Progress in backreaction
a personal overview

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Looking for a factor of 2

- Homogeneous and isotropic models which have ordinary matter and gravity disagree with cosmological observations by a factor of 2.
- This could be due to the known breakdown of homogeneity and isotropy related to structure formation.
- There have been many studies of the effects of inhomogeneities over the years, and several things are now understood better.
- This brief review outlines my bias about the field.

First light

- 1962: The effect of inhomogeneities on averages is first analysed. (Shirokov and Fisher)
- 1983: The issue is discussed in detail under the name **fitting problem**. (Ellis)
- Studies in the **observational cosmology** program and questions about the foundations of the FRW model follow.
- Point of view: *how can we do cosmology with as few model assumptions as possible?*

- The justification of the FRW model did not become a mainstream issue, likely because until the 90s the observations were not very precise.
- There were various (often flawed) calculations of the effect of fluctuations on the average expansion rate, called **backreaction**.
- 1995: Backreaction is rigorously shown to reduce to a boundary term in Newtonian gravity. (Buchert and Ehlers)
- 1999: Backreaction is shown **not** to reduce to a boundary term in GR. (Buchert)
- Realisation: *a universe which contains structures is not necessarily described by a FRW model on average.*

The backreaction conjecture

- With the advent of better SN and CMB observations in 1998+, the limit of validity of the Standard CDM model was reached: the predicted distance and expansion rate are too small by a factor of 2.
- It was suggested that inhomogeneities could be the reason. (Buchert, Wetterich, Schwarz, SR)
- A new period, with a more narrow focus: *Assuming that the early universe is nearly-FRW in the manner motivated by inflation, what happens as the local symmetry breaks due to structure formation?*

Devil in the details

- 2003: The expansion rate is calculated using proper variables at (first order)^2, getting a 10^{-5} effect. (SR)
- 2004: The calculation is done correctly (i.e. at second order), confirming the magnitude. (Kolb et al)
- 2005: It is claimed that superhorizon perturbations lead to acceleration. (Kolb et al)
- 2005: It is shown that superhorizon perturbations cannot lead to acceleration. (Geshnizjani et al, Flanagan et al, Hirata and Seljak, SR)
- 2006: It is understood and shown how subhorizon fluctuations **can** lead to acceleration. (Kai et al, SR, Chuang et al, Paranjape and Singh)

- 2008: It is understood and shown how the magnitude of the change in the expansion rate and the10 billion year timing emerge from the physics of structure formation. (SR)

Light in the middle

- Light propagation studies have evolved mostly separately from backreaction questions. This has changed only recently.
- 2007: It is pointed out that the FRW metric can be tested by comparing distance and expansion rate. (Clarkson et al)
- 2008-2009: Relation between distance and average expansion rate is derived in the non-FRW case with statistical homogeneity and isotropy. (SR)
- It seems that if the average expansion rate is close to FRW, the light observables are close to FRW. (Although the matter is not entirely clear.)

Slightly perturbed

- Inhomogeneities can lead to acceleration, and fluctuations are of the order of the observed signal.
- But do the fluctuations cancel in the average?
- This is a question of the large-scale balance between fast and slow regions.
- In Newtonian gravity, but not in GR, there is a cancellation due to conservation of energy.
- 2010: A new perturbation formalism adapted to cosmology is presented, in which backreaction is small if the metric is close to FRW. (Green and Wald)
- 2011: It is shown that backreaction is is small in ordinary perturbation theory to all orders. (SR)

Status report

- If backreaction is significant, then:
  1. The universe cannot be described in terms of a linearly perturbed FRW metric: understanding the breakdown.
  2. Non-Newtonian aspects of gravity are important at the homogeneity scale: understanding the Newtonian limit.
- It seems that light propagation can to first order be treated in terms of the average expansion rate, but:
  1. This should be established rigorously.
  2. Corrections should be calculated (CMB, weak lensing).

- Whether backreaction is important remains an unresolved issue, with several open lines of inquiry.