



⟨Quantum|Gravity⟩Society

Time Travel and Quantum Gravity

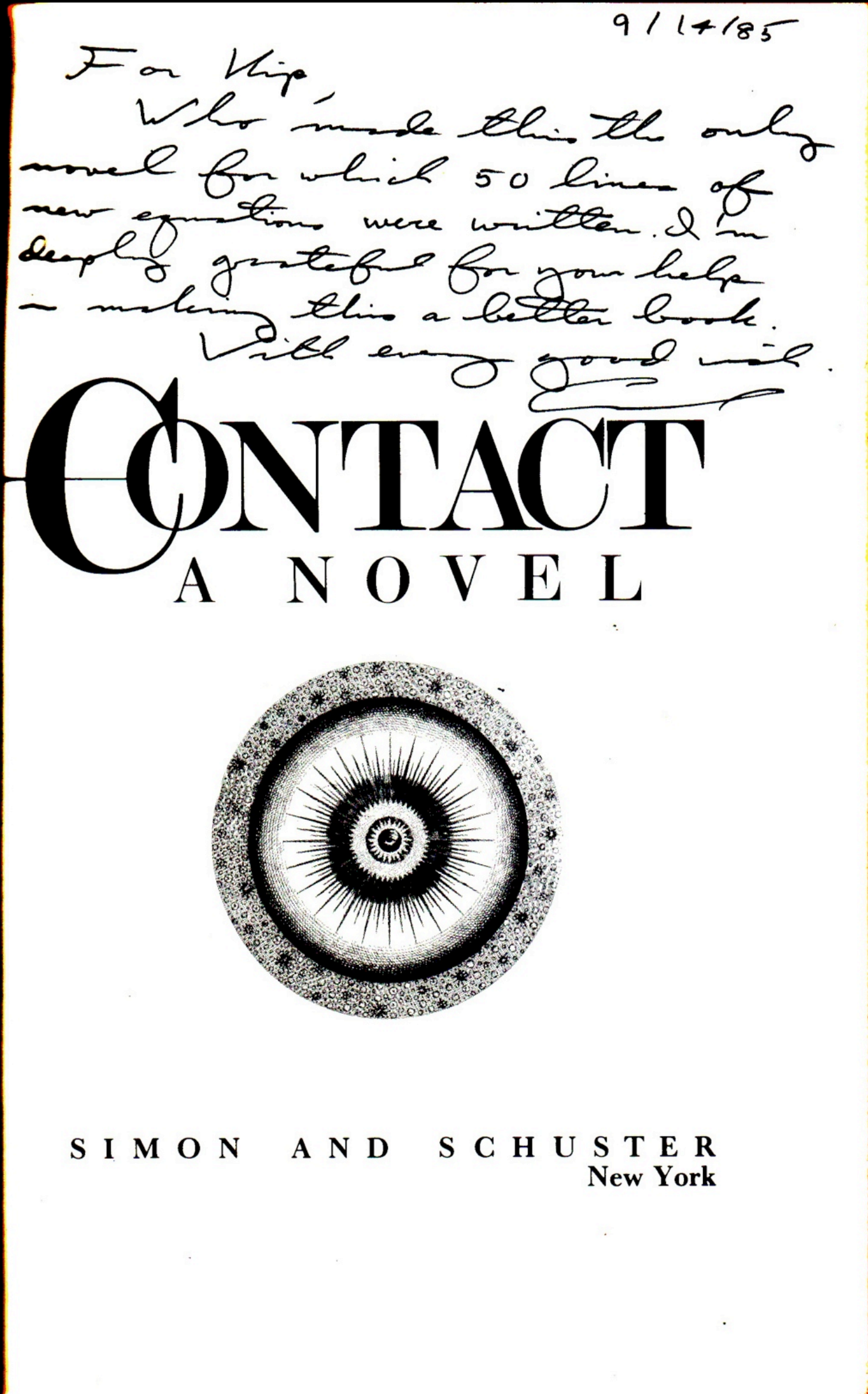
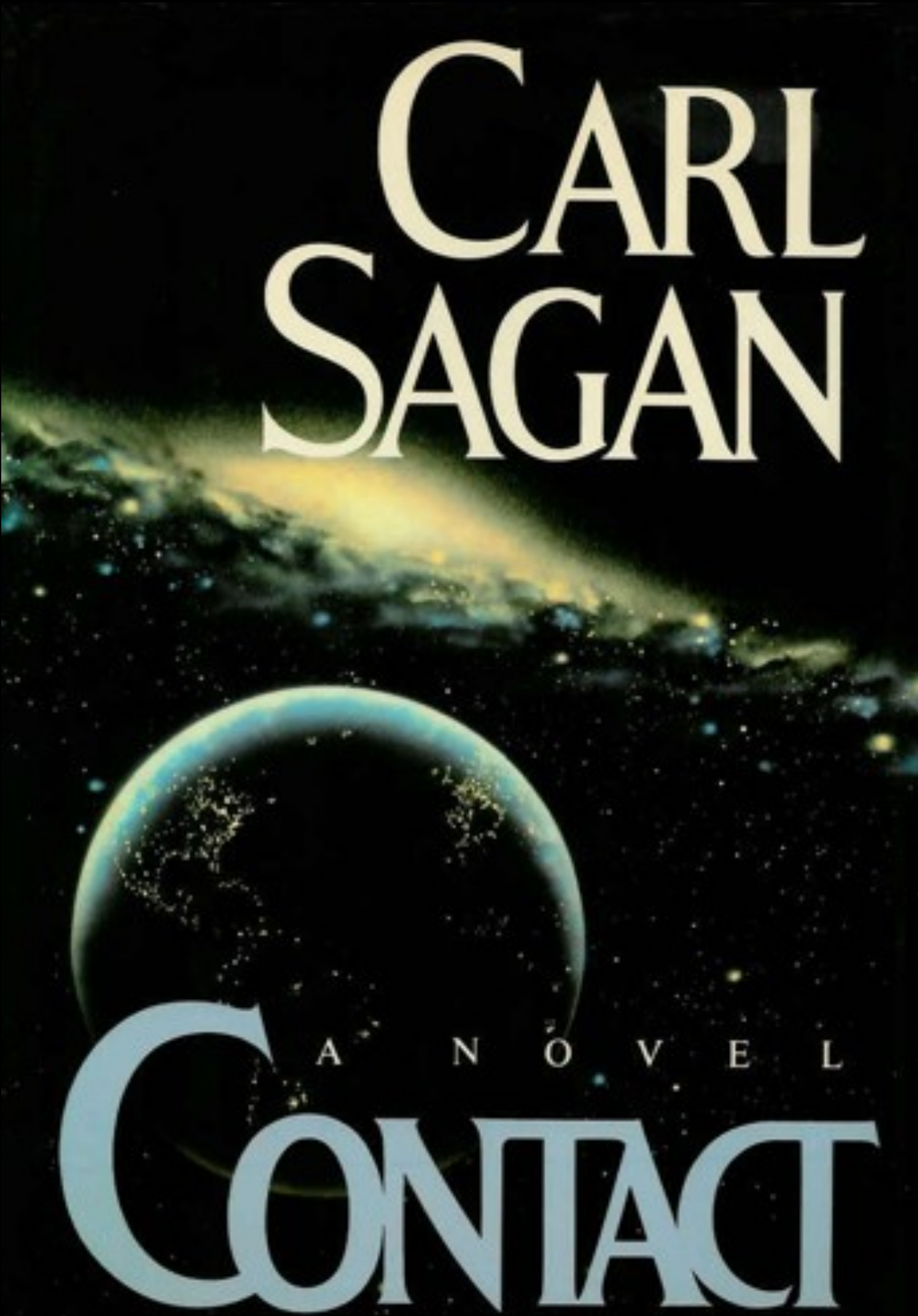
Kip Thorne

Time Travel and Quantum Gravity

Kip Thorne

Quantum Gravity Institute, Vancouver BC, 17 August 2022

Genesis of my work on Time Travel: 1985



25 light years



Earth

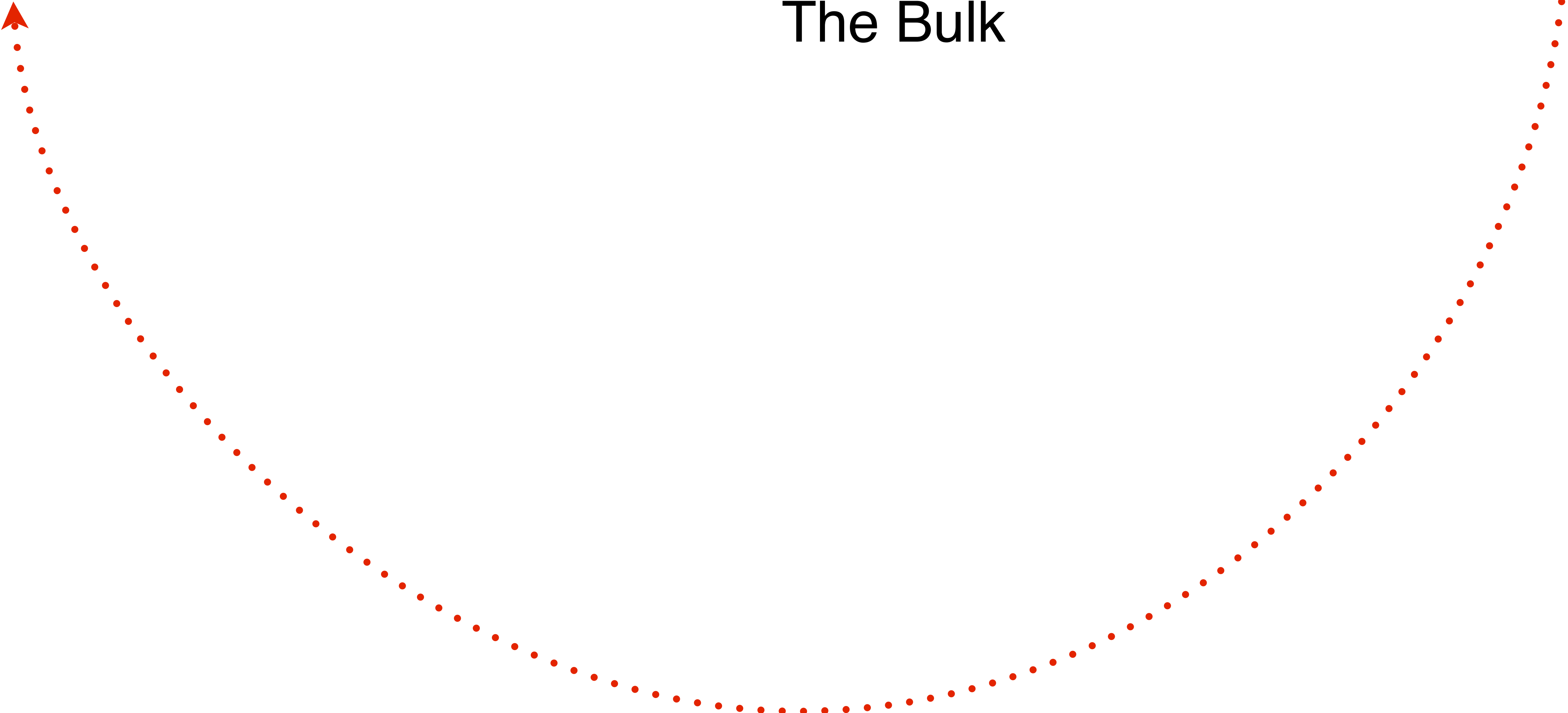


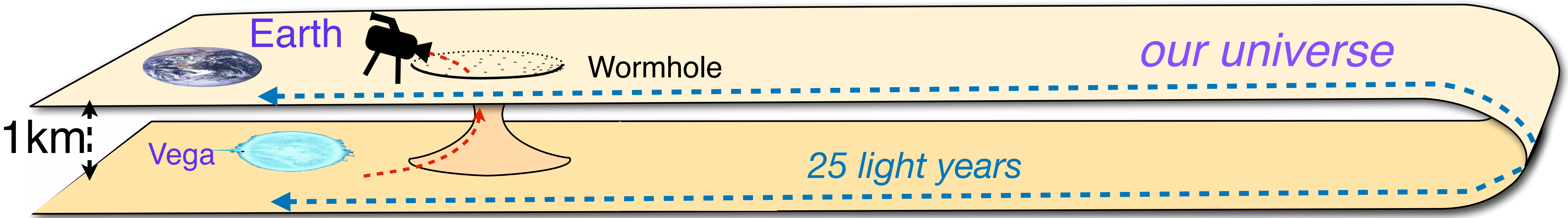
Our universe

Vega



The Bulk

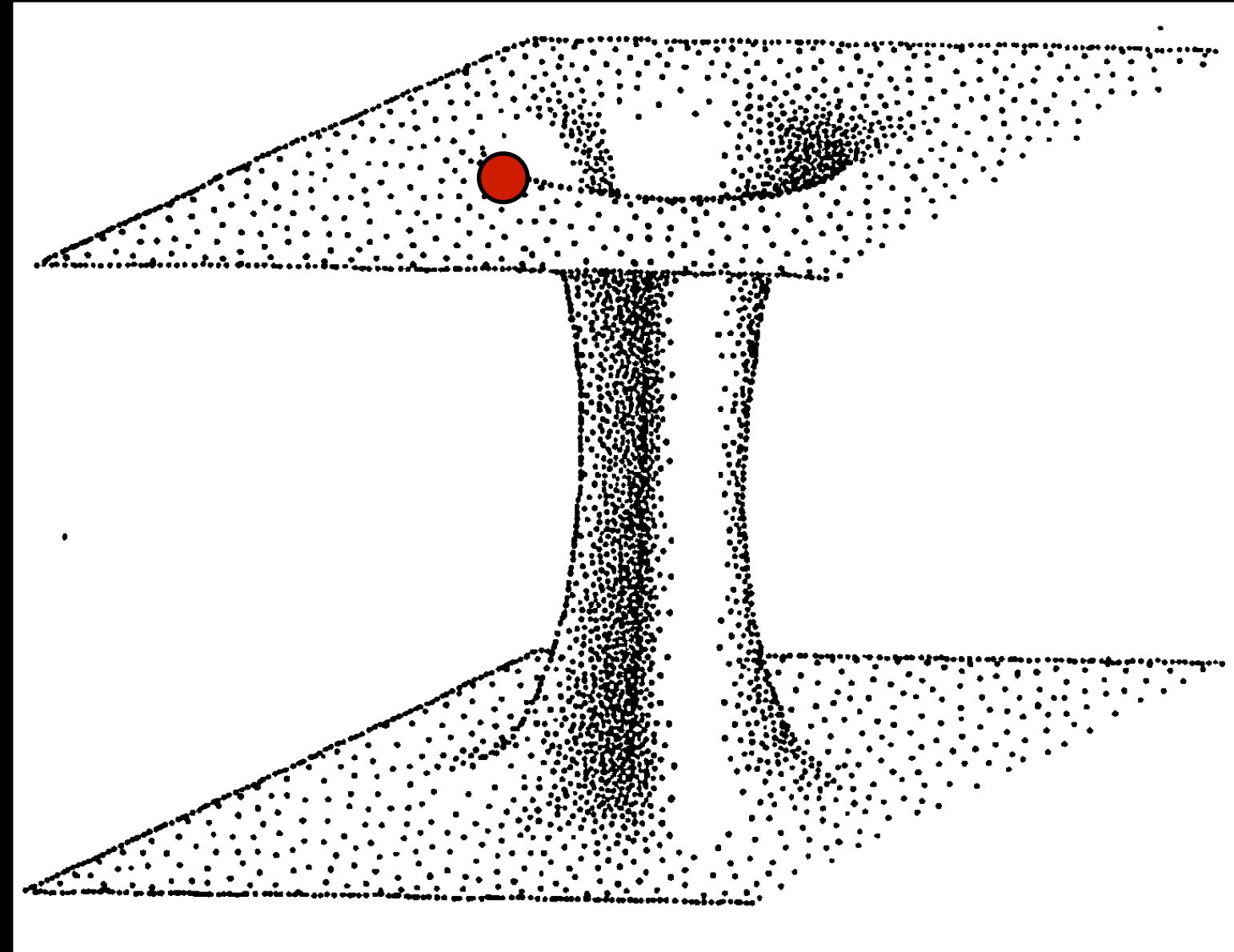




The Bulk



Wormholes Self Destruct



How hold it open?

