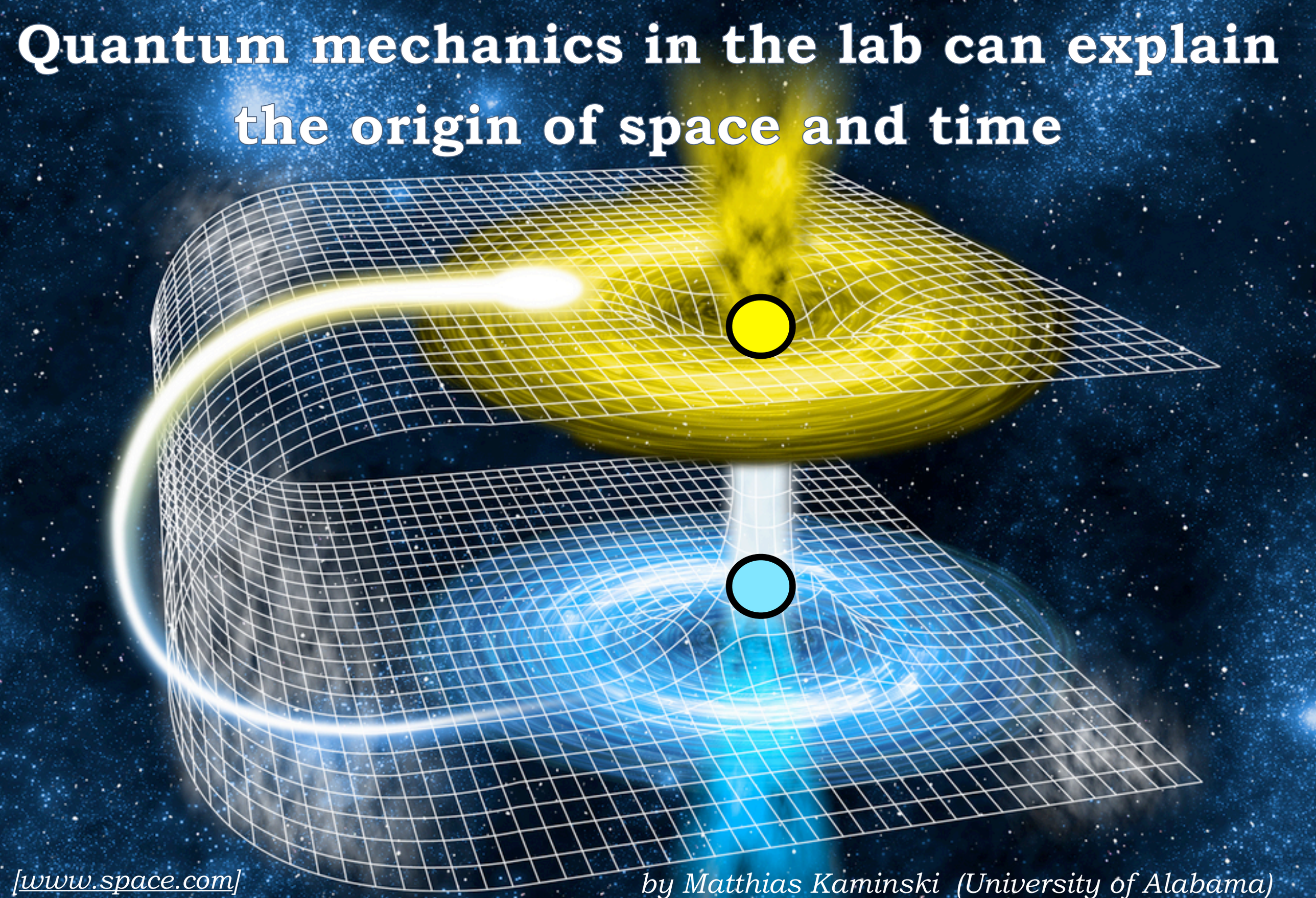
Quantum mechanics in the lab can explain the origin of space and time



[www.space.com]

by Matthias Kaminski (University of Alabama)

SCIAS Guest Lectures, Welz-Haus, Würzburg, Germany, May 28th, 2024

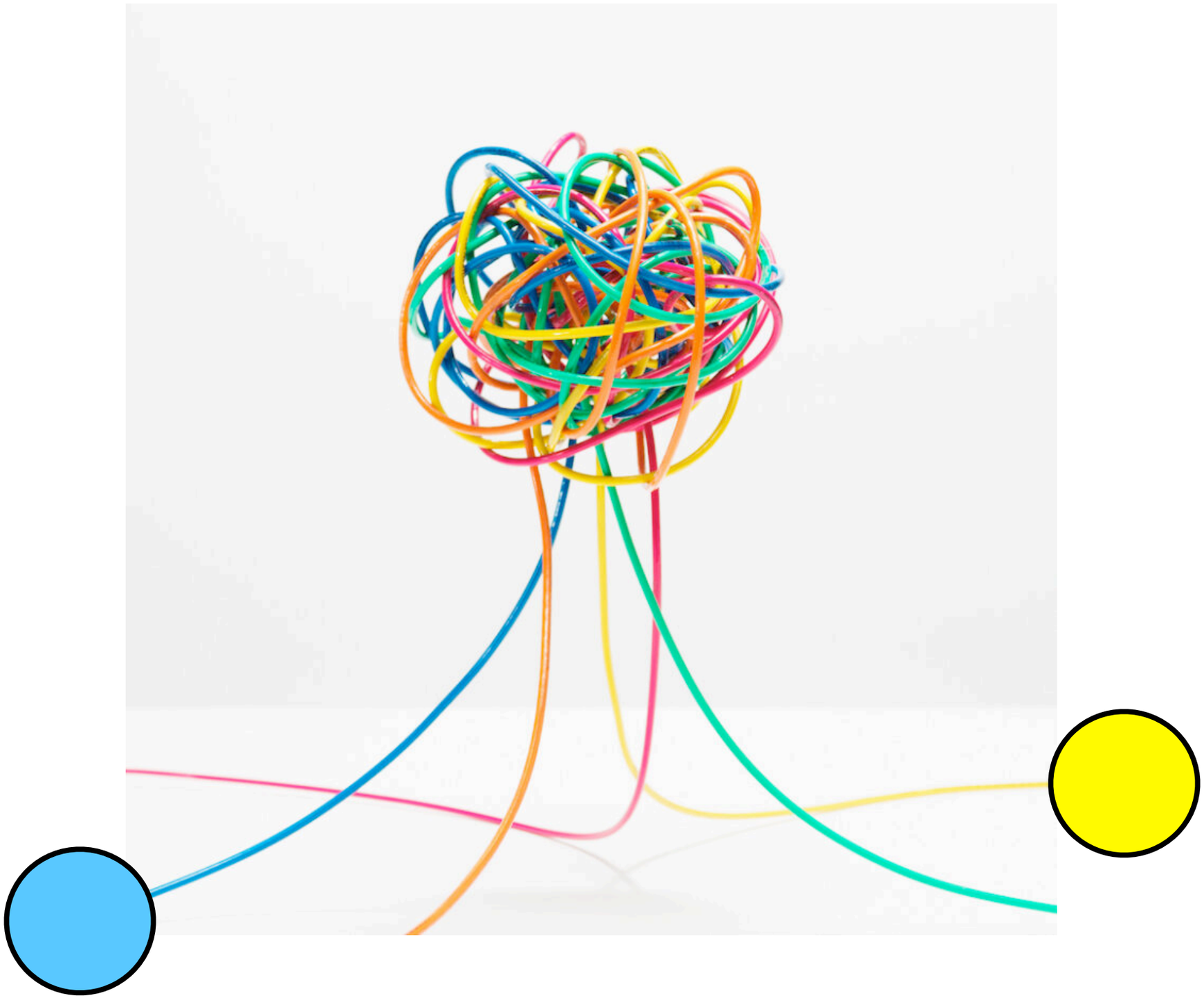
The Quantum Mechanic's Guide to Spacetime

by Matthias Kaminski (University of Alabama)

SCIAS Guest Lectures, Welz-Haus, Würzburg, Germany, May 28th, 2024

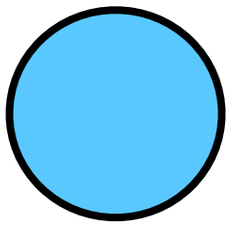
Entanglement

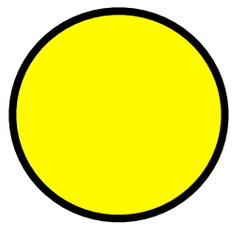
Entanglement



entangled particle pair

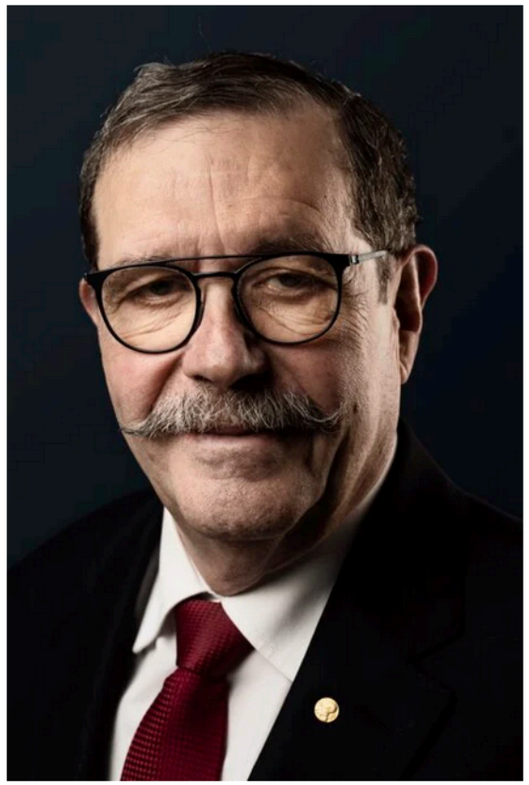
Entanglement





entangled particle pair

The Nobel Prize in Physics 2022



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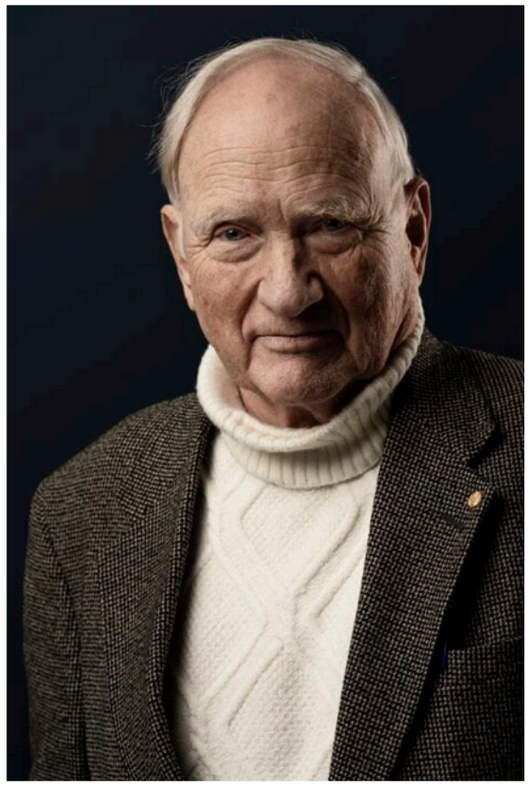
Alain Aspect

Prize share: 1/3



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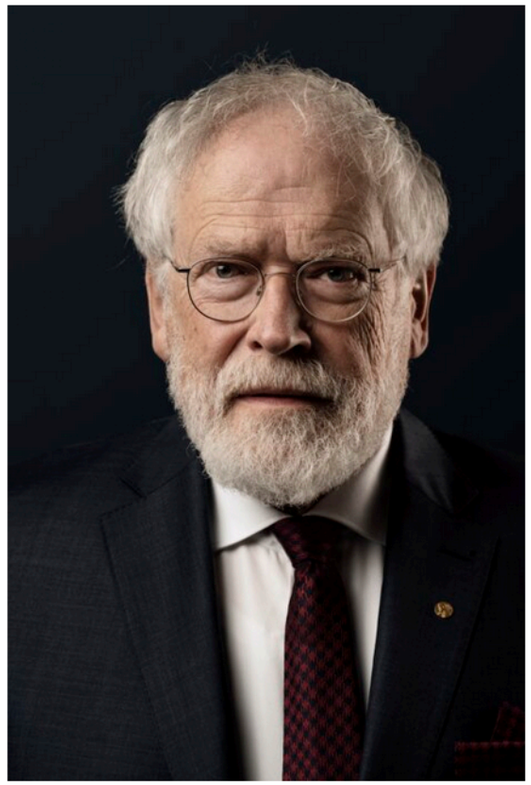
John F. Clauser

Prize share: 1/3



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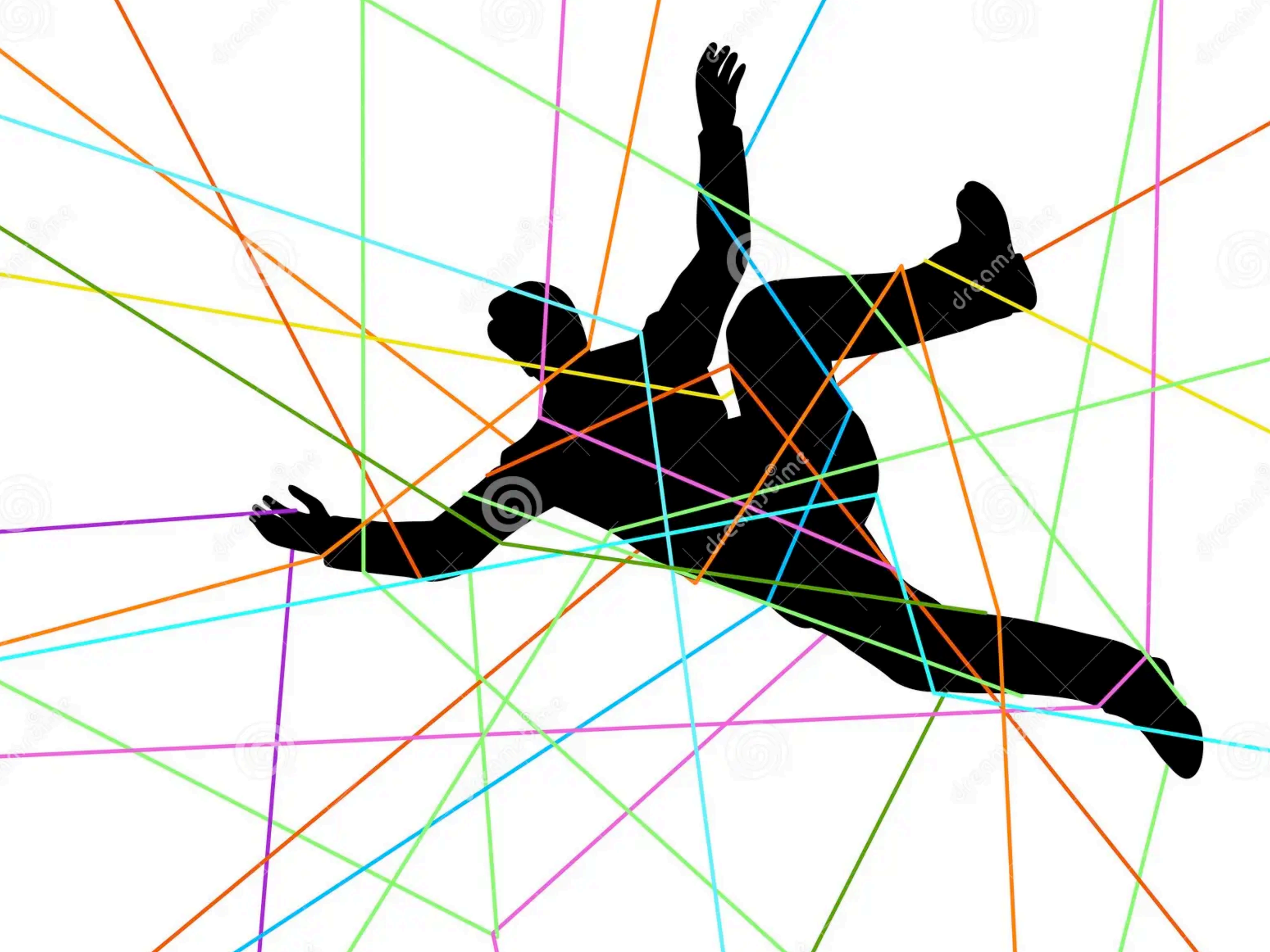
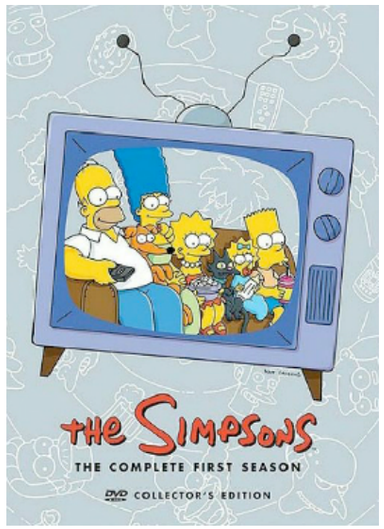
Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

