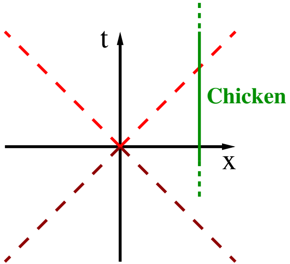
Does the chicken survive the firewall?

Jorma Louko

School of Mathematical Sciences, University of Nottingham

Observer-dependent entropy

Victoria University of Wellington, 12–14 December 2018



Plan

1. **Black hole information loss: Firewall?**

   $\longrightarrow$ **Correlation breakdown in quantum field theory**

2. **'Atom': Pointlike system in quantum field theory**
3. **Rindler Firewall**

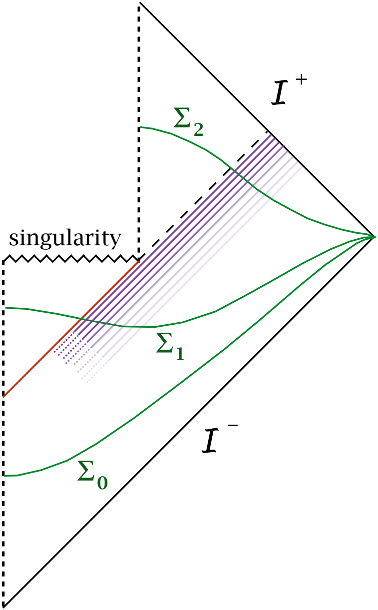
   $\longrightarrow$ **Evolution of entanglement**

4. **Wall creation**
   - **Scalar field in $1 + 1$ and $3 + 1$**
   - **Spinor field in $1 + 1$**
5. **Summary**

1. Black hole information: Firewall?

Almheiri et al 2013

Suppose BH evaporates fully and the process preserves unitarity



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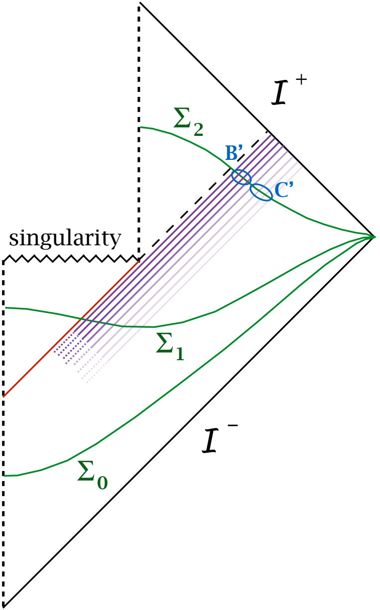

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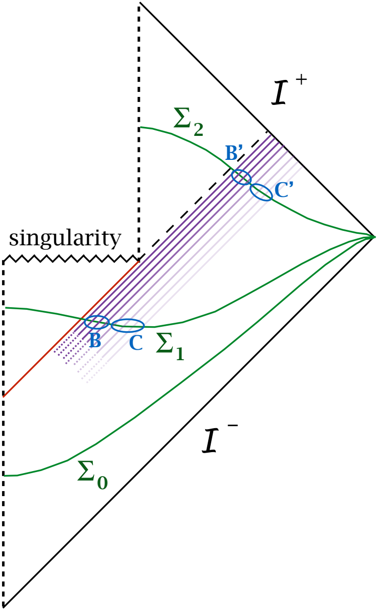

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- Hawking $\Rightarrow$
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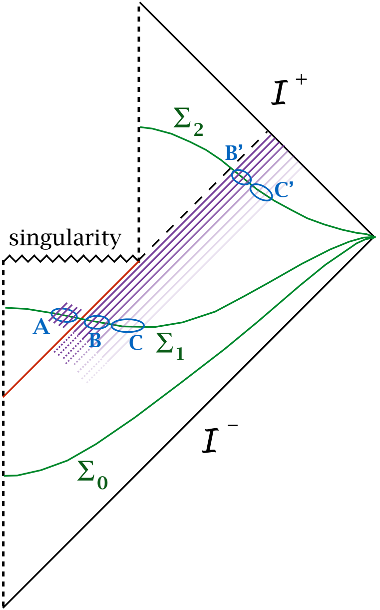

