What Is Dark Energy, Why Do We Need It, and What Does It Do?

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Until we see the background of darkness we cannot admire the light as a single and created thing.

– G. K. Chesterton, *Heretics*
Ch. IV, "Mr. Bernard Shaw"

Outline

Cosmological Models

The Standard Model of Cosmology

Λ: Standard Views on What

what is a cosmological model (CM)?

physical requirements and desiderata:

1. always represents universe *at a particular scale*: distribution of galaxies, galaxy clusters, intergalactic nebulæ and dust, and so on
2. for our purposes: large enough so that distribution of visible (baryonic, photonic) matter looks more or less homogeneous (~galactic clusters and larger, $\gtrsim$100 `Mpc`) "at late times" (all bets are off for the very early universe)
3. specifies the *core of the CM*:
   - **3.1** spacetime geometry: 4-d manifold with Lorentz metric, with a "reasonable" topology
   - **3.2** matter content (equations of motion, equations of state, stress-energy tensors, ...)
   - **3.3** interaction of geometry and matter—for our purposes, unless explicitly stated otherwise, the ***Einstein Field Equation (EFE)*** (*viz*., GR):[1]

$$G_{ab} = 8\pi T_{ab} + \Lambda g_{ab}$$

1. I use geometrized units, $c = \hbar = G = 1$.

what is a cosmological model (cont.)?

physical requirements and desiderata (cont.):

4. all appropriately related and sufficiently articulated so as to determine joint dynamical evolution of geometry and matter, so as to support, depending on fixed scale, derivation or construction of representations of (at least):
   - 4.1 cosmic microwave background radiation (CMB)
   - 4.2 emission and absorption of radiation from discrete sources
   - 4.3 structure formation from relatively small scales (globular clusters, *e.g.*)
   - 4.4 to relatively large scales (galactic super-clusters, *e.g.*)
   - 4.5 redshift-to-luminosity relations
5. satisfies minimal observational constraints (at the least, compatibility with observations): the CM's core must have "at late times" an expanding Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime as a smooth limit, in a relevant technical sense[2]

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2. And so we ignore the possibility of exotic *observationally indistinguishable spacetimes* in the sense of Geroch (1977), Glymour (1977), Malament (1977), and Manchak (2008, 2009).

what is a cosmological model (cont.)?

epistemological and methodological requirements and desiderata:

1. easy to describe and use
2. $\Rightarrow$ in our current epistemic state, necessarily follows that CM has spatiotemporal symmetries or some other such special properties (such as conditions on the Weyl tensor) that render it mathematically, conceptually and physically tractable
3. supports the construction or derivation of observational claims based on the physical representations of local, quasi-local and global structures ("schematizing the observer"—see Curiel 2025)
4. $\Rightarrow$ must be able to incorporate or be otherwise appropriately related to subsidiary theories (of terrestrial physics, *e.g.*, such as of the atmosphere, and of observational instruments)
5. stable under small perturbations, in an appropriate technical sense (else small inaccuracies may lead to radically different observational claims)

standard choices for matter fields

one or more of:

1. fluid with physically well motivated—one hopes—equation of state
2. mixture of such fluids, each with its own 4-velocity
3. particles with dynamics given by a kinetic theory
4. scalar field
5. Maxwell field
6. cosmological constant[3]

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3. I will defend in the 3rd lecture the claim that Λ should be thought of as "matter" and not "geometry".

physical quantities

1. ξ^a: the 4-velocity of matter (averaged at each point, uniquely picked out by symmetry or other background conditions)
2. $\Rightarrow$ the (instantaneous) spatial 3-metric:

$$h_{ab} := \xi^a \xi^b + g_{ab}$$

3. θ: rate of expansion of 3-volume of matter
4. $\Rightarrow H := \theta/3$: the *generalized Hubble parameter*[4]
5. $\Rightarrow$ *average length scale* or *scale factor*:

$$a \quad \text{such that} \quad \frac{\dot{a}}{a} := H$$

6. $\sigma_{ab}(= \sigma_{(ab)})$: rate of matter shear ($\sigma_{an}\xi^n = 0$)
7. $\tau_{ab}(= \tau_{[ab]})$: rate of matter twist ("rotation"; $\tau_{an}\xi^n = 0$)
8. $C^a{}_{bcd}$: the Weyl (conformal) tensor (not determined point-by-point by matter distribution, like rest of curvature)