[nobelprize.org (2022)]





1905

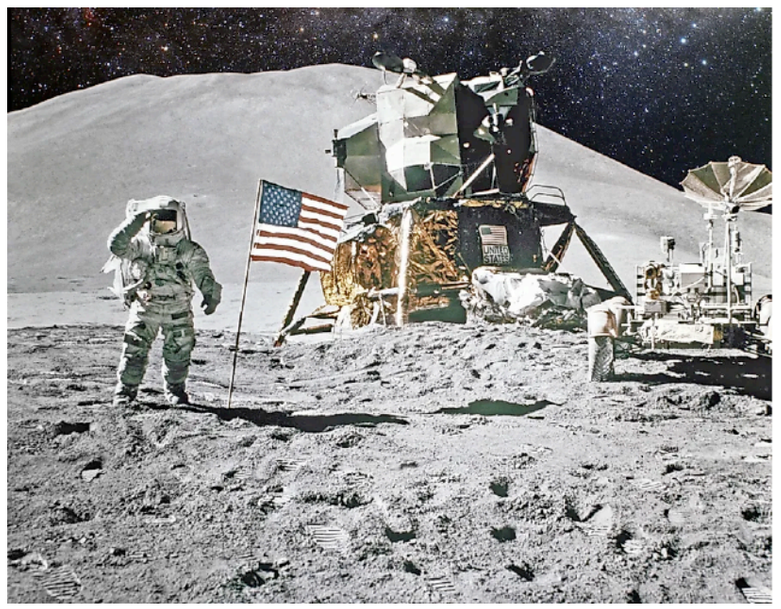
1945

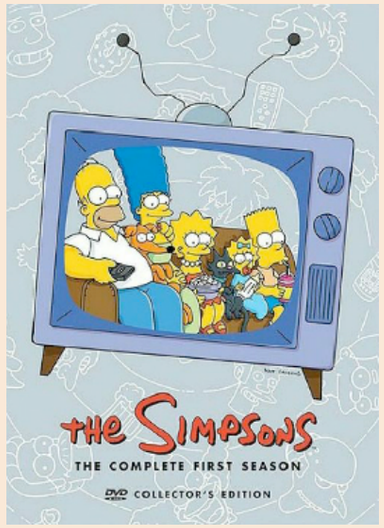
1969

1989

2008

Today





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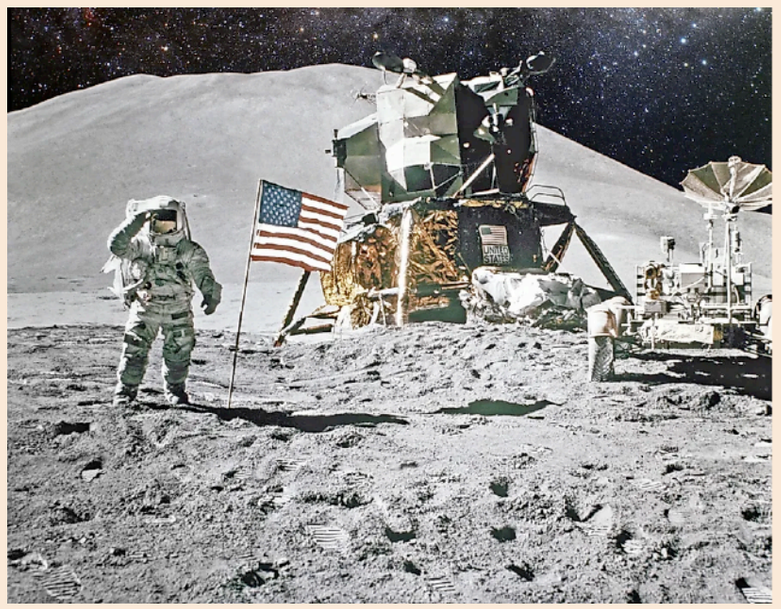
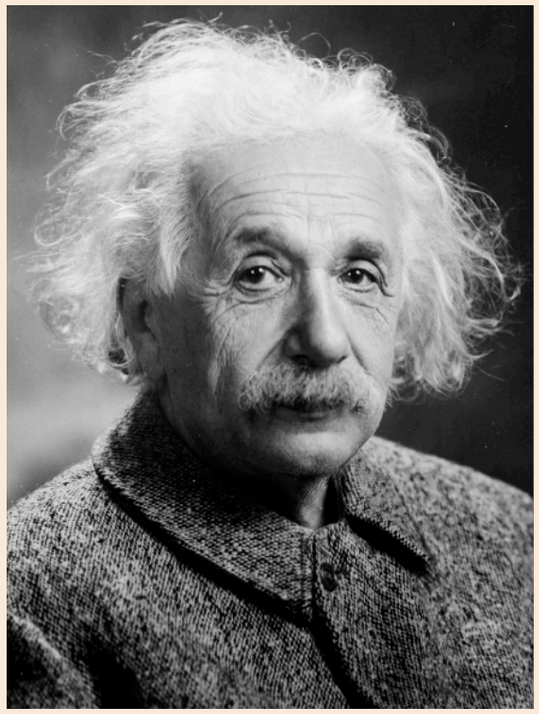


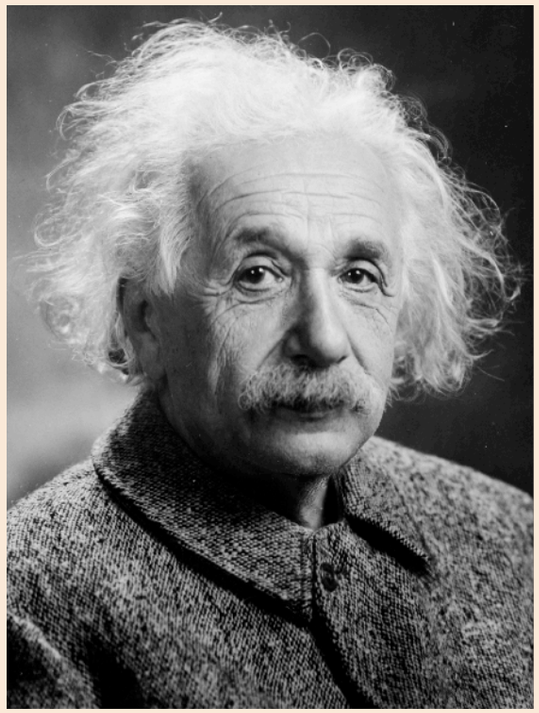
Create particles from energy



$$E = mc^2$$

Einstein (1905)

Create particles from energy



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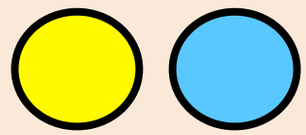

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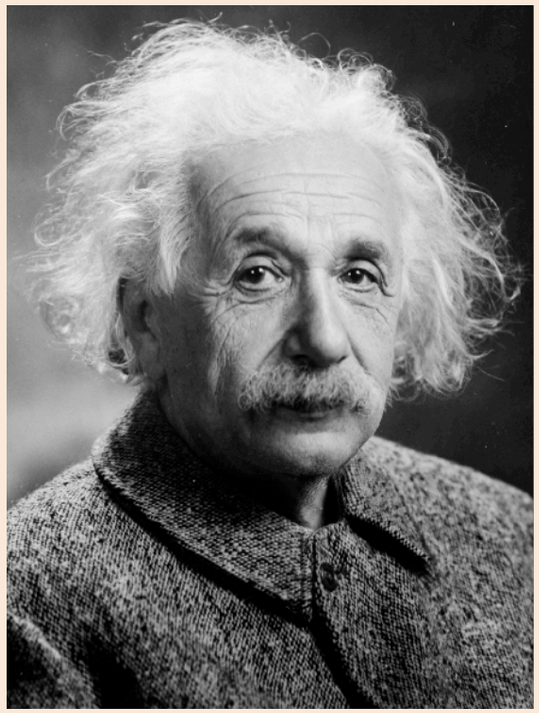

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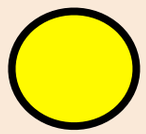

Einstein (1905)

Particles spin!

Heisenberg (1920s)

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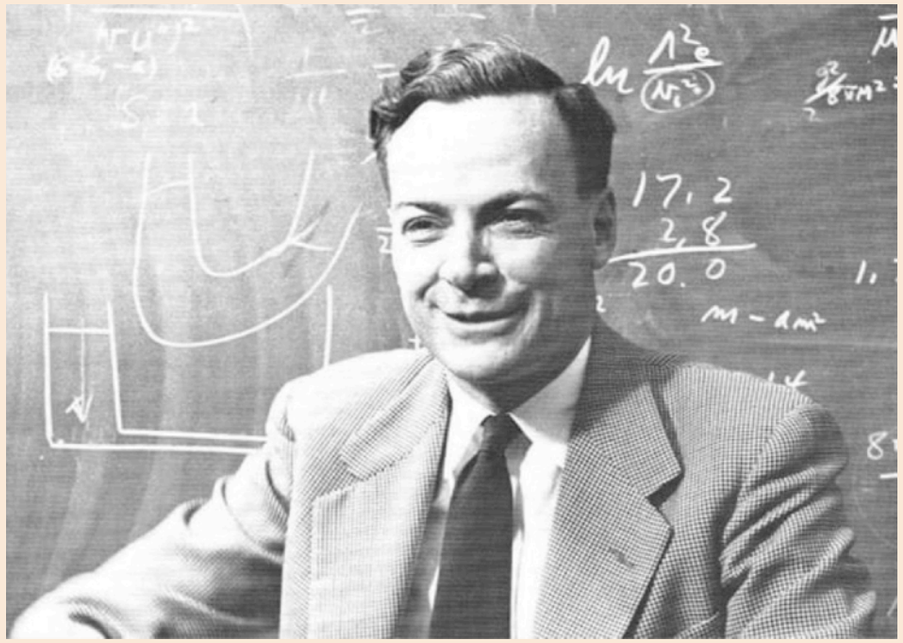

Feynman (1960s)

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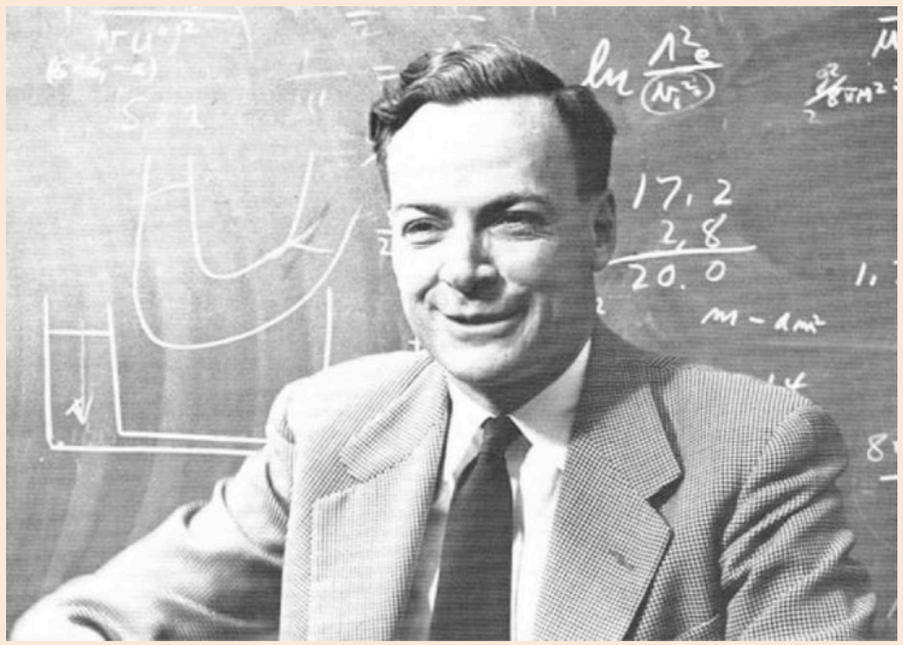
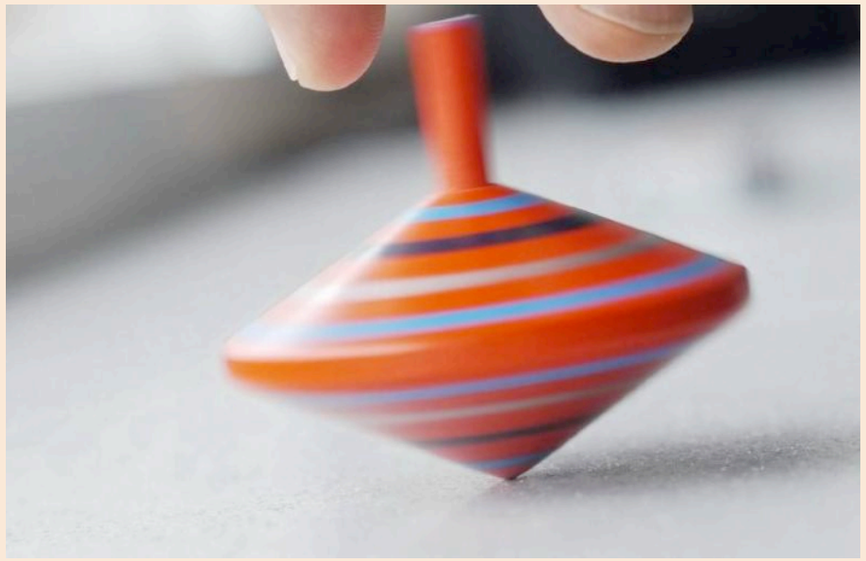
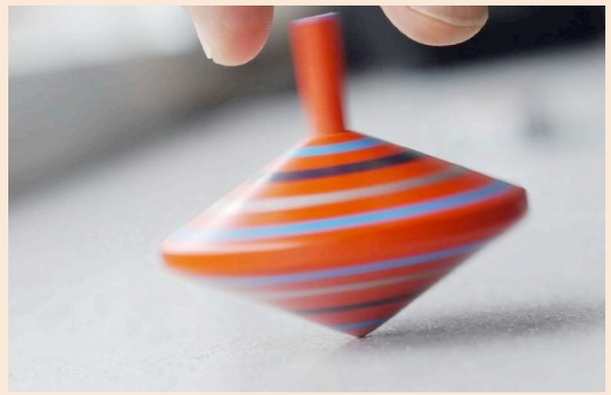


Feynman (1960s)



Quantum mechanical entanglement

von Neumann / Schrödinger (1930s)



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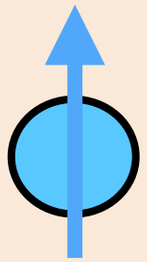
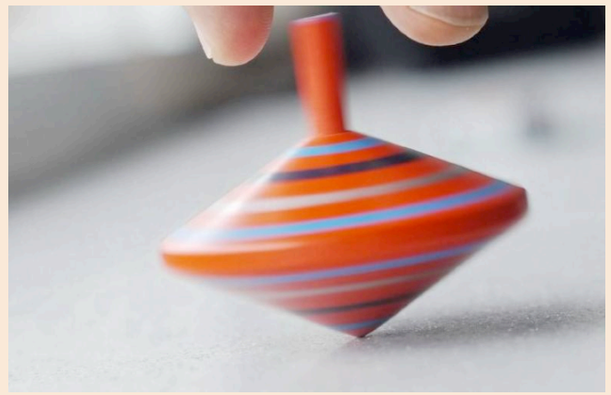


The spin of this particle is up with 50% probability.



