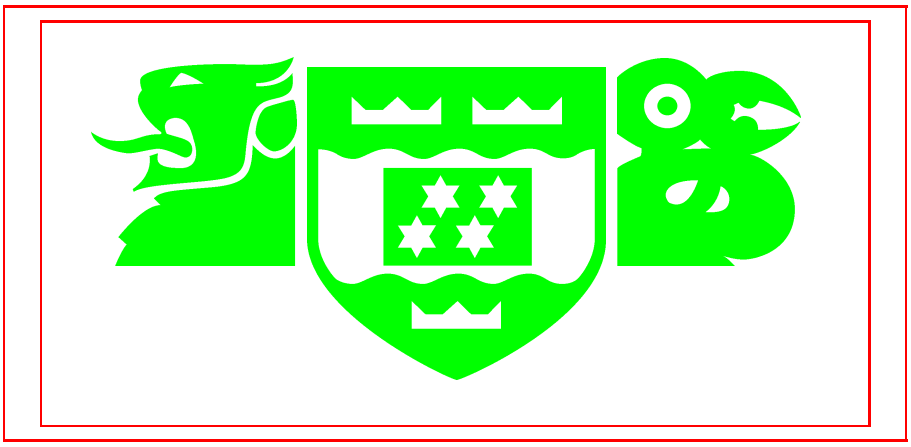

Quantum Physics of Chronology Protection

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Why is chronology even an issue?

Observation:

- The Einstein equations are local:

$$G^{\mu\nu} = 8\pi\, G_{\text{Newton}}\, T^{\mu\nu}.$$

- These equations do not constrain global features — such as topology.

- In particular, they do not constrain *temporal topology*.

Consequence:

- General relativity (Einstein gravity) *seems* to be infested with time machines.

An infestation of dischronal spacetimes:

- Goedel's universe.

- van Stockum time machines.
  (Tipler cylinders/Spinning cosmic strings.)

- Gott time machines.

- Kerr and Kerr–Newman geometries.

- Wormholes — quantum.
  (Wheeler's Spacetime foam.)
  [Spatial topology change $\Rightarrow$ time travel.]

- Wormholes — classical.
  (Morris–Thorne traversable wormholes.)

So what?

- Time travel is problematic, if not downright repugnant, from a physics point of view.

- One can either learn to live with it or do something about it —

  1. Radical re-write conjecture.

  2. Novikov: consistency conjecture.
     "You can't change recorded history".

  3. Hawking:
     chronology protection conjecture.

  4. Boring physics conjecture;
     (canonical gravity on steroids).

- I'll concentrate on explaining chronology protection.

Closed chronological curves (CCCs):

- Definition: any closed timelike curve (CTC) is a time machine.

