17. Time Travel 2

Topics:
1. MTY Traversible Wormnhole
2. Ori-Soen Spacetime
3. Gödel Spacetime
4. Tipler Cylinder Spacetime
5. Gott Cosmic String Spacetime

Def. 1. A *time travel spacetime* is a solution to the Einstein equations that admits closed timelike curves (CTCs).

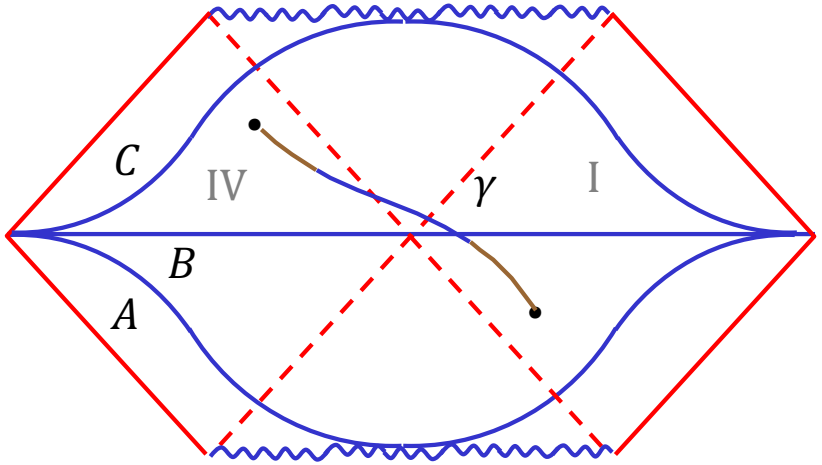
Def. 2. A *time machine spacetime* is a time travel spacetime in which the CTCs are generated by the operation of a device (the time machine).

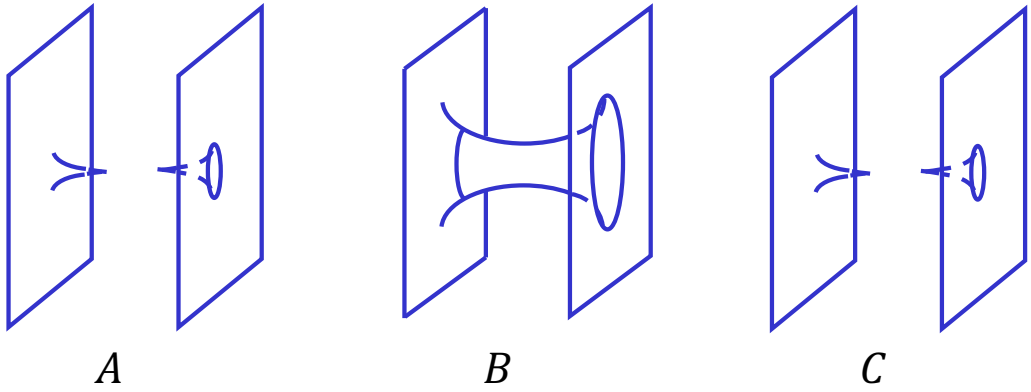
- All of the following are time travel spacetimes.
  - *Whether or not some are, in addition, time machine spacetimes is still open to debate.*

1. MTY Traversible Wormhole

- Morris, M. and K. Thorne (1988) 'Wormholes in spacetime and their use for interstellar travel', *Am. J. Phys.* **56**, 395.
- Morris, M., K. Thorne, U. Yurtserver (1988) 'Wormholes, time machines and the weak energy condition', *Phys. Rev. D* **49**, 3990.

- *Recall the Einstein-Rosen wormhole*: It doesn't stay open long enough.





- A worldline γ connecting two points in I and IV during the time the wormhole is open must at some point become spacelike.

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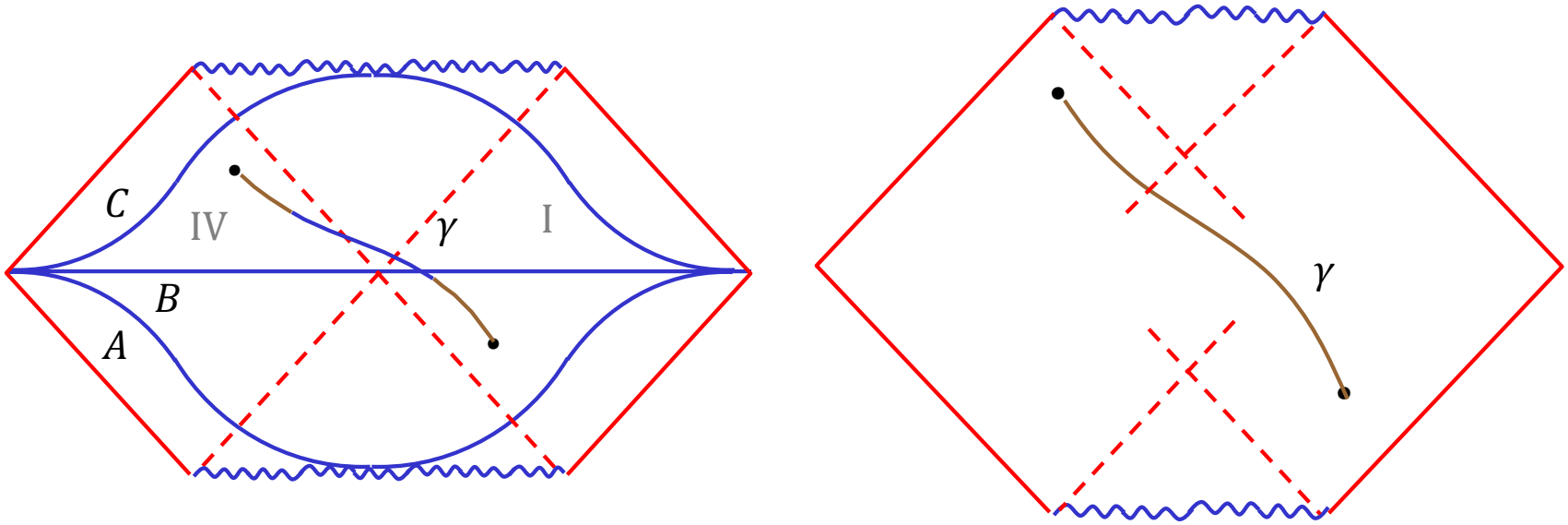
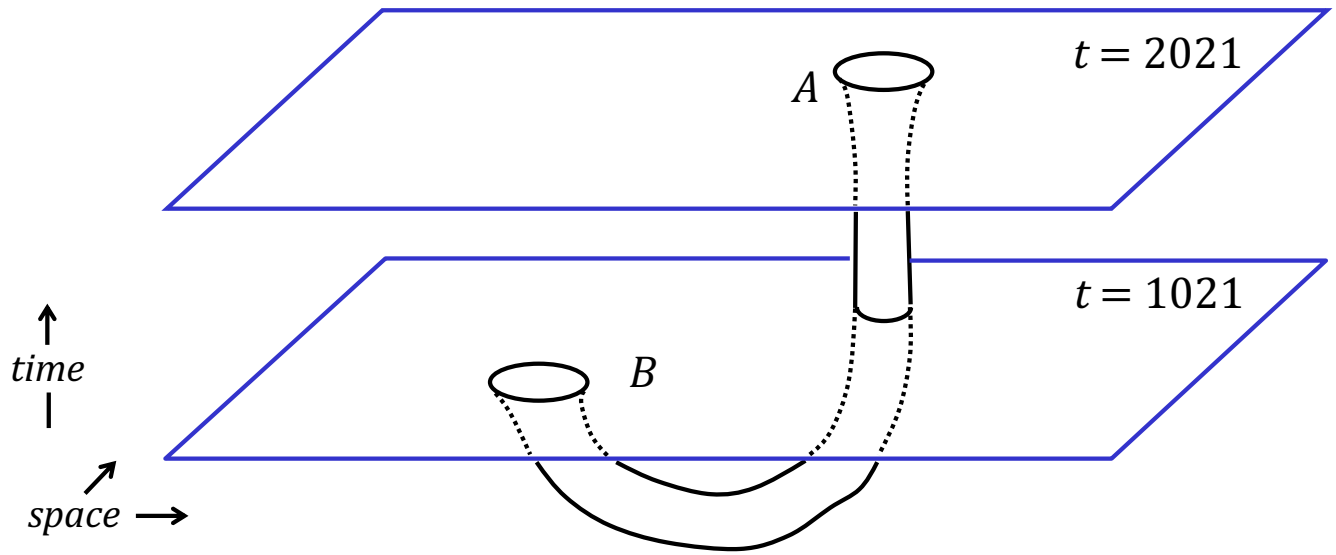


- A worldline γ connecting two points in I and IV during the time the wormhole is open must at some point become spacelike.
- To keep wormhole open long enough for use, need to "stretch" the Schwarzschild spacetime so that γ is everywhere timelike!
  - *Mathematically, this requires negative energy in the Einstein equations.*
  - *But: In what sense is such a traversible wormhole a legitimate time machine?*

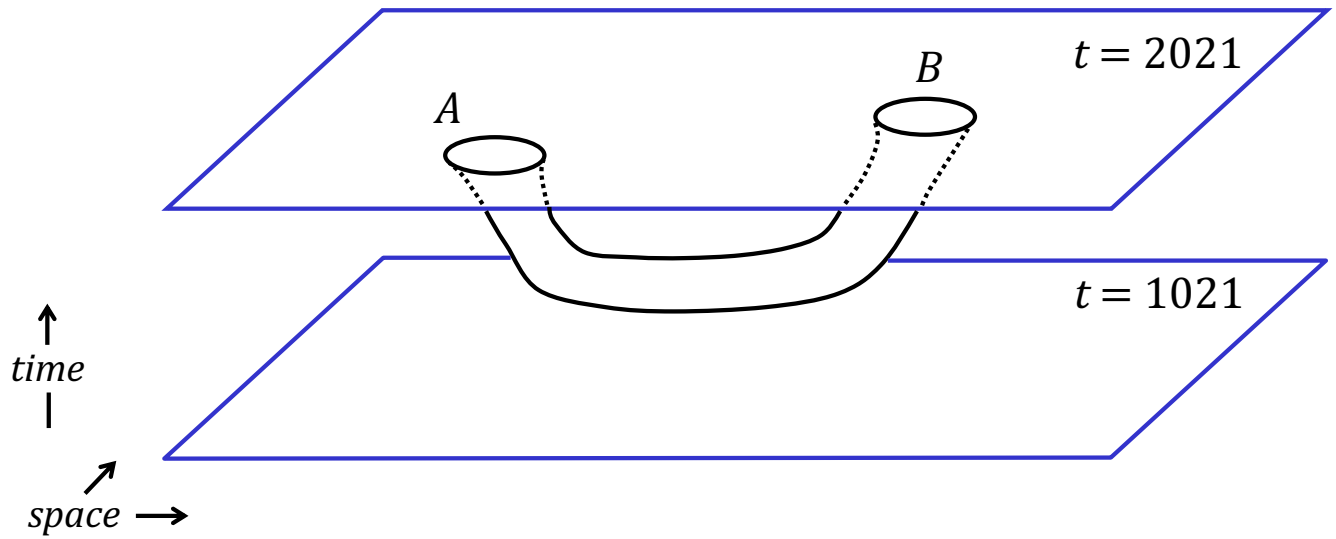


<u>General wormhole</u>: A and B are separated by spatial and temporal distances.

- *If spatial distance is so great that it would take a timelike traveler longer to get from B to A than temporal distance, then the wormhole shouldn't count as a time machine.*

<u>Example</u>: Suppose A is on Earth and B is in a galaxy 2000 light-years away.

- *If you jump through A, you go back in time 1000 years, but it would take you more than 2000 years to get back to the Earth!*

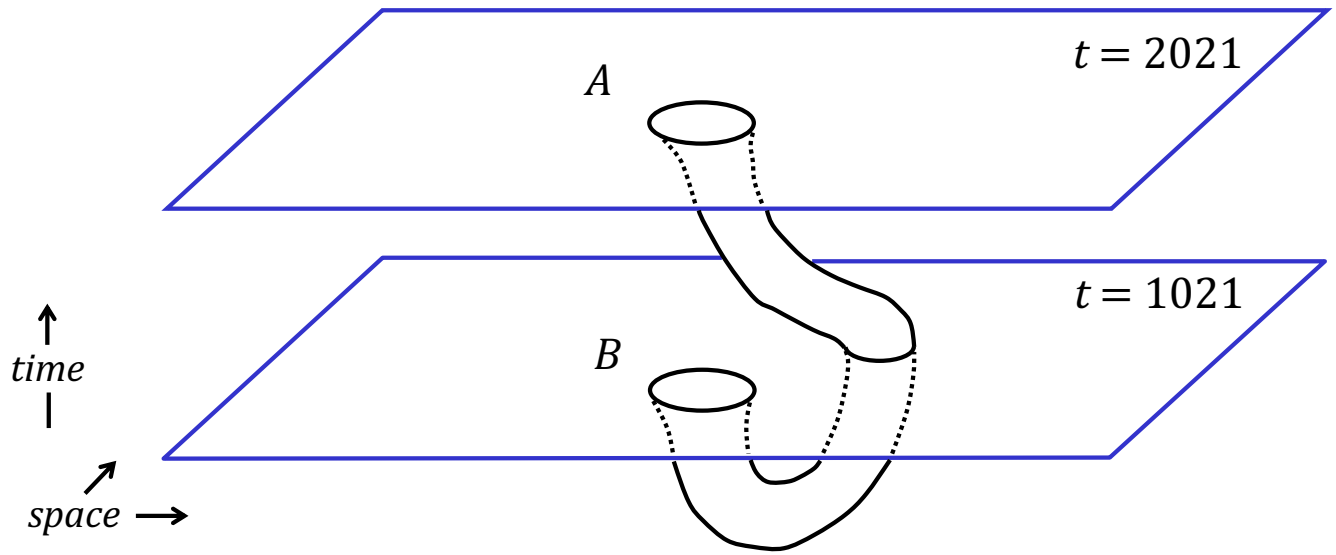


<u>Temporally-localized wormhole</u>: Mouths are separated in space only.

- *A convenient way to travel, but not a time machine!*

- How to construct a time machine from a temporally localized wormhole:

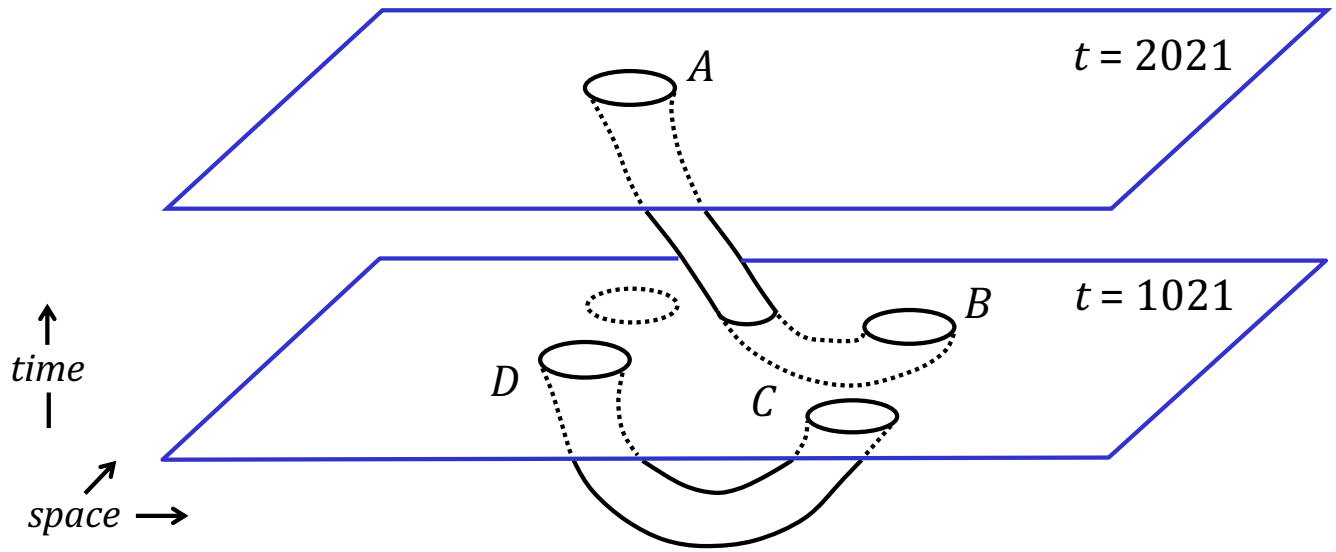
1. Take one mouth on a twin-paradox trip (*special relativistic time dilation*).
2. Place one mouth closer to an intense gravitational source (*general relativistic gravitational red-shift*).



<u>Spatially-localized wormhole</u>: Mouths are separated in time only.

