Self-consistent dynamics along closed time-like curves

how to shoot your past self and get away with it

Ä. Baumeler, FC, T. Ralph, S. Wolf, M. Zych
Reversible time travel with freedom of choice
arXiv:1703.00779

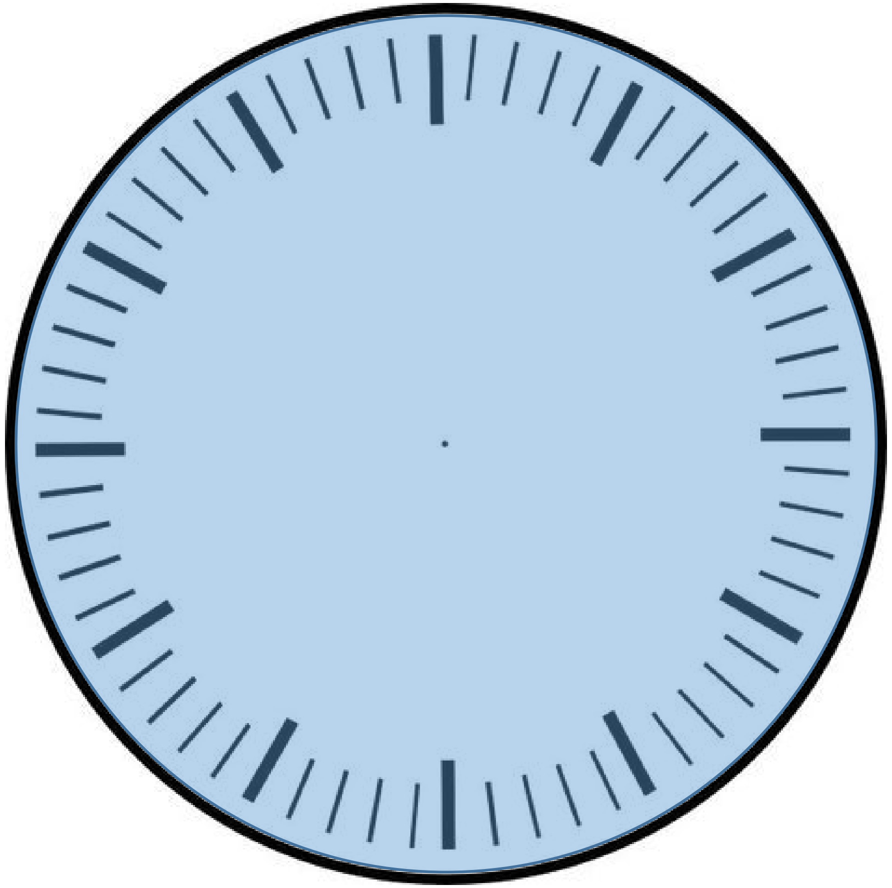
G. Tobar, FC
Reversible dynamics with closed time-like curves and freedom of choice
arXiv:2001.02511

Paul Scherrer Institute/online
19 May 2022

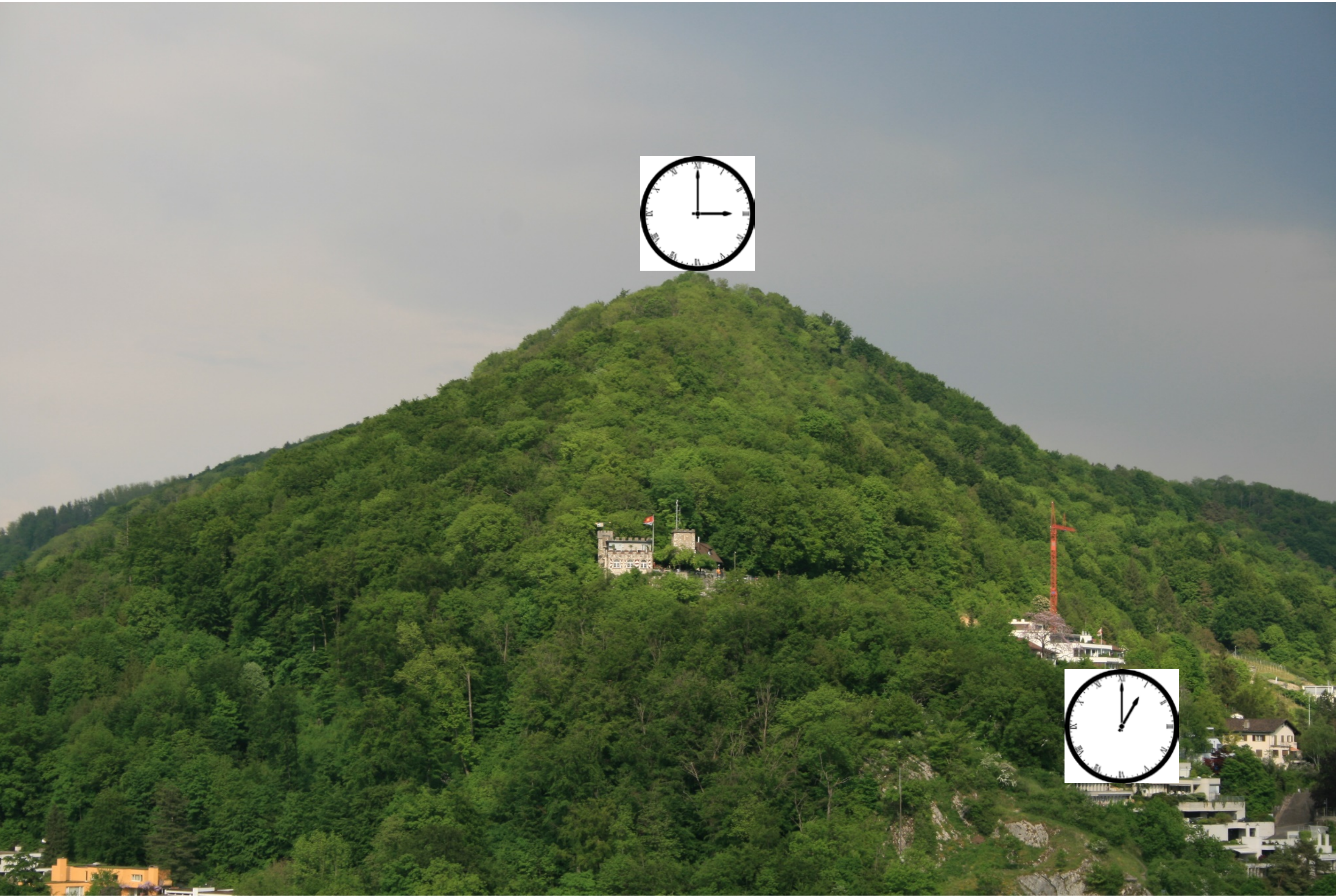
Art from “The Arrival”

Is time travel possible?

