The 3rd Cosmological Paradigm

less grandly, beyond ΛCDM

Quantum Connections 2021

On the occasion of Frank Wilczek's 70th birthday

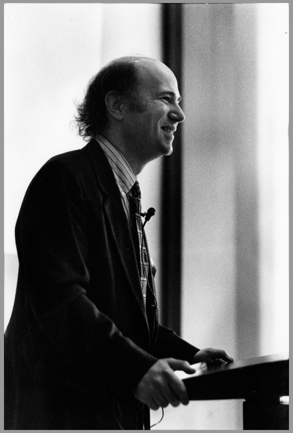
a cosmic perspective

June 22, 2021

Michael S. Turner
Kavli Foundation
Kavli Institute for Cosmological Physics @ UChicago

Frank began his academic career at UChicago as an undergraduate math major
The late Peter Freund gave him a gentle but effective nudge toward physics

Fermilab Ben Lee Symposium 1977



Fond memories of collaborating with Frank: 8 papers, starting at the KITP at UCSB, two in Sweden (Nobel Symposium), all fun, all cosmology

It all started with a December 1981 preprint from Andrei Linde

Volume 48, Number 20 PHYSICAL REVIEW LETTERS 17 May 1982

Reheating an Inflationary Universe

Andreas Albrecht and Paul J. Steinhardt
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

and

Michael S. Turner
Astronomy and Astrophysics Center, The University of Chicago, Chicago, Illinois 60637

and

Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 15 March 1982)

A numerical analysis of the evolution of the Higgs expectation value and the temperature of the universe during the symmetry-breaking phase transition in an SU(5) theory with radiatively induced symmetry breaking is presented. It is shown that there is sufficient inflation (exponential expansion) to explain the cosmological homogeneity, isotropy, flatness, and monopole puzzles, and also that the universe reheats to a temperature $O(10^{14}$ GeV) so that the usual scheme for baryogenesis can proceed.

First slow-roll calculations (done on an HP calculator) and back-to-back PRLs with Albrecht and Steinhardt's seminal "new inflation"

Flight of fancy & first of many physics papers about metastable vacua

Nature Vol. 298 12 August 1982 **633**

LETTERS TO NATURE

Is our vacuum metastable?

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In spontaneously broken gauge theories of particle interactions there are sometimes several local minima of the effective potential. Any of these minima can serve as a vacuum in the sense that we can expand the fields around their values at the minimum, interpret the quantized fluctuations around the minimum as particles, and compare the properties of these particles with experiment. One might think that only the state with absolutely minimum energy could be what we ordinarily call our vacuum, as the other local minima will inevitably decay into this lowest one. However, this is not necessarily the case, because it is possible for the lifetime of a metastable vacuum to be very long, even when compared with the age of the

($V \sim 10^{84}$ cm^3), the probability that an energetically less favourable minimum has decayed during the age of the Universe is exponentially <1 so long as

$$\varepsilon \ll 0.6\,\lambda^{-1/3} \qquad (2)$$

a condition which is easily satisfied.

We now examine the second and third issues in the context of the simplest unified model of particle interactions, the minimal SU(5) theory[7].

At zero temperature the effective potential can be written as[8,9]:

$$V(h, A) = \frac{-\mu^2}{2}\,\mathrm{tr}\,A^2 + \frac{a}{4}(\mathrm{tr}\,A^2)^2 + \frac{b}{2}\,\mathrm{tr}\,A^4 - \frac{\nu^2}{2}h^\dagger h + \frac{\lambda}{4}(h^\dagger h)^2 + \alpha(h^\dagger h)\,\mathrm{tr}\,A^2 + \beta h^\dagger A^2 h \qquad (3)$$

where the discrete symmetry $A \to -A$ has been imposed, h is an SU(5) vector **5** Higgs field, and A is an SU(5) adjoint **24** Higgs field (traceless hermitian matrix). To reproduce the standard (and thus far very successful) SU(5) phenomenology, there must be a local minimum where A acquires a large vacuum expectation value of the form,

First CDM paper (not all the details right and an erratum to prove it)

Volume 125, number 1 PHYSICS LETTERS 19 May 1983

FORMATION OF STRUCTURE IN AN AXION-DOMINATED UNIVERSE

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Frank WILCZEK
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and

A. ZEE
Department of Physics, University of Washington, Seattle, WA 98195, USA

Received 1 March 1983

We consider the formation of structure in a Universe dominated by axions of mass $\approx 10^{-5}$ eV ($f_a \approx 10^{12}$ GeV). Because of their high phase space density and very low temperature, it is not difficult for axions to find their way into galactic haloes. With a suitable initial spectrum of density fluctuations, the present observed structure of the universe could have evolved. However, the Zel'dovich spectrum, which is predicted by some inflationary universe scenarios, is difficult to accommodate.

Volume 125B, number 6 PHYSICS LETTERS 16 June 1983

M.S. Turner, F. Wilczek and A. Zee, Formation of structure in an axion-dominated universe, Phys. Lett. 125B (1983) 35.

Our conclusion that the Zel'dovich spectrum might be unacceptable is based on the fact that our simple analysis indicated that when axions begin to dominate the mass density ($t = t_a$) $\delta\rho/\rho$ is relatively flat from $10^{12} M_\odot$ to $10^{15} h^{-4} M_\odot$ (we estimated the effective α to be about 0.1). Bardeen, Peebles, and Primack have since told us that their independent numerical calculations of the spectrum when $t = t_a$ are not as flat as our estimate indicated, and may in fact be steep enough in this region (10^{12}–$10^{15} h^{-4} M_\odot$) to make the Zel'dovich spectrum viable [P.J.E. Peebles, Dominion Astrophysical Observatory preprint (1983)]. We suspect that our underestimation of the steepness of the spectrum is due to two effects. (1) as mentioned in the text, mass scales which enter the horizon long before $t = t_a$ grow by a factor of O(3) by $t = t_a$, while scales which cross the horizon just before $t = t_a$ do not, (2) for constant curvature perturbations (this is the geometric definition of the Zel'dovich spectrum, and is precisely what is predicted in the inflationary scenarios) mass scales which cross the horizon when the universe is matter-dominated ($t \gg t_a, M \gg 10^{15} \times h^{-4} M_\odot$) are smaller in amplitude by a factor of $5\sqrt{2}$ than those which cross the horizon when the universe is radiation-dominated ($t \ll t_a, M \ll 10^{15} h^{-4} M_\odot$). If the resulting spectrum of density perturbations at $t = t_a$ for an initial Zel'dovich spectrum is sufficiently steep (effective $\alpha \gtrsim 1/3$ for the mass range 10^{12}–$10^{16} M_\odot$), then, as White and Rees [19] have argued, the clustering hierarchy should be successfully reproduced. Furthermore, because the spectrum is, by usual standards, relatively flat up to $10^{15} h^{-4} M_\odot$, there may be sufficient power on large scales to produce voids and filaments. (Melott has recently run a numerical simulation with such an initial spectrum and claims that a preliminary analysis indicates the existence of large scale structure like voids and filaments.)

We thank Jim Bardeen, Marc Davis, Jim Peebles and Joel Primack for pointing out to us that the actual spectrum of density perturbations at $t = t_a$ is steeper than our simplified analysis led us to believe.

* * *

Motivation for Sam Ting's AMS

PHYSICAL REVIEW D VOLUME 42, NUMBER 4 15 AUGUST 1990

Positron line radiation as a signature of particle dark matter in the halo

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(Received 23 February 1989; revised manuscript received 21 February 1990)

We suggest a new signature for particle dark-matter annihilation in the halo: high-energy, positron line radiation. Because the cosmic-ray positron spectrum falls rapidly with energy and the contribution of conventional sources is only expected to be about 5% of the cosmic-ray electron flux, monoenergetic e^+'s from halo annihilations can be a significant and distinctive signal for very massive dark-matter particles (masses greater than about 30 GeV). If the e^+e^- annihilation channel has an appreciable branch—a few percent or more—the e^+ signal could be observable in a future detector, such as have been proposed for ASTROMAG. A significant e^+e^- branching ratio can occur for neutralinos or Dirac neutrinos. In spite of the fact that a heavy Dirac neutrino is no longer an attractive dark-matter candidate and the fact that the e^+e^- branching ratios expected for the currently popular models of the neutralino are very small, the positron signature is so distinctive that we believe it is worthy of note: If seen, it is a "smoking gun" for particle dark matter in the halo. We also note that the positron signature will be of general importance for any future particle dark-matter candidate whose annihilation into e^+e^- is not suppressed.

Nobel Symposium in Graftavallens with a helicopter ride to a cocktail hour (Stephen Hawking in love) and 2 papers

VOLUME 66, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 1991

Inflationary Axion Cosmology

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(Received 26 September 1990)

If Peccei-Quinn (PQ) symmetry is broken after inflation, the initial axion angle is a random variable on cosmological scales; based on this fact, estimates of the relic-axion mass density give too large a value if the axion mass is less than about 10^{-6} eV. This bound can be evaded if the Universe underwent inflation after PQ-symmetry breaking and if the observable Universe happens to be a region where the initial axion angle was atypically small, $\theta_1 \lesssim [m_a/(10^{-6}\text{ eV})]^{0.59}$. We show consideration of fluctuations induced during inflation severely constrains the latter alternative.

This work was supported by NASA (at Fermilab through Grant No. NAGW-1340), the DOE (at The University of Chicago and Fermilab), and by the NSF (at Princeton) and was initiated at the Nobel Symposium on the Birth and Early Evolution of the Universe, held at Graftavallens, Sweden, 1990. M.S.T. thanks the Aspen Center for Physics for its hospitality.

[1]R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978); S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978). For a recent review of the axion, see R. D. Peccei, in *CP Violation,* edited by C. Jarlskog (World Scientific, Singapore, 1989); for a recent review of the astrophysical and cosmological constraints to the axion, see M. S. Turner, Phys. Rep. (to be published).

[2]M. S. Turner, Phys. Rev. Lett. **59**, 2489 (1987).

Graftavallens 2

VOLUME 65, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1990

Relic Gravitational Waves and Extended Inflation

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(Received 30 August 1990)

In extended inflation, a new version of inflation where the transition from an inflationary to a radiation-dominated Universe is accomplished by bubble nucleation, bubble collisions supply a potent —and potentially detectable—source of gravitational waves. The energy density in relic gravitons from bubble collisions is expected to be about 10^{-5} of closure density. Their characteristic wavelength depends upon the reheating temperature T_{RH}: $\lambda \sim (10^4\ \mathrm{cm})[(10^{14}\ \mathrm{GeV})/T_{RH}]$. If black holes are produced by bubble collisions, they will evaporate producing shorter-wavelength gravitons.

Axino dark matter and fun with a fantastic student Krishna Rajagopal

Nuclear Physics B358 (1991) 447–470
North-Holland

COSMOLOGICAL IMPLICATIONS OF AXINOS

Krishna RAJAGOPAL*

Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA

Michael S. TURNER**

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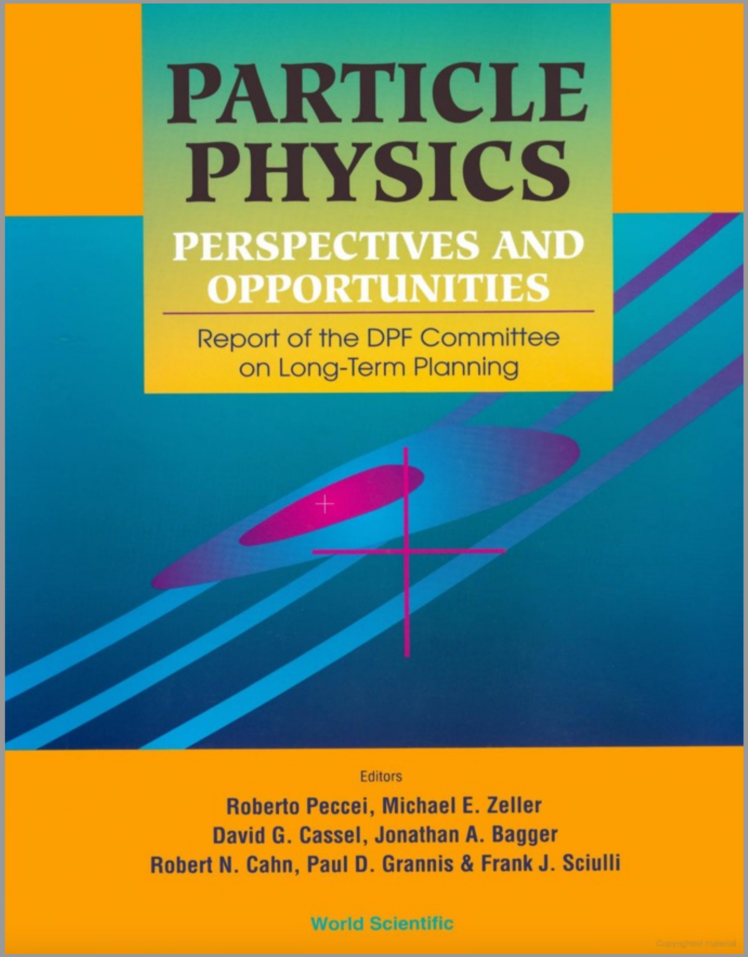
Received 2 January 1991

Axinos are the supersymmetric partners of axions. They arise in models incorporating both low-energy supersymmetry and the axion solution of the strong *CP* problem. In the present state of knowledge several of the key properties of axinos, which control their cosmological consequences, are poorly determined. But generically there are very significant cosmological consequences, and we attempt to survey the possibilities here. In a wide variety of models the axino is the lightest *R*-odd particle, and destabilizes the more conventional candidates for this title (photino, higgsino, ...) on cosmological time scales. While this consideration perhaps casts some shadow over an important class of dark matter candidates, it turns out that in a large class of models the axino itself becomes a plausible dark matter candidate. In other models the axino is heavy, and unstable. Even then axinos are of cosmological interest, because their decay can be the dominant mechanism for production of the lightest *R*-odd particle.



