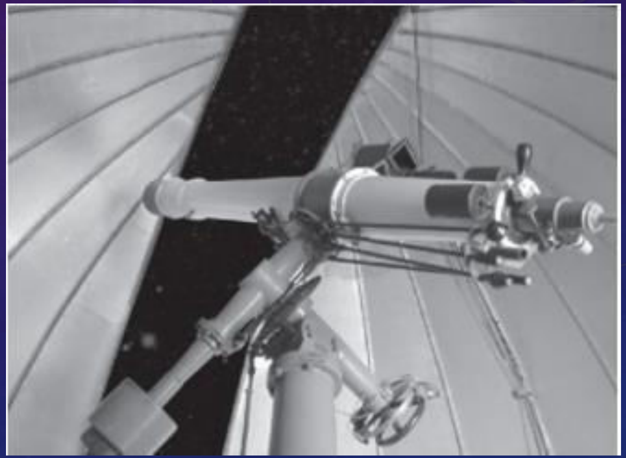
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

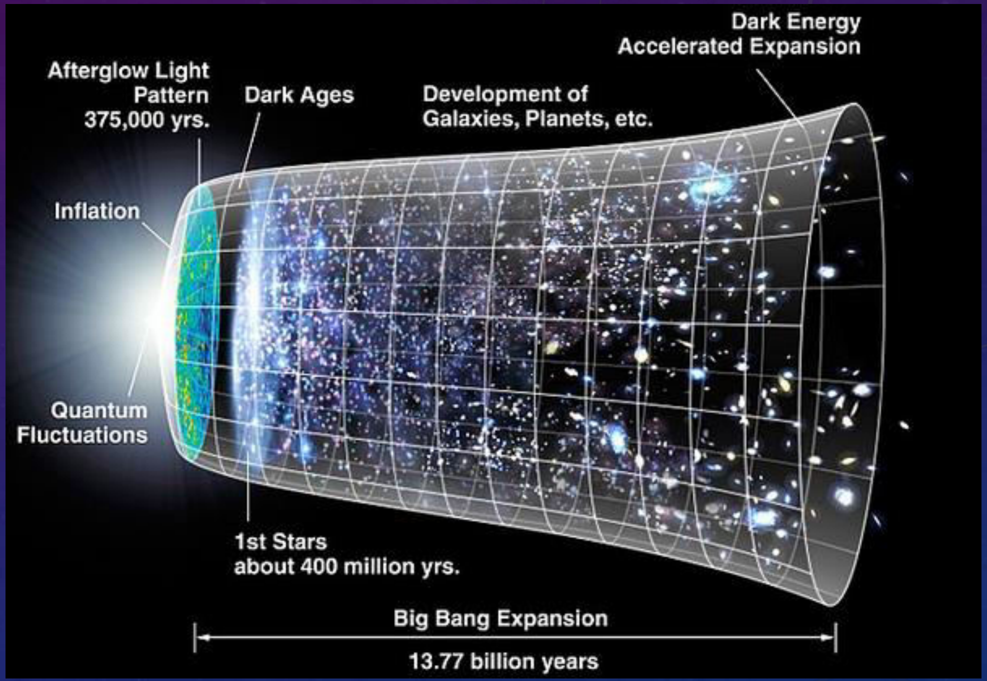
UFOP
Universidade Federal de Ouro Preto

OURO PRETO POSSUI UM DOS PRIMEIROS OBSERVATÓRIOS DO BRASIL.
ENSINO DE ASTRONOMIA DESDE 1891 NA ESCOLA DE MINAS (CRIADA EM 1876).



SERIES OF 3 TALKS

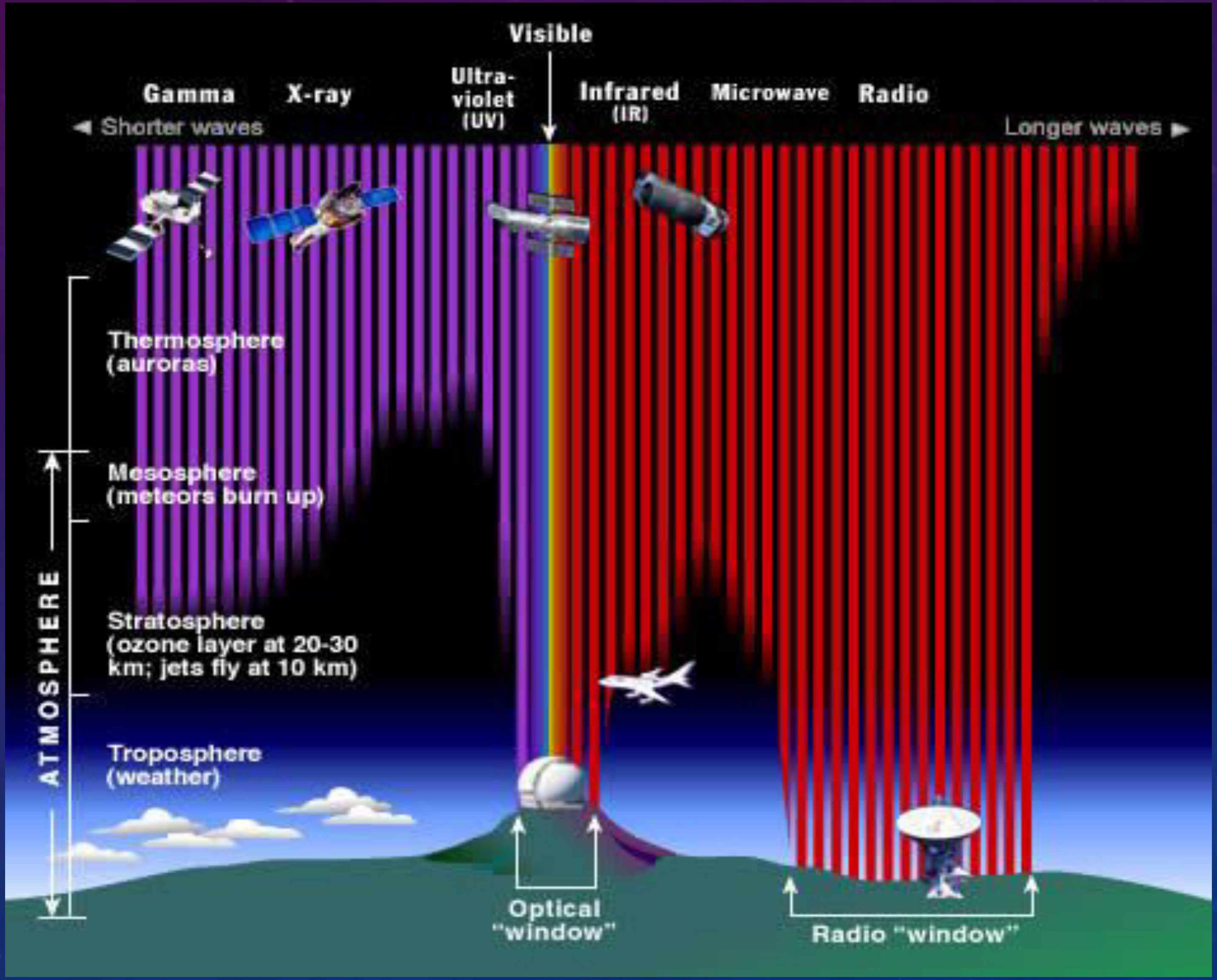
- (BASIC) Talk 1: The rise of Cosmology along the 20th century as a research field and basic assumptions
- (THEORY) Talk 2: How we have modelled and mapped the dark sector of the universe
- (OBSERVATIONS) Talk 3: The latest results and the state of the art

