Limits on cosmology as a testable science

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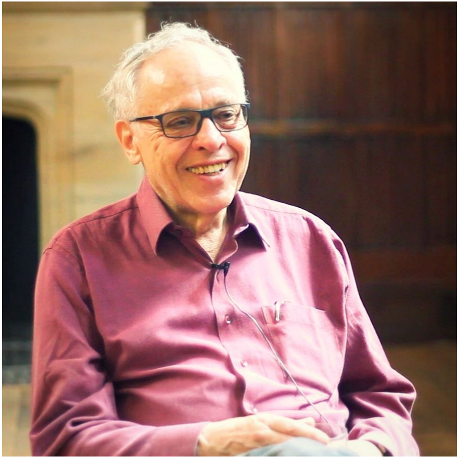
Dark Matters Meeting,
IAP Paris, December 2017
Celebrating Joe Silk's 75th birthday



A huge contribution ... thanks, Joe

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The standard model of cosmology

Static model (Einstein), *taken for granted by all*, gives way to a dynamic geometric model (Friedmann, Lemaître, Robertson, Walker):

- RW Metric
- Einstein Field Equations $\Rightarrow$ Friedmann equation
- Conservation equations
- Matter description: dust, radiation, kinetic theory, scalar field
- Perturbed FLRW Metric, Inflation
- Structure formation: numerical simulations

Underlying view

Local physics everywhere determines global dynamics (bottom-up physics causation). But this does not determine topology

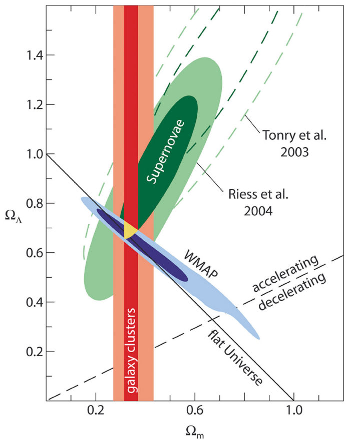
Reviews: Leclercq, Pisani, Wandelt: arXiV 1403.1260.
Uzan: arXiv:1606.06112

A consensus model: Epochs

Epoch	Start time	Matter source
Start	Ill defined	Unknown
Inflation	10^{-35} *secs*	Scalar field dominated
Hot Big Bang	10^{-3} *secs*	Radiation dominated
Visible universe	$380,000$ *years*	Dark Matter dominated
Accelerating Universe	10 *Gyrs*	Dark energy dominated
Future	13.87×10^{10}*years*	Dark energy or curvature

Table 1: *The main epochs in the history of the Universe.*

A consensus model: parameters



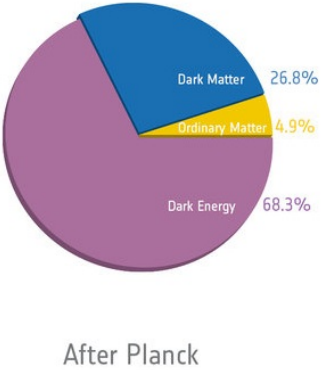


Figure: (Left) Constraints on the cosmological density parameters obtained from the Hubble diagram, structure formation studies, and CMB measurements before Planck (Right) Fractions of the different energy components after Planck plus nucleosynthesis.

The three fundamental problems

A huge success combining theory and observations and simulations, but with specific difficulties because of its nature

A unique subject

Cosmology is the ultimate historical science, informed by experimental physics and astronomical observations. It therefore runs into problems not encountered by other experimental or historical sciences

Specifically

1. the uniqueness of the universe,
2. limits of what will ever in a practicable sense be possible in observational terms (the visual horizon)
3. limits on our ability to test the relevant physics that governs its dynamics at early times (the physics horizon).

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The uniqueness of the universe

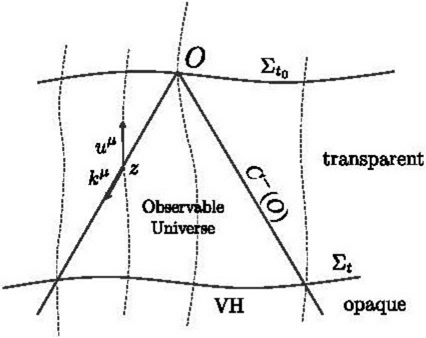
There is only one universe

There is only one universe we see from one spacetime point

- We only can observe our universe on one past light cone
- We have to deduce 4-d spacetime structure from a 2-d image. Distance estimations are therefore key
- We can't see many copies of the universe to deduce laws governing how universes operate. We have to therefore compare the one universe with simulations of what might have been
- Can't rerun the experiment to see what happens

Cosmic variance: observation of unique universe vs statistics

Do variations from our model need explaining, or do we just accept them as statistical variation? e.g. CBR anomalies: just Cosmic Variance?