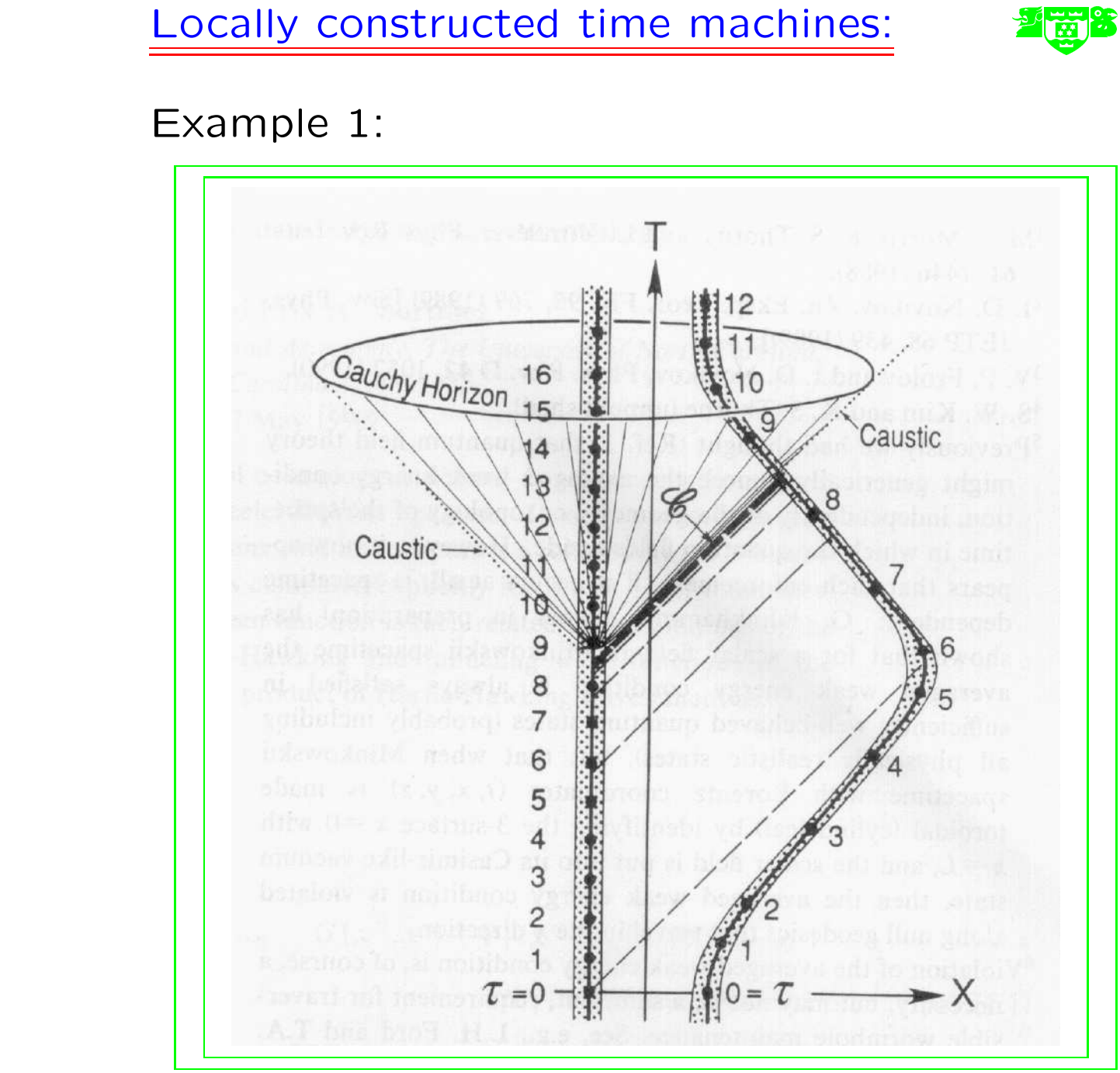
- A closed null curve (CNC) is almost as bad.

- If the closed chronological curves are cosmological, completely permeating the spacetime, apply the GIGO principle.
(garbage in — garbage out.)

- If the closed chronological curves are "confined" to some region we can begin to say something interesting.

- This situation corresponds to a "locally constructed" time machine.

Locally constructed time machines:

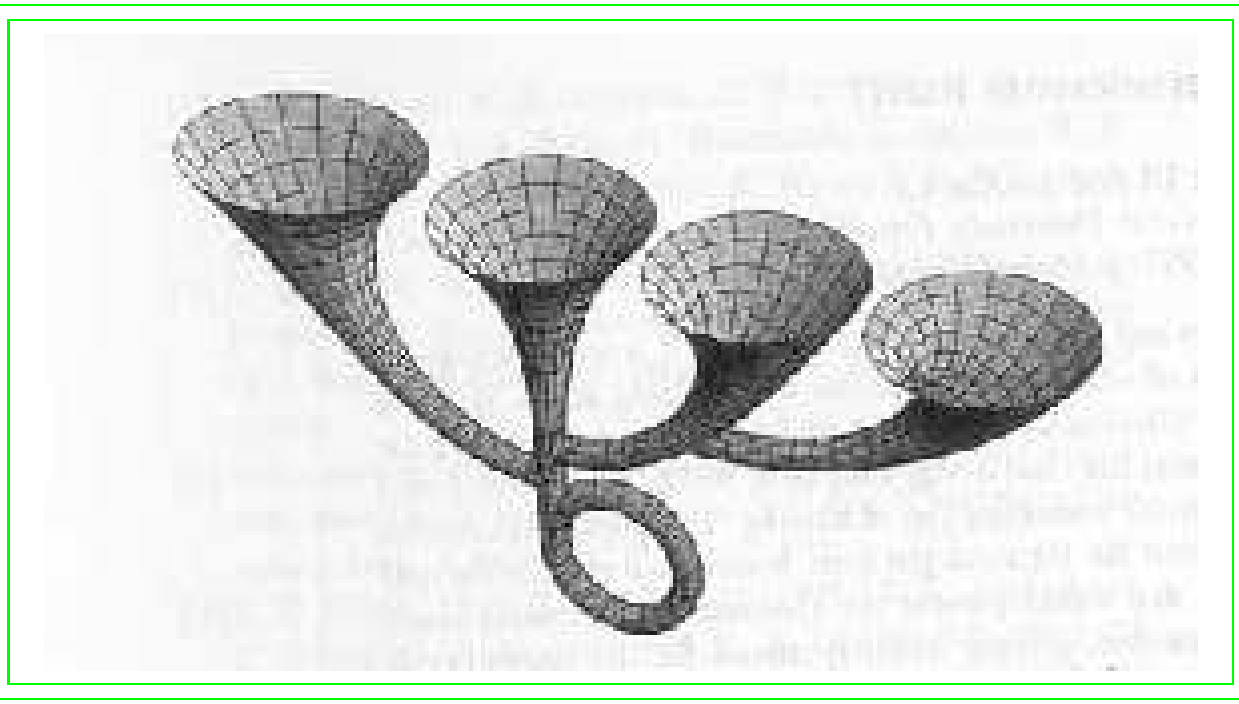


Example 1:

Morris–Thorne traversable wormholes...

Locally constructed time machines:

Example 2:



Gott–Li bootstrap universe...

Lorentzian signature "no boundary" proposal...

[PRD 58 (1998) 023501]

Having your cake and eating it too:

- Stephen Hawking's chronology protection conjecture permits a rich structure of strange and interesting objects without indulging in a free-for-all.

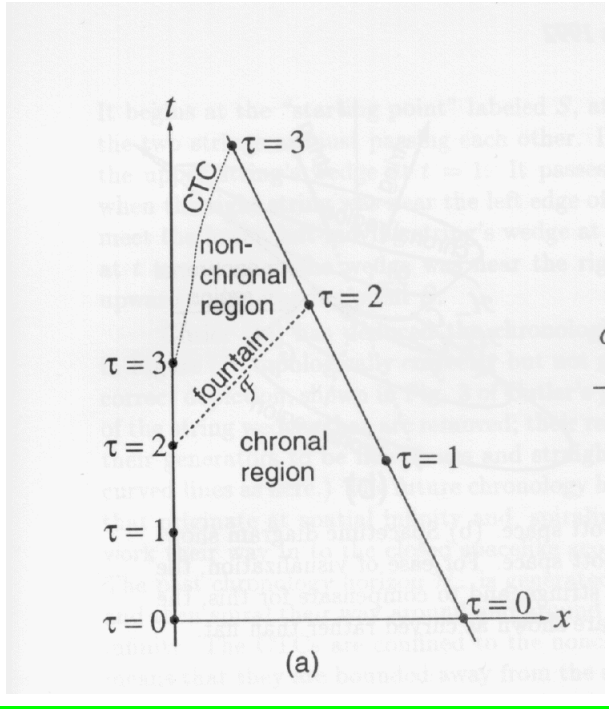
- GR community originally hoped to be able to settle this issue using classical, or at worst semi-classical, methods...

Stephen Hawking: [PRD 46 (1992) 603-611]

> "It seems that there is a Chronology Protection Agency which prevents the appearance of closed timelike curves and so makes the universe safe for historians."
>
> "There is also strong experimental evidence in favour of the conjecture — from the fact that we have not been invaded by hordes of tourists from the future."
>
> "The laws of physics do not allow the appearance of closed timelike curves."

Definitions:

- Chronology violating region.
- Chronology horizon.
- Compactly generated chronology horizon.
- "First" CNC: "fountain".



Classical chronology protection:

- Consider a photon that travels round the fountain.