Snowmass 1994:
Two Nobel Prize winners and me.
This should be a blockbuster:
0 citations

The first paradigm: the Hot Big Bang

1925 to 1980

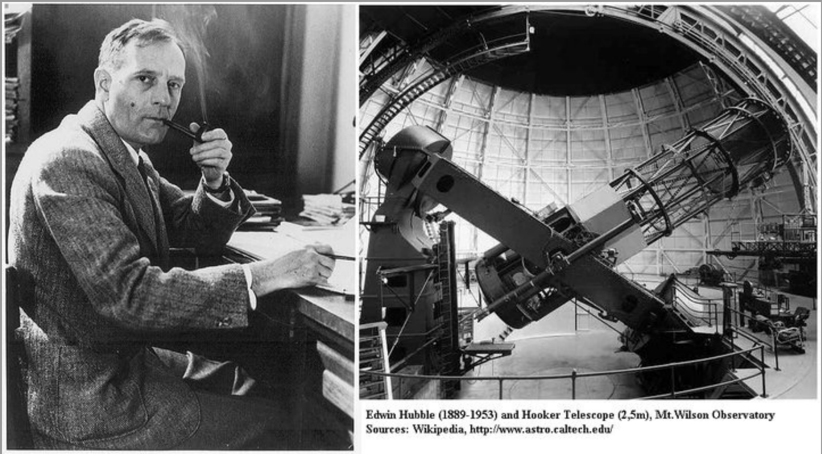
Many contributors

1925 – 1970s

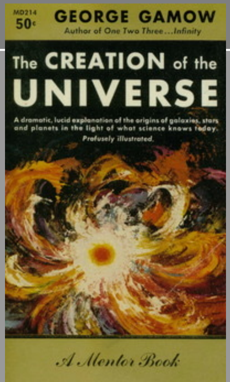
Hubble, Lemaitre, Einstein, Friedmann, Gamow, Hoyle, Penzias & Wilson, Wagoner-Fowler-Hoyle, Peebles, …

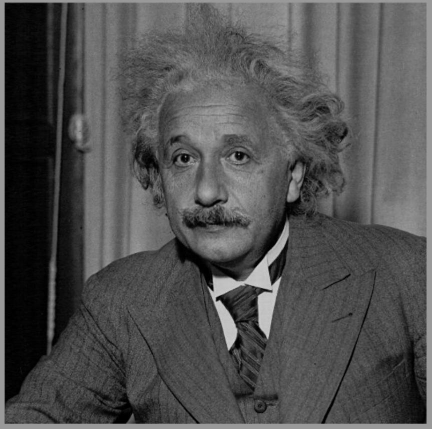
Three basic elements

- General Relativity
- Expansion of a Universe full of galaxies
- Cosmic Microwave Background



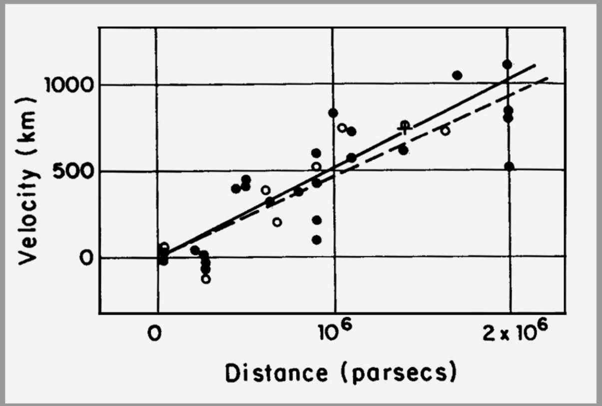
Edwin Hubble (1889-1953) and Hooker Telescope (2,5m), Mt.Wilson Observatory
Sources: Wikipedia, http://www.astro.caltech.edu/

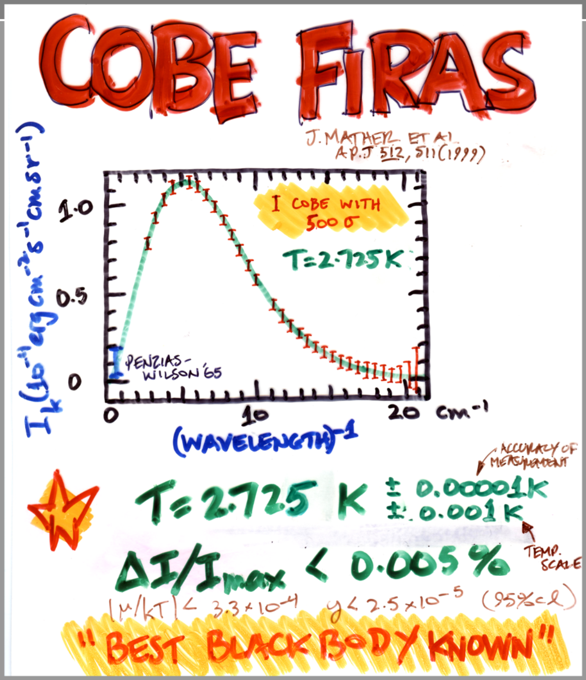


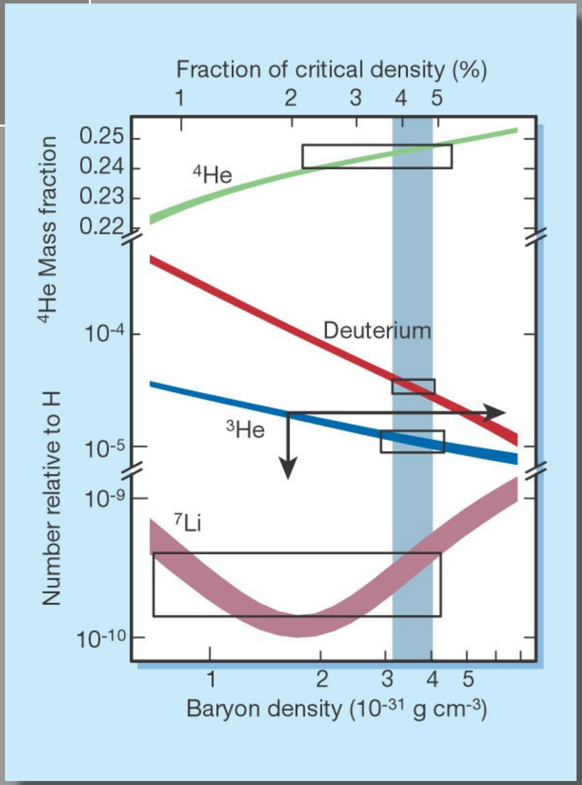


The evidence

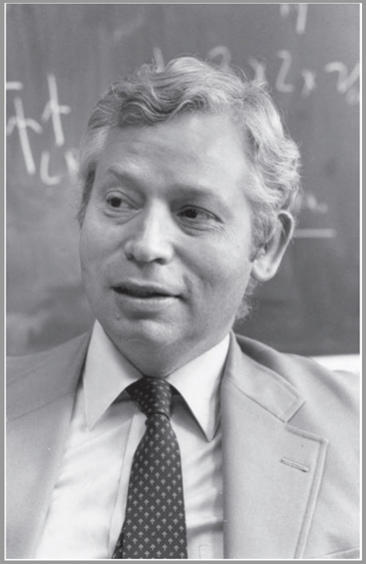
- Few hundred redshifts (z to 0.1)
- CMB is a blackbody (hot, dense beginning is the only explanation
- Light element abundances