Travel to the future



Travel fast forward



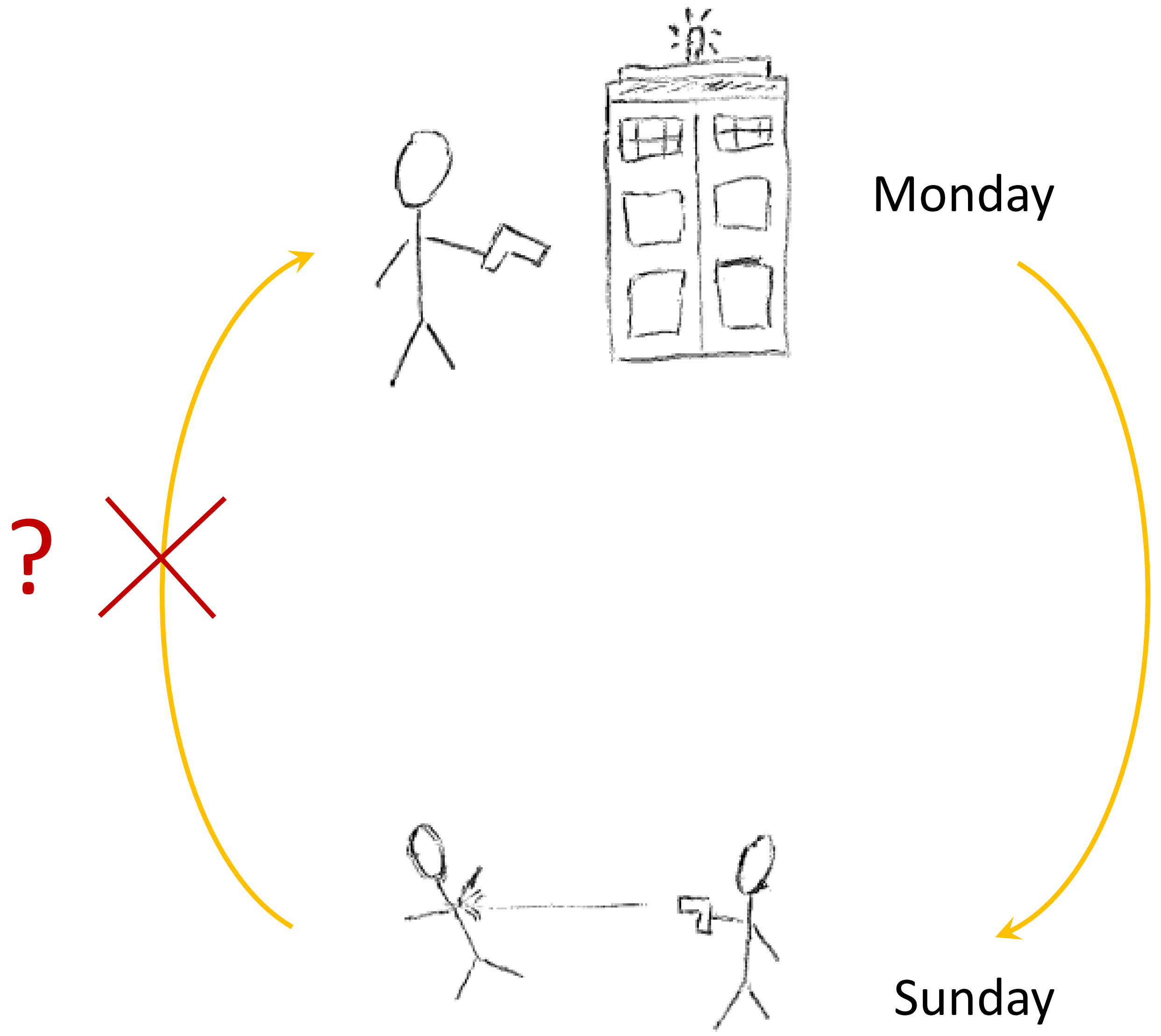
General relativity:
time dilation

"Lower is slower"

Tested to high precision

Crucial for GPS

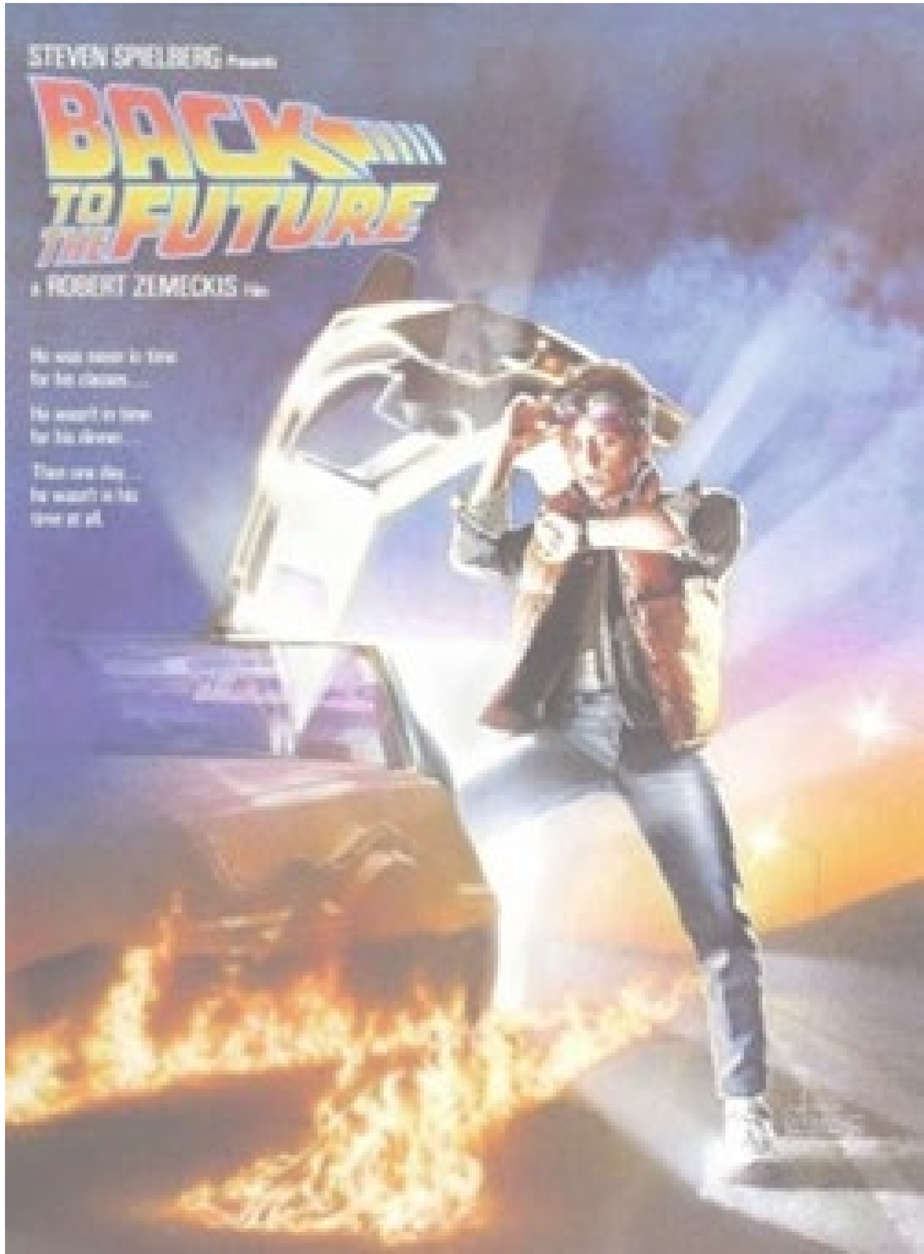
Travel *to the past*?



