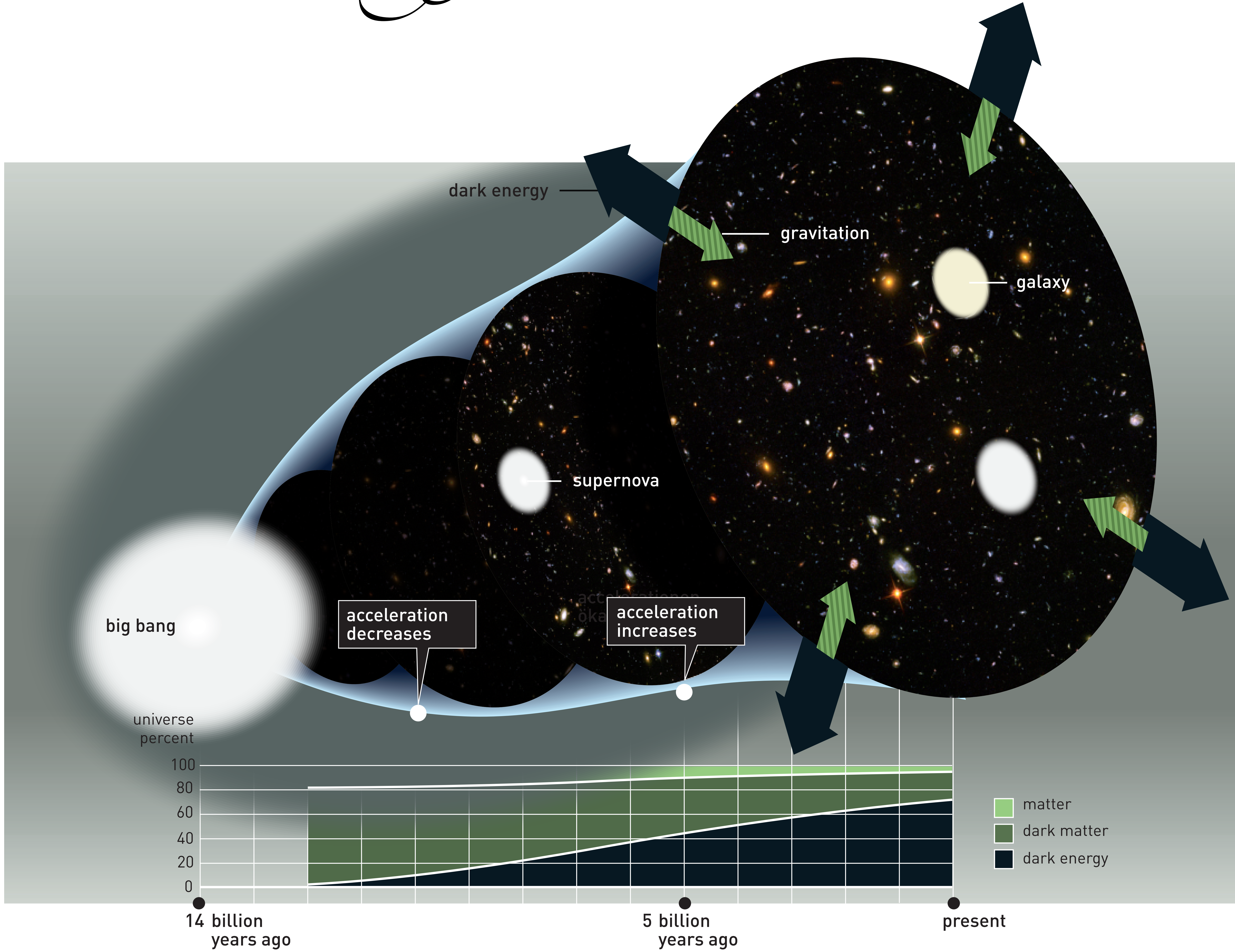
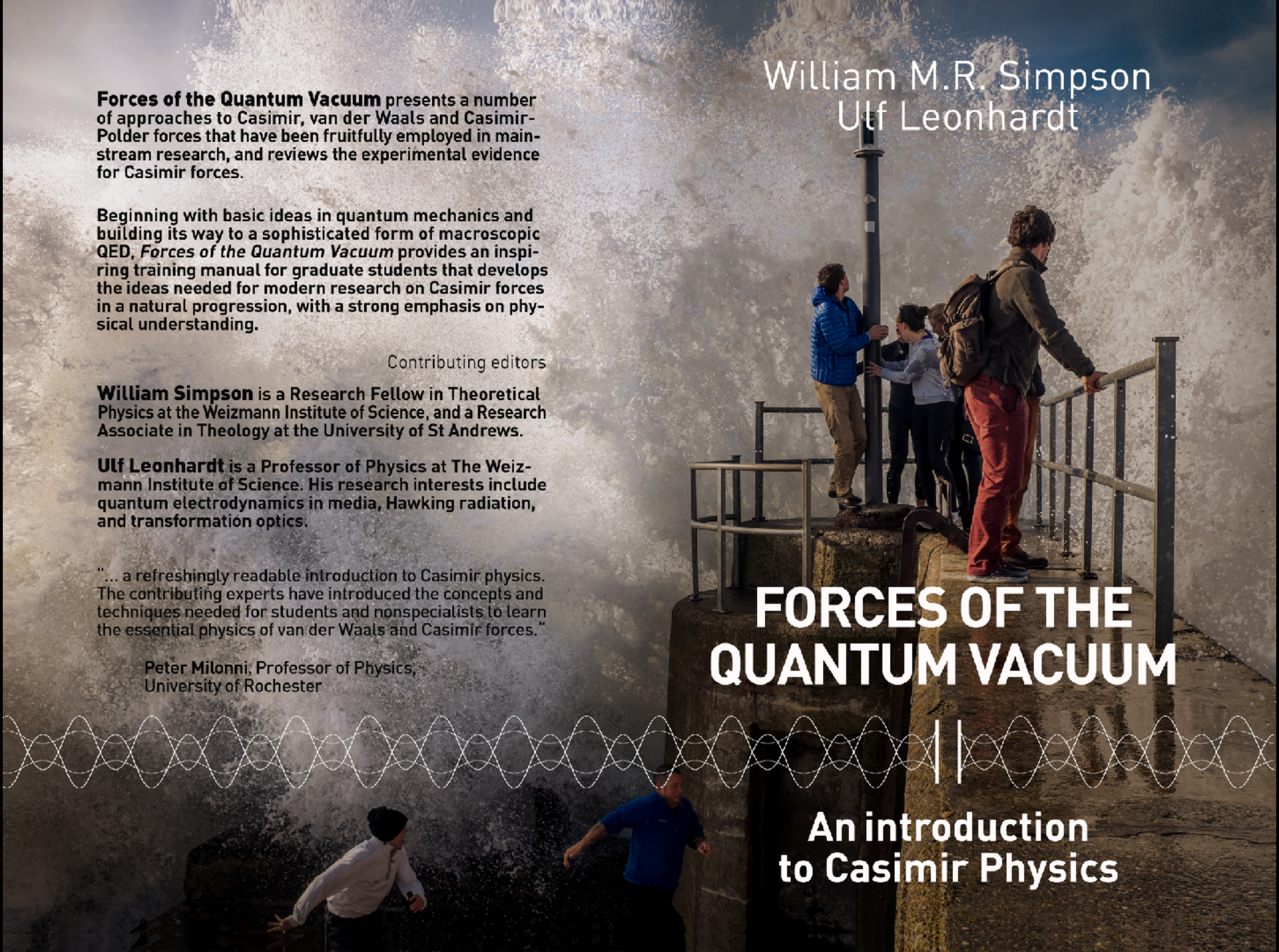
Casimir effect meets the cosmological constant

Ulf Leonhardt, Weizmann Institute of Science, 5 May 2022

Dark energy – cosmological constant





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"... a refreshingly readable introduction to Casimir physics. The contributing experts have introduced the concepts and techniques needed for students and nonspecialists to learn the essential physics of van der Waals and Casimir forces."

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University of Rochester

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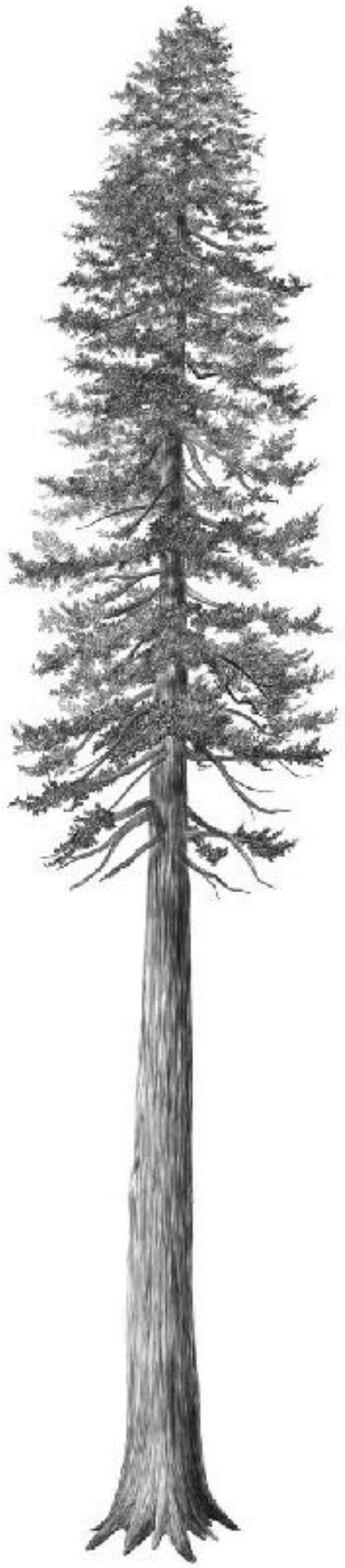
FORCES OF THE QUANTUM VACUUM

An introduction to Casimir Physics



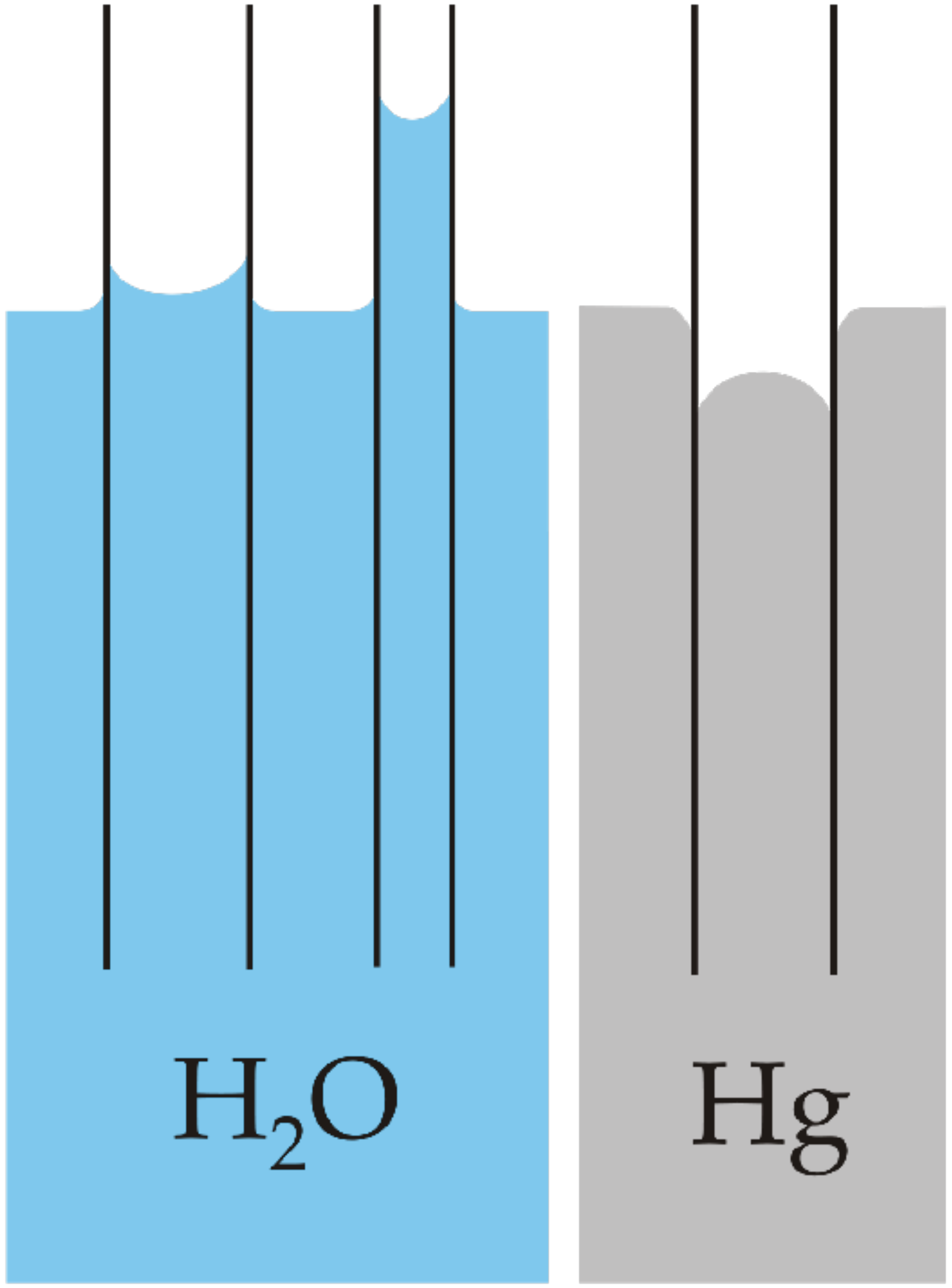
Redwood
Sequoia sempervirens

The limits to tree height

George W. Koch[1], Stephen C. Sillett[2], Gregory M. Jennings[2] & Stephen D. Davis[3]

[1]*Department of Biological Sciences and the Merriam-Powell Center for Environmental Research, Northern Arizona University, Flagstaff, Arizona 86011, USA*
[2]*Department of Biological Sciences, Humboldt State University, Arcata, California 95521, USA*
[3]*Natural Science Division, Pepperdine University, Malibu, California 90263-4321, USA*

Trees grow tall where resources are abundant, stresses are minor, and competition for light places a premium on height growth[1,2]. The height to which trees can grow and the biophysical determinants of maximum height are poorly understood. Some models predict heights of up to 120 m in the absence of mechanical damage[3,4], but there are historical accounts of taller trees[5]. Current hypotheses of height limitation focus on increasing water transport constraints in taller trees and the resulting reductions in leaf photosynthesis[6]. We studied redwoods (*Sequoia sempervirens*), including the tallest known tree on Earth (112.7 m), in wet temperate forests of northern California. Our regression analyses of height gradients in leaf functional characteristics estimate a maximum tree height of 122–130 m barring mechanical damage, similar to the tallest recorded trees of the past. As trees grow taller, increasing leaf water stress due to gravity and path length resistance may ultimately limit leaf expansion and photosynthesis for further height growth, even with ample soil moisture.



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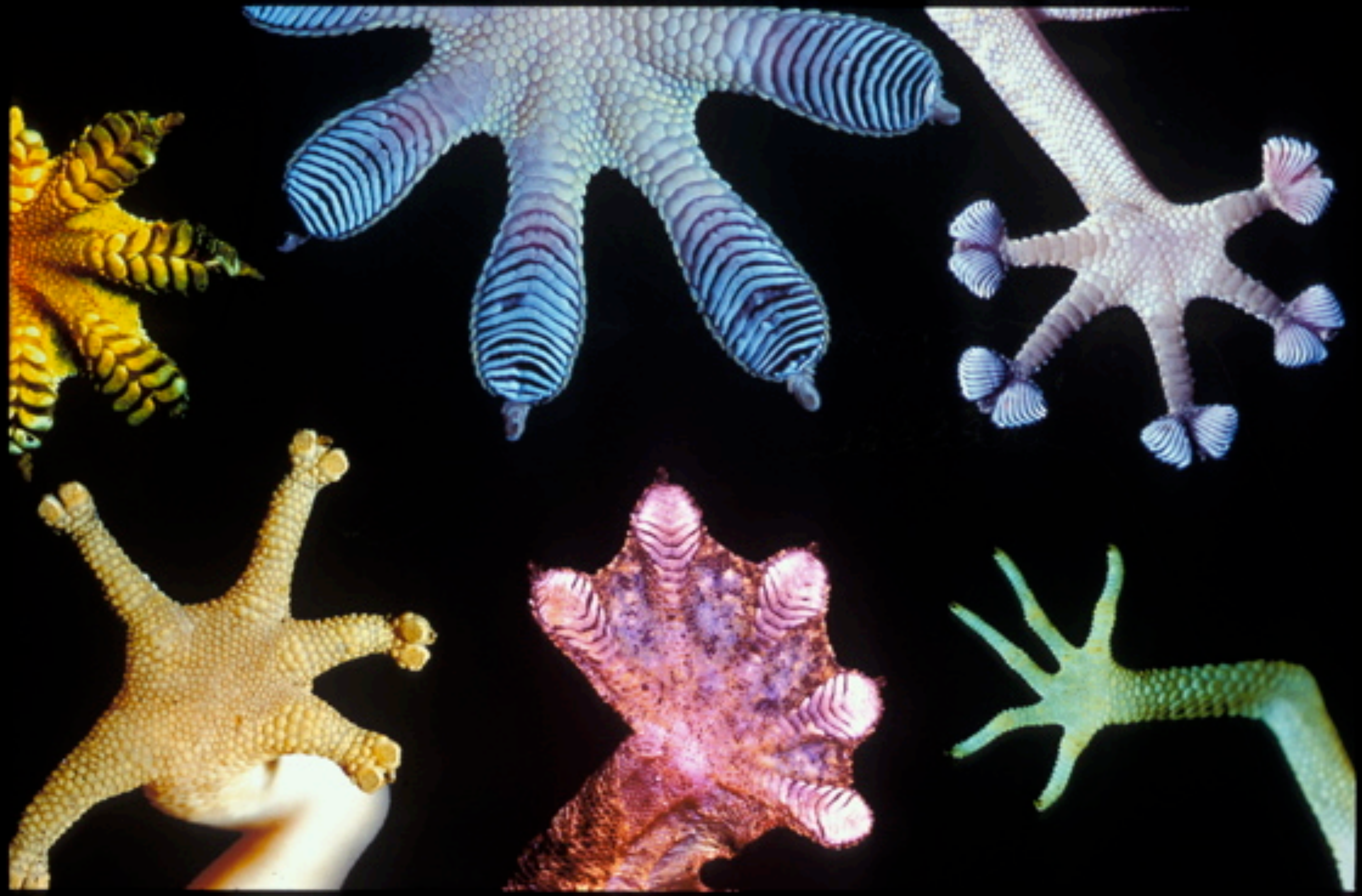
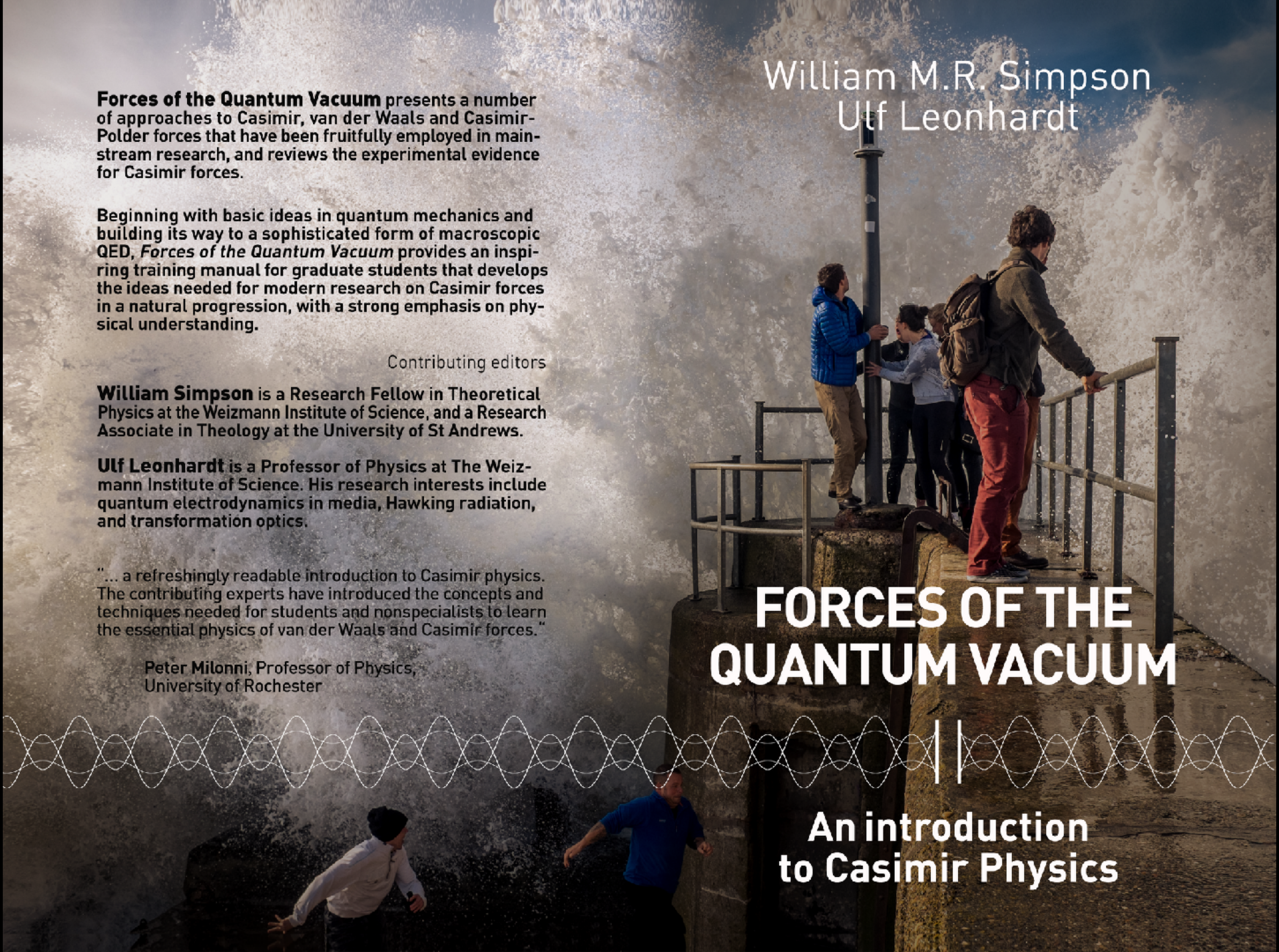
Casimir force in nature: gecko feet





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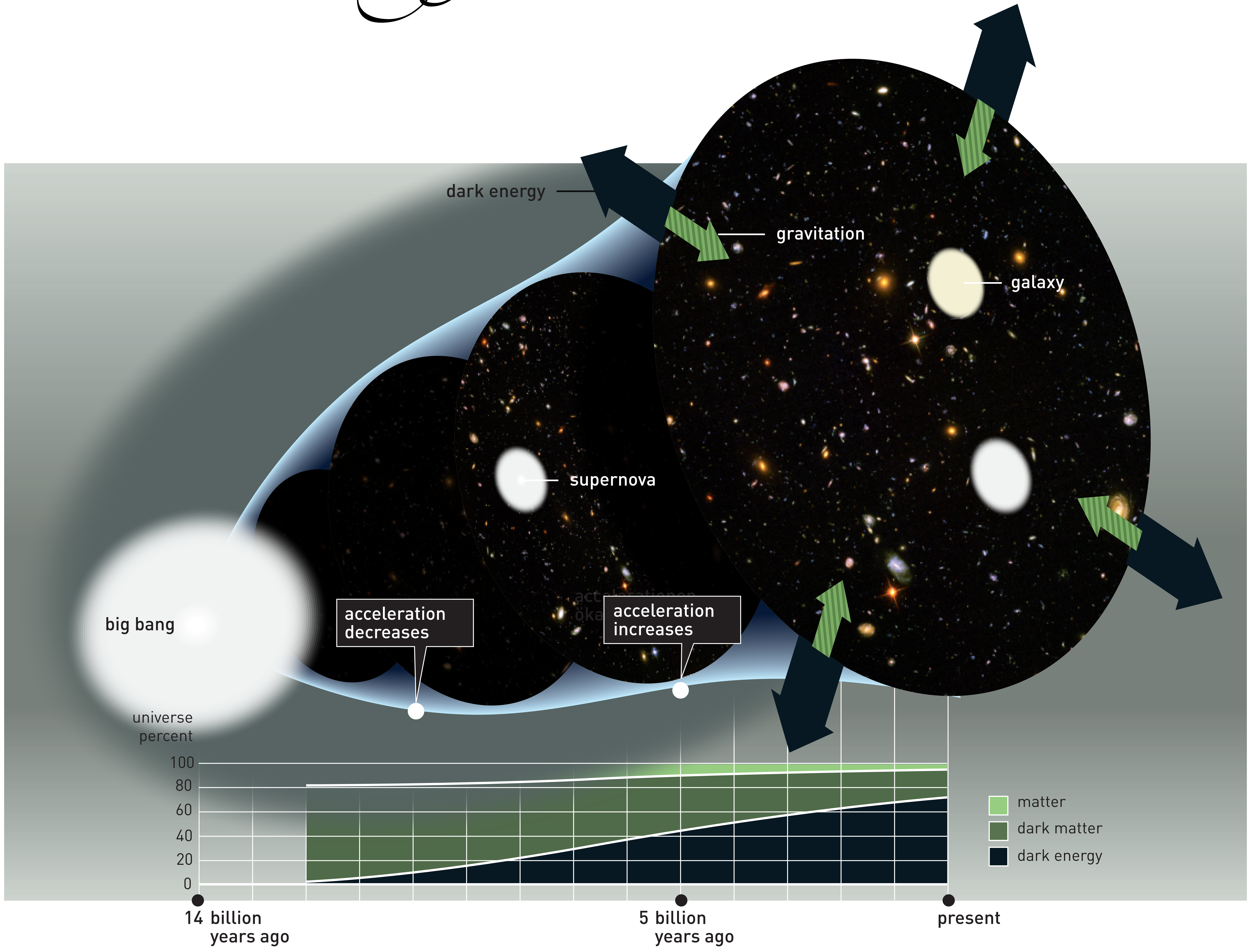
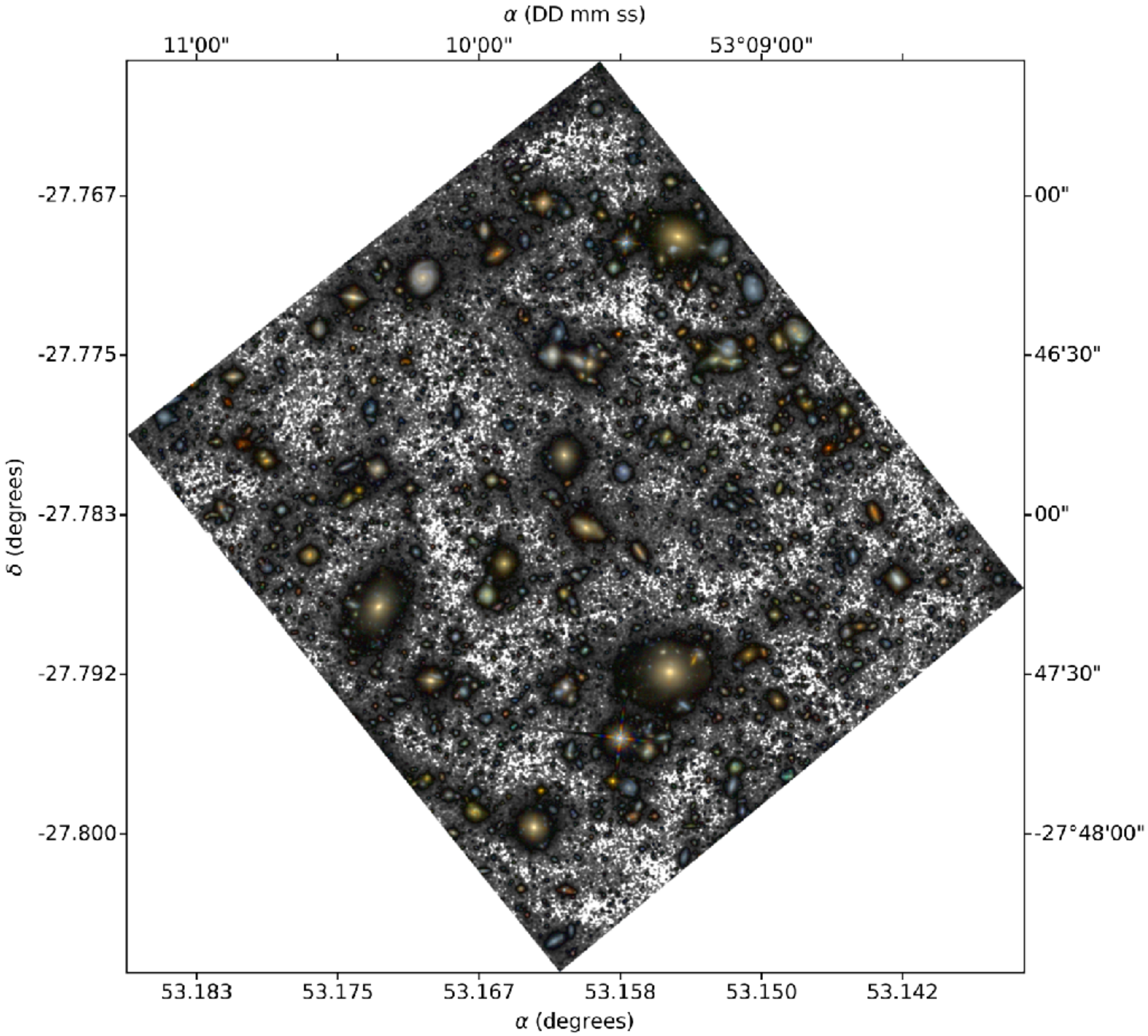