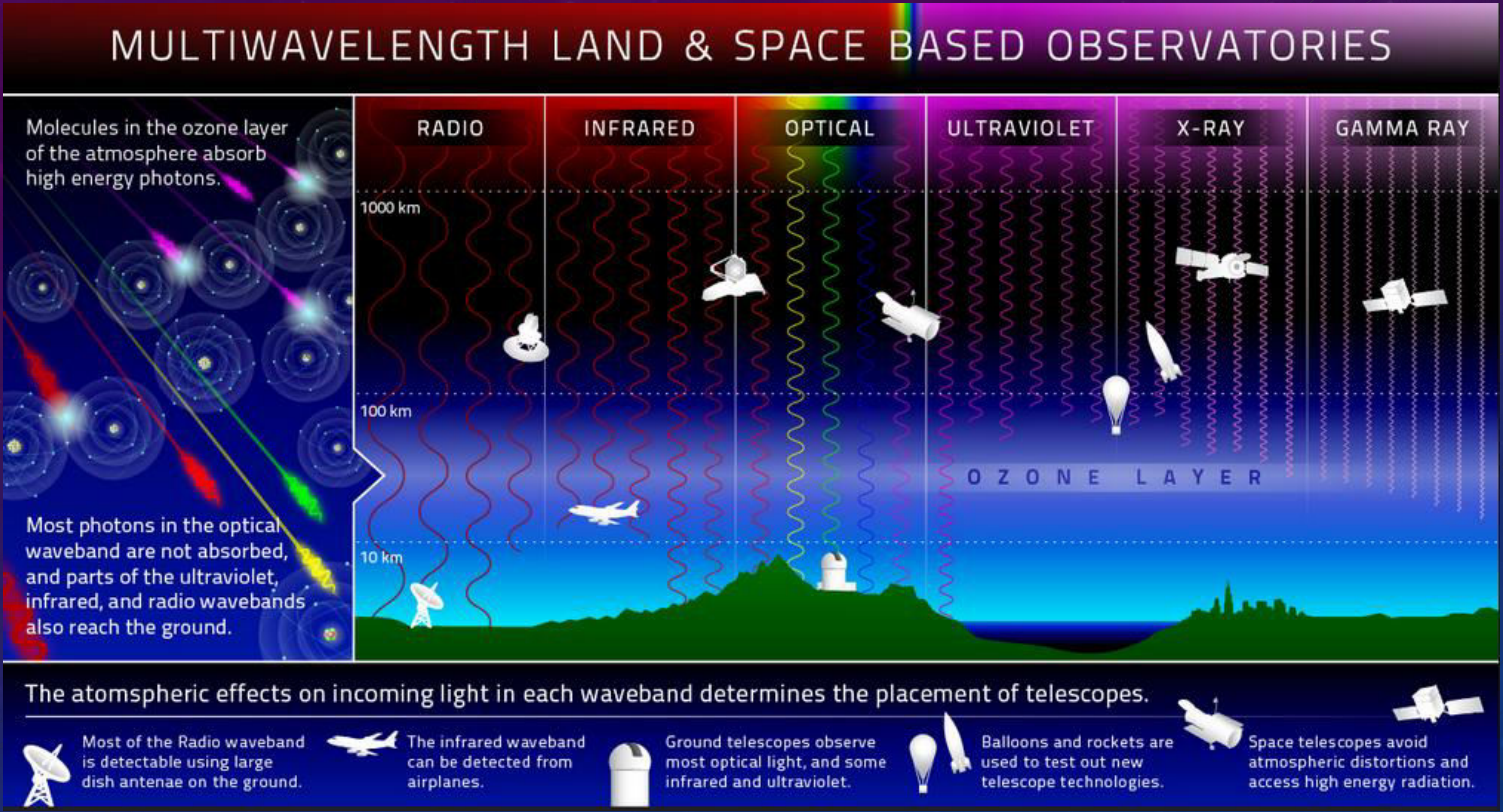


Then, as precision increases, the array of possible interpretations permitted by uncertainties in the observation will be correspondingly reduced. Ultimately, when a definite formulation has been achieved, free from systematic errors and with reasonably small probable errors, the number of competing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