The past light cone $C^-(O)$ of the event O ('here and now') and its visual horizon, based on the last scattering surface Σ_t when the universe became transparent. This is the whole of what we can see by any electromagnetic radiation. All structure formation observations are within here.

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Visual Horizons and Particle Horizons

Largest scales: we can't see beyond the horizon ...

- Observational Horizon: Our Visual Horizon is the furthest matter we can have received radiation from

The furthest out matter visible by EM radiation is that we see on the Last Scattering Surface (COBE, WMAP, Planck, Bicep2): the visual horizon is unaffected by inflation

Absolute limits on observational verification

Different for different messengers

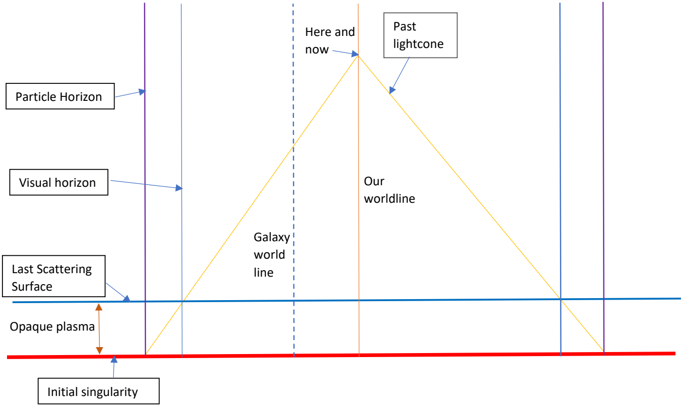
Will be larger in the future but we won't be there

- Particle horizon: furthest matter we can have interacted with and which can affect what we see up to the visual horizon, which lies inside the particle horizon.

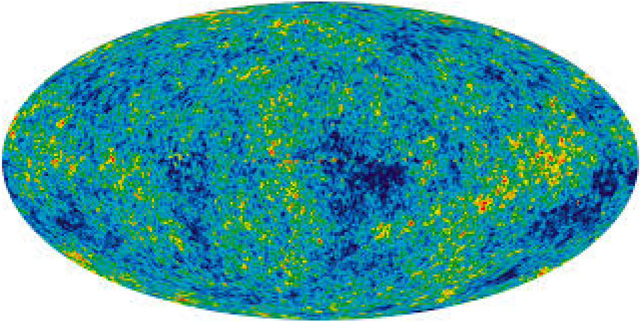
Rindler (1957): Concepts; Penrose (1963): conformal diagrams

Visual Horizons

Limits to all observations (conformal diagram)



The matter comprising the Visual Horizon



The matter comprising the visual horizon is that imaged by satellites such as Planck. It is the furthest out matter we can see, and we can only see it as it was 13.8 billion years ago. It is however affected by matter further out but inside the particle horizon: effectively by effects up to a distance of 1.15 times the Hubble radius today (GE and Uzan: 1612.01084).

A Small Universe? - Everything Visible

Is the universe closed on a scale smaller than the visual horizon? Then we can see round it since decoupling: multiple images of galaxies in the sky

- Many possible spatial topologies for $k = 0$, $k = +1$, $k = -1$
- Can test by direct observations but difficult
- Can test by number counts but not easy
- Can test by identical rings in CMB sky: very good test but very computationally intensive

Small Universe

We probably don't exist in small universe but case is not entirely closed

- If we did it would be only case we could see all matter in the universe, could actually predict the future from visible initial data, and see our own galaxy at different times in its history. No horizons exist!

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Our ability to experimentally test the physics relevant to cosmology dies away as we try to understand the earlier times

- Nucleosynthesis Ok (modulo Lithium issues)
- Baryosynthesis not (key issue)
- Inflation not *except* if inflaton is Higgs
- Pre-inflation (quantum gravity?) is not

Unknown Physics: The Physics Horizon

We don't know what the physics of the really early universe is because we can't test it: energies are too high e.g. inflation 10^{16} GeV $= 10^{25}$ eV whereas LHC can get 14 TeV $= 14 \times 10^{12}$ eV

The relevant physics is unknown and probably untestable by direct experiment

The links between physics and cosmology

An unfulfilled promise

The promise of unifications of different branches of physics (gravitational, atomic, nuclear, particle physics, and quantum gravity) with cosmology has not been fulfilled in the latter two cases.

