Poincare-Einstein approach to Penrose's Conformal Cyclic Cosmology

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What is Conformal Cyclic Cosmology?

- The **Conformal Cyclic Cosmology**, or CCC, is a certain mathematical frame for **cosmology. As Roger Penrose** once told me, it emerged because he wanted to have some answer to a question which he was asked many times**.** This annoying question was: '**What was before the Big Bang?**'**.**
- Perhaps by an accident, CCC perfectly fits this **Conference**, whose title is '**Conformal Geometry**, **Analysis** and **Physics**'**.** And **CCC** strongly uses concepts from **Conformal Geometry**, to speculate about **Physics**, in terms of mathematical models, which require quite a nontrivial Mathematical **Analysis.**

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In the 2015 article

'The equations of Conformal Cyclic Cosmology'

Paul Tod summarized the main **mathematical** ingredients of **Penrose's CCC** as follows:

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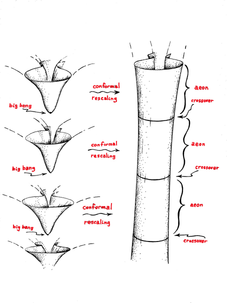
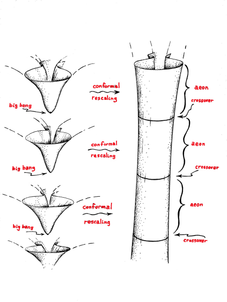


- The Universe consists of **eons**, each being a **time oriented** spacetime, i.e. a 4-dimensional **Lorentzian manifold**, whose **conformal compactifications** have **spacelike** $\mathscr{I}$s. The **Weyl tensor** of the 4-metric on each $\mathscr{I}$ **is zero**.
- Eons are ordered, and the **conformal compactifications** of consecutive eons, say **the past one** and **the present one**, are **glued together** along $\mathscr{I}^+$ **of the past eon**, and $\mathscr{I}^-$ **of the the present eon**.

Penrose's Conformal Cyclic Cosmology



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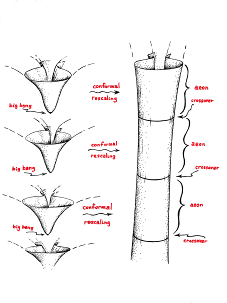

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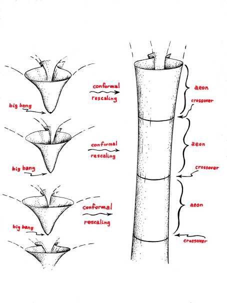

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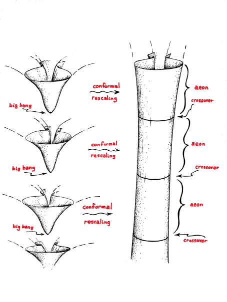

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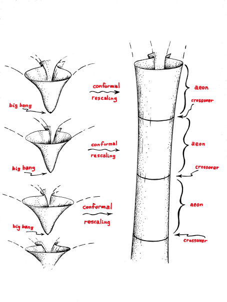

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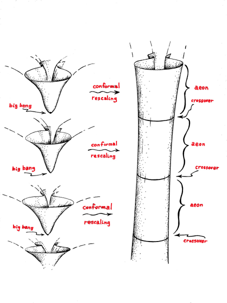

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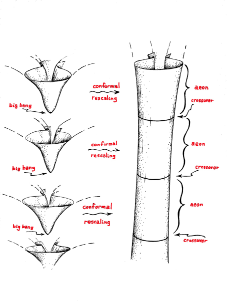

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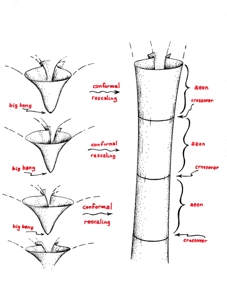

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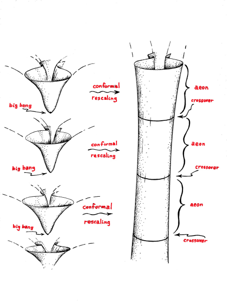

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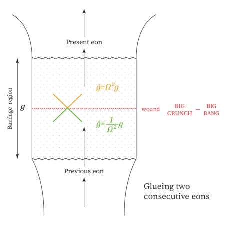

- The **matching surface** of the past and the present eons is called the **wound** of the Universe, and the **vicinity of the wound** is called the **bandage region** for the two eons. The **whole bandage region is equipped with** the following **three metrics**, which are **conformally flat at the wound**:
  - a Lorentzian metric g which is regular everywhere,
  - a Lorentzian metric $\check{g}$, which represents the physical metric of the **present eon**, and which is **singular** at the wound,
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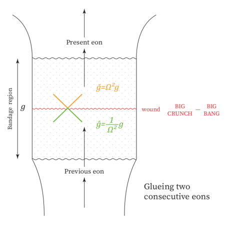

