

Does relativistic cosmology software handle emergent volume evolution?

Boud Roukema + Justyna Borkowska
Institute of Astronomy NCU

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Overview

1. physics question: Λ CDM vs GR
 - Rubin–LSST: need GR cosmo simulations to extract physics
 - Are the GR cosmo simulations accurate?
2. method
3. results
 - Borkowska & Roukema 2021 (CQG, [ArXiv:2112.14174](https://arxiv.org/abs/2112.14174))

1.1 Λ CDM vs GR

- ▶ cosmic expansion and structure formation are governed by $\mathbf{G} = 8\pi\mathbf{T} \dots$
 - ▶ ... together — GR
 - ▶ ... semi-decoupled — Λ CDM:
 - ▶ expansion affects structure formation
 - ▶ expansion is **rigid** — unaffected by structure formation
- ▶ dark energy is a phenomenological, probably not fundamental, effect

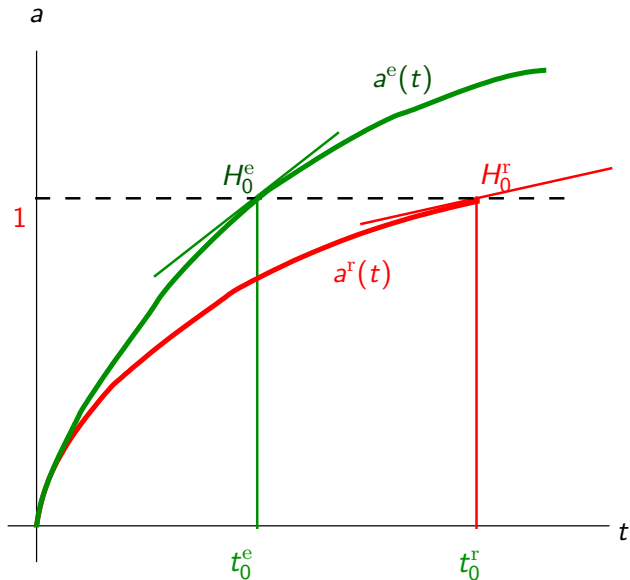
1.2 GR simulations

- ▶ GR cosmology simulations – recently developed
- ▶ fast and/or with shortcuts
 - ▶ INHOMOGENEOUS – relativistic Zel'dovich approximation
 - ▶ GEVOLUTION – Poisson gauge 2nd order expansions
 - ▶ GRAMSES
- ▶ full (in principle)
 - ▶ EINSTEIN TOOLKIT/FLRWSOLVER – BSSN formalism
 - ▶ COSMOGRAPH – BSSN

2.1 Hubble constants

- ▶ Λ CDM = EdS + structure formation?
- ▶ EdS = reference model
- ▶ result = effective model ($\approx \Lambda$ CDM?)
- ▶ redefine H_0 's
- ▶ EdS H_0^r must be about 37.7 km/s/Mpc
- Rácz+2017 (MNRAS, [ArXiv:1607.08797](#)) + Roukema+2017 (A&A, [ArXiv:1608.06004](#))

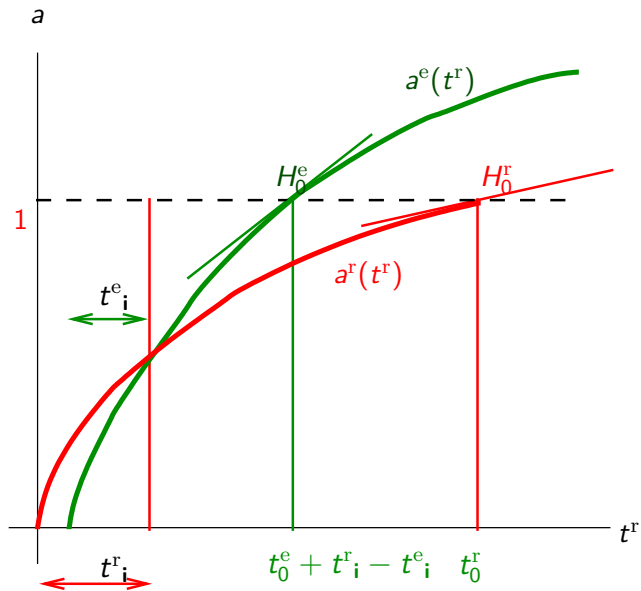
2.2 schematic



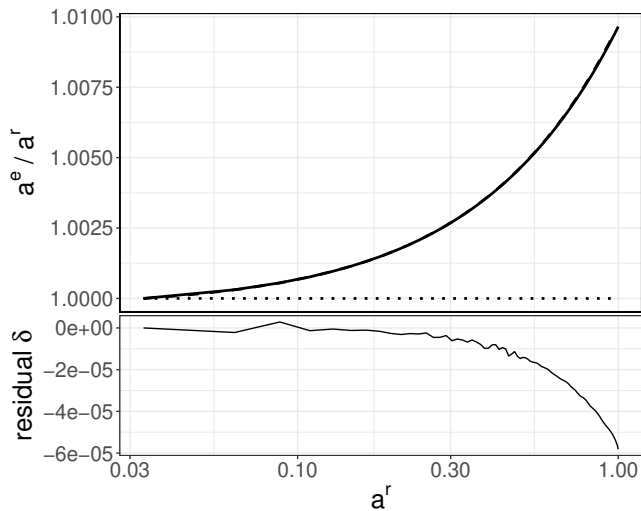
2.3 calibrate GR sim?

