Epistemological Problems of Dark Energy

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I know noble accents
And lucid, inescapable rhythms;
But I know, too,
That the blackbird is involved
In what I know.

– Wallace Stevens
"Thirteen Ways of Looking at a Blackbird", VIII

If a lunatic scribbles a jumble of mathematical symbols it does not follow that the writing means anything merely because to the inexpert eye it is indistinguishable from higher mathematics.

– Eric Temple Bell (1937)
Men of Mathematics

Outline

The Standard Model of Cosmology (Cont.)

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:[1]

1. galactic Hubble redshift—not definitive, but *strongly* favors
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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1. I don't have time to discuss support for other components of ΛCDM, except of course for Λ itself. See López-Corredoira 2017 for a survey of alternative explanations of expansion.

epistemic value of observations:

- taken together: consilience (or "concordance of evidence"):

  evidence from independent, unrelated sources converge on the same result

- each on its own: method of successive approximations (Harper 2011; Smith 2014; Smith and Seth 2020):

  remove previous discrepancies in new models by improved application of theory accounting for systematic dependencies

VERY HIGH QUALITY EVIDENCE!

observational tensions (inconsistencies?) in the support for expansion:[2]

1. most seriously, the Hubble discrepancy: "local" versus "cosmological" measurements disagree to a *very* high confidence level[3]
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...

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2. See López-Corredoira (2017), Huterer and Shafer (2018), Di Valentino et al. (2021), and Perivolaropoulos and Skara (2022).

3. I am skeptical of the methodological soundness of derivations of the confidence levels. I will discuss why tomorrow.

with regard to disagreements between, *e.g.*, the results of different determinations of Hubble's constant and the measurements, I think—for reasons discussed later—one can reasonably doubt the theoretical structuring of raw observational data, and believe that there are other sources of error unaccounted for, rather than doubt ΛCDM…

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}![4]
5. why so close to flatness ("fine-tuning")?[5]
6. why are matter and Λ density essentially equal in current epoch ("cosmic coincidence")?
7. basis for structure extrapolation beyond cosmological horizon?

4. Often claimed that inflation solves this. It doesn't.

5. Ditto 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

so, what is Λ?

it's just this thing, ya know?

correct, but unilluminating—can we do better?

standard story

Λ is vacuum energy

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

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

- by homogeneity and isotropy, $\langle \lambda \rangle$ must be a constant, $\Lambda_{\mathsf{v}} := \langle \lambda \rangle$
- 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 (what is standardly written in the EFE as 'Λ')

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 $\lambda \gg m$:

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

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. $\Rightarrow \langle\lambda\rangle \approx 10^{71}\mathtt{GeV}^4$

this is big

a rough—but for our purposes, adequate—calculation of Λ_{eff} from the observed Hubble parameter goes as follows:

1. local energy conservation in FLRW (which holds to a *very* high degree of approximation) entails

$$\dot{a}^2 = \frac{1}{3}a^2(8\pi G\mu + \Lambda_{\text{eff}})$$

2. recall $\frac{\dot{a}}{a} = H$, so $a^{-2} \lesssim H^2$
3. we know that energy-mass density of ordinary matter is not much greater than its critical value (*viz.*, that of a flat FLRW): $|\mu - \langle\lambda\rangle| \lesssim 3H^2/8\pi G$
4. putting it all together: $\Lambda_{\text{eff}} \lesssim H^2$
5. today, $\frac{\dot{a}}{a} = H \approx 65\text{–}75\texttt{kms}^{-1}\text{Mpc}^{-1}$
6. thus, $\Lambda_{\text{eff}} \lesssim 10^{-47}\texttt{GeV}^4$

this is small

they differ by $\sim 10^{125}$

worst prediction in physics history![6]

6. One can reduce this to $\sim 10^{50}$ by getting fancy with EFT argot (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! ("fine-tuning problem")
2. show that "naive" calculation of Λ_v is wrong; some possibilities:
   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 some unknown, new physics consistent with GR + QFT not accounted for
   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. modify dispersion relations in the trans-Planckian regime (Mersini et al. 2001)
5. call upon quantum gravity (QG) to save the day—too many, and too speculative, even for this most speculative branch of cosmology, to my mind

grounds for adjudication among alternatives?

standard story: determined by various theoretical, epistemic and evidential virtues (not always easily distinguished from each other) one endorses and how one ranks them:

1. empirical adequacy
2. other standard ones discussed *ad nauseum* (simplicity, explanatory power, . . .)
3. problem-solving adequacy
4. feasibility of incorporation into accepted frameworks and theories
5. testability (sometimes comparative with competitors)

how much each virtue is "empirical", how much "theoretical", how much "evidential/epistemic" is a complex matter, depending always in part on investigative context for dark energy, almost none are easily evaluated, if at all

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.*

Bondi (1955, p. 155–156):

> *It is fashionable nowadays to divide astronomical research into two categories, "theoretical" and "observational". These terms are ill-defined and lack sure philosophical significance, but it is nevertheless true that most astronomers would have little doubt or disagreement on how to classify most published papers. . . .*
>
> *¶*
>
> *There is undoubtedly a widespread opinion that astronomical theory is, by and large, airy speculation, that it changes from day to day in its most fundamental tenets, that it is based on ill-considered hypotheses and that its reliability should accordingly be assessed to be low. By contrast the results of observational work are, according to this opinion, solid incontrovertible facts, permanent and precise achievements, that will never change and whose reliability is accordingly high.*
>
> *¶*
>
> *[I]n the present, state of astronomy, conflicts between observation and theoretical results continually arise. In the past, credence in such a conflict has generally been given to the observational result, and theoretical advances of considerable significance have been held up by undue reliance on the observations. . . . [I]n such a conflict it is far wiser to keep an open mind or even to lean to the side of the theory.*

Bondi (1955, p. 158):

> *The purely factual part of the vast majority of observational papers is small. It is also important to realise that these basic facts are frequently obtained at the very limit of the power of the instruments used, and hence are of considerable uncertainty. To refer to observational results as "facts" is an insult to the labours of the observer, a mistaken attempt to discredit theorists, a disservice to astronomy in general and exhibits a complete lack of critical sense. . . .*
>
> *¶*
>
> *Present-day observational astronomy may fairly be called the science of extracting the maximum information from the fundamentally meagre data that can be obtained about outer space, an endeavour to stretch both observation and interpretation to the very limit.*
>
> *¶*
>
> *A similar examination of physical theories in astronomy reveals that their primary basis is very sound indeed, since it rests on established terrestrial physics. . . . [I]n observational work long chains of inferences are based on frequently somewhat uncertain data, whereas in physical theories of astronomy, though long chains of inferences are also used, they are generally based on much more reliable experimental data. There is, therefore, no reason to expect any marked difference in the degrees of reliability of so-called theory and of observation, unless indeed it is that theoretical results are of greater reliability.*

in normal astrophysics, theories are under epistemic control because they are straighforward extensions of theories we test and use in terrestrial physics:

1. Newtonian mechanics of rigid and elastic bodies and of fluids
2. thermodynamics
3. Maxwell theory
4. magnetohydrodynamics
5. plasma physics
6. classical and quantum statistical mechanics (SM)
7. condensed matter physics
8. basic QM (spectral lines, electron gases, radiative decay, nuclear fusion, . . .)
9. . . .

in cosmology, however, this all raises three important questions:

1. is observational knowledge in cosmology by its very nature more or less certain than theoretical knowledge?
2. as an empirical test, have cosmological theories in the past been shown to be in error more or less frequently than observational results?
3. is an error in cosmological observation likely to persist for longer or shorter than an error in a cosmological theory?

- in cosmology, and most especially that part dealing with dark energy, we do not know how to answer those three questions
- $\Rightarrow$ because our theories and models *are not under epistemic control* (to be discussed soon)

- what is it we wish to have?
- epistemic security or potential understanding?
- do we begin with empirically secure matters or clear and rigorous theoretical principles?
- there is always a trade-off
- but in the field of dark energy, we struggle with both sides

- The Standard Model of Cosmology (Cont.)
- Λ: Standard Views on What
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- **Theory, Models and Data in the Age of High-Precision Astronomy**
- Epistemic Control and the Regime of Applicability
- Representation
- Confirmation in Cosmology

Maraston and Strömbäck (2011, p. 2786, their emphasis):

> *In this era of precision astrophysics, interpretative models, such as stellar population and galaxy models, need to keep pace with the fast observational development.*

- new high-resolution empirical data does not necessarily provide improved scientific knowledge and understanding on its own
- higher spectral resolution (*e.g.*) demands concomitant improvements in theoretical models and methods to provide ways of manipulating, structuring and interpreting the data
- likewise, the physical variables that are the target of high-resolution observational programs cannot be measured without theoretical models that employ significant theoretical resources
- and improvements in the observational resolutions require concomitant improvements in those models

simulations in particular today play a powerful and ineliminable evidential role in cosmology, in:

1. calibrating data
   (*e.g.*, specifying demographics of target population in determining accurate redshifts using photometry—Coil et al. 2007)
2. estimation of physical parameters from data
   (*e.g.*, generation of a simple stellar population (SSP) to describe evolution of SEDs—Conroy 2013)
3. finding and controlling for selection biases
   (*e.g.*, misclassification of faint stars as galaxies—Newman et al. 2013)
4. providing further sources of "raw data"
   (*e.g.*, supplementing empirical spectral libraries with theoretically generated ones—Maraston and Strömbäck 2011)
5. providing detailed models of specific types of astronomical systems
   (*e.g.*, in determining prior evolution before observation in models of galaxy mergers initiating quasar activity—Hopkins et al. 2005)

for discussion of related issues, physical and philosophical: Maraston and Strömbäck (2011), Anderl (2018), Jacquart (2020), and Gallagher and Smeenk (2023) evidential uses of simulations present their own peculiar epistemological problems:

- evidence must in *some* substantive sense be "independent of theory"—in what sense?
- how to guard against theoretical biases—determining the scientific conclusions by fitting to current theory, *viz.*, "theory-ladenness", or "simulation-ladenness"—creeping into inferences and conclusions?

all becomes even more poignant when one realizes that all the extraordinary high-precision data we're collecting now *cannot be interpreted AT ALL without the use of heavy-duty theoretical machinery such as simulations*

- testing theories of dark energy requires a great chain with many links joining high theory to material measures
- far more than a sudden juxtaposition of, on the one hand, the EFE, modifications thereof, models of novel scalar fields, . . . , and, on the other hand, the "simple readout" of observation
- the point: *it is not just theories of dark energy under test*
- tests *test more* than bare fundamental laws—they engage the long chain of theory, solutions, approximation, simulations, numerical calculations, . . .
- the very idea of a test in this sphere is more rightly attributed to *that whole chain* of links binding equations and other theoretical structures to the structured observational data themselves the product of much theory
- an expansion of the too-simple philosophical picture of a pure and simple theory/observation dichotomy. . .

several possible goals, in structuring data so as to bring observation into substantive contact with theory for purposes of testing, among them:

1. minimize "amount" of theory used, rely only on most empirically entrenched principles, laws, *etc.*,
2. consilient triangulation, using different theories to structure different "independent" observations relevant to same epistemic goal (must spell out what counts as "independent" here)
3. using different observations to try to control for systematic errors and to winnow out effects of unknown errors

in the arena of dark energy theories, we still struggle with all three

- it is appreciated that one must analyze and control for errors and selection (and other) biases in empirical data, in ever more sophisticated ways as precision and resolution increases
- perhaps not so widely recognized that theoretical models, both in themselves and when used to structure and interpret data, *require the analogous*: delimiting the *regime of applicability* of those theoretical tools
- we must have the theories and their relations to possible observations under *epistemic control*

epistemic control includes at a minimum:

1. understanding the physical theory's regime of applicability and so, *a fortiori*, its breakdown scales
2. understanding the theory's relations to other valuable theories (theories precedent to the theory itself, *e.g.*, NGT *vis-à-vis* GR, and theories laterally and antecedently related, *e.g.*, fluid dynamics *vis-à-vis* solid state and *vis-à-vis* molecular kinetics, respectively)—not just by approximation and limiting relations and such, but also *relations among concepts*
3. understanding what will and will not count as evidence in favor and against
4. understanding the asymptotics of physically important quantities and dynamics
5. understanding what approximations and idealizations are justified
6. understanding the conditions under which we do and do not need explicit schematization of the observer, and understanding how to do it
7. understanding as well what kinds of physicalities the different parts of the physical theory's formalism and structures all respectively can have and when ("exist or not" is too crude)

- it is characteristic of appropriately unified kind of physical system, treated by a single theory, that there exist a set of scales at each of which all theoretical quantities simultaneously lose definition
- every theory, in so far as it treats an appropriately unified kind of physical system, not only has a regime of applicability, but it has a *single, unified* one, bounded on all sides by scales characterized by the values of different combinations of its quantities
- for Navier-Stokes fluids, *e.g.*, the definitions of pressure, fluid flow, viscosity, ..., break down at spatial and temporal scales a few orders of magnitude greater than the mean free-path of the constituent molecules
- all quantities also lose definition when the fluid enters a strong enough state of turbulence, which can be characterized by (*inter alia*) a ratio of the fluid's kinetic energy to a measure of its viscous damping—a scale independent of that characterized by the mean free-path

This seems, indeed, to be one of the markers of a physical theory:

- the existence of a set of characteristic scales for its physical quantities
- at each of which all the theory's physical quantities simultaneously lose definition—
- "places" where all the kinematically and dynamically relevant structures of the theory break down all at once
- in the sense that the theory becomes inadequate for an appropriate treatment of any system beyond the determined boundaries

- although we perhaps naively tend to think of scales determined by spatial, temporal and energetic quantities when considering how and where theories break down in their capacity to provide sound representations of phenomena, any quantity in any theory can provide such a measure
- velocity provides a breakdown scale for Newtonian mechanics
- acceleration and scalar curvature provide different breakdown scales for various theories of gravity, such as GR
- no breakdown scale, moreover, can be a single number holding for all systems the theory treats
- Navier-Stokes theory, for instance, becomes inadequate for different fluids at different energies and spatial and temporal scales

- often it is not a bound on a single quantity, such as a value of energy, a value of spatial length, *etc.*: classical Maxwell theory, *e.g.*, breaks down when the ratio of the field's amplitude to its frequency approaches $\hbar$
- nor is it ever the case that there is a single characteristic scale for each theory
- Navier-Stokes theory breaks down:
    1. when various measures of flow complexity indicate the fluid is approaching turbulence
    2. when the fluid is too viscous
    3. over time scales comparable to equilibration time after a sharp disturbance
    4. when temperatures become large enough that heat loss due to emission of blackbody radiation becomes non-neglible
    5. when ambient electromagnetic field becomes strong enough to ionize the fluid's constituent molecules
    6. and on and on

- all of which shows, moreover, that sometimes a breakdown scale is determined by physical quantities not even representable in the theory (such as the electromagnetic field for Navier-Stokes)
- sometimes, moreover, approximations used to construct models of particular behavior, such as surface waves in fluid dynamics, have characteristic breakdown scales different from those of the material in which the phenomena manifest (Lamb 1932, ch. IX)
- in such cases, the theory can provide appropriate and adequate models of the systems in the relevant states, only not in the way the approximations definitive of the behavior at issue require

A breakdown scale, then, is something like the following:

> a measure of or function of or relation among quantities, such that, when the joint state of the system and its environment imply that the values of some of the system's quantities do not satisfy the measure, function or relation, then the theory can no longer provide good models of the system

- breakdown scales can *never* be determined by analysis of *the formalism and theoretical machinery of the theory alone*, without input from knowledge acquired by experimentation in particular and empirical investigation in general
- they are rather fixed by knowledge that one can gather only from investigations grounded in that part of the epistemic content of the theory not captured by the formalism by itself, largely in experimental and observational practice
- as such, they change with the increasing scope and depth of our experimental reach

what does it mean to say that the theory cannot provide good models of systems outside its breakdown scales?

- one of the most important markers of this is that the system's quantities lose unambiguous definition with respect to the theory's resources for modeling them
- for a Navier-Stokes fluid, for example, different sorts of thermometers that allow spatial discrimination on scales only a couple of orders of magnitude greater than the mean free path of the fluid's molecules will record markedly different "temperatures" depending on characteristics of the joint system that one can ignore at larger scales—the fine details of the fluid's convective flow in relation to the geometry of the thermometric system, for instance, and even the transparency of each thermometer to the fluid's particles[7]
- as the fluid approaches turbulence, to take another example, the values of all its quantities begin to vary rapidly in time and eventually cannot be measured by any conventional means—the quantities are no longer well defined

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7. See, *e.g.*, Benedict (1969) for detailed exposition of the complex interplay among theory, model and experiment one must take account of in attempting to define a physical quantity such as temperature based on the behavior of real measuring devices.

without knowledge of a theory's regime of applicability, and in particular when a given system of interest lies in its scope, we have *no grounds whatsoever* for trusting what the theory purports to say about the system

– but it is exactly such knowledge we lack for all theories about dark energy

– we have no idea what their respective regimes of applicability are, for we have no direct experimental or observational knowledge of their postulated constituents

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Λ: Standard Views on What

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The vague accuracy of events
dancing two by two with language,
which they forever surpass

– William Carlos Williams
Paterson

'represent'

standard philosophical senses of designative, depictive or verisimilous representation of world by mathematics of physical theories

e.g.:

- Tarskian relation of designation between elements of mathematical space ("the space of states") and states of physical system: semantic view (designative—Suppes 1960; van Fraassen 1980)
- or possible-worlds semantics (depictive—Lewis 1970; Butterfield 1984)
- or existence of "homomorphism" kind between mathematical stuff and stuff in the world *à la* the structuralists (verisimilous—da Costa and French 2003; Giere 2010)