Fill it with “exotic matter”

- negative mass (energy)
- repels gravitationally

Violate ANEC

$$\int T_{\alpha\beta} \frac{dx^\alpha}{d\zeta} \frac{dx^\beta}{d\zeta} d\zeta < 0$$

Dennis Gannon (1975)

Average energy density, as seen traveling through wormhole at light speed, is negative

Vacuum Fluctuations

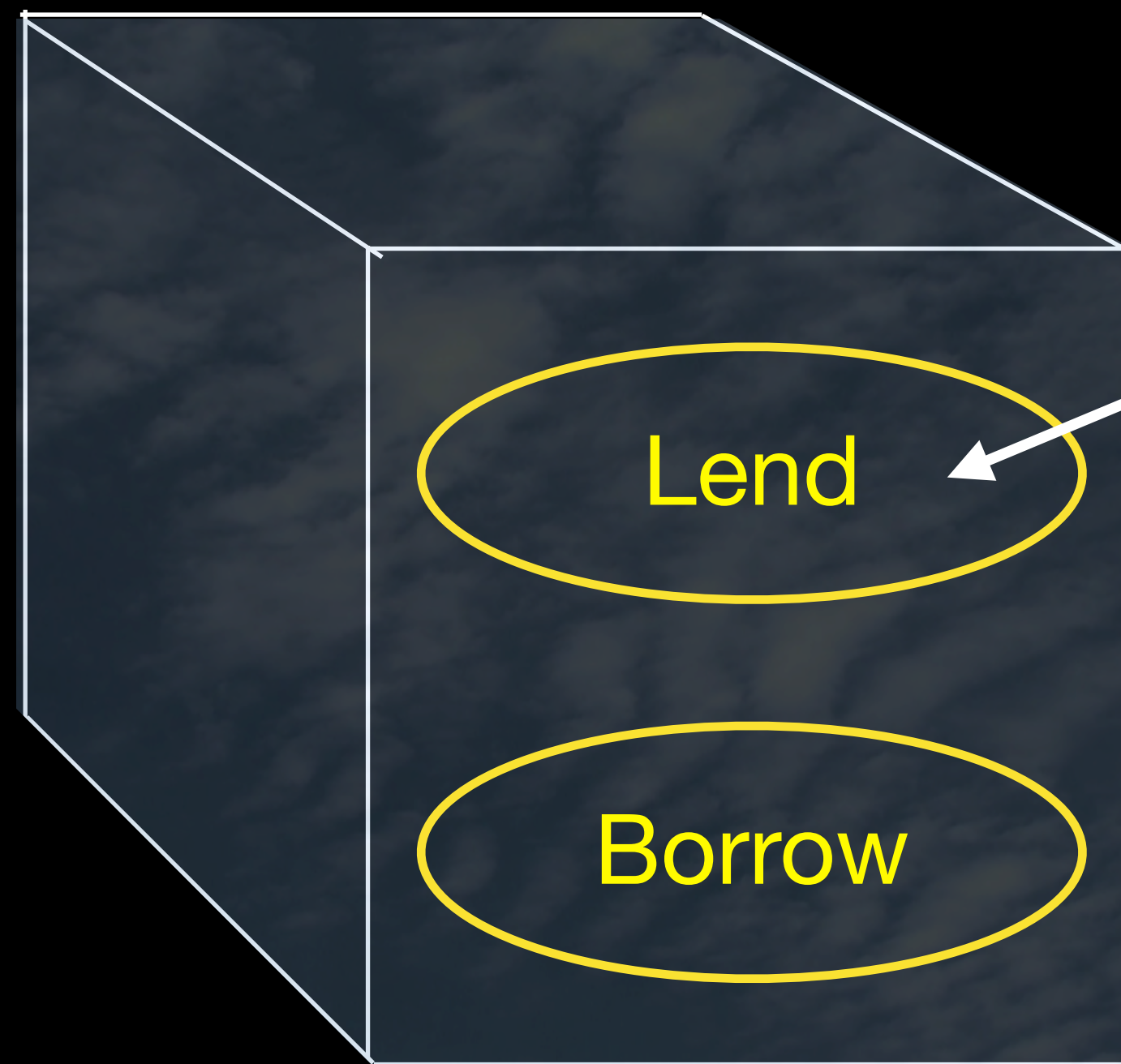
Foundation for Exotic Matter:

Ubiquitous!

Example: Big Bang Birth of our Universe

Example: Hawking Rad'n from black hole

Example: Laser Beam's Photons



Exotic

Lend

Borrow



Random arrival caused by
beating of vacuum fluctuations
against steady laser light

Manipulating Vacuum Fluctuations:

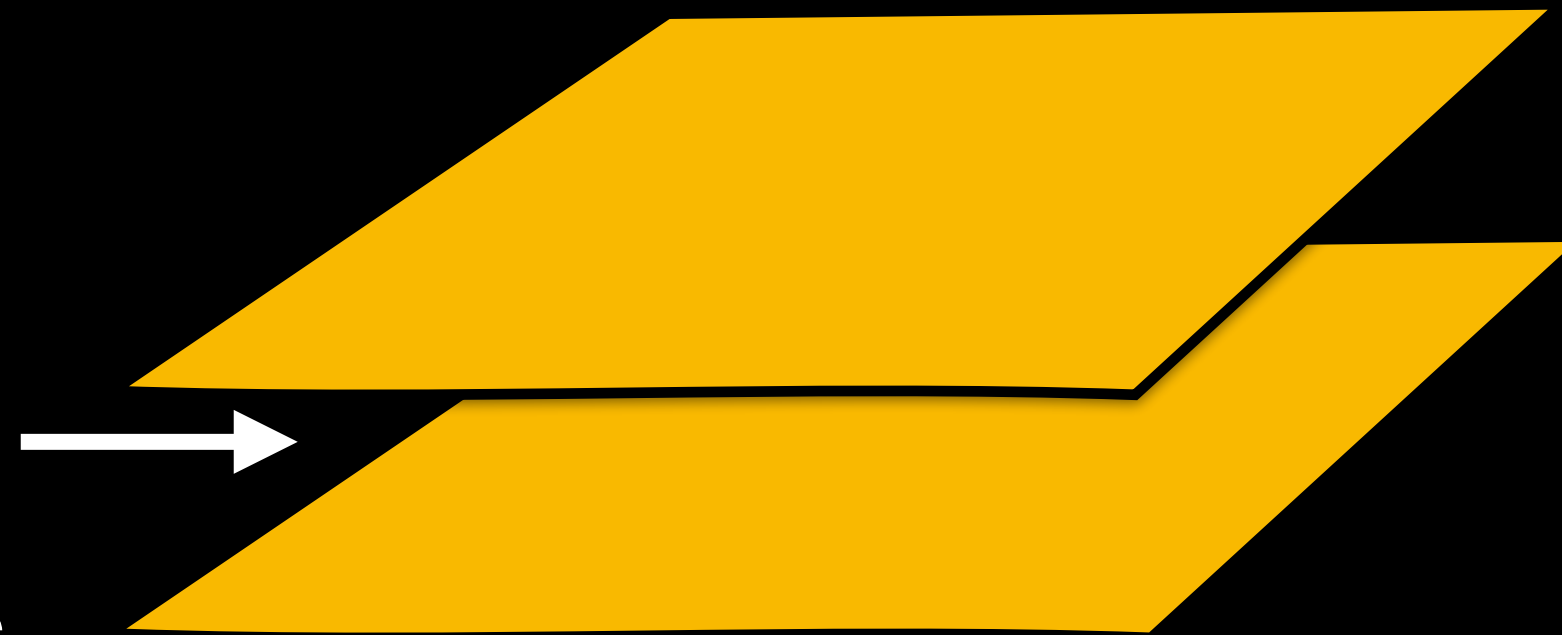
- *foundation for Quantum Precision Technology*
- *used crucially, for example, in LIGO today*

Carlton Caves 1981 Bill Unruh 1983

Holding Wormhole Open?

Electrically Conducting Plates

suppress
tangential
electric field
& fluctuations

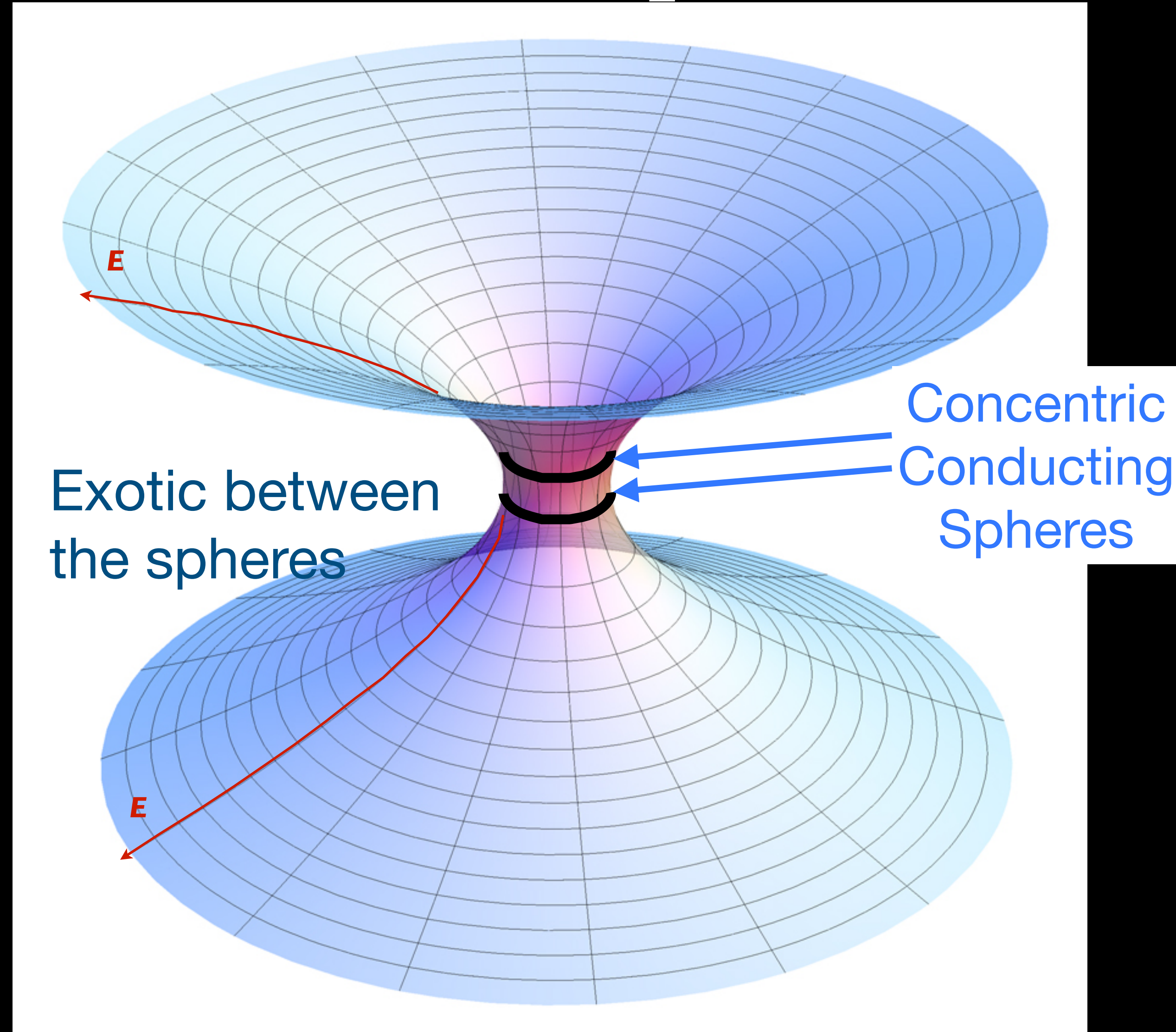


Exotic between plates

Casimir Vacuum

BUT: To hold wormhole open
energy of spheres plus that
of vacuum must be negative.
Likely not possible

Extensive QFT research on violations of ANEC:
Likely not possible in wormhole - but not sure



A. Everett & T. Roman, *Time travel and Warp Drives* (U Chicago Press 2012)

Wormholes in our Universe

☐ Can they occur naturally? - **Almost certainly No**

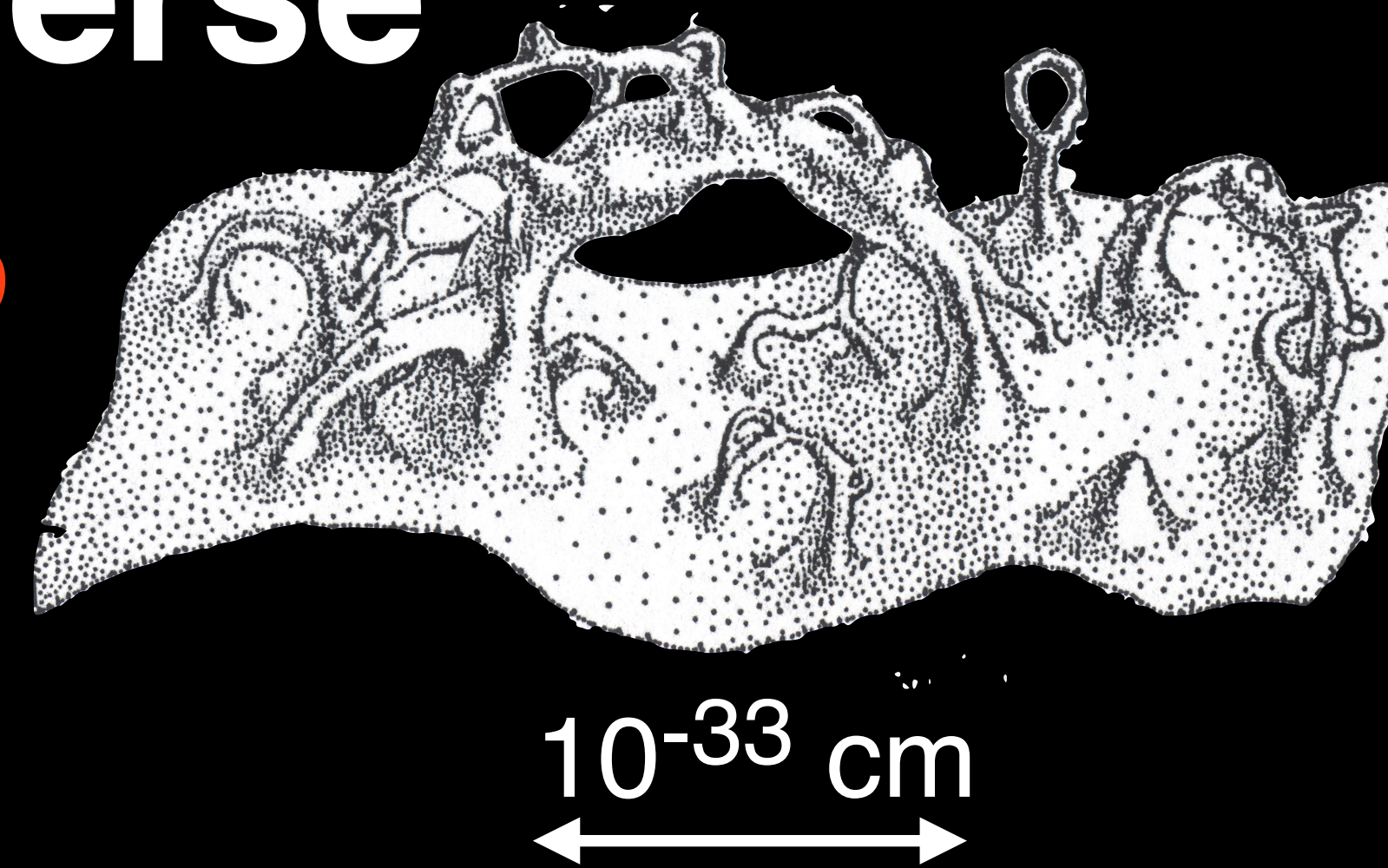
☐ Can they be made by an infinitely advanced civilization? **Possibly**

☐ Can they be held open by an infinitely advanced civilization?