The sci-fi problem

Reconcile time loops with linear story-telling

- Self consistency
  - Predestination, Interstellar, Tenet
- Parallel universes
  - Terminator, Back to the Future (II)
- Magic
  - Back to the Future (I)



The physics problem

- No good Cauchy surfaces in the presence of CTCs (closed time-like curves)
- We cannot interpret dynamics as evolution from past to future
- Single (classical) universe ⇒ global constraints
  - Overdetermination?
  - Restriction of free choice?

Violation of local physics?

- Quantum
  - Many worlds
  - Path integral

⇒ nonlinearity

PLAN

- Wormholes and CTCs – early works.
- Framework for classical dynamics with freedom of choice near CTCs.
- Examples: non-trivial time travel with freedom of choice.
- Physical realisation.
- Quantum time travel and indefinite causal order.

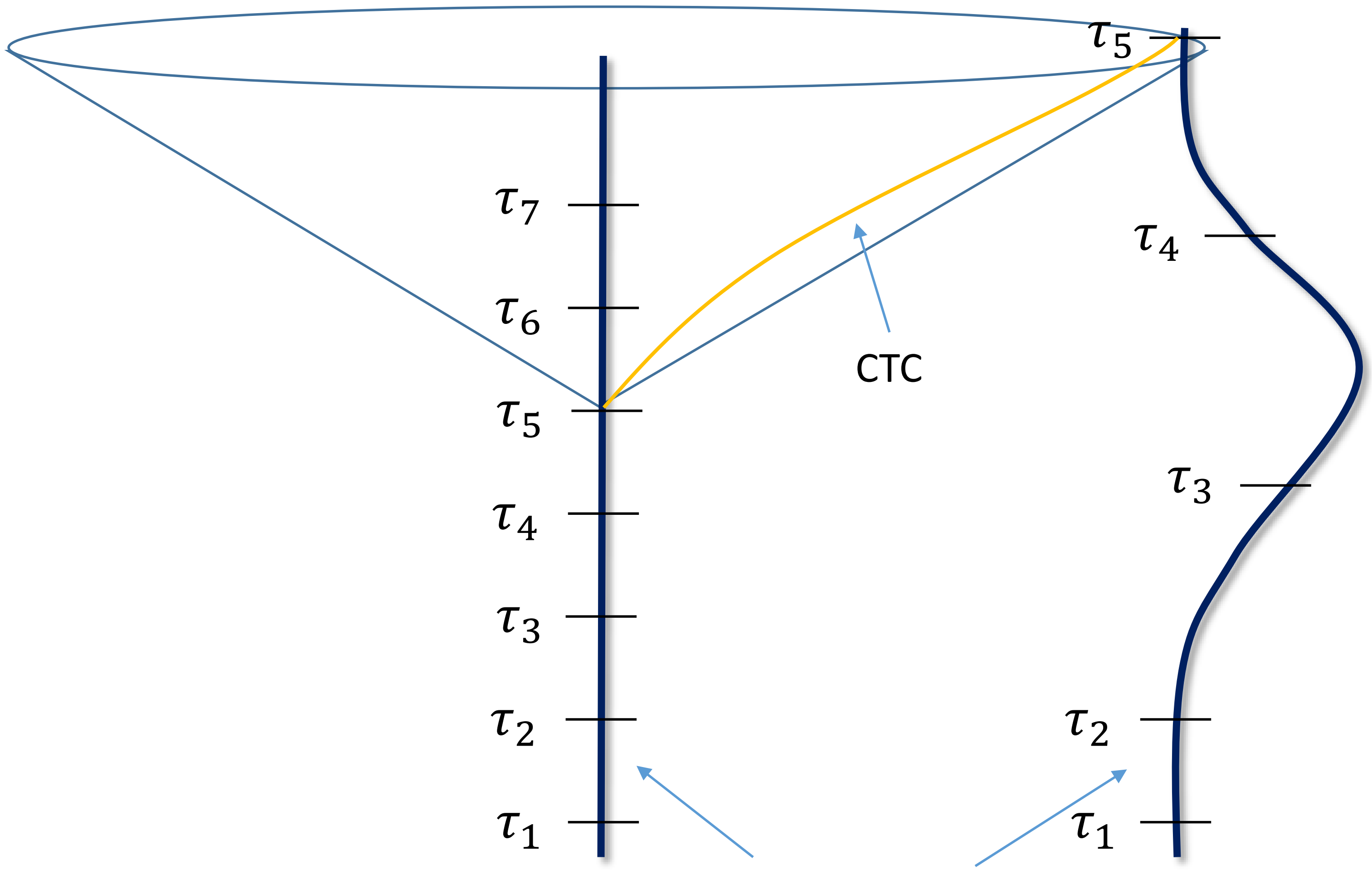
Wormholes

Minkowski metric, except for two spherical spatial regions “cut out” and identified