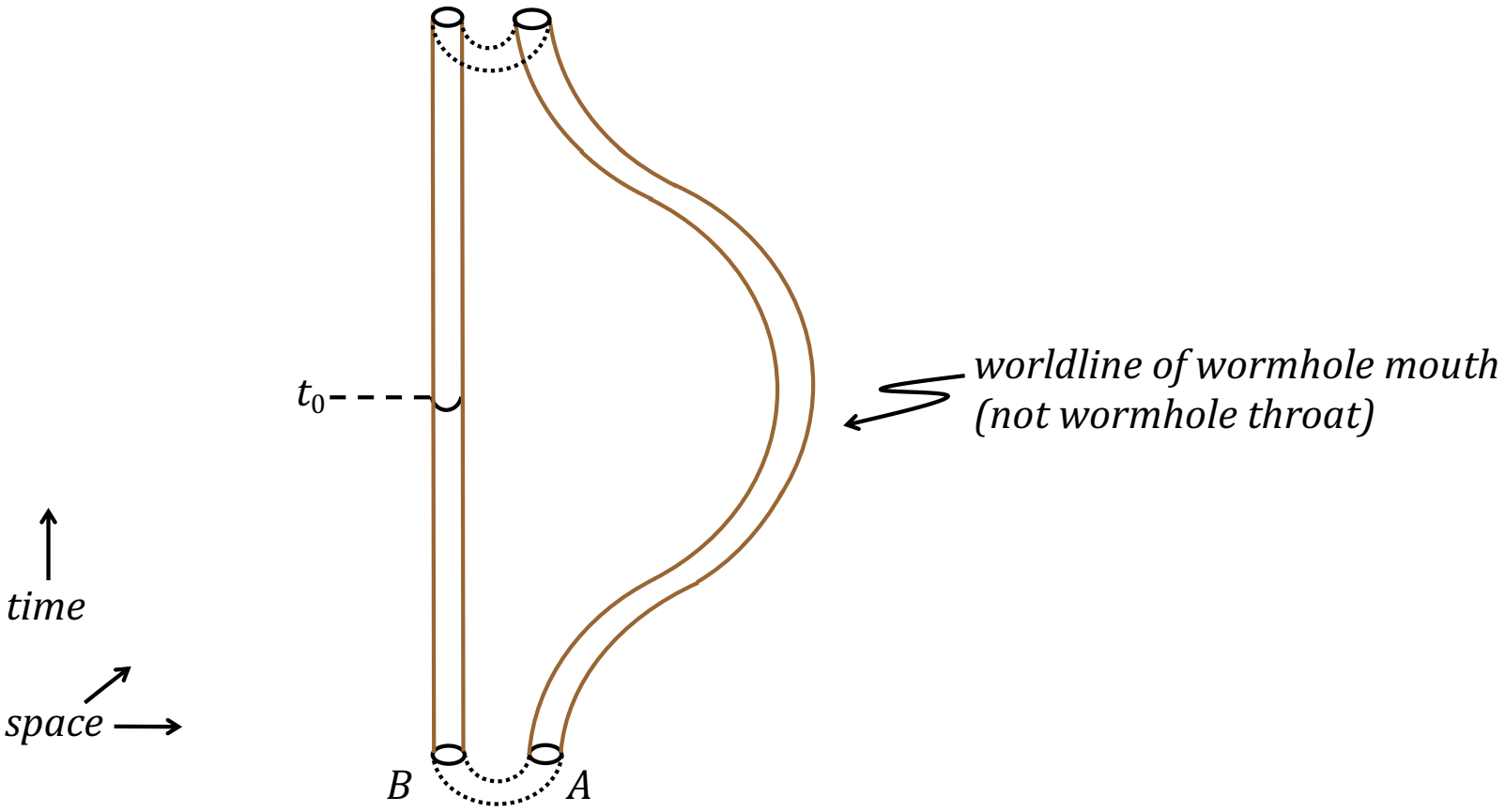
- *At last a time machine!*

- <u>*Radiation feedback problem*</u>: Light entering A exits B in the past; re-enters A again with former self; re-enters A again with former selves... *etc*.
  - *Feedback becomes infinite almost instantaneously and BOOM!*



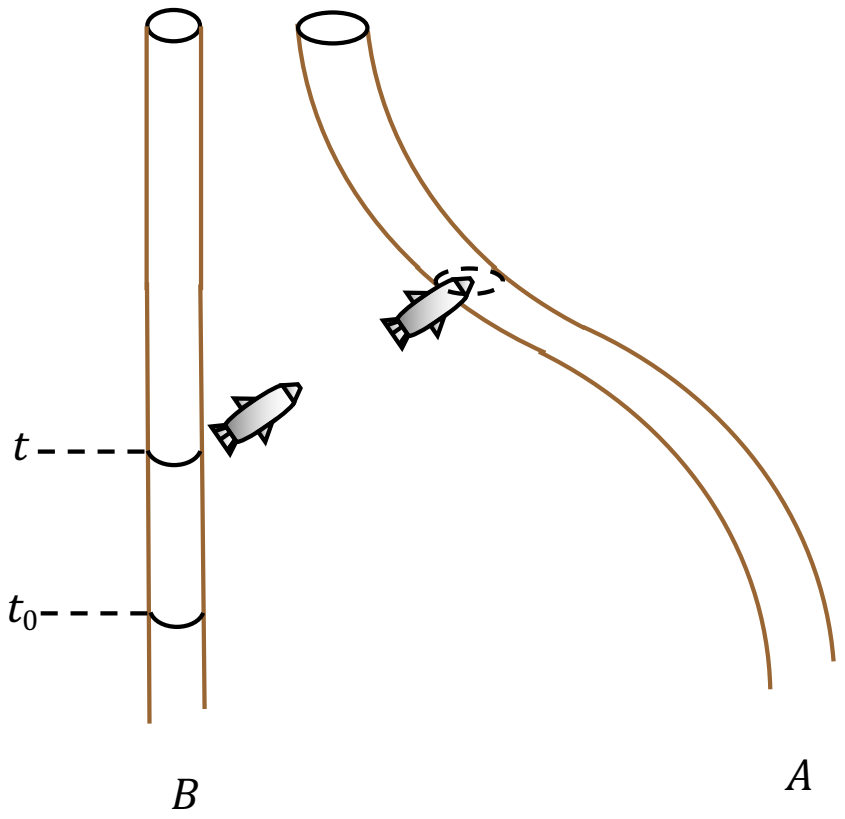
- *Roman Configuration*: Two or more traversible wormholes, each one of which doesn't count as a time machine, but entire configuration does.
- *A* and *B* are far enough apart spatially to prevent radiation feedback.
  - *Use (temporally-localized) wormhole CD to get back to spatial location of A in the past.*

Causal structure of wormhole time machine



- Wormhole time-machine constructed *via* twin-paradox time dilation.
- There exists at time t_0 on B's clock such that, for any time $t > t_0$, a timelike traveler can travel from B to A, and back through the wormhole throat to B to arrive at a time earlier than t.

Causal structure of wormhole time machine:



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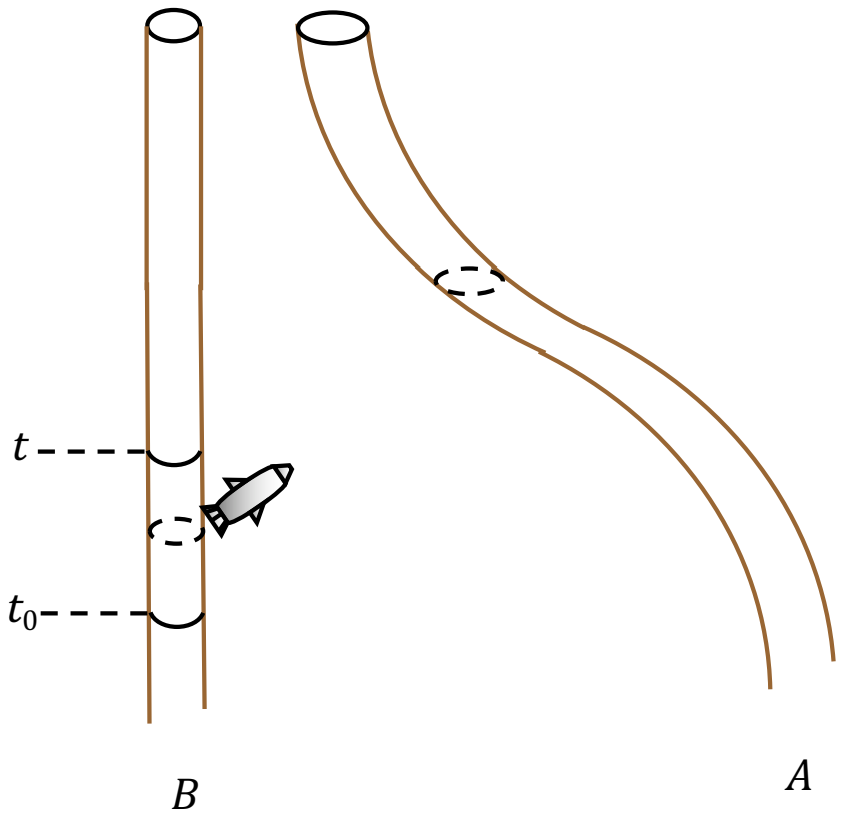

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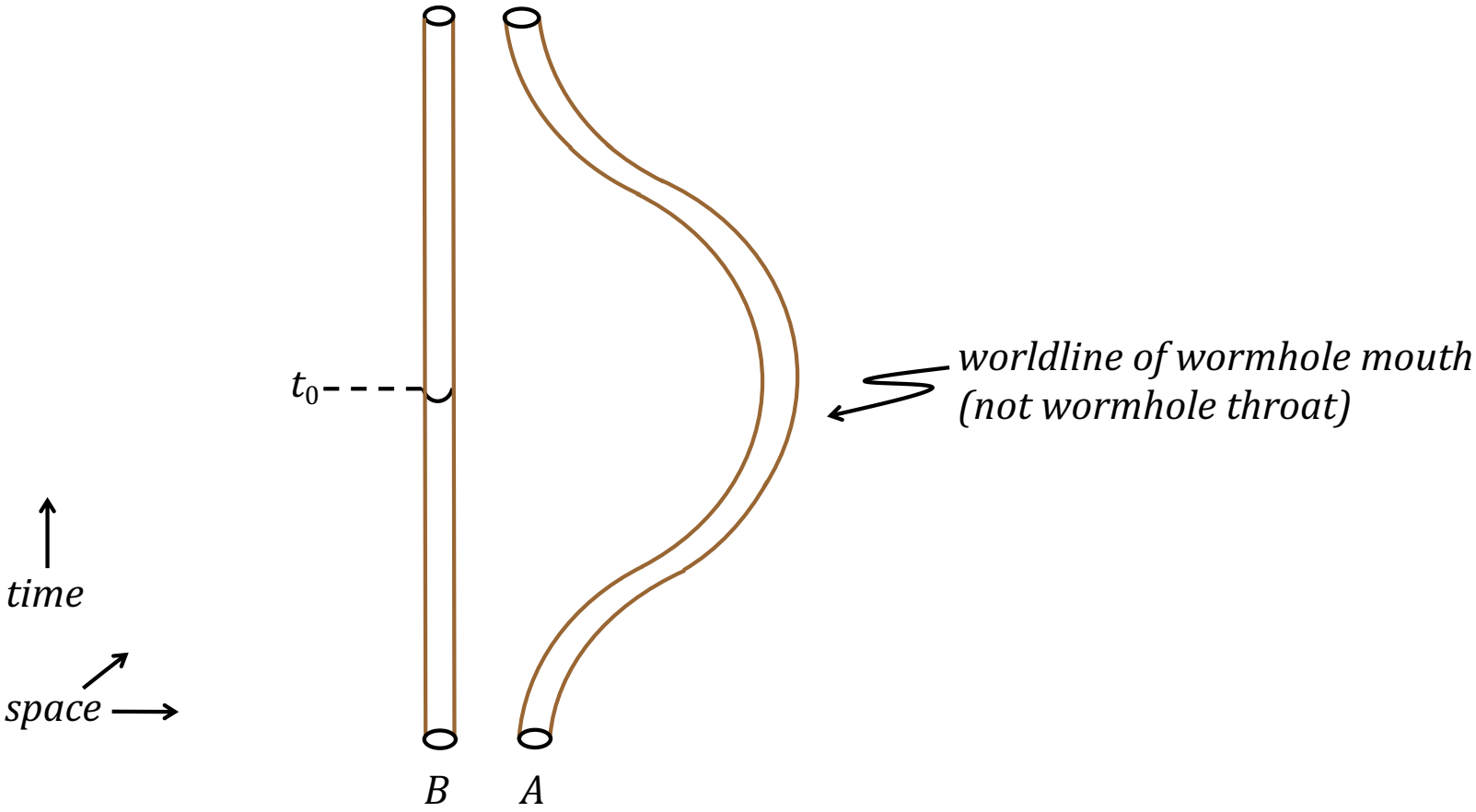

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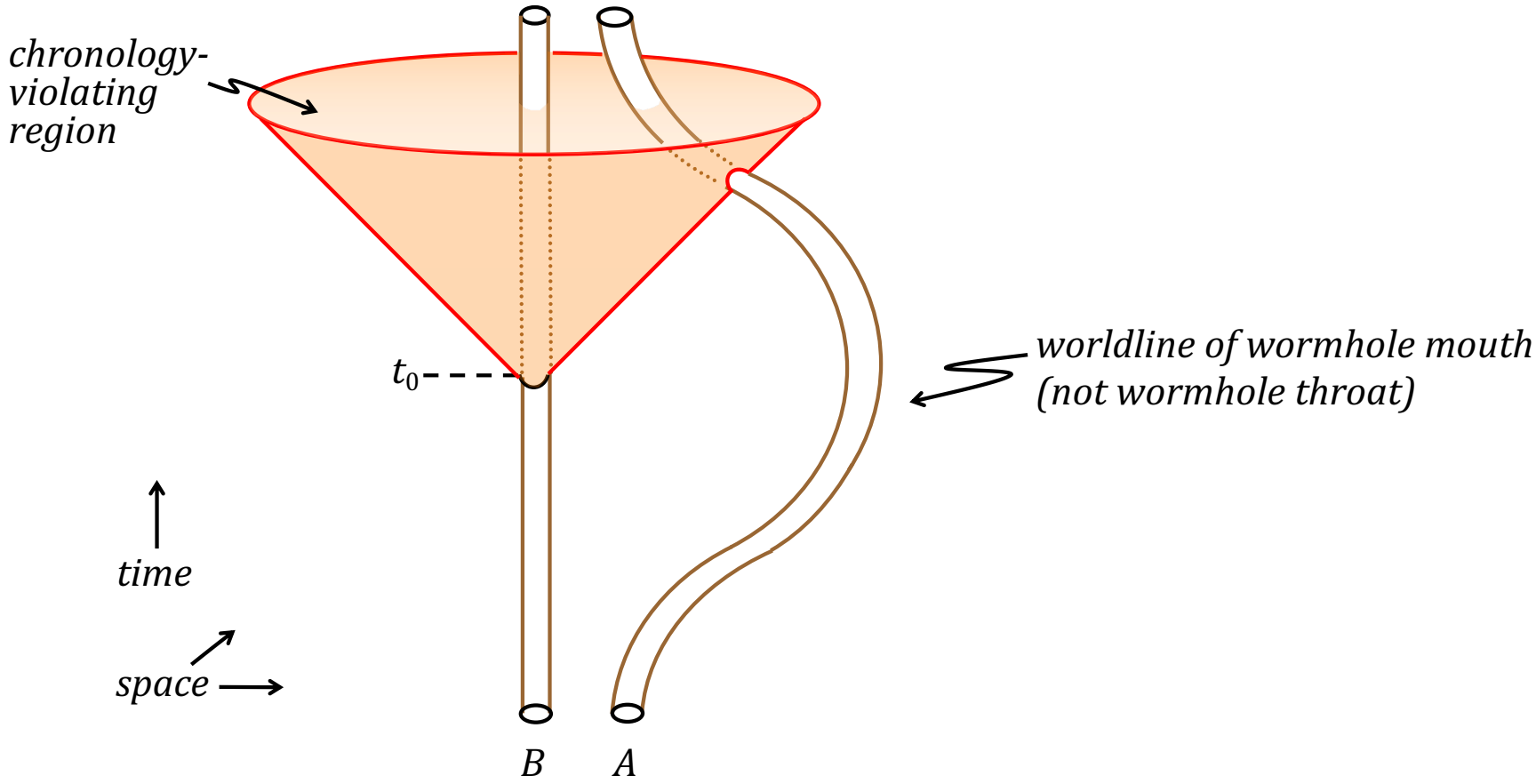
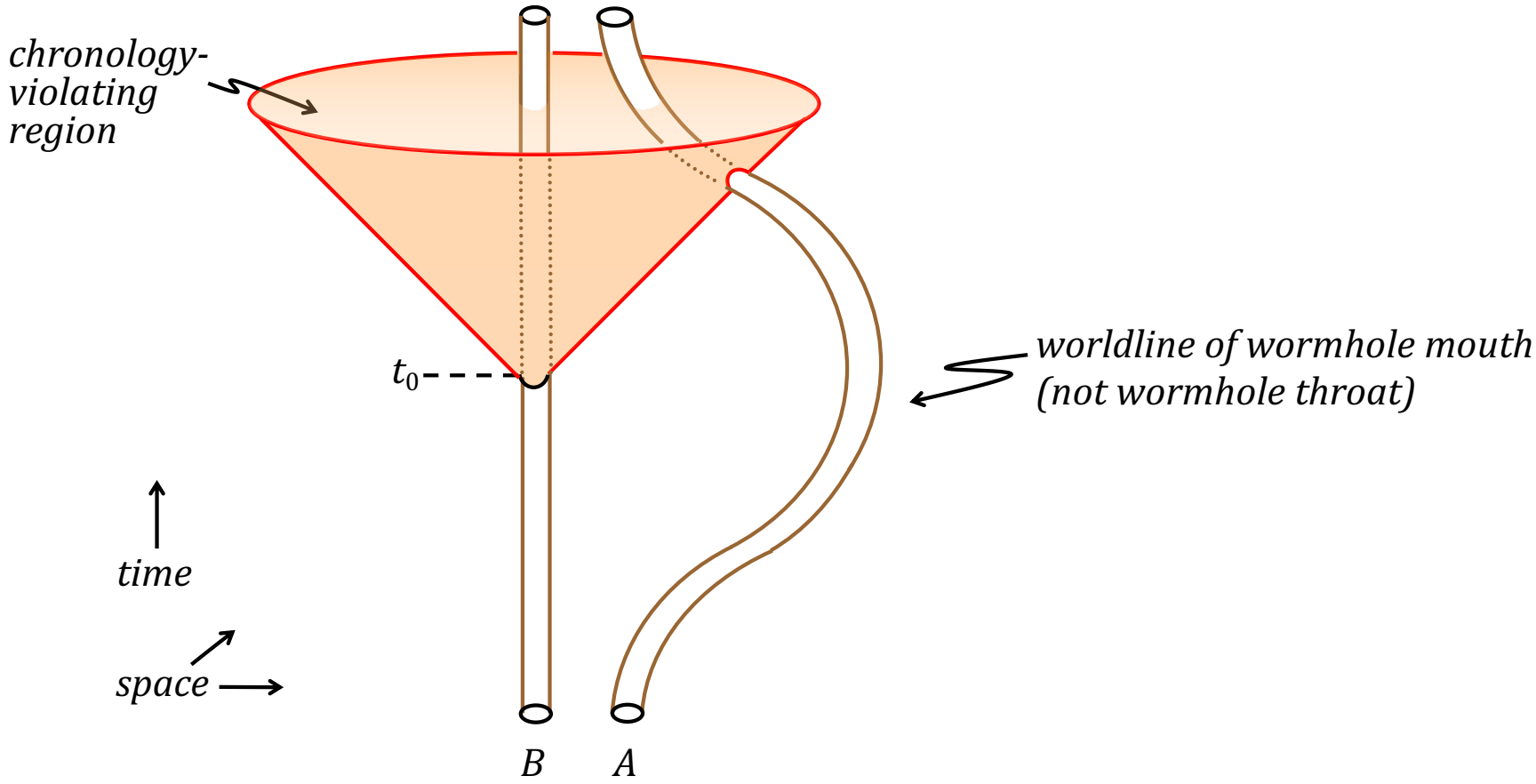


- Wormhole time-machine constructed *via* twin-paradox time dilation.
- There exists at time t_0 on B's clock such that, for any time $t > t_0$, a timelike traveler can travel from B to A, and back through the wormhole throat to B to arrive at a time earlier than t.
- Chronology-violating region is the interior of the lightcone of the event at t_0.