Probably not. Requires too much exotic matter.

**BUT: When speculating beyond the frontiers of firm knowledge,
I've been proved wrong many times**

**So don't take my wormhole pronouncements,
too seriously**



Wormholes in our Universe

❑ Can they occur naturally? - **Almost certainly No**

❑ Can they be made by an infinitely advanced civilization? **Possibly**

❑ Can they be held open by an infinitely advanced civilization?

Probably not. Requires absurdly large amounts of exotic matter.



10^{-33} cm

BUT: W

I've been

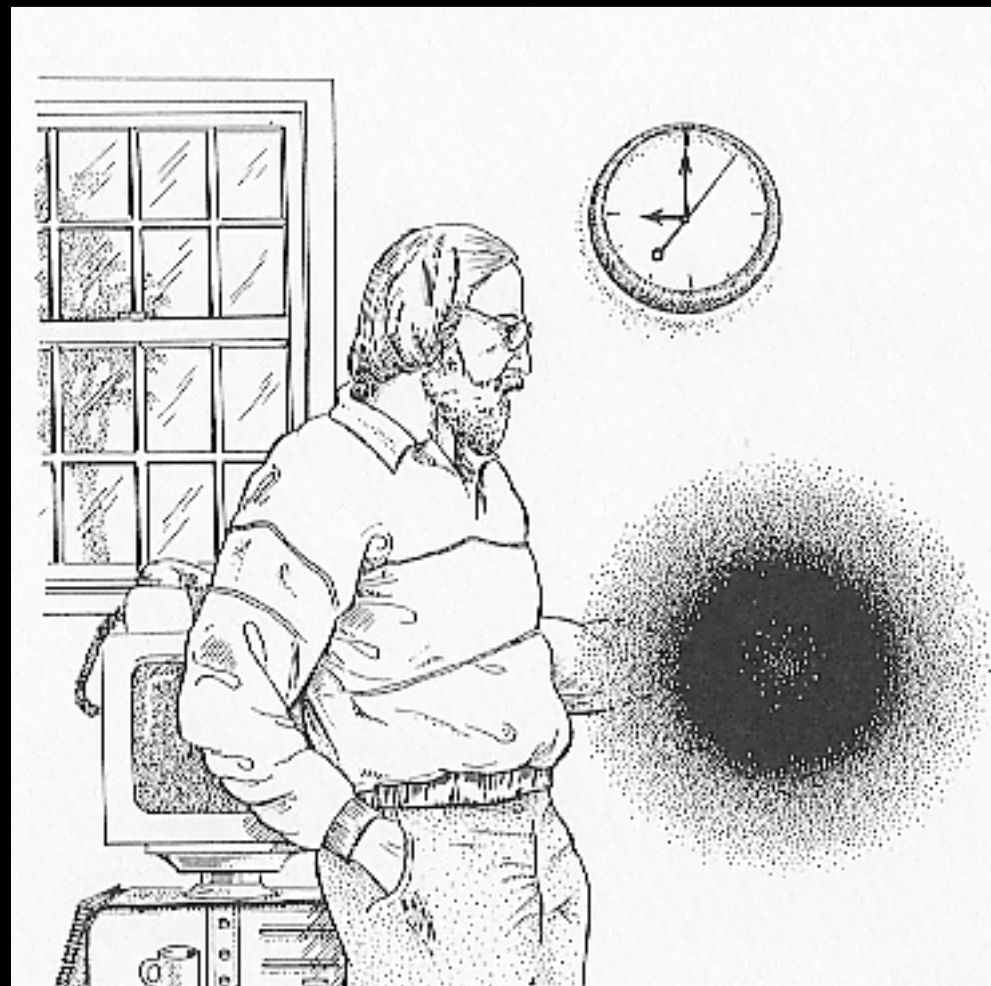
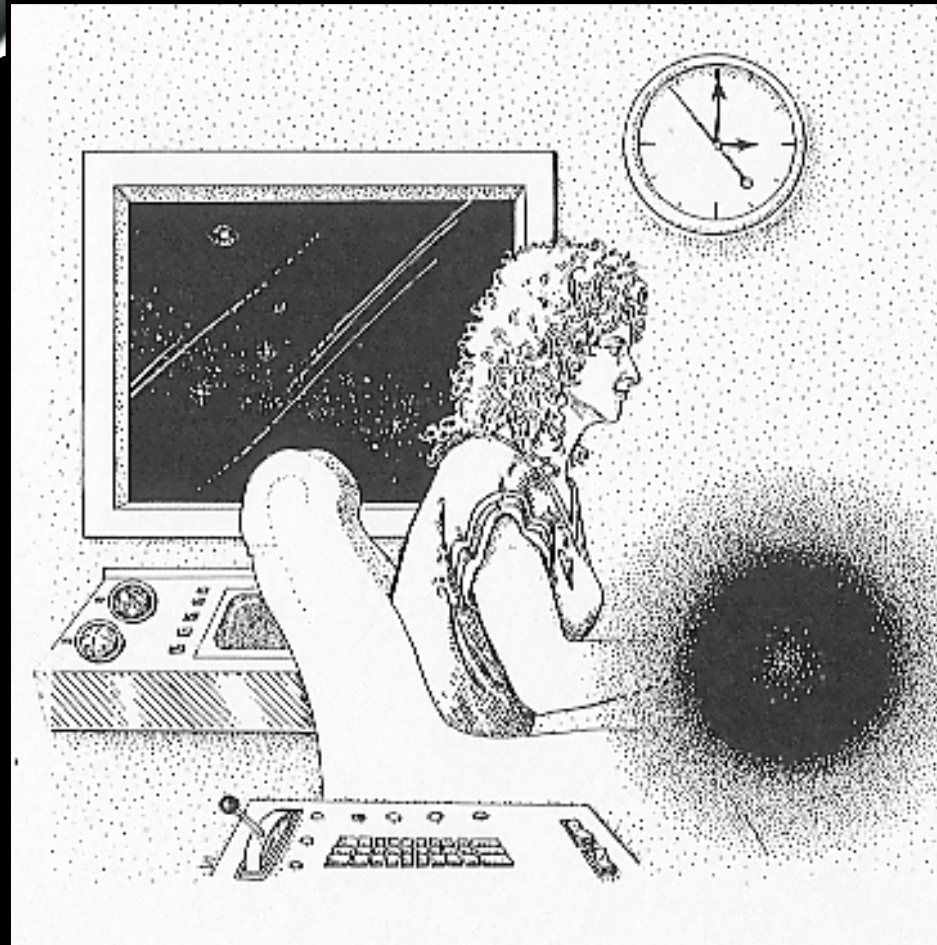
**Extreme Thought Experiments:
Powerful for Probing Laws of Physics**

**wledge,
acularly**

**So don't take my wormhole pronouncements,
too seriously**

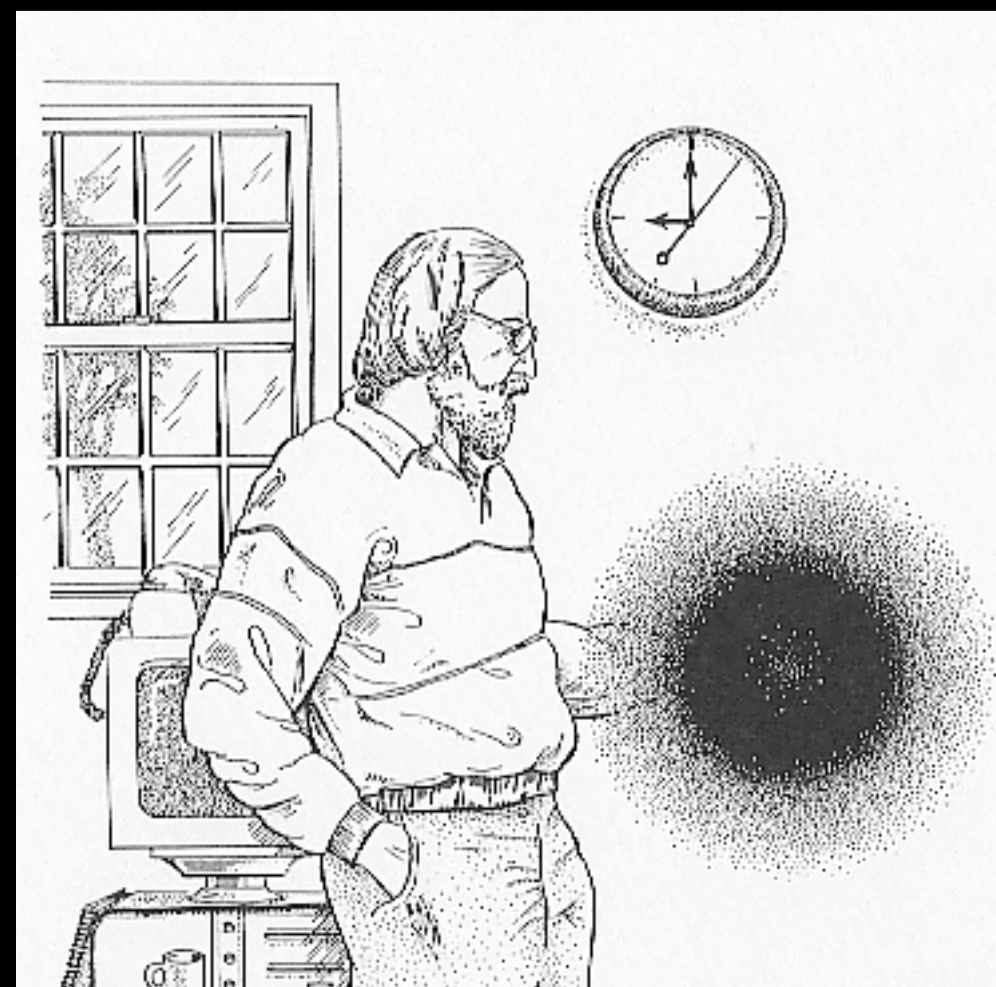
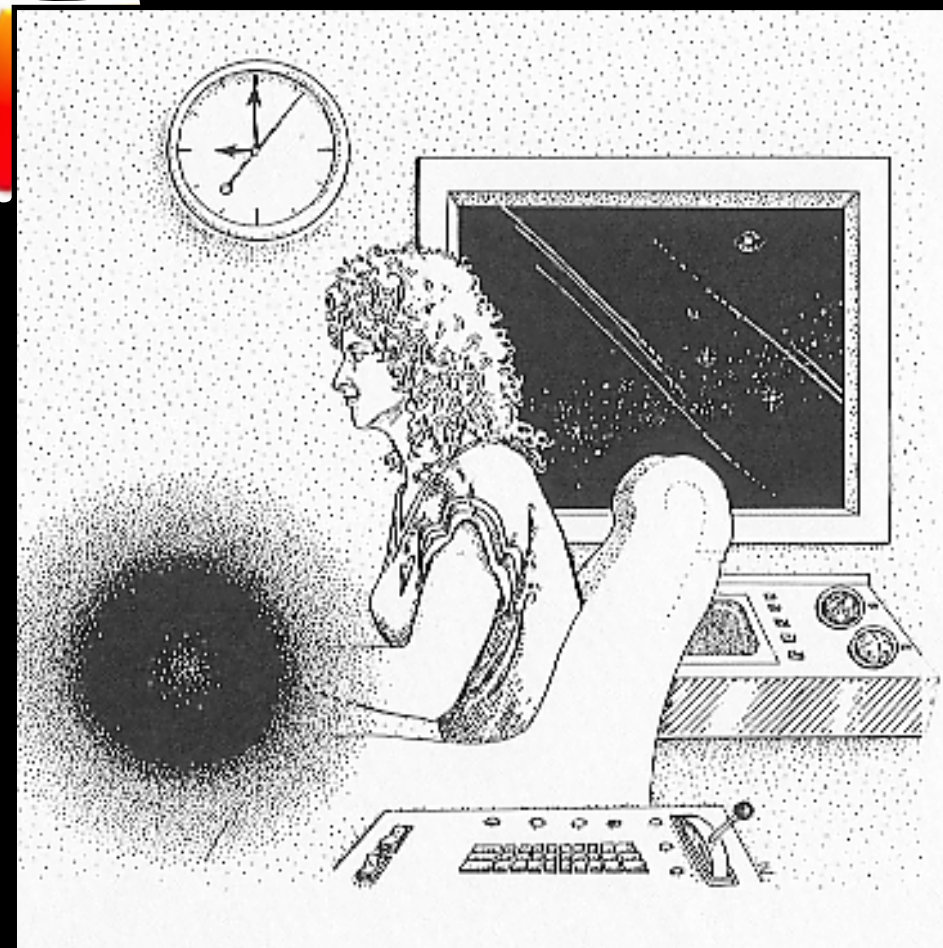
Can An Infinitely Advanced Civilization Transform a Wormhole Into a Time Machine?

- Move one mouth out at high speed, then back



Can An Infinitely Advanced Civilization Transform a Wormhole Into a Time Machine?