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

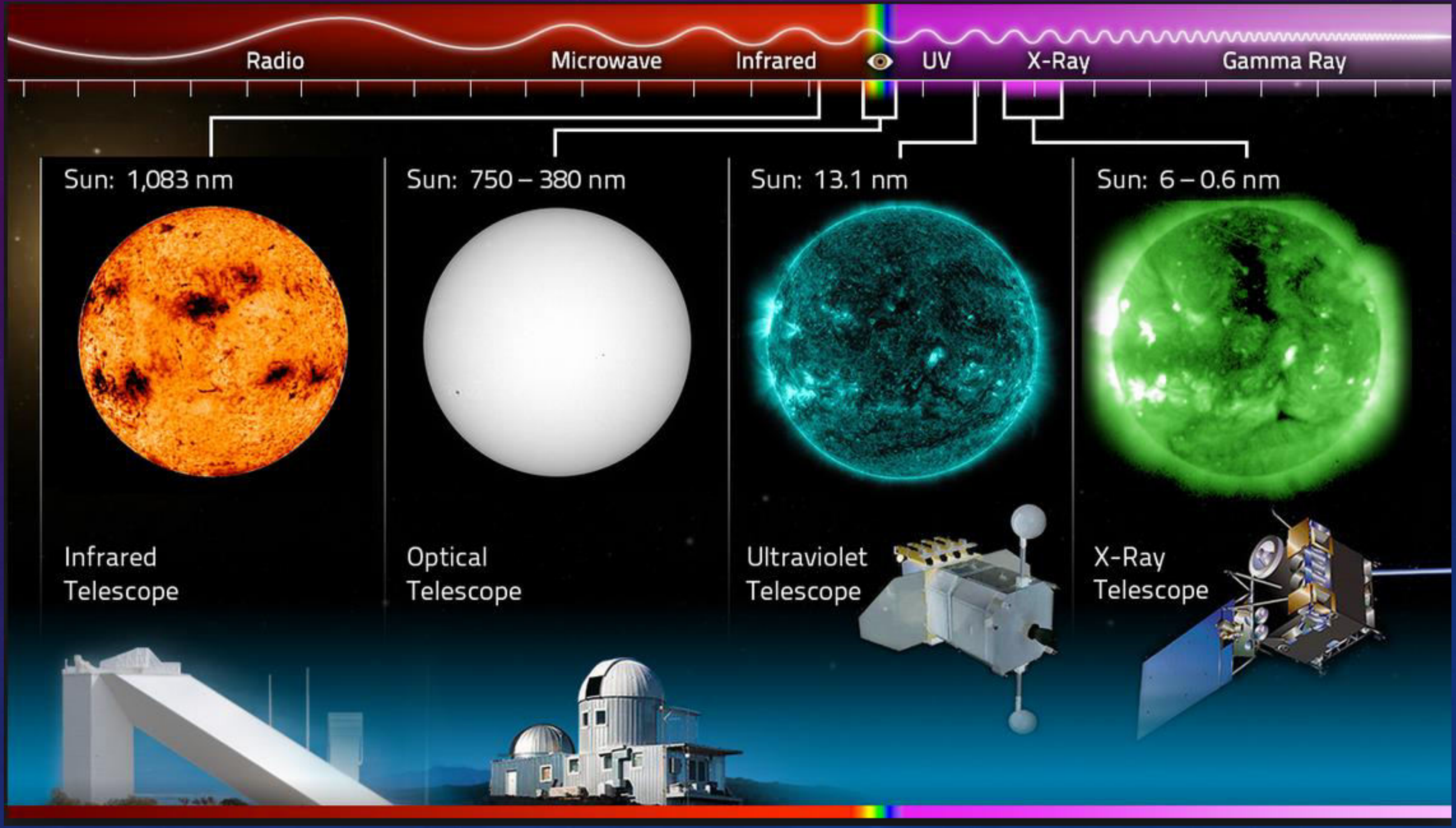
COMO OBSERVAMOS?
COMO DIFERENTES PARTES DO ESPECTRO ATRAVESSAM A ATMOSFERA

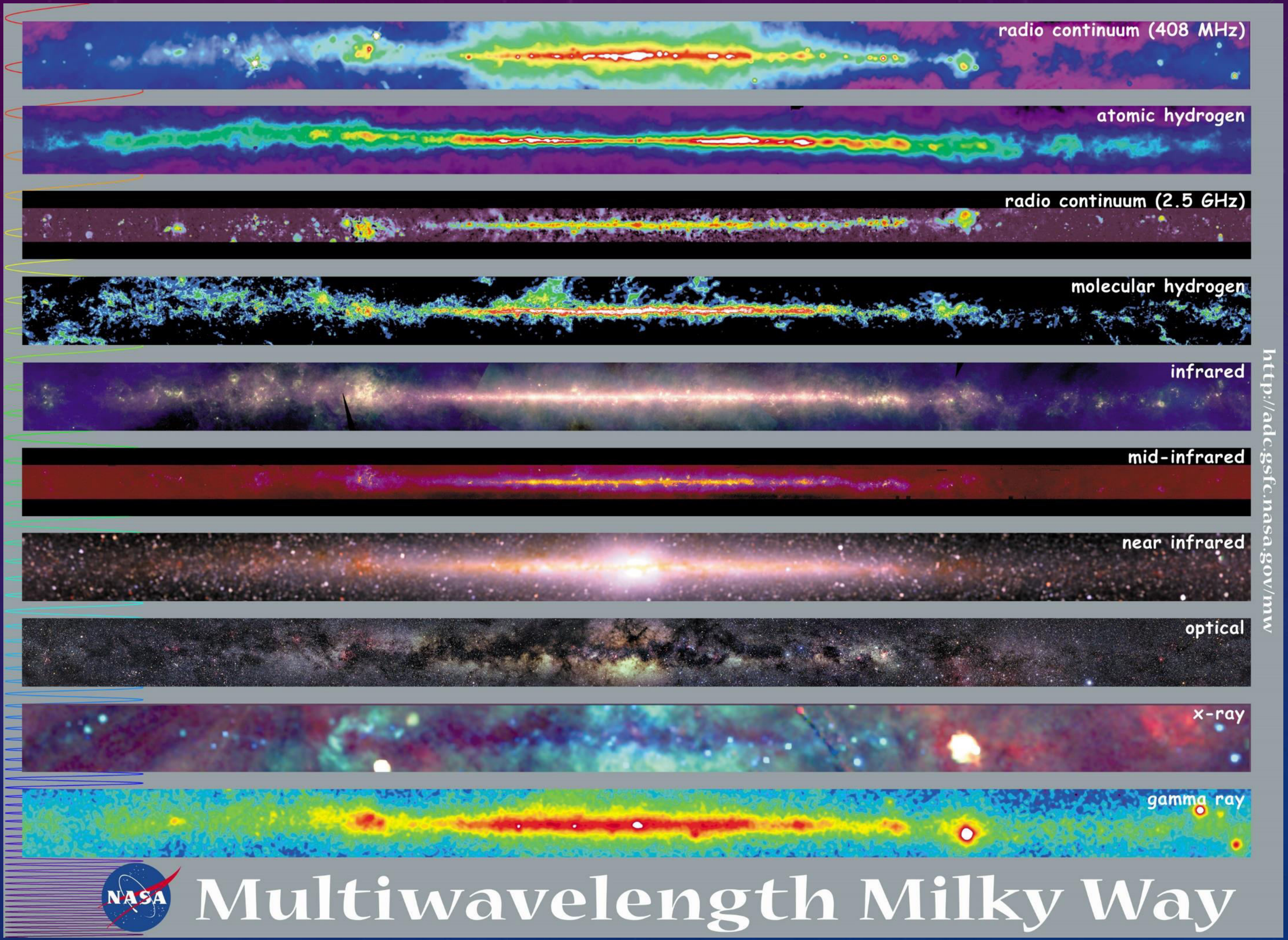


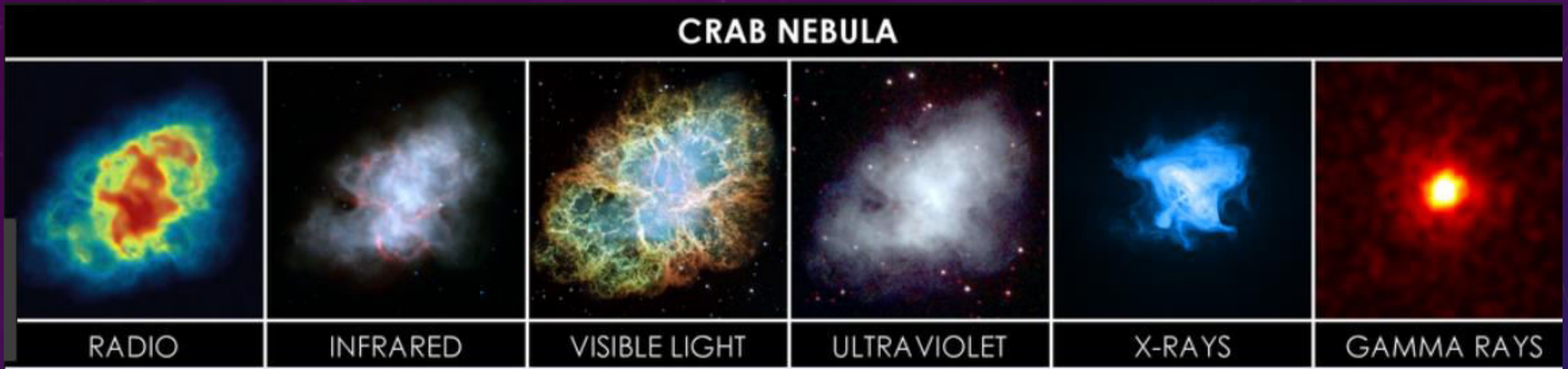


MULTIWAVELENGTH LAND & SPACE BASED OBSERVATORIES
Molecules in the ozone layer of the atmosphere absorb high energy photons.
Most photons in the optical waveband are not absorbed, and parts of the ultraviolet, infrared, and radio wavebands also reach the ground.
RADIO
INFRARED
OPTICAL
ULTRAVIOLET
X-RAY
GAMMA RAY
1000 km
100 km
10 km
OZONE LAYER
The atomspheric effects on incoming light in each waveband determines the placement of telescopes.
Most of the Radio waveband is detectable using large dish antenae on the ground.
The infrared waveband can be detected from airplanes.
Ground telescopes observe most optical light, and some infrared and ultraviolet.
Balloons and rockets are used to test out new telescope technologies.
Space telescopes avoid atmospheric distortions and access high energy radiation.