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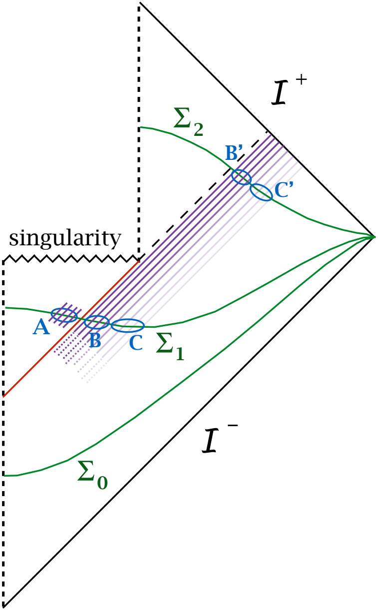
Contradicts entanglement monogamy theorem ?!?



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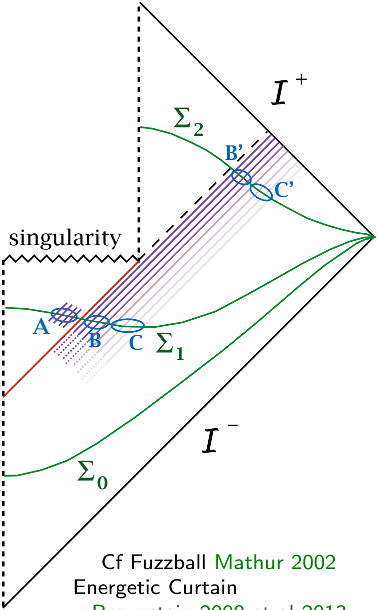
Almheiri at al (AMPS) 2013 **resolution proposal:**

A–B correlations broken by "drama" at the shrinking horizon even for macroscopic BH

"Firewall"



Cf Fuzzball Mathur 2002
Energetic Curtain
Braunstein 2009 et al 2013

2. 'Atom': Pointlike system in quantum field theory

(Unruh-DeWitt detector)

Quantum field

D	spacetime dimension
ϕ	real scalar field
$\|0\rangle$	(initial) state

Two-state detector (atom)

$\|\|0\rangle\rangle$	state with energy 0
$\|\|1\rangle\rangle$	state with energy ω
$\mathsf{x}(\tau)$	detector worldline, τ proper time

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Interaction: one of

$$H^{(0)}_{\text{int}}(\tau) = c\chi(\tau)\mu(\tau)\phi\big(\mathsf{x}(\tau)\big) \qquad \longleftarrow \text{usual UDW}$$

$$H^{(1)}_{\text{int}}(\tau) = c\chi(\tau)\mu(\tau)\tfrac{\mathrm{d}}{\mathrm{d}\tau}\phi\big(\mathsf{x}(\tau)\big) \qquad \longleftarrow \text{derivative-coupling}$$

c	coupling constant
χ	switching function, C_0^∞
μ	detector's monopole moment operator

Probability of transition

$$\|0\rangle\!\rangle \otimes |0\rangle \longrightarrow \|1\rangle\!\rangle \otimes |\text{anything}\rangle$$

in first-order perturbation theory:

$$P(\omega) = c^2 \underbrace{\left|\langle\!\langle 0\|\mu(0)\|1\rangle\!\rangle\right|^2}_{\substack{\text{detector internals only:} \\ \text{drop!}}} \times \underbrace{F(\omega)}_{\substack{\text{trajectory and } |0\rangle: \\ \text{response function}}}$$

$$F^{(0)}(\omega) = \int_{-\infty}^{\infty} \mathrm{d}\tau' \int_{-\infty}^{\infty} \mathrm{d}\tau'' \, \mathrm{e}^{-i\omega(\tau'-\tau'')} \, \chi(\tau')\chi(\tau'') \, W(\tau', \tau'')$$

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$$W(\tau', \tau'') = \langle 0|\phi\big(\mathsf{x}(\tau')\big)\phi\big(\mathsf{x}(\tau'')\big)|0\rangle \qquad \text{Wightman function}$$

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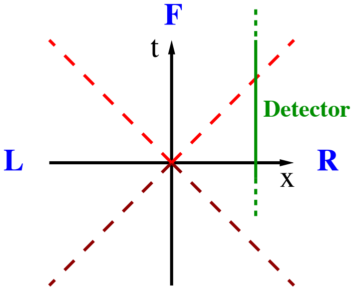
Wightman function

(distribution!)