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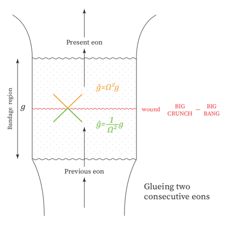

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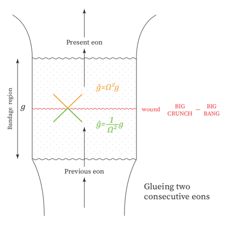

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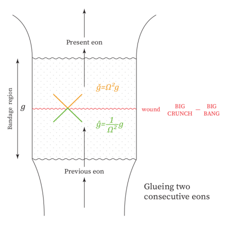

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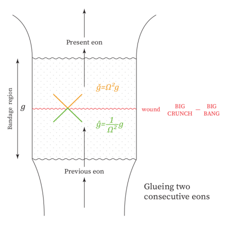

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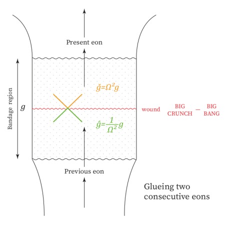

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- In the bandage region, the **three metrics** g, $\check{g}$ and $\hat{g}$, are **conformally related.**
- How to make this relation specific is debatable, but Penrose proposes that
  $\check{g} = \Omega^2 g$, and $\hat{g} = \frac{1}{\Omega^2} g$, with $\Omega \to 0$ on the wound.
- The metric $\check{g}$ **in the present eon** is a **physical metric there.** Likewise, the metric $\hat{g}$ **in the past eon** is a **physical metric there.**
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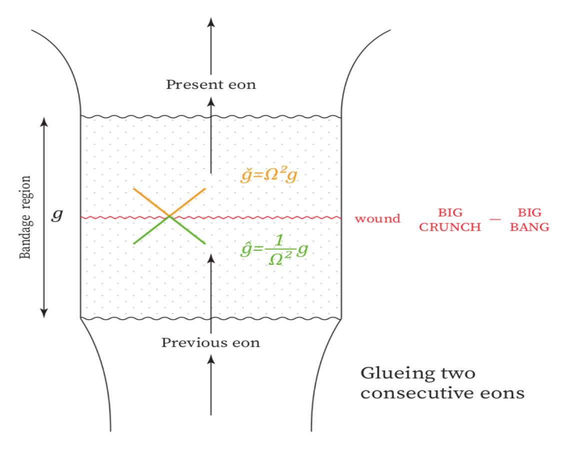
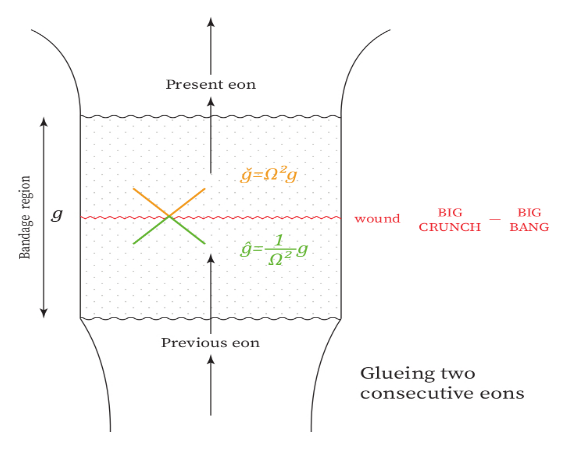

Present eon
$\check{g}=\Omega^2 g$
Bandage region
g
wound
BIG CRUNCH — BIG BANG
$\hat{g}=\frac{1}{\Omega^2}g$
Previous eon
Glueing two consecutive eons

Penrose's Conformal Cyclic Cosmology



- **Question**: How to make a model of Penrose's bandage region of two eons?
- One needs a function Ω, **vanishing on some spacelike hypersurface**, and a **regular** Lorentzian 4-metric g **conformally flat at this hypersurface**, such that **if** $\hat{g} = \frac{1}{\Omega^2} g$ **satisfies Einstein equations** with some physically reasonable energy momentum tensor, **then** $\check{g} = \Omega^2 g$ **also satisfies Einstein equations** with possibly different, but still physically reasonable energy momentum tensor.
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Einstein spaces which are mapped conformally on each other.

Von

H. W. Brinkmann in Cambridge (Mass., U. S. A.).

§ 1.

Introduction.