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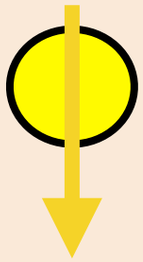
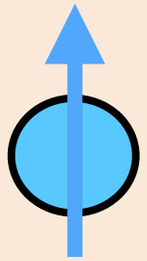


This particle has opposite spin (to add up to zero)



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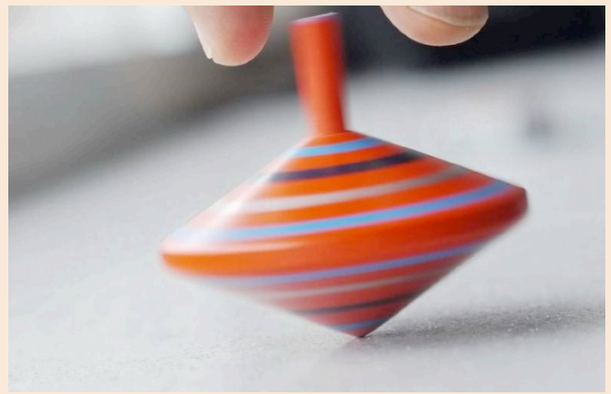

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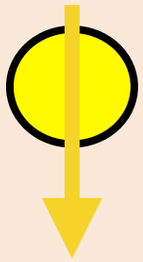

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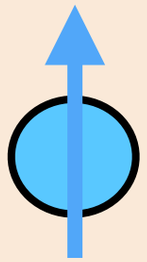

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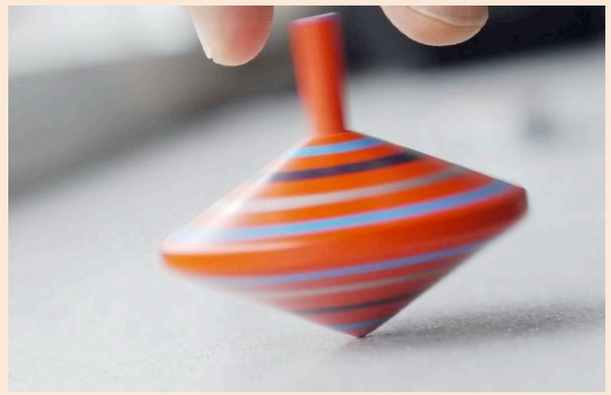
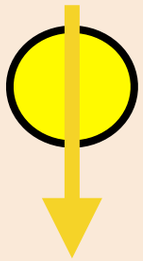


Quantum mechanics: The two particles can only be described together, not separately. They are entangled .

Physics Nobel Prize: [Aspect/ Clauser/ Zeilinger (2022)]

Quantum mechanical entanglement

von Neumann / Schrödinger (1930s)



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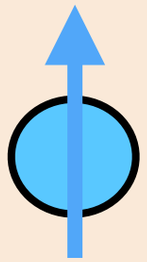

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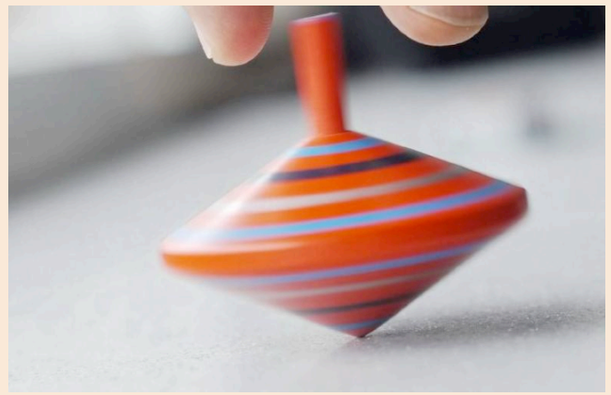

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$$|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle$$

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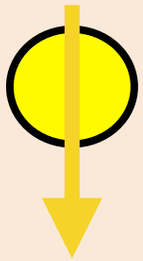

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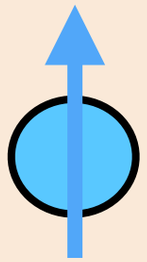

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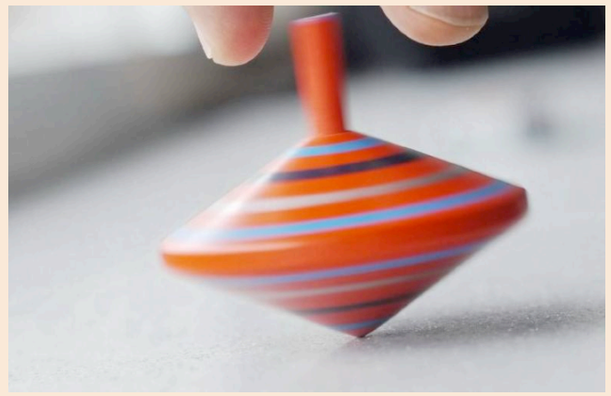

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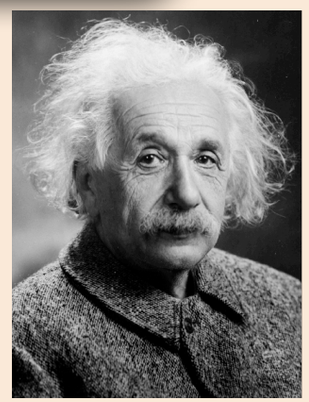
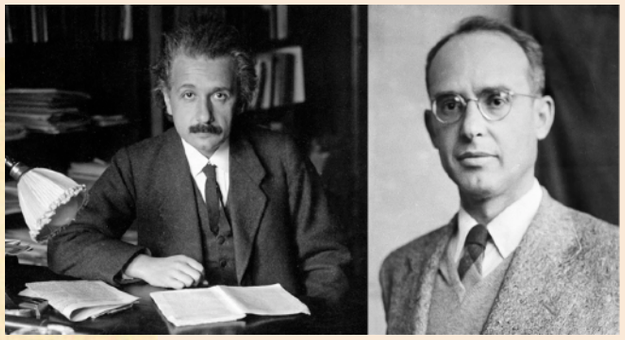
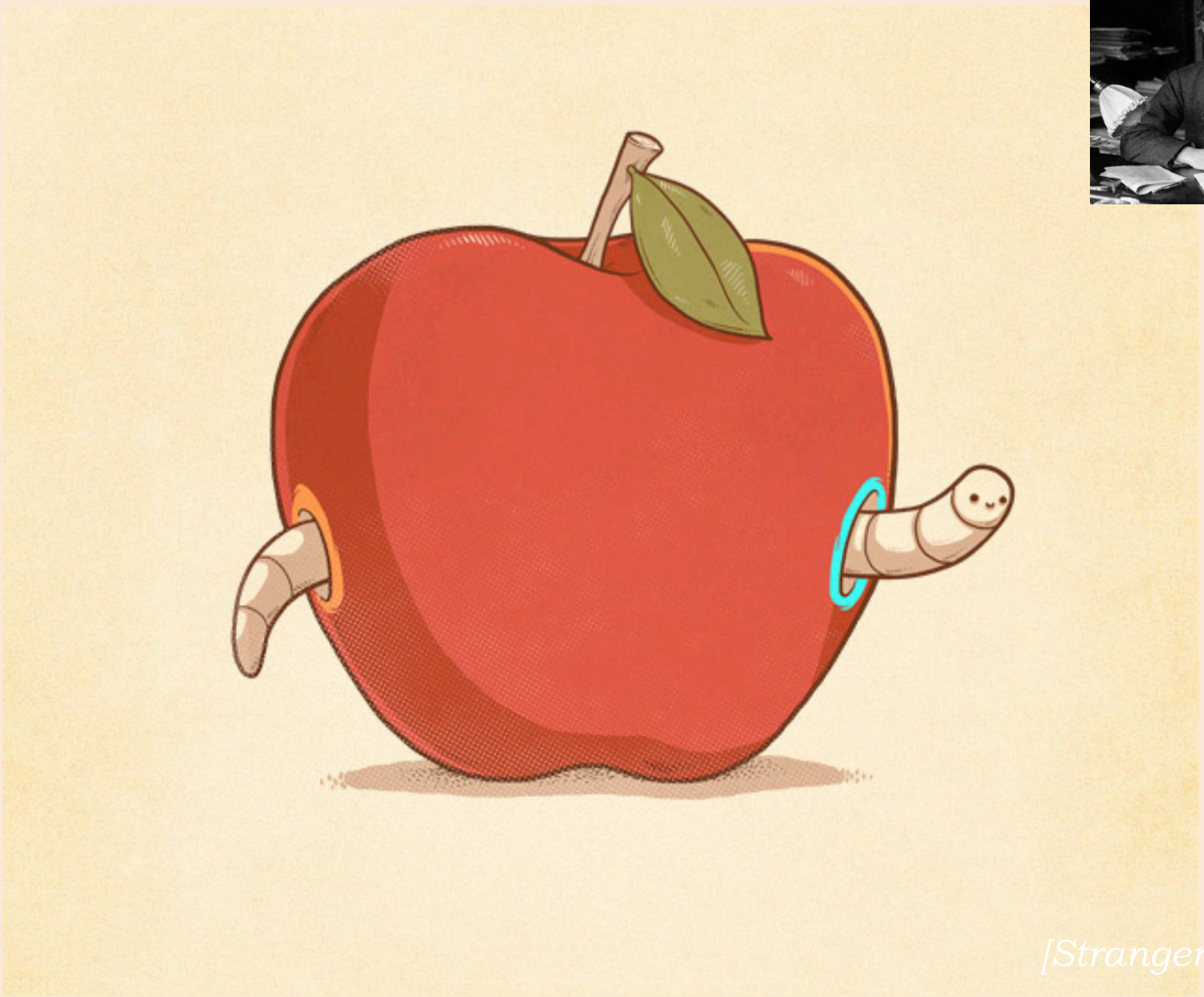


"Spooky action at a distance."
Einstein in letter to Max Born (1947)

Wormholes

[Einstein/ Rosen (1935)]





[Stranger Things, Youtube]

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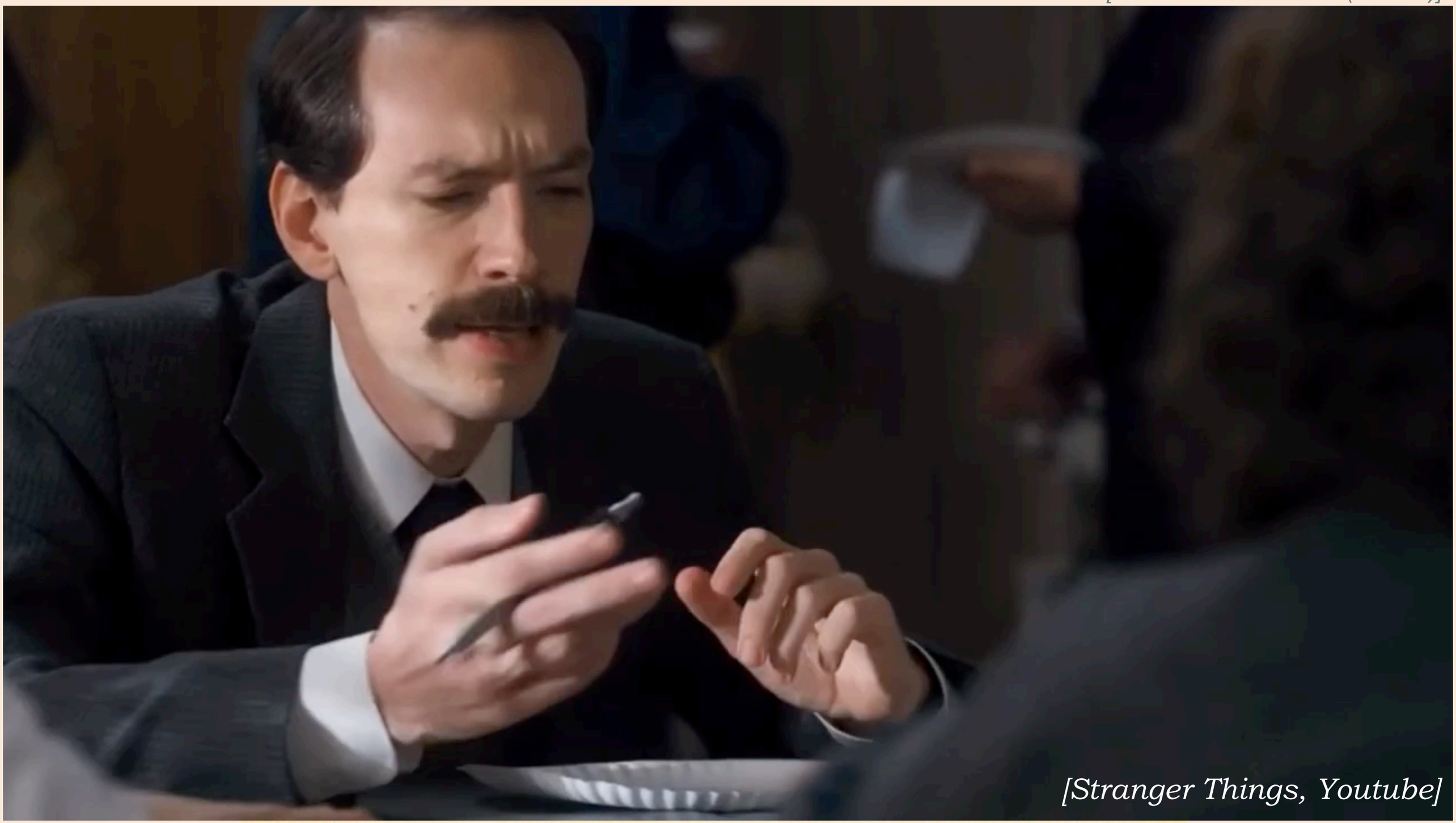

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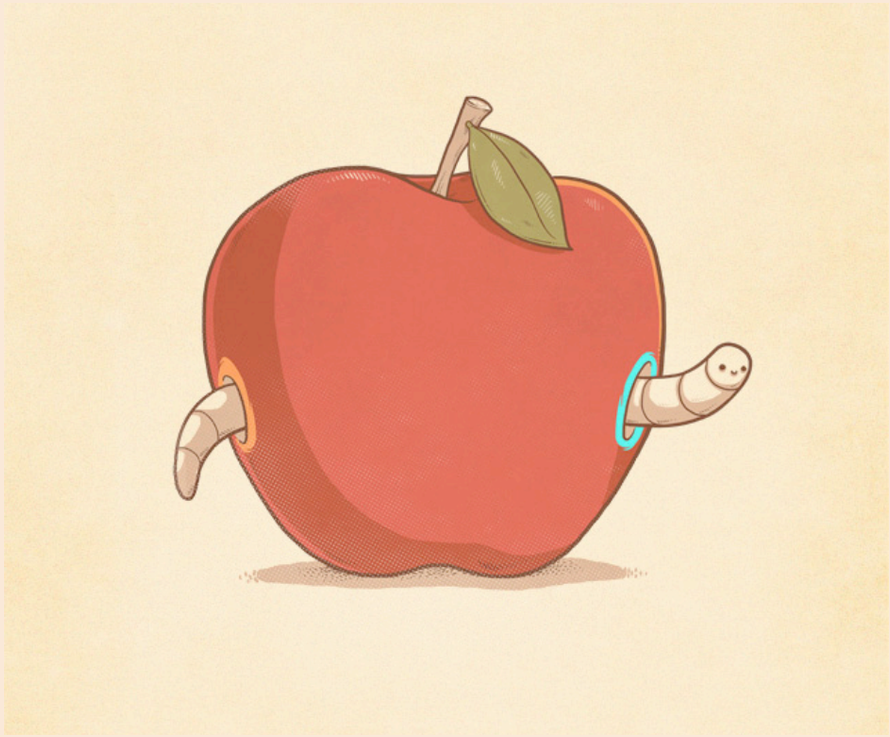

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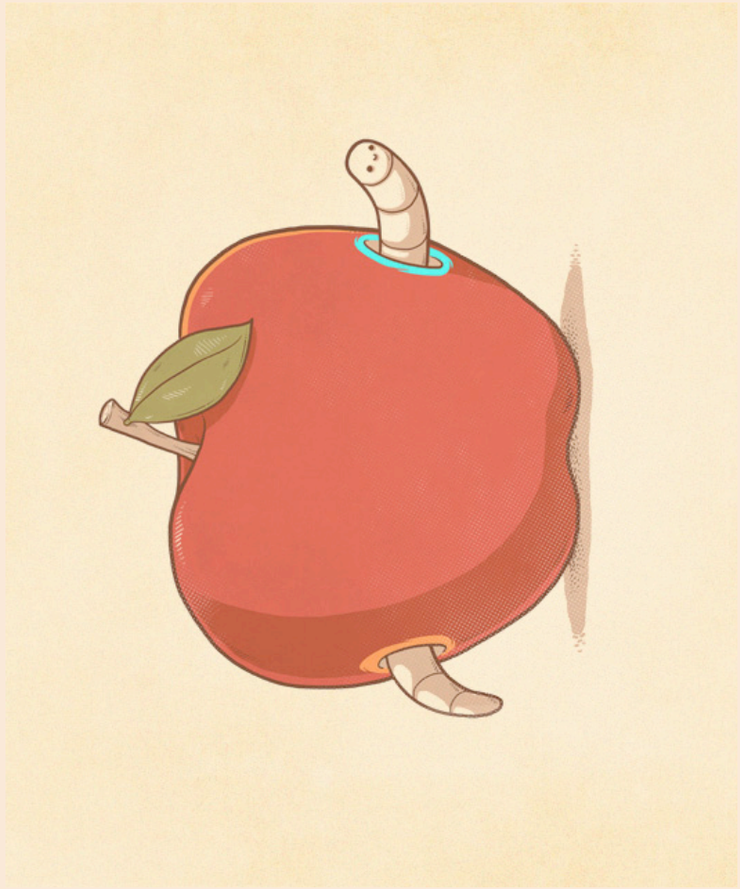