3. Rindler Firewall

JL 2014 (Suggested by Marolf)



1+1 Minkowski

$\phi(t, x)$ massless

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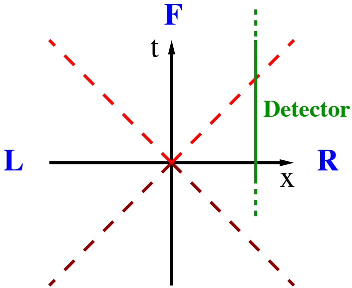

Recall Minkowski vacuum $|0_M\rangle$: **R** and **L** correlated $\Rightarrow$ Unruh effect

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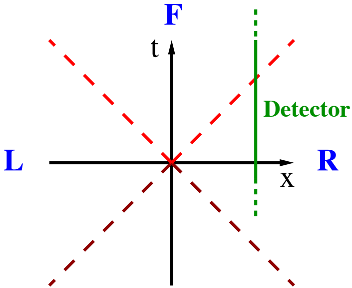

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Define mixed state ρ_{FW}:

1. In **R**: $\rho_{\mathbf{R}} := \mathrm{Tr}_{\mathbf{L}}\big(|0_M\rangle\langle 0_M|\big)$ indistinguishable from $|0_M\rangle$
   In **L**: $\rho_{\mathbf{L}} := \mathrm{Tr}_{\mathbf{R}}\big(|0_M\rangle\langle 0_M|\big)$ indistinguishable from $|0_M\rangle$
2. In **R** $\cup$ **L**: $\rho_{FW} := \rho_{\mathbf{R}} \otimes \rho_{\mathbf{L}}$ No correlations between **R** and **L**
3. Evolved into **F** by null propagation

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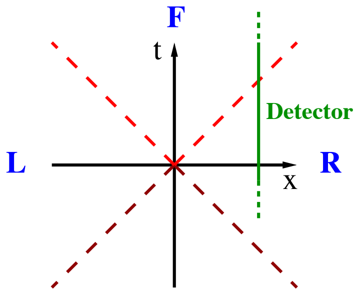

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Firewall: ρ_{FW} is singular (non-Hadamard) at $t = |x|$. How strong?

Rindler Firewall

- ω: detector energy gap
- $F^{(1)}(\omega) \propto$ transition probability
- $\chi(\tau)$ switching: $\propto$ coupling strength
- Firewall crossing at $\tau = 0$
- μ: infrared cutoff

$$
\begin{aligned}
& F^{(1)}_{\mathrm{FW}}(\omega) - F^{(1)}_{|0_{\mathrm{M}}\rangle}(\omega) \\
& \quad = \frac{[\chi(0)]^2}{2\pi} \ln\left(|\omega|/\mu\right) \\
& \qquad + \frac{\chi(0)}{2\pi} \int_0^\infty \mathrm{d}s \, \cos(\omega s) \, \frac{[\chi(0) - \chi(-s)]}{s} \\
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Sharp kick at Firewall crossing

Severed correlations across Firewall

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$$F^{(1)}_{\mathrm{FW}}(\omega) - F^{(1)}_{|0_{\mathrm{M}}\rangle}(\omega)$$

$$= \frac{[\chi(0)]^2}{2\pi} \ln(|\omega|/\mu) \longleftarrow$$

dominant at adiabatic and large gap limits

$$+ \frac{\chi(0)}{2\pi} \int_0^\infty \mathrm{d}s \, \cos(\omega s) \, \frac{[\chi(0) - \chi(-s)]}{s}$$

$$+ \frac{\chi(0)}{2\pi} \int_0^\infty \mathrm{d}s \, \frac{[1 - \cos(\omega s)]}{s} \, \chi(s)$$

Sharp kick at Firewall crossing

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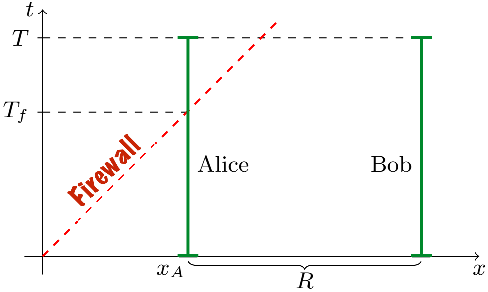
Entanglement across Rindler Firewall

