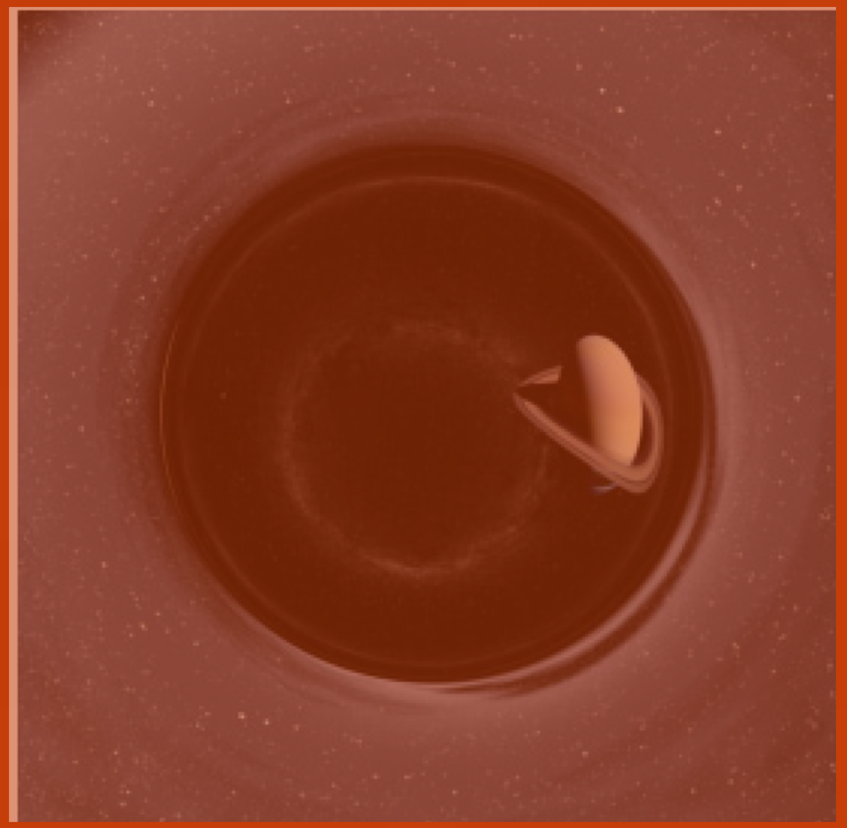
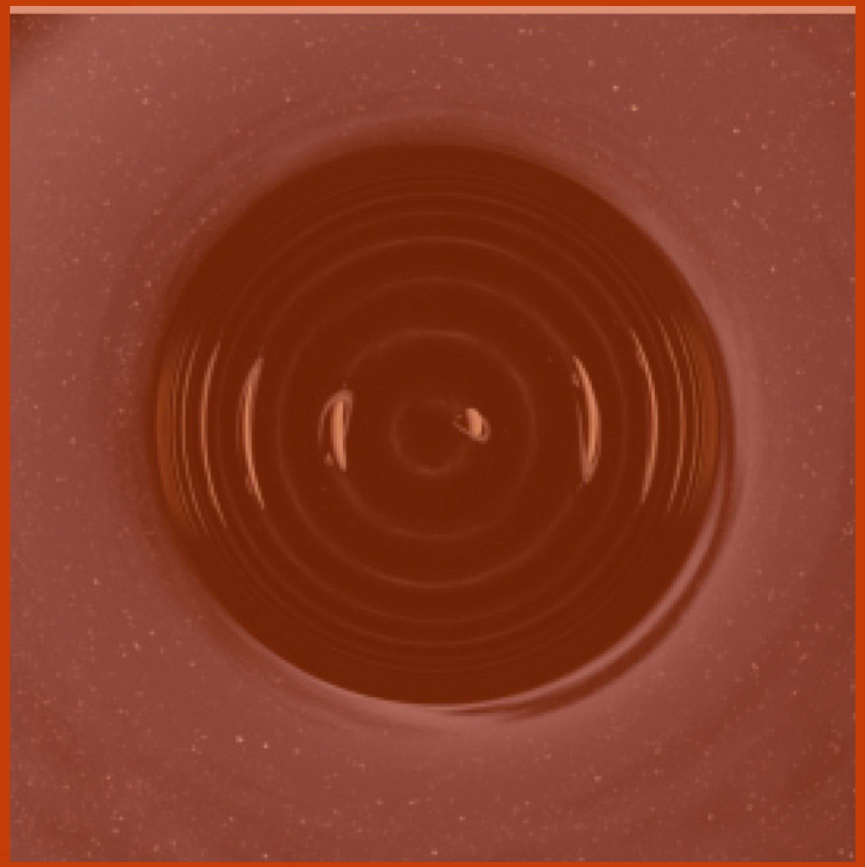
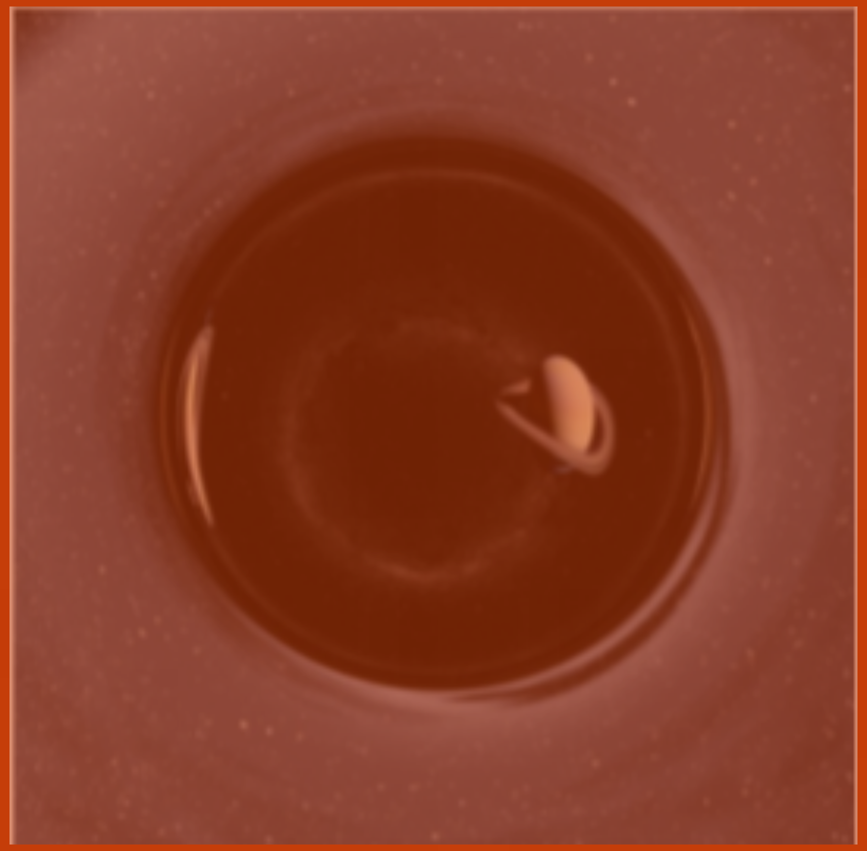
Quantum systems and traversable wormholes

Carlos Sabín
ComFuturo Researcher
IFF, CSIC







ComFuturo
Ciencia, Juventud
y Talento

Fundación General CSIC

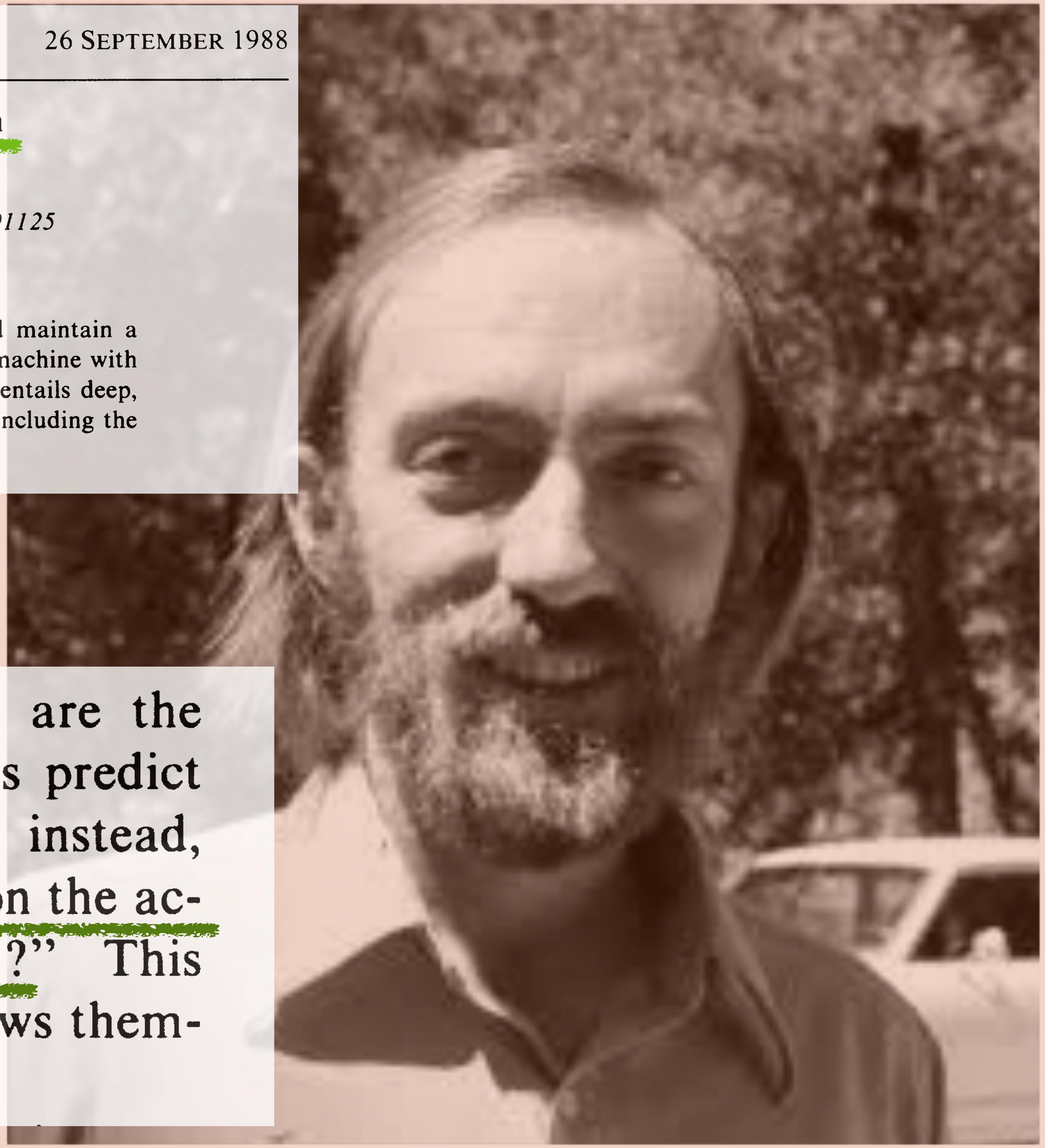
VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

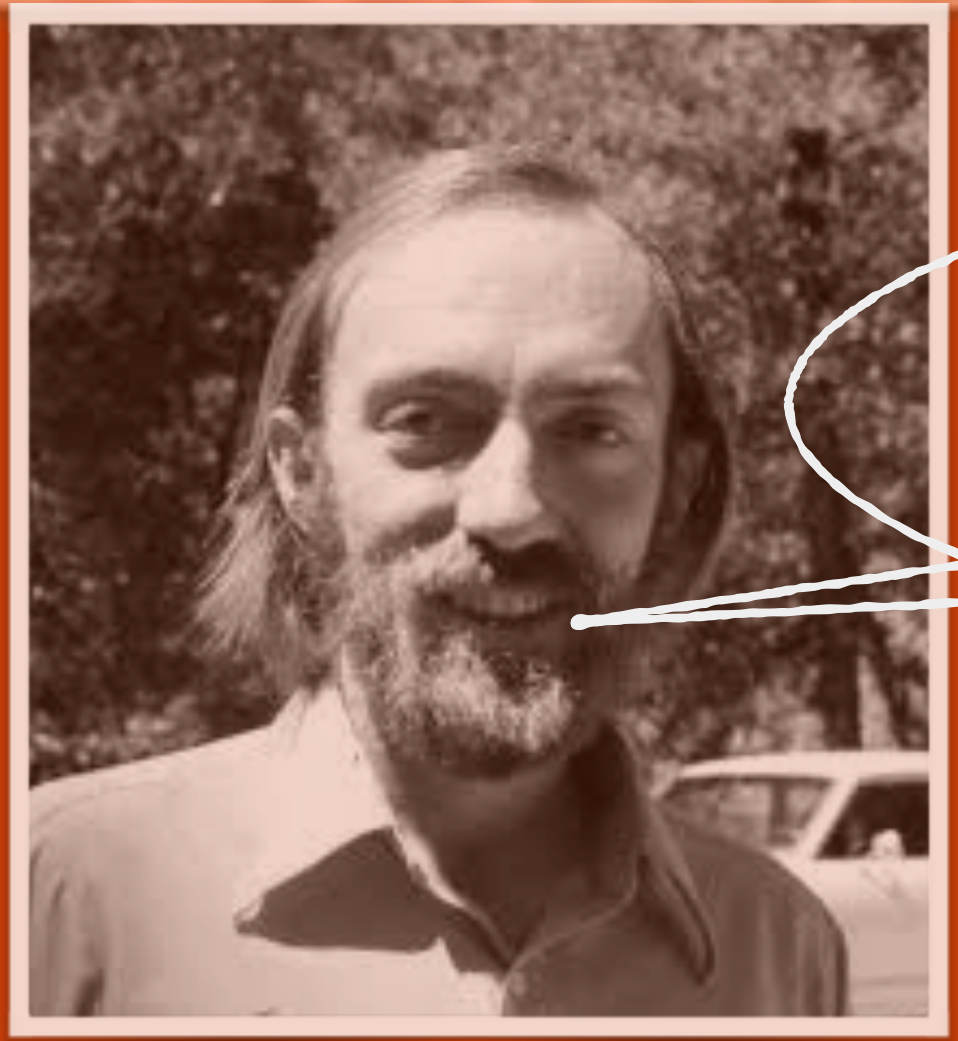
Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

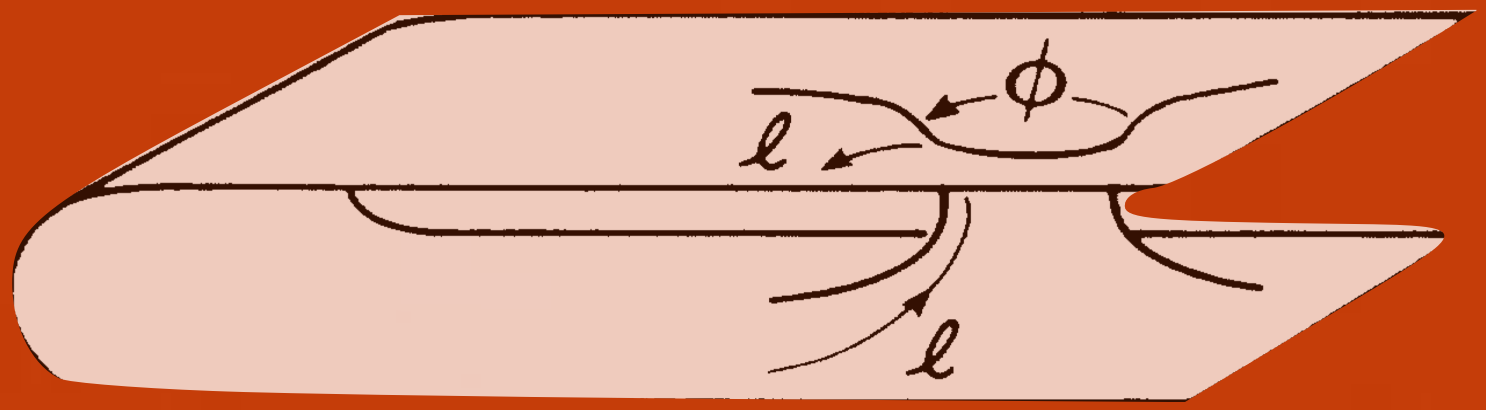
It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

Normally theoretical physicists ask, "What are the laws of physics?" and/or, "What do those laws predict about the Universe?" In this Letter we ask, instead, "What constraints do the laws of physics place on the activities of an arbitrarily advanced civilization?" This will lead to some intriguing queries about the laws themselves.