4. Sometimes called, misleadingly, the *Hubble constant*. It is not in general a constant over time, and it is not even a constant on any spacelike slices except in the special case of homogeneous and isotropic models.

the stress-energy tensor T_{ab}

$$\boxed{T_{ab} = \mu \xi_a \xi_b + 2q_{(a}\xi_{b)} + p h_{ab} + \pi_{ab}}$$

where (more physical quantities):

1. mass-energy density:
$$\mu := T_{mn}\xi^m \xi^n$$
2. spatial 3-momentum density (= mass-energy flux relative to ξ^a):
$$q^a := -T_{mn}\xi^m h^{na}$$
3. isotropic pressure:
$$p := \frac{1}{3} T_{mn} h^{mn}$$
4. (trace-free) anisotropic pressure (“stress”):
$$\pi^{ab} := T_{mn} h^{m(a} h^{b)n}$$

so:

“stress-energy = mass-energy + momentum flux + pressure + stress”

- the particular, detailed physics is then encoded in equations of state and other imposed conditions relating the physical quantities
- commonly fixed perfect fluid (*e.g.*) requires:
  1. spatial 3-momentum and stress vanish:
  $$q^a = \pi_{ab} = 0 \quad \Leftrightarrow \quad T_{ab} = \mu\xi_a\xi_b + ph_{ab}$$
  2. idiosyncratic equation of state: $p = p(\mu, s)$, where s is local entropy density (or other hydrodynamic/thermodynamic quantities)[5]
  3. generally also *energy conditions*, *e.g.*, weak energy condition (WEC):
  $$T_{mn}\zeta^m\zeta^n \geq 0 \text{ for all timelike vectors } \zeta^a$$
  ("everyone sees positive mass-energy")
  4. adiabatic speed of sound $\nu^2 := \left.\frac{\partial p}{\partial \mu}\right|_{s=\text{const}}$ obeys
  $$0 \leq \nu \leq 1$$
  ("matter is locally stable (≥ 0), doesn't violate causality (≤ 1)")
  5. further imposing $p = 0 \Rightarrow$ "dust" ("cold dark matter")

5. Think of ideal-gas law: $p = nRT/V$.

relations among quantities

the Raychaudhuri equation:

$$\dot{\theta} = -\frac{1}{3}\theta^2 - \sigma_{mn}\sigma^{mn} + \omega_{mn}\omega^{mn} - \frac{1}{2}(\mu + 3p) + \Lambda$$

"rate of neighboring geodesics converging or diverging depends on present con-/di-vergence, shear, twist and stress-energy density"

encodes relative behavior of neighboring "particles" of fluid—sometimes called *the basic equation of gravitational attraction*

relations among quantities (cont.)

fix (and recall) a few more definitions, and derivations therefrom:

1. $H = \frac{\dot{a}}{a}$ $(= \theta/3)$, (generalized) *Hubble parameter*
2. $q = -\frac{1}{H^2}\frac{\ddot{a}}{a}$, *deceleration parameter* (~3-momentum density)
3. $\Omega := \frac{\mu}{3H^2}$, *(mass-energy) density parameter*
4. $\omega := \frac{p}{\mu}$, *pressure-to-density ratio* (or *barotropic index*)
5. $\Omega_\Lambda := \frac{\Lambda}{3H^2}$, *cosmological constant parameter* ("dark energy density")

relations among quantities (cont.)

then applying the Raychaudhuri equation gives:

$$q = \frac{\sigma_{mn}\sigma^{mn} - \omega_{mn}\omega^{mn}}{H^2} - \frac{\nabla_n \xi^n}{3H^2} + \frac{1}{2}\Omega(1 + 3\omega) - \Omega_\Lambda$$

