On observable signals of non-singular cosmologies

czechLISA

Prague Relativity Group Summer 2023 meeting

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UNIVERZITA KARLOVA
Matematicko-fyzikální
fakulta

Ongoing (unpublished) work with Dr Peter Taylor (Dublin City University)

Recent Research Questions

[1] Based on the article Phys.Rev.D 105 (2022) 8, 085001 arXiv:2109.04486 (A.C. in collaboration with Dr Peter Taylor, DCU).

[2] Phys.Rev.D 105 (2022) 12, 123513 arXiv:2204.00359 (A.C).

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(a) highlight disparities between singular and non-singular theories? Are these potentially observable?

(b) shed light on pre-bounce physics? (i.e. the equation of state pre-bounce)

(c) better understand the importance of quantum effects at early times?

Outline of talk

1. Model:
   Quantum-corrected[3] non-singular bouncing cosmology
2. Framework:
   The Unruh-DeWitt particle detector model
3. Results:
   From an analytic model towards more realistic measuring scenarios

[3] with the correction originating from Loop Quantum Cosmology e.g. [Rovelli & Wilson-Ewing Phys.Rev.D 90 (2014) 2, 023538]

The cosmological model

Cosmological model

Overview

We work within the framework of the (flat) Friedmann-Lemaître-Robertson-Walker (FLRW) metric

$$ds^2 = -dt^2 + a^2(t)\left(dr^2 + r^2 d\Omega^2\right),$$

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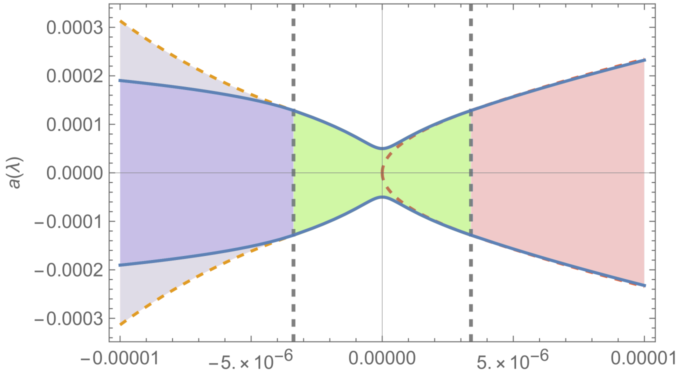

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Classical regions

- We assume that the dynamics of the classical regions of the universe are captured accurately by the classical Friedman equation

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  - (ii) ~~a quantum-corrected radiation-dominated *bounce phase*~~
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- We approximate the scale factor in each era by the dominant form in that era.

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where $w = 0$ is the equation of state parameter for matter.

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Indeed, the general form for the dominant scale factor in the classical regions with $w > -1$ is given by

$$a(t) = \left(\alpha_i \pm \frac{3}{2}(1 + w_i)\sqrt{\frac{\kappa \rho_i}{3}} t \right)^{2/3(1+w_i)} \quad \text{for } i = \{c, m\}.$$

while at late times (for $w = -1$) we have

$$\frac{\dot{a}}{a} = \sqrt{\frac{\Lambda}{3}} \quad \Longrightarrow \quad a(t) = \alpha_\Lambda e^{\sqrt{\frac{\Lambda}{3}} t},$$

which is, of course, the scale factor for de Sitter space.

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- We wish to explore whether a study of particle detection can lead to observable signals of the equation of state pre-bounce
- Question 1: *can disparities be observed between various bouncing models – characterised by different choices of w_c?*

Quantum corrected bounce phase

In the radiation-dominated era which surrounds the bounce at $t = 0$, the classical Friedmann equation receives a correction

$$H^2 = \frac{\kappa}{3}\rho(t)\left(1 - \frac{\rho(t)}{\rho_{crit}}\right),$$

which originates from Loop Quantum Cosmology and has been argued to accurately capture quantum gravity effects in the early universe.