"Of all thought experiments, perhaps the most helpful are those that push the laws of physics in the most extreme ways" (Kip S. Thorne, Proceedings 13th Conference GR and Gravitation 1993)



Quantum simulators as tools to explore the frontiers of theoretical physics.

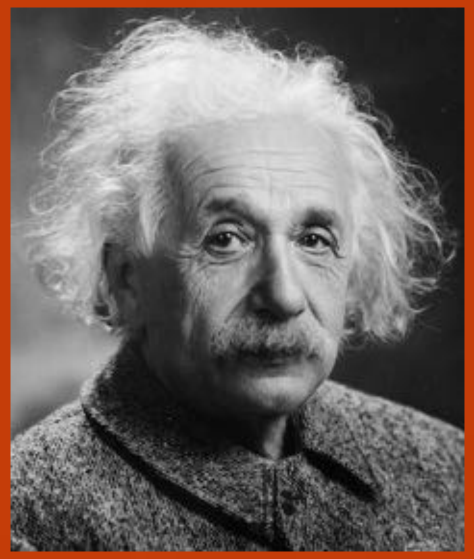
A brief history of wormholes

JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

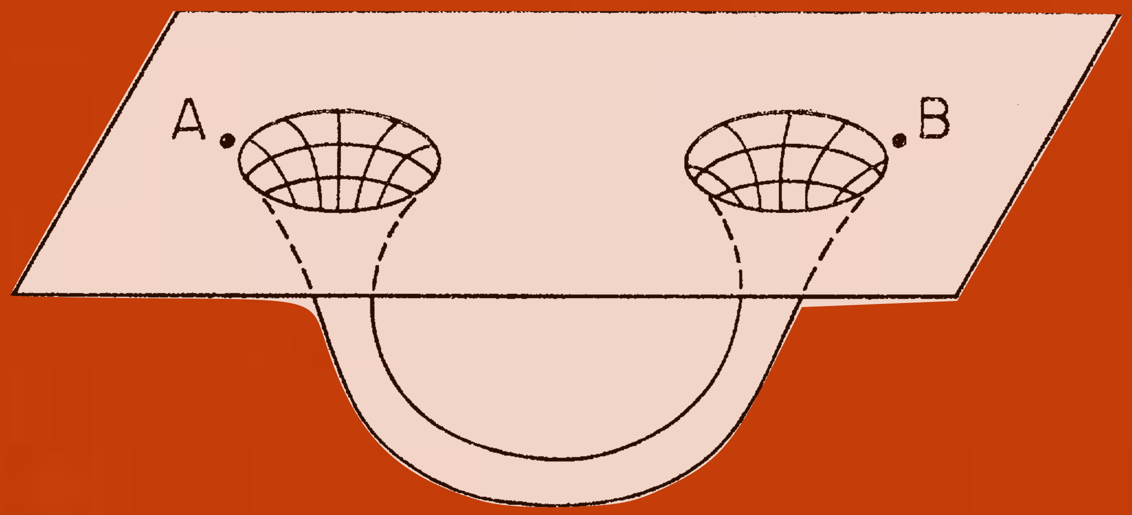
A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)



ER bridges =wormholes in Schwarzschild spacetime

$$ds^2 = -\left(1 - \frac{2m}{r}\right) dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2),$$



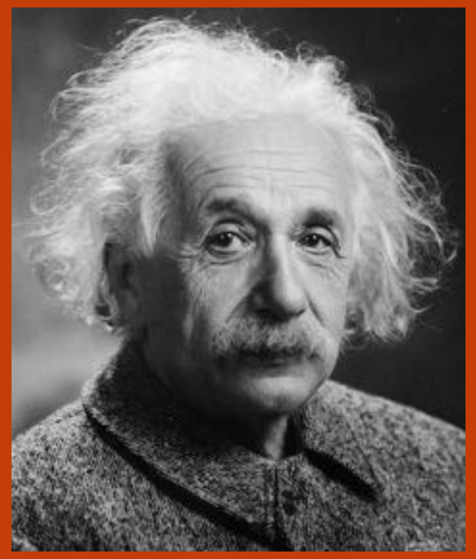
A brief history of wormholes

JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

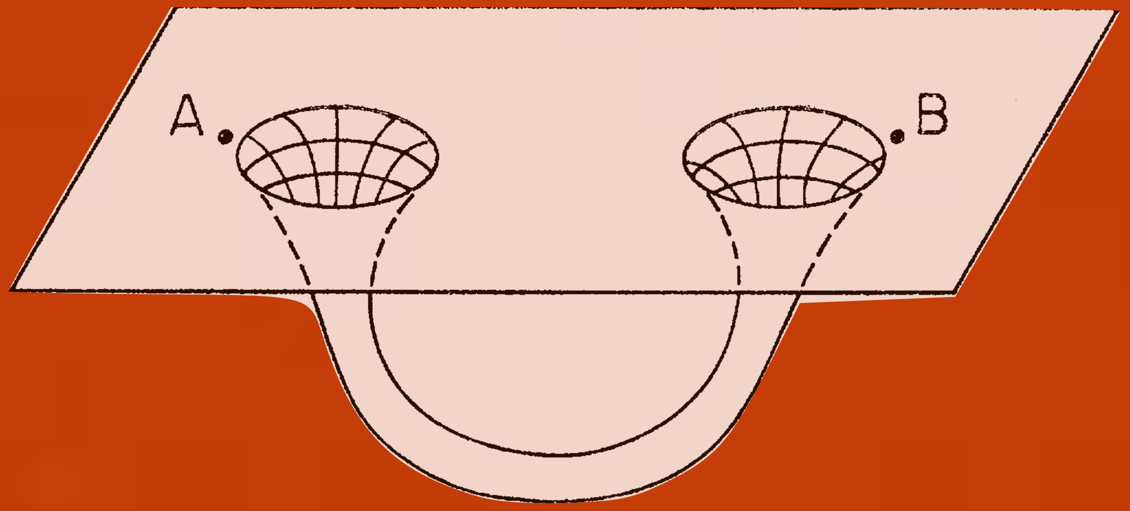
A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)

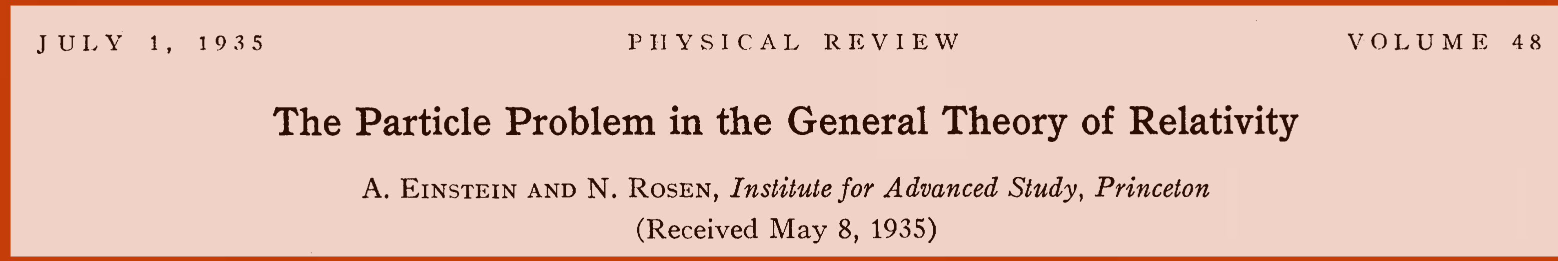


ER bridges =wormholes in Schwarzschild spacetime

$$ds^2 = -\left(1 - \frac{2m}{r}\right) dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2 + r^2 (d\theta^2 + \sin^2\theta d\phi^2),$$



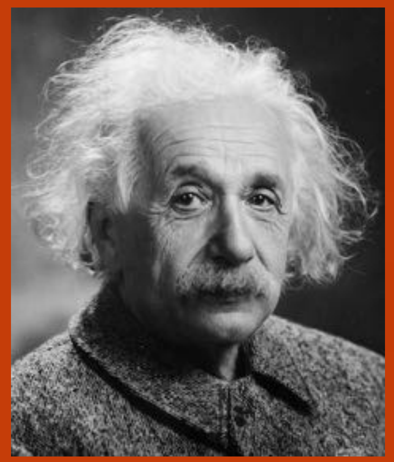
A brief history of wormholes

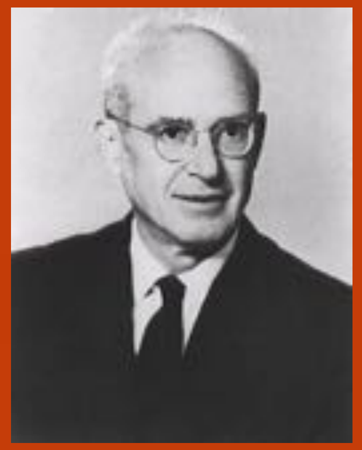

JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

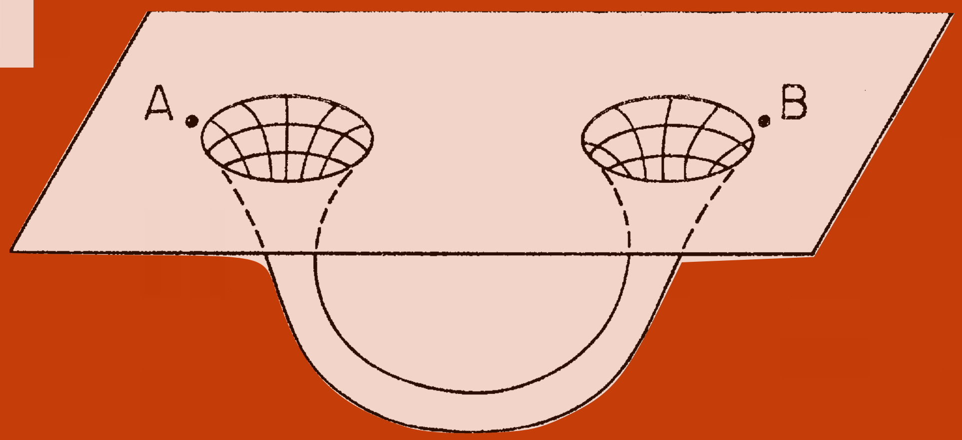
A. Einstein and N. Rosen, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)





ER bridges =wormholes in Schwarzschild spacetime



$$ds^2 = -\left(1 - \frac{2m}{r}\right) dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2$$
$$+ r^2 (d\theta^2 + \sin^2\theta d\phi^2),$$

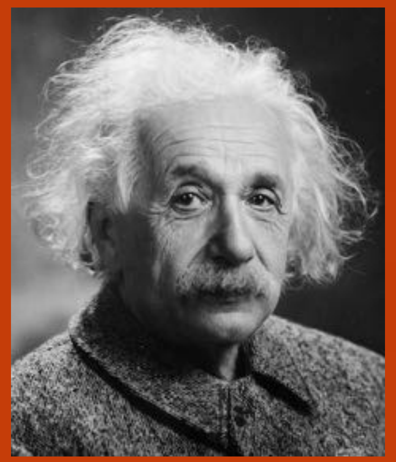
A brief history of wormholes

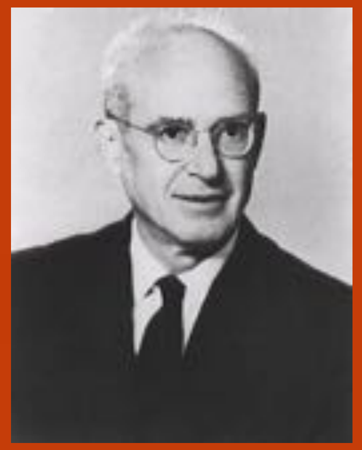
JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