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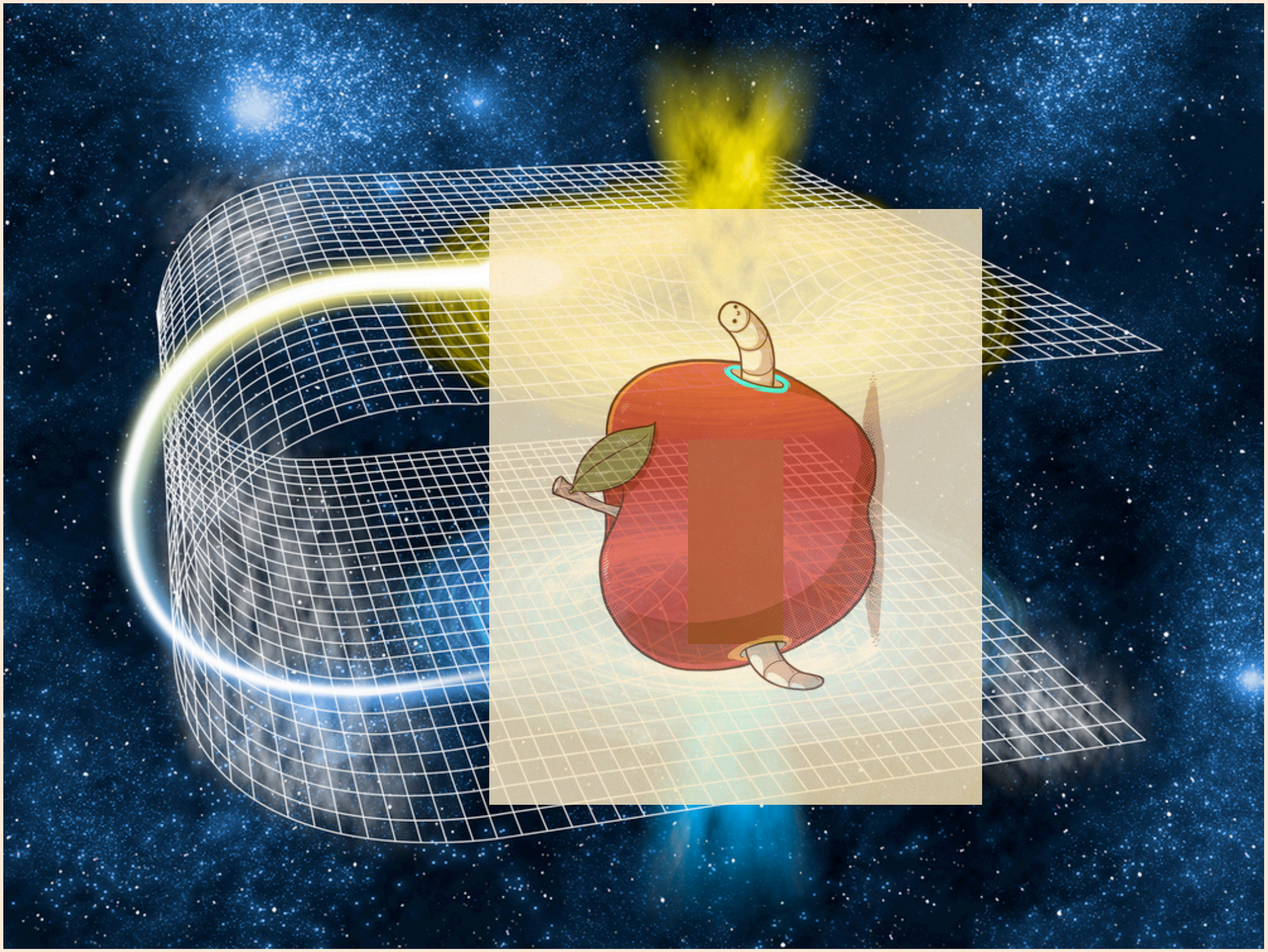

shortcut through an extra-dimension (4D)

Wormholes

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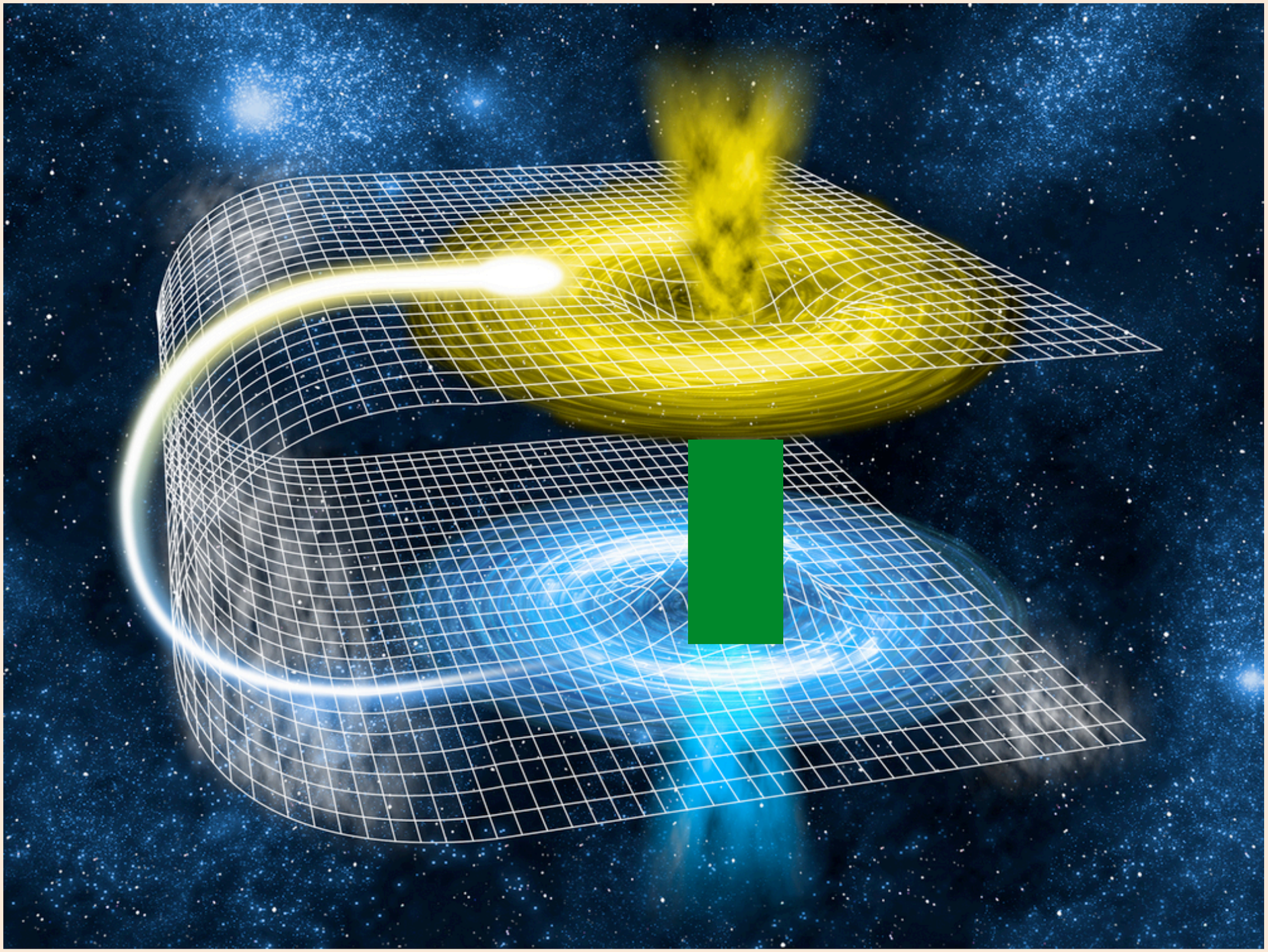

shortcut through an extra-dimension (4D)

SHARKNADO 3D

Holography (AdS/CFT)

The world as a hologram: *[Susskind (1995)]*

['t Hooft (1993)]
[Maldacena (1998)]
[Ammon/Erdmenger (2015)]

Remember 3D shark?
Now imagine 4D!

Holography (AdS/CFT)

The world as a hologram: *[Susskind (1995)]*

3D blue shark 3D red shark 3D screen

extra-dimension

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Holography (AdS/CFT)

The world as a hologram: *[Susskind (1995)]*

Our 3D quantum mechanical world (3D screen)

mathematically corresponds to

a theory of 4D space plus time (4D cinema)

['t Hooft (1993)]
[Maldacena (1998)]
[Ammon/Erdmenger (2015)]

extra-dimension

Remember 3D shark?
Now imagine 4D!

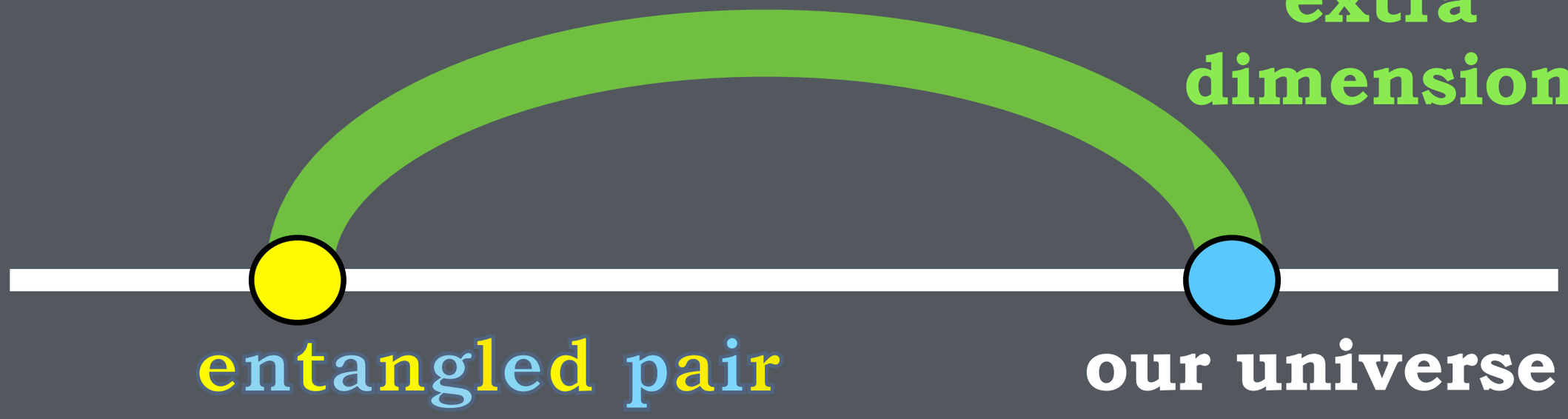
3D blue shark **3D red shark** 3D screen

our universe

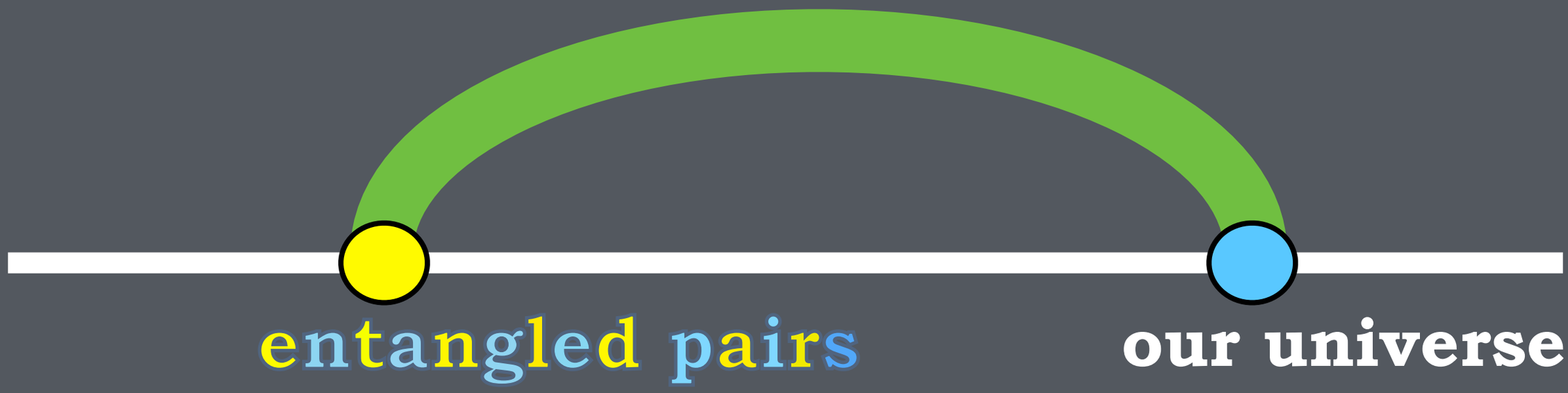

entangled pair
our universe

Holography: entangled pair corresponds to wormhole

[Maldacena/ Susskind (2013)]



many wormholes
***create* extra dimension**



[Van Raamsdonk; Science (2020)]

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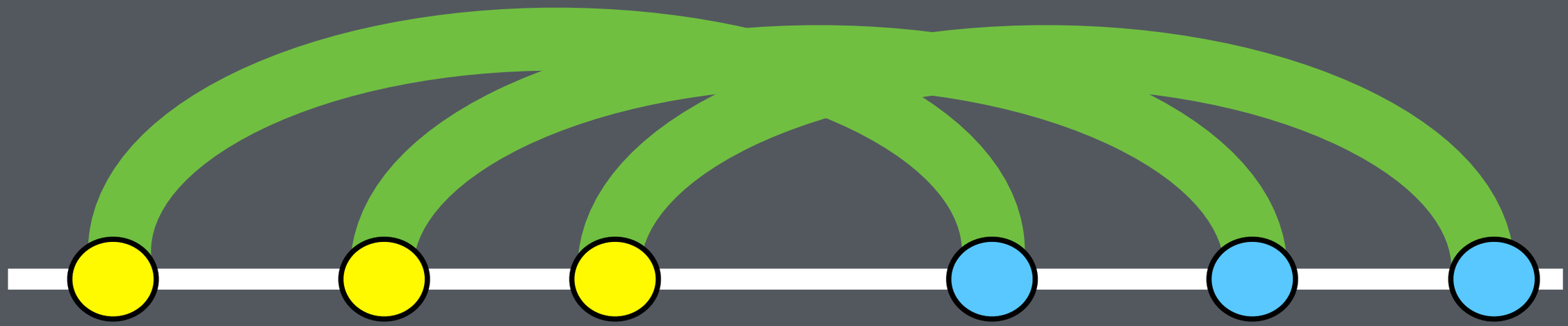

[Van Raamsdonk; Science (2020)]

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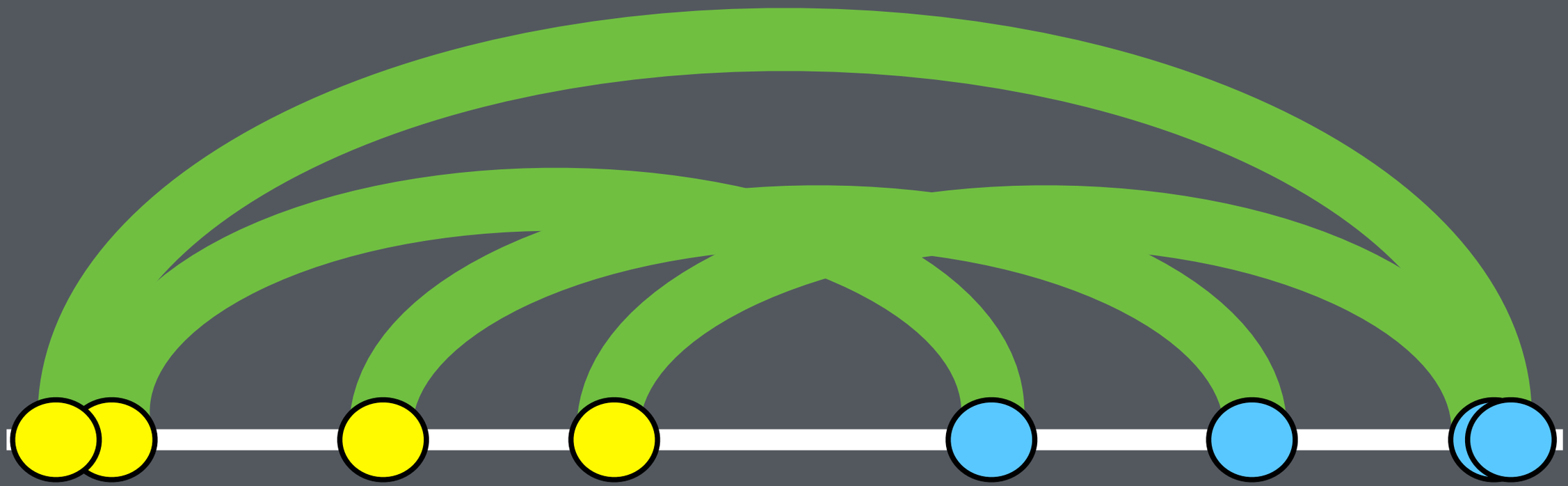

