

- MODERN COSMOLOGY - ALMOST PERFECT BUT INCOMPLETE

HERMANO VELTEN

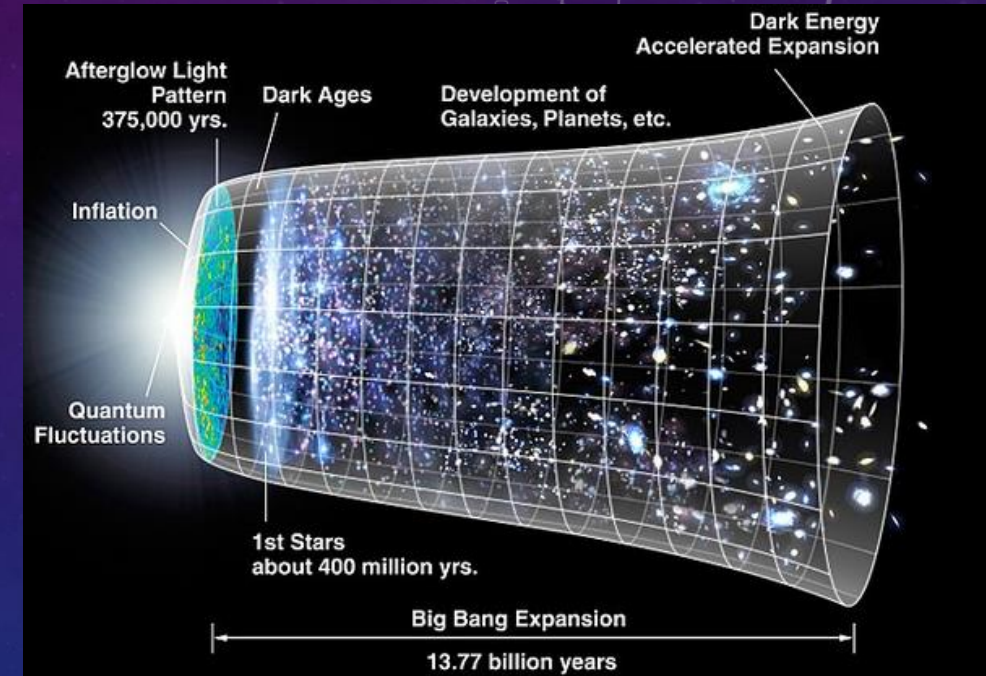
UNIVERSIDADE FEDERAL DE OURO PRETO

VERÃO QUÂNTICO 2021

GUARAPARI, ES, BRAZIL. OCTOBER 07-12, 2021.

SERIES OF 3 TALKS

- **(BASIC)** Talk 1: The rise of Cosmology along the 20th century as a research field and basic assumptions
- **(THEORY)** Talk 2: How we have modelled and mapped the dark sector of the universe
- **(OBSERVATIONS)** Talk 3: The latest results and the state of the art



Then, as precision increases, the array of possible interpretations permitted by uncertainties in the observation will be correspondingly reduced. Ultimately, when a definite formulation has been achieved, free from systematic errors and with reasonably small probable errors, the number of competing interpretations will be reduced to a minimum.”

Edwin Hubble, The Law of Red-Shifts, 1953, MNRAS 113, 658

FROM TRADITIONAL TO MODERN COSMOLOGY

THE 20TH CENTURY SAGA

- Two dramatic shifts in paradigm: 1) from a Mathematical Science to a Physical Science
2) from a Physical Science to an Observational Science
- Then turned into a EXACT Science: 1) method of prediction and
2) falsification (comparing to observations)

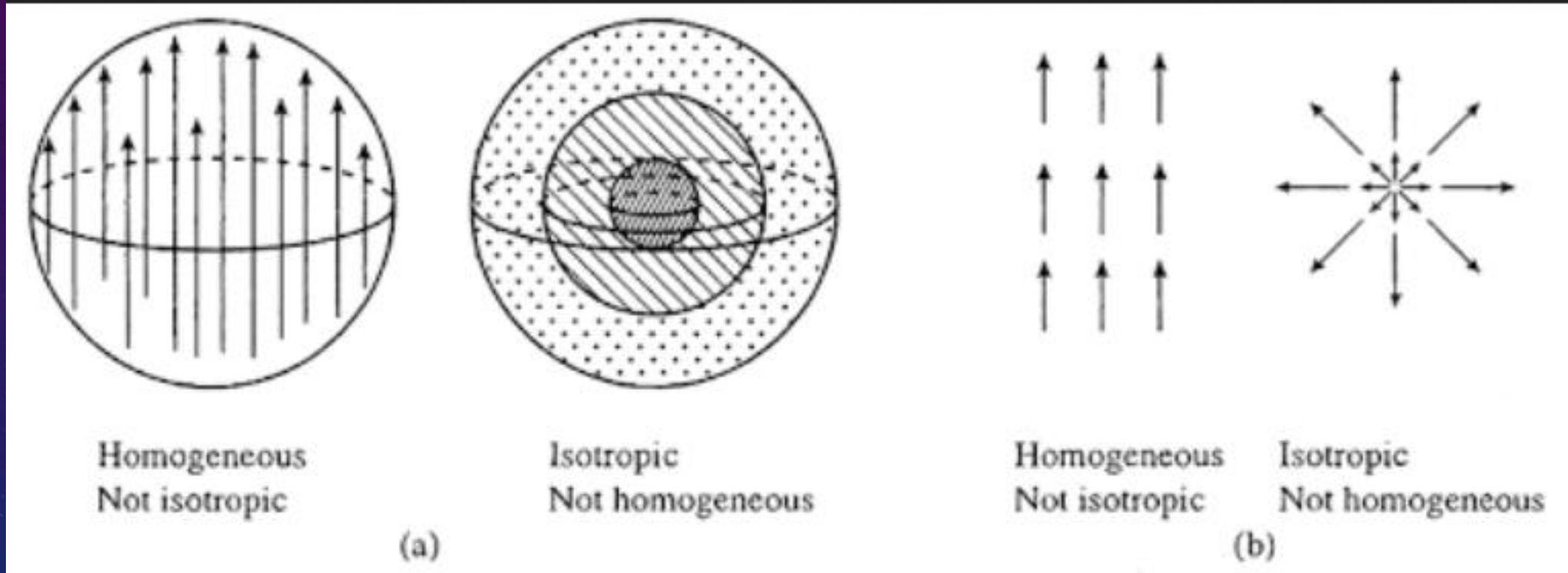
These transitions were allowed by to great revolutions:

- 1) Space era - dedicated satellite missions;
- 2) Computer era – allowing modelling of complex cosmological and astrophysical models.

PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

The Copernican Principle: There should be no SPECIAL observers

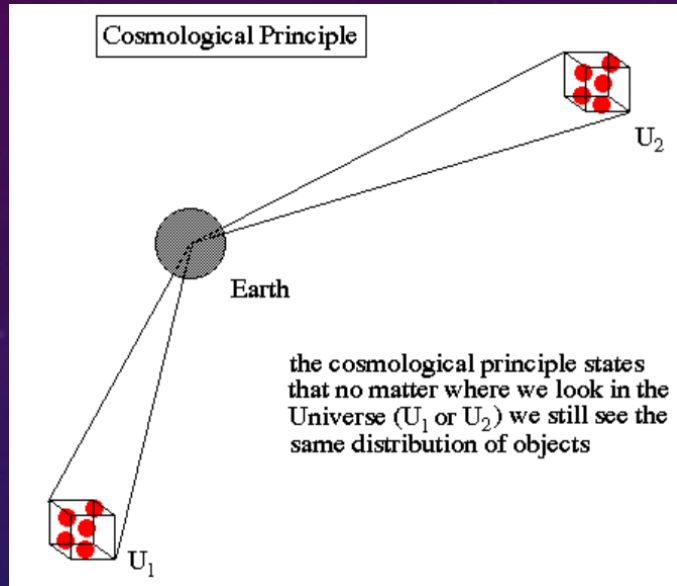
Homogeneity and isotropy: Extending the Copernican Principle to cosmology



PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

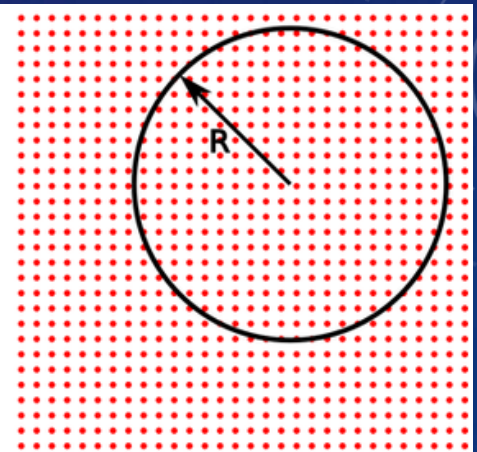
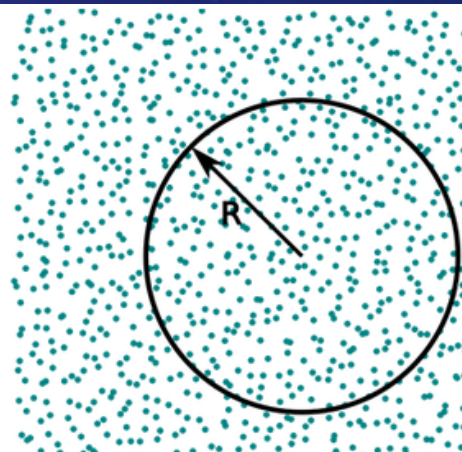
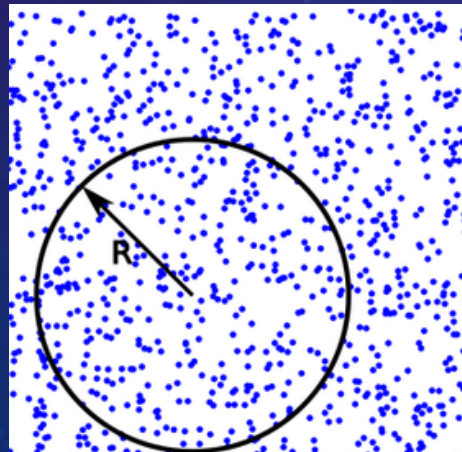
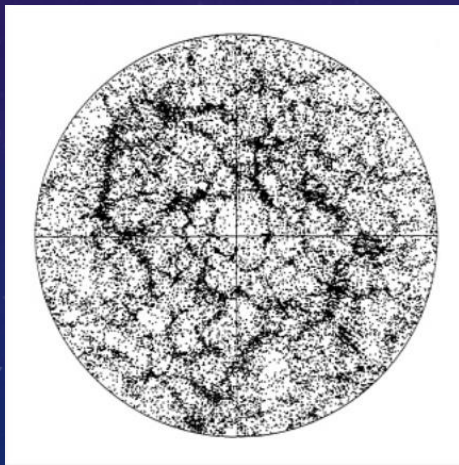
The cosmological principle:

Derives from the CP but it can not be proved (in a mathematical sense).



Corollary: The laws of physics are universal. The same physical laws and models that apply here on the Earth also work in distant stars, galaxies, and all parts of the Universe

HUGE SIMPLIFICATION



COSMOLOGICAL PRINCIPLE VS HOMOGENEITY SCALE IN THE UNIVERSE

A structure in the early universe at $z \sim 1.3$ that exceeds the homogeneity scale of the R-W concordance cosmology

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Luis E. Campusano,² Ilona K. Söchting³ and Matthew J. Graham⁴

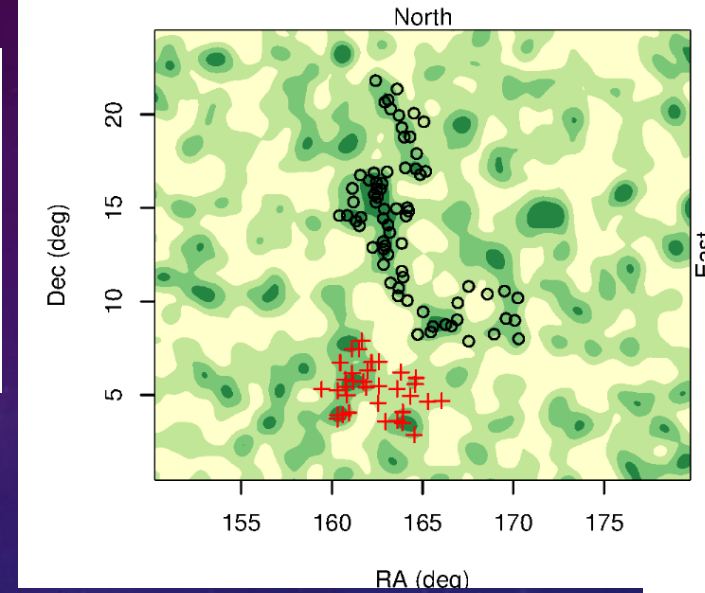
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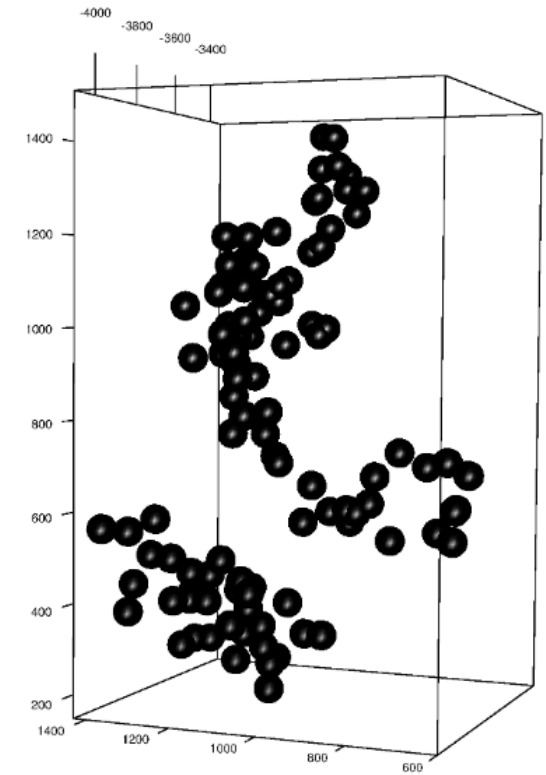
⁴ *California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA*

Clowes R. G., Harris K. A., Raghunathan S., Campusano L. E.,
Söchting I. K., Graham M. J., 2013, MNRAS, 429, 2910



ABSTRACT

A Large Quasar Group (LQG) of particularly large size and high membership has been identified in the DR7QSO catalogue of the Sloan Digital Sky Survey. It has characteristic size ($\text{volume}^{1/3}$) ~ 500 Mpc (proper size, present epoch), longest dimension ~ 1240 Mpc, membership of 73 quasars, and mean redshift $\bar{z} = 1.27$. In terms of both size and membership it is the most extreme LQG found in the DR7QSO catalogue for the redshift range $1.0 \leq z \leq 1.8$ of our current investigation. Its location on the sky is $\sim 8.8^\circ$ north (~ 615 Mpc projected) of the Clowes & Campusano LQG at the same redshift, $\bar{z} = 1.28$, which is itself one of the more extreme examples. Their boundaries approach to within $\sim 2^\circ$ (~ 140 Mpc projected). This new, huge LQG appears to be the largest structure currently known in the early universe. Its size suggests incompatibility with the Yadav et al. scale of homogeneity for the concordance cosmology, and thus challenges the assumption of the cosmological principle.



(STATISTICAL) HOMOGENEITY SCALE IN THE UNIVERSE

The Cosmological Principle should be understood in a statistical sense

Seeing patterns in noise: Gigaparsec-scale ‘structures’ that do not violate homogeneity

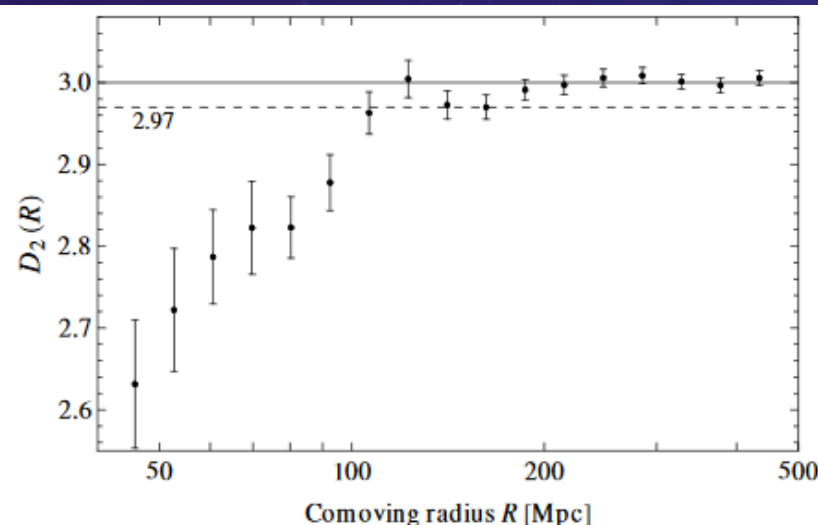
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Mon.Not.Roy.Astr.Soc.434:398,2013

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ABSTRACT

Clowes et al. (2013) have recently reported the discovery of a Large Quasar Group (LQG), dubbed the Huge-LQG, at redshift $z \sim 1.3$ in the Data Release 7 quasar catalogue of the Sloan Digital Sky Survey. On the basis of its characteristic size ~ 500 Mpc and longest dimension > 1 Gpc, it is claimed that this structure is incompatible with large-scale homogeneity and the cosmological principle. If true, this would represent a serious challenge to the standard cosmological model. However, the homogeneity scale is an average property which is not necessarily affected by the discovery of a single large structure. I clarify this point and provide the first fractal dimension analysis of the DR7 quasar catalogue to demonstrate that it is in fact homogeneous above scales of at most $130 h^{-1}$ Mpc, which is much less than the upper limit for Λ CDM. In addition, I show that the algorithm used to identify the Huge-LQG regularly finds even larger clusters of points, extending over Gpc scales, in explicitly homogeneous simulations of a Poisson point process with the same density as the quasar catalogue. This provides a simple null test to be applied to any cluster thus found in a real catalogue, and suggests that the interpretation of LQGs as ‘structures’ is misleading.



3 TESTING HOMOGENEITY WITH REDSHIFT CATALOGUES

3.1 Fractal analysis

The simplest test of homogeneity that can be applied to any point set is based on the average of the number of neighbouring points $N_i(< R)$ contained within a sphere of radius R centred on the i th member of the point set, with the requirement that the entire sphere lies within the distribution of points:

$$N(< R) = \frac{1}{M} \sum_{i=1}^M N_i(< R), \quad (1)$$

where M is the number of sphere centres. For a homogeneous distribution $N(< R) \propto R^D$, where D is the number of dimensions, three in this case. The correlation dimension $D_2(R)$ is calculated as the derivative

$$D_2(R) = \frac{d \ln N(< R)}{d \ln R}, \quad (2)$$

and quantifies the deviation from this homogeneous scaling.

For any given catalogue of objects that trace the matter density of the Universe, $N(< R)$ can be related to the two-point correlation function $\xi(r)$ by

$$N(< R) = \bar{\rho} \int_0^R (1 + b^2 \xi(r)) 4\pi r^2 dr, \quad (3)$$

where $\bar{\rho}$ is the mean matter density and b is the bias of the tracer population. Note that the relationship in eq. (3) requires the as-

See also: Gonçalves, R., et al *JCAP* 03 (2021) 029

It is fair to say that the homogeneity scale is around
 $200/h$ Mpc



Physica D: Nonlinear Phenomena

Volume 38, Issues 1–3, September 1989, Pages 273–278



The fractal galaxy distribution

P.J.E. Peebles

Mon. Not. R. Astron. Soc. **298**, 1212–1222 (1998)

Searching for the scale of homogeneity

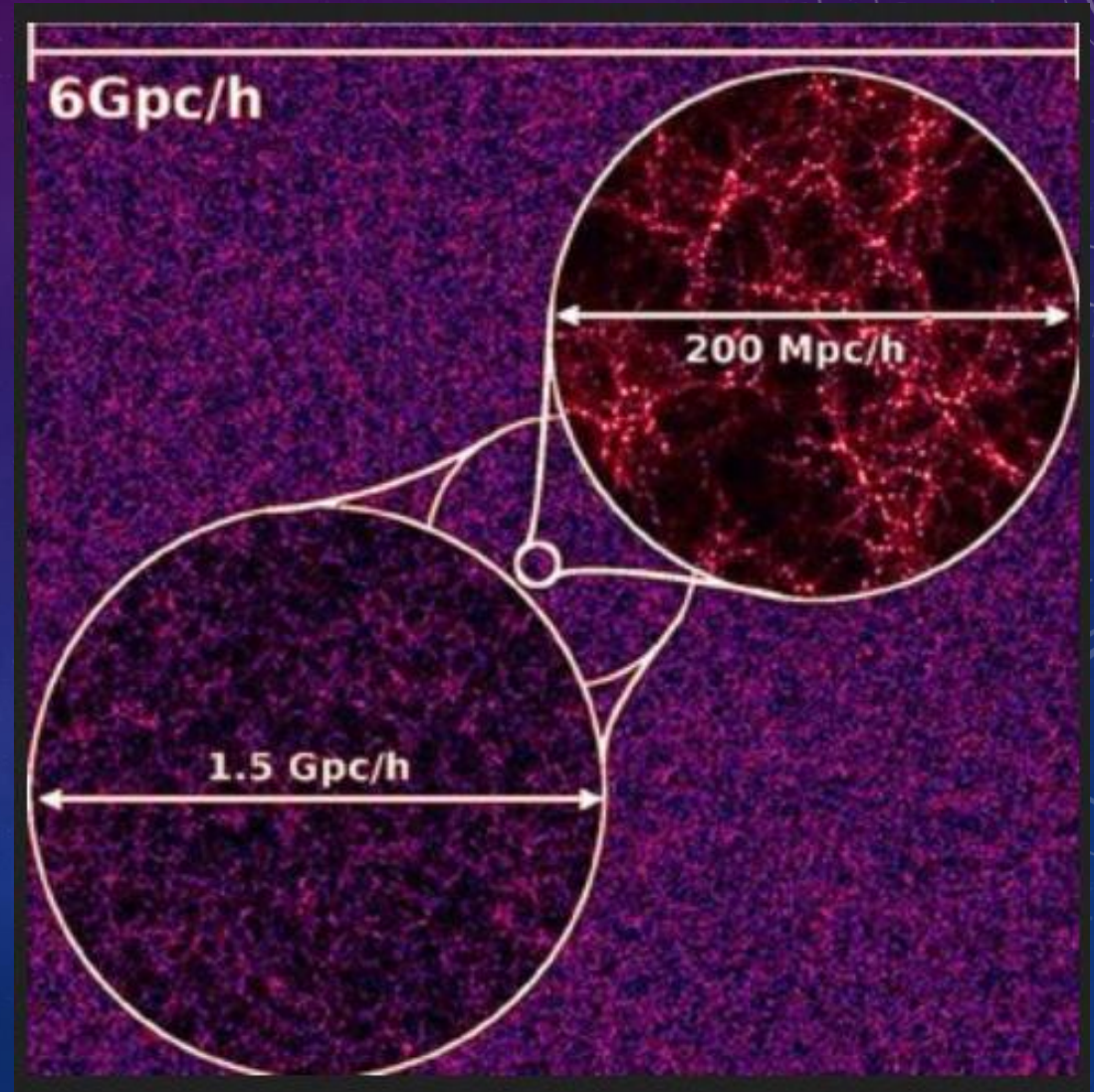
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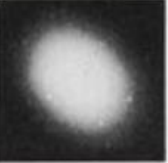
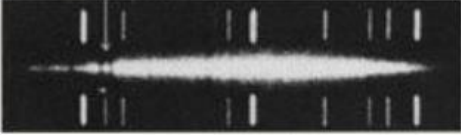
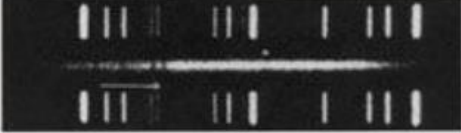
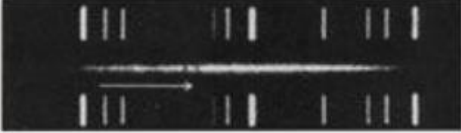
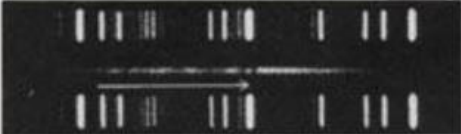
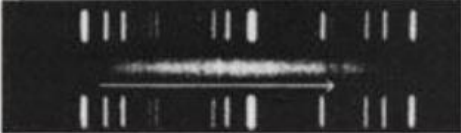
³School of Mathematics and Statistics, University of Plymouth, Drake Circus, Plymouth PL4 8AA

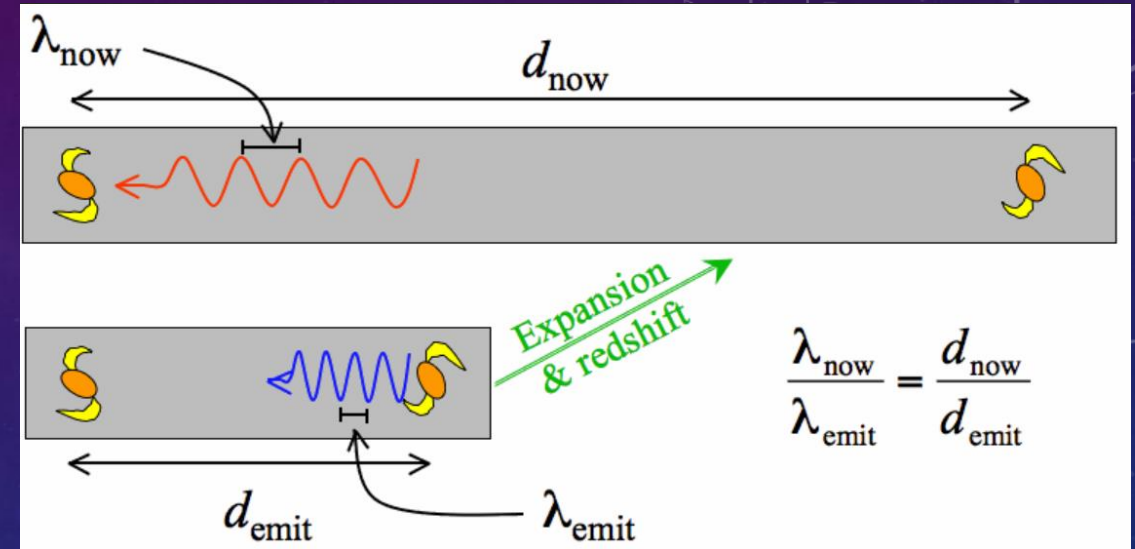
⁴Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE



PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Redshift is proportional to distance

Galaxy Cluster	Distance (light-years)	Redshifts & Velocities
 Virgo	78,000,000	 1,200 km s ⁻¹
 Ursa Major	1,000,000,000	 15,000 km s ⁻¹
 Corona Borealis	1,400,000,000	 22,000 km s ⁻¹
 Bootes	2,500,000,000	 39,000 km s ⁻¹
 Hydra	3,960,000,000	 61,000 km s ⁻¹



$$z = \frac{\Delta\lambda}{\lambda}$$

EXPANSION OF THE UNIVERSE (LEMAITRE-HUBBLE LAW)



Edwin Hubble (1889 - 1953)



First: the Discovery of galaxies beyond the Milk Way

ANOTHER UNIVERSE SEEN BY ASTRONOMER

***Dr. Hubble Describes Mass of
Celestial Bodies 700,000 Light
Years Away.***

CHICAGO, Jan. 21 (AP).—For years astronomers have speculated as to whether various nebulous formations in the heavens belongs to this universe or were "island" universes of their

THE STATUS OF “OBSERVATIONAL COSMOLOGY” IN THE 1920?

- 1) The notion of GALAXY did not exist
- 2) Great debate on the distance to the nebulae
- 3) Edwin Hubble uses the method proposed by H. Leavitt to know the distance from the Andromeda nebulae and finds a value close to 1 million light-years (today we know this distance is > 2 million light-years).
- 4) Harlow Shapley estimate the size of the Milkyway as 300.000 light-years (today we know it is 100.000 light-years)

Conclusion: Andromeda is beyond the set of stars we see in the night sky



V. Flório Pires de Andrade e O. Freire Júnior,
“Via Láctea: ilha isolada? A Via Láctea e as
nebulosas espirais numa reportagem da
Popular Science, 1922”, *Cad. Astro.*, vol. 2, nº 1,
p. 79, fev. 2021.

THE LEMAITRE-HUBBLE LAW

Lemaître (1927 vs.1931)

Therefore

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \quad (22)$$

is the apparent Doppler effect due to the variation of the radius of the universe. *It equals the ratio of the radii of the universe at the instants of observation and emission, diminished by unity.*

v is that velocity of the observer which would produce the same effect. When the light source is near enough, we have the approximate formulæ

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R} dt = \frac{R'}{R} r$$

where r is the distance of the source. We have therefore

$$\frac{R'}{R} = \frac{v}{cr} \quad (23)$$

From a discussion of available data, we adopt

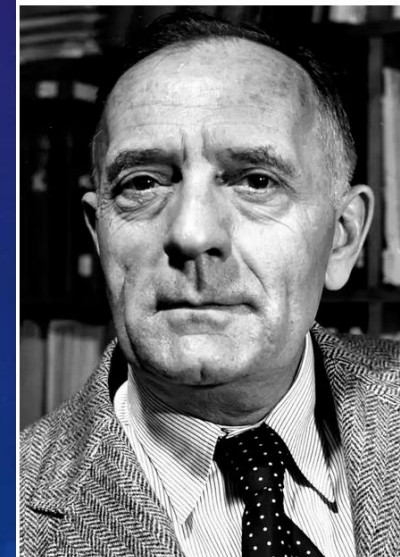
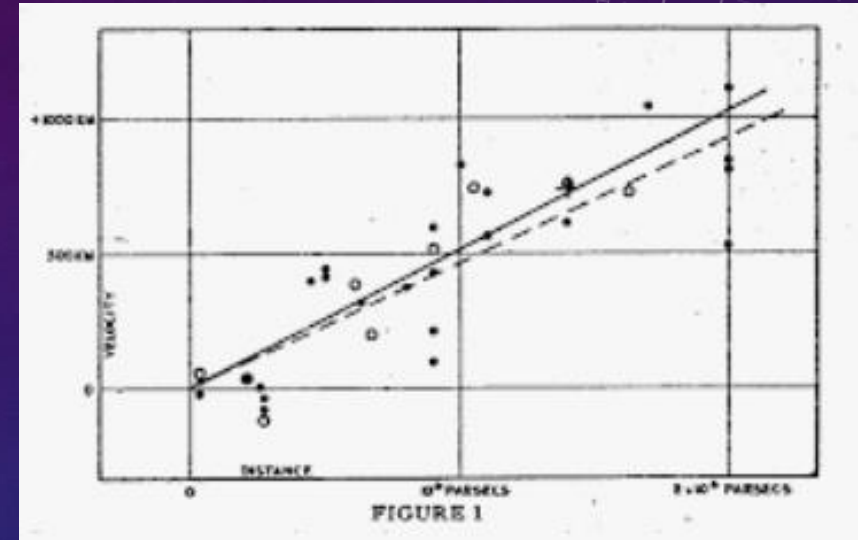
$$\frac{R'}{R} = 0.68 \times 10^{-27} \text{ cm}^{-1} \quad (24)$$

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg ⁽¹⁾, et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315^\circ$, $\delta = 62^\circ$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs ⁽²⁾.

Nous adopterons donc

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3,08 \times 10^{18} \times 3 \times 10^{10}} = 0,68 \times 10^{-27} \text{ cm}^{-1} \quad (24)$$

Text translated
by Eddington

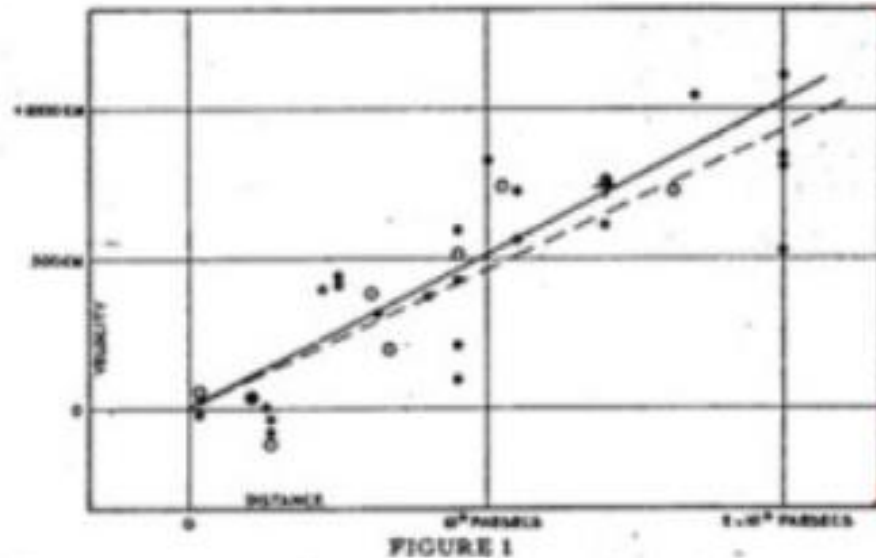
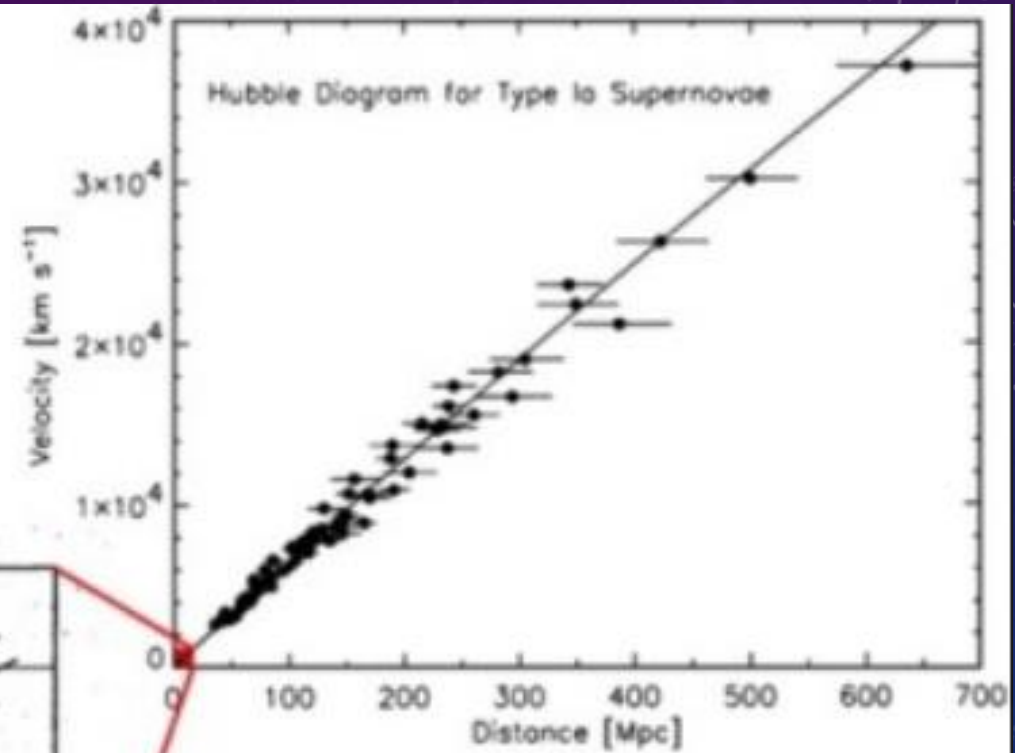
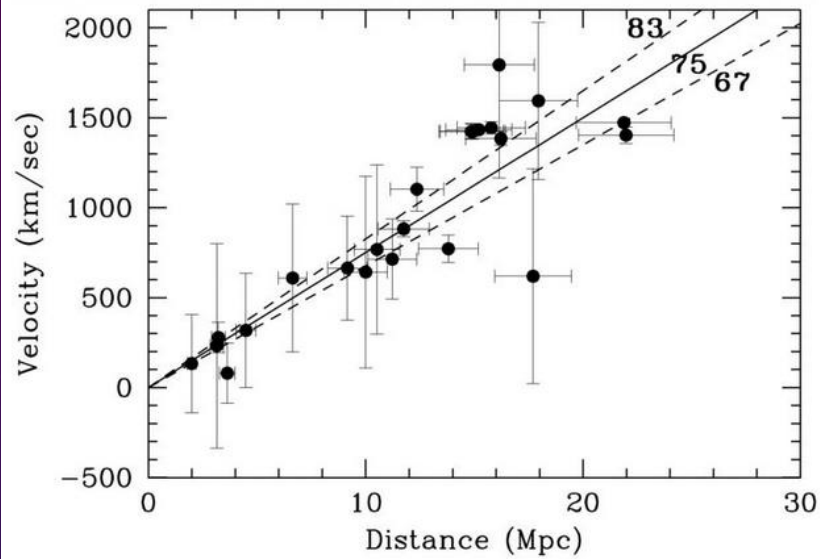


Edwin Hubble (left), Georges Lemaître (right)

original ...

Hubble's Law (modern data)

Hermano Velten



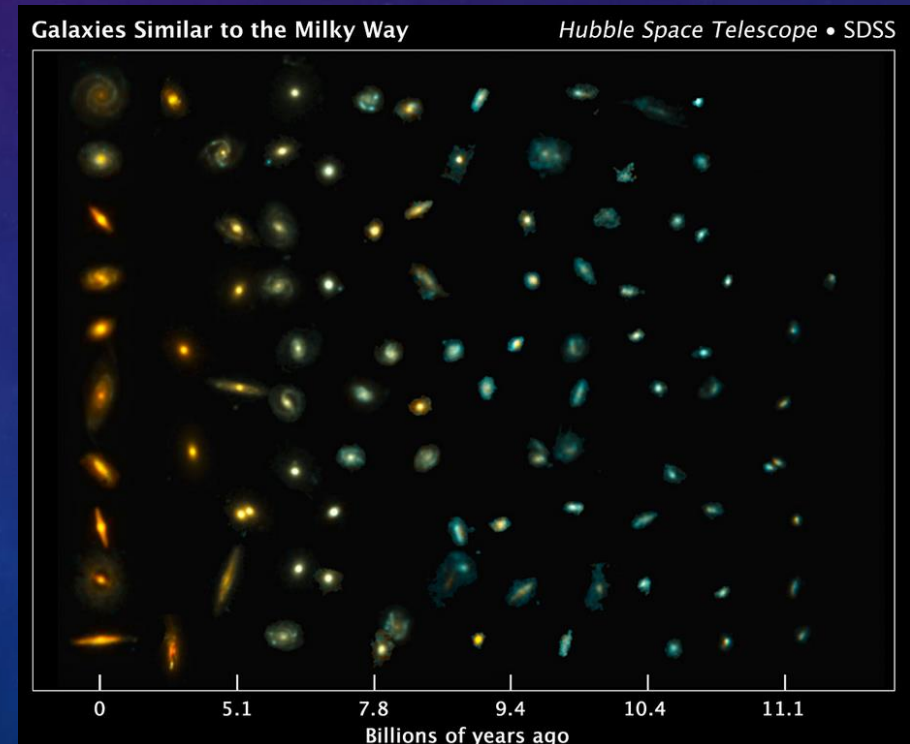
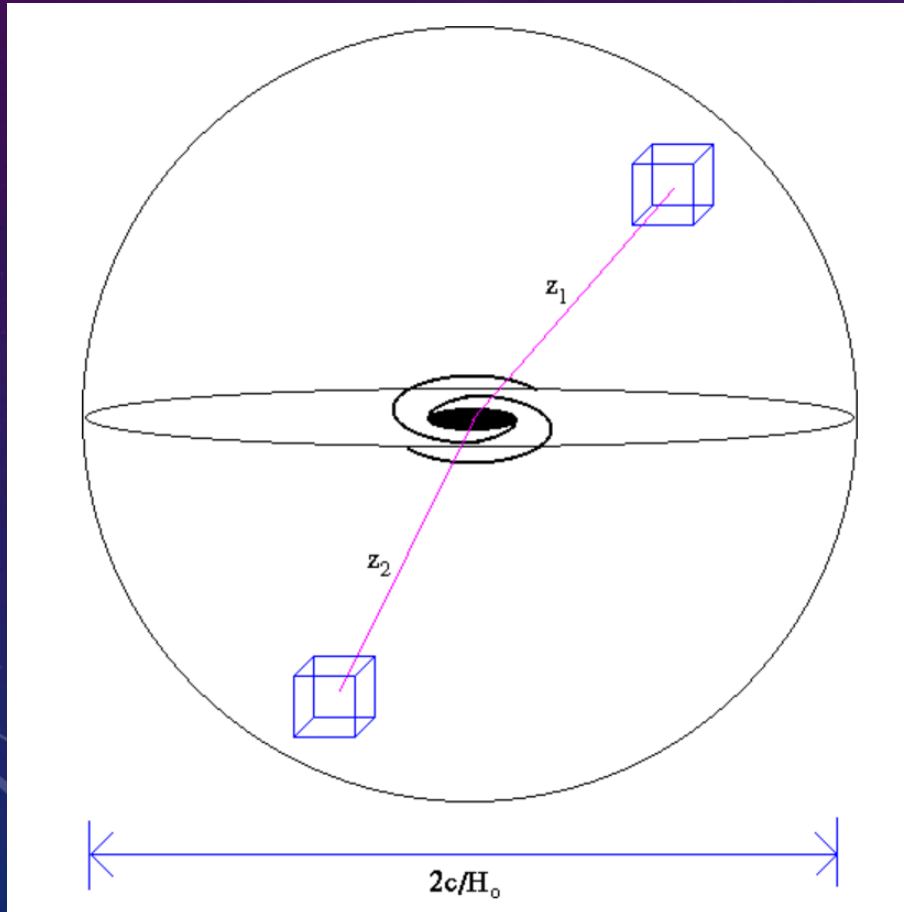
$$v = H_0 r$$

PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Lookback time:

the farther away an object is from the Earth, the longer it takes for its light to reach us

Particularly useful to study galaxy evolution: the ability to study the changes in galaxies with time by observing them at various distances means equals different epochs

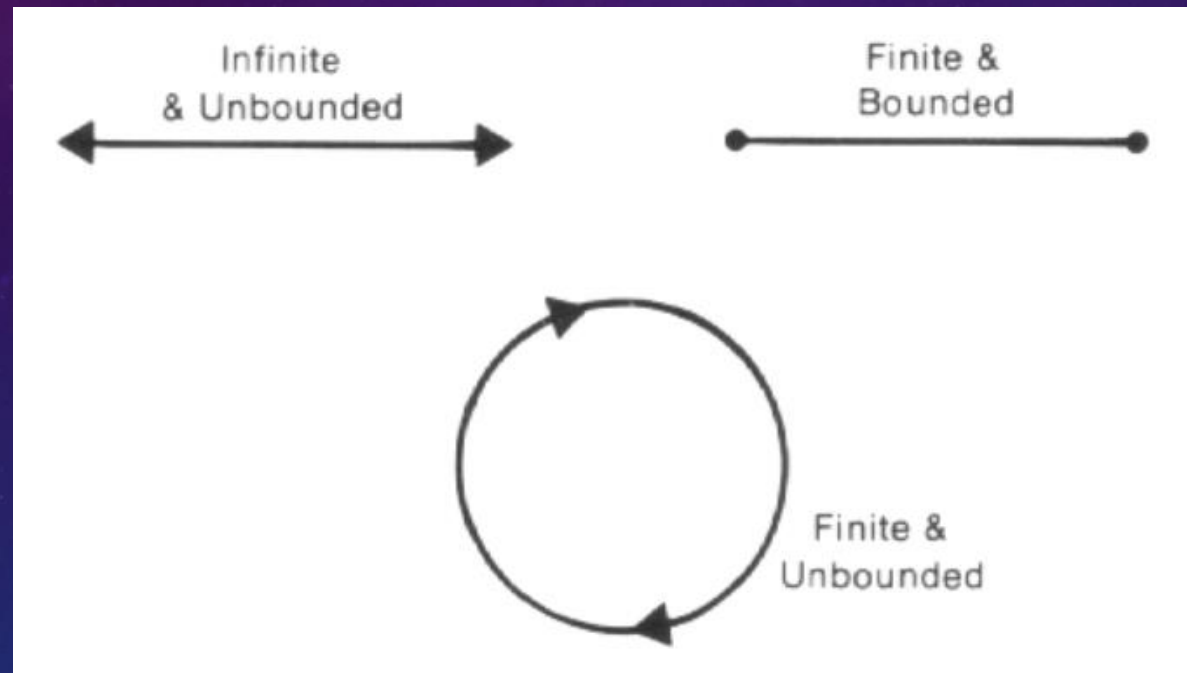


PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Cosmic Edge

FAQ by students: Where is the border of the universe? What do we find beyond the border?

Answer: The Universe has to contain the properties of everything. Invoking an outside property of the Universe is logically inconsistent.