- On every trip its energy is boosted:

$$E \to h\,E \to h^2\,E \to h^3\,E \ \ldots$$

with $\qquad h \geq 1.$

Simple cases:

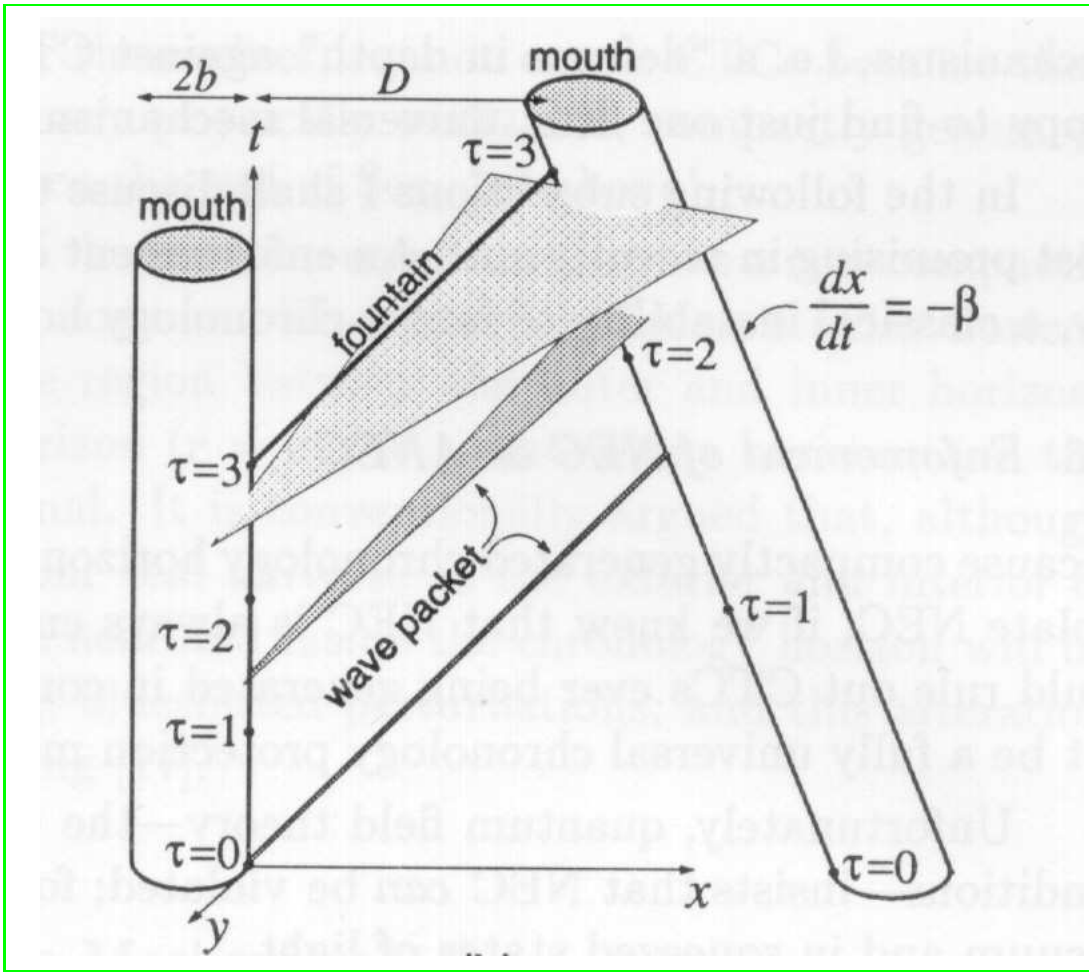
$$h = \sqrt{\frac{1+\beta}{1-\beta}}$$

Questions:

- Will this classical effect destabilize the chronology horizon?

- Will quantum physics amplify or ameliorate the effect?