O SOL VISTO EM DIFERENTES FREQUÊNCIAS

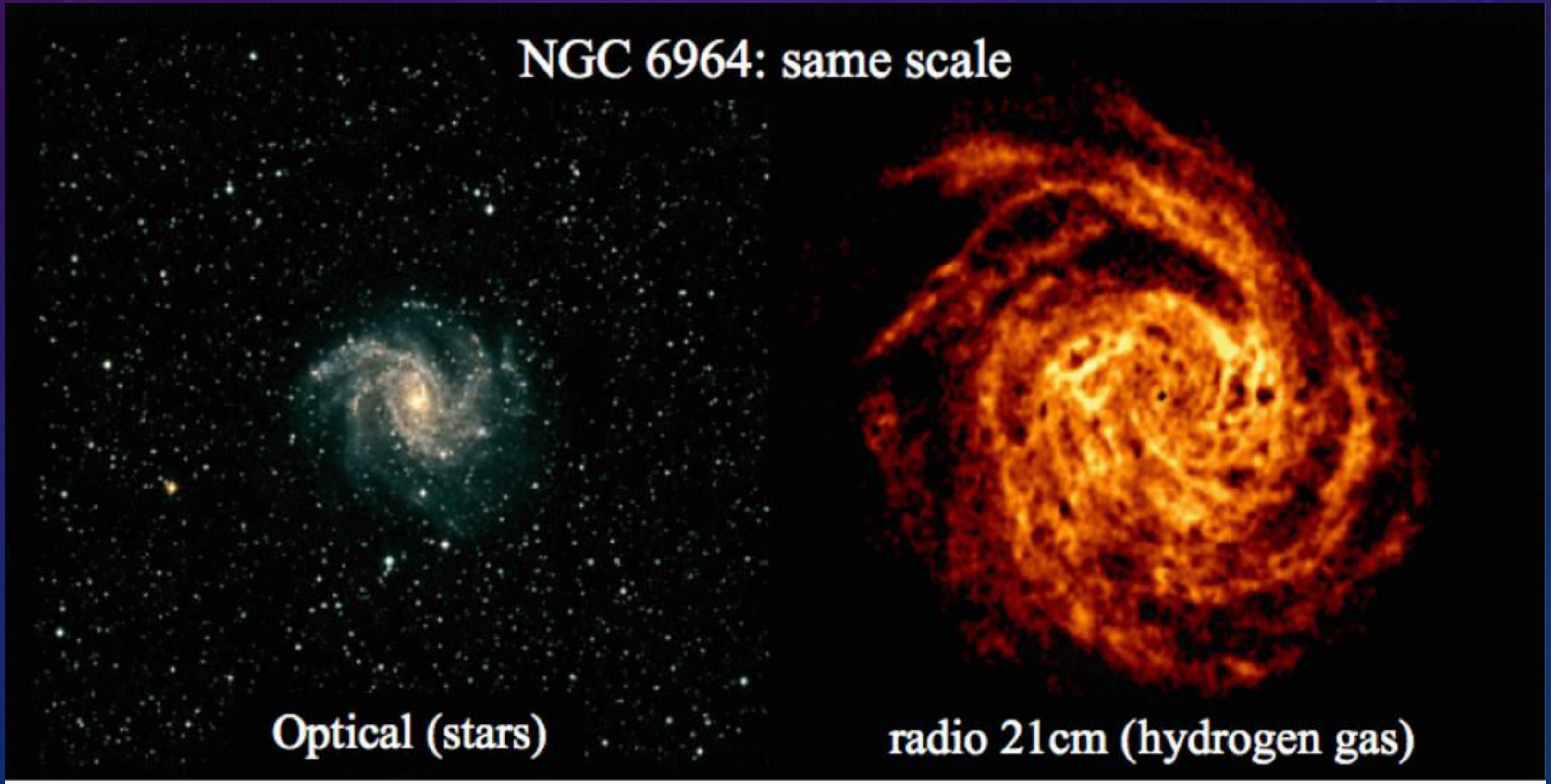



radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way



The crab nebula in radio, infrared, visible, ultraviolet, x-ray and gamma-ray wavelengths.

Sources: Radio: NRAO/AUI and M. Bietenholz, J.M. Uson, T.J. Cornwell; Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota); Visible: NASA, ESA, J. Hester and A.Loll (Arizona State University); Ultraviolet: NASA/Swift/E. Hoversten, PSU, X-ray: NASA/CXC/SAO/F. Seward et al.; Gamma: NASA/DOE/Fermi LAT/R. Buehler



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.

BEGINNING OF COSMOLOGY 1922

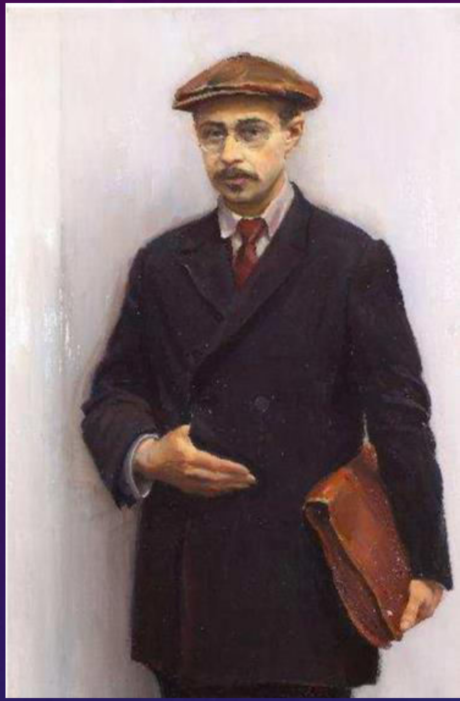


Figure 2. 1913-1914 years. Left-to-right, first line: unknown (P. Ehrenfest?), A. Friedmann, G. Weihardt, unknown. Second line: E. Friedmann, A. Shohat, E. Weihardt, Ya. Tamarkin, unknown, unknown, M. Petelin. Third line: V. Smirnov.

Translation of Friedmann's letter to Ehrefest:
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 Einstein[1]) und de Sitter[2]) zu zwei möglichen Typen des Weltalls; Einstein erhält die sogenannte Zylinderwelt, in der der Raum[3]) 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 kann[4]). 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 Grundgeschwindigkeit[5]) — 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:

$$R_{ik} - {}^1/_2\, g_{ik}\, \overline{R} + \lambda g_{ik} = -\varkappa T_{ik} \quad (i, k = 1, 2, 3, 4), \qquad \text{(A)}$$

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:

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

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

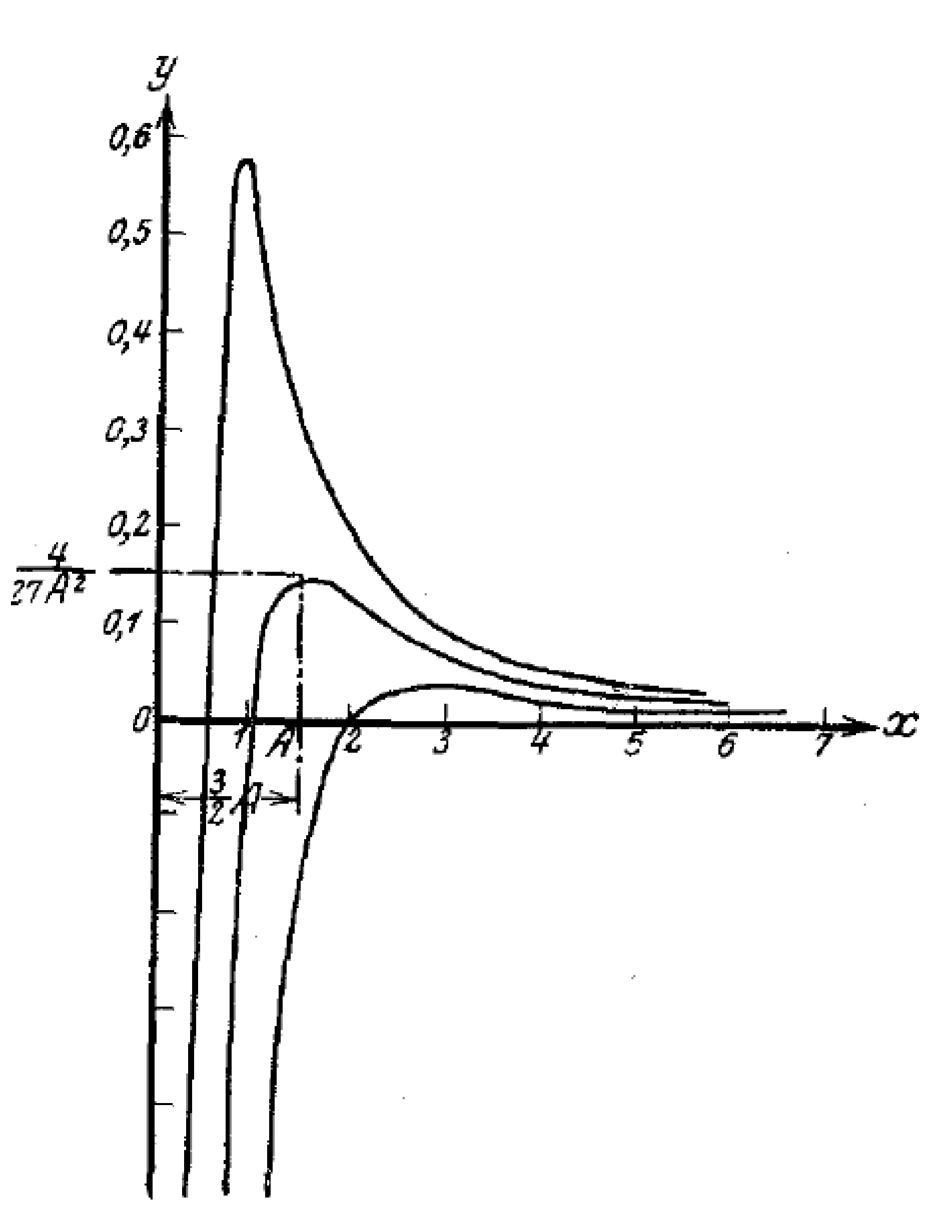
$$\frac{3R'^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \varkappa c^2 \varrho, \qquad (5)$$