M. S. Morris and K. S. Thorne,
American Journal of Physics, **56**, 395 (1988)

Wormholes

Accelerate a mouth → time dilation → CTCs



M. S. Morris, K. S. Thorne, and U. Yurtsever, *Phys. Rev. Lett.* **61**, 1446 (1988)

Wormholes

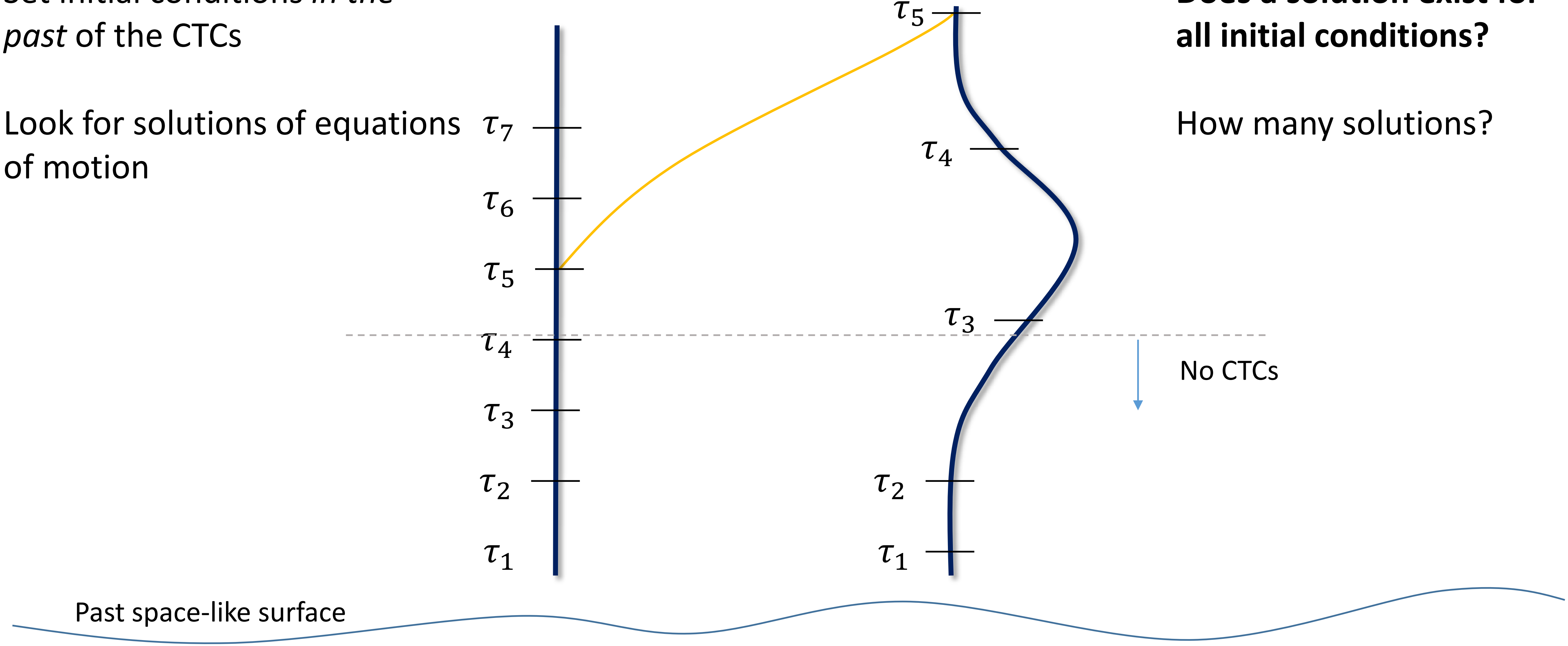
Exit can be *earlier* than entrance

Physics around wormholes

traditional approach

Set initial conditions *in the past* of the CTCs

Look for solutions of equations of motion



Does a solution exist for all initial conditions?

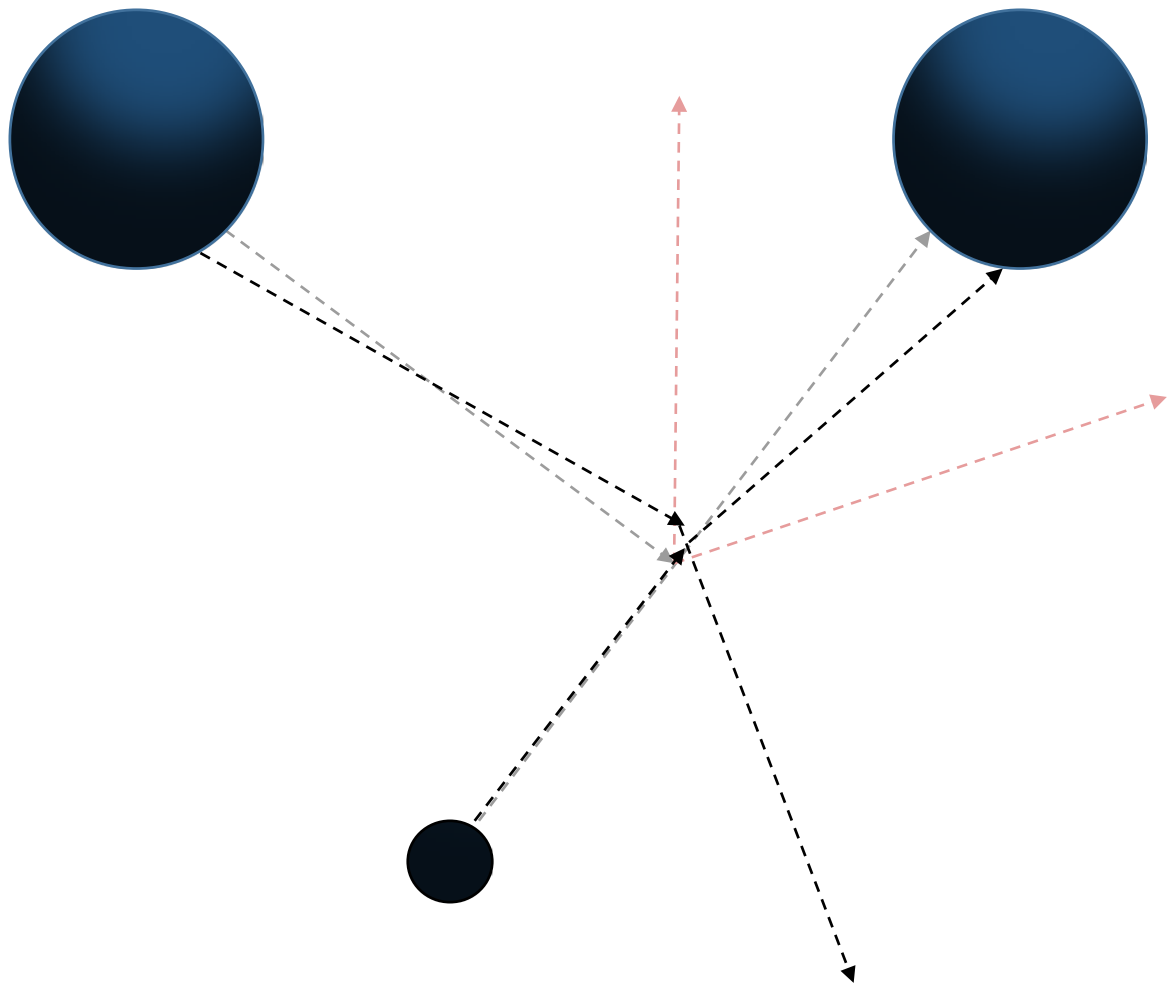
How many solutions?

Physics around wormholes

Send billiard ball towards a mouth

Inconsistency? (No solution?)