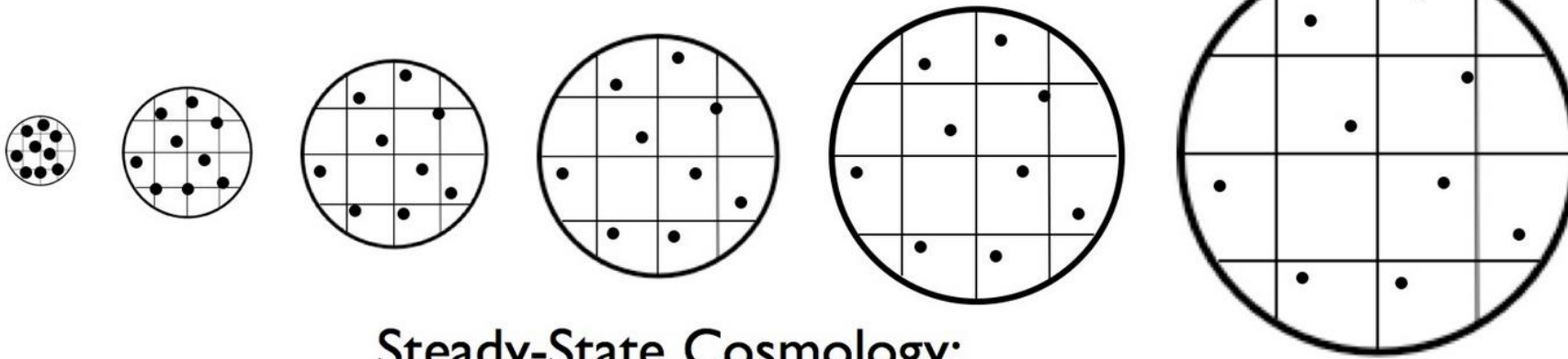
A corollary to this point is that the Universe must be boundless. This does not necessary mean that the Universe is infinite, although this is the simplest solution.

PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Expanding – diluting - universe

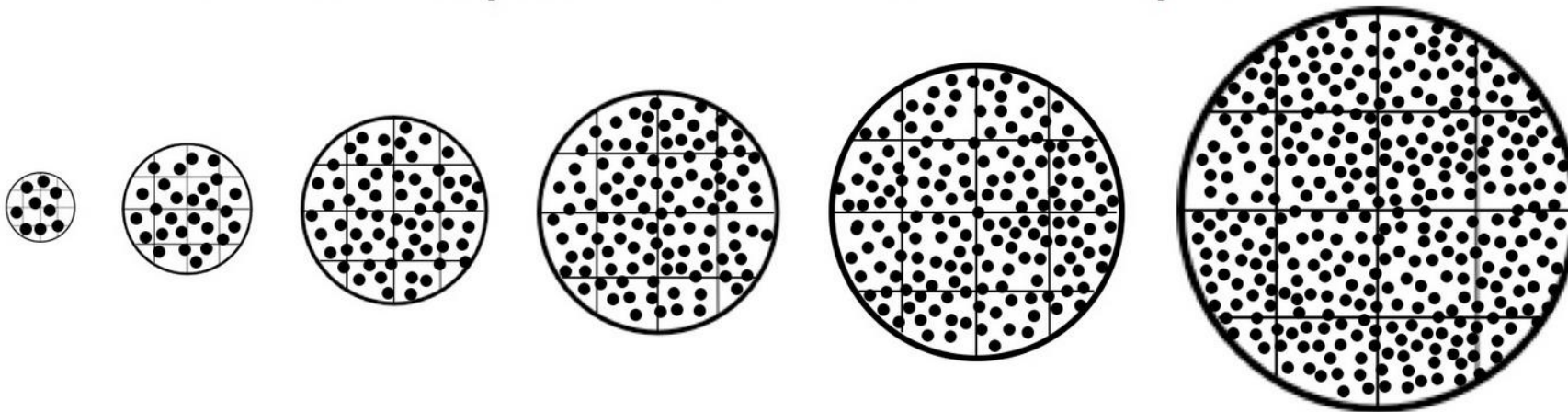
Big Bang Cosmology

Matter dilutes as the Universe expands

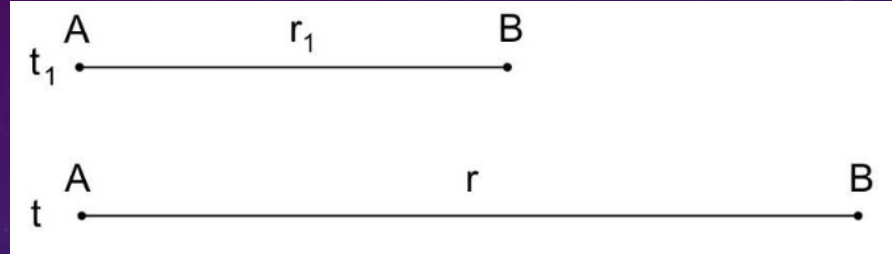
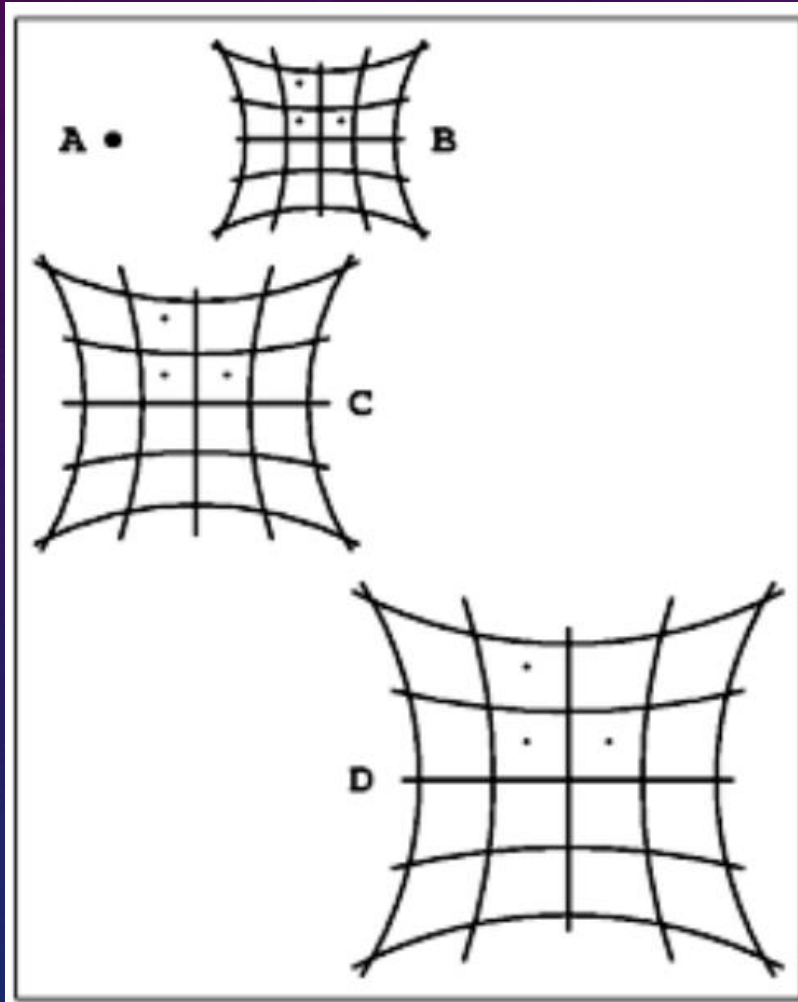


Steady-State Cosmology:

Matter is constantly created as the Universe expands



PARAMETERIZING THE EXPANDING UNIVERSE: THE SCALE FACTOR



$$\mathbf{v} = \frac{d\mathbf{r}}{dt} = \frac{\mathbf{r}_1}{R(t_1)} \frac{dR(t)}{dt}$$

$$\mathbf{r} = \frac{R(t)}{R(t_1)} \mathbf{r}_1$$

$$H(t) = \frac{1}{R(t)} \frac{dR}{dt} = \frac{\dot{R}}{R}$$

$$a(t) = \frac{R(t)}{R(t_0)}$$

MODELLING THE EXPANDING UNIVERSE

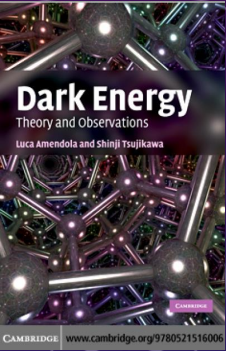
The metric of an expanding space
Jargon: FLRW metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a^2(t) d\sigma^2$$

$$d\sigma^2 = \gamma_{ij} dx^i dx^j = \frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2)$$

$$K = +1, -1, 0 \quad (\text{CLOSED, OPEN, FLAT})$$

In practise modern cosmologists use to adopt a FLAT metric from the beginning. This is supported by Cosmic Microwave Background (CMB) observations



MODELLING THE EXPANDING PERFECT FLUID

Perfect fluid description and conservation:

$$\nabla_\mu T^\mu_\nu \equiv \frac{\partial T^\mu_\nu}{\partial x^\mu} + \Gamma^\mu_{\alpha\mu} T^\alpha_\nu - \Gamma^\alpha_{\nu\mu} T^\mu_\alpha = 0.$$

$$\frac{\partial T^\mu_0}{\partial x^\mu} + \Gamma^\mu_{\alpha\mu} T^\alpha_0 - \Gamma^\alpha_{0\mu} T^\mu_\alpha = 0.$$

Conservation is assumed!

$$\frac{\partial \rho}{\partial t} + \frac{\dot{a}}{a} [3\rho + 3\mathcal{P}] = 0.$$

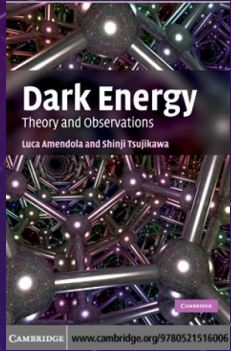
$$\rho_s(a) \propto \exp \left\{ -3 \int^a \frac{da'}{a'} [1 + w_s(a')] \right\}$$
$$\underset{w_s = \text{const}}{\propto} a^{-3(1+w_s)}.$$

$$T^\mu_\nu = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & \mathcal{P} & 0 & 0 \\ 0 & 0 & \mathcal{P} & 0 \\ 0 & 0 & 0 & \mathcal{P} \end{pmatrix}$$

EOS

Equation of state parameter

$$w_s \equiv \frac{\mathcal{P}_s}{\rho_s}$$



COSMOLOGICAL FLUIDS

$$\rho = g_* \int \frac{d^3 p}{(2\pi \hbar)^3} E(p) f(p) = \frac{g_*}{2\pi^2} \int_m^\infty dE \frac{(E^2 - m^2)^{1/2}}{\exp[(E - \mu)/T] \pm 1} E^2$$

$$P = g_* \int \frac{d^3 p}{(2\pi \hbar)^3} \frac{pv}{3} f(p) = g_* \int \frac{d^3 p}{(2\pi \hbar)^3} \frac{p^2}{3E} f(p)$$

$$= \frac{g_*}{6\pi^2} \int_m^\infty dE \frac{(E^2 - m^2)^{3/2}}{\exp[(E - \mu)/T] \pm 1}.$$

Non-relativistic matter

$$\rho = g_* m \left(\frac{mT}{2\pi} \right)^{3/2} \exp[-(m - \mu)/T],$$

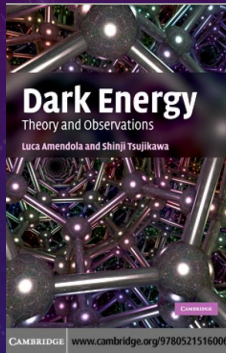
$$P = g_* T \left(\frac{mT}{2\pi} \right)^{3/2} \exp[-(m - \mu)/T] = \frac{T}{m} \rho$$

Relativistic species

$$\rho = \begin{cases} (\pi^2/30)g_* T^4, & \text{(Bosons)} \\ (7/8)(\pi^2/30)g_* T^4, & \text{(Fermions)} \end{cases}$$

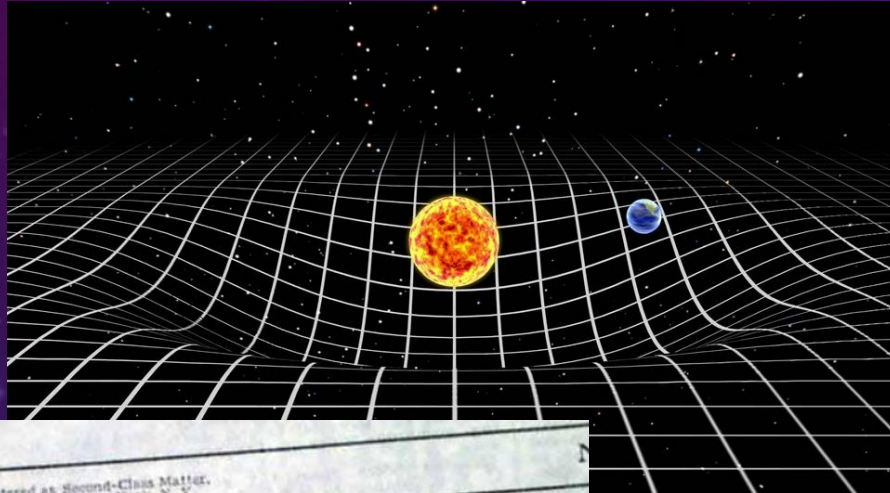
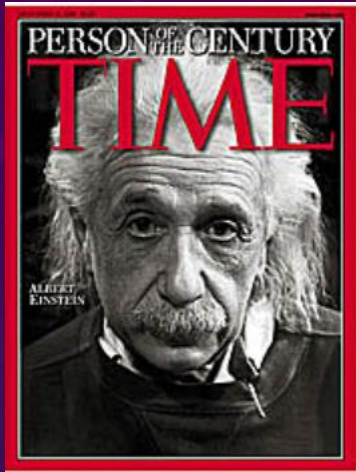
$$P = \rho/3,$$

Dominant component	w	ρ	P	T
matter	0	a^{-3}	a^{-5}	a^{-2}
radiation	1/3	a^{-4}	a^{-4}	a^{-1}
vacuum energy	-1	a^0	a^0	



IT IS TIME TO MAKE A CHOICE: HOW TO DEAL WITH THE GRAVITATIONAL INTERACTION?

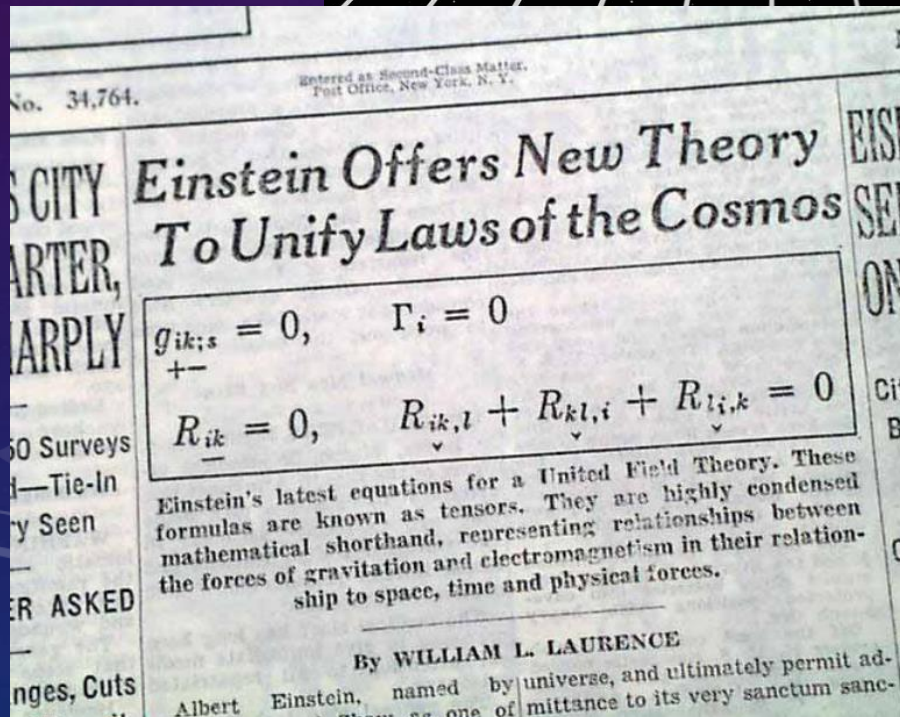
GENERAL RELATIVITY



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}.$$

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R.$$

$$R_{\mu\nu} = \Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma^{\alpha}_{\mu\alpha,\nu} + \Gamma^{\alpha}_{\beta\alpha}\Gamma^{\beta}_{\mu\nu} - \Gamma^{\alpha}_{\beta\nu}\Gamma^{\beta}_{\mu\alpha}.$$



100 Years of General Relativity and Counting ...

Tests of general relativity (GR) require strong gravity, massive objects and/or high-precision measurements—conditions we don't readily find on Earth. Einstein proposed three tests of GR when he first published the theory in 1915: the precession of Mercury's orbit, the bending of starlight near the Sun, and the gravitational redshift of light. These represented just the beginning of a long list of tests which could be performed to bolster the case for GR. The timeline below shows a sampling of tests which have confirmed GR's predictions over the past century, with a preference for astrophysical confirmations. The dates reflect the publication of the results, not necessarily the date of observation.

1915 Mercury's orbit

For over two centuries astronomers had known that the perihelion of Mercury's orbit precesses faster than predicted by Newtonian gravity, but they did not have a good explanation for why. The answer fell out of general relativity, with the accelerated precession attributed to Mercury's proximity to the sun.



1920 Deflection of starlight

Both Newtonian gravity and general relativity predict that massive objects will deflect starlight, but the effect is more pronounced in GR. In 1919, Arthur Eddington and Frank Dyson led separate teams in Principe and Brazil to photograph stars near the sun during a total eclipse. The results confirmed the predictions of GR.



1975 First binary pulsar

According to general relativity, accelerated masses radiate gravitational waves, which results in the loss of energy. This means that stars in binary systems will gradually grow closer over time. The discovery of pulsar PSR 1913+16 in a binary system gave astronomers a unique opportunity to test this prediction, since pulsars are the most accurate clocks in the universe. Precise timing of radio pulses from PSR 1913+16 over 18 years provided the first evidence of gravitational radiation.

1979 Gravity's lens

General relativity predicts that massive objects warp space-time, resulting in a deflection of light passing nearby. With enough mass and the right alignment, it could act as a lens and produce multiple images of a more distant object. The discovery of the "Twin Quasar" or SBS 0957+561 provided the first confirmation of a gravitational lens.



2011 Earth-warped space-time

A basic premise of general relativity is that all massive objects warp space-time. The more massive the object, the stronger the effects. Launched in 2004, Gravity Probe B was designed to measure how Earth warps and drags space-time as it rotates. The satellite took data for about 17 months, but researchers needed about 5 years for a full analysis. The final results confirm GR's prediction that space-time is twisted around the Earth as it rotates.



Coming soon

Astronomers have already observed gravitational waves (GWs) through their effects on binary systems. The next step to verifying this prediction of general relativity would be to watch GWs pass through the solar system. Scientists expect to begin detecting GW signals from various sources in the coming years.

2016- Ground-based laser measurement

Between 2002 and 2010, scientists at the Laser Interferometer Gravitational-wave Observatory monitored precise laser measurements to attempt detection of passing gravitational waves. Upgrades to the system, called Advanced LIGO, are scheduled to be completed in 2016. Scientists expect it will be capable of seeing GWs from merging neutron stars.

2017- Timing pulsars

Astronomers have begun using collections of millisecond pulsars in hopes of finding slight changes in their timing caused by a gravitational wave passing near Earth. This method is called Pulsar Timing Arrays and, as of 2014, three ongoing projects anticipate results within the decade.

2025- Observatories in space

Within a couple of decades, astronomers anticipate placing a laser-based GW detector in orbit around the sun. The European Space Agency's planned eLISA mission—short for Evolved Laser Interferometric Space Antenna—will observe GWs from a wide variety of sources, including merging supermassive black holes in distant galaxies.

1959 Gravity's redshift

One of the central ideas of general relativity is the equivalence principle, which asserts that everything responds to gravity, whether light or matter. Simply stated, all things fall equally in a gravitational field. Einstein proposed that this could be measured by observing how light became redder as it traveled upward, away from a gravitational source. Physicists Robert Pound and Glen Rebka performed an experiment in a tower at Harvard University that demonstrated just this effect—the first laboratory test of GR.

1965 First black hole

General relativity predicts there are some places where space-time becomes so distorted that not even light escapes. We call these objects black holes. One of the first X-ray sources observed beyond the solar system was Cygnus X-1. Astronomers couldn't readily identify an optical or radio counterpart to the source. Within a few years, they observed extremely rapid changes in the object's X-ray signals, indicating a very small dense object. This made Cygnus X-1 the first candidate black hole. Today, overwhelming evidence shows that it is, indeed, a genuine black hole.



1996 High-precision navigation

Clocks on satellites circling the Earth will appear to tick just a bit faster to observers on the ground, according to general relativity, due to the lower curvature of space-time farther from Earth's surface. Satellite-based high-precision navigational systems, such as GPS in the U.S., demonstrate the validity of GR every day, since they must account for the effects of GR and special relativity. GPS was commercialized in 1996 when President Clinton declared it to be a "dual-use" system for civilian and military alike.

1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030

2016: GRAVITATIONAL WAVES -ANOTHER VERIFICATION OF GR PREDICTIONS

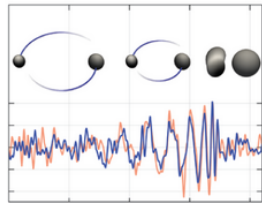
PHYSICAL REVIEW LETTERS

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Volume 116, Issue 6

12 February 2016

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On the Cover

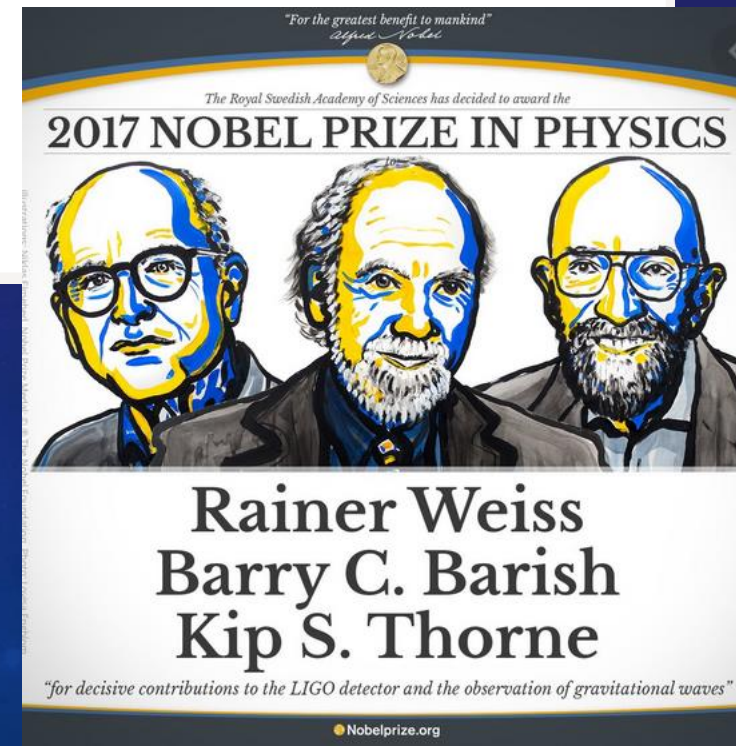
First direct detection of gravitational waves by the LIGO Hanford (Livingston) detectors in red (blue) from the inspiral of two large black holes. Selected for an Editors' Suggestion and a [Viewpoint](#) in *Physics*.

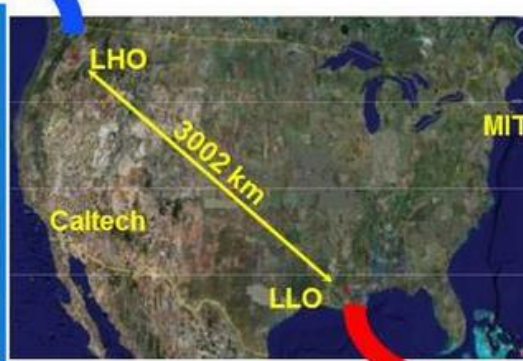
From the article:

[Observation of Gravitational Waves from a Binary Black Hole Merger](#)

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. **116**, 061102 (2016)



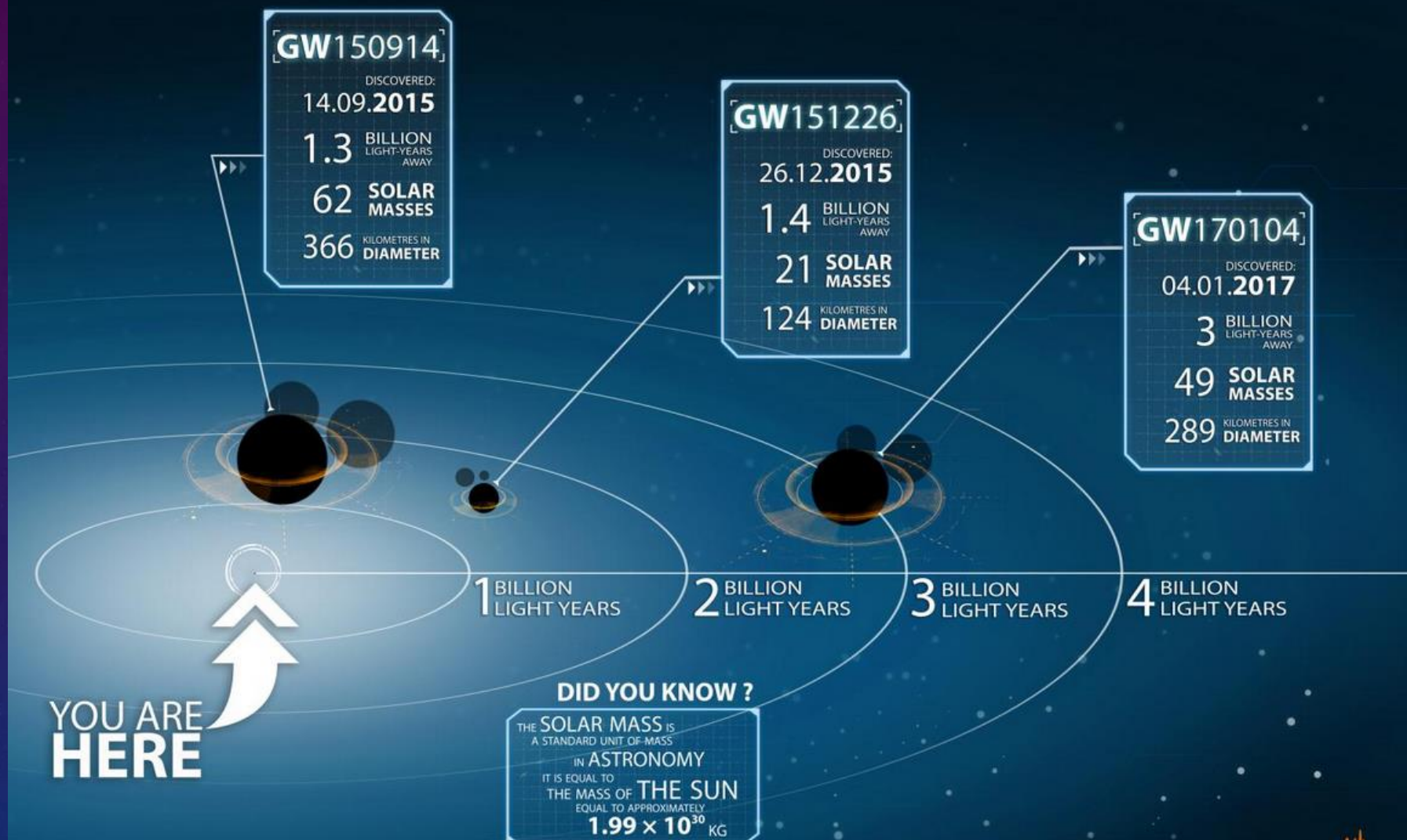


The general locations of the LIGO Hanford and LIGO Livingston interferometers. (Caltech/MIT/LIGO Lab)



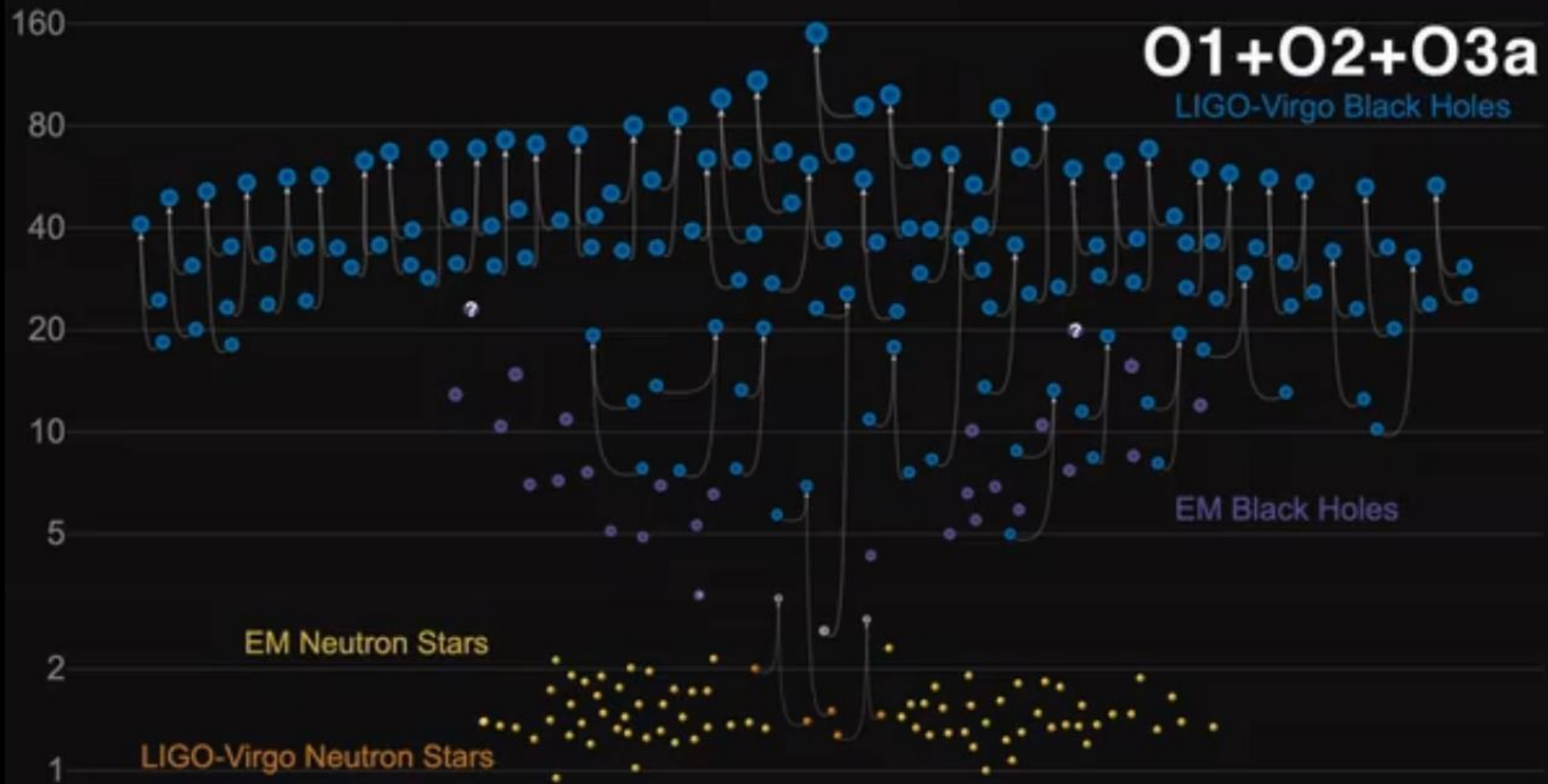
Aerial views showing the locations and extents of the LIGO Hanford and LIGO Livingston interferometers.

[LIGO'S **GRAVITATIONAL-WAVE** DETECTIONS]



Masses in the Stellar Graveyard

in Solar Masses



TESTING ANOTHER IMPORTANT GR PREDICTION: THE SPEED OF GWS

Gravitation and Astrophysics

Evading the Vainshtein Mechanism with Anomalous Gravitational Wave Speed: Constraints on Modified Gravity from Binary Pulsars

Jose Beltrán Jiménez, Federico Piazza, and Hermano Velten
Phys. Rev. Lett. **116**, 061101 (2016) – Published 9 February 2016

[Show Abstract](#)

PDF

HTML

Featured in Physics

Editors' Suggestion

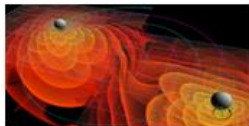
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102 (2016) – Published 11 February 2016

PDF

HTML

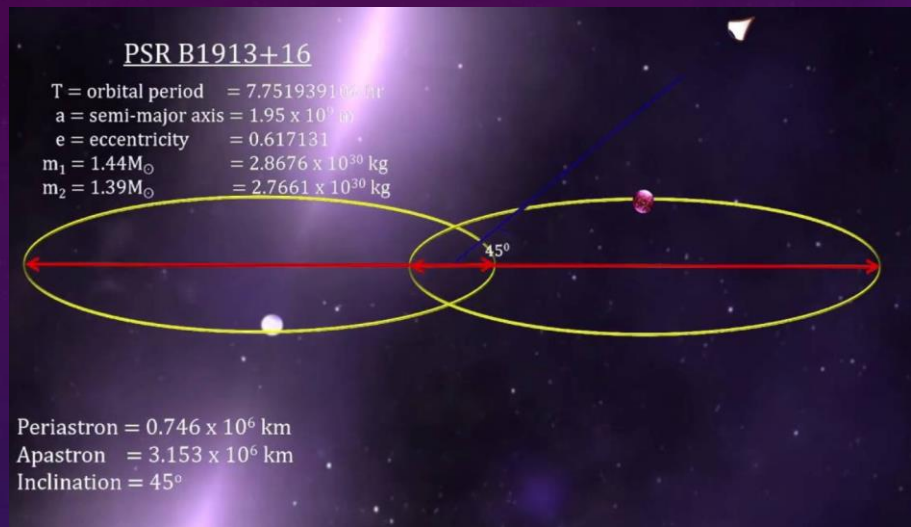
Physics Viewpoint: [The First Sounds of Merging Black Holes](#)



Gravitational waves emitted by the merger of two black holes have been detected, setting the course for a new era of observational astrophysics.

[Show Abstract](#)

The Hulse-Taylor pulsar system

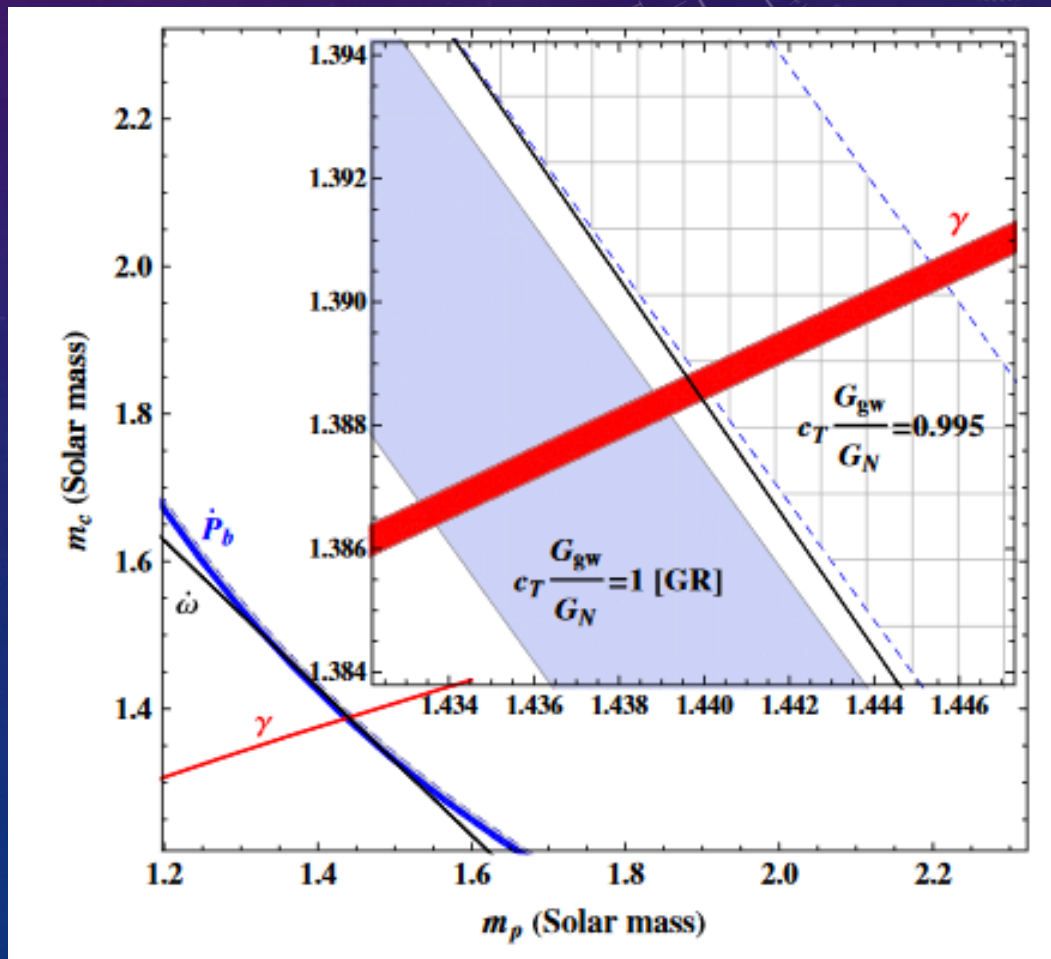


General binary period decay formula allowing for a general speed of gravitational waves and and general matter coupling for the radiative sector

$$\dot{P}_b = - \left(\frac{G_{\text{gw}}}{G_N} \frac{c}{c_T} \right) \frac{192\pi G_N^{5/3}}{5c^5} \left(\frac{P_b}{2\pi} \right)^{-5/3} (1 - e^2)^{-7/2} \times \left(1 + \frac{73e^2}{24} + \frac{37e^4}{96} \right) m_p m_c (m_p + m_c)^{-1/3},$$

We have constrained the speed of GWs at the 1% level!

$$0.995 \lesssim \frac{G_{\text{gw}}}{G_N} \frac{c}{c_T} \lesssim 1.00$$



GW170817



<https://www.ligo.caltech.edu/image/ligo20171016e>

FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

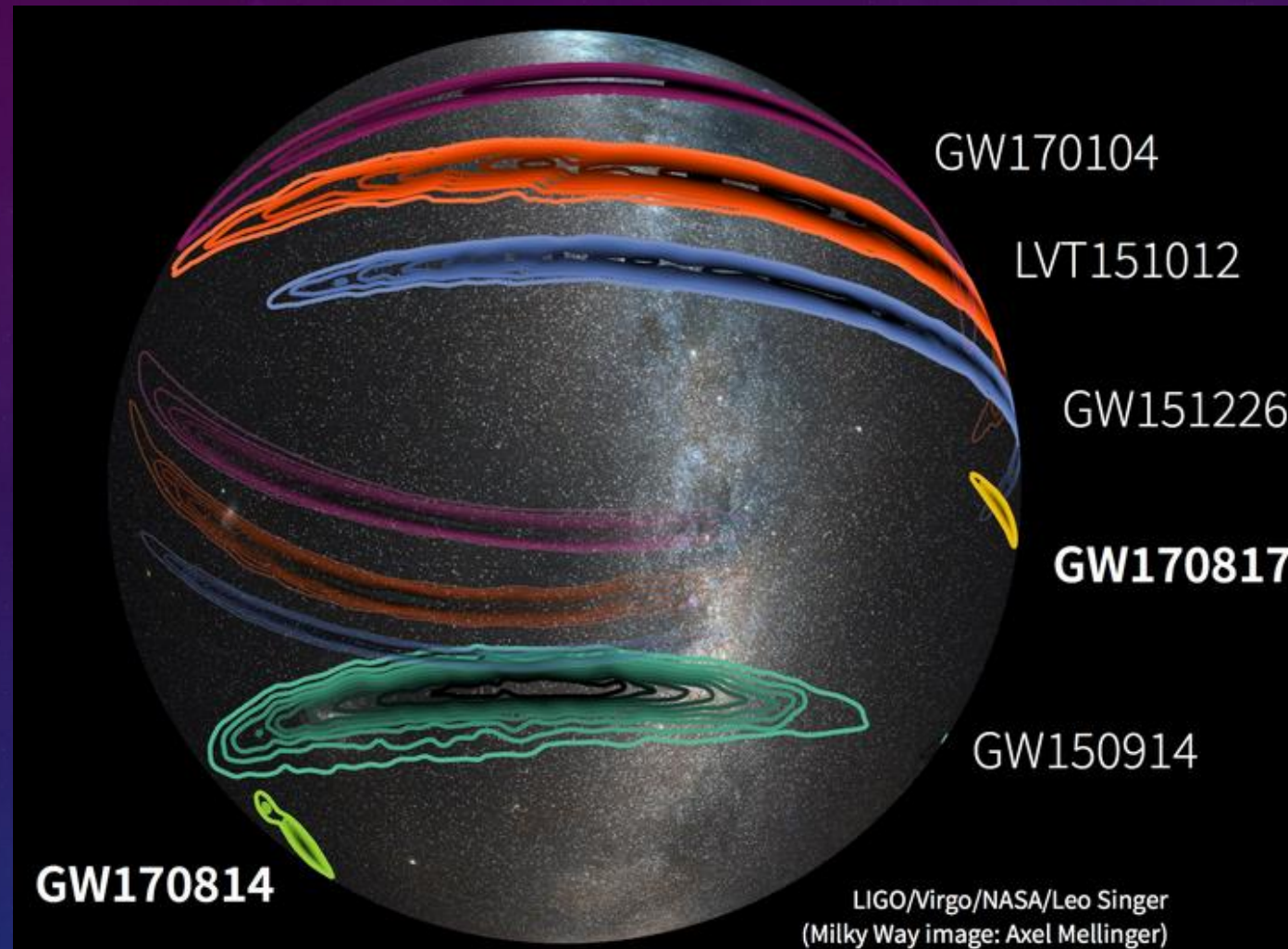
Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

Gravitational wave lasted over 100 seconds

On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.

The speed of GWs is equal to c !



$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$

BEGINNING OF COSMOLOGY 1922

Alexander A. Friedmann: *the Man who Made the Universe Expand*

E. A. TROPP,
V. Ya. FRENKEL
and
A. D. CHERNIN



Figure 2. 1913-1914 years. Left-to-right, first line: unknown (P. Ehrenfest?), A. Friedmann, G. Weihardt, unknown. Second line: E. Friedmann, A. Shohat, E. Weihardt, Ya. Tamarkin, unknown, M. Petelin. Third line: V. Smirnov.



Translation of Friedmann's letter to Ehrenfest:

I'm sending you a brief note regarding the question about the possible shape of the universe more general than the cylindrical world of Einstein, and the spherical world of De Sitter; aside from these two cases there appears also a world, the space of which possesses a curvature radius varying with time; it seemed to me that a question of this sort may interest you or De Sitter. In the near future I will send you a German translation of this note, if you find the question considered in it interesting, then please be so kind to have it placed in some journal.

Über die Krümmung des Raumes.

Von **A. Friedman** in Petersburg.

Mit einer Abbildung. (Eingegangen am 29. Juni 1922.)

§ 1. 1. In ihren bekannten Arbeiten über allgemeine kosmologische Fragen kommen Einstein¹⁾ und de Sitter²⁾ zu zwei möglichen Typen des Weltalls; Einstein erhält die sogenannte Zylinderwelt, in der der Raum³⁾ konstante, von der Zeit unabhängige Krümmung besitzt, wobei der Krümmungsradius verbunden ist mit der Gesamtmasse der im Raume vorhandenen Materie; de Sitter erhält eine Kugelwelt, in welcher nicht nur der Raum, sondern auch die Welt in gewissem Sinne als Welt konstanter Krümmung angesprochen werden kann⁴⁾. Dabei werden wie von Einstein so auch von de Sitter gewisse Voraussetzungen über den Materietensor gemacht, die der Inkohärenz der Materie und ihrer relativen Ruhe entsprechen, d. h. die Geschwindigkeit der Materie wird als genügend klein vorausgesetzt im Vergleich zu der Grundgeschwindigkeit⁵⁾ — der Lichtgeschwindigkeit.

Das Ziel dieser Notiz ist, erstens die Ableitung der Zylinder- und Kugelwelt (als spezielle Fälle) aus einigen allgemeinen Annahmen, und zweitens der Beweis der Möglichkeit einer Welt, deren Raumkrümmung konstant ist in bezug auf drei Koordinaten, die als Raumkoordinaten gelten, und abhängig von der Zeit, d. h. von der vierten — der Zeitkoordinate; dieser neue Typus ist, was seine übrigen Eigenschaften anbetrifft, ein Analogon der Einsteinschen Zylinderwelt.