Martín-Martínez and JL 2015

Detector pair:
Alice and Bob



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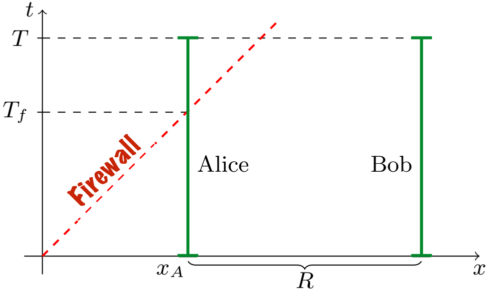
Initial state:

$$\frac{1}{\sqrt{2}}\left(|{\downarrow}\rangle_A\,|{\downarrow}\rangle_B + |{\uparrow}\rangle_A\,|{\uparrow}\rangle_B\right)$$

Entanglement maximal:

Negativity $= \frac{1}{2}$



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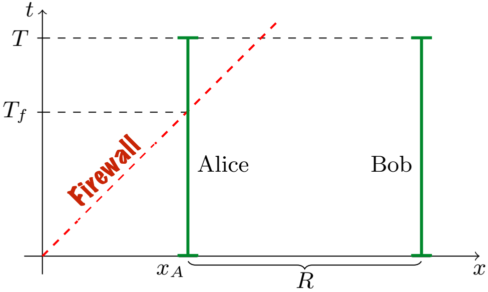

Final state:
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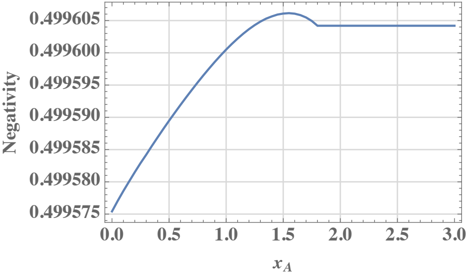
- Firewall crossing has a modest effect



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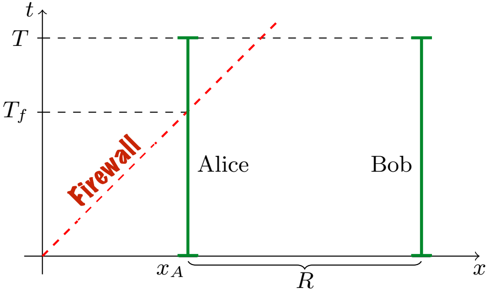

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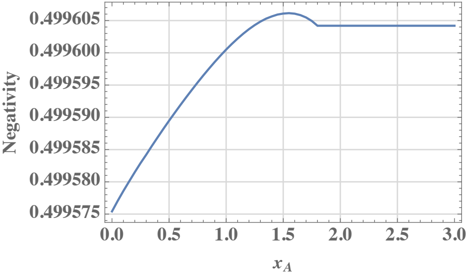
- sign of effect: not fixed!

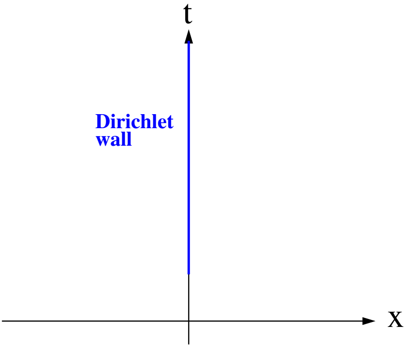


4(a). Wall creation: scalar field in $1+1$ Brown and JL 2015

1+1 Minkowski

$\phi(t, x)$ massless

$$\partial_t^2\phi - \partial_x^2\phi = 0$$



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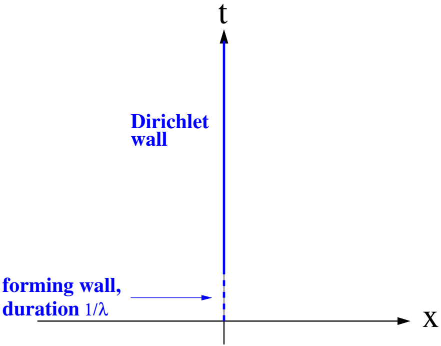

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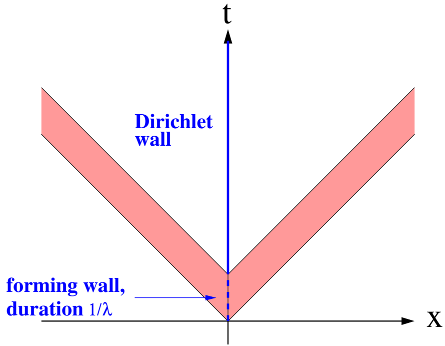