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Again, we solve to find

$$a(t) = \left(\Omega_{crit} + \left(\sqrt{a_b^4 - \Omega_{crit}} + 2\sqrt{\frac{\kappa\rho_r}{3}}t\right)^2\right)^{1/4},$$

which we have expressed in terms of the critical density parameter

$$\Omega_{crit} = \frac{\rho_r}{\rho_{crit}},$$

and where $a_b = a(0)$ is the value of the scale factor at the bounce.

Quantum corrected bounce phase

To realise a bounce, the scale factor

$$a(t) = \left(\Omega_{crit} + \left(\sqrt{a_b^4 - \Omega_{crit}} + 2\sqrt{\frac{\kappa\rho_r}{3}}t\right)^2\right)^{1/4},$$

must conform to the bounce conditions

$$H(t)\Big|_{t=0} = 0 \quad \text{and} \quad \dot{H}(t)\Big|_{t=0} > 0,$$

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From the first of these we see that at $t = 0$, we require

$$H(0) = 0 \quad \Longrightarrow \quad \Omega_{crit} = a_b^4,$$

so that

$$a(t) = \left(a_b + \frac{4\kappa\rho_r}{3}t^2\right)^{1/4}.$$

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Overview

In terms of dimensionless time $T = (4.7)t/t_m$ we can write our scale factor across the entire evolution as the piecewise function

$$a(T) = \begin{cases} a_r \left(1 - \bar{\Omega}_c(w)(T - T_r)\right)^{2/3(1+w_c)} & T < T_r \\ a_b \left(1 + \bar{\Omega}_r T^2\right)^{1/4} & T_r \leq T < T_m \\ a_m \left(1 + \bar{\Omega}_m(T - T_m)\right)^{2/3} & T_m \leq T < T_\Lambda \\ a_\Lambda \, e^{\bar{\Omega}_\Lambda(T - T_\Lambda)} & T \geq T_\Lambda \end{cases},$$

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where we have defined the 'density parameters'

$$\bar{\Omega}_c(w) \equiv \frac{3}{2}(t_m/b)(1+w_c) a_r^{\frac{-3(1+w_c)}{2}} \sqrt{\frac{\kappa\rho_r}{3}}, \quad \bar{\Omega}_r \equiv \frac{(t_m/b)^2}{a_b^4} \frac{4\kappa\rho_r}{3},$$

$$\bar{\Omega}_m \equiv \frac{(t_m/b)}{a_m^{3/2}} \frac{3}{2} \sqrt{\frac{\kappa\rho_m}{3}}, \quad \bar{\Omega}_\Lambda \equiv (t_m/b)\sqrt{\frac{\Lambda}{3}},$$

for convenience.

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Continuity dictates

$$a_r = a_b(1+\bar{\Omega}_r T_r^2)^{\frac{1}{4}}, \; a_m = a_b(1+\bar{\Omega}_r T_m^2)^{\frac{1}{4}}, \; a_\Lambda = a_m \left(1 + \bar{\Omega}_m (T_\Lambda - T_m)\right)^{\frac{2}{3}},$$

where $a(T_m) \equiv a_m$ is the value of the scale factor at $T = T_m$, etc., while smoothness of the scalar factor further imposes

$$\bar{\Omega}_c(w) = -\frac{3(w+1)\bar{\Omega}_r T_r}{4\left(1 + \bar{\Omega}_r T_r^2\right)}, \; \bar{\Omega}_m = \frac{3\bar{\Omega}_r T_m}{4\left(1 + \bar{\Omega}_r T_m^2\right)}, \; \bar{\Omega}_\Lambda = \frac{2\bar{\Omega}_r T_m}{4 + \bar{\Omega}_r (3T_\Lambda + T_m) T_m}.$$