- ▶ need exact analytical inhomogeneous cosmological solution
- ▶ spherically symmetric (LTB) don't match T^3 simulations
- ▶ instead:
 - flat FLRW + flat perturb \rightarrow new flat FLRW

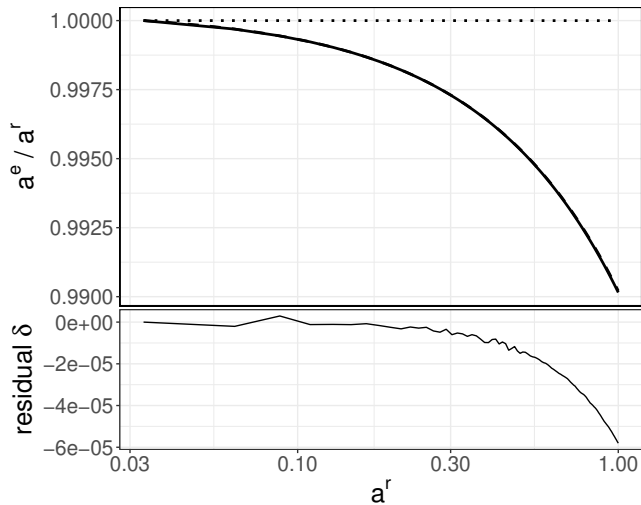
2.4 expansion: rigid + extra



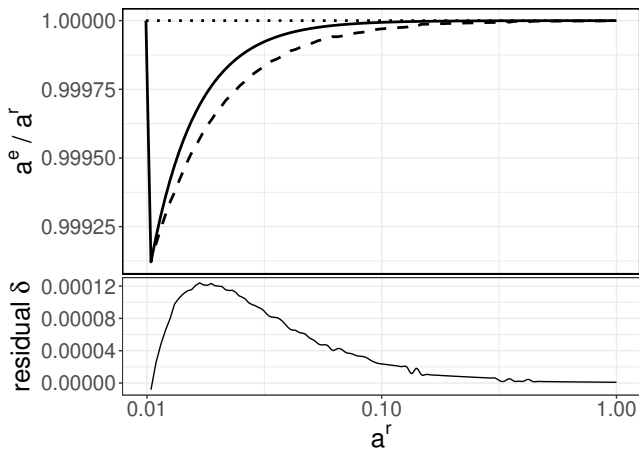
3.1 results: INHOMOGENEOUS $I_i > 0$



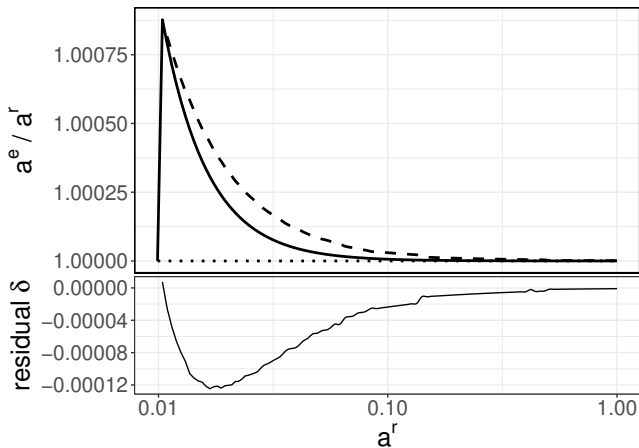
3.2 results: INHOMOGENEOUS $I_i < 0$



3.3 results: GEVOLUTION $\Phi_i > 0$



3.4 results: GEVOLUTION $\Phi_i < 0$



Conclusion

- ▶ GR cosmo simulations *can* be calibrated
- ▶ with 10^{-3} perturbation, INHOMOG, GEVOLUTION $\sim 0.01\%$ accuracy
- ▶ GEVOLUTION: handling of growing mode may be too restrictive
 - Borkowska & Roukema 2021 (CQG, [ArXiv:2112.14174](https://arxiv.org/abs/2112.14174))
- ▶ Rubin–LSST DESC: need modular pipeline
 - Peper, Roukema & Bolejko 2023 (MNRAS, [ArXiv:2304.00591](https://arxiv.org/abs/2304.00591))