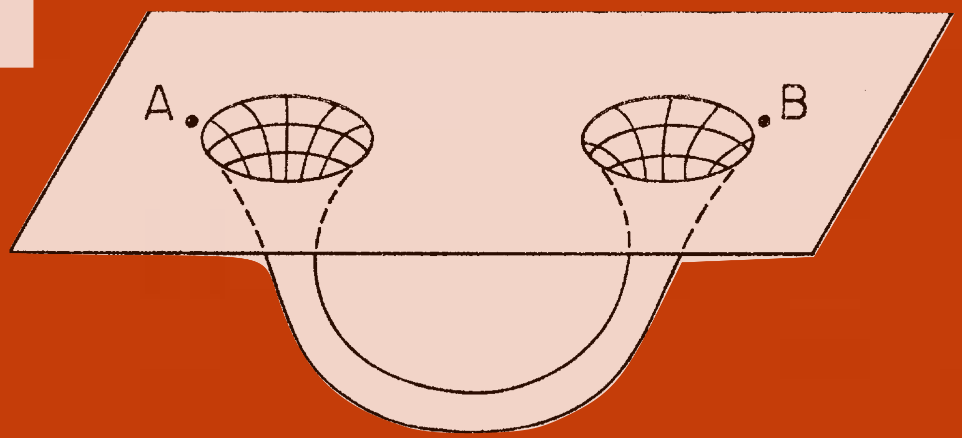
A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)





ER bridges =wormholes in Schwarzschild spacetime



$$ds^2 = -\left(1 - \frac{2m}{r}\right)dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2),$$

ER bridges = non- traversable wormholes

PHYSICAL REVIEW VOLUME 128, NUMBER 2 OCTOBER 15, 1962

Causality and Multiply Connected Space-Time

ROBERT W. FULLER*
Pupin Physical Laboratories, Columbia University, New York, New York

AND

JOHN A. WHEELER†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

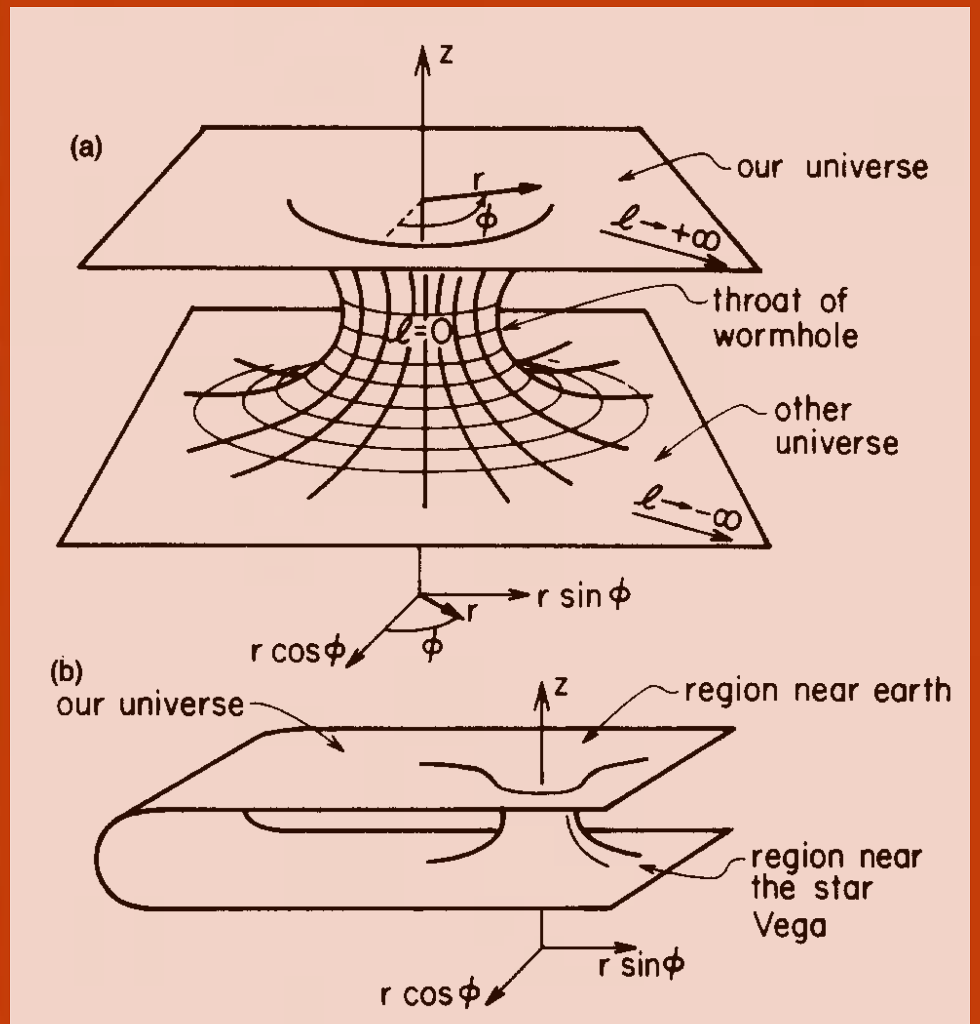
Kruskal time evolution of embeddings of space like surfaces in Schwarzschild metric (Am. J. Phys 80, 203 (2012))

A brief history of wormholes

Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

Michael S. Morris and Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

(Received 16 March 1987; accepted for publication 17 July 1987)

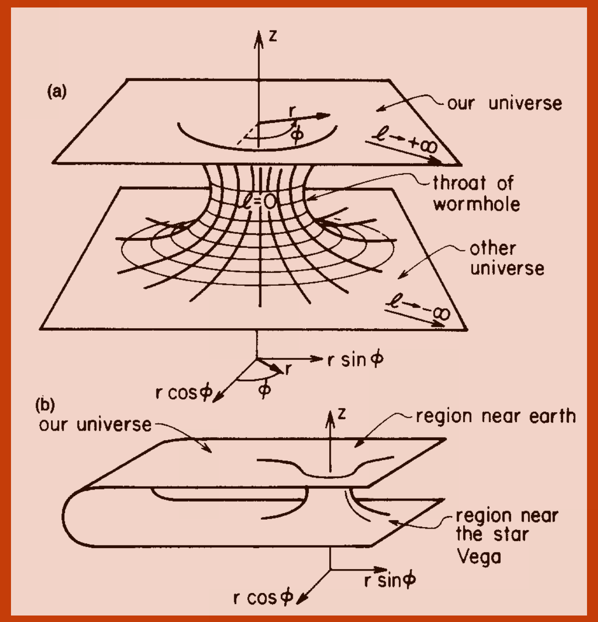


Traversable wormholes!

But… “negative energy”

$$ds^2 = -e^{2\Phi}c^2\,dt^2 + dr^2/(1-b/r) + r^2(d\theta^2 + \sin^2\theta\,d\phi^2).$$

A brief history of wormholes



Traversable wormholes!

But… "**negative** energy"

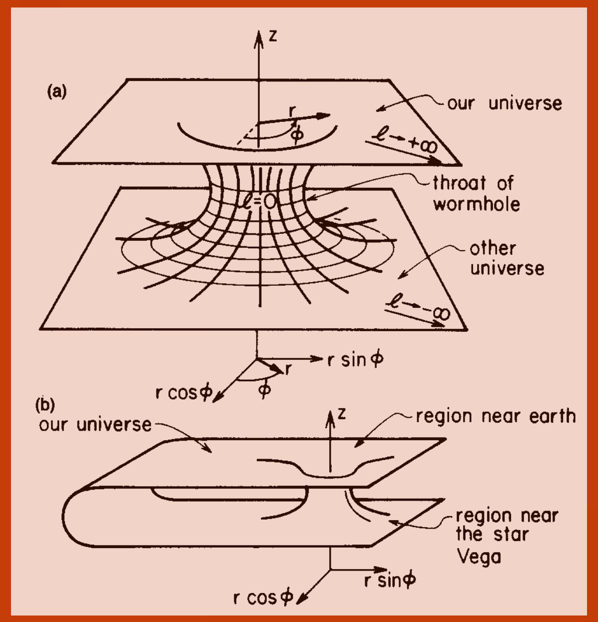
Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

Michael S. Morris and Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

(Received 16 March 1987; accepted for publication 17 July 1987)

$$ds^2 = -e^{2\Phi}c^2\,dt^2 + dr^2/(1-b/r) + r^2(d\theta^2 + \sin^2\theta\,d\phi^2).$$

A brief history of wormholes



Traversable wormholes!

Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

Michael S. Morris and Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

(Received 16 March 1987; accepted for publication 17 July 1987)

But… "negative energy"

$$ds^2 = -e^{2\Phi}c^2\,dt^2 + dr^2/(1-b/r) + r^2(d\theta^2 + \sin^2\theta\,d\phi^2).$$

VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

Wormholes, Time Machines, and the Weak Energy Condition

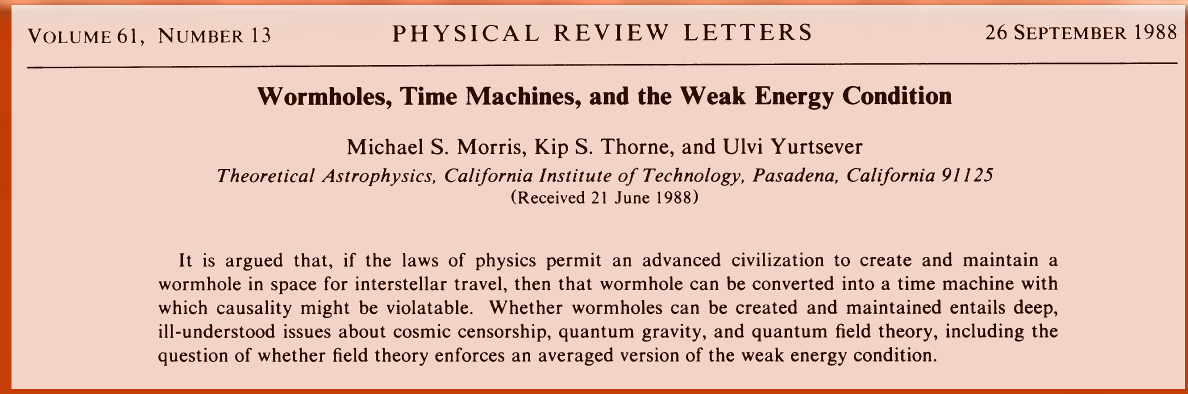
Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

(Received 21 June 1988)

It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

And…

How to turn the wormhole into a time machine


VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

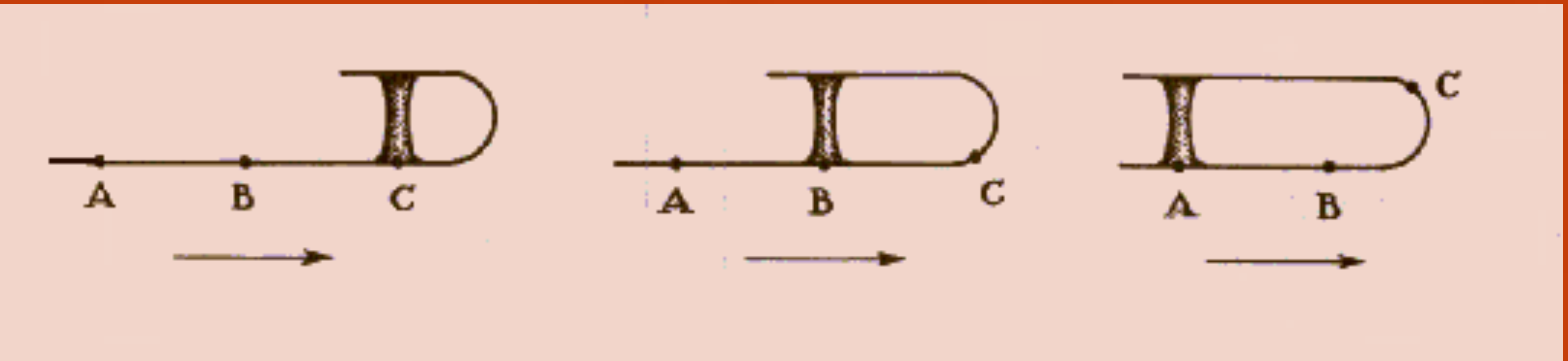
Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

And… How to turn the wormhole into a time machine

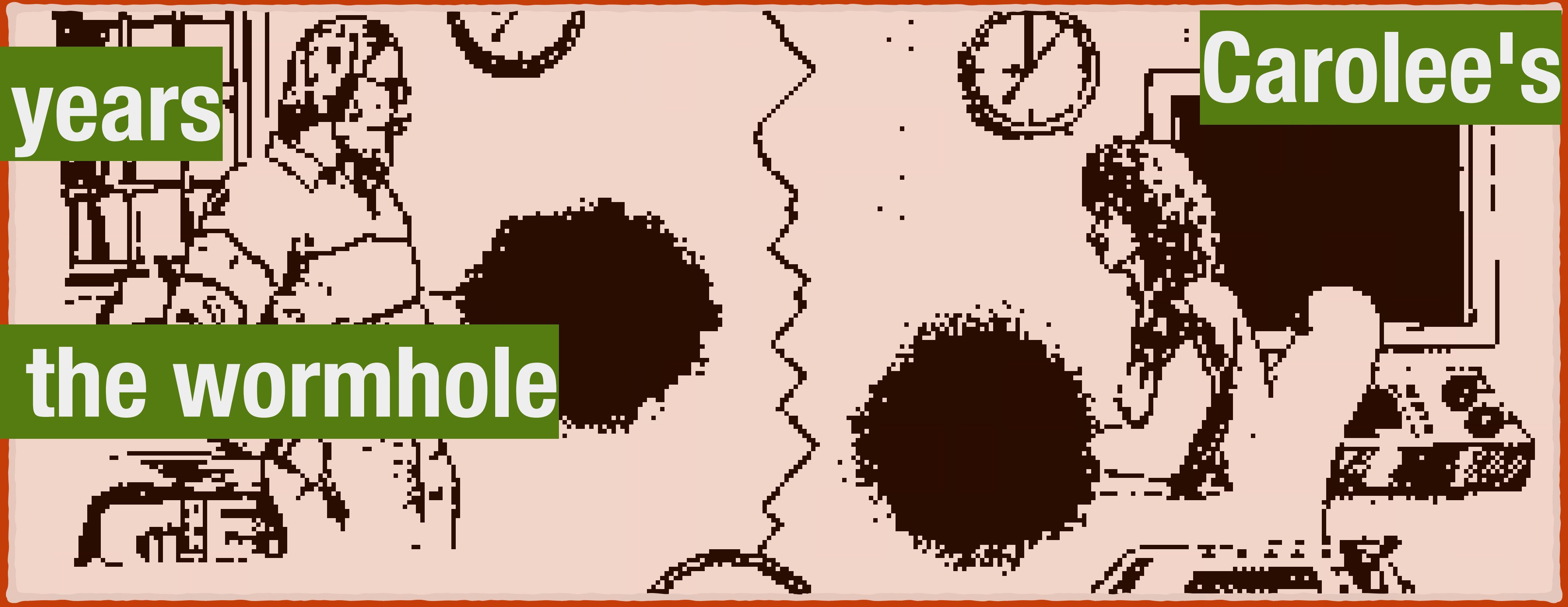
Relative motion of wormhole mouths



Acceleration → twin paradox effect for external observers **but not through the wormhole!**