"rate of spatial expansion fixed by shear, twist and stress-energy density"

- in the present day, observational constraints—smallness of cosmic background radiation (CBR) anisotropies—entails that 1st 2 terms on RHS are small
- what we know about matter (baryonic and dark) implies that $p \ll \mu$, so ω is small
- $\Rightarrow$ in present day, $q \approx \frac{1}{2}\Omega - \Omega_\Lambda$

$\Rightarrow$ positive Λ would cause accelerated spatial expansion if it dominates the density of matter: $\ddot{a}\ (\propto -q) > 0$

Cosmological Models

The Standard Model of Cosmology

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observations:[6] "local" spatial near-perfect isotropy (from CMB)
assumptions: simple perfect fluid[7]

then:

1. $$\dot{\xi}^a = \sigma_{ab} = \tau_{ab} = 0 \quad \Leftrightarrow \quad C^a{}_{bcd} = 0$$

   1.1 LHS captures local spatial isotropy (fluid not locally accelerating, shearing or twisting): no privileged directions
   1.2 RHS that spacetime is conformally flat

2. LHS or RHS imply local spatial homogeneity: no privileged places $\Rightarrow$ local state of fluid is same everywhere on "natural" spacelike slices
$$\nabla_a p + \xi_a \xi^n \nabla_n p = 0$$
(3-d convective or material derivative)

6. I'll discuss these in more detail below.

7. *Viz.*, no viscosity, shear-stress or heat flux; linear equation of state $p = (1-\gamma)\mu$, for $0 \leq \gamma \leq 1$.

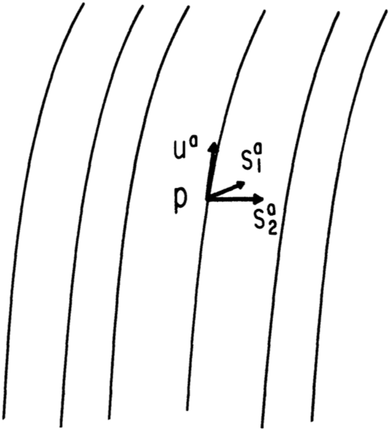

Fig. 5.2. The world lines of isotropic observers in spacetime. By definition of isotropy, for any two vectors s_1^a, s_2^a at p which are orthogonal to u^a, there exists an isometry of the spacetime which leaves p fixed and rotates s_1^a into s_2^a.

(from Wald 1984)

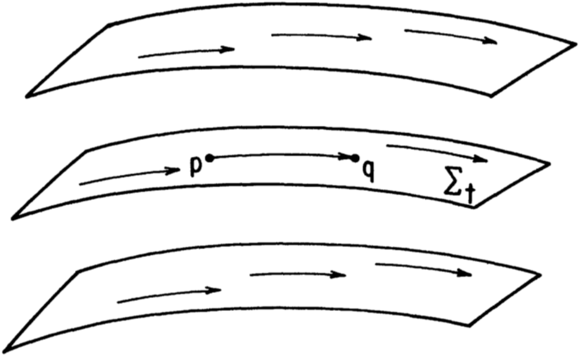

Fig. 5.1. The hypersurfaces of spatial homogeneity in spacetime. By definition of homogeneity, for each t and each $p, q \in \Sigma_t$ there exists an isometry of the spacetime which takes p into q.

(from Wald 1984)

assume:

Copernican Principle

We are not privileged observers, *i.e.*, we do not occupy a physically, and so not an observationally, special place in the universe.

$$\Rightarrow \textbf{implies}^{8} \Rightarrow$$

Cosmological Principle

The universe is everywhere spatially isotropic and homogeneous.