mit

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

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

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



EINSTEIN'S OPINION ON FRIEDMANN'S WORK

AGAINST

IN FAVOR

Bemerkung zu der Arbeit von A. Friedmann[1]) „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 (D_3) charakterisierten Ansatzes führt dies auf die Beziehung

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

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.

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

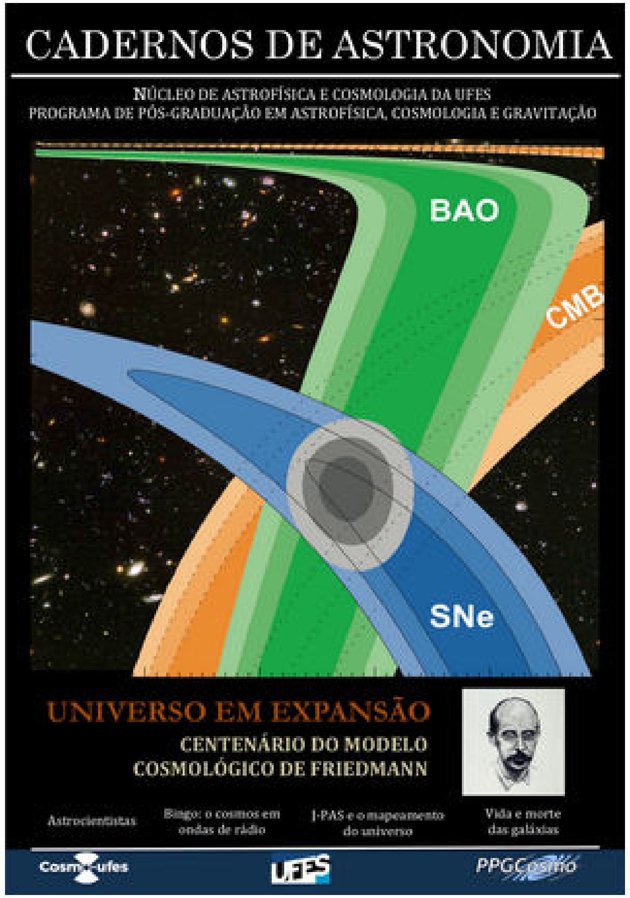
Von **A. Einstein** in Berlin.

(Eingegangen am 31. Mai 1923.)

Ich habe in einer früheren Notiz[1]) an der genannten Arbeit[2]) 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.

v. 3 n. 1 (2022): Universo em Expansão: Centenário do Modelo Cosmológico de Friedmann



O artigo do matemático russo Alexander Friedmann, publicado em 1922 na revista alemã *Zeitschrift für Physik*, representou uma profunda mudança na nossa visão do cosmo. Pela primeira vez na história da ciência, o universo passa a ser visto como um sistema dinâmico: ele pode expandir ou contrair, mas não seria estático. Isto se contrapunha à concepção vigente até então em que prevaleciam os modelos cosmológicos estáticos. As observações de galáxias longínquas, realizadas pouco depois, indicaram um universo em expansão, uma das possibilidades evocadas por Friedmann. O conceito de expansão do universo tornou-se elemento essencial do atual modelo cosmológico padrão, e permeia todas as atividades científicas em astrofísica e cosmologia, tanto teóricas como observacionais.

A Seção Temática da presente edição dos Cadernos de Astronomia gravita em torno da celebração do centenário da publicação do artigo de Alexander Friedmann, tanto pela sua importância para a física e astronomia quanto para a própria visão que temos hoje do cosmo. Ressalta também o protagonismo do Brasil em projetos observacionais em astrofísica e cosmologia. Além disso, a Seção Textos Clássicos traz uma tradução inédita do artigo seminal de Friedmann.

CADERNOS DE ASTRONOMIA – vol. 3, n°1 (2022)
Seção Textos Clássicos

O universo dinâmico de Friedmann

Hermano Velten[1] e Winfried Zimdahl[2]

[1]*Universidade Federal de Ouro Preto*
[2]*Universidade Federal do Espírito Santo*

Resumo
Apresenta-se uma tradução do alemão, do artigo seminal de Alexander Friedmann publicado em 1922, onde encontram-se as bases de um modelo cosmológico dinâmico.