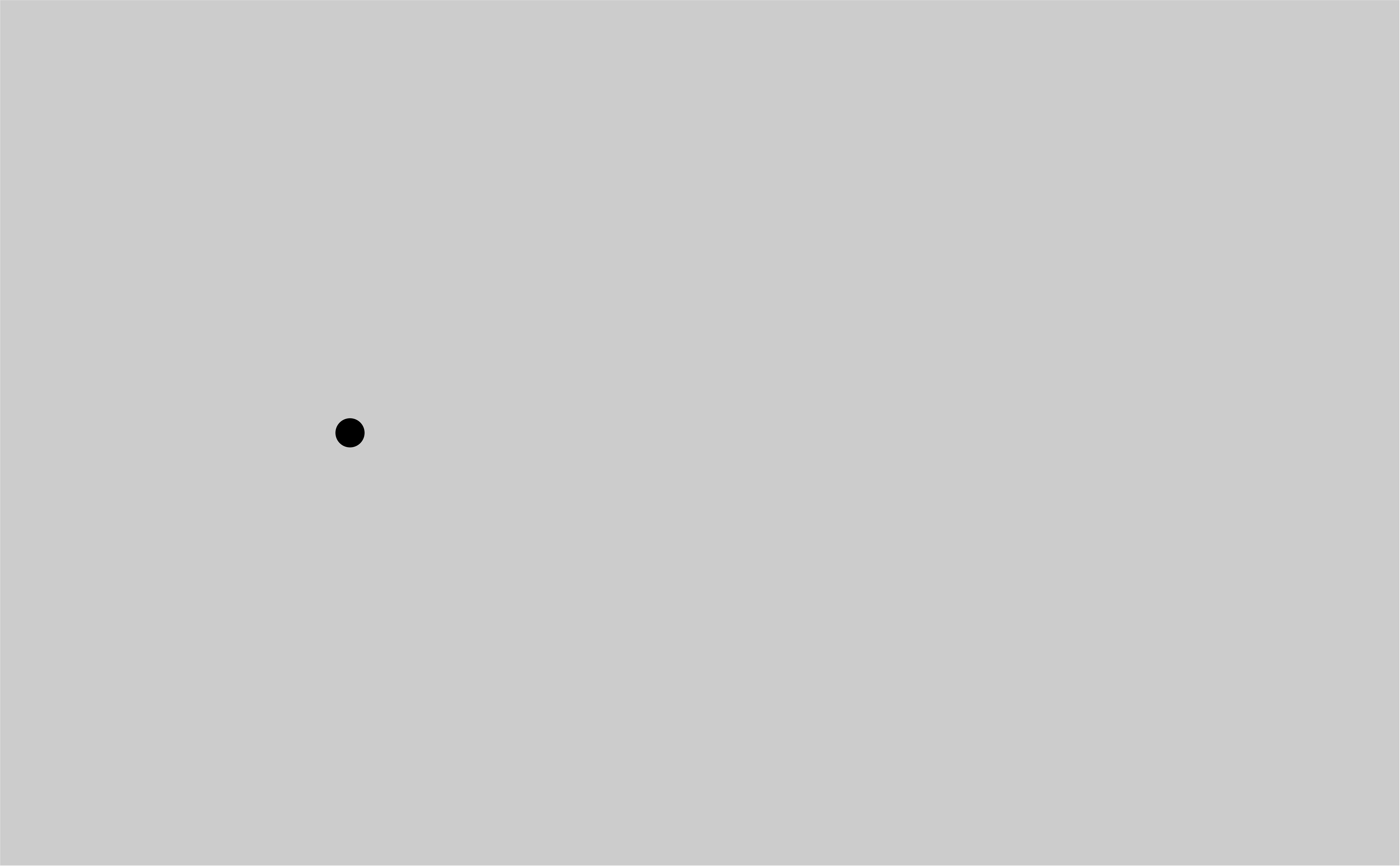
2011

The Cosmological Principle: homogeneity and isotropy

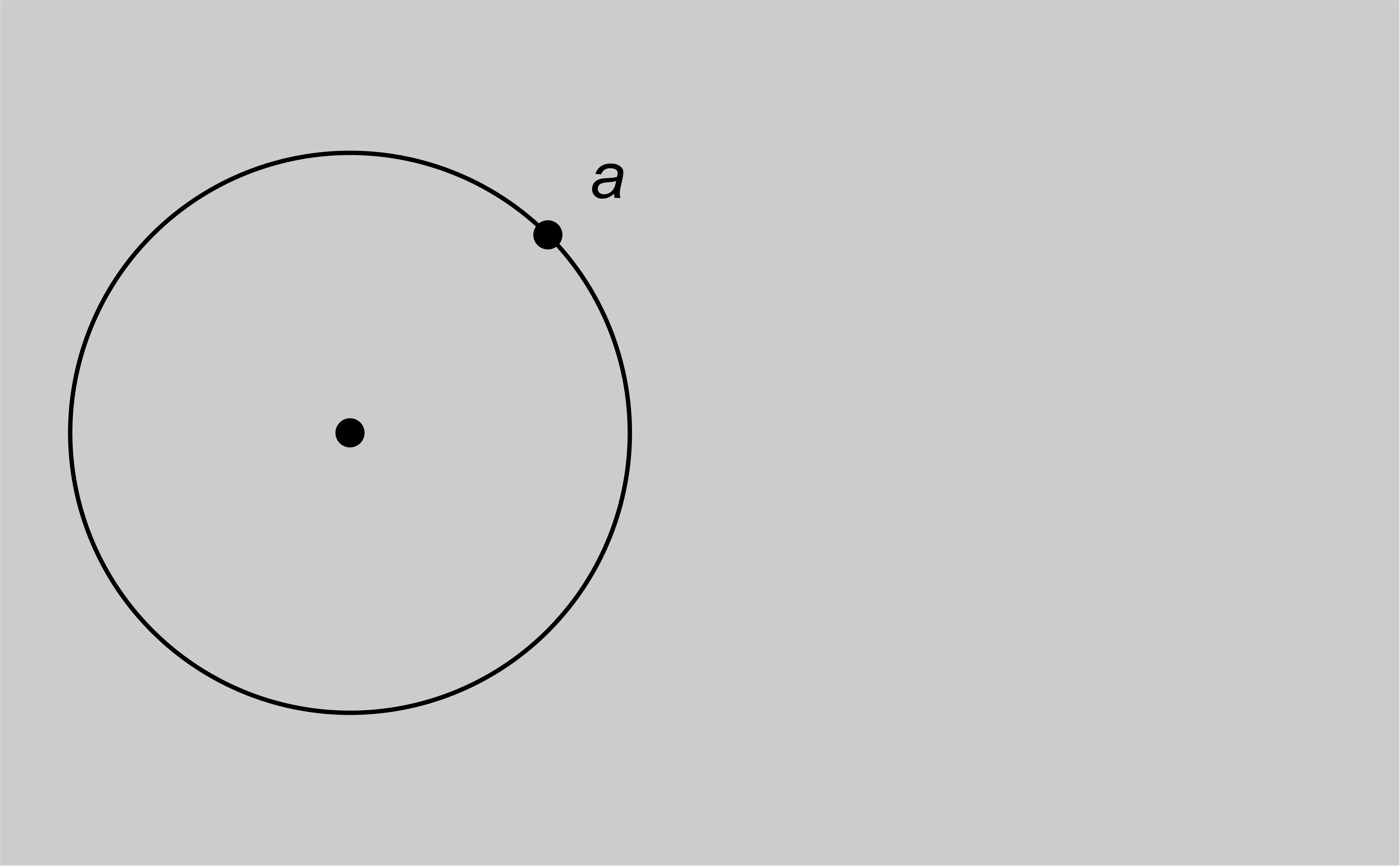


The Cosmological Principle: homogeneity and isotropy

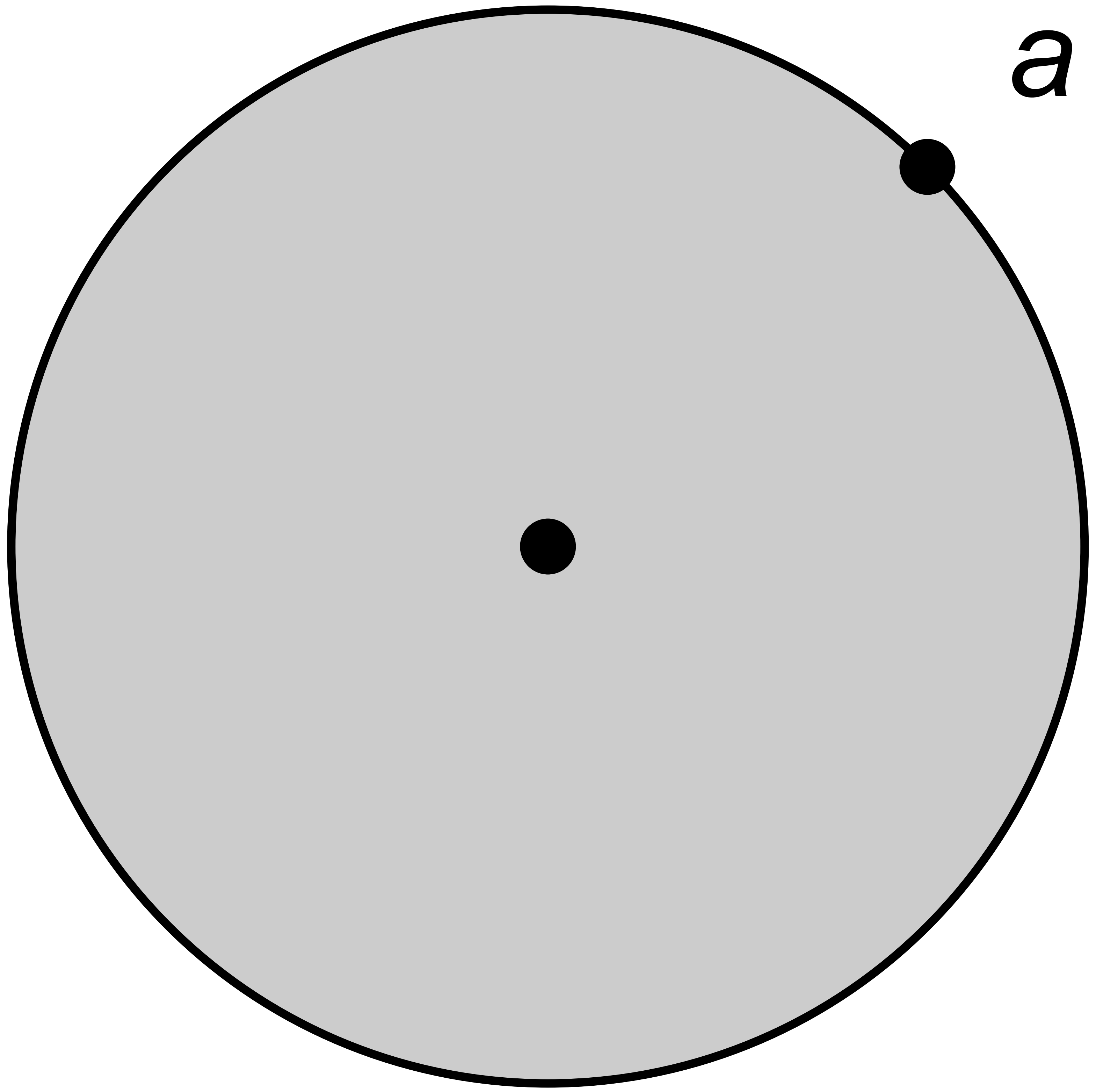
Take an arbitrary point in homogeneous space



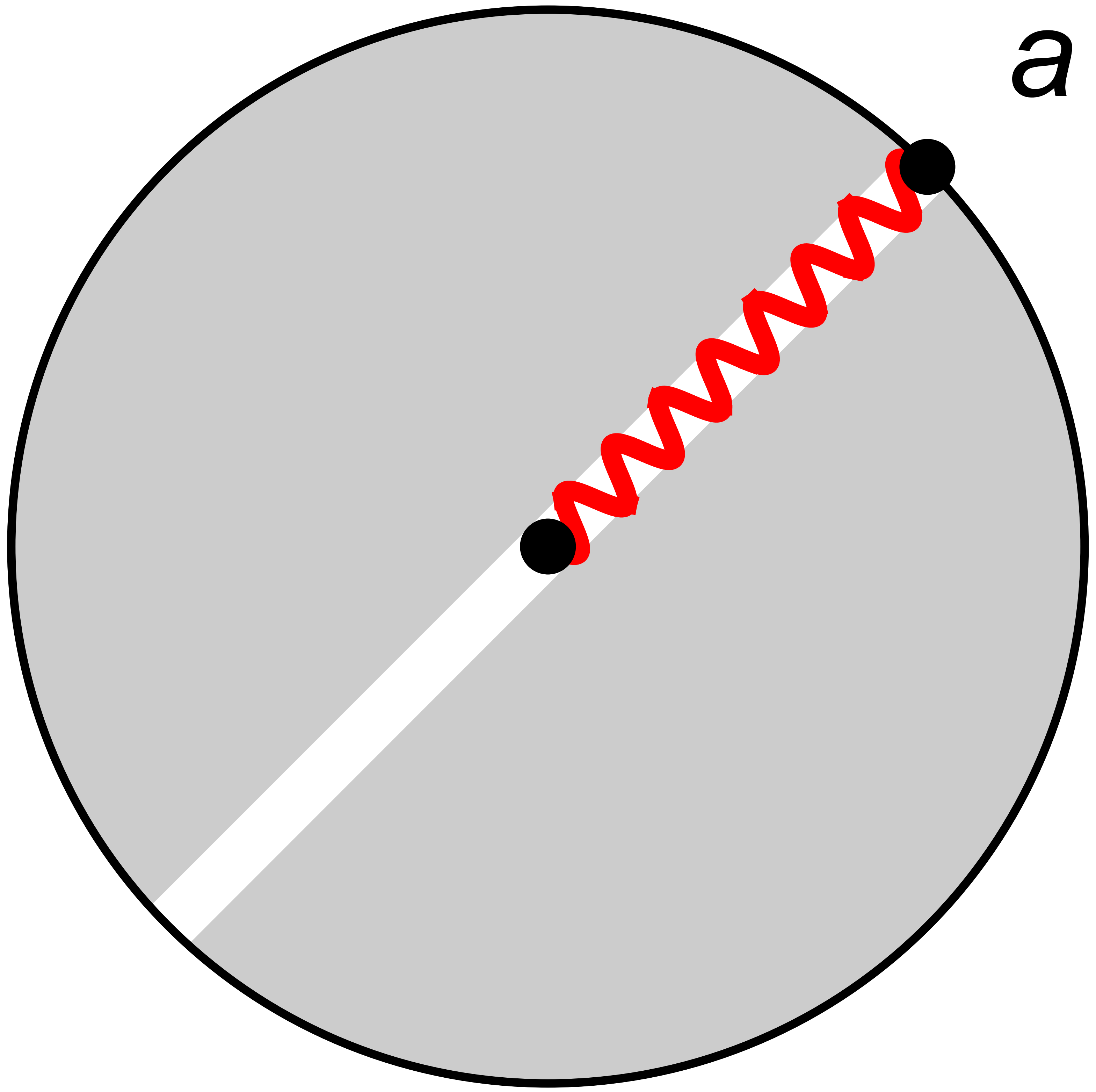
Pick another point and consider their distance *a*



Acceleration on particle at distance *a*: Gauss' law

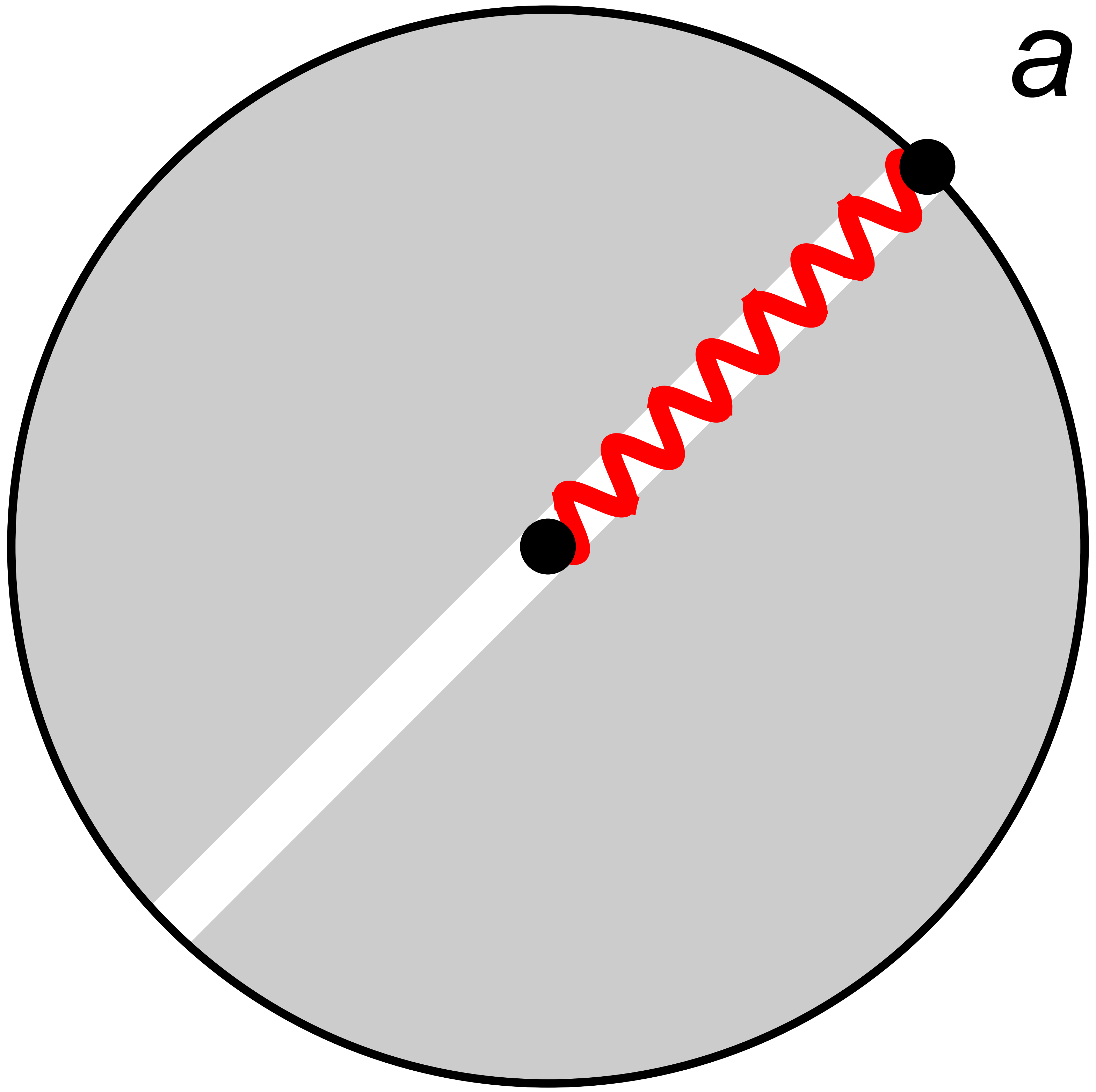


Acceleration on particle at distance *a*: Gauss' law



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho$$

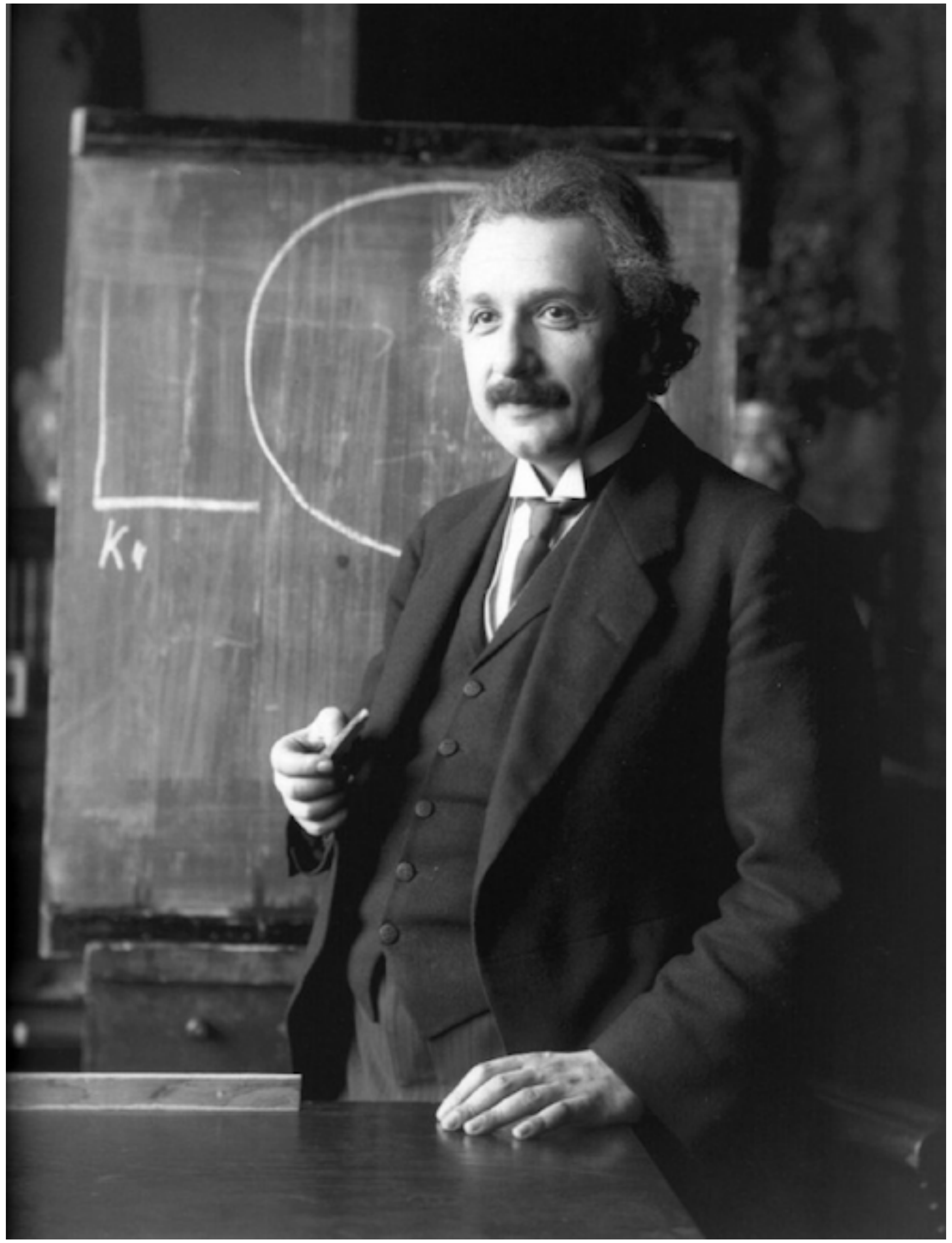
Relativistic acceleration on particle at distance *a*

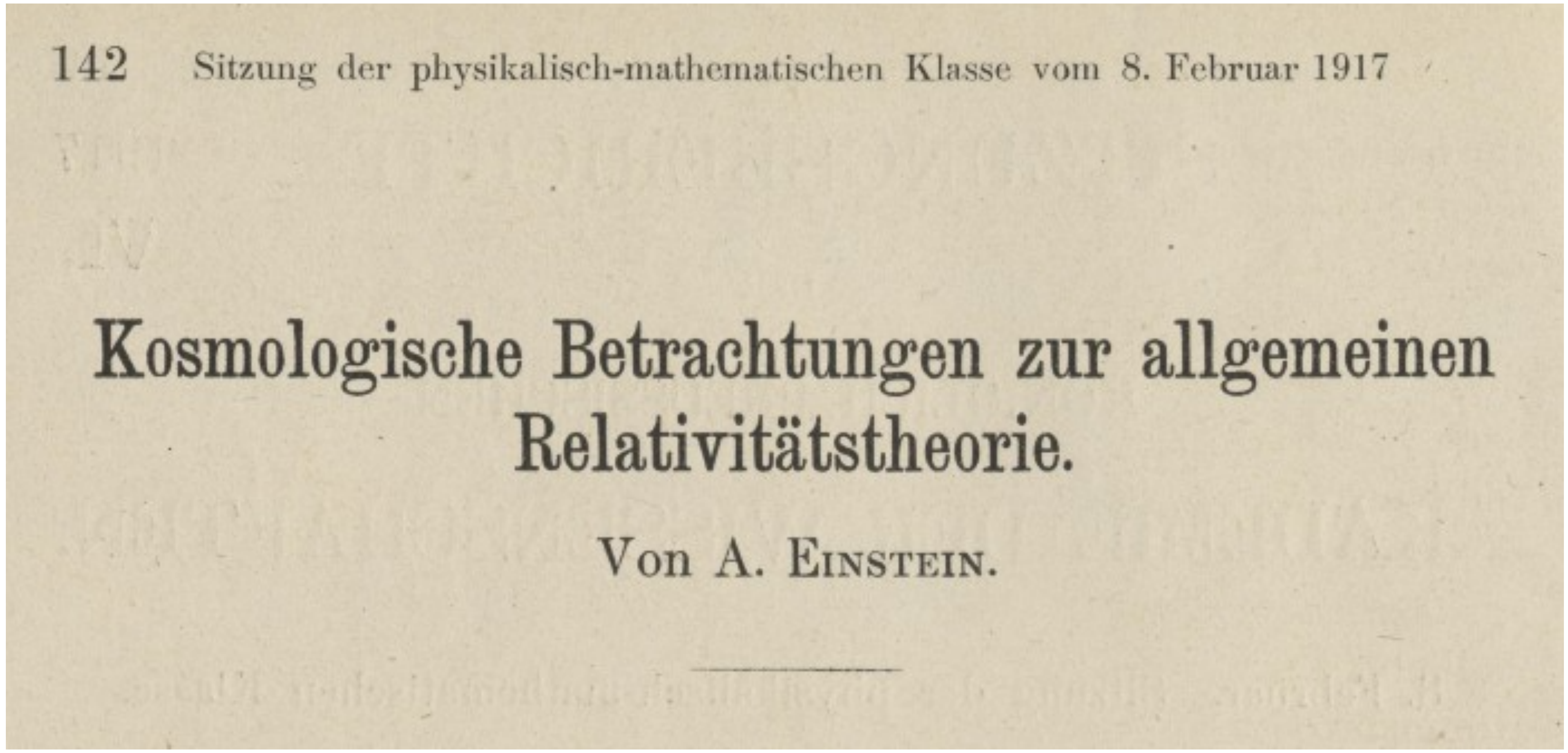


$$\varepsilon = \rho c^2$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p)$$