8. This is a "physics implication", not a logical nor mathematical one.

now assume:

topological simplicity

the spacetime manifold has topology $\mathbb{R} \times \Sigma$, where Σ is a 3-d, connected topological manifold consisting of one or some Cartesian product or connected sum of some of (Ringström 2013):

1. $\mathbb{R}$
2. $\mathbb{S}$
3. $\mathbb{S}^2$
4. $\mathbb{S}^3$

except $\mathbb{S}^2 \times \mathbb{S}$ is not allowed

caveat: in fact, related but more complex ("exotic", "not natural") topologies mathematically—physically?—permitted, but almost never seriously considered; I briefly discuss below

$\Rightarrow$ FLRW spacetimes!

general FLRW metric (M, g_{ab}) in "natural" coordinates:

$$\mathsf{d}s^2 = -\mathsf{d}t^2 + a^2(t)(\mathsf{d}r^2 + f^2(r)\mathsf{d}\Omega^2)$$

where

$$f(r) = \begin{cases} \sin(r) & \text{spherical} \\ r & \text{flat} \\ \sinh(r) & \text{hyperbolic} \end{cases}$$

the metric constrains topology:

open universe

Σ has flat or hyperbolic (negatively curved) intrinsic geometry
$\Rightarrow \Sigma$ is non-compact as a topological space (*not* "as a submanifold of spacetime manifold M")—usually $\mathbb{R}^3$

closed universe

Σ has spherical (positively curved) intrinsic geometry
$\Rightarrow \Sigma$ is compact as a topological space (*not* "as a submanifold of M")—often, *e.g.*, $\mathbb{S}^2 \times \mathbb{R}^1$ or $\mathbb{S}^3$ or $\mathbb{T}^3$ $(= \mathbb{S}^1 \times \mathbb{S}^1 \times \mathbb{S}^1)$

caveat: one can have flat or hyperbolic geometries on compact 3-manifolds by making topological identifications or taking quotients by "nice" subgroups of the isometries of the standard geometry—but the sentiment among cosmologists is that this is not "natural" (*cf.*, *e.g.*, Wald 1984, p. 95)...

PHILOSOPHY![9]

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9. Rousseau: "When the word 'natural' enters the room by the door, philosophy jumps out the window."

properties of FLRW:

- globally hyperbolic ("initial-value problem (IVP) well posed"[10])
- $q = \frac{1}{2}\Omega - \Omega_\Lambda$ is now exact
- $\Rightarrow$ *cannot be static if non-trivial matter or Λ!*
  (if Ω or Ω_Λ, and $\frac{1}{2}\Omega - \Omega_\Lambda$, $\neq 0$, then $\ddot{a}(\propto - q) \neq 0$)
- $\Rightarrow$ *no strict (local or quasi-local) energy conservation!*
- cosmological/particle horizons
- except under *extremely special* conditions (*e.g.*, Bekenstein 1975), initial or final (or both) singularities—big bang, big zip, big crunch, big rip[11]
- can have *sudden singularities* (Barrow 2004a, 2004b)—physically important quantities (*e.g.*, derivatives of a—pressure!) can diverge in interior, but interior is causally geodesic complete

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10. In fact, the IVP for pure dust and some fluids is *not* well posed, but we put that aside.

11. Hawking (1965), Hawking and Ellis (1965), Geroch (1966), Hawking (1966a, 1966b, 1966c), Geroch (1967), Hawking (1967), and Caldwell et al. (2003)—see Harada et al. (2018) for complete classification.

