Dark Energy in Cosmology

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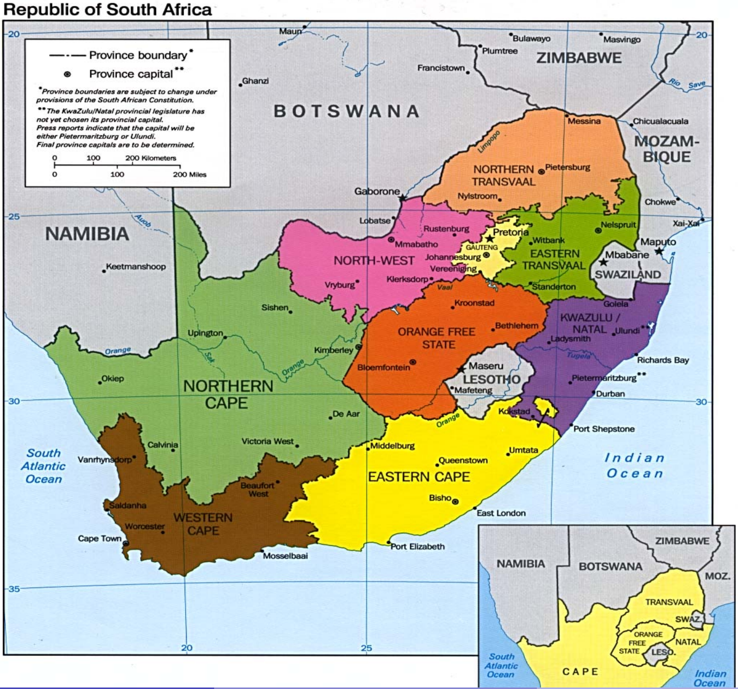
Figure: University of Zululand

Figure: Mangosuthu University of Technology


Republic of South Africa
Province boundary*
Province capital**
*Province boundaries are subject to change under provisions of the South African Constitution.
**The KwaZulu/Natal provincial legislature has not yet chosen its provincial capital. Press reports indicate that the capital will be either Pietermaritzburg or Ulundi. Final province capitals are to be determined.
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EASTERN TRANSVAAL
KWAZULU / NATAL
ORANGE FREE STATE
NORTHERN CAPE
EASTERN CAPE
WESTERN CAPE
South Atlantic Ocean
Indian Ocean
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Bulawayo
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Plumtree
Francistown
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Gaborone
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Lobatse
Rustenburg
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Nelspruit
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Vereeniging
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Ladysmith
Kimberley
Richards Bay
Bloemfontein
Maseru
Pietermaritzburg
Okiep
Mafeteng
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De Aar
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Outline

Introduction

- 1998 - 2 independent teams were observing distant supernovae
- Found that their brightness decreased faster than predicted by big bang model [Reiss et al, Astronomical J. 116, 1009 (1998), Perlmutter et al, Astrophys. J. 517, 565 (1999)]
- This additional dimming corresponds to additional distance
- $\implies$ accelerated expansion [note: alternative explanations such as inhomogeneous cosmological models - can also explain the accelerated expansion without requiring DE: Bolekjo & Korzynski IJMPD 26, 1730011 (2017)]
- Began around 6 billion yrs ago
- Supported by cosmic microwave background radiation, large scale structure, baryon acoustic oscillations & weak lensing
- Both groups awarded Nobel prize
- Accelerating universe $\implies$ existing theories incomplete
- To explain the accelerating universe, usual explanation is the existence of dark energy (DE), matter with negative pressure

ΛCDM model

- Einstein's FE's with cosmological constant Λ are

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = T_{ab} \tag{1}$$

- For the Robertson-Walker metric

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{(1-kr^2)} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right], \tag{2}$$

- Friedmann-Lemaitre-Robertson-Walker (FLRW) models:

$$3\frac{\dot{a}^2}{a^2} + \frac{3k}{a^2} - \Lambda = \rho \tag{3}$$

Friedmann eq

$$2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} - \Lambda = -p \tag{4}$$

