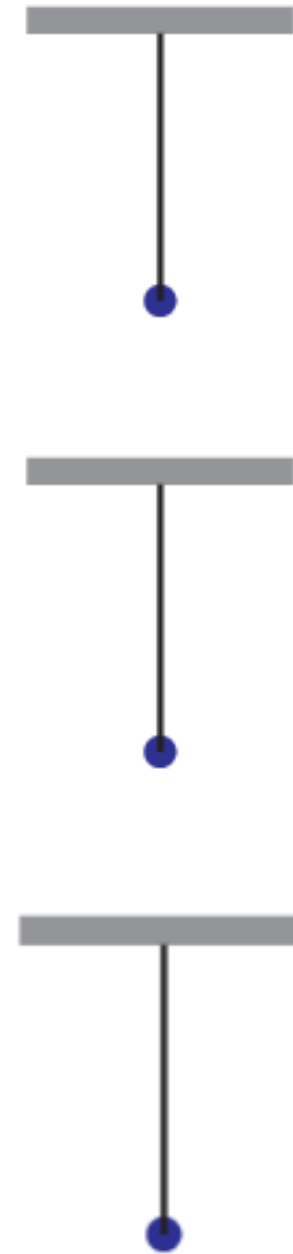
Quantenmechanik:



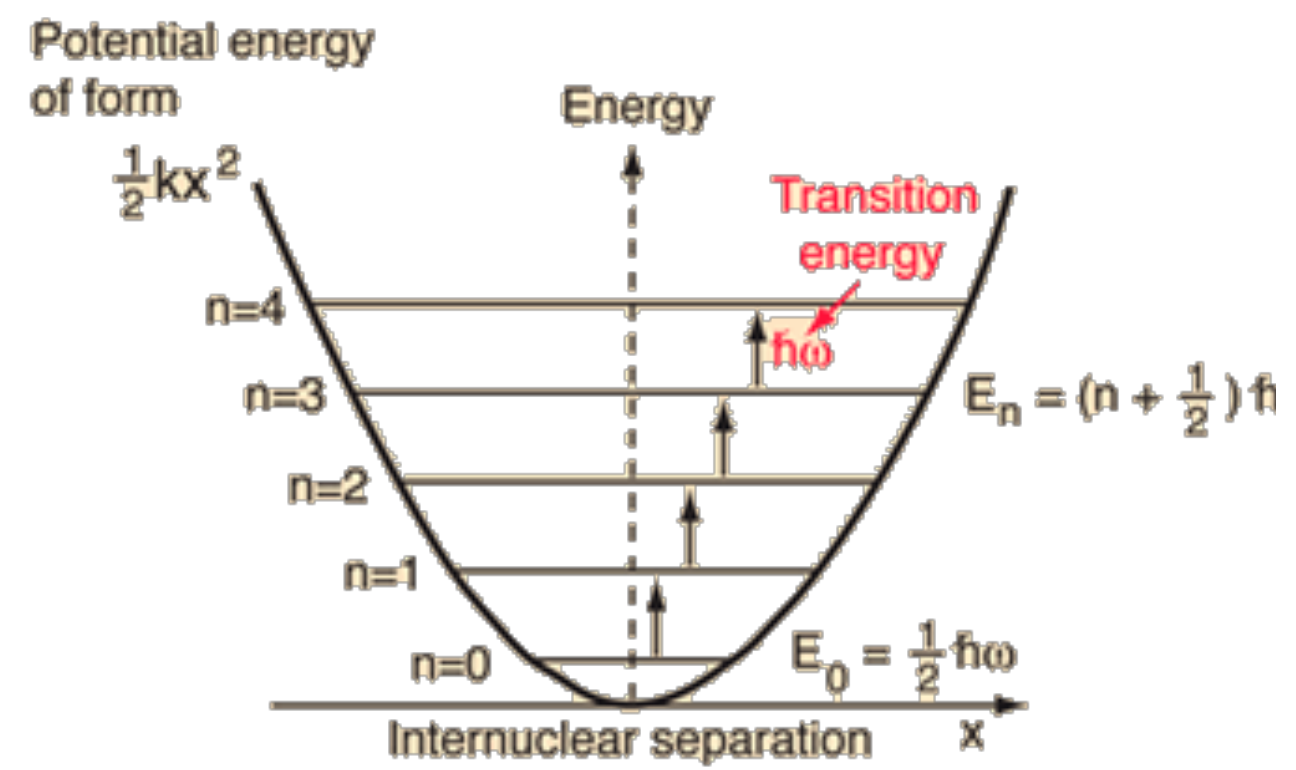
Newton:

$$E \sim \omega^2 \alpha^2$$

$$E = 0$$



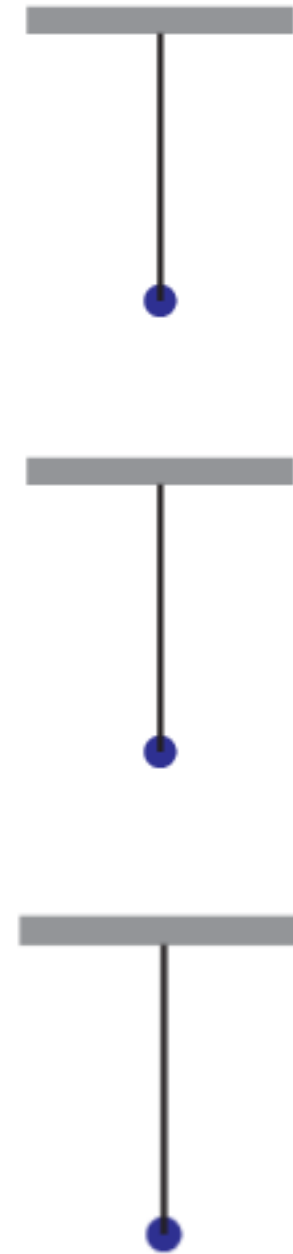
Quantenmechanik:



Newton:

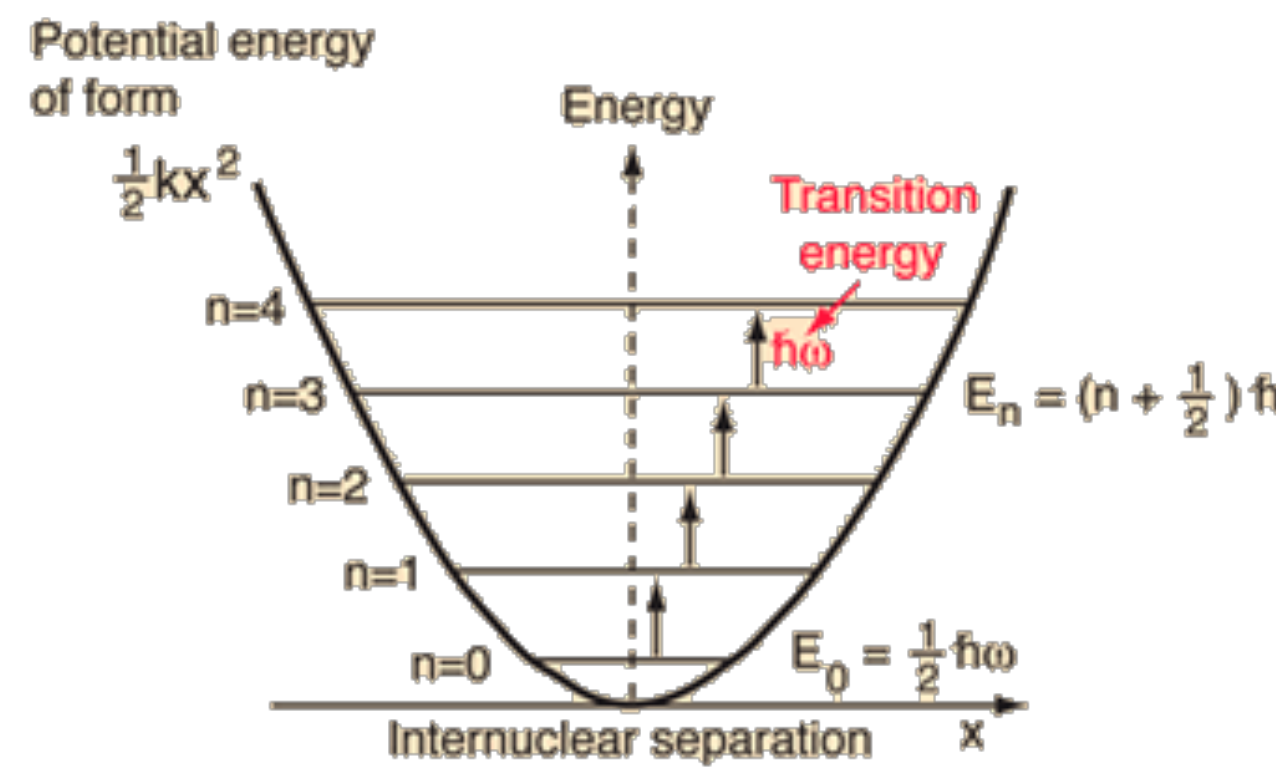
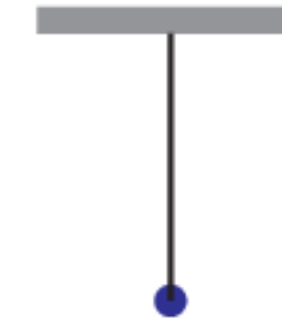
$$E \sim \omega^2 \alpha^2$$

$$E = 0$$



Quantenmechanik:

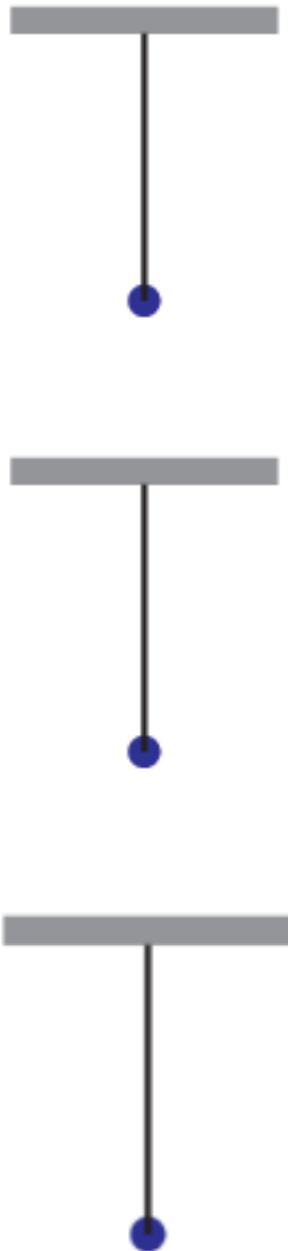
$$E_1 = \hbar \omega$$



Newton:

$E \sim \omega^2 \alpha^2$

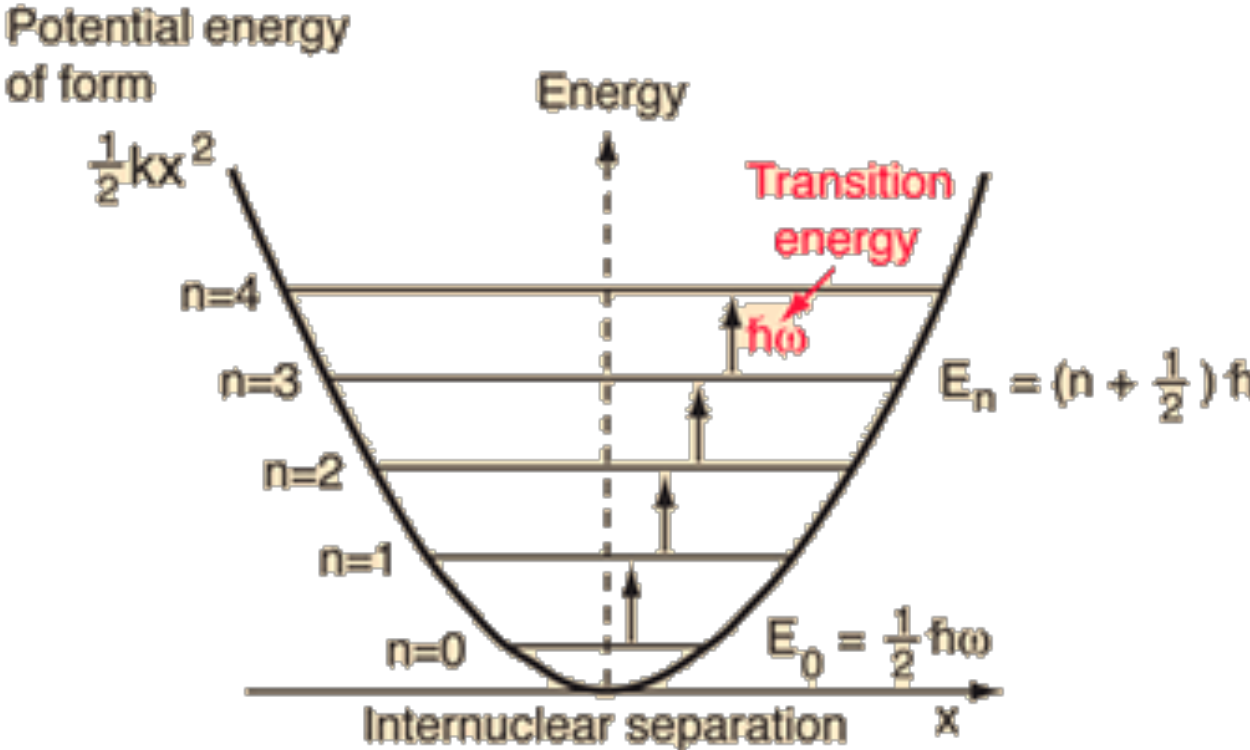
$E = 0$



Quantenmechanik:

$E_1 = \hbar \omega$

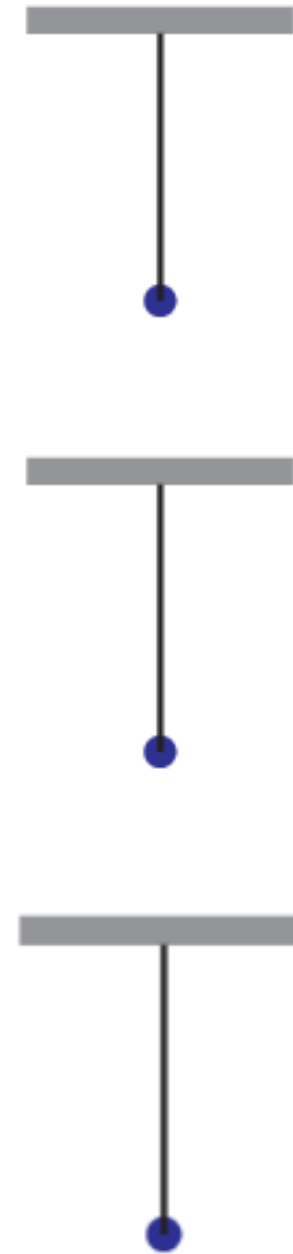
$E_0 = 0$



Newton:

$$E \sim \omega^2 \alpha^2$$

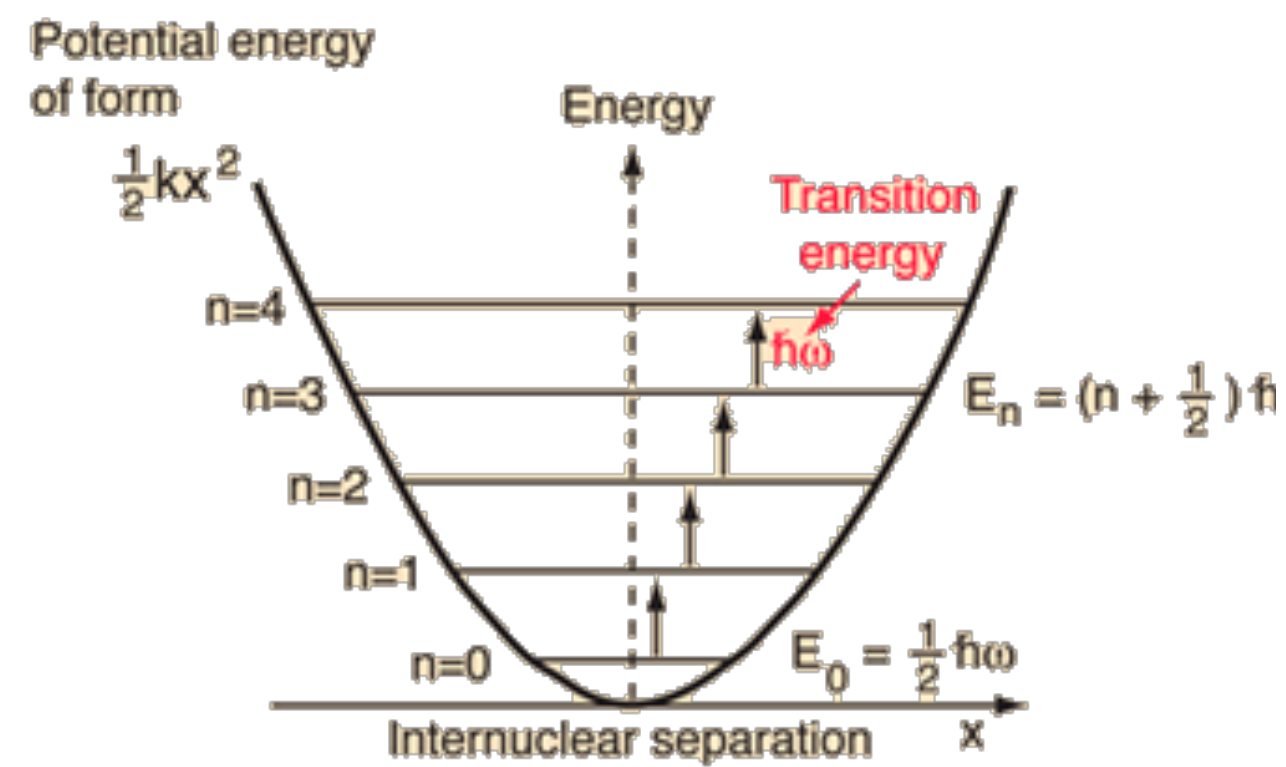
$$E = 0$$



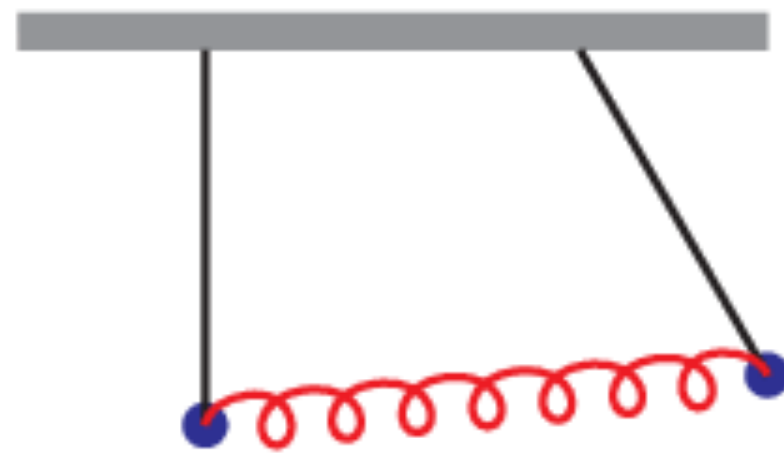
Quantenmechanik:

$$E_1 = \hbar \omega$$

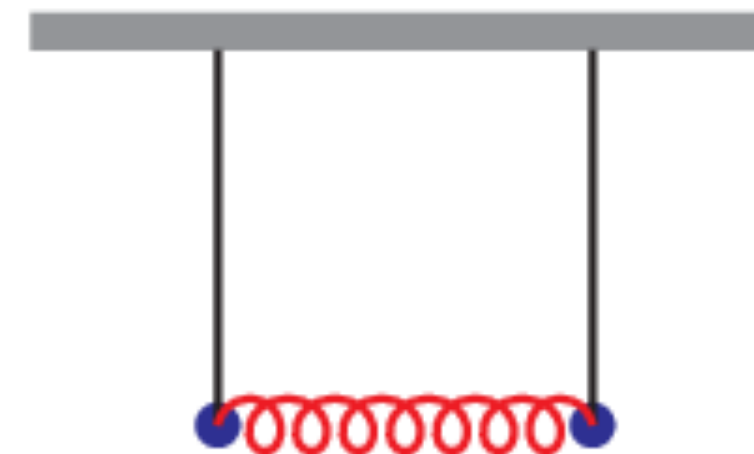
$$E_0 = 0$$



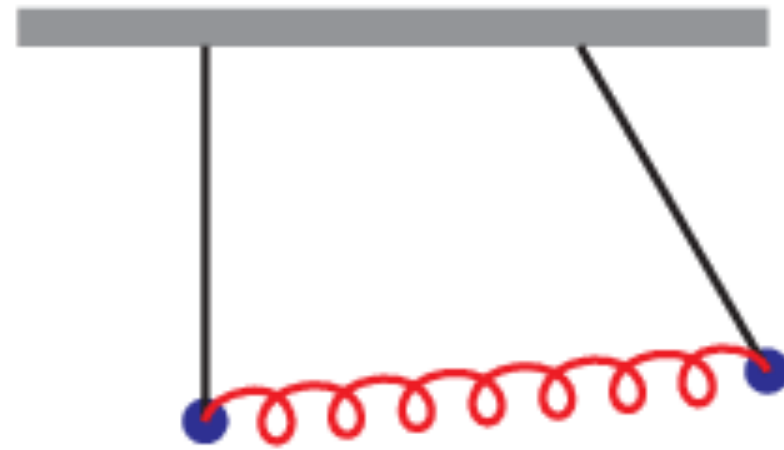
klassische Mechanik



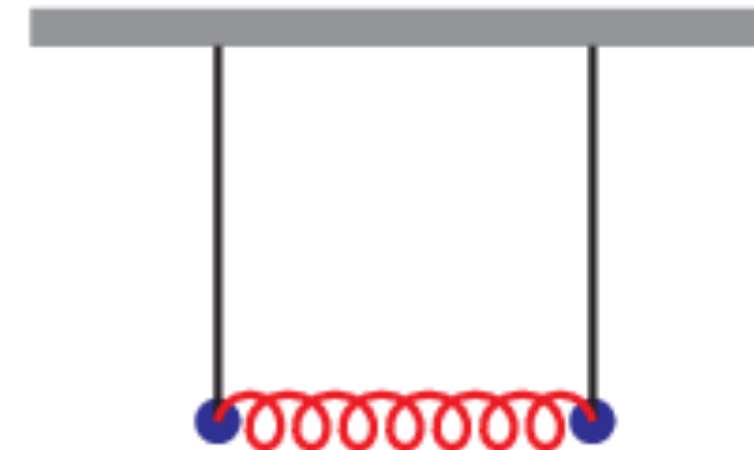
Quantenmechanik



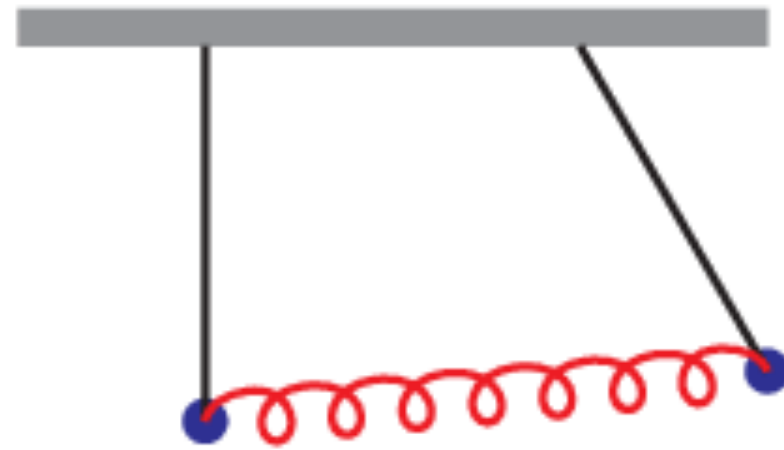
klassische Mechanik



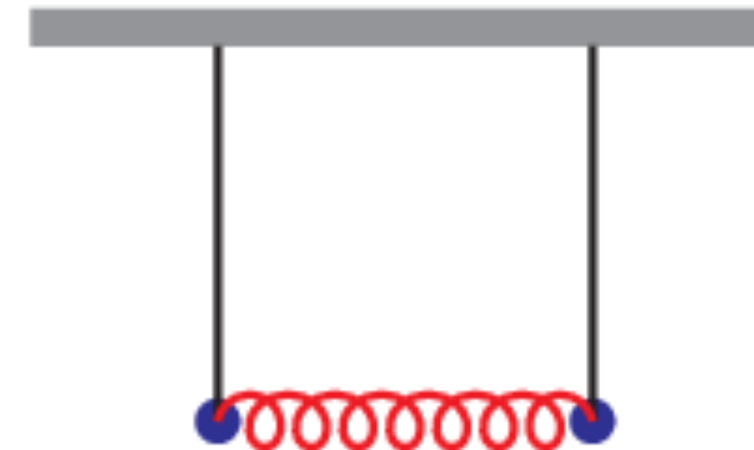
Quantenmechanik



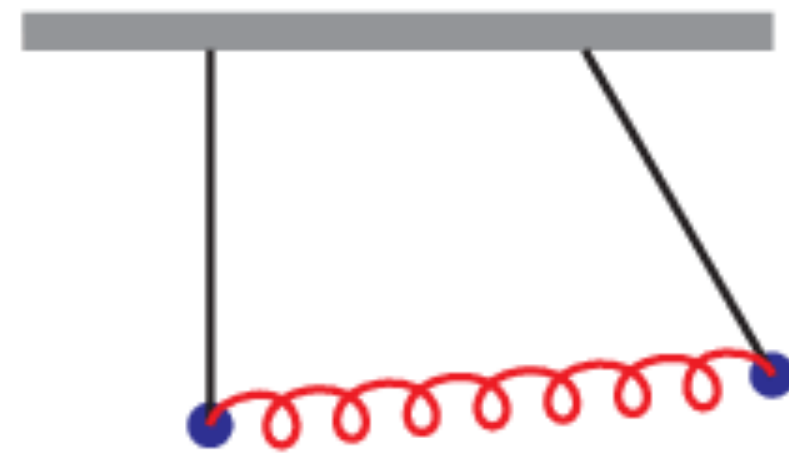
klassische Mechanik



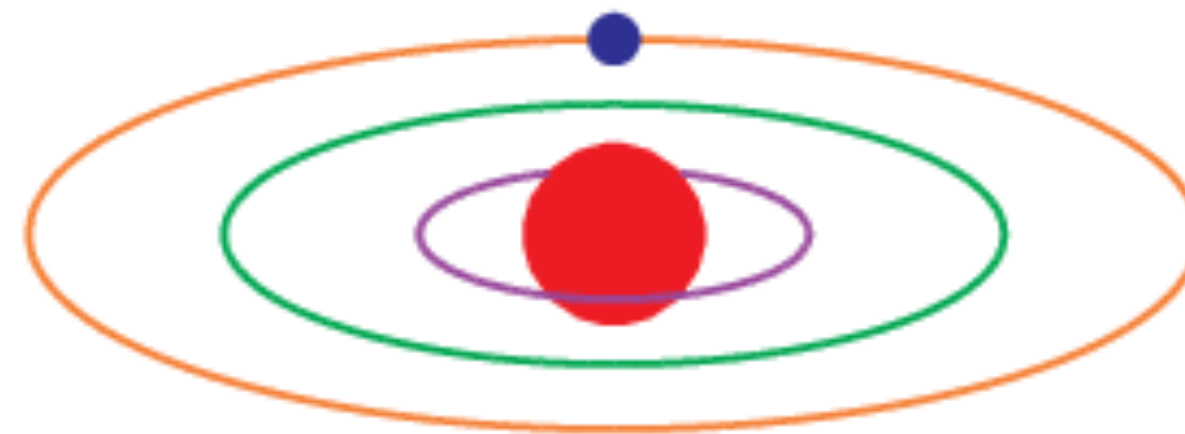
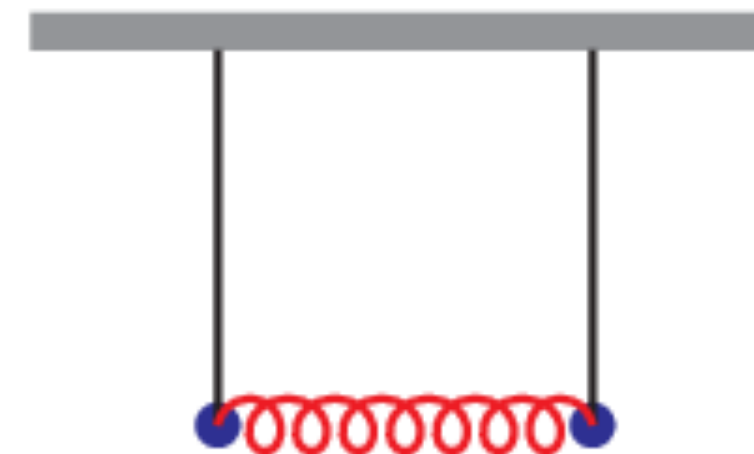
Quantenmechanik



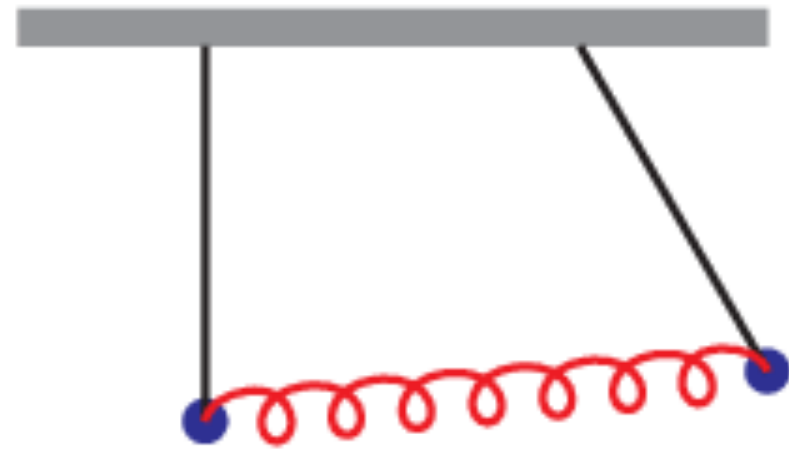
klassische Mechanik



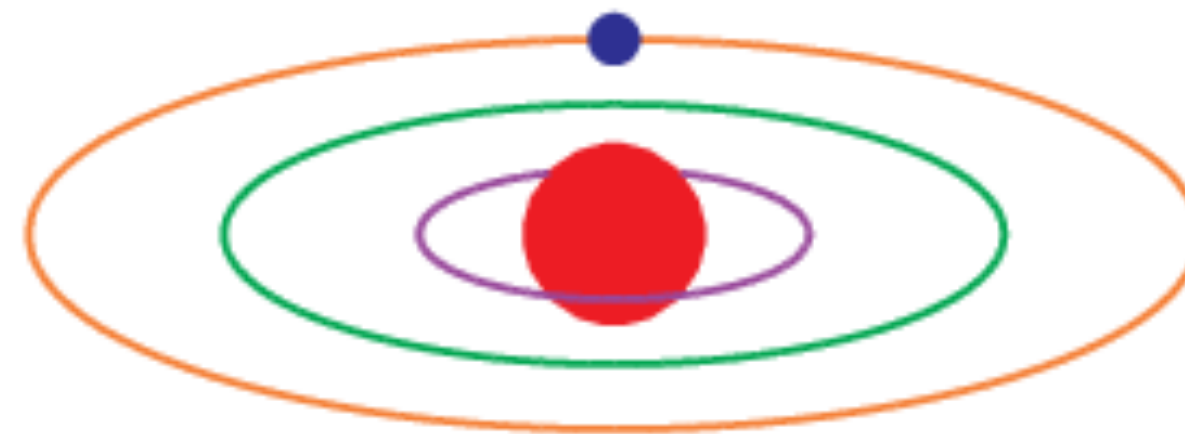
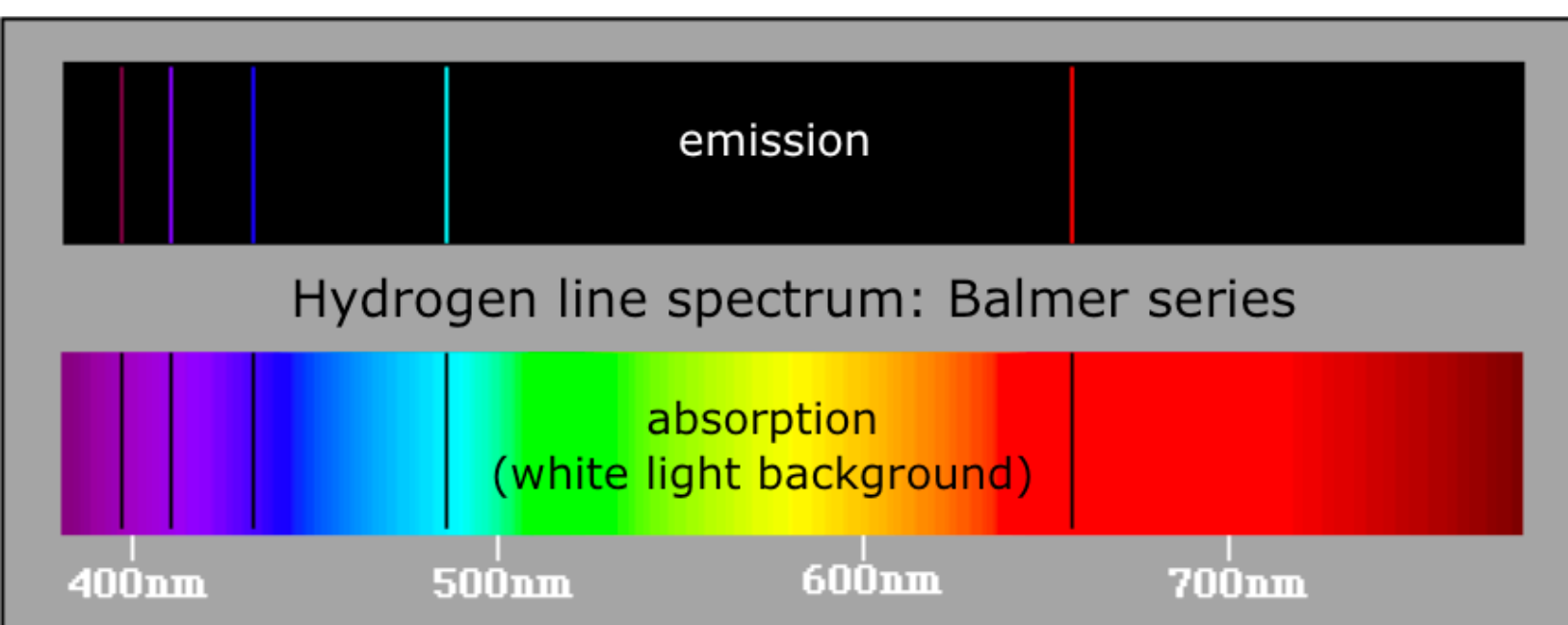
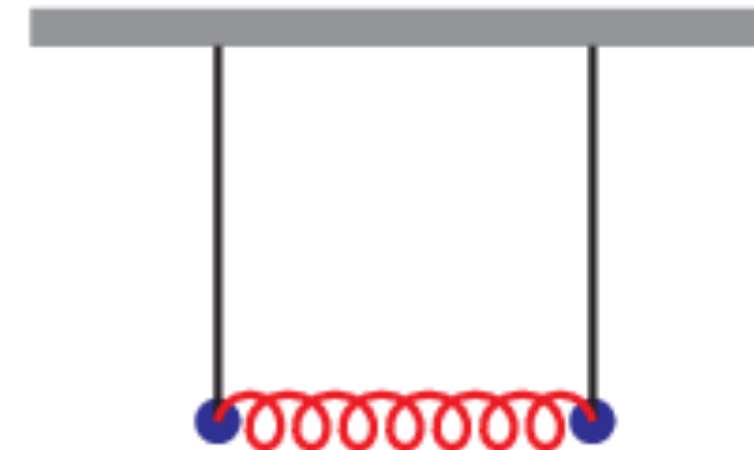
Quantenmechanik



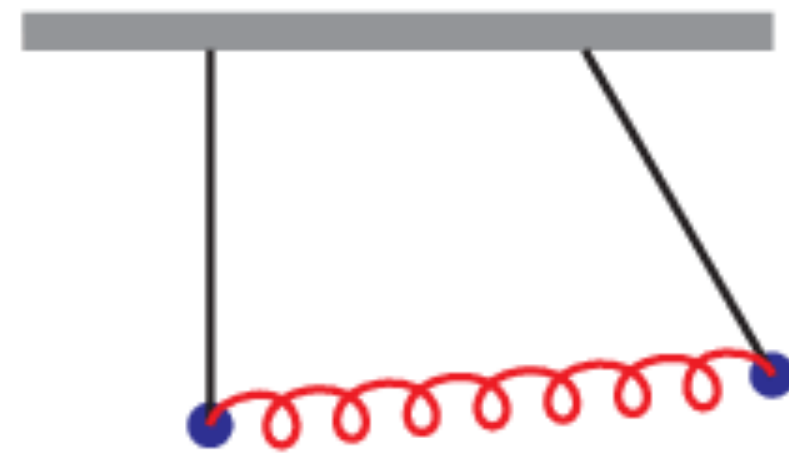
klassische Mechanik



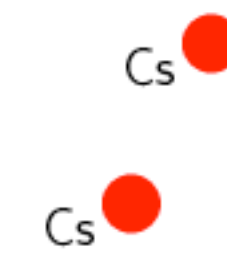
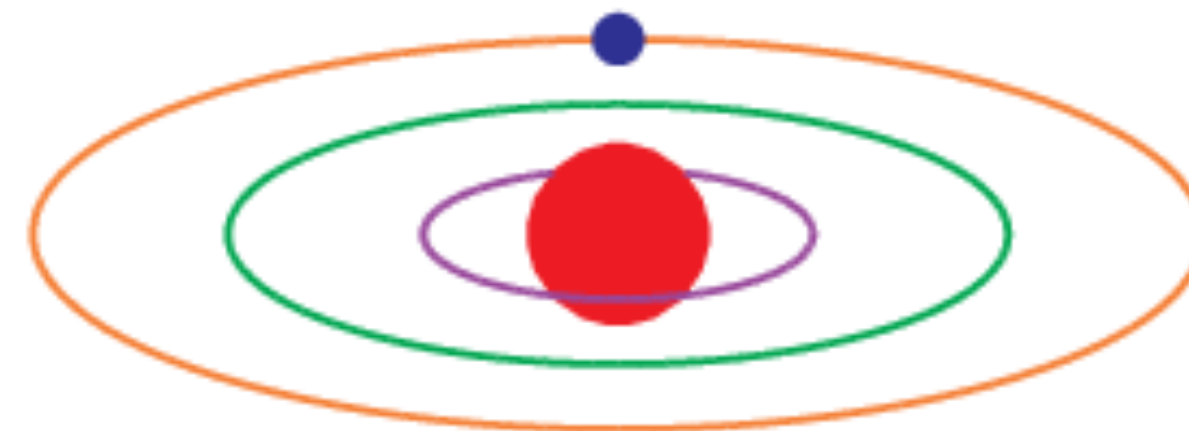
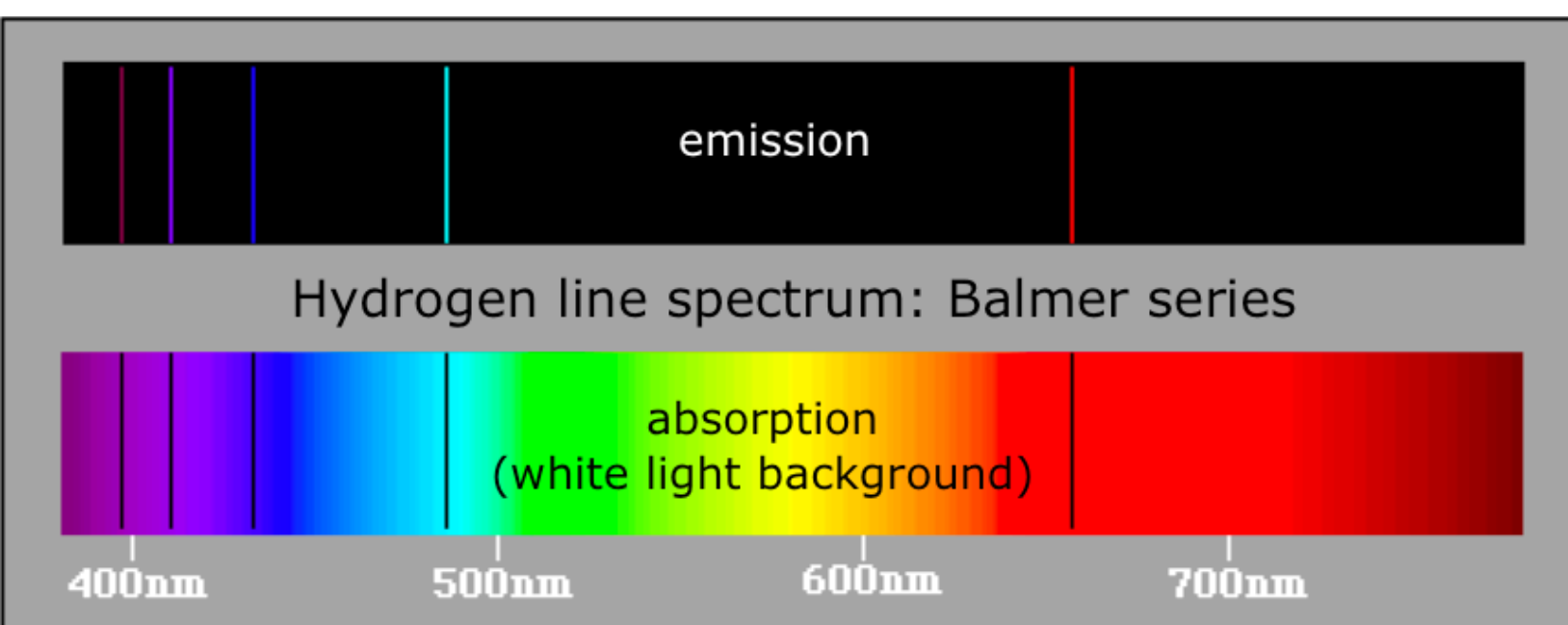
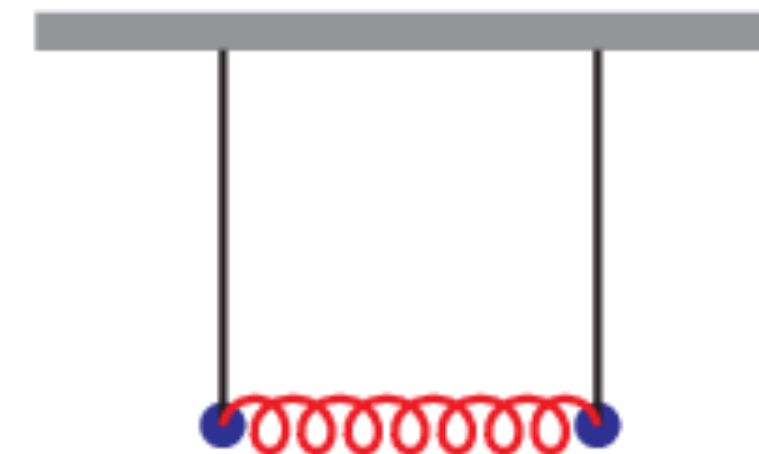
Quantenmechanik



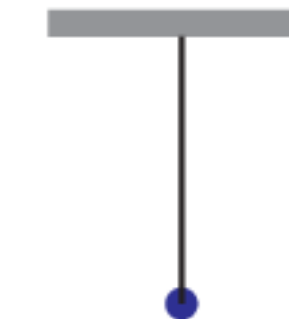
klassische Mechanik



Quantenmechanik



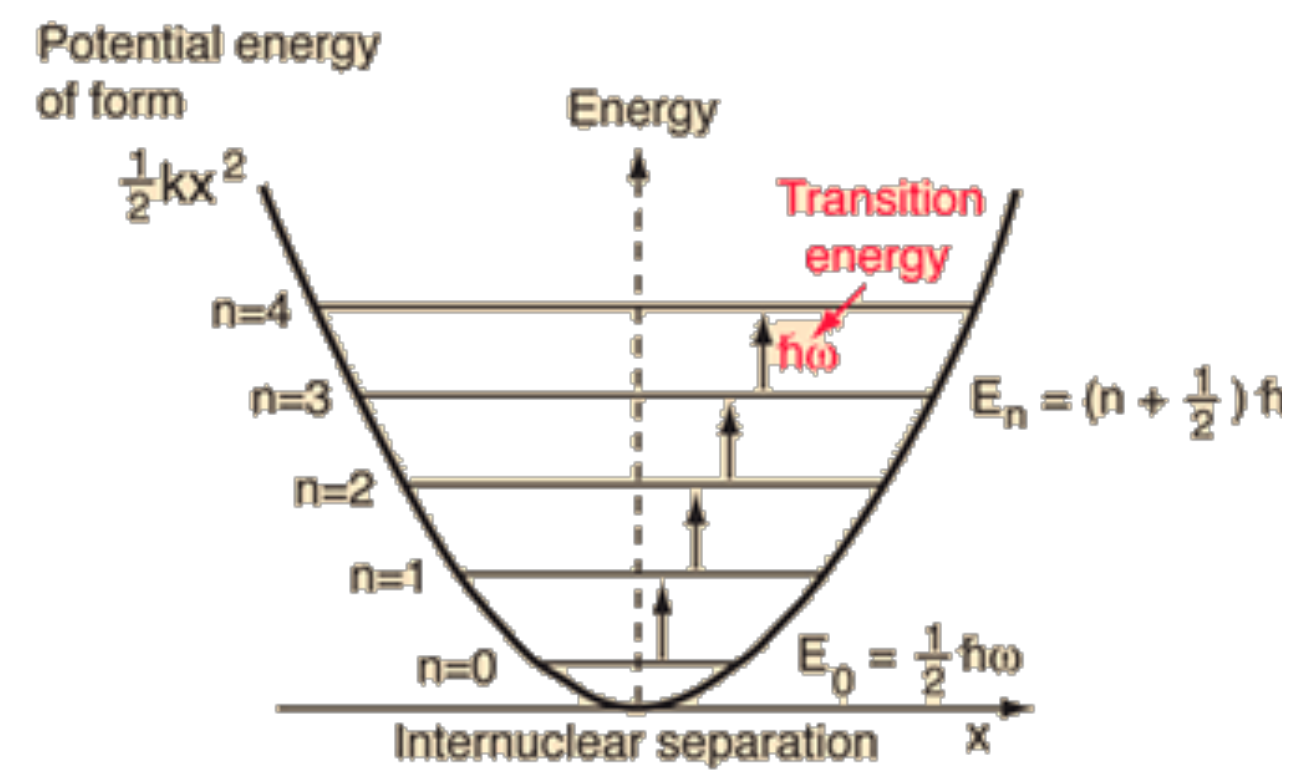
Quantenmechanik:



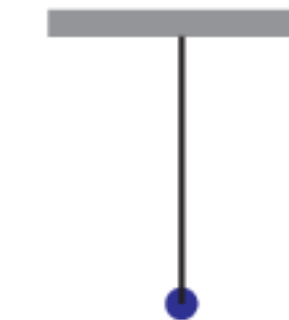
$$E_1 = \hbar\omega$$



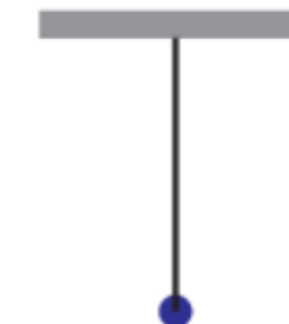
$$E_0 = 0$$



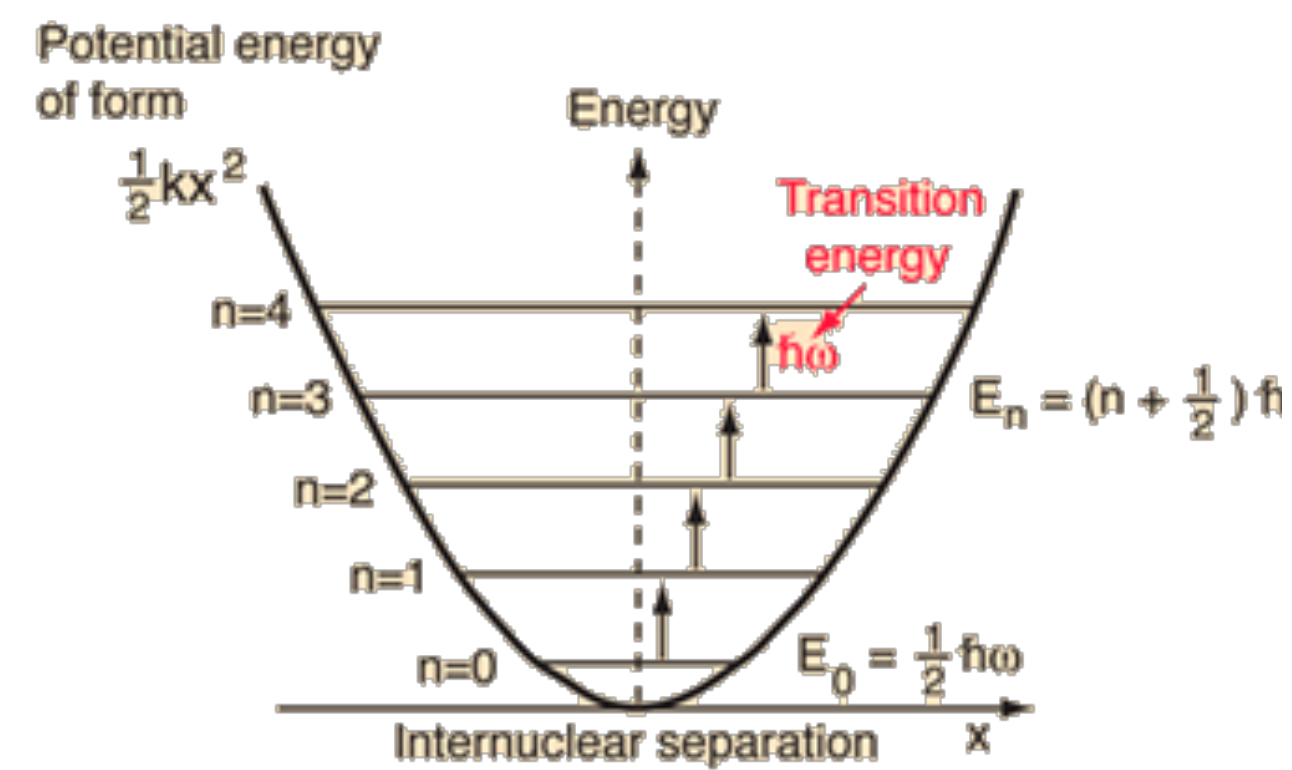
Quantenmechanik:



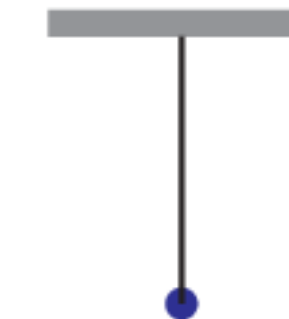
$$E_1 = \hbar\omega$$



$$E_0 = 0$$



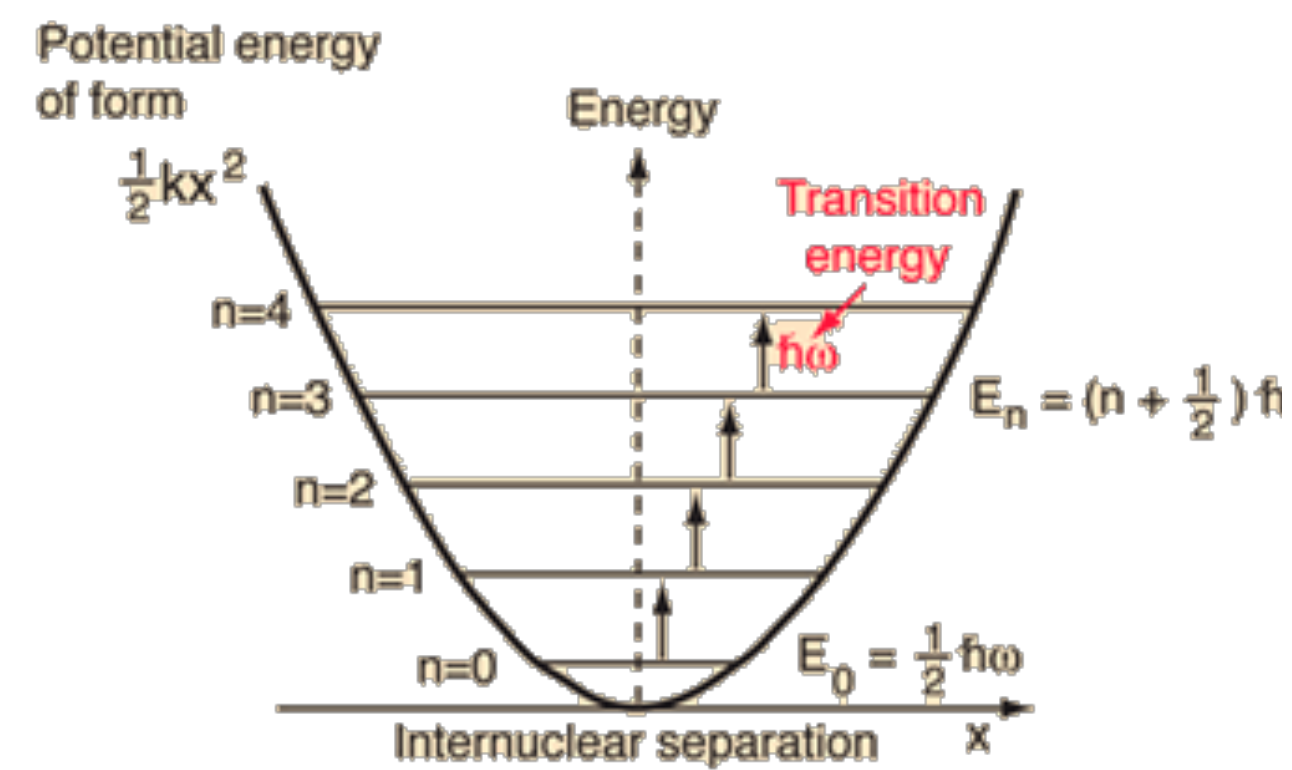
Quantenmechanik:



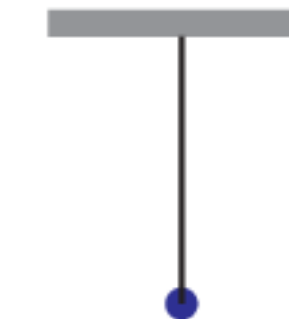
$$E_1 = \hbar\omega$$



$$E_0 = 0 + \frac{1}{2}\hbar\omega$$



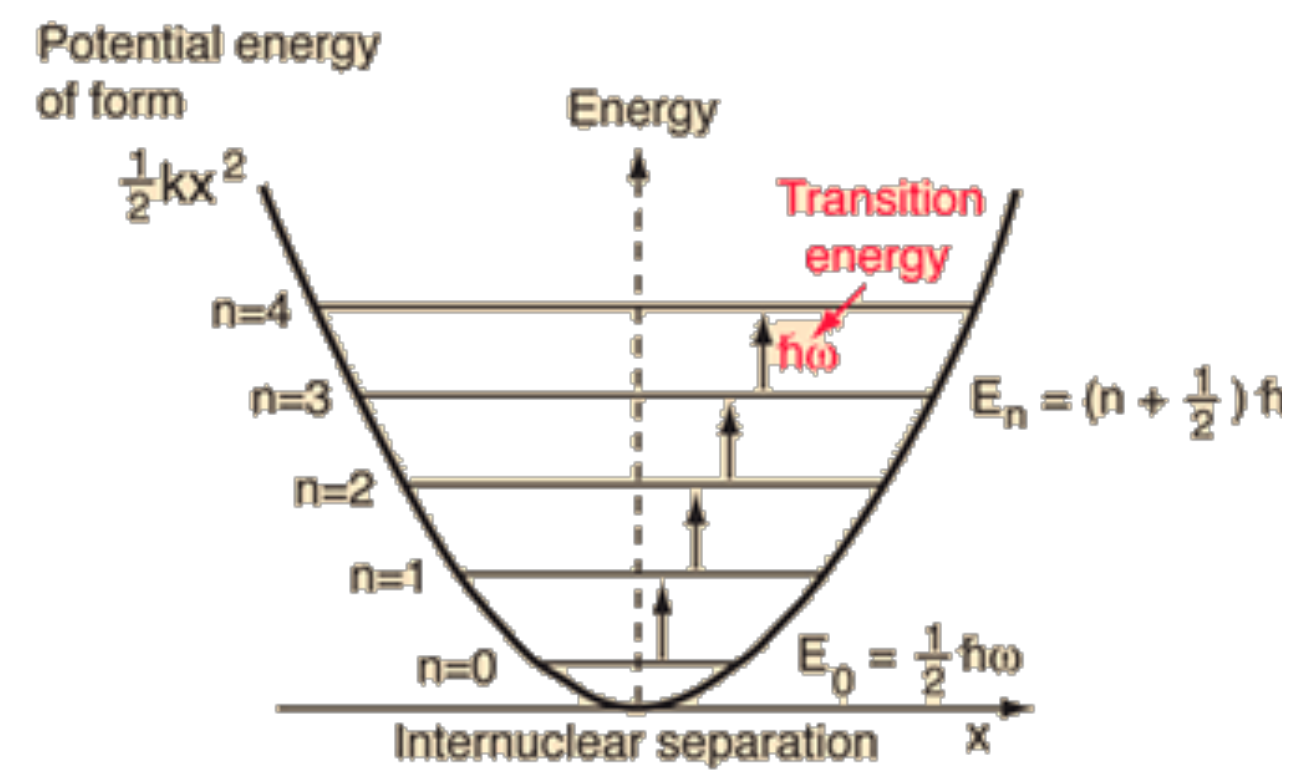
Quantenmechanik:



$$E_1 = \hbar\omega$$



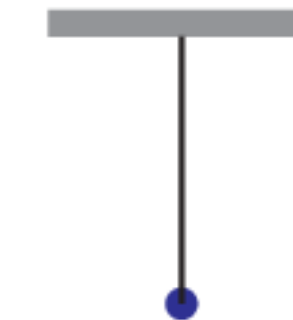
$$E_0 = 0 + \frac{1}{2}\hbar\omega$$



$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

Heisenberg'sche
Unschärferelation

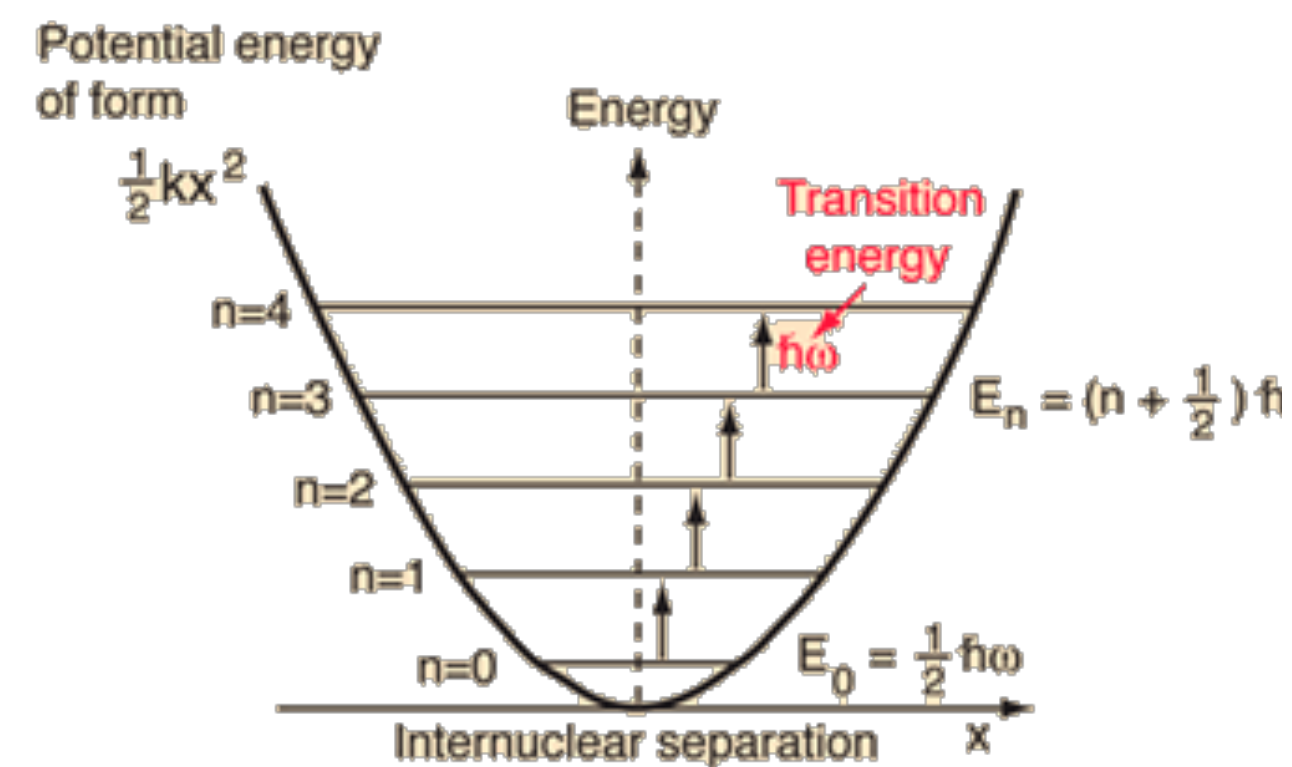
Quantenmechanik:



$$E_1 = \hbar\omega$$



$$E_0 = 0 + \frac{1}{2}\hbar\omega$$



$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

Heisenberg'sche
Unschärferelation

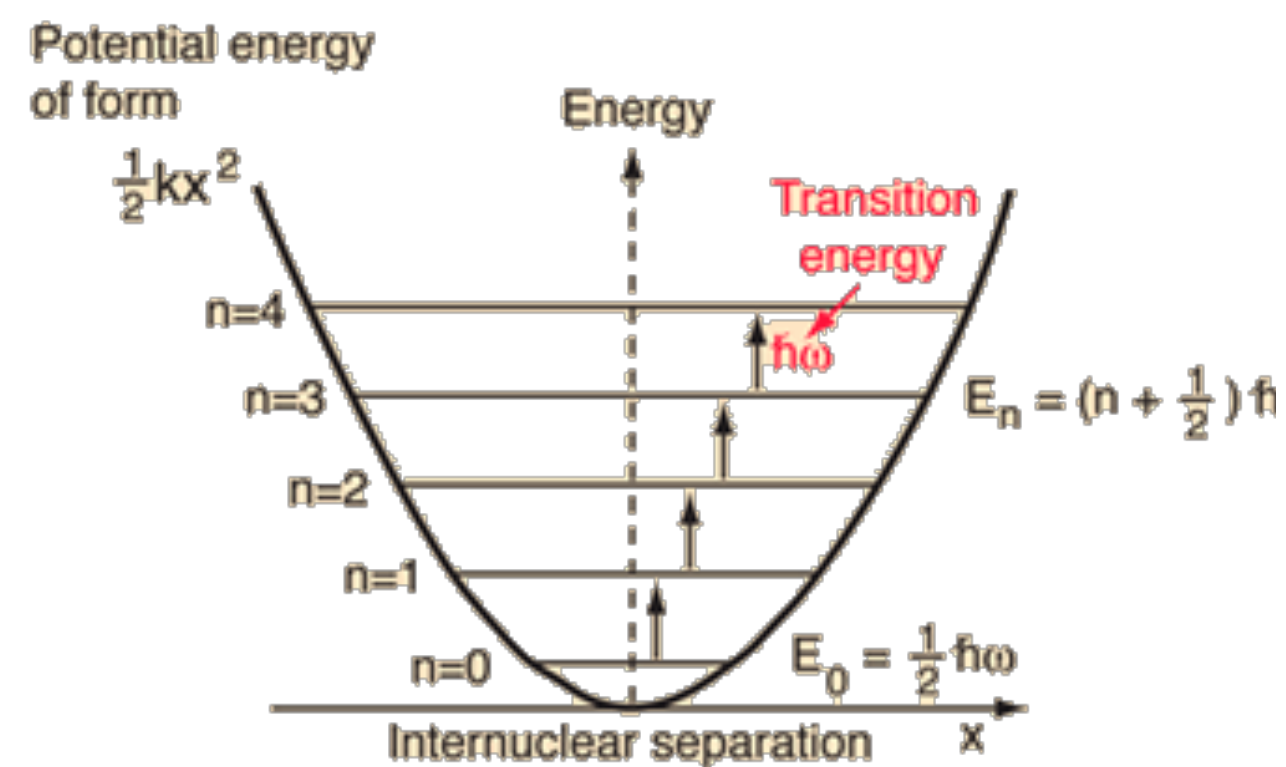
Quantenmechanik:



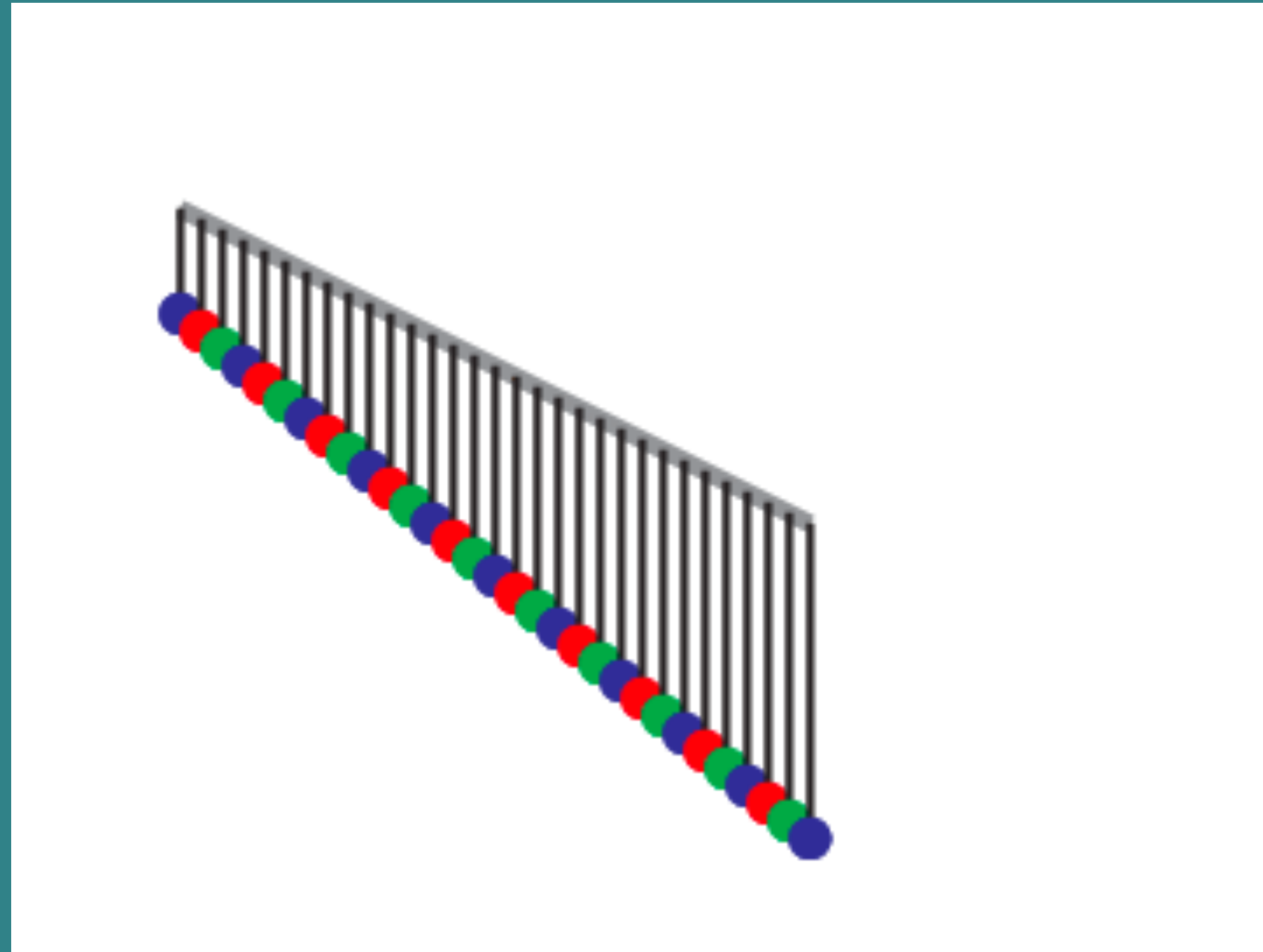
$$E_1 = \hbar\omega + \frac{1}{2}\hbar\omega$$