Causal structure of wormhole time machine:



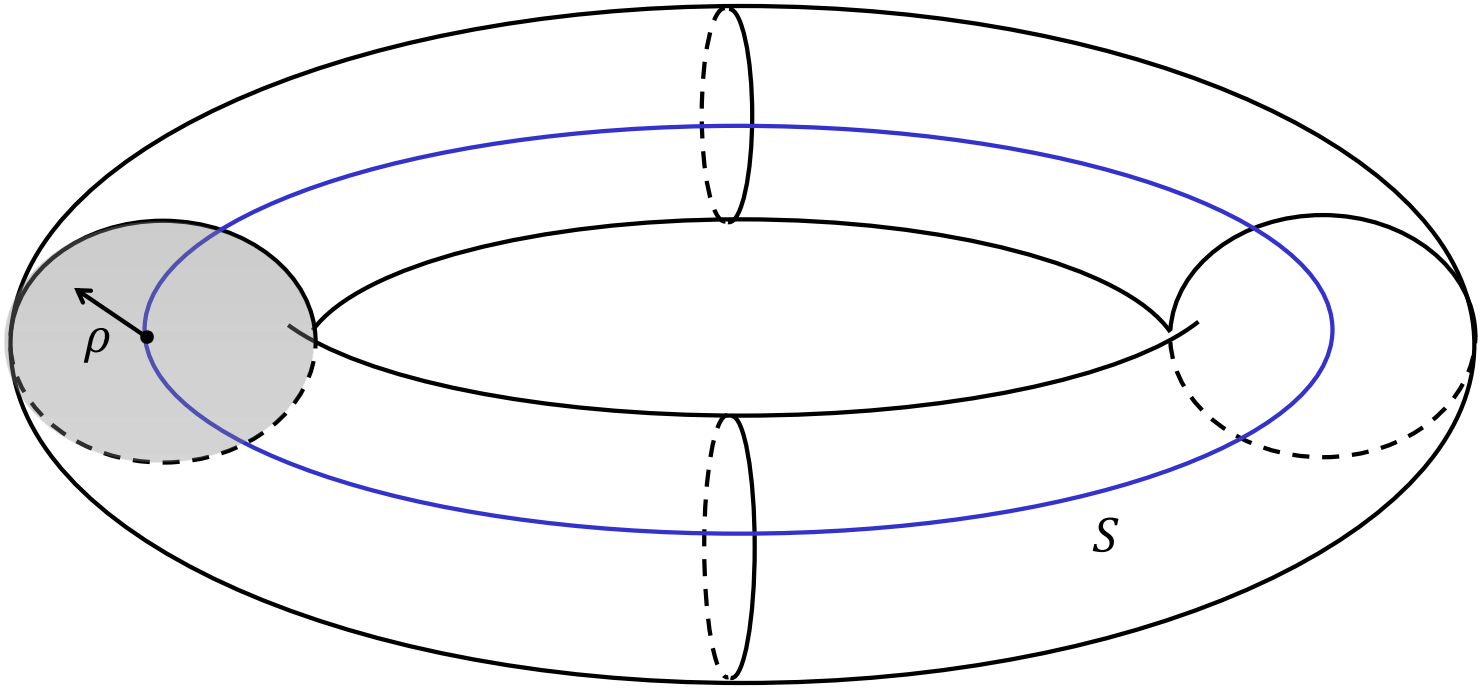
Problems:

1. Negative-energy matter leads to quantum mechanical instabilities.
2. Availability?

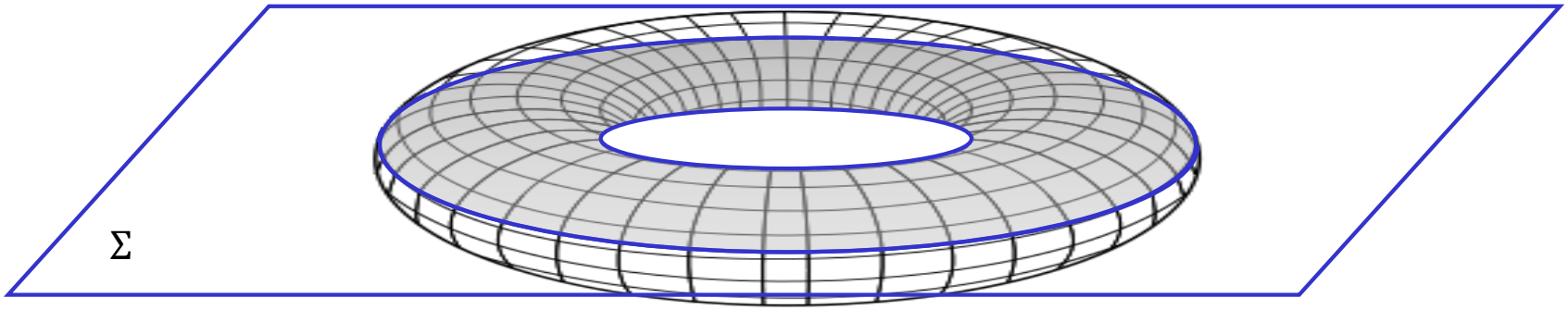
- *One Solution for* (1): Use *ringhole* wormholes: mouths are tori, not spheres (Gonzales-Diaz, P. 1996 *Phys. Rev. D* **54**, 6122).

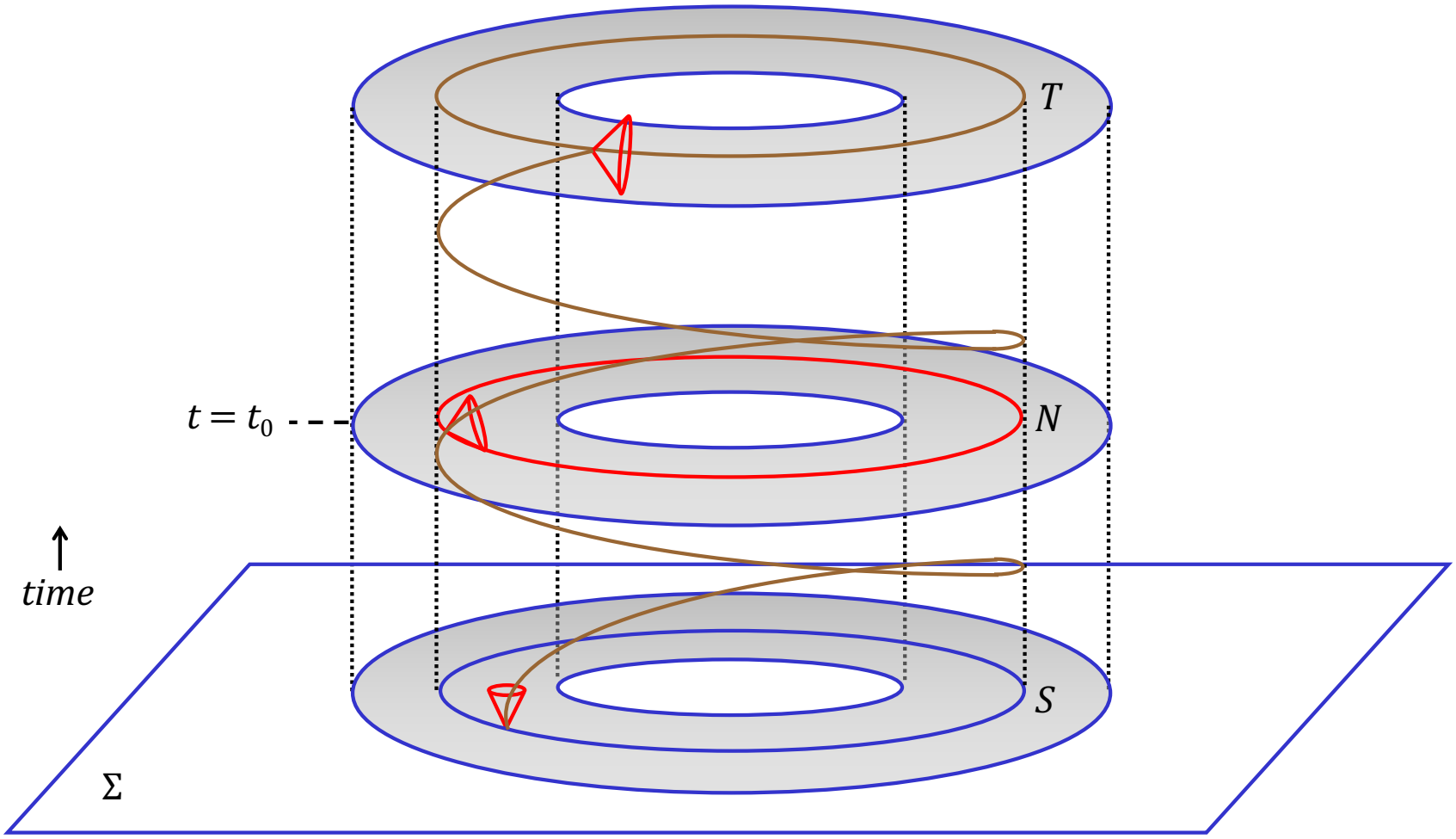
2. Ori-Soen Spacetime

- Ori, A. (1993) 'Must time-machine construction violate the weak energy condition?', *Phys. Rev. Lett.* **71**, 2517.
- Ori, A. and Y. Soen (1994) 'Causality violation and the weak energy condition', *Phys. Rev. D* **49**, 3990.

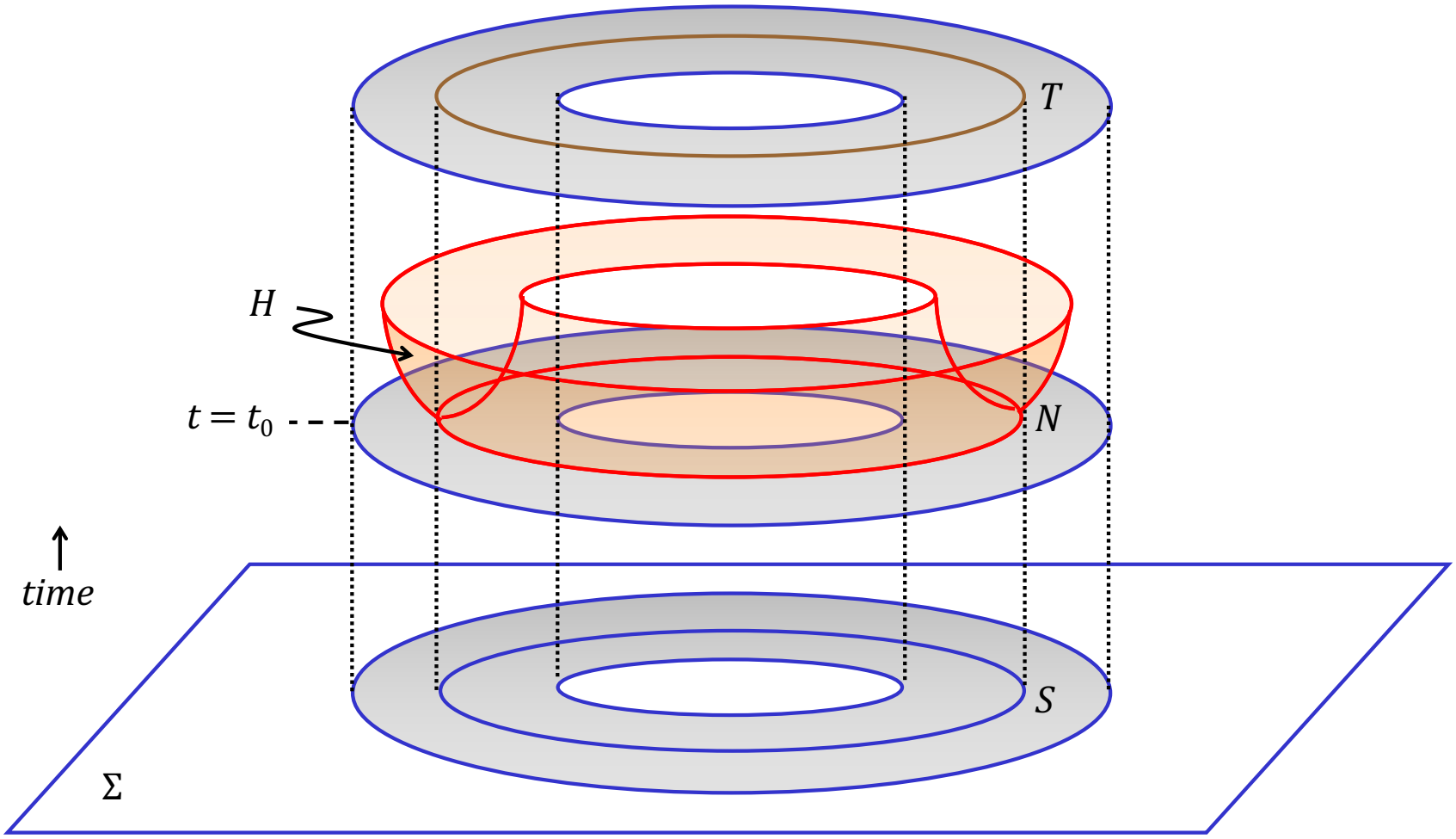


- Spacetime with a region shaped like a torus (doughnut).
  - *CTCs develop inside torus to the future of a spacelike hypersurface* Σ.
- Closed spacelike curve *S* inside torus: after a given time t_0, this and others near it become timelike.
- Size of cross-section described by ρ coordinate.
  - *The curve S goes through the point* $\rho = 0$.

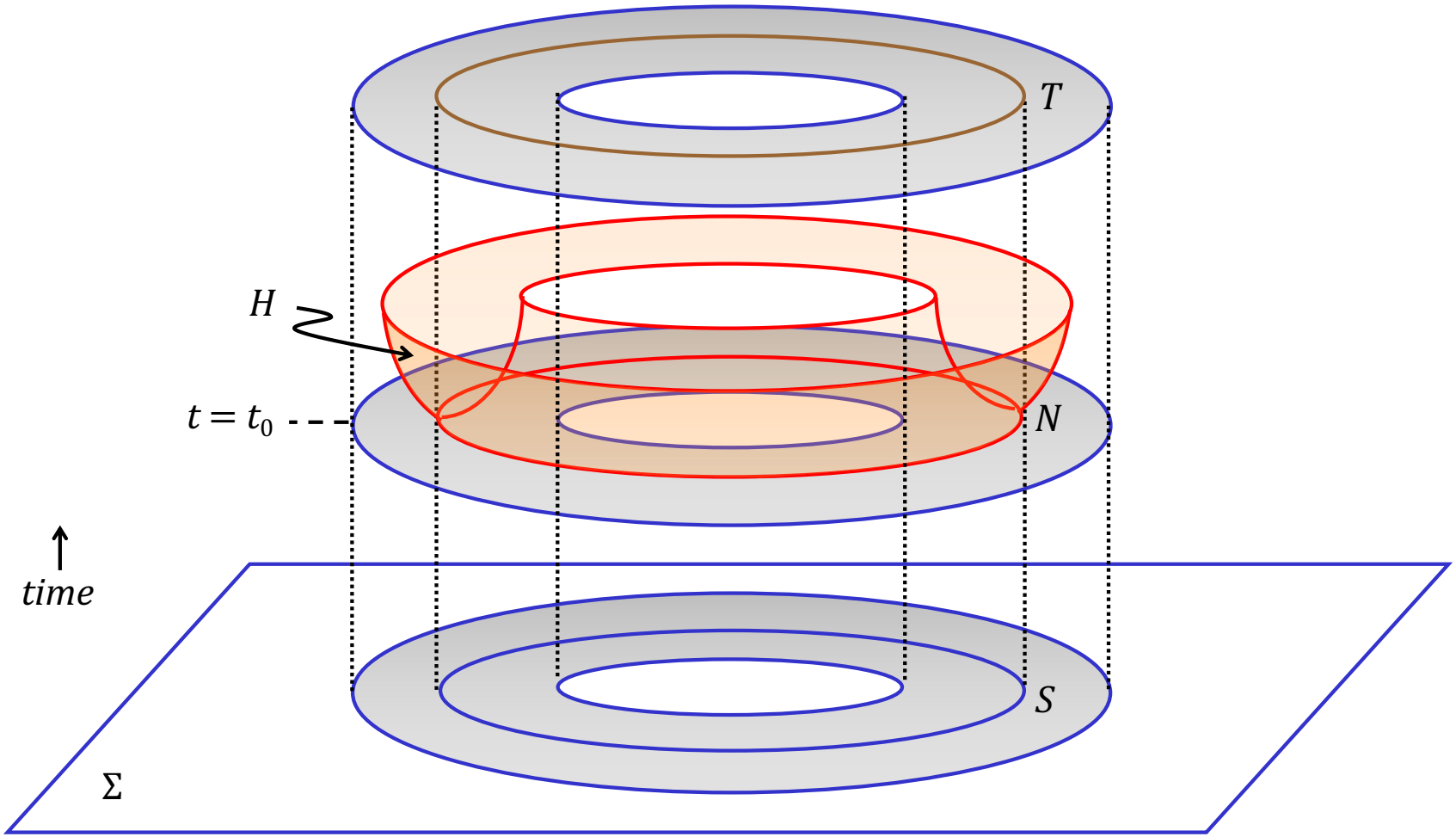

Σ



- Before t_0, the closed curve S through $\rho = 0$ is spacelike.
- At t_0, the closed curve N through $\rho = 0$ is lightlike.
- After t_0, the closed curve T through $\rho = 0$ is timelike.
- Timelike worldline of an accelerating time traveler.