- In the cases of the inflaton and dark energy, we are often faced with a form of 'saving the phenomenon' where running the field equations backwards (Synge's g-method) is used to propose relevant effective potentials for a scalar field (this is possible because the energy conservation equation is in this case equivalent to the Klein-Gordon equation);
- but the resulting potential has no solid basis in physics
- unless the inflaton is the electroweak Higgs (possible: *Encyclopaedia Inflationaris*). In that case: an incredible unification

The links between physics and cosmology

The Synge Trick

Matter equation of state determines evolution (EFE) which then determines evolution of matter (Conservation Eqns): $T_{ab} \Rightarrow R_{ab} \Rightarrow g_{ab}$.
But can run the field equations backwards (The Synge Trick) to get any desired geometry from some "matter": $g_{ab} \Rightarrow R_{ab} \Rightarrow T_{ab}$ (exact result).

Theorem: FLRW scalar field dynamics

Can choose $V(\phi)$ to get almost any desired result $a(t)$ because KG equation and conservation eqns imply each other (Madsen and GE)

Applications:

- The inflaton
- Dark energy

The fact we can determine such a potential does not guarantee there is a corresponding field out there, unless we experimentally confirm it
Phenomenological approaches often result in unphysical conclusions: e.g. matter with $w < -1 \;\Leftrightarrow$ negative inertial mass density $(\rho + p < 0)$

Was there a start?
Singularity Theorems

Did the universe have a start? (Lemaître)

- FLRW singularities, given energy conditions
- Raychaudhuri equation and anisotropies (Ehlers)
- Hawking-Penrose singularity Theorems: refocussing of past light cone, plus energy conditions implies singularity
- Existence of CMB is sufficient to give the required refocussing (Hawking-GE)

A crisis for physics (Wheeler)

A start to space, time, matter/fields, physics itself. Physics loses its ability to predict to earlier times because physics did not apply (no spacetime!)

Not taken seriously sometimes. Actually implies need for quantum gravity applied to cosmology. Various proposals - but quantum gravity is untested.

But what about scalar fields?

Inflation implies existence of scalar fields that violate the energy conditions: $\rho + 3p < 0$

- Alleged inflationary singularity theorems - exclude exponential and bouncing models by fiat (although $k = 0$ de Sitter is indeed singular)
- Emergent models - but stability
- Bouncing models - but inhomogeneity

Quantum gravity and quantum cosmology?

Untestable theories (except for some weak constraints)

Proposals for how a physical origin of the universe could have taken place run into the limits of testable scientific theorising

We proceed by extrapolation from the known to the unknown. No guarantee whatever this is correct.

Special initial conditions, or modified gravity?

Major problems for inflation pointed out strongly by Roger Penrose (*Fashion Faith and Fantasy*) because gravitational degrees of freedom in the extremely early universe are not excited whereas all the matter degrees of freedom are maximally excited. Inflation is not a cure (Penrose) because initial conditions needed are incredibly unlikely in the space of all spacetimes.

Special initial conditions in cosmology

The local arrow of time is a consequence of global initial conditions (a very low energy initial state), which *inter alia* is required to allow inflation to start (Penrose)

Might possibly be met by a quantum gravity theory where gravity is turned off at extremely early times, as suggested by Greene and collaborators (arXiv 0911.0693).

This might be a pointer towards the correct form of quantum gravity

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The multiverse and the Anthropic principle

Does a multiverse exist?

Multiverses: the 9 claimed types (Brian Greene, Tegmark)

- Implied by physics? - Eternal chaotic inflation. But physics not tested
- Anthropic explanation? - The issue of vacuum energy
- But unimodular gravity can also solve it, also see Unruh 1703.00543
- Claimed measures a problematic issue: infinities, non-uniqueness, cannot be tested
- Observable predictions: issue of underdetermination
- Claimed conflation of Everett with other forms?

Is this science? It is good hypothesis making - but where is the confirmation?

Limits on testing

Visual horizons prevent direct testing of any multiverse proposal, except bubble collisions may occur in a subset and possibly leave a trace.

The defense

Martin Rees

Rees: "The strongest reason for thinking about 'multiverses' (or, at least, about physical reality embracing far more than the observable universe) that this is a consequence of speculative but serious theories – eternal inflation, the 'landscape" of vacuum states, etc."

"It's not just – or indeed primarily – because of 'fine tuning' arguments, which are in any case I think oversold."