Carolee goes to a **distant star** with one mouth and comes back

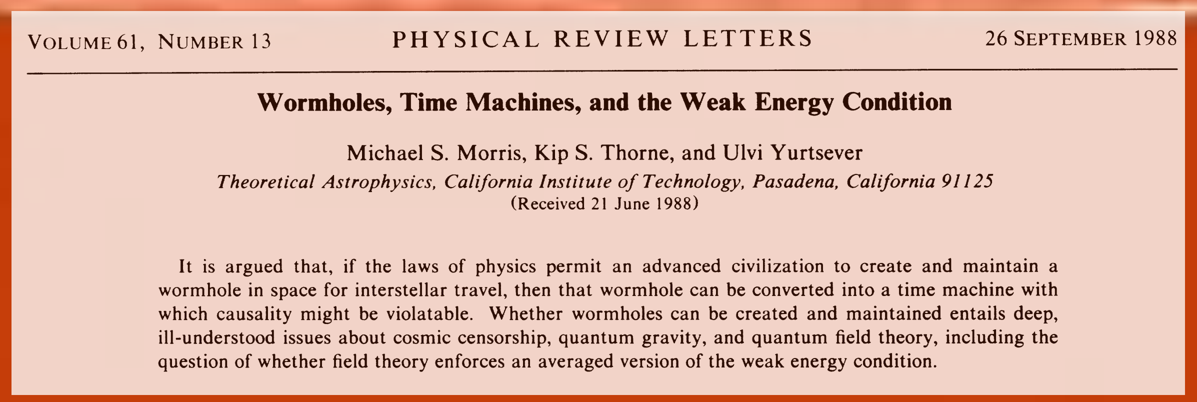
Kip´s proper time: **10 years**



Carolee's proper time: **12 hours**

But **same time through the wormhole**

When she´s back, if Kip traverses the wormhole from her mouth to his, he accesses his own **past**



VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

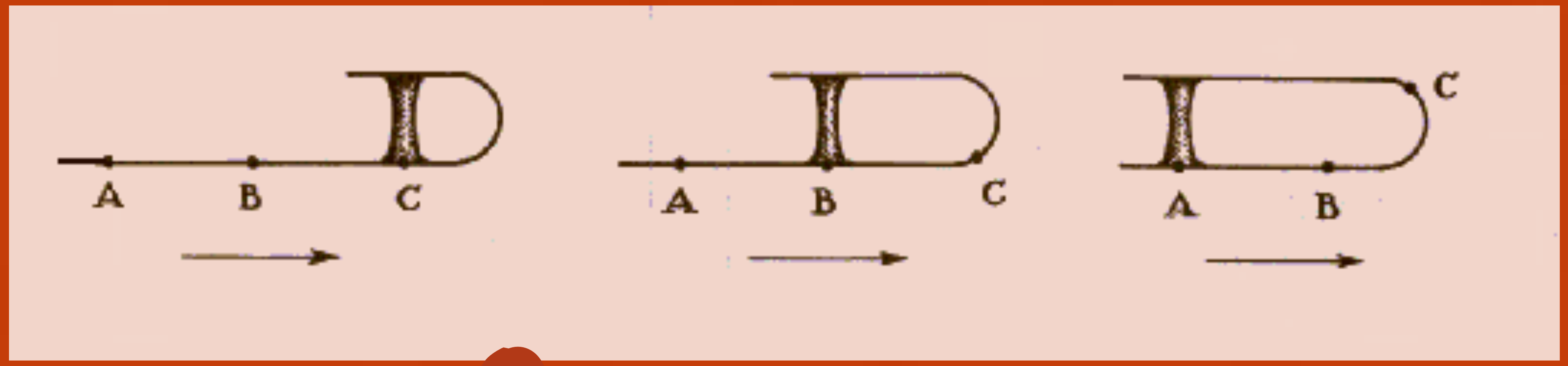
Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

And… How to turn the wormhole into a time machine

Relative motion of wormhole mouths



Acceleration → twin paradox effect for extern… ers **but not through the wormhole!**

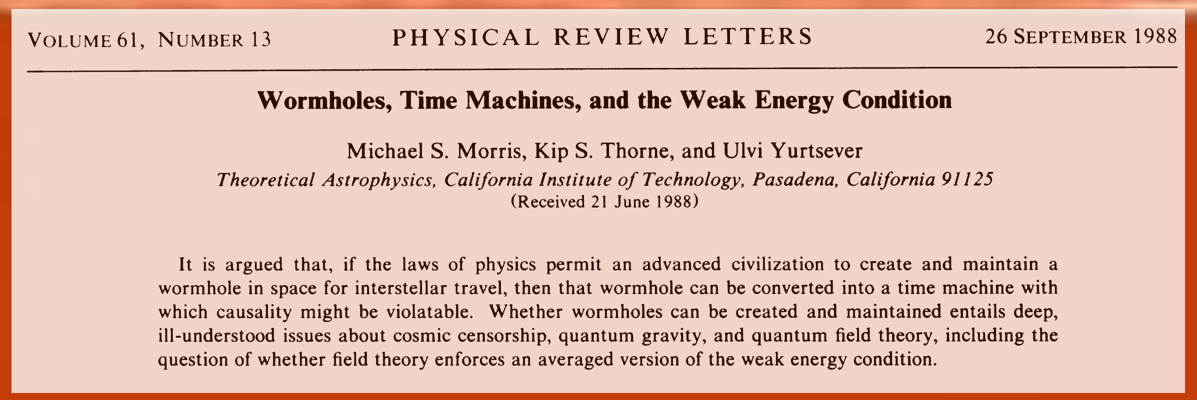
Carolee goes to a **distant star** with one mout…

Kip´s proper time: **10 year…**

Carolee's proper time: **12 hours**

But **same time through the w…**

When she´s back, if Kip traverses the wormhole from her mouth to his, he accesses his own **past**


VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

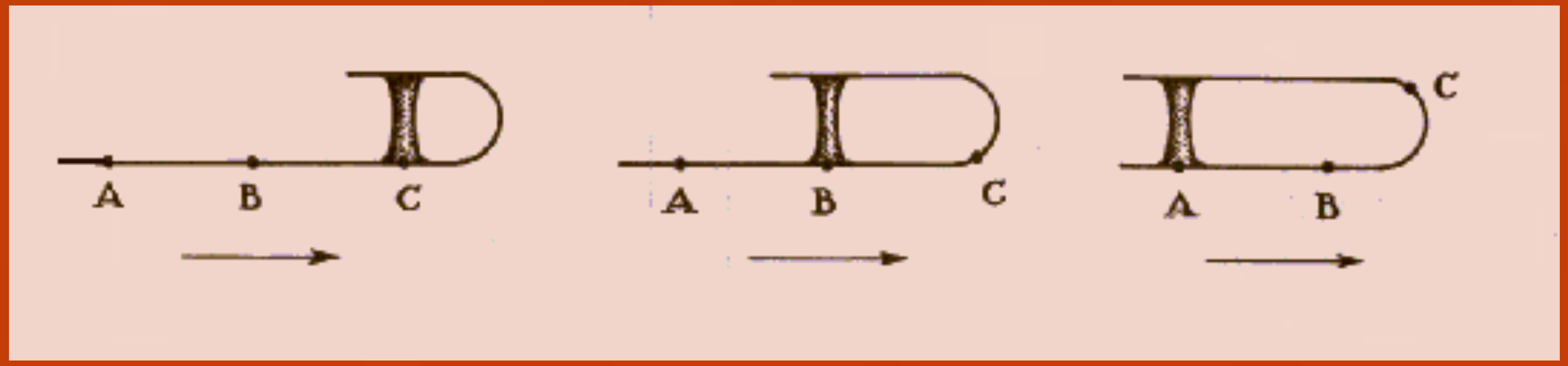
Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

And… How to turn the wormhole into a time machine

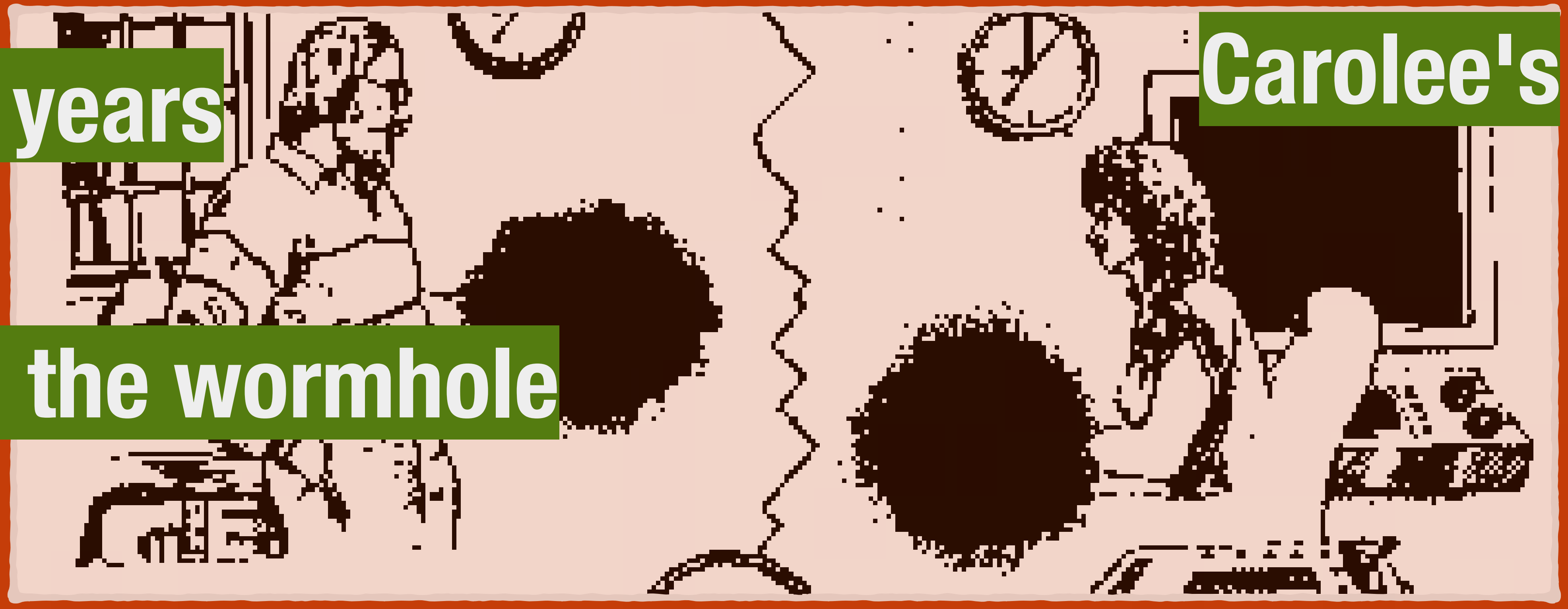
Relative motion of wormhole mouths



Acceleration → twin paradox effect for external observers **but not through the wormhole!**

Carolee goes to a **distant star** with one mouth and comes back

Kip´s proper time: **10 years**

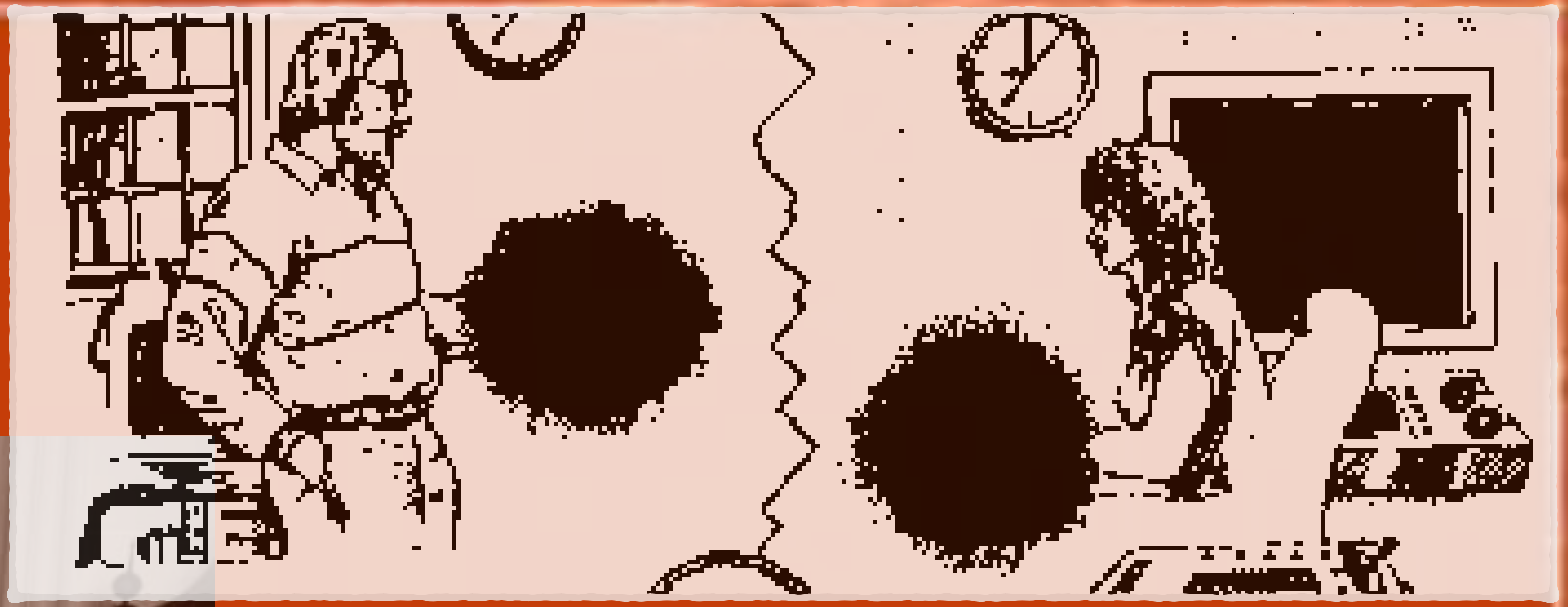


Carolee's proper time: **12 hours**

But **same time** **through the wormhole**

When she´s back, if Kip traverses the wormhole from her mouth to his, he accesses his own **past**