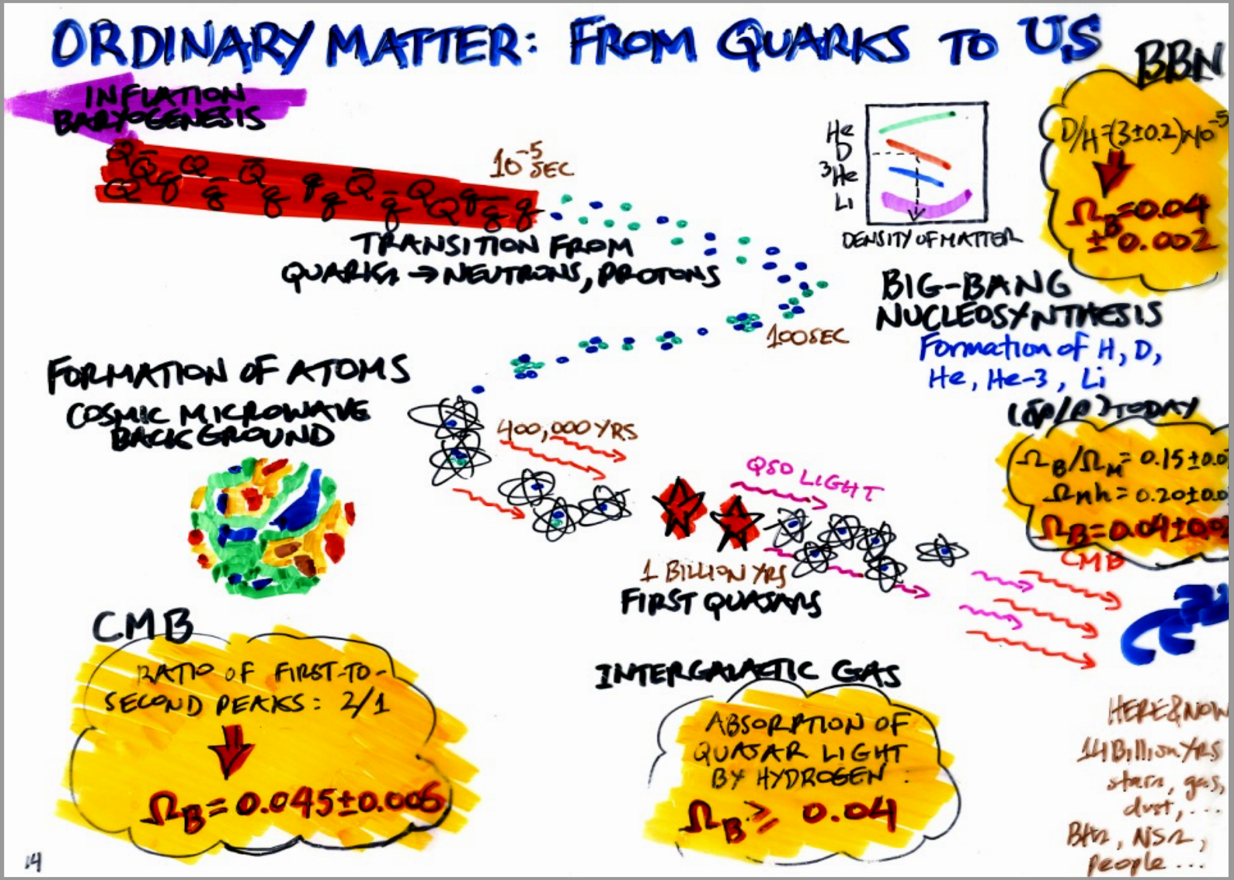


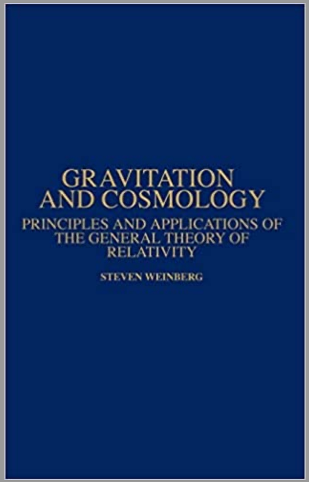




1972 Steve Weinberg coins "The Standard Model" and puts it all together from hadron soup to atoms and galaxies







Except for the quark soup part: "the hadron wall" at 10^{-5} sec

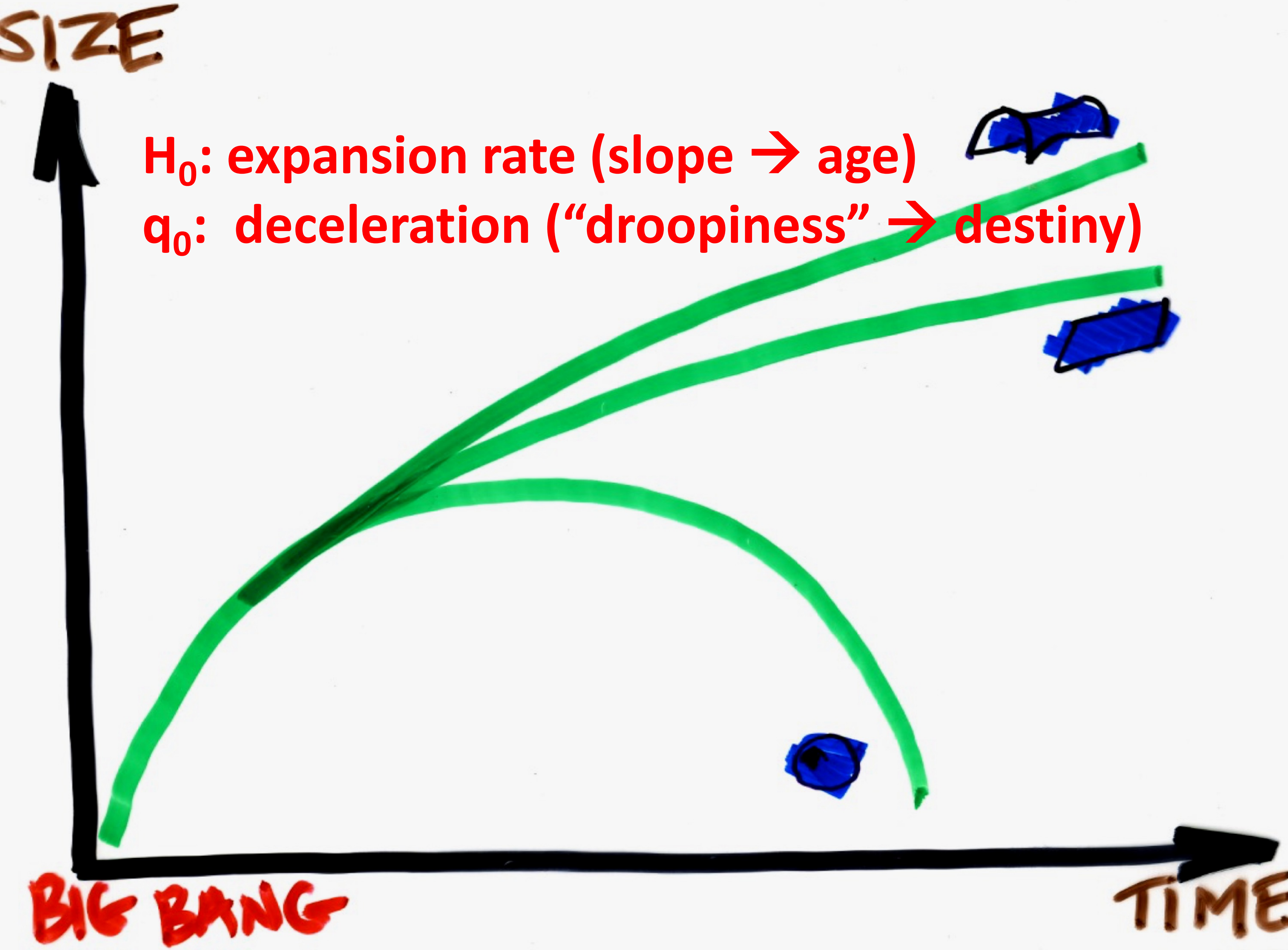
Allan Rex Sandage: just 2 numbers

COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

ALLAN R. SANDAGE

Allan Sandage has been a staff member at the Mount Wilson and Palomar Observatories since he received his PhD from Cal Tech in 1953. His main interests are stellar evolution, observational cosmology, form of the redshift laws, quasars and distance scales. In 1960 Sandage and Thomas Matthews were the first to isolate the quasars.


SIZE
H_0: expansion rate (slope → age)
q_0: deceleration (“droopiness” → destiny)
BIG BANG
TIME

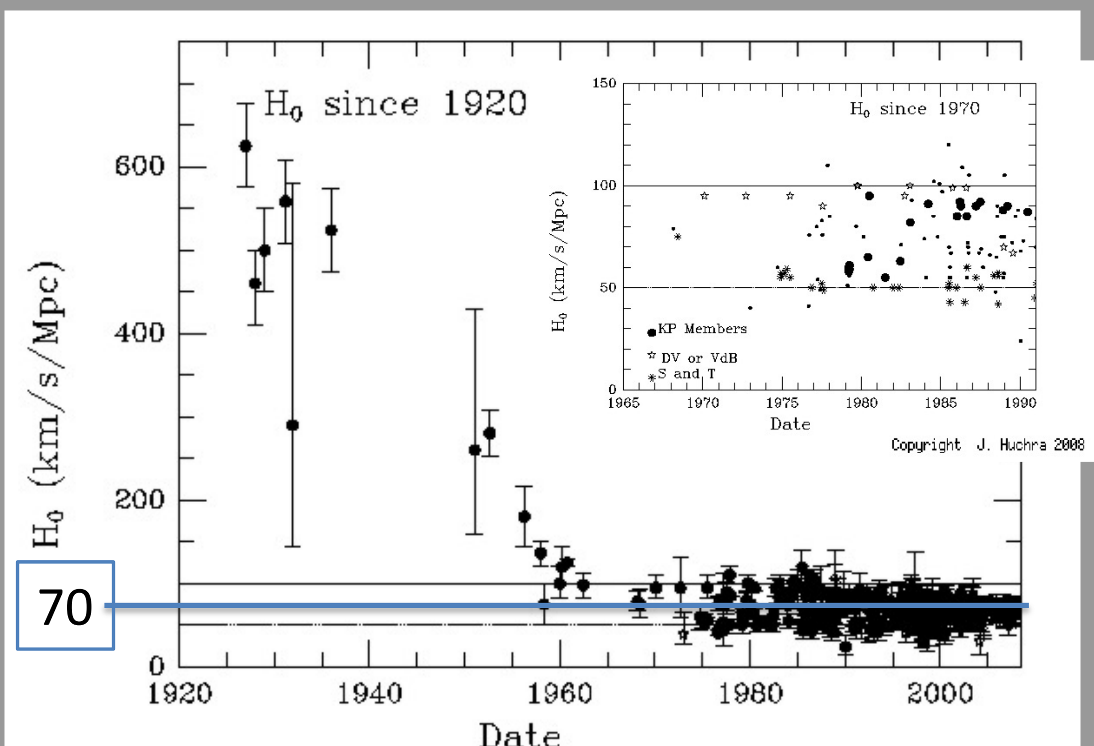
H_0 reined in, part one

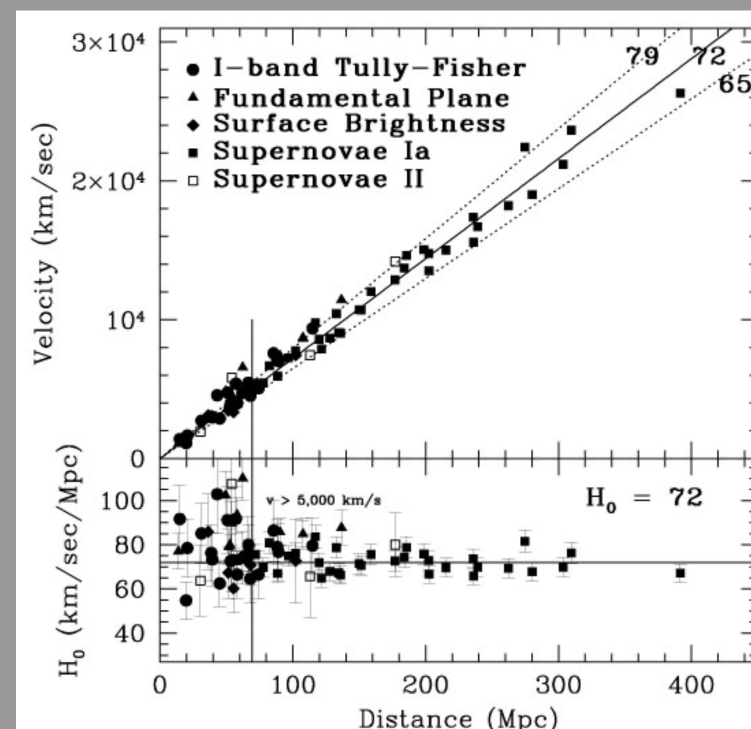
Final Results from the *Hubble Space Telescope* Key Project to Measure the Hubble Constant*

Wendy L. Freedman[1], Barry F. Madore[1,2], Brad K. Gibson[3], Laura Ferrarese[4], Daniel D. Kelson[5], Shoko Sakai[6], Jeremy R. Mould[7], Robert C. Kennicutt, Jr.[8], Holland C. Ford[9], John A. Graham[5]
+Show full author list

The Astrophysical Journal, Volume 553, Number 1
Citation Wendy L. Freedman *et al* 2001 *ApJ* **553** 47

$H_0 = 72 \pm 2 \pm 6$ km/s/Mpc





… and q_0 is not even measurable!

The Astrophysical Journal, 769:133 (8pp), 2013 June 1
doi:10.1088/0004-637X/769/2/133

BEYOND H_0 AND q_0: COSMOLOGY IS NO LONGER JUST TWO NUMBERS

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Received 2012 September 7; accepted 2013 April 9; published 2013 May 14

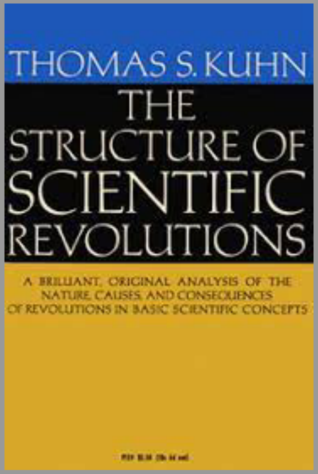
ABSTRACT

For decades, H_0 and q_0 were the quest of cosmology, as they promised to characterize our "world model" without reference to a specific cosmological framework. Using Monte Carlo simulations, we show that q_0 cannot be directly measured using distance indicators with both accuracy (without offset away from its true value) and precision (small error bar). While H_0 *can* be measured with accuracy and precision, to avoid a small bias in its direct measurement (of order 5%) we demonstrate that the pair H_0 and Ω_M (assuming flatness and $w = -1$) is a better choice of two parameters, even if our world model is not precisely ΛCDM. We illustrate this with analysis of the Constitution set of supernovae and indirectly infer $q_0 = -0.57 \pm -0.04$. Finally, we show that it may be possible to directly determine q_0 with both accuracy and precision using the time dependence of redshifts ("redshift drift").

Key words: cosmological parameters – methods: numerical – supernovae: general

Online-only material: color figures

PS: … and one astronomer (the referee) learned the difference between precision and accuracy (note definitions in ABSTRACT!)

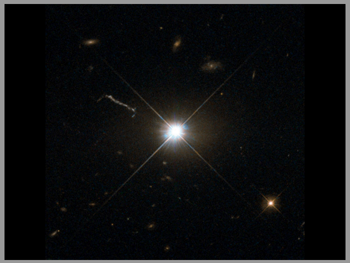


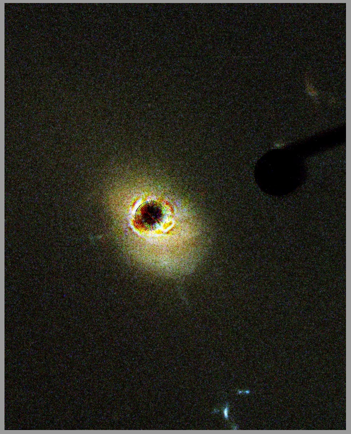
The old paradigm is broken by phenomena it cannot explain and/or new opportunities emerge

- Structure formation and ***<u>dark matter(!!)</u>***
- Baryon asymmetry
- Smooth beginning, long-lived expansion and seeds for galaxies
- Asymptotic freedom → quark soup beginning, grand unification → no hadron wall and new ideas

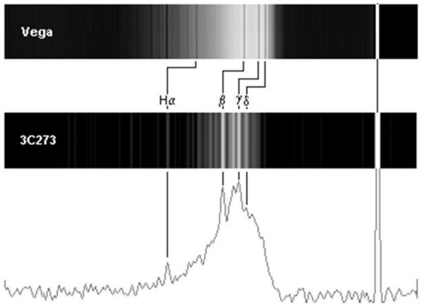
1963: The year the Universe changed

Discovery of quasars and the relativistic Universe


3C273


3C273
Host galaxy

QUASARS: Quasi-Stellar Radio Objects. **Maarten Schmidt** examined **3C273** (3C=Third Cambridge Catalog of Radio sources) and found its distance from its redshift to be 2 billion light years--not a star, and L = 10^{40} watts--1,000 L (MW)!!