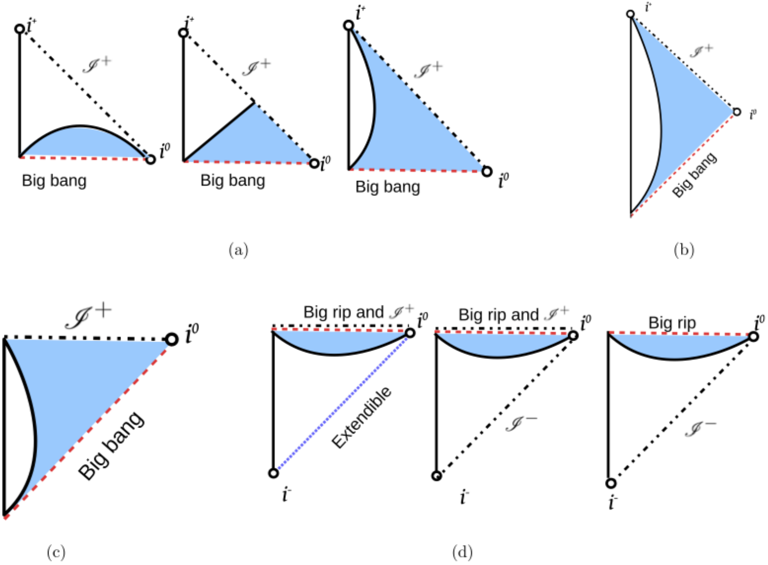

Figure 4. The conformal diagrams for the flat FLRW solutions. The red dashed lines denote spacetime singularities, while the blue short-dashed line denotes a regular null hypersurfaces at finite affine distance. In figure (a), the left, middle and right

(from Harada et al. 2018)

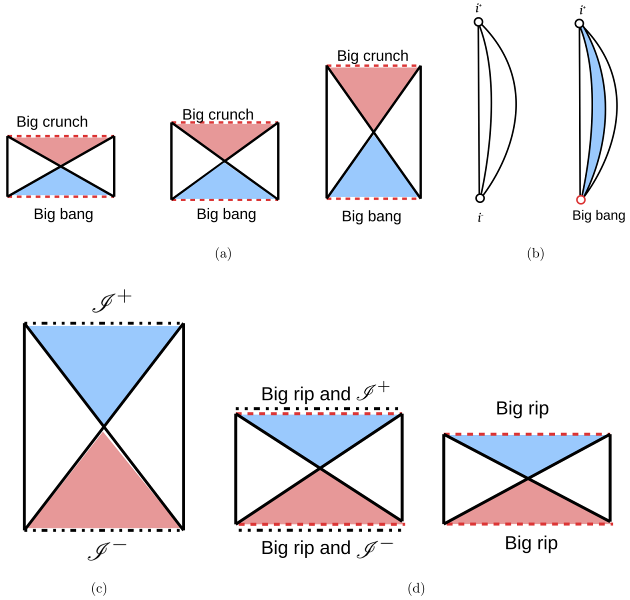

Figure 5. The conformal diagrams for the positive-curvature FLRW solutions.
(from Harada et al. 2018)

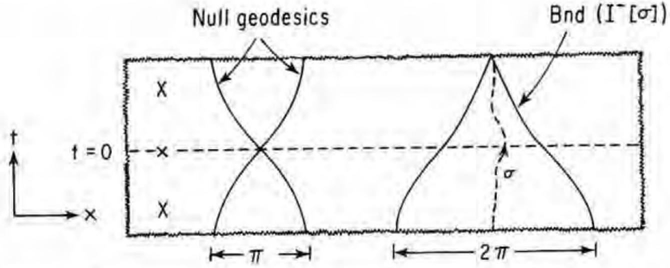

Figure 1. The covering space of two-dimensional De Sitter space-time, i.e., the t, x plane with metric $ds^2 = dt^2 - (\cosh^2 t)\, dx^2$. Light cones narrow rapidly to the vertical as $|t| \to \infty$. Every future-extendible timelike curve σ has an observational horizon of x-width 2π. Two-dimensional De Sitter space-time arises by identifying all points $(t, x + 2n\pi)$ for integers n. By introducing coordinates $\bar{t} = \sinh t$, $\bar{x} = (\cosh t)(\cos x)$, $\bar{y} = (\cosh t)(\sin x)$, it assumes the familiar form of a hyperboloid of one sheet $-\bar{t}^2 + \bar{x}^2 + \bar{y}^2 = 1$ in $\mathbf{R}^3$ with metric $ds^2 = -d\bar{t}^2 + d\bar{x}^2 + d\bar{y}^2$.