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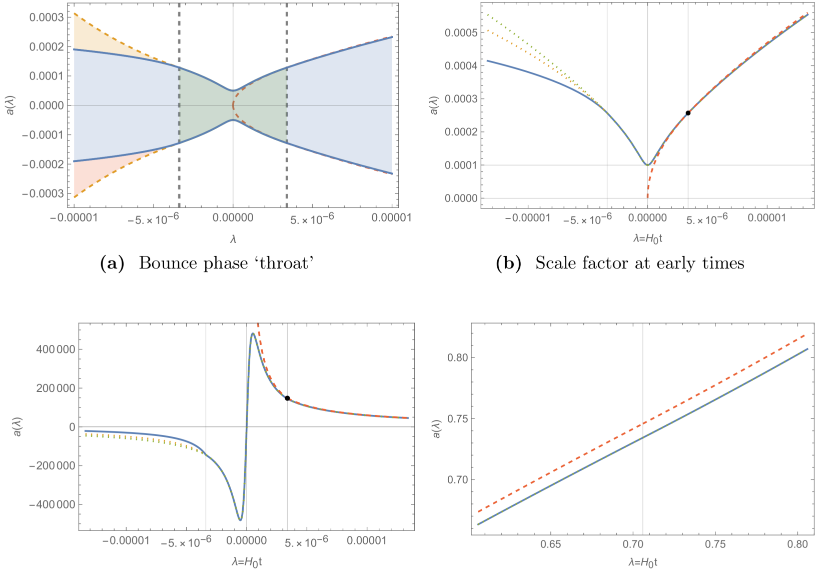
- Question 2: *How important are quantum effects in the early universe?*



(a) Bounce phase 'throat'

(b) Scale factor at early times

(c) Hubble parameter at early times

(d) Scale factor at late times

Figure 1: *Spacetime diagrams:*

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  a particle is what a particle detector detects!

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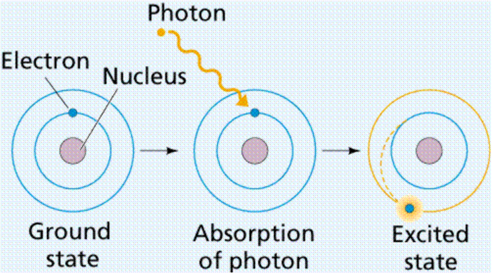

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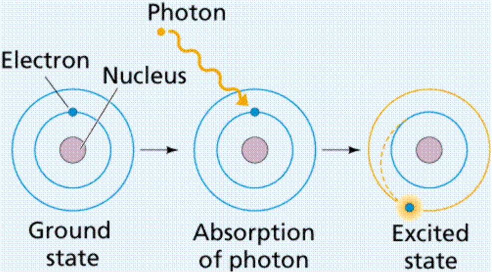

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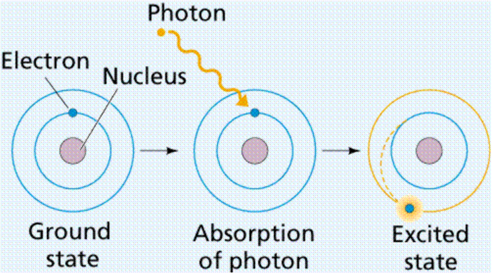

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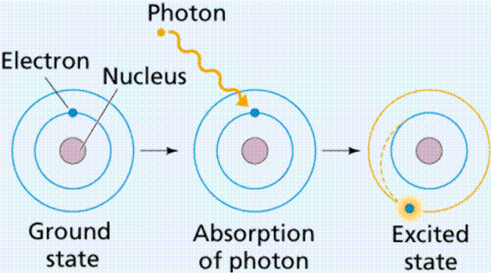

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- Conversely, the detector can de-excite by emitting quanta.

Particle Detector Theory & Response

Suppose that the particle detector travels along a world line $x^\mu(\tau)$. Interaction between the detector and the quantum field $\hat{\varphi}(x)$ is governed by the Hamiltonian[4]

$$H_{int} = c\chi(\tau)\hat{\mu}(\tau)\hat{\varphi}(x).$$

Interaction is turned on and off via the *switching function* $\chi(\tau)$. The probability that the detector will transition from ground state to excited state is described by

$$P(\omega) = c^2|\langle E|\mu(0)|E_0\rangle|^2\mathcal{F}(\omega),$$

where the *response function* is defined via

$$\mathcal{F}(\omega) = 2\lim_{\epsilon\to 0^+}\Re\int_{-\infty}^{\infty} du\,\chi(u)\int_0^{\infty} ds\,\chi(u-s)e^{-i\,\omega\,s}W_\epsilon(u,u-s).$$