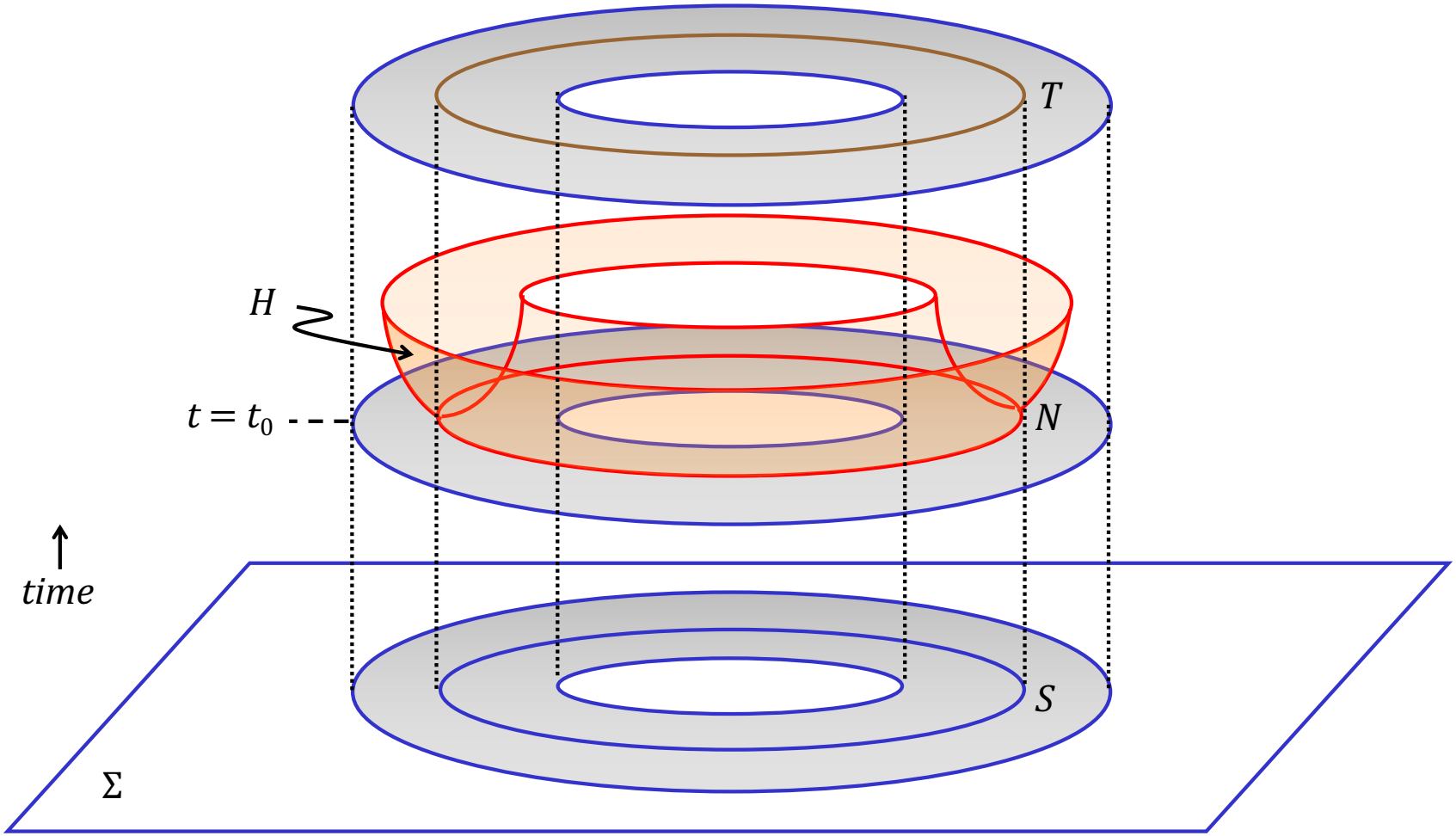


- <u>*Causal Structure*</u>: Σ is a nonflat spacelike partial Cauchy surface.
- *H* is the future Cauchy horizon of Σ.
  - *It extends upward from N (at $t = t_0$) and remains inside the interior of the torus.*
- The chronology-violating region is inside *H*.



Properties:

- No exotic matter required.
- Spacetime is flat far from torus and topologically trivial.
- Partial Cauchy surfaces Σ exist.
- Future Cauchy horizon is compactly generated.



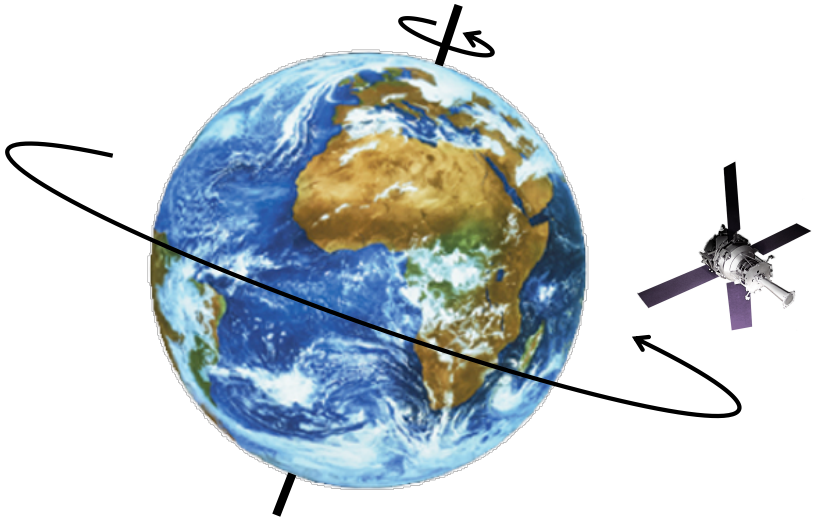
Problems:

1. Partial Cauchy surfaces are curved.
2. Is corresponding matter distribution physically possible?

Lense-Thirring Effect Time-Travel Spacetimes

- *Lense-Thirring Effect* = dragging of spacetime by a massive rotating object.

Rotating Earth: like a bowling ball in molasses...



Gravity Probe B

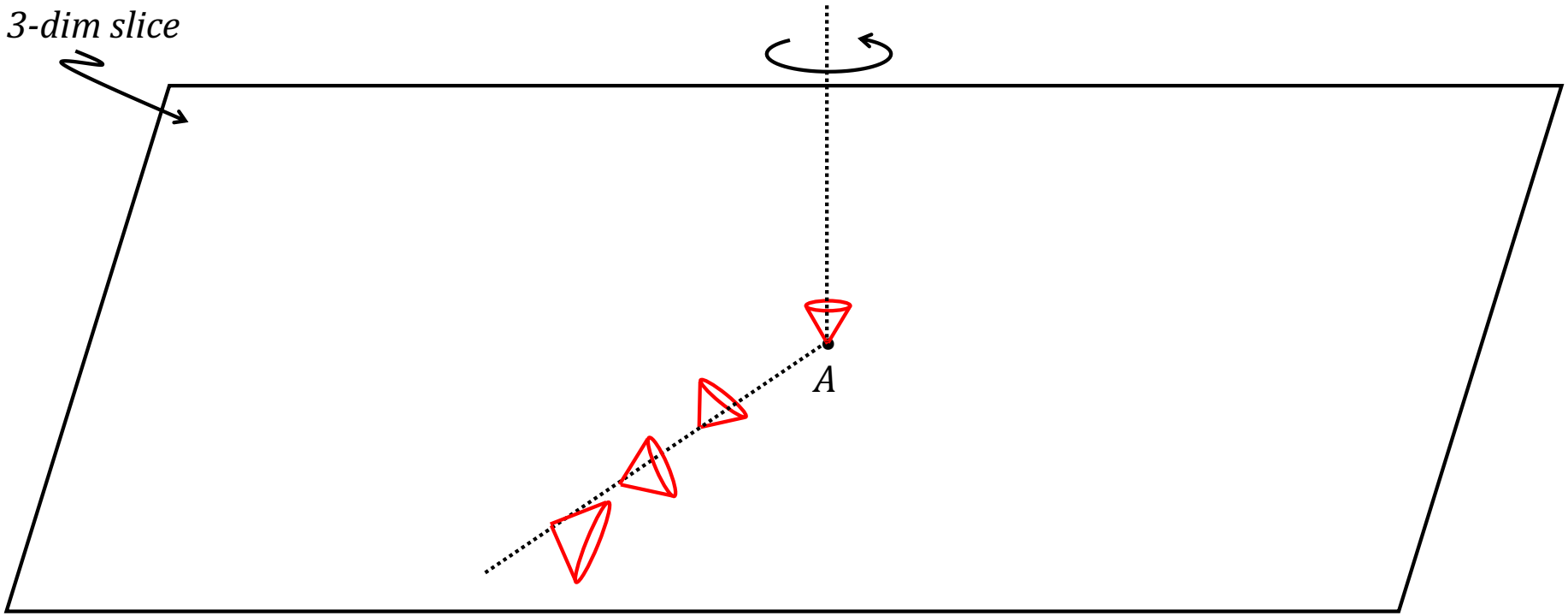
Gyroscope in orbit (2004-05): gets dragged along with the molasses (but very imperceptivity).

- For gyroscope in orbit around Earth, Lense-Thirring Effect causes axis of spin to go out of alignment by an angle of 39.2 milli-arcseconds per year (width of a human hair from 10 miles away!)
- Gravity Probe B experiment (*Phys. Rev. Letters* 2011): gyroscope drift in Earth orbit of 37.2 milli-arcseconds per year.

Def. A *Lense-Thirring Effect time-travel spacetime* is a spacetime in which rotating matter drags a spacetime region to create CTCs.

3. Gödel Spacetime

- Gödel, K. (1949) 'An example of a new type of cosmological solution of Einstein's equations of gravitation', *Rev. Mod. Phys.* **21**, 477.



- Spacetime with rotating homogeneous mass distribution with axis of rotation about any point *A*.
- *Lens-Thirring Effect*: The spacetime is dragged with the rotating mass to the extent that CTCs form.
- Lightcones tip over and flatten as we proceed away from *A* through concentric circles.

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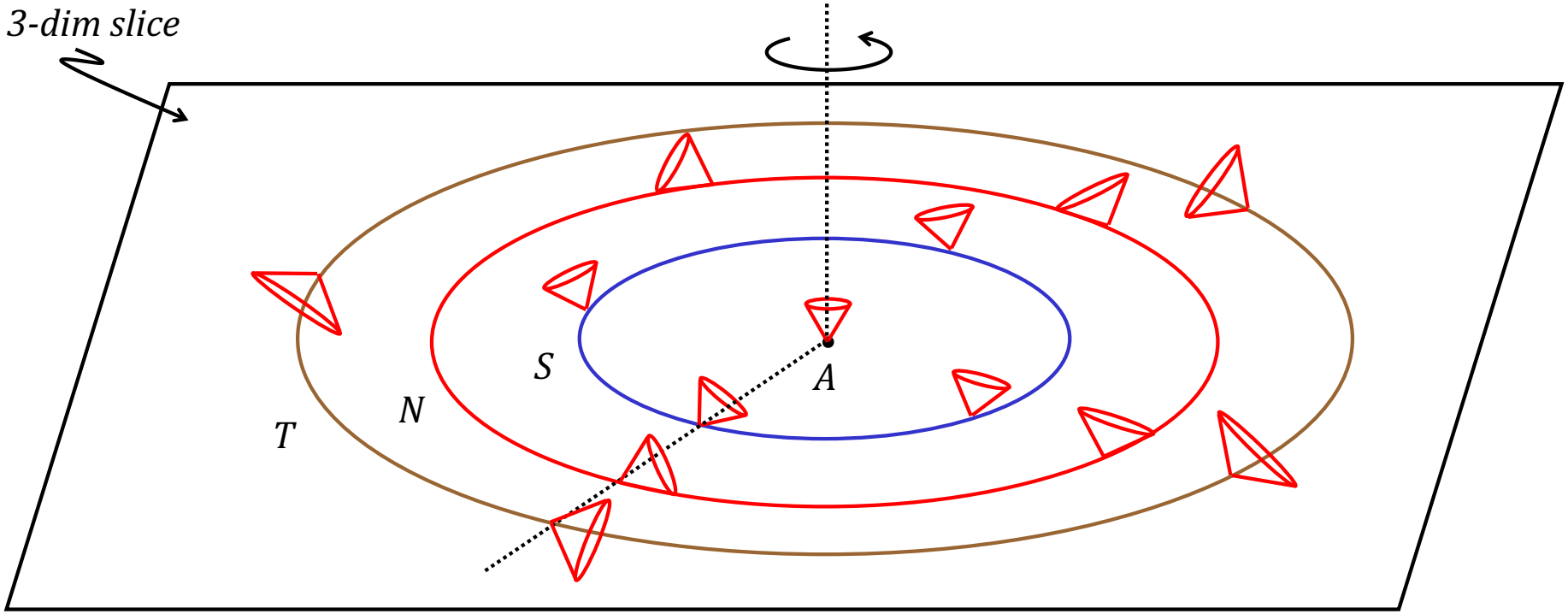
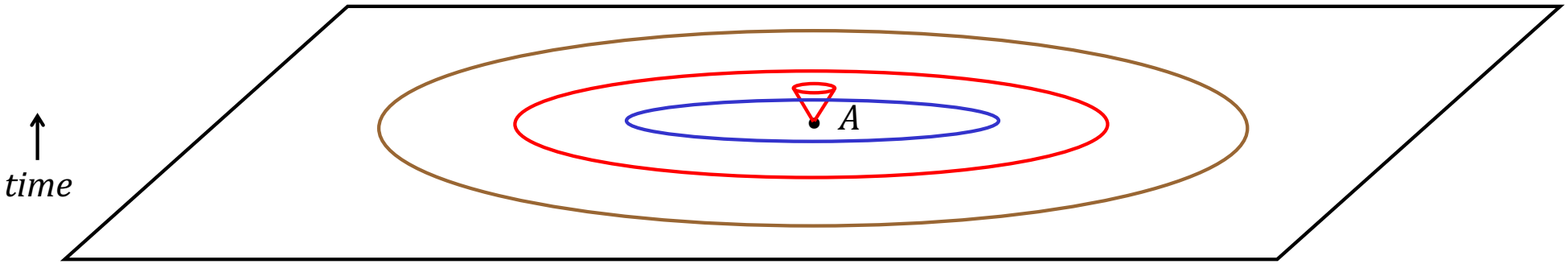
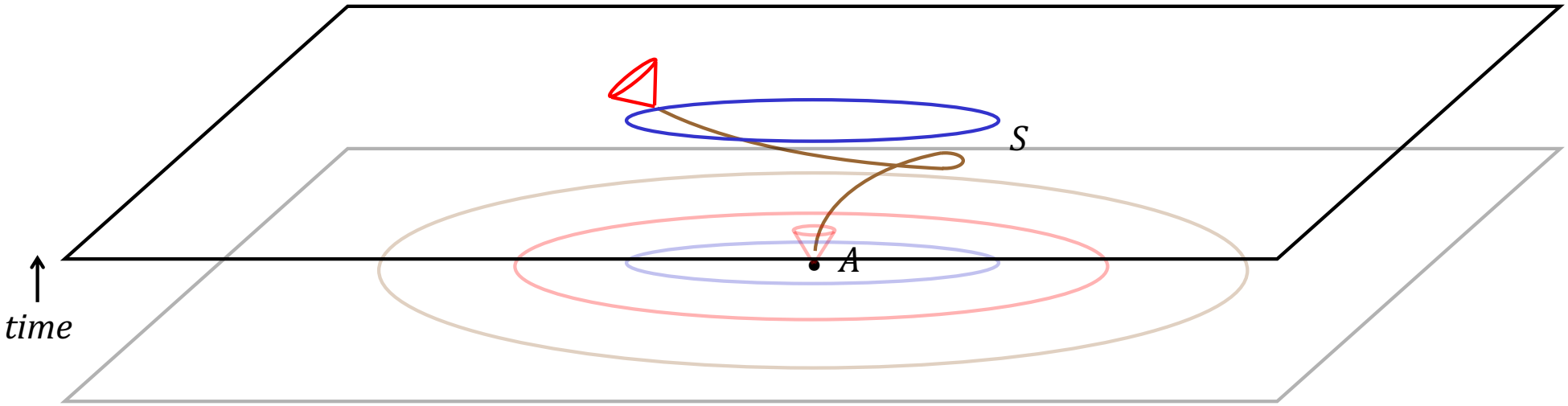


- Close to A, circles are closed spacelike curves S.
- Further out, circles are closed lightlike curves N.
- Still further, circles become CTCs T.



- To access a CTC, observer *A* must accelerate outwards along a spiraling trajectory.



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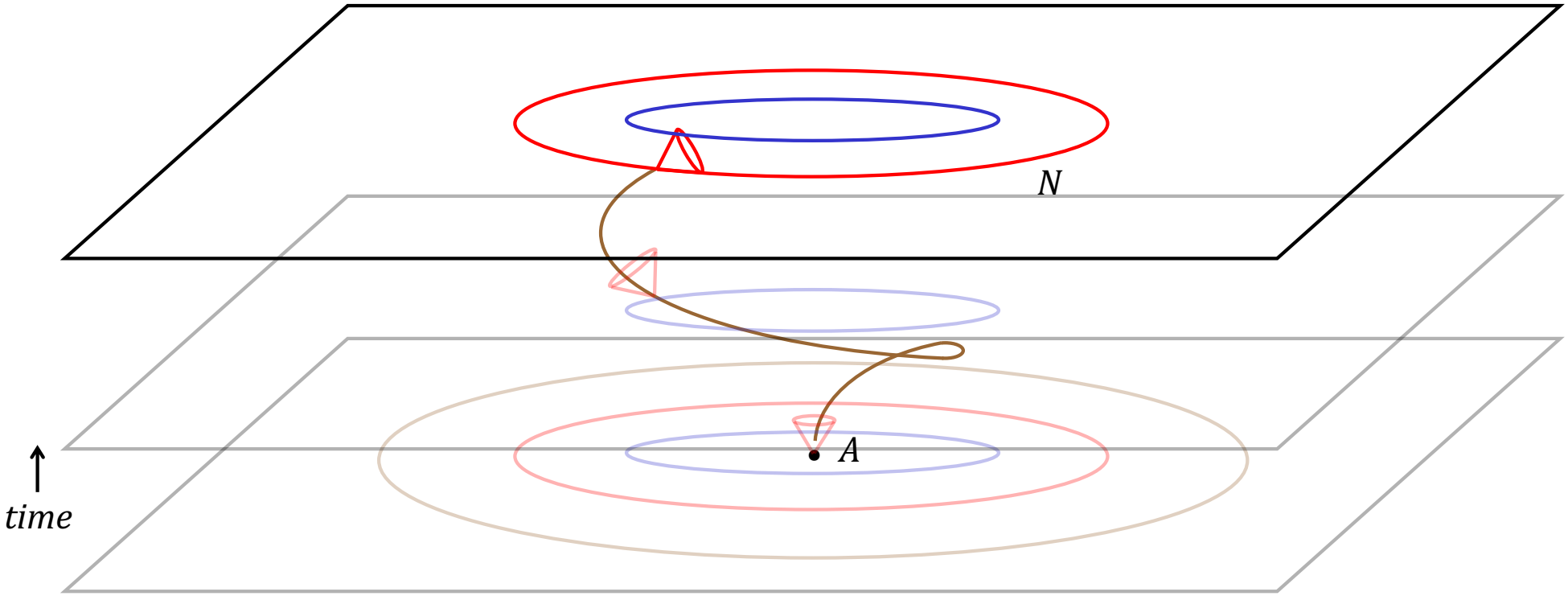