Einstein's cosmological constant Λ - "dark energy"



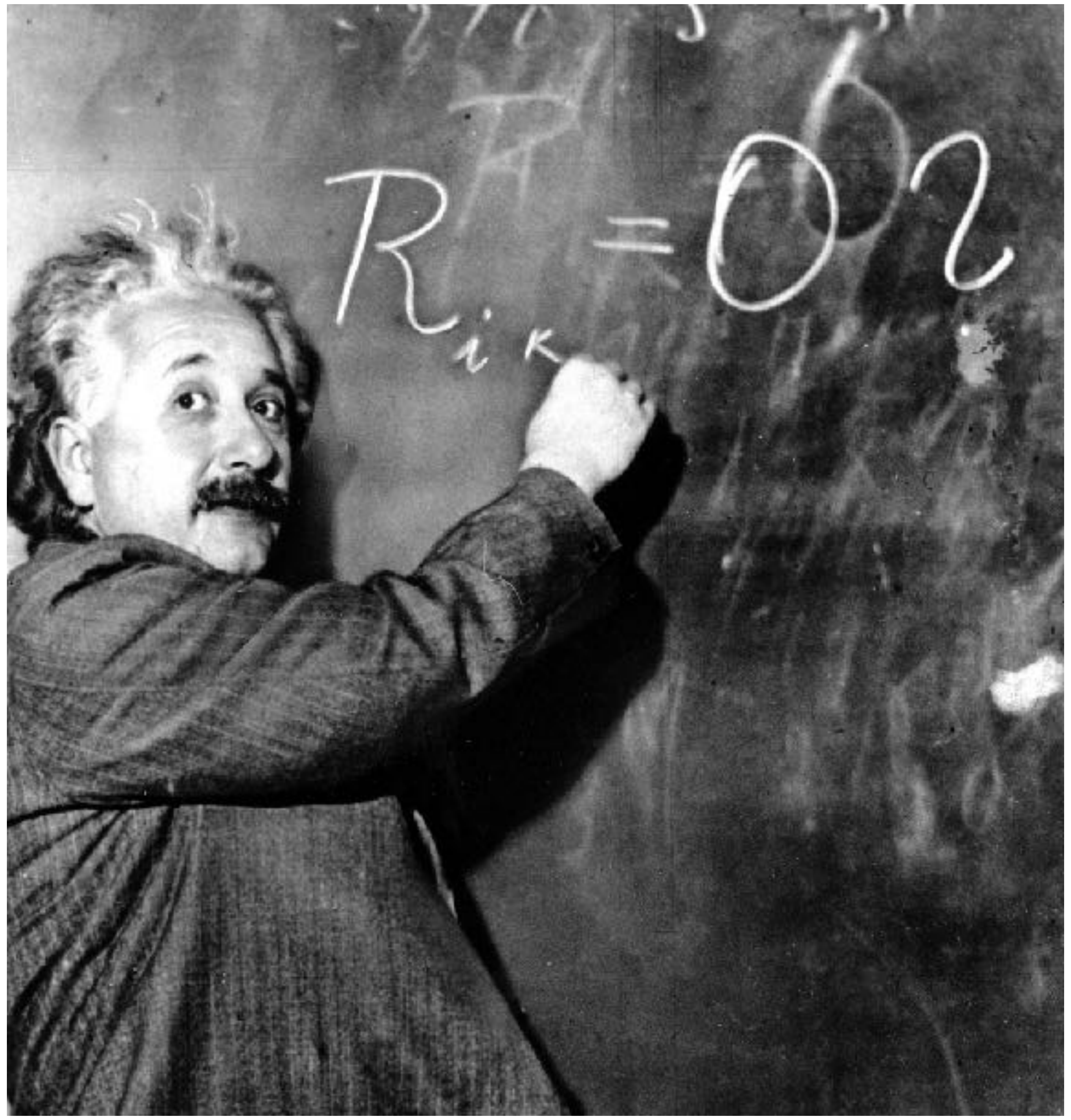


142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

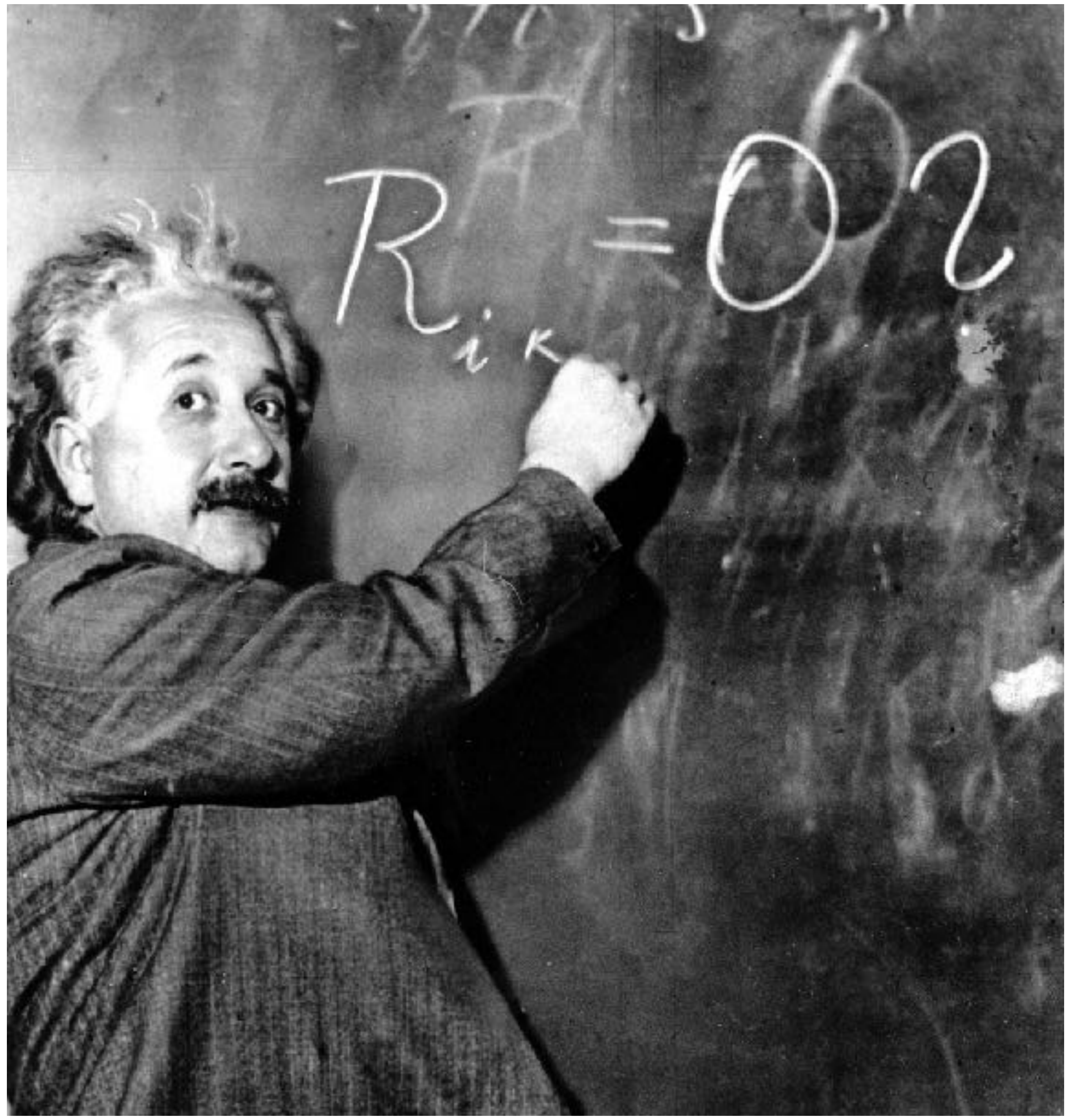
Einstein's cosmological constant Λ - "dark energy"



$$R_\mu^\nu - \frac{R}{2}\delta_\mu^\nu - \Lambda\delta_\mu^\nu = \frac{8\pi G}{c^4}T_\mu^\nu$$

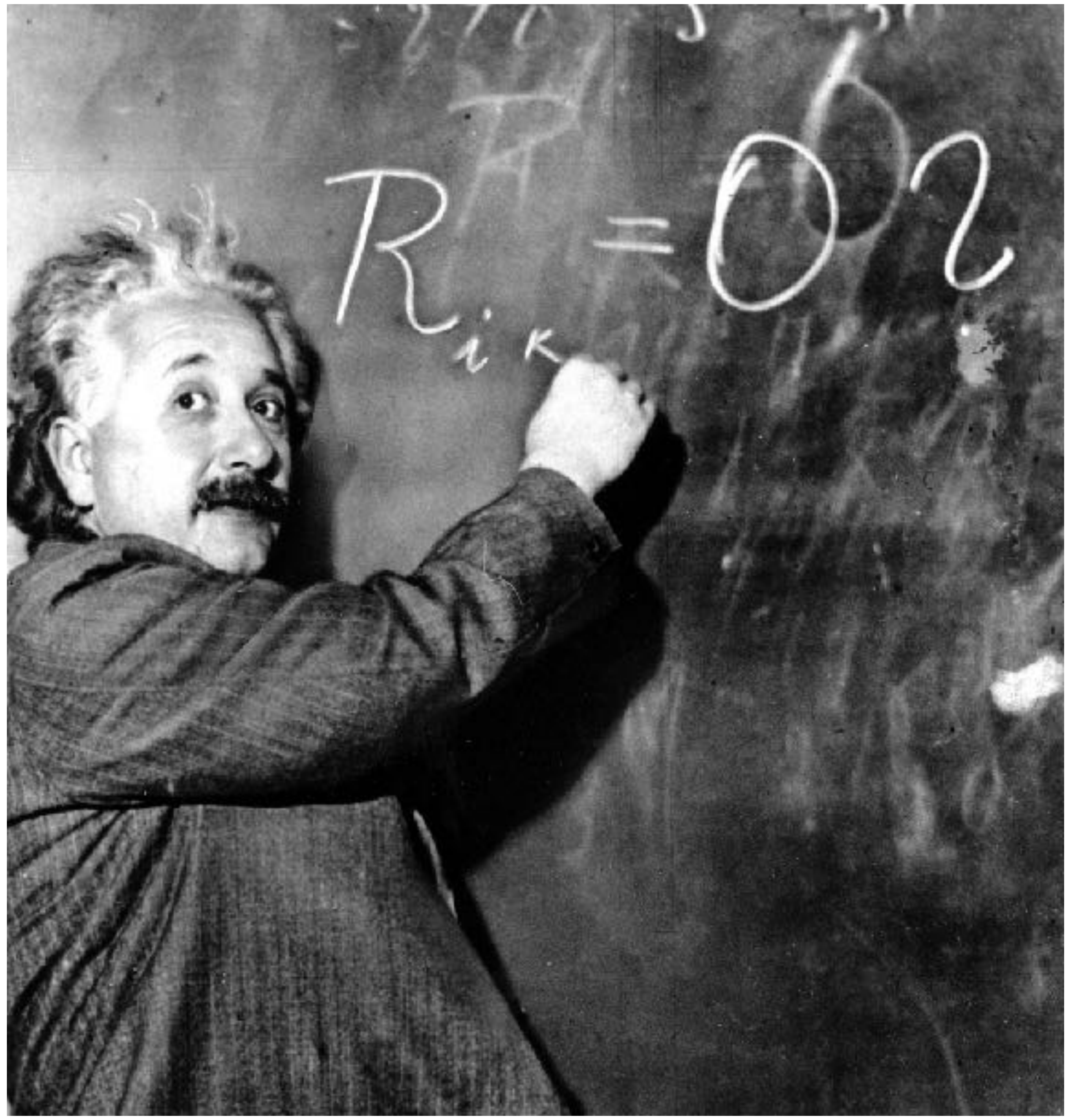
Einstein's field equations with cosmological term

Einstein’s cosmological constant Λ - “dark energy”



$$R^{\nu}_{\mu} - \frac{R}{2}\delta^{\nu}_{\mu} = \frac{8\pi G}{c^4}\left(T^{\nu}_{\mu} + \varepsilon_{\Lambda}\delta^{\nu}_{\mu}\right)$$

Einstein's cosmological constant Λ - "dark energy"



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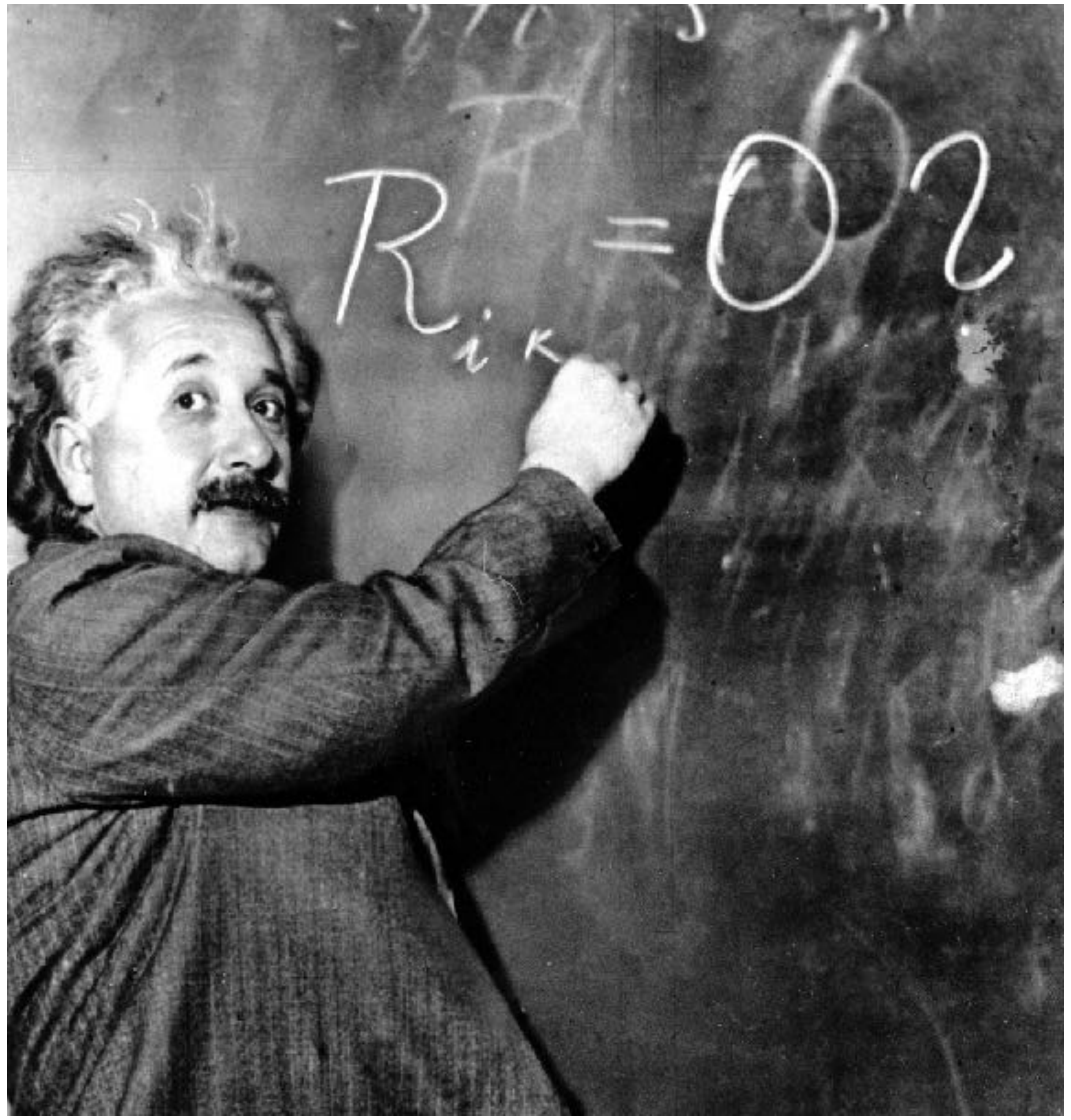
$$T_\mu^\nu = \begin{pmatrix} \varepsilon & & & \\ & -p & & \\ & & -p & \\ & & & -p \end{pmatrix} = \varepsilon_\Lambda \mathbb{1}$$

Einstein's cosmological constant Λ - "dark energy"



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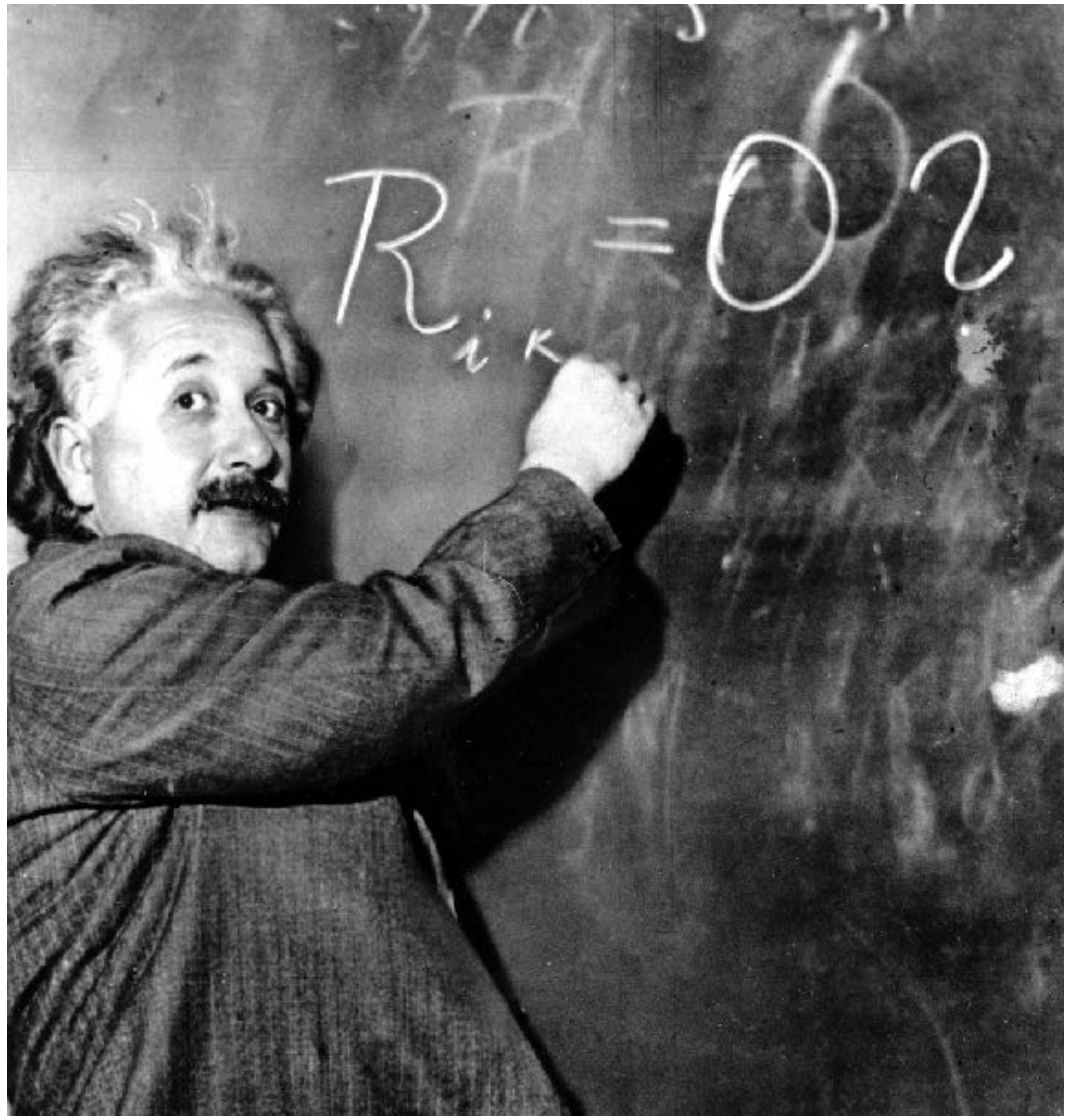
$$\Rightarrow \quad p_{\Lambda} = -\varepsilon_{\Lambda}$$

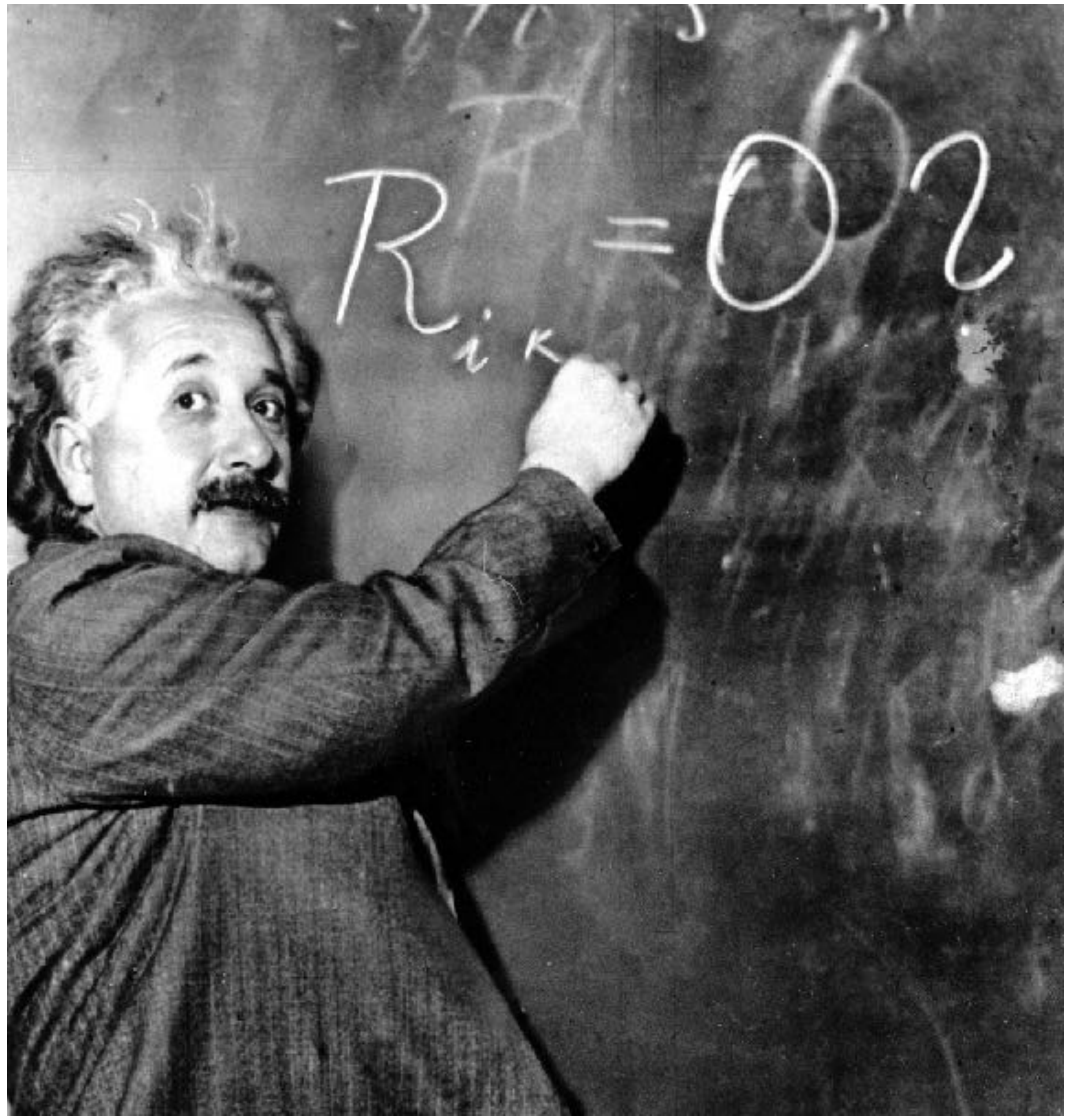
Einstein's cosmological constant Λ - "dark energy"



$$p_\Lambda = -\varepsilon_\Lambda$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p)$$

Einstein's cosmological constant Λ - "dark energy"



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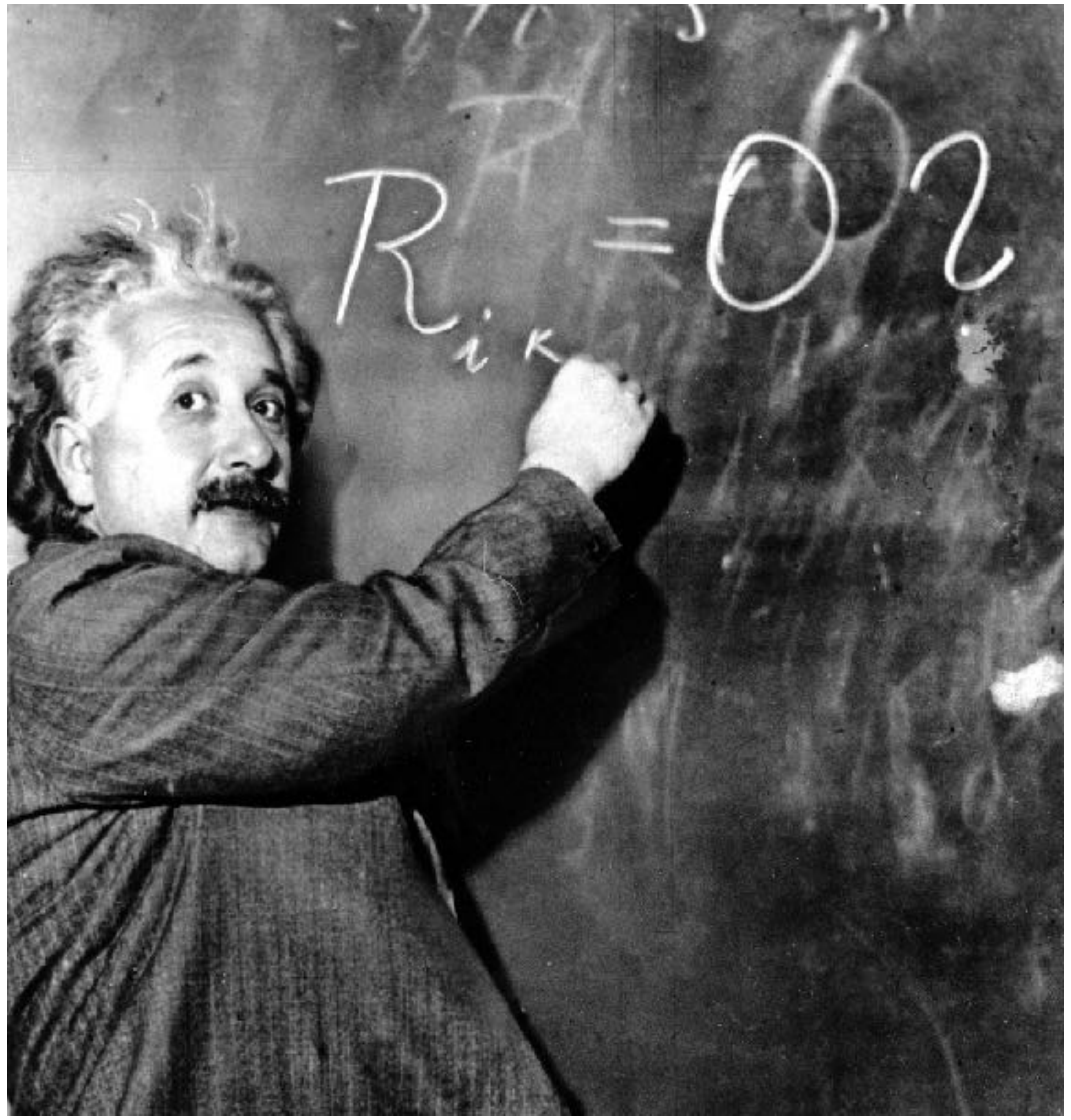
Acceleration!

