Dark energy – observational properties and theoretical modelling

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Practical definitions of dark matter and dark energy

Determining the Universe evolution from observations

Null diagnostics

Outcome of all observations

Theoretical models

Conclusions

Two kinds of dark entities

Two kinds of "dark" entities – dark matter (DM) and dark energy (DE) – are seen through gravitational interaction only. Astronomical approach: determine their effective energy-momentum tensor (EMT) using observational data and some preferred conventional type of gravitational field equations.

DM - non-relativistic, gravitationally clustered.
DE - relativistic, unclustered.
Definition of their effective EMT – through equations.

DM - through the generalized Poisson equation applied to scales $\lesssim$ 100 Mpc where clustering of visible matter is seen.

$$\frac{\triangle\Phi}{a^2} = 4\pi G(\rho - \rho_0(t))$$

$\Phi(\mathbf{r}, t)$ is measured using the motion of 'test particles' in it.
a) Stars in galaxies $\longrightarrow$ rotation curves.
b) Galaxies $\longrightarrow$ peculiar velocities.
c) Hot gas in galaxies $\longrightarrow$ X-ray profiles.
d) Photons $\longrightarrow$ gravitational lensing (strong and weak).

Outcome of observations: DM is non-relativistic, has a dust-like EMT with $p \ll \rho, \quad p > 0$ $(c = 1)$, is collisionless in the first approximation, $\sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$, and has the same spatial distribution as visible matter for scales exceeding a few Mpc.

Ground experiments: very weakly interacting with baryonic matter, $\sigma < 10^{-43}\ \mathrm{cm}^2$ for $m \sim (50 - 100)$ GeV.

Dark energy

Two cases where DE shows itself:
1) inflation in the early Universe – primordial DE,
2) present accelerated expansion of the Universe – present DE.

Quantitative and internally self-consistent definition of its effective EMT - through gravitational field equations conventionally written in the Einsteinian form:

$$\frac{1}{8\pi G}\left(R_{\mu}^{\nu}-\frac{1}{2}\,\delta_{\mu}^{\nu}R\right)=-\left(T_{\mu\,(vis)}^{\nu}+T_{\mu\,(DM)}^{\nu}+T_{\mu\,(DE)}^{\nu}\right)$$

$G = G_0 = const$ - the Newton gravitational constant measured in laboratory.
In the absence of direct interaction between DM and DE:

$$T_{\mu\,(DE);\nu}^{\nu}=0$$

Possible forms of DE

- Physical DE.
  New non-gravitational field of matter. DE proper place – in the rhs of gravity equations.
- Geometrical DE.
  Modified gravity. DE proper place – in the lhs of gravity equations.
- Λ - intermediate case.

Generically, DE can be both physical and geometrical, e.g. in the case of a non-minimally coupled scalar field or, more generically, in scalar-tensor gravity. So, there is no alternative "(either) dark energy or modified gravity".

Background evolution

Neglecting the spatial curvature (less than 1% of the critical density):

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$$

The reconstruction programme: determination of the Universe evolution in the past from observational data.
The basic quantity to be found: the Hubble parameter $H \equiv \frac{\dot{a}}{a}$ as a function of redshift $z \equiv \frac{a(t_0)}{a} - 1$.

All components of the Riemann tensor can be expressed through $H(z)$ and $\frac{dH(z)}{dz}$.

EMT of present DE from the definition above:

$$\rho_{DE} = \frac{3H_0^2}{8\pi G}\left(h^2(z) - \Omega_{m0}(1+z)^3\right)$$

$$p_{DE} = \frac{3H_0^2}{8\pi G}\left(-h^2(z) + \frac{1}{3}\frac{dh^2(z)}{dz}\right)$$

where $h(z) = \frac{H(z)}{H_0}$, $H_0 = H(t_0)$ is the Hubble constant and Ω_{m0} is the present density of non-relativistic matter in terms of the critical one.

The DE effective equation of state $w_{DE} \equiv \frac{p_{DE}}{\rho_{DE}}$.

$w_{DE} > -1$ – normal case,
$w_{DE} < -1$ – phantom case,
$w_{DE} \equiv -1$ – the exact cosmological constant.

Luminosity distance from SNIa

The largest clean set at present: the Union 2.1 set (H. Suzuki *et al.*, Astroph. J. **746**, 85, (2012)): consists of 580 type Ia supernovae sampling the redshift range $0.015 \leq z \leq 1.414$. It provides us with the luminosity distance $D_L(z) = (1+z)\int_0^z \frac{dz}{H(z)}$.

$$H^{-1}(z) = \frac{d}{dz}\left(\frac{D_l(z)}{1+z}\right)$$

The main problem of the reconstruction programme: differentiation is not a proper operation in the presence of observational errors.

Ways to avoids it:

- Comparison of concrete theoretical models with data.
- Best fit to some arbitrary chosen analytical expressions for $H(z)$ or w_{DE}. The most widely known is the CPL (Chevallier-Polarski-Linder) fit

$$w_{DE} = w_0 + w_1 \frac{z}{1+z}$$

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- Smoothing.
  Many working proposals, e.g. A. Shafieloo et al., MNRAS **300**, 1081 (2006) and A. Shafieloo, arXiv:1204.1109.
- The principal components method and many others.

Acoustic oscillations in matter and CMB perturbation spectra

Origin of the effect: the Universe was isotropic at least from the BBN time $\longrightarrow$ half of large-scale scalar (density) perturbations – the so called decaying mode – are absent. Standing acoustic waves at the radiation-dominated stage.