(from Malament 1977)

there are many other classes of spacetimes often studied as cosmological models, *e.g.* :

- one can rather assume only spatial homogeneity and allow non-trivial spatial anistropies $\Rightarrow$ the *Bianchi CMs* (Stephani et al. 2003; Griffiths and Podolský 2009)
- one can allow certain kinds of controlled spatial inhomogeneities, *e.g.*, the *Szekeres models* (Stephani et al. 2003; Griffiths and Podolský 2009)
- one can construct models by perturbing FLRW models in certain controlled kinds of ways, *e.g.*, Mukhanov et al. (1992)

- from middling to the largest scales we can access, FLRW models work better than any others for most purposes:
  1. FLRW metric approximates "real" metric ~1 part in 10^4
  2. but take care: derivatives of "real" metric *not* always close to FLRW's, so can be significant differences in geodesic behavior and curvature
- when accounting for smaller scales (*e.g.*, stellar systems, or the early universe), one of those others may work as well as or better than FLRW
- the others are also often studied on their own, as (relatively) simple, tractable models, to gain insight into some particular aspect of CMs in general, or into the mathematical, physical and conceptual structures of GR and the EFE in general

unless otherwise stated, for simplicity we will focus on FLRW models, which manifest all the conceptual and physical issues of interest to us[12]

12. See López-Corredoira (2014) for a philosophical/sociological discussion of why alternative models are not more extensively studied by the cosmological community.

early- to mid-90s pre-supernova situation

observations strongly favored near-flat FLRW with $\Lambda \approx 0$:[13]

1. expansion from hot Big Bang
2. $\Rightarrow$ galactic redshifts
3. $\Rightarrow$ CMB
4. large-scale structure formation
5. relative abundance of light elements (`H` and `He`; *almost* `Li`)

13. Peebles et al. (1991), Ellis and van Elst (1999), and Peebles (2020)

late 90s supernova of post-supernovæ observations

in the late 1990s, teams of astronomers, astrophysicists and cosmologists determined by measuring redshifts of Type Ia supernovæ that the universe is spatially expanding at an accelerating rate ($\ddot{a} \propto -q = \frac{1}{2}\Omega - \Omega_\Lambda > 0$):[14]

$$\boxed{\Lambda \ > \ 0}$$

$\boxed{\Rightarrow \Lambda\text{-Cold Dark Matter } (\Lambda\text{CDM}) \text{ Standard Model of Cosmology}^{15}}$

14. Perlmutter, *et al.* (Supernova Cosmology Project Collaboration) (1997, 1998a), Riess, *et al.* (Supernova Search Team Collaboration) (1998), and Bahcall et al. (1999). For evidence for CDM and how it constrains CMs, see, *e.g.*, Young (2017a).

15. Also sometimes called 'the concordance model'.

summary of ΛCDM

spacetime geometry flat, spatially expanding FLRW ("spatially homogeneous and isotropic")

matter radiation (photons, neutrinos), ordinary matter (baryons and leptons), CDM, cosmological constant (Λ)—all idealized as perfect fluids, with Λ's barotropic index $\omega_\Lambda = -1$

geometry-matter interaction GR (EFE)

observational support for expansion

not necessarily accelerated, but as opposed to static:[16]

1. galactic Hubble redshift—not definitive, but *strongly* favors[17]
2. CMB as function of redshift (temperature $\propto (1 + z)$)—measure absorption lines from high-z systems, primarily rotational excitations of abundant molecules
3. time-dilation: measure rate of ticks for "cosmic clocks" at different z (primarily Type Ia supernovæ)
4. "cosmic chronometers": Hubble parameter from variation in age of elliptical galaxies by redshift
5. Tolman test: galaxy surface-brightness varies as $(1 + z)^n$, where $n = -1$ for static and $n = -4$ for expanding
6. several other less compelling, more unsettled ones...

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16. I don't have time to discuss support for other components of ΛCDM, except of course for Λ itself.