GEDANKEN



PHYSICAL REVIEW D VOLUME 46, NUMBER 2 15 JULY

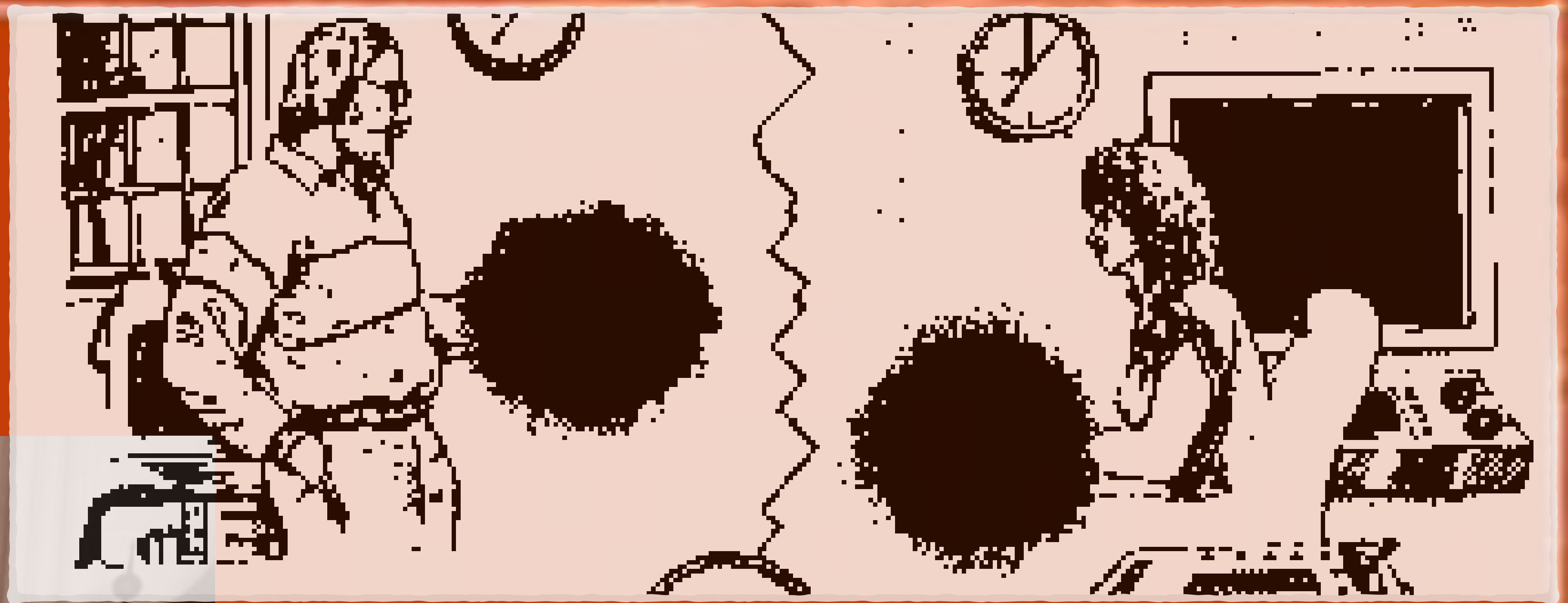
Chronology protection conjecture

S. W. Hawking
Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Silver Street, Cambridge CB3 9EW, United Kingdom
(Received 23 September 1991)

machine. It seems there is a chronology protection agency, which prevents the appearance of closed timelike curves and so makes the universe safe for historians.

Do quantum effects prevent CTCs?

CENSORED



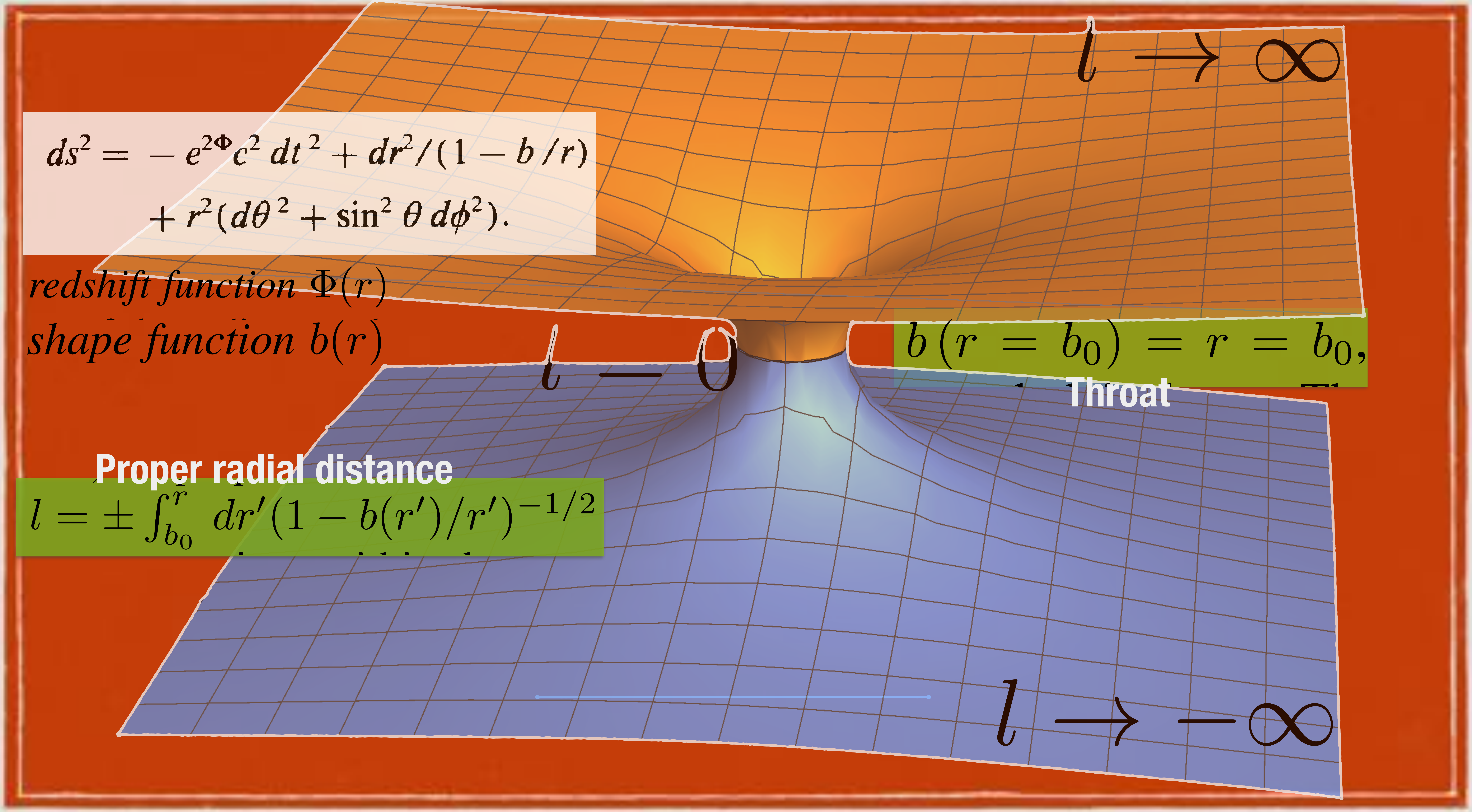
PHYSICAL REVIEW D VOLUME 46, NUMBER 2 15 JULY

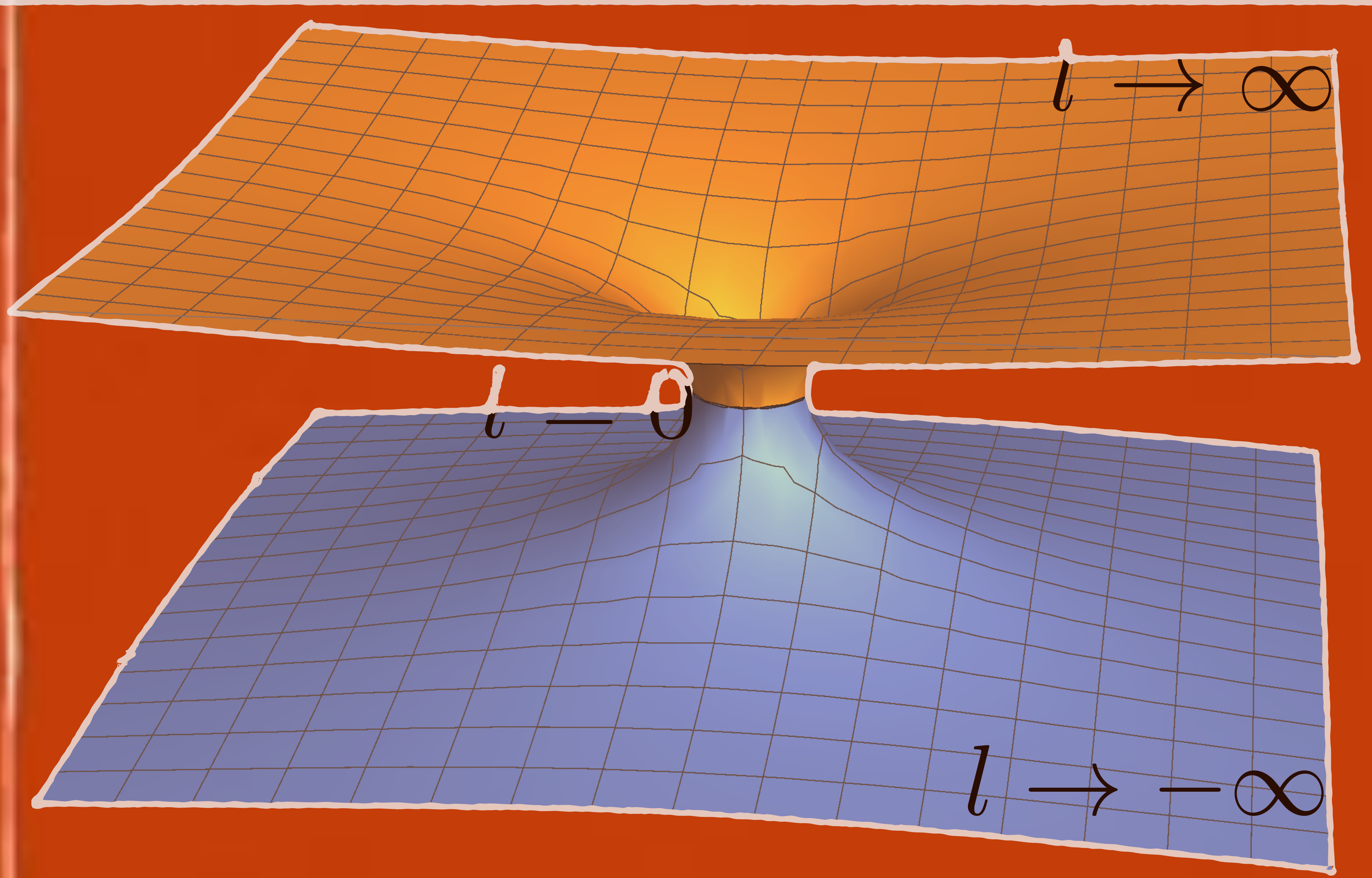
Chronology protection conjecture

S. W. Hawking
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, United Kingdom
(Received 23 September 1991)

machine. It seems there is a chronology protection agency, which prevents the appearance of closed timelike curves and so makes the universe safe for historians.

Do quantum effects prevent CTCs?


$ds^2 = -e^{2\Phi}c^2\,dt^2 + dr^2/(1-b/r)$
$+\,r^2(d\theta^2 + \sin^2\theta\,d\phi^2).$
redshift function $\Phi(r)$
shape function $b(r)$
$l \to \infty$
$l = 0$
$b(r = b_0) = r = b_0,$
Throat
Proper radial distance
$l = \pm\int_{b_0}^{r} dr'(1 - b(r')/r')^{-1/2}$
$l \to -\infty$



$$ds^2 = -e^{2\Phi}c^2\,dt^2 + dr^2/(1 - b/r) + r^2(d\theta^2 + \sin^2\theta\,d\phi^2).$$

massless wormhole $\Phi(r) = 0$ and 1+1 D

$$ds^2 = -c^2\,dt^2 + \frac{1}{1 - \frac{b(r)}{r}}\,dr^2$$

Conformal invariance of K-G equation in 1+1 D

$$ds^2 = -c^2\,(1 - \frac{b(r)}{r})\,dt^2 + dr^2$$

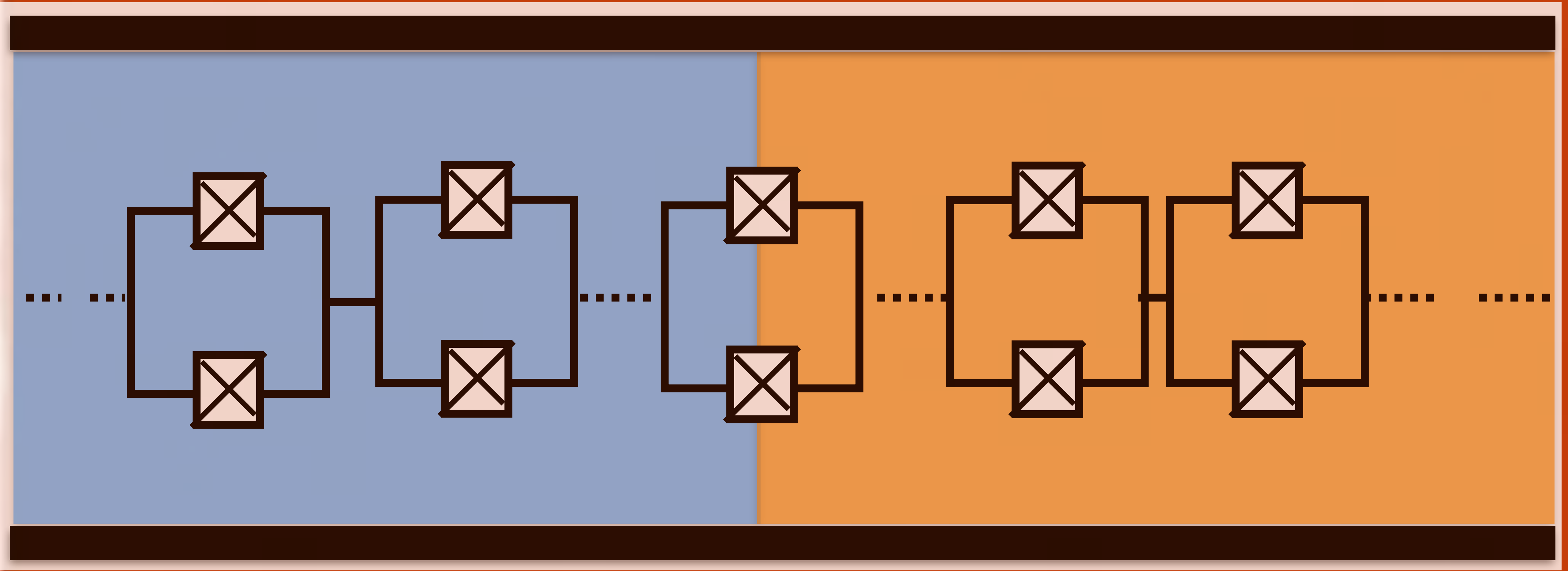
Effective speed of light:

$$c^2(r) = c^2\,(1 - \frac{b(r)}{r})$$

Effective speed of light: $$c^2(r) = c^2\left(1 - \frac{b(r)}{r}\right)$$

Quantum simulation

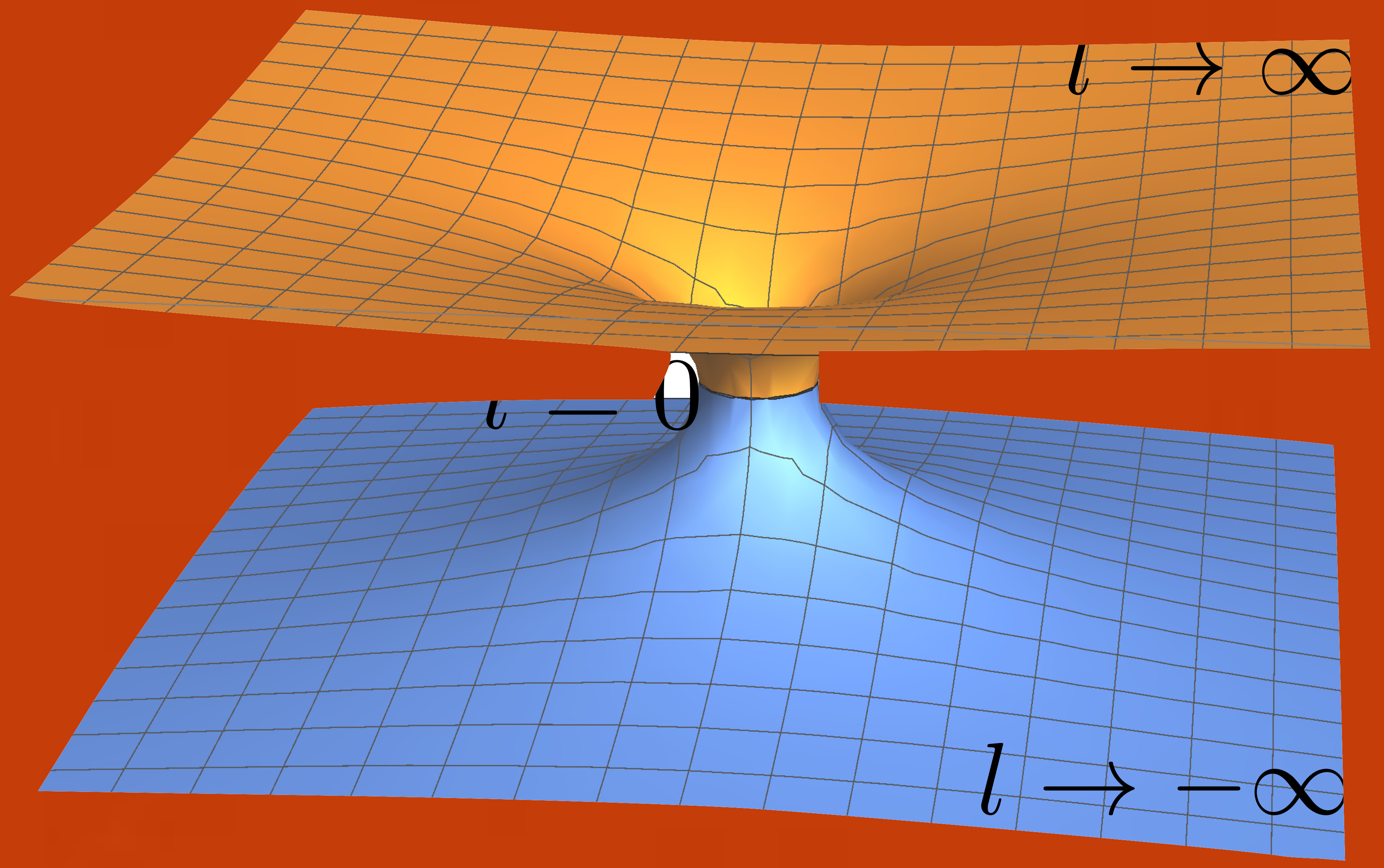
SQUID array embedded in a superconducting transmission line



$$c^2(\phi_{ext}) = c^2 \cos\frac{\pi\phi_{ext}}{\phi_0}$$

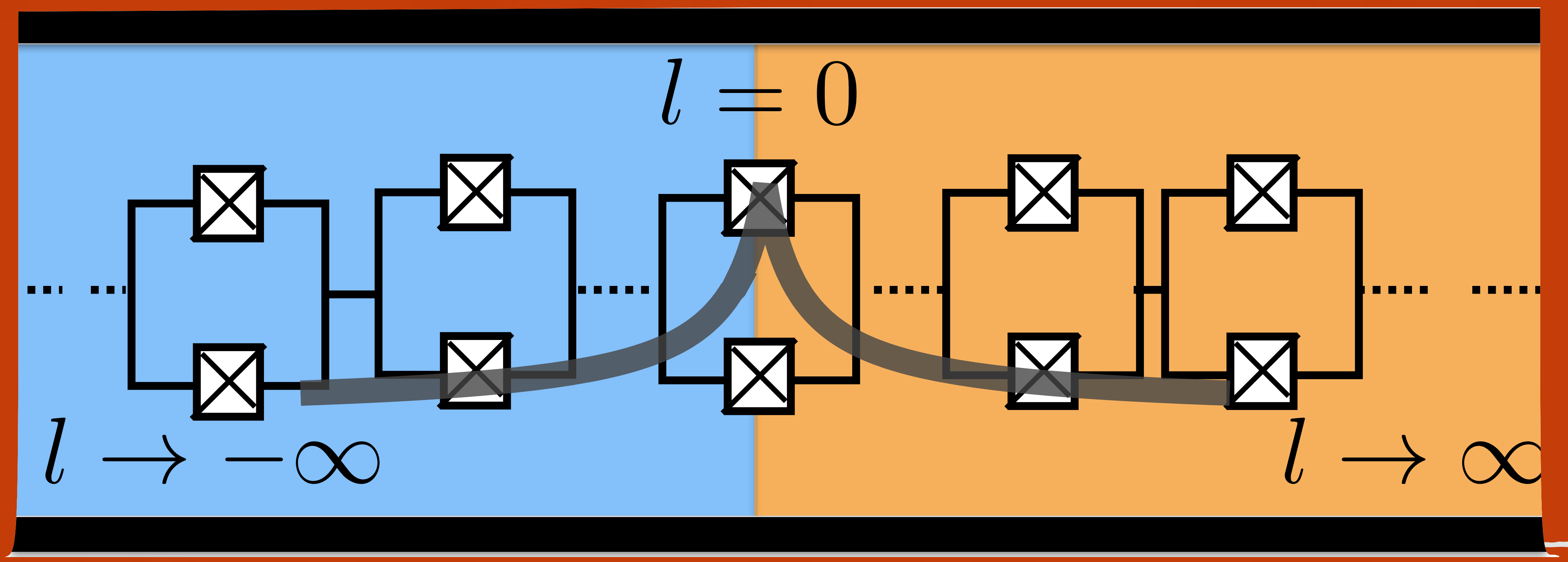
External magnetic flux

C.S. PRD 94, 081501 (2016)



$$c^2(r) = c^2\,(1 - \frac{b(r)}{r})$$

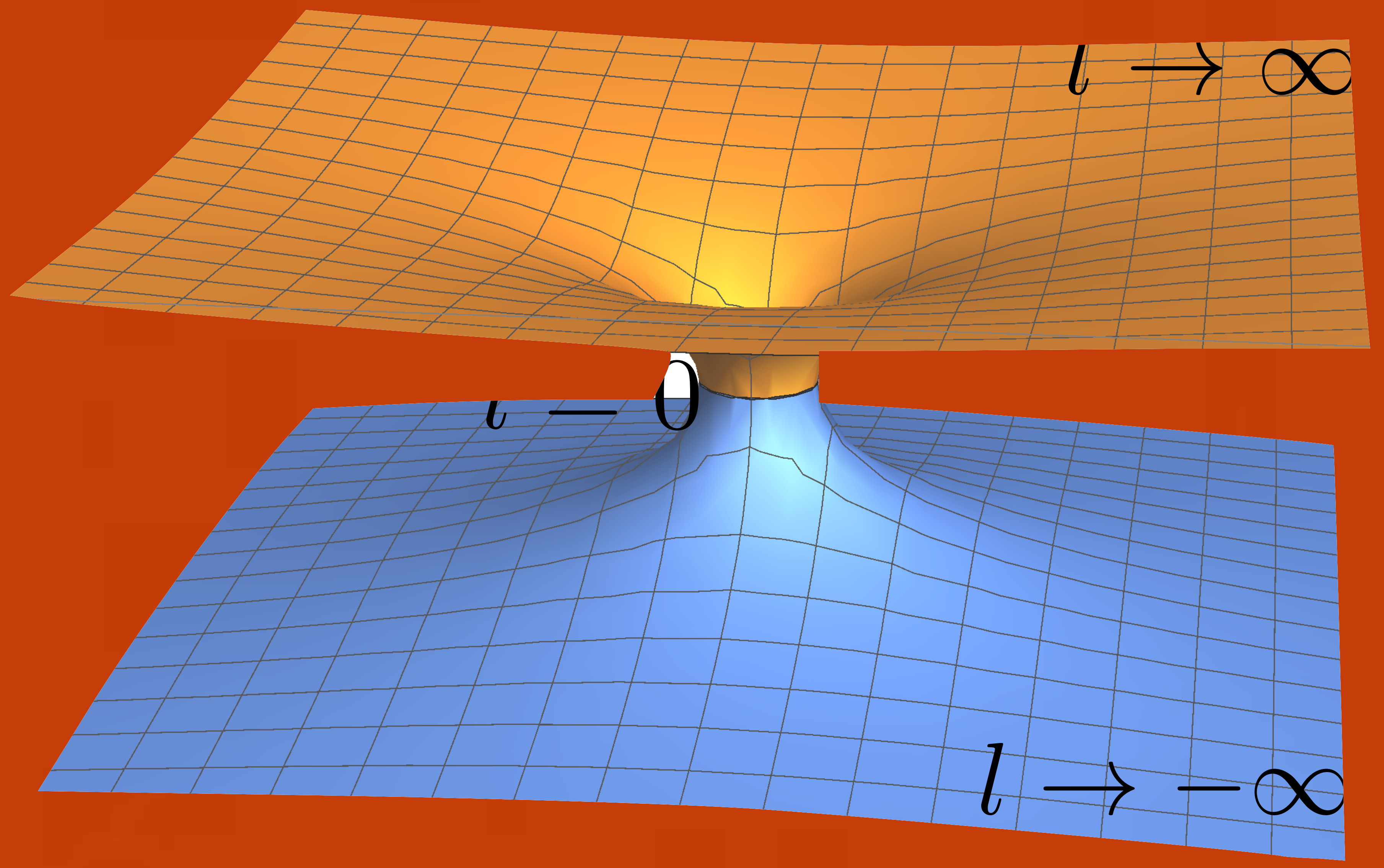
$$\phi_{ext}(r) = \frac{\phi_0}{\pi}\arccos(1 - \frac{b(r)}{r}).$$



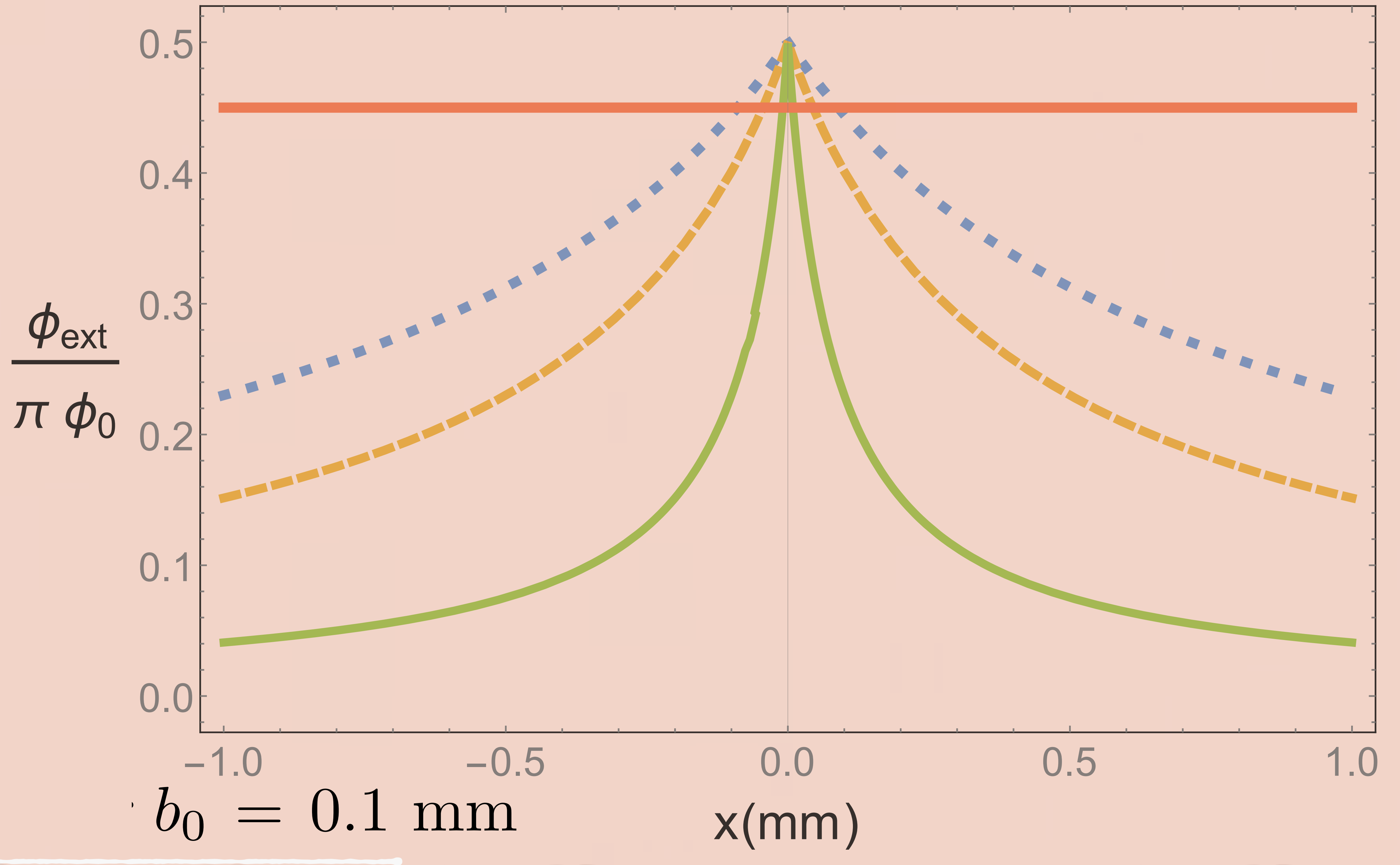
$$c^2(\phi_{ext}) = c^2 \cos\frac{\pi\phi_{ext}}{\phi_0}$$