Raychaudhuri eq

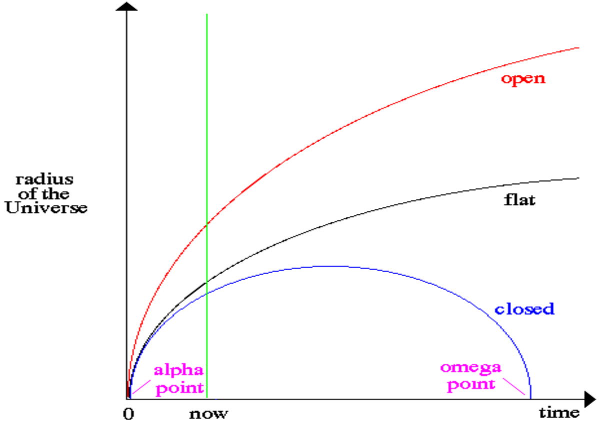
- Hubble parameter H determines expansion rate of universe:

$$H = \frac{\dot{a}}{a} \tag{5}$$

- Deceleration parameter q implies a small correction as matter slows down expansion

$$q = -\frac{\ddot{a}a}{\dot{a}^2} \tag{6}$$

- There was such confidence in the universe's expansion slowing down that a negative sign was assigned to q to make its value positive
- $q > 0 \iff \textit{deceleration}, \quad q < 0 \iff \textit{acceleration}$


radius of the Universe
open
flat
closed
alpha point
omega point
0
now
time

- From the equations (3), (4) & (5), we get

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{7}$$

- Critical density ρ_{crit} defined as present density for $k = 0, \Lambda = 0$:

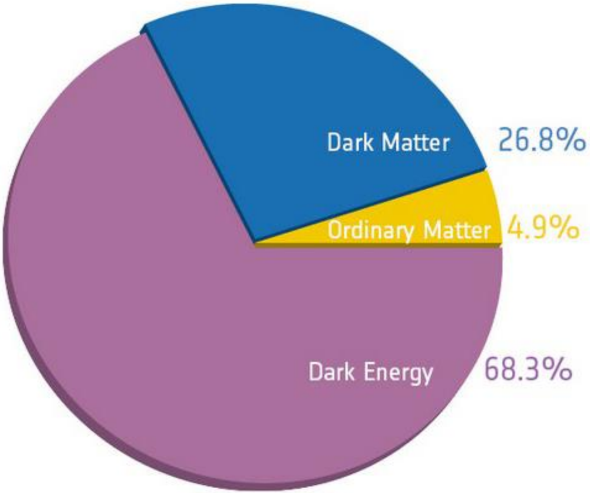
$$\rho_{crit} = 3H_o^2 \tag{8}$$

- Similarly, one can define other density parameters as

$$\Omega_x \equiv \frac{\rho_x}{\rho_{crit}} = \frac{\rho_x}{3H_o^2} \tag{9}$$

where $x = b$ (baryons), c (CDM), m (baryons+CDM), r (radiation), k (curvature) or Λ (DE)

- What is the proportion of each of these components? See figure below:


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

- We may write the Friedmann eq (7) as:

$$H^2 = H_o^2 \left[\frac{\Omega_c + \Omega_b}{a^3} + \frac{\Omega_r}{a^4} - \frac{\Omega_k}{a^2} + \frac{\Omega_\Lambda}{a^{3(1+\omega)}} \right] \tag{10}$$

where the equation of state (EOS) ω for DE is

$$\omega = p_\Lambda / \rho_\Lambda \tag{11}$$

- For the usual ΛCDM model, $\Omega_k = 0$, $\omega = -1$ (so $p_\Lambda = -\rho_\Lambda$), and Ω_r is negligible, so we get