17. See López-Corredoira 2017 for a survey of alternative explanations of expansion.

observational tensions (inconsistencies?) in support for expansion:[18]

1. most seriously, the Hubble discrepancy: "local" versus "cosmological" measurements disagree to what is claimed to be a *very* high confidence level[19]
2. another Hubble problem: apparent magnitude vs. redshift diagram for elliptical galaxies in clusters better fits a static than expanding universe (and possibly signature of anisotropies)
3. redshift as inferred from CMB: some discrepancies among studies of different systems, and even different studies of same systems
4. time-dilation: no detectable effects for gamma-ray bursts nor quasars
5. "cosmic chronometers": questionable assumptions about homogeneity of ages of stars in elliptic galaxies
6. angular size vs. redshift: apparent angular diameter for galaxies of given linear size shows z^{-1} *static* dependence, not the sharper one predicted by expansion, but *many* theoretical and observational lacunæ need filling in to make this more decisive
7. several other even more unsettled ones. . .

18. "Tests and Problems of the Standard Model in Cosmology"; "Dark Energy Two Decades After: Observables, Probes, Consistency Tests"; "In the Realm of the Hubble Tension—A Review of Solutions"; "Challenges for ΛCDM: An Update"

19. I am skeptical of the methodological soundness of derivations of the confidence levels. I will discuss later.

if ΛCDM correct, then composition of mass-energy in universe at current epoch is:

dark energy (Λ)	~72%
dark matter	~24%
ordinary (baryonic) matter	~4%

MOST OF MASS/ENERGY IN UNIVERSE IN A COMPLETELY UNKNOWN FORM!!!

a sampling of theoretical *cum* philosophical issues, problems for ΛCDM:

1. there's only one universe: how can science work without repeatable experiments? what do "likelihood" claims mean? (Smeenk 2012, 2013; Curiel 2015)
2. what are dark matter and dark energy?
3. does our ignorance indicate a breakdown in GR or Standard Model of particle physics (QFT)?
4. origin of homogeneity and isotropy? many parts of visible past universe were never in causal contact with many other parts—photons in CMB in different parts of sky have no common causal past, but it's isotropic to ~1 part in 10^{-5}![20]
5. why so close to flatness ("fine-tuning")?[21]
6. why are matter and Λ density essentially equal in current epoch ("cosmic coincidence")?
7. why are anisotropies in CMB almost perfectly Gaussian and scale-invariant?[22]
8. basis for structure extrapolation beyond cosmological horizon?

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20. Often claimed that inflation solves this. It doesn't.
21. Ditto about inflation.
22. Tritto about inflation.

theoretical *cum* philosophical issues, problems for ΛCDM (cont.):

9. physical significance, observability of spatial topology: as intimated above, assumptions of spatial isotropy and homogeneity, while severely constraining possible spatial topologies compared to class of all topological 3-manifolds, nonetheless permits infinite number of topologies of form (Ringström 2013): connected sum of elements K_i, L_j and $\#_1^k(\mathbb{S}^2 \times \mathbb{S})$, where L_j are quotients of $\mathbb{S}^3$ by elements of some "nice" isometry subgroup of the standard Riemannian geometry on $\mathbb{S}^3$, and the K_i are too difficult to describe (relatively) simply

10. FLRW unstable against small perturbations in directions of initial, final singularities (Ringström 2021); if initial singularities are unstable, may militate for special initial conditions, *à la* the Past Hypothesis—although generally FLRW is not adequate for *very* early universe anyway

11. ADM mass identically $= 0$ in closed models

Cosmological Models

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Λ: Standard Views on What

so, what is Λ?

it's just this thing, ya know?

correct, but unilluminating—can we do better?