Exploring multiverses

This is a legitimate science: consider them, explore their consequences.
The problem comes when it is claimed that they have been proven to exist

But at present we have no proof Coleman-de Luccia tunnelng takes place, no established scalar field with a ϕ^2 potential (inferring one backwards from CMB data is just the Synge g-trick), the landscape is not established physics, and the supposed mechanism linking them is an *ad hoc* contrivance. It may not be possible to fill the gaps.

Infinities: two views

Particularly problematic are claimed infinities (Vilenkin, Linde, Guth).

Many claims of infinities in cosmology, particularly in multiverses
Infinite replication of life on Earth[1] "Mapping the multiverse: How far away is your parallel self?" *New Scientist* 6 February 2017

Alternative view

What are definitely not scientific claims are the variety of statements that there physically exist an infinite number of anything (universes, galaxies, people, whatever) in a Multiverse.

Rees defence: And the issues of infinity arise just as acutely in the old steady state theory.

Response: another reason to not believe in those theories

[1] GE and Brundrit QJRAS 20 (1979)37

Claimed physically existing infinities

Infinity is not a big number. It is a quantity that is unattainable no matter how long you wait or what you do Thus it does not occur in the real physical universe. As stated eloquently by David Hilbert, while the concept of infinity is needed for various mathematical purposes,

> *"The infinite is nowhere to be found in reality, no matter what experiences, observations, and knowledge are appealed to".*

This is in stark contrast to the various claims it exists in physical reality.

Claimed infinities in cosmology are not science

There is no way to prove they exist. The claim is completely untestable. Hence it is not a scientific claim.

They may be what the universe tends to in the far distant future but not what what can be shown to be currently present.
If your theory predicts it: that theory must be tested to infinite accuracy to make good the prediction. Not possible.

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From physics to philosophy?

Some workers are claiming we need to change the criteria for what is a scientific theory because of this problem of proof as regards multiverses (and similar for string theory): our theory is so good you have to believe it.

Thus they want to redefine science. Criteria for a scientific theory?

- Test theories observationally and recognise role of auxiliary hypotheses (refined view of Popper,Kuhn,and particularly Lakatos)
- Do we go with non-empirical theory confirmation? (Dawid) or weakened empirical requirements (Susskind, Carroll)?
- Treat Bayesian arguments with caution (needs new data, not theory)

Retrogressive steps?

Transition from philosophy to physics

Cosmology was once just regarded as philosophy (Rutherford). Now it is included in the annual Particle Physics Data Group Report. Don't lose this by becoming flaky!

COMMENT

Defend the integrity of physics

Attempts to exempt speculative theories of the Universe from experimental verification undermine science, argue **George Ellis** and **Joe Silk**.

This year, debates in physics circles took a worrying turn. Faced with difficulties in applying fundamental theories to the observed Universe, some researchers called for a change in how theoretical physics is done. They began to argue — explicitly — that if a theory is sufficiently elegant and explanatory, it need not be tested experimentally, breaking with centuries of philosophical tradition of defining scientific knowledge as empirical. We disagree. As the philosopher of science Karl Popper argued: a theory must be falsifiable to be scientific.

Chief among the 'elegance will suffice' advocates are some string theorists. Because string theory is supposedly the 'only game in town' capable of unifying the four fundamental forces, they believe that it must contain a grain of truth even though it relies on extra dimensions that we can never observe. Some cosmologists, too, are seeking to abandon experimental verification of grand hypotheses that invoke imperceptible domains such as the kaleidoscopic multiverse (comprising myriad universes), the 'many worlds' version of quantum reality (in which observations spawn parallel branches of reality) and pre-Big Bang concepts.

These unprovable hypotheses are quite different from those that relate directly to the real world and that are testable through observations — such as the standard model of particle physics and the existence of dark matter and dark energy. As we see it, theoretical physics risks becoming a no-man's-land between mathematics, physics and philosophy that does not truly meet the requirements of any.

The issue of testability has been lurking ▶

ILLUSTRATION BY VASAWA

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Testing the foundations

Solvable items

Some issues we will probably be able to solve

- Structure formation issues, e.g. dark halos, central cusp
- Hubble constant issue (nearby and far measurements)
- Constraints on inflation from CMB polarisation, scalar to tensor ratio
- CMB Non-Gaussianity (Joe: 'only robust prediction of inflation')

A key item is checking the basics of our standard model. We are able to do so in crucial areas: consistency tests on standard model

- CMB spectral distortions and reciprocity theorem (1301.1312)
- Concordance of CMB and matter dipoles (GE, Baldwin MNRAS 1984)
- Primordial element abundances far out same as nearby
- CBR temperature far out scales as $T = T_0(1+z)$
- Copernican principle (Hubble discrepancy??)