For historical documents see: <https://www.lorentz.leidenuniv.nl/Friedmann/>

SOME DETAILS OF FRIEDMANN'S WORK

Die Annahmen der ersten Klasse sind die folgenden:

1. Die Gravitationspotentiale genügen dem Einsteinschen Gleichungssystem mit dem kosmologischen Gliede, das man auch gleich Null setzen darf:

$$R_{ik} - \frac{1}{2} g_{ik} \bar{R} + \lambda g_{ik} = -\kappa T_{ik} \quad (i, k = 1, 2, 3, 4), \quad (A)$$

Unsere Aufgabe ist nun die Bestimmung R und ρ aus den Gleichungen (A). Es ist klar, daß die Gleichungen (A) mit verschiedenen Indizes nichts liefern; die Gleichungen (A) für $i = k = 1, 2, 3$ geben eine Beziehung:

$$\frac{R'^2}{R^2} + \frac{2 R R''}{R^2} + \frac{c^2}{R^2} - \lambda = 0, \quad (4)$$

die Gleichung (A) mit $i = k = 4$ liefert die Beziehung:

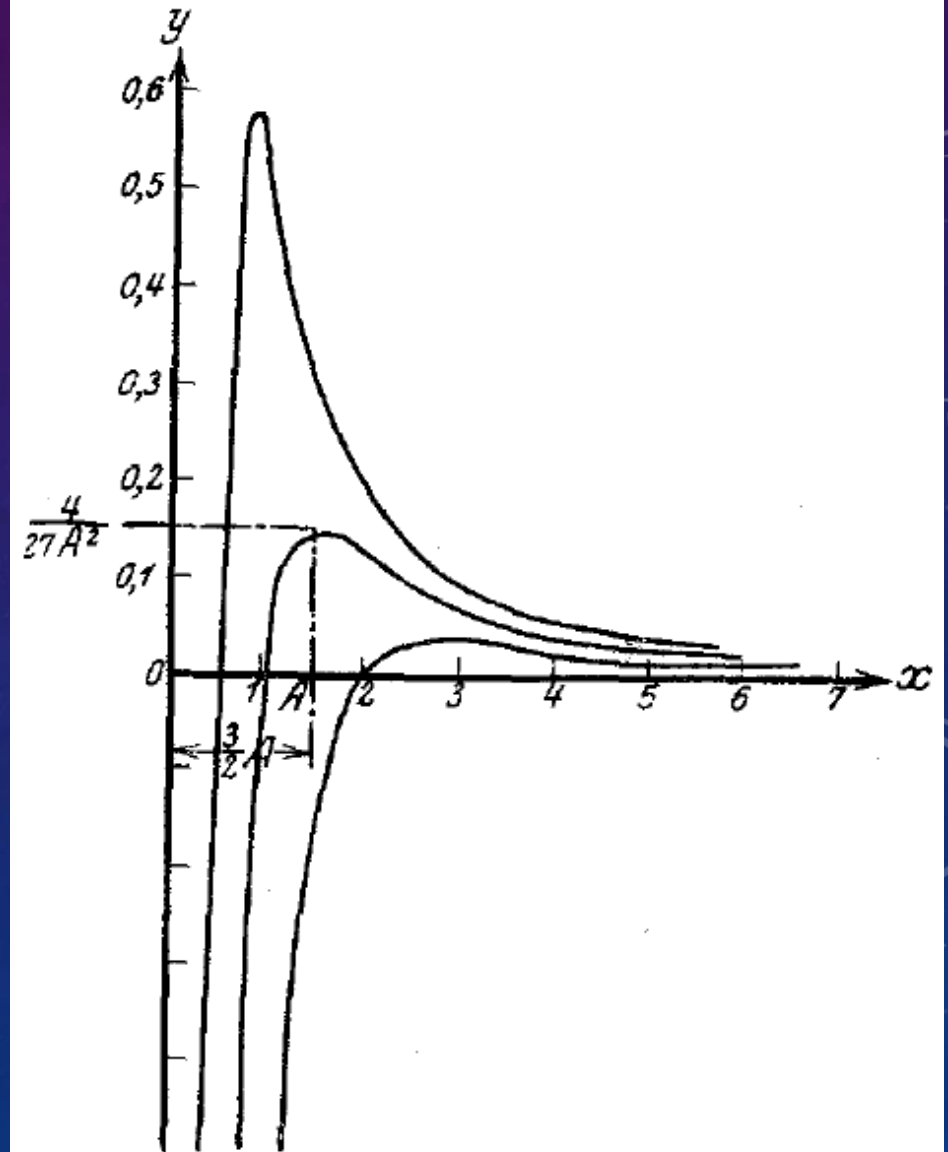
$$\frac{3 R'^2}{R^2} + \frac{3 c^2}{R^2} - \lambda = \kappa c^2 \rho, \quad (5)$$

mit

$$R' = \frac{dR}{dx_4} \quad \text{und} \quad R'' = \frac{d^2 R}{dx_4^2}.$$

Da $R' \neq 0$ ist, so gibt die Integration der Gleichung (4), wenn wir noch t für x_4 schreiben, folgende Gleichung:

$$\frac{1}{c^2} \left(\frac{dR}{dt} \right)^2 = \frac{A - R + \frac{\lambda}{3 c^2} R^3}{R} \quad (6)$$



EINSTEIN'S OPINION ON FRIEDMANN'S WORK AGAINST IN FAVOR

326

Bemerkung zu der Arbeit von A. Friedmann¹⁾ „Über die Krümmung des Raumes“.

Von A. Einstein in Berlin.

(Eingegangen am 18. September 1922.)

Die in der zitierten Arbeit enthaltenen Resultate bezüglich einer nichtstationären Welt schienen mir verdächtig. In der Tat zeigt sich, daß jene gegebene Lösung mit den Feldgleichungen (A) nicht verträglich ist. Aus jenen Feldgleichungen folgt nämlich bekanntlich, daß die Divergenz des Tensors T_{ik} der Materie verschwindet. Im Falle des durch (C) und (D₃) charakterisierten Ansatzes führt dies auf die Beziehung

$$\frac{\partial \rho}{\partial x_4} = 0,$$

welche zusammen mit (8) die zeitliche Konstanz des Weltradius R erfordert. Die Bedeutung der Arbeit besteht also gerade darin, daß sie diese Konstanz beweist.

Berlin, September 1922.

¹⁾ ZS. f. Phys. 10, 377—386, 1922.

Berichtigung

zu der Arbeit

E. Goldstein, Über Magnetkanalstrahlen und Isolator-Entladungen.

S. 180, Zeile 12 v. u. lies flacher statt flachem

S. 184, „ 9 v. o. „ geeigneterem statt geeignetem

S. 185. „ 20 v. o. „ Zustandekommen der statt Zusammen kommender

228

Notiz zu der Arbeit von A. Friedmann „Über die Krümmung des Raumes“.

Von A. Einstein in Berlin.

(Eingegangen am 31. Mai 1923.)

Ich habe in einer früheren Notiz¹⁾ an der genannten Arbeit²⁾ Kritik geübt. Mein Einwand beruhte aber — wie ich mich auf Anregung des Herrn Krutkoff an Hand eines Briefes von Herrn Friedmann überzeugt habe — auf einem Rechenfehler. Ich halte Herrn Friedmanns Resultate für richtig und aufklärend. Es zeigt sich, daß die Feldgleichungen neben den statischen dynamische (d. h. mit der Zeitkoordinate veränderliche) zentrisch-symmetrische Lösungen für die Raumstruktur zulassen.

¹⁾ ZS. f. Phys. 11, 326, 1922.

²⁾ Ebenda 10, 377, 1922.

FRIEDMAN EQUATIONS AND BACKGROUND DYNAMICS

$$R_{00} = -3(H^2 + \dot{H}), \quad R_{0i} = R_{i0} = 0, \quad R_{ij} = a^2(3H^2 + \dot{H} + 2K/a^2)\gamma_{ij},$$

$$R = 6(2H^2 + \dot{H} + K/a^2).$$

$$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2},$$

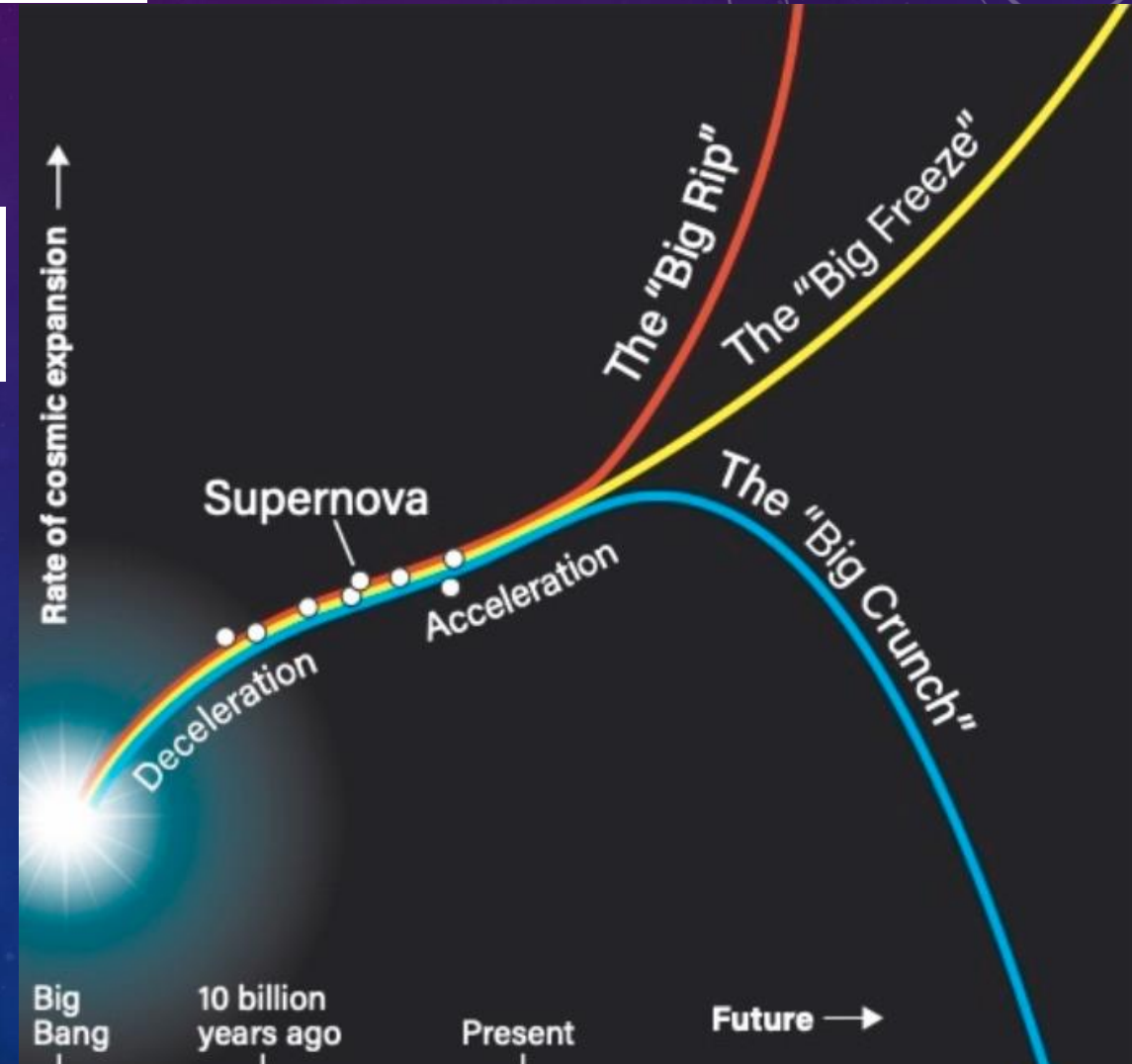
$$3H^2 + 2\dot{H} = -8\pi G P - \frac{K}{a^2}$$



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

$$\Omega_M + \Omega_K = 1,$$

$$\Omega_M \equiv \frac{8\pi G\rho}{3H^2}, \quad \Omega_K \equiv -\frac{K}{(aH)^2}$$



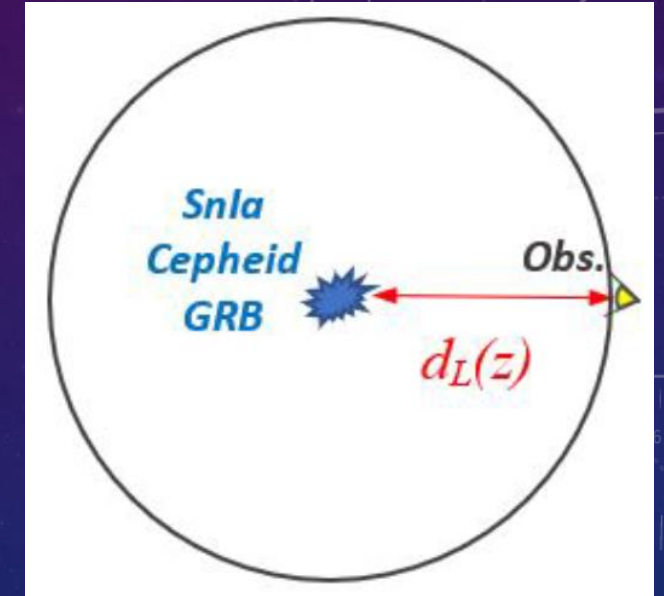
WHY IS IT INTERESTING TO MEASURE DISTANCES?

If we measure **DISTANCES** we can infer the **EXPANSION RATE**

Luminosity Distance

$$l = \frac{L}{4\pi d_L^2}$$

$$d_L(z)_{th} = c(1+z) \int_0^z \frac{dz'}{H(z')}$$



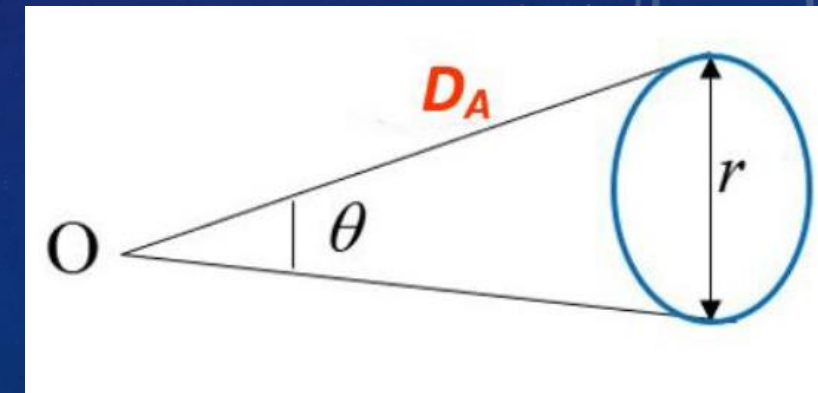
Apparent magnitude

$$m(z)_{th} = M + 5 \log_{10} \left[\frac{d_L(z)}{Mpc} \right] + 25$$

Angular distance

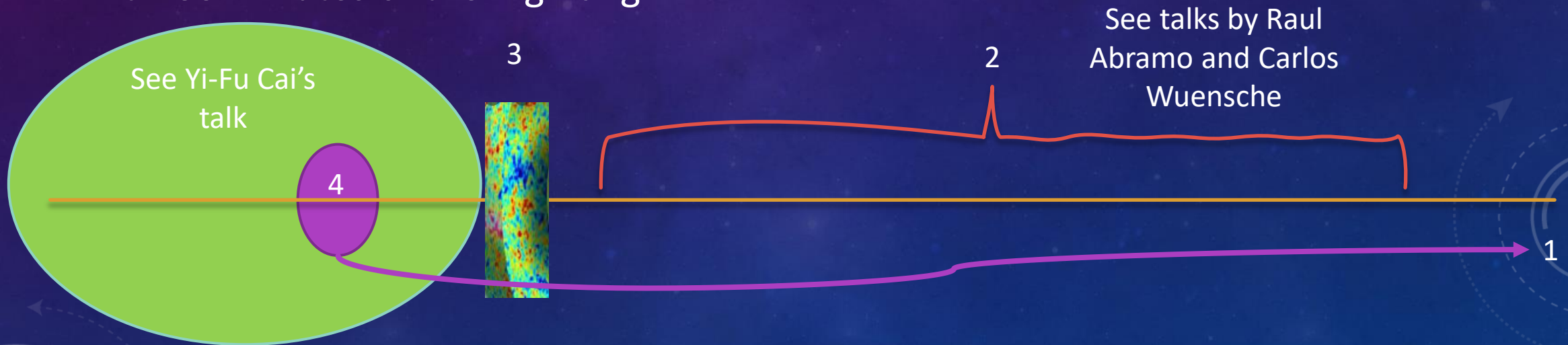
$$D_A(z) = \frac{r}{\theta}$$

$$D_A(z)_{th} = \frac{c}{(1+z)} \int_0^z \frac{dz'}{H(z')}$$



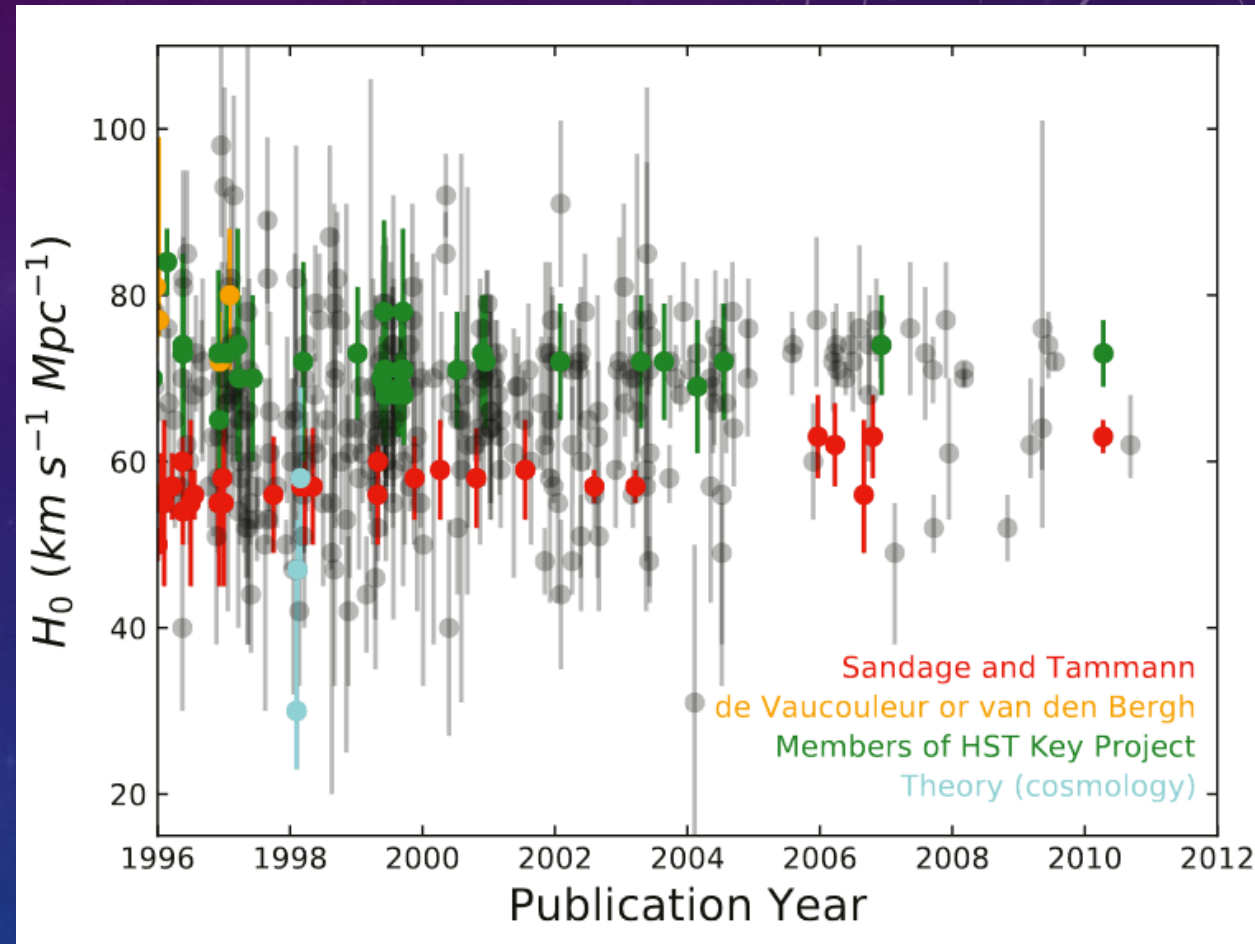
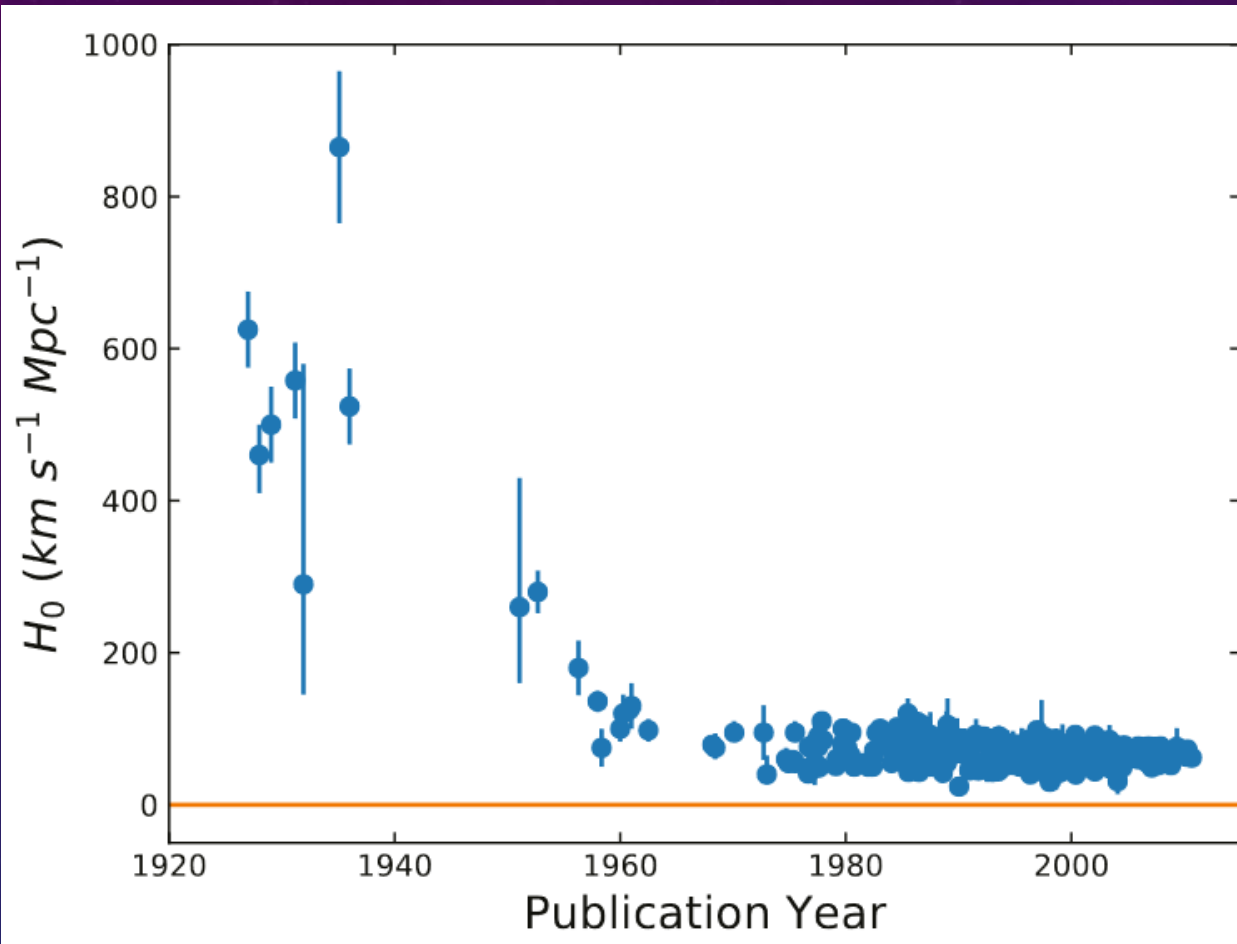
FOUR IMPORTANT EPOCHS WHICH ASTROPHYSICS CAN PROBE

- 1) The current Universe, presumably at an age of about 13.8 billion years;
- 2) The evolution of structure over the past 12 billion years;
- 3) A snapshot of the plasma state of the Universe at an age of about 380,000 years, and;
- 4) Abundances of remaining nuclear reactions taking place within the first three minutes of the Big Bang.



Our task is to provide a theoretical model able to tie these 4 observed eras into a coherent evolution

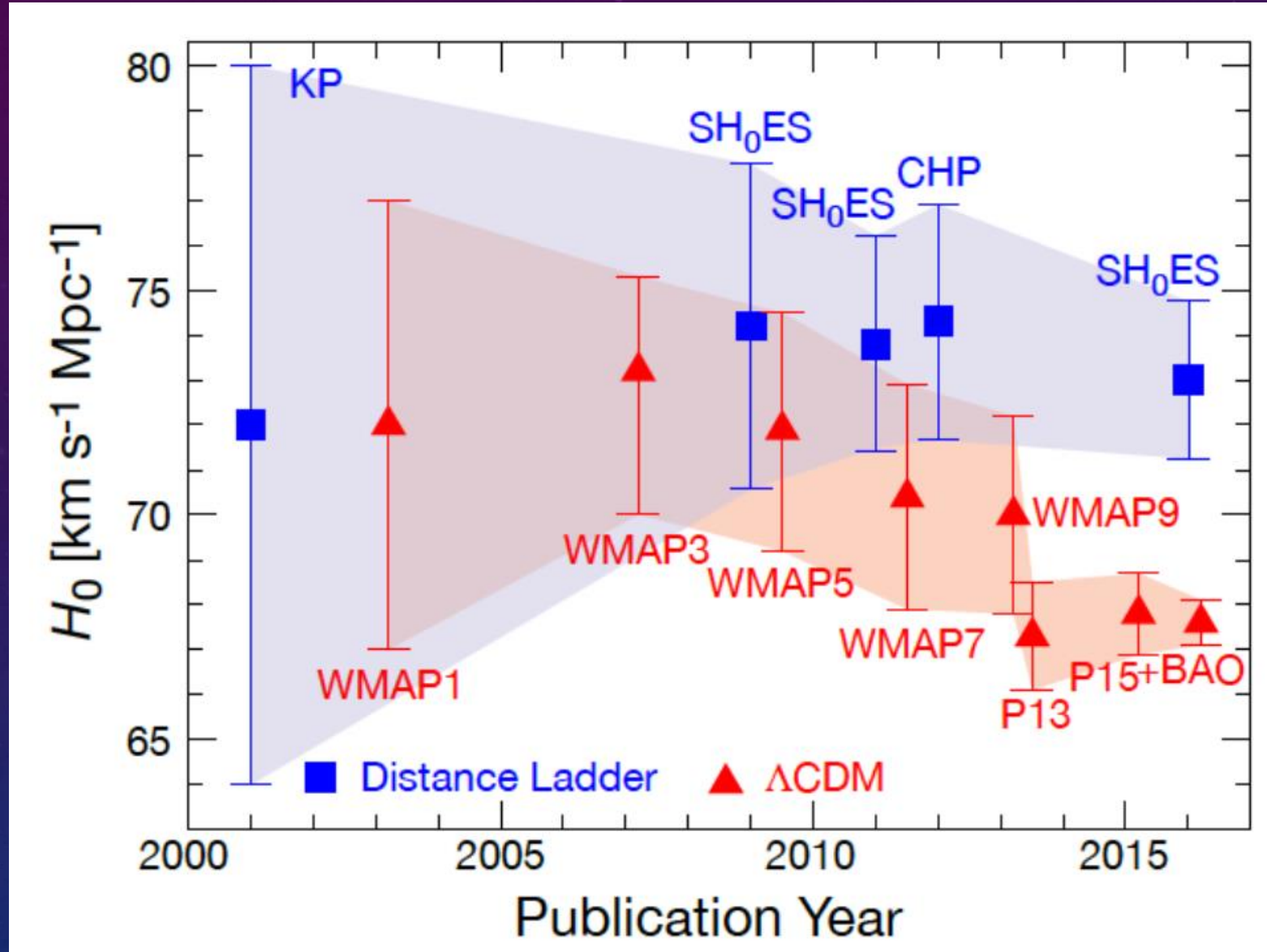
1) THE UNIVERSE TODAY

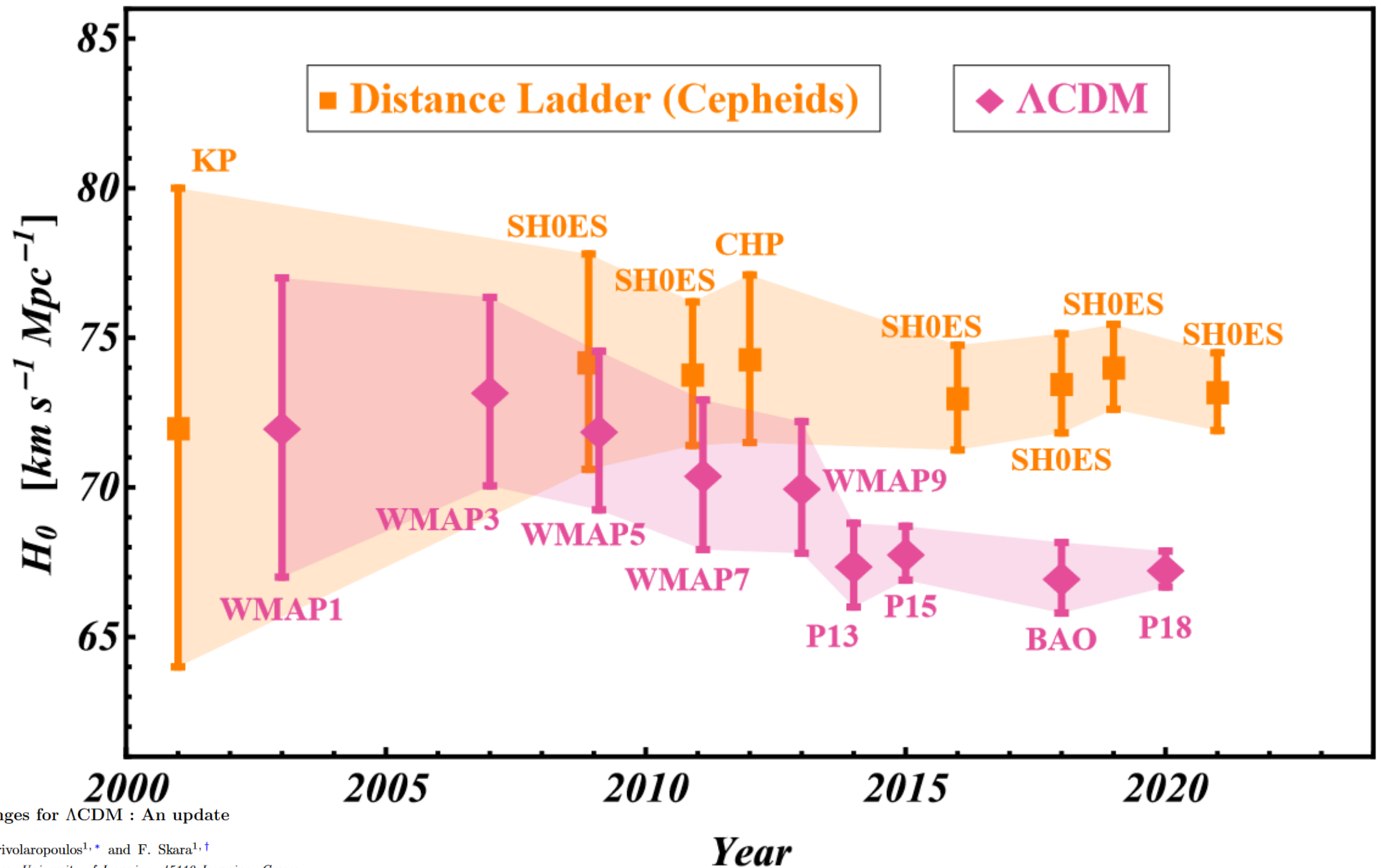


Bruno Leibundgut

SPATIUM No. 47, May 2021

INTRODUCING THE COSMIC TENSION ON H_0





Challenges for Λ CDM : An update

L. Perivolaropoulos^{1,*} and F. Skara^{1,†}

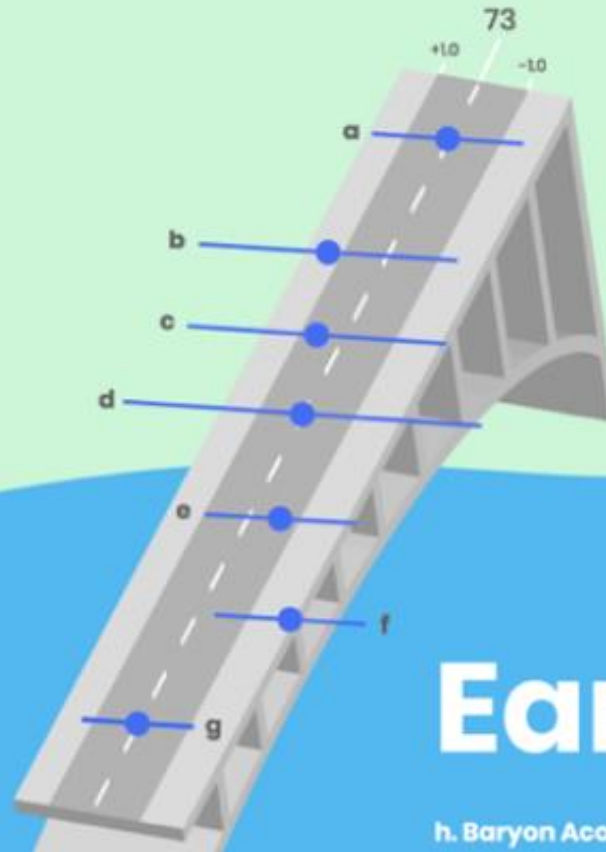
¹Department of Physics, University of Ioannina, 45110 Ioannina, Greece

(Dated: May 20, 2021)

INTRODUCING THE COSMIC TENSION ON H_0

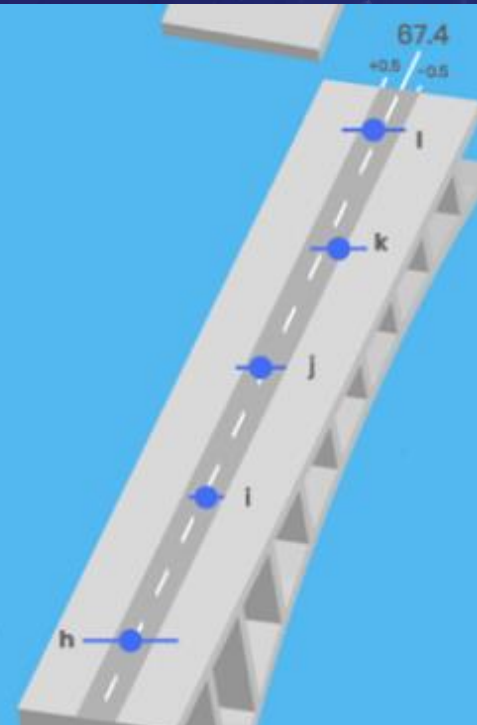
Late Route

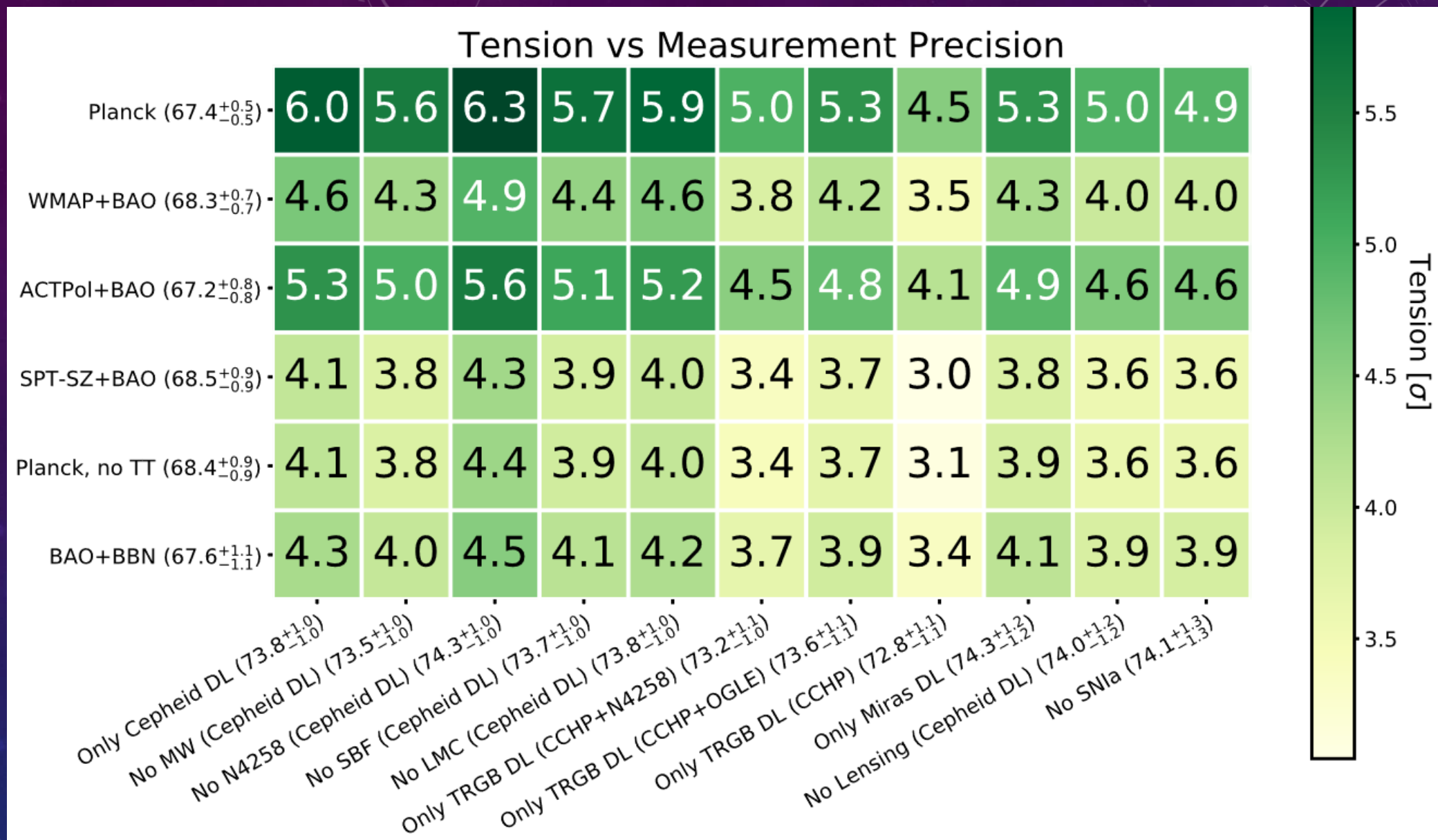
- a. Gravitational Lensing (H0LiCOW)
- b. Surface Brightness Fluctuations in Galaxies
- c. Masers
- d. Mira variables
- e. Tip of Red Giant Branch 1
- f. Tip of Red Giant Branch 2
- g. Cepheid variables



Early Route

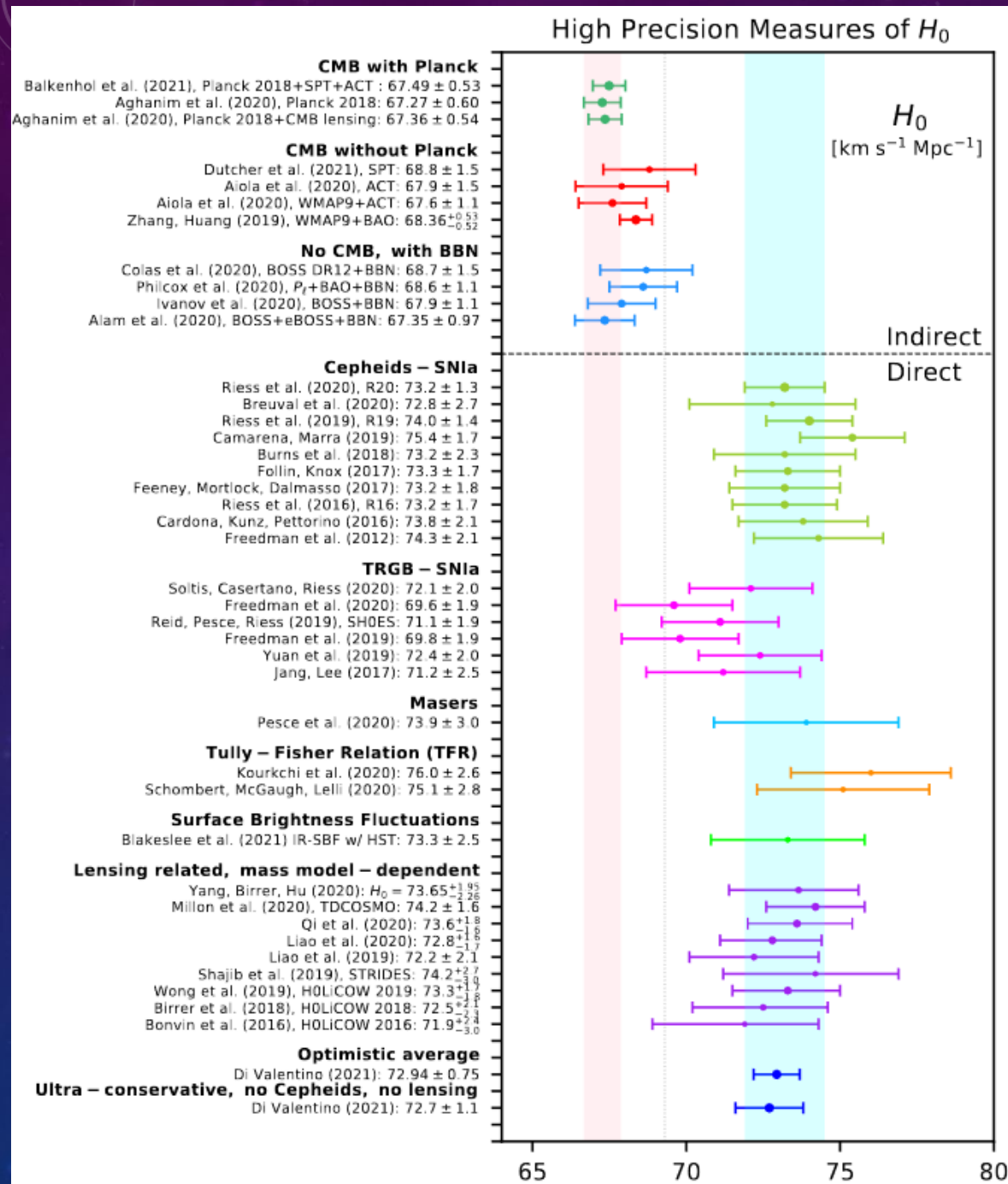
- h. Baryon Acoustic Fluctuation + Big Bang nucleosynthesis
- i. Cosmic Microwave Background (Planck)
- j. Wilkinson Microwave Anisotropy Probe (CMB) + Baryon Acoustic Oscillations
- k. Atacama Cosmology Telescope Polarimeter (CMB) + Baryon Acoustic Oscillations
- l. South Pole Telescope Sunyaev-Zel'dovich effect survey (CMB) + Baryon Acoustic Oscillations





In the Realm of the Hubble tension – a Review of Solutions †

Eleonora Di Valentino^{1*}, Olga Mena², Supriya Pan³, Luca Visinelli⁴, Weiqiang Yang⁵, Alessandro Melchiorri⁶, David F. Mota⁷, Adam G. Riess^{8,9}, Joseph Silk^{8,10,11}



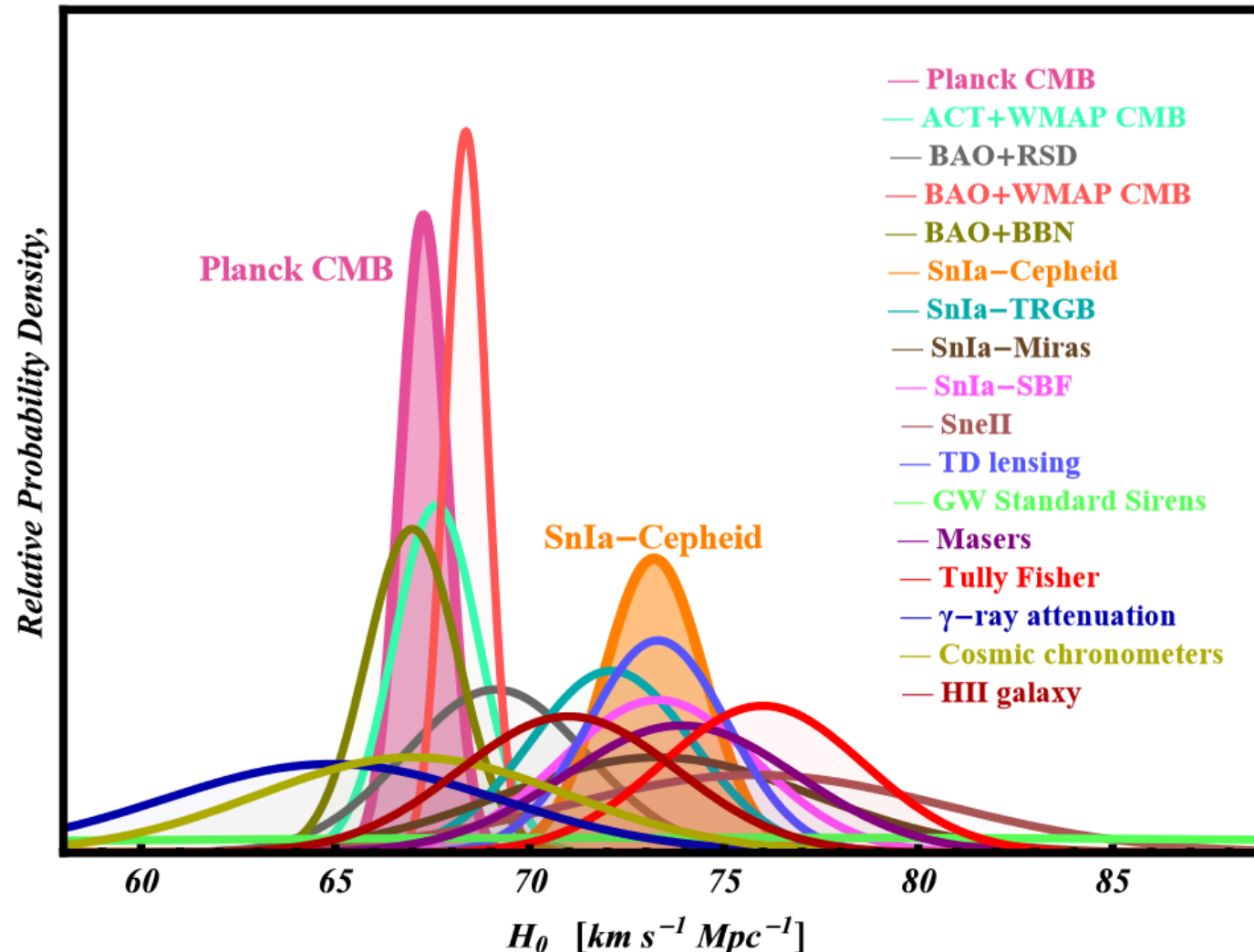
Challenges for Λ CDM : An update

L. Perivolaropoulos^{1,*} and F. Skara^{1,†}

¹*Department of Physics, University of Ioannina, 45110 Ioannina, Greece*

(Dated: May 20, 2021)

H_0 Measurements (most do not assume Λ CDM)



EARLY TIME MODIFICATIONS PREFERRED OVER LATE TIME ONES?