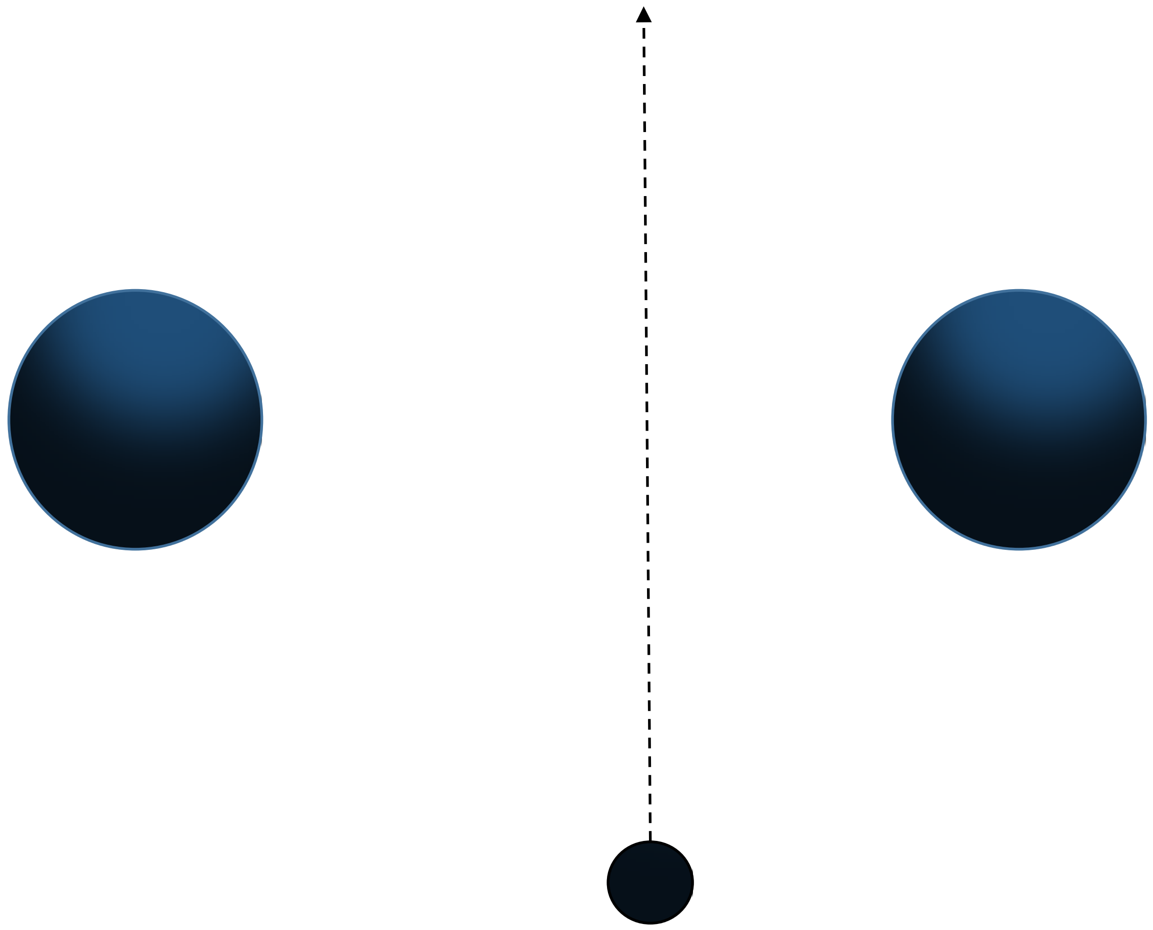
Consistent solutions *always exist*
(for the cases studied)



F. Echeverria, G. Klinkhammer, and K. S. Thorne,
Phys. Rev. D **44**, 1077 (1991)

Physics around wormholes

Typically, multiple solutions exist



Novikov principle: only self-consistent solutions happen

Conjecture: all initial conditions have a self-consistent solution

- Arbitrary preparation possible
- The physics of a device or agent in the past is not affected by the presence of CTCs in the future. “No new physics” principle.

How about operations in the CTC era?

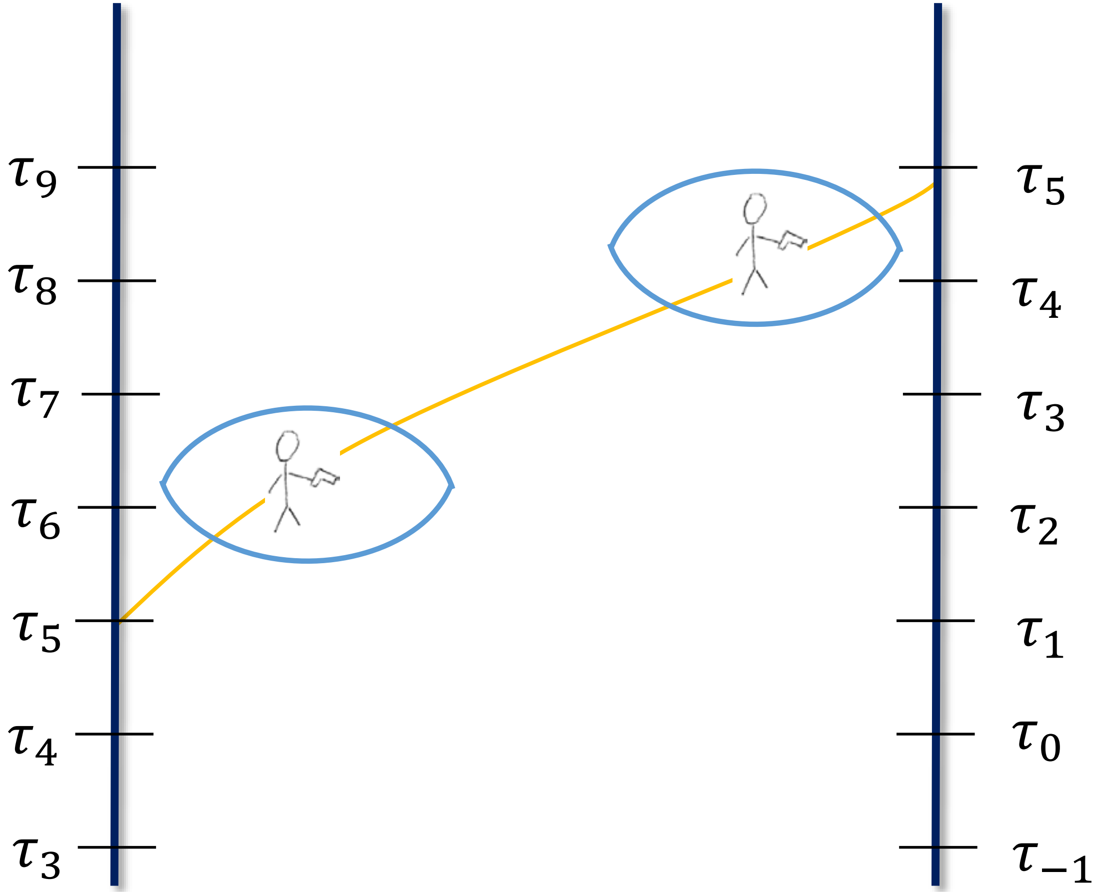
I. D. Novikov, *Phys. Rev. D* **45** (1989)