The Copernican principle

Philosophy to science

Is the universe in fact spatially homogeneous? - perturbed FLRW is background for all analyses

- We can only see on one light cone from one point
- Copernican Principle (Bondi 1960, Weinberg) was a philosophical assumption (number counts susceptible to source evolution)

Theorem (Mustapha-Hellaby-GE, Celerier)

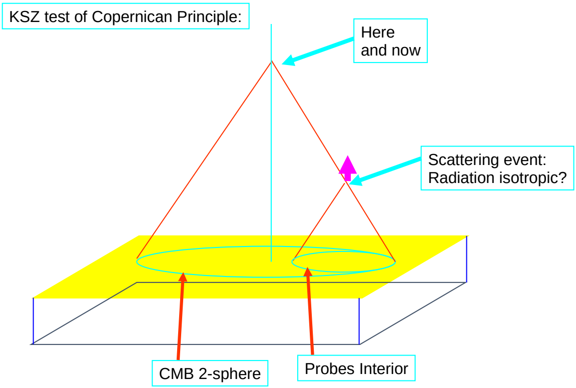
Can model any background model observations by an inhomogeneous LTB model with no Λ-term. Isotropy does not imply homogeneity.

- Spherical symmetry everywhere implies spatial homogeneity (Walker)
- Spherical symmetry of free CMB everywhere in an expanding geodesic frame implies FLRW (Ehlers-Geren-Sachs); the result is stable (Stoeger-Maartens-GE), but not directly testable

CP can now be observationally tested: good standard candles, time drift of redshift, kinetic SZ effect. Seems OK (Zhang and Stebbins 2011)

KSZ test of CP

KSZ effect lets us probe the LSS in the interior of the past light cone,



Standard model is a huge success: size and age of universe, expansion of the universe, epochs, structure formation, ...

What about the future? What can we hope to know, and what might remain outside what we can know forever?

1	The nature of dark matter

What can we ever know
GE

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9	Infinities	No	Not possible

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4	The nature of the inflaton	Maybe	We may get a theory
5	Start to the universe?		

What can we ever know

Joe Silk

Standard model is a huge success: size and age of universe, expansion of the universe, epochs, structure formation, ...

What about the future? What can we hope to know, and what might remain outside what we can know forever? New theories may arise and solve presently untestable issues

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5	Start to the universe?	Probably not	Can't go behind inflation
6	Topology of the universe		

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8	Far future universe		

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Challenges for the future

The challenge:
Prove me wrong! There is a lot to be done: can you find ways around the limits I have suggested?

A solid model

The standard model is well established from the Hot Big Bang era on, with some puzzles unresolved: issues that are under investigation. But there are limits on what we will ever know
(Bill McCrea: cosmic uncertainty principle)

Let's avoid hype that misleads the public ....

"Scientists think they have found proof of a parallel universe"
(CMB cold spot)

Its back to the issue of cosmic variance.

New York Post

LIVING

Scientists think they found proof of a parallel universe

By News.com.au

May 18, 2017 | 3:33pm | Updated

Composite; NASA

ORIGINALLY PUBLISHED BY:

news.com.au

NASA detects huge Earth 'bubble'

Scientists believe they may have discovered evidence of a parallel universe that crashed into our own in a galactic impact mirroring a car crash.

Since 2004, when it was first spotted by NASA, scientists have been baffled by the discovery an unusually cold region of space which is 1.8 billion light years across and colder than its surroundings.

CERN Researchers Apologize For Destruction Of 5 Parallel Universes In Recent Experiment

GENEVA—Expressing deep regret over the catastrophic incident that occurred within the Large Hadron Collider, officials from the European Organization for Nuclear Research, also known as CERN, held a press conference Monday to apologize for the destruction of five parallel universes in a recent experiment.

"We are sorry to report that in conducting research involving high-powered proton-proton collisions, we inadvertently caused the implosion of five universes nearly identical to our own," said CERN Director-General Fabiola Gianotti, adding that billions of people worldwide might have experienced momentary vertigo around 9:45 a.m. as a result of several of their alternate identities being wiped from existence.

CERN Researchers Apologize For Destruction Of 5 Parallel Universes In Recent Experiment

"I'd like to emphasize that there is no need to worry, as we were able to contain the damage before our own time stream disintegrated into oblivion like the others. Furthermore, in order to perform an investigation, the LHC will be shut down for the remainder of the afternoon."

At press time, a team of CERN researchers in a parallel universe was preparing to perform the exact same experiment