To H_0 or not to H_0 ?

George Efstathiou 

Monthly Notices of the Royal Astronomical Society, Volume 505, Issue 3, August 2021, Pages 3866–3872, <https://doi.org/10.1093/mnras/stab1588>

Published: 05 June 2021 **Article history** ▼

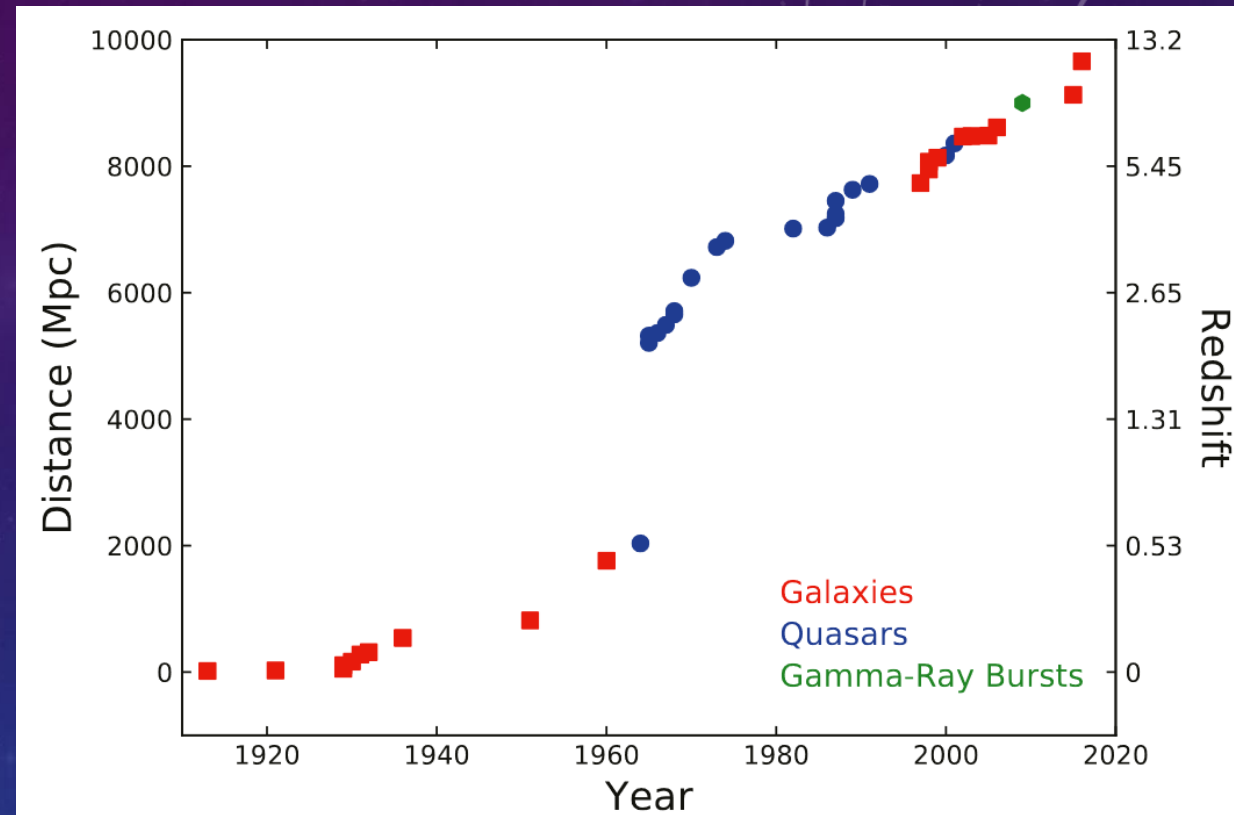
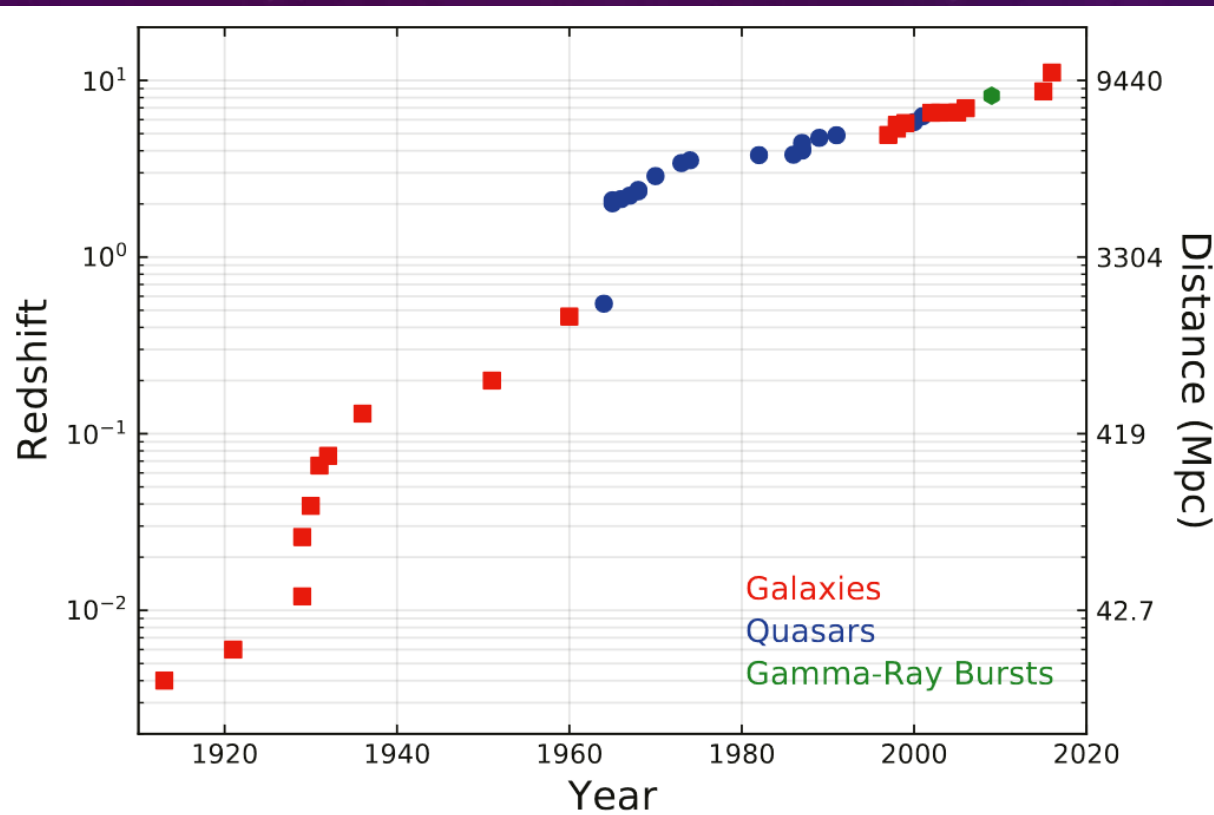
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ABSTRACT

This paper investigates whether changes to late-time physics can resolve the ‘Hubble tension’. It is argued that many of the claims in the literature favouring such solutions are caused by a misunderstanding of how distance ladder measurements actually work and, in particular, by the inappropriate use of a distance ladder H_0 prior. A dynamics-free inverse distance ladder shows that changes to late-time physics are strongly constrained observationally and cannot resolve the discrepancy between the SH0ES data and the base Λ CDM cosmology inferred from *Planck*. We propose a statistically rigorous scheme to replace the use of H_0 priors.

It is, therefore, unlikely that changes to the late time expansion history can resolve the ‘Hubble tension’.

2) THE UNIVERSE OVER THE PAST 12 BILLION YEARS

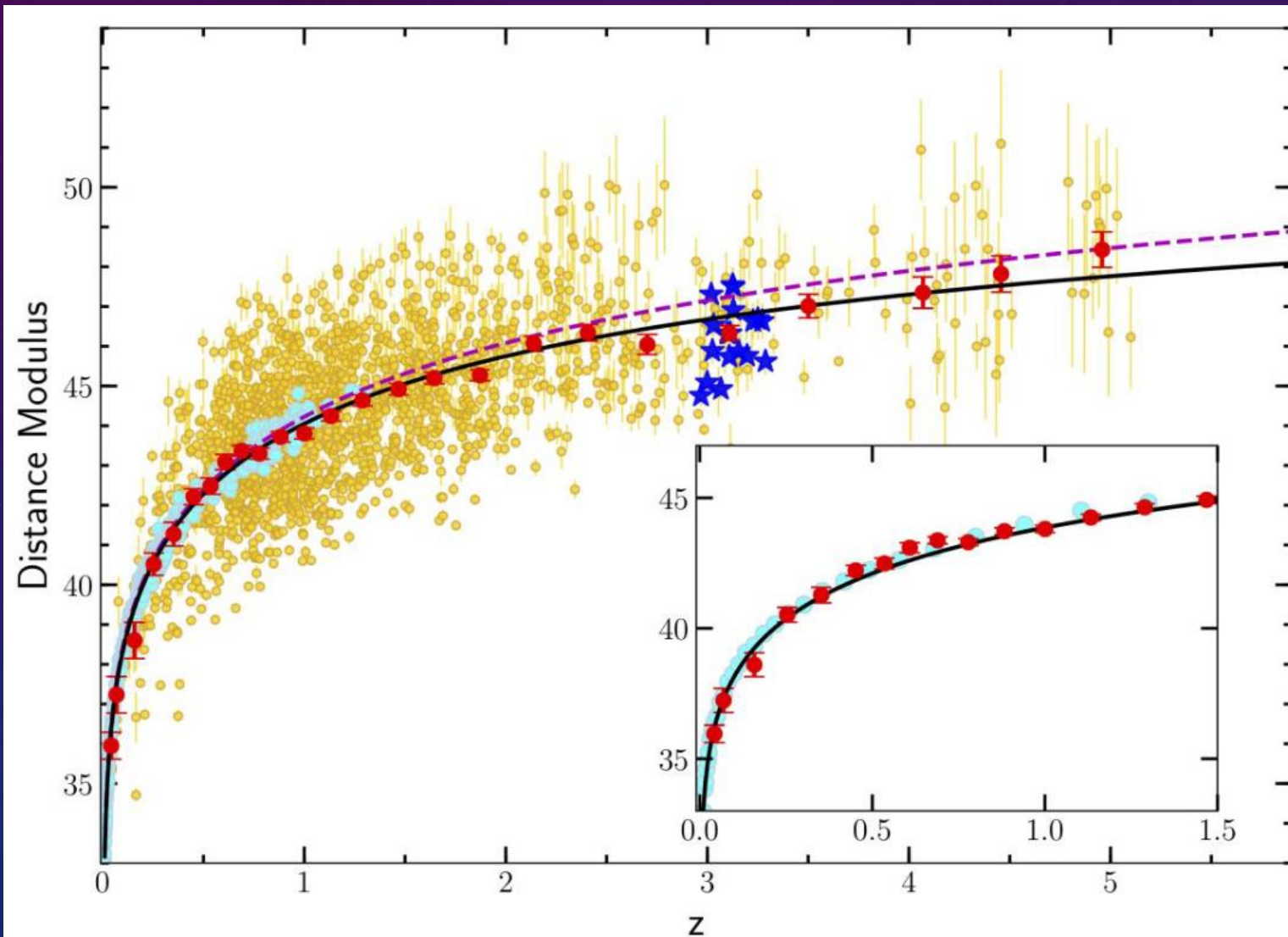


Bruno Leibundgut

SPATIUM No. 47, May 2021

Cosmological constraints from the Hubble diagram of quasars at high redshifts

[G. Risaliti](#) & [E. Lusso](#)



3) COSMIC MICROWAVE BACKGROUND (CMB)

PREDICTION: The CMB was first predicted by G. Gamow, R. Alpher and R. Herman in 1948 $T \sim 5K$

PHYSICAL REVIEW

VOLUME 73, NUMBER 7

APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*

Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland

AND

H. BETHE

Cornell University, Ithaca, New York

AND

G. GAMOW

The George Washington University, Washington, D. C.

February 18, 1948

AS pointed out by one of us,¹ various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,² the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances³ it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe⁴ the density dependence on time is given by $\rho \propto 1/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0 , satisfying the relation:

$$\int_{t_0}^{\infty} (10^4/\rho) dt \leq 5 \times 10^4, \quad (2)$$

which gives us $t_0 \geq 20$ sec. and $\rho_0 \leq 2.5 \times 10^8$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron

No. 4124 November 13, 1948

NATURE

775

with $T \propto 1/t$ and $R_0 = 1.9 \times 10^9 \sqrt{-1}$ light-years. The integrated values of ρ_{mat} and ρ_{rad} intersect at a reasonable time, namely, 3.5×10^{14} sec. $\approx 10^7$ years, and the masses and radii of condensations at this time become, according to the Jeans' criterion, $M_c = 3.8 \times 10^7$ sun masses, and $R_c = 1.1 \times 10^3$ light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K. We hope to publish the details of these calculations in the near future.

Our thanks are due to Dr. G. Gamow for the proposal of the topic and his constant encouragement during the process of error-hunting. We wish also to thank Dr. J. W. Follin, jun., for his kindness in performing the integrations required for the determination of α , on a Reeves Analogue Computer. The work described in this letter was supported by the United States Navy, Bureau of Ordnance, under Contract NOrd-7386.

RALPH A. ALPHER
ROBERT HERMAN

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

¹ Gamow, G., *Phys. Rev.*, **70**, 572 (1946).

If we take a figure of 2.4×10^8 years as a reasonable estimate of the age of the crust, it follows that the original amount of potassium-40 would have been 2^{10} , or about 1,000 times greater than the present amount. Of this quantity, approximately two-thirds would have been transformed to argon; that is, the total quantity of argon present in the surface materials of the earth should be about 430 times the known amount of argon in the atmosphere.

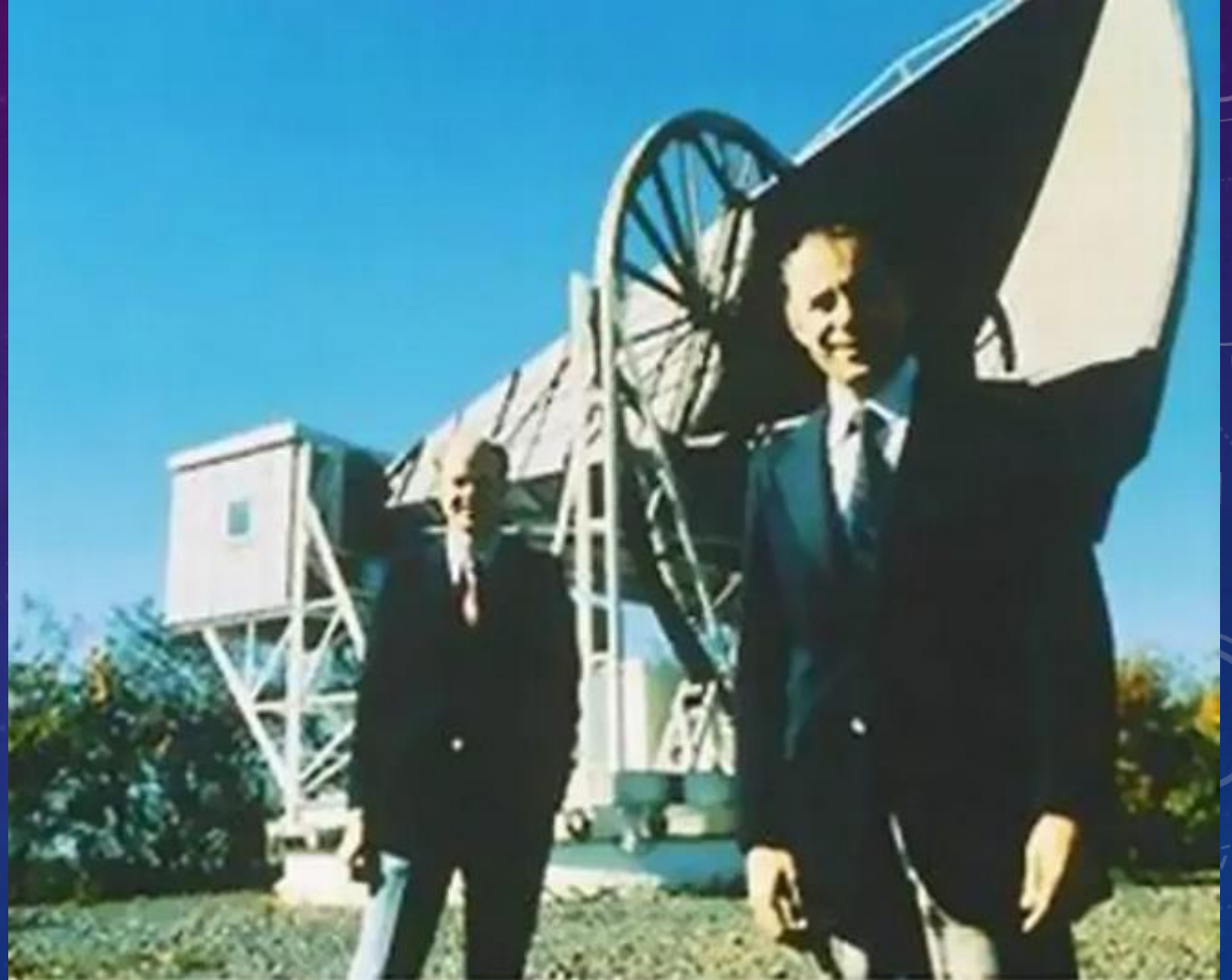
It might be assumed that the bulk of the argon generated in the solid crust was retained in the crust, but even this assumption will only reduce the discrepancy. From the quantity of sodium retained in the ocean, F. W. Clarke⁵ estimates that an amount of solid material equal to about 5 per cent of the postulated shell has undergone erosion. It is hard to imagine that, if during this process the sodium was extracted from the rock, the argon would not also escape, and this process would supply a quantity of argon more than twenty times that of atmospheric argon. If, on the other hand, we assume that the argon of the atmosphere⁶, which is 99.6 per cent A^{40} , is derived from the eroded layer only, we easily arrive at an age of the crust of about 1.3×10^8 years, which differs by a factor of about 2 from the accepted estimates of geological ages. A correction to these results should be applied for the amount of argon in solution in the ocean; but it can easily be shown that this correction is of no importance.

² Two other possibilities may be considered: (a) that

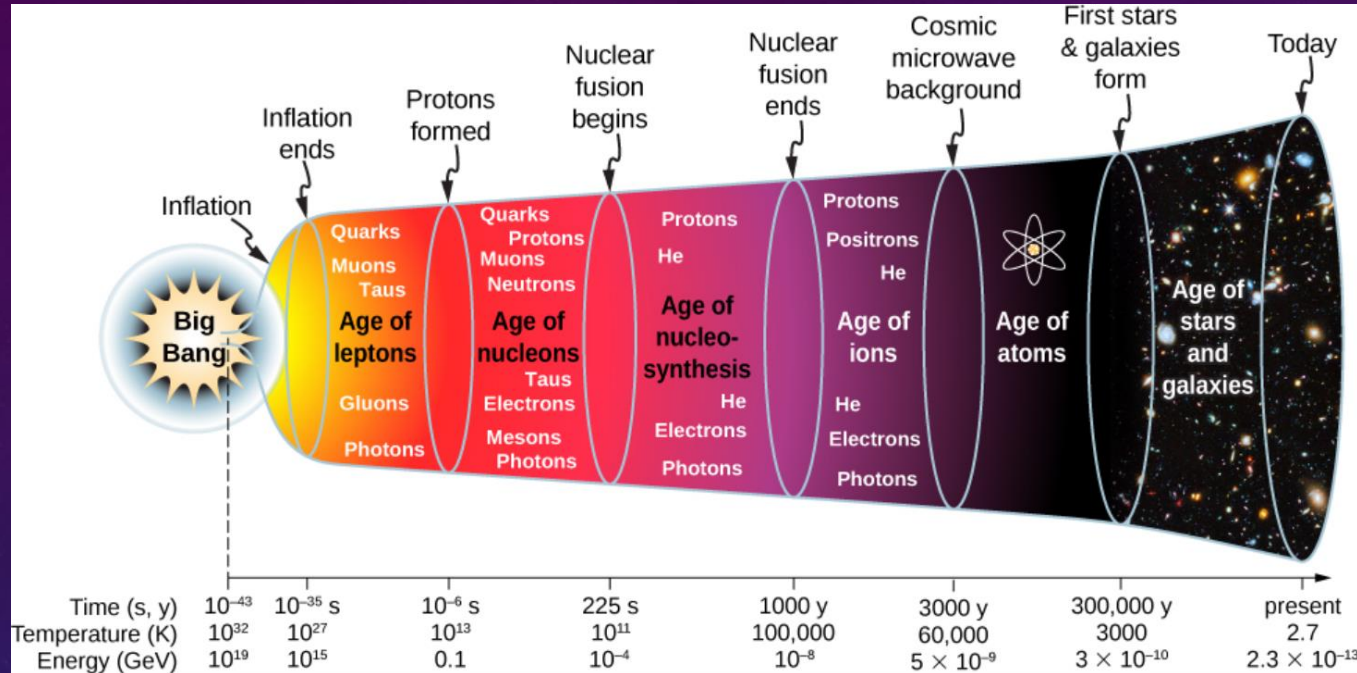
The original paper (letter) by Alpher and Hermann which makes the first prediction of the cosmic microwave background (CMB). It was published in *Nature* magazine on the 13th of November 1948.

COSMIC MICROWAVE BACKGROUND (CMB)

- The first Discovery in 1965 by A. A. Penzias and R.W. Wilson
- The Nobel Prize 1978

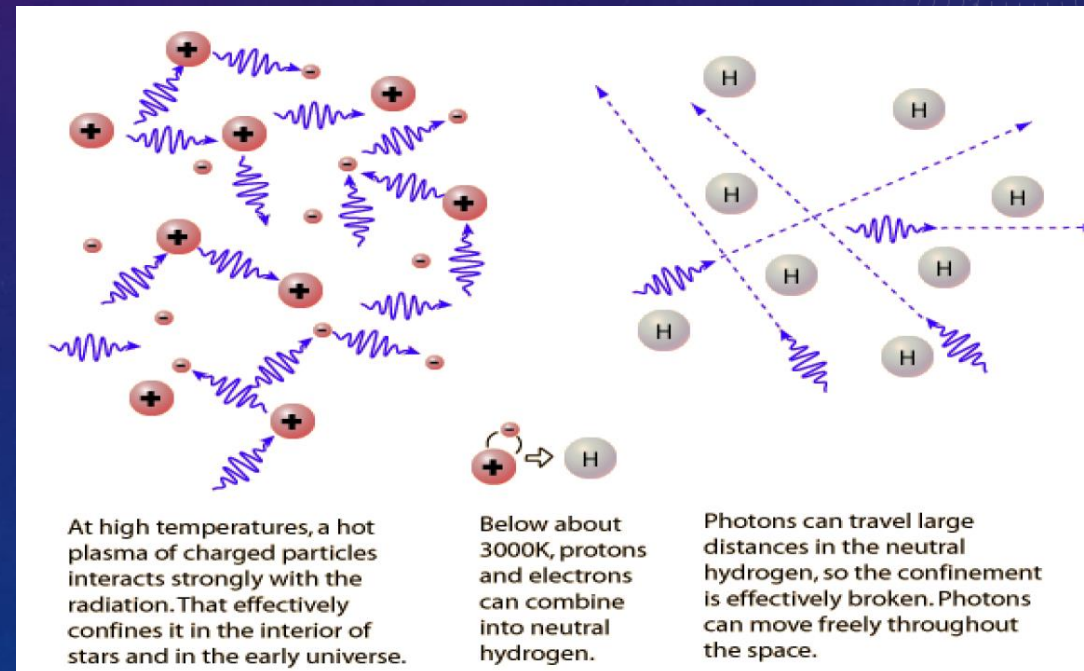


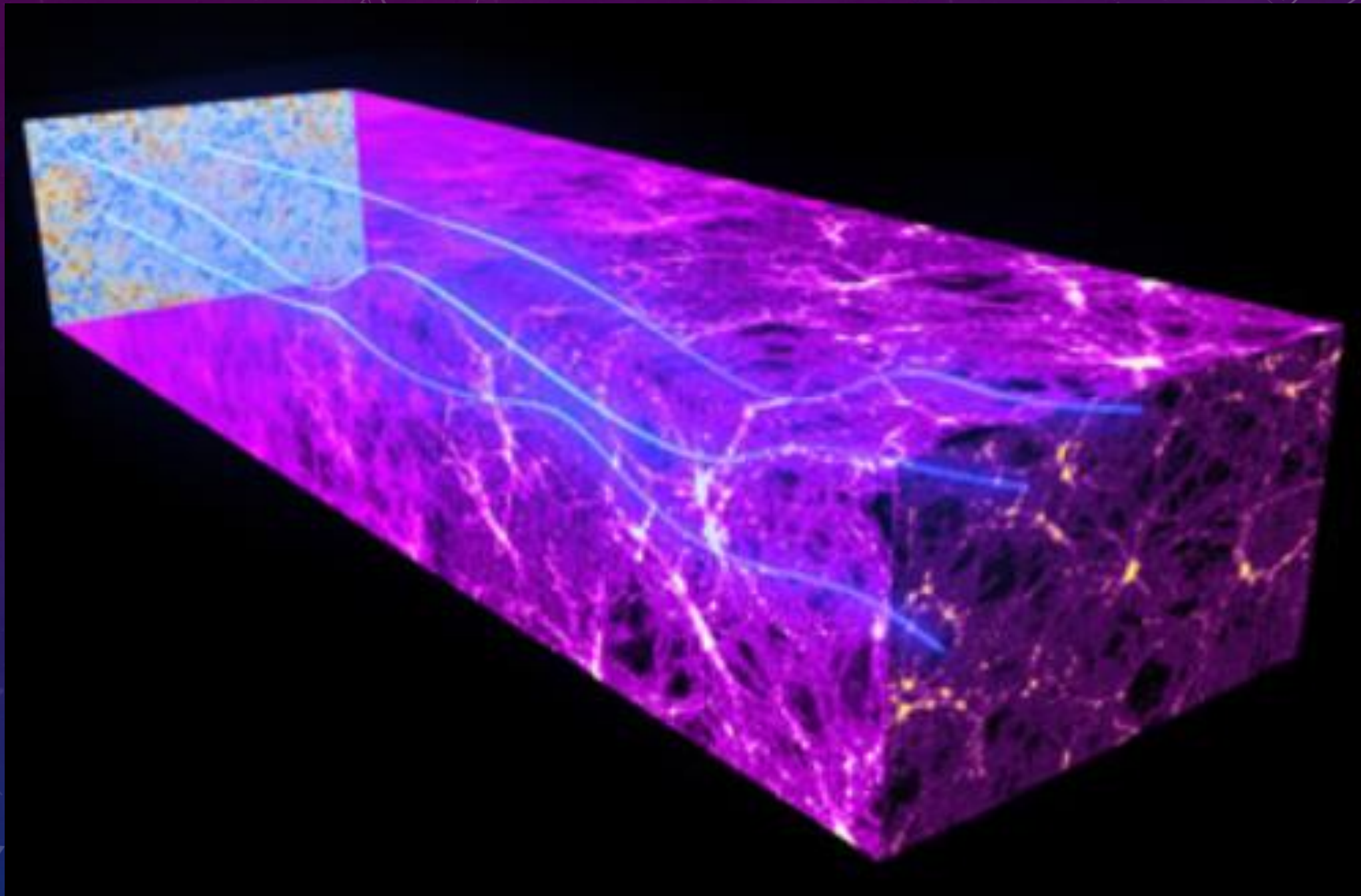
COSMIC MICROWAVE BACKGROUND (CMB)



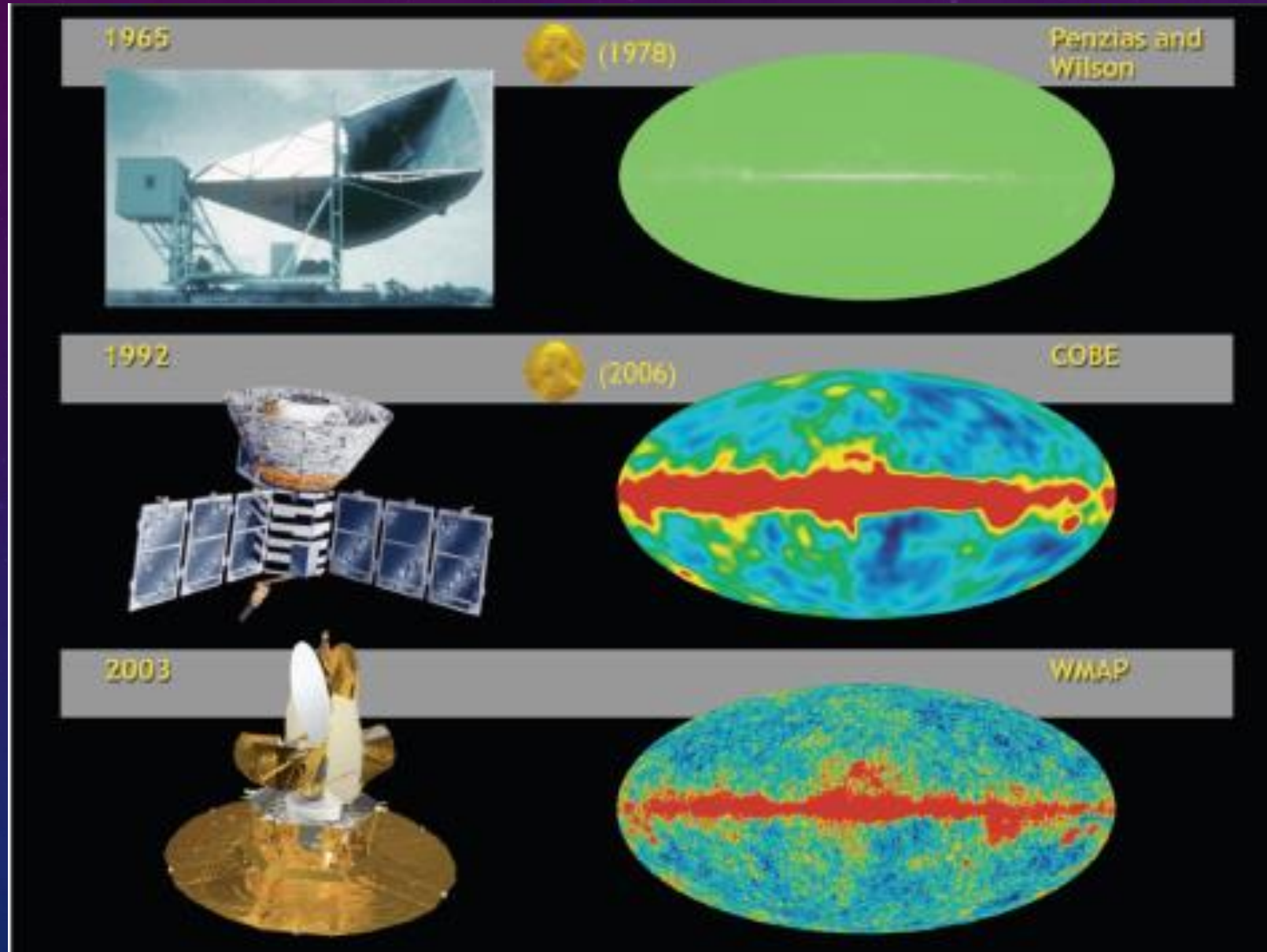
It is early to show this plot. But it shows the moment the CMB is released.

Radiation decoupled from charged particles





COSMIC MICROWAVE BACKGROUND (CMB)

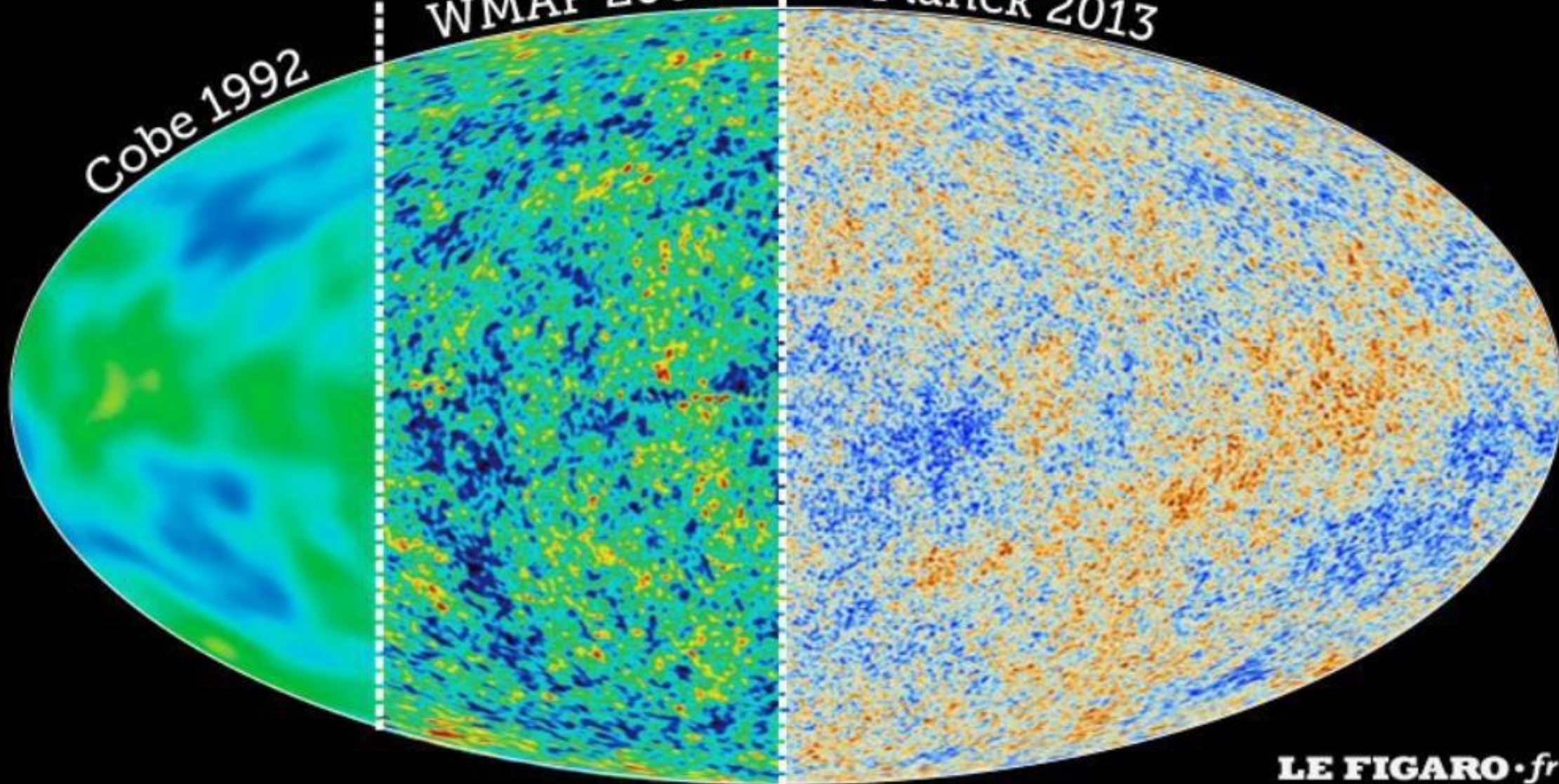


Cobe 1992

WMAP 2003

Planck 2013

LE FIGARO · fr



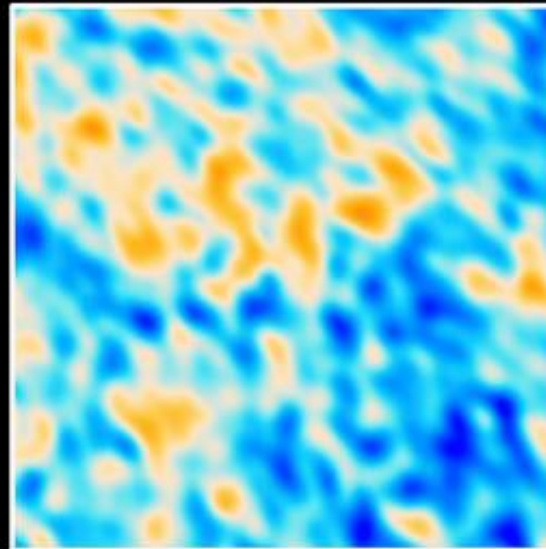
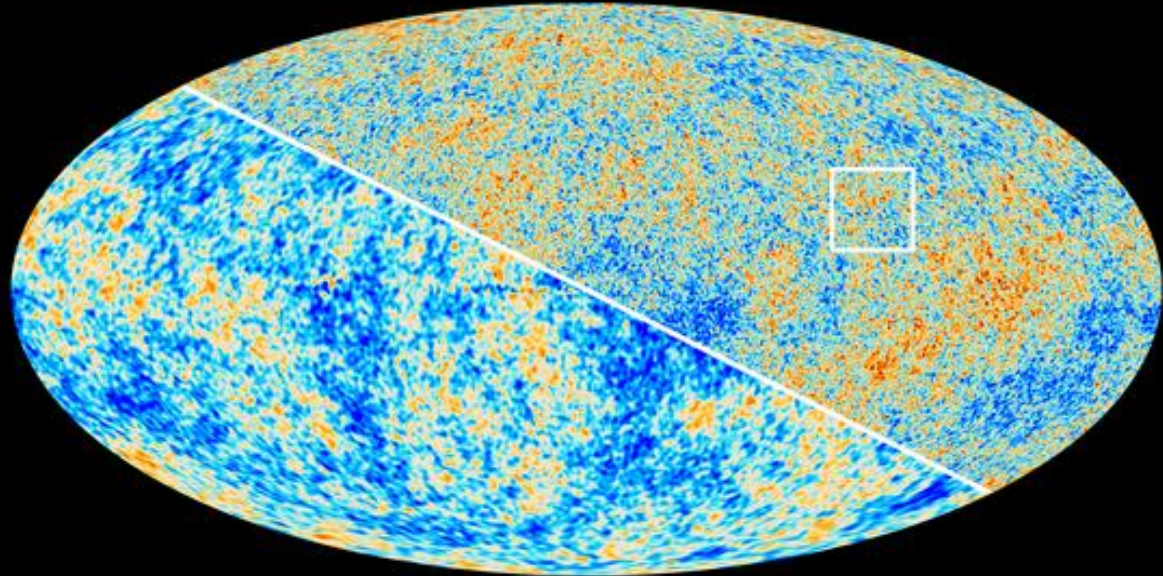
PLANCK satellite



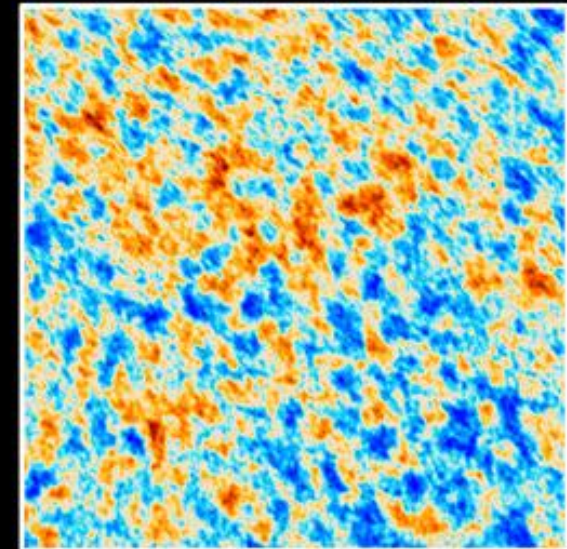
Launch: 2009.
Took data until 2013.