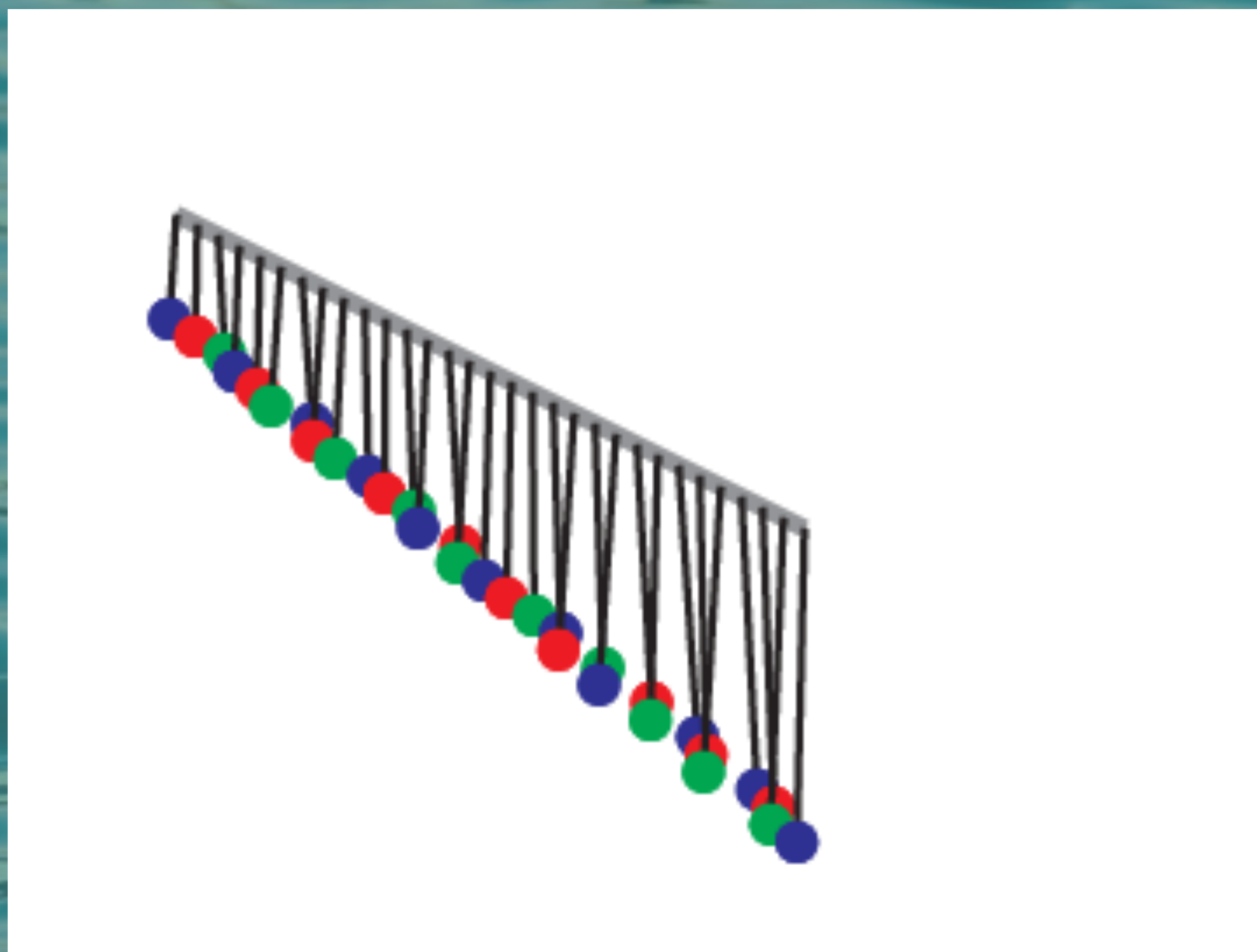
$$E_0 = 0 + \frac{1}{2}\hbar\omega$$



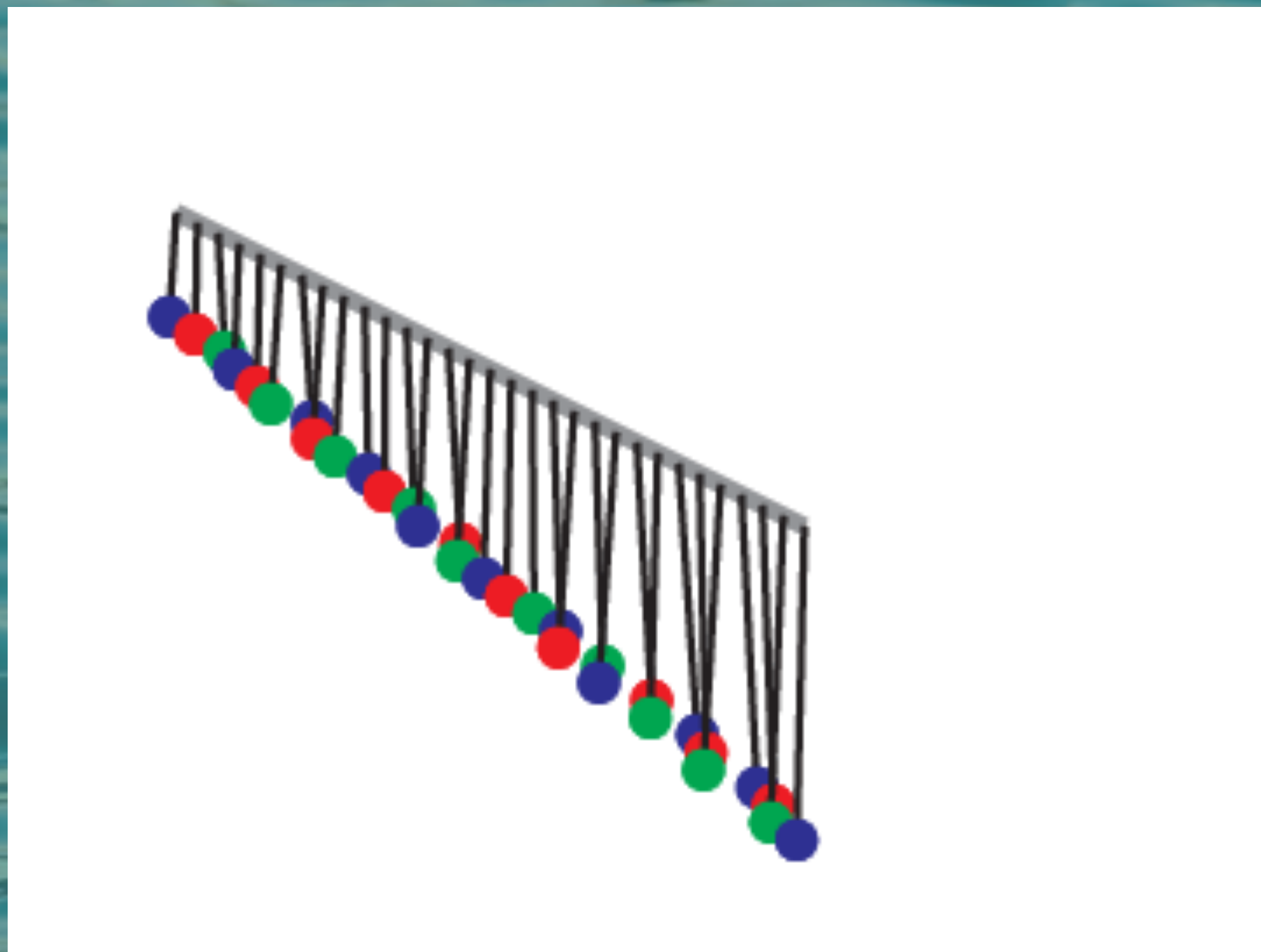
Vakuum

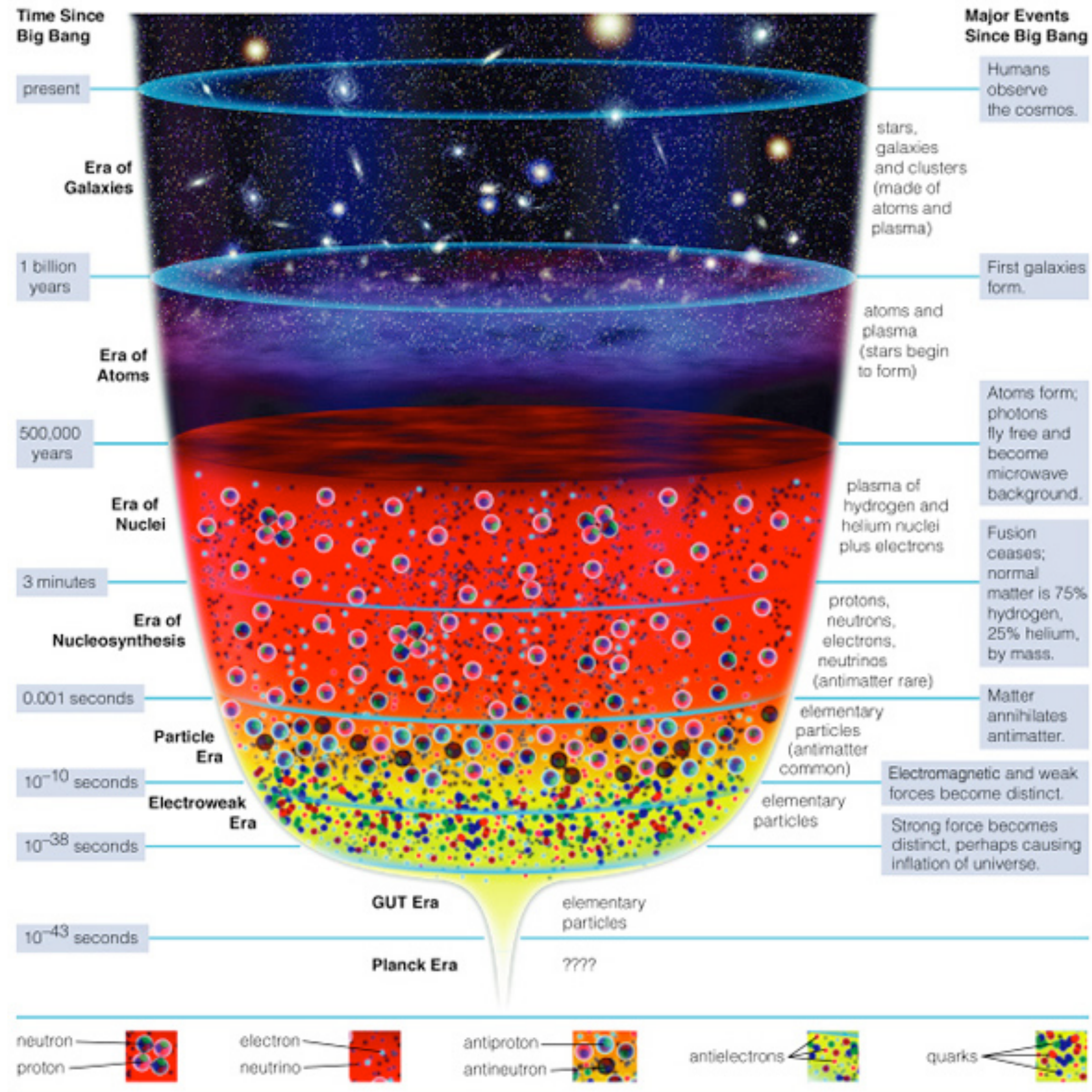


Quanten-Vakuum



Quanten-Vakuum

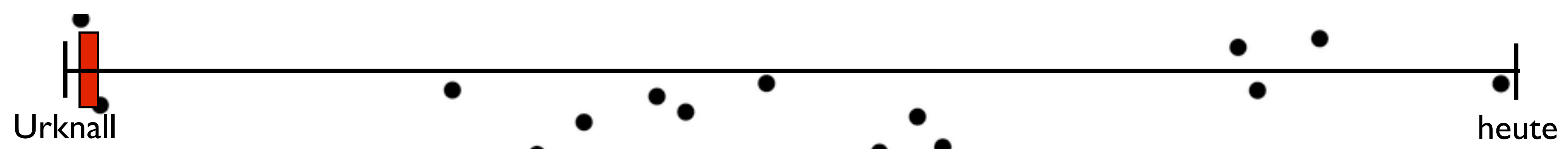




Urknall

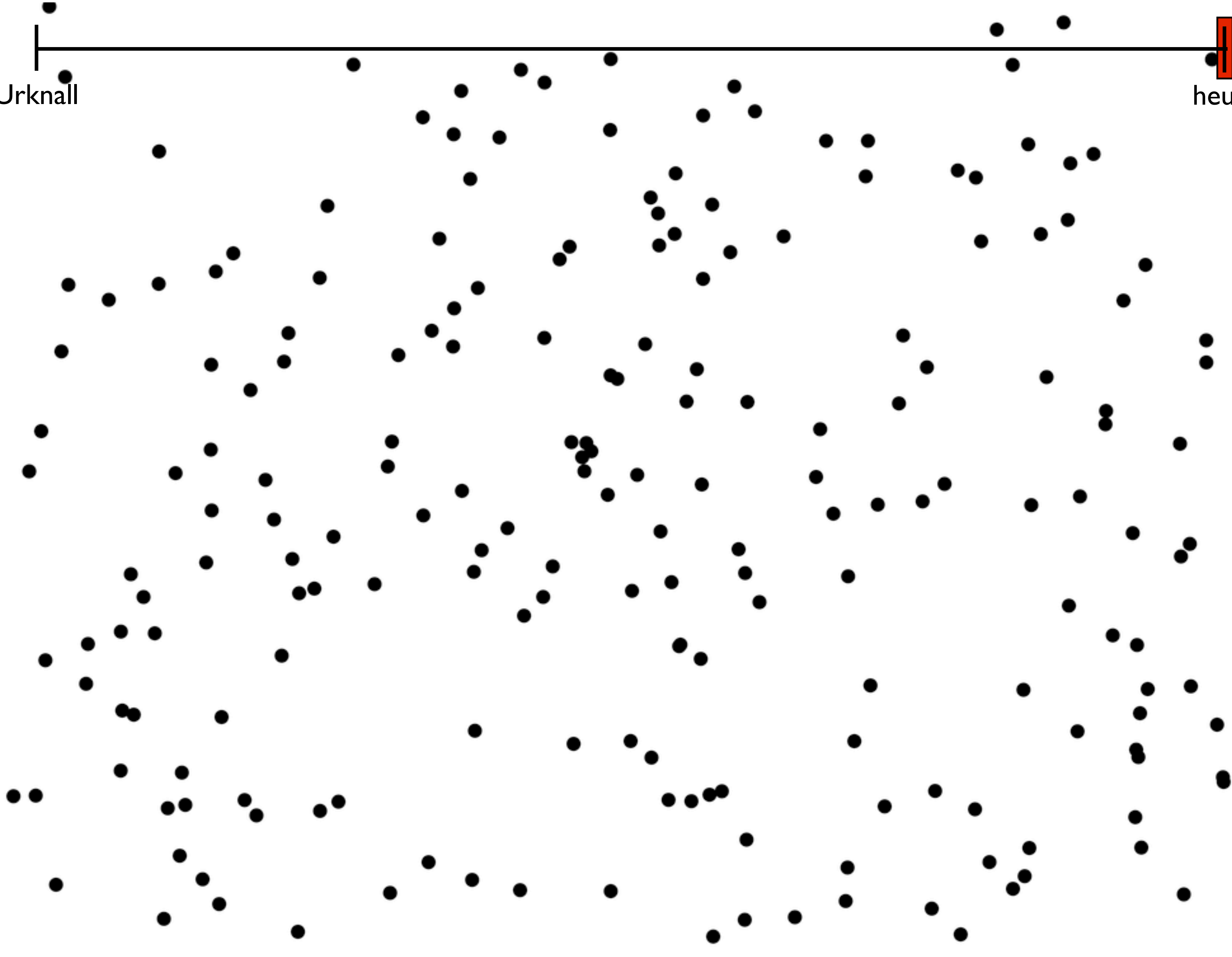
heute

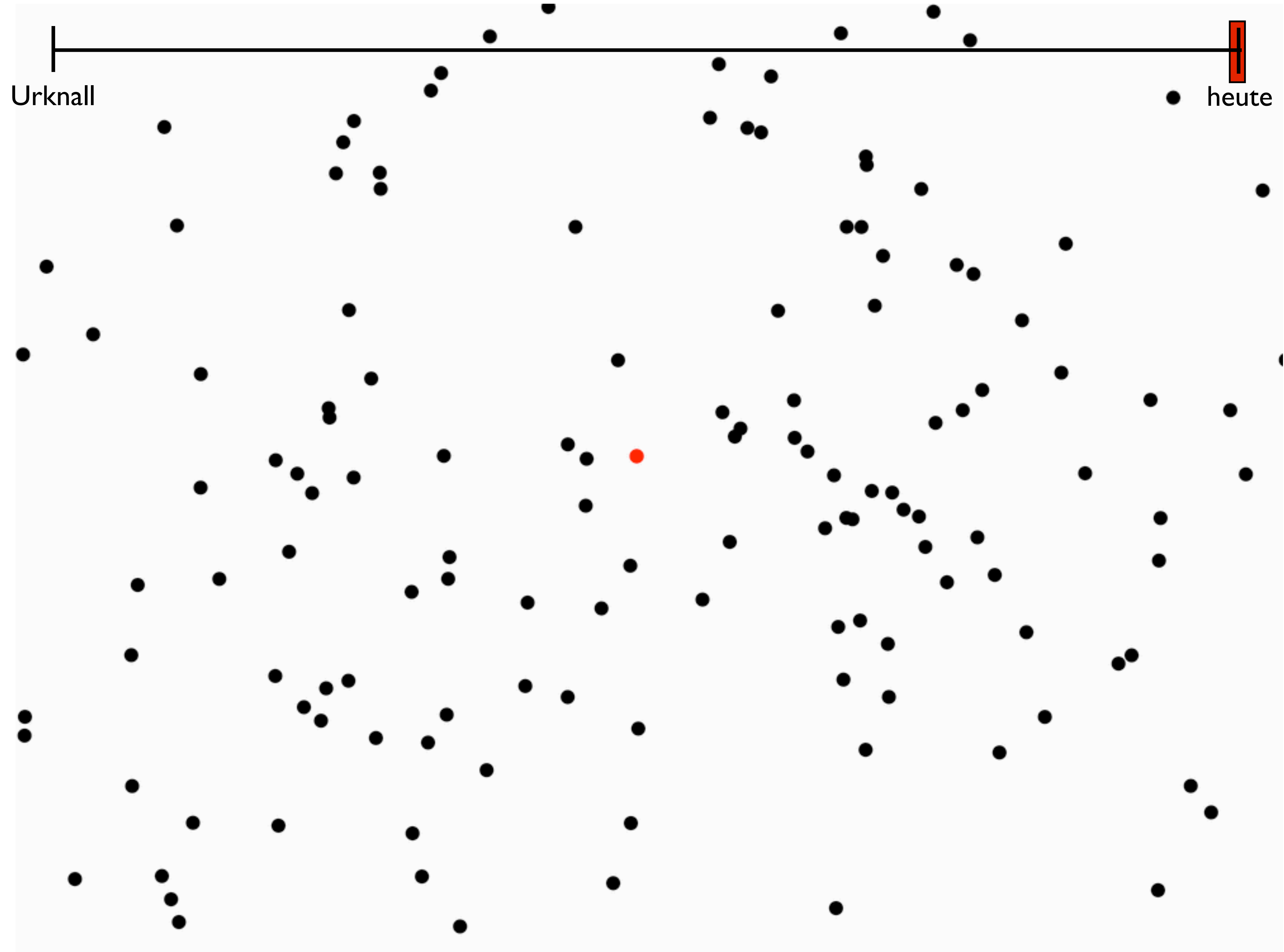
$t < 400,000$ Jahre