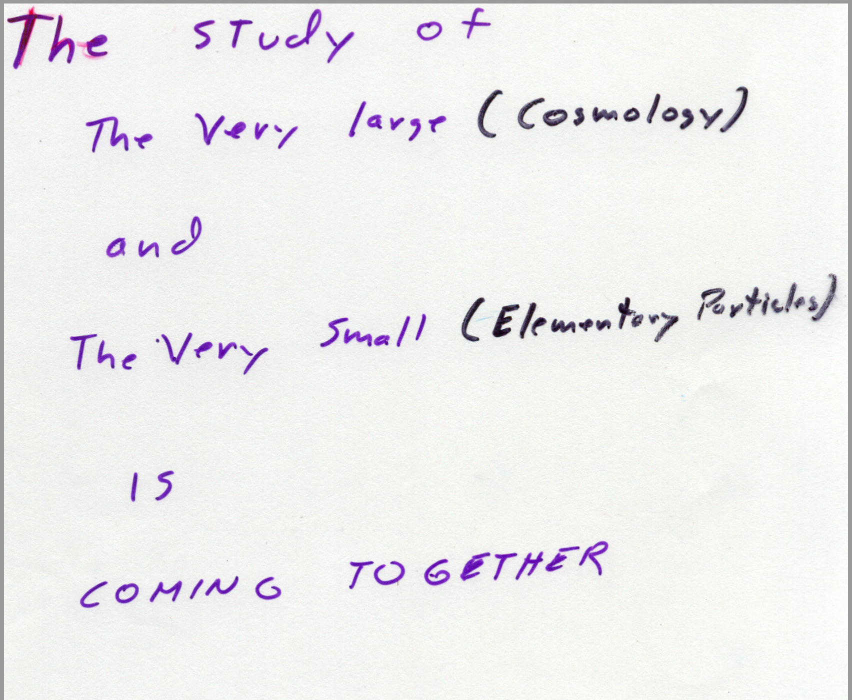
The remarkable redshift of 0.158

2008 Kavli Prize to Schmidt and Lynden-Bell

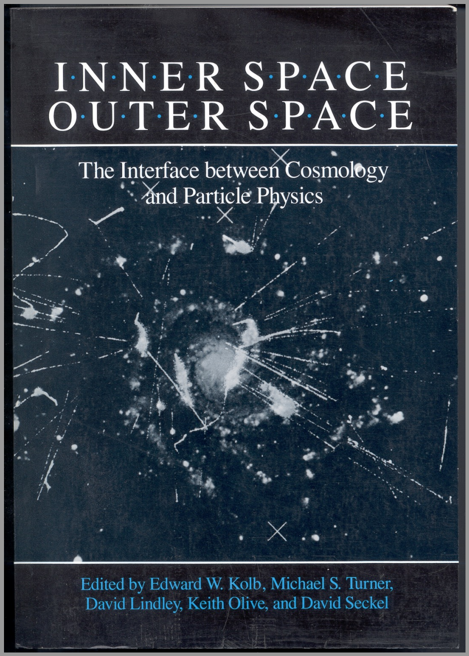
The second paradigm: ΛCDM

1980 to present

The coming together of the very big and the very small



David Schramm circa 1980



Fermilab Symposium May 1983

Coming together of cosmology and particles has changed the vocabulary, the players and the experimental techniques

Dark Matter

WIMPs

Inflation

Baryogenesis

Dark Energy

CDM

Quark Soup

The ΛCDM story of the Universe

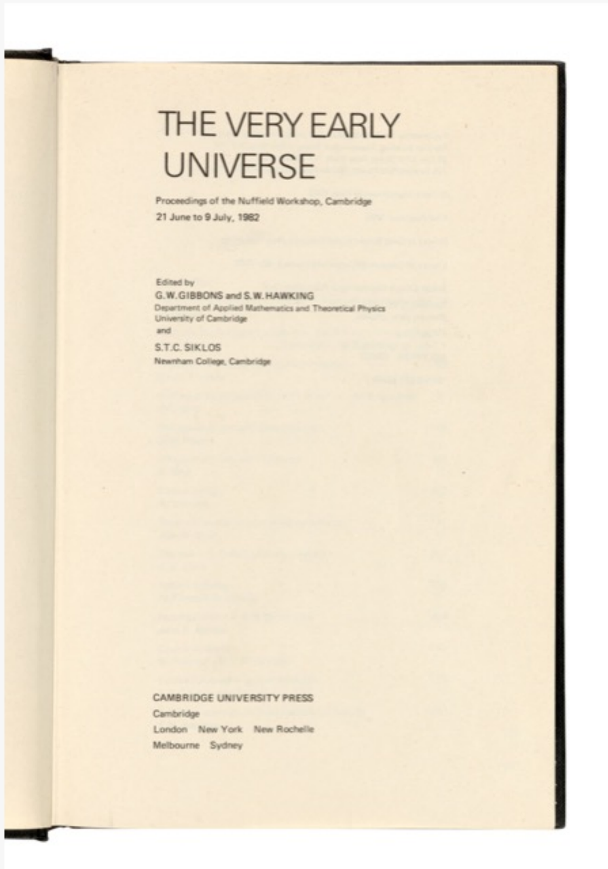
… very-early accelerated expansion driven by the potential energy of a scalar field gives rise to a very-large, smooth, spatially flat patch that will become all that we can see today. Quantum fluctuations during this accelerated phase grow into the seeds for galaxies. The conversion of potential field energy into heat produces the quark soup that evolves a baryon asymmetry and long-lived dark matter particles. The excess of quarks over antiquarks becomes neutrons and protons, later some light elements and finally atoms. The gravity of the dark matter particles drives the formation of structure from galaxies to superclusters and a mere 5 billion years ago the repulsive gravity of dark energy (Λ) again drove accelerated expansion …

… has revealed new physics too

- The repulsive gravity of **Dark Energy** explains cosmic acceleration and Λ (quantum vacuum energy) is the default dark energy candidate
- A very early burst of tremendous expansion – **Inflation** – explains our smooth, flat Universe with seeds for galaxies grown from quantum fluctuations
- The gravity of slowly-moving **Dark Matter** particles (CDM) holds all cosmic structures together
- **Baryogenesis** produces an excess of matter over anti-matter and the survival of a small number of baryons today (few per billion photons)