C.S. PRD 94, 081501 (2016)

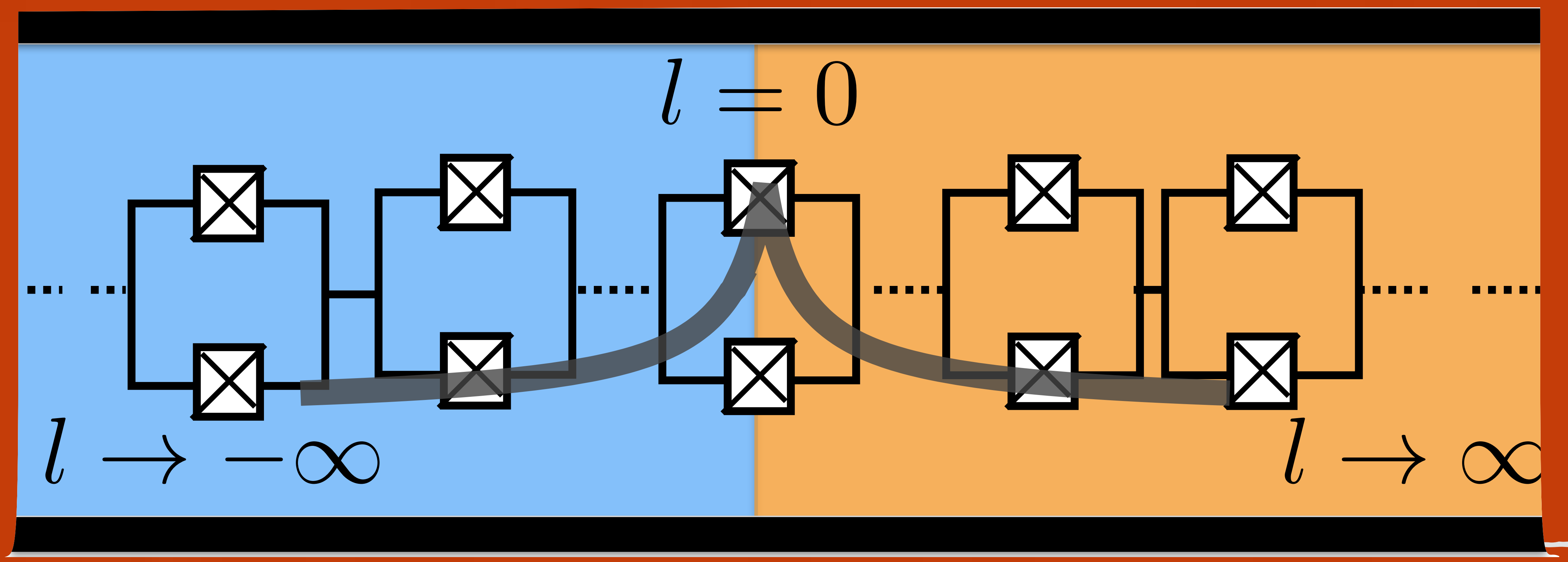
$$\phi_{ext}(r) = \frac{\phi_0}{\pi} \arccos\left(1 - \frac{b(r)}{r}\right).$$



Example: $b(r) = \frac{b_0^2}{r}$ **Ellis 1973, Morris-Thorne 1988**



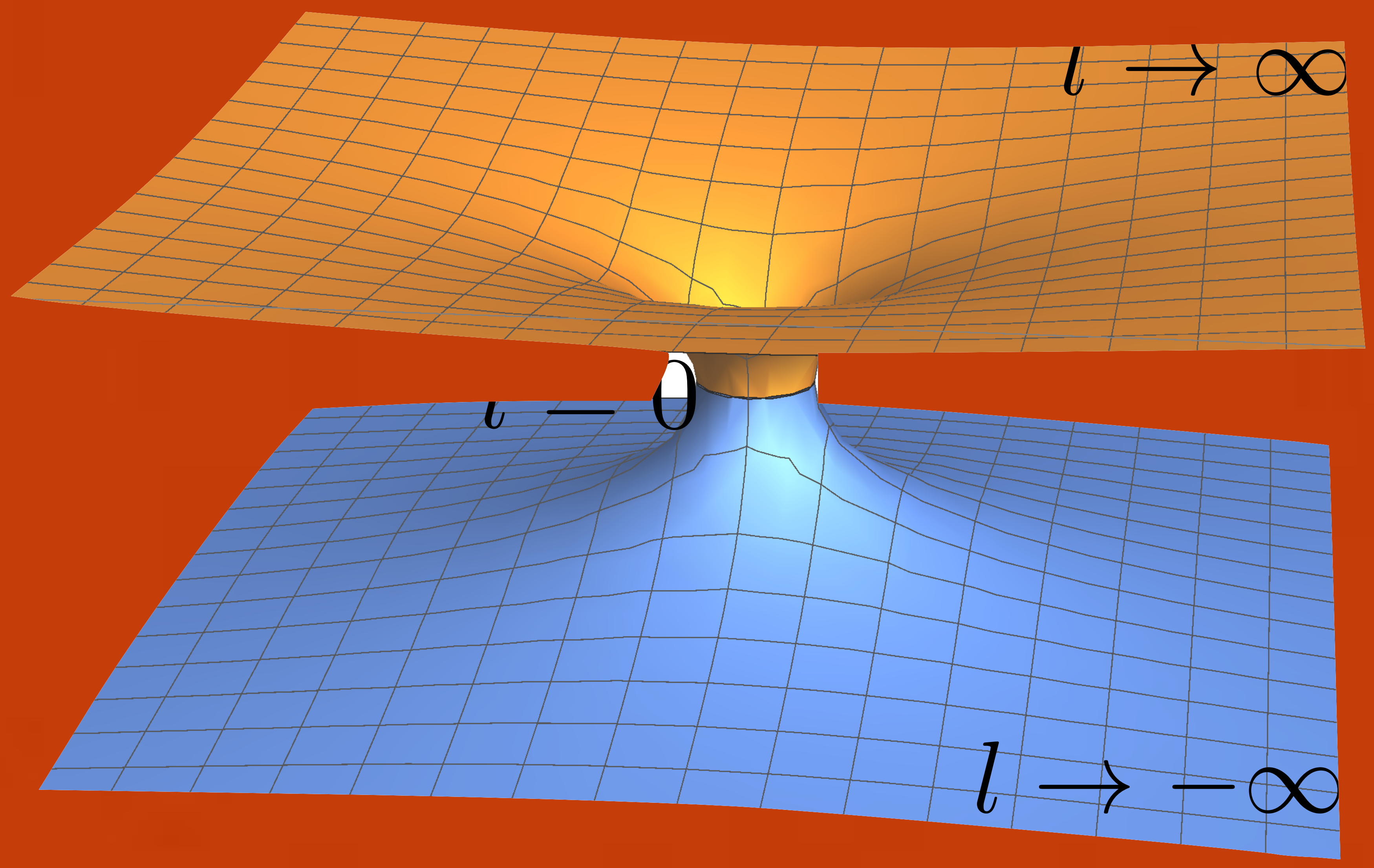
|x|=r-b$_0$



C.S. PRD 94, 081501 (2016)

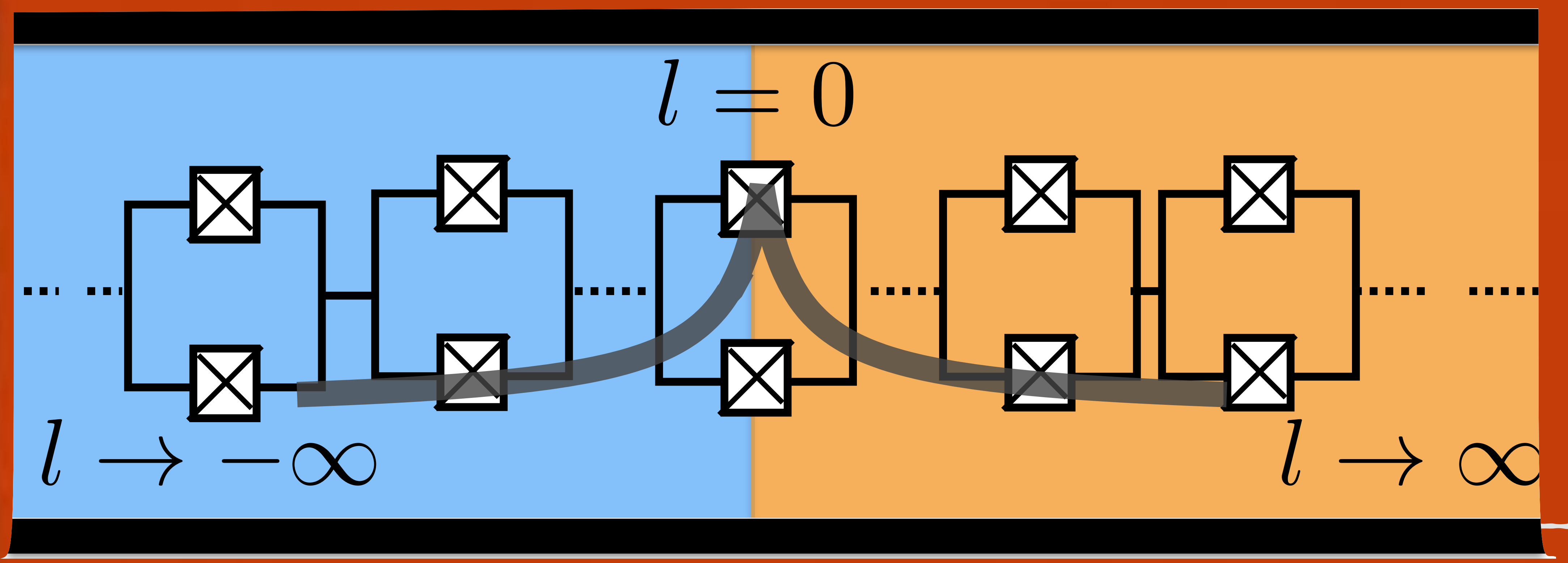
Time machine

$$ds^2 = -c^2 e^{2\Phi(r)}(1+g(t)\,l\,F(l)\cos\theta)^2 dt^2 + \frac{1}{1-\frac{b(r)}{r}}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2),$$

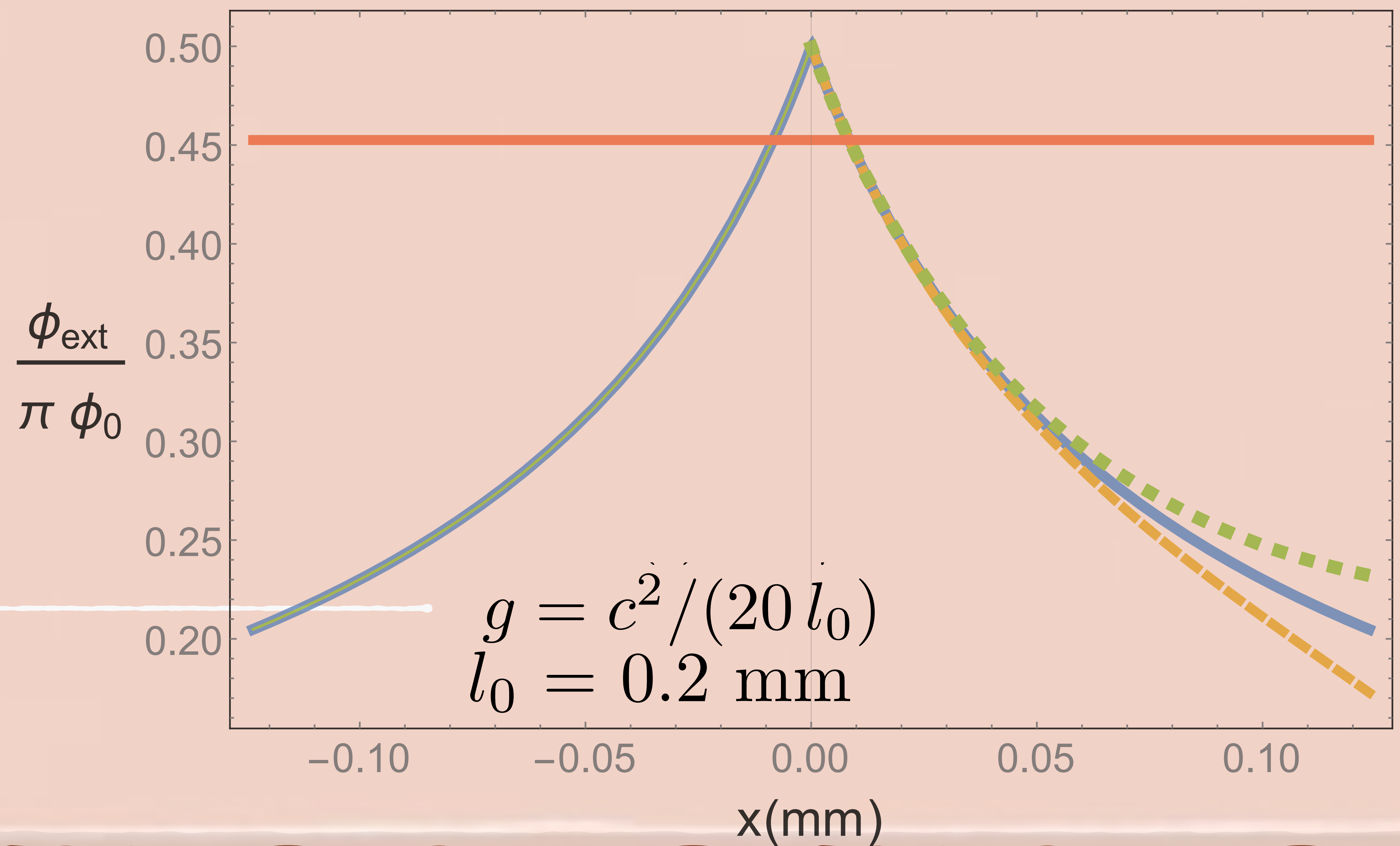


Acceleration $g(t)$ Form factor $F(l)$

$$\phi_{ext}(r,t) = \frac{\phi_0}{\pi}\arccos(1-\frac{b(r)}{r})(1+g(t)\,l\,F(l))^2$$



Interval of constant acceleration



C.S. PRD 94, 081501 (2016)

Effective CTCs in this simulated Universe?