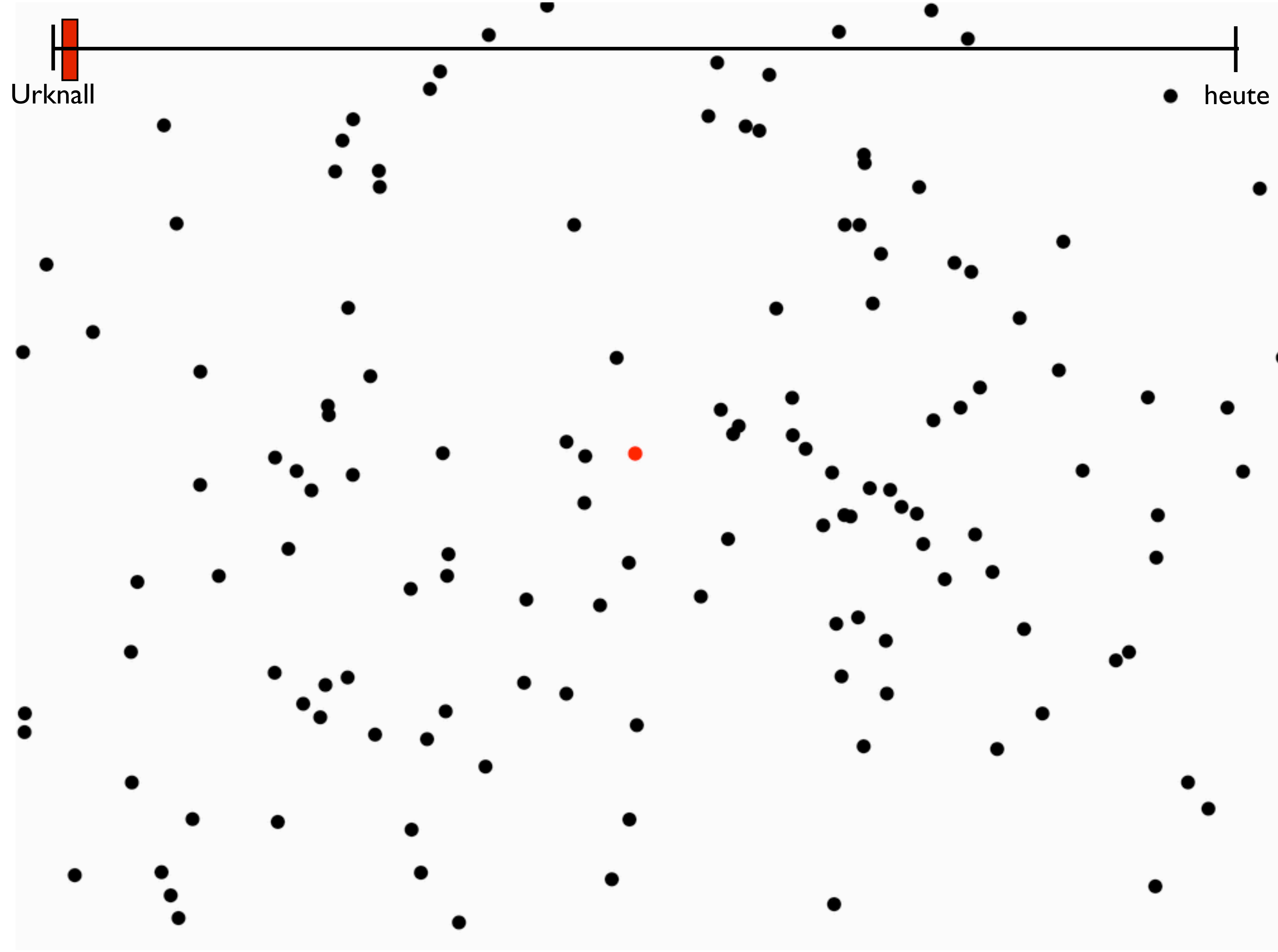


Urknall

heute

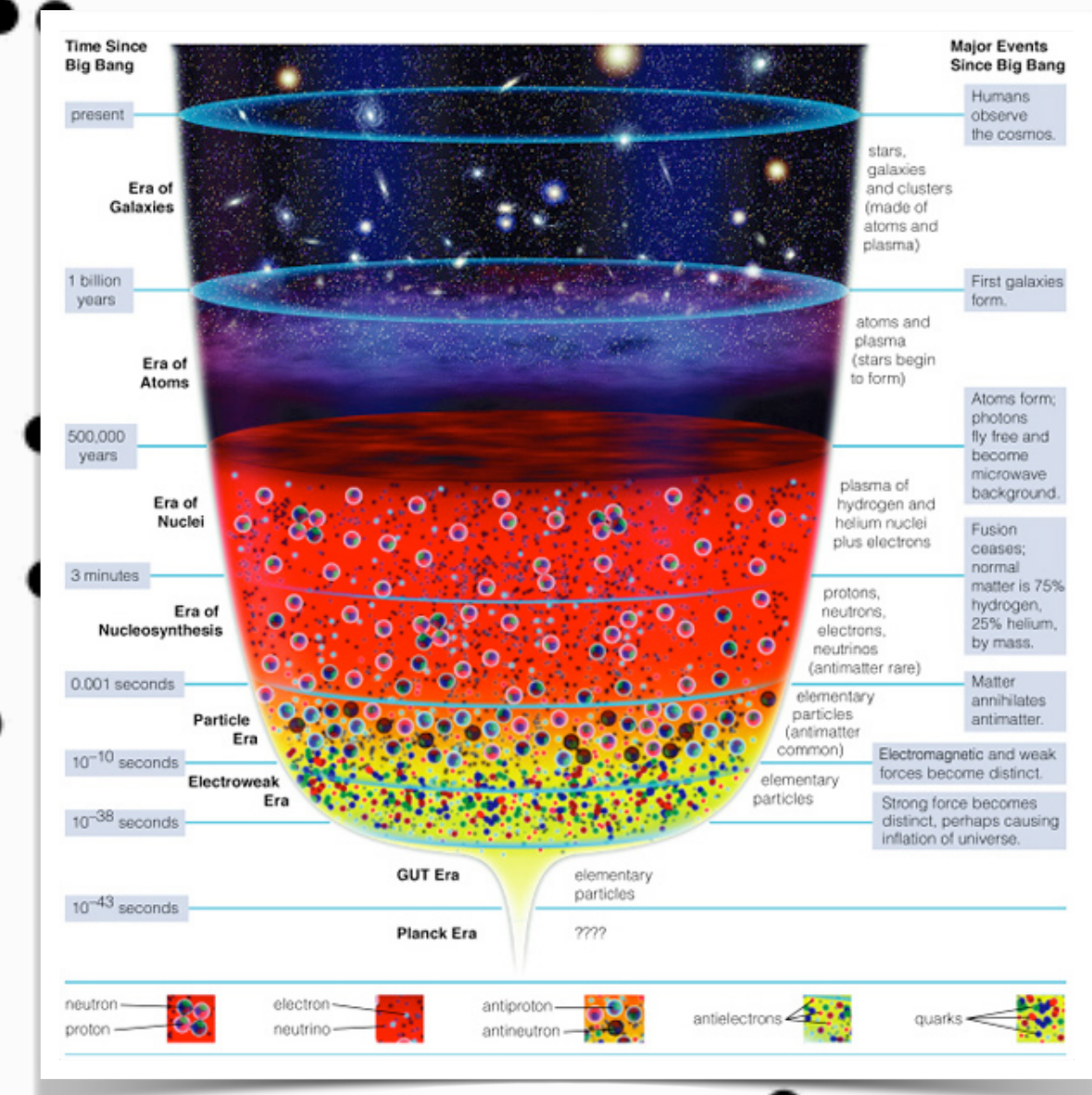


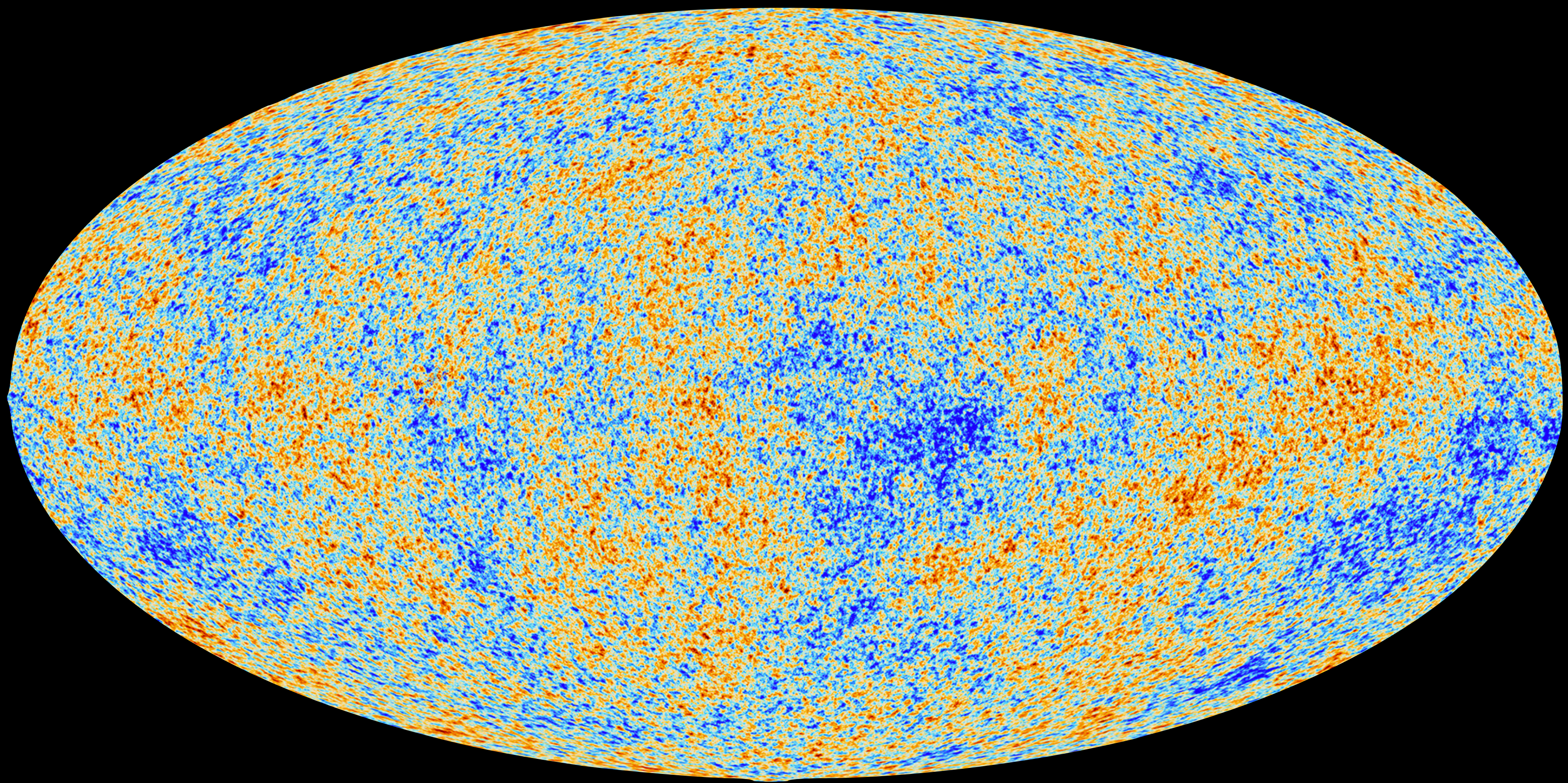


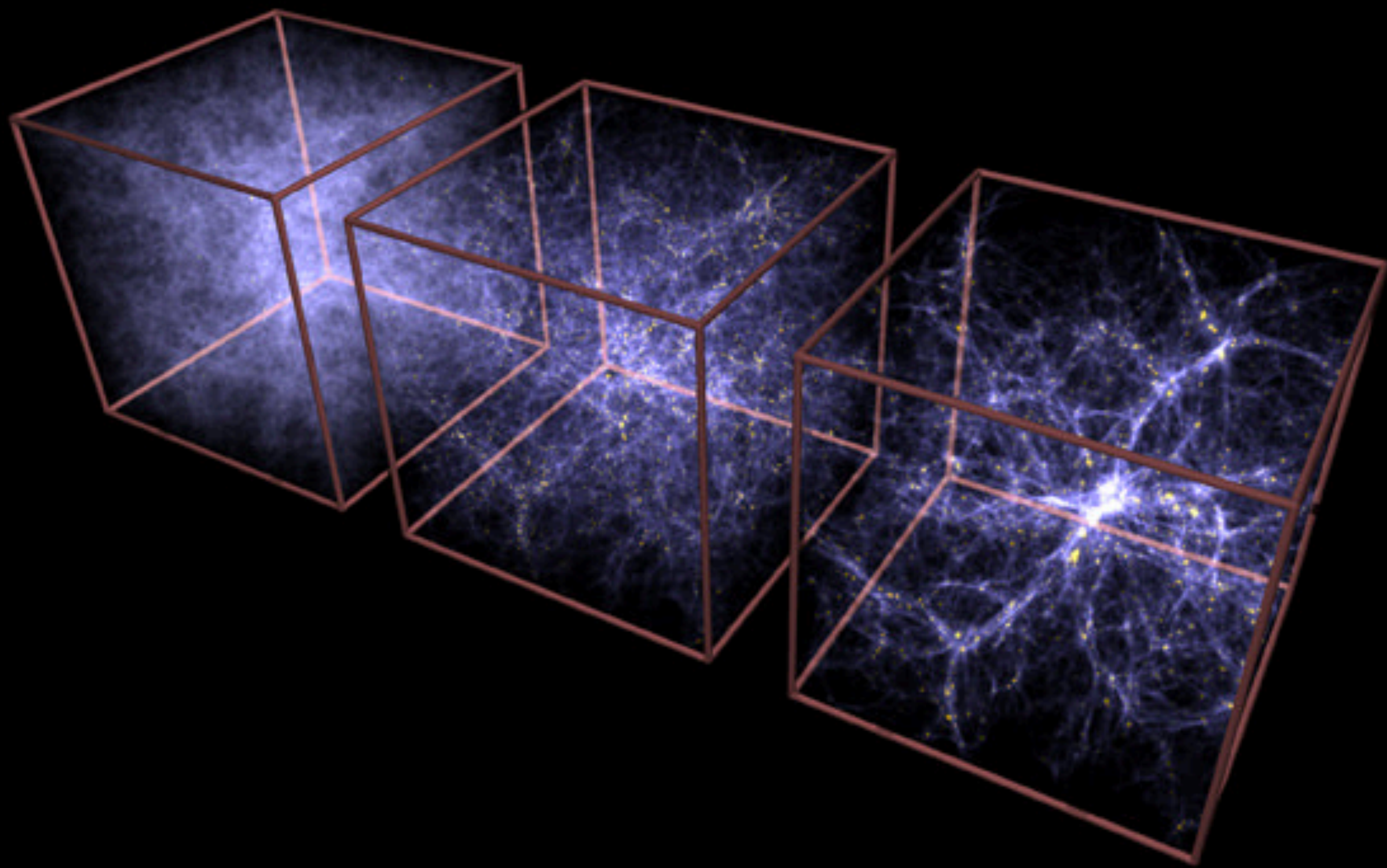


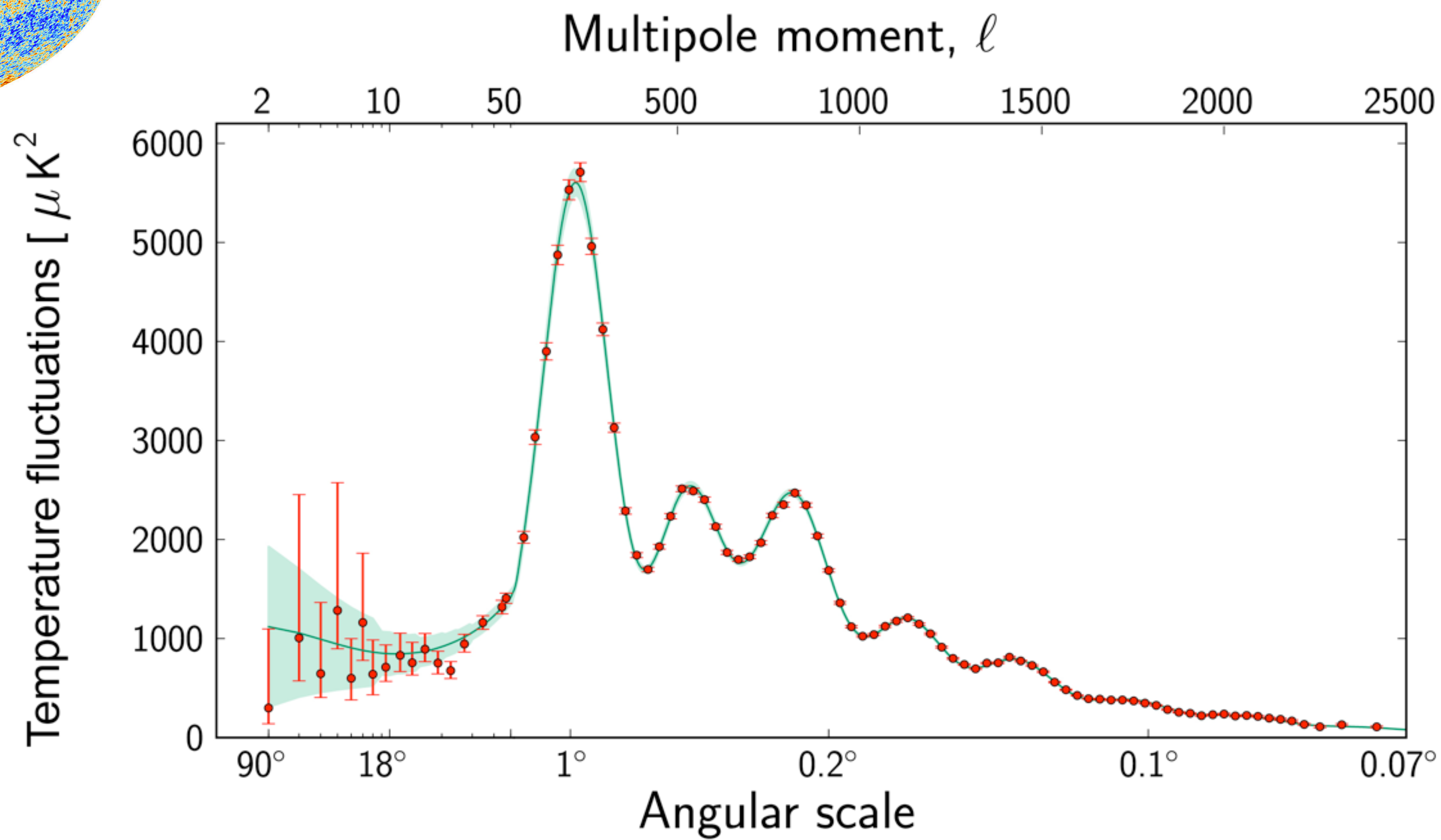
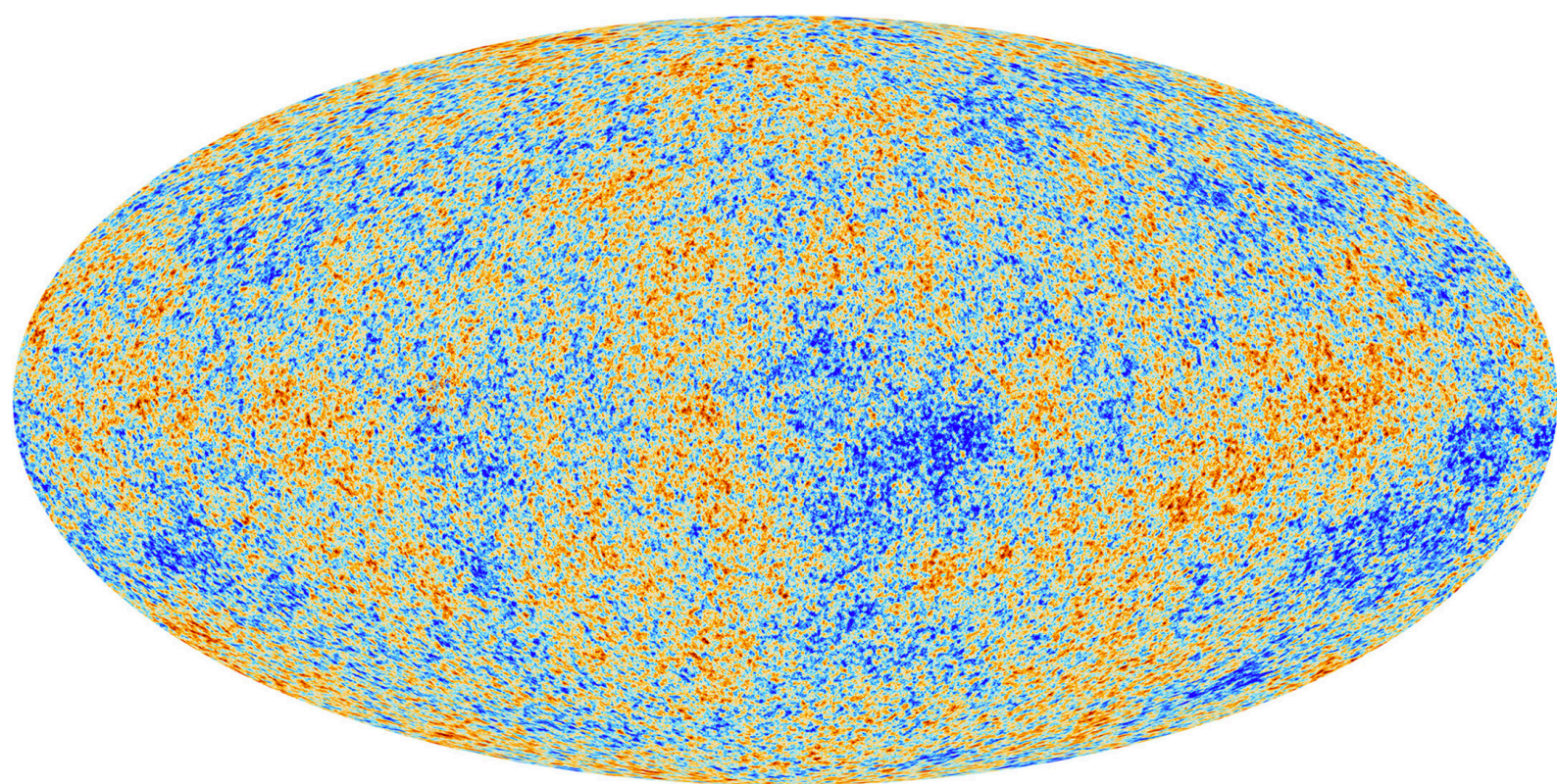
Urknall

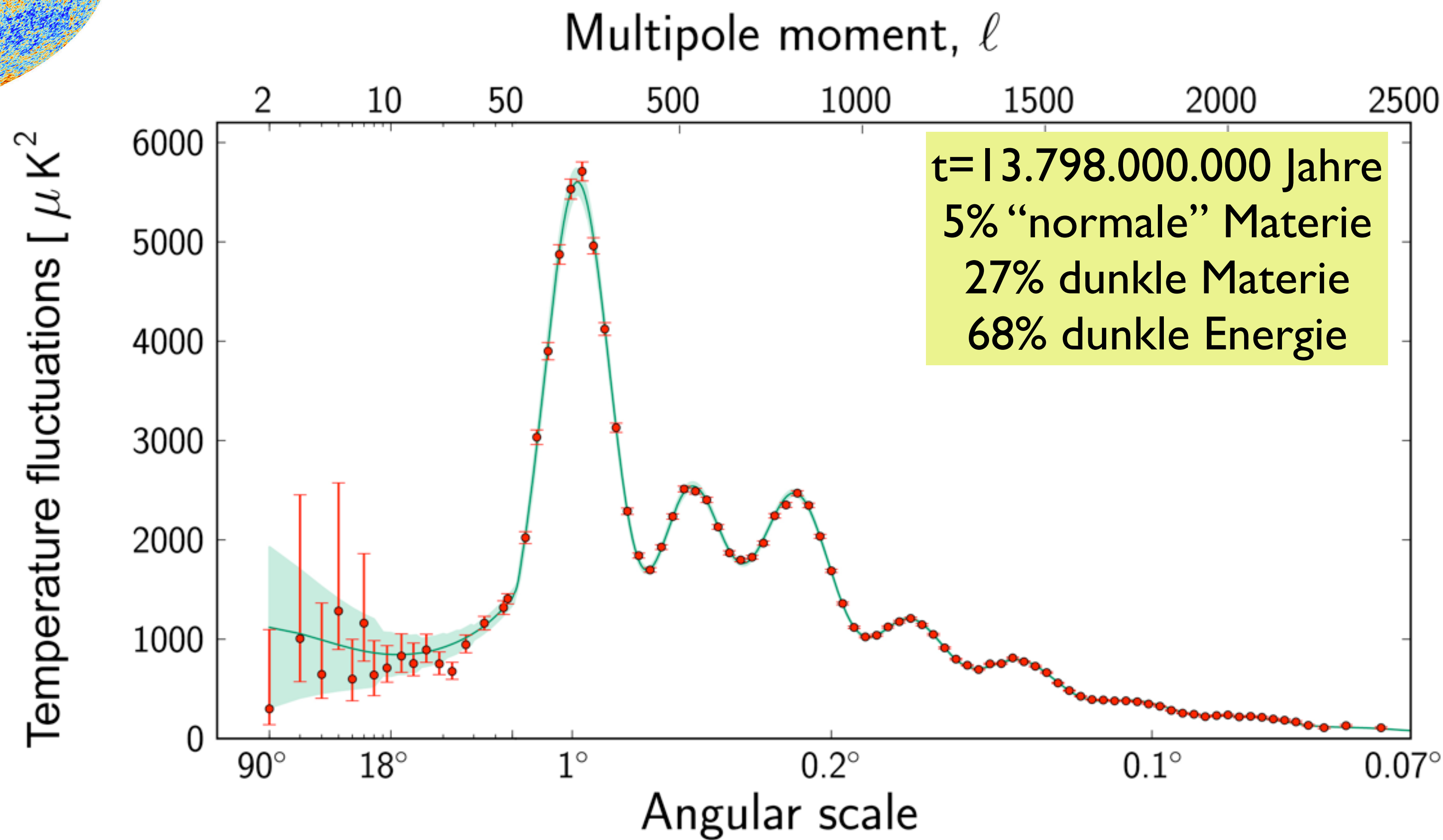
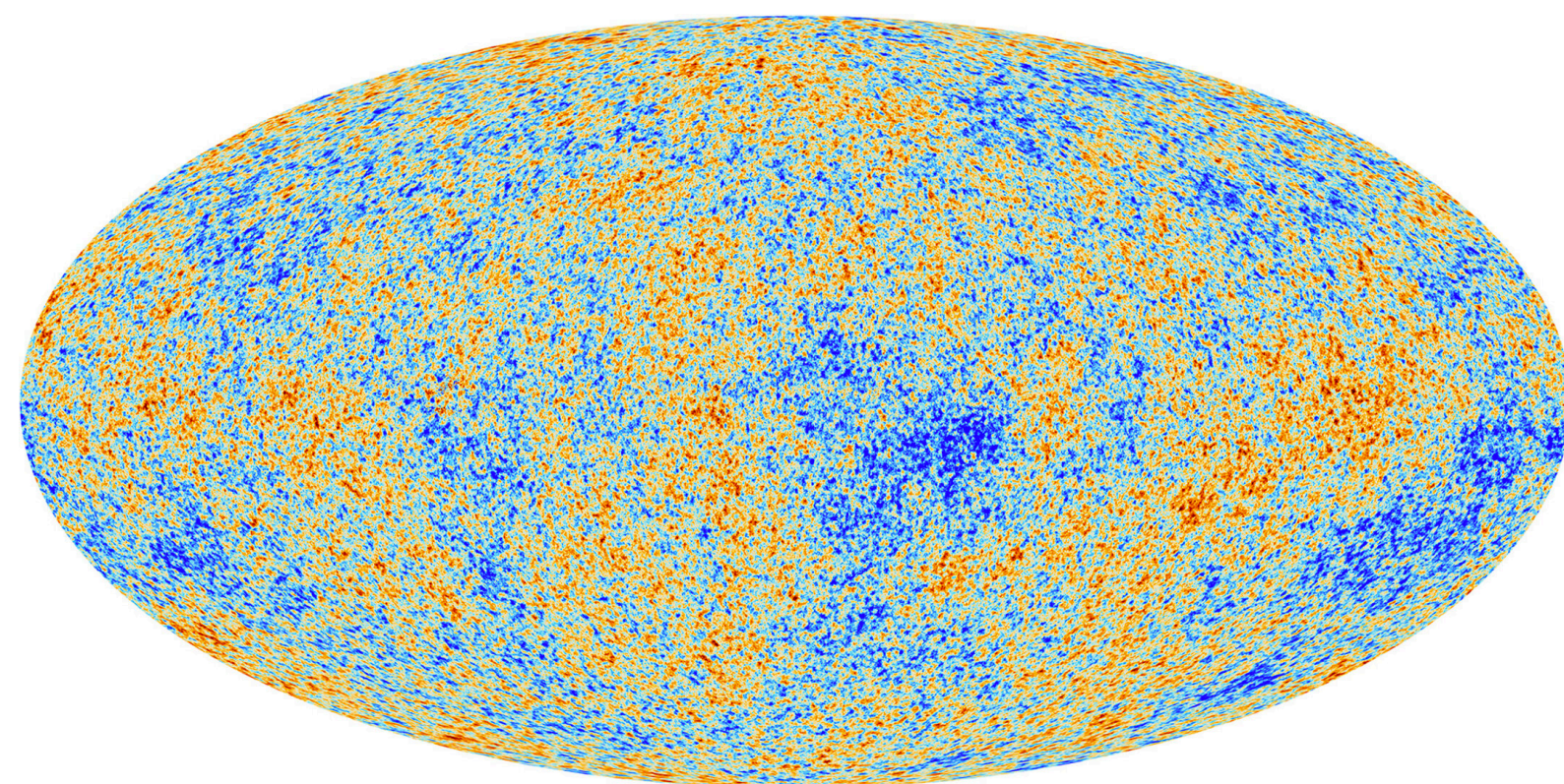
● heute