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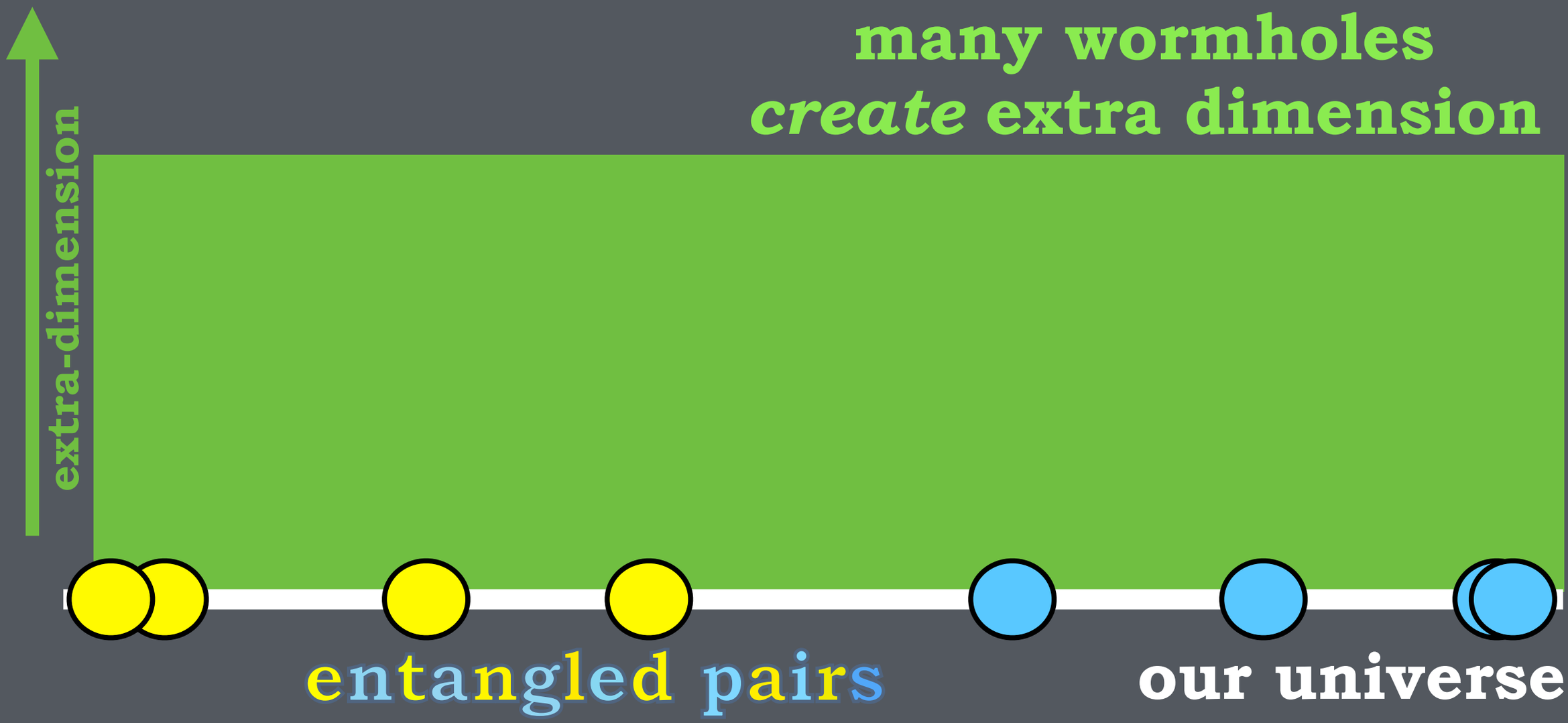
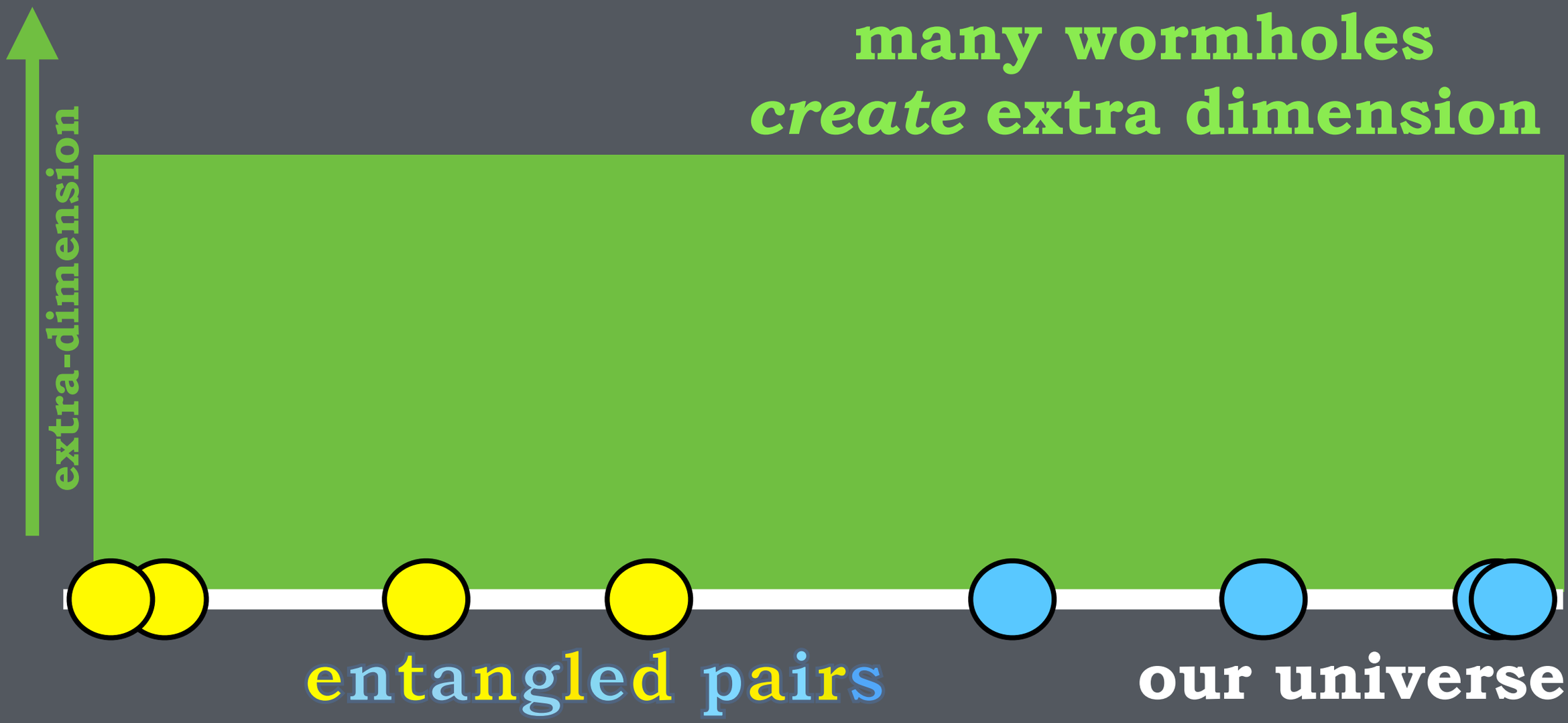


entangled pairs **our universe**

[Van Raamsdonk; Science (2020)]

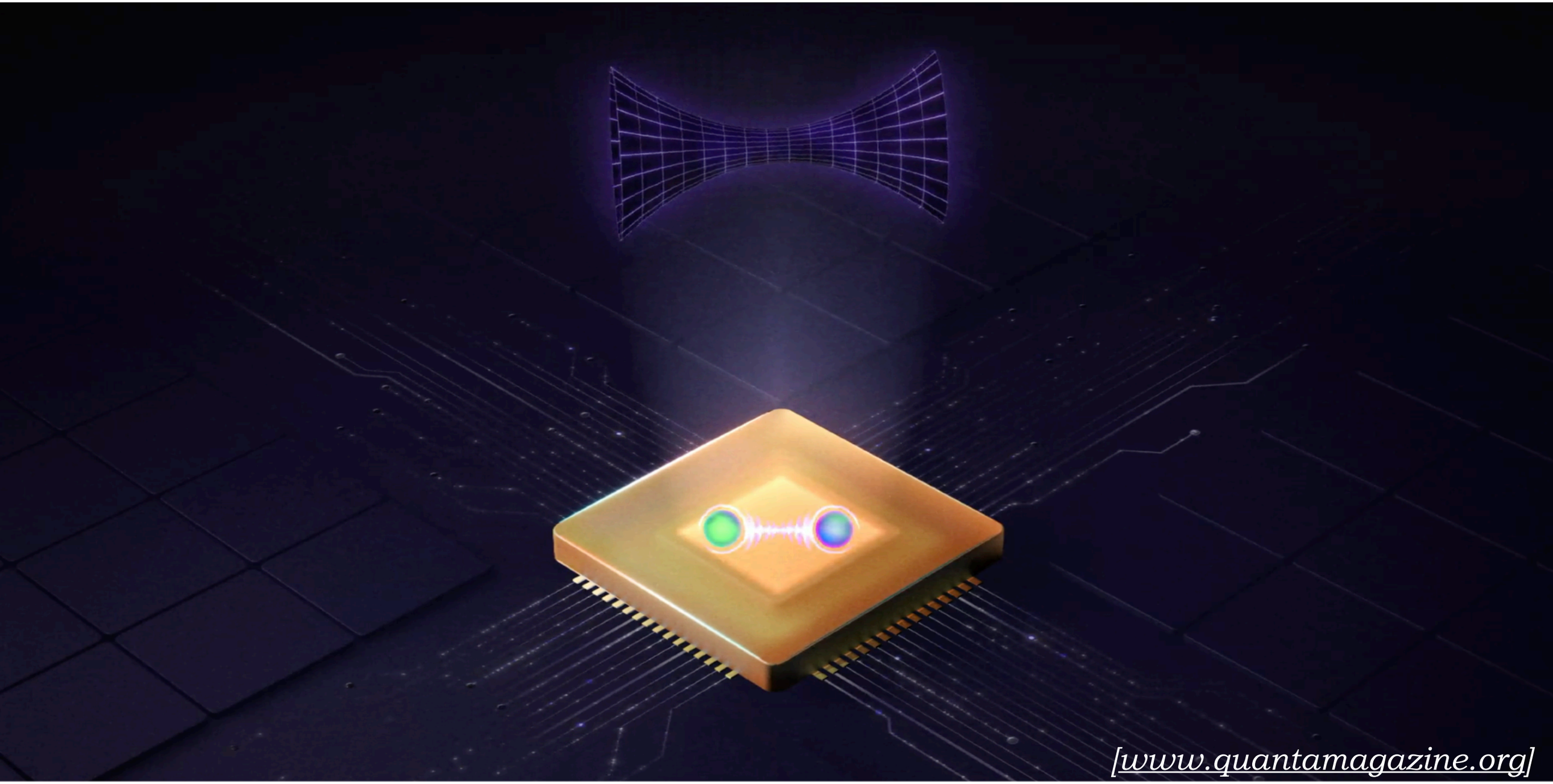
Spacetime is created by quantum entanglement



[Van Raamsdonk; Science (2020)]

Experiment: Simulation on Quantum Computer

[Jafferis et al.; Nature (2022)]



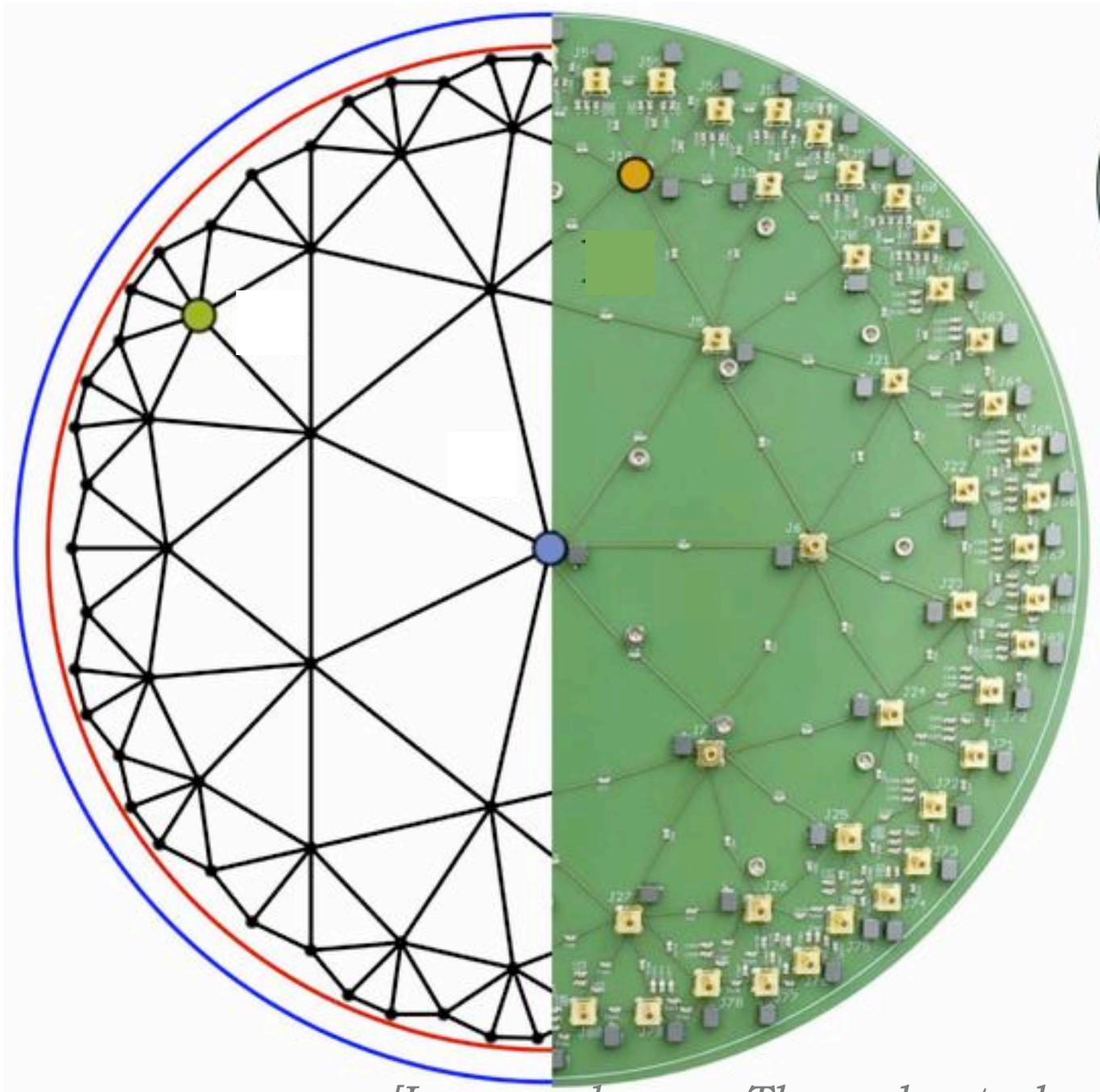
[www.quantamagazine.org]

Examine spacetime with “quantum glasses”.