Birth of modern cnflation

Nuffield Workshop, Cambridge, June 1982



Hawking's own copy of the Nuffield Workshop of 1982

Stephen Hawking, G. Gibbons & S. Siklos. 1983

Price Realised
GBP 4,375

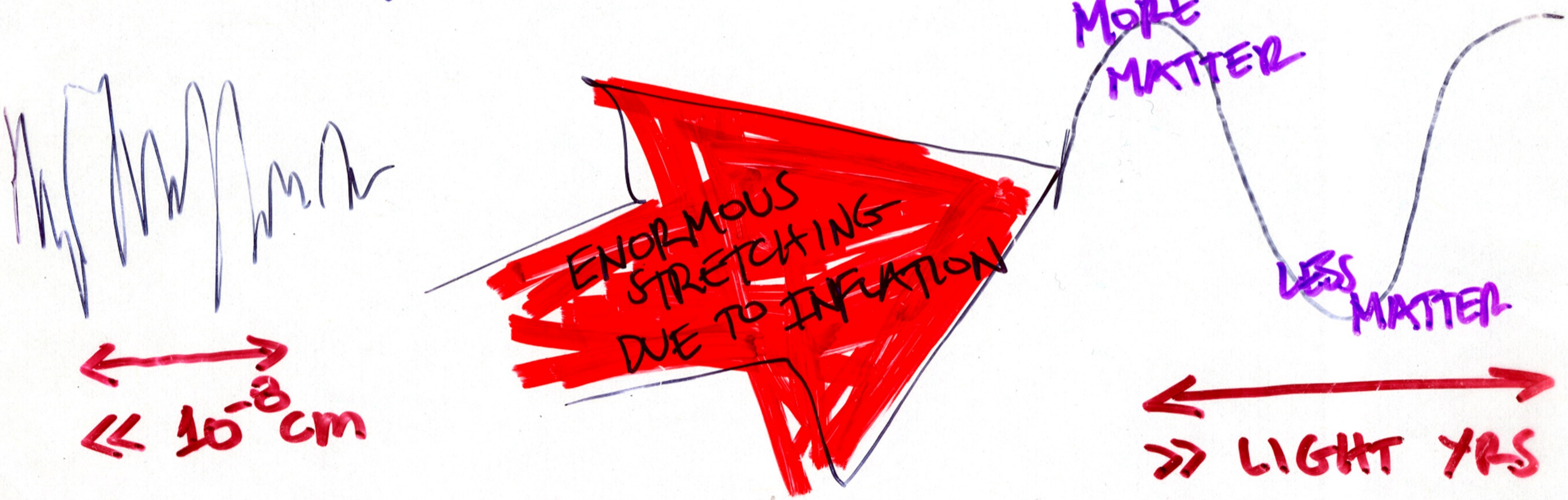
Estimate
GBP 500 - GBP 800

Closed: **16 Jul 2020**

Save | Share

FLUCTUATIONS: MICRO TO MACRO

Bardeen-Steinhardt-MST; Guth-Pi; Hawking; Starobinskii 1982



QUANTUM FLUCTUATIONS ON SUBATOMIC SCALE

"LUMPY" DIS-TRIBUTION OF MATTER ON MACRO SCALE

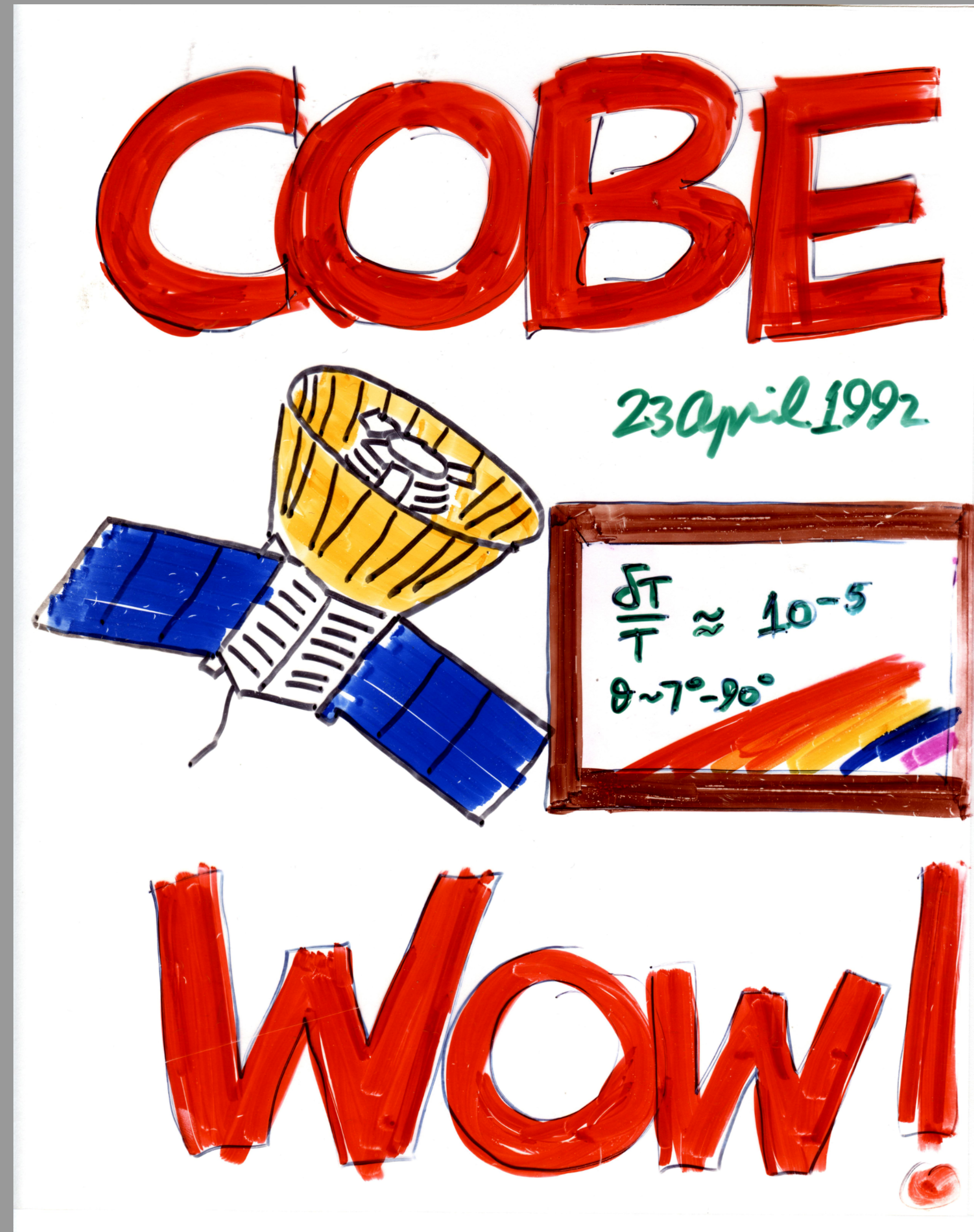
"RIPPLES" IN THE MICROWAVE ECHO

TEMPERATURE VARIATION $\approx 30\,\mu K$

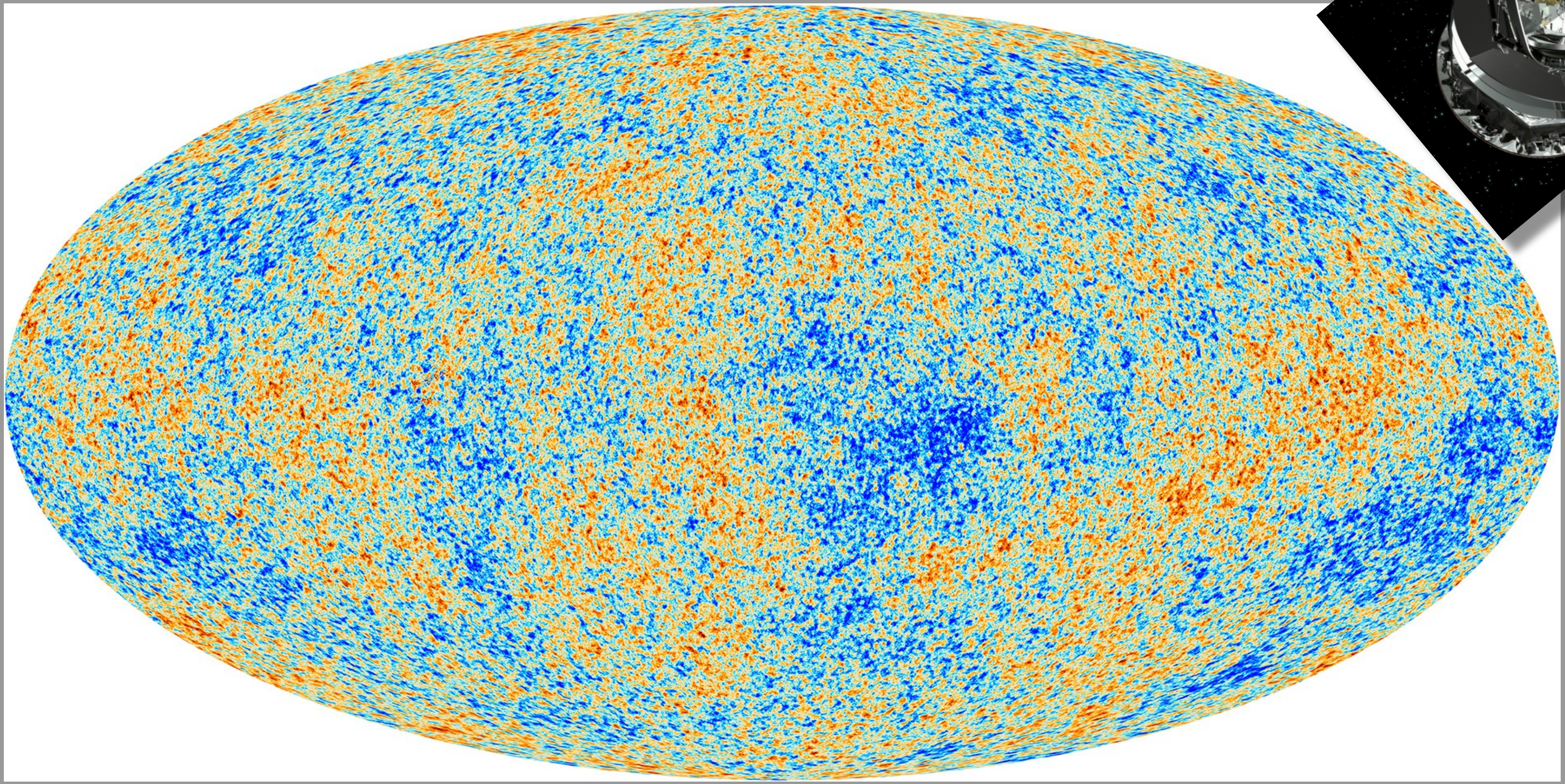
→ EVIDENCE FOR "PRIMEVAL LUMPINESS" THAT SEEDED STRUCTURE (STARS, GALAXIES, CLUSTERS OF GALAXIES, SUPERCLUSTERS VOIDS, WALLS, ...)

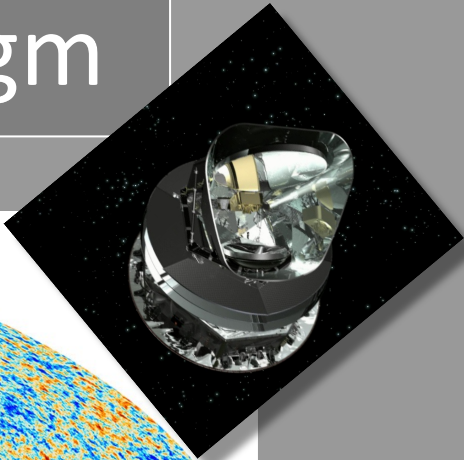
S. HAWKING: "GREATEST DISCOVERY OF ALL TIME"

ONLY A SLIGHT OVERSTATEMENT



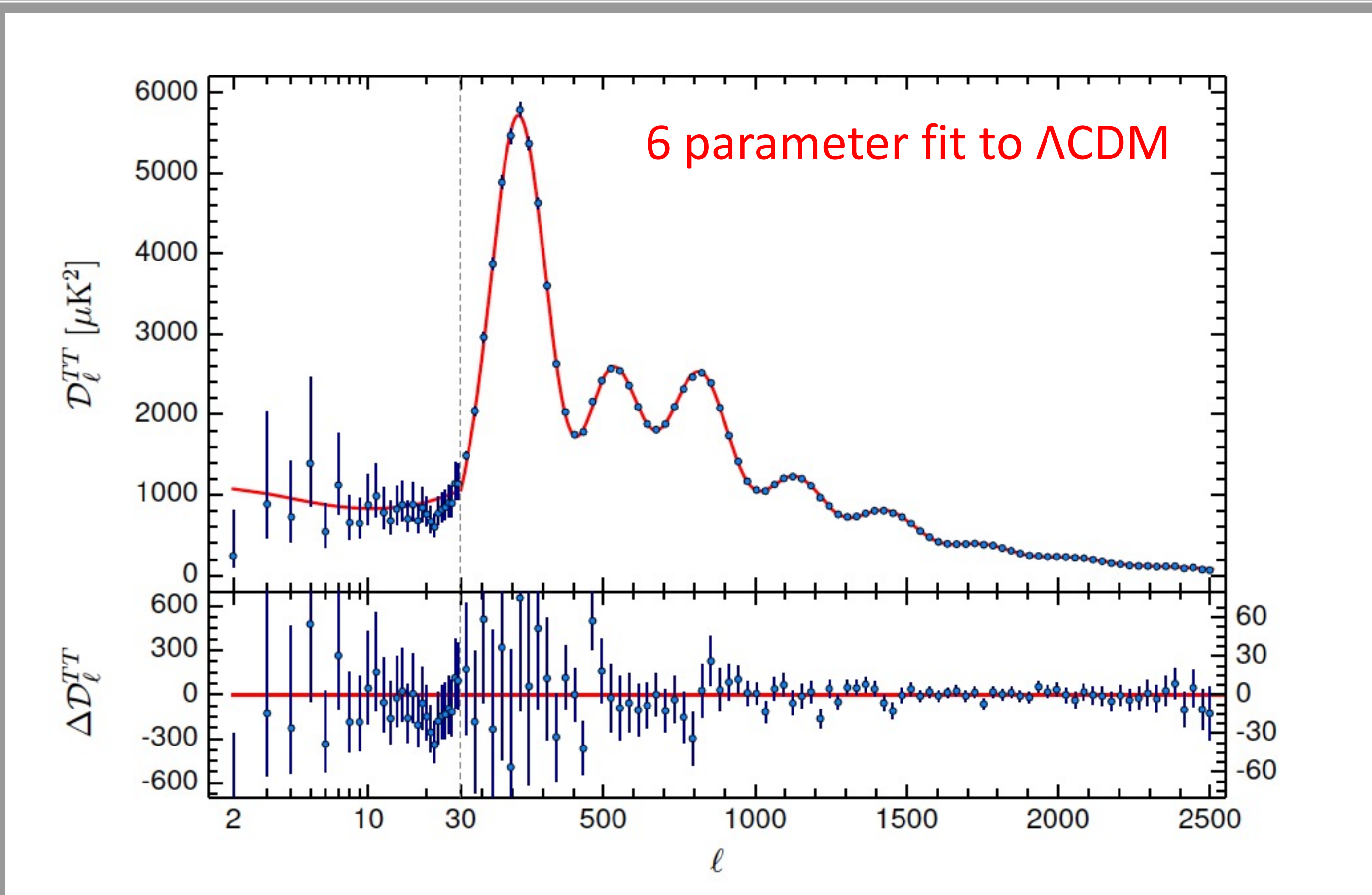
The remarkable ΛCDM paradigm

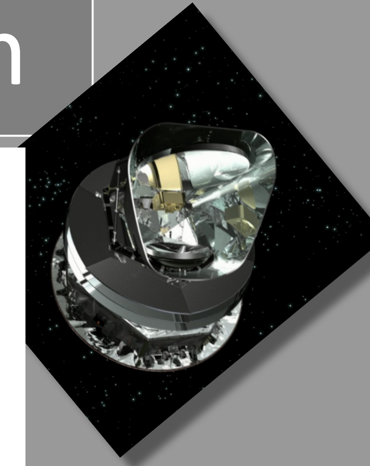




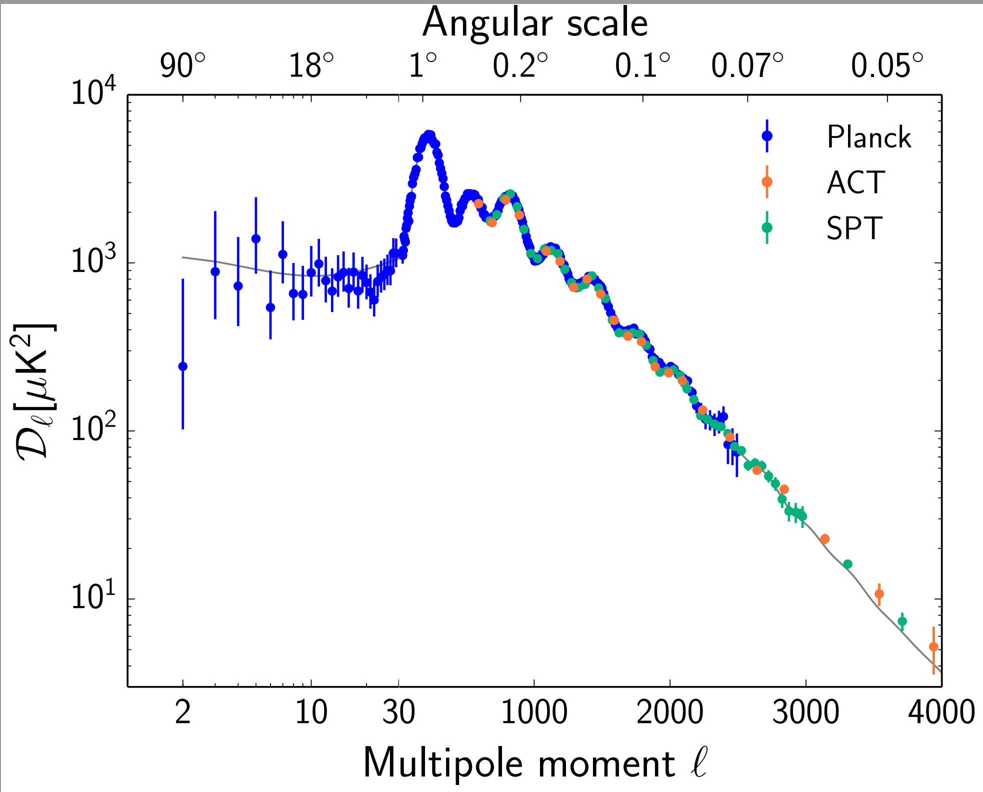
6 numbers describe the Universe from
the big bang until today

