Vaishnav Rao

Cosmology

Pre-class reading 1

1. **About me**:

I am currently studying the stellar populations formed within the starburst outflow of M82 using HST. By deriving detailed star formation histories of these populations, I’m working on constraining the cadence of the starburst outflow. I have, in the past, also tried finding ultra-faint dwarf satellites in the halo of the of the M81 group of galaxies using deep ground based data from Subaru.

The result that I am really proud of is that I found that starburst outflow in M82 is episodic in nature. In the last ~500 Myr, it induced star formation in the CGM of M82 due to interactions with tidal streamers ~150 Myr ago and ~30 Myr ago.

I have taken a 500 level general relativity course in my undergraduate that only briefly covered cosmology. I have also taken a 500 level gravitational wave astronomy that used GR concepts. Though I do not remember a lot of the details, I should be able to refresh my knowledge by looking at my notes or re-reading Weinberg’s book, which was used as the basis for the GR course.

2.

Cosmological initial conditions:
Cosmological initial conditions, set by quantum fluctuations during the inflationary epoch, provide the foundation for the large-scale structure of the universe. These fluctuations seeded density perturbations in the dark matter distribution, which grew under gravity to form the "cosmic web" of filaments, voids, and halos where galaxies and stars later formed. However, these initial conditions do not entirely pre-determine the formation of every galaxy, star, or planet. While they define the large-scale framework and gravitational potential wells where structures can develop, baryonic physics introduces significant complexity and randomness.

Processes such as gas cooling, star formation, feedback from supernovae and AGN, and galaxy mergers play critical roles in shaping individual galaxies. These processes are very nonlinear and sensitive to local conditions such as gas density, metallicity, and angular momentum. For instance, two dark matter halos of similar mass can host galaxies with vastly different properties depending on their merger histories or feedback efficiency. On smaller scales, the formation of individual stars and planets depends on local dynamics within molecular clouds, which are influenced by turbulence, magnetic fields, and radiation pressure. Thus, while initial conditions set the stage for structure formation, the detailed outcomes are determined by a combination of deterministic physics and chaotic processes.

Diversity in galaxy properties:
The wide variety of galaxy properties for a given halo mass arises from differences in baryonic processes and environmental factors. For example:

- Feedback Effects: Processes like supernova explosions and AGN activity regulate star formation by heating or expelling gas from galaxies. The efficiency of these feedback mechanisms can vary significantly between galaxies
- Gas Cooling Rates: The ability of gas to cool and condense into stars depends on factors like metallicity and density. Halos with similar masses may host galaxies with different star formation rates due to variations in cooling efficiency
- Mergers and Interactions: Galaxy mergers (major or minor) can trigger bursts of star formation or cause tidal stripping

- Environment: Galaxies in dense environments like clusters experience processes such as ram-pressure stripping or AGN feedback from other galaxies.

LCDM model:
The Cold Dark Matter (CDM) model has become the standard framework for understanding galaxy formation because it successfully explains CMB anisotropies, hierarchical clustering of galaxies into filaments, walls, and voids, flat rotation curves in spiral galaxies, and the abundances of light elements formed during Big Bang nucleosynthesis.

However, on small scales, there are problems like the core-cusp problem of DM halos, missing satellites problem, or the plane of satellites problem, where LCDM apparently falls short. Though I do not understand it fully, I attended a conference in Durham where Carlos Frenk commented on all of this and tried to explain why they aren't necessarily problems for cosmology.

Though there are other models of cosmology out there, they aren't without their own problems. It seems LCDM has the fewest of these problems, which is why I conclude that, for now, there doesn't seem to be any viable alternative to LCDM.

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Friedmann equation:

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right) + \frac{\Lambda c^2}{3}$$ time component

Substitute & eliminate

$$\frac{\ddot{a}}{a} + \frac{2\dot{a}^2}{a^2} + \frac{2Kc^2}{a^2} = 4\pi G\left(\rho - \frac{P}{c^2}\right) + \Lambda c^2$$ space-component

This is obtained by solving Einstein's equation:

$$R_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

for a uniform fluid, in a homogeneous isotropic Universe: $g_{\mu\nu}$: Robertson-Walker metric

Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

EOS:

$$\frac{d\rho}{da} + 3\left(\frac{\rho + P/c^2}{a}\right) = 0$$

$\rho_{m,0}$, $\rho_{r,0}$, $\rho_{\Lambda,0}$ at time t_0

energy densities: matter, radiation, vacuum/Dark energy

$\rho = \rho_m + \rho_{rad} + \rho_{vac}$ at any time

Redshift dependences of energy density:

Substitute into Friedmann equation

$$\rho_m \propto a^{-3} \rightarrow \rho_m = \rho_{m,0}\left(\frac{a_0}{a}\right)^3$$

$$\rho_{rad} \propto a^{-4} \rightarrow \rho_{rad} = \rho_{rad,0}\left(\frac{a_0}{a}\right)^4$$

$$\rho_{vac} \propto a^{0} \rightarrow \rho_{vac} = \rho_{\Lambda,0}$$

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi G}{3}\left[\rho_{m,0}\left(\frac{a_0}{a}\right)^3 + \rho_{r,0}\left(\frac{a_0}{a}\right)^4 + \rho_{\Lambda,0}\right] - \frac{Kc^2}{a^2}}$$

Newtonian derivation:

$$\ddot{R} = -GM/R^2 \xrightarrow{\text{integrate}} \frac{1}{2}\dot{R}^2 - \frac{GM}{R} = E$$

$$R = a(t)R_0$$

↳ scale factor

$$\frac{\dot{a}^2}{a^2} - \frac{8\pi G\bar{\rho}}{3} = \frac{-Kc^2}{a^2}$$, where $K = -2E/(cR_0)^2$

Similar to Friedmann equation

However, $\ddot{a}$ acceleration term does not contain $3P/c^2$ factor → relativistic correction as pressure/energy acts as a source of gravity.

Λ term can be added in by hand as it was also added in by hand by Einstein.