Data releases: 2013, 2016,
2018

The Cosmic Microwave Background as seen by Planck and WMAP

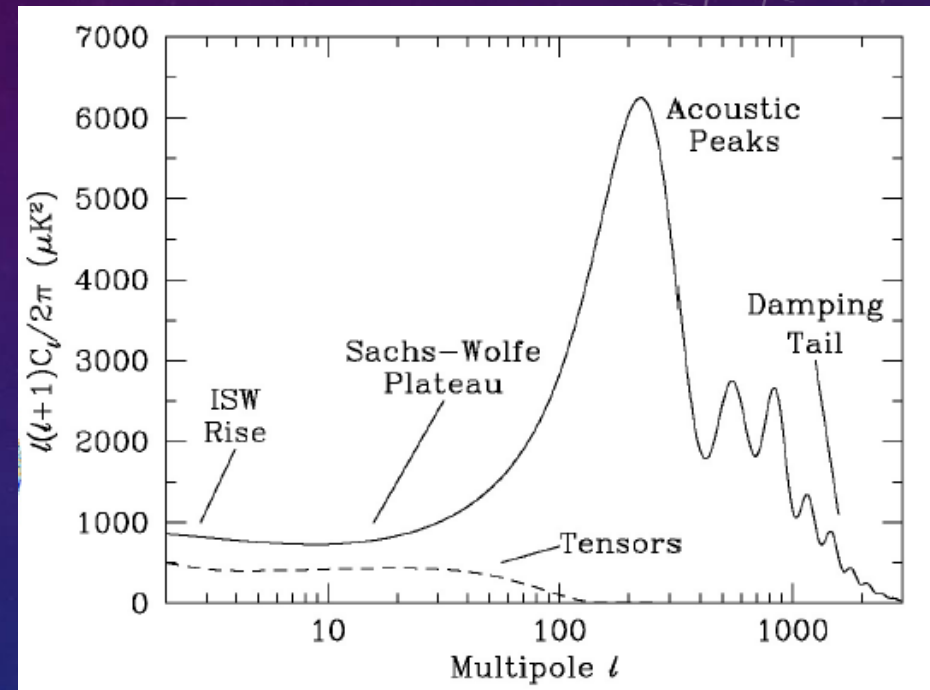
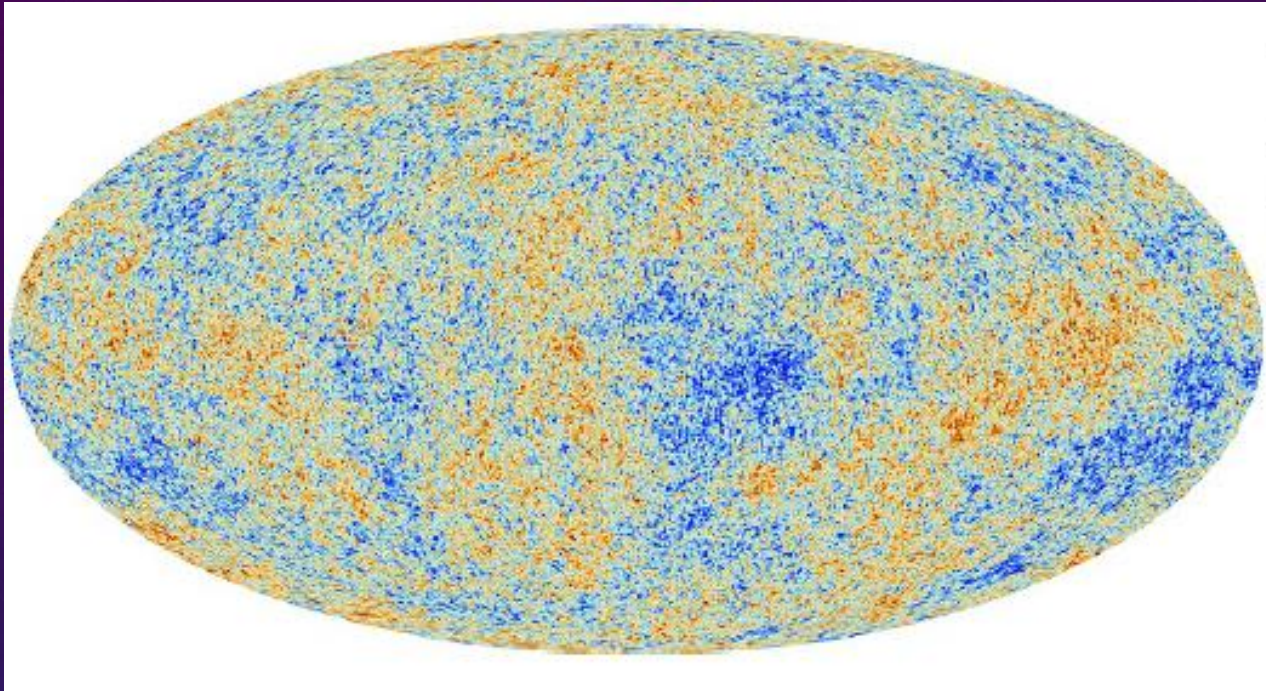


WMAP



Planck

THE SACHS-WOLFE FORMULA



$$\frac{\delta T}{T}(\vec{e}) = \left[\frac{\delta T_{\gamma}}{T} + \phi - \vec{e} \cdot \vec{v}_{\gamma} \right]_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta \frac{\partial}{\partial \eta} (\phi + \psi)$$

Contribution
from the LSS

Contribution acquired along
the CMB photons travel

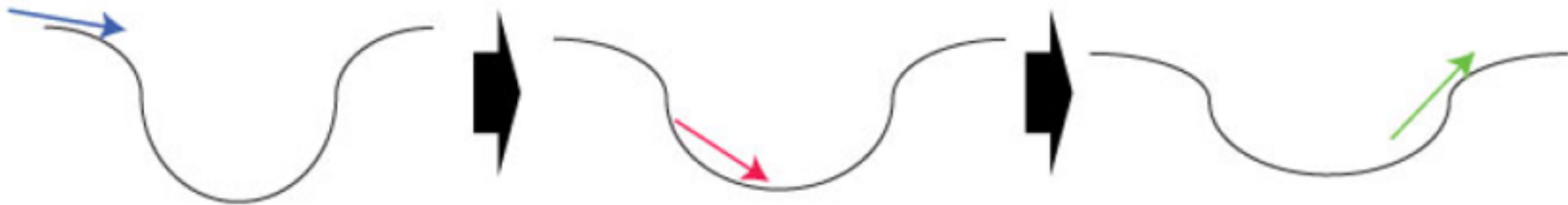
It is wrong to say that CMB is a picture of the young universe.
It also captures features from the cosmological expansion

$$\left(\frac{\Delta T}{T}\right)_k^{ISW} = 2 \int_{a_d}^{a_0} \frac{\partial \Phi_k}{\partial a} da = 2 (\Phi_k(a_0) - \Phi_k(a_d))$$

Photon enters well
at a certain energy

Photon gains energy on its
path into the gravitation well

Photon loses less energy
than it gained on the way out
of the shallower well



Gravitational well of galaxy supercluster - the depth shrinks as the universe (and cluster) expands

4) PRIMORDIAL ABUNDANCES

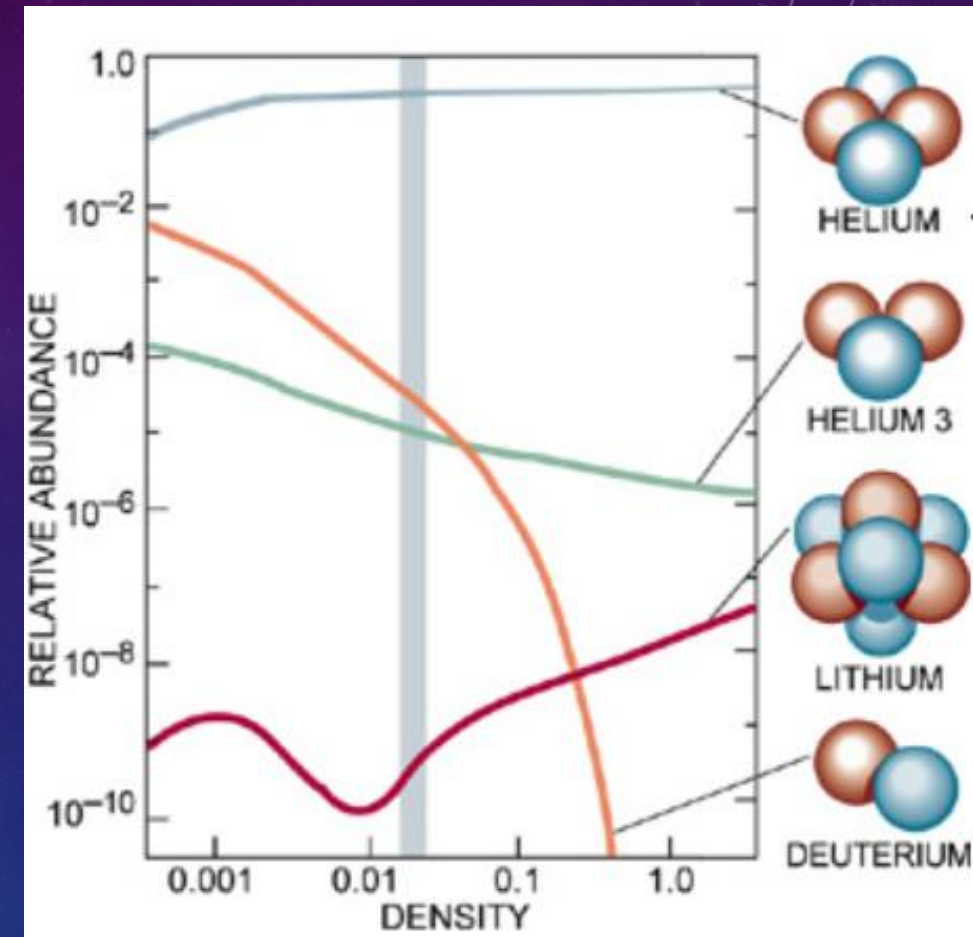
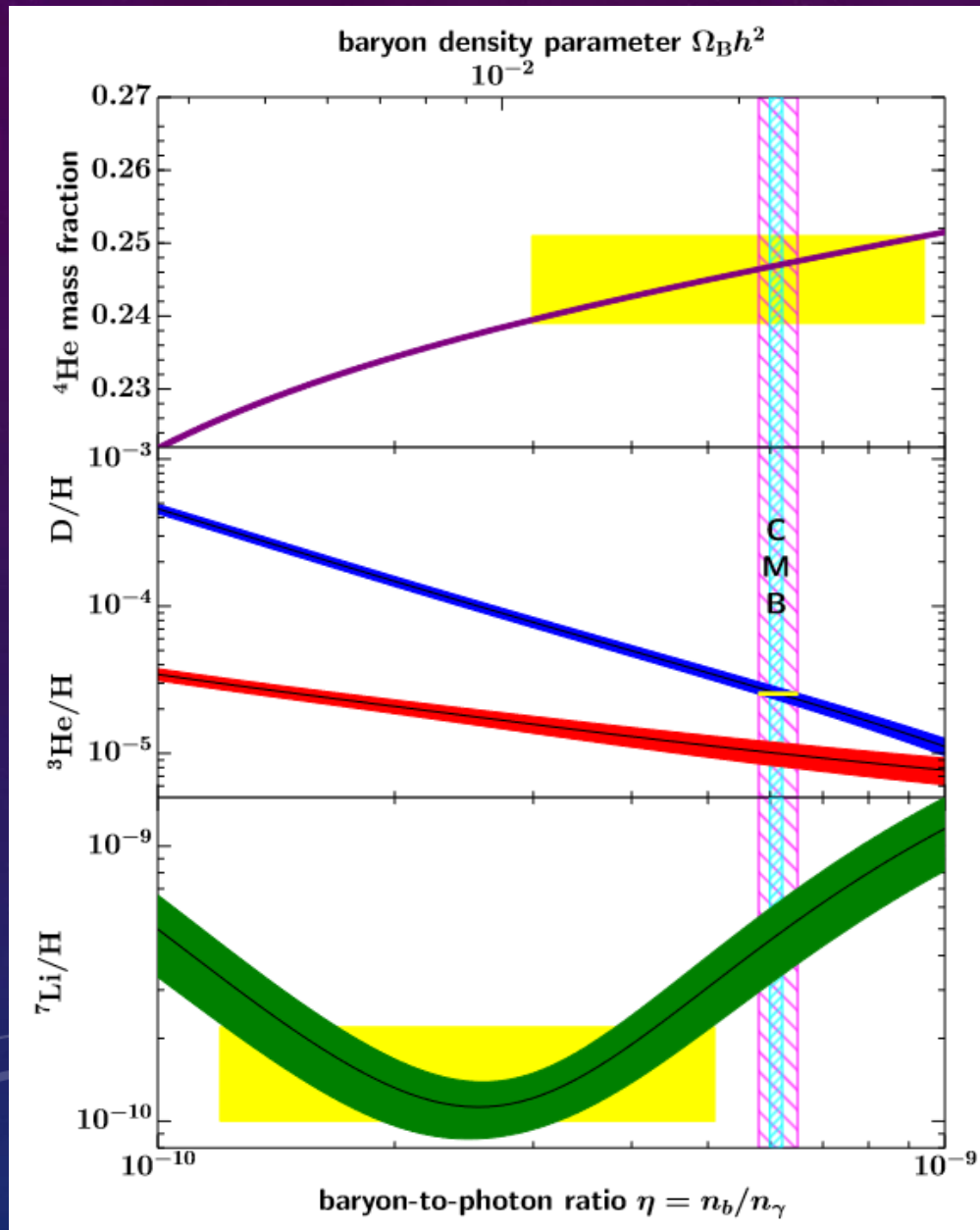


Figure 24.1: The primordial abundances of ${}^4\text{He}$, D , ${}^3\text{He}$, and ${}^7\text{Li}$ as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN $\text{D}+{}^4\text{He}$ concordance range (both at 95% CL).

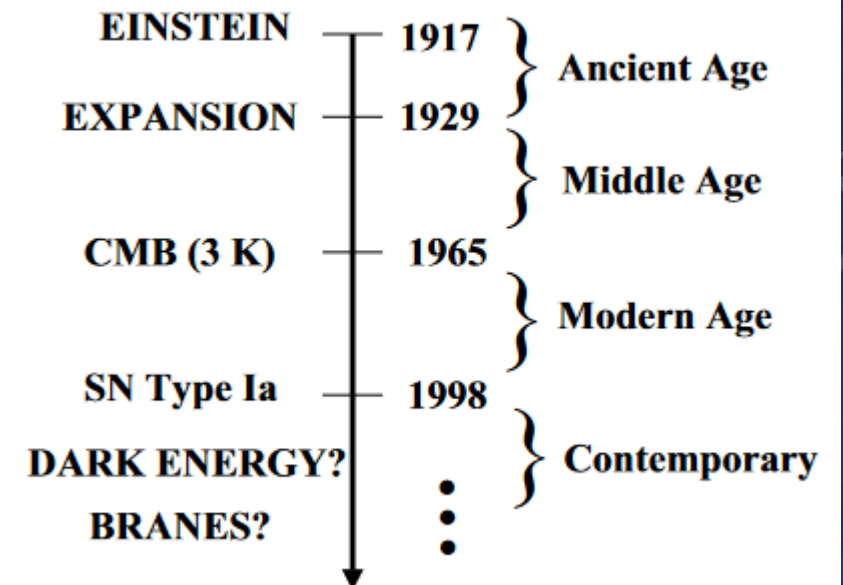
THE STANDARD COSMOLOGICAL MODEL CHRONOLOGY

- 1915: Einstein has formulated GR
- 1917: Einstein, De Sitter try to build the first cosmological models (**Prejudice: Static/Stationary universe**)
- 1922: A. Friedmann
- 1927: G. Lemaitre
- 1933: Robertson, Walker
- 1929 Hubble's law (first confirmation)
- 1930-1965: Accumulation of proofs in favour of FLRW
- 1965: CMB Discovery (full confirmation)
- 1992: COBE measures CMB anisotropy
- 1998: SNe studies reveal that expansion is accelerating
- 2003: WMAP observes several peaks in CMB anisotropy
- 2013: PLANCK: Density content revision



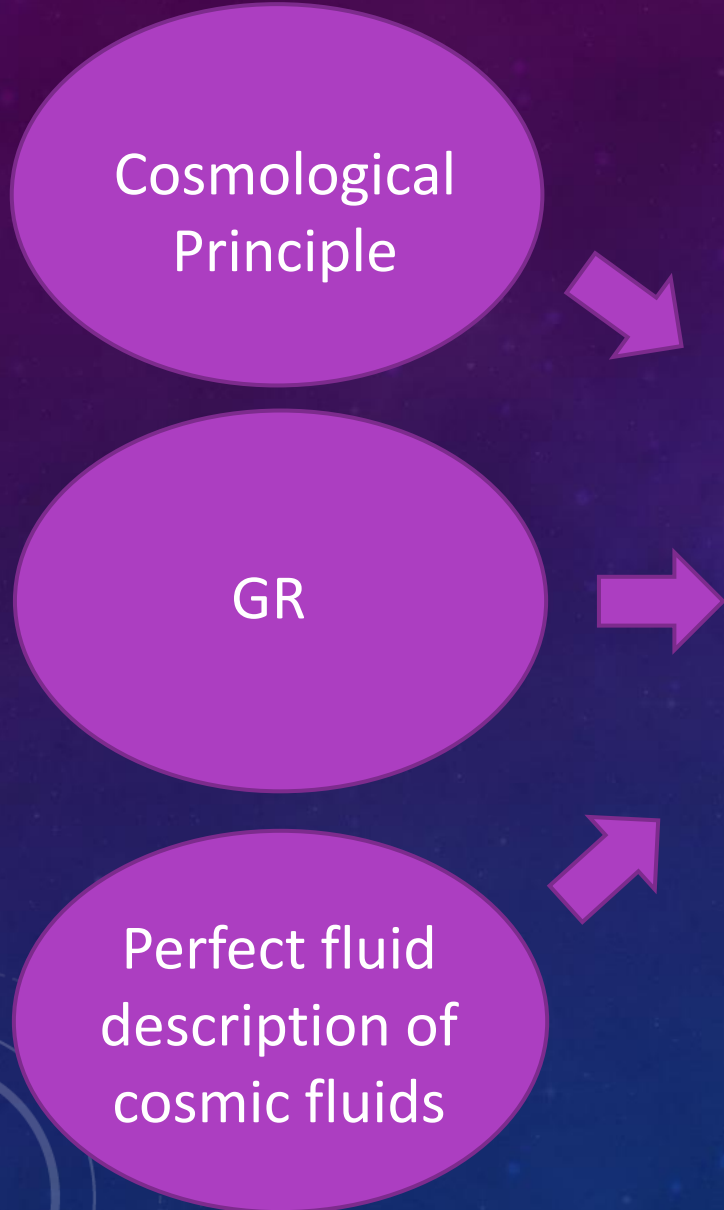
Investigate most general
**HOMOGENEOUS, ISOTROPIC, NON-
STATIONARY** solutions of GR

COSMOLOGY : TIME LINE

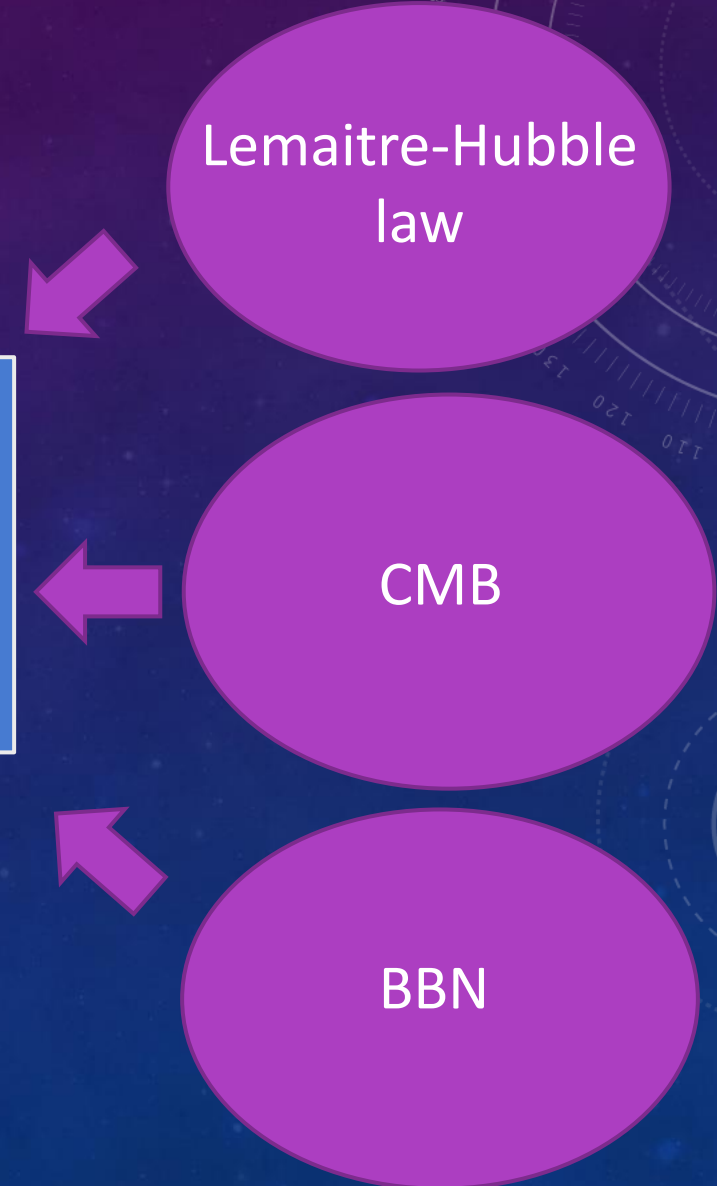


SUMMARY: PILLARS OF THE STANDARD COSMOLOGY

Theory



Observations



Standard
Cosmological
Model

DARK MATTER

The background is a gradient of dark blue and purple, speckled with small white dots representing stars. On the right side, there are faint, stylized circular diagrams. One large diagram at the top right features concentric circles with radial tick marks and numerical labels (100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210) along its outer edge. Below it, another diagram shows concentric circles with arrows indicating a clockwise direction. In the bottom left corner, a partial diagram shows concentric circles with an arrow pointing counter-clockwise.

DARK MATTER EVIDENCES

- Astrophysical evidences

Isolated systems like galaxies and galaxy clusters.

- Cosmological evidences

Take into account universe expansion

Dark matter as a key element for viable structure formation

FRITZ ZWICKY 1898-1974



The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\bar{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot}. \quad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500, \quad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 86

OCTOBER 1937

NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the luminosities and internal motions of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal motions alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal viscosity due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\bar{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary statistical mechanics to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

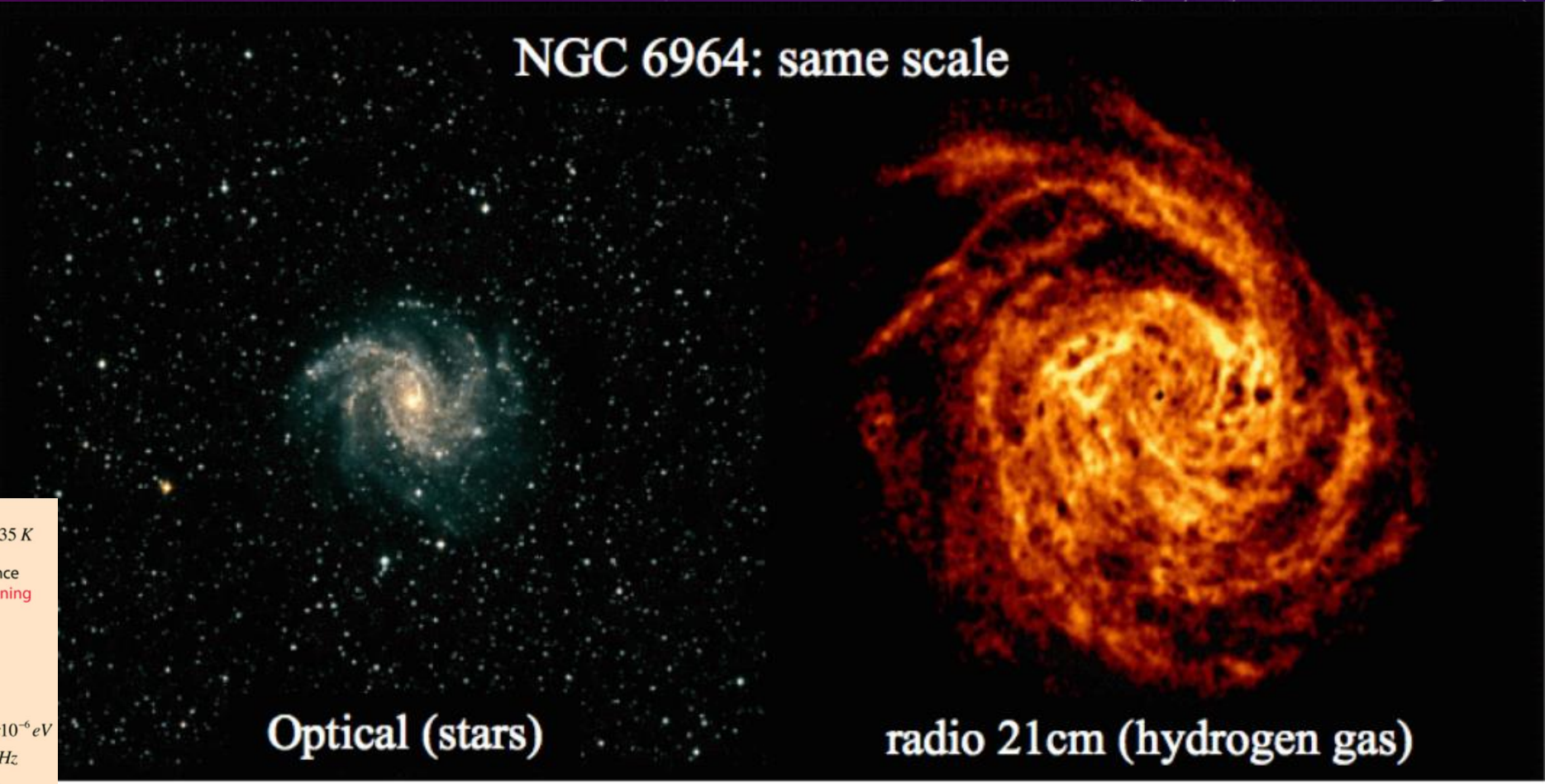
As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

VERA RUBIN 1980

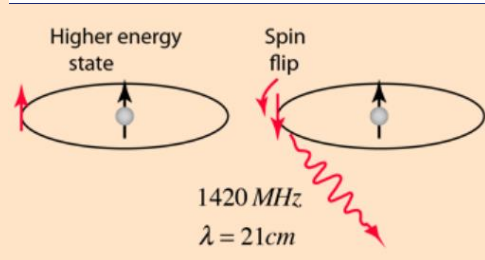
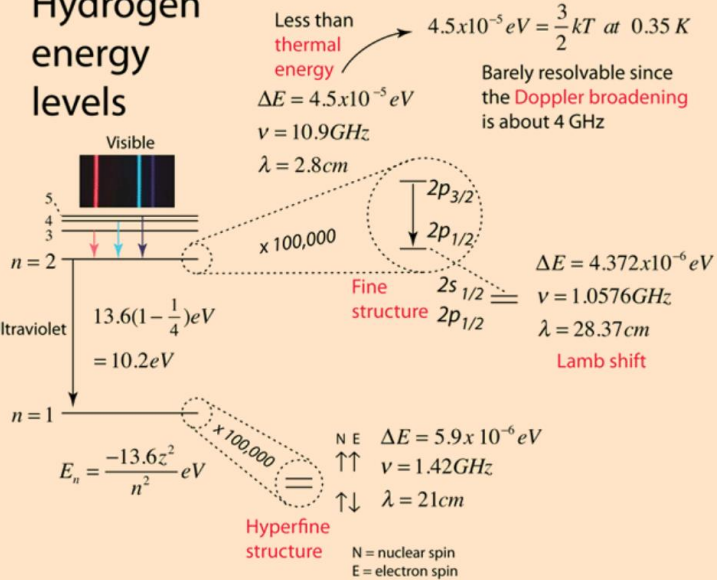


GALAXY ROTATION CURVES

Multi-wavelength observations allows to see beyond the luminous disk



Hydrogen energy levels



21cm radiation first observed in 1951 by Harold Ewen and Edward M. Purcell

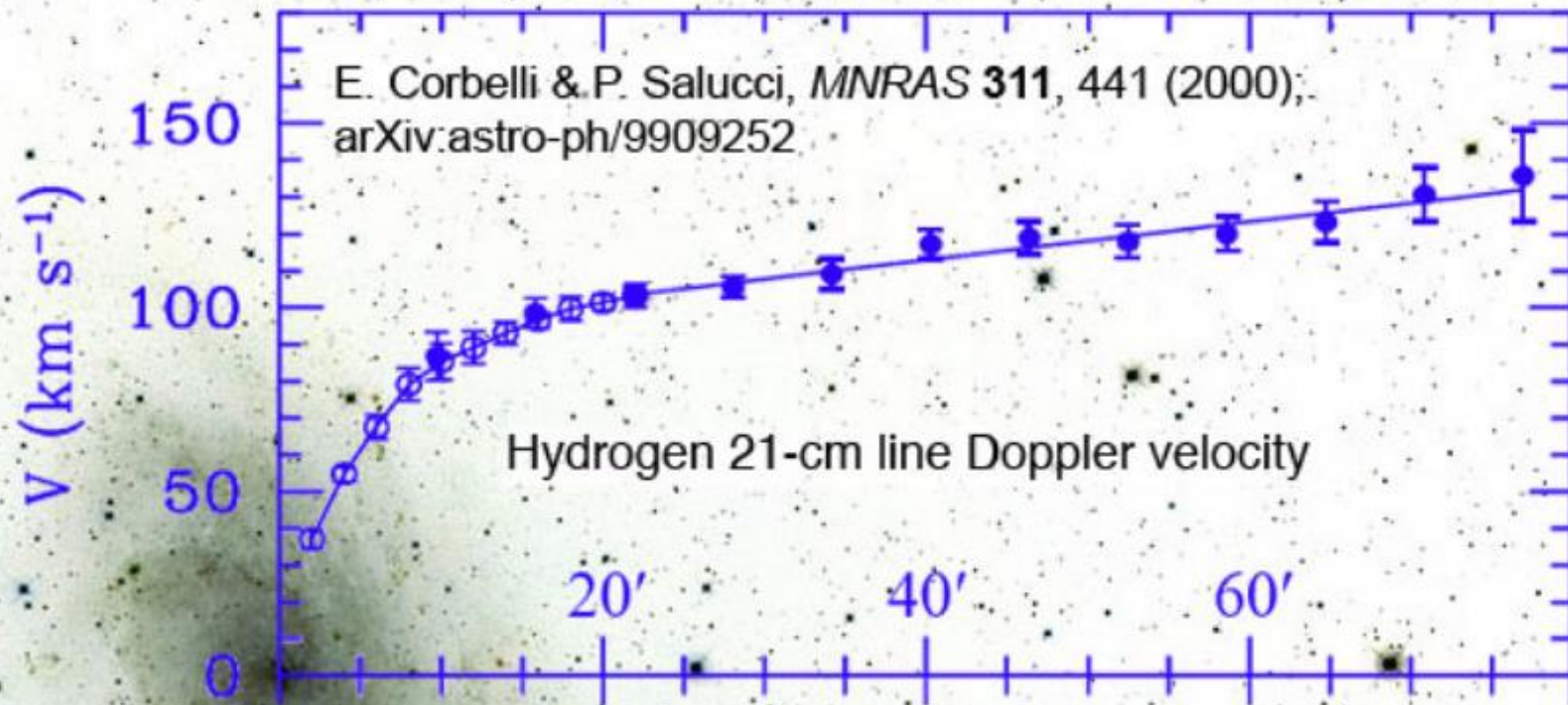
M33 (NGC 598, "Triangulum")

Montage by A. F. Mayer

Distance estimate: 0.92 Mpc

(source: The Extragalactic Distance Database)

Optical Negative



DISTANT GALAXIES LACK DARK MATTER

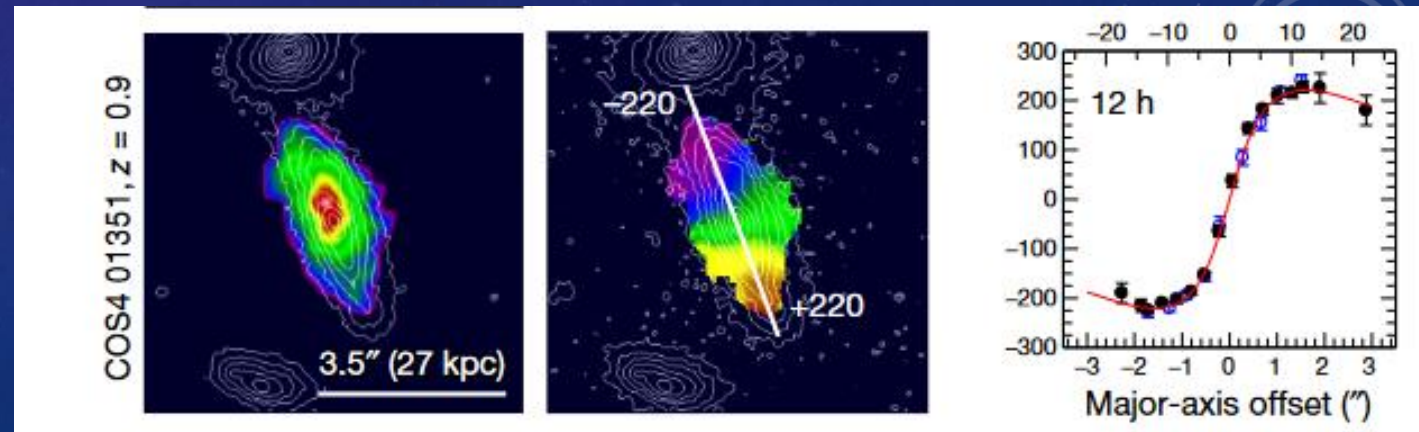
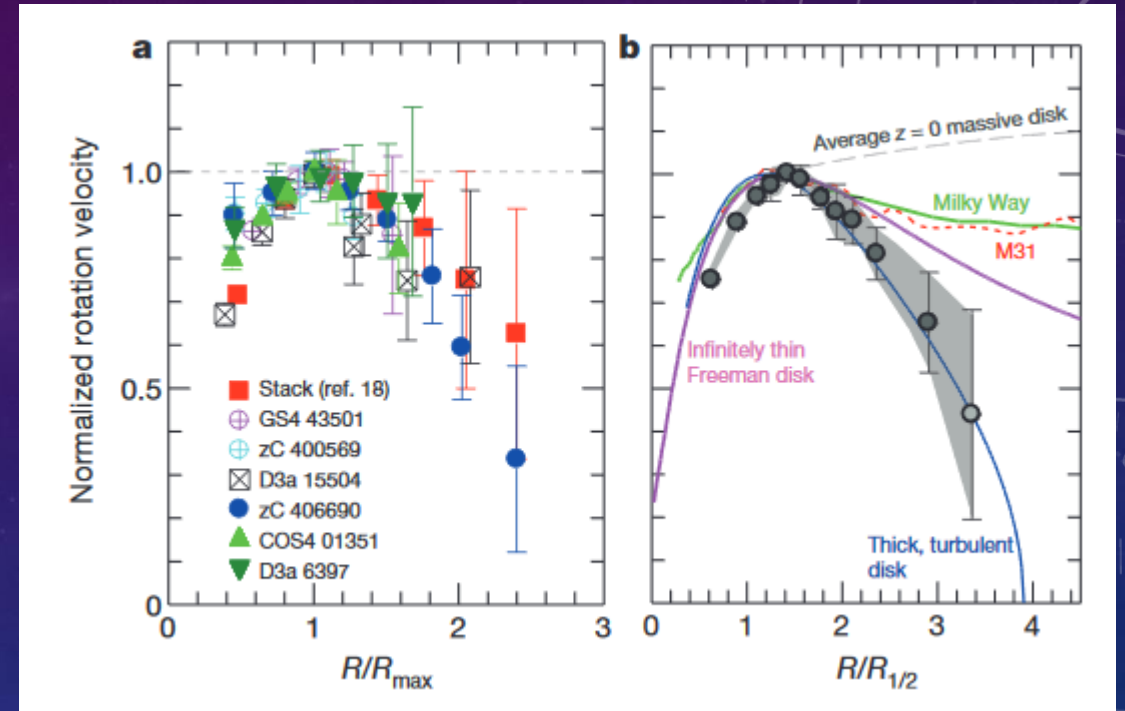
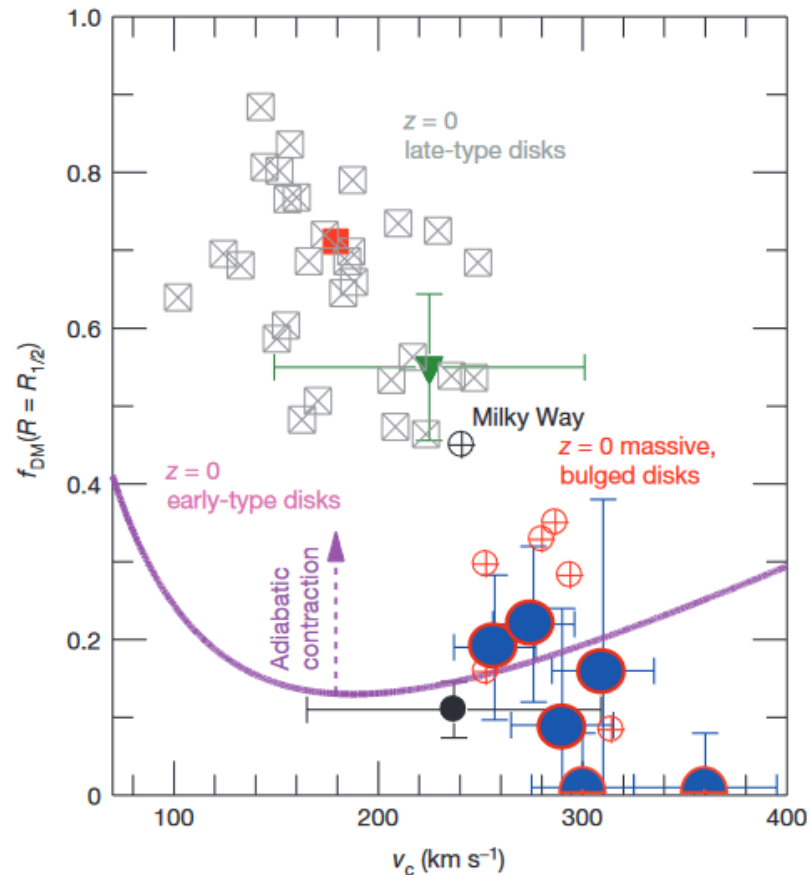
Sample in the redshift range $0.9 < z < 2.4$

Published: 16 March 2017

Strongly baryon-dominated disk galaxies at the peak of galaxy formation ten billion years ago

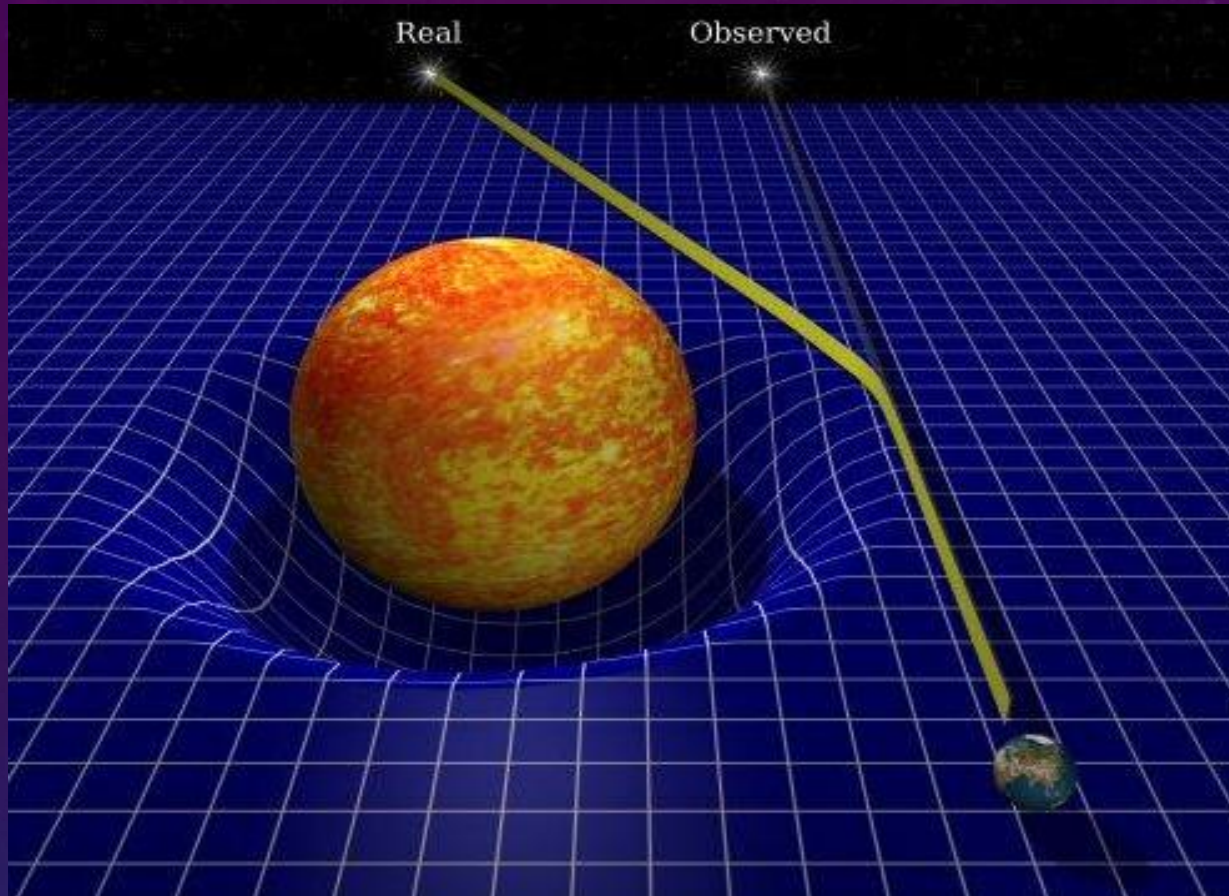
R. Genzel , N. M. Förster Schreiber , [...] D. Wilman

Nature **543**, 397–401 (2017) | [Cite this article](#)

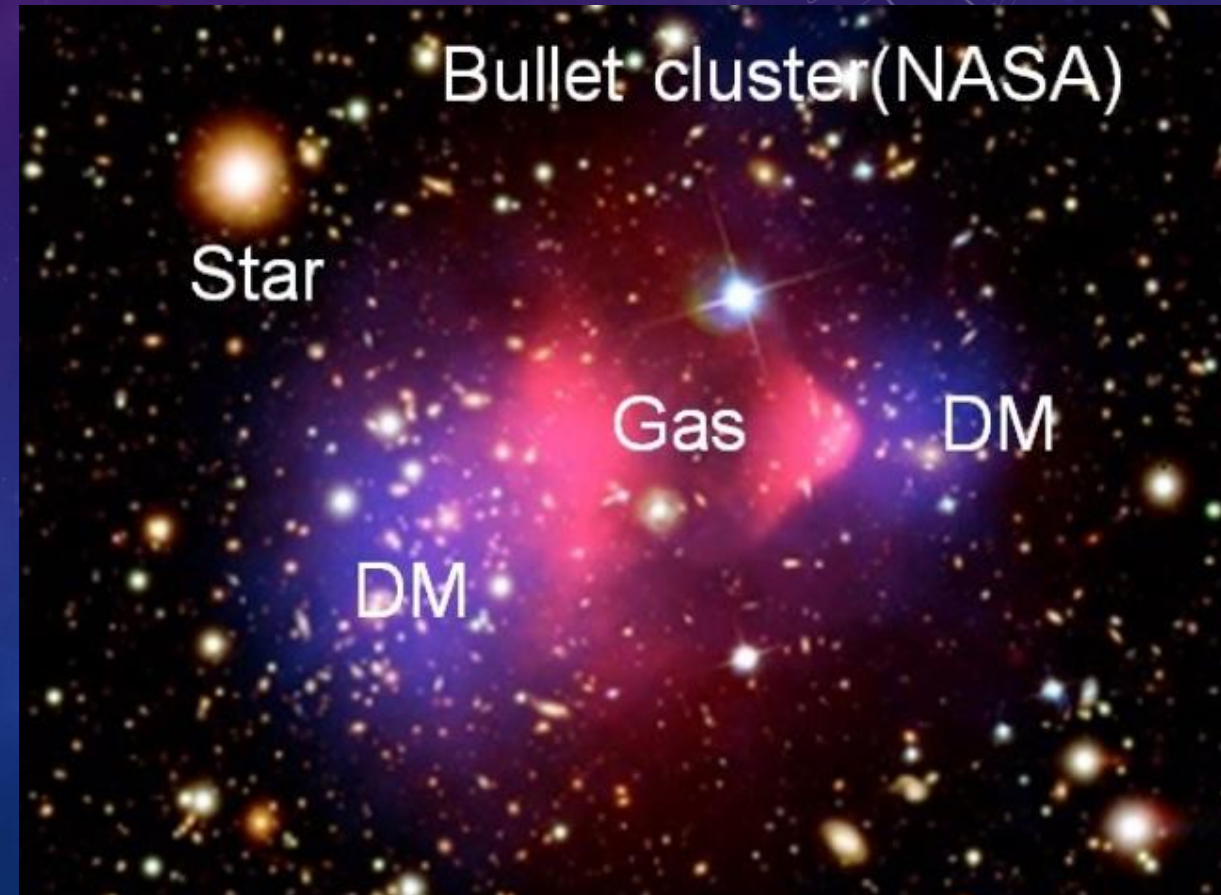


GRAVITATIONAL LENSING

Hermano Velten



$$\theta = \frac{4GM}{rc^2}$$



LARGE SCALE STRUCTURE FORMATION

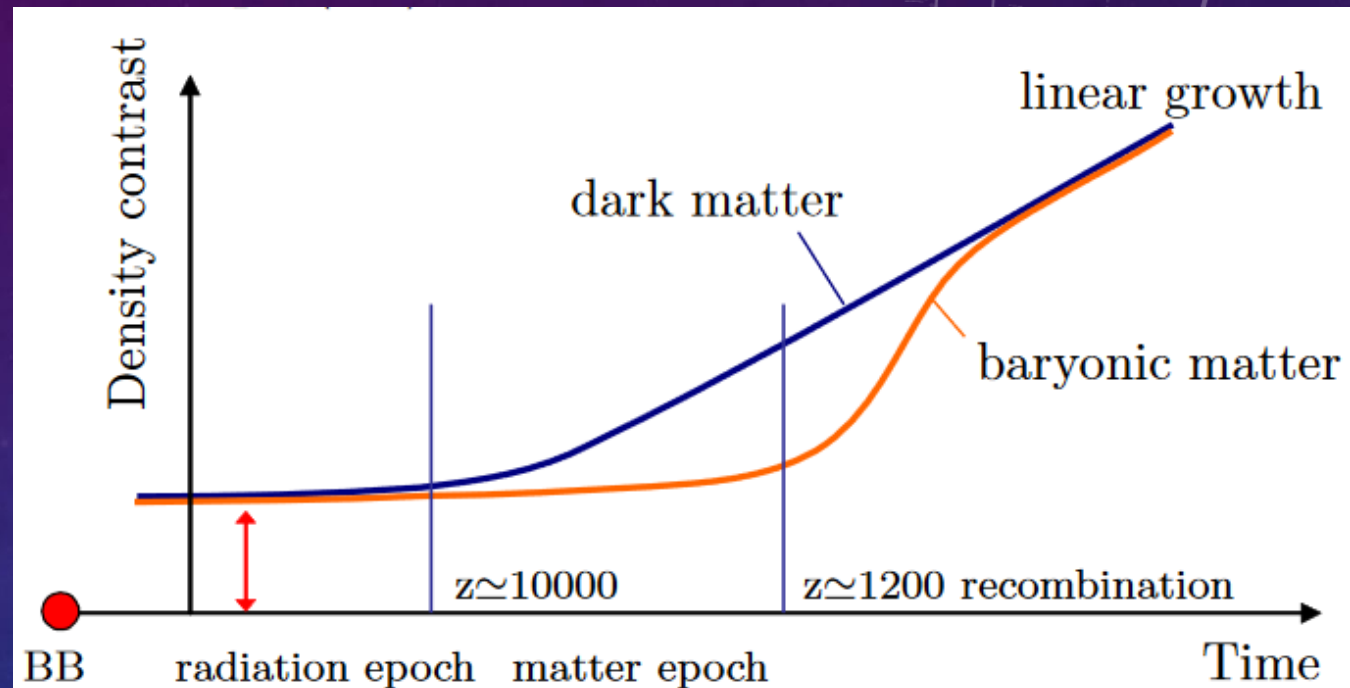
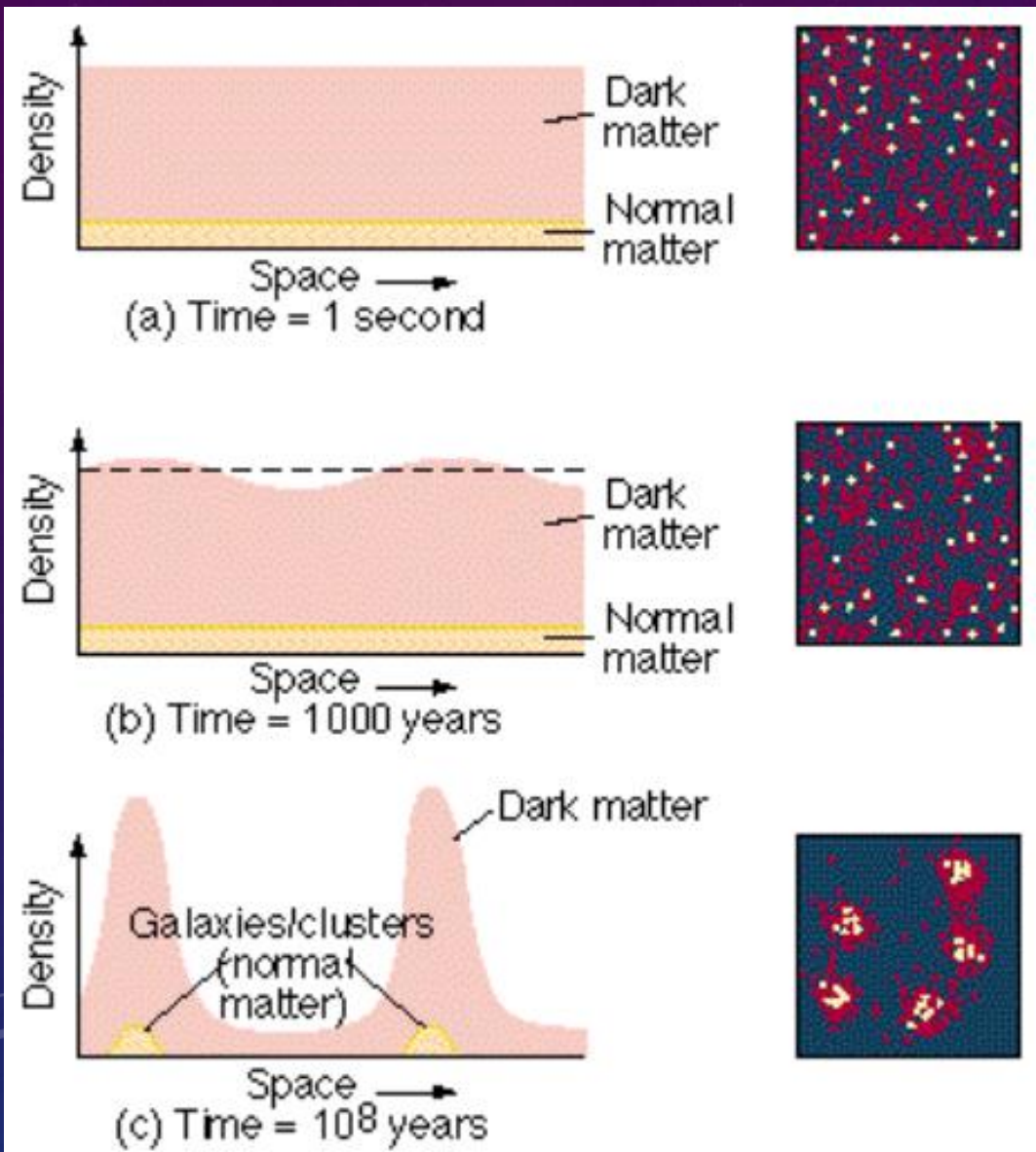


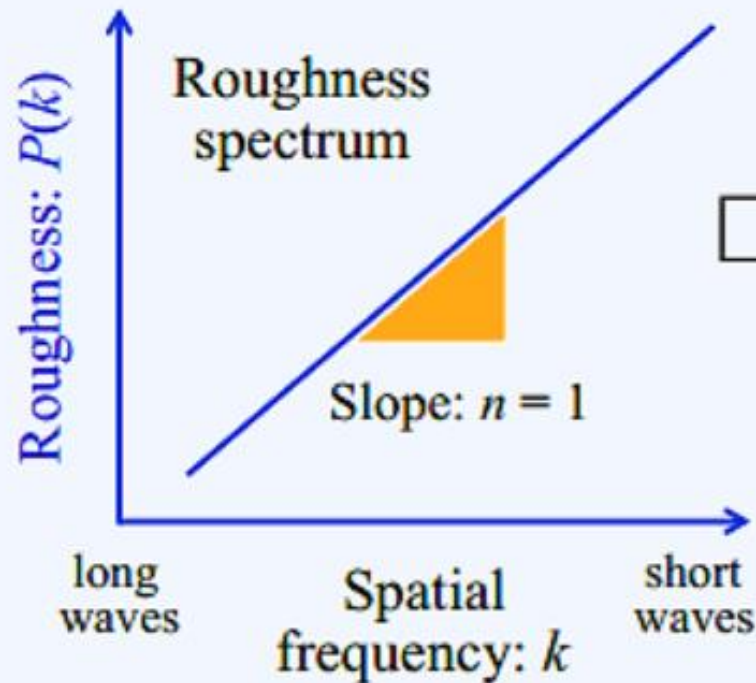
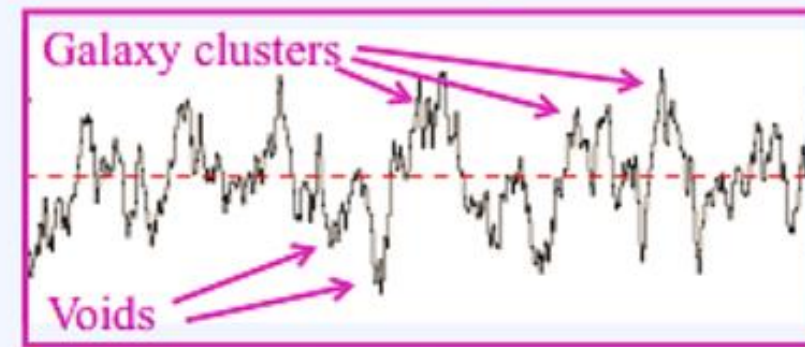
Figure 2.4: Growth of matter density contrast. After the recombination the baryonic is free to evolve and fall into the dark matter halos which formed earlier. Afterward both matter grow together.