Trip lasts 30 years as seen by me
1 year as seen by Carolee

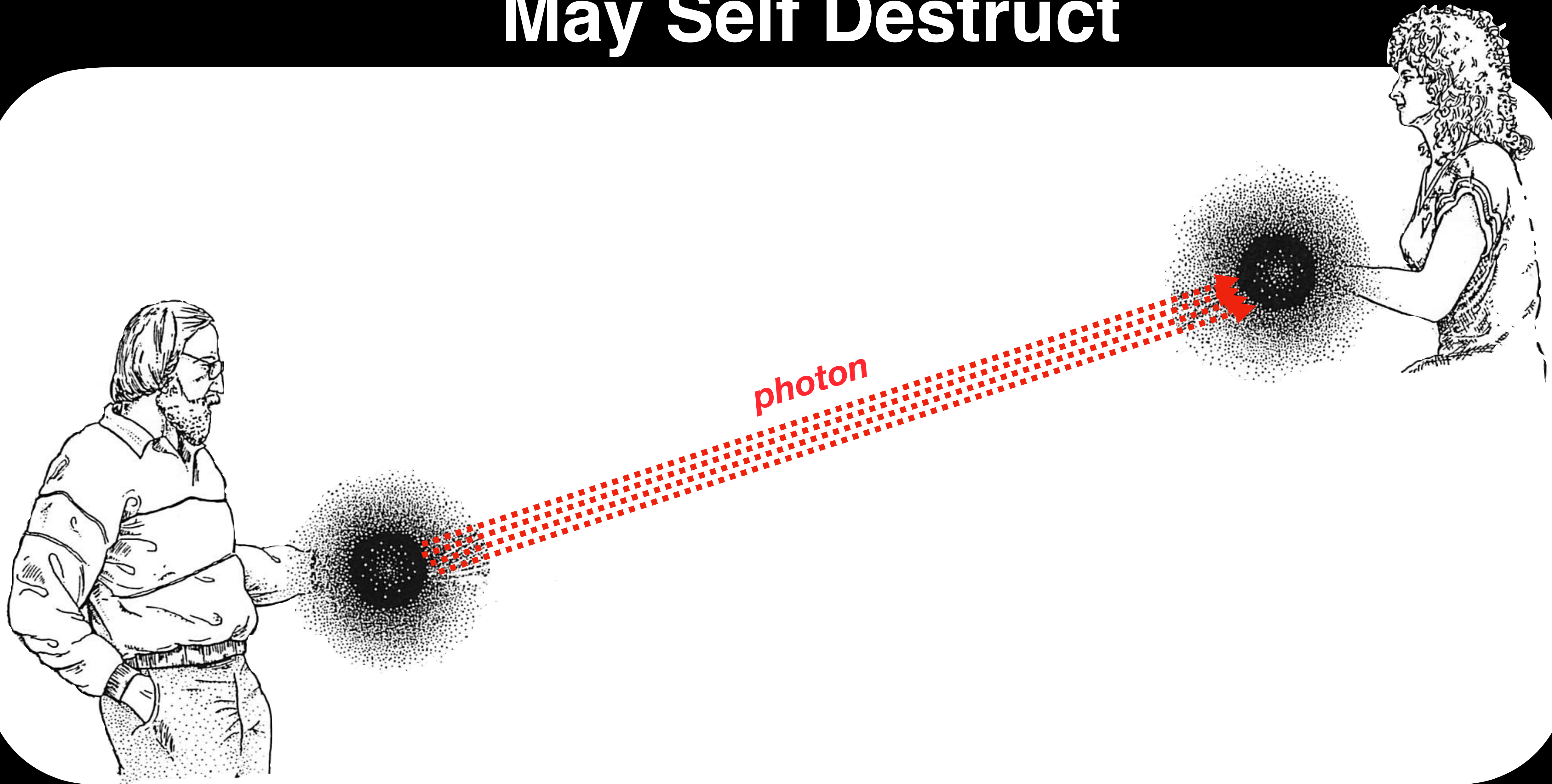


Looking through space,
Carolee sees me old

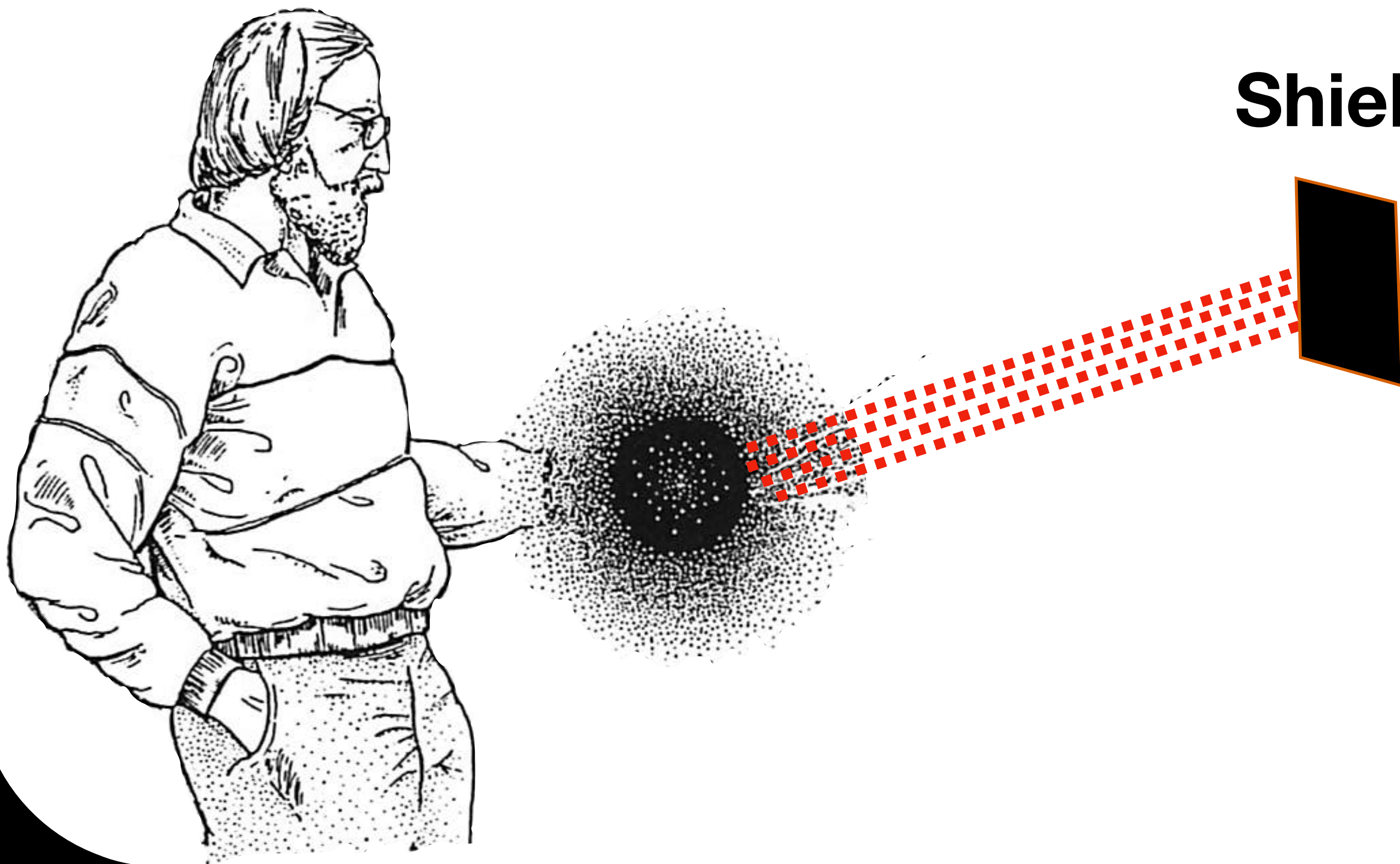
Looking through wormhole,
she sees me young

**Wormhole
is now a
time machine!**

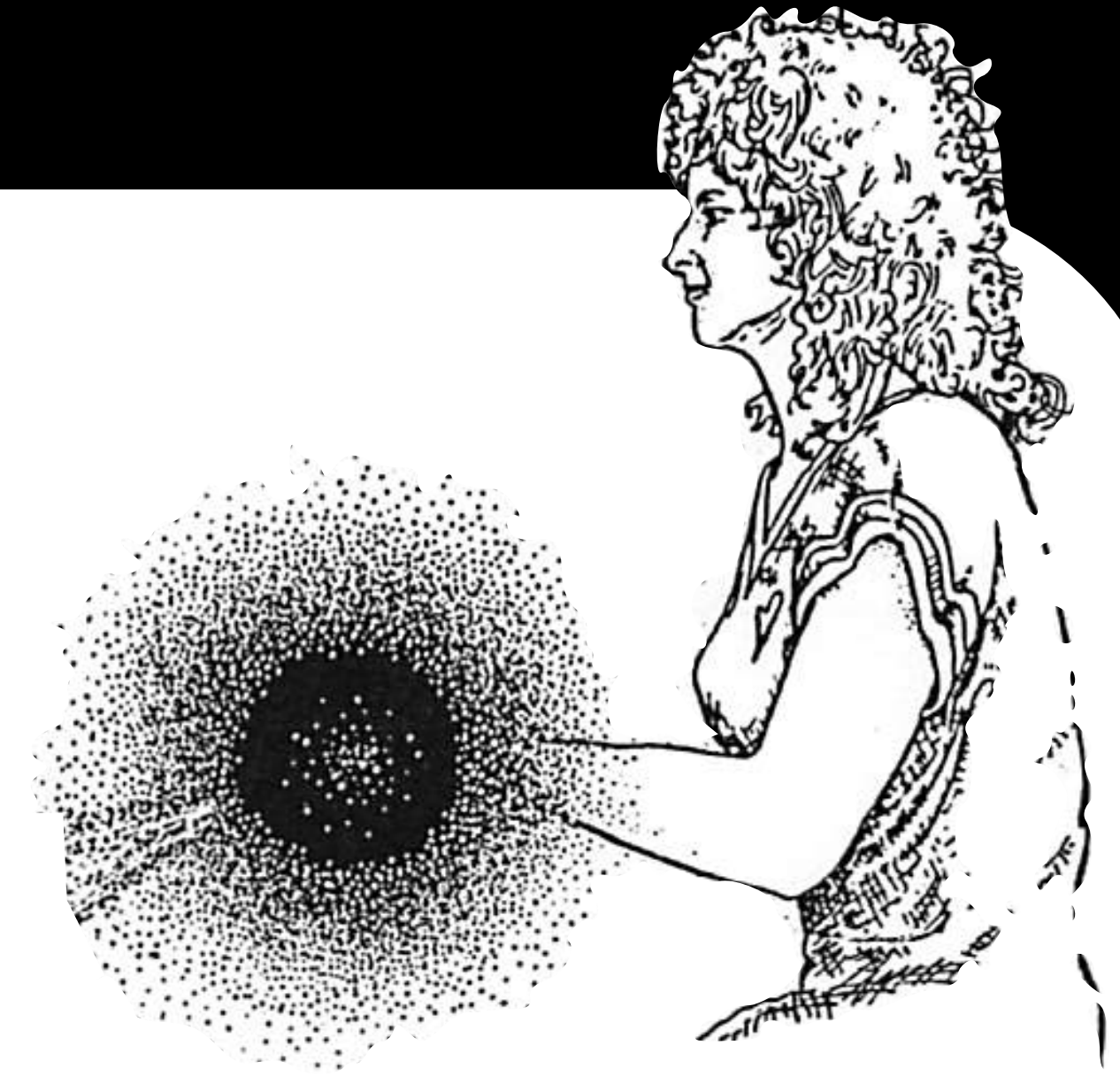
At Moment it is Created Time Machine May Self Destruct



At Moment it is Created Time Machine May Self Destruct



Shield

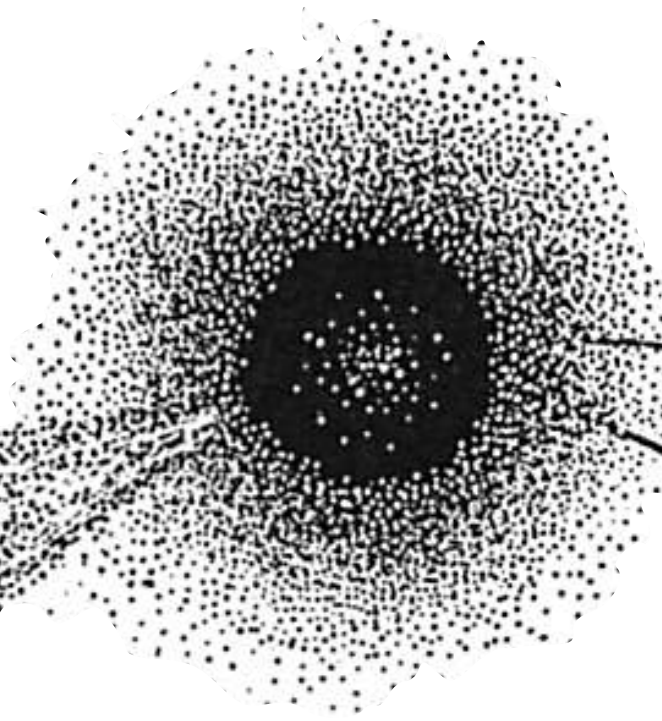
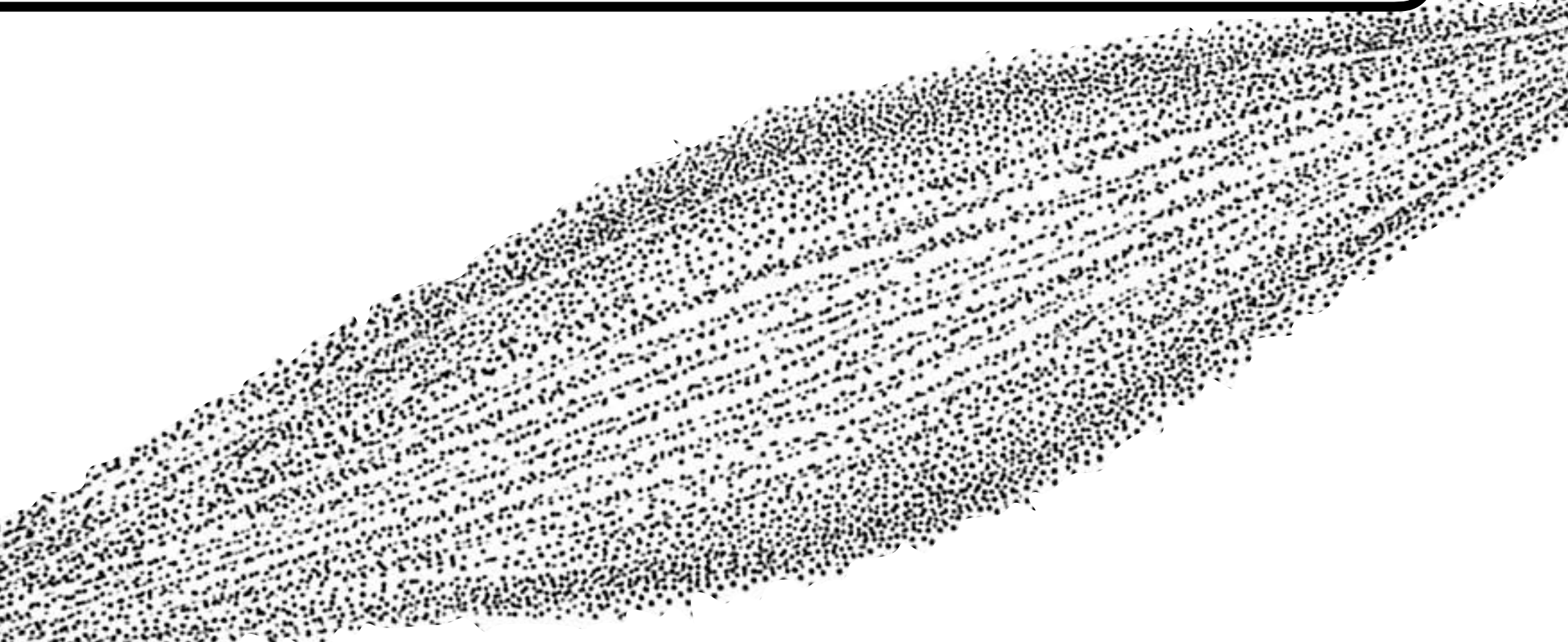
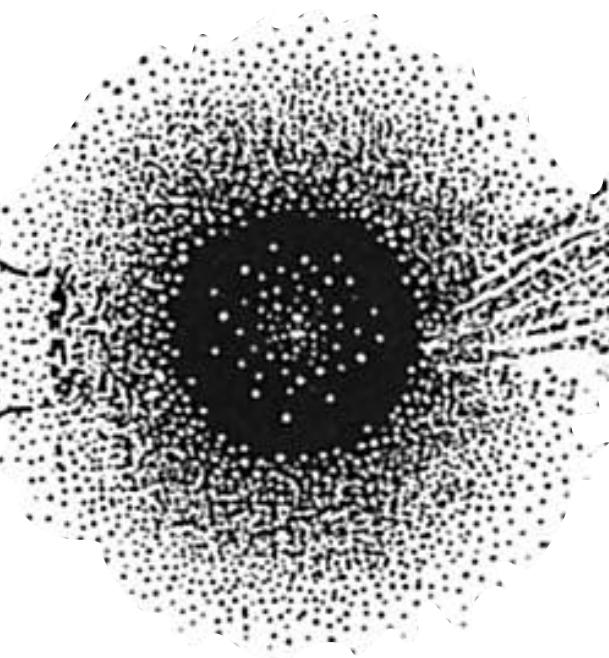


**But ultra-high frequency
vacuum fluctuations
cannot be shielded**

At Moment it is Created Time Machine May Self Destruct

Is the explosion strong enough
to destroy the wormhole?