- Total energy radiated: $\langle E_{\rm tot}\rangle \propto \lambda \ln(\lambda/\mu) \xrightarrow[\lambda\to\infty]{} \infty$

  Divergent for sharp wall formation Cf Anderson and DeWitt 1986

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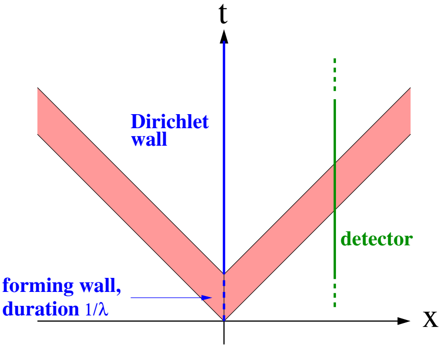

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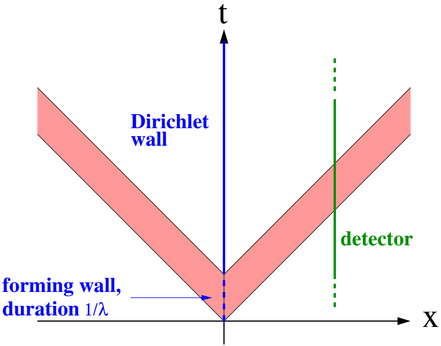

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  Transition probability finite for sharp wall formation

Moral: sharp wall formation singular gravitationally but nonsingular for a matter coupling

4(b). Point wall creation in $3+1$

Zhou et al 2016

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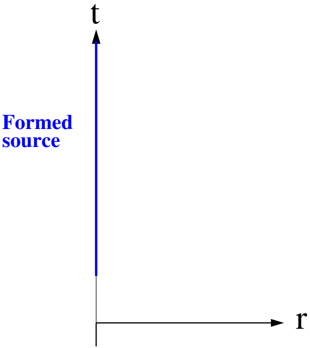

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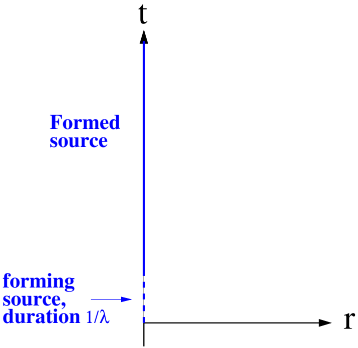
$\theta(t)$: origin boundary condition

(spherically symmetric sector)



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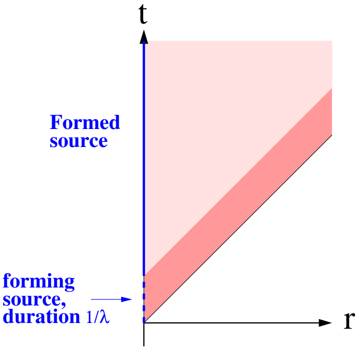

- $\langle T_{00} \rangle$ well defined; time-dependent even for $t > r + \lambda^{-1}$

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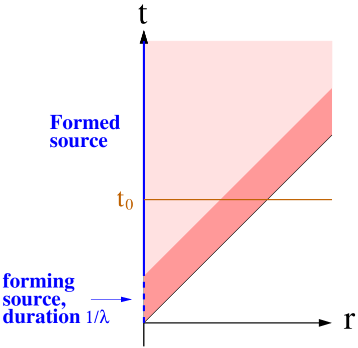

- $\langle T_{00} \rangle$ well defined; time-dependent even for $t > r + \lambda^{-1}$
- $t = t_0 > \lambda^{-1}$: $\langle T_{00} \rangle \rightarrow \begin{cases} \infty, & r \rightarrow 0_+ \\ -\infty, & r \rightarrow t_{0\,-} \end{cases} \quad \Rightarrow \quad \langle E_{\text{tot}} \rangle =$ "$\infty - \infty$" **not defined**

4(b). Point wall creation in $3+1$

Zhou et al 2016

3+1 Minkowski

$\phi(t, \mathbf{x})$ massless

$$\partial_t^2 \phi - \nabla^2 \phi = 0$$

$$\rightarrow \boxed{\partial_t^2 \phi - \Delta_{\theta(t)} \phi = 0}$$

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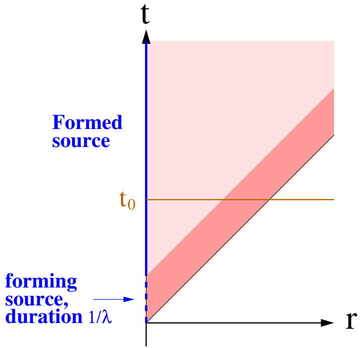