Einstein's cosmological constant Λ - "dark energy"



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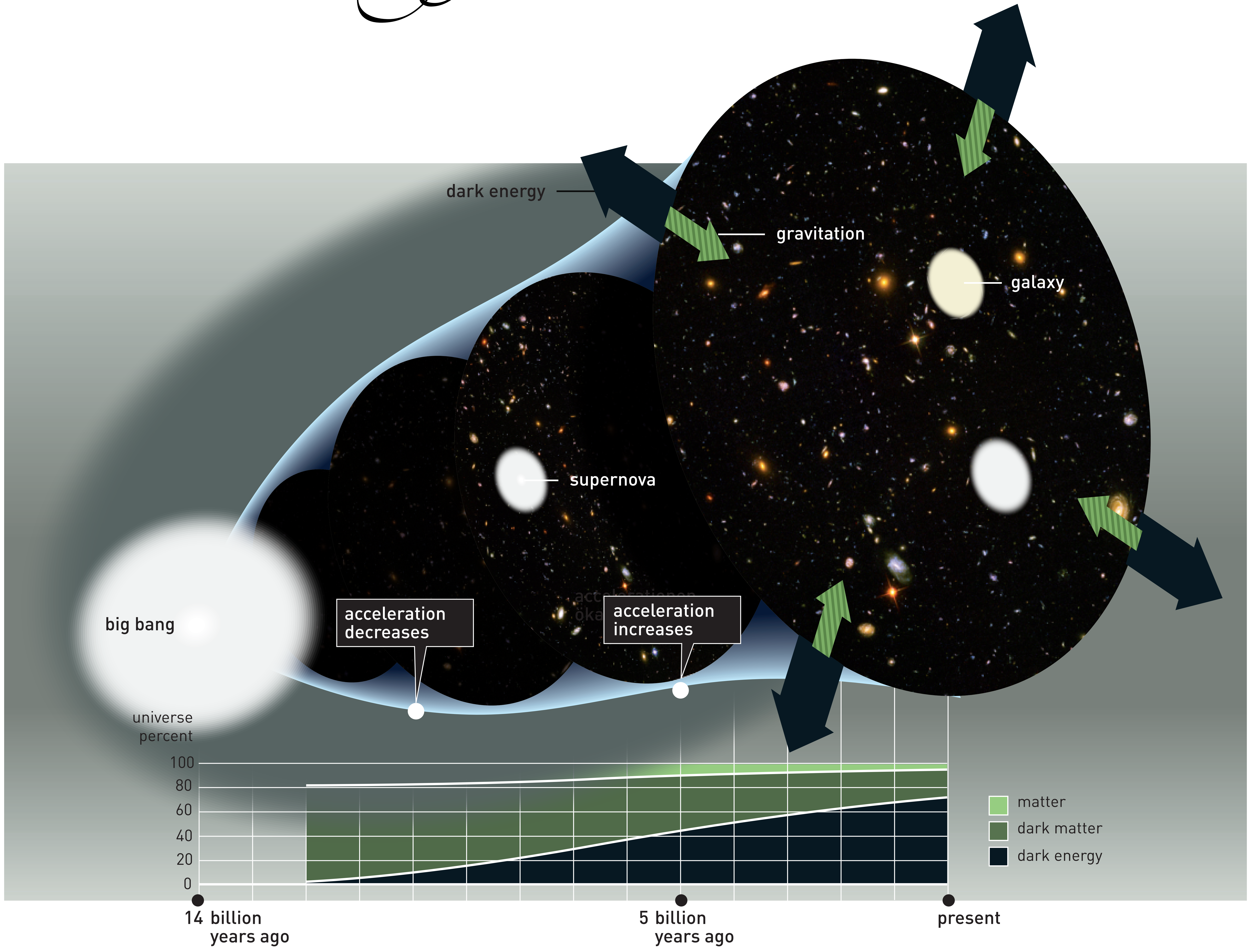
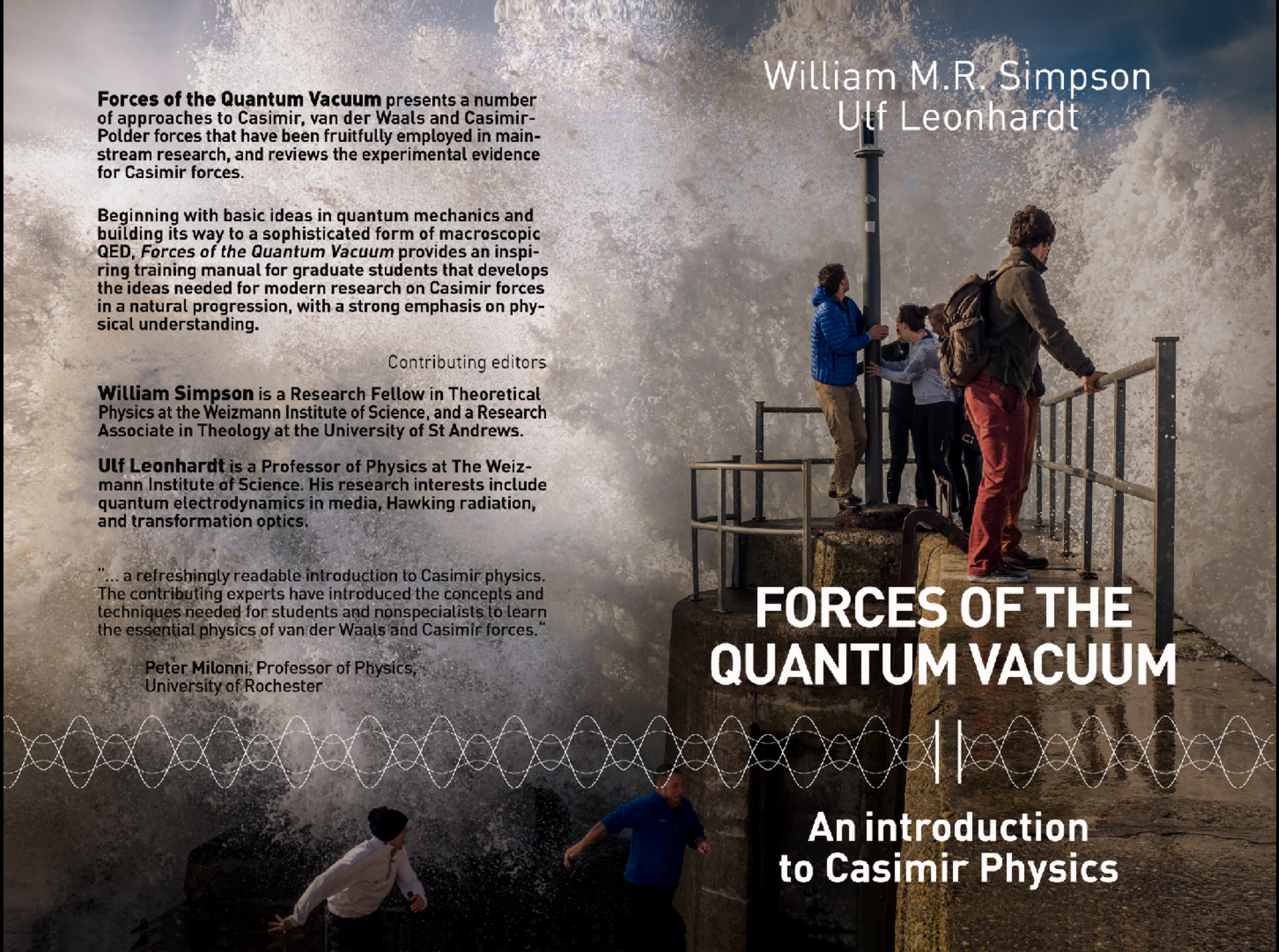
70% of all ε at present time

Dark energy – cosmological constant





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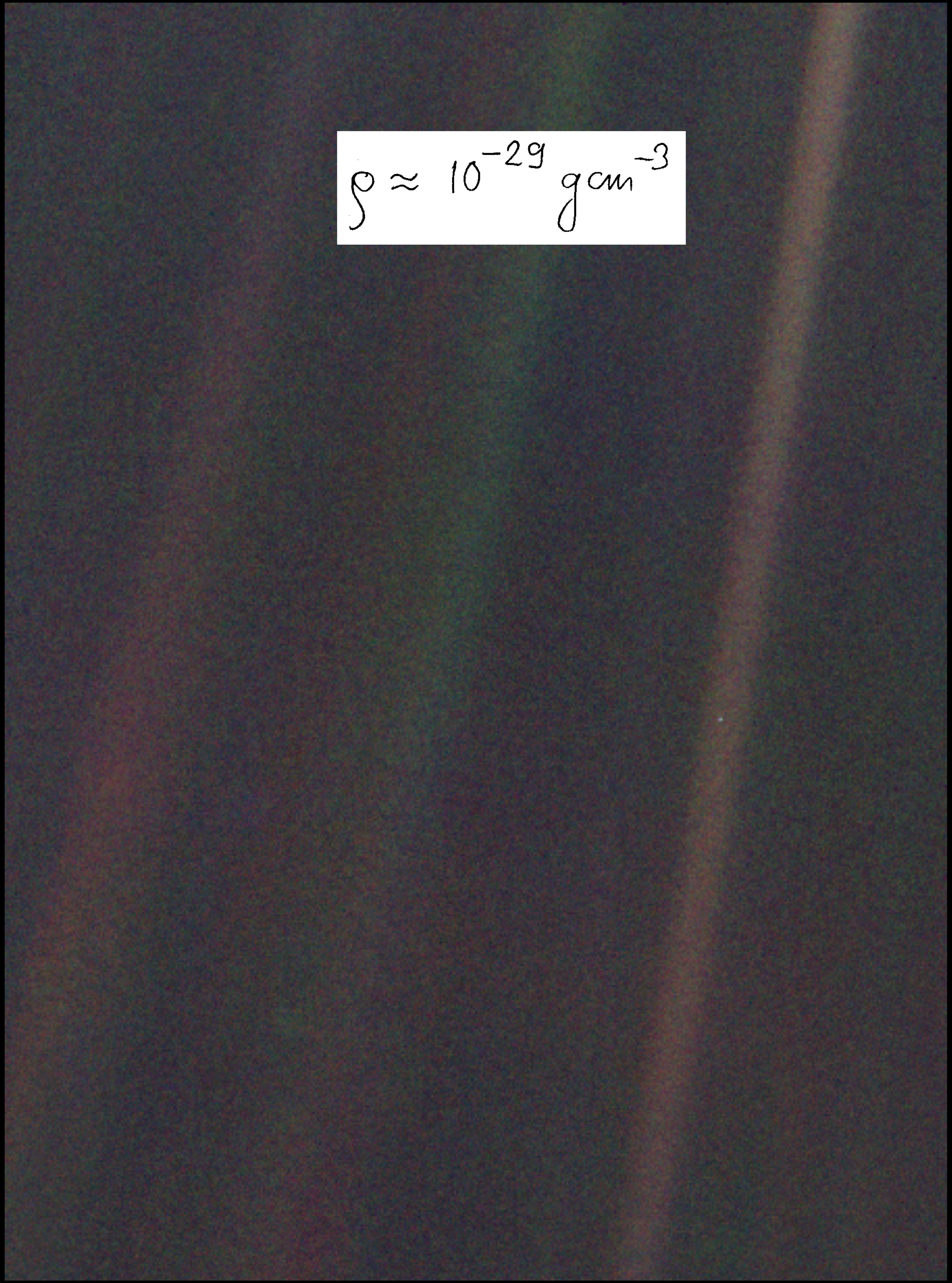
$\rho \approx 10^{-29}\, g\, cm^{-3}$

The gravity of vacuum fluctuations

SOVIET PHYSICS USPEKHI VOLUME 11, NUMBER 3 NOVEMBER-DECEMBER 1968

530.12 : 531.51

THE COSMOLOGICAL CONSTANT AND THE THEORY OF ELEMENTARY PARTICLES

Ya. B. ZEL'DOVICH

Institute of Applied Mathematics, USSR Academy of Sciences

Usp. Fiz. Nauk 95, 209–230 (May, 1968)

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$$T_\mu^\nu \Big|_{vac} = \varepsilon_\Lambda \delta_\mu^\nu$$

The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

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$$\boxed{\varepsilon_{Th} = \frac{\hbar c}{\ell_p^4}}$$

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$$\varepsilon_{Th} = \frac{\hbar c}{\ell_p^4}$$

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \approx 1{,}6 \cdot 10^{-37}\, cm$$

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Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

$$\varepsilon_{Th} = \frac{\hbar c}{\ell_p^4}$$

$$\rho_{Th} = \frac{\varepsilon_{Th}}{c^2} = \frac{m_p}{\ell_p^3}$$

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \approx 1{,}6 \cdot 10^{-37}\,cm$$

$$m_p = \sqrt{\frac{\hbar c}{G}} \approx 2{,}2 \cdot 10^{-5}\,g$$

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$$\rho_{Th} = \frac{\varepsilon_{Th}}{c^2} = \frac{m_p}{\ell_p^3}$$

$$m_p = \sqrt{\frac{\hbar c}{G}} \approx 2,2 \cdot 10^{-5}\,\mathrm{g}$$

$$\rho \approx 10^{-29}\,\mathrm{g\,cm^{-3}}$$

$$\Rightarrow \log_{10}(\rho_{Th}/\rho) \approx 120$$

A general argument? : general covariance of the vacuum

$$T_\mu^{\ \nu}\Big|_{vac} = \varepsilon_\Lambda \, \delta_\mu^{\ \nu}$$

The vacuum

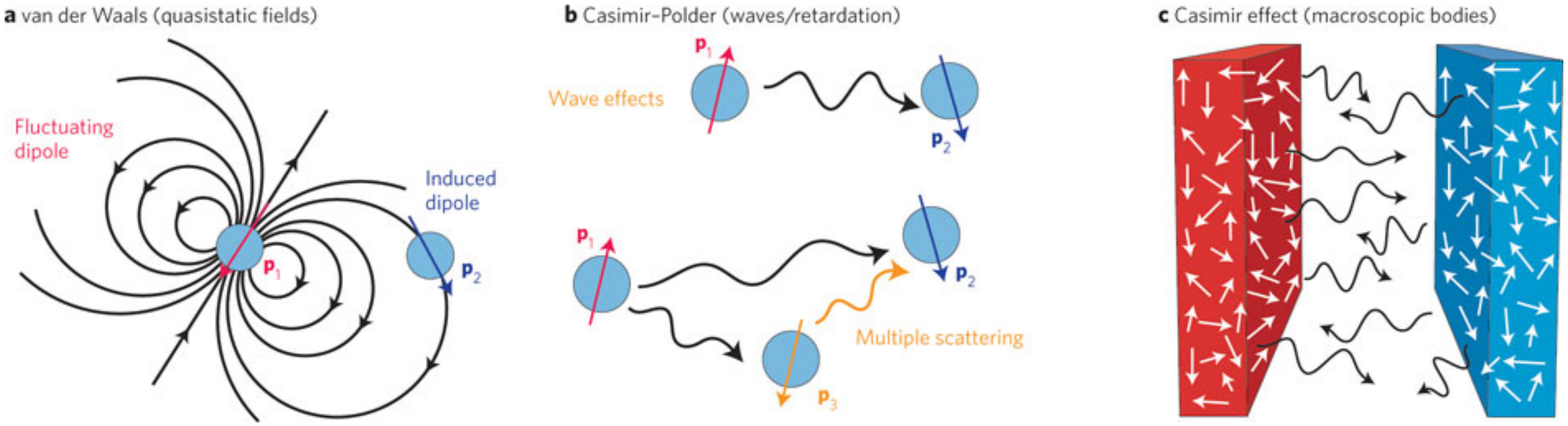
The vacuum state $|0\rangle$

Unruh-Fulling-Davies effect: view of an accelerated observer

nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 31 MARCH 2011 | DOI: 10.1038/NPHOTON.2011.39

The Casimir effect in microstructured geometries

Alejandro W. Rodriguez[1,2], Federico Capasso[1]* and Steven G. Johnson[2]



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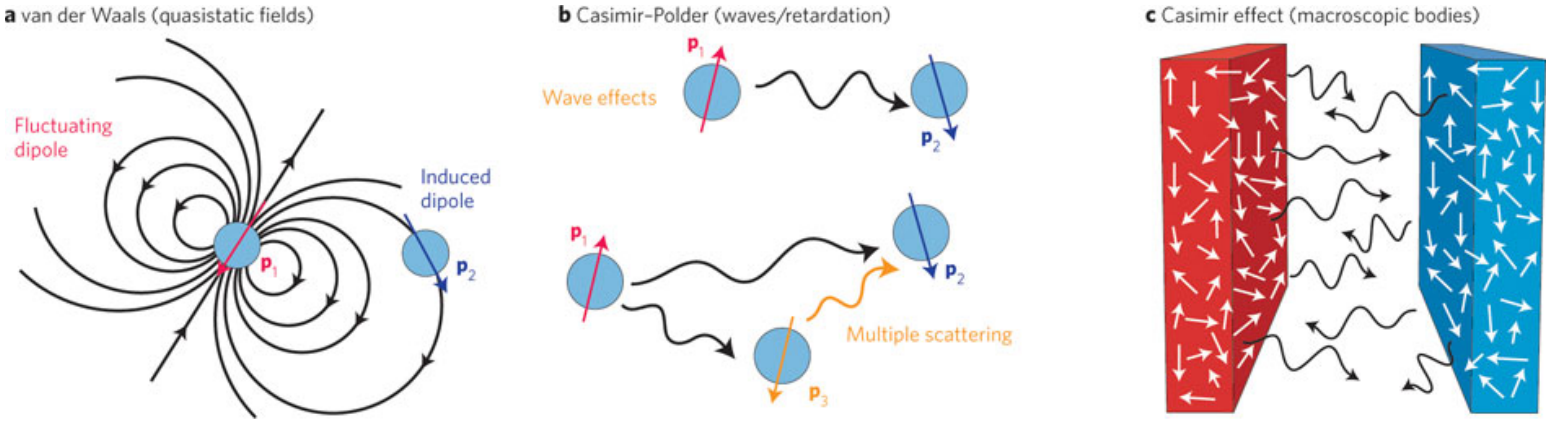
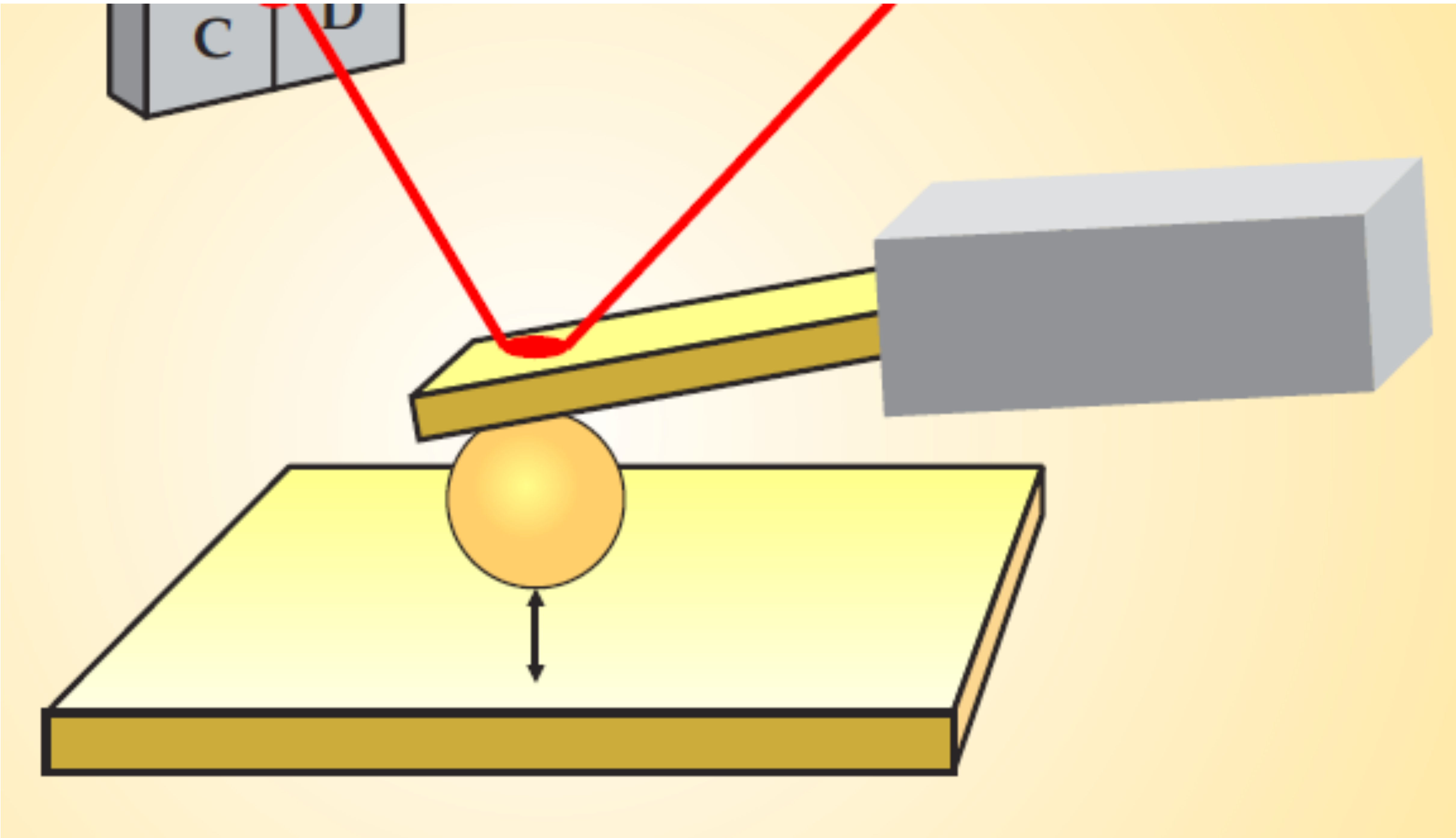


VOLUME 78, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JANUARY 1997

Demonstration of the Casimir Force in the 0.6 to 6 μm Range

S.K. Lamoreaux*
Physics Department, University of Washington, Box 35160, Seattle, Washington 98195-1560
(Received 28 August 1996)

Precision measurements and manipulations of Casimir forces



RESEARCH

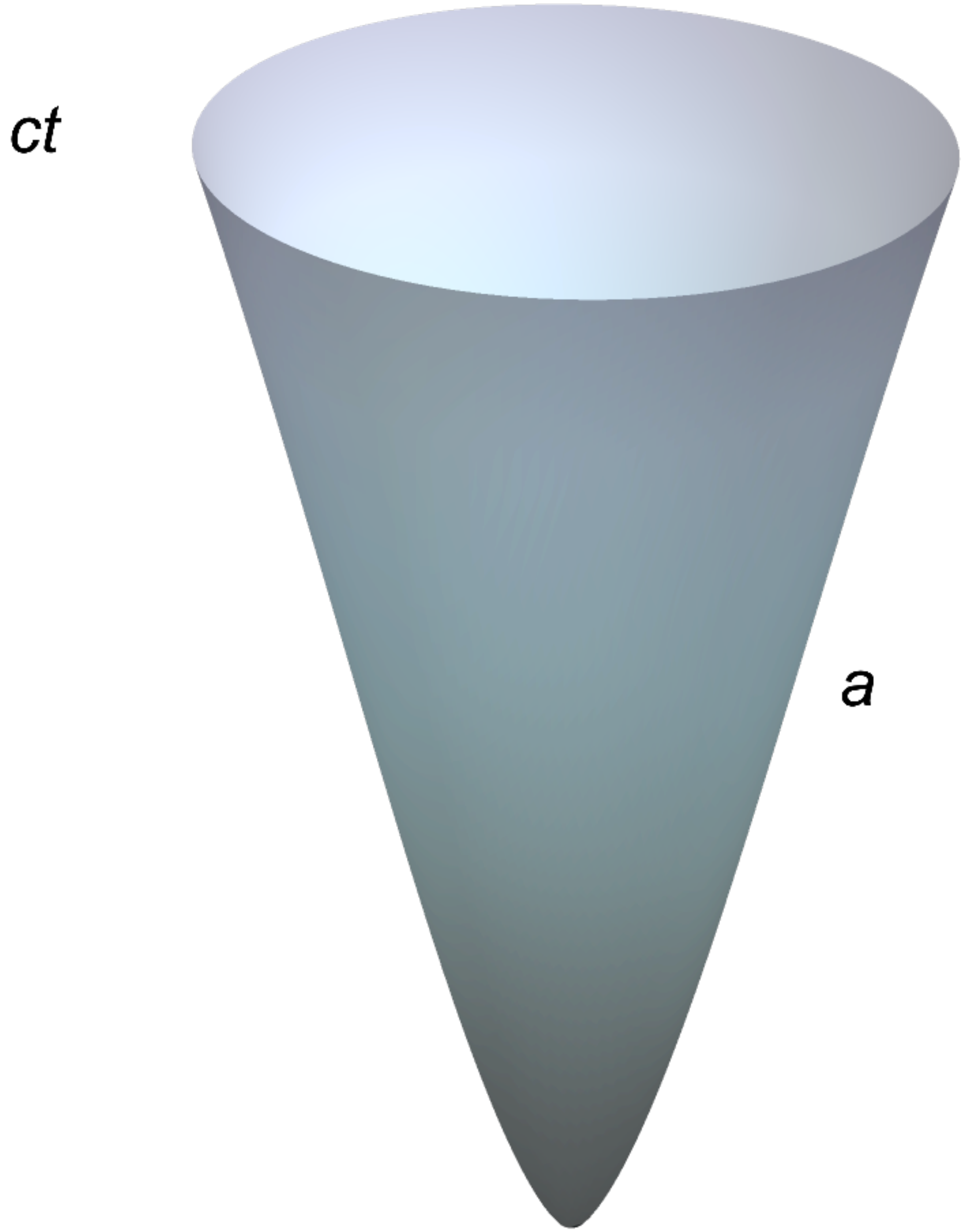
PHYSICS

Science **364**, 984–987 (2019) 7 June 2019

Stable Casimir equilibria and quantum trapping

Rongkuo Zhao[1*], Lin Li[1*], Sui Yang[1*], Wei Bao[1*], Yang Xia[1], Paul Ashby[2], Yuan Wang[1], Xiang Zhang[1,3]†

Optical analogue of expanding, spatially flat universe



$$d\ell = a(t)\,dr$$

$$n = a$$

Ulf Leonhardt and Thomas Philbin

GEOMETRY AND LIGHT

The Science of INVISIBILITY

Lifshitz theory

SOVIET PHYSICS

USPEKHI

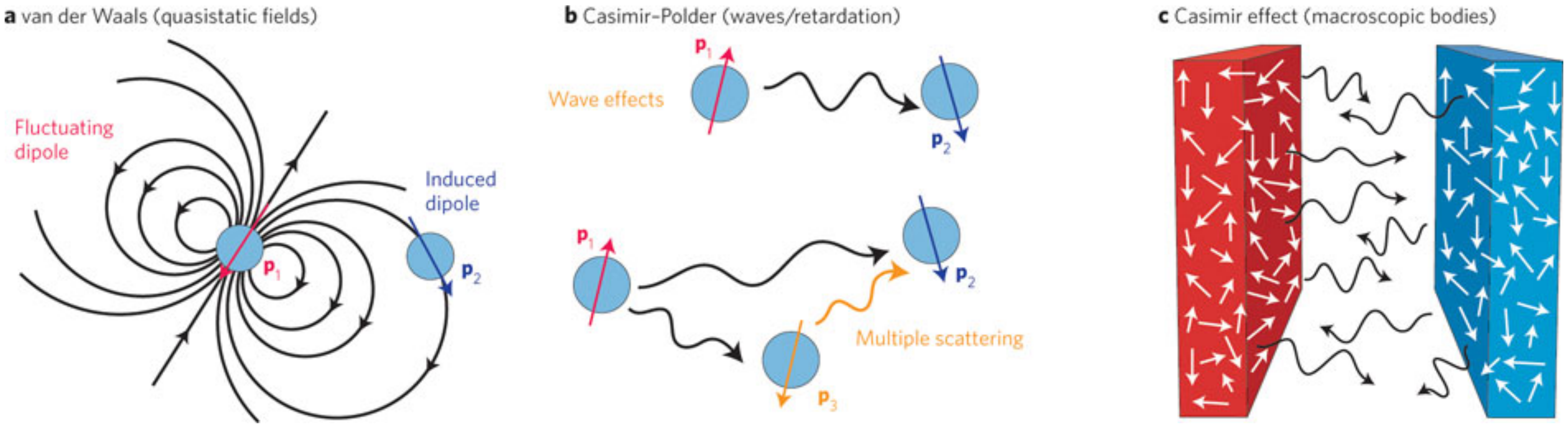
A Translation of Uspekhi Fizicheskikh Nauk