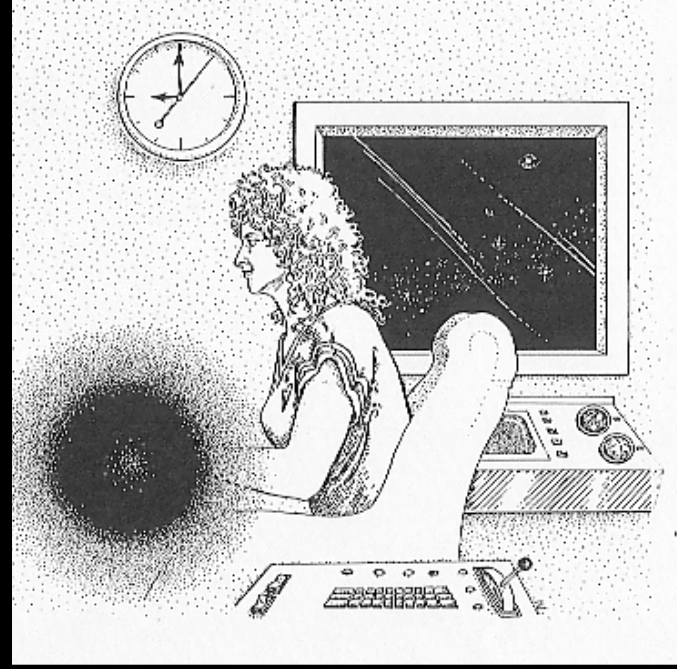
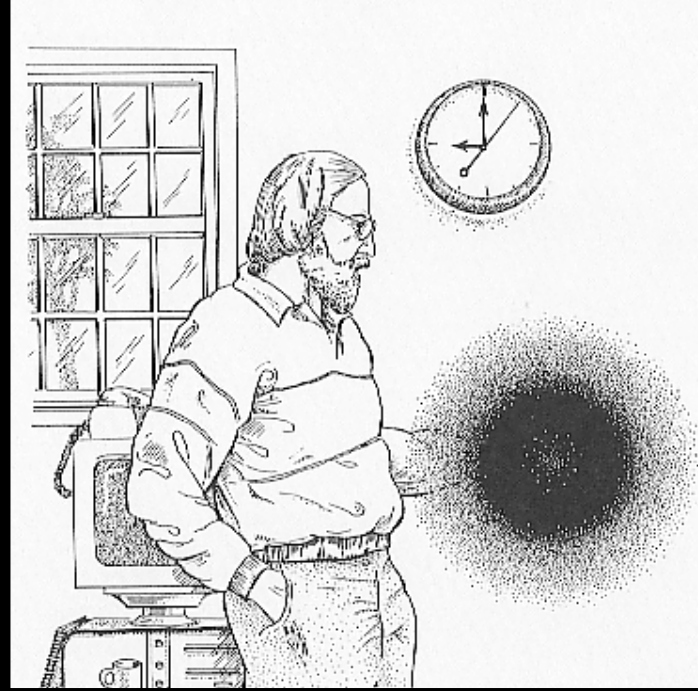
Only the laws of **quantum gravity** know



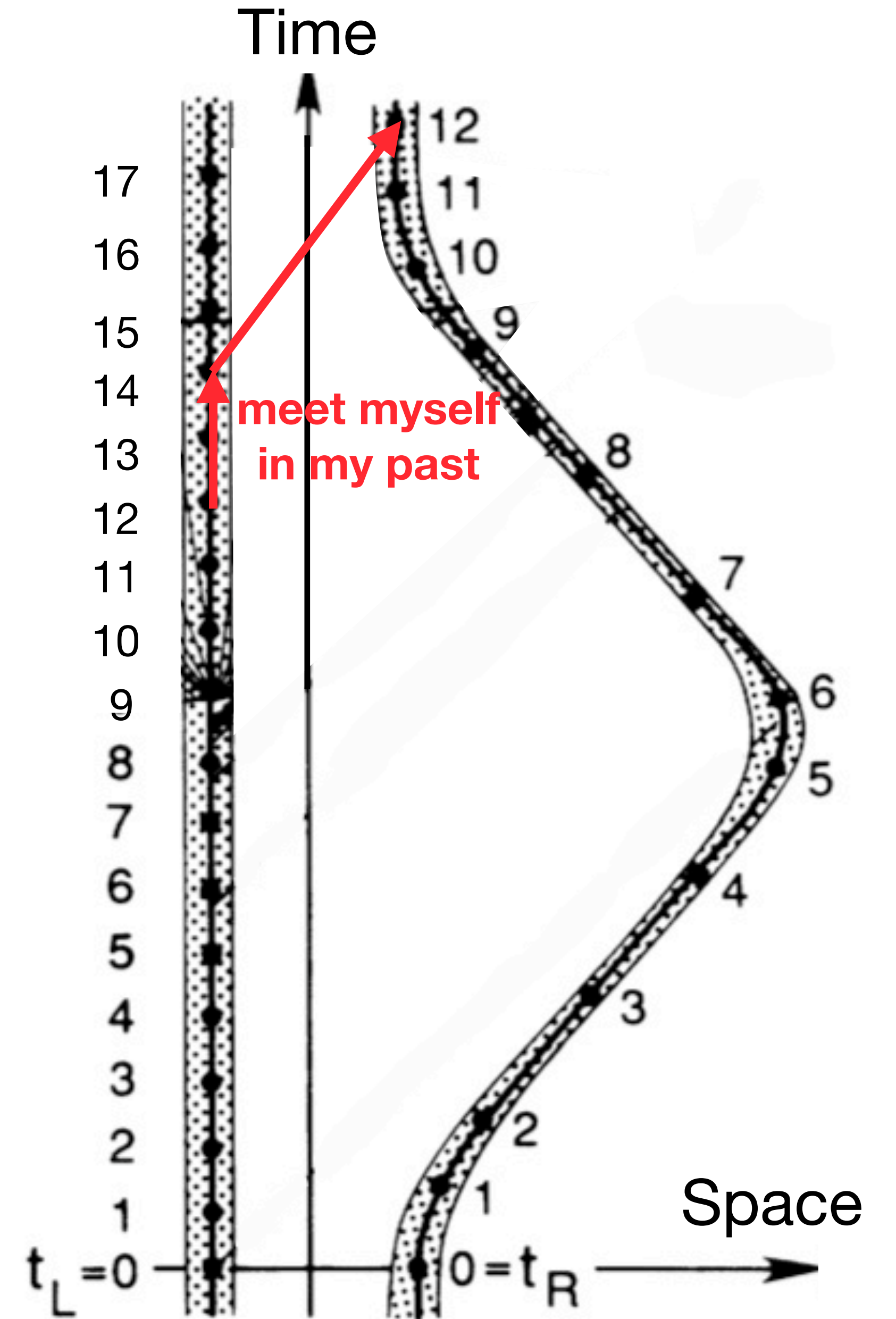
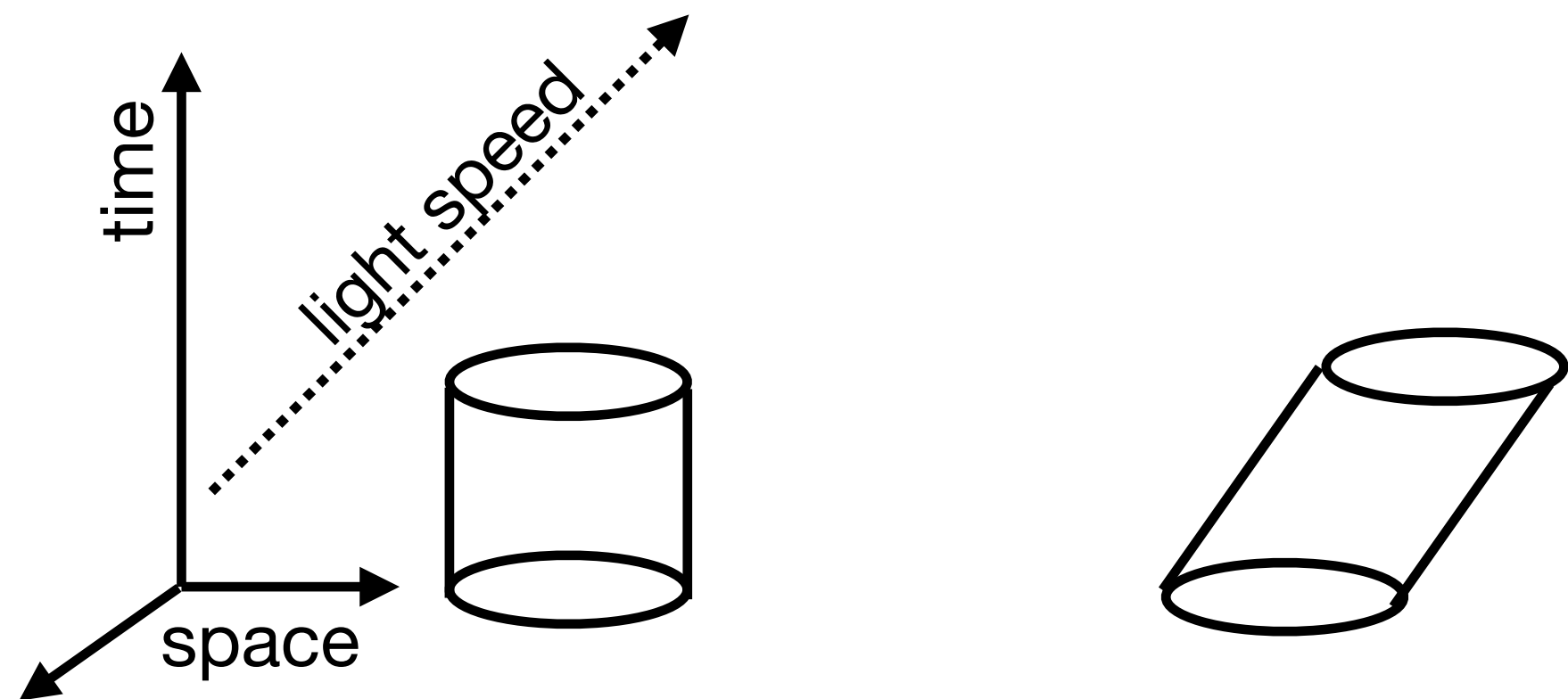
**Stephen Hawking:
Chronology Protection Conjecture**

Space-Time diagram for Time-Machine Creation & Self Destruction

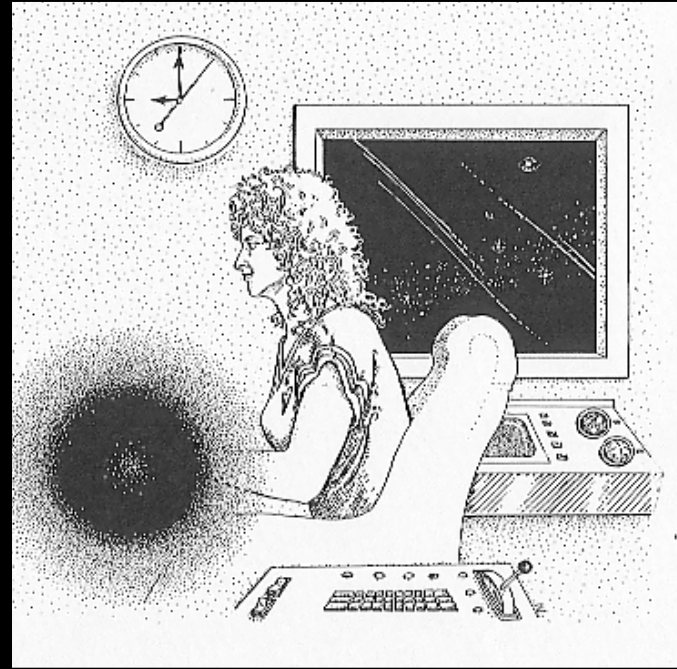
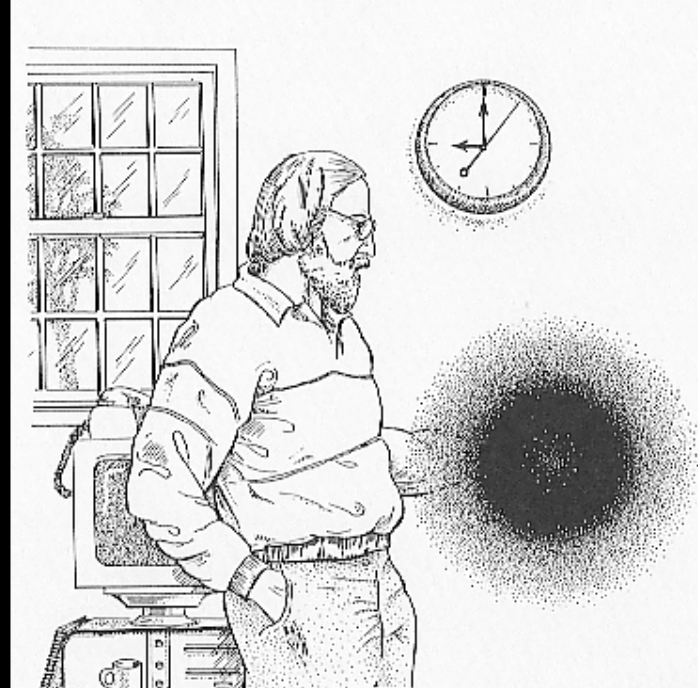
Very Short Wormhole