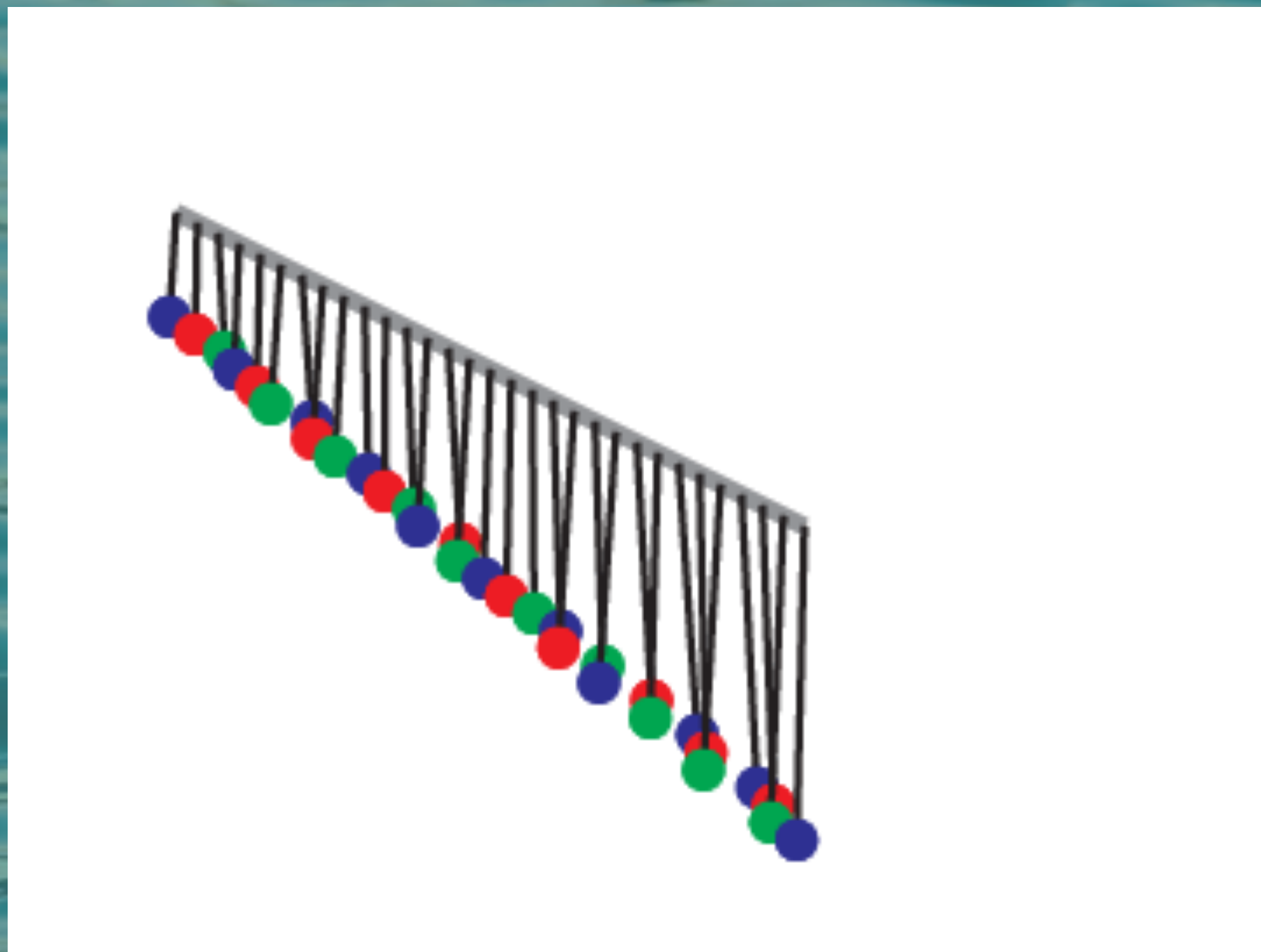




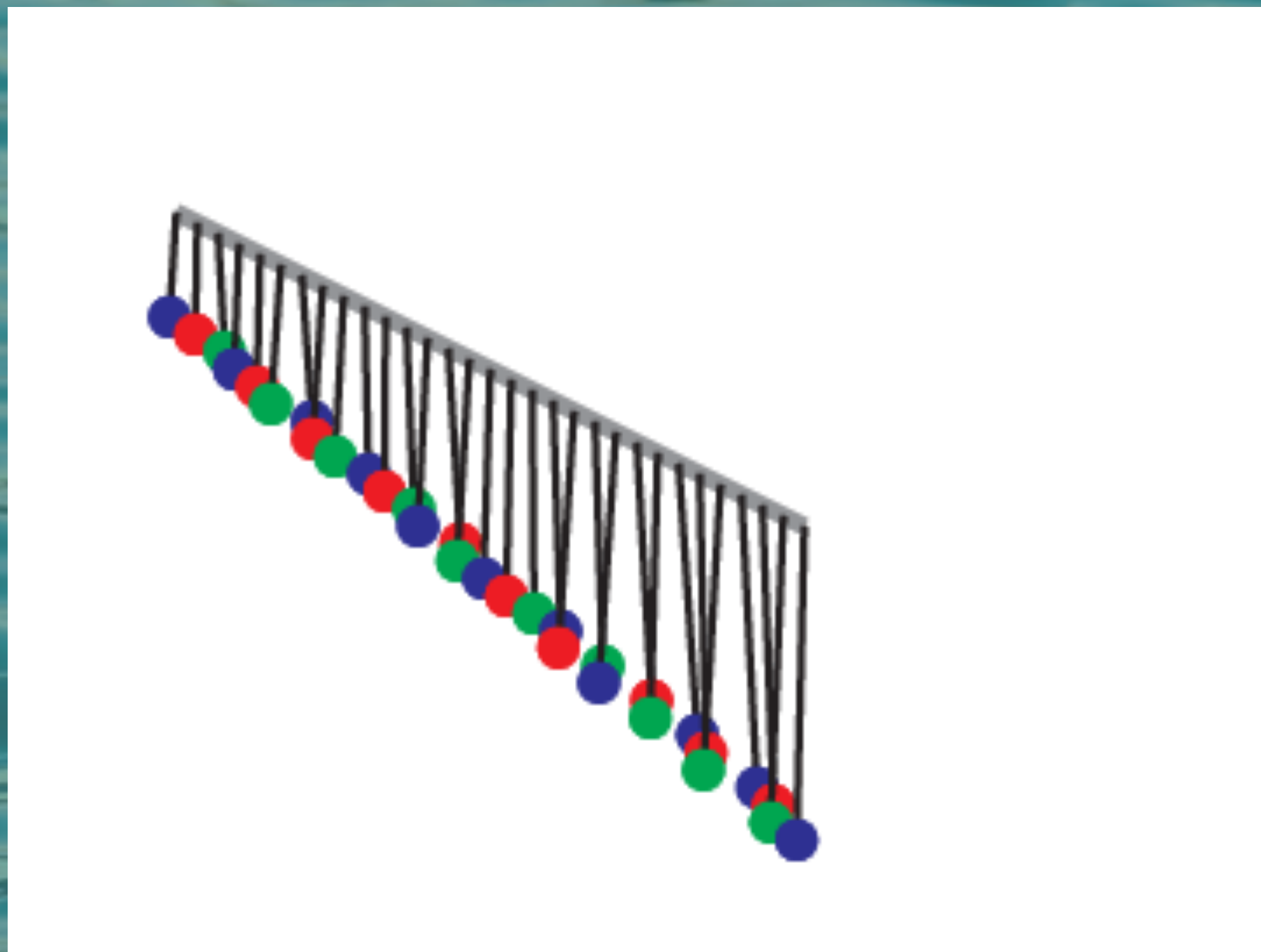




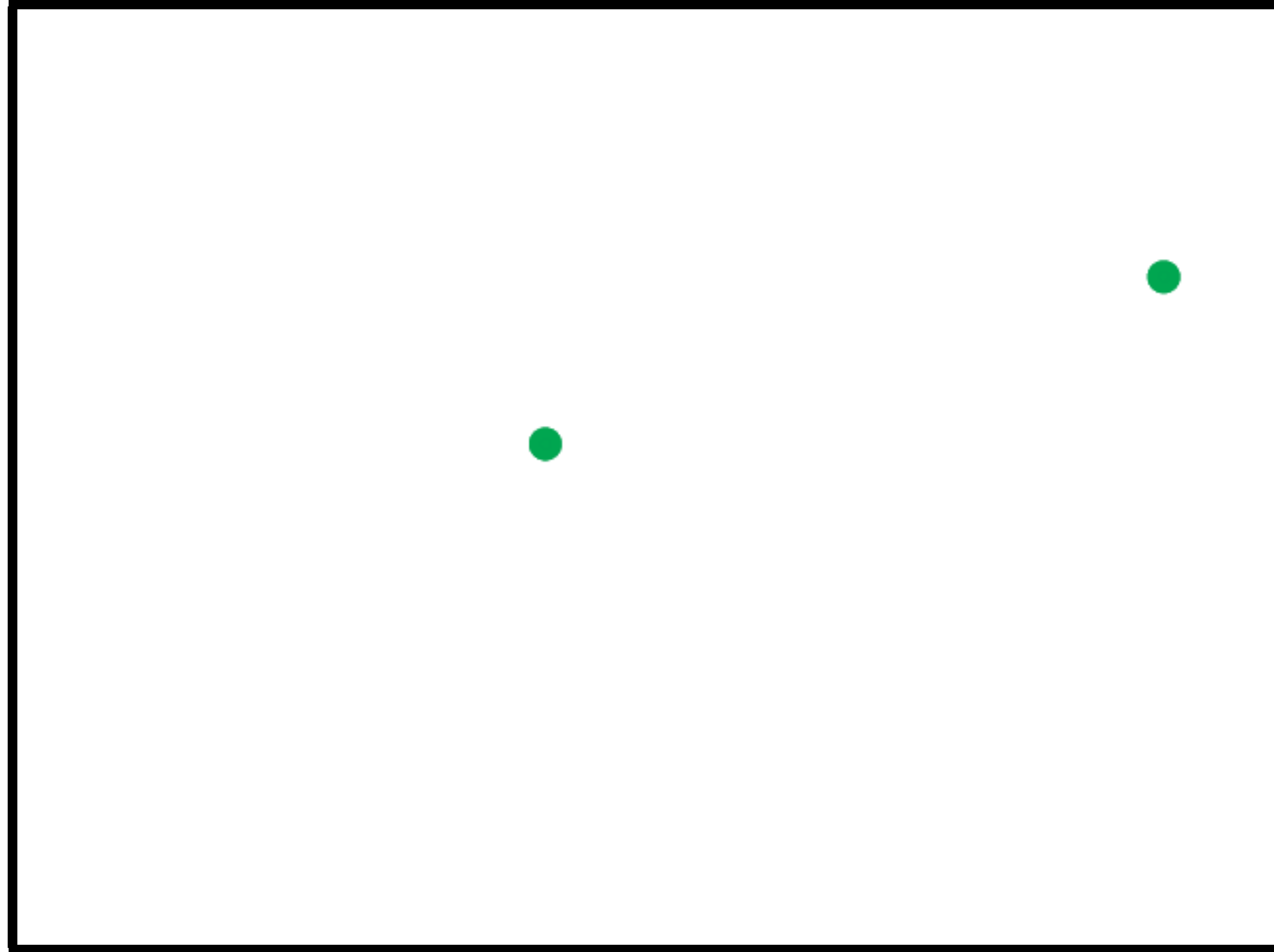
Quanten-Vakuum



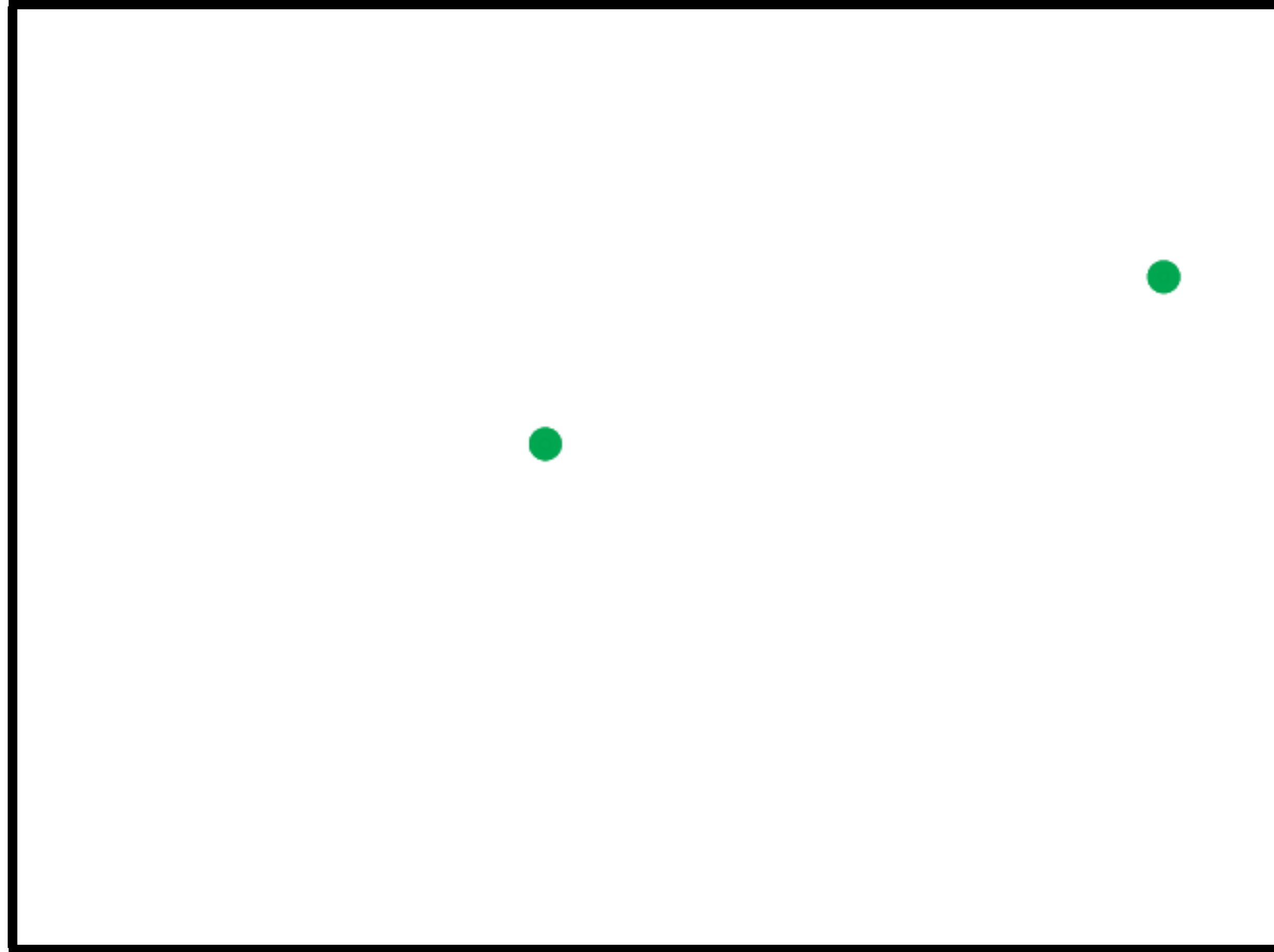
Quanten-Vakuum



Quanten-Vakuum



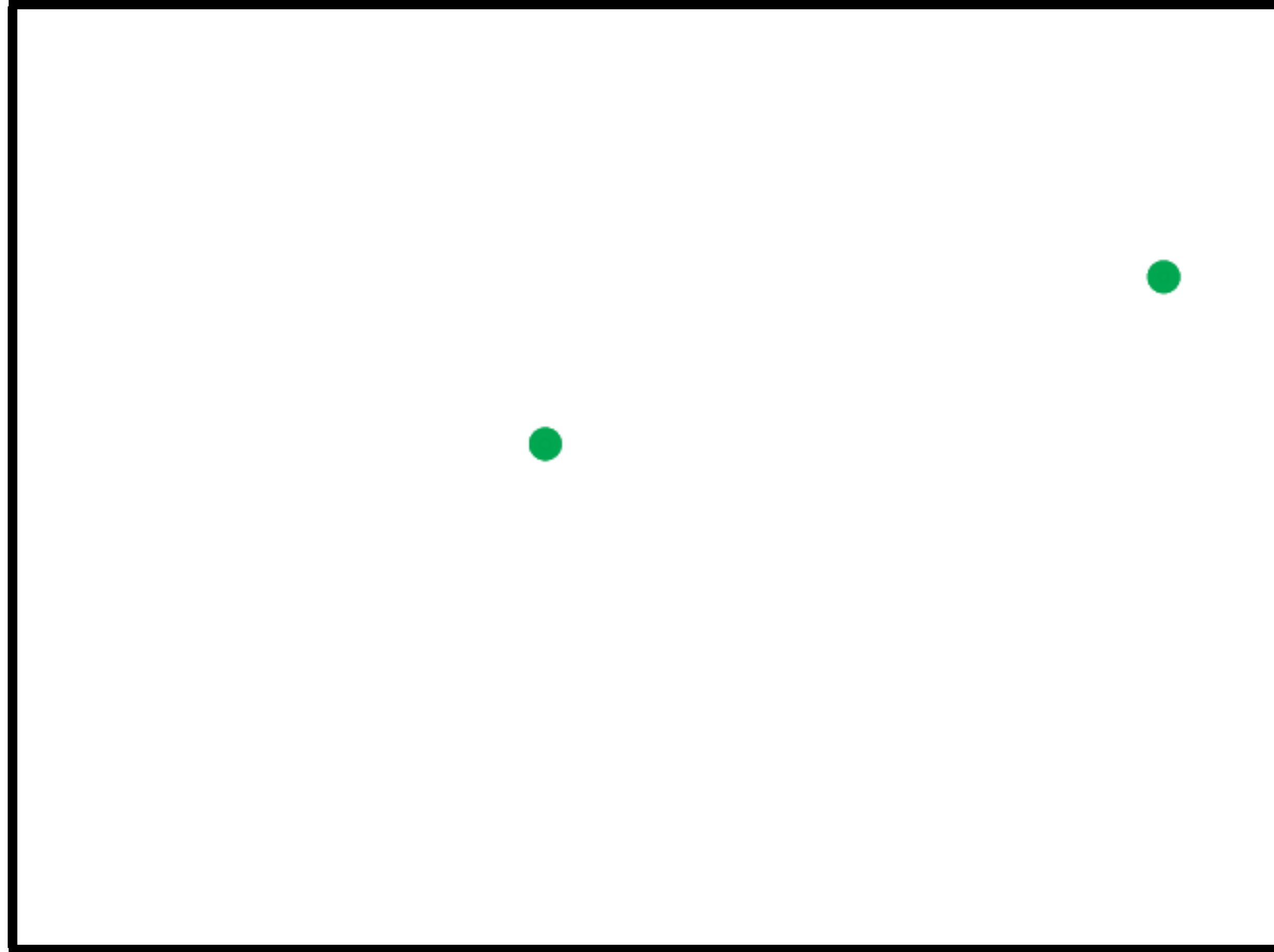
Quanten-Vakuum



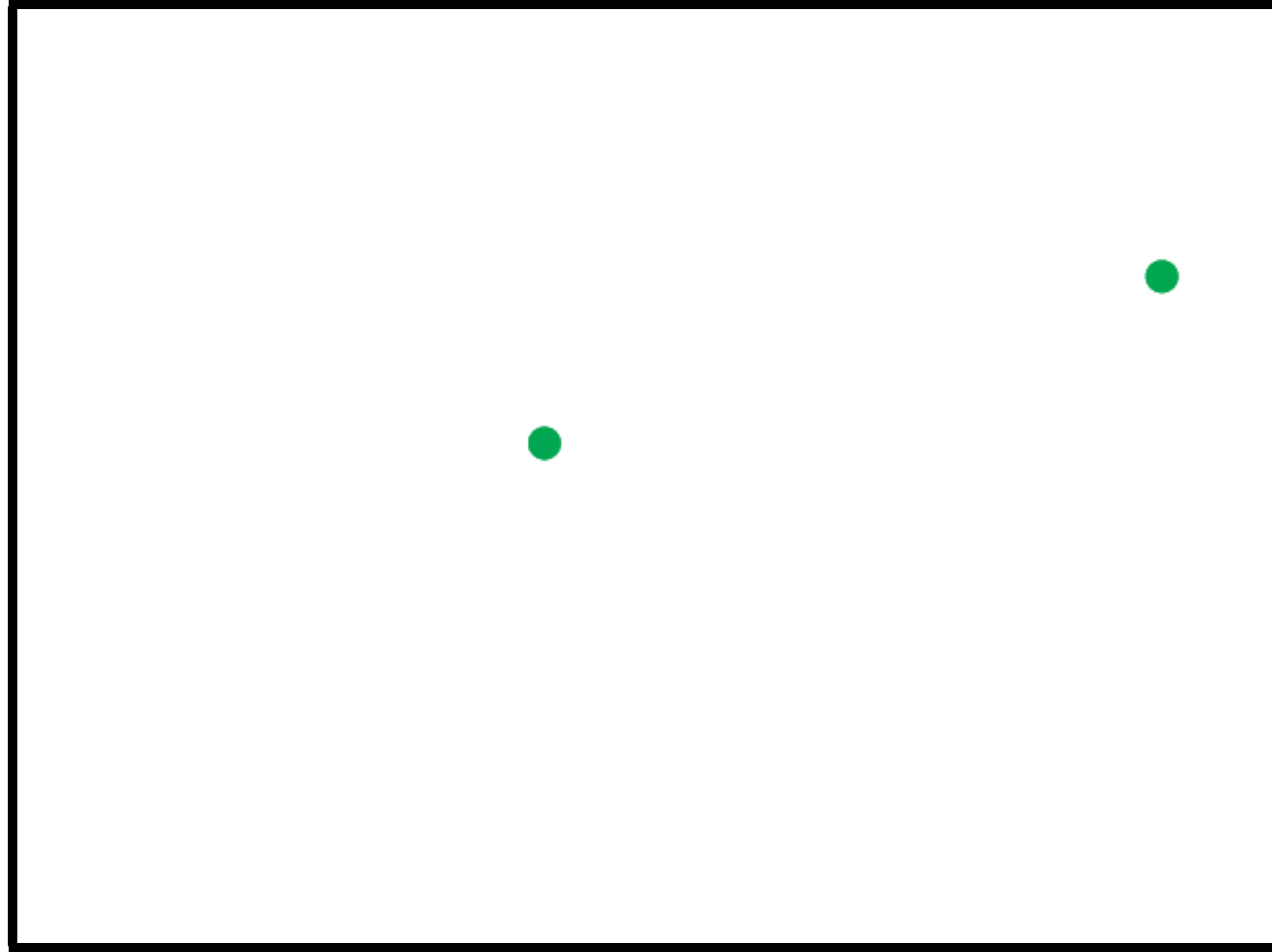


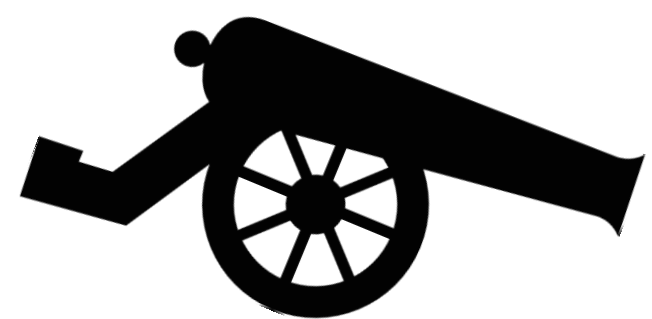


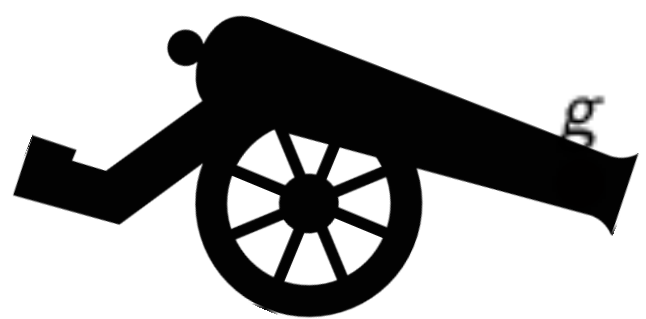
Quanten-Vakuum

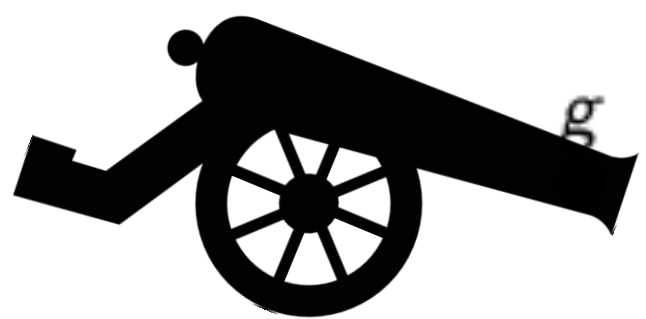


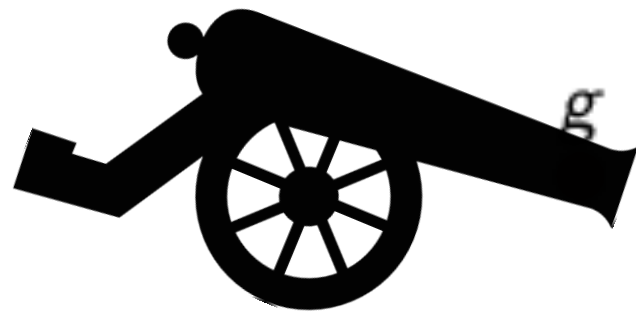
Quanten-Vakuum



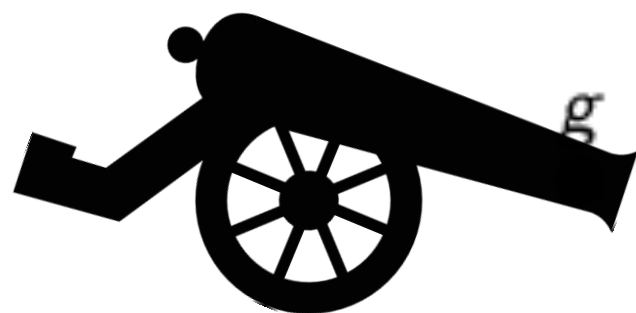






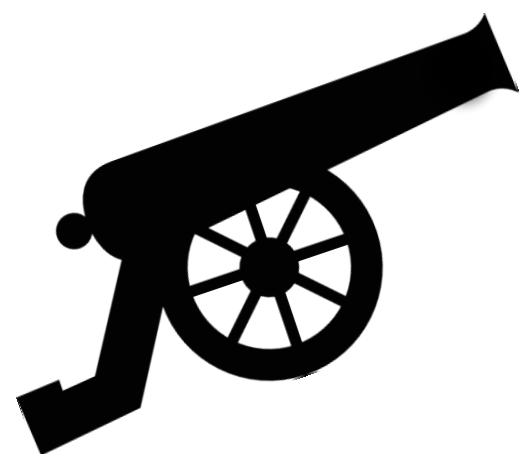
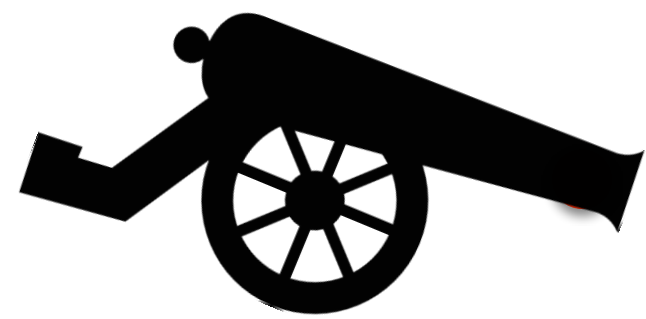