Stronger version of the principle

- "No new physics" for every local region without CTCs
- In a CTC-free region, all operations available in ordinary space-time are possible
- "Dynamics" is the solution to a boundary conditions problem

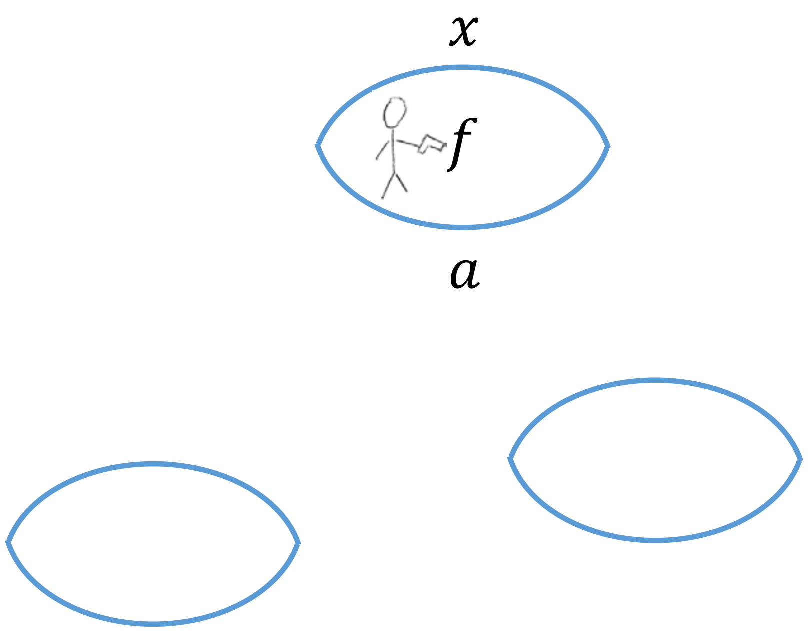
↓

e.g., determine states on past boundaries as a function of states on the future boundaries



Framework for dynamics near CTCs

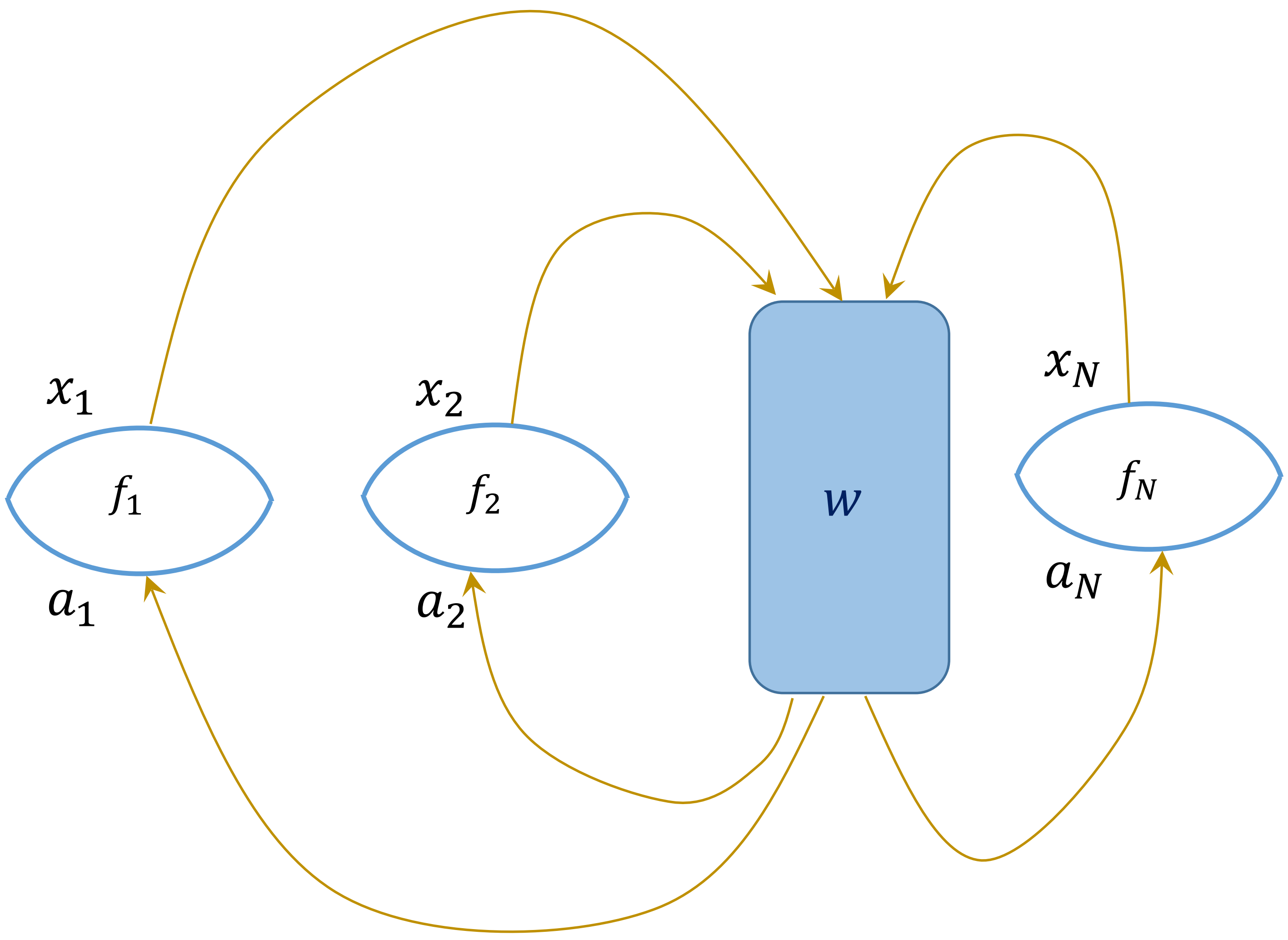
- N local regions (without CTCs), with past and future boundary
- Classical state space associated to each boundary
  a= input, x= output
- Local (deterministic) operation: $x = f(a)$



Process function

- $\{a_1, \dots, a_N\} = w(x_1, \dots, x_N)$
- Consistency condition:

$$\forall f = \{f_1, \dots, f_N\}$$
$$\exists\, a = \{a_1, \dots, a_N\}$$
Such that
$$w \circ f(a) = a$$