At the sharp-switching limit, the *transition rate* is

$$\dot{\mathcal{F}}_\tau(\omega) = 2\int_0^{\Delta\tau} ds\,\left(\cos\omega s\,W(\tau,\tau-s)+\frac{1}{4\pi^2 s^2}\right)-\frac{\omega}{4\pi}+\frac{1}{2\pi^2\Delta\tau}.$$

[4] c is a coupling constant and $\hat{\mu}(\tau)$ the detector's monopole moment operator.

Particle detector theory

Analytic model

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Particle detector theory

Analytic model

- Recall that in our analytic model we have assumed that the dominant scale factor for each cosmological era is the entire contribution for that era.
- This allows us to have better control over the transition rate integral as it passes through intervals.
- For a comoving ($t = \tau$) detector, the transition rate is given by

$$\dot{\mathcal{F}}(\omega) = \frac{1}{2\pi^2} \int_0^{\Delta\tau} ds \left(\frac{\cos \omega s}{\sigma^2(\tau, s)} + \frac{1}{s^2} \right) + \frac{1}{2\pi^2 \Delta\tau} - \frac{\omega}{4\pi},$$

where

$$\sigma^2(\tau, s) = -a(\tau)a(\tau - s) \left[\eta(\tau) - \eta(\tau - s)\right]^2,$$

encodes the spacetime and trajectory

$$\eta(\tau) = \int \frac{d\tau}{a(\tau)}$$

of the detector.

Particle detector theory

We must carefully separate the integral into intervals so that the correct form of the scale factor (and conformal time trajectory) enters into the integral at the appropriate time.

e.g. contraction phase $\longrightarrow$ radiation-dominated era:

$$\dot{\mathcal{F}}_{cr}(\omega) = \frac{1}{2\pi^2}\left[\int_{\tau_0}^{\tau_r} ds \frac{\cos(\omega\tau - \omega s)}{\sigma_{cr}^2(\tau, \tau - s)} + \int_{\tau_r}^{\tau} ds \left(\frac{\cos(\omega\tau - \omega s)}{\sigma_{rr}^2(\tau, \tau - s)} + \frac{1}{(\tau - s)^2}\right)\right] + \frac{1}{2\pi^2}\left(\frac{1}{\tau - \tau_r}\right) - \frac{\omega}{4\pi},$$

with

$$\sigma_{ij}^2(\tau, s) = -a_j(\tau)a_i(\tau - s)\left(\eta_j(\tau) - \eta_i(\tau - s)\right)^2,$$

Particle detector theory

We must carefully separate the integral into intervals so that the correct form of the scale factor (and conformal time trajectory) enters into the integral at the appropriate time.

e.g. contraction phase $\longrightarrow$ Dark Energy dominated era:

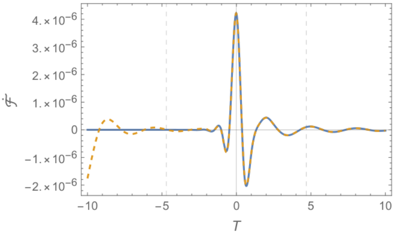
$$\dot{\mathcal{F}}_{c\Lambda}(\omega) = \frac{1}{2\pi^2}\left[\int_{\tau_0}^{\tau_r} ds \frac{\cos(\omega\tau - \omega s)}{\sigma^2_{c\Lambda}(\tau, \tau - s)} + \int_{\tau_r}^{\tau_m} ds \frac{\cos(\omega\tau - \omega s)}{\sigma^2_{r\Lambda}(\tau, \tau - s)} + \int_{\tau_m}^{\tau_\Lambda} ds \frac{\cos(\omega\tau - \omega s)}{\sigma^2_{m\Lambda}(\tau, \tau - s)} + \int_{\tau_\Lambda}^{\tau} ds \left(\frac{\cos(\omega\tau - \omega s)}{\sigma^2_{\Lambda\Lambda}(\tau, \tau - s)} + \frac{1}{(\tau - s)^2}\right) + \frac{1}{\tau - \tau_\Lambda}\right] - \frac{\omega}{4\pi},$$

