Conservative cosmologist's cry for help: inhomogeneities as an alternative to dark energy

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Outline

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Accelerating expansion?

- The usual conception: acceleration of the expansion has been detected by $N\sigma$

- We only observe light, not the expansion of the universe nor its acceleration

- Observations + Assumptions $\longrightarrow$ Conclusions

  Examples:

  Supernovae light + Homogeneous universe $\longrightarrow$ Accelerated expansion

  Sunlight + Geocentric universe $\longrightarrow$ Sun revolves around the Earth

Dark energy?

- To make a FRW universe accelerate, negative pressure $p < -\rho/3$ is needed:

$$3\frac{\ddot{a}}{a} = -4\pi G(\rho - 3p)$$

$\Longrightarrow$ observations usually taken as an evidence for dark energy

- The main reasons to seek alternatives to dark energy

1. Fine-tuning $-$ $\Lambda \sim 10^{-120}\ G^{-1}$
2. Violates the cosmological principle $-$ $\Omega_\Lambda(\mathrm{now}) \sim \Omega_M(\mathrm{now})$
3. No detections in the lab $-$ no connection to the established field theories

Basics of cosmological inhomogeneities

- A dust universe cannot accelerate locally, no matter what kind of inhomogeneities
- The basic idea: inhomogeneities can have the same effect on the *observable* light as accelerating expansion in the homogeneous models (Célérier)
- We see a lumpy universe, so inhomogeneities certainly exist!
- The main question: do the *existing* inhomogeneities have observational significance not taken into account by FRW + linear perturbations?
- At least three mechanisms could potentially mimic dark energy:
  1. Average acceleration via backreaction of gravitational collapse
  2. Selection effects in the light propagation
  3. The observed large voids

1. Small scale lumpiness – backreaction driven acceleration

- The number of degrees of freedom in the universe $> 10^{80}$
  $\Longrightarrow$ exact treatment beyond computation
- Question: how to encapsulate relevant physics of the 10^{80} d.o.f. in ~ 10 parameters?
- An answer: $\langle\ \ldots\ \rangle$
- The conventional approach: $\langle \mathbf{g} \rangle \Longrightarrow$ FRW models
- $\mathbf{g} \hat{=}$ gravitational potentials, so $\mathbf{G}(\mathbf{g}, \partial_\mu \mathbf{g}, \partial_\mu \partial_\nu \mathbf{g})$ more directly related to physics
  $\Longrightarrow$ Use $\langle \mathbf{G}(\mathbf{g}) \rangle$ instead of $\mathbf{G}(\langle \mathbf{g} \rangle)$ (G.F.R. Ellis)
- $\langle \mathbf{G}(\mathbf{g}) \rangle - \mathbf{G}(\langle \mathbf{g} \rangle) =$ backreaction $\neq 0$ due to nonlinearity of GR
- Averaged acceleration equation gets modified by the backreaction (Buchert)

$$3\frac{\ddot{a}}{a} = -4\pi G \langle \rho \rangle + \mathcal{Q} \qquad , \qquad \mathcal{Q} \equiv \frac{2}{3}(\langle \theta^2 \rangle - \langle \theta \rangle^2) - \langle\, \sigma^{\mu\nu} \sigma_{\mu\nu} \rangle$$

- $\mathcal{Q}$ large when collapsing ($\theta < 0$) and expanding ($\theta > 0$) regions coexist
- A problem: the connection of averaged quantities to observations?

$$3\frac{\dot{a}^2(t)}{a^2(t)} = 8\pi G \langle \rho_M \rangle - \frac{1}{2}\langle R^{(3)} \rangle - \frac{1}{2} Q$$

2. Selection effects in the light propagation

- You cannot see a galaxy, if there is another one in the foreground (Dyer & Roeder)
  $\Longrightarrow$ The light we see is special

- A reminder: the gravitational field can be decomposed into local and nonlocal parts:
  - the Einstein field $\mathbf{G}$
  - the Weyl field $\mathbf{C}$

- We only observe light that has mostly traveled in vacuum where $\mathbf{G} = 0$, but $\mathbf{C} \neq 0$

- In e.g. FRW models, the situation is just the opposite: $\mathbf{G} \neq 0$, but $\mathbf{C} = 0$
  $\Longrightarrow$ An averaged metric cannot capture this effect!

- The more structure has formed, the emptier regions light travels through

- Empty regions expand faster, so the expansion "accelerates" along the path of light

- A problem: the effect difficult to quantify

3. Large voids – inhomogeneities at intermediate scales

- The universe has large voids, such as the recently observed one of size 300 Mpc, also seen as a cold spot in the CMB (Rudnick et. al.)
- We could live inside a void expanding faster than the global average (Tomita)
- Observations are made along our past light cone, so the variation of the expansion rate along the light cone is what matters, not just the time variation
- Along the past light cone: $\dfrac{d}{dz} = \dfrac{dr}{dz}\dfrac{\partial}{\partial r} + \dfrac{dt}{dz}\dfrac{\partial}{\partial t} \approx \dfrac{\partial}{\partial r} - \dfrac{\partial}{\partial t}$

  $\Longrightarrow$ negative $\partial/\partial r$ mimics positive $\partial/\partial t$

  Standard ΛCDM: $d_L(z) = H_0^{-1}(0)\left[z + \left(\frac{1}{4} + \frac{3}{4}\Omega_\Lambda\right) z^2 + \mathcal{O}(z^3)\right]$

  Local void model: $d_L(z) = H_0^{-1}(0)\left[z + \left(\frac{1}{4} - \frac{H_0'(0)}{H_0^2(0)}\right) z^2 + \mathcal{O}(z^3)\right]$

- To mimic acceleration, the expansion must *decrease* as distance grows: $H_0'(r) < 0$
- This is exactly what an observer inside a void would see!
- A problem: living inside a void violates the cosmological principle?

Conclusions

- Inhomogeneities can have the same effect on the *observable* light as dark energy
- Inhomogeneities offer a natural alternative to dark energy:
  - Inhomogeneities certainly exist!
  - No factors of 10^{-120}
  - Connects the start of the acceleration era with the growth of structure
- Three candidates to explain dark energy as an inhomogeneity induced illusion:
  - Backreaction of collapsing structures at small scales
  - Selection effects in the light propagation
  - The observed voids at intermediate scales
- Inhomogeneities have all the qualitative ingredients to mimic dark energy
- No quantitative model *yet* exists that would account for all the observations
  $\Longrightarrow$ Lots of rewarding research to be done in this subject!