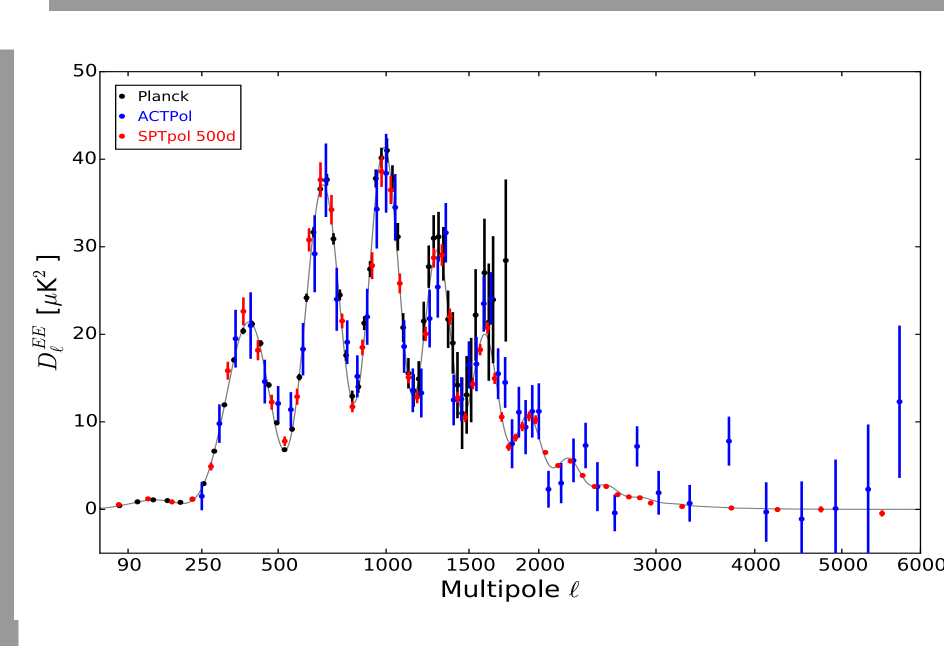
The remarkable ΛCDM paradigm



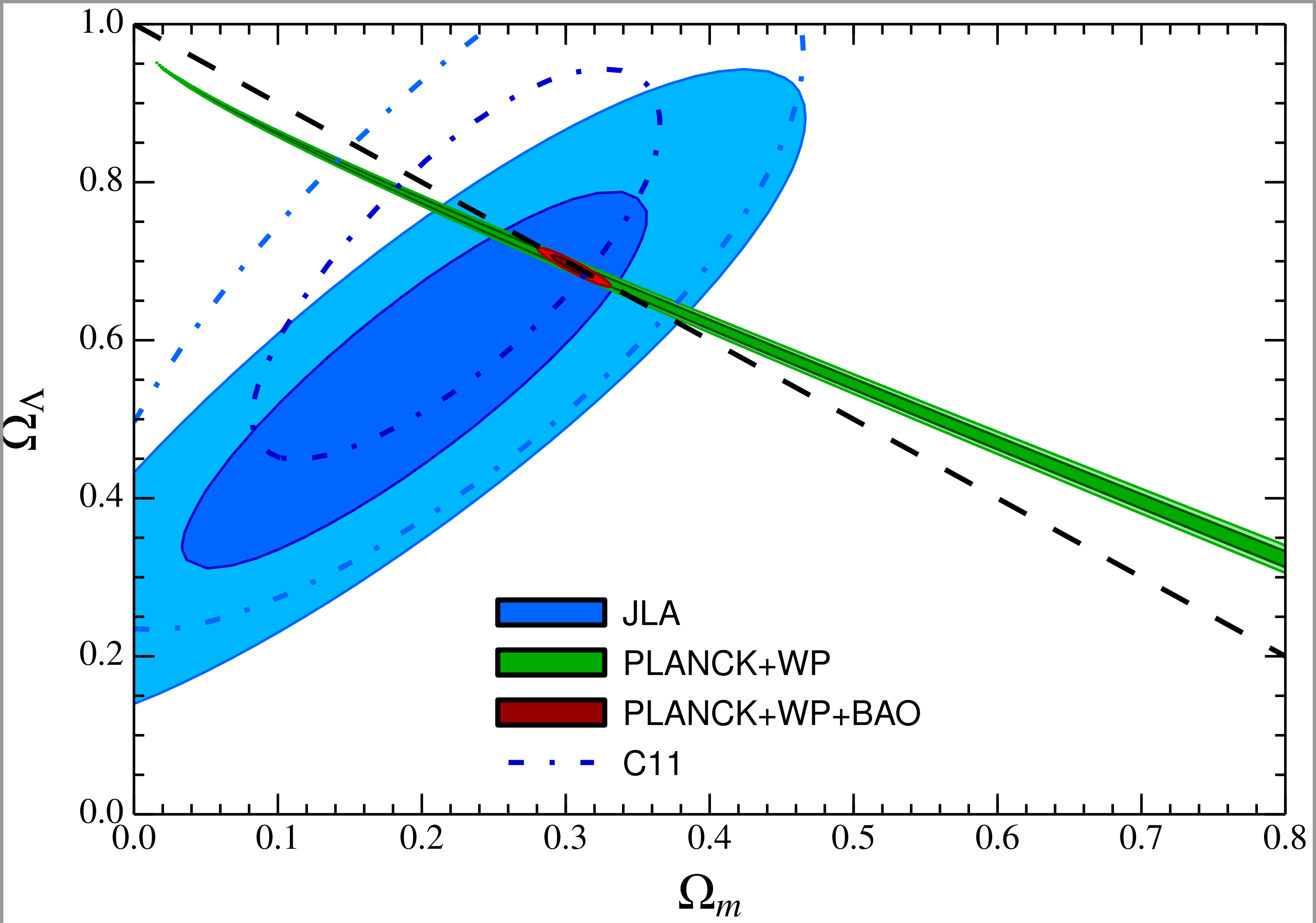


6 numbers describe the Universe from
the big bang until today

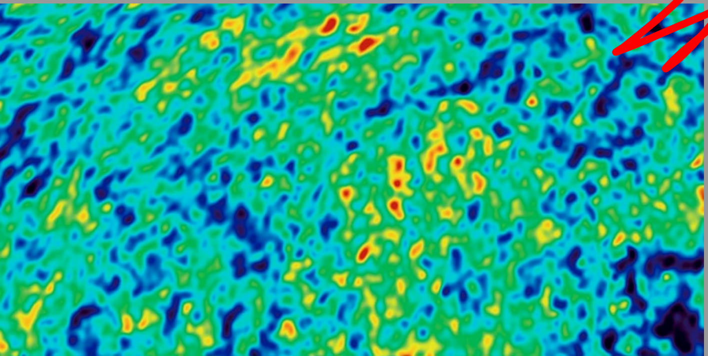

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
Planck
ACT
SPT
$\mathcal{D}_\ell [\mu K^2]$
2
10
30
1000
2000
3000
4000
Multipole moment ℓ


Planck
ACTPol
SPTpol 500d
50
40
30
20
10
0
D_ℓ^{EE} [μK^2]
90
250
500
1000
1500
2000
3000
4000
5000
6000
Multipole ℓ

Λ fits perfectly!



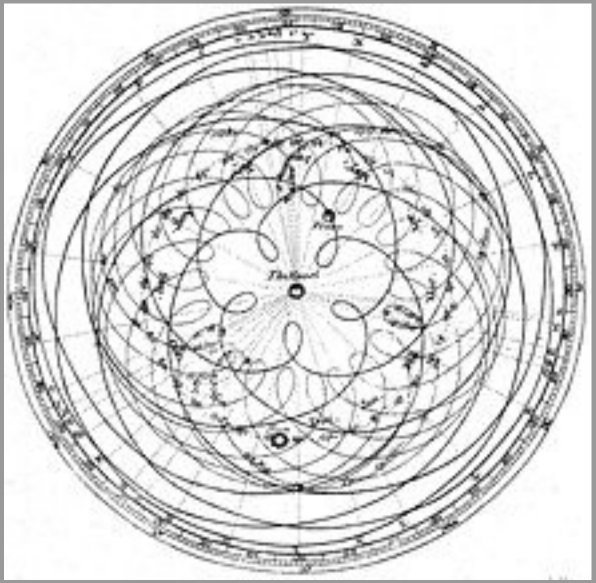
Grandest quantum connection



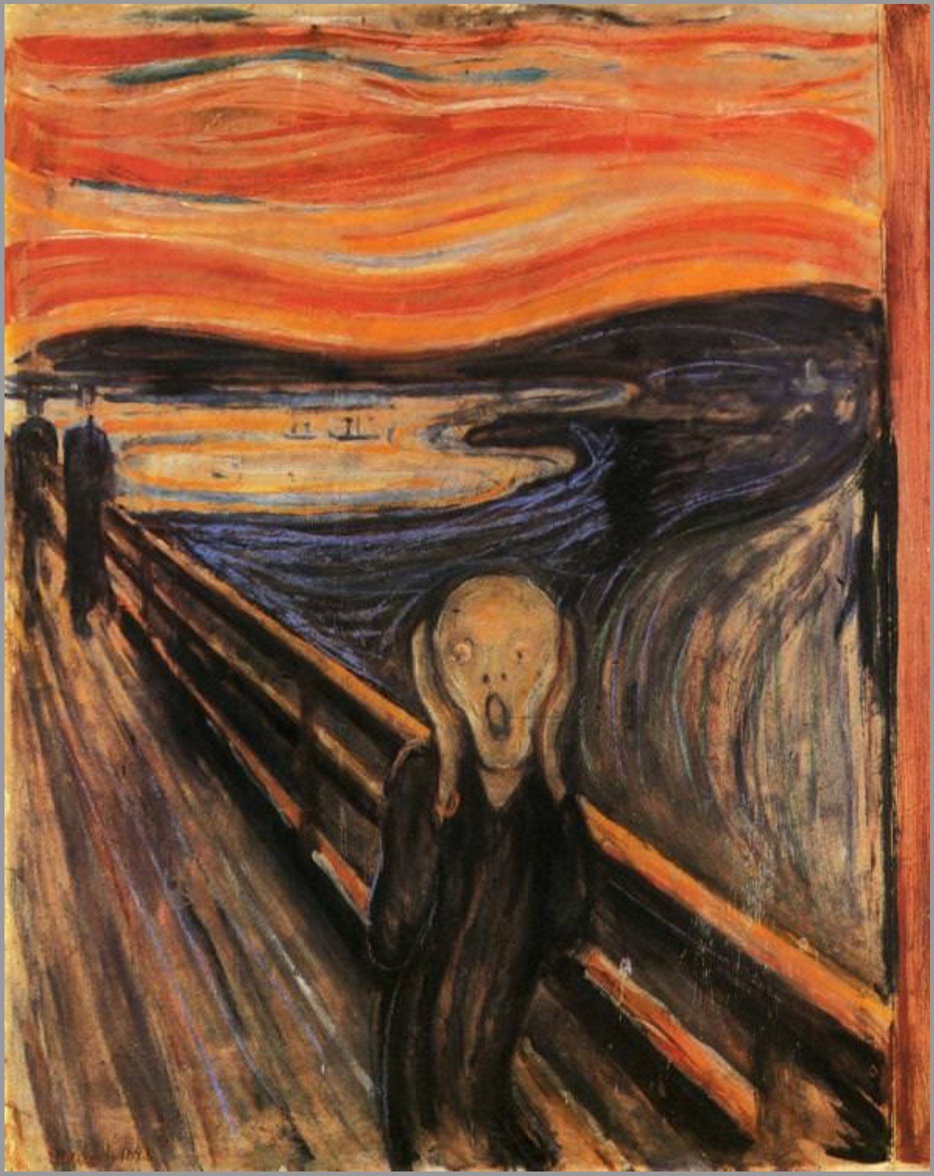
ΛCDM: More than we hoped for, now less than we want to settle for

- Cosmic acceleration is still the most profound mystery in all of science – not to mention the lightness of the quantum vacuum
- No standard model – let alone fundamental model – of inflation
- Dark matter particle still unidentified!
- Baryogenesis details too!
- ΛCDM: New physics or just epicycles?

<u>At very least, baryogenesis, dark matter, inflation and dark energy are pushing the paradigm to its limits</u>



What to do about the multiverse



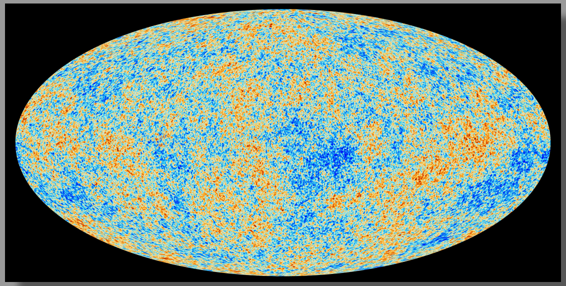
- Most important discovery since Copernicus?
- Answer to the before the "Big Bang" question?
- Is it science? (not testable!)
- Many true believers

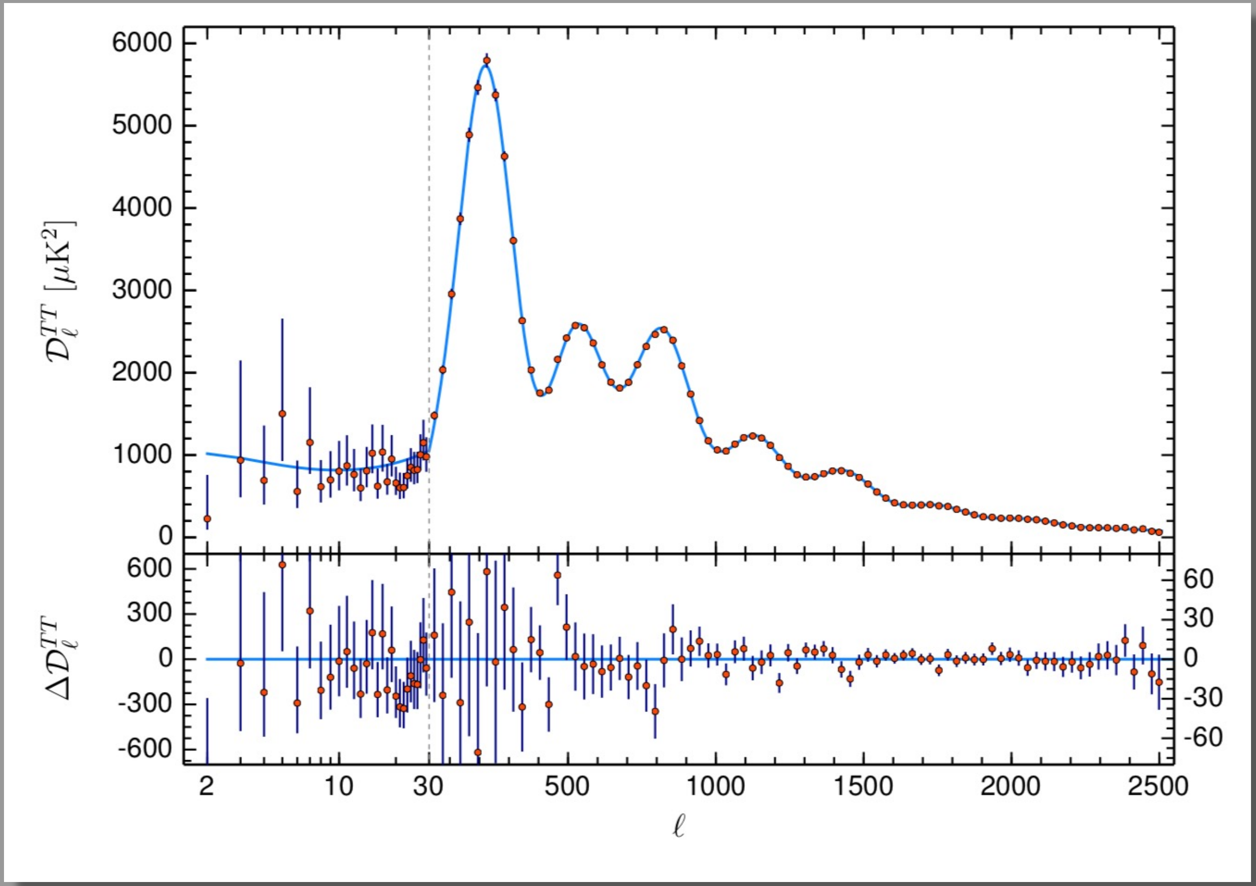
The third paradigm: ______

- How expansive: origin of space, time and the Universe? Laws of physics too?
- What will trigger the 3rd paradigm? When?
- Not the story of us! Astrophysical cosmology as interesting as it is, is not what I am talking about!