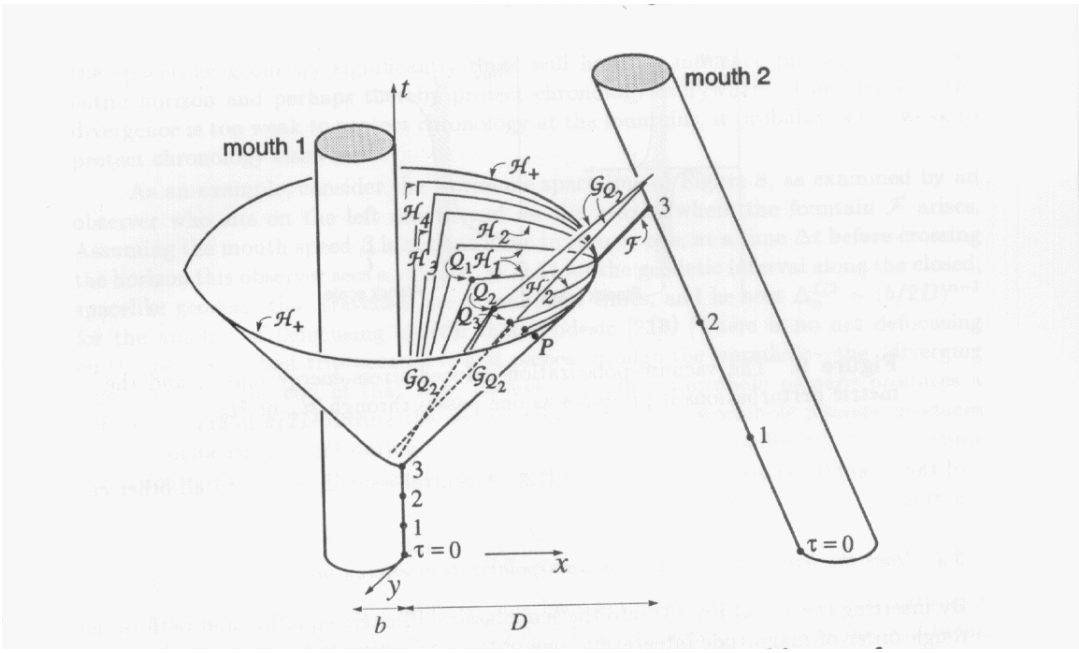
Wave packet defocussing:



- Question: Will this defocussing effect stabilize the chronology horizon?

- (That would be *bad*).

Quantum chronology protection:



Polarized hypersurfaces:

- There is an entire nested structure of self-intersecting null curves that wrap through the wormhole N times.

- $N \to \infty$ approaches the chronology horizon.

Renormalized stress energy tensor:

$$\langle 0|T_{\mu\nu}(x)|0\rangle = \lim_{y\to x}\langle 0|T_{\mu\nu}(x,y)|0\rangle.$$

$$\langle 0|T_{\mu\nu}(x,y)|0\rangle = D_{\mu\nu}(x,y)\{G_R(x,y)\}.$$

- G_R — renormalized Green function.
- $D_{\mu\nu}$ — second–order differential operator.
- Adiabatic approximation:

$$\langle 0|T_{\mu\nu}(x)|0\rangle = \hbar \sum_{\gamma}{}' \frac{\Delta_\gamma(x,x)^{1/2}}{\pi^2 s_\gamma(x,x)^4}\, t_{\mu\nu}(x;\gamma) + O(s_\gamma(x,x)^{-3}).$$

- $t_{\mu\nu}(x;\gamma)$ complicated function of metric and tangent vectors.

Blowups happen?

- $\langle T_{\mu\nu} \rangle \to \infty$ as $s[\gamma] \to 0^+$.

- This happens at every "polarized hypersurface".

- Unless there is an "accidental" zero in the Van Vleck determinant — $\Delta_\gamma(x, x)$.

- Unfortunately, there are special configurations (e.g., "Roman ring") where this happens.

- So generically $\langle T_{\mu\nu} \rangle \to \infty$;
  But for exceptional situations $\langle T_{\mu\nu} \rangle \to finite$.

- Need a better argument to guarantee chronology protection.

Breakdown of semiclassical quantum gravity:

- Theorem: The two-point function is not of Hadamard form at the chronology horizon.
  [Kay, Radzikowski, Wald;
  CMP 183 (1997) 533-556.]

- That is: At the chronology horizon

$$G_{\mu\nu} \neq 8\pi\, G_{\text{Newton}}\, \langle T_{\mu\nu} \rangle,$$

  simply because $\langle T_{\mu\nu} \rangle$ does not exist...

- This does not necessarily mean $\langle T_{\mu\nu} \rangle \to \infty$.

- More prosaically $\langle T_{\mu\nu} \rangle \to undefined$.

- Need to go beyond semi-classical quantum gravity (scqg).