standard story:

$$\boxed{\Lambda \text{ is vacuum energy}}$$

- even in lowest energy state ("vacuum"), quantum fields fluctuate, and so have non-zero stress-energy expectation value: "zero-point energy"
- in GR, all forms of material stress-energy contributes to stress-energy tensor (and thus to spacetime curvature)
- by Lorentz invariance ("equivalence principle"), expectation value of stress-energy tensor operator for vacuum energy has form

$$\langle \hat{T}_{ab} \rangle = \langle \mu \rangle g_{ab}$$

- by homogeneity and isotropy $\langle \mu \rangle$ must be a constant, $\Lambda_{\mathsf{v}} := \langle \mu \rangle$
- so this must contribute to the total "effective" cosmological constant in the EFE:

$$\Lambda_{\mathsf{eff}} = \Lambda_{\mathsf{E}} + \Lambda_{\mathsf{v}}$$

  where Λ_{E} is the "pure Einstein" cosmological constant, whatever that may be

EFE now:

$$\boxed{G_{ab} \;=\; 8\pi T_{ab} + \Lambda_{\mathsf{eff}}\, g_{ab}}$$

what magnitude do we expect for Λ_{v}?

1. consider quantum scalar field of mass m
2. sum zero-point energies for normal modes up to wave-number cutoff $\lambda \gg m$:

$$\langle\mu\rangle = \int_o^\lambda \frac{1}{2}\sqrt{k^2+m^2}\,\frac{4\pi k^2}{(2\pi)^3}\mathrm{d}k \;\approx \frac{\lambda^4}{16\pi^2}$$

3. taking GR to be accurate up to the Planck scale, it's reasonable to set $\lambda \approx (8\pi G)^{-1/2}$ (explicitly including Newton's constant G)
4. $\Rightarrow \langle\mu\rangle \approx 10^{71}\mathtt{GeV}^4$

$$\boxed{\text{this is big}}$$

observationally derived order of magnitude for Λ_{eff} (based on measurements of Hubble parameter):

$$\sim 10^{-47}\texttt{GeV}^4$$

$$\boxed{\text{this is small}}$$

they differ by ~10^{125}

$\boxed{\text{worst prediction in physics history!}^{23}}$

23. One can reduce this to ~10^{50} by getting fancy with EFT argot, *à la* Burgess (2015), but the technical complications are not worth the gain in foundational understanding for our purposes, and many parts of the calculations involve questionable application of standard EFT techniques.

what to do?

1. stipulate that Λ_E has exact value required to cancel Λ_v in Λ_eff – must match up to ~120 decimal places!
2. show that "naive" calculation of Λ_v is wrong:
   - **2.1** fundamental assumption of EFT, that IR is independent of UV, is incorrect, because gravity mixes all length scales
   - **2.2** vacuum state in curved spacetime has properties not accounted for by effective flat-spacetime calculation
   - **2.3** not accounting for some unknown, new physics consistent with GR + QFT
   - **2.4** modify GR, QFT, or both

most commonly considered alternatives:

1. promote Newton's constant to dynamical degree of freedom by allowing it to depend on scalar field $\phi(t, r)$: *scalar-tensor theories*, most general known as *Horndeski theories* (Horndeski 1974; Kobayashi 2019)
2. promote Λ to dynamical degree of freedom, treating as scalar field with kinetic and potential terms: quintessence, K-essence, tachyon, phantom, dilatonic, ... (Caldwell 2002; Copeland et al. 2006; Scherrer 2022)
3. modify gravitational field equations, most often $f(R)$ theories, "add higher-order curvature terms to Einstein-Hilbert action" (de Felice and Tsujikawa 2010)
4. modifed dispersion relations in the trans-Planckian regime (Mersini et al. 2001)
5. call upon quantum gravity (QG) to save the day—I won't discuss such models, however; too many, and too speculative, even for this most speculative branch of cosmology

Burgess (2015):

> *Normally such a large disagreement with data immediately spawns many new candidate theories, designed to remove the discrepancy without ruining the success of other experimental tests. More experiments are then required to decide which of the new proposals is the one chosen by Nature. The same is not true for the vacuum energy, for which there is not even one candidate modification of theory which all agree can provide a potentially viable way to reconcile observations with predictions.*

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