What are our aspirations?

ΛCDM 6 numbers: new version of q_0/H_0?

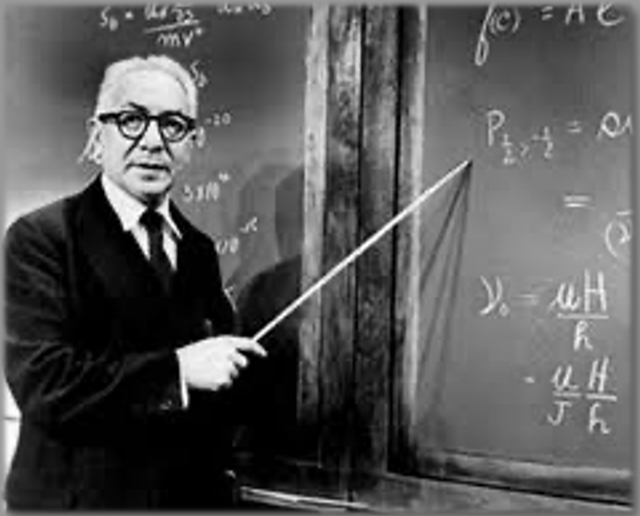




1. Baryon density
2. Matter density
3. Density perturbation amplitude
4. Tilt
5. Sound horizon
6. Optical depth

A very complicated Universe

- Atoms : Democritus to 1964
- + photons: 1964
- + neutrinos (e, μ): 1967
- + exotic dark matter: 1981
- + CDM: 1983/4
- + massive neutrinos: 1998
- + dark energy: 1998
- + τ neutrino: 2000
- Done? Not likely!
- Why is $\Omega_{CDM}/\Omega_B \approx 5$?

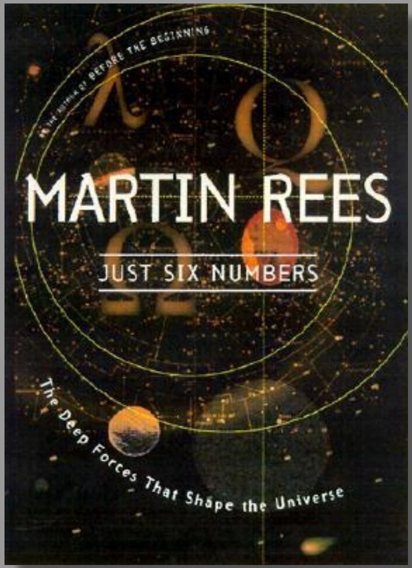


I.I. Rabi
Who ordered that?

How much room for more:
- UR: ~$0.2\rho_{CMB}$
- NR: ~$0.1\rho_{crit}$
- Other leftovers: ??

How many numbers should it take to determine our Universe?

Lord Rees of Ludlow: just 6 numbers



1. 3 dimensions of space
2. Weak gravity = 10^{-36} x EM
3. Energy release in 4 H → He is $0.007mc^2$
4. Flat Universe
5. Small Λ
6. Density perturbations: $Q = 10^{-5}$

My aspiration: zero numbers

once given the ”laws of physics”

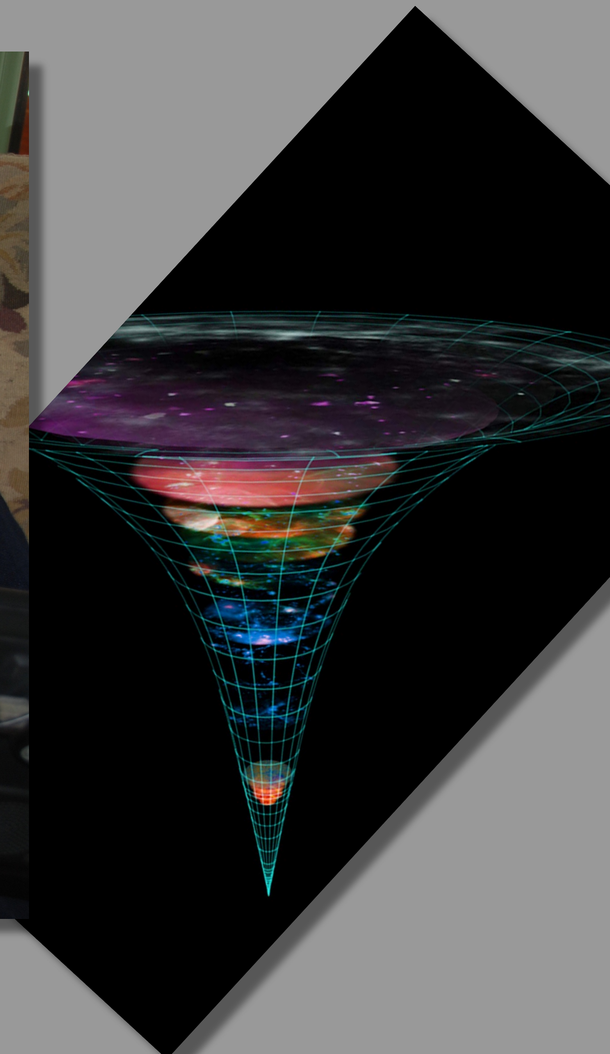
- Laws of physics (not initial conditions or parameters) determine the present large-scale features of the Universe and statistical properties (climate not weather)
- Agnostic to the uniqueness of “TOE”, the “watchmaker,” and to the existence of a multiverse/“ensembiverse”
- Successes:
  - Big bang nucleosynthesis (no need to specify initial chemical abundances; nuclear physics + expansion determines the primordial mix)
- Partial successes:
  - Baryogenesis (no need to specify initial baryon asymmetry or large entropy per baryon; baryon number + C/CP violation + expansion determine the outcome)
  - Structure formation (once the initial homogeneity is specified, gravity + expansion and hydro determine the outcome)

Murray Gell-Mann: 0 numbers

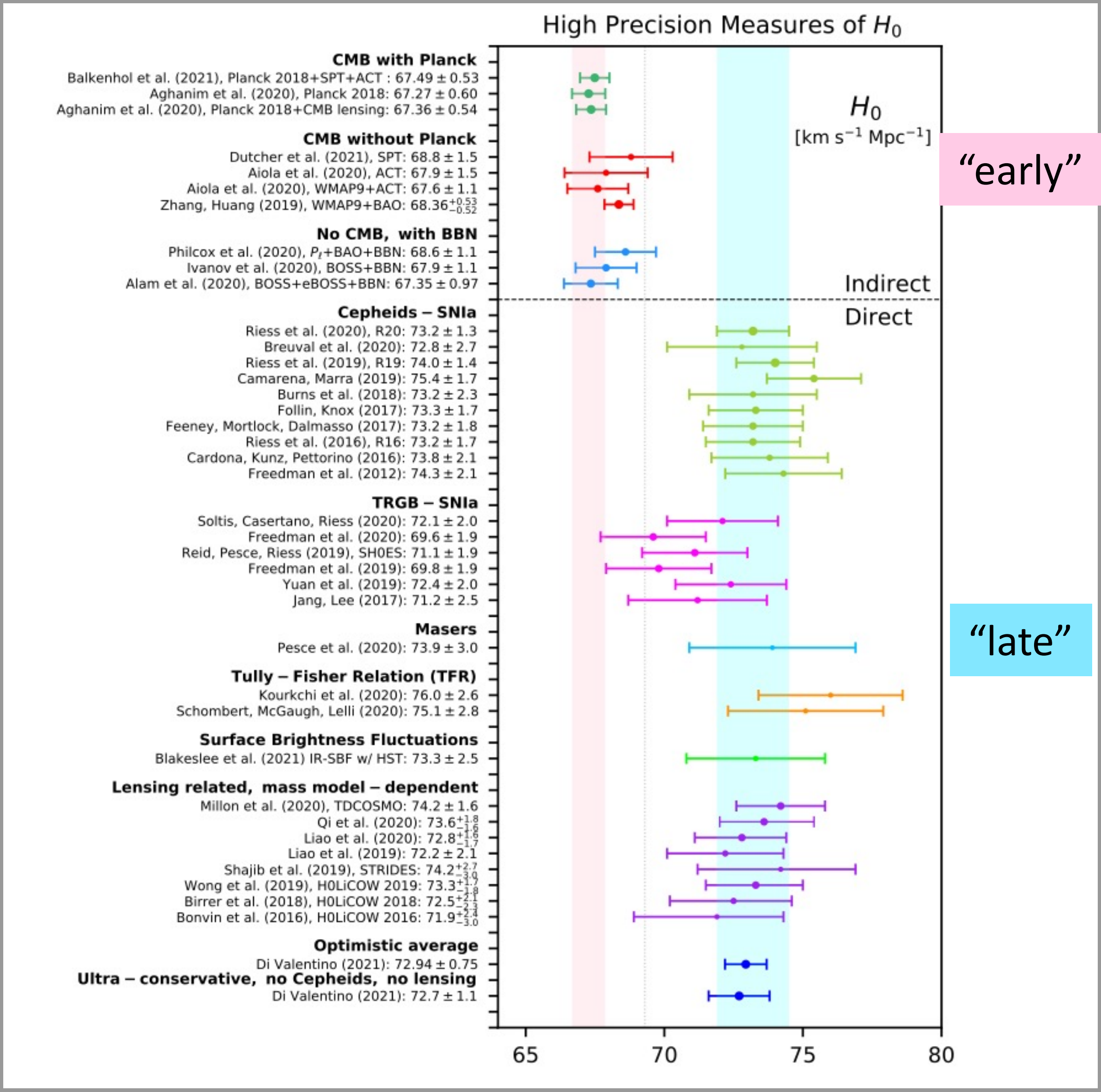
There is a unique Theory Of Everything (the TOE) – a string theory – and the rest is "weather"*

*paraphrasing here, he said environmental science

Hartle-Hawking: 0 numbers
wavefunction of the Universe determines the initial state (Ψ is specified by the TOE)



Hubble troubles: a path forward?



"early"

"late"

- Indirect (pink): 68.5 ± 0.5 km/s/Mpc

George Efstathiou (Planck)

- Direct (cyan): 73.2 ± 1.3 km/s/Mpc

Adam Riess (SHoES)

- 5 sigma difference!

arXiv:2103.01183

Measuring different things!

- Direct (today):
  - NB: "v easy, d hard"
  - Distance ladder: standard candles – Cepheids, TRB, SNe1a
  - Time delay (jump ladder)
  - Both agree

$$H_0 = \frac{\dot{\mathrm{R}}}{\mathrm{R}} = \frac{\text{galaxy velocity}}{\text{galaxy distance}}$$

$$\text{distance} \sim \frac{\text{time delay}}{\theta^2}$$

- Indirect (early via CMB)

$$d_{\mathrm{CMB}} = \frac{v_{\mathrm{sound}} t_{\mathrm{CMB}}}{\theta_{\mathrm{sound}}} = H_0^{-1} \int \frac{dz}{[\Omega_M (1+z)^3 + \Omega_\Lambda]^{1/2}}$$

- Direct and indirect could both be correct and paradigm wrong! Or, one or both measurements could be wrong and ΛCDM correct

Gravitational-lensing measurements push Hubble-constant discrepancy past 5σ

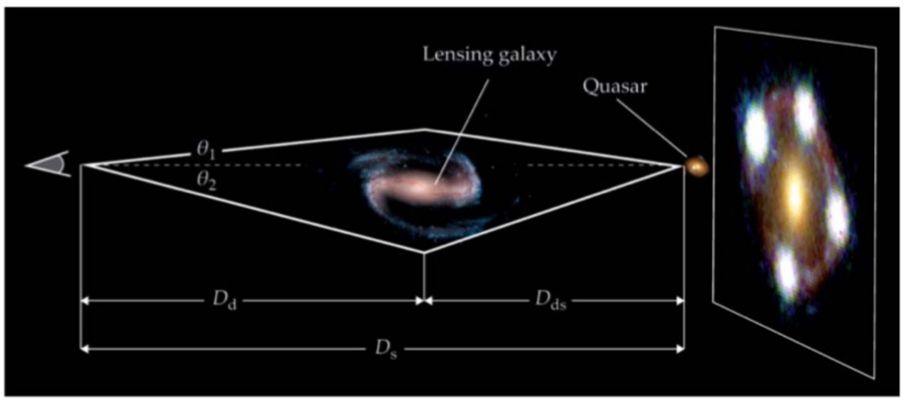


FIGURE 1. STRONG GRAVITATIONAL LENSING by a foreground galaxy can cause a quasar to appear as several distinct images. Observing the relative time delays among those images provides information about the combination of distances between Earth, the lensing galaxy, and the quasar. Given that the angles θ_1 and θ_2 are small, the difference in path lengths shown here is proportional to $D_d D_s / D_{ds}$; the difference in light travel time, which includes the effects of general relativity and the universe's expansion, is proportional to that same value. (Image by Freddie Pagani.)