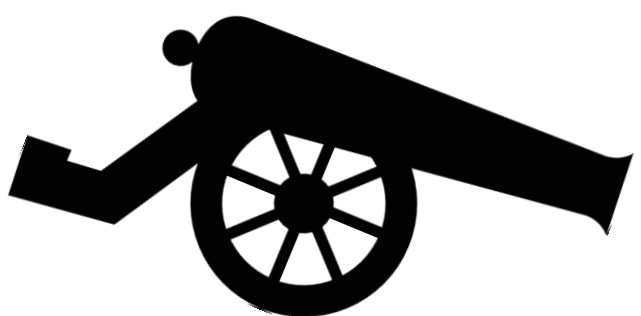
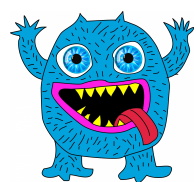
LEPTONS	QUARKS	mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
			≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
			0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
			<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

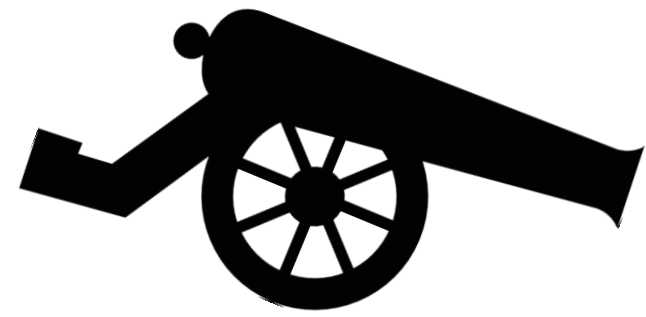
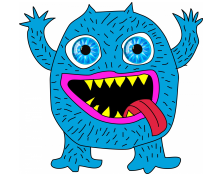
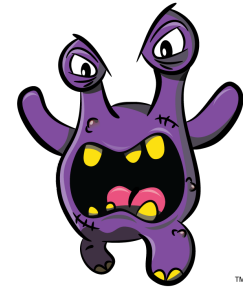


QUARKS	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ u up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ c charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ t top	mass → 0 charge → 0 spin → 1 g gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0 H Higgs boson
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ d down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ s strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ b bottom	mass → 0 charge → 0 spin → 1 γ photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ e electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ μ muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$ τ tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1 Z Z boson	GAUGE BOSONS
	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$ ν_e electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_μ muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_τ tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1 W W boson	

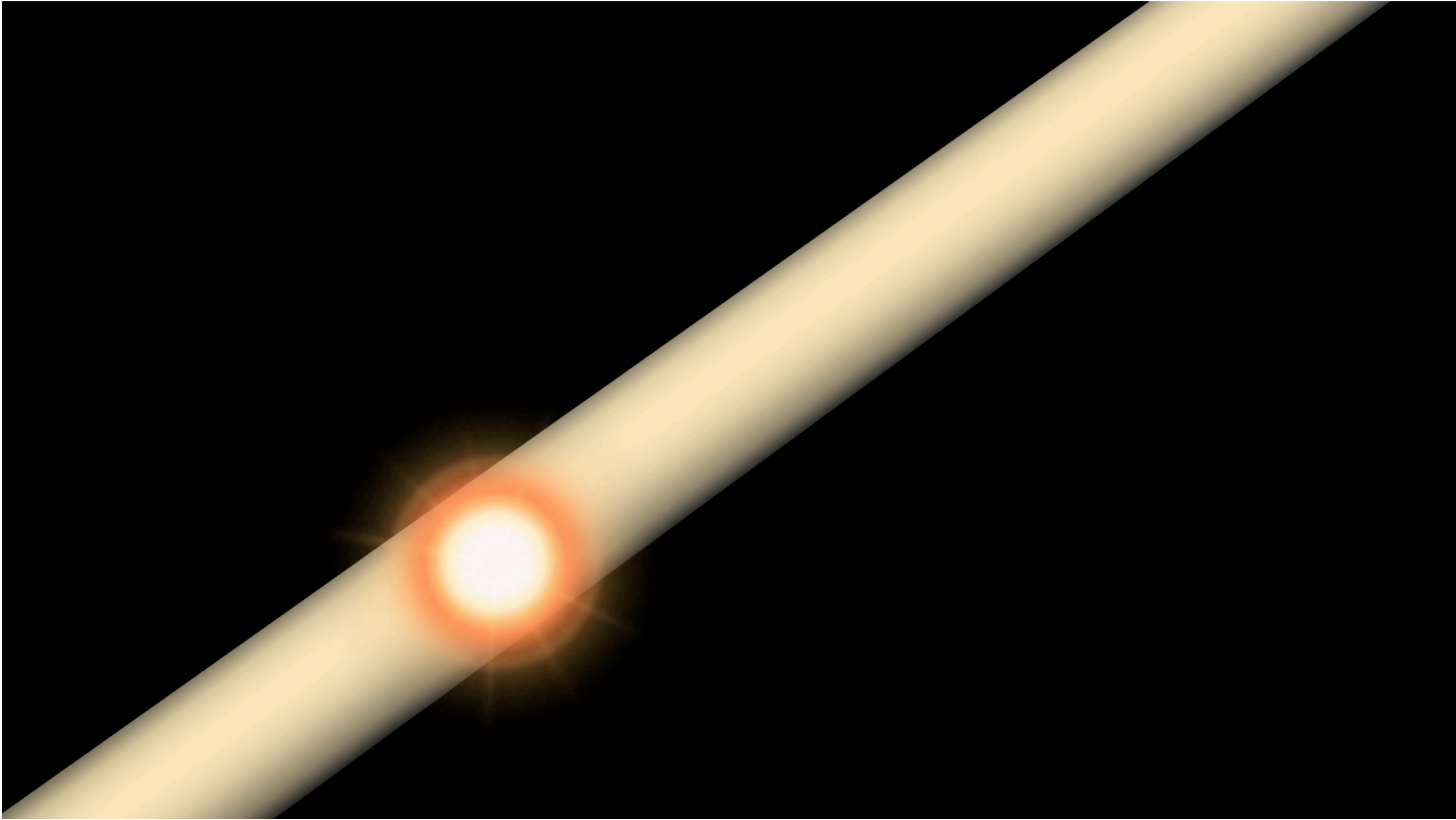
$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \\
 & + \bar{\psi}(x) i \not{D} \psi(x) + h.c. \\
 & + \varphi(x) \gamma \psi(x) \phi(x) \\
 & + |D_\mu \phi(x)|^2 - V(\phi(x))
 \end{aligned}$$

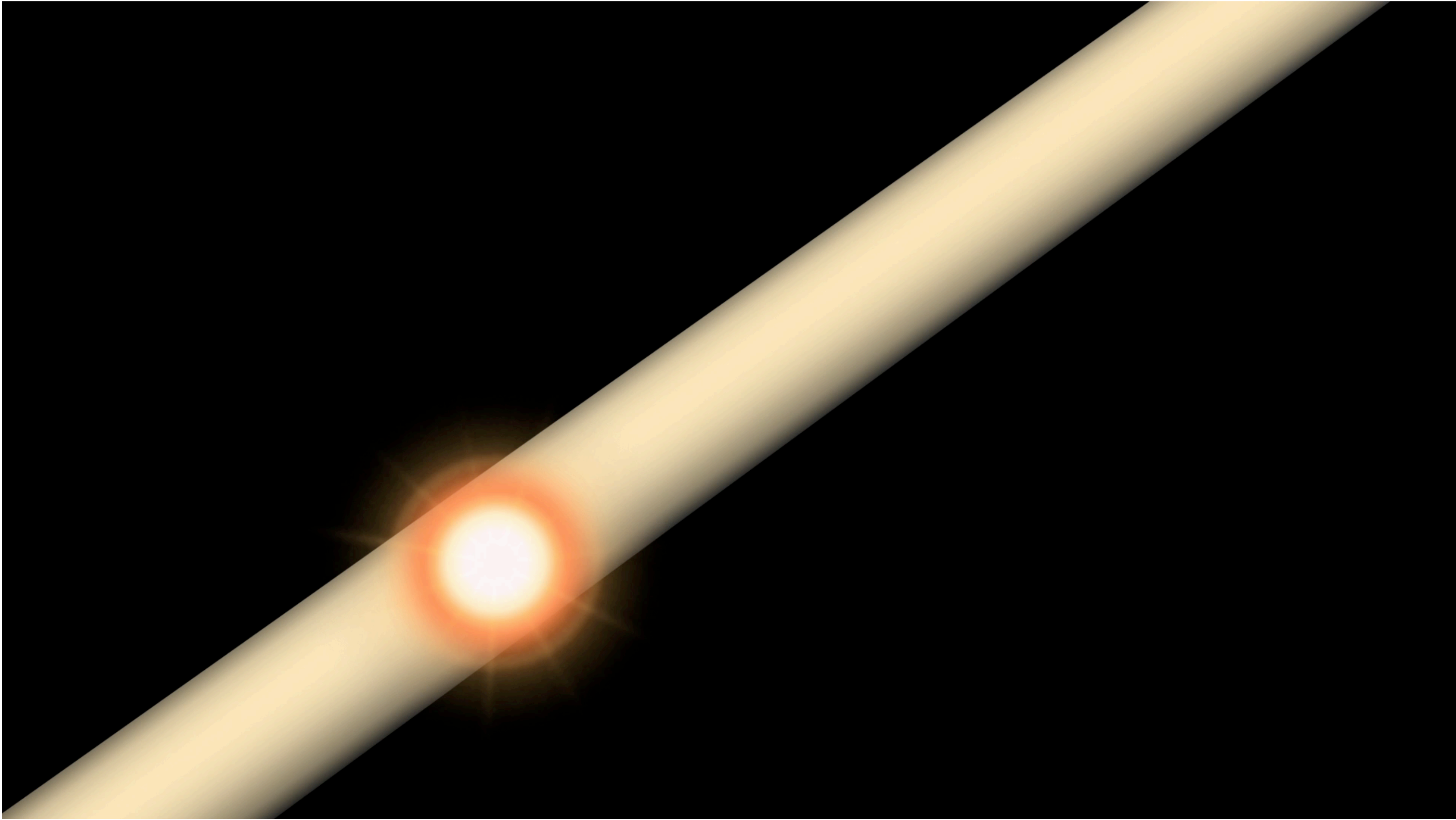


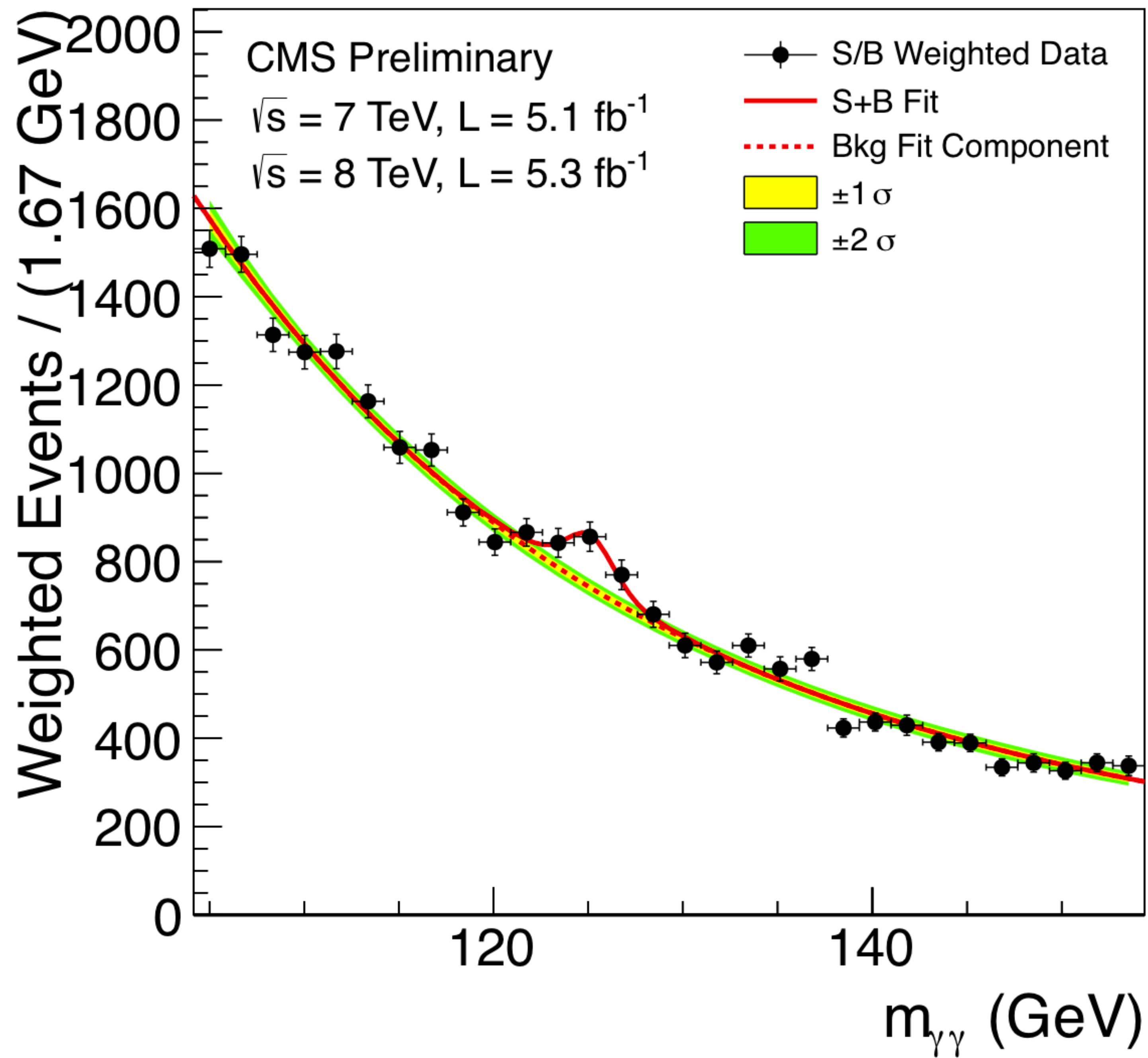


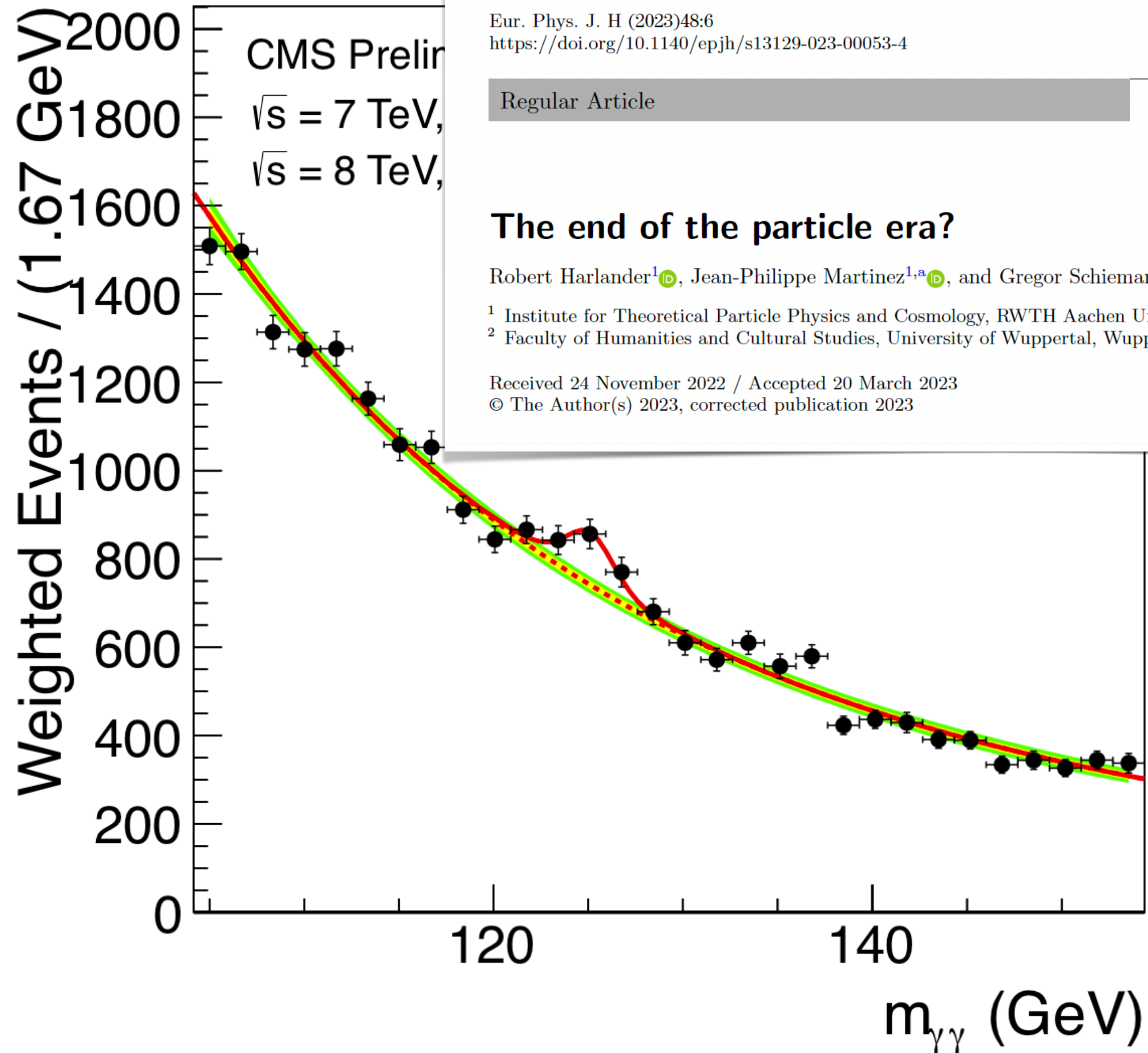












Eur. Phys. J. H (2023)48:6
<https://doi.org/10.1140/epjh/s13129-023-00053-4>

THE EUROPEAN
PHYSICAL JOURNAL H



Regular Article

The end of the particle era?