Comment criticizing this experiment: [Kobrin/ Schuster/ Yao; preprint (2023)]

Our Experiment: Black Hole on Electrical Circuit

[Dey, Chen, Kaminski, Thomale, Erdmenger, et al.; preprint (2024)]

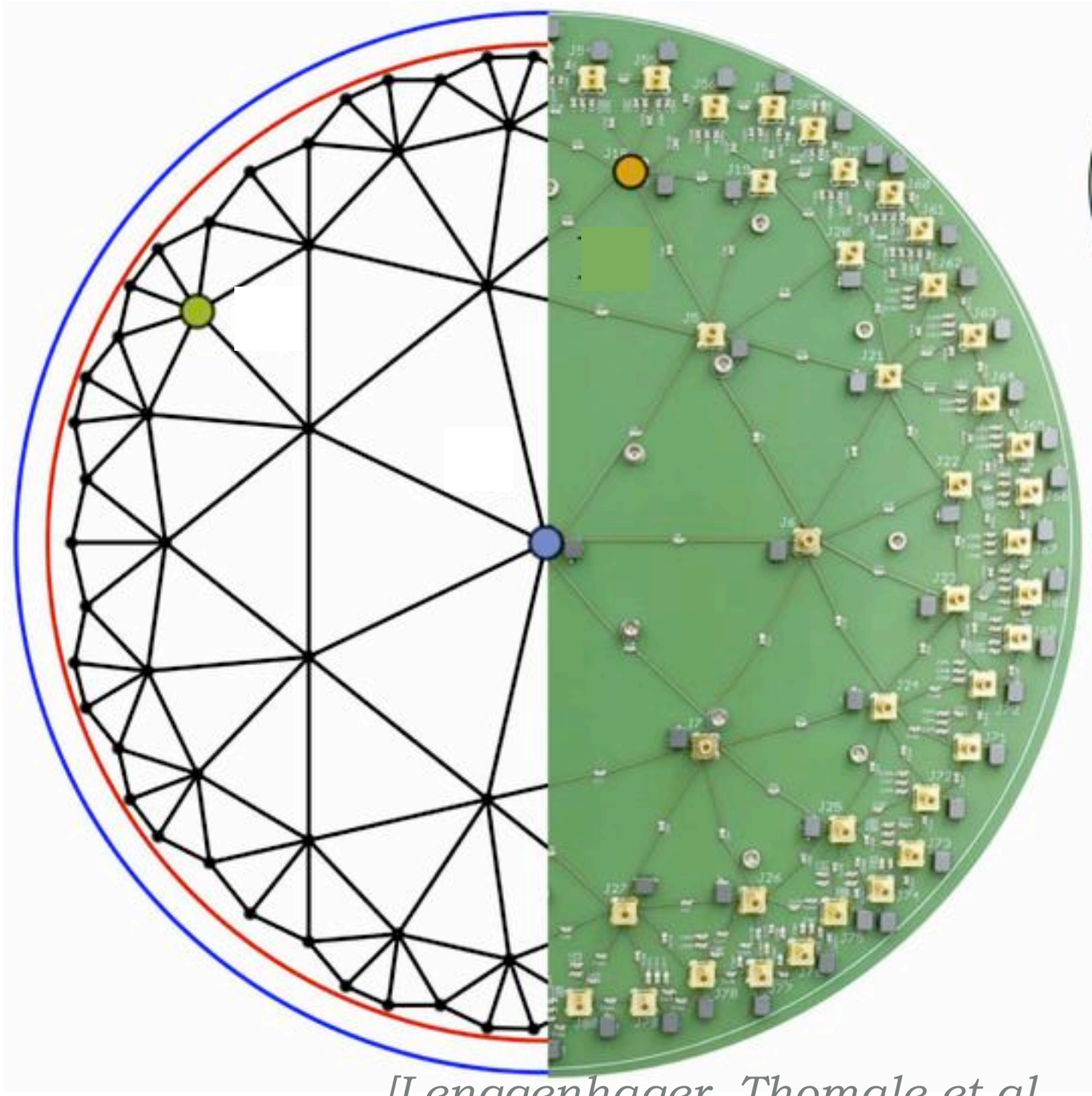


[Lenggenhager, Thomale et al., Nat. Commun. (2022)]

Our Experiment: Black Hole on Electrical Circuit

[Dey, Chen, Kaminski, Thomale, Erdmenger, et al.; preprint (2024)]

Realize the wormhole *and* entangled pair simultaneously



[Lenggenhager, Thomale et al., Nat. Commun. (2022)]

entangled pair

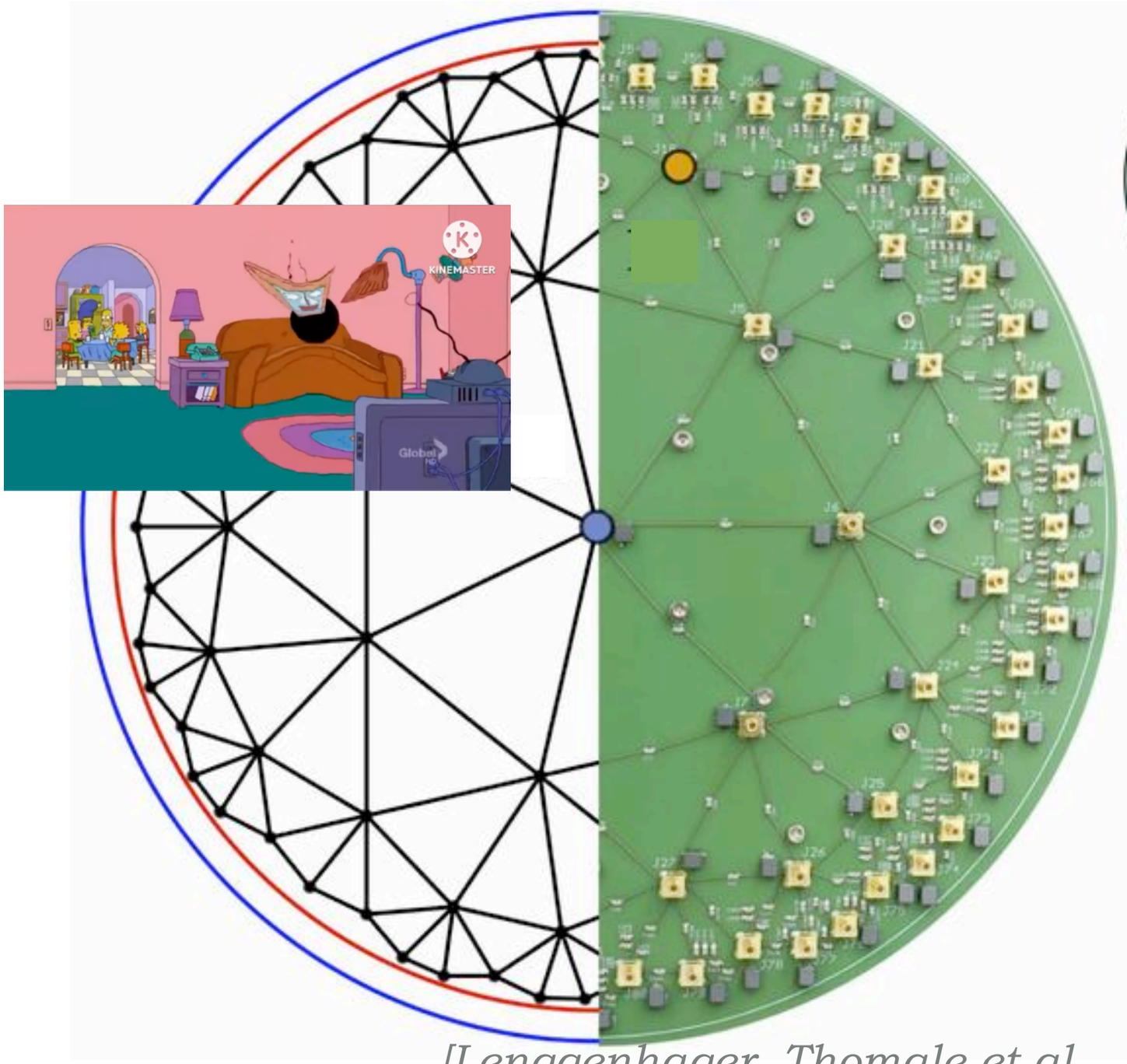
extra-dimension with wormhole

Our Experiment: Black Hole on Electrical Circuit

[Dey, Chen, Kaminski, Thomale, Erdmenger, et al.; preprint (2024)]

Realize the wormhole *and* entangled pair simultaneously

Model black hole on electrical circuit board



entangled pair

extra-dimension with wormhole

[Lenggenhager, Thomale et al., Nat. Commun. (2022)]

Our Experiment: Black Hole on Electrical Circuit

[Dey, Chen, Kaminski, Thomale, Erdmenger, et al.; preprint (2024)]

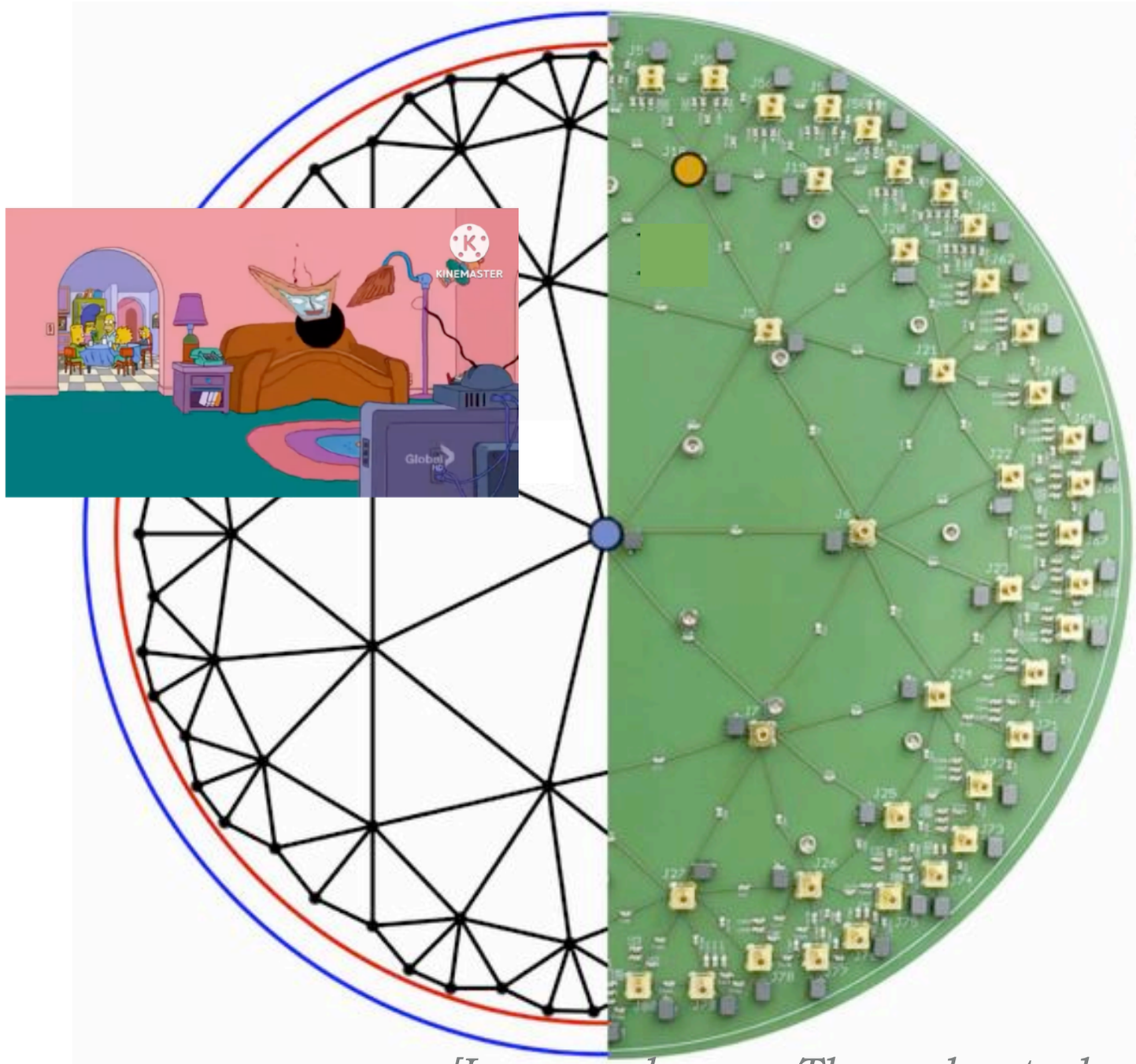
Realize the wormhole *and* entangled pair simultaneously

Model black hole on electrical circuit board

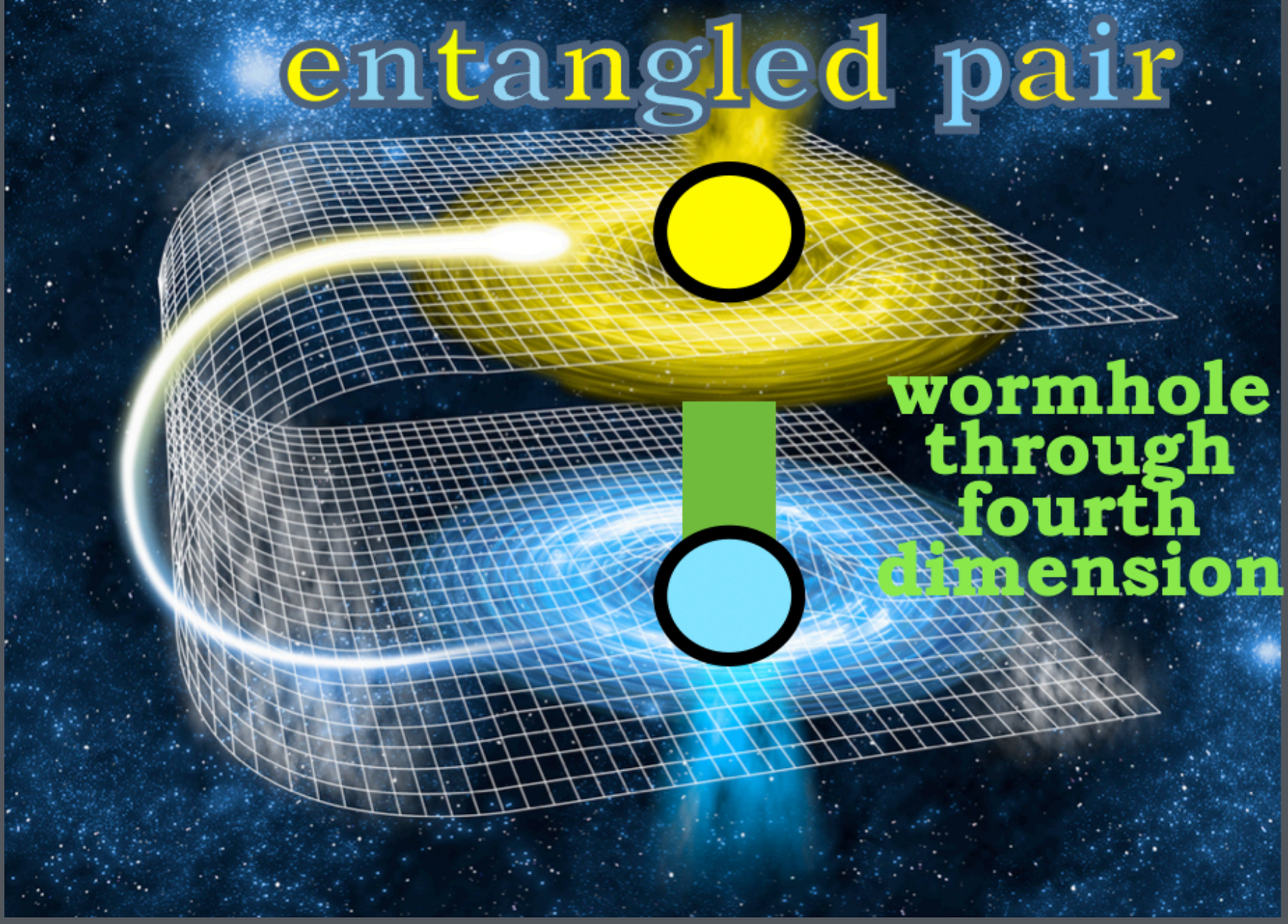
Testing holography in the lab

entangled pair

extra-dimension with wormhole



[Lenggenhager, Thomale et al., Nat. Commun. (2022)]



- wormhole = entangled pair
- space originates from entanglement
- wormhole on quantum computer
- holography on electrical circuits
- quantum gravity in the lab?