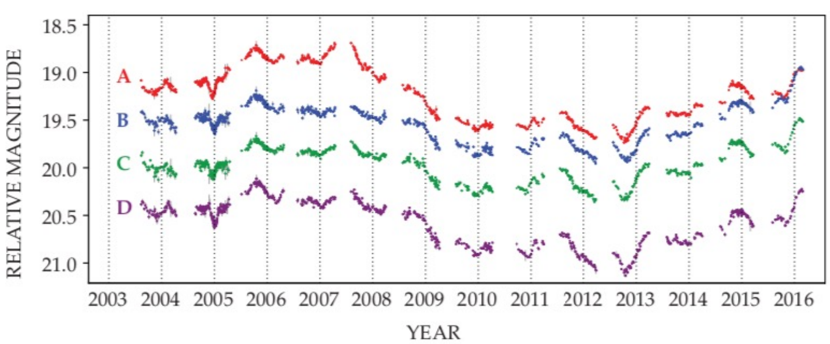


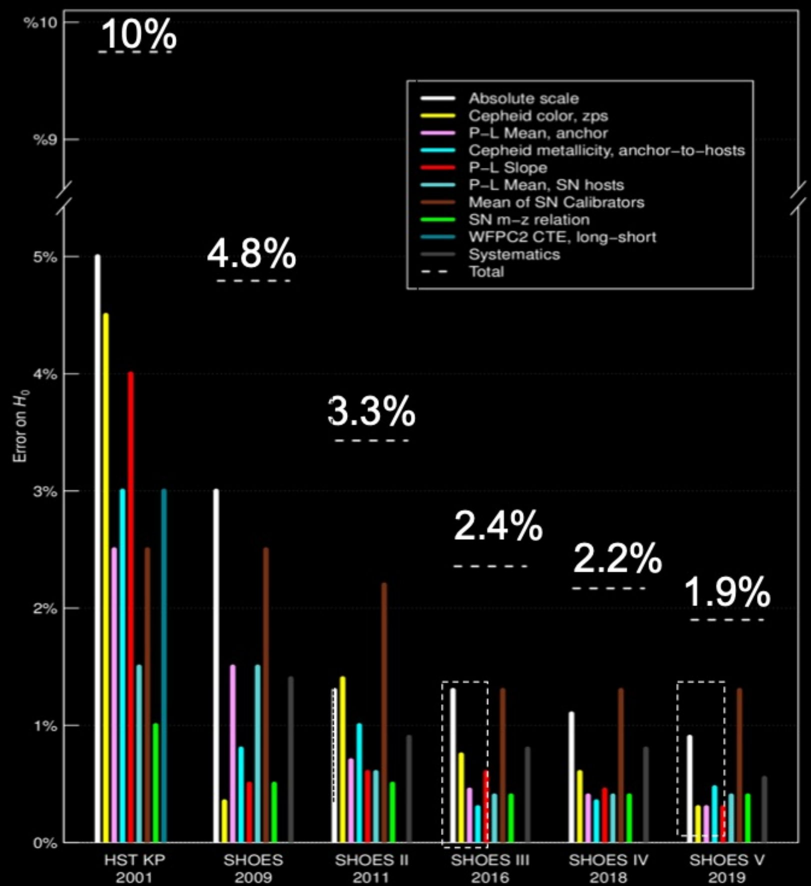
FIGURE 2. LIGHT CURVES from the four lensed images of the quasar shown in figure 1, collected over 13 years by five telescopes from the COSMOGRAIL (Cosmological Monitoring of Gravitational Lenses) collaboration. Fluctuations in the quasar's intensity appear first in images A and C, then in image B, and finally, about two weeks later, in image D. (Adapted from ref. 3.)

$$\text{distance} \sim \frac{\text{time delay}}{\theta^2}$$

Adam Riess: KICP 2018

Note steady progress from 10% to 1.9%

Distance Ladder Error Budgets for H_0 (w/ SN+Cepheids) 2001-2019



2016-2019 Improvements:

Anchors

- MW parallax & HST fluxes (Riess + 2018a,b)
- LMC DEBs & HST fluxes (Riess + 2019a)
- NGC 4258 masers (Reid, Pesce, Riess 2019)
- WFC3 CRNL (Riess + 2019b)

2019-2020 Improvements:

Cepheid-SN Ia Calibrators

- Doubling: 19→38

Gaia DR3

v4

“New physics”

- The two discrepant measurements could both could be right if our current paradigm (ΛCDM) – in a classic Kuhnian paradigm shift – is wrong!
- New ingredients to ΛCDM
  - Early dark energy
  - Oscillations, rock & rock
  - *??*

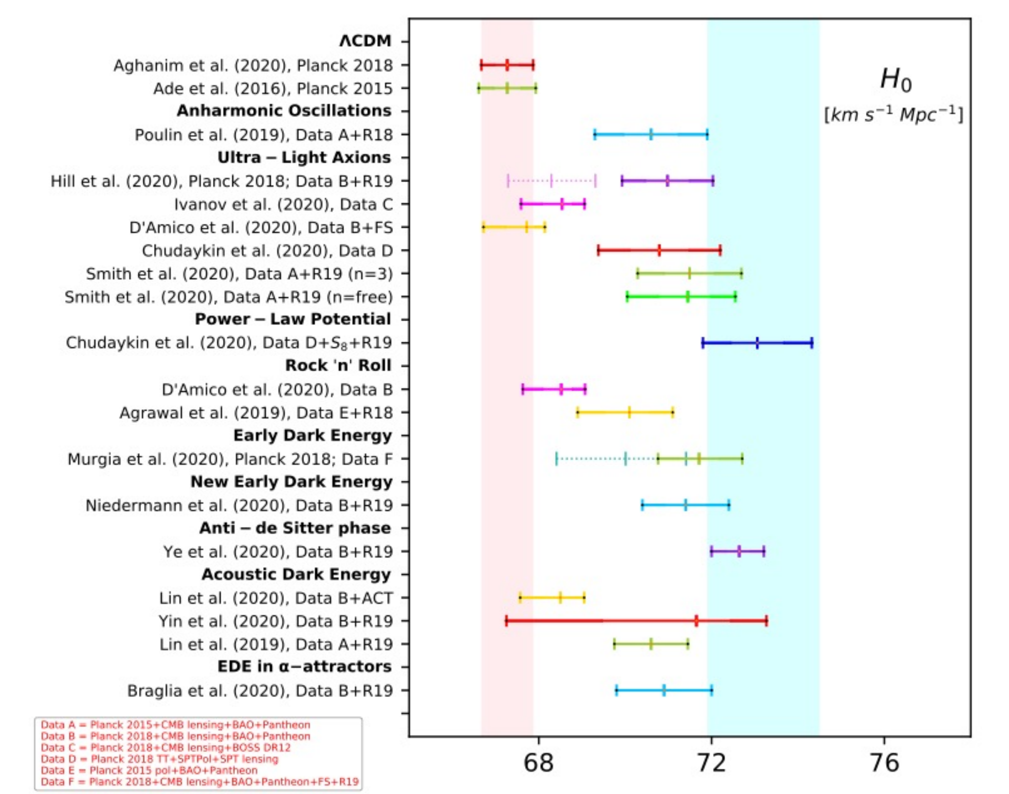
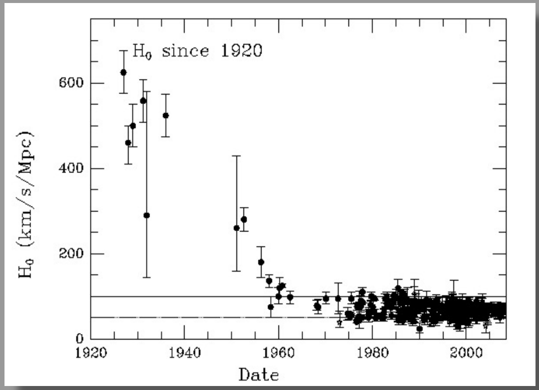


Figure 4. Whisker plot with the 68% marginalized Hubble constant constraints for the models of Section 4. The cyan vertical band corresponds to the H_0 value measured by R20 [2] and the light pink vertical band corresponds to the H_0 value estimated by *Planck* 2018 [11] in a ΛCDM scenario. For each line, when more than one error bar is shown, the dotted one corresponds to the *Planck* only constraint on the Hubble constant, while the solid one to the different dataset combinations reported in the red legend, in order to appreciate the shift due to the additional datasets.



Or one or both measurements could be wrong: precision cosmology is hard, accurate cosmology is harder! And remember the checkered history of H_0

ΛCDM paradigm shift: adding one (odious) thing, solved FIVE problems with Inflation + CDM. H_0 doesn't look quite as compelling

General Relativity and Gravitation, Vol. 27, No. 11, 1995

The Cosmological Constant Is Back†

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

A diverse set of observations now compellingly suggest that the universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the favored value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges — and opportunities — that this poses for particle physics and for extending our understanding of the evolution of the universe back to the earliest moments.

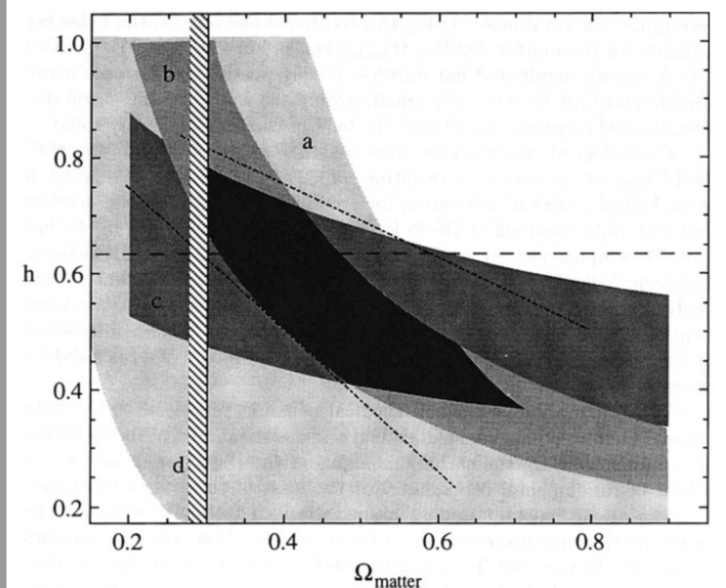


Figure 1. Constraints on the matter density in a flat universe as a function of the Hubble constant $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Shaded regions indicate allowed regions of parameter space. Region (a) comes from combining big-bang nucleosynthesis limits with x-ray observations of clusters, (b) arises from considerations of clustering on large scales, (c) is based on age determinations of globular clusters, (d) is a lower limit based on virial estimates of the density of clustered matter on large scales. The horizontal dashed line is a one sigma lower limit on the Hubble constant from recent Hubble Space Telescope measurements. The diagonal dashed lines represent the allowed limits of phase spaced based on combining COBE normalization of cold dark matter models with estimates of matter density fluctuations on galactic and cluster scales. The dark shaded region indicates the region allowed by all constraints.

What could possibly go wrong

- Initial conditions might matter
  - Axion dark matter: depends upon the initial misalignment of the axion field, a random variable if PQ symmetry breaking occurs before inflation
  - Penrose is right: it is all about the initial singularity
- Universe is often just beyond the reach of our biggest ideas and most powerful instruments
  - No TOE or too many missing pieces

Back to the “numbers question”

1. Zero : <u>Unifying physical theory</u> is all that is needed
   - Gell-Mann, Hartle-Hawking

2. Handful: <u>Descriptive</u> (largely theory agnostic)
   - For example, the “CMB 6” or H_0/q_0

3. Handful: <u>Anthropic/multiverse</u> (infer from first principles what is needed for our existence!)*
   - Rees, West Coast, …

*That is why it is often called the narcissistic principle

And then, the limits of cosmology

- Limited by past light cone (GFR Ellis)
- "The iron curtains": CMB, neutrinosphere, <u>inflation</u>
- Testability in an historical science
  - e.g., what constitutes proof of inflation? dark matter?
- Technology (hard and soft)
  - Dogs cannot understand QM; can we understand the Universe?
- Nature of science: theories are disprovable, not provable & the assumption of objective reality

… but hopefully not by our passion to understand our Universe