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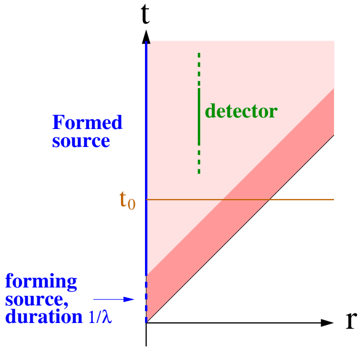

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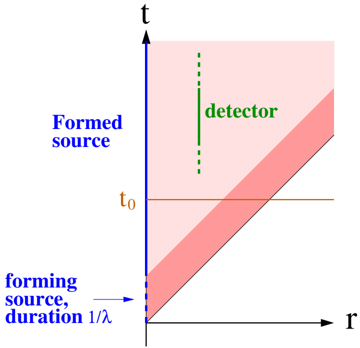

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Moral: sharp wall formation (quite) singular both gravitationally and for a matter coupling

4(c). Spinor wall creation in $1+1$

Wan Mokhtar and JL (tba)

1+1 Minkowski

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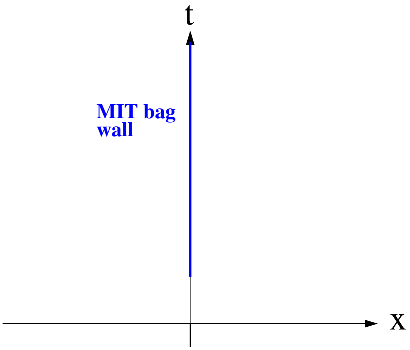

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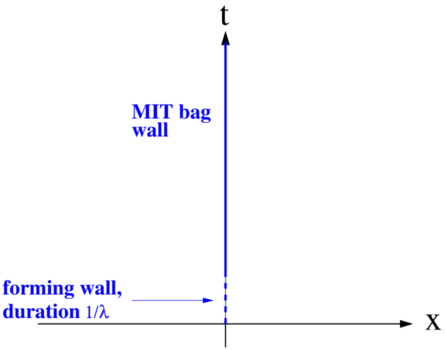

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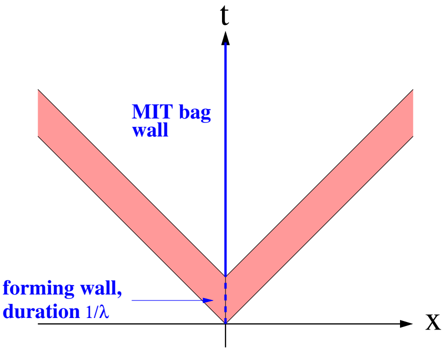

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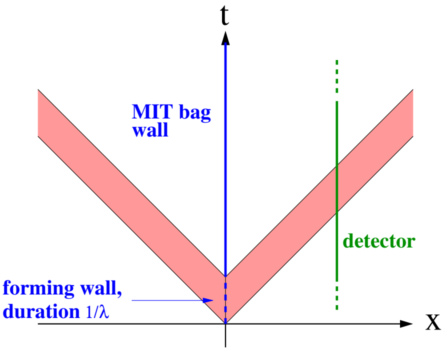

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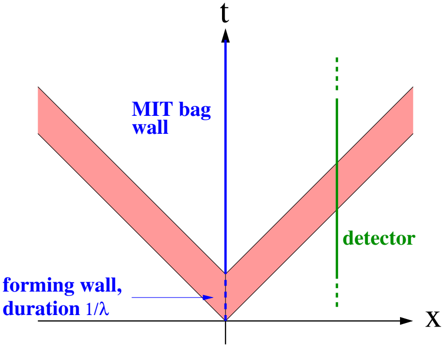

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Summary

- **Rapid creation of a (pointlike) wall tends to be singular!**
  - Both gravitationally and for a model atom's response
  - 1+1 scalar field exceptional
- **Model for a black hole firewall?**
  - Spacetime will react. How?
  - $G_{\mu\nu} = 8\pi \langle T_{\mu\nu} \rangle$? May or may not suffice...
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Is information lost? Jury very much out!