SOVIET PHYSICS USPEKHI (Russian Vol. 73, Nos. 3-4 SEPTEMBER-OCTOBER 1961

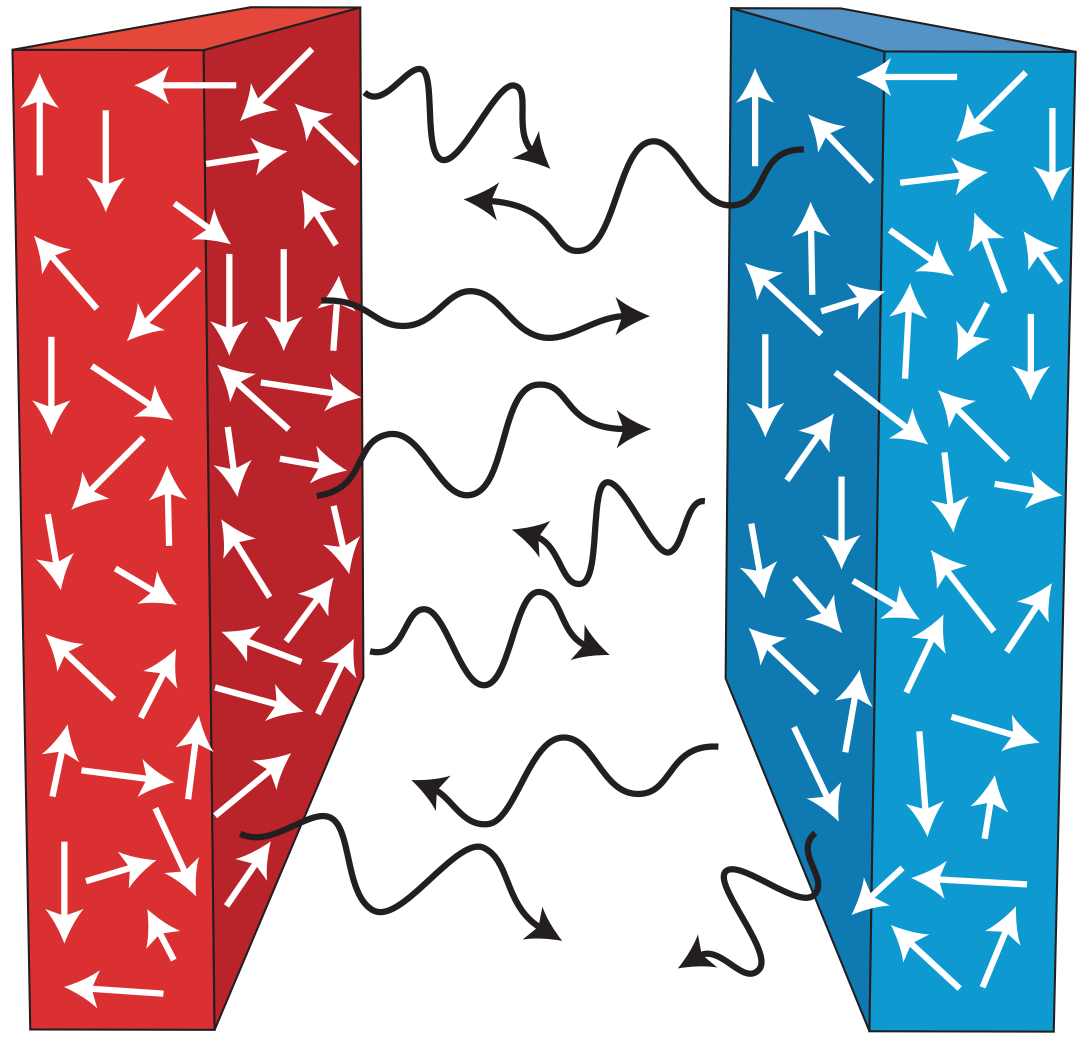
GENERAL THEORY OF VAN DER WAALS' FORCES

I. E. DZYALOSHINSKII, E. M. LIFSHITZ, and L. P. PITAEVSKII

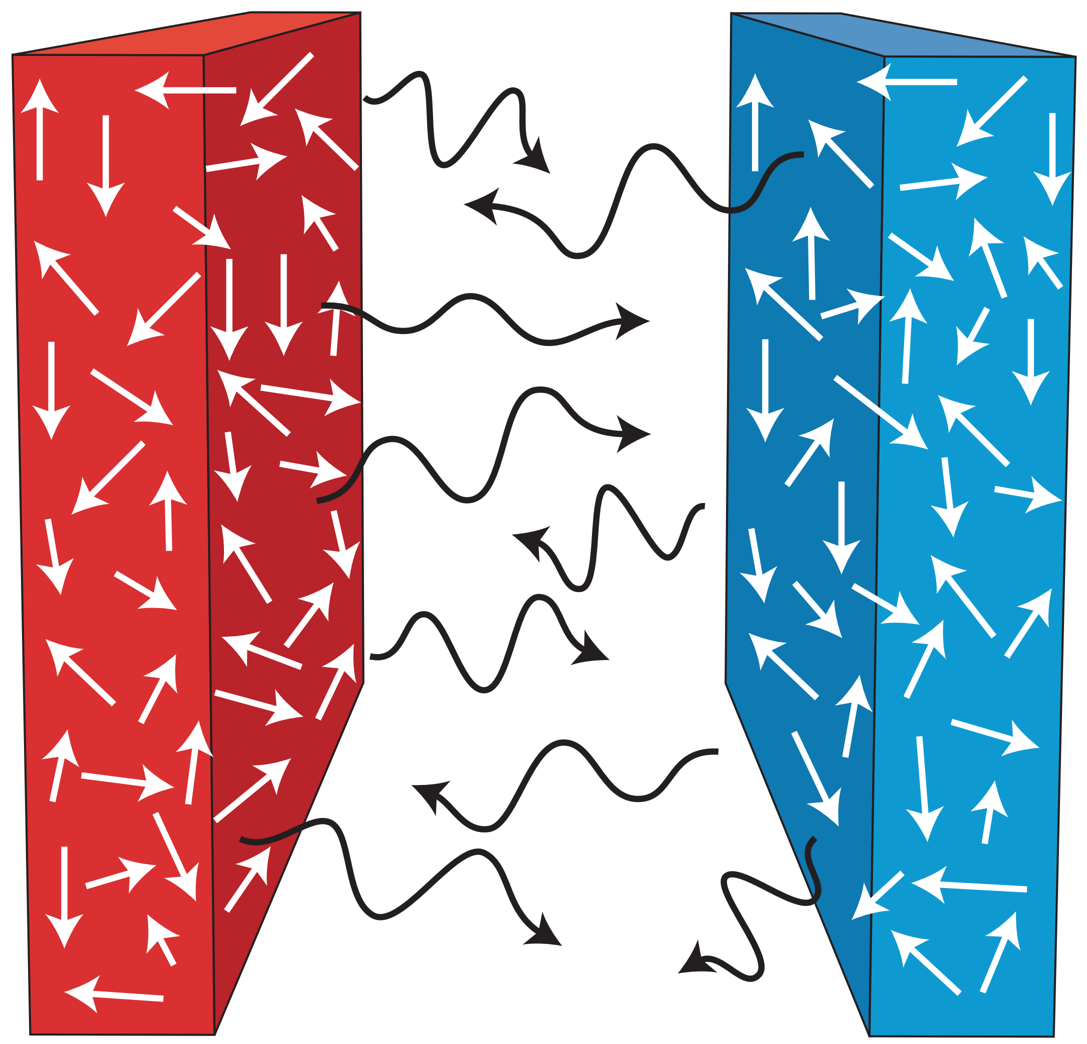
Usp. Fiz. Nauk **73**, 381-422 (March, 1961)



Renormalization: bare vacuum energy is infinite

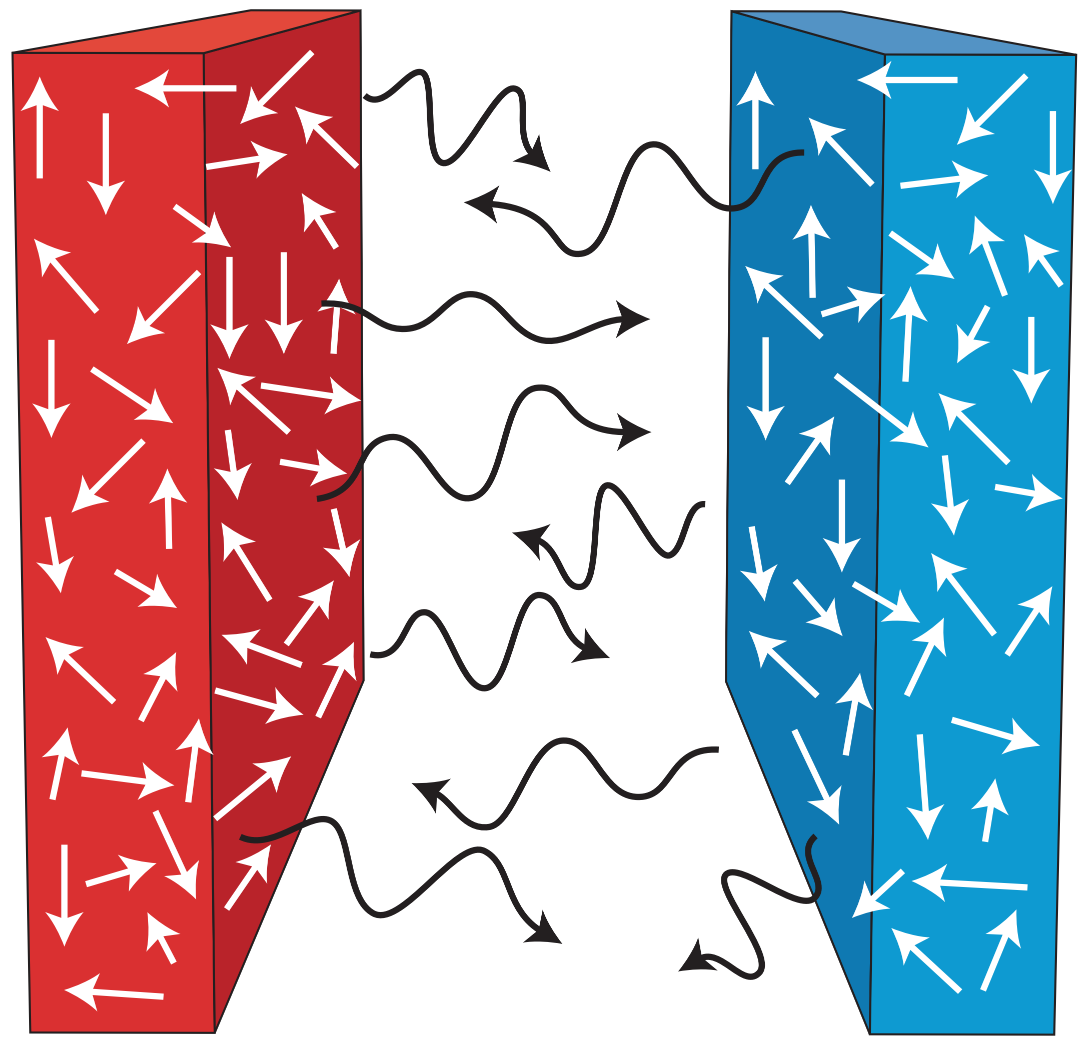


Renormalization: compare vacuum energy at finite distance



with

Renormalization: compare vacuum energy at finite distance



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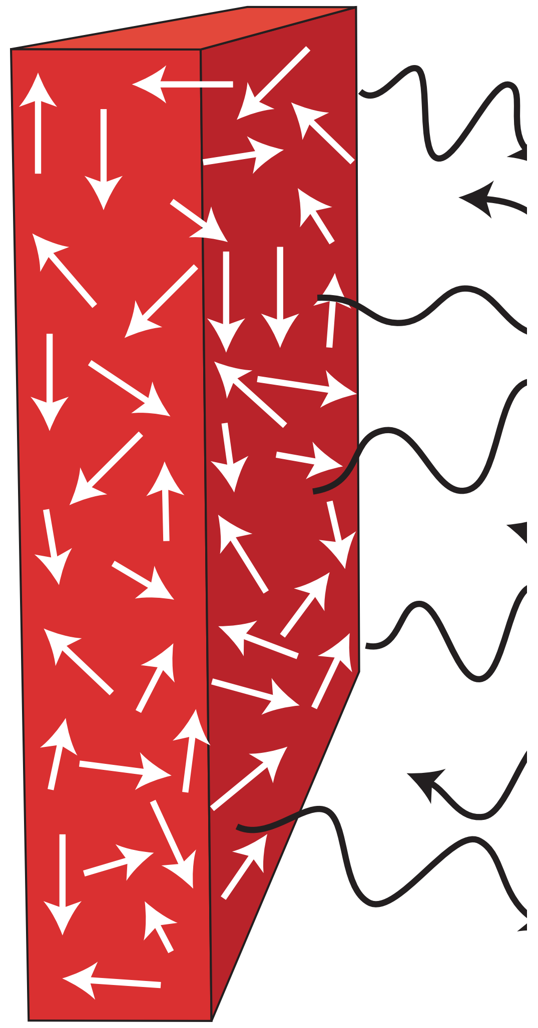
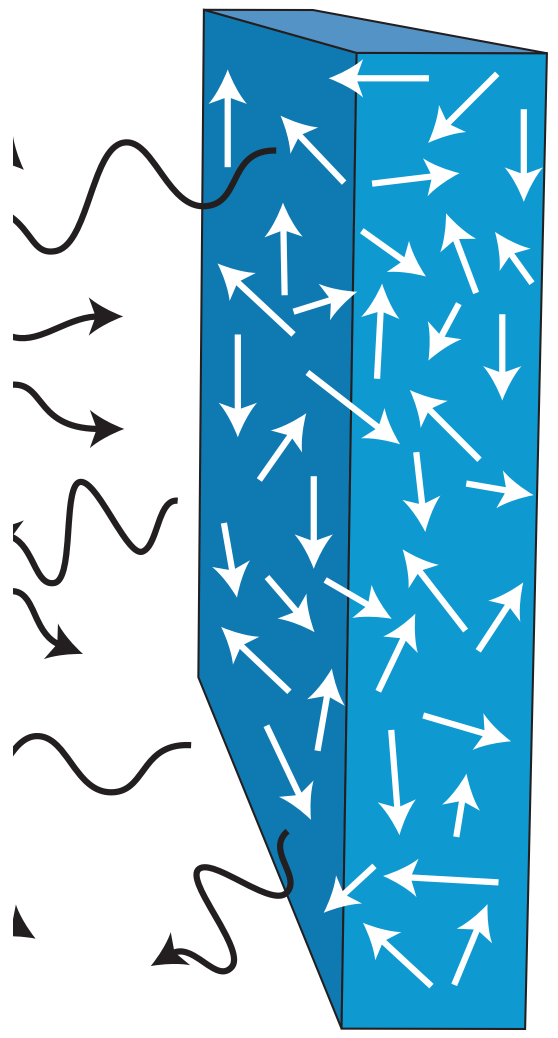
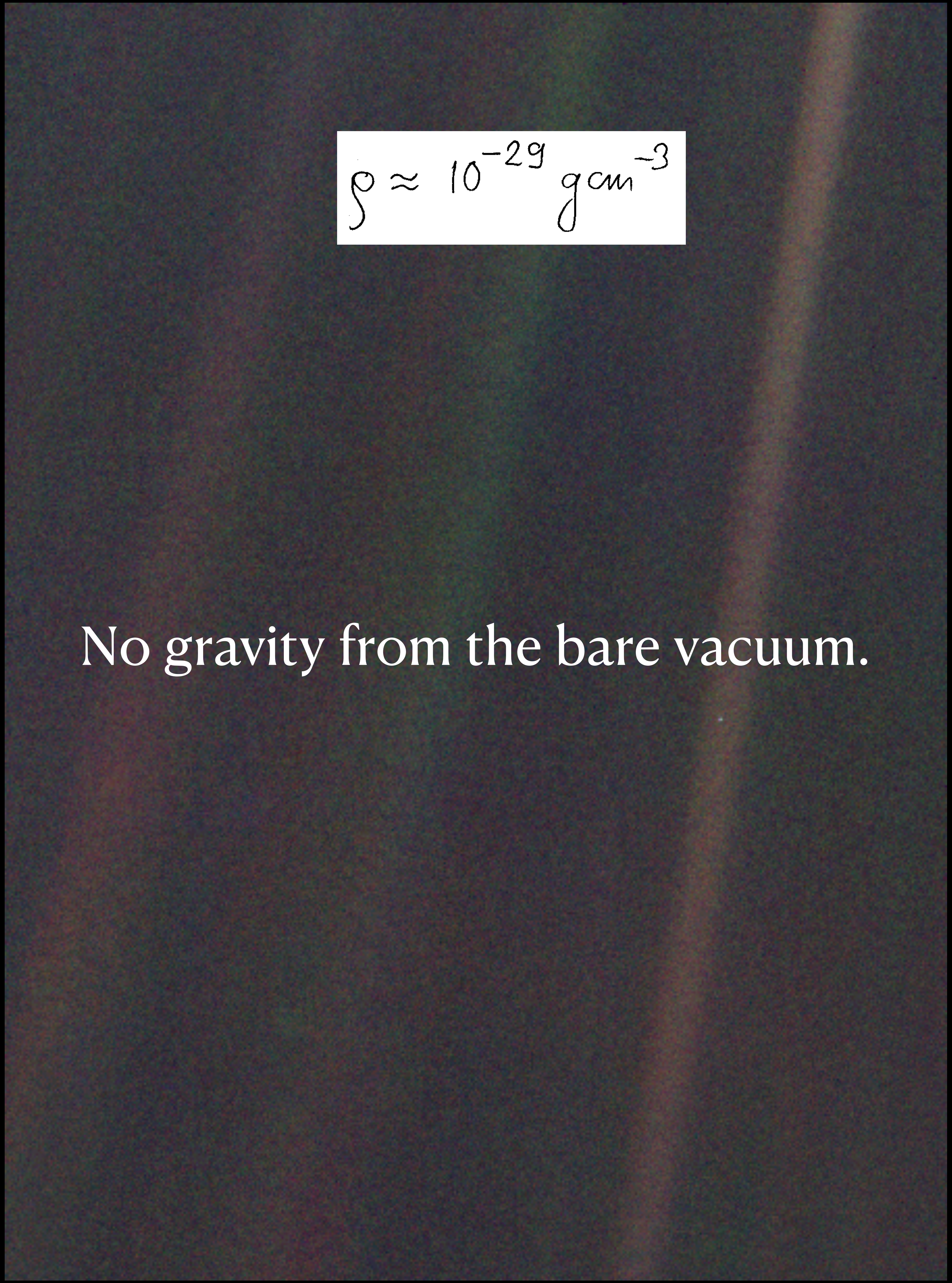




Einstein's field equations: all energy is supposed to curve space-time

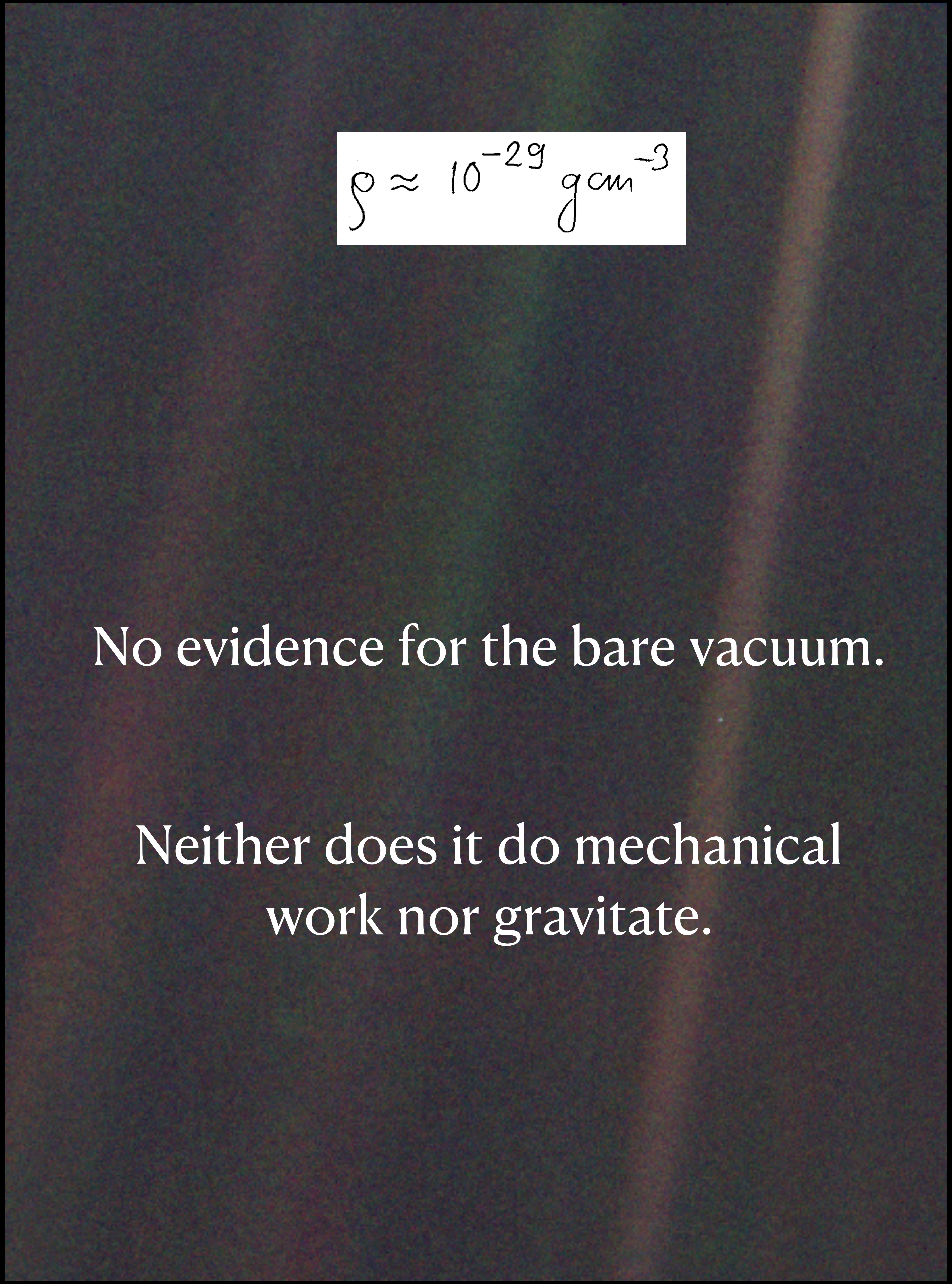
$$\underbrace{R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu}}_{\text{GEOMETRY OF SPACETIME}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{DENSITY OF MATTER AND ENERGY}}$$

All energy should gravitate

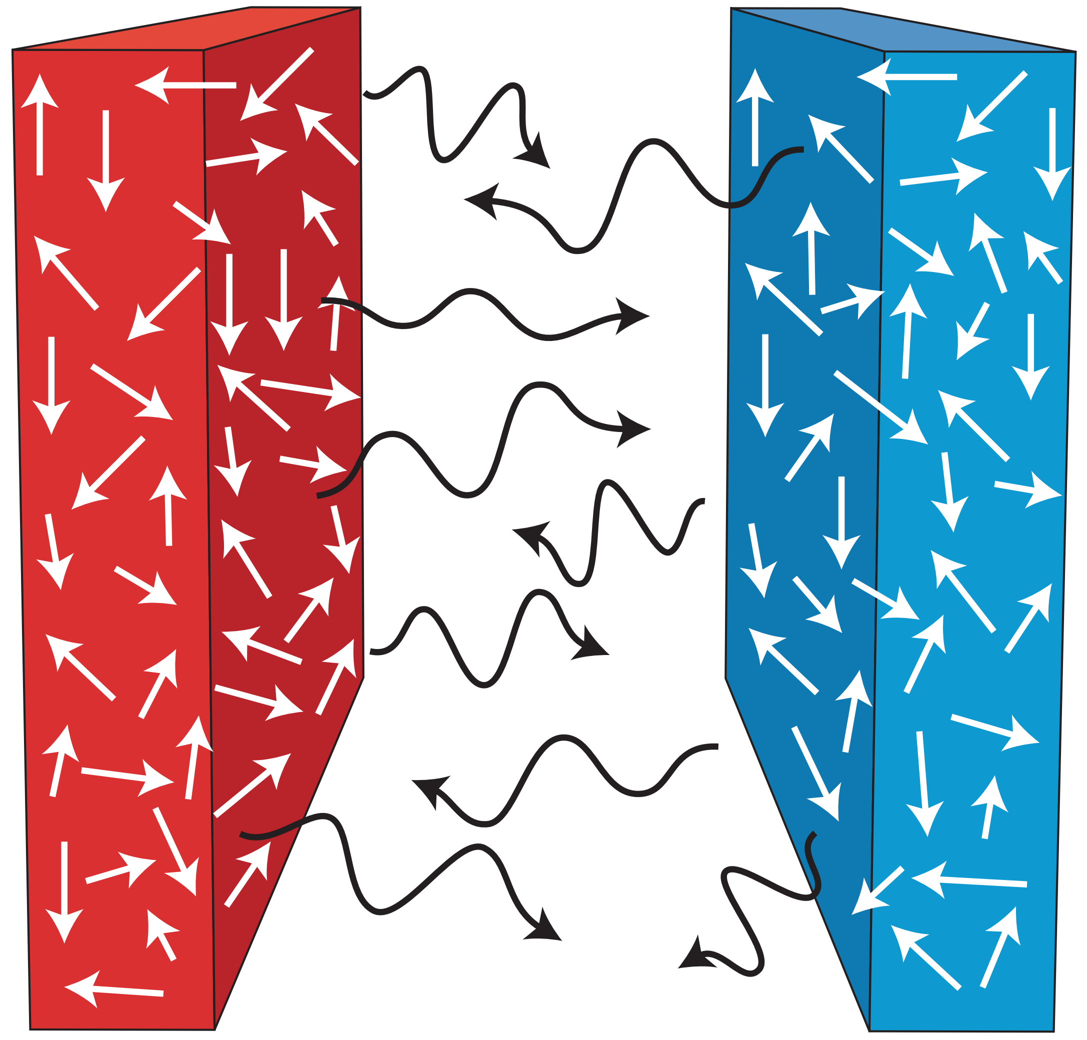


$$\rho \approx 10^{-29}\ g\,cm^{-3}$$

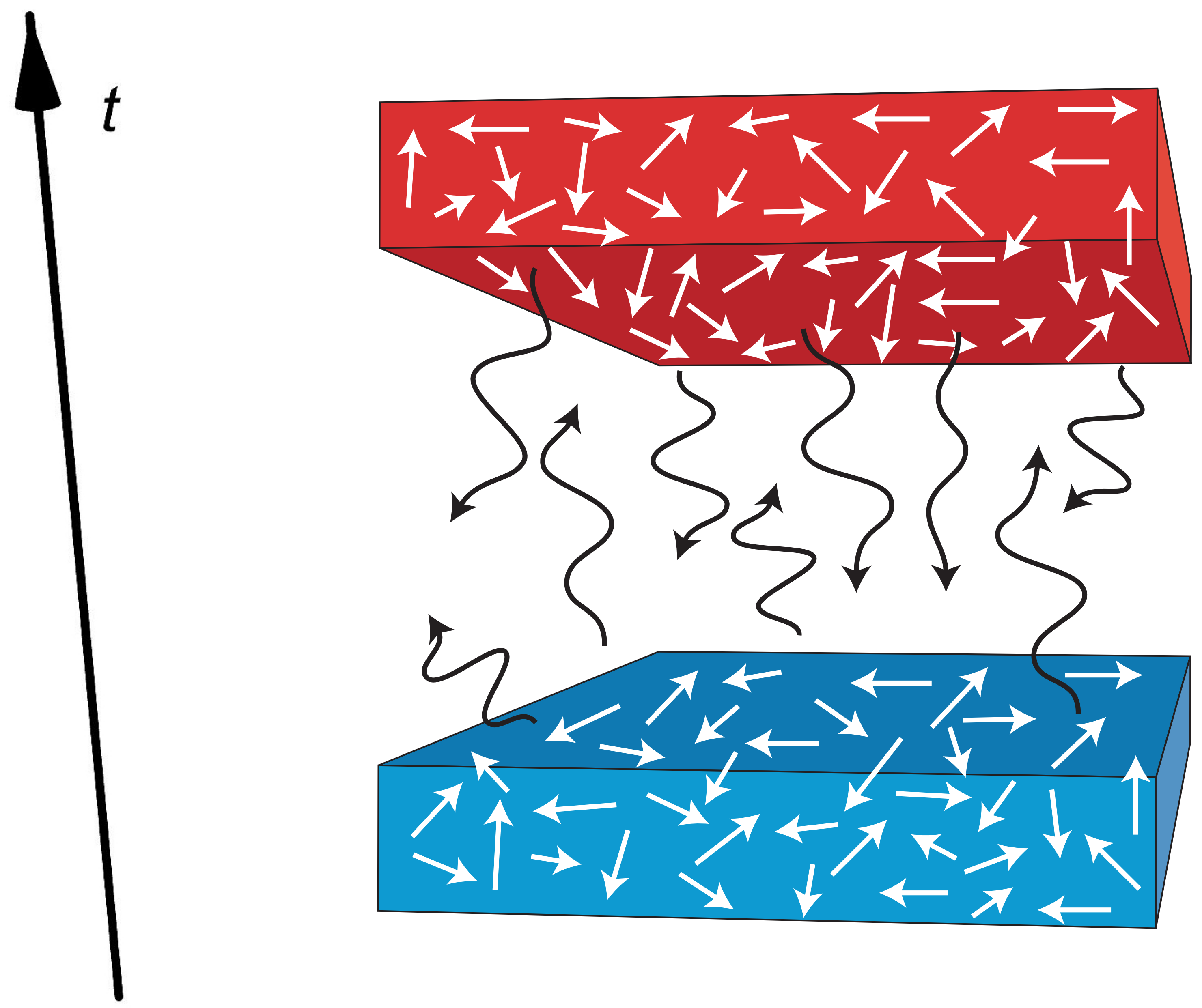
No gravity from the bare vacuum.