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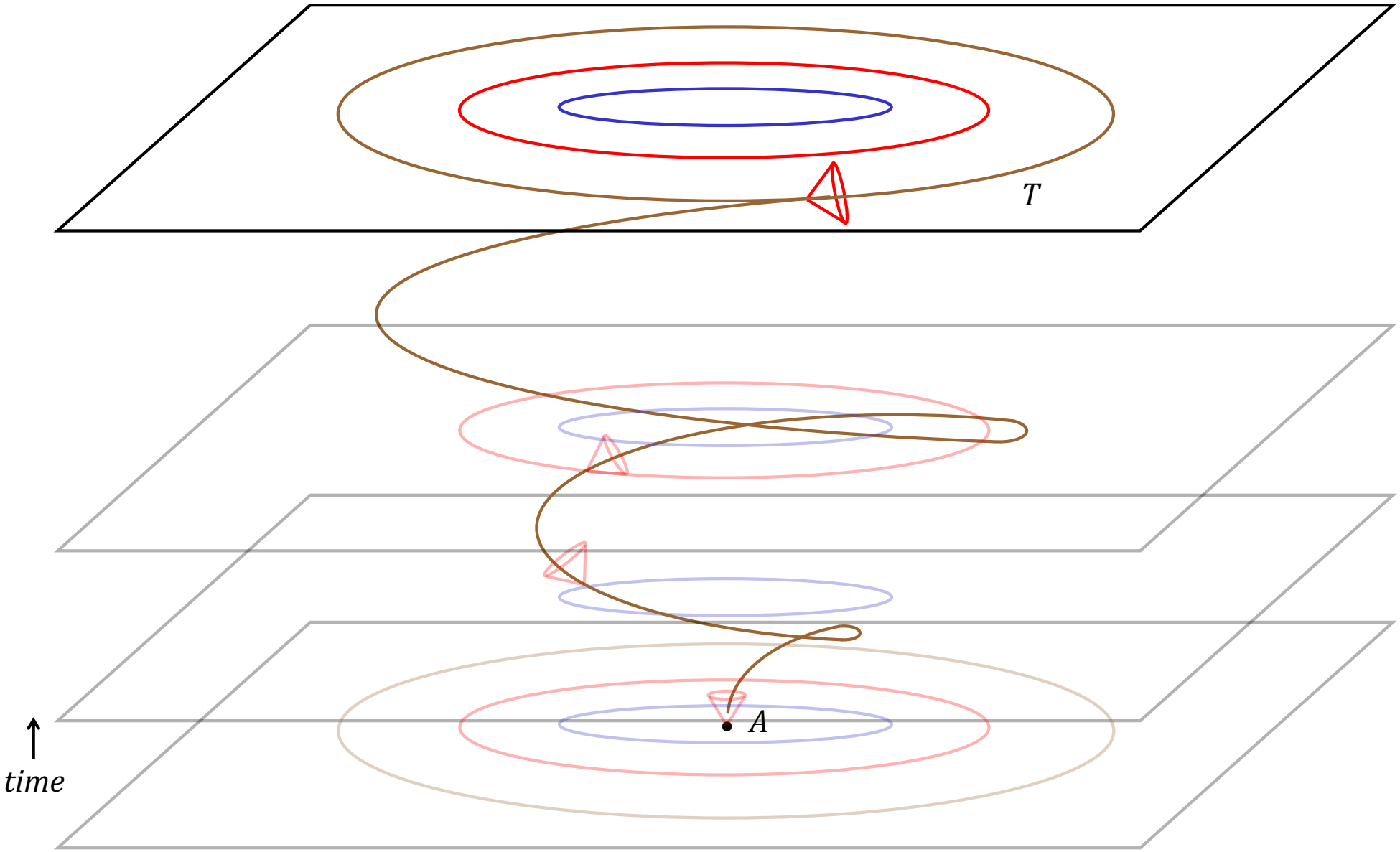

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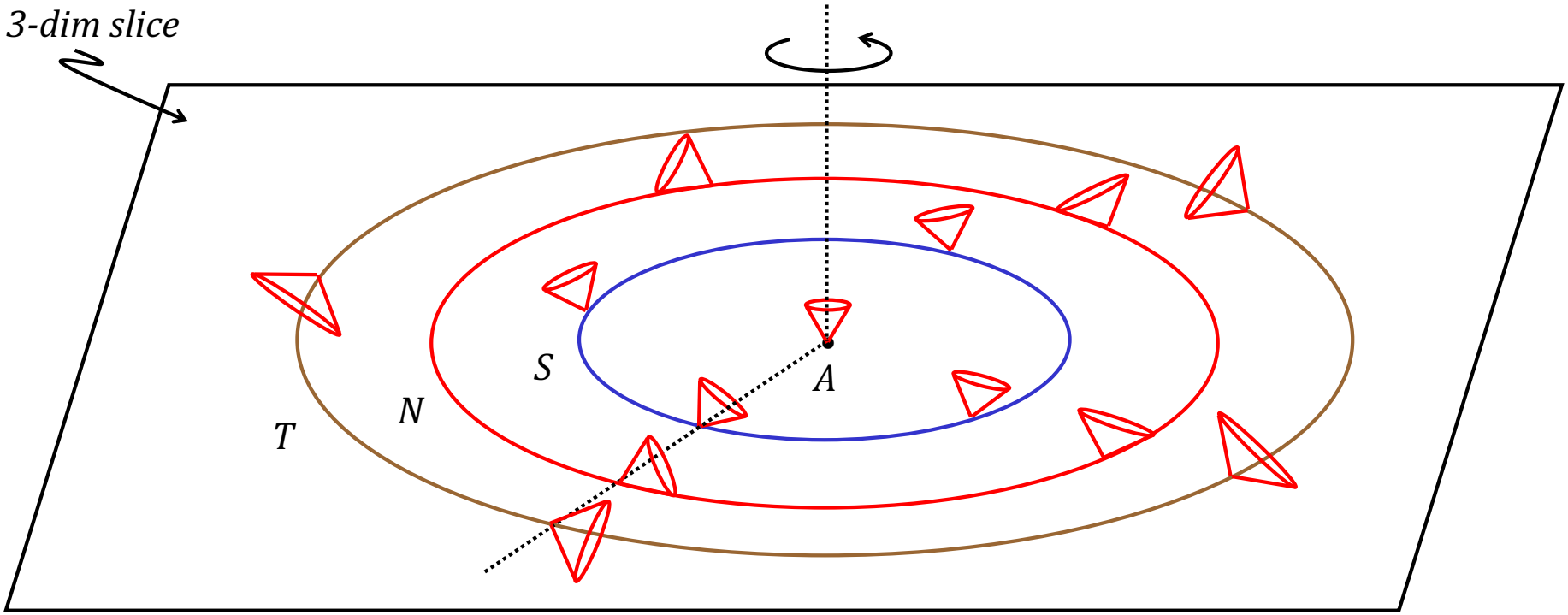
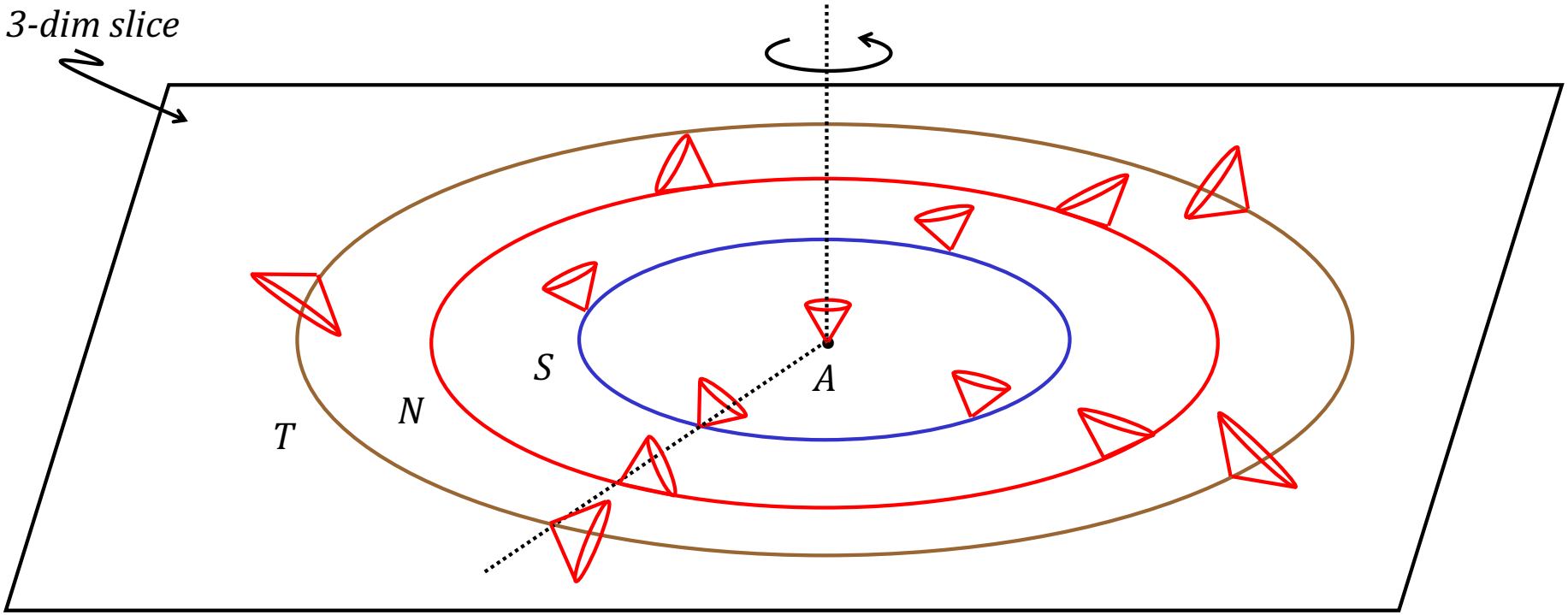


Properties:

- CTCs like *T* are not geodesics: To access them requires substantial acceleration.
- Gödel spacetime is static and rotationally symmetry about each matter worldline (homogeneous).
  - *Hence all matter observers see what A sees.*

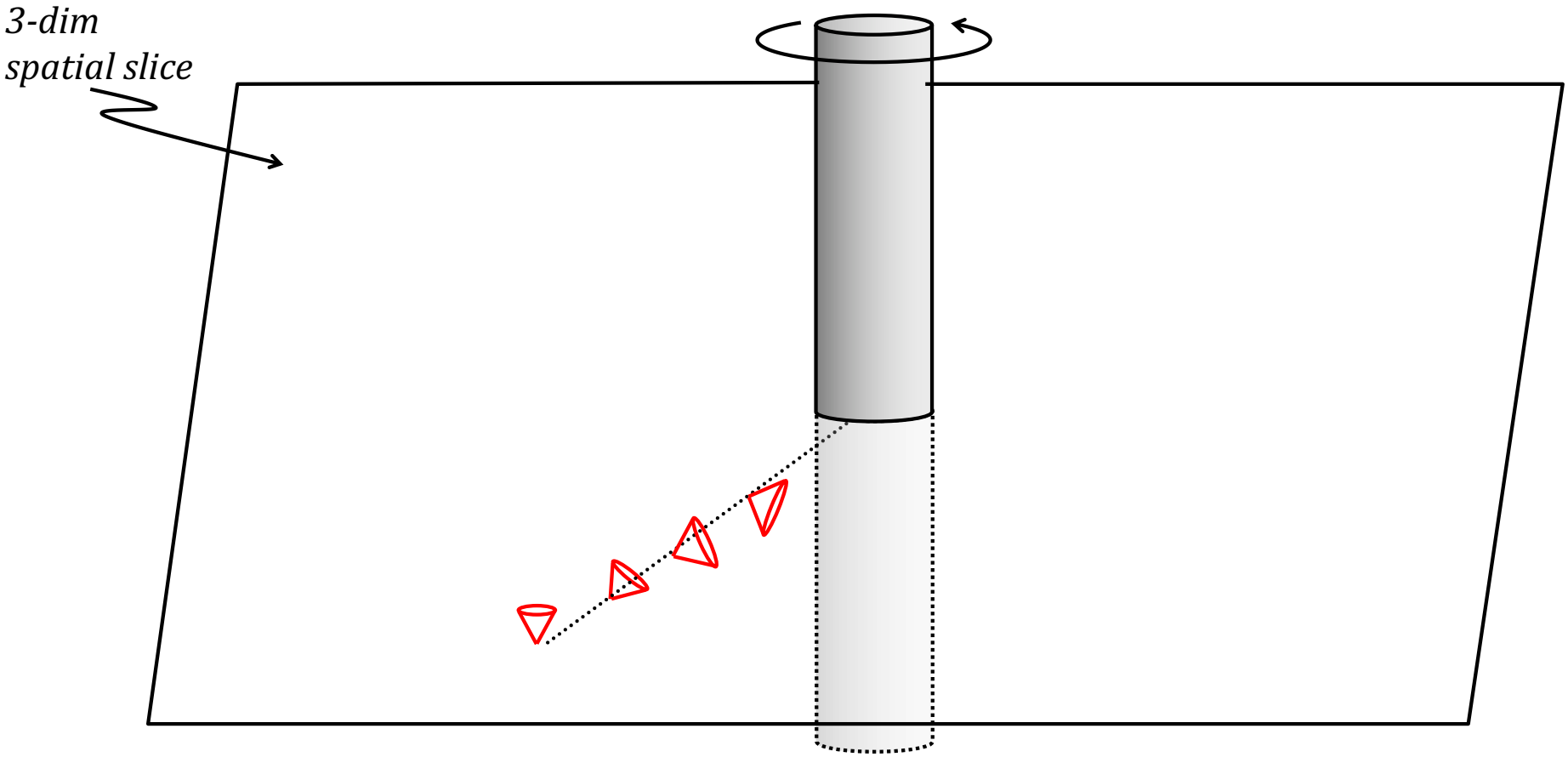


Problems:

1. No partial Cauchy surfaces exist; hence no way to describe CTCs as due to a time machine.
2. *Physically irrelevant*: Observations indicate our universe is expanding and non-rotating.

4. Tipler Cylinder Spacetime

- Tipler, F. (1974) 'Rotating cylinders and the possibility of global causality violation', *Phys. Rev. D* **9**, 2203.



- Asymptotically flat spacetime with rotational symmetry and massive rotating cylinder at center.
- *Lens-Thirring Effect*: The spacetime is dragged with the rotating cylinder to the extent that CTCs form.
- Lightcones tip over and flatten as we approach cylinder through concentric circles.

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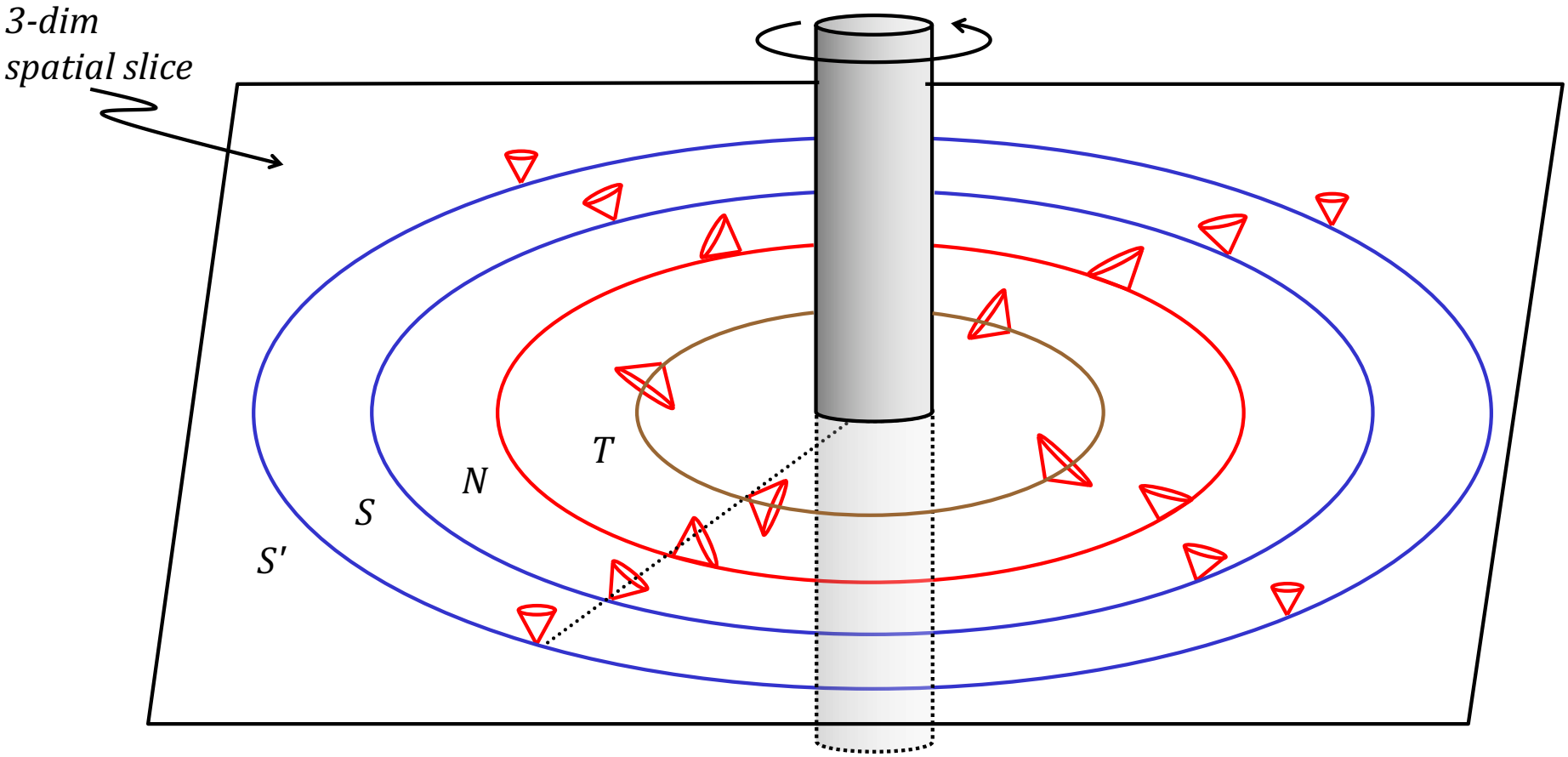
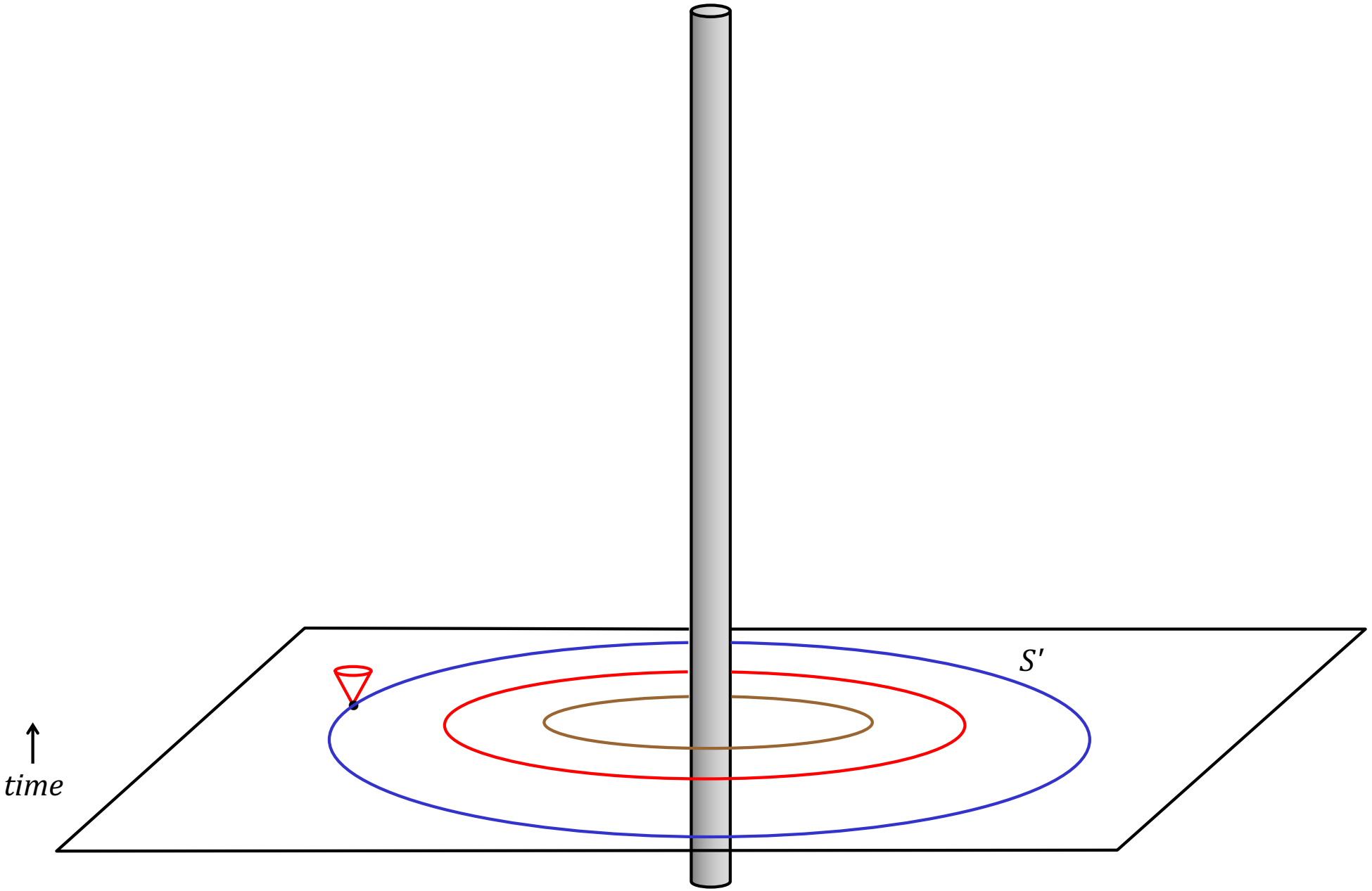


- Far from cylinder, circles are closed spacelike curves S' and lightcones are straight (spacetime is flat).
- Closer to cylinder, circles are still closed spacelike curves S, but lightcones are begining to tip.
- Closer in, circles are closed lightlike curves N.
- Still closer, circles become CTCs T.