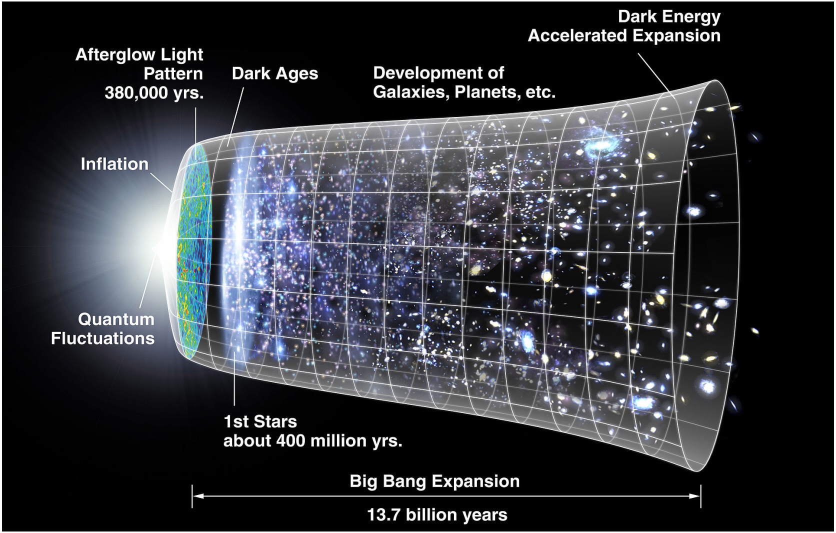
$$H^2 = H_o^2 \left[\frac{\Omega_m}{a^3} + \Omega_\Lambda \right] \tag{12}$$

- This has the soln

$$a(t) = \left(\frac{\Omega_m}{\Omega_\Lambda} \right)^{1/3} sinh^{2/3} \left(\frac{t}{t_\Lambda} \right) \tag{13}$$

where $t_\Lambda \equiv 2/(3H_0\sqrt{\Omega_\Lambda})$

- Transition redshift ($\ddot{a} = 0$) occurs at redshift $z \approx 0.66$


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Current picture of universe

- 4 phases: Initial inflation, radiation era, matter era, current accelerated expansion
- We only interested in matter & DE eras, and transition from deceleration to acceleration
- Note - so far - perfect fluid
- Negligible heat conduction & viscosity
- ΛCDM model above "simplest", fits observations well.
- The density is const, and the model will continue to have accelerated expansion forever into the future - see later
- DE problem - most important problem in theoretical cosmology today
- No of papers with DE in title - 52005 (WoS)

Despite the fact that the Lambda CDM model fits current astronomical observations well, there are outstanding problems:

- The fine tuning problem - Λ is 120 orders of magnitude different from vacuum energy
- The coincidence problem - why is dark energy and dark matter of the same order today
- Some "tensions" in cosmology today, e.g., H_0
- The initial big-bang singularity
- Does Einstein's GR need to be modified on large scales?
- Predictability and testability of the inflationary paradigm
- Existence of anomalies in the CMB and on small scales
- Particle nature of dark matter
- Hence look at other models or modified gravity

- There are 2 broad ways to solve DE problem
- One way is exotic fluid with large (-)ve pres (DE):
- ΛCDM model (most popular, $p/\rho = \omega = -1$)
- Study of alternative cosmologies (& theories) has led to much progress
- quintessence ($\omega > -1$)
- phantom DE ($\omega < -1$)
- anthropic principle
- tuning mechanisms (field which cancels Λ)
- holographic principle (choose ρ from a principle)
- quintom DE (time varying ω which crosses -1)
- Alternative/modified theories of gravity - no shortage of these

Bulk Viscosity

When can bulk viscosity arise?

- Decoupling of photons during radiation era
- Decoupling of radiation and matter during the recombination era
- During entropy production via string creation
- Diring GUT phase transitions

Why consider bulk viscosity?

- Explain photon to baryon ratio
- Generate inflation without additional scalar field
- Models without initial singularity due to a violation of the strong energy condition
- Description of particle creation in strong gravitational field
- Can mimic variable cosmological parameter - cosmological constant problem
- Equations equivalent to those of Chaplygin gas
- Candidate for dark energy

- Friedmann eq (7) with $k = \Lambda = 0$ is

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{\rho}{3} \tag{14}$$

- For a perfect fluid, normally assumed that the EOS is:

$$p = \omega\rho, \ \omega = const \tag{15}$$

- To incorporate bulk viscosity, take p to be:

$$p' = \omega\rho - 3\eta H \tag{16}$$

where η is the coefficient of bulk viscosity.