It is well known that a Euclidean n-space, that is, a Riemann space whose squared line element is

$$ds^2 = dx_1^2 + dx_2^2 + \dots + dx_n^2$$

can, for $n \geqq 3$, be mapped conformally on itself only by inversions and similarity transformations (Liouville's theorem). An analogous question arises when, instead of Euclidean space, we consider those spaces which satisfy Einstein's gravitational equations for "empty space" and which we call *Einstein spaces*. A difference arises, however, out of the fact that for $n \geqq 4$ two Einstein spaces need not be isometric, hence we set the problem as follows: When can an Einstein space be mapped conformally on some (possibly different) Einstein space and in how many ways can it be so mapped? The present paper is devoted to the solution of this problem. The related question: When can an Einstein space be mapped conformally on itself? will be answered also in the course of the investigation.

- In particular, **in dimension four in Lorentzian signature**, Brinkman **found all conformal classes** which contain at least **two different Ricci flat metrics**.
- **In bandage regions of CCC the problem is similar** to this of Brinkmann. Here, the **same function** Ω should provide two scales: Ω and $-\frac{1}{\Omega}$, for the 'healing' metric g, which make the corresponding **conformally related metrics** $\check{g} = \Omega^2 g$ and $\hat{g} = \Omega^{-2} g$ into **two solutions of the Einstein equations**. This seems to make the problem of finding possible candidates for bandage metrics **very restrictive**.
- The situation would be really bad if not the fact that now, the **two solutions** $\hat{g}$ and $\check{g}$ **of the Einstein equations** may have **different energy momentum tensors**: a **prescribed** energy momentun tensor **on the** $\hat{M}$ **part**, and a **reasonable** energy momentum tensor **on the** $\check{M}$ **part**.

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Creating a bandage region model

I will now outline how to effectively make a bandage region model. This will be done in a number of steps.

- **Step one**: How to create **a metric** $\hat{g}$ **of the past eon**?
- **Step two**: How to **pick up the scale** Ω once $\hat{g}$ is determined?
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Creating a bandage region model: preparations

- I start with a **conformally flat data on a spacelike hypersurface** $\mathscr{I}$ and **evolve it back in time to the past eon.**
- But I do it in a **Poincare-Einstein way** of
  Charles Fefferman and **Robin Graham**!
- I will briefly review the **Fefferman-Graham result specialized to the 4-dimensional Lorentzian situation**, now.
- Their result **shows how to uniquely** associate **an Einstein Lorentzian 4-metric** $\hat{g}$ on $\hat{M}$ with a **3-dimensional Riemannian metric** h_0 **on the conformal boundary** $\partial\hat{M} = \mathscr{I}$ of $\hat{M}$.

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Creating a bandage region model: Fefferman-Graham Theorem

- Start with a **conformal class of Riemannian 3-metrics** $[h_0]$ with a representative h_0 on $\mathscr{I}$.
- Consider a symmetric rank 2 tensor $h(t)$ on $\mathscr{I}$ in terms of its **power series expansion** $h(t) = \sum_{i=0}^{\infty} h_i t^i$, and define a **Lorentzian 4-metric**

$$\hat{g} = \frac{-\mathrm{d}t^2 + h(t)}{t^2}$$

on $\hat{M} =]-\epsilon, 0[\times \mathscr{I}$ with $t \in]-\epsilon, 0[$.

- Choose an **arbitrary** symmetric rank 2 tensor h on $\mathscr{I}$ which is **trace-free** and **divergence-free** w.r.t. h_0.
- Then the **conditions**

$$Ric(\hat{g}) = 3\hat{g}$$

and

$$\left(\mathrm{the-trace-free-part-of}\ h_3\right) = h$$

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$$Ric(\hat{g}) = 3\hat{g}$$

and

$$\left(\mathrm{the-trace-free-part-of}\ h_3\right) = h$$

uniquely determine $h(t)$, and in turn $\hat{g}$, **up to infinite order at** $t = 0$.

- Start with a **conformal class of Riemannian 3-metrics** $[h_0]$ with a representative h_0 on $\mathscr{I}$.
- Consider a symmetric rank 2 tensor $h(t)$ on $\mathscr{I}$ in terms of its **power series expansion** $h(t) = \sum_{i=0}^{\infty} h_i t^i$, and define a **Lorentzian 4-metric**

$$\hat{g} = \frac{-\mathrm{d}t^2 + h(t)}{t^2}$$

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Step one: The past eon metric $\hat{g}$

So my **proposal for constructing the past eon metric** $\hat{g}$ from the conformally flat class h_0 on $\mathscr{I}$ is very similar:

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- Impose the **Einstein conditions**

$$\hat{Ric}(\hat{g}) - \frac{1}{2}\hat{R}\hat{g} + \hat{\Lambda}\hat{g} = \hat{T}$$

  on $\hat{g}$, where $\hat{T}$ is the **energy momentum tensor suitable for the past eon.** If the energy momentum tensor $\hat{T}$ in $\hat{M}$ is not too wild, I **expect the similar uniqueness result** as in the FG case.
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- When $\hat{g}$ is determined according to the procedure I described, its manifold $\hat{M}$ **has a natural spacelike boundary at** $t = 0$: i.e. at $\partial\hat{M} = \{0\} \times \mathscr{I}$, where the metric $\hat{g}$ blows up.
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Step four: The physical content of the present eon

- The described procedure **defined the present eon manifold** $\check{M} = [0, \epsilon[\times \mathscr{I}$ and its metric $\check{g} = t^2(-\mathrm{d}t^2 + h(t))$.
- Now all choices have been made, and the **physical content** of $\check{M}$ should be **read off** from the **right hand side** of the **Einstein's equations**

$$\check{Ric}(\check{g}) - \frac{1}{2}\check{R}\check{g} + \check{\Lambda}\check{g} = \check{T}.$$

- So the **physics in the new eon** is **determined by** a **discrete flip** of $-\frac{1}{t} \to t$ rather, than via a differential equation for Ω.
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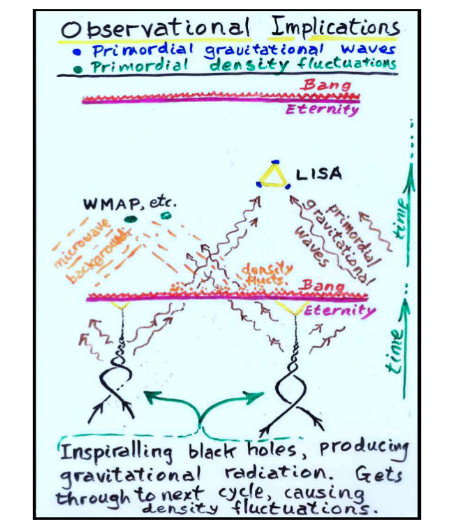
Does this procedure give reasonable results?



Well...

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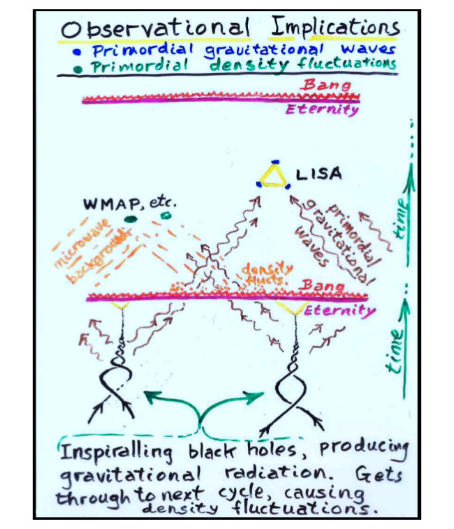

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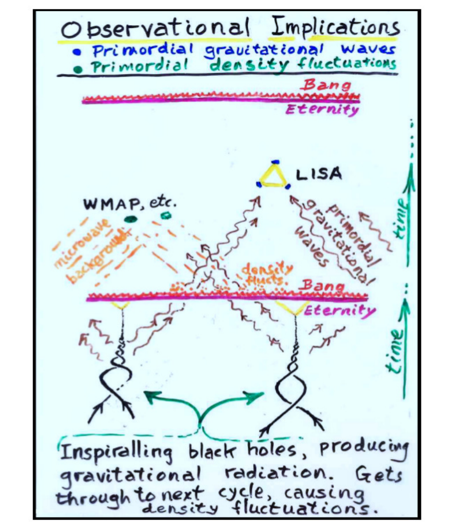

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Does this procedure gives reasonable results?

- I assumed that in the past eon **only one spherical wave remained.**
- More specifically, I assumed that I have a conformally flat metric h_0 on $\mathscr{I}$;
- that the metric $\hat{g} = t^{-2}(-\mathrm{d}t^2 + h_t)$ in the Poincare-Einstein/Fefferman-Graham expansion is
  - (a) **spherically symmetric**, and
  - (b) **satisfies Einstein's equations** $\hat{Ric}(\hat{g}) - \frac{1}{2}\hat{R}\hat{g} + \hat{\Lambda}\hat{g} = \hat{T}$ with **energy momentum** $\hat{T}$ of **pure radiation**: i.e. $\hat{T} = K \otimes K$, with K being **null.**

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HAPPY BIRTHDAY ROBIN!

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THANK YOU FOR YOUR ATTENTION!