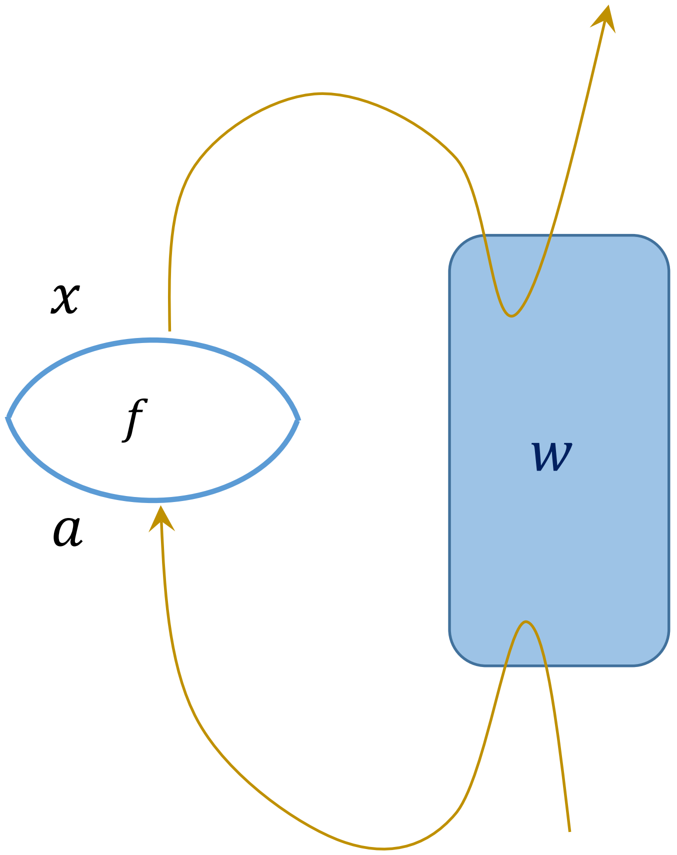
w describes the CTC dynamics

What type of dynamics is possible?

Single region

$w(x)$ =constant

Cannot send information back to yourself



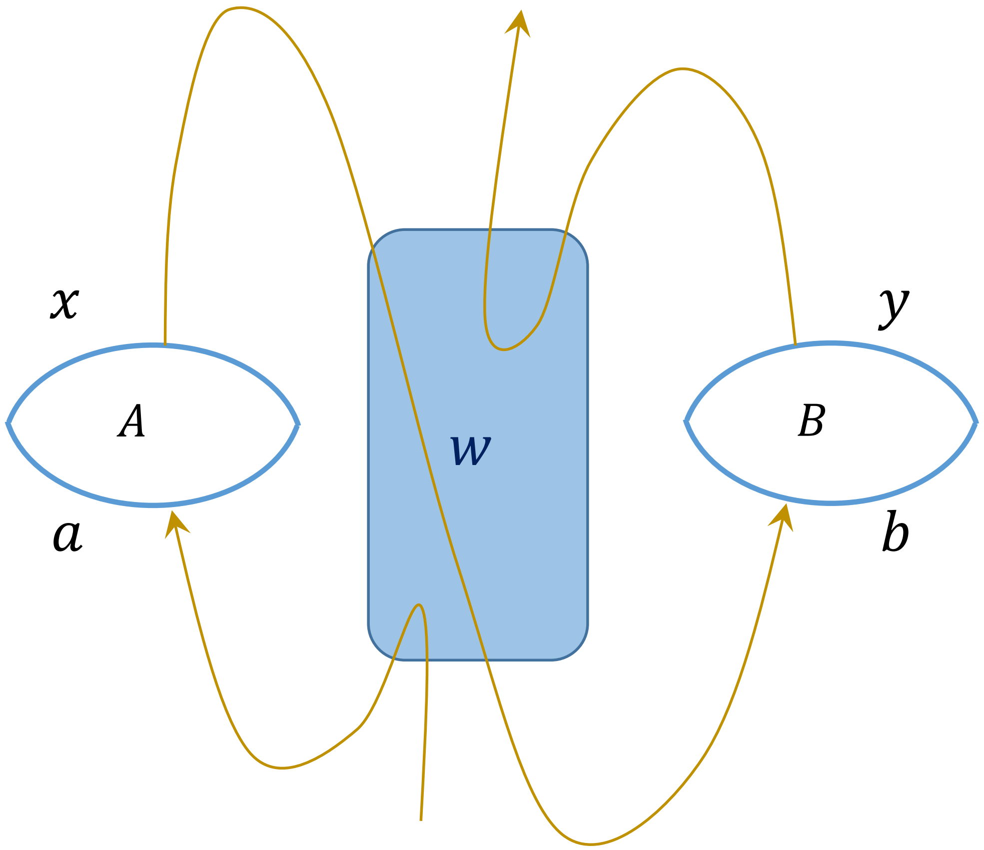
Two regions

$$w = \{w_A, w_B\}$$

$$a = w_A(y)$$
$$b = w_B(x)$$

At least one of the two components must be constant

$$a = a_0$$
$$b = w_B(x)$$



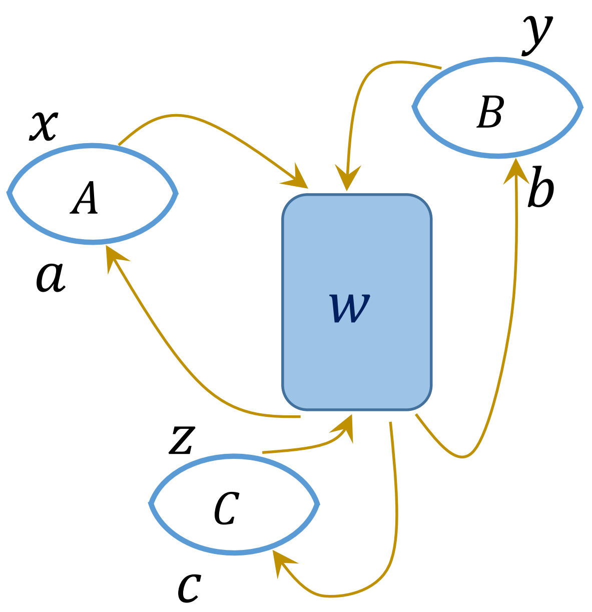
Only one-way signalling

Three regions

Example

$$a, \dots, z = 0, 1$$

$$a = (y \oplus 1) z$$
$$b = (z \oplus 1) x$$
$$c = (x \oplus 1) y$$



$z = 0$ ↓

$a = 0$
$b = x$

$A \rightsquigarrow B$
$B \not\rightsquigarrow A$

$z = 1$ ↓

$a = y \oplus 1$
$b = 0$

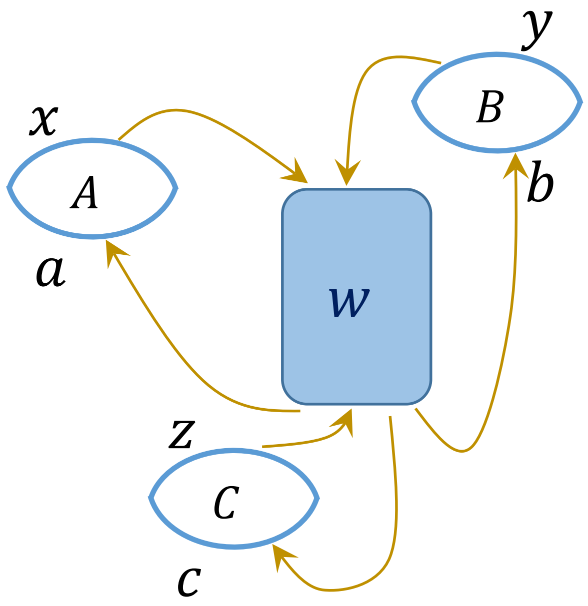
$B \rightsquigarrow A$
$A \not\rightsquigarrow B$