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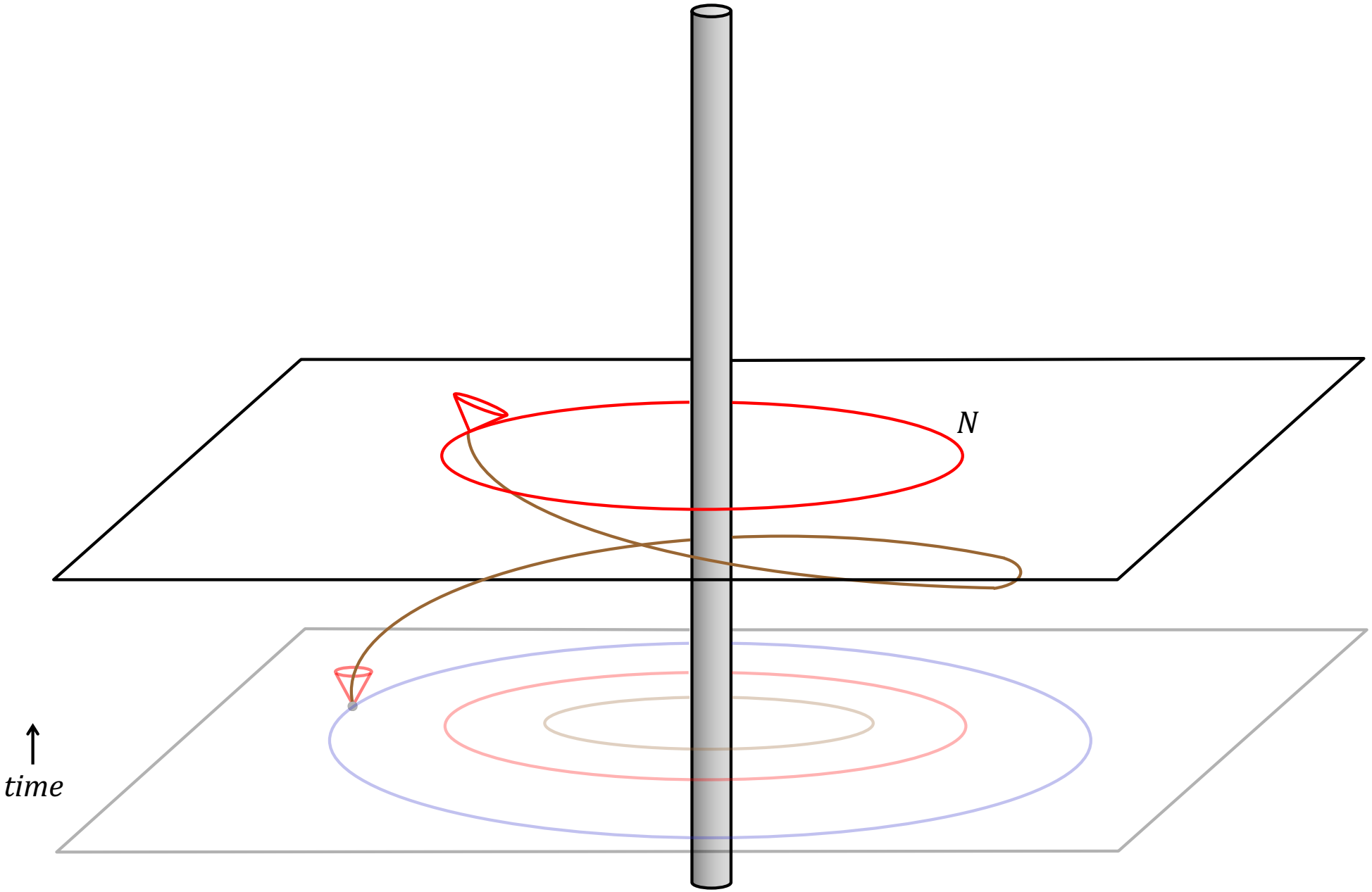

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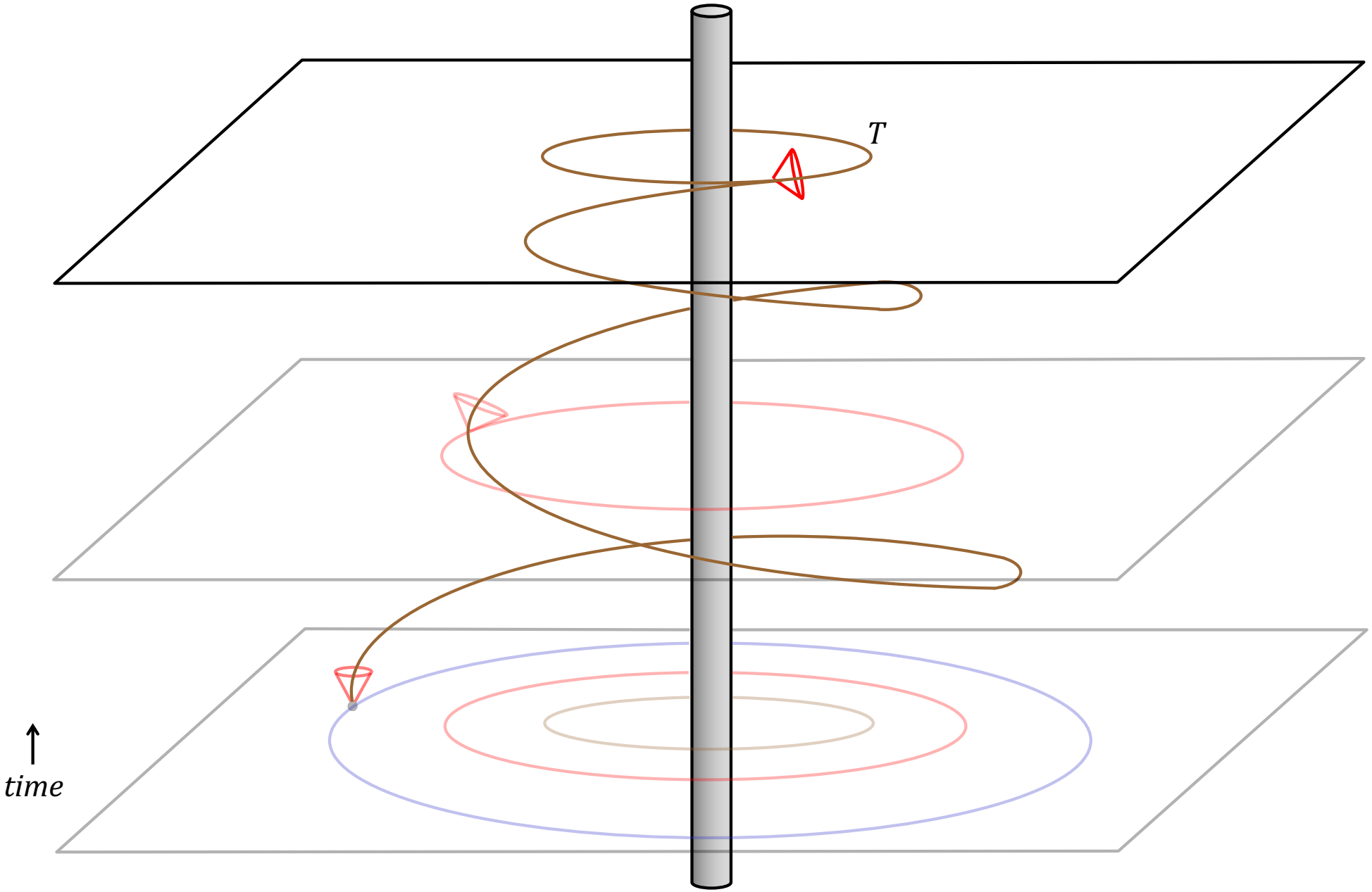

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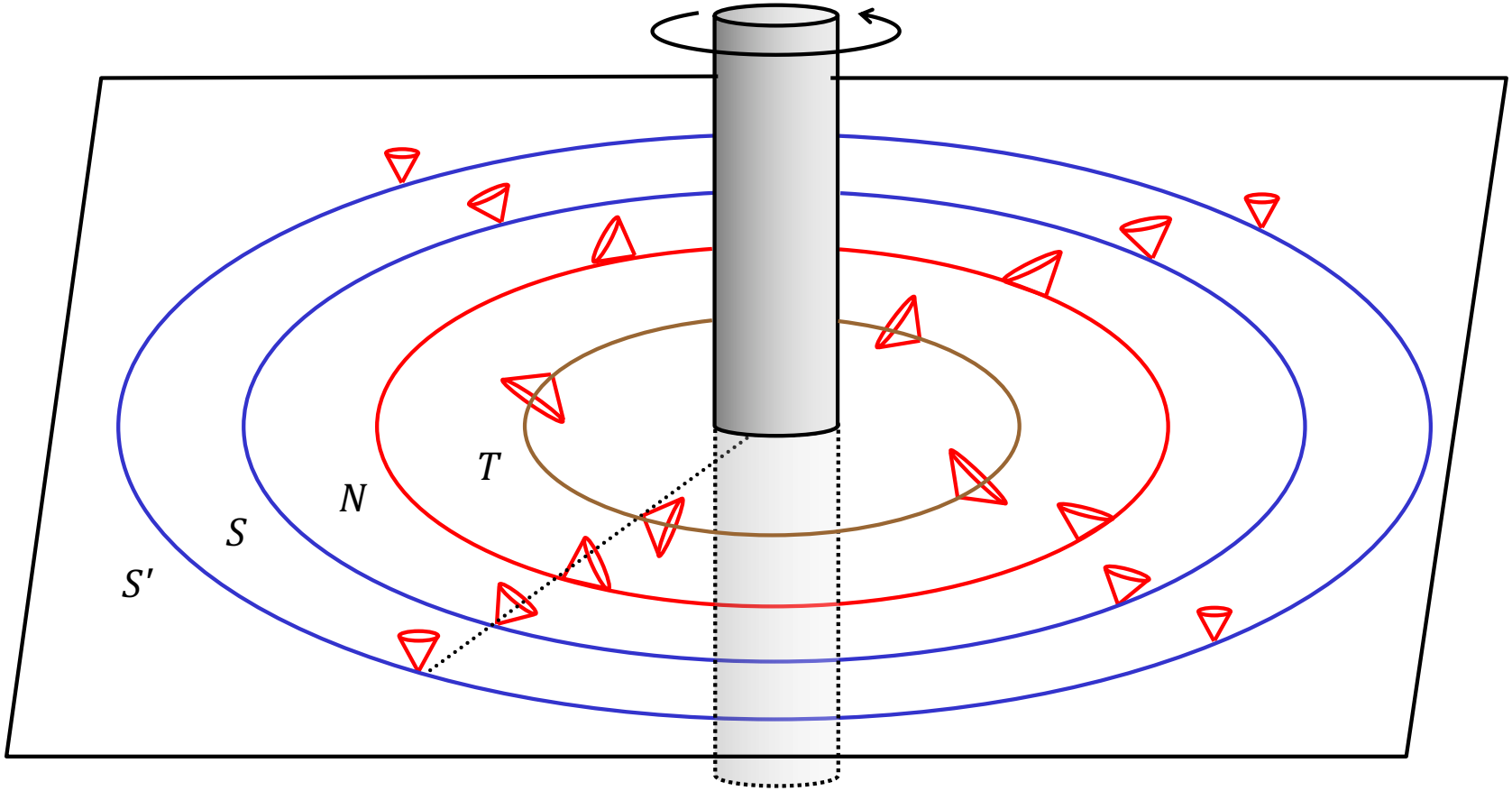


Properties:

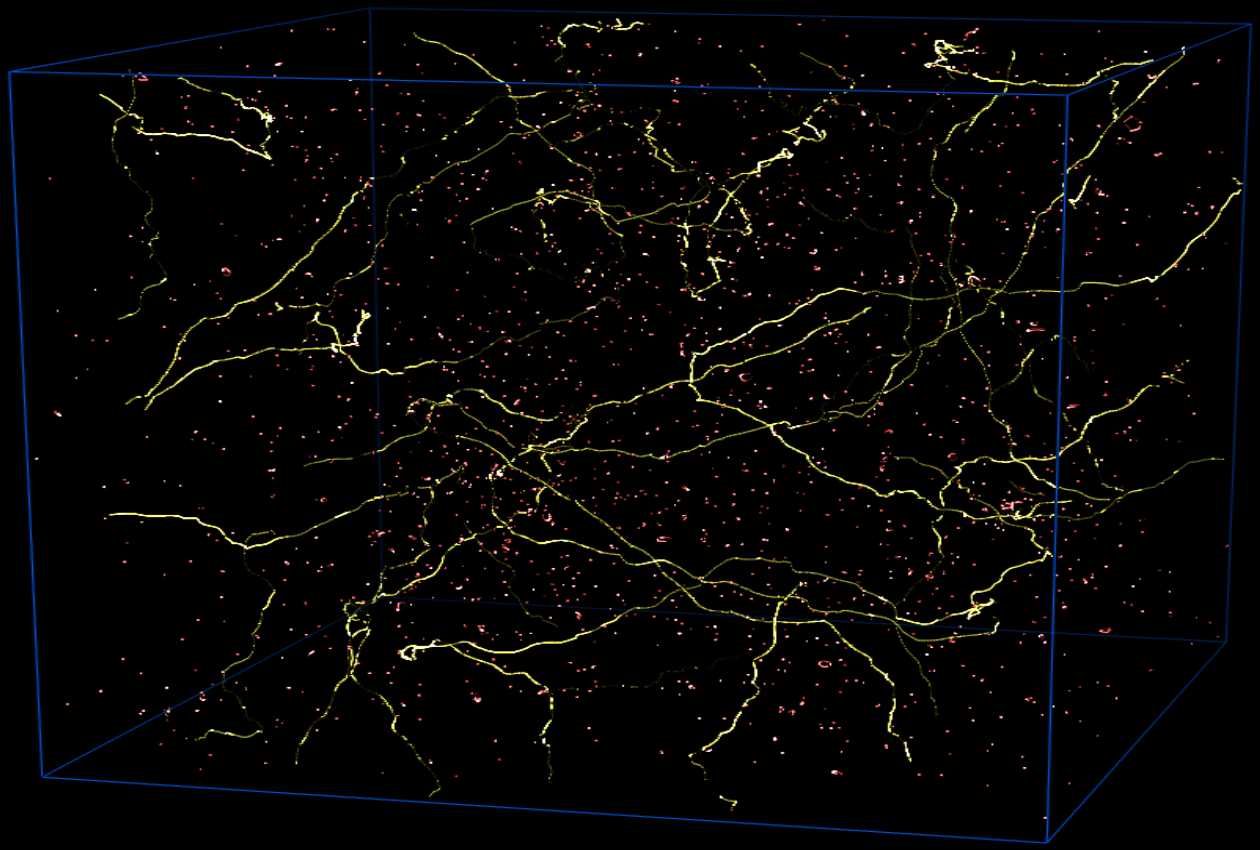
- Centrifugal forces are balanced by gravitational attraction.
- Spacetime is asymptotically flat.

Problem:

Physically irrelevant: Requires an infinite cylinder.