I. Acoustic oscillations in CMB angular temperature fluctuations (the effect is seen in CMB polarization, too).

Leads to a very accurate measured shift parameter

$$\mathcal{R} = \sqrt{\Omega_{m0}} \int_0^{z_{rec}} \frac{dz}{h(z)} = 1.725 \pm 0.018$$

(E. Komatsu et al., Astroph. J. Suppl. **192**, 18 (2011)). Precise but degenerate test.

II. Baryon acoustic oscillations (BAO).

Large galaxy catalogs are needed. What is obtained is the following effective distance measure:

$$D_V(z) = H_0^{-1}\left[\frac{z}{h(z)}\left(\int_0^z \frac{dx}{h(x)}\right)^2\right]^{1/3}$$

Measured for 6 points by now:
$z = 0.106, 0.2, 0.35, 0.44, 0.6, 0.73$ – from SDSS DR7 (W. J. Persival *et al.*, MNRAS **401**, 2148 (2010)), WiggleZ (C. Blake *et al.*, MNRAS **415**, 2892 (2011); MNRAS **418**, 1707 (2011)) and 6dFGS (F. Beutler *et al.*, MNRAS **416**, 3017 (2011)) catalogs.

Null diagnostics

Aim: falsifying the cosmological constant with minimal assumptions.
The *Om* characteristic (V. Sahni, A. Shafieloo and A. A. Starobinsky, Phys. Rev. D **78**, 103502 (2008), see also C. Zunckel and C. Clarkson, Phys. Rev. Lett. **101**, 181301 (2008)):

$$Om(z_1, z_2) = \frac{h^2(z_1) - h^2(z_2)}{(1+z_1)^3 - (1+z_2)^3}$$

If *Om* considered as a function of one of its arguments (with the second one being fixed) is identically constant, then the model is the ΛCDM one and $Om = \Omega_{m0}$. Its calculation does not require the knowledge of the values of H_0 and Ω_{m0}.

Its variant customized for the usage of BAO data: the *Om*3 diagnostic (A. Shafieloo, V. Sahni and A. A. Starobinsky, arXiv:1205.2870):

$$Om3(z_1, z_2, z_3) = \frac{Om(z_1, z_2)}{Om(z_2, z_3)}$$

where z_2 lies between z_1 and z_3. If $Om3$ considered as a function of z_2 for fixed z_1 and z_3 is identically equal to unity, then the model is the ΛCDM one once more.

Outcome of all observations

$T^{\nu}_{\mu\,(DE)}$ is very close to $\Lambda\delta^{\nu}_{\mu}$ for the concrete solution describing our Universe;

$$|< w_{DE} > +1| < 0.1$$

at about 2σ confidence level. E.g., $w_{DE} = -1.010 \pm 0.058$ assuming $w_{DE} = const$

(C. L. Reichart *et al.*, arXiv:1203.5775).

Effective energy density of present DE:

$$\rho_{DE} = \frac{\epsilon_{DE}}{c^2} = 6.72 \times 10^{-30}\ \frac{\Omega_{DE}}{0.73}\ \left(\frac{H_0}{70}\right)^2\ \mathrm{g/cm^3}\ ,$$

$$\frac{G^2\hbar\epsilon_{DE}}{c^7} = 1.30 \times 10^{-123}\ \frac{\Omega_{DE}}{0.73}\ \left(\frac{H_0}{70}\right)^2\ .$$

Thus, at the present level of knowledge only one constant is needed for quantitative description of present DE.

In the language of "coincidences" – present DE introduces only one new coincidence as yet.

Models of dynamical present DE

Practical use of the remarkable similarity between primordial DE driving inflation and present DE: the same types of models may be used (and have been used indeed) for description of these two kinds of DE.

Single inflation	Quintessence
$(R + R^2)$-inflation	$f(R)$ dark energy
Extended inflation	Scalar-tensor DE
k-inflation	k-essence
Brane inflation	Brane DE
String inflation	String DE
Galileon inflation	Galileon DE

Many of them, e.g. scalar-tensor models, admit phantom behaviour of present DE in the absence of ghosts.

Model requirements for models of present DE

- Stability of the Minkowski space-time with respect to perturbations with $\omega^2 \gg H_0^2$:
  a) absence of ghosts,
  b) absence of tachyons.
- Laboratory and Solar System tests.
  No deviation from the Newton law up to 50 μ.
  No deviation from the Einstein values of the post-Newtonian coefficients β and γ up to 10^{-4} in the Solar system.
- Stability of matter- and radiation-dominated stages in the past. They should also be generic.
- Absence of additional singularities in the past after BBN preventing predictable Cauchy evolution to the future.
- Compatibility with inflation in the very early Universe (optional but desirable).

Conclusions

- Present DE certainly exists and constitutes about 70% of the right-hand side of gravitational field equations written in the Einsteinian form for a homogeneous isotropic background of the Universe.
- No statistically significant deviation of its effective energy-momentum tensor from that of an exact cosmological constant has been found as yet (typical accuracy is about 10% or even better). Quantitatively, only one constant is needed for description of present DE.
- No additional terms in equations describing perturbations in the non-relativistic matter component (baryons and cold DM) at scales much less than the Hubble one has been found – DE practically does not cluster with non-relativistic matter.

- Many theoretical models for present DE alternative to a cosmological constant. They all have their counterparts in inflationary models (= models of primordial DE).
- Still remarkable qualitative analogy between primordial and present DE suggests that the present DE need not be absolutely stable and eternal.
- In the language of "coincidences" – present DE introduces only one new coincidence as yet.
- Many new and much better data (up to $\sim 1\%$ accuracy) are expected from numerous independent observational projects in future – some very interesting things may be found!