Green function:

The adiabatic approximation gives —

$$G_R(x,y) = \hbar \frac{\Delta_{\gamma_0}(x,y)^{1/2} \varpi_{\gamma_0}(x,y)}{4\pi^2} + \hbar \sum_\gamma{}' \frac{\Delta_\gamma(x,y)^{1/2}}{4\pi^2} \times \left[\frac{1}{\sigma_\gamma(x,y)} + \upsilon_\gamma(x,y) \ln|\sigma_\gamma(x,y)| + \varpi_\gamma(x,y) \right].$$

- The sum runs over nontrivial geodesics.
- $\sigma_\gamma(x,y) = \pm\frac{1}{2} s[\gamma(x,y)]^2$ is the geodetic interval.
- $\Delta_\gamma(x,y)$ is the Van Vleck determinant.
- $\upsilon_\gamma(x,y)$ and $\varpi_\gamma(x,y)$ are smooth as $x \to y$.

Retaining only the most singular terms as $\sigma \to 0^+$:

$$G_R(x,y) = \hbar \sum_\gamma{}' \frac{\Delta_\gamma(x,x)^{1/2}}{2\pi^2 s_\gamma(x,x)^2} + O\left[\ln(s_\gamma(x,x))\right].$$

Reliability of csqft:

- Near the chronology horizon $\exists$ arbitrarily short self-intersecting spacelike geodesics

$$\mathrm{d}s^2 = \mathrm{d}z^2 + g_{ab}^{(2+1)}\,\mathrm{d}x^a\,\mathrm{d}x^b.$$

  (Not necessarily smooth.)

- $\Phi(z+s) = \Phi(z)$.

- $s < L_{\text{Planck}} \Rightarrow$
  modes with $p_z > P_{\text{Planck}}$ excited.

- That is: Close enough to the chronology horizon $\exists$ Planck scale physics.

- Region invariantly defined by looking at length of self-intersecting spacelike geodesics.

Quantum physics wins:

- $g_{ab}(z+s) = g_{ab}(z)$.

- Close enough to the chronology horizon
  $\exists$ Planck scale metric fluctuations.

- Should not trust semi-classical quantum gravity there.

- Generically, csqft (curved-space qft) is not enough to guarantee chronology protection.

- Full quantum gravity is unavoidable.
  (strings/branes, quantum geometry, Lorentzian lattice qg, canonical qg, whatever...)

Quantum gravity:

- Canonical quantum gravity (on steroids) and Lorentzian lattice quantum gravity both satisfy chronology protection by fiat.

- (Impose global hyperbolicity $\Rightarrow$ stable causality $\Rightarrow$ cosmic time.)

- This is effectively a restriction on the configuration space of the theory.

- Perhaps the answer lies in kinematics, not dynamics.

Quantum gravity:

- Quantum geometry and string/brane models do not (yet) seem to be able to address these issues.
  - Quantum geometry (currently) has enough troubles getting a "continuum limit". (The relativity community is still quite hopeful.)
  - String/brane models (currently) address chronology protection only within the low-energy limit — where they are a special case of csqft. (The string/brane community is still quite hopeful.)

String/brane models:

- Using a very strong version of the AdS/CFT conjecture you can (sometimes) relate the onset of chronology violation to "unphysical" behaviour in the dual gauge model.

- This means you are restricting the configuration space of the gauge theory dual model (the CFT), in order to restrict the configuration space of the spacetime side of the duality (the asymptotically AdS geometry).

- No general theorems yet.

- The fact that one is yet again formulating chronology protection in terms of kinematical restrictions on configuration space is tantalizing...

Conclusions:

- Chronology protection is a useful organizing principle.

- Chronology protection keeps life "interesting", without letting things get *too* "interesting".

- Chronology protection forces us to think about full-fledged quantum gravity.

- Chronology protection forces us to think about the quantum gravity/ semiclassical gravity interface.

Speculations:

- Maybe we should call it the "chronology protection principle"?.

- Maybe we should just build it into our fundamental theories by fiat by suitably restricting configuration space?

- Maybe the physical theory of gravity consists of (Einstein equivalence principle) plus (Einstein equations) plus (configuration space constraints).

- View the configuration space constraints as inherited from the high-energy fundamental quantum gravity theory...