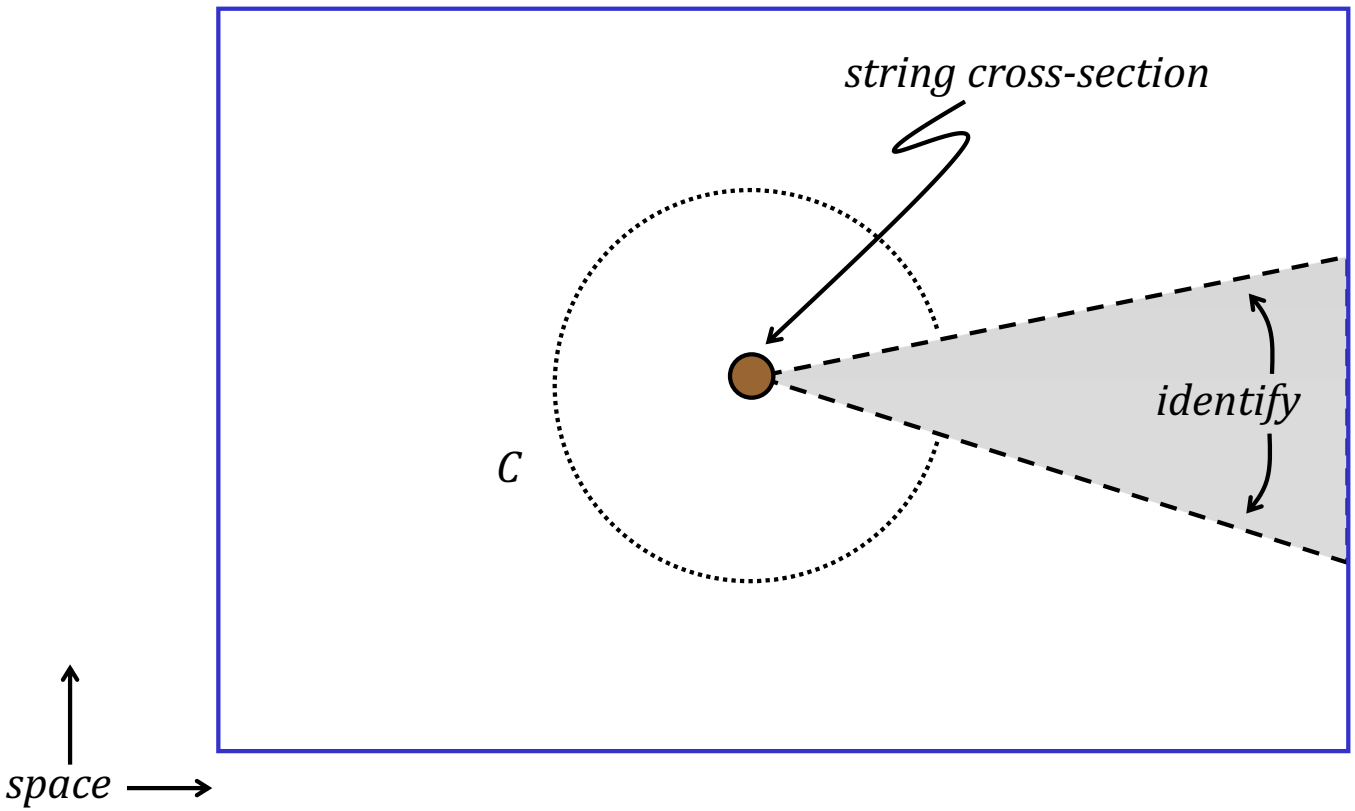
5. Gott Cosmic String Spacetime

- Gott, R. (1991) 'Closed timelike curves produced by pairs of moving cosmic strings: Exact solutions', *Phys Rev Let* **61**, 1446.



- Cosmic string: thin strand of extremely dense matter.
- Mathematically: 1-dim topological defect in a matter field during phase transitions in early universe.
  - *Density = 10 million billion tons per centimeter.*
  - *Length = millions of light-years.*
  - *Width = one proton!*

Spacetime in region of a cosmic string: conical



- Take spatial slice of Minkowski spacetime and cut out a wedge with vertex at the string.
- For string density = 10 million billion tons/cm, the cut-out wedge subtends an angle of 3.8 sec of arc (very small but noticable).
- Circumference of circle $C < 2\pi \times$ radius.

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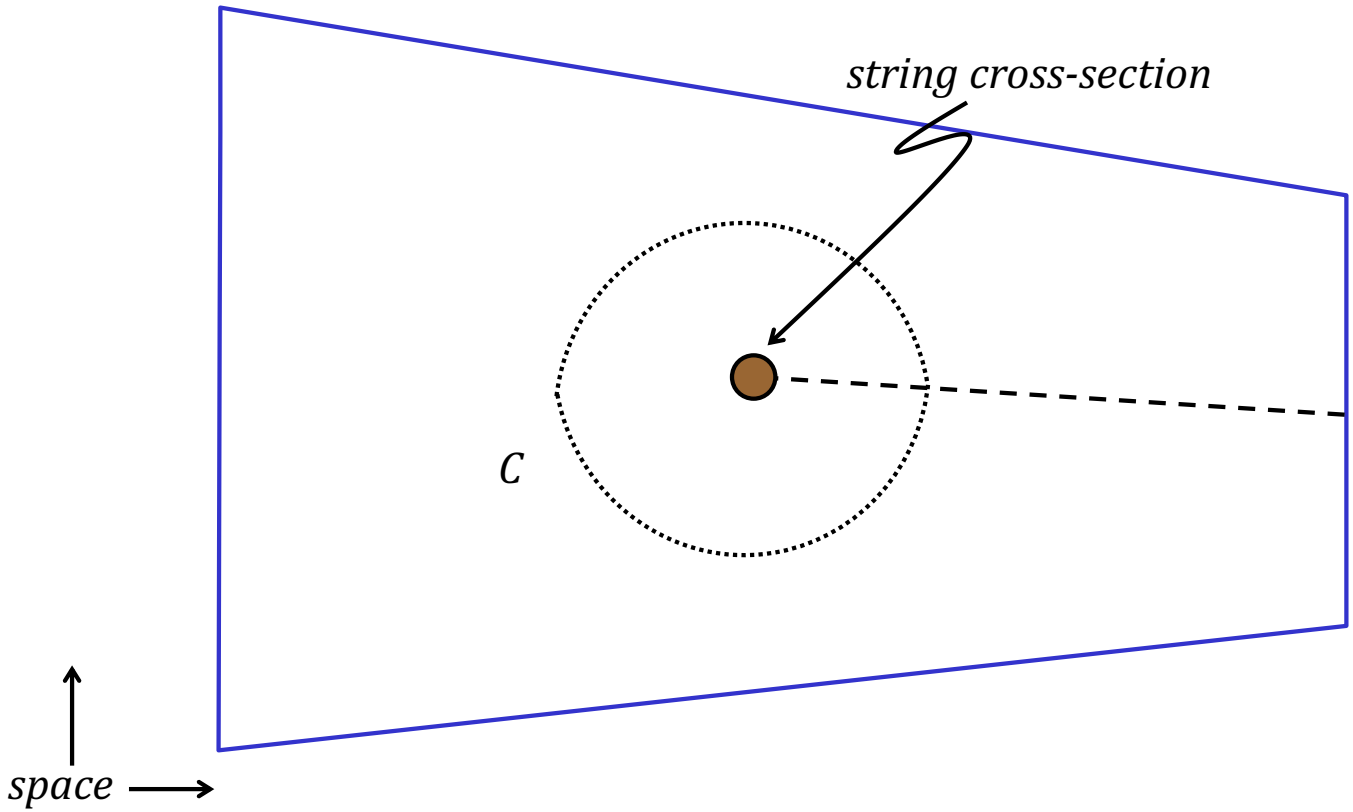

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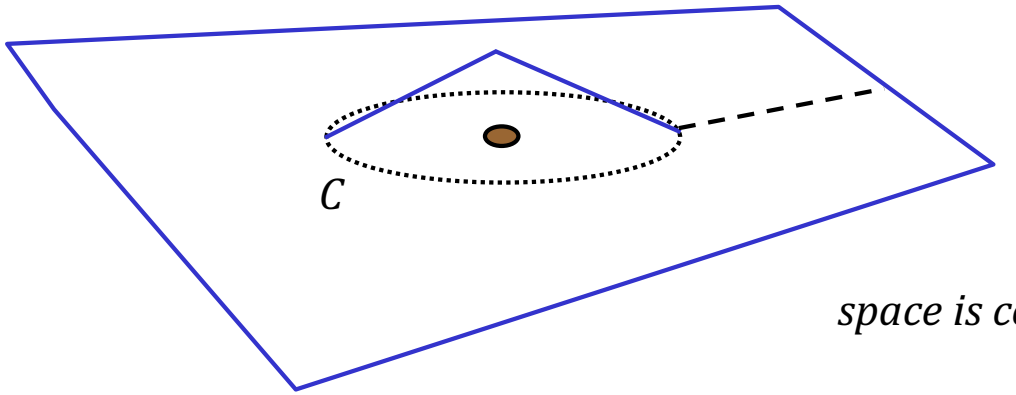
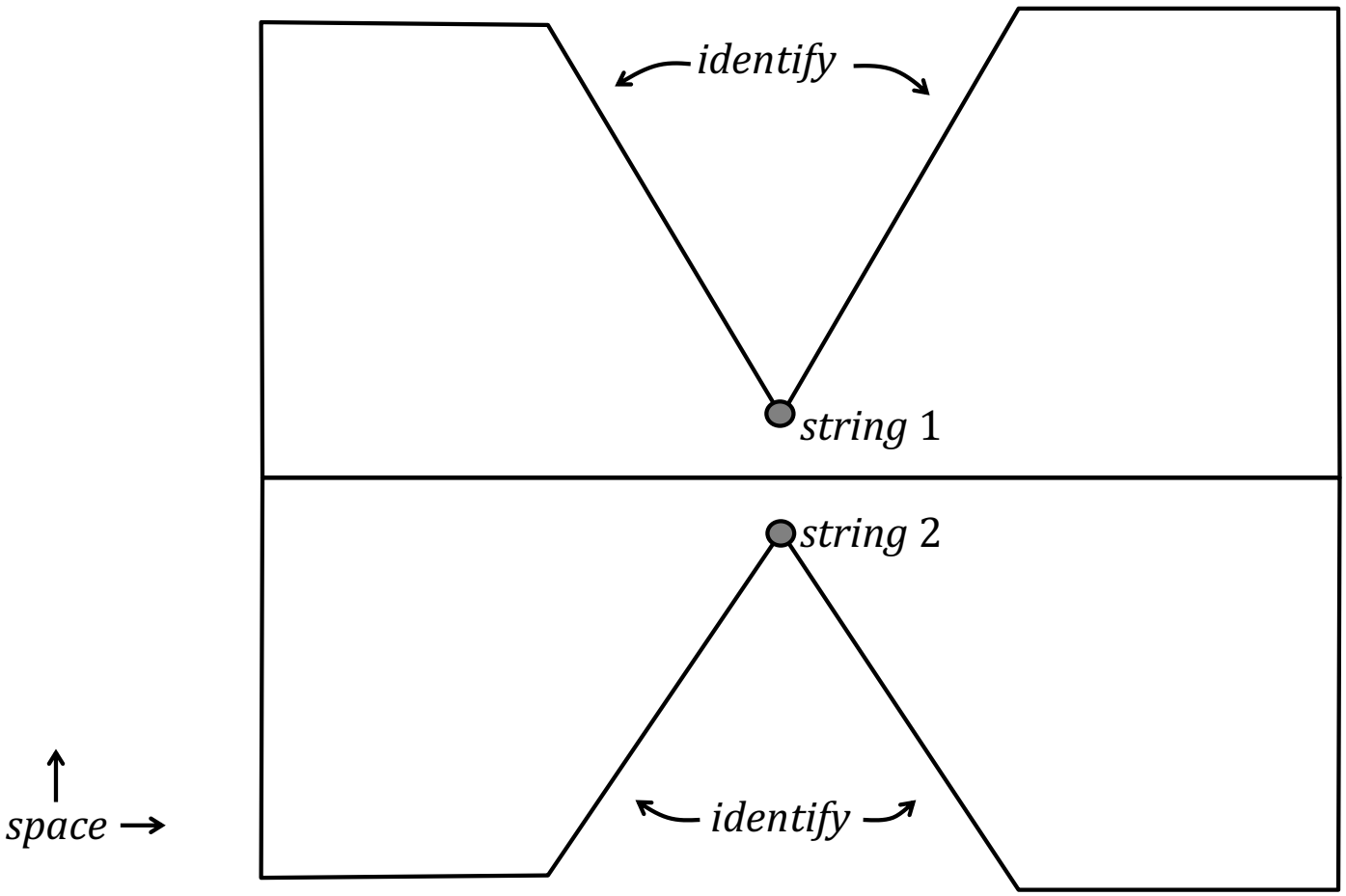


space is conically curved

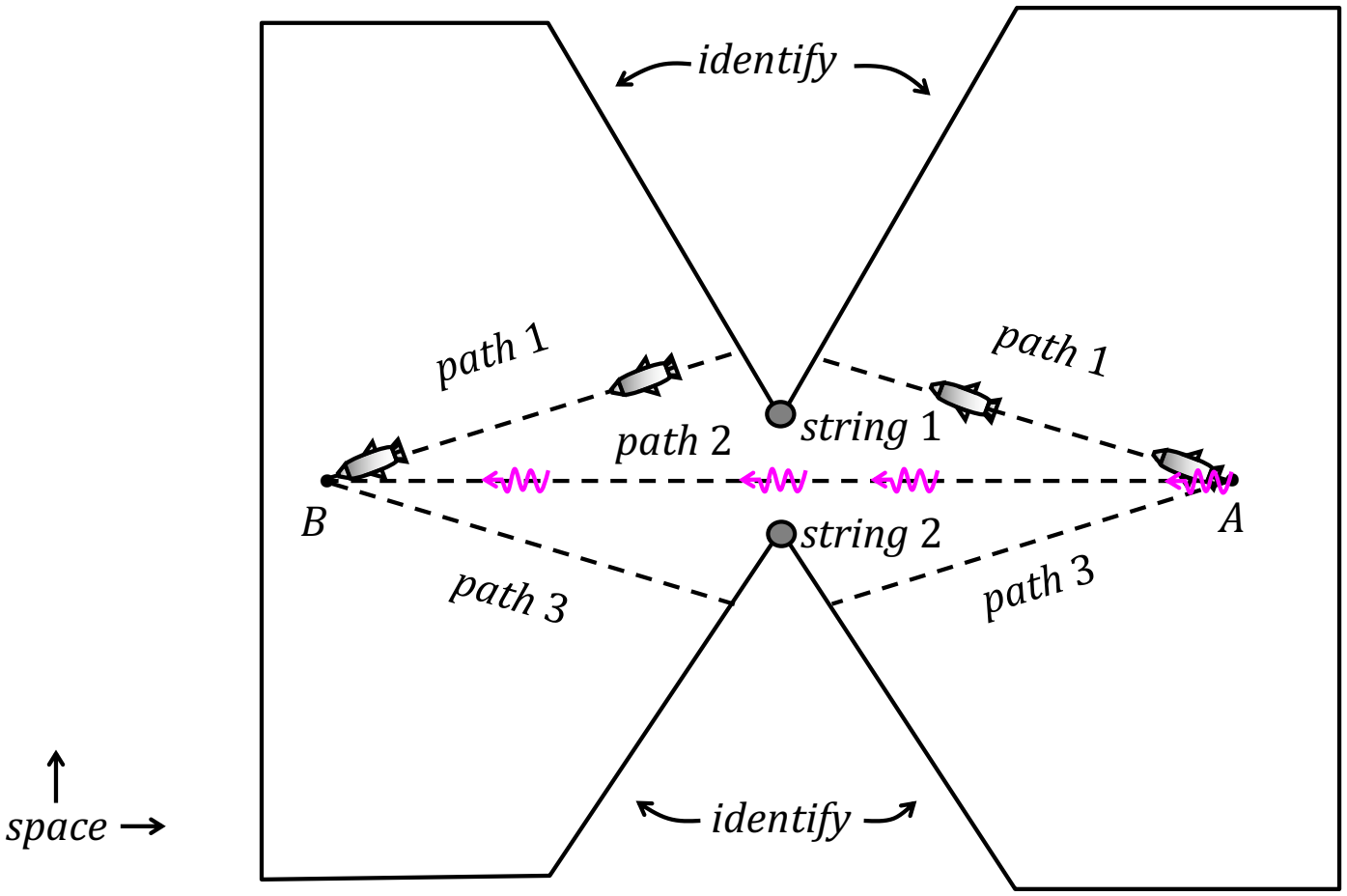
- Take spatial slice of Minkowski spacetime and cut out a wedge with vertex at the string.
- For string density = 10 million billion tons/cm, the cut-out wedge subtends an angle of 3.8 sec of arc (very small but noticable).
- Circumference of circle $C < 2\pi \times$ radius.

Time travel using cosmic strings:



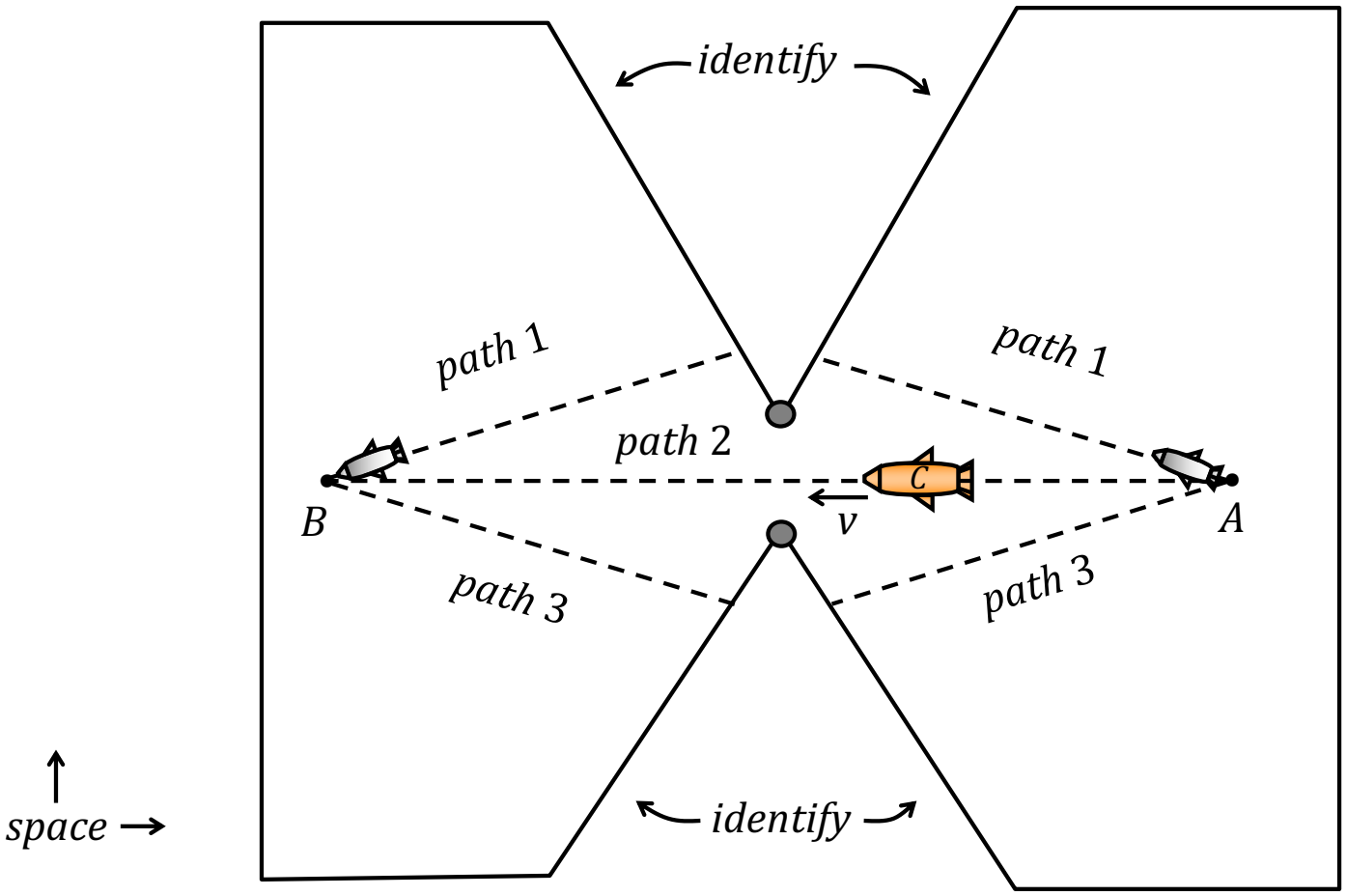
- *Goal*: To construct a spacetime with *CTCs*.
- *Initial Set-up*: Spacetime with 2 parallel cosmic strings