with

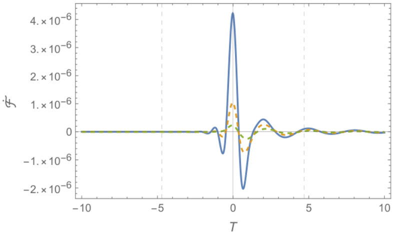
$$\sigma^2_{ij}(\tau, s) = -a_j(\tau)a_i(\tau - s)\left(\eta_j(\tau) - \eta_i(\tau - s)\right)^2,$$

Early results

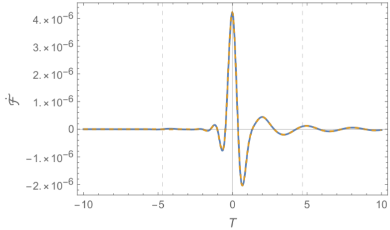
General Features



(a) Sensitivity to T_i

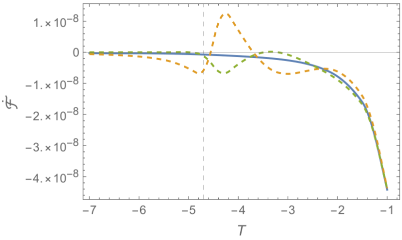


(b) Sensitivity to a_b

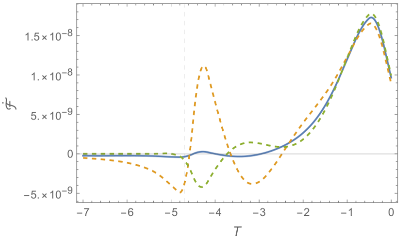


(c) Sensitivity to w_c

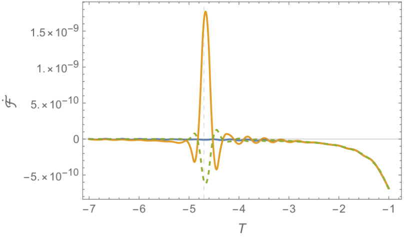
The equation of state in the contraction phase



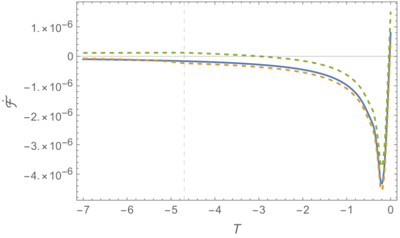
(a) $\dot{\mathcal{F}}(T)$ pre-bounce with $a_b \approx 4.25 \times 10^{-5}$



(b) $\dot{\mathcal{F}}(\tau)$ pre-bounce with $a_b \approx 1.25 \times 10^{-4}$



(a) $\dot{\mathcal{F}}(\tau)$ pre-bounce with $\omega = 20$

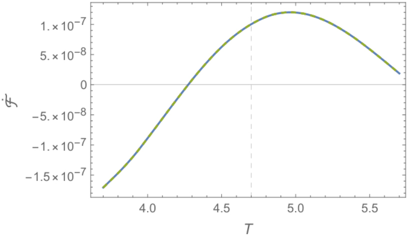


(b) $\dot{\mathcal{F}}(\tau)$ pre-bounce with $\omega = 1/100$

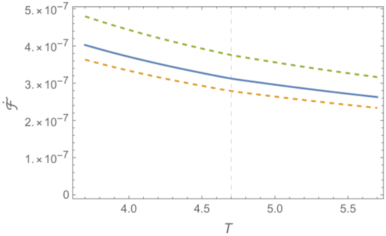
Blue: $w_c = 1/3$, Yellow: $w_c = 4$, Green: $w_c \to -1$

Cai et. al Phys.Rev.D 87 (2013) 8, 083511; Steinhardt and Ijjas Class.Quant.Grav. 35 (2018) 13, 135004