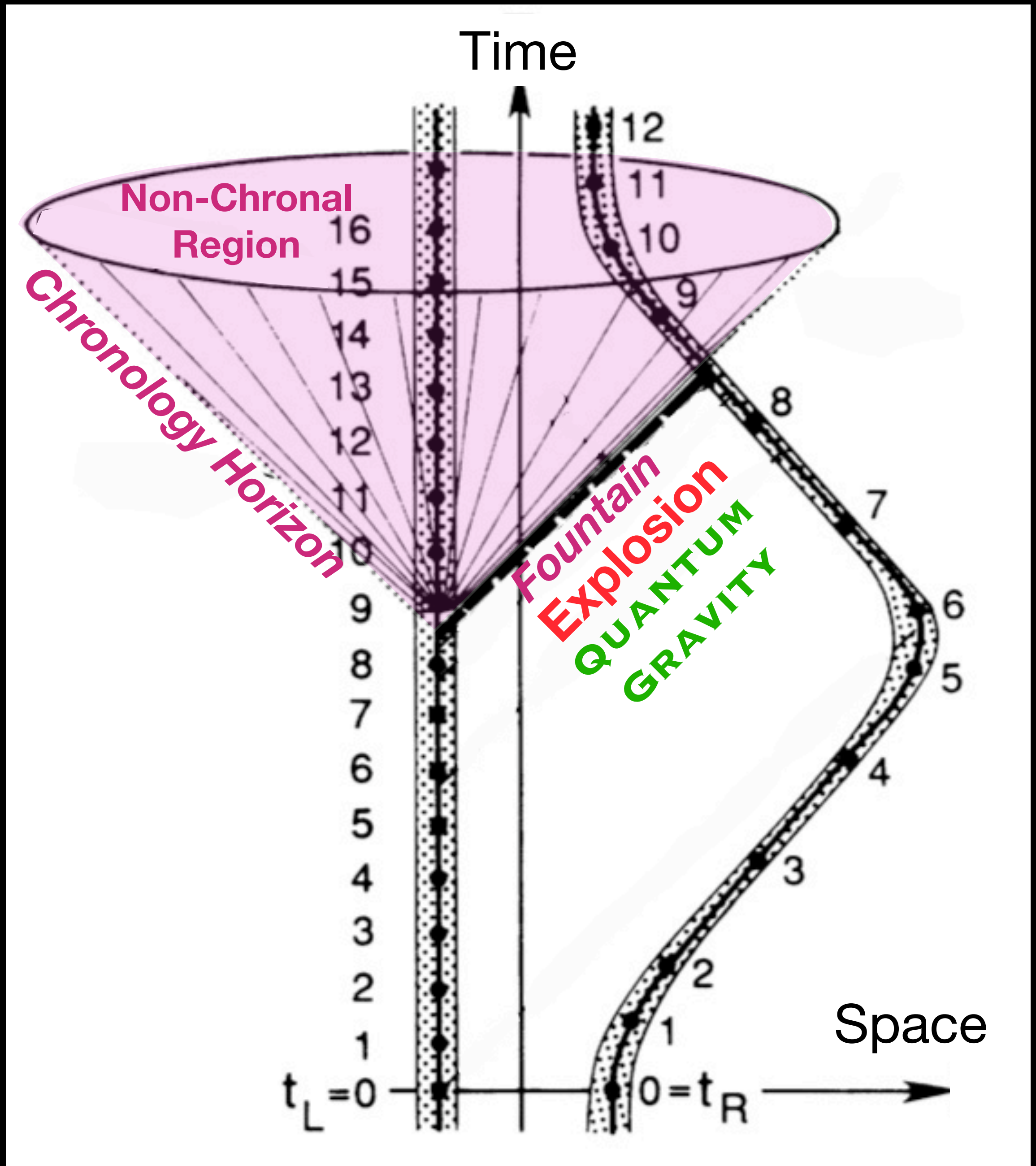
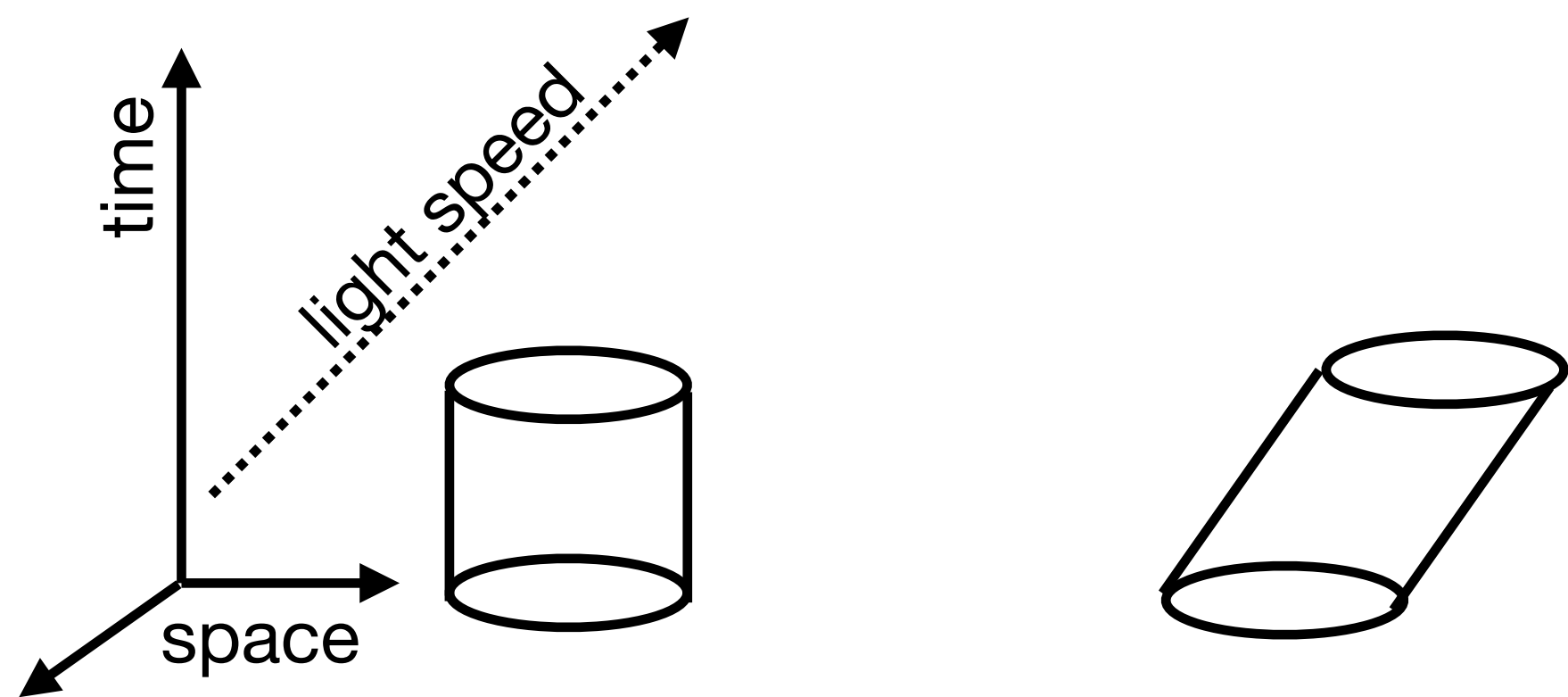
Suppress one dimension



Very Short Wormhole



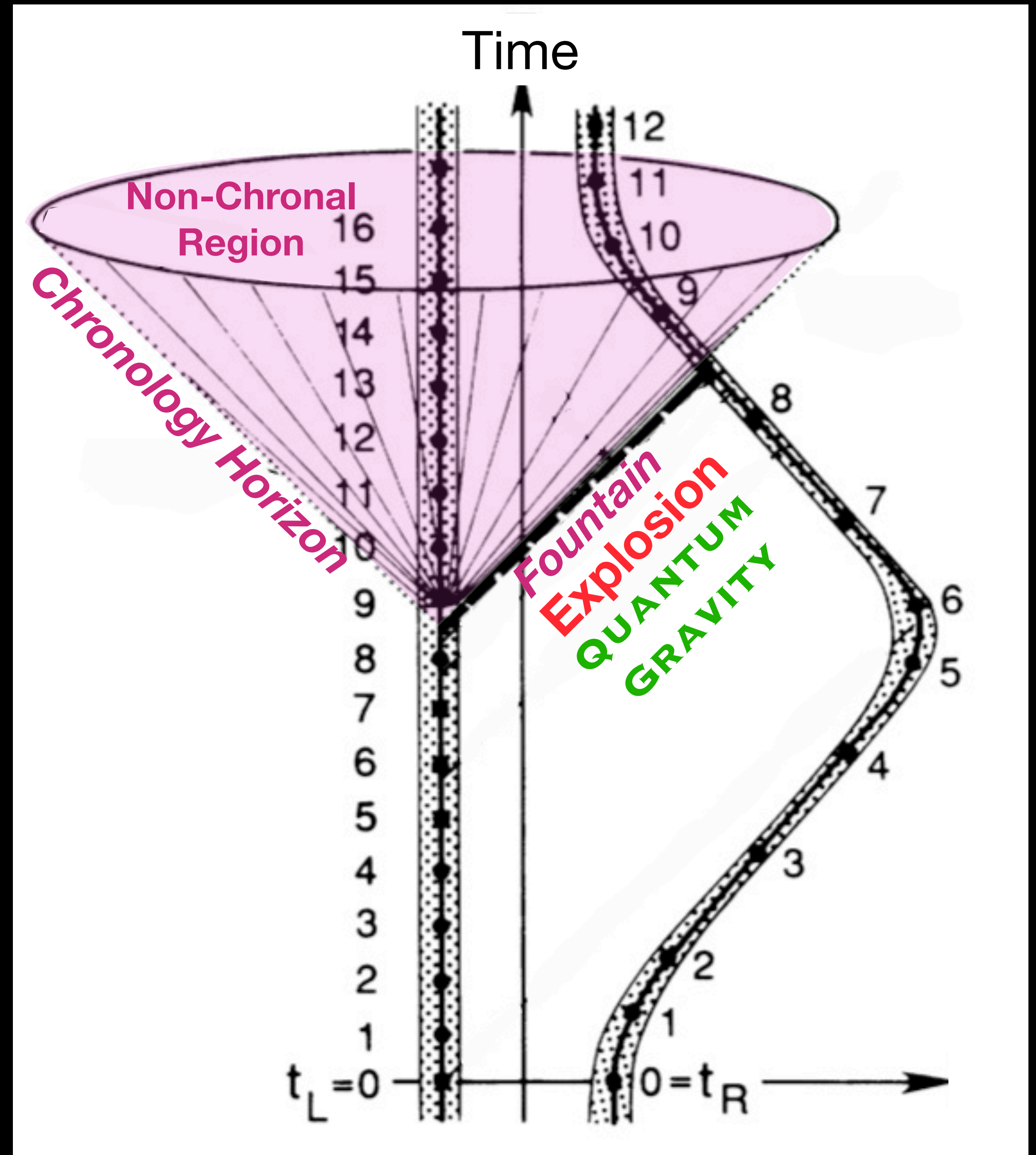
Suppress one dimension



- Some Chronology Horizons do not have Fountains - P. Cruscial & J Isenberg (1997)
- But there is still some sort of “explosion” (pathology of renormalized energy density) at origins of horizon - Kay, Radzikowski, Wald (1997)
- I suspect here too **only quantum gravity** knows what happens

Beautiful Reviews:

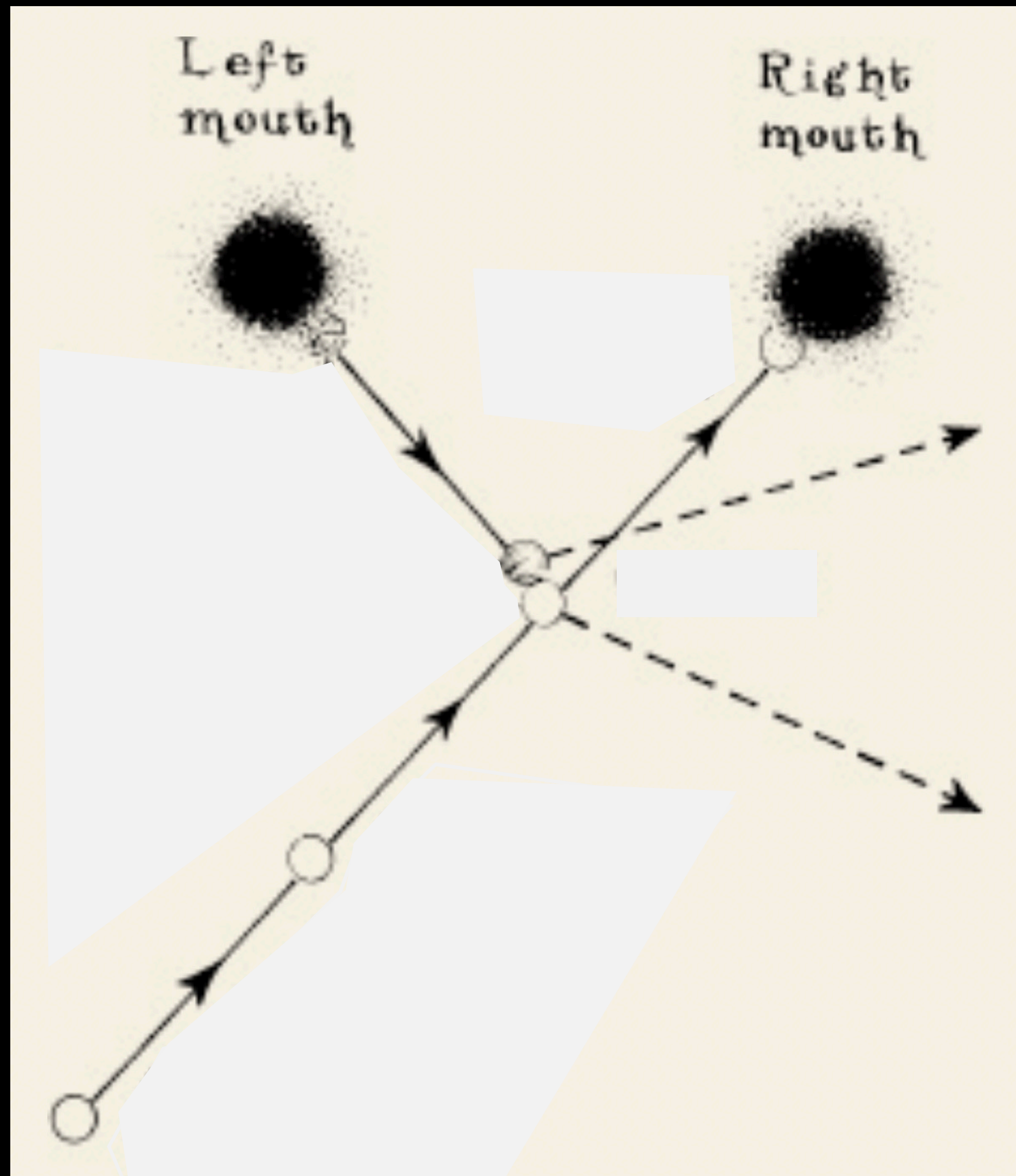
- Not terribly technical: A. Everett & T. Roman, *Time travel and Warp Drives* (U Chicago Press 2012)
- Very technical: J. Friedman, “Topological Censorship and Chronology Protection” (2008) arXiv: 0801.0735



Suppose Quantum Gravity Does Allow Time Travel How Can the Laws of Physics Accommodate This?

Grandfather Paradox?