[Van Raamsdonk; Science (2020)]

[Jafferis et al.; Nature (2022)]

[Dey, Chen, Thomale, Kaminski, et al.; preprint (2024]

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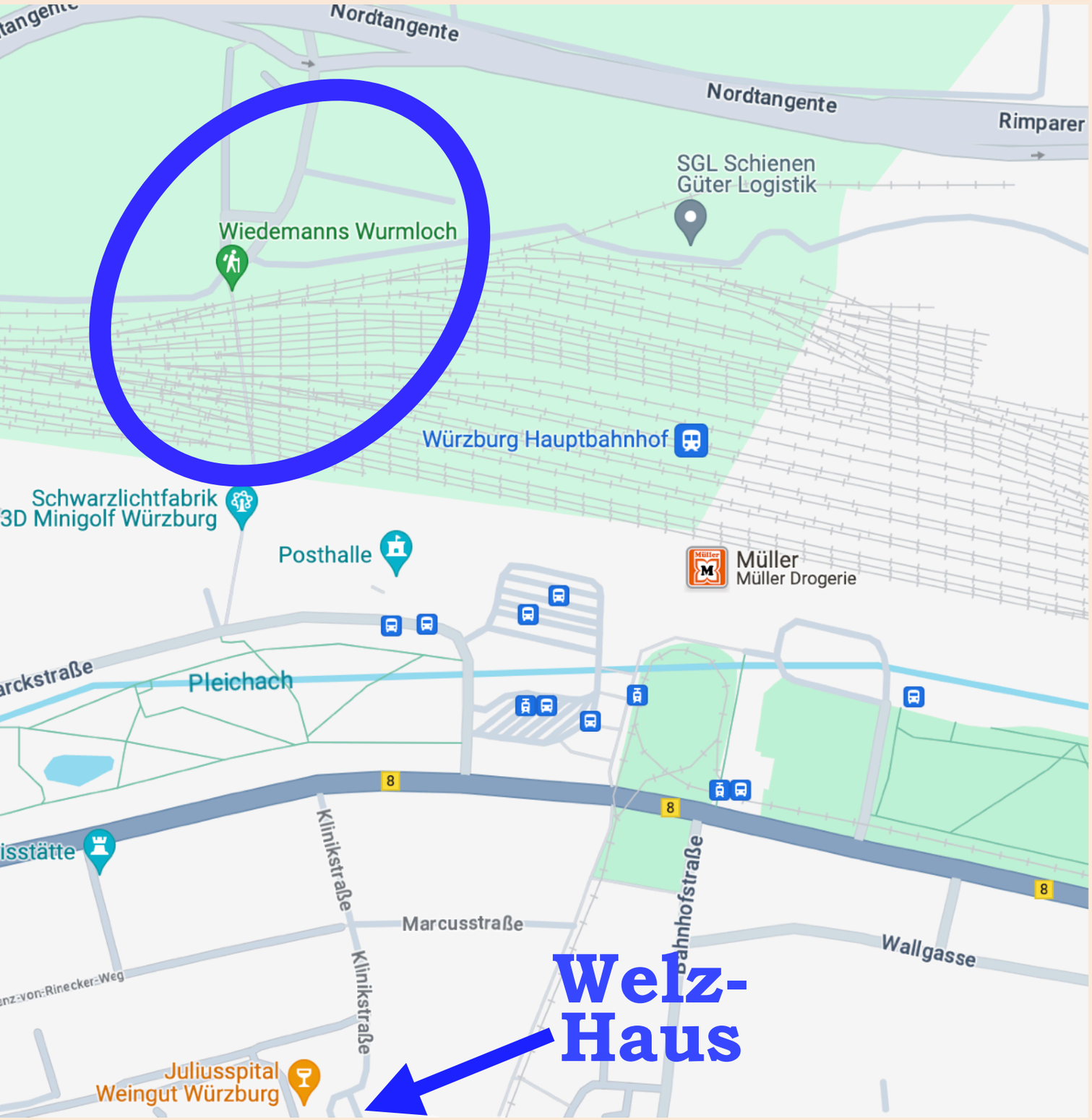
Theoretische Festkörperphysik
Lehrstuhlinhaber: Prof. Dr. Ronny Thomale

U.S. DEPARTMENT OF ENERGY

THE UNIVERSITY OF ALABAMA | College of Arts & Sciences

Wormhole in Würzburg



[Google Maps]

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Prof. Dr. Navid Abbasi

Lubljana University, Slovenia


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Prof. Dr. Dirk Rischke


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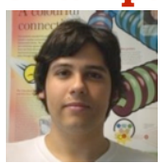
Prof. Dr. Ho-Ung Yee

Urbana-Champaign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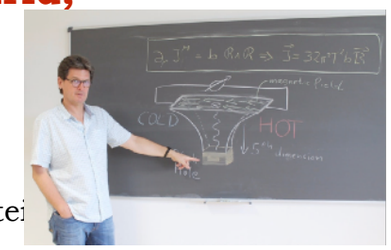


Bielefeld University, Germany


Dr. Gergely Endrődi

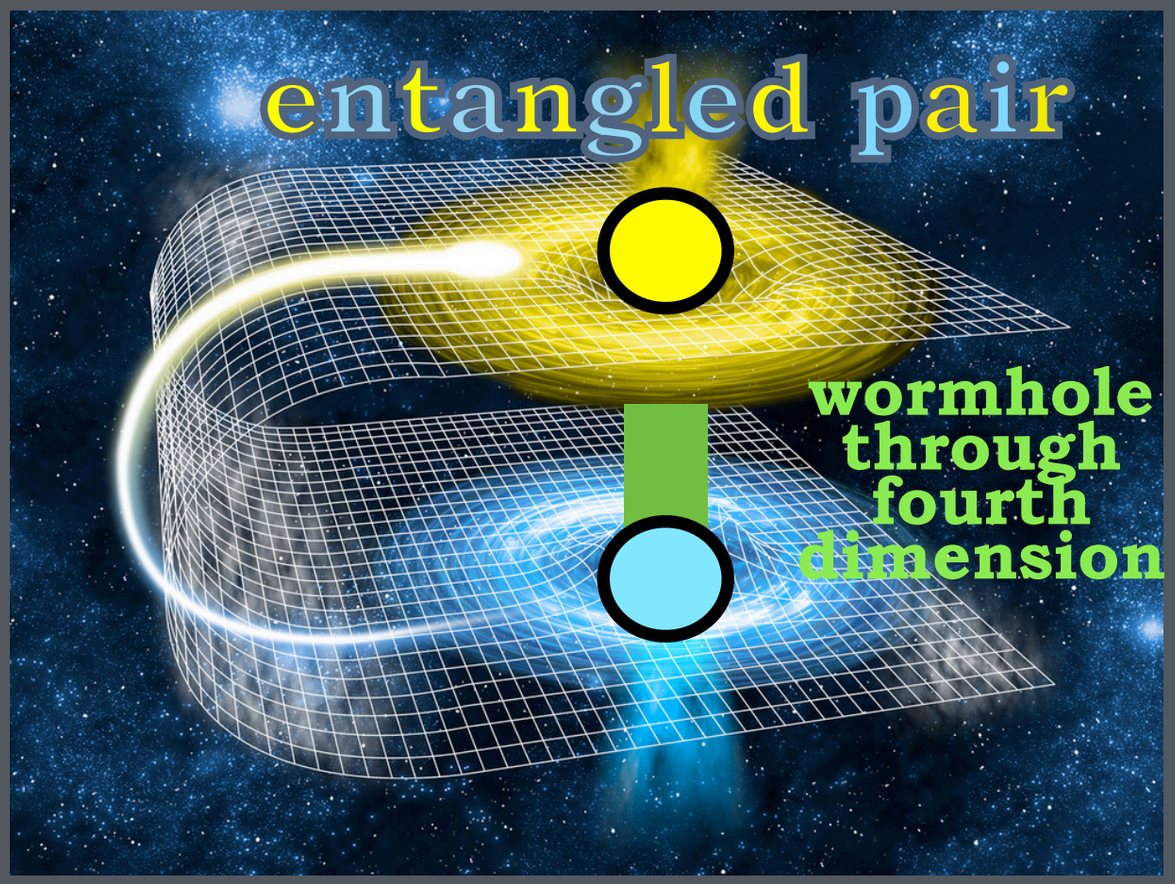
APPENDIX

Quantum mechanics in the lab

(entanglement on quantum computer)

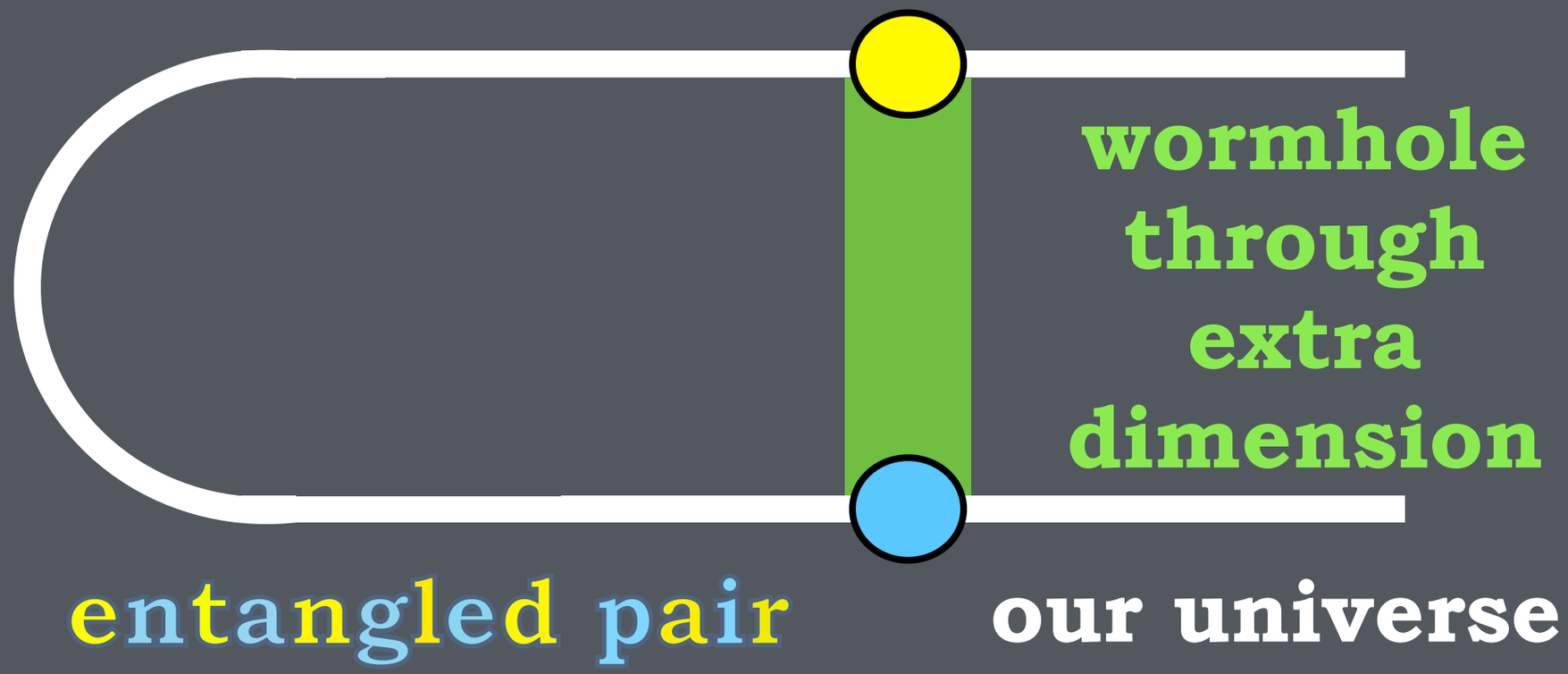
can explain the origin of space and time

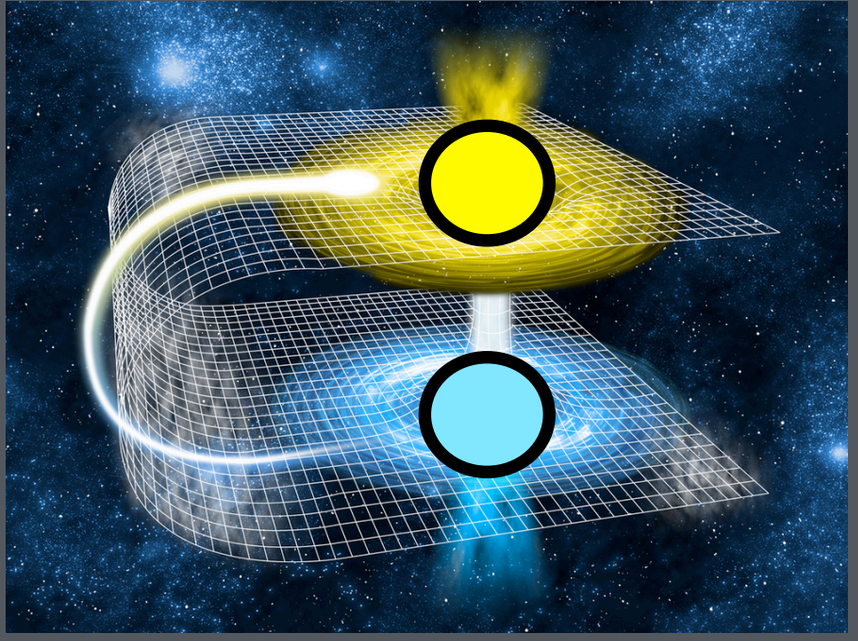
(wormhole in holographically dual gravity)

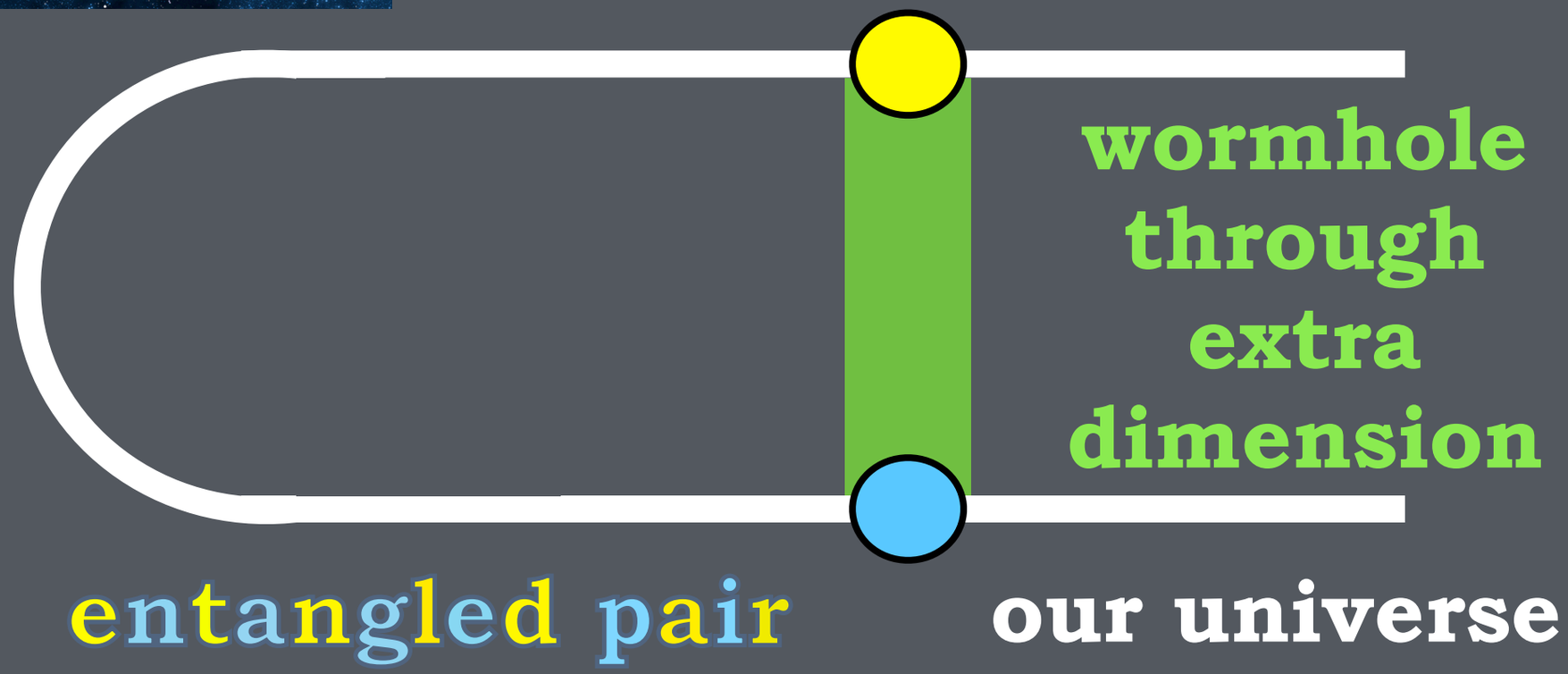


[Van Raamsdonk; Science (2020)]