The Motto

meaning is fixed by ontology

- even instrumentalists and empiricists (*e.g.*, Carnap and van Fraassen) subscribe to (*e.g.*) Tarskian-like semantics such as to give empirical content to the mathematical formalism of theories
- $\Rightarrow$ meaning of mathematical formalism determined by standard representational relations with respect to a fixed ontology
- even though not realists about ontology

natural accompaniment:

> *empirical content accrues to the mathematical formalism of theory largely if not wholly by virtue of this kind of representation—any physical significance the mathematics has derives from it*

van Fraassen (1980, p. 8, his emphasis):

> *Science aims to give us, in its theories, a literally true story of what the world is like; and acceptance of a scientific theory involves the belief that it is true. This is the correct statement of scientific realism.*

the breakdown of theories

we use theories to model systems, and to model them well, *i.e.*, fruitfully, in a way that teaches us much and also displays our conceptual mastery of them and their behavior...

even when the systems are in states such that the models are in no way predictively accurate

when, that is, there can be no question of the math representing the system in any standard sense.

- predictive accuracy of Navier-Stokes theory irremediably breaks down, *e.g.*, as a fluid approaches turbulence—it leaves its *regime of adequacy*
- nevertheless, even while the dynamical equations of the theory no longer yield accurate predictions by any reasonable measure, other parts of the theory, the kinematical relations among its quantities (*e.g.*, that the shear-stress tensor is symmetric, and that heat flux is always independent of the pressure gradient), still are meaningfully applied to model some aspects and features of the system in those states
- it is still in its *regime of propriety* (Curiel 2017, 2025)

- we use those kinematical, *not the dynamical*, relations, among other purposes, to guide the design of instruments to probe the systems (Curiel 2025)
- indeed, satisfaction of the kinematical constraints *is necessary for the dynamics to be well posed* (Curiel 2022) $\Longrightarrow$ *cannot even investigate the possible truth of dynamical claims unless kinematical constraints are satisfied*
- shows that the theory can capture something of deep physical significance about the systems even when it is not descriptively, much less predictively, accurate of them

but, again, there can be no question of standard representation without predictive accuracy *standard views cannot capture at all a large part—I think, indeed, the large majority—of the empirical content of physical theories*

– *indeed, standard views of representation cannot even get off the ground without the prior fixing of a regime of applicability*

– *an almost wholly pragmatic affair that requires much of the meaning of the theory's terms to have been already fixed, and which in turn provides the basis for much of that meaning* without knowledge of the theory's regimes of propriety, of adequacy, of applicability—

we have no epistemic control over the theory at all

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- one of the problems with traditional confirmation theory (a prejudice inherited from Popper):

  any discrepancy between theory and observation theory is viewed as a disconfirmation

- but that is deeply wrong, from an epistemological standpoint
- often, a violation rather serves to show the boundary of the regime of applicability
- other times, it shows merely that we are awaiting better calculational techniques, or the capacity to incorporate more details in our models, which we suspect to be relevant but do not yet know how to handle
- the interesting question, then, is when a mis-match between prediction and experimental result constitutes a crisis (to use the Kuhnian locution) for a theory, a true anomaly

consider the case of the calculation of Lithium-7 abundance due to early universe nucleosynthesis, a prediction of ΛCDM

- the calculated prediction differs from observed values by a factor of at least 2 or 3
- but no one seriously worries that this constitutes a crisis for QFT, GR or ΛCDM:
    1. the two main sources of observational data from which measured abundance values are calculated—baryon-to-photon ratios derived from the CMB, and the abundance directly observed in Population II stars—themselves disagree, suggesting that better measurements are needed to truly test the predictions
    2. while the theoretical discrepancies with both measured values are "relatively small", they are still unacceptable but nonetheless not so gross that it freaks people out
    3. $\Rightarrow$ because we can plausibly believe that more accurate calculations, taking into account more and finer details of interactions and dynamics, higher-order effects, and so on, will significantly lessen the discrepancies

- no one has yet argued convincingly that this cannot be done, as Le Verrier (1859) did for Mercury's anomalous precession, generating a true crisis in astronomy and the theory of Newtonian gravitational theory in the second half of the 19th Century
- in light of the fact that successive theoretically improved models, taking ever more systematic dependencies of the systems into account, and observationally improved data have whittled the discrepancy for Lithium down, we feel soothed and comforted (the method of successive approximations—Smith 2014; Harper 2011; Smith and Seth 2020)
- it's nothing like the case of Mercury, where everything was tried, both theoretically and experimentally, and nothing worked to lessen the discrepancy even the slightest bit

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