(a) Density Fluctuation of Cosmic Structure

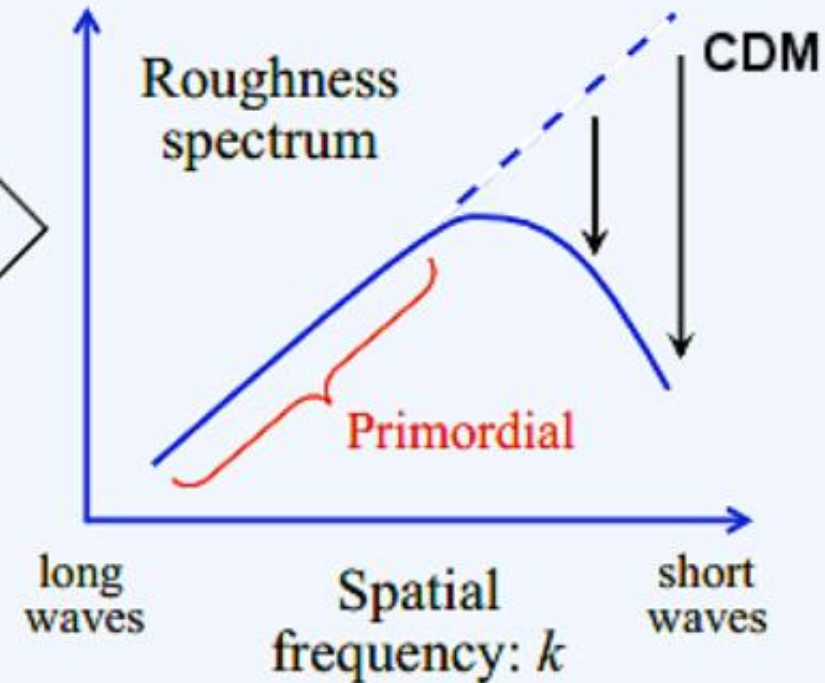
Primordial roughness



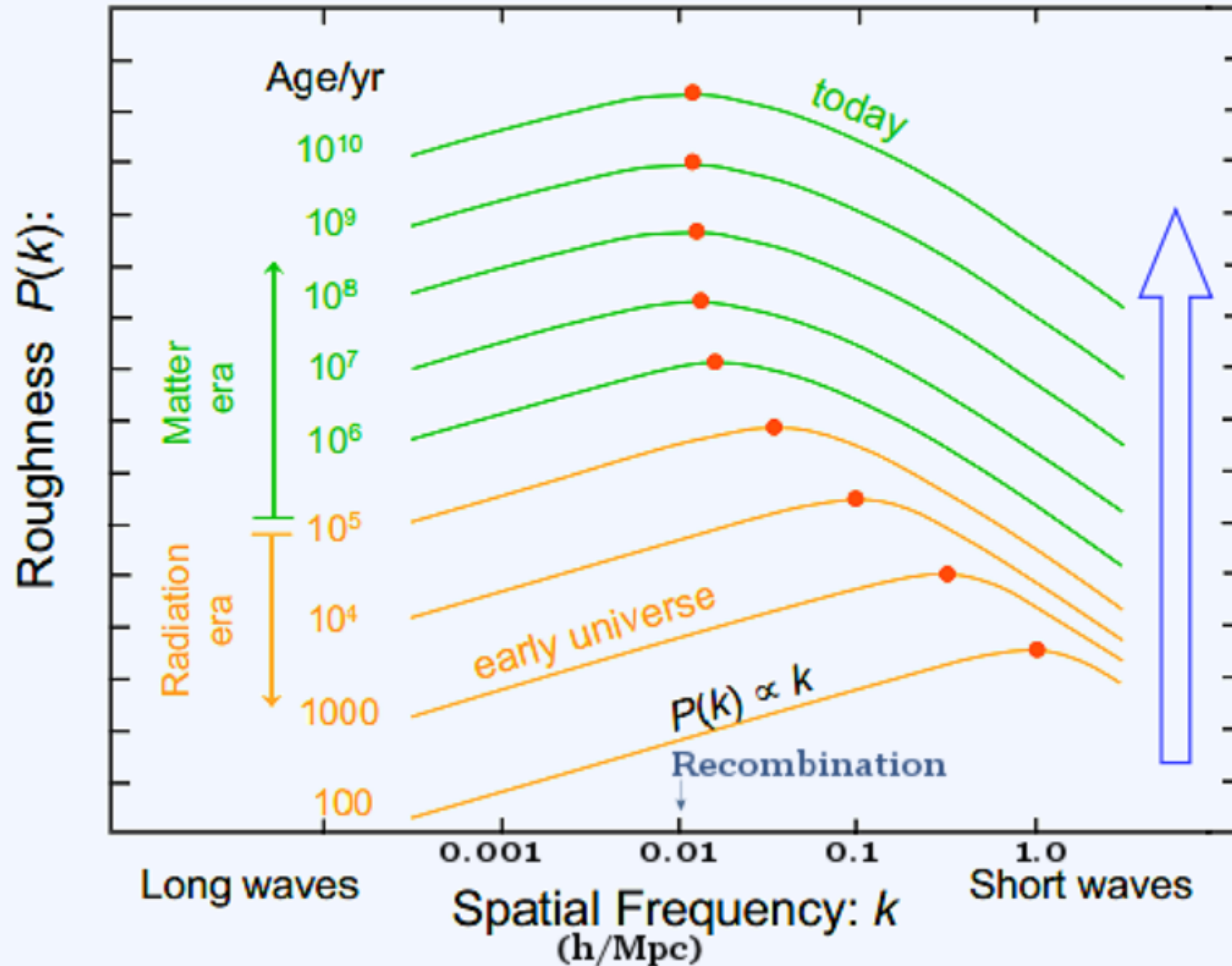
Today's roughness



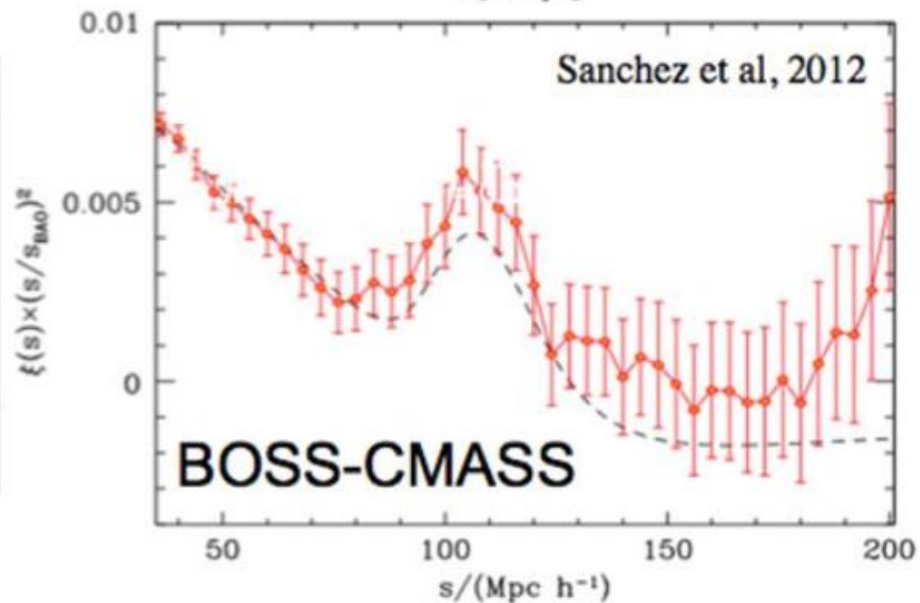
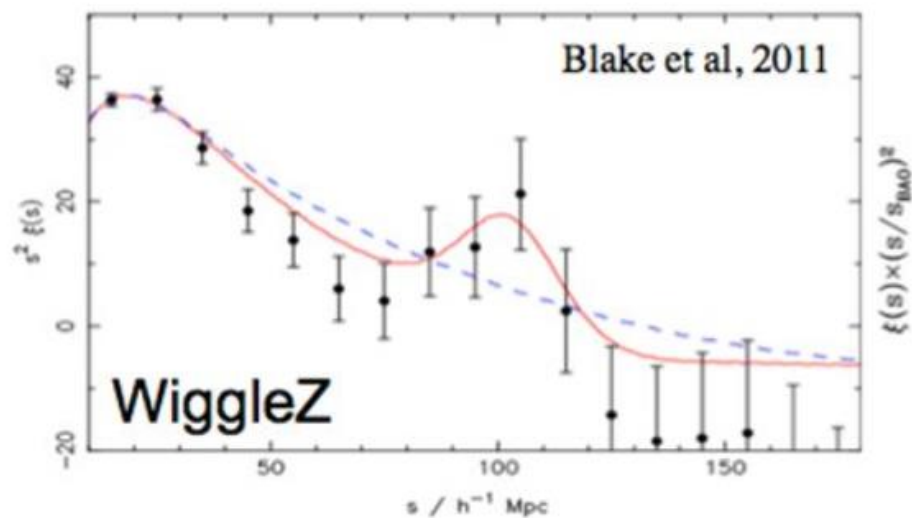
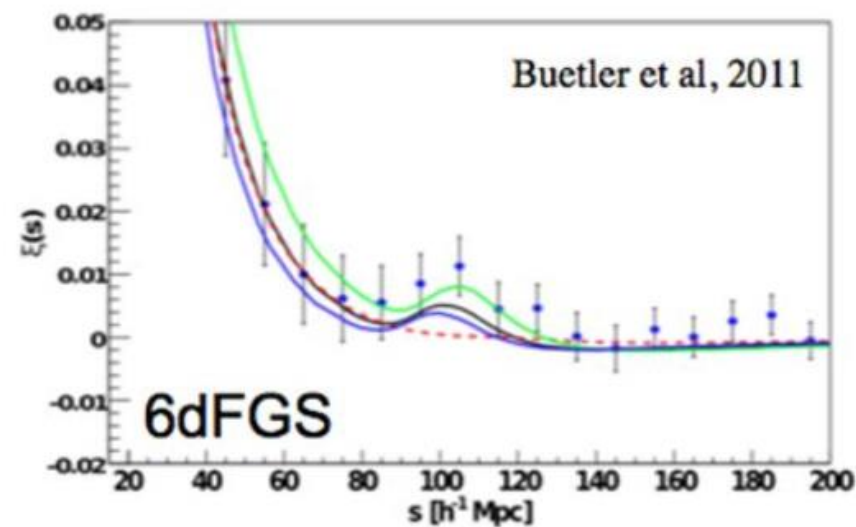
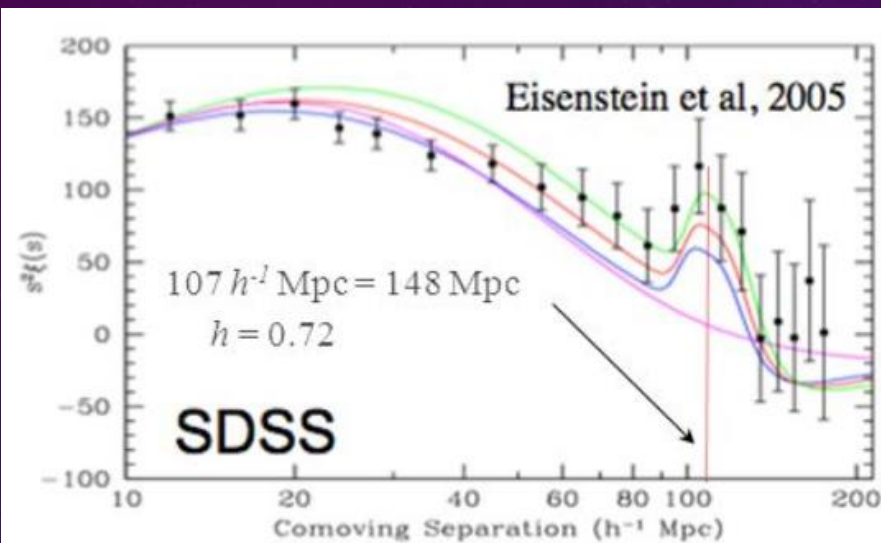
time



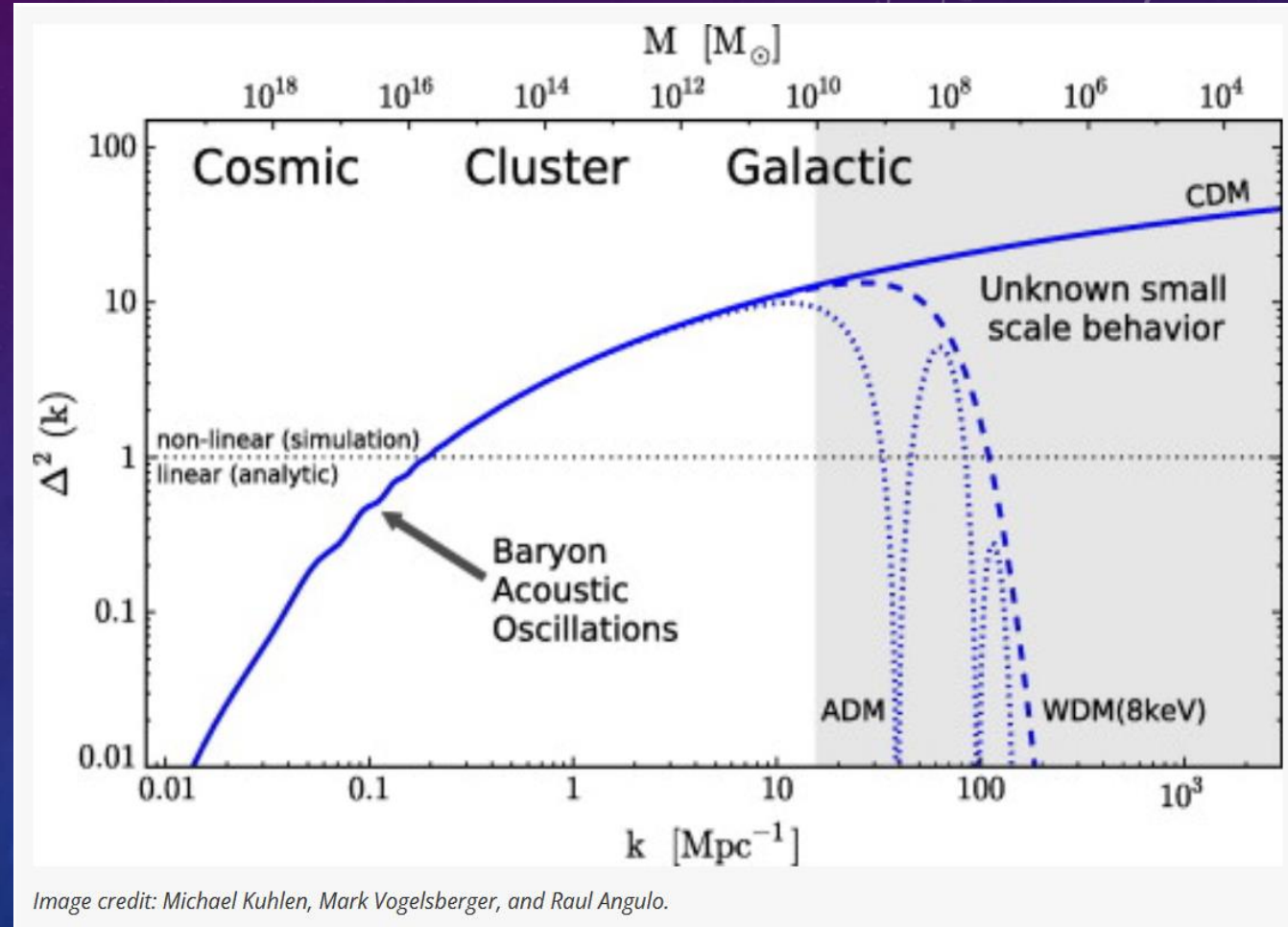
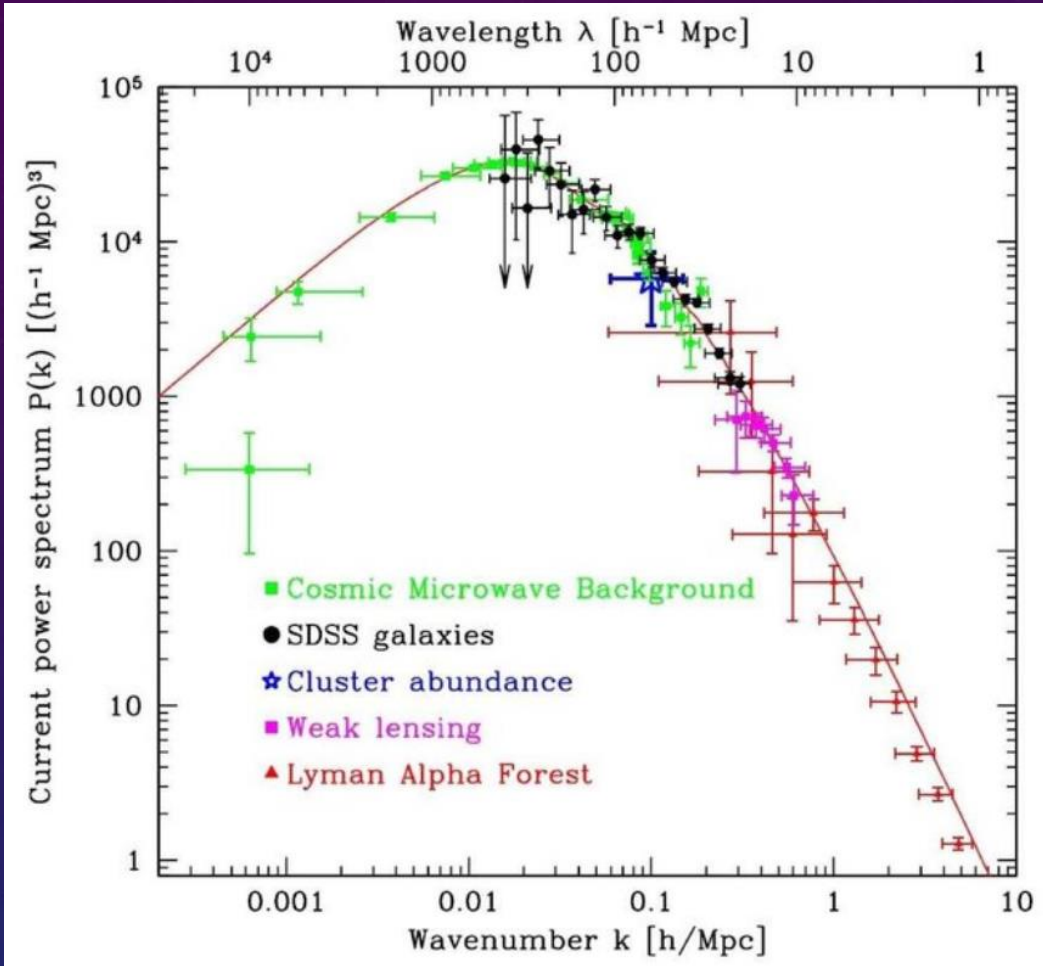
(b) Evolution of the power spectrum



BARYON ACOUSTIC OSCILATIONS



COSMOLOGICAL EVIDENCES FOR CDM



The dark matter particle?

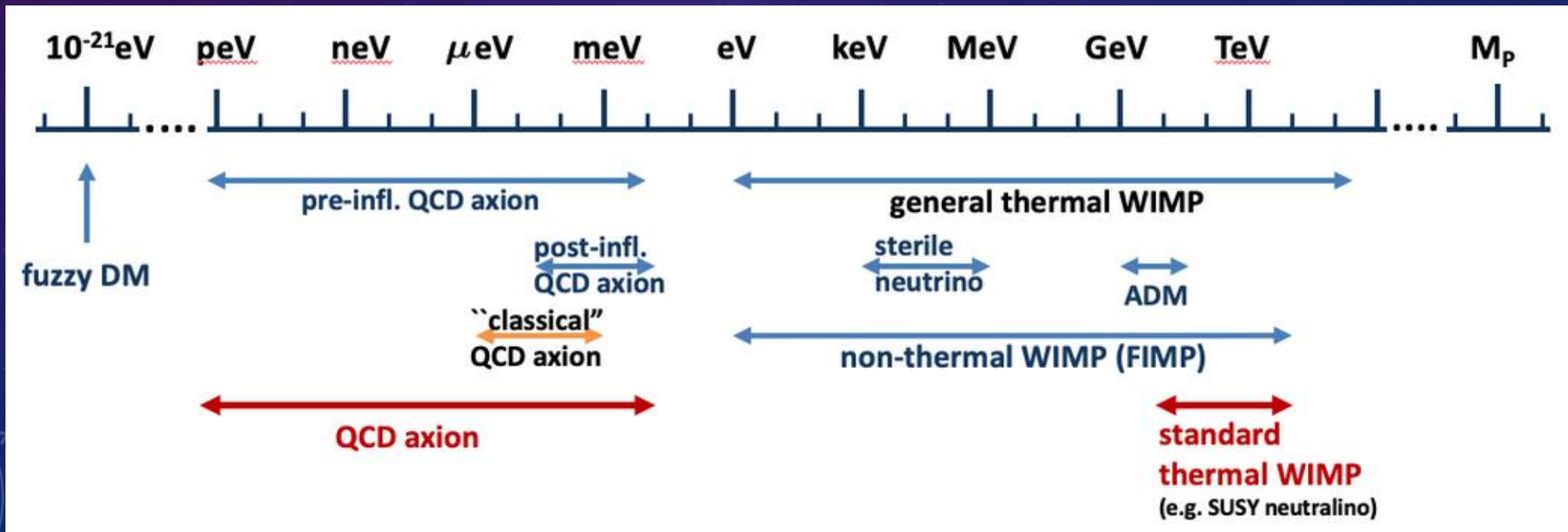
Minimum requirements for such particle candidate

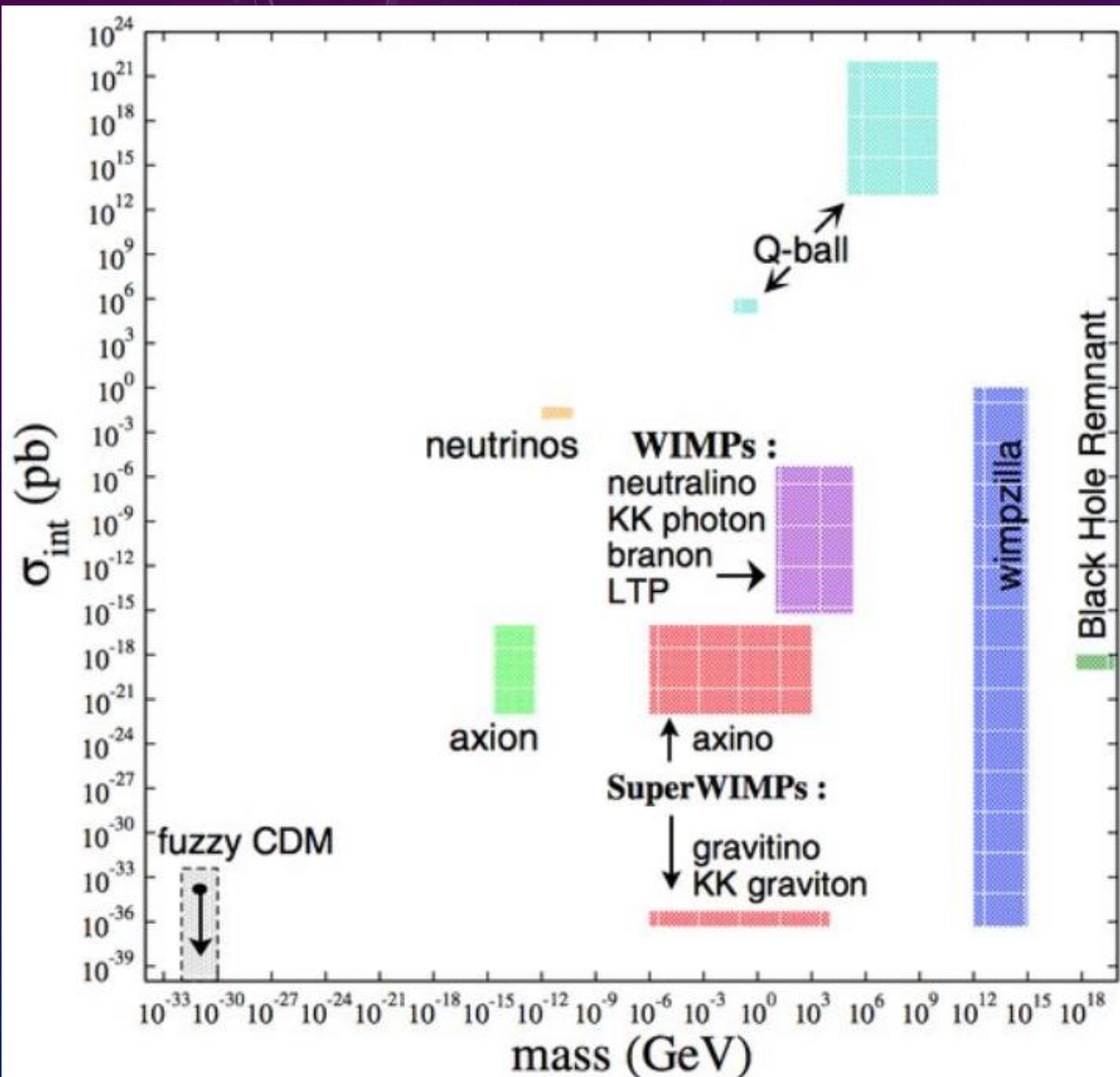
- 1) To Interact gravitationally;
- 2) Electrically neutral, otherwise it had already been detected;
- 3) Very small cross section (explains the lack of positive direct detection results);

Hot dark matter: light and fast (**non competitive models**)

Cold dark matter: heavy and slow (**prevailing view**)

Warm dark matter: something between Hot and Cold e Hot!

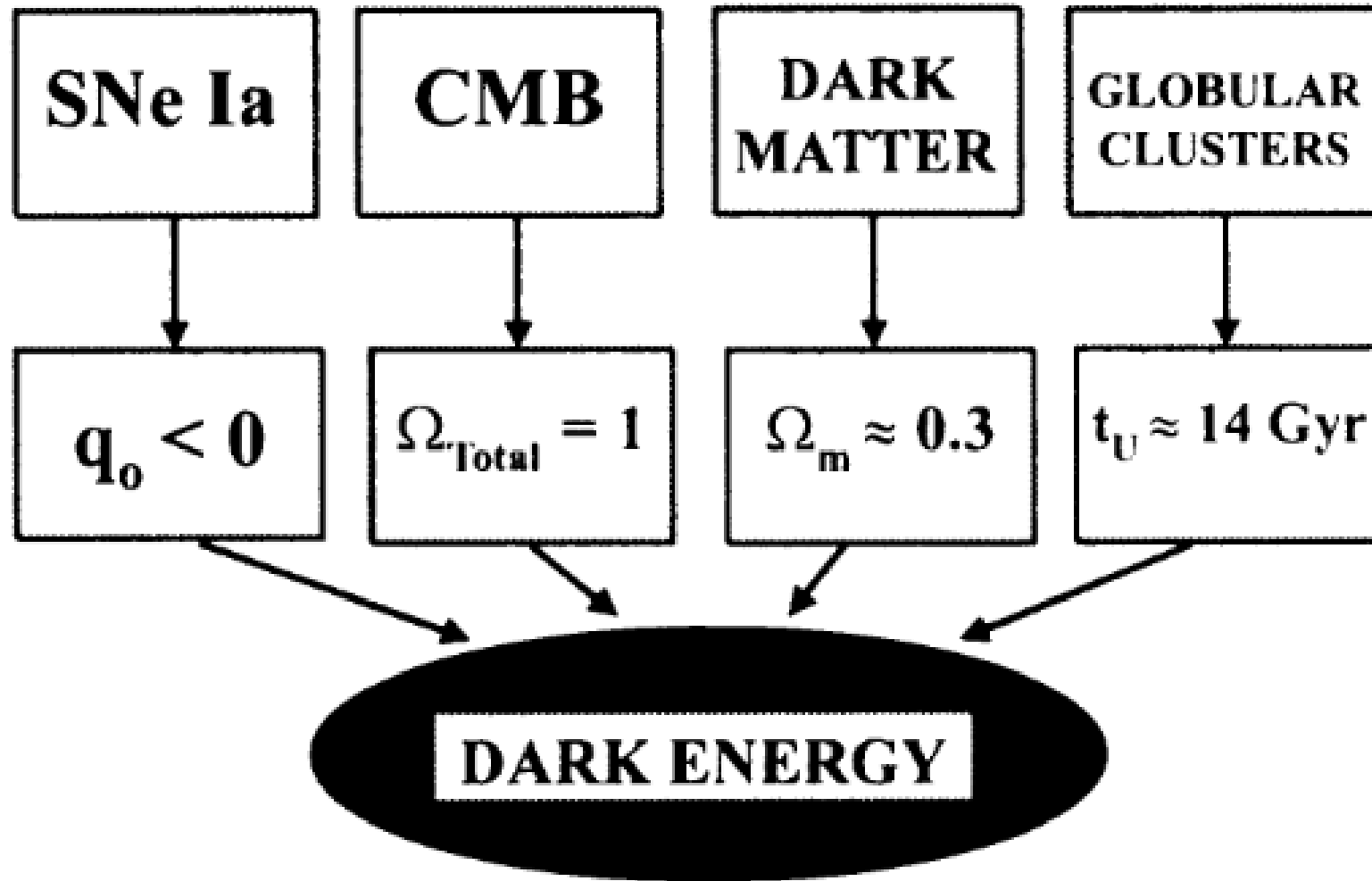




DARK ENERGY



DARK ENERGY : GENEALOGY



SUPERNOVAE AND THE ACCELERATED EXPANSION OF THE UNIVERSE: THE DARK ENERGY PHENOMENA





The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



Brian Schmidt,
Saul Perlmutter,
& Adam Riess.

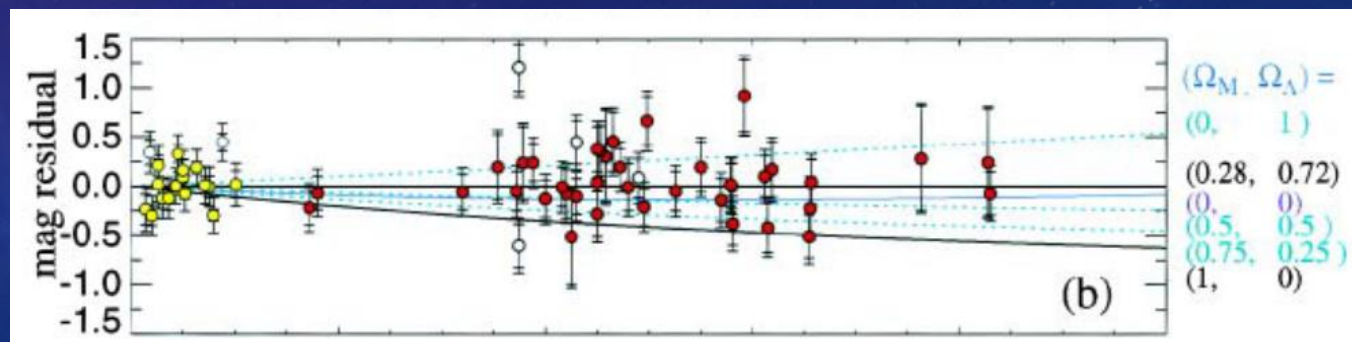
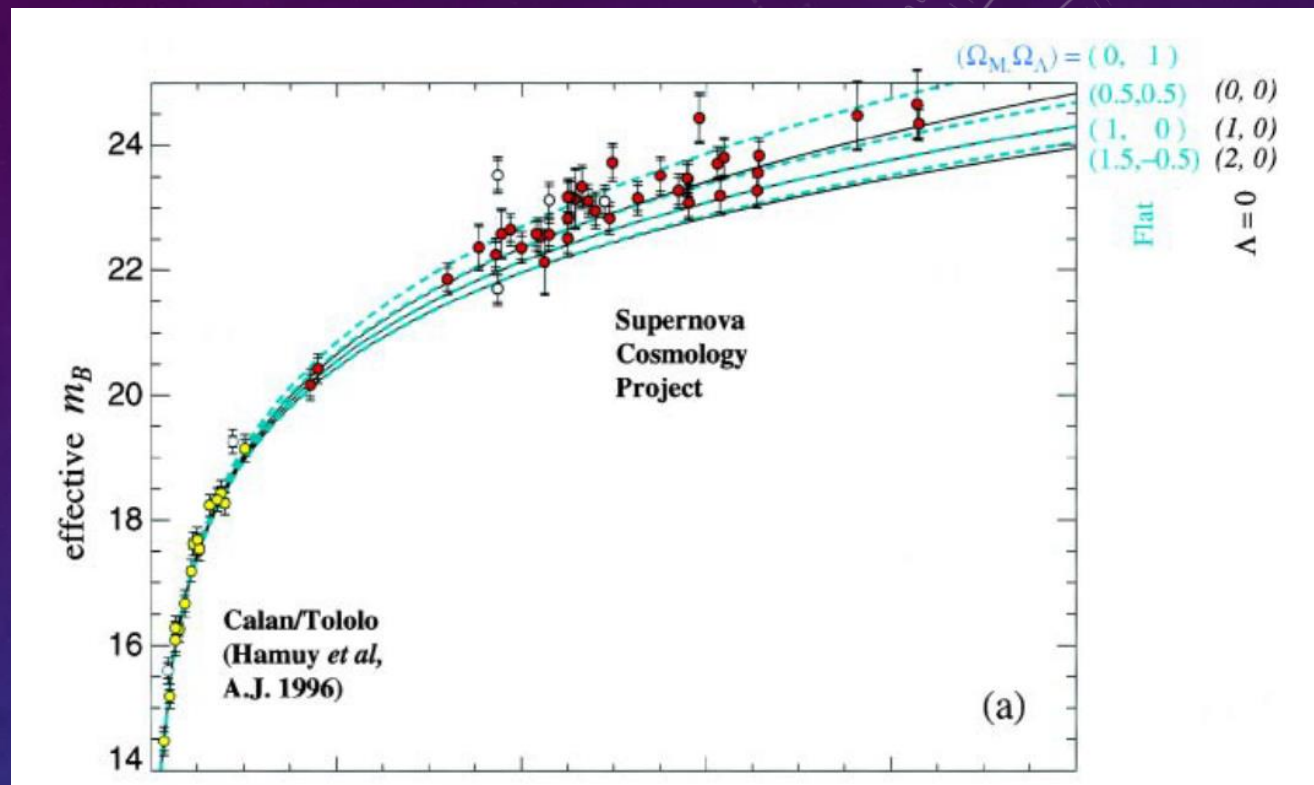


In 1998/9, published observations of **Type Ia supernovae** by

- The **High-z Supernova Search Team**
- The **Supernova Cosmology Project**

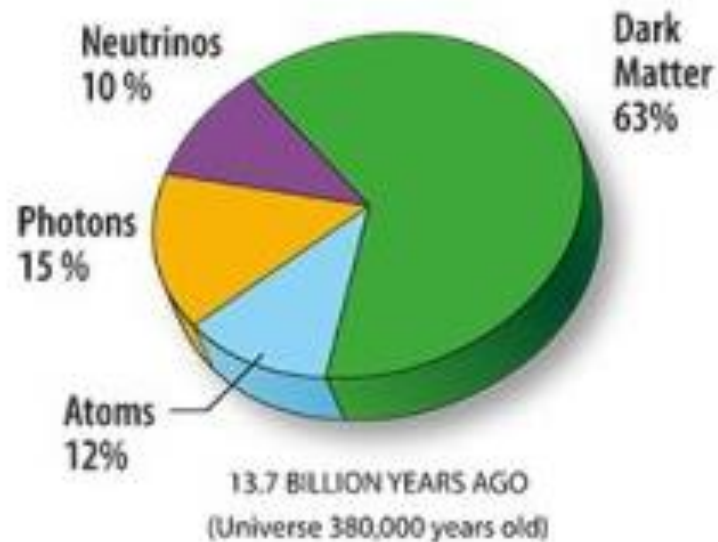
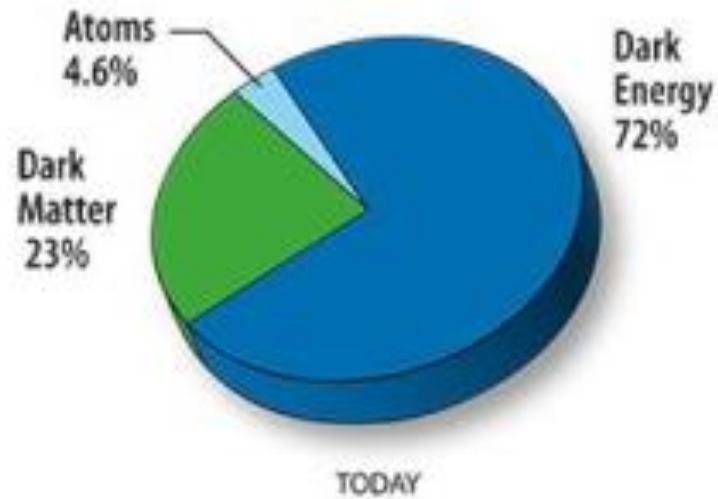
suggested that the expansion of the universe is *actually accelerating* – a total surprise to everyone.

The 2011 Nobel Prize in Physics was awarded for this work.