- From the Friedmann (3) & Raychaudhuri (4) eqns, we can alse derive a conservation eq:

$$\dot{\rho} + 3H(\rho + p') = 0 \tag{17}$$

- From the previous eqns, we get a single eq to be solved:

$$2\dot{H} + 3(\omega + 1)H^2 = 3\eta H \tag{18}$$

Coeff of viscosity usually, but not always, taken to have the form of a power law of the energy density

$$\eta = \alpha\rho^m, \quad \alpha \geq 1, const \tag{19}$$

Eq (19) then becomes:

$$2\dot{H} + 3(\omega + 1)H^2 = 3\alpha\rho^m H \tag{20}$$

- Eqns (17) & (20) then have the soln for all $m \neq 1/2$ [Barrow, Nucl Phys B310(88)743]

$$a = e^{ct}, \quad \rho = \rho_0 = [\sqrt{3}\alpha/(\omega + 1)]^{2/(1-m)} = 3H_0^2 \tag{21}$$

- Soln also called de Sitter soln
- $m < 1/2 \implies$ expansion from initial singularity towards de Sitter state as $t \to \infty$
- Agrees with 'cosmic no-hair conjecture' - the proposition that all expanding universes with a positive cosmological constant asymptotically approach de Sitter space-time
- Here no positive Λ needed
- Although initial singularity in this case, can get solns with no singularity as strong energy condition violated can occur ($m > 1/2$)
- For $m = 1/2$, power law soln obtained - acceleration possible

Some remarks

- Above treatment of viscosity based on Eckart theory of first order dynamics
- Problems - causality, equilibrium states unstable (except for the exp soln)
- Soln - use Isreal-Stewart theory of nonlinear second order causal thermodynamics
- Can get desired solns with earlier radiation & matter-dominated eras [Acquaviva & Beesham PRD 90(14)023503, CQG 32(15)215026] - see below:

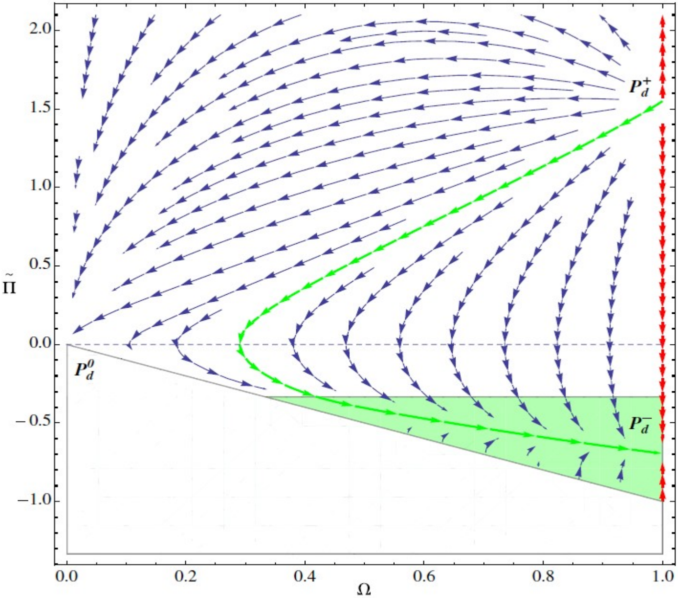


Figure: Nonlinear viscosity [Acquaviva, Beesham PRD 90(14)023503]

This model has some very desirable features. There exist a set (of measure nonzero) of trajectories which:

- Start off at a source P_d^+ , which represents the radiation dominated era
- Pass through a transient saddle point P_d^0, the matter dominated era, when structure formation can take place, and
- Finally end up at a possible sink P_d^-, which represents the currently observed expanding stage (either polynomial or exponential)
- Primordial inflation not included - this has been done by some other authors
- very nice model

Cosmography

- Cosmography - kinematics of cosmology, relations independent of theory
- Expand scale factor $a(t)$ (or some other parameter) in Taylor series about present time t_o:

$$a(t) = a(t_o) + \dot{a}(t_o)(t - t_o) + \frac{1}{2}\ddot{a}(t_o)(t - t_o)^2 + \cdots \tag{22}$$

  which can also be written as:

$$\frac{a(t)}{a(t_o)} = 1 + H_o(t - t_o) + \frac{q_o}{2}{H_o}^2(t - t_o)^2 + \cdots \tag{23}$$

  where it can be seen that H & q arise naturally in the expansion
- H & q simplest cosmograhic parameters