$\rho \approx 10^{-29}\, g\, cm^{-3}$
No evidence for the bare vacuum.
Neither does it do mechanical work nor gravitate.

Casimir cosmology: turn from space

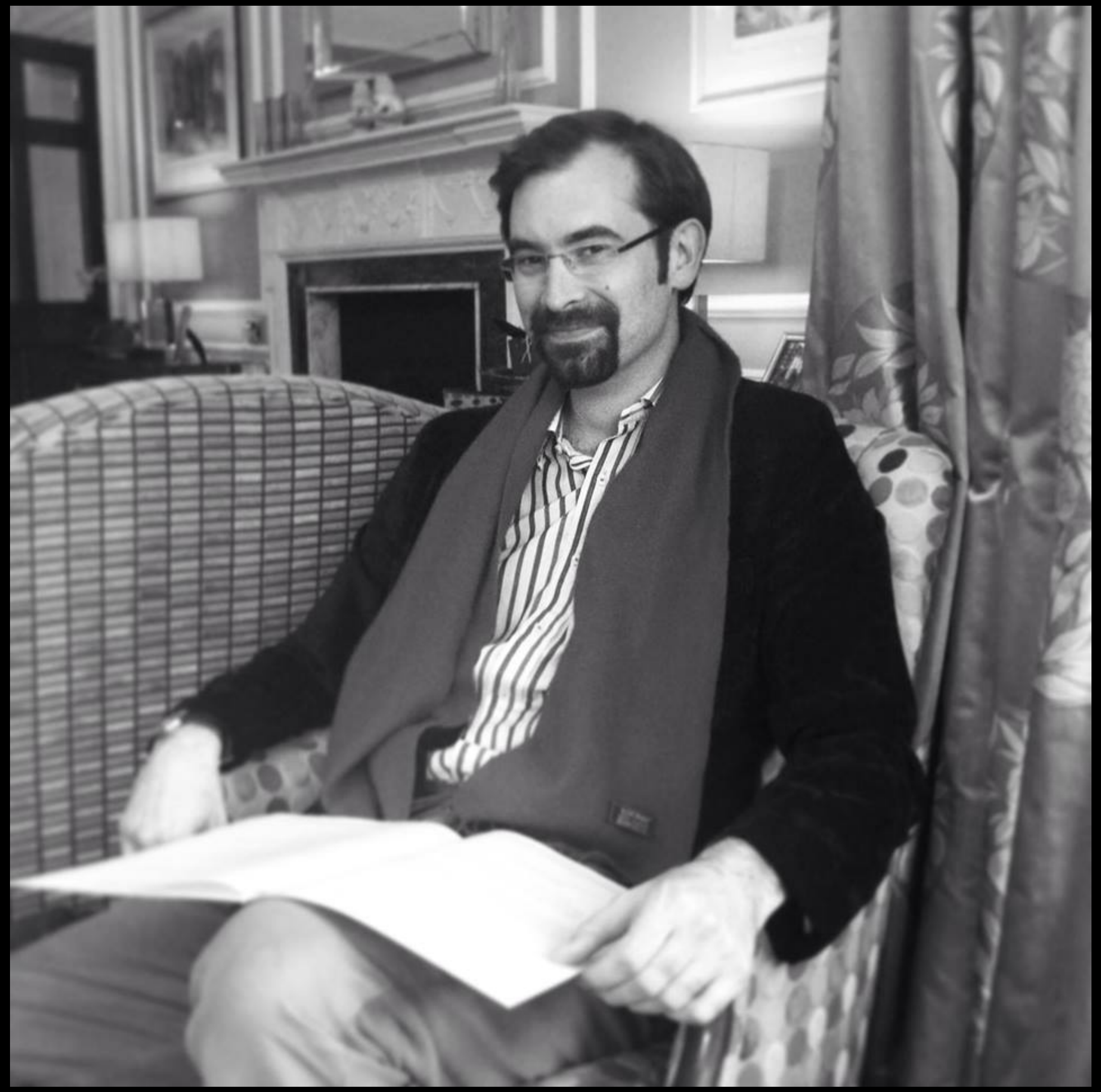


Casimir cosmology: turn from space to time



Casimir cosmology: continuous *n(t)*

Surprises in Casimir physics with three students and a postdoc



William Simpson
PhD student
2010-14

Itay Griniasty
PhD student
2013-19

Yael Avni
Masters
2015-17

Efi Shahmoon
postdoc
2014

Annals of Physics 411 (2019) 167973

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journal homepage: www.elsevier.com/locate/aop

Lifshitz theory of the cosmological constant

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A R T I C L E I N F O

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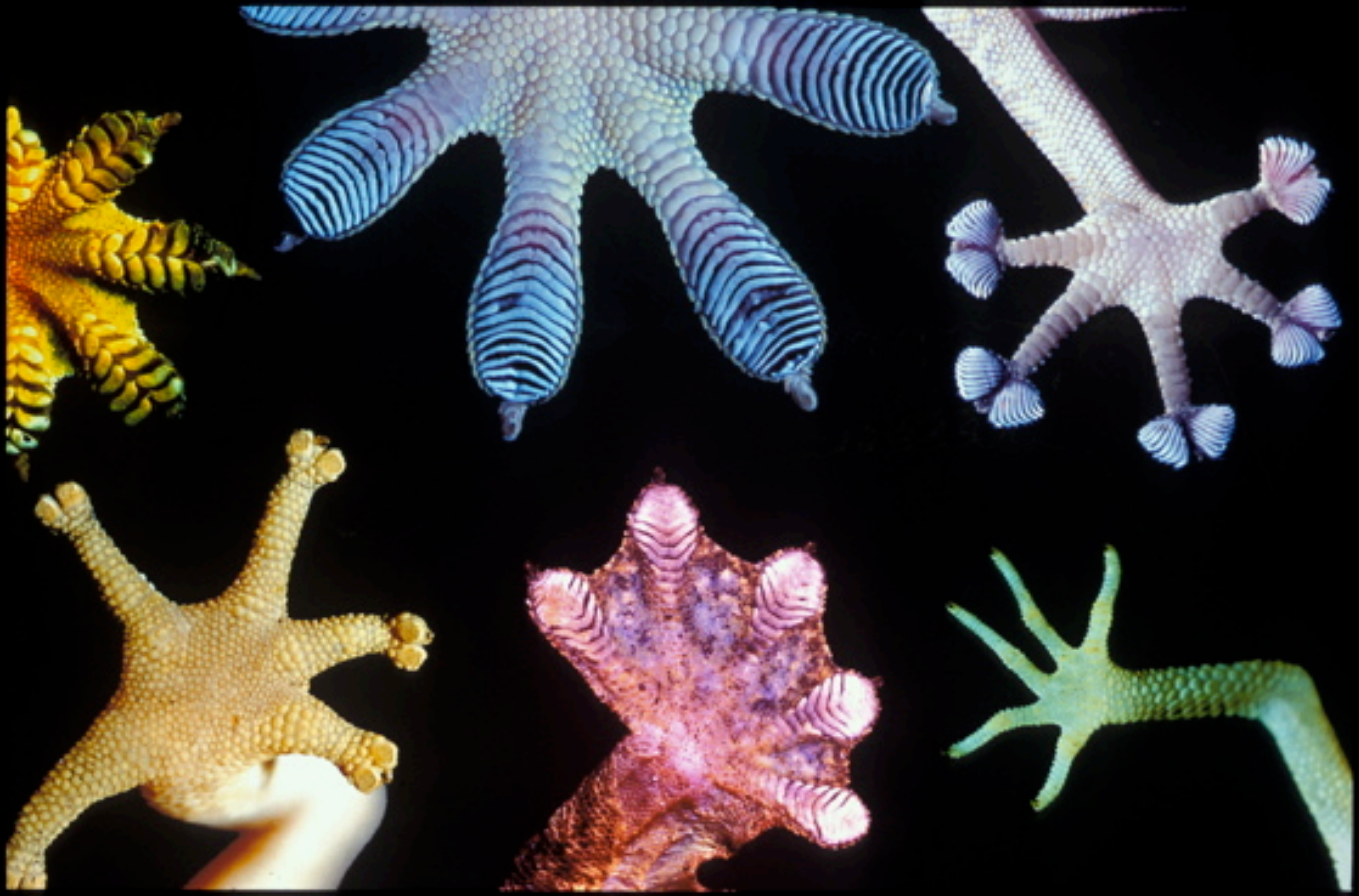
Dielectrics
Vacuum fluctuations
Dark energy

A B S T R A C T

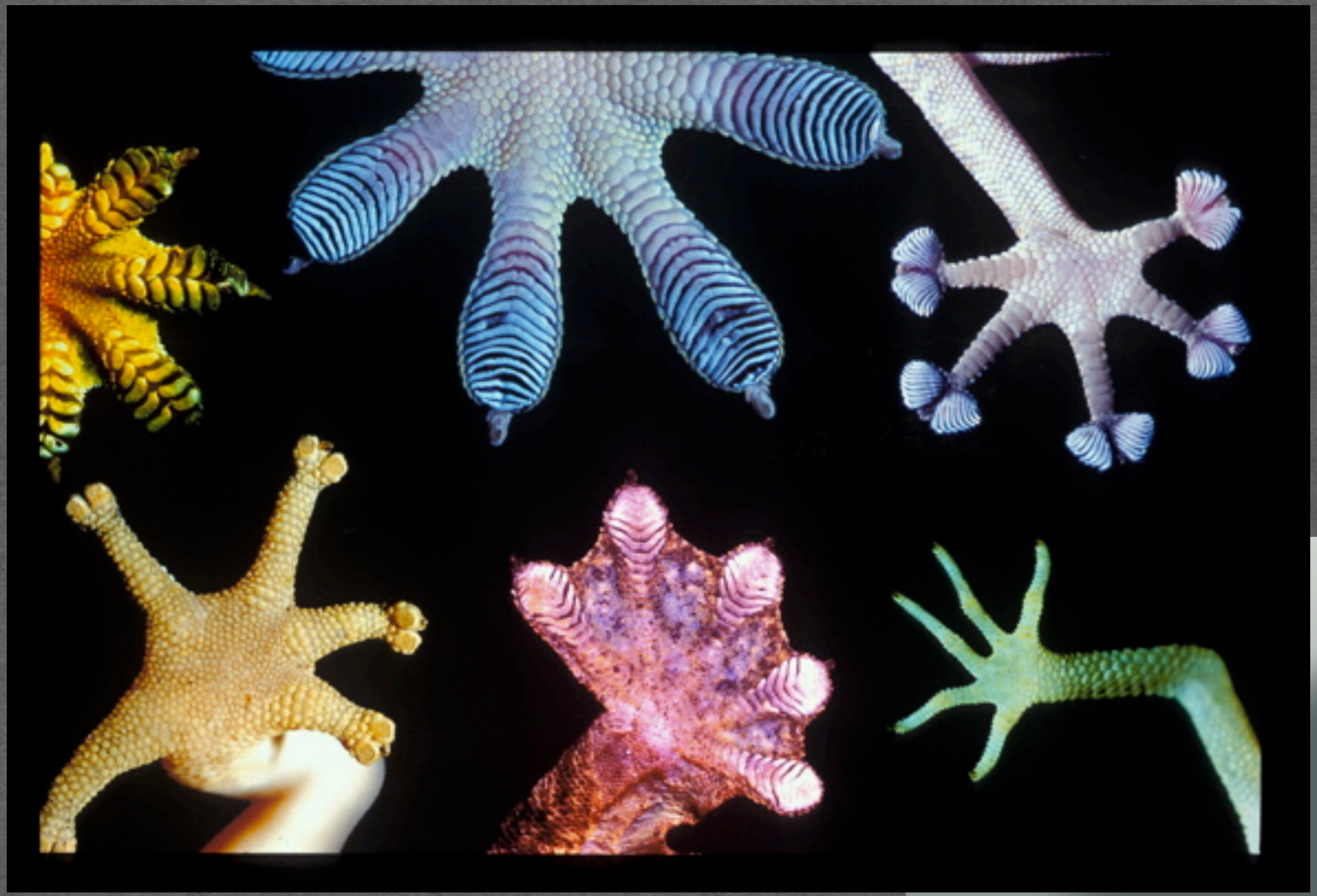
Astrophysics has given empirical evidence for the cosmological constant that accelerates the expansion of the universe. Atomic, Molecular, and Optical Physics have proven experimentally that the quantum vacuum exerts forces – the van der Waals and Casimir forces – on neutral matter. It has long been conjectured (Zel'dovich, 1968) that the two empirical facts, the cosmological constant and the Casimir force, have a common theoretical explanation, but all attempts of deriving both from a unified theory in quantitative detail have not been successful so far. In AMO Physics, Lifshitz theory has been the standard theoretical tool for describing the measured forces of the quantum vacuum. This paper develops a version of Lifshitz theory that also accounts for the electromagnetic contribution to the cosmological constant. Assuming that the other fields of the Standard Model behave similarly, gives a possible quantum-optical explanation for what has been called dark energy.

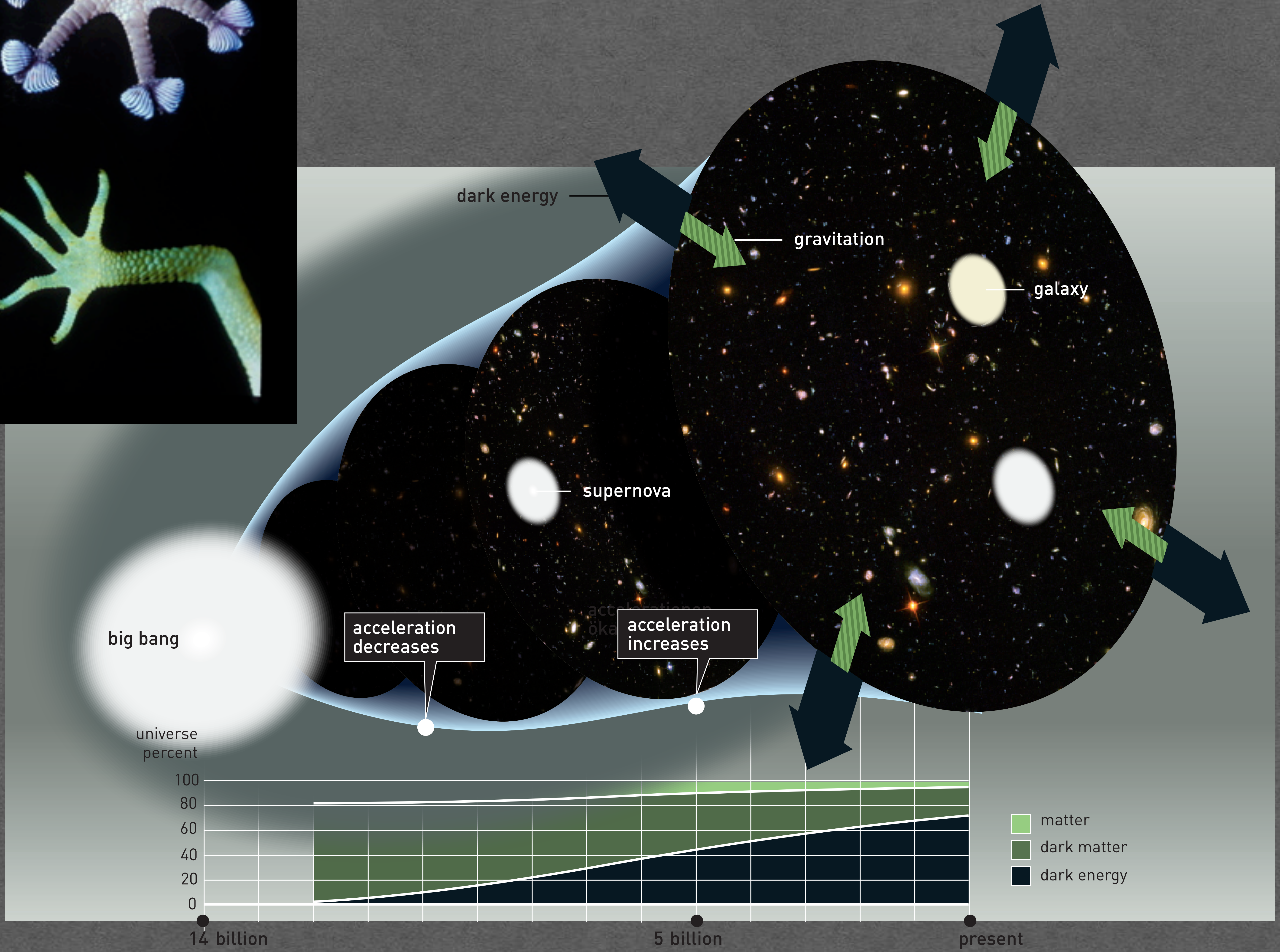
Two years of work in solitude

Casimir force in cosmology?

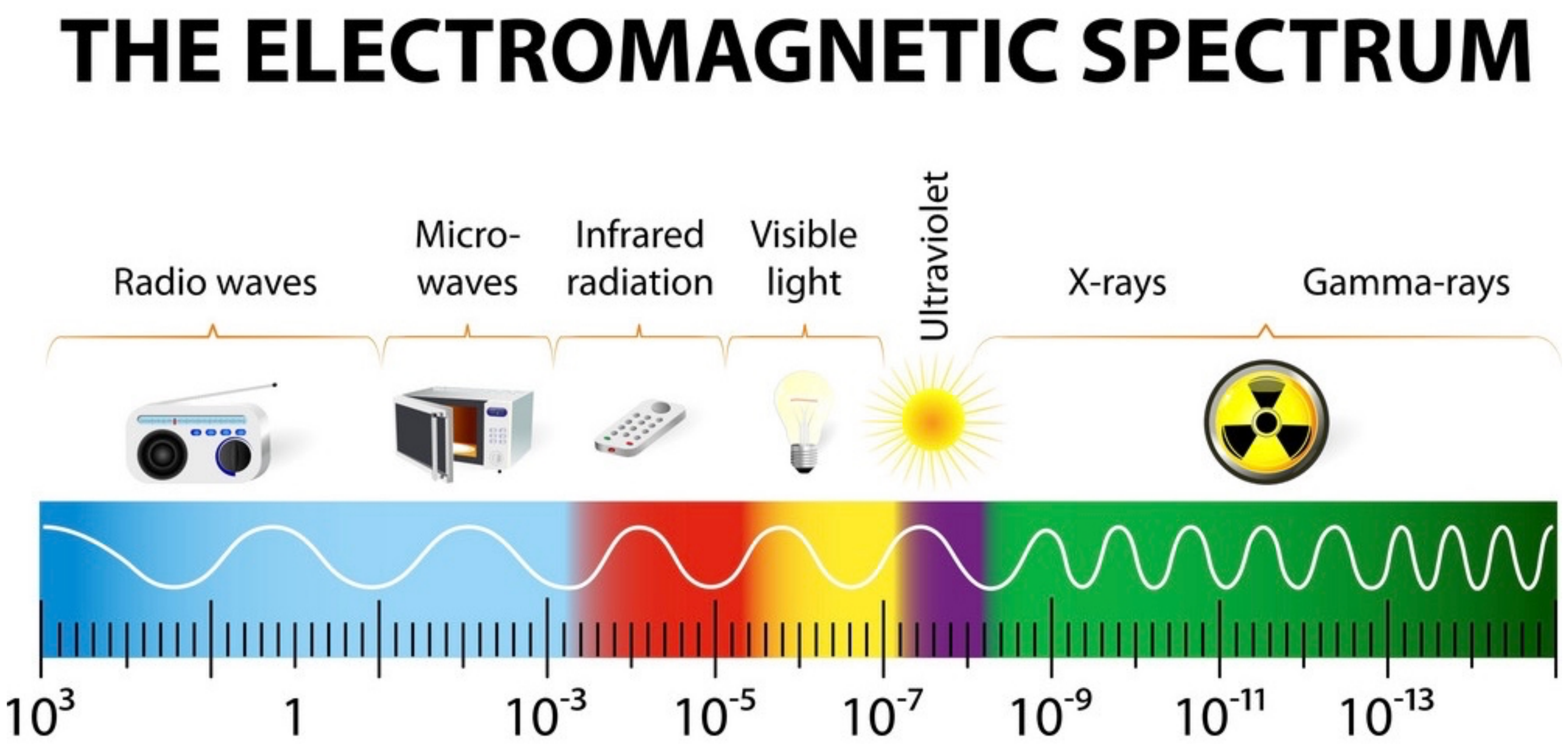


What's the difference?



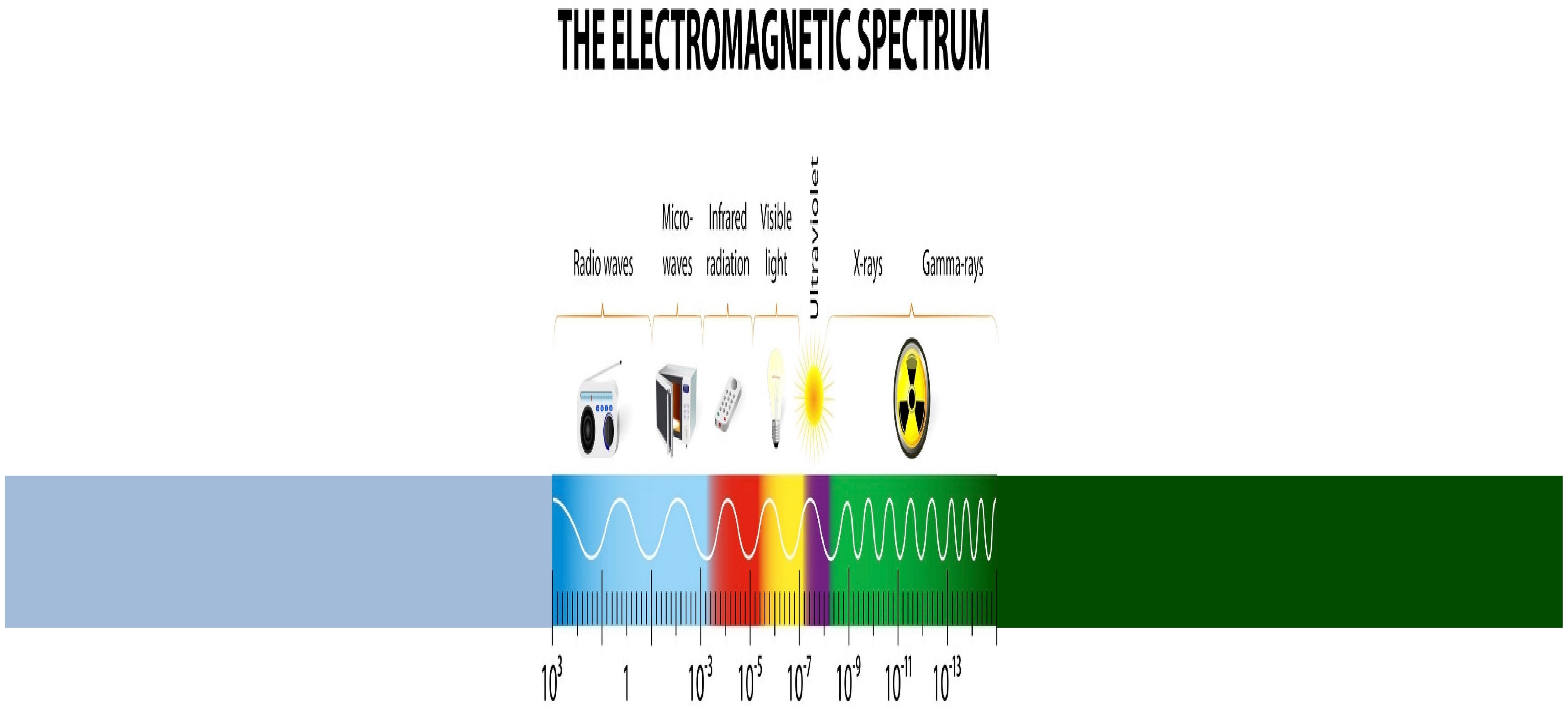


Equivalence principle: space-time is the same for everything



Equivalence principle: space-time is the same for everything

Horizon



Planck

The result(s)

$$\frac{4\pi G}{3c^2}\varepsilon_{VAC} = -\alpha_\Delta \Delta \quad , \quad \alpha_\Delta \sim \frac{1}{9\pi}$$

$$\Delta = \partial_t^3 \frac{1}{H} + H\partial_t^2 \frac{1}{H}$$

UL, Ann. Phys. (NY) **411**, 167972 (2019)