Incompatible with causal order

Three regions

Example

$$a = (y \oplus 1)z$$
$$b = (z \oplus 1)x$$
$$c = (x \oplus 1)y$$



Compatible with *arbitrary* local operations.
Operations determine unique solution.

$$\left.\begin{aligned} x &= a \\ y &= b \\ z &= c \end{aligned}\right\} \rightarrow \begin{aligned} a &= (b \oplus 1)c \\ b &= (c \oplus 1)a \\ c &= (a \oplus 1)b \end{aligned} \rightarrow a = (b \oplus 1)b(a \oplus 1) = 0$$

$$b = 0$$
$$c = 0$$

$$\left.\begin{aligned} x &= a \\ y &= b \\ z &= c \oplus 1 \end{aligned}\right\} \rightarrow \begin{aligned} a &= 1 \\ b &= 0 \\ c &= 0 \end{aligned}$$

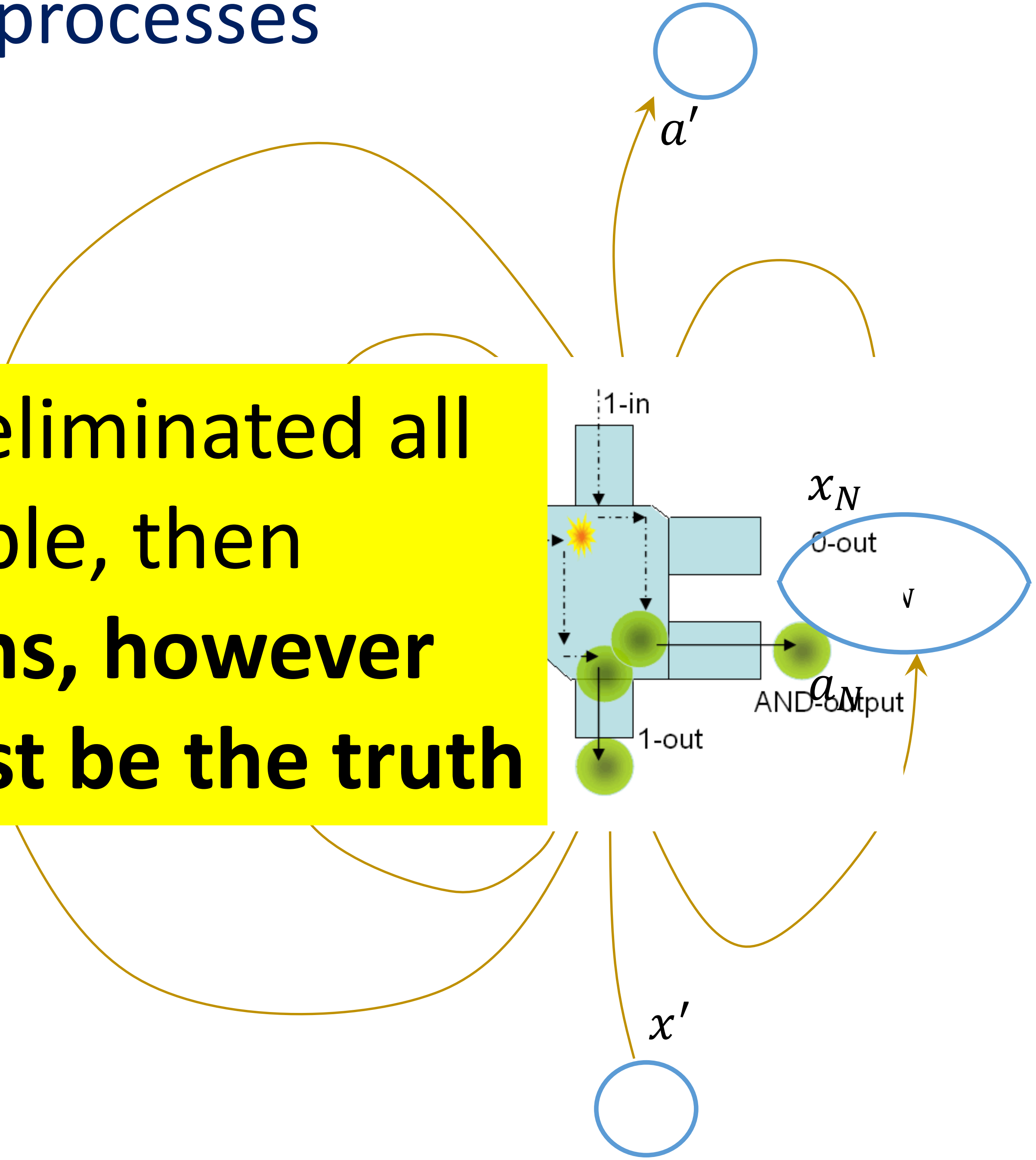
Reversible processes

Every process can be extended to a reliable one

$w \rightarrow w'$, $\exists($

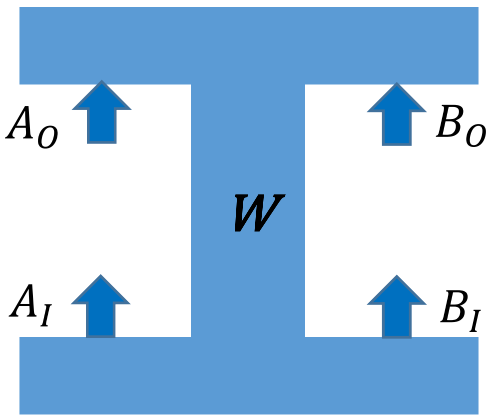
Can be realised physical systems!

When you have eliminated all which is impossible, then **whatever remains, however improbable, must be the truth**



E. Fredkin and T. Toffoli, *Int J Theor Phys* **21**, 219 (1982)

Quantum framework



Local operations → quantum operations

Process function → process matrix
Unifies and generalises state, evolution

Linear! Can be unitary

Bipartite non-ordered processes

Applications to laboratory scenarios

O. Oreshkov, FC, and Č. Brukner, *Nat. Commun.* **3**, 1092 (2012)

Conclusions

- Time travel perhaps not possible, but fun to study
- Classical, reversible time travel logically possible
  Physically?
- What does a time travel experience? (Patch different regions together.)
- Quantum causal structures: relevant for quantum gravity?