Time travel using cosmic strings:



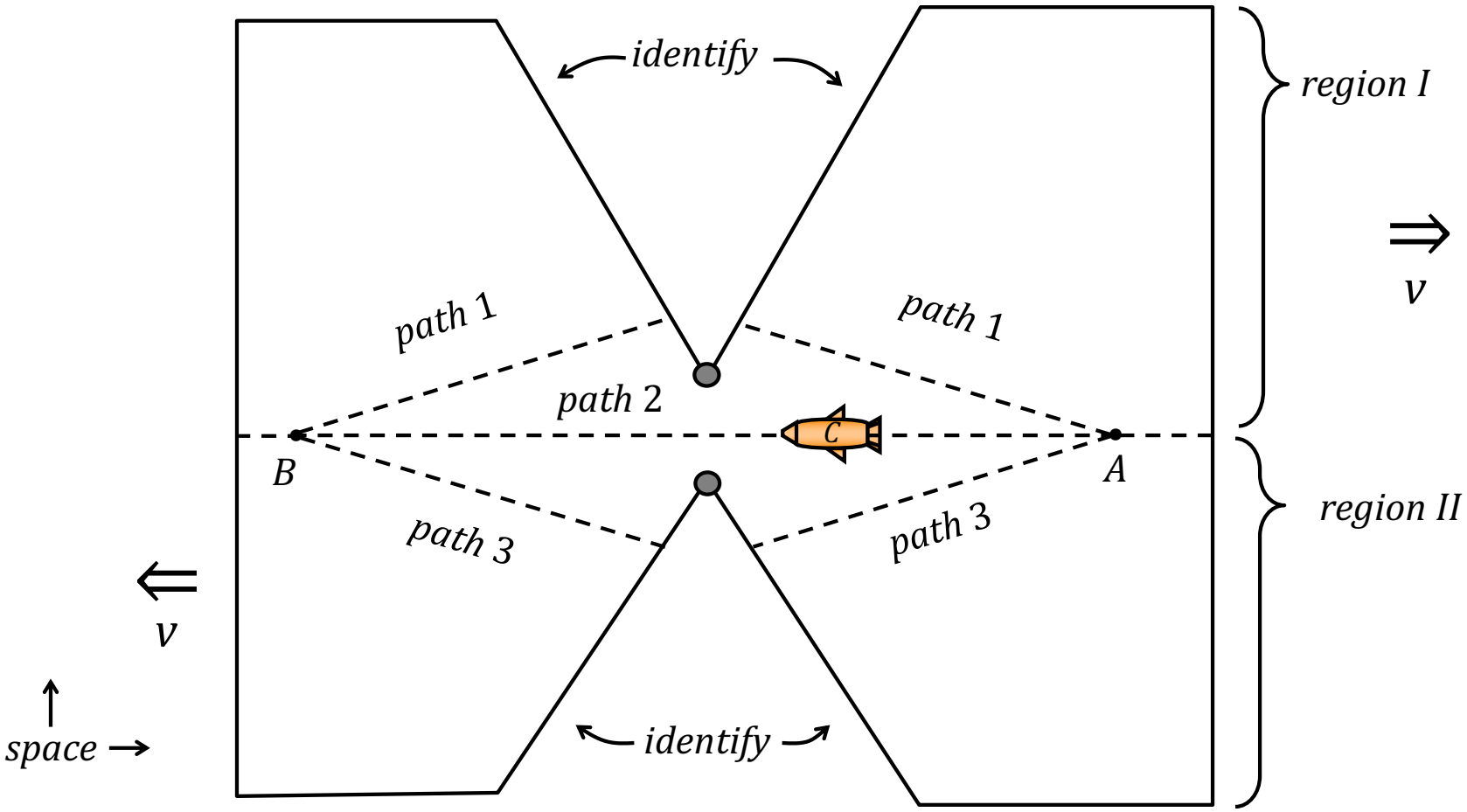
- *Goal*: To construct a spacetime with *CTCs*.
- *Initial Set-up*: Spacetime with 2 parallel cosmic strings
  - *Paths 1, 2, 3 are all geodesics.*
  - *Paths 1 and 3 are shorter than path 2.*
  - *A rocket traveling on path 1 can beat a light signal traveling on path 2.*

Time travel using cosmic strings:

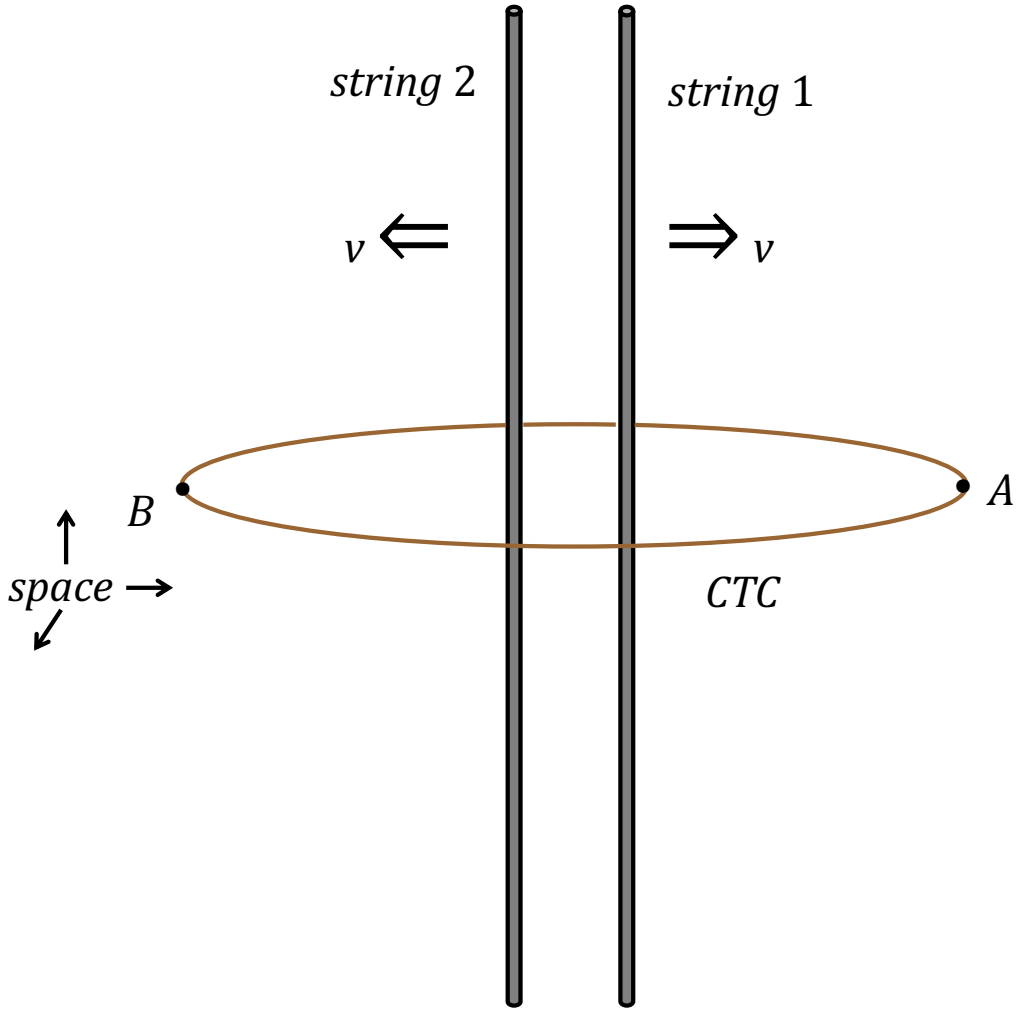


- From the point of view of an observer *C* moving at constant speed *v* along path 2, the rocket is traveling *faster than light!*
- *C* see's the rocket's departure from *A* occuring *after* its arrival at *B!*
- The same holds for the rocket's return from *B* back to *A* along path 3.
- *Now*: Transform to *C*'s rest frame.

Time travel using cosmic strings:

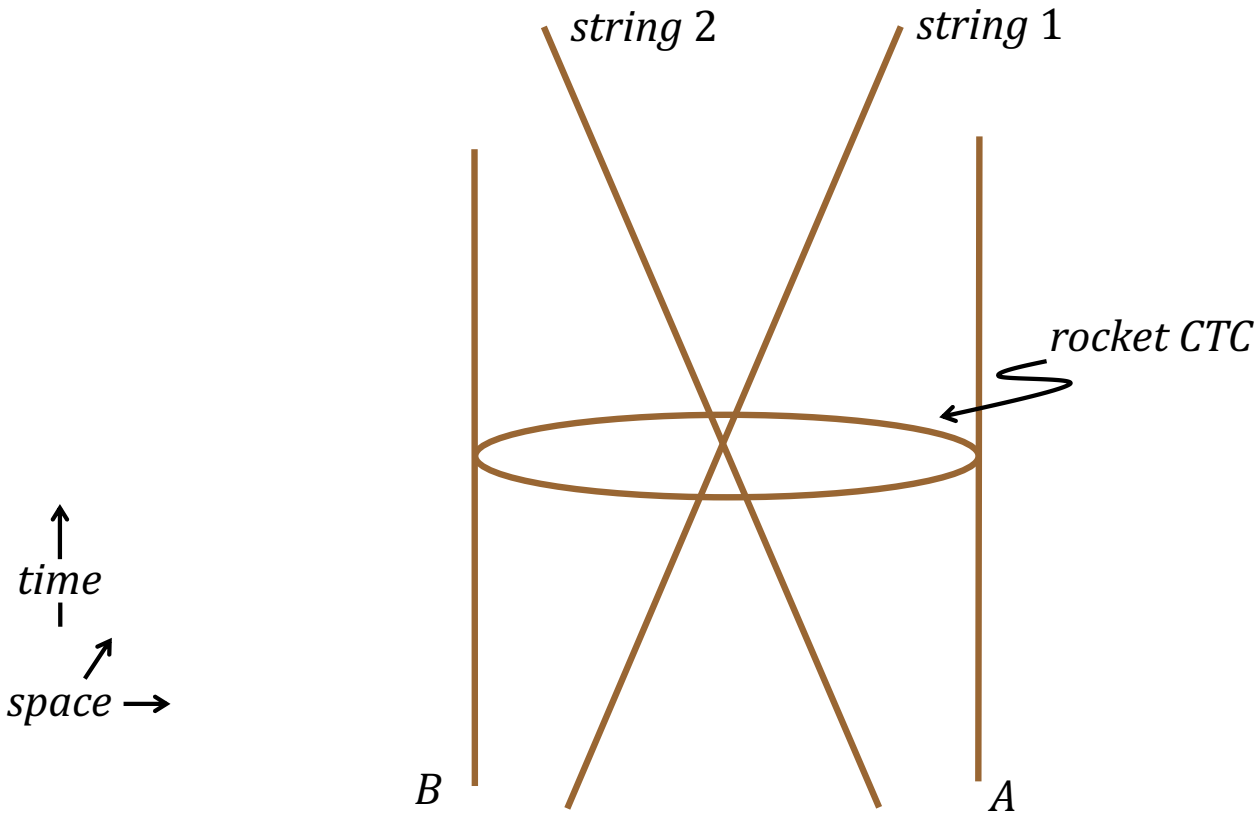


- Take region I and set it in motion to right at constant speed v.
- Take region II and set it in motion to left at constant speed v.
- *Equivalent to*: A spacetime that satisfies the Einstein equations in which there are two cosmic strings moving past each other at constant relative velocity $2v$. CTCs (path 1 + path 3) form in their near vicinity!

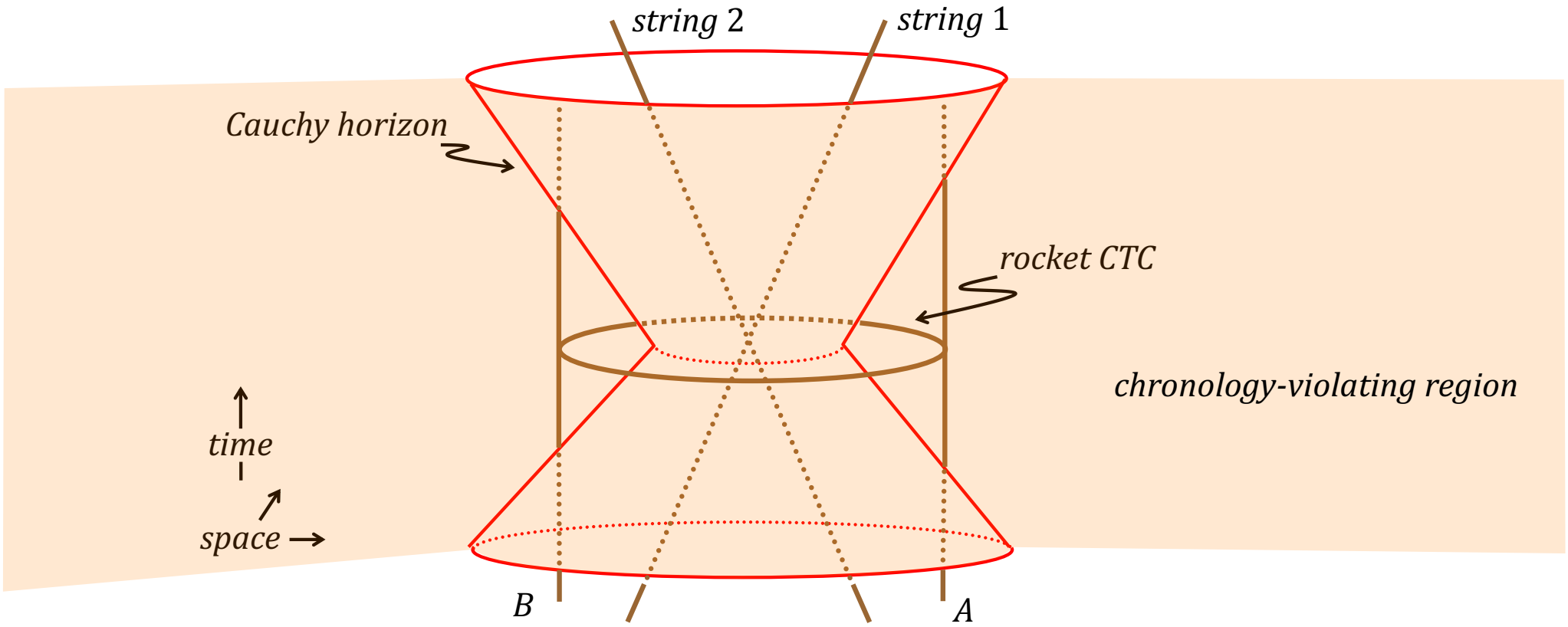


- Relative angular momentum between strings creates Lens-Thirring effect: drags timelike curve consiting of paths 1 and 3 into a closed loop.

Causal structure of Gott Cosmic String spacetime

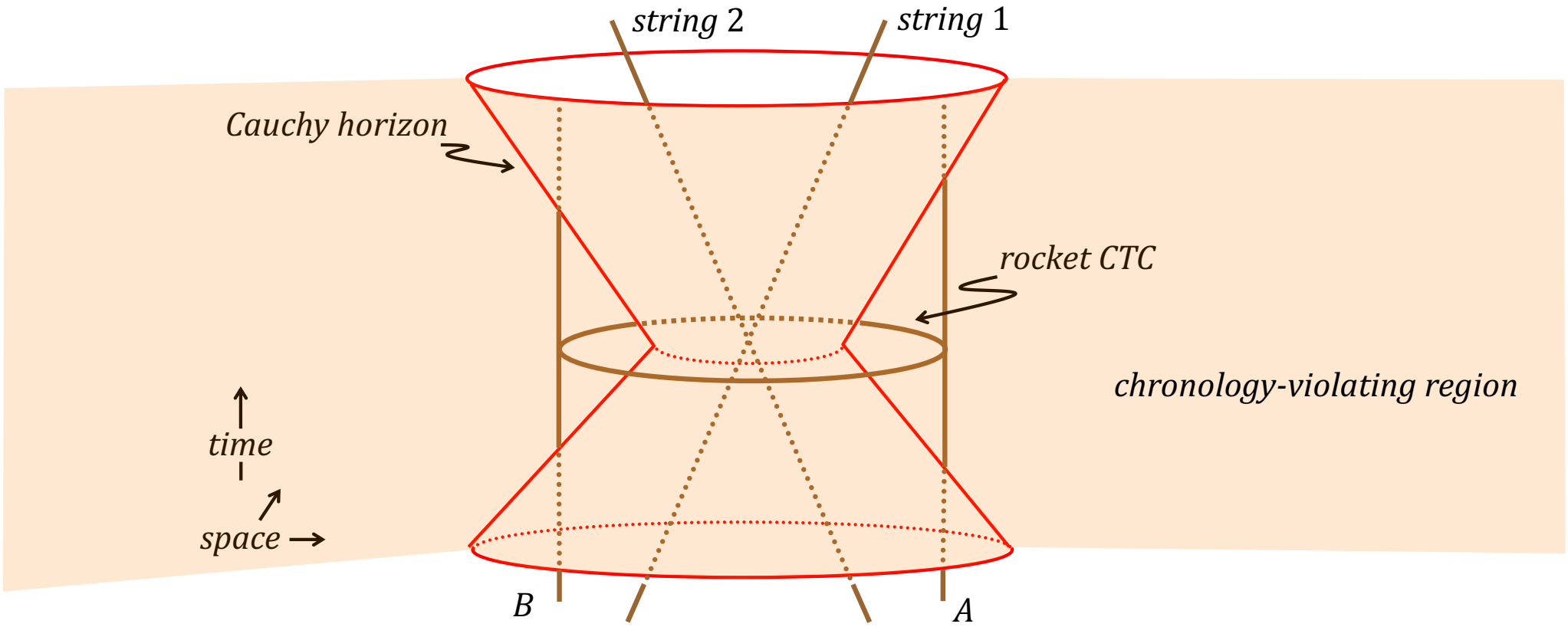


Causal structure of Gott Cosmic String spacetime:



- Cauchy horizon is an hour-glass surface centered at string crossing region.
- Chronology-violating region is the exterior of the Cauchy horizon.

Causal structure of Gott Cosmic String spacetime:



Properties:

- No need for exotic matter.
- Chronology-violating region exists for finite period of time -- possible reason why we haven't been invaded by hordes of tourists from the future.

Problem:

Cauchy horizon is not compactly generated (generators come in from past infinity).

- *So no sense in which you throw a switch (on a Cauchy surface) and turn on the time-machine.*