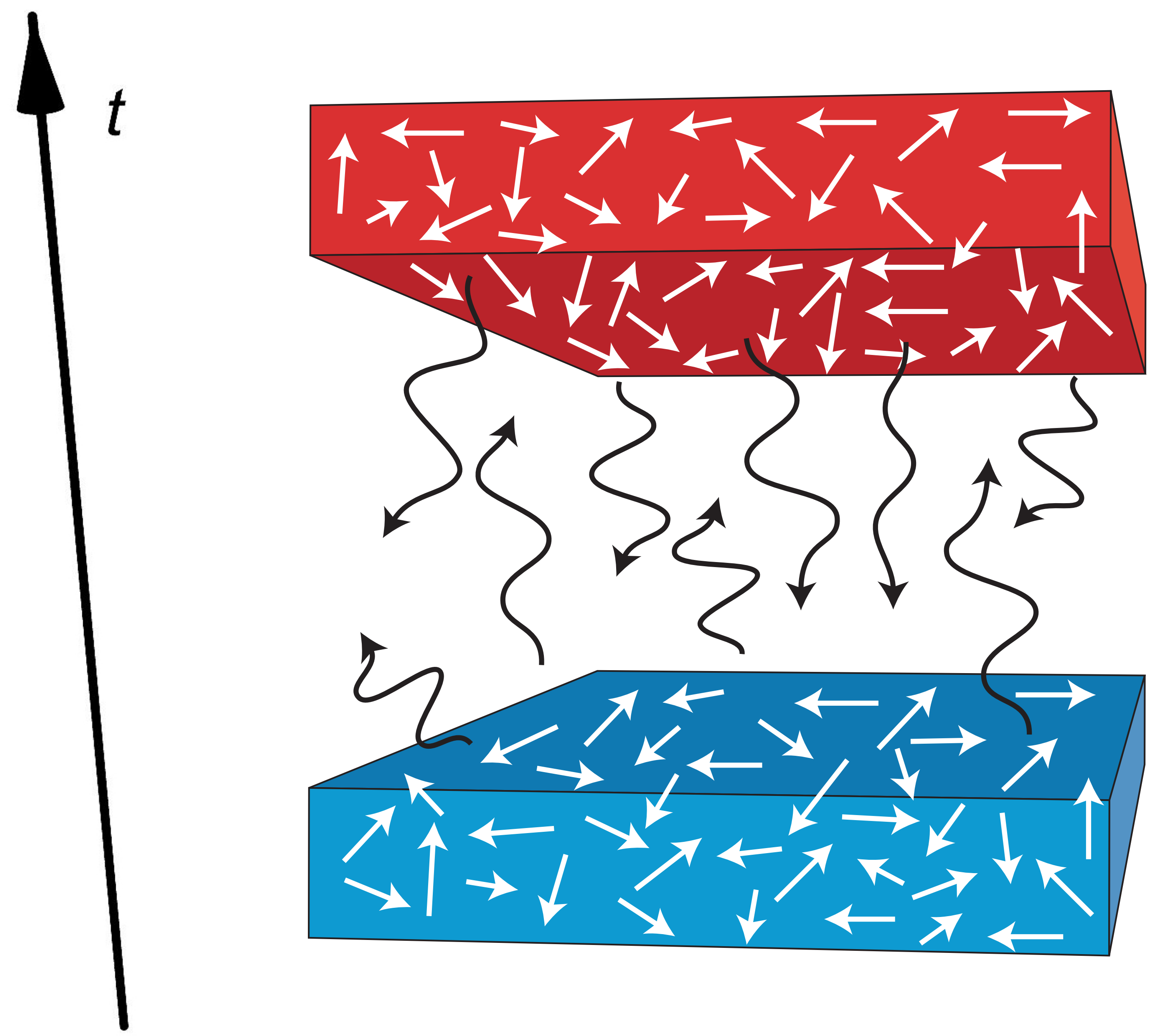
$$\Delta = \partial_t^3 \frac{1}{H}$$

D. Berechya & UL, MNRAS **507,** 3473 (2021)

$$\Delta = \partial_t^3 \left(\frac{1}{H} - \frac{a}{a_{-1}H_{-1}}\right)$$

UL 2022

Renormalised vacuum energy depends on changes in n



The anomaly

PHYSICAL REVIEW D VOLUME 17, NUMBER 6 15 MARCH 1978

Trace anomaly of a conformally invariant quantum field in curved spacetime

Robert M. Wald

Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

(Received 19 August 1977)

Energy conservation: a thermodynamic argument

$$dE = -p\,dV = d(\varepsilon V) = V\,d\varepsilon + \varepsilon\,dV$$

Energy conservation: a thermodynamic argument

$$dE = -p\,dV = d(\varepsilon V) = V\,d\varepsilon + \varepsilon\,dV$$

$$\frac{dV}{V} = 3\frac{da}{a} \Rightarrow \quad d\varepsilon = -3(\varepsilon + p)\,da$$

Energy conservation: a thermodynamic argument

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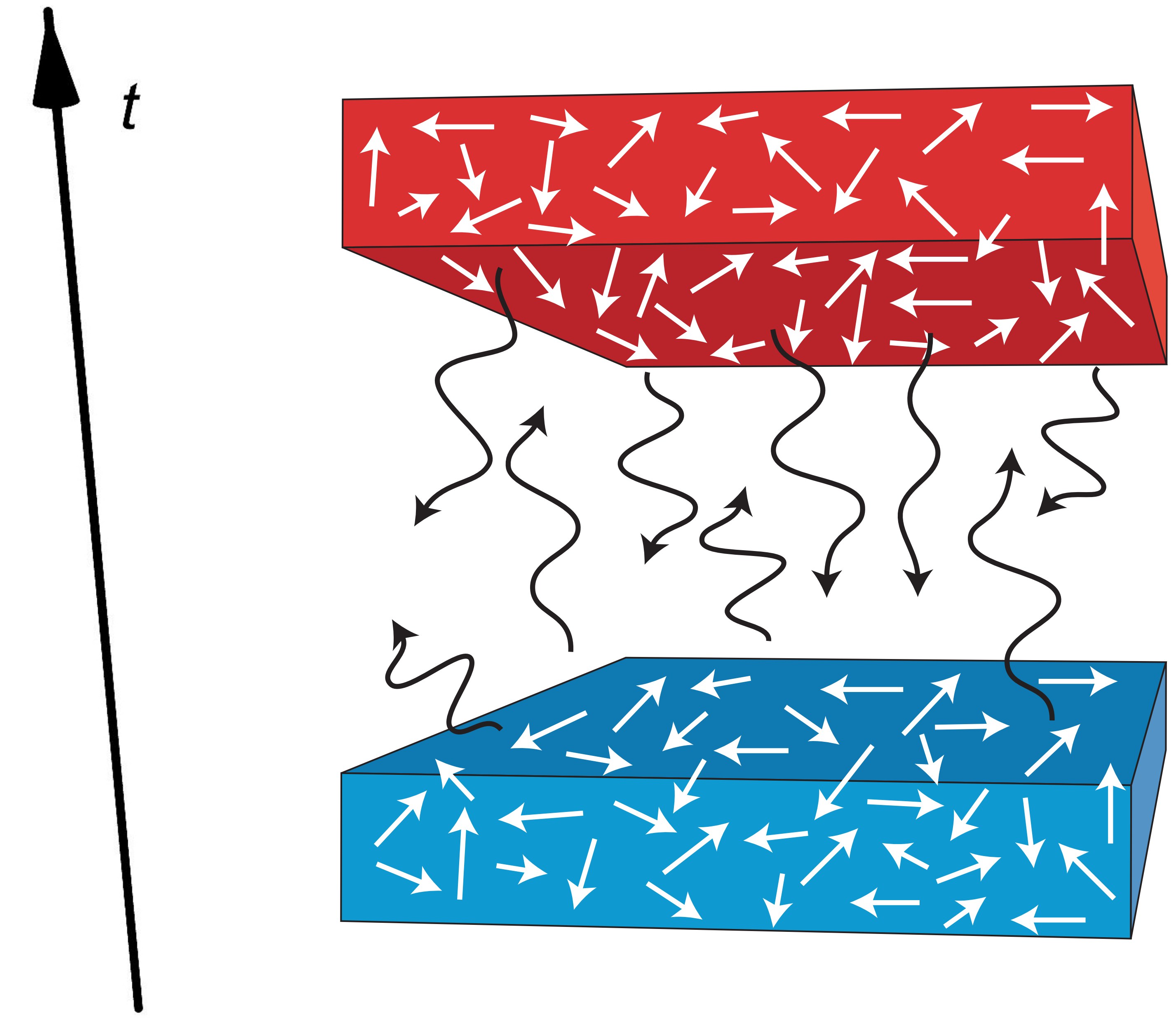
Friedman

The anomaly: a thermodynamic argument



$$\dot{\varepsilon} = -3H(\varepsilon + p)$$

$$\varepsilon = \varepsilon_{VAC} + \varepsilon_{\Delta}\,, \quad p_{\Delta} = -\varepsilon_{\Delta}$$

Casimir cosmology: astrophysics, analogues & more

Dror Berechya

Masters 2020

PhD student

2021-

Itai Efrat

Masters

2019-21

Nikolay Ebel

Masters

2020-

PHYSICAL REVIEW B **104**, 235432 (2021)

Editors' Suggestion

Van der Waals anomaly: Analog of dark energy with ultracold atoms

Itai Y. Efrat and Ulf Leonhardt

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 761001, Israel

Comparison with astronomical data

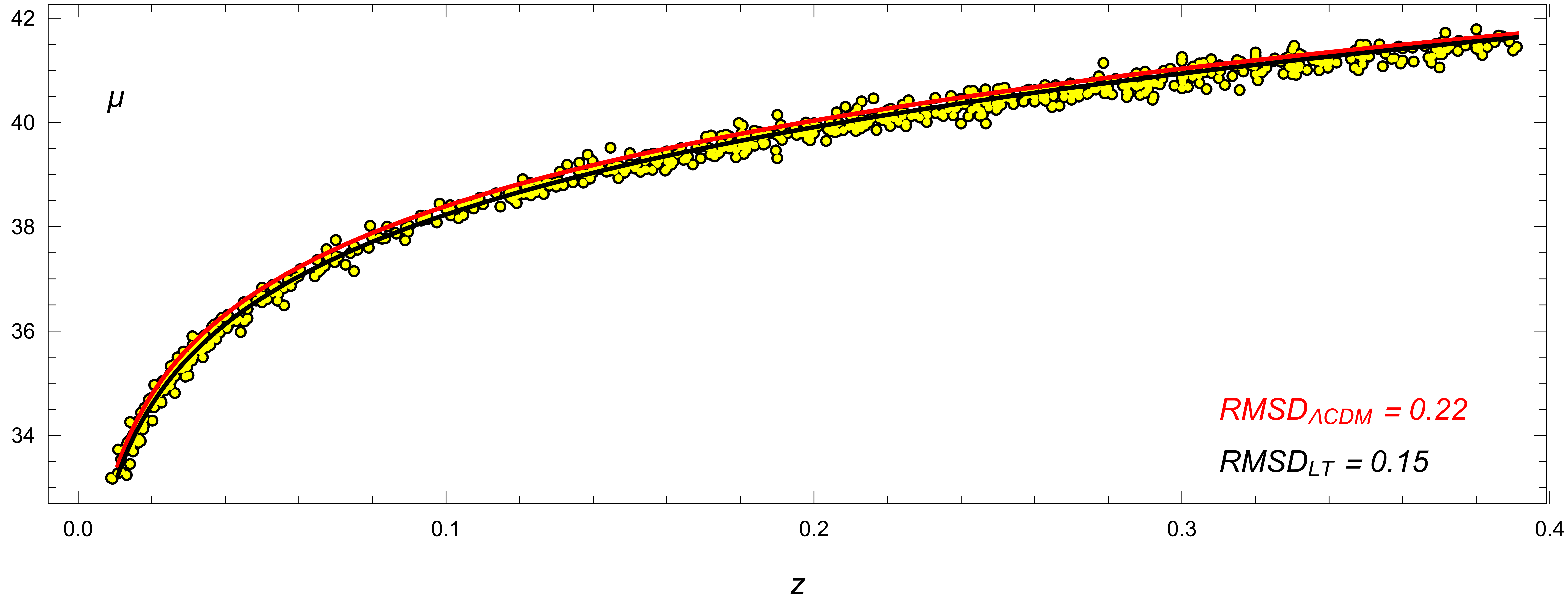
MNRAS **507,** 3473–3485 (2021)
Advance Access publication 2021 August 6
https://doi.org/10.1093/mnras/stab2345

Lifshitz cosmology: quantum vacuum and Hubble tension

Dror Berechya ★ and Ulf Leonhardt★
Weizmann Institute of Science, Rehovot 7610001, Israel

Accepted 2021 August 9. Received 2021 June 15; in original form 2020 November 24

Comparison with Pantheon supernova data



Hubble diagram

Casimir cosmology: continuous $n(t)$, varying Λ

meeting report

COSMOLOGY

Tensions between the early and late Universe

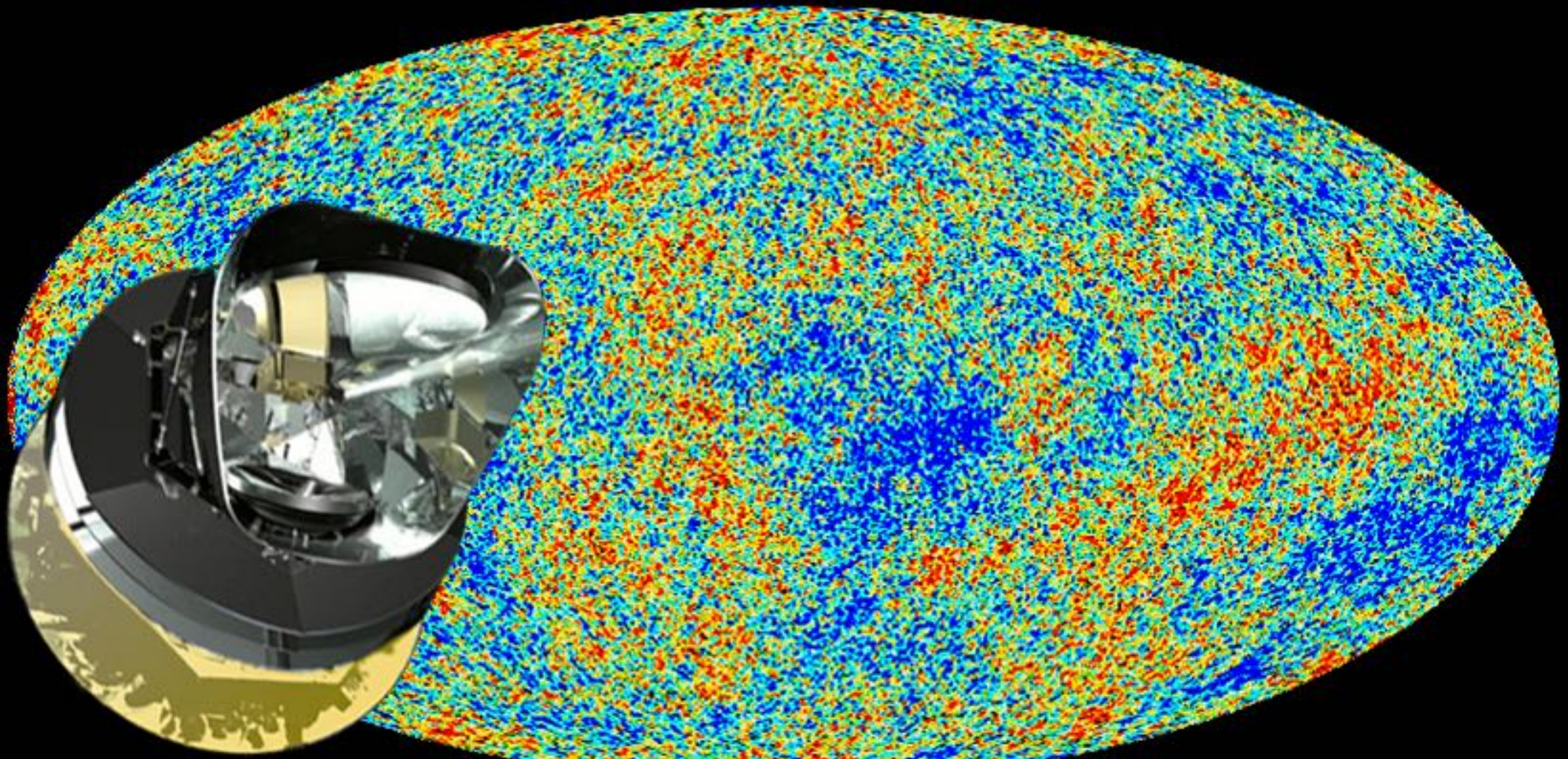
A Kavli Institute for Theoretical Physics workshop in July 2019 directed attention to the Hubble constant discrepancy. New results showed that it does not appear to depend on the use of any one method, team or source. Proposed solutions focused on the pre-recombination era.

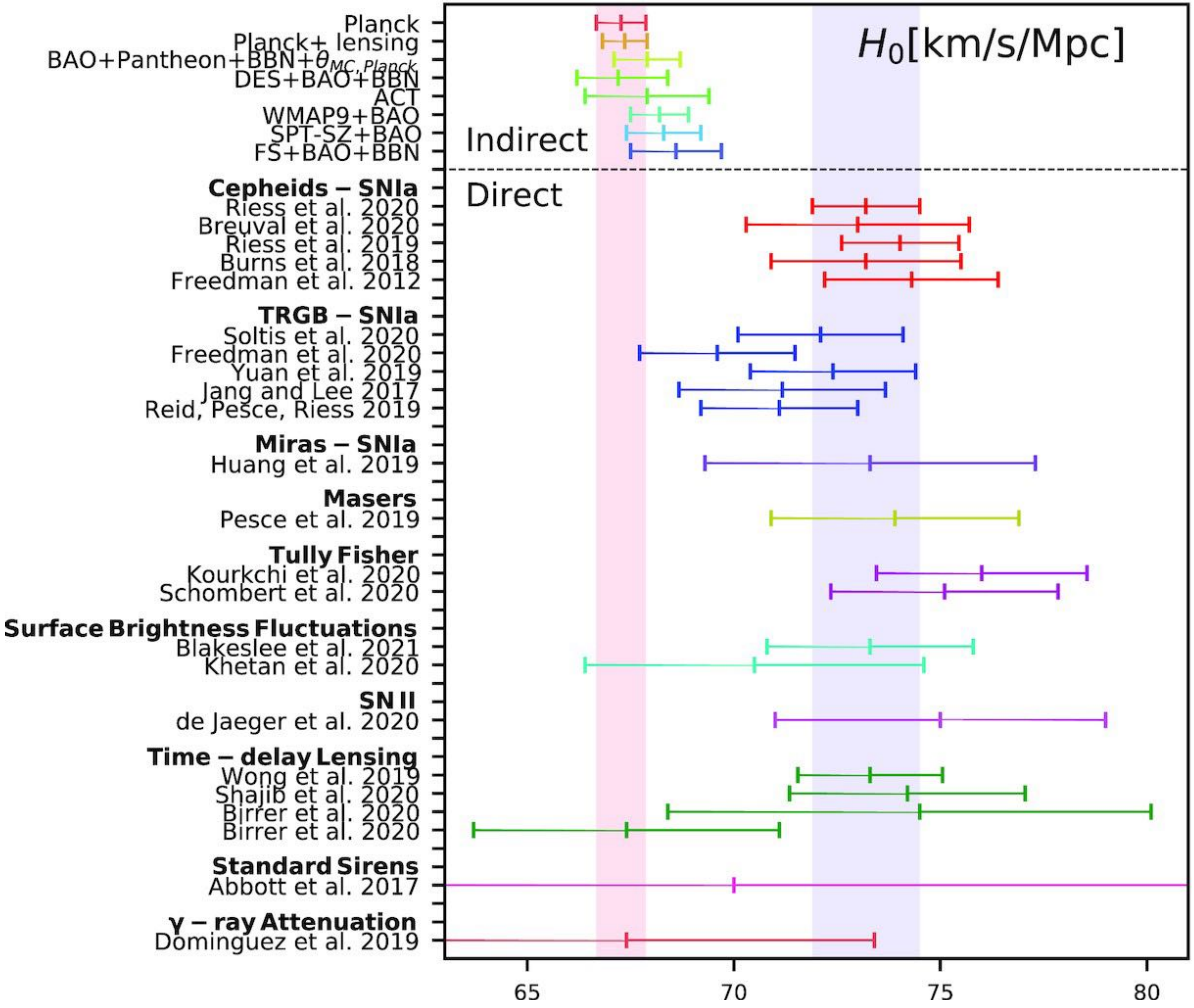
A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the *Hubble Space Telescope* and the SH0ES Team

Adam G. Riess,[1,2] Wenlong Yuan,[2] Lucas M. Macri,[3] Dan Scolnic,[4] Dillon Brout,[5] Stefano Casertano,[1] David O. Jones,[6] Yukei Murakami,[2] Gagandeep S. Anand,[1] Louise Breuval,[2] Thomas G. Brink,[7] Alexei V. Filippenko,[7,8] Samantha Hoffmann,[1] Saurabh W. Jha,[9] W. D'arcy Kenworthy,[2] John Mackenty,[1] Benjamin E. Stahl,[7] and Weikang Zheng[7]

arXiv:2112.04510

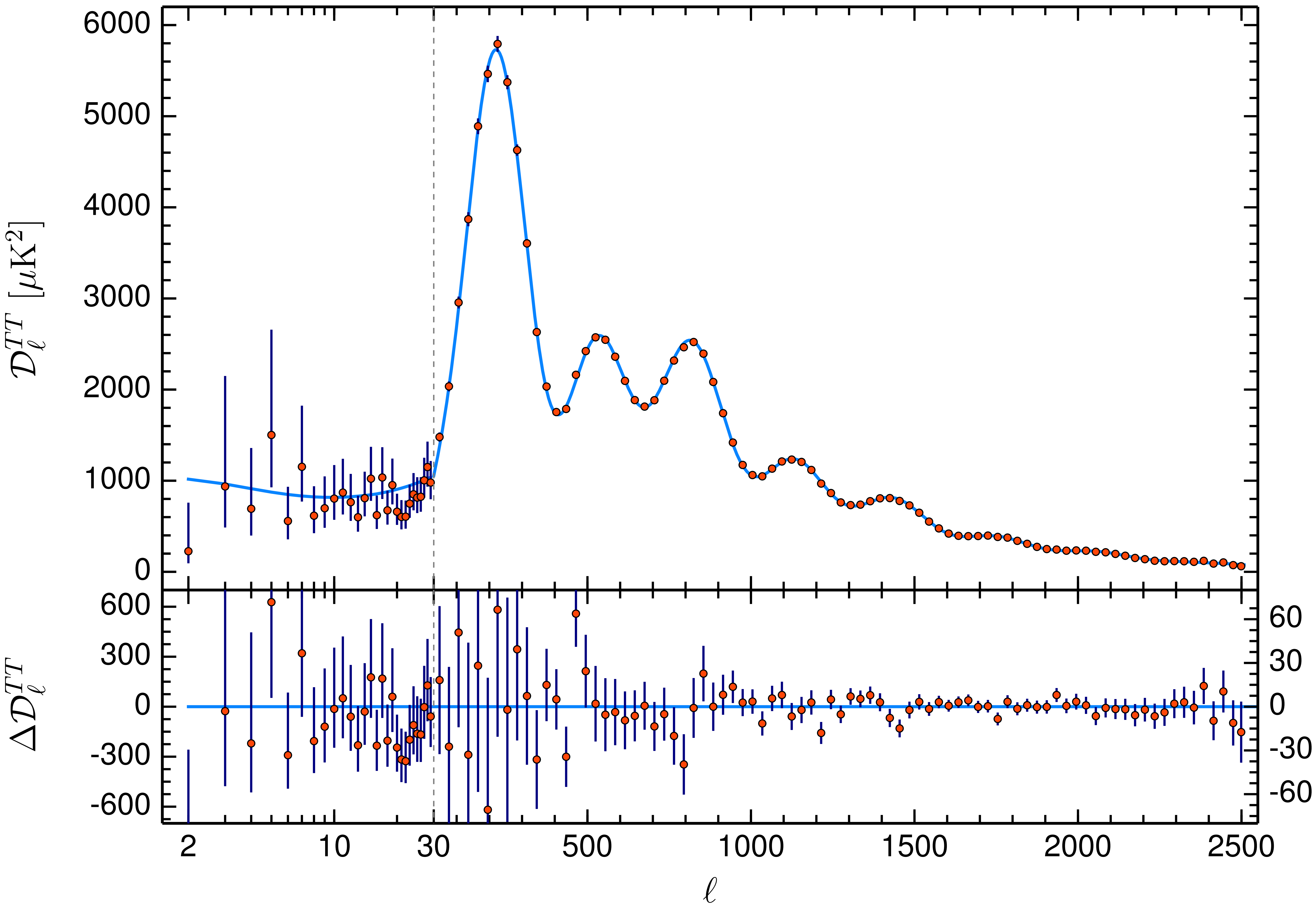
Indirect determination of Hubble constant from Cosmic Microwave Background