COSMIC ENERGY BUDGET

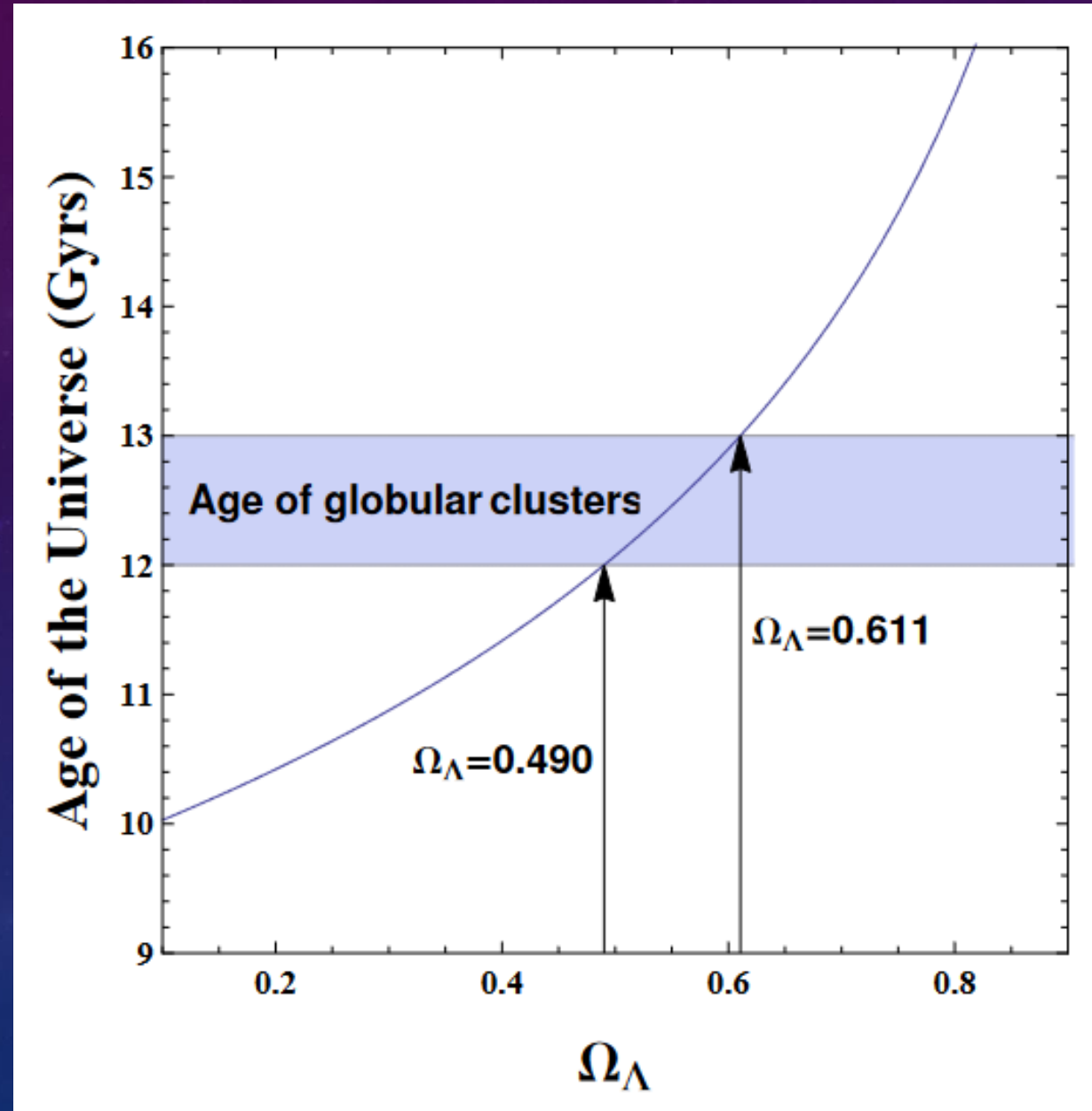
Hermano Velter



$$H^2 = H_0^2 \{ \Omega_{Bar} + \Omega_{Pho} + \Omega_{Neu} + \Omega_{DM} + \Omega_{DE} \}$$

$$H^2 = H_0^2 \left[\frac{\Omega_{b0} + \Omega_{dm0}}{a^3} + \frac{\Omega_{r0}}{a^4} + \Omega_{\Lambda} \right]$$

DARK ENERGY AND THE AGE OF THE UNIVERSE



ROBUST EVIDENCE FOR ACCELERATION FROM SUPERNOVAE DATA

Marina Seikel, Dominik J Schwarz

Published in: *JCAP* 02 (2008) 007 •

Marina Seikel, Dominik J. Schwarz

Published in: *JCAP* 02 (2009) 024 •

Hermano Velten, Syrios Gomes (Nov 26, 2019)

Published in: *Phys.Rev.D* 101 (2020) 4, 043502

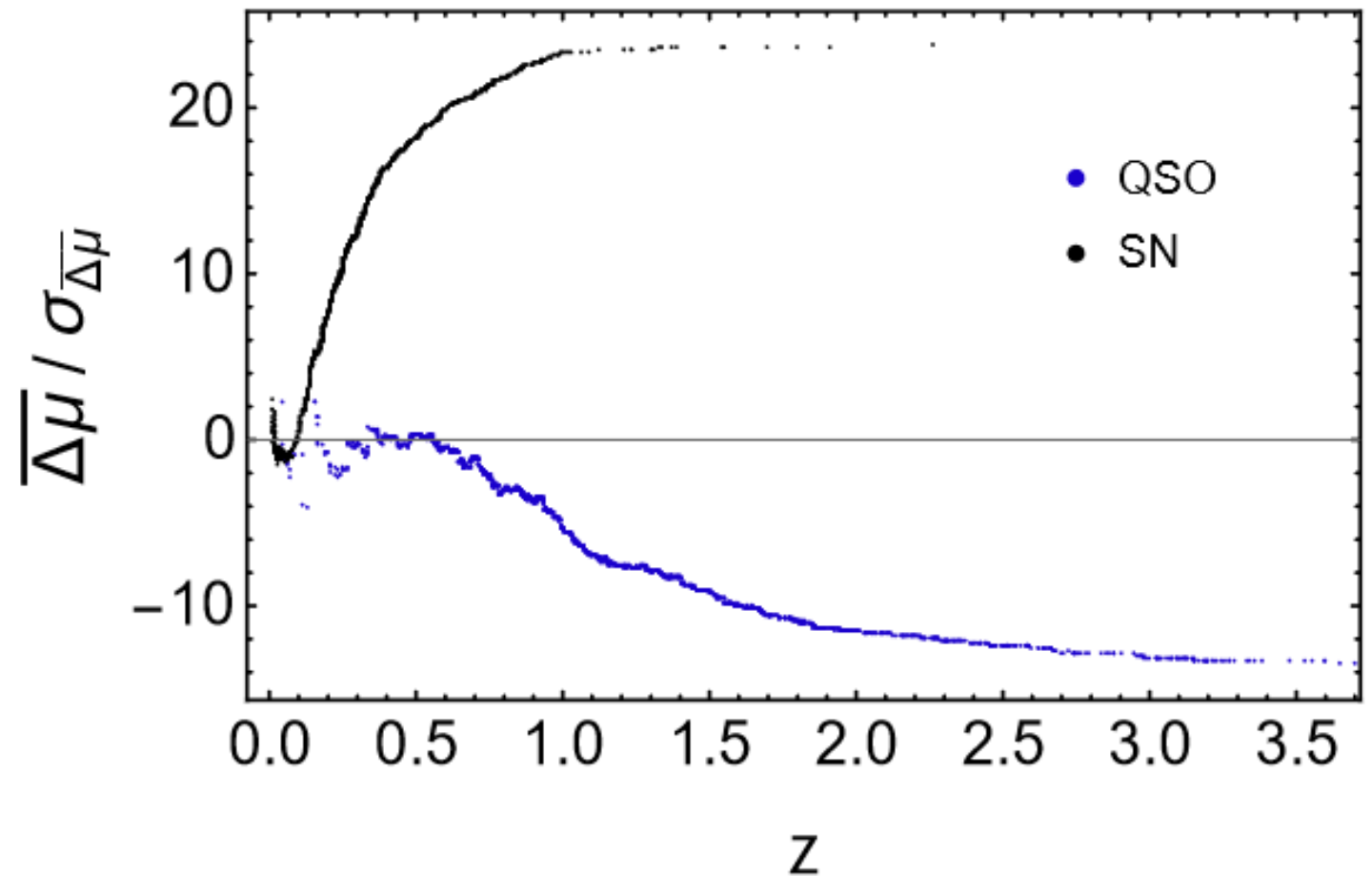
$$\begin{aligned}\Delta\mu_{obs}(z_i) &= \mu_{obs}(z_i) - \mu(q=0) \\ &= \mu_{obs}(z_i) - 5\log\left[\frac{1}{H_0}(1+z_i)\ln(1+z_i)\right] - 25,\end{aligned}$$

TABLE I. Averaged evidence (in σ of C.L.) for acceleration for different SNHD samples. For the samples indicated with *no low-z data* at $z < 0.1$ have been not considered.

Sample	$\overline{\Delta\mu} / \sigma_{\overline{\Delta\mu}}$ Evidence	# of Objects	Mean redshift
FULL JLA	+20.40	740	0.32
JLA no low-z	+22.33	588	0.40
Pantheon Λ CDM	+23.73	1048	0.32
Pantheon Λ CDM no low-z	+28.25	837	0.39
Pantheon w CDM	+24.23	1048	0.32
Pantheon w CDM no low-z	+28.73	837	0.39
Pantheon CPL	+23.62	1048	0.32
Pantheon CPL no low-z	+28.14	837	0.39

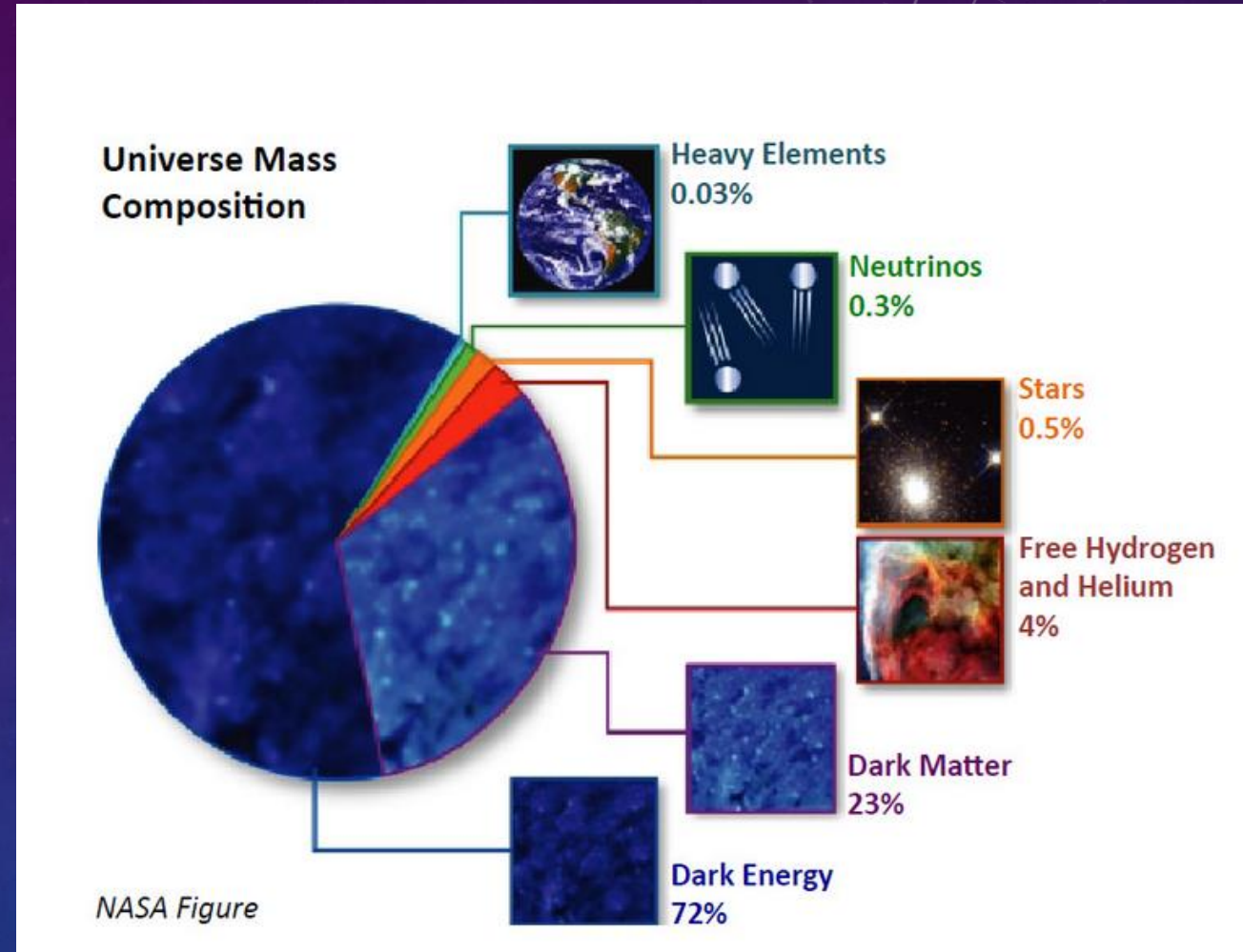
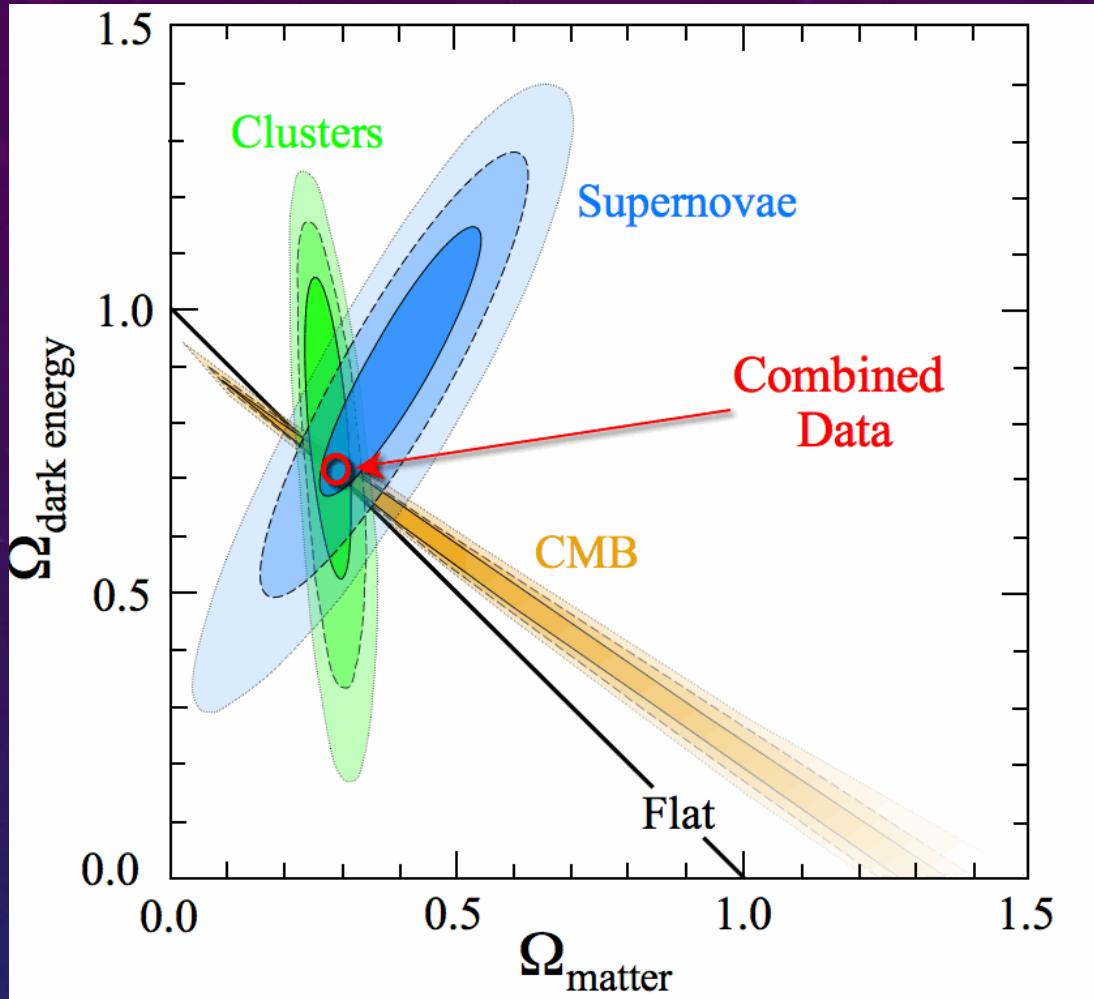
Hermano Velten, Syrios Gomes, Vinicius C. Busti

Published in: *Phys.Rev.D* 97 (2018) 8, 083516 • e-

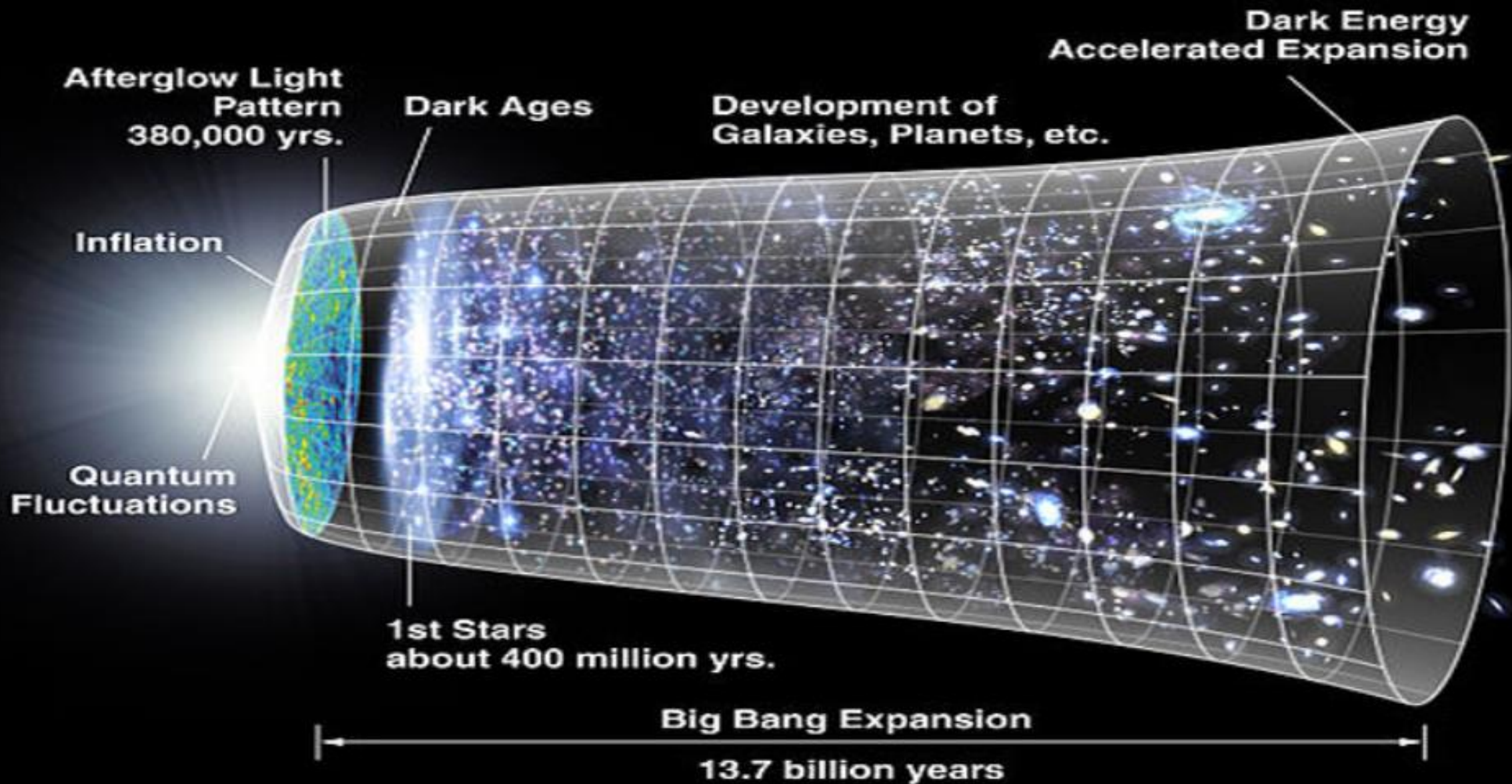


CONCORDANCE COSMOLOGICAL MODEL

Hermano Velten



DM AND DE CORRESPOND TO 95% OF THE COSMIC ENERGY BUDGET
WE HAVE NO DIRECT EVIDENCES THESE PARTICLES/FIELDS



SIMPLE DARK ENERGY MODELS

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_{\text{tot}} + 3p_{\text{tot}}) = -\frac{4\pi G}{3} \sum \rho_w(1 + 3w)$$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \rho_{\text{tot}}$$

Simplest evolution of the late time cosmological background

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_{\text{m}0}}{a^3} + (1 - \Omega_{\text{m}0}) e^{-\int da \frac{1+w_{\text{DE}}}{a}}$$

DARK ENERGY EQUATIONS OF STATE

- The constant EoS

$$w_{\text{DE}} = w_0;$$

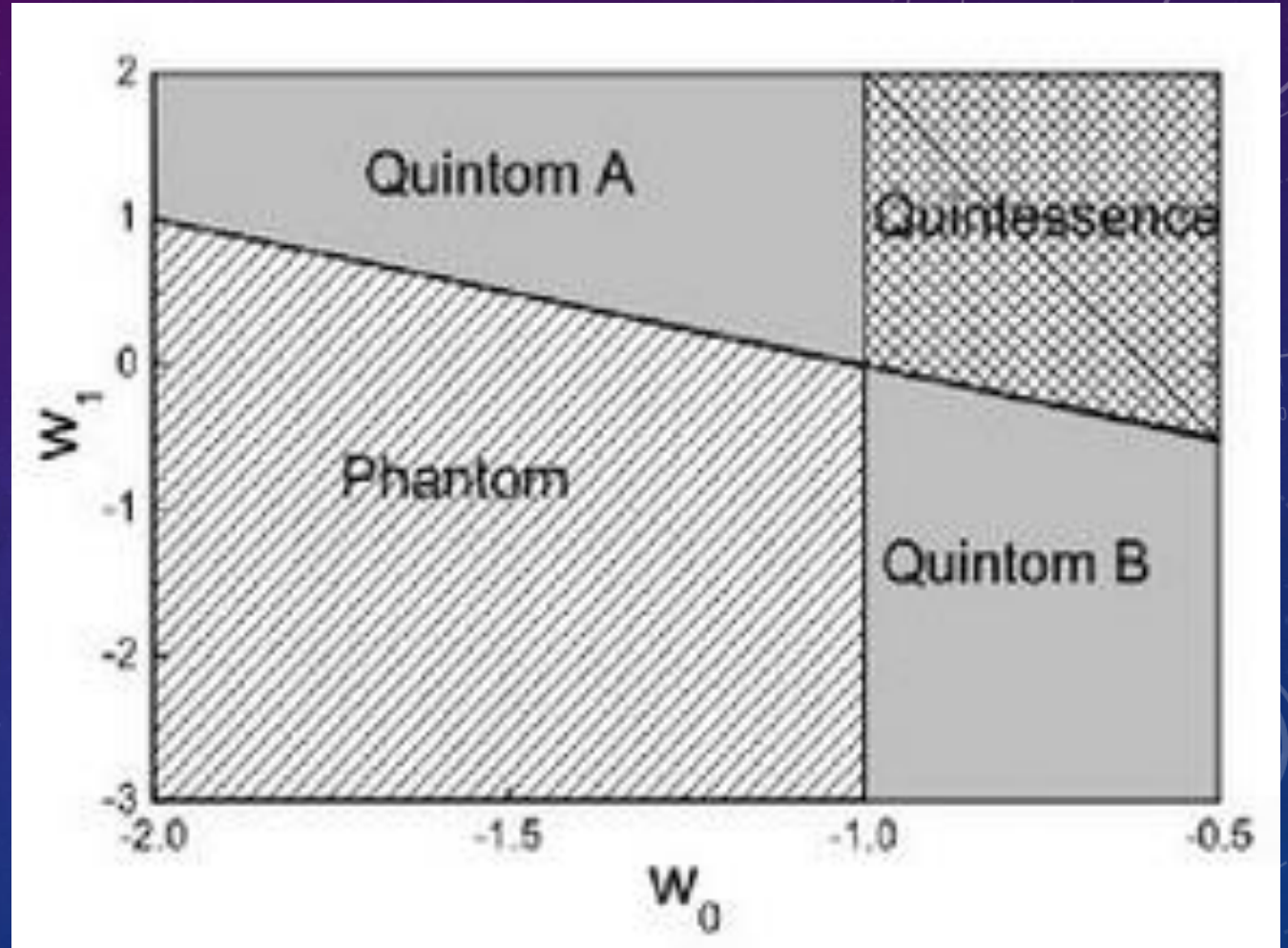
- The Chevallier-Polarski-Linder (CPL) [19, 20]

$$w_{\text{DE}}(a) = w_0 + w_1(1 - a);$$

- The Wetterich-logarithmic one [21]

$$w_{\text{DE}}(a) = \frac{w_0}{[1 + w_1 \ln(1/a)]^2}.$$

Vacuum :	$w = -1$
Quintessence:	$w \geq -1$
Phantom:	$w < -1$
Quintom:	w across -1



MORE ON DARK ENERGY MODELS

Quintessence models

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R + \mathcal{L}_\phi \right] + S_M, \quad \mathcal{L}_\phi = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi),$$

$$T_{\mu\nu}^{(\phi)} = -\frac{2}{\sqrt{-g}} \frac{\delta(\sqrt{-g} \mathcal{L}_\phi)}{\delta g^{\mu\nu}} \\ = \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left[\frac{1}{2} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi + V(\phi) \right]$$

$$w_\phi \equiv \frac{P_\phi}{\rho_\phi} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$$

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

Early Dark Energy
Phantoms

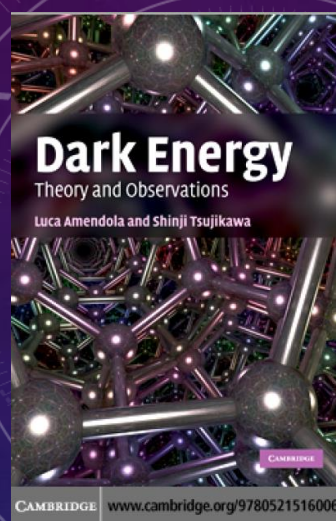
K-essence
Coupled Dark Energy

Unified models (Accelerating dark matter models)



Chaplygin / Bulk Viscous models

Modified gravity as DE (see Radouane's talk)



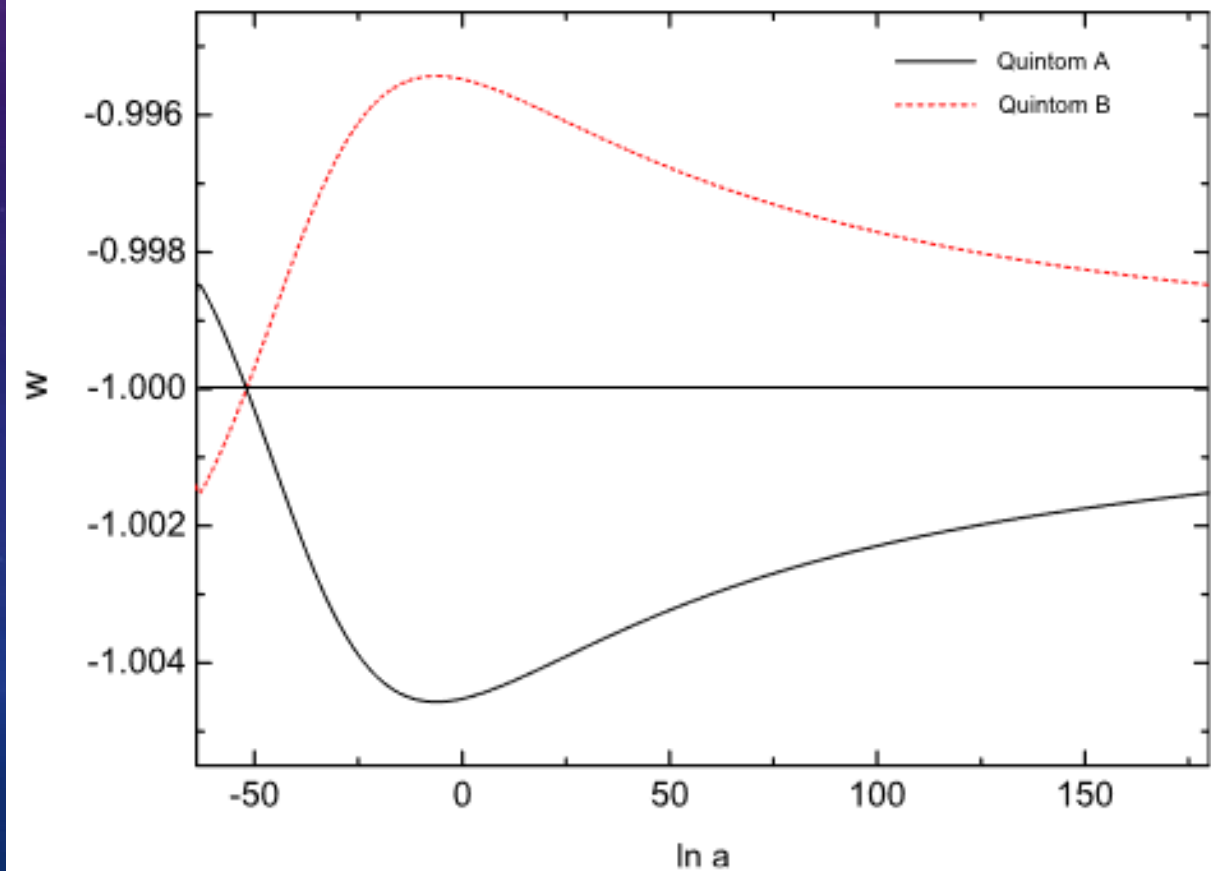
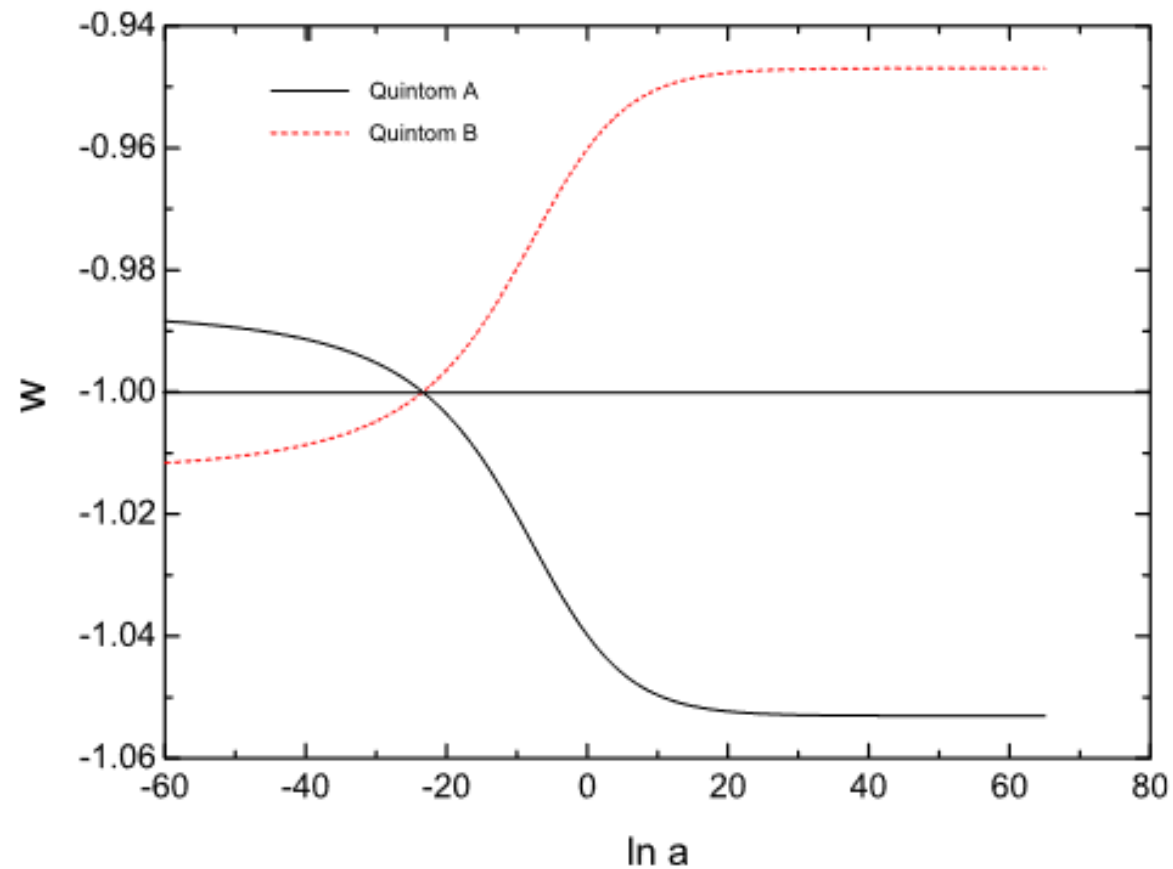
Quintom cosmology: Theoretical implications and observations

Yi-Fu Cai^a, Emmanuel N. Saridakis^{b,*}, Mohammad R. Setare^{c,d}, Jun-Qing Xia^e

Physics Reports 493 (2010) 1–60

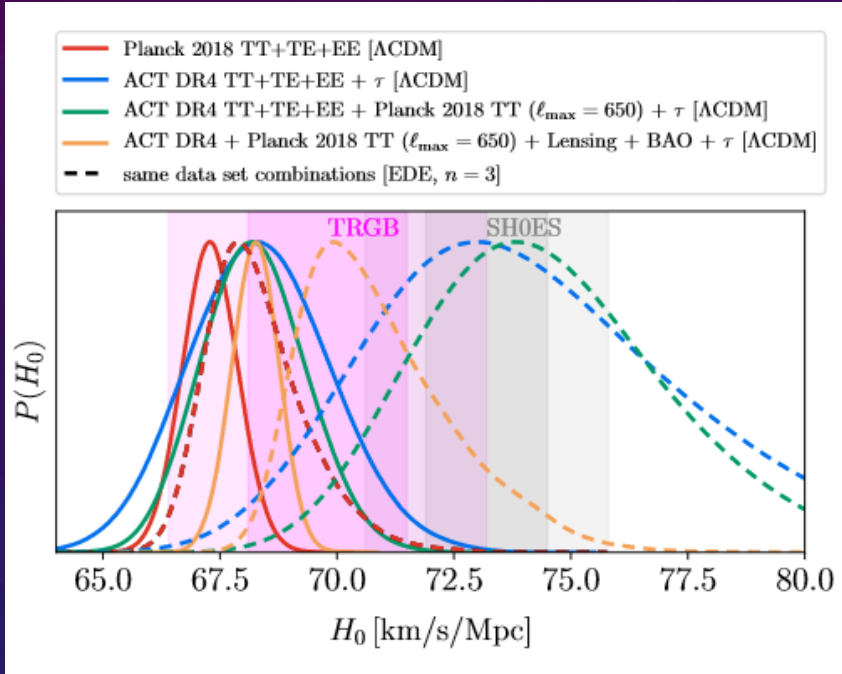
$$V = V_0(e^{-\frac{\phi}{M}} + e^{-\frac{2\sigma}{M}})$$

$$V = m_1^2 \phi^2 + m_2^2 \sigma^2$$



The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy

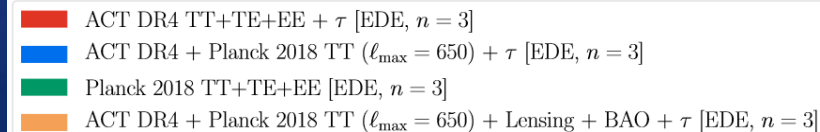
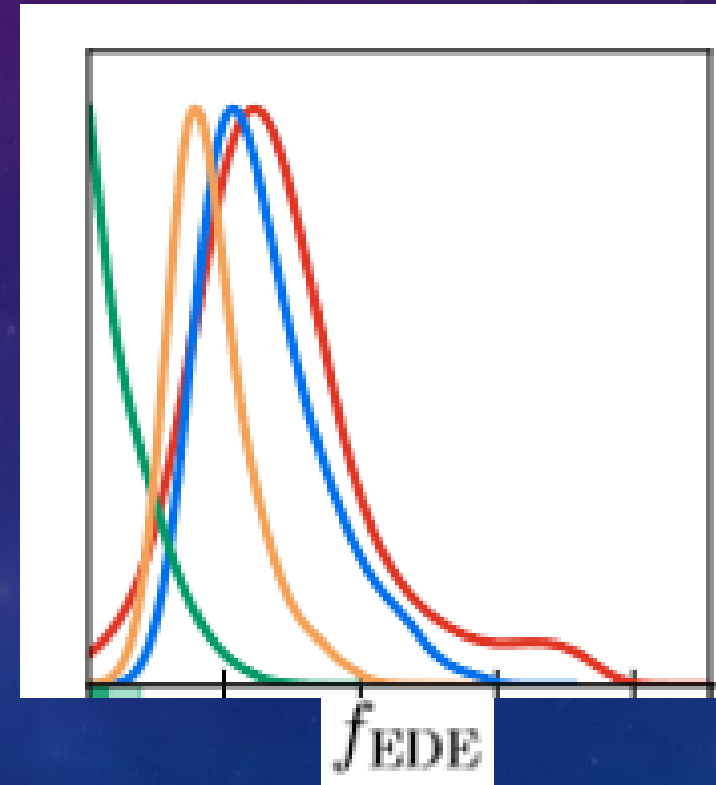
J. Colin Hill^{1,2}, Erminia Calabrese³, Simone Aiola², Nicholas Battaglia⁴, Boris Bolliet¹,
 Steve K. Choi^{5,4}, Mark J. Devlin⁶, Adriaan J. Duivenvoorden⁷, Jo Dunkley^{8,7}, Simone
 Ferraro^{9,10}, Patricio A. Gallardo¹¹, Vera Gluscevic¹², Matthew Hasselfield², Matt Hilton^{13,14}, Adam



We summarize the main takeaways from our analysis in the following. The ACT DR4 data alone (red contours in Figs. 1 and 2) allow a non-negligible amount of EDE, but the uncertainties are too large to yield a clear preference:

$$f_{\text{EDE}} = 0.142^{+0.039}_{-0.072} {}^{+0.15}_{-0.13} \quad (68\%/95\% \text{ CL})$$

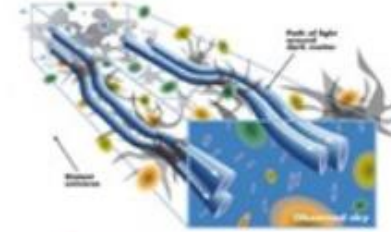
$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))^n$$



PROBES OF DARK MATTER AND DARK ENERGY

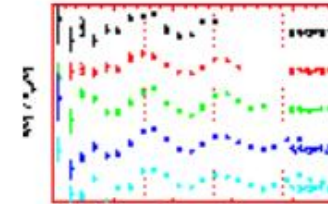
Cosmic Shear

Evolution of dark matter perturbations
Angular diameter distance
Growth rate of structure



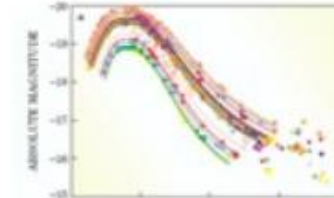
Baryon Wiggles

Standard ruler
Angular diameter distance



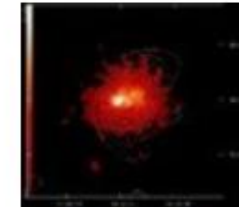
Supernovae

Standard candle
Luminosity distance



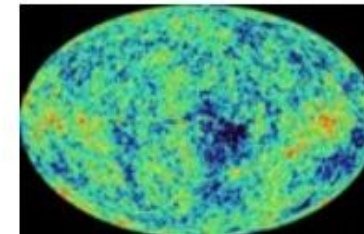
Cluster counts

Evolution of dark matter perturbations
Angular diameter distance
Growth rate of structure



CMB

Snapshot of Universe at $\sim 400,000$ yr
Angular diameter distance to $z \sim 1000$
Growth rate of structure (from ISW)



(PANTHEON) SUPERNOVAE COSMOLOGY

THE ASTROPHYSICAL JOURNAL

The Complete Light-curve Sample of Spectroscopically Confirmed SNe Ia from Pan-STARRS1 and Cosmological Constraints from the Combined Pantheon Sample

D. M. Scolnic^{21,1}, D. O. Jones² , A. Rest^{2,3}, Y. C. Pan⁴, R. Chornock⁵, R. J. Foley⁴, M. E. Huber⁶, R. Kessler¹ , G. Narayan³ , A. G. Riess^{3,2}  [+ Show full author list](#)

Published 2018 May 29 • © 2018. The American Astronomical Society. All rights reserved.

1048 SN data

Table 12

Cosmological Constraints From Different Combinations of Probes When Assuming the w CDM Model. The Value of $w = -1$ Corresponds to the Cosmological Constant Hypothesis

Sample	w	Ω_m	H_0
CMB+BAO	-0.991 ± 0.074	0.312 ± 0.013	67.508 ± 1.633
CMB+H0	-1.188 ± 0.062	0.265 ± 0.013	73.332 ± 1.729
CMB+BAO+H0	-1.119 ± 0.068	0.289 ± 0.011	70.539 ± 1.425
SN+CMB	-1.026 ± 0.041	0.307 ± 0.012	68.183 ± 1.114
SN+CMB+BAO	-1.014 ± 0.040	0.307 ± 0.008	68.027 ± 0.859
SN+CMB+H0	-1.056 ± 0.038	0.293 ± 0.010	69.618 ± 0.969
SN+CMB +BAO+H0	-1.047 ± 0.038	0.299 ± 0.007	69.013 ± 0.791

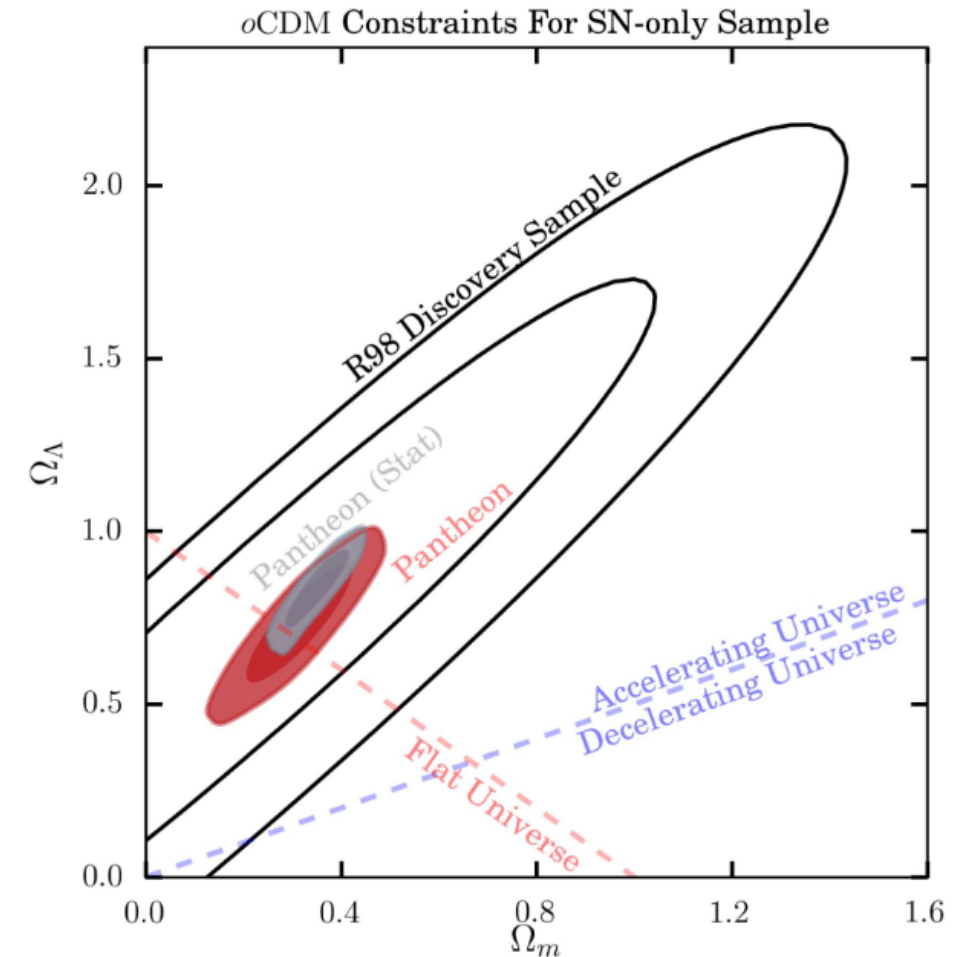


Figure 18. Evidence for dark energy from SN-only constraints. Here we show confidence contours at 68% and 95% for the Ω_m and Ω_Λ cosmological parameters for the Λ CDM model for both the Riess et al. (1998) discovery sample and the Pantheon sample. The Pantheon constraints with systematic uncertainties are shown in red, and those with only statistical uncertainties are shown in gray (line).