- Assume cosmological principle - homogeneity & isotropy
- Expand some measurable quantity in Taylor series around present time
- Improvement - Padé approximations:
- For a function $f(x)$, the Padé approximate of order (m, n) is given by a ratio between two polynomials, i.e.

$$f(x) = \frac{a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n}{1 + b_1 x + b_2 x^2 + \cdots + b_m x^m}, \tag{24}$$

  where the a_i's and b_i's are constants.
- Convergence radii are greater than Taylor ones
- Let q be expanded about present time (redshift, scale factor, etc)
- Simplest - $q = const$, but cannot yield a transition from deceleration to acceleration (no "signature" flip)

Linearly varying q

- Hence, variable q was considered which yields the transition
- After const q, next simplest is linearly varying q:

$$q(x) = q_o + q_1 x \tag{25}$$

- Some parametrisations considered:

$$q(z) = q_o + q_1 z \tag{26}$$

$$q(a) = q_o + q_1 a \tag{27}$$

$$q(t) = q_o + q_1 t \tag{28}$$

- Akarsu & Dereli IJTP 51(12)612 & Akarsu et al EPJP 129(14)22
- Linearity in one parameter $\not\Rightarrow$ linearity in another

Nonlinear q

- 2 interesting parametrisations
- $f(R, T)$ theory: Start off with [Nagpal et al EPJC 78(2018)946]

$$H(a) = \alpha(1 + a^{-n}) \tag{29}$$

  where $\alpha > 0$ and $n > 1$
- For q, this yields

$$q(z) = \frac{(n-1)(1+z)^n - 1}{1 + (1+z)^n}. \tag{30}$$

- see fig
- Can get model which fits in with observations

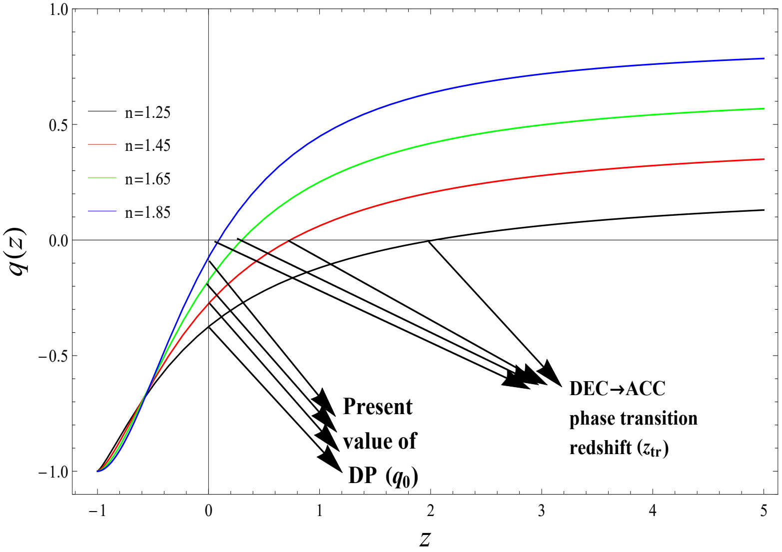


Figure: Plot of deceleration parameter q vs redshift z for different n

q with double flip

- Singh & Beesham IJGMMP 15(2018)1850145. Choose

$$q = \frac{1 + \alpha t^n + \beta t^{2n}}{1 + t^{2n}} \tag{31}$$

- matter source: self interacting scalar field
- allows for a double signature flip - from early inflation to deceleration, and then from deceleration to late-time acceleration
- Some problems with amount of inflation
- Variable EOS
- See fig below:

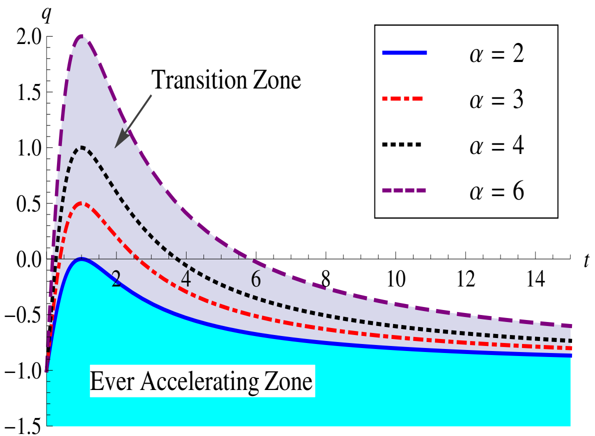


Figure: Plot of q against t

ANOTHER PARAMETRISATION

- Let $b = b(a)$. Then consider:

$$\frac{\ddot{a}}{a} + b\frac{\dot{a}^2}{a} = 0 \tag{32}$$

- Then soln of (32) is

$$\int e^{\int (b/a)da} da = t + k \tag{33}$$

where k is a const

- Choose

$$\int (b/a)da = ln\ L(a), \quad L(a) = \frac{1}{\alpha\sqrt{1+a^2}} \tag{34}$$

- Then

$$a(t) = sinh(\beta t) \tag{35}$$

Alternative explanations (no shortage)

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Evidence for strong progenitor age dependence of type Ia supernova luminosity standardization process

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ABSTRACT
Supernova (SN) cosmology is based on the assumption that the width-luminosity relation (WLR) and the color-luminosity relation (CLR) in the type Ia SN luminosity standardization would not show absolute magnitude differences with progenitor age. Unlike this expectation, recent age datings of stellar populations in host galaxies have shown significant correlations between progenitor age and Hubble residual (HR). Here we show that this correlation originates from a strong progenitor age dependence of the zero-points of the WLR and the CLR, in the sense that SNe from younger progenitors are fainter each at given light-curve parameters x_1 and c. This 4.6σ result is reminiscent of Baade's discovery of the zero-point variation of the Cepheid period-luminosity relation with age, and, as such, causes a serious systematic bias with redshift in SN cosmology. Other host properties show substantially smaller and insignificant offsets in the WLR and CLR for the same dataset. We illustrate that the differences between the high-z and low-z SNe in the WLR and CLR, and in HR after the standardization, are fully comparable to those between the correspondingly young and old SNe at intermediate redshift, indicating that the observed dimming of SNe with redshift may well be an artifact of over-correction in the luminosity standardization. When this systematic bias with redshift is properly taken into account, there is little evidence left for an accelerating universe, in discordance with other probes, urging the follow-up investigations with larger samples at different redshift bins.

International Journal of Modern Physics D

Fitting of supernovae without dark energy

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With data from Pantheon, we have at our disposal a sample of more than a thousand supernovae Ia covering a wide range of redshifts with good precision. Here we make fits to the corresponding Hubble–Lemaître diagram with various cosmological models,

....

The inclusion of dark energy (and thus accelerated expansion of the universe) is not necessary in view of this analysis. There is degeneracy in several variables: dark energy, extinction, evolution, partially non-cosmological redshifts (although requiring calibration of M far from compatibility with local SNe measurements), and possibly other paramaters that we have not explored here.

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Accelerated expansion induced by dark matter with two charges

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ABSTRACT

The accelerated expansion of the Universe has been established through observations of supernovae, the growth of structure, and the cosmic microwave background. The most popular explanation is Einstein's cosmological constant, or dynamic variations hereof. A recent paper demonstrated that if dark matter particles are endowed with a repulsive force proportional to the internal velocity dispersion of galaxies, then the corresponding acceleration of the Universe may follow that of a cosmological constant fairly closely. However, no such long-range force is known to exist. A concrete example of such a force is derived here, by equipping the dark matter particles with two new dark charges. This result lends support to the possibility that the current acceleration of the Universe may be explained without the need for a cosmological constant.

On cosmic acceleration without dark energy

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Abstract. We elaborate on the proposal that the observed acceleration of the Universe is the result of the backreaction of cosmological perturbations,

Future of the Universe

GENERAL RELATIVITY (ΛCDM $\omega = -1$)

- The DE energy density $\rho_\Lambda = const$ as universe expands, unlike ordinary matter, which gets diluted
- $\implies$ acceleration continues indefinitely into the future
- Reference: Ashoke Sen - Future of the Universe - (https://www.youtube.com/watch?v=t8kKJ4ABxIk)
- Size of universe doubles approx every 12 billion yrs
- Impossible to reach faraway observers due to accelerated expansion

- Assume we travel at speed c. How far can we reach? We can only reach a dist of about 18 billion lyrs (one lyr $\approx$ $5.9x10^{15}m$) - present horizon
- Objects further than that are moving so fast that not even light from us can reach them
- They are outside our horizon
- As universe expands, more & more objects go outside our horizon
- Extremely challenging implications
- Idea of mutliverse - multiple universes that cannot communicate with one another!