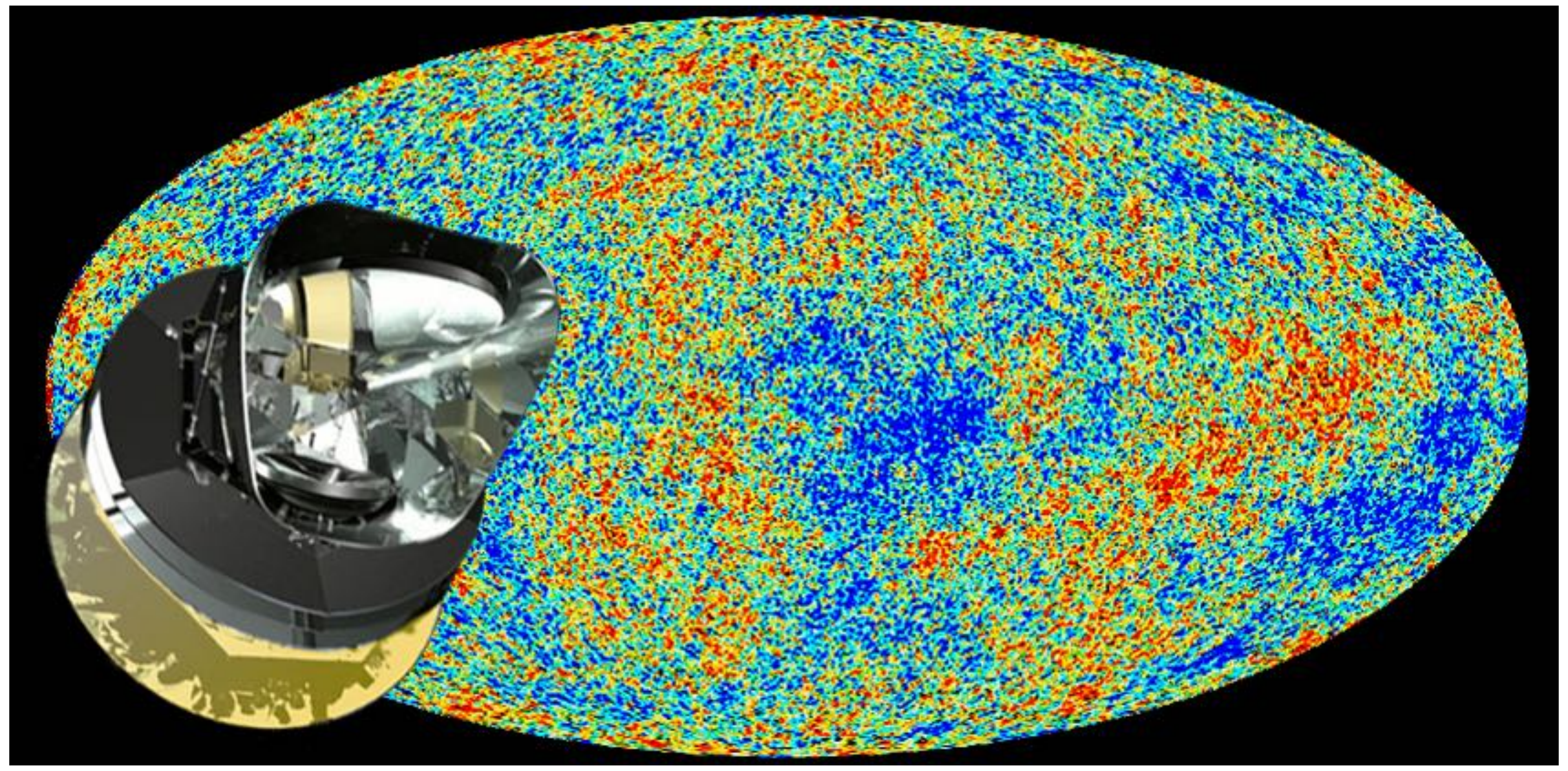




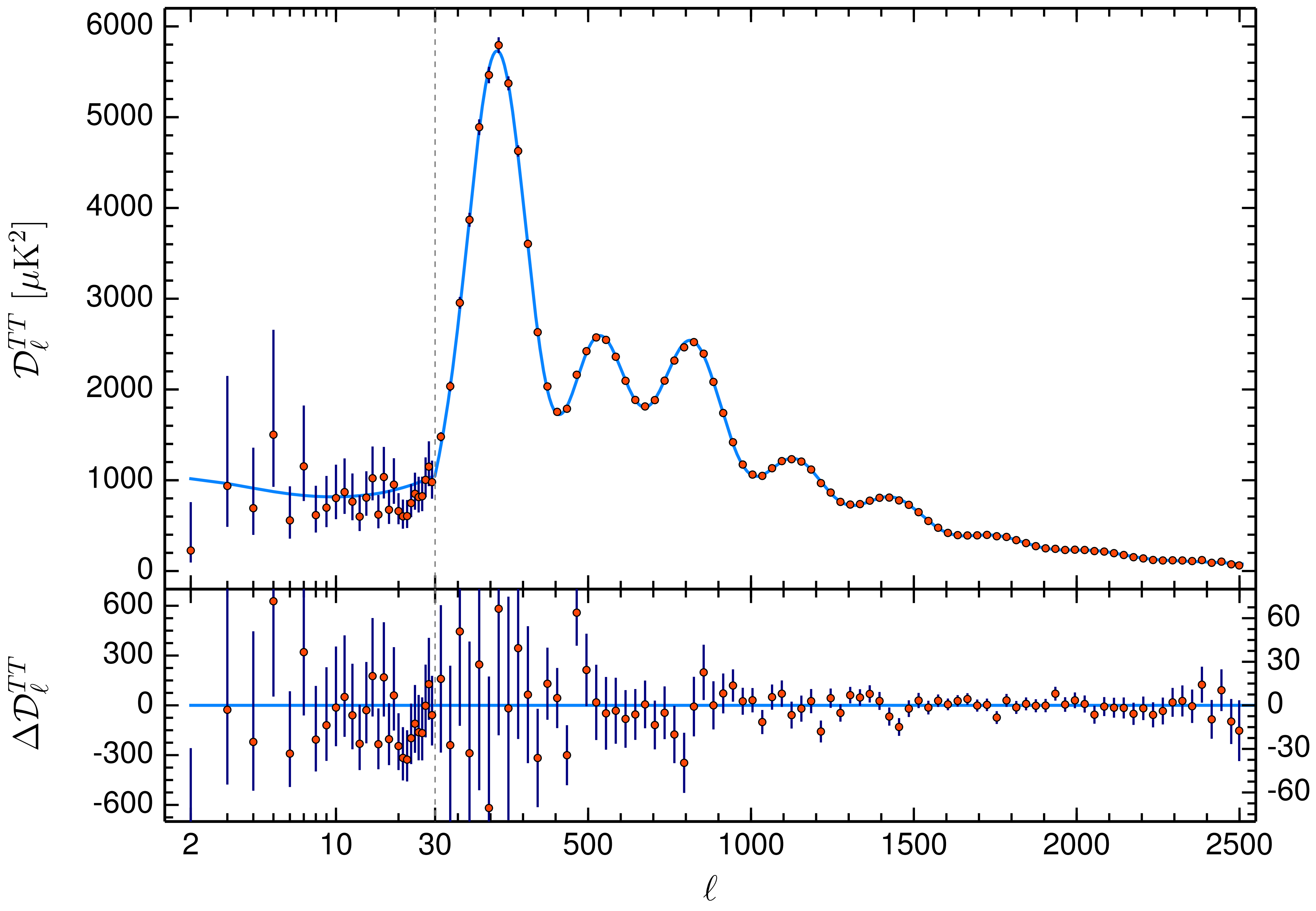
E. Di Valentino, MNRAS **502**, 2065 (2021)

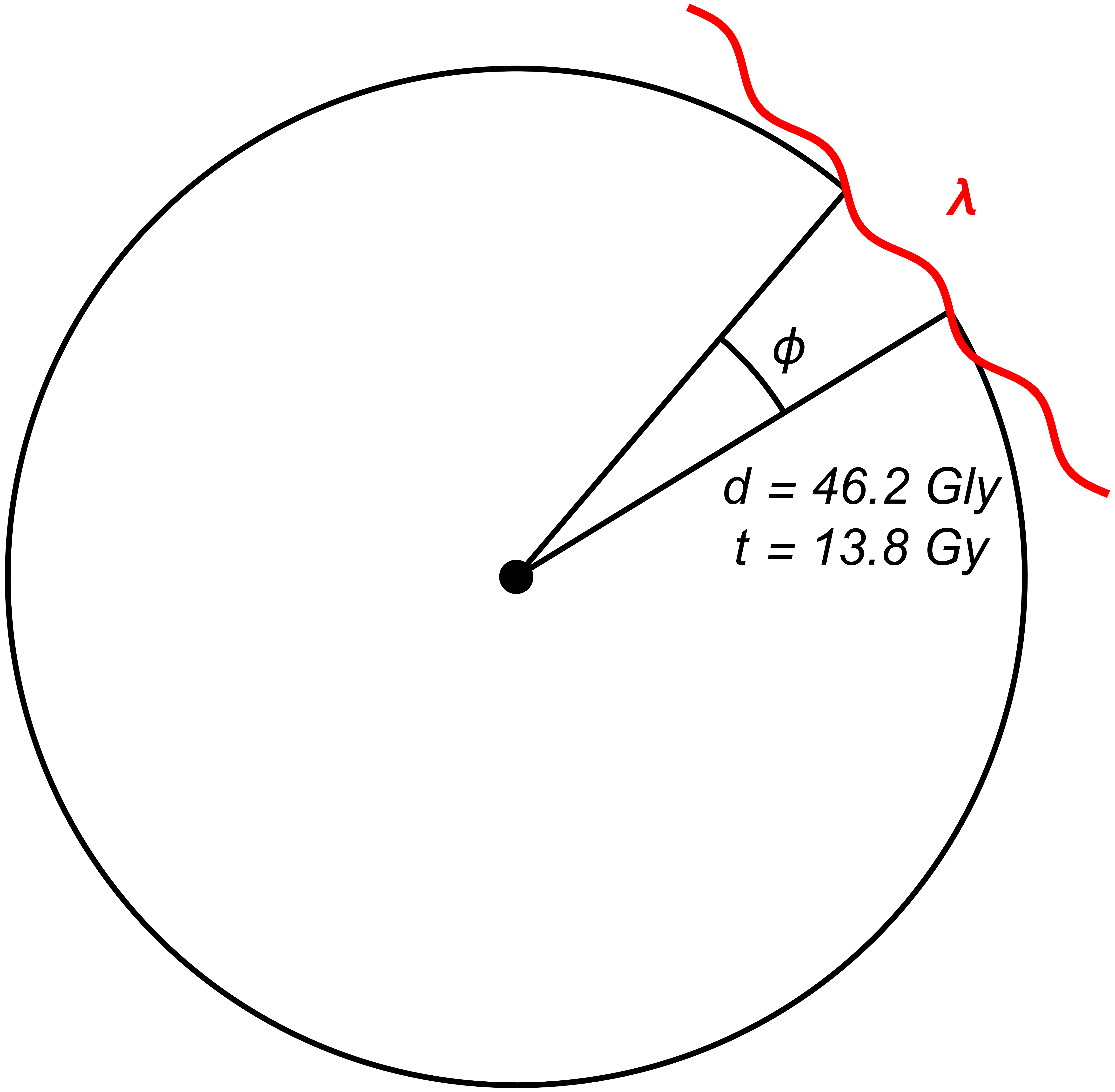
Correlations in the Cosmic Microwave Background



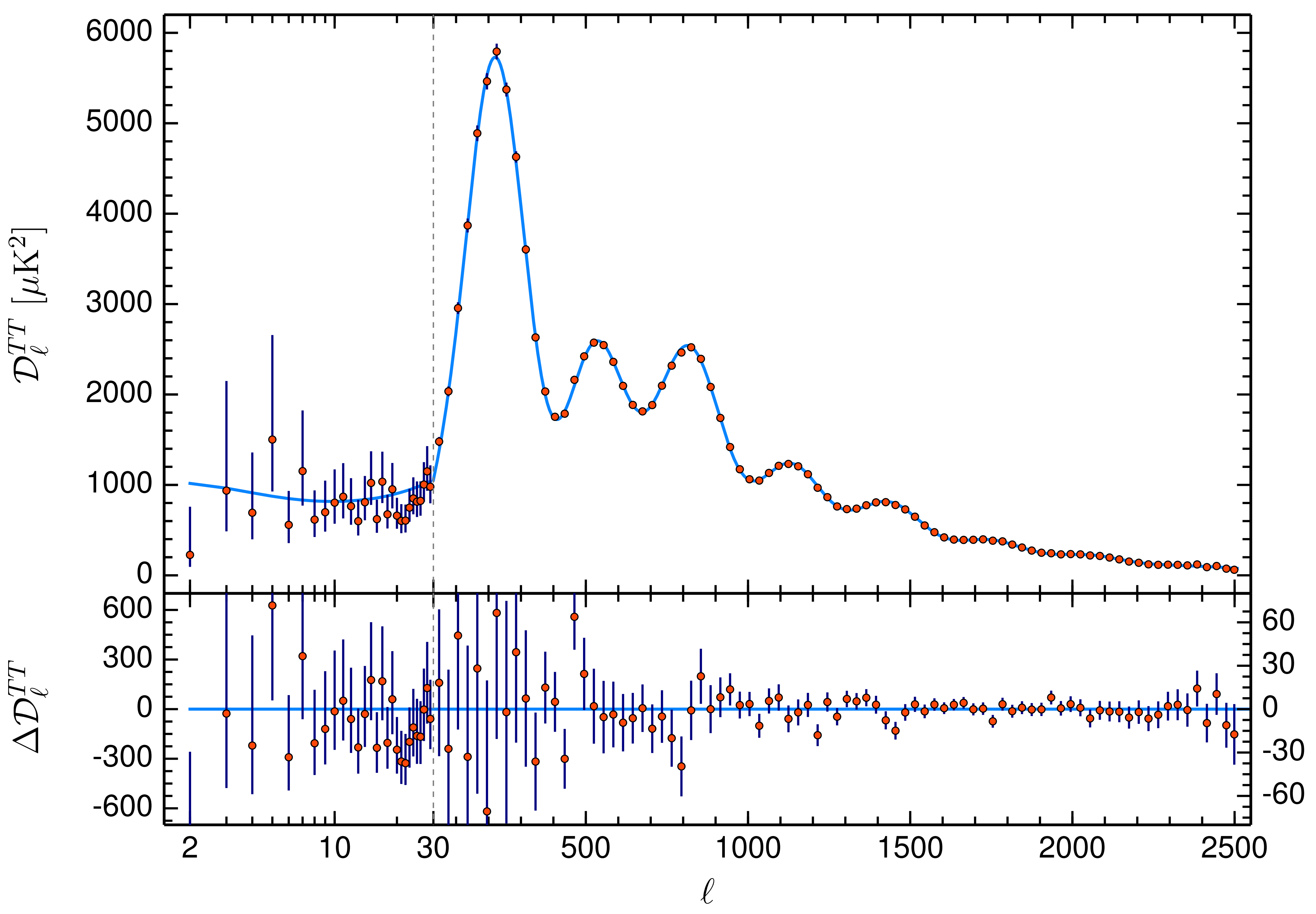


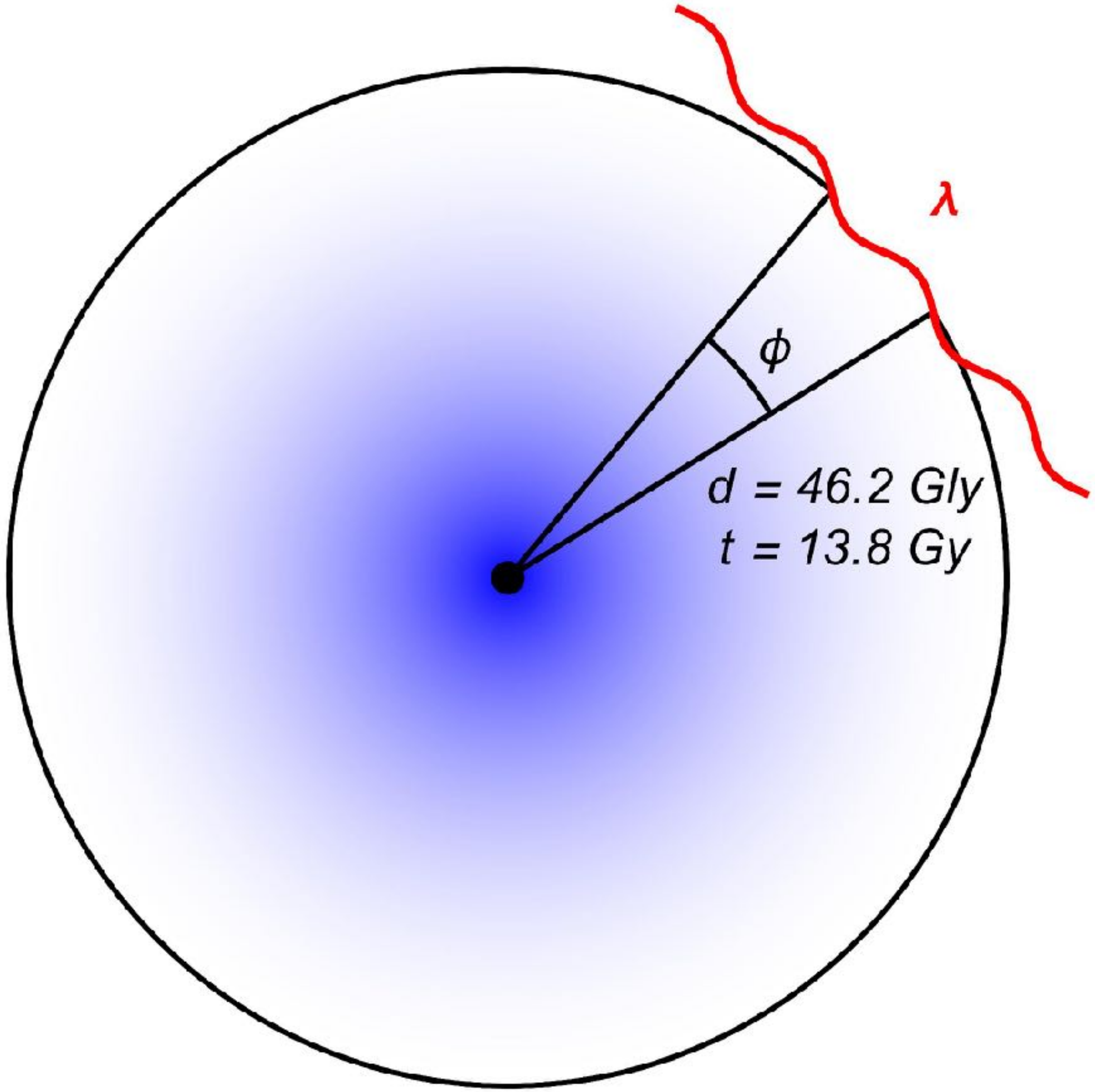
Correlations in the Cosmic Microwave Background



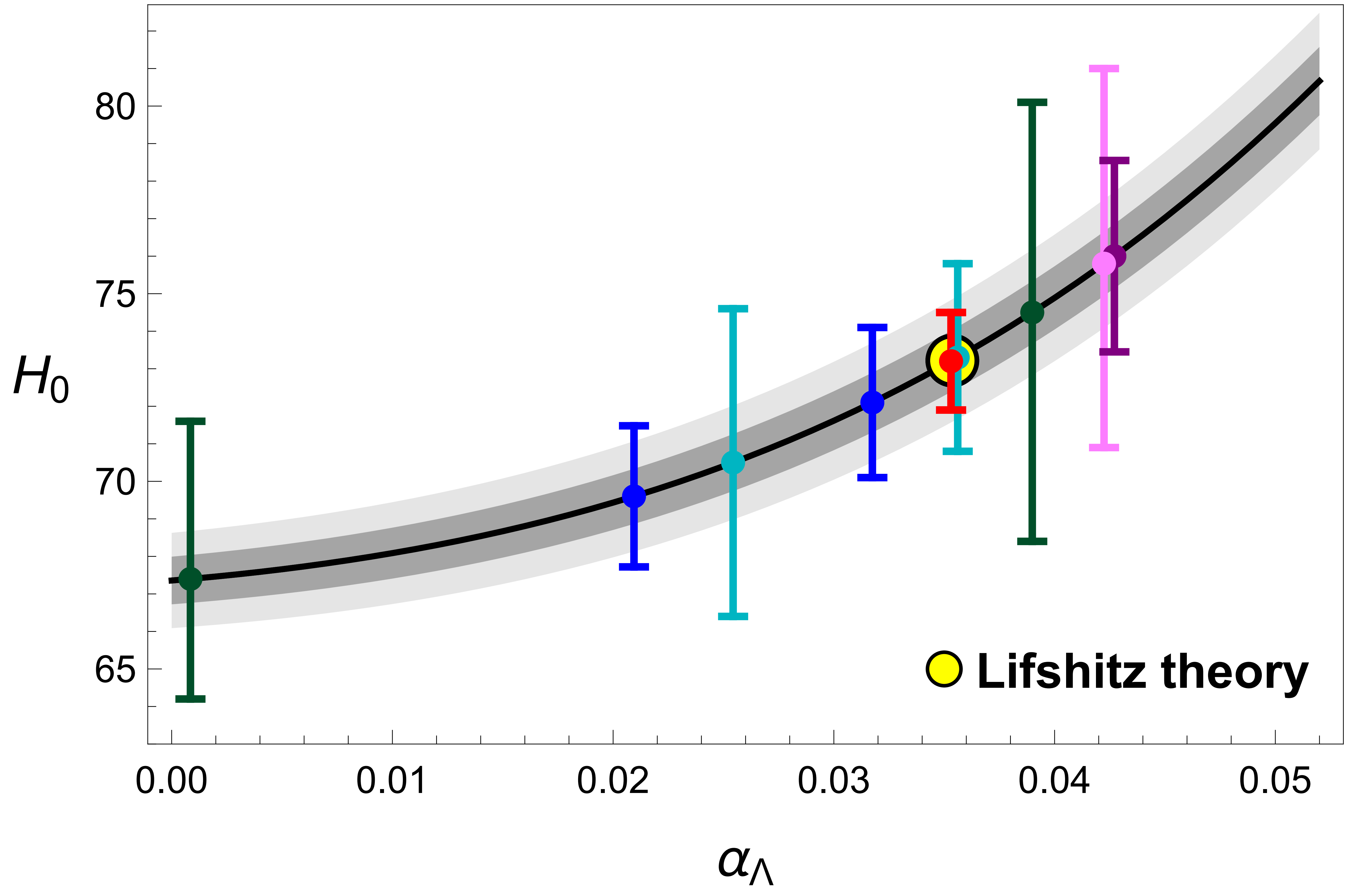


Correlations in the Cosmic Microwave Background





Observed Hubble constant is consistent with Lifshitz theory



Direct measurements of H_0 usinge various metods:

Cepheids – SN Ia   TRGB – SN Ia   Tully Fisher

SBF   SN II   Time–delay Lensing

10^2 theories

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Classical and Quantum Gravity

Class. Quantum Grav. **38** (2021) 153001 (110pp) https://doi.org/10.1088/1361-6382/ac086d

Topical Review

In the realm of the Hubble tension—a review of solutions*

Eleonora Di Valentino[1,], Olga Mena[2], Supriya Pan[3], Luca Visinelli[4], Weiqiang Yang[5], Alessandro Melchiorri[6], David F Mota[7], Adam G Riess[8,9] and Joseph Silk[8,10,11]**

10^2 theories, new fields, new GR, new cosmology

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Class. Quantum Grav. **38** (2021) 153001 (110pp)
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No new fields.

No new fields, but new ideas in fields as old as QED

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Why only QED?

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Experimental tests?

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Astronomical tensions?

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Astronomical tensions?

Renormalization?

No new fields, but new ideas in fields as old as QED

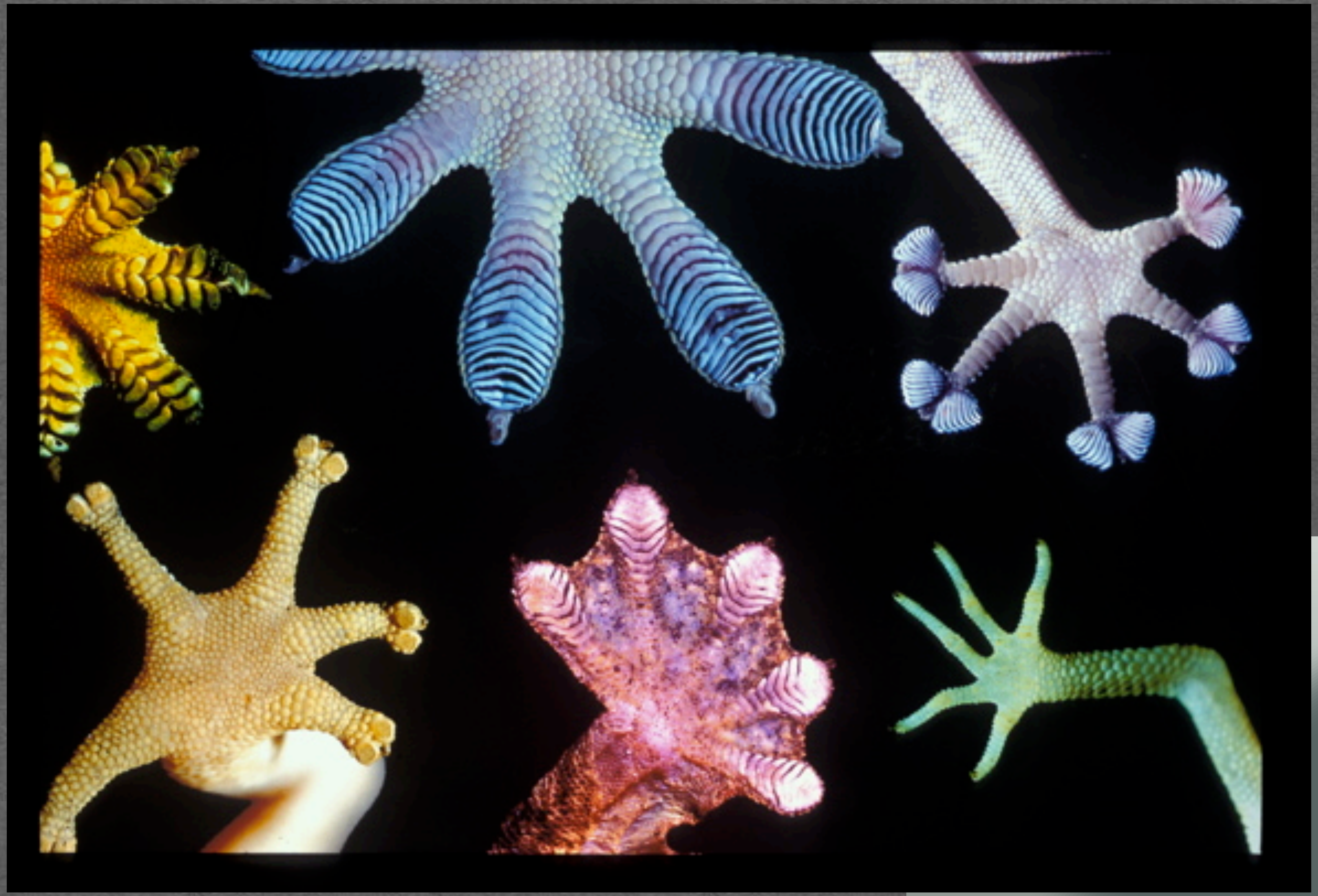
Why only QED?

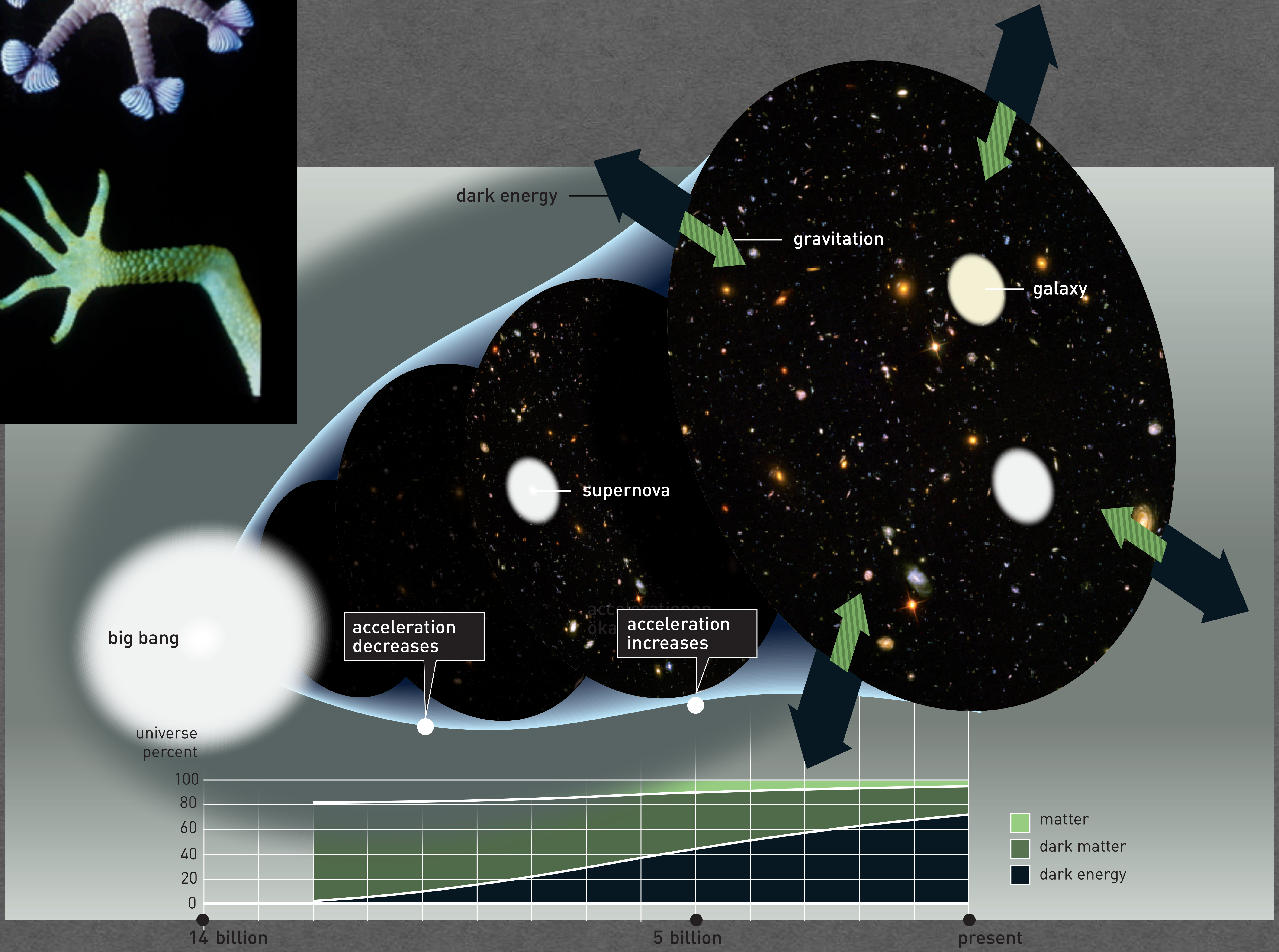
Experimental tests?

Astronomical tensions?

Renormalization?

...





dark energy
gravitation
galaxy
supernova
big bang
acceleration decreases
acceleration increases
universe percent
100
80
60
40
20
0
14 billion
5 billion
present
matter
dark matter
dark energy

Let there be light!