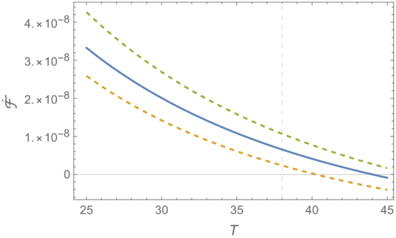
The equation of state in the contraction phase



(a) Near T_m with $\tilde{\omega} = 2$ and $a_b \approx 4 \times 10^{-5}$



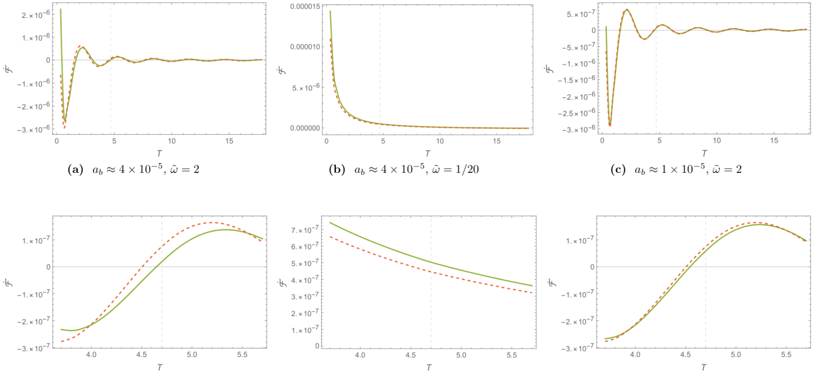
(b) Near T_m with $\omega = \frac{1}{100}$ and $a_b \approx 4 \times 10^{-5}$



(c) Near T_{CMB} with $\omega = \frac{1}{100}$ and $a_b \approx 4 \times 10^{-5}$

Blue: $w_c = 1/3$, Yellow: $w_c = 4$, Green: $w_c \to -1$

Observable signals of non-singular theories?



(a) $a_b \approx 4 \times 10^{-5}$, $\tilde{\omega} = 2$ **(b)** $a_b \approx 4 \times 10^{-5}$, $\tilde{\omega} = 1/20$ **(c)** $a_b \approx 1 \times 10^{-5}$, $\tilde{\omega} = 2$

(d) $a_b \approx 4 \times 10^{-5}$, $\tilde{\omega} = 2$ **(e)** $a_b \approx 4 \times 10^{-5}$, $\tilde{\omega} = 1/20$ **(f)** $a_b \approx 1 \times 10^{-5}$, $\tilde{\omega} = 2$

- Both detectors are released shortly after $t = 0$
- Disparities can be observed so long as the bounce size is sufficiently small

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  (i) highlight disparities between theories with different pre-bounce physics
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  within an analytic 'toy model'.
- In this model we assumed that a detector was released and began detecting pre-bounce.

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Summary and outlook

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Summary and outlook

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  - This is because the analytic model assumes (rather crudely) that only the dominant form of the scale factor describes the spacetime in each era whereas a numerical model can allow subdominant scale factors to contribute.
  - In the numerical model, the Wightman two-point function will 'see' the history of the spacetime even for a detector which begins measuring today.
  - Early signs are good in that we can see disparities in particle rate between singular and non-singular theories but it remains to be seen whether such disparities could truly be observed!

Thank you for listening

Additional slides

Cosmological Model

Global description of the universe

Our model has the modified density parameter equation

$$1 = \Omega_0^{(c)} + \Omega_0^{(r)} \left(1 - \Omega_{crit}\right) + \Omega_0^{(m)} + \Omega_0^{(\Lambda)},$$

where all parameters are evaluated today.

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- We can view this equation as a *cosmological balancing equation* which balances the makeup of the universe in terms of radiation, matter, and dark energy.
- In our quantum-corrected model we have both a correction to the radiation density via $\Omega_{crit} = a_b^4$ and some additional energy or matter which enters through the contraction phase density $\Omega_0^{(c)}$, the precise nature of which depends on the choice of equation of state parameter in the contraction phase w_c.