(PANTHEON) SUPERNOVAE COSMOLOGY

Dynamical Dark Energy

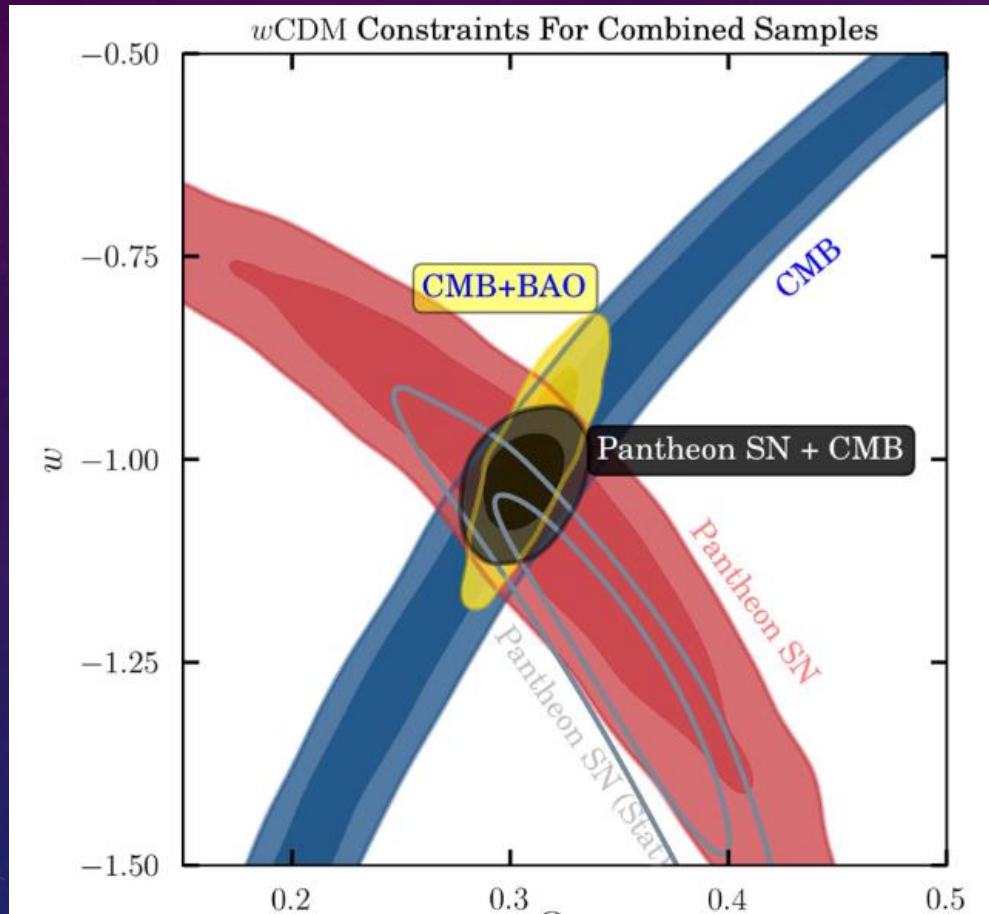
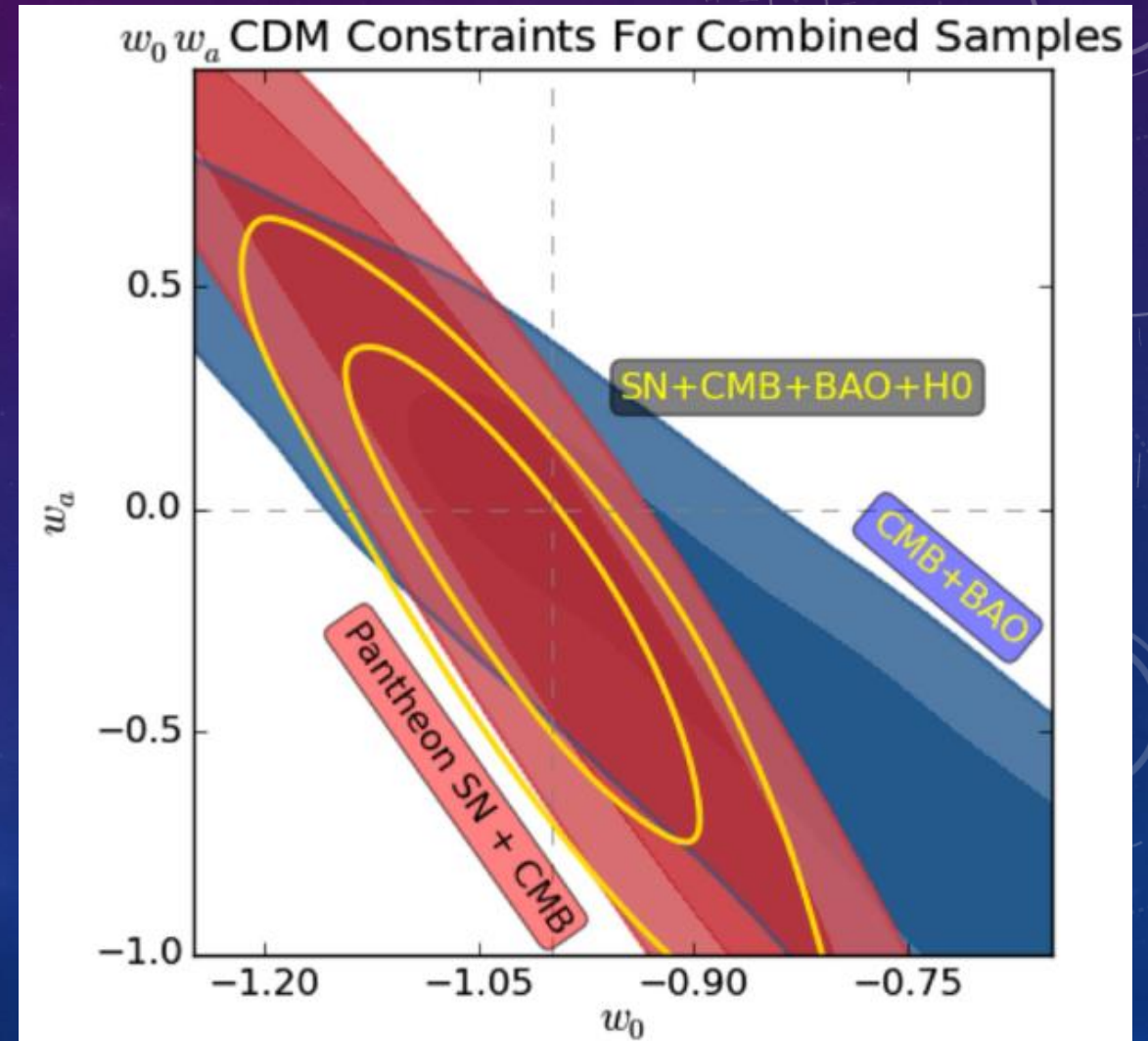


Figure 20. Confidence contours at 68% and 95% for the Ω_m and w cosmological parameters for the w CDM model. Constraints from CMB (blue), SN with systematic uncertainties (red), SN with only statistical uncertainties (gray), and SN+CMB (black) are shown.



THE PLANCK 2018 RESULTS

A&A 641, A6 (2020)
<https://doi.org/10.1051/0004-6361/201833910>
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Planck 2018 results

Astronomy
&
Astrophysics
Special issue

Planck 2018 results

VI. Cosmological parameters

Planck Collaboration: N. Aghanim⁵⁴, Y. Akrami^{15,57,59}, M. Ashdown^{65,5}, J. Aumont⁹⁵, C. Baccigalupi⁷⁸, M. Ballardini^{21,41}, A. J. Banday^{95,8},

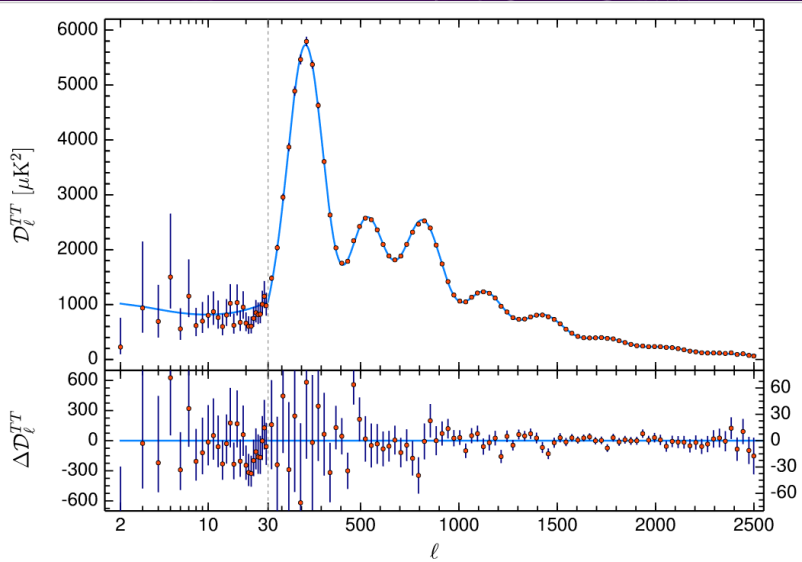


Table 1. Base- Λ CDM cosmological parameters from *Planck* TT,TE,EE+lowE+lensing.

Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] – [1])/ σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	–0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	–0.3	0.1198 ± 0.0012
$100\theta_{\text{MC}}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	–0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	–0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	–0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	–0.3	0.1428 ± 0.0011
H_0 [km s ^{–1} Mpc ^{–1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	–0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	–0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$. . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	–0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	–0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	–0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

THE PLANCK 2018 RESULTS

the independent constraints of Eq. (6) from *Planck* CMB lensing+BAO. Including CMB lensing sharpens the determination of H_0 to a 0.8% constraint:

$$H_0 = (67.36 \pm 0.54) \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (68\%, \text{ TT, TE, EE} + \text{lowE} + \text{lensing}). \quad (14)$$

This value is our “best estimate” of H_0 from *Planck*, assuming the base- Λ CDM cosmology.

Since we are considering a flat universe in this section, a constraint on Ω_m translates directly into a constraint on the dark-energy density parameter, giving

$$\Omega_\Lambda = 0.6847 \pm 0.0073 \quad (68\%, \text{ TT, TE, EE} + \text{lowE} + \text{lensing}). \quad (15)$$

In terms of a physical density, this corresponds to $\Omega_\Lambda h^2 = 0.3107 \pm 0.0082$, or cosmological constant $\Lambda = (4.24 \pm 0.11) \times 10^{-66} \text{ eV}^2 = (2.846 \pm 0.076) \times 10^{-122} m_{\text{Pl}}^2$ in natural units (where m_{Pl} is the Planck mass).

3.3. Optical depth and the fluctuation amplitude

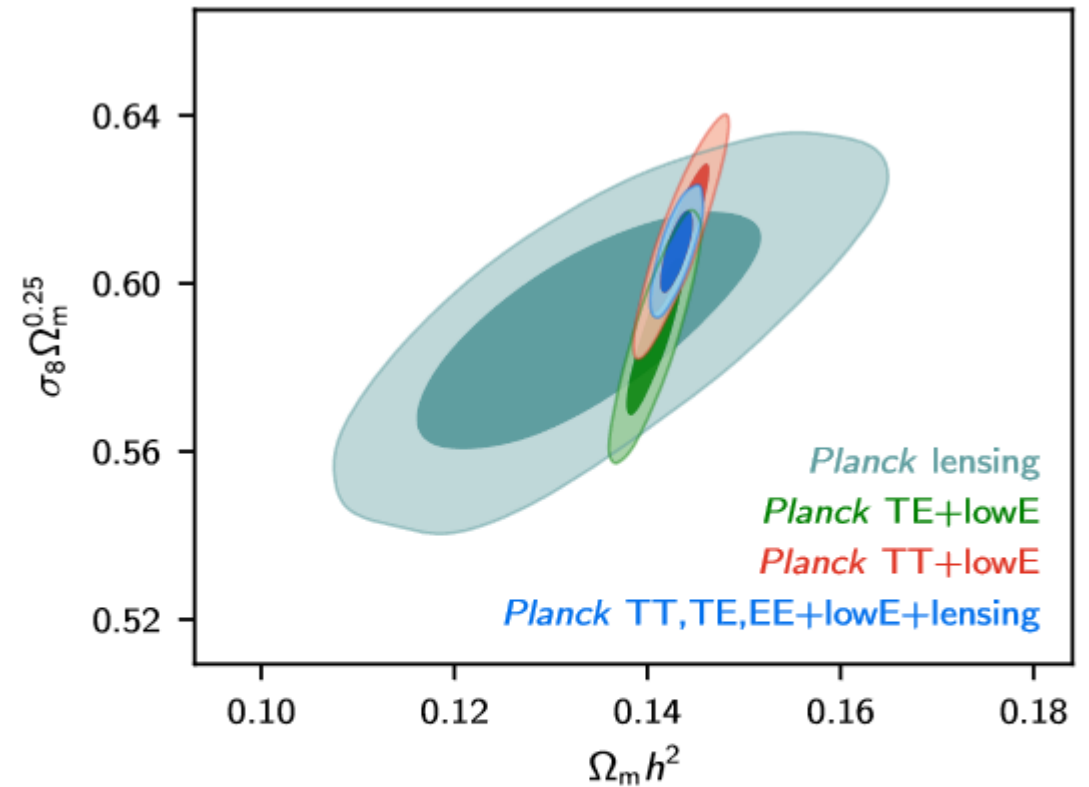


Fig. 6. Base- Λ CDM 68% and 95% marginalized constraint contours for the matter density and $\sigma_8 \Omega_m^{0.25}$, a fluctuation amplitude parameter that is well constrained by the CMB-lensing likelihood. The *Planck* TE, TT, and lensing likelihoods all overlap in a consistent region of parameter space, with the combined likelihood substantially reducing the allowed parameter space.

- (i) cosmic shear using 100 million source galaxies,
- (ii) Galaxy clustering, and
- (iii) the cross-correlation of source galaxy shear with lens galaxy positions, galaxy–galaxy lensing

DES-2020-0617
FERMILAB-PUB-21-221-AE

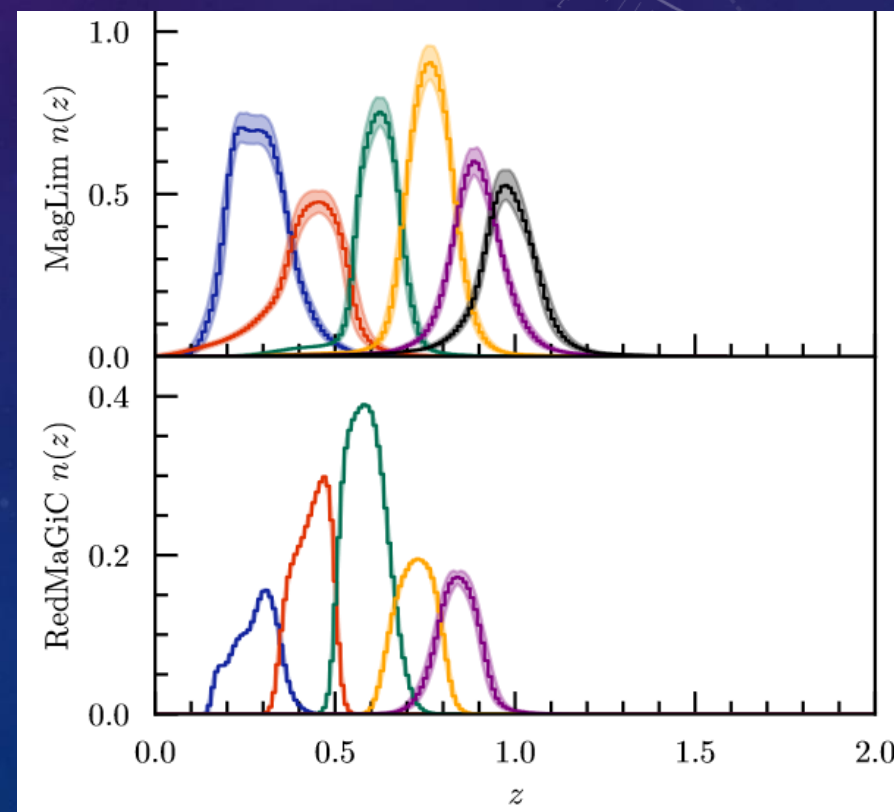
Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing

T. M. C. Abbott,¹ M. Aguena,² A. Alarcon,³ S. Allam,⁴ O. Alves,^{5,6,2} A. Amon,⁷ F. Andrade-Oliveira,^{6,2} J. Annis,⁴ S. Avila,⁸

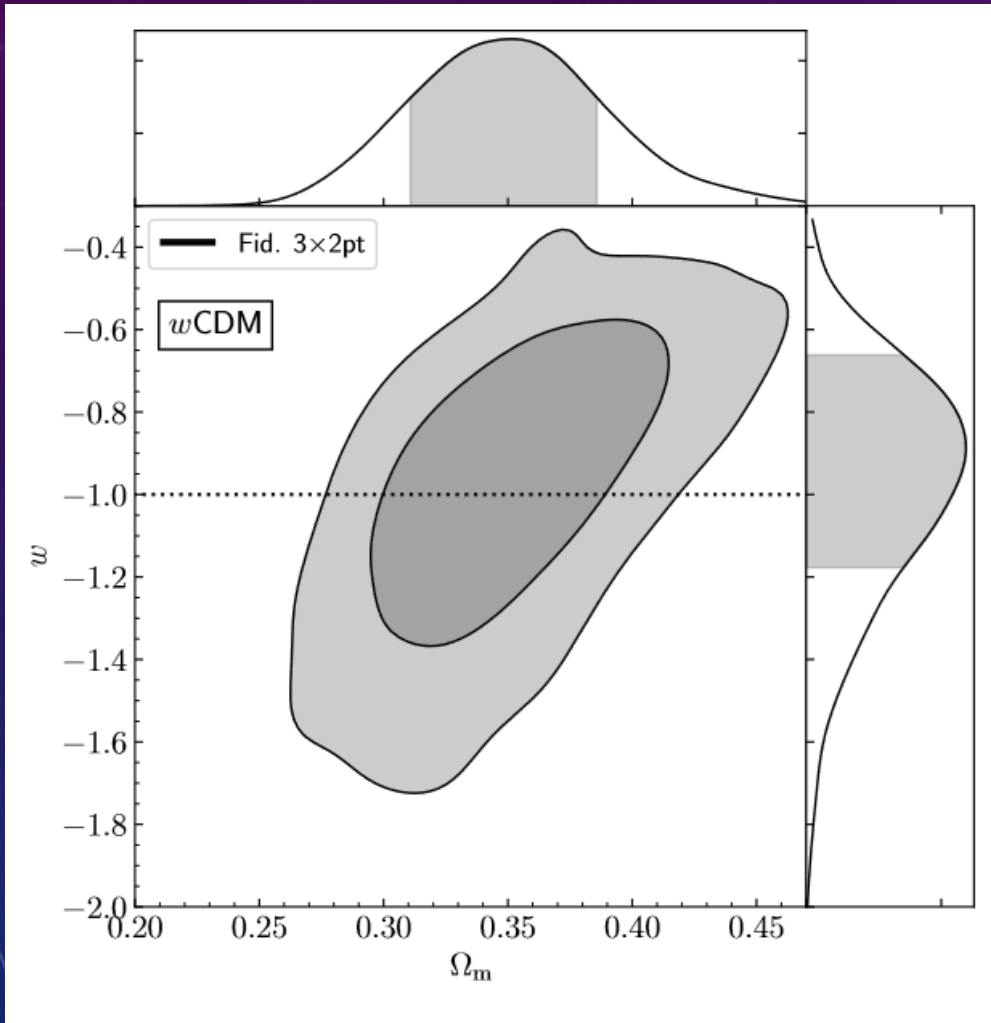
$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

$$\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696).$$

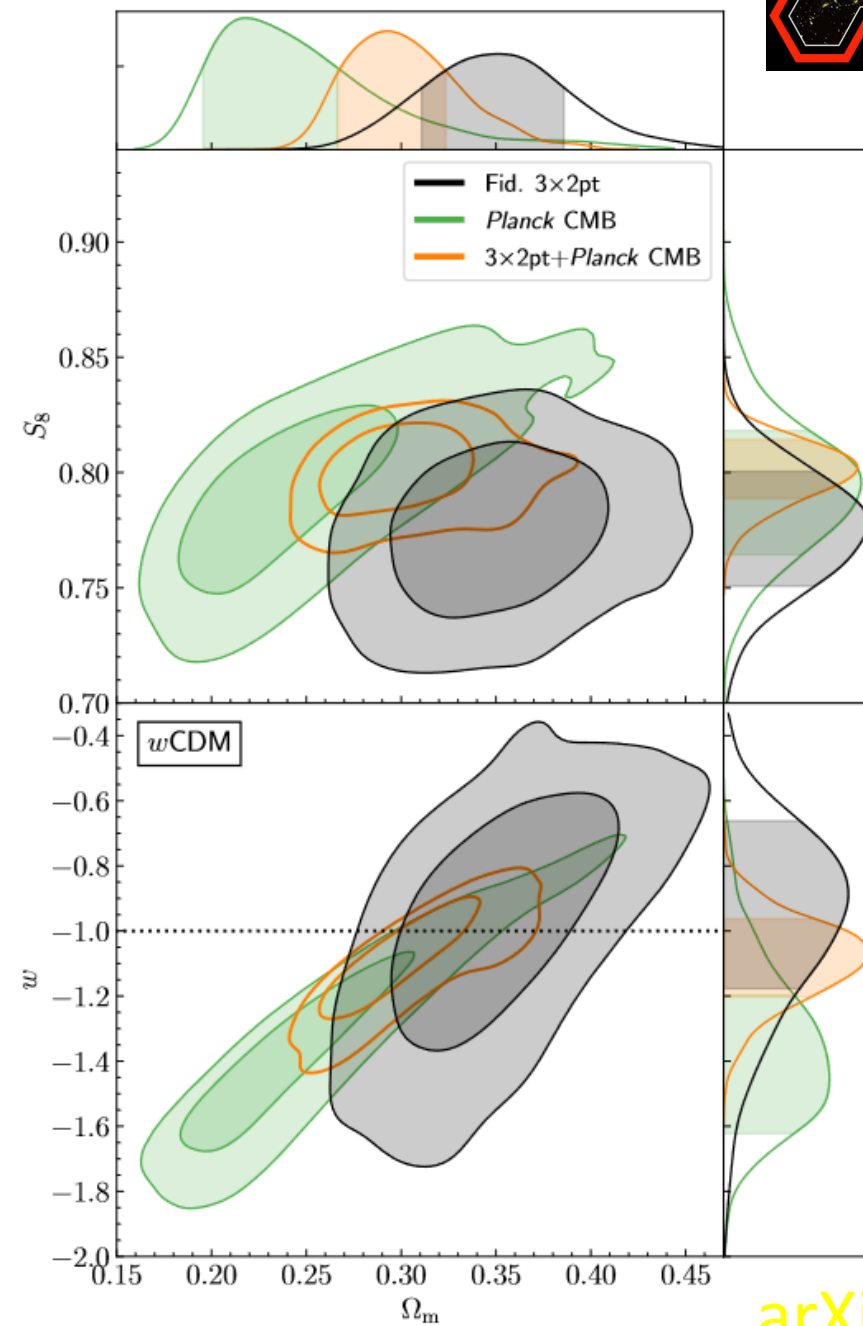
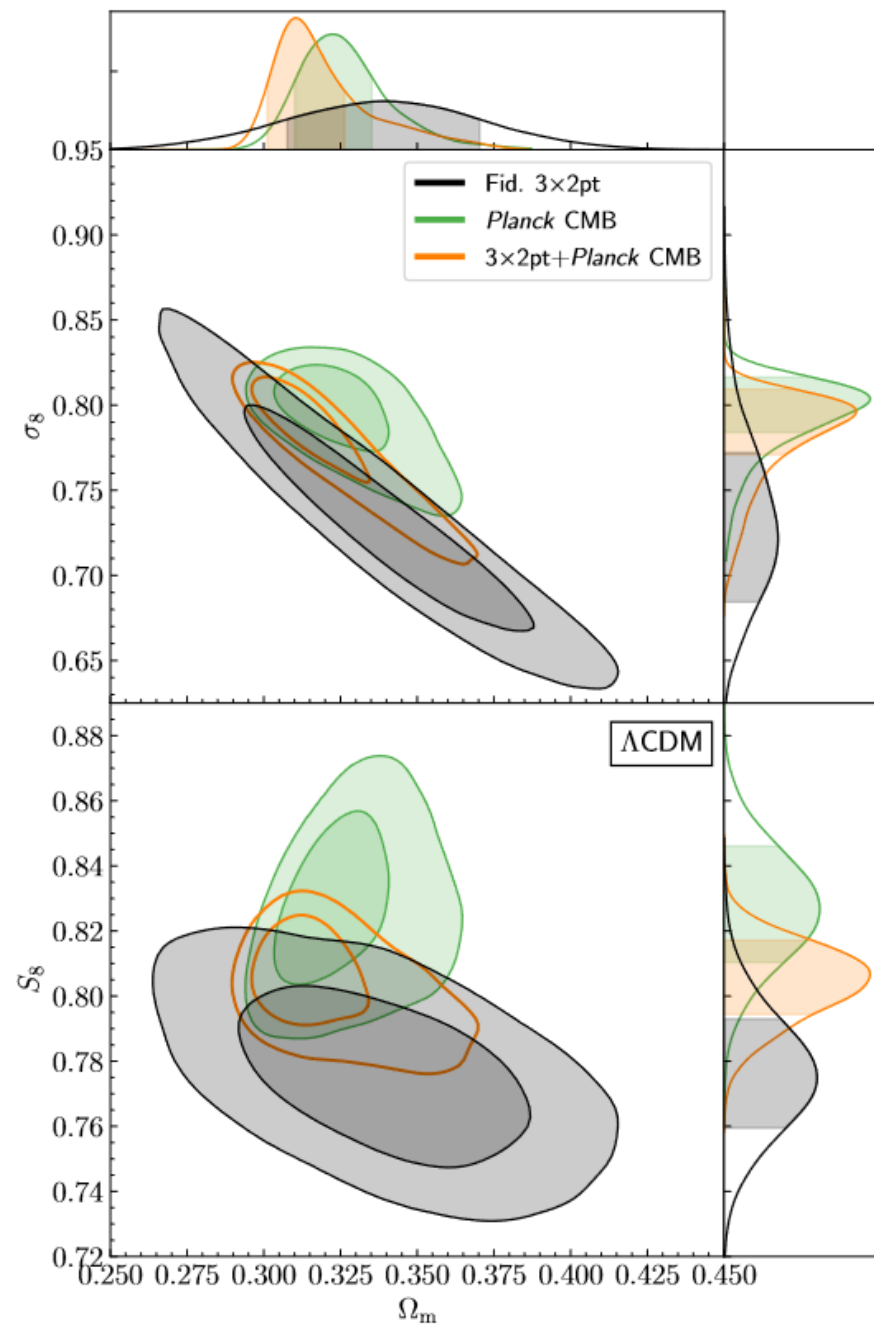


arXiv:2105.13549



$$\Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339),$$

$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03).$$



$$\sum m_\nu < 0.13 \text{ eV (95\% CL),}$$

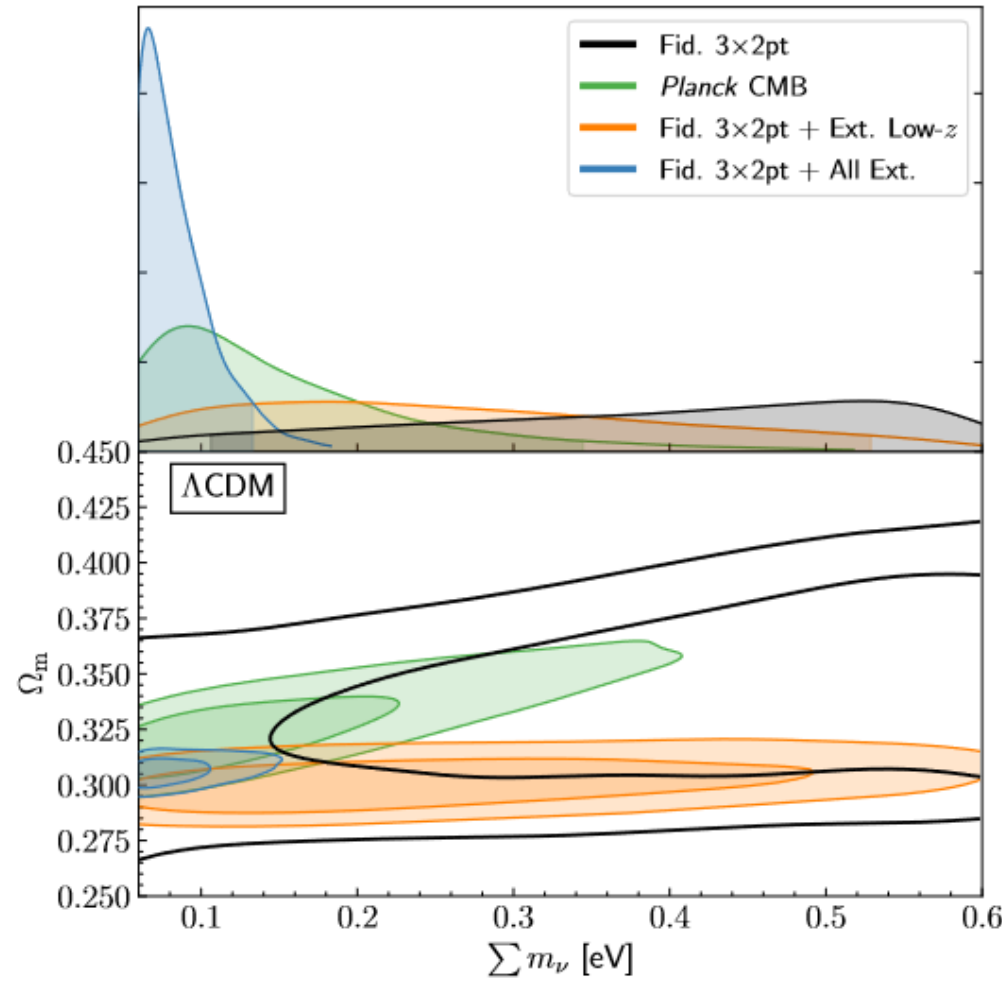
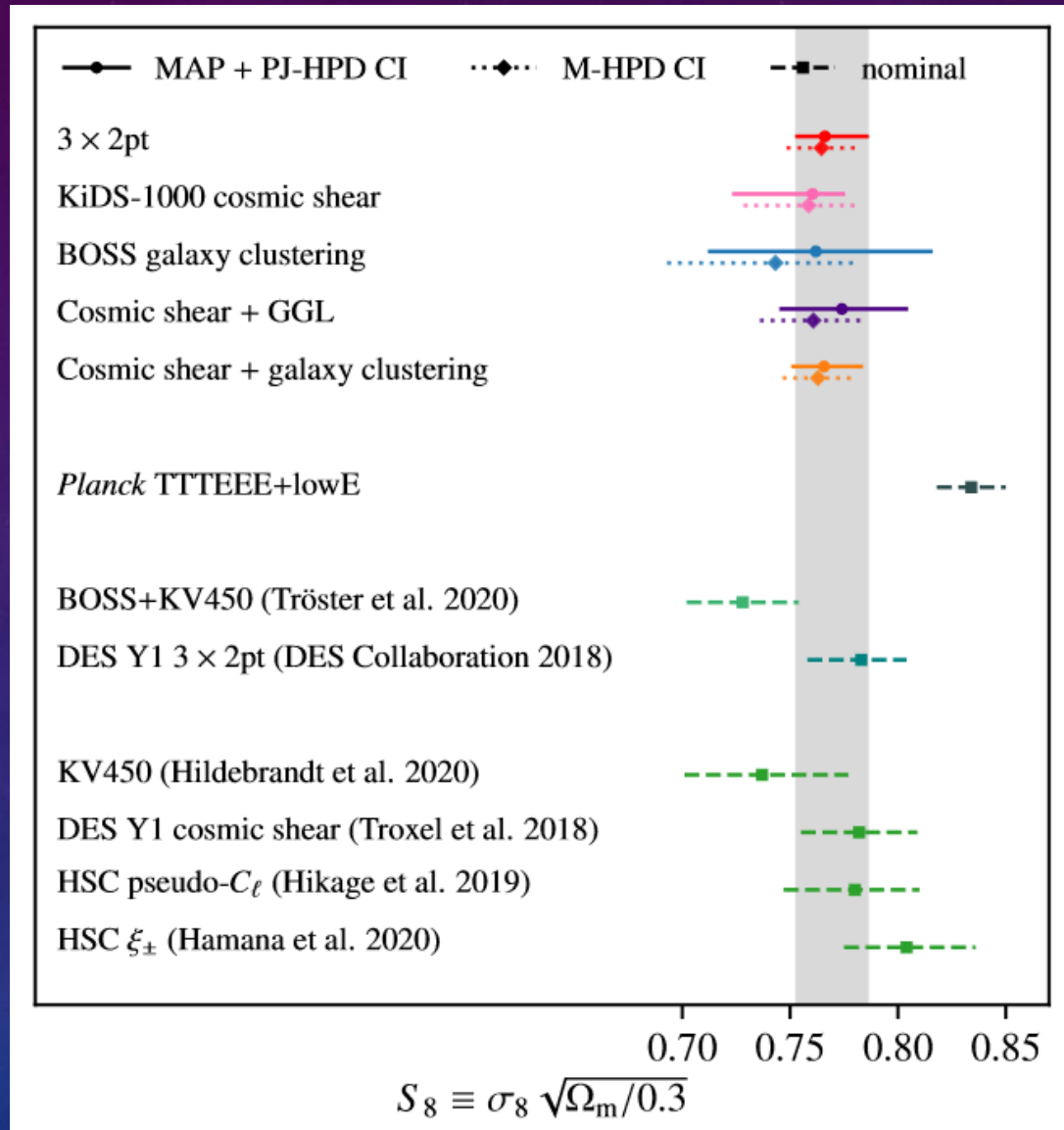
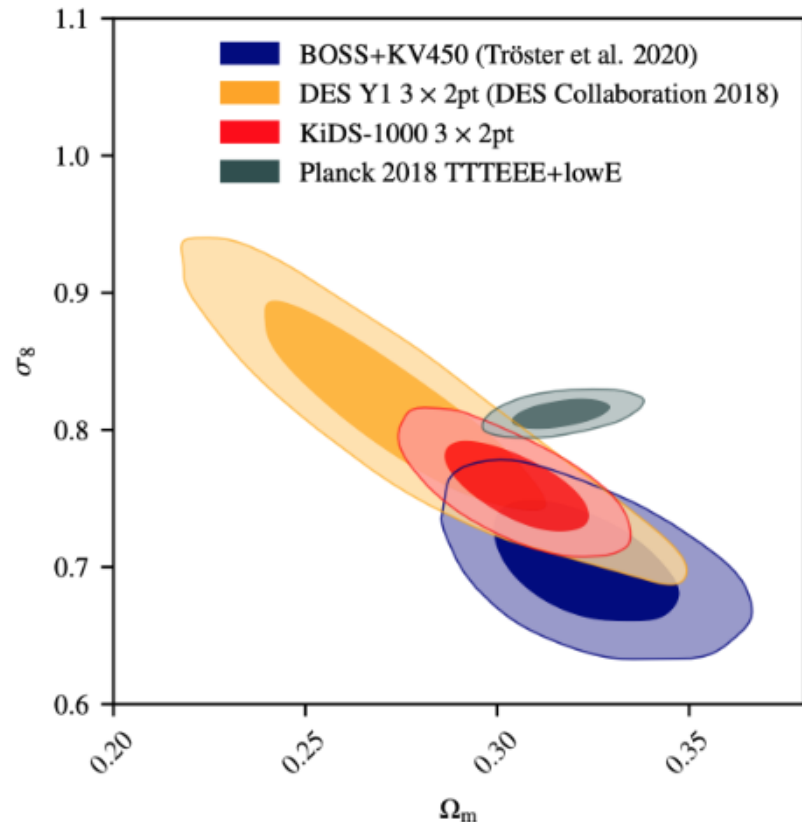


FIG. 21. Marginalized constraints on the sum of neutrino masses in the Λ CDM model. We show the DES fiducial 3x2pt constraints (black), DES 3x2pt combined with external BAO, RSD, and SNe Ia (orange), *Planck* CMB constraints (green), and DES 3x2pt combined with all of these external data sets. The upper panel shows the one-dimensional marginalized posteriors for $\sum m_\nu$, with shaded 95% confidence regions. The lower panel shows 68 and 95% CL for Ω_m and $\sum m_\nu$.

CHALLENGES

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$

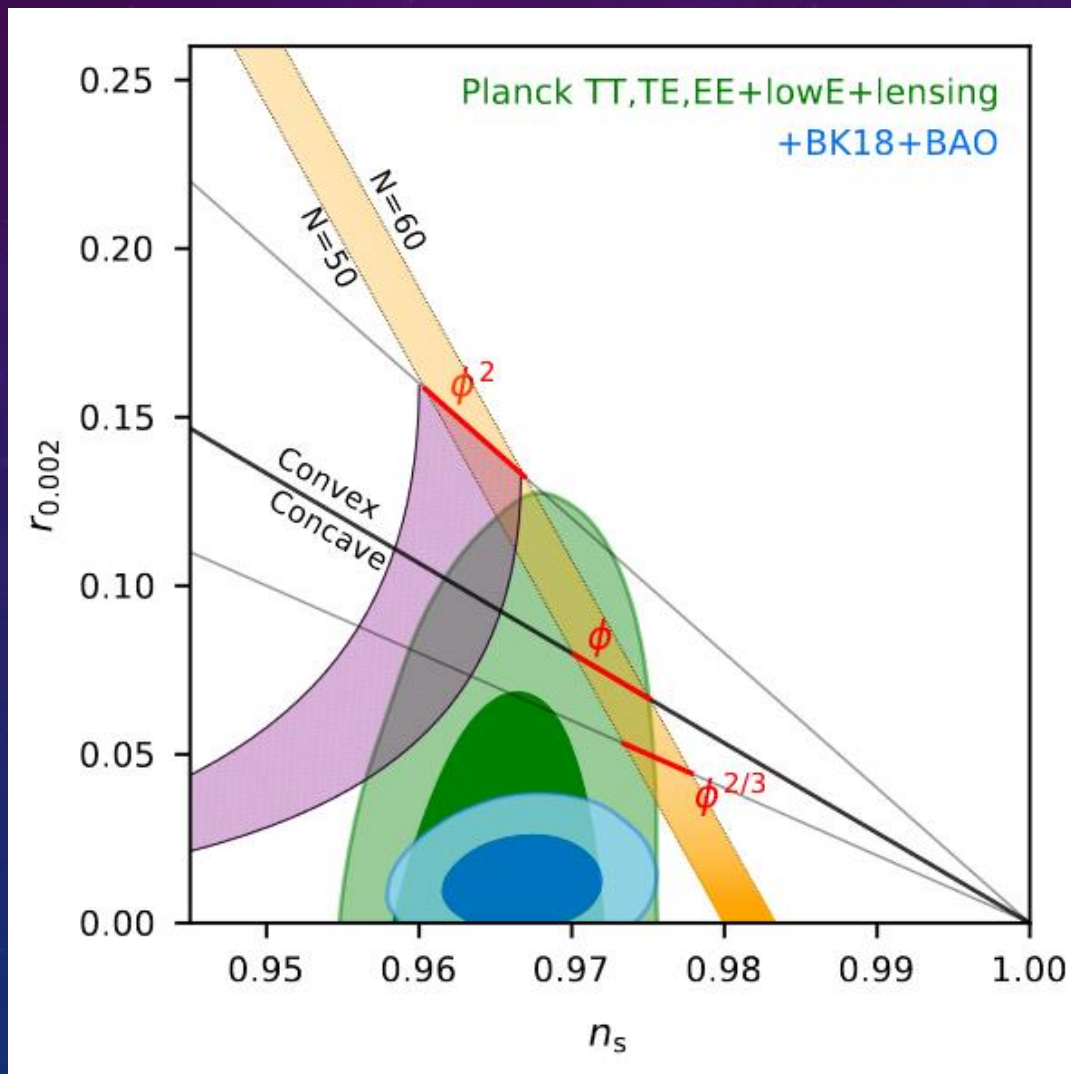
$$\sigma^2(R) \equiv \langle \delta^2(\mathbf{x}; R) \rangle = \int \Delta^2(k) \tilde{W}^2(kR) \frac{dk}{k}.$$



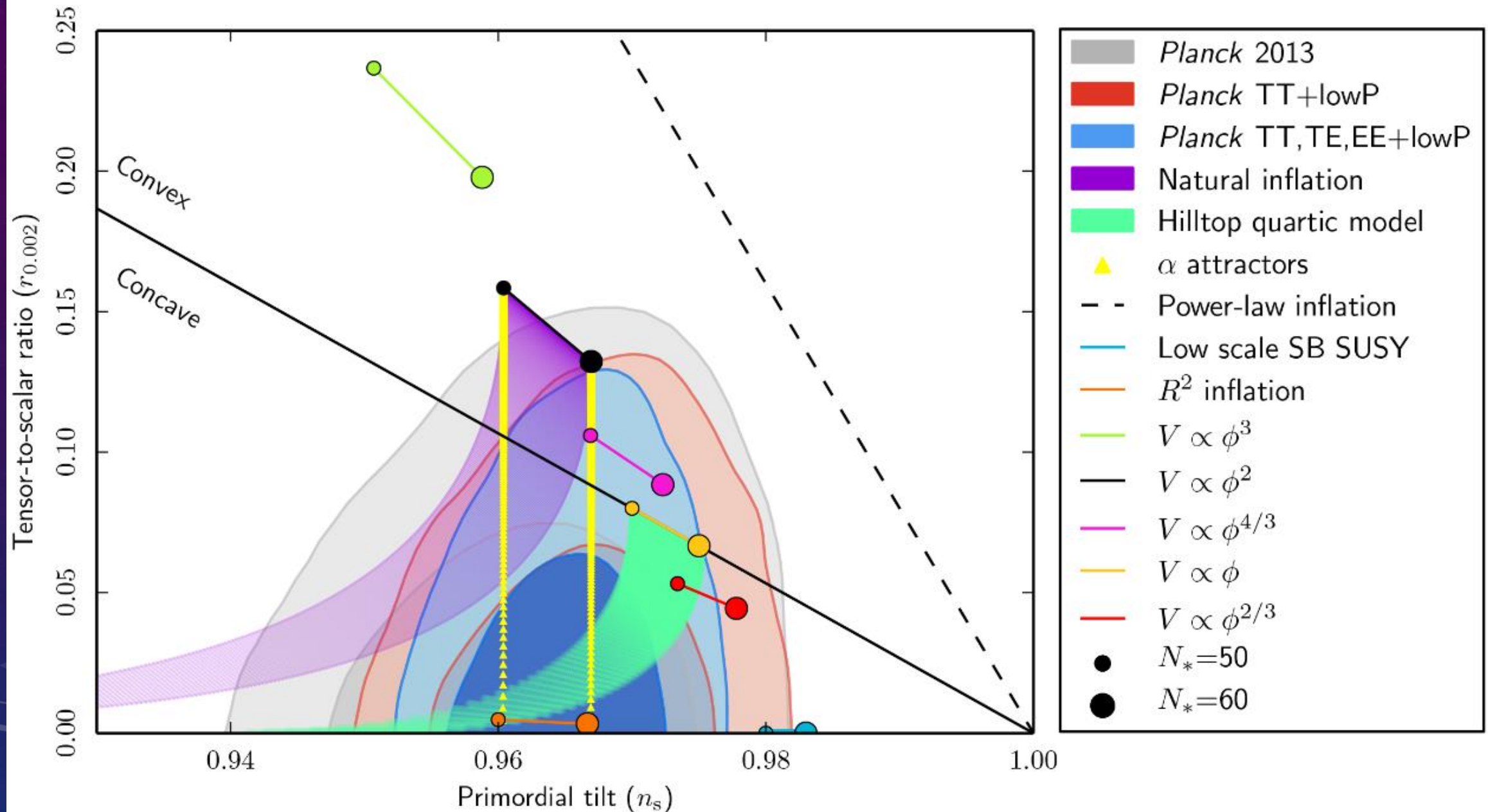
KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints

BICEP / Keck XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season

BICEP/Keck Collaboration: P. A. R. Ade,¹ Z. Ahmed,² M. Amiri,³ D. Barkats,⁴ R. Basu Thakur,⁵ C. A. Bischoff,⁶ D. Beck,^{2,7} J. J. Bock,^{5,8} H. Boenish,⁴ E. Bullock,⁹ V. Buza,¹⁰ J. R. Cheshire IV,⁹ J. Connors,⁴ J. Covi,¹¹ M. Covi,¹¹ A. Covi,¹¹ F. V. Davies,¹² M. Diserens,⁴ L. Duval,¹³ M. Eiben,⁴



PLANCK 2015



CHALLENGES 2021

Challenges for Λ CDM : An update

L. Perivolaropoulos^{1,*} and F. Skara^{1,†}

¹*Department of Physics, University of Ioannina, 45110 Ioannina, Greece*
(Dated: May 20, 2021)

A number of challenges of the standard Λ CDM model has been emerging during the past few years as the accuracy of cosmological observations improves. In this review we discuss in a unified manner many existing signals in cosmological and astrophysical data that appear to be in some tension (2σ or larger) with the standard Λ CDM model as defined by the Planck18 parameter values. In addition to the major well studied 5σ challenge of Λ CDM (the Hubble H_0 crisis) and other well known tensions (the growth tension and the lensing amplitude A_L anomaly), we discuss a wide range of other less discussed less-standard signals which appear at a lower statistical significance level than the H_0 tension (also known as 'curiosities' in the data) which may also constitute hints towards new physics. For example such signals include cosmic dipoles (the fine structure constant α , velocity and quasar dipoles), CMB asymmetries, BAO $\text{Ly}\alpha$ tension, age of the Universe issues, the Lithium problem, small scale curiosities like the core-cusp and missing satellite problems, quasars Hubble diagram, oscillating short range gravity signals etc. The goal of this pedagogical review is to collectively present the current status of these signals and their level of significance, with emphasis to the Hubble crisis and refer to recent resources where more details can be found for each signal. We also briefly discuss possible theoretical approaches that can potentially explain the non-standard nature of some of these signals.

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