[Jafferis et al.; Nature (2022)]


wormhole through extra dimension
entangled pair
our universe




wormhole through extra dimension
entangled pair
our universe

our universe


our
universe
Alpha
Centauri
Our
Sun

wormhole through extra (fourth) dimension

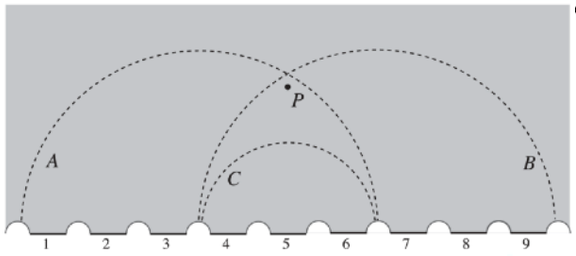
our universe

Alpha Centauri

Our Sun

Geometric picture: three faces of *minimal surfaces*

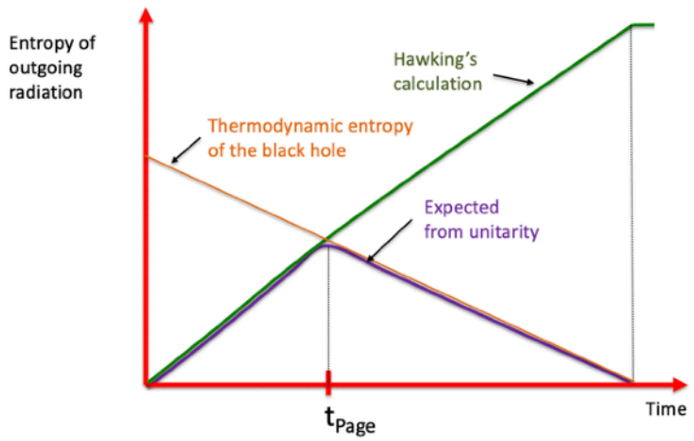
[Cartwright,Kaminski; JHEP (2021)]



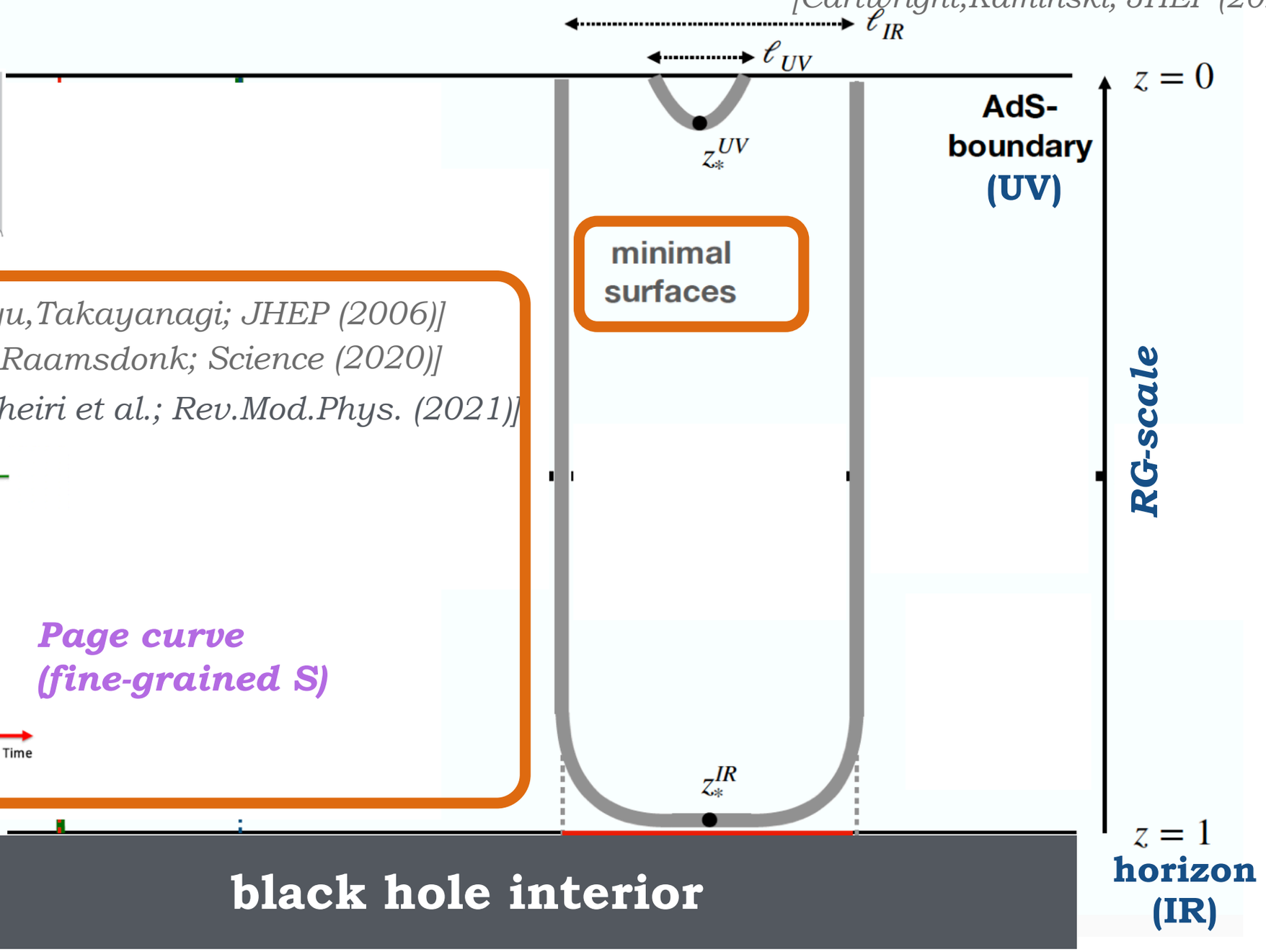
1) Entanglement entropy: *[Ryu,Takayanagi; JHEP (2006)]*

2) Emergent spacetime: *[Van Raamsdonk; Science (2020)]*

3) Fine-grained entropy: *[Almheiri et al.; Rev.Mod.Phys. (2021)]*



Page curve (fine-grained S)

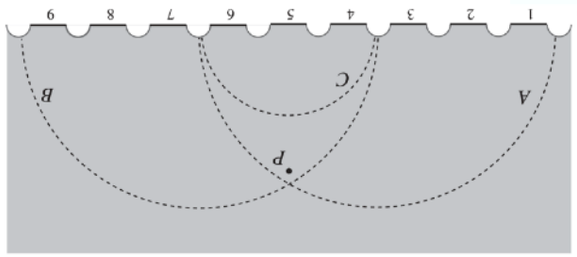


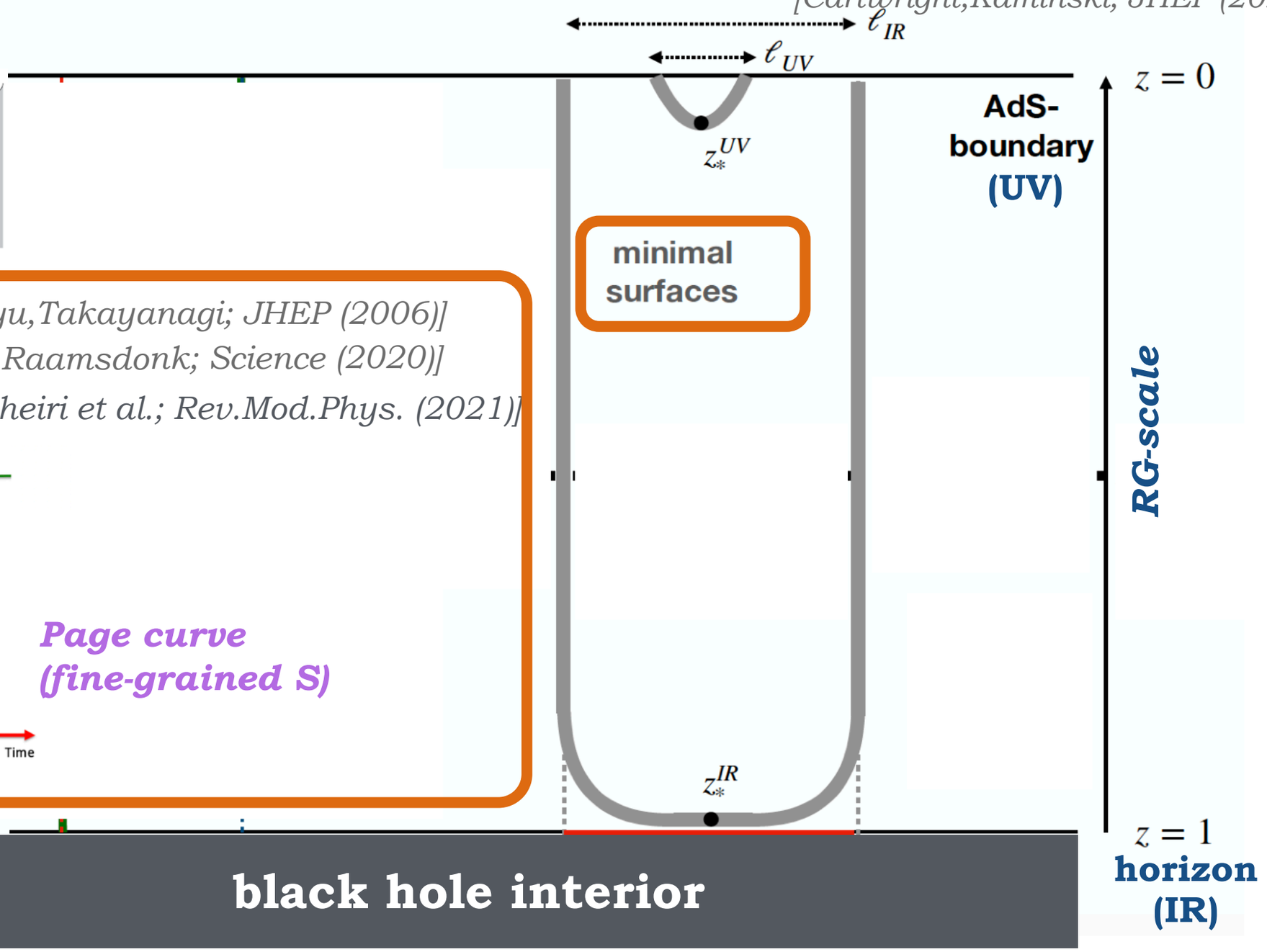
➡ **Entanglement = Spacetime**

[Van Raamsdonk; Gen.Rel.Grav. (2010)]

Geometric picture: three faces of *minimal surfaces*

[Cartwright,Kaminski; JHEP (2021)]





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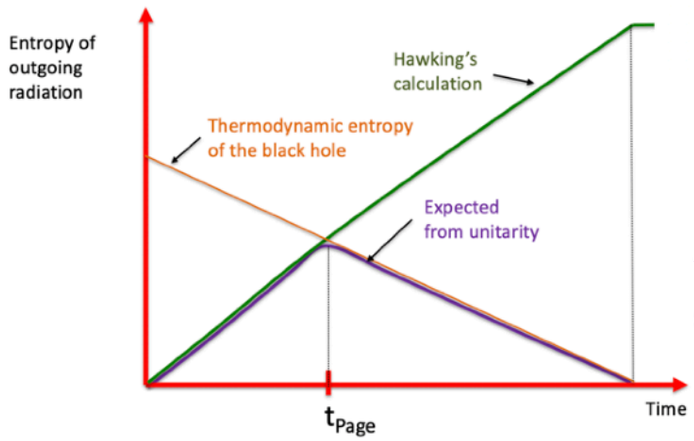


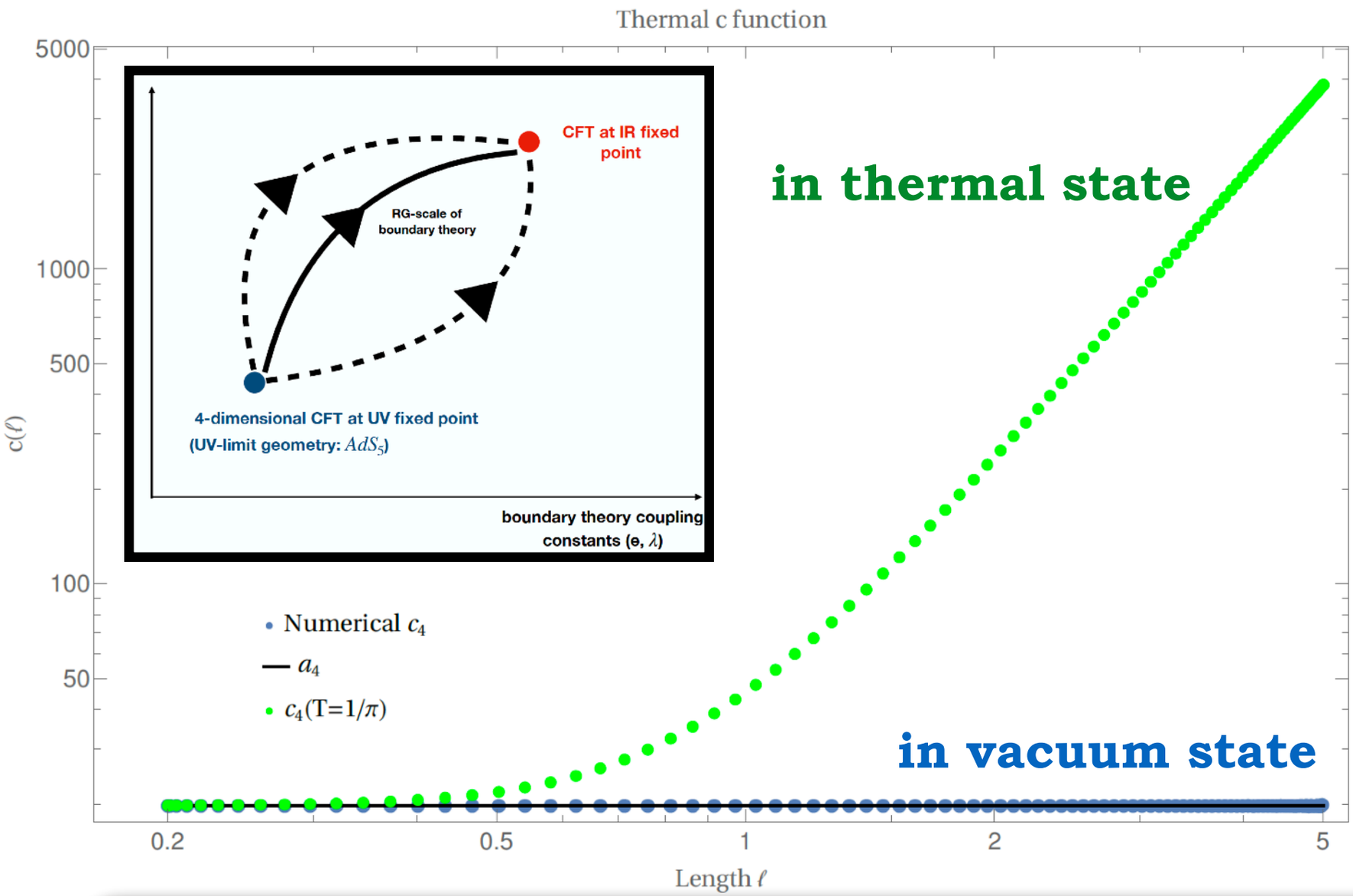
Page curve (fine-grained S)

➡ Entanglement = Spacetime

[Van Raamsdonk; Gen.Rel.Grav. (2010)]

Entropic c-function *increases* in *thermal* state

[Cartwright,Kaminski; JHEP (2021)]



$$a_4 = \beta_4 \frac{\ell^3}{H^2} \frac{\partial S_a}{\partial \ell}$$

[Casini,Huerta; Phys.Lett.B (2004)]

[Nishioka,Takayanagi; JHEP (2007)]

[Myers,Sinha; JHEP (2011)]

H: IR-regulator

β_4: known constant

➡ **c-function increases in thermal state (violates c-theorem?)**

➡ **constant in vacuum of CFT (c-theorem valid)**

➡ **IR limit: thermal entropy**

[Zamolodchikov; JETP Lett.(1986)]
[Komargodski,Schwimmer; (2011)]
[Osborn; Phys.Lett.B(1988)]
[Cardy; Phys.Lett.B(1988)]