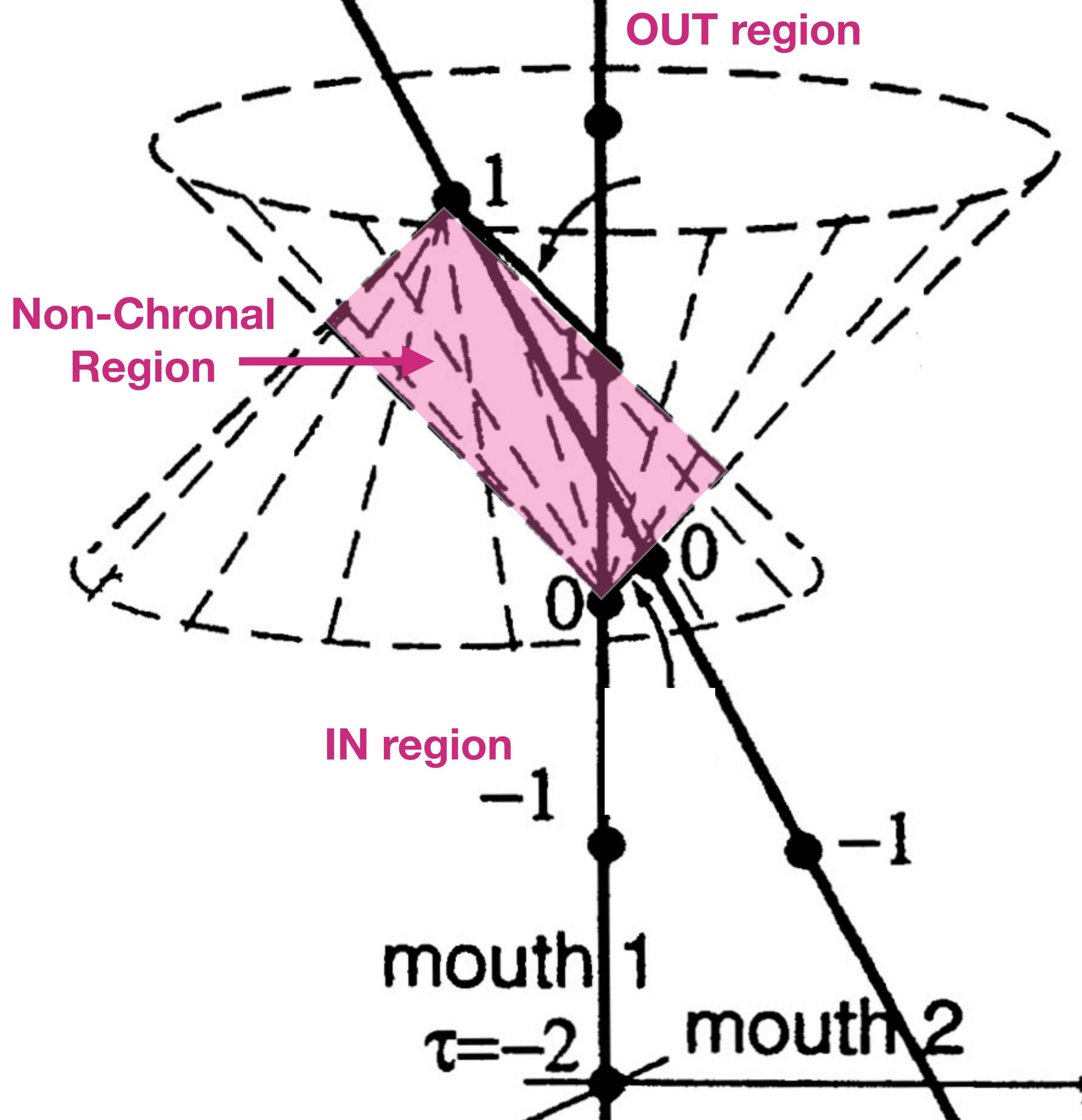
Polchinsky's Paradox



Nature is Quantum Mechanical! What does Quantum Theory Predict?
A specific probability for each (classical) history .

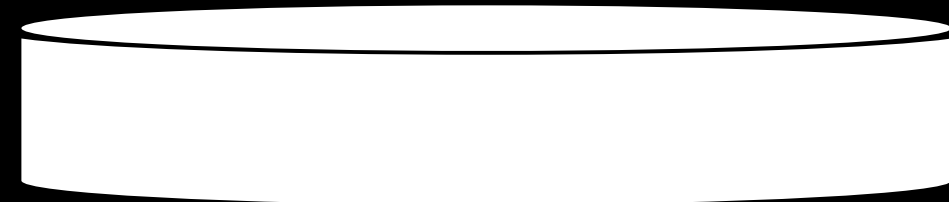
Quantum Fields? (e.g. electromagnetic field)

Wormhole mouths
move past each other
at constant speed



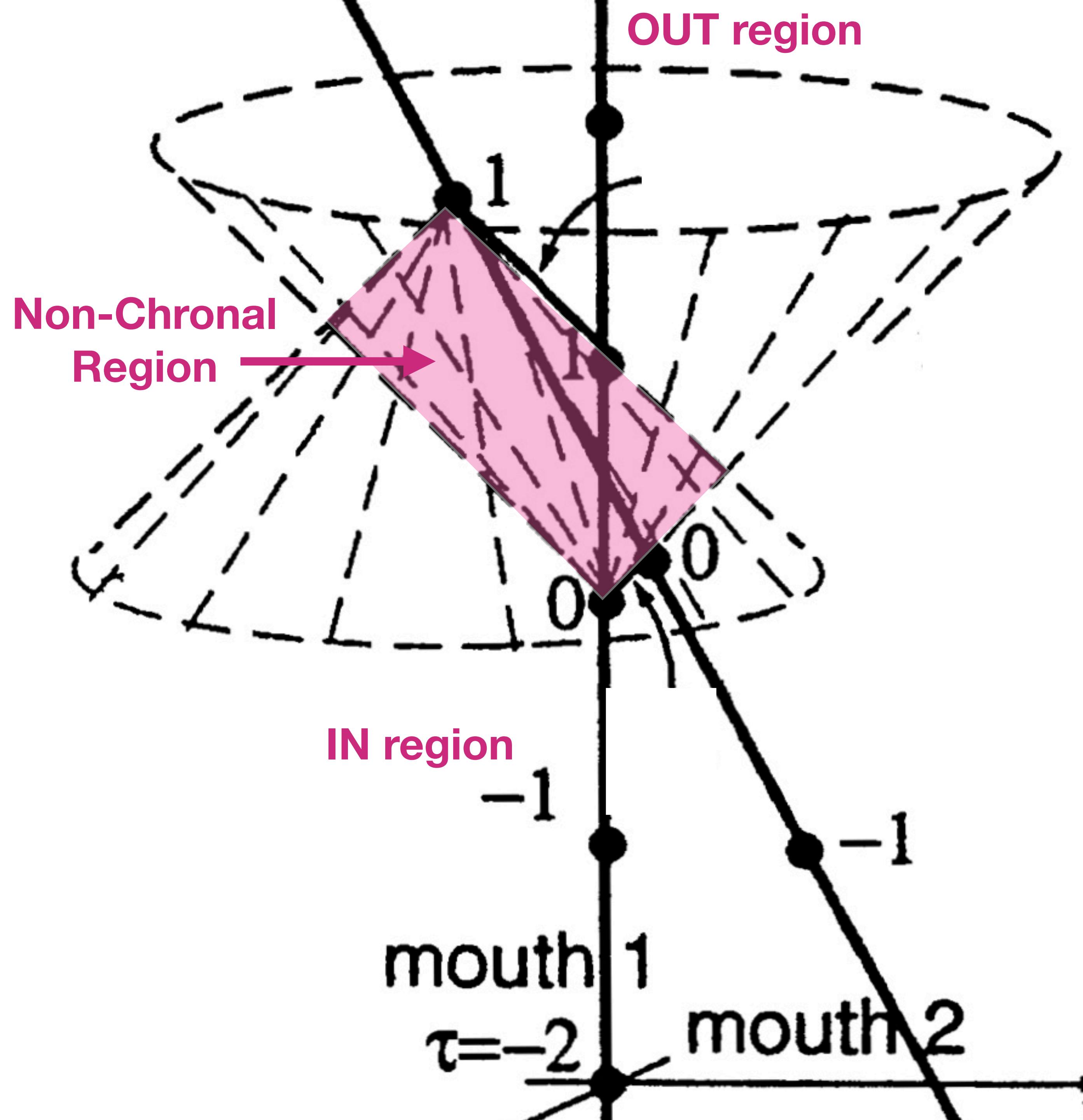
Quantum Fields? (e.g. electromagnetic field)

Wormhole mouths
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Disk that includes
exotic matter:

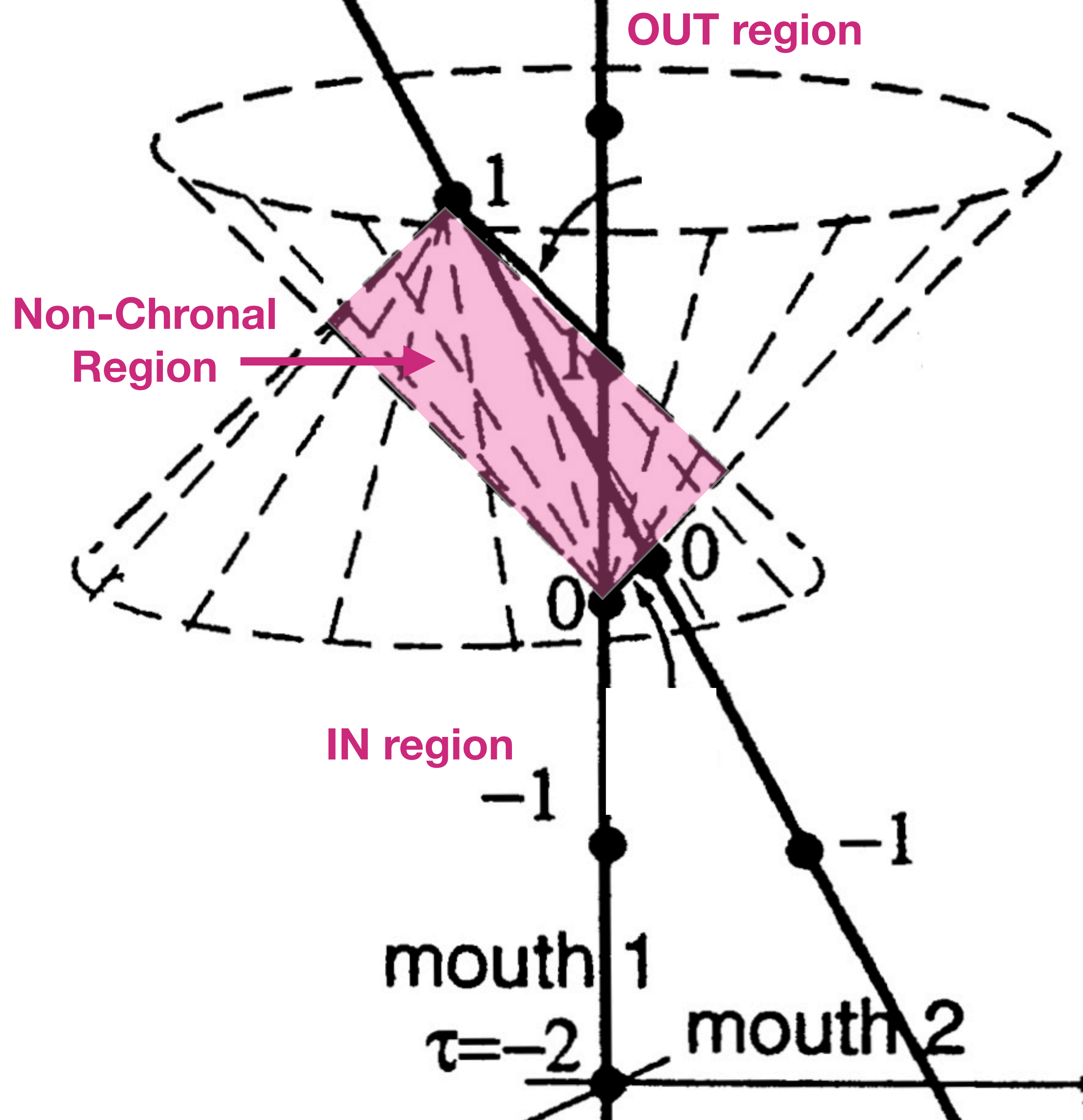
- Spin up to near light speed [Non-Chronal Region forms]
- Spin back down [Non-Chronal Region gone]



Quantum Fields? (e.g. electromagnetic field)

Wormhole mouths
move past each other
at constant speed

- Specify probabilities (quantum states) for field in IN region
- Use quantum field laws to deduce probabilities in non-chronal region and OUT region
- STANDARD formulation of quantum laws *cannot* make predictions
- FEYNMAN'S sum-over-histories formulation *can* make predictions
- (In absence of time travel, the two formulations give *same* predictions)

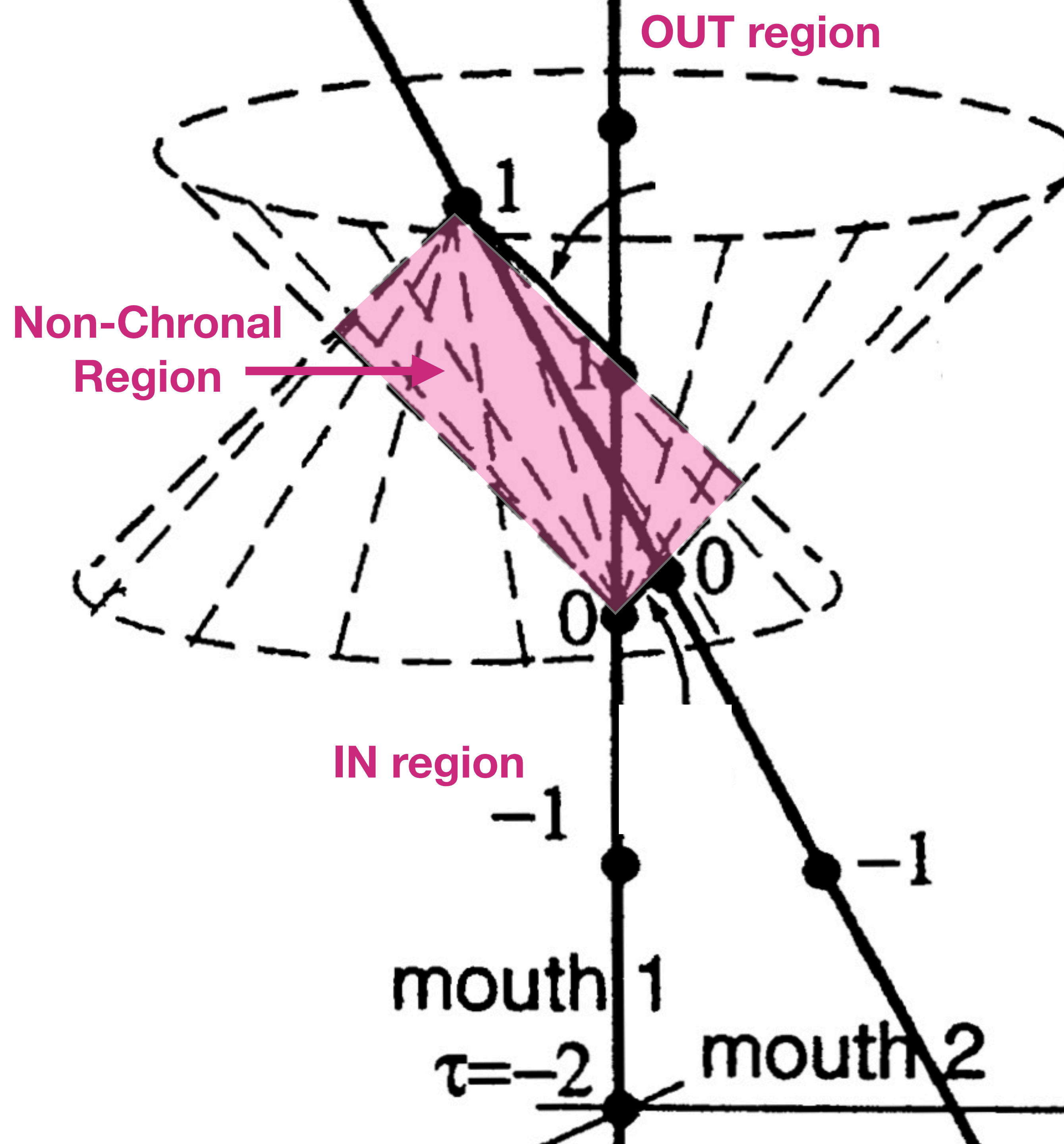


Predictions via Feynman's formulation of quantum laws:

- J Friedman, N Papastamatiou & J Simon (1992) - [self interacting fields, e.g. $\lambda \phi^4$]
- J Hartle (1994) [Hartle / Gell-Mann QM]

Evolution from IN to OUT: Non-unitary information is lost

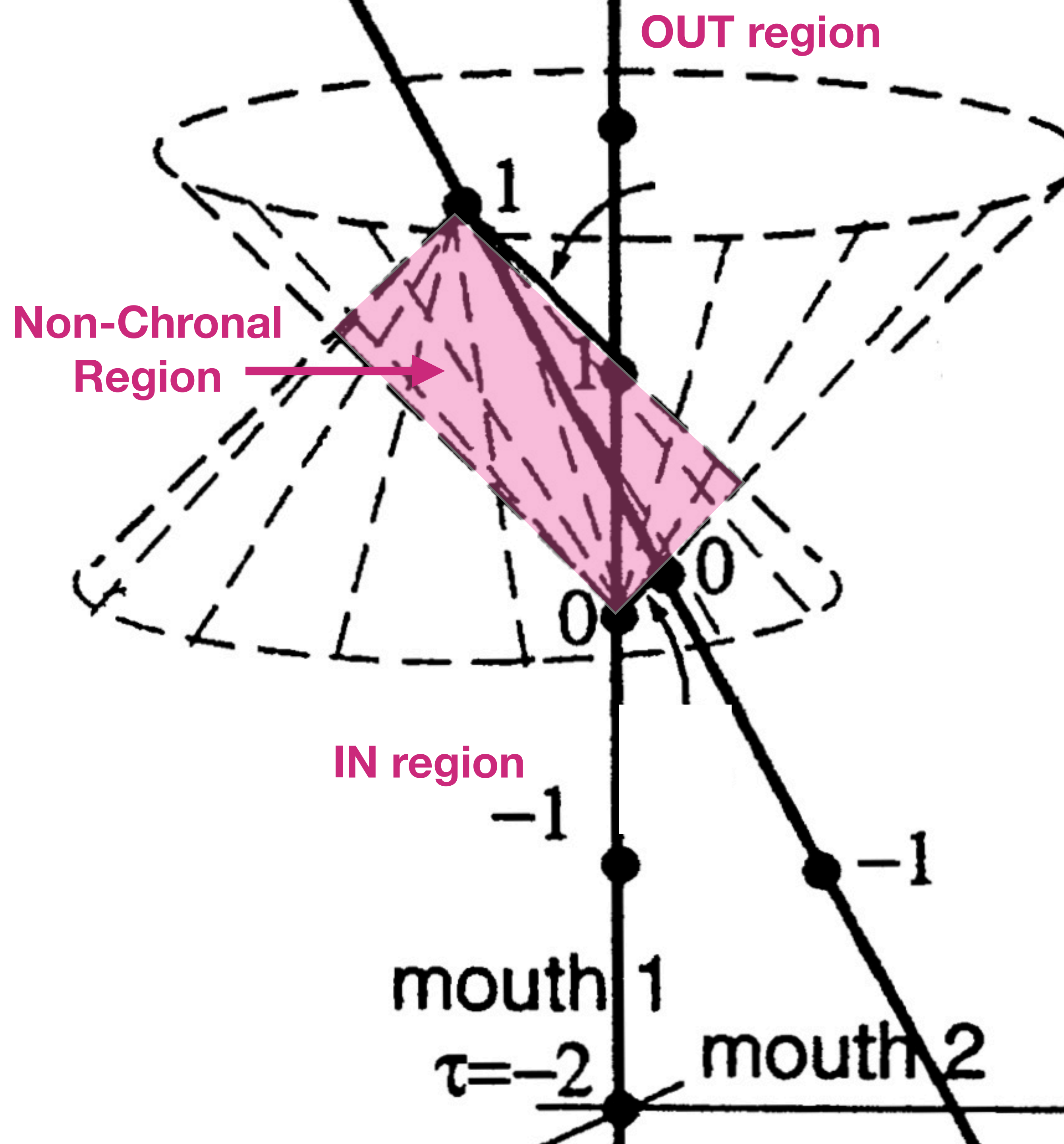
- Reminds me of the Black-Hole Information-Loss Paradox
- My unconventional view: In black hole evaporation information may be truly lost.
- Why? Final stage of evaporation governed by **laws of quantum gravity**. Must include histories with backward time travel, and that causes the information loss.



*Predictions via Feynman's formulation
of quantum laws:*

- J Friedman, N Papastamatiou & J Simon (1992) - $[\lambda \phi^4]$
- J Hartle (1994) [Hartle / Gell-Mann QM]

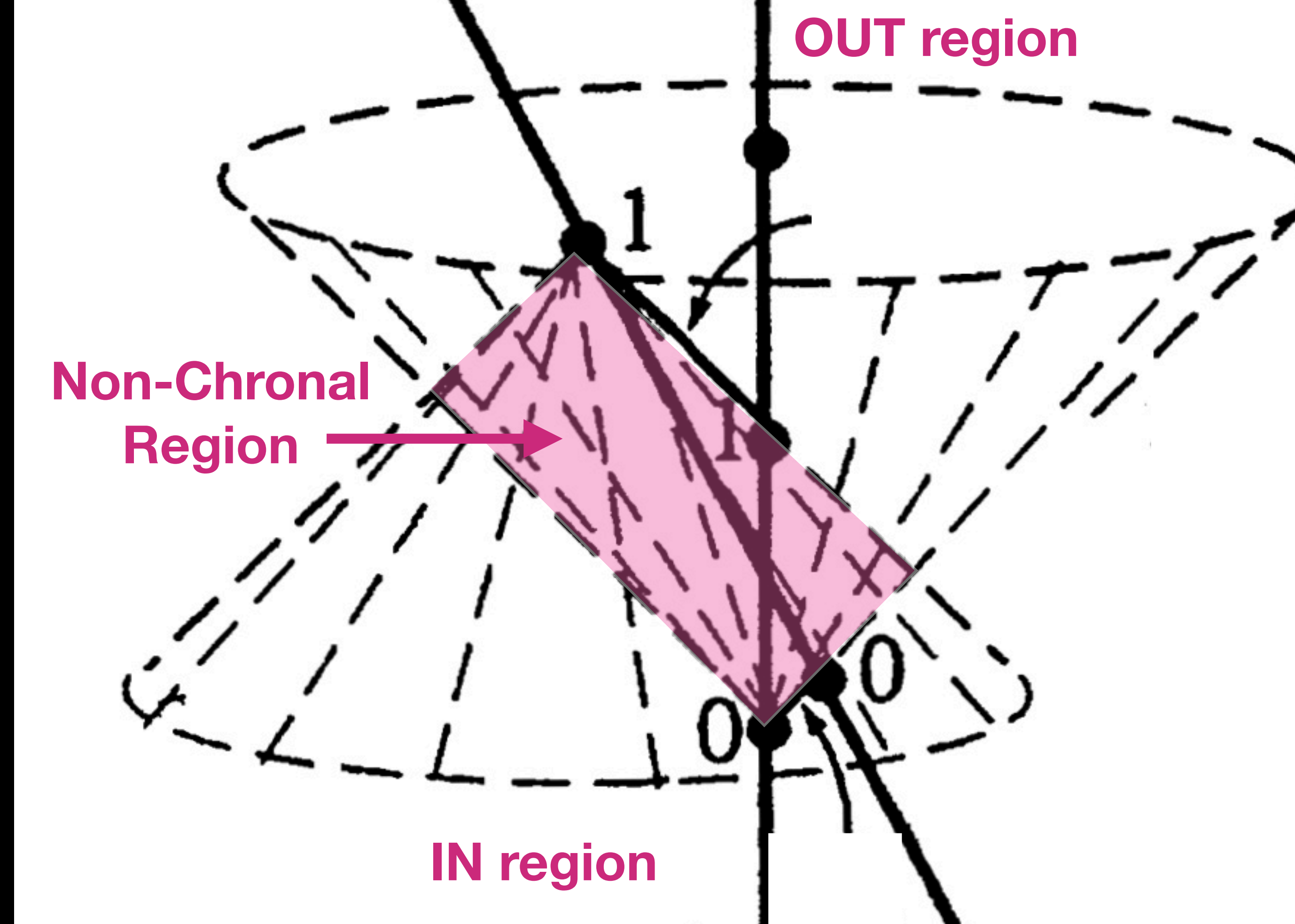
Evolution from IN region to IN region:
Probabilities are influenced by the
presence or absence of the Non-
Chronal Region!!!



**Predictions via Feynman's formulation
of quantum laws:**

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Evolution from IN region to IN region:
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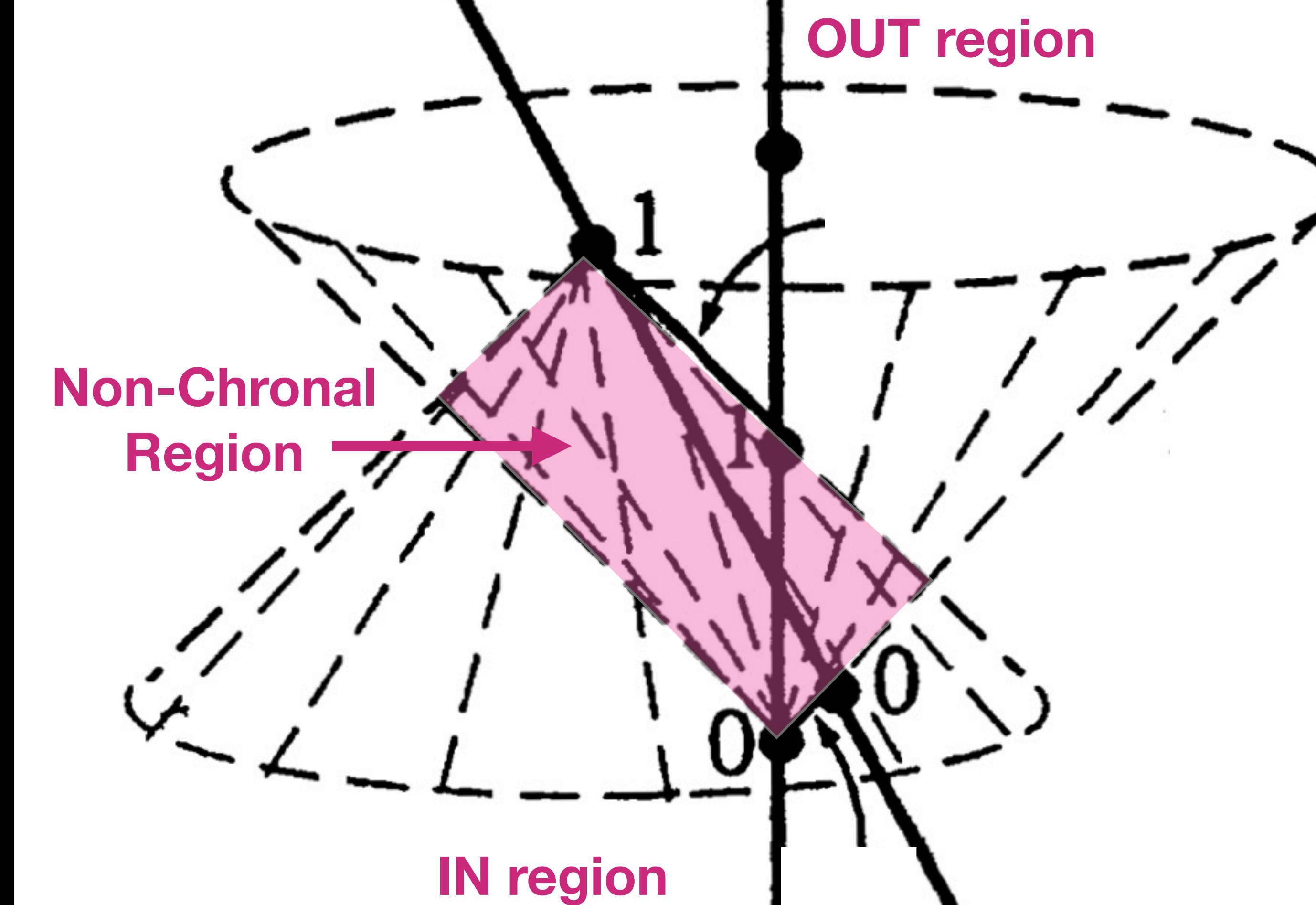


Friedman, Papastamatiou and Simon paraphrased: It is plausible that that there is negligible causality violation to the past of a Non-Chronal region *unless* one designs an experiment explicitly to probe that region. Such an experiment, however, can violate causality in the IN region to the past of the Non-Chronal region.

***Predictions via Feynman's formulation
of quantum laws:***

- J Friedman, N Papastamatiou & J Simon (1992) - $[\lambda \phi^4]$
- J Hartle (1994) [Hartle / Gell-Mann QM]


Evolution from IN region to IN region:
Probabilities are influenced by the
presence or absence of the Non-
Chronal Region!!!



Hartle: "If nonchronal regions are sparse in the future history of spacetime, then we might expect ... the resulting violation of causality to be negligible. If, however, there were a roiling sea of nonchronal regions near a generic final [cosmological] singularity, then the probabilities for causality violation might be more interesting. The present generalized quantum mechanics provides a way of estimating them."

Conclusions - Quantum Gravity

- Extreme thought experiments are powerful tools for probing ill-understood physics
- The laws of quantum gravity appear to control whether backward time travel is possible — “time machine self destruction”
- The laws of quantum gravity, implemented via Feynman’s sum-over-histories, may require including histories with backward time travel [Closed Timeline Curves ... CTCs]. If so, then:
 - Information may be truly lost in black hole formation & evaporation [nonunitary evolution]
 - Macroscopic Non-Chronal regions may cause some weirdness in causality, even before they arise.

A wide-field astronomical image of a starry sky. The background is filled with numerous small, distant stars. In the center, there is a prominent, glowing, reddish-brown structure, likely a nebula or a galaxy, with a bright, white, star-like core. The overall color palette is dark, with the reddish-brown of the central structure and the white of the core providing the main points of interest.

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