Robert Harlander¹, Jean-Philippe Martinez^{1,a}, and Gregor Schiemann²

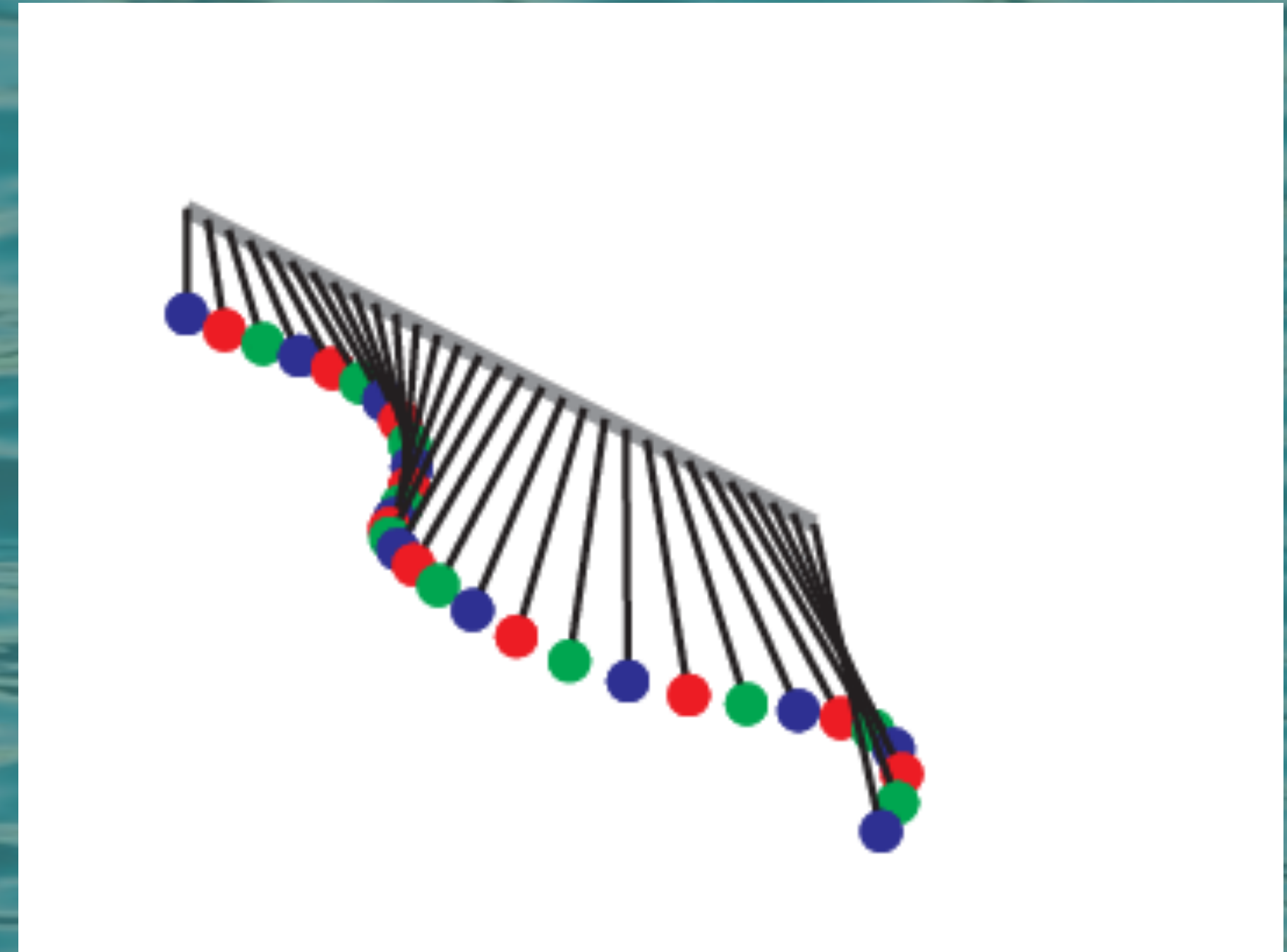
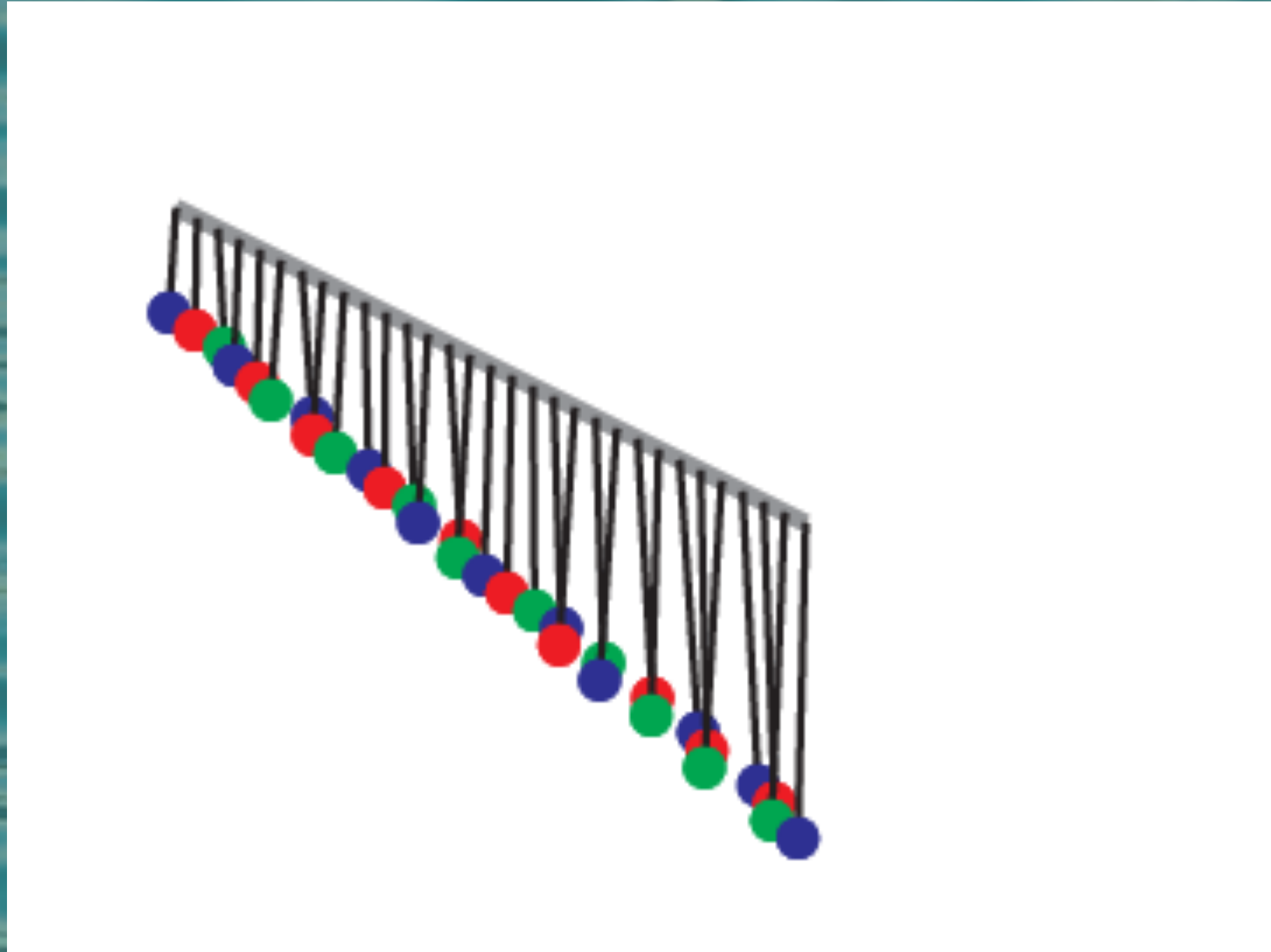
¹ Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Aachen, Germany

² Faculty of Humanities and Cultural Studies, University of Wuppertal, Wuppertal, Germany

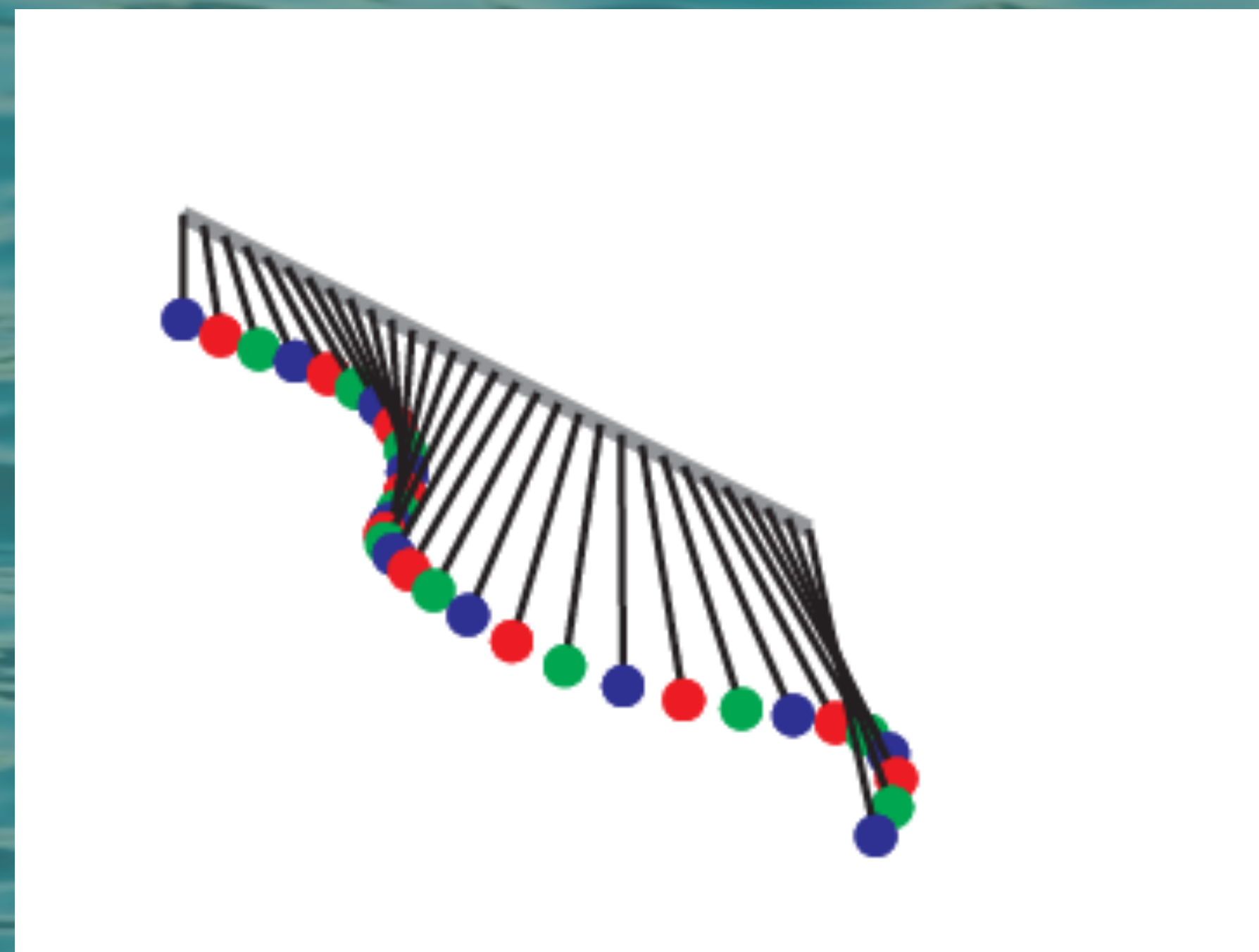
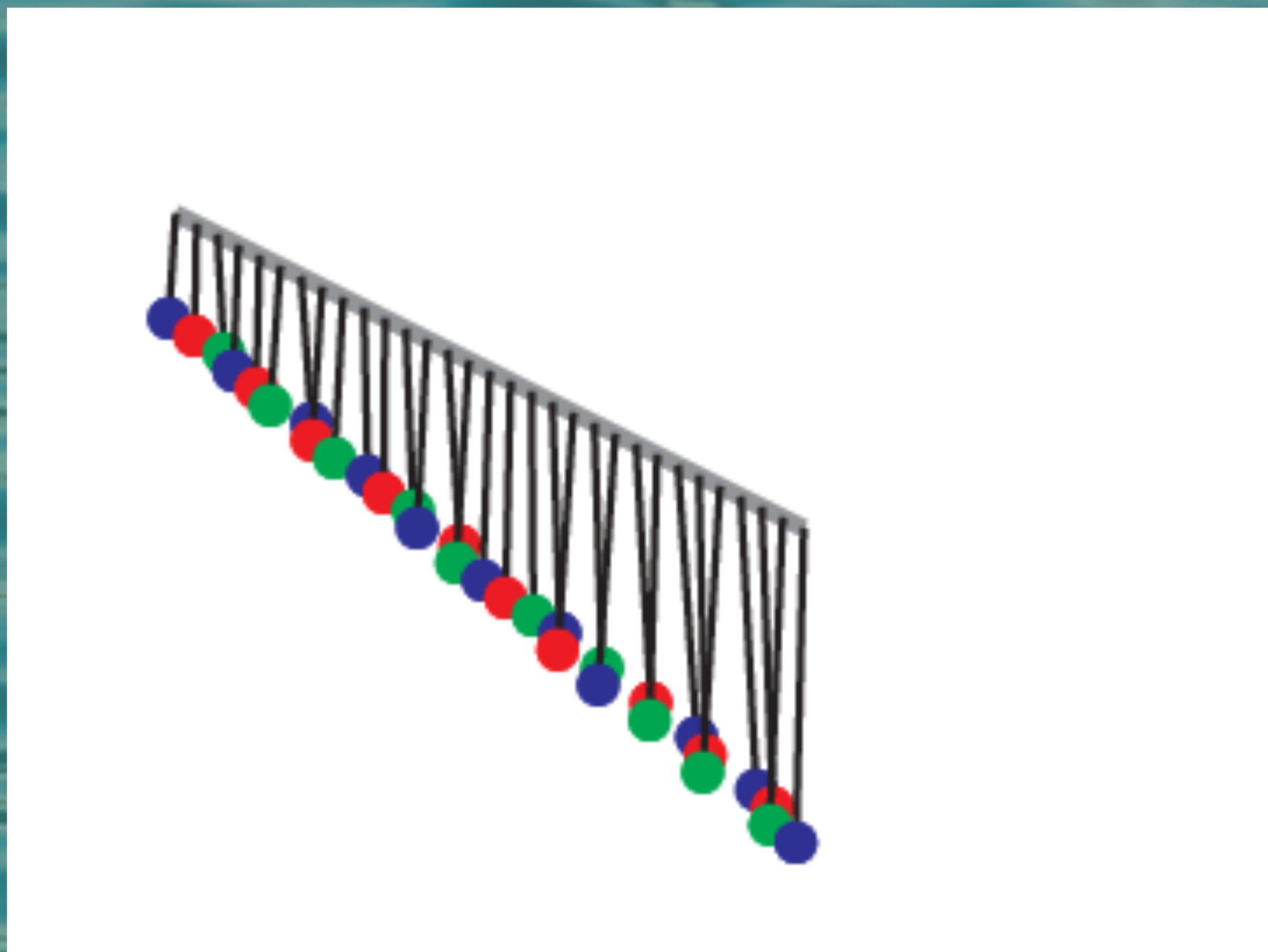
Received 24 November 2022 / Accepted 20 March 2023

© The Author(s) 2023, corrected publication 2023

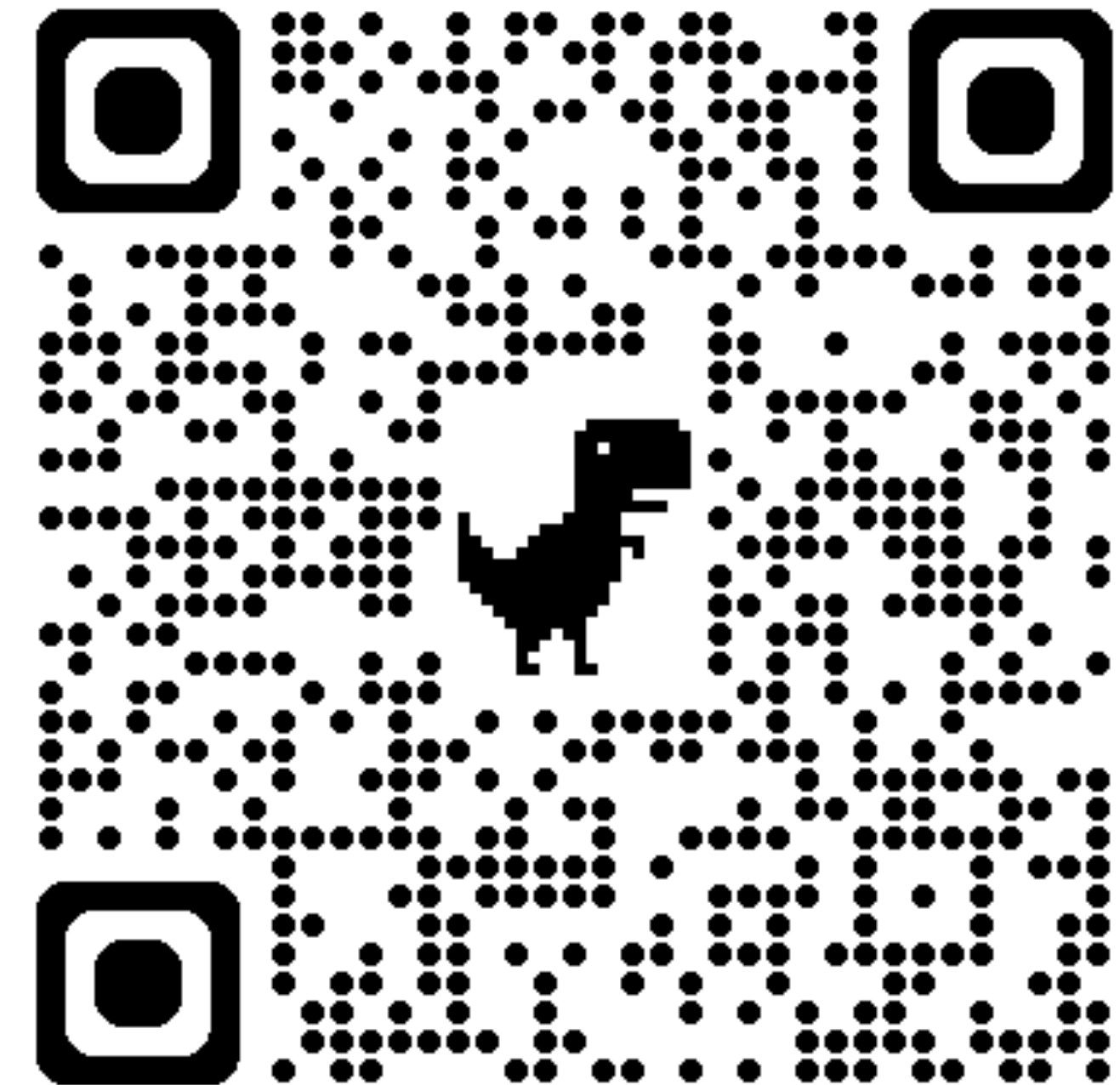
Quanten-Vakuum



Quanten-Vakuum



Danke!





Robert Harlander

Institute for Theoretical Particle Physics and Cosmology
Faculty of Mathematics, Computer Science and Natural Sciences
RWTH Aachen University
52056 Aachen, Germany

phone: +49-241-80-27045
fax: +49-241-80-22187
harlander(at)physik.rwth-aachen.de
Office: 28A414, Campus Melaten

- Home -

Brief CV

Research

Teaching

Outreach

Conferences

Software

Press

collaborations:

LHC and Philosophy

Welcome! (deutsche Version)

[detailed help]

multi-search window

Submit



What's new? (older news)

- 10 Nov 2023, 09:45pm: Von nichts kommt ... alles! Die Schatzkammer des leeren Raums (public talk)

07 Nov 2023

- Lattice proceedings 2023 on meson mixing and lifetimes

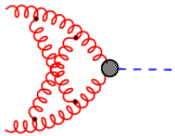
30 Oct 2023

- New preprint on AutoEFT

28 Sep 2023

- Nature Physics comments on our "End of the particle era?"

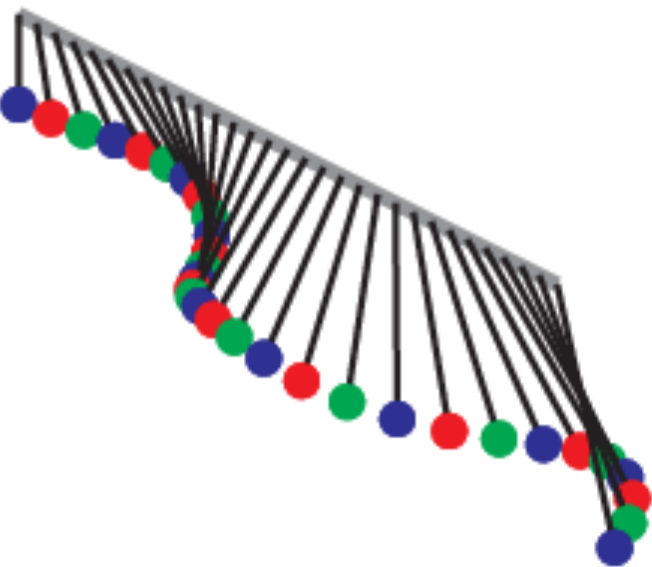
25 Sep 2023



One of my favorite Feynman diagrams

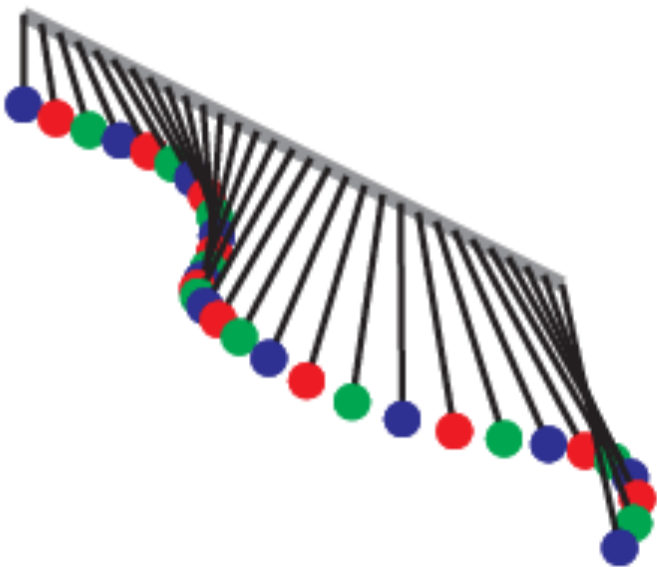


Auto
EFT





Auto
EFT



aximate



Robert Harlander

[- Home -](#)

Brief CV

Research

Teaching

Outreach

Conferences

Software

Press

collaborations:

LHC and Philosophy

Institute for Theoretical Particle Physics and Cosmology

Faculty of Mathematics, Computer Science and Natural Sciences

RWTH Aachen University

52056 Aachen, Germany

phone: +49-241-80-27045

fax: +49-241-80-22187

harlander(at)physik.rwth-aachen.de

Office: 28A414, Campus Melaten

Welcome!

(deutsche Version)

[detailed help]

multi-search window

Submit

A

u

t

o

E

F

T

What's new?

(older news)

• 10 Nov 2023, 09:45pm: Von nichts kommt ... alles! Die Schatzkammer des leeren Raums (public talk)

07 Nov 2023

• Lattice proceedings 2023 on meson mixing and lifetimes

30 Oct 2023

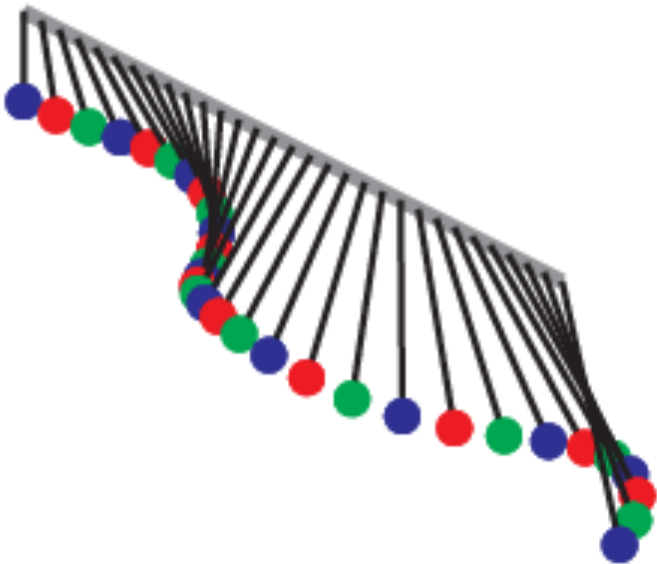
• New preprint on AutoEFT

28 Sep 2023

• Nature Physics comments on our "End of the particle era?"

25 Sep 2023

One of my favorite Feynman diagrams



aximate

Navigation icons: back, forward, search, etc.



toploop.fg - FeynGame v2.0.0

File Edit View Help

default x +

+

t

b

c

s

u

d

e

μ

τ

ν_e

ν_μ

ν_τ

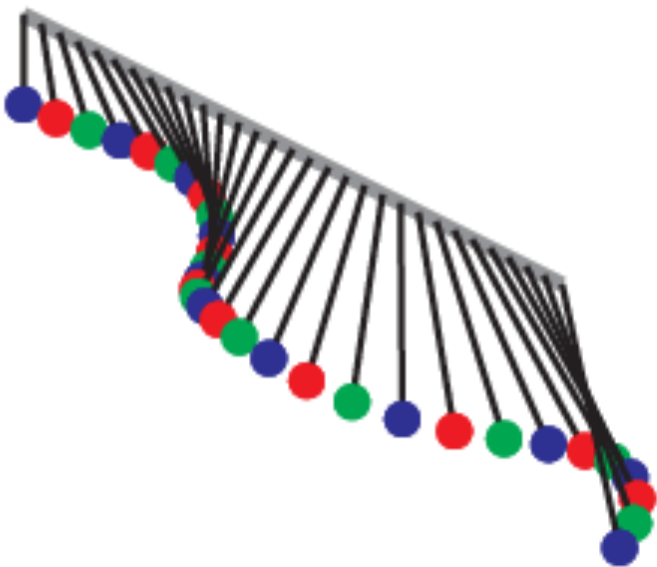
γ

Z

W

g

H



[◀ ◁](#) [▶ ▷](#) [⏮ ⏪](#) [⏩ ⏭](#) [🔍](#)