- Multiverse sounds like a movie or tv show, but is a reality, not science fiction
- What is the radius of the universe that we can see?
- The CMBR is coming from points at that distance
- The radius of the observable universe is about 46 billion lyrs
- This is about 2.5 times the radius of the present horizon
- $\implies$ observed universe has already split into 15 acausal parts, i.e., parts that cannot communicate with one another
- The size of the actual universe is likely to be much larger, containing a larger number of parts that cannot communicate with one another

Future of Civilization

- Our nearest galaxy is Andromeda
- Will Andromeda eventually go out of our horizon or merge with our Milky Way?
- It will merge with us in about 10 billion yrs
- What about other galaxies outside our local group?
- Most of them will eventually move out of our horizon
- Before that we could establish civilizations there (if we could get there)
- Eventually, we will lose touch with them forever

- What about the very far future?
- Local group of galaxies will be the only ones that will be within our horizon
- When the last star in that galaxy dies, life in its current form will not be possible
- This is expected to happen in about 10^{13} - 10^{14} yrs from now
- Very sad and lonely end to our civilization
- Quantum effects $\implies$ sadder end, but more exciting and adventurous

Conclusion

- We have given a description of the standard ΛCDM model
- Future of universe - constant ρ_{DE}, accelerated expansion forever
- Some alternative models - bulk viscous, Chaplygin gas, etc
- DE has lead to a much richer class of different evolutions, some with singularities and others without
- Those with finite time future singularities can be classified
- Study of alternative models and modified gravity theories has led to this wider class of behaviour
- Modified gravity theories have parameters that can be adjusted to suit observations, so which to choose?

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Symmetries in Black Holes, Dark Matter and Dark Energy

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Deadline for manuscript submissions:
30 September 2023

Message from the Guest Editor

Dear Colleagues,

There has recently been a renewed interest in black holes, dark matter and dark energy. This is due to the confirmation of gravitational waves in 2015 from the inspiraling and collision of two black holes, and more recently, the detection of a black hole shadow, published in 2019. Since then, several more verifications have been made. From the theoretical point of view, there are many symmetries relating to black holes, such as black hole symmetry, ladder symmetries, hidden symmetries, gauge symmetries, love symmetries and the symmetry in black hole jets. The cosmic censorship hypothesis also remains an unresolved issue.

In 1998, two teams observing distant supernovae found that they were further than expected, leading to the prediction of the acceleration of the universe at later stages, rather than deceleration, as was previously believed. The most widely accepted explanation for this acceleration is the existence of exotic matter with negative pressure, dubbed dark energy. Dark energy is interpreted as the leftover of mostly cancelled vacuum energy due to spontaneous mirror symmetry breaking. Carroll symmetries, which arise from Poincare symmetry...

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Special Issue

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Modelling of the Universe

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Deadline for Submissions: **10 March 2024**
Submission link:https://ojs.wiserpub.com/index.php/CM/about/submissions

Special Issue Information

Human civilization has been curious about stars, galaxies and the universe from the very beginning. We began efforts to understand the universe about 2000 years ago. The science of the universe came into its present form after the proposal of general relativity by Einstein. Many modified theories of general relativity have been proposed which have their own merits and demerits. This special issue is intended to include each and every aspect of cosmic evolution and the universe.

Articles in the following areas are most welcome:

(1) Cosmology-the early and the late Universe
(2) Stellar structure and evolution
(3) Quantum gravity
(4) Quantum processes in astrophysics and cosmology
(5) Cosmological tensions
(6) Advances in computational techniques
(7) Observational Cosmology

Keywords:

Gravity
Modified gravity
Stars
Quantum mechanics
Accelerated expansion of the Universe
Cosmological data analysis
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