The impedance of the array might grow large and generate quantum fluctuations of the superconducting phase

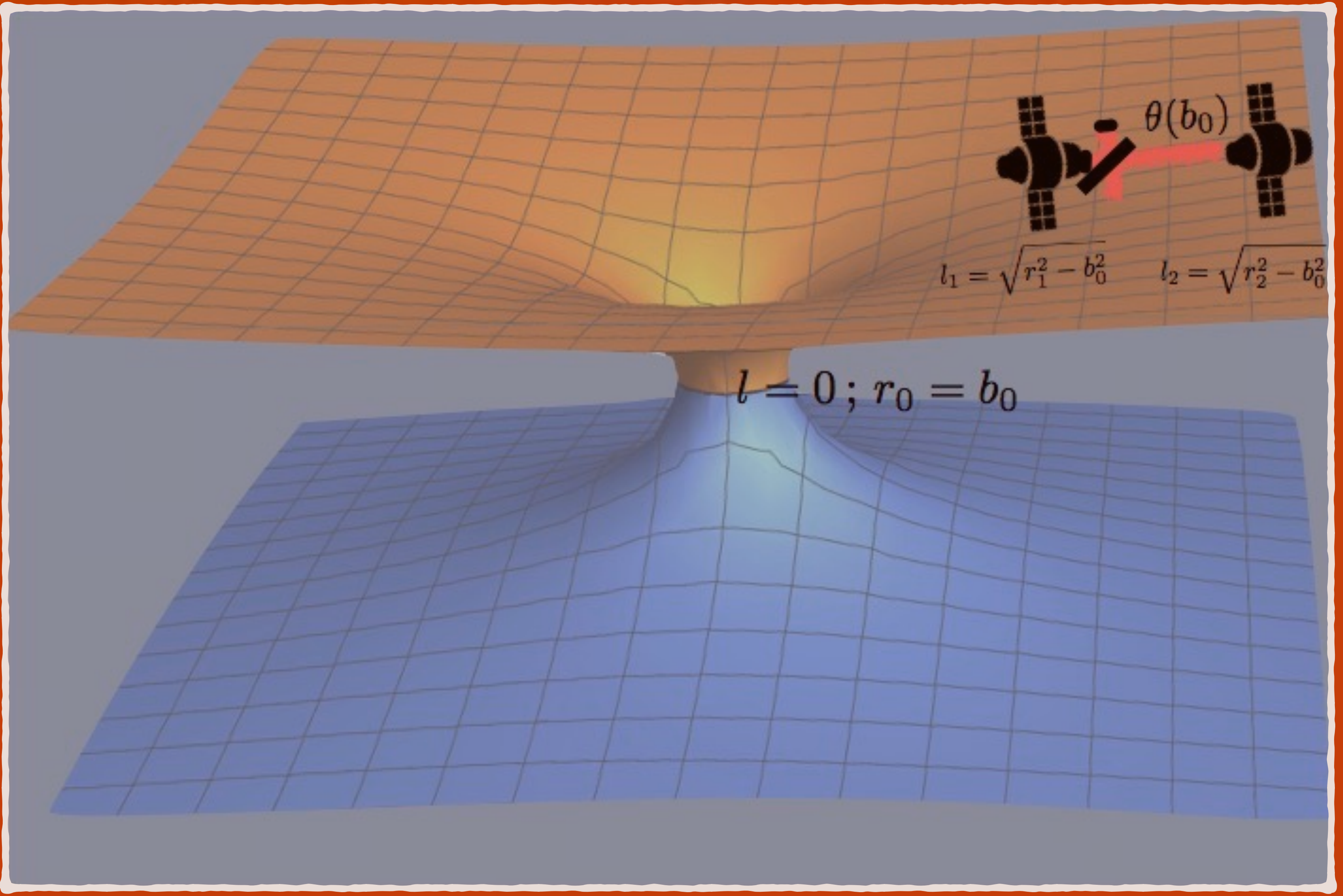
Killer paradox, from “Into S. Hawking´s universe”

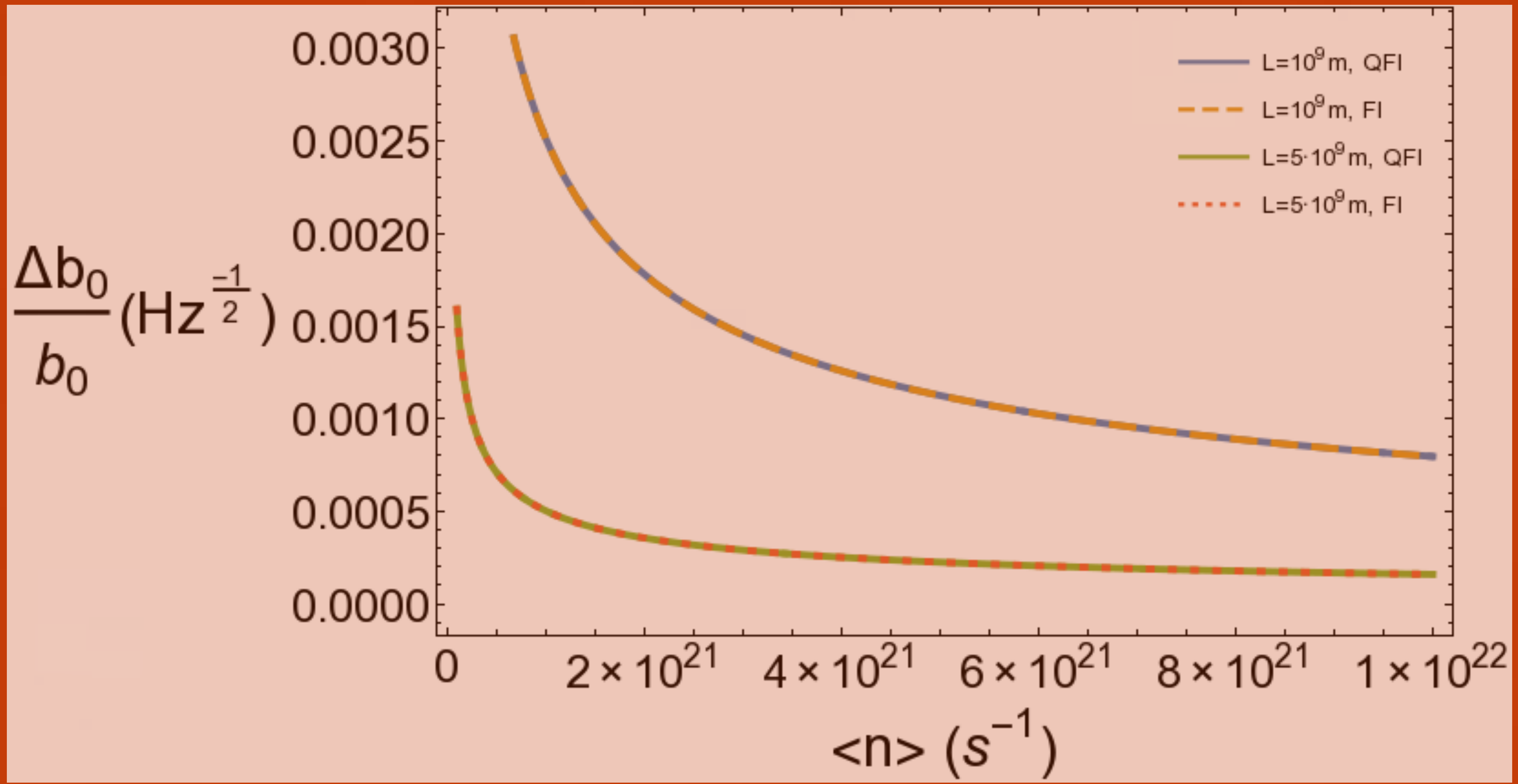
Effective chronology protection?

C.S. PRD 94, 081501 (2016)

Quantum detection?

Space-based laser interferometry (LISA)





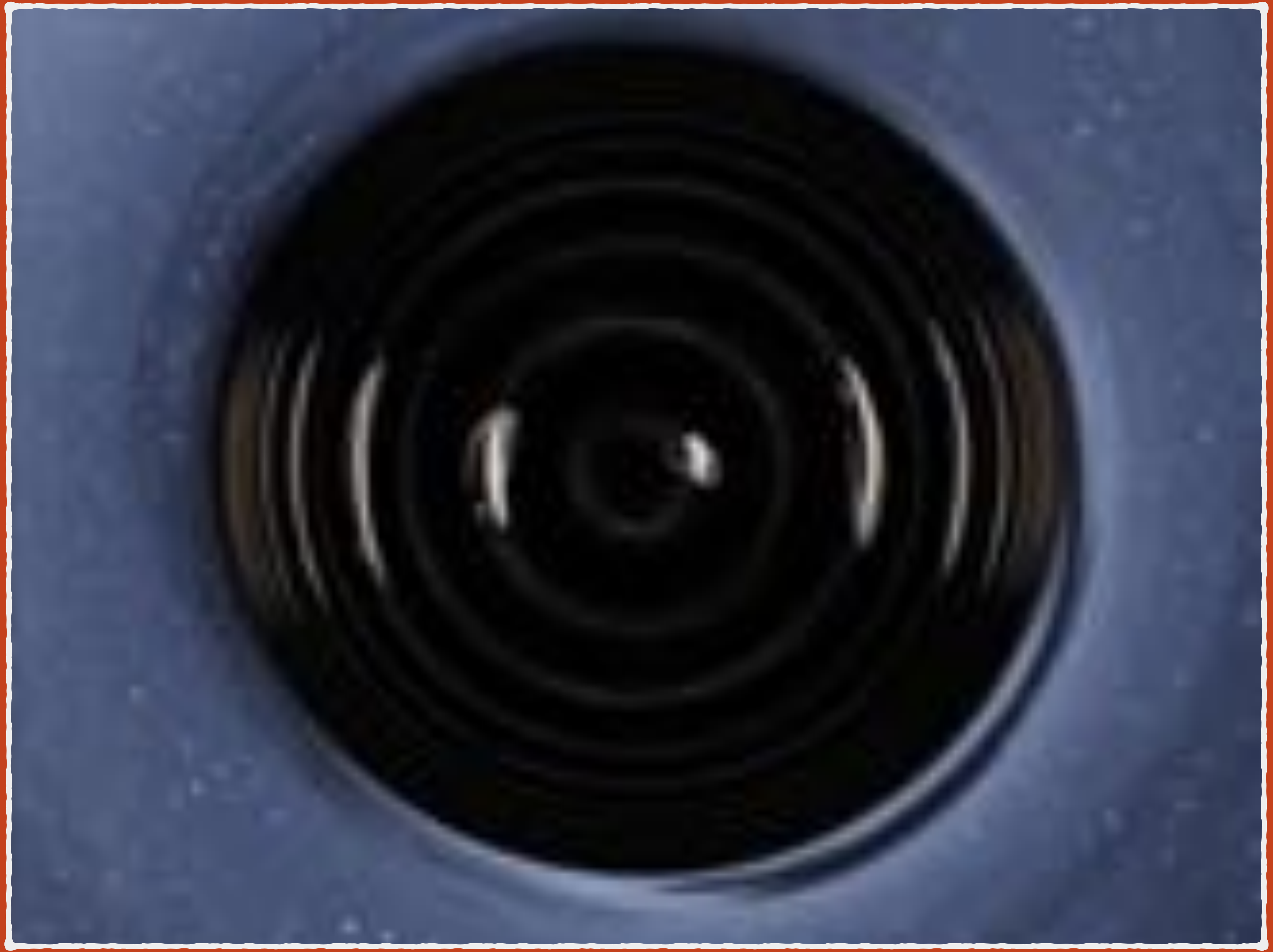
Quantum metrology techniques

Estimation of the throat size of a distant wormhole

Alternative to gravitational lensing schemes

C.S.Sci. Rep. 7, 716 (2017)

Conclusions



- ☐ We have introduced an analogue quantum simulator of a 1+1 D wormhole spacetime and shown how to turn it into a time machine.
- ☐ An analogue chronology-protection mechanism emerges naturally in this superconducting setup.
- ☐ The detection of a real wormhole might be in principle possible with space-based laser interferometers.

Do not go gentle into that good night,
Old age should burn and rave at close of day;
Rage, rage against the dying of the light.

Though wise men at their end know dark is right,
Because their words had forked no lightning they
Do not go gentle into that good night.

Good men, the last wave by, crying how bright
Their frail deeds might have danced in a green bay,
Rage, rage against the dying of the light.

Wild men who caught and sang the sun in flight,
And learn, too late, they grieved it on its way,
Do not go gentle into that good night.

Grave men, near death, who see with blinding sight
Blind eyes could blaze like meteors and be gay,
Rage, rage against the dying of the light.

And you, my father, there on the sad height,
Curse, bless, me now with your fierce tears, I pray.
Do not go gentle into that good night.
Rage, rage against the dying of the light.
(Dylan Thomas)