Abstract
This is a translation from German to Brazilian Portuguese of the seminal work by Alexander Friedmann, published in 1922, where the basics of a dynamical cosmological model are developed

---

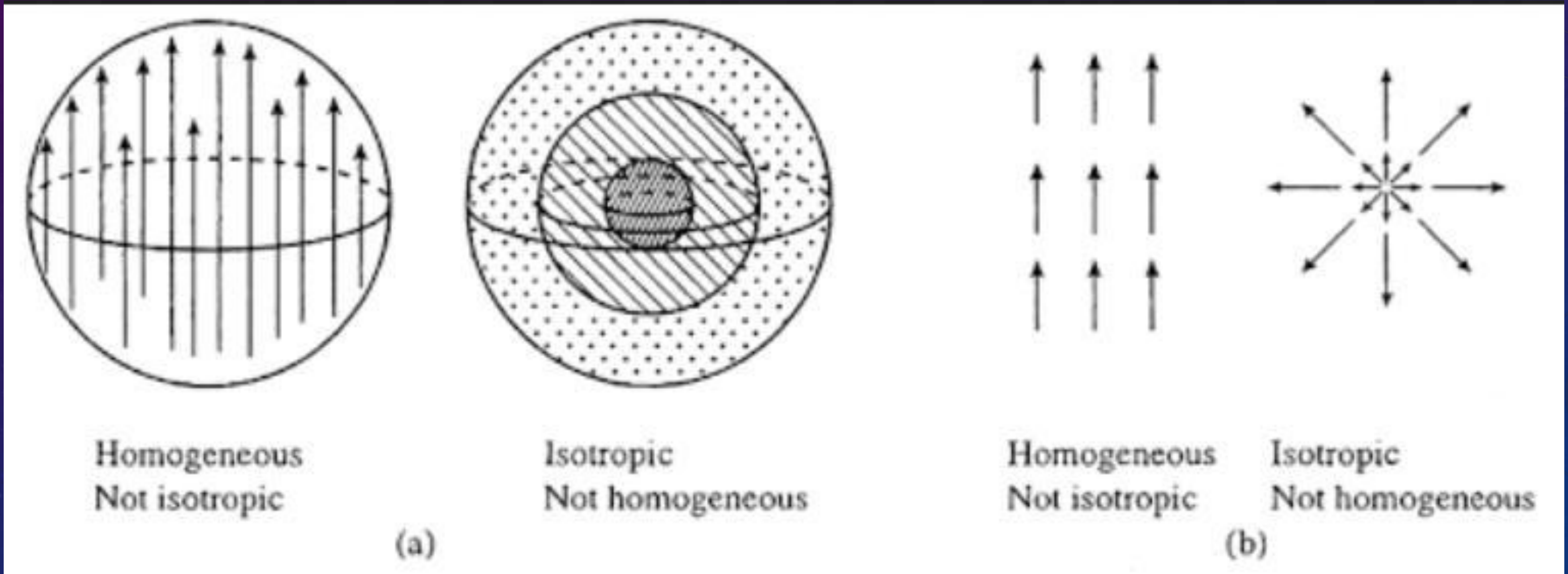
7. Nossos conhecimentos são totalmente insuficientes para conduzir cálculos numéricos e decidir qual é o nosso universo; é possível que o problema da causalidade e o problema da força centrífuga joguem luz sobre esta questão. Ainda se observa que a grandeza "cosmológica" λ que aparece nas nossas fórmulas permanece indefinida, uma vez que trata-se de uma constante excedente na tarefa; possivelmente considerações da eletrodinâmica podem levar à sua avaliação. Se usarmos $\lambda = 0$ e $M = 5 \, . \, 10^{21}$ massas solares, então o período do universo será da ordem de 10 bilhões de anos. Estes números podem apenas servir como uma ilustração da aplicação dos nossos cálculos.

Petrogrado, 29 de maio de 1922.

PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

The Copernican Principle: There should be no SPECIAL observers

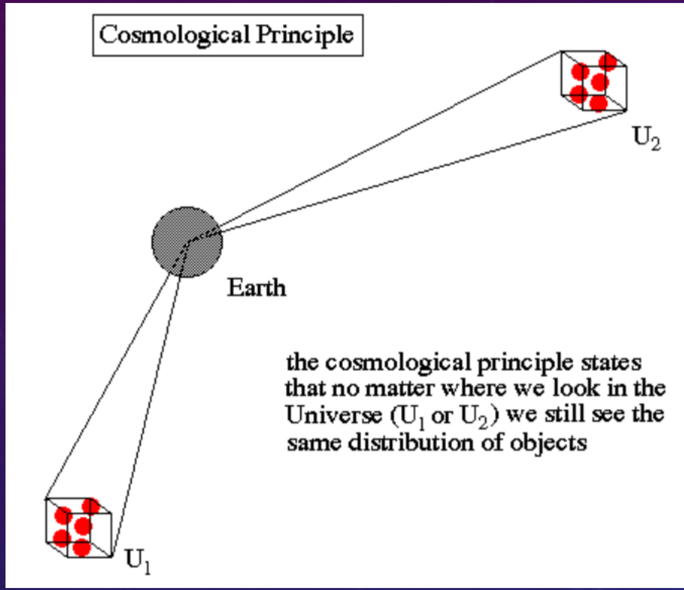
Homogeneity and isotropy: Extending the Copernican Principle to cosmology



PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

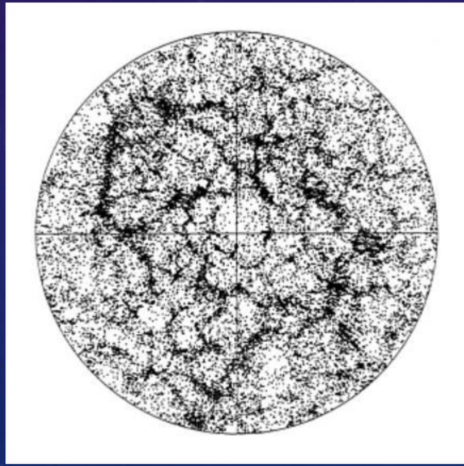
The cosmological principle:

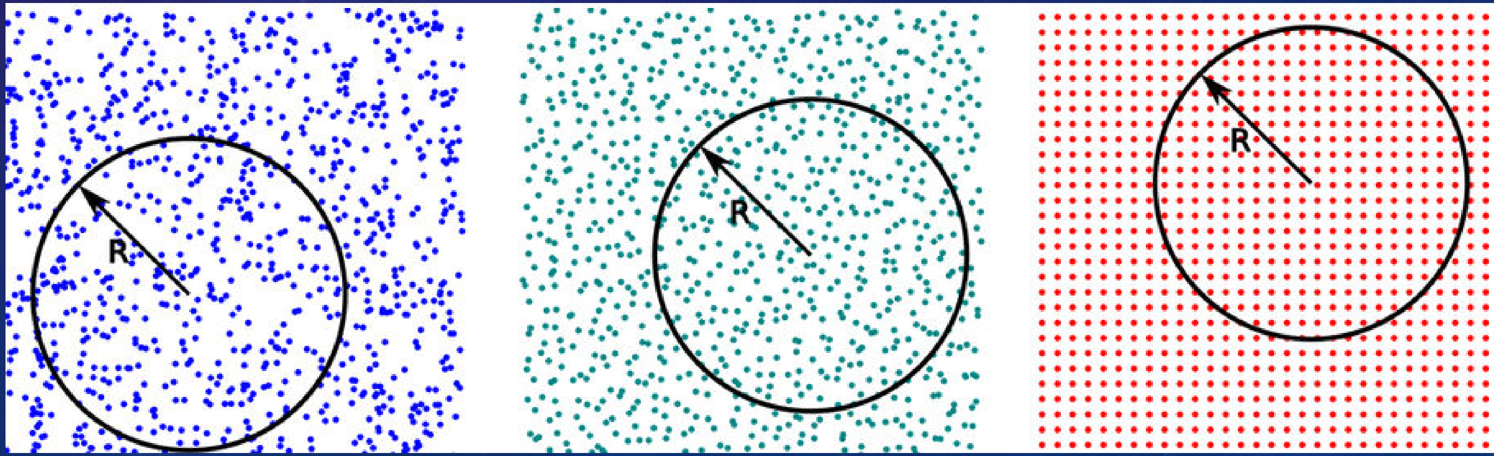
Derives from the CP but it can not be proved (in a mathematical sense).

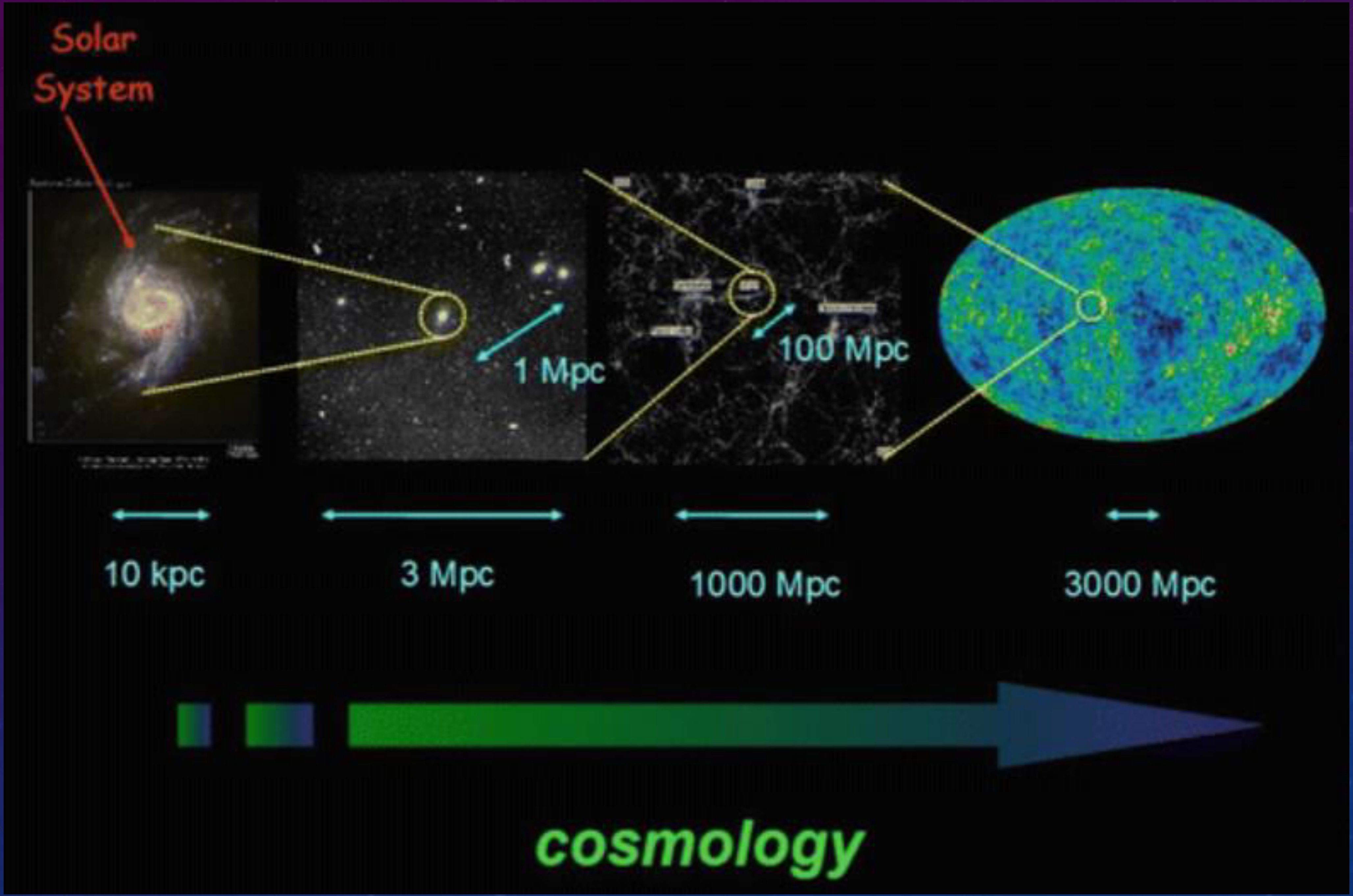


Corollary: The laws of physics are universal. The same physical laws and models that apply here on the Earth also work in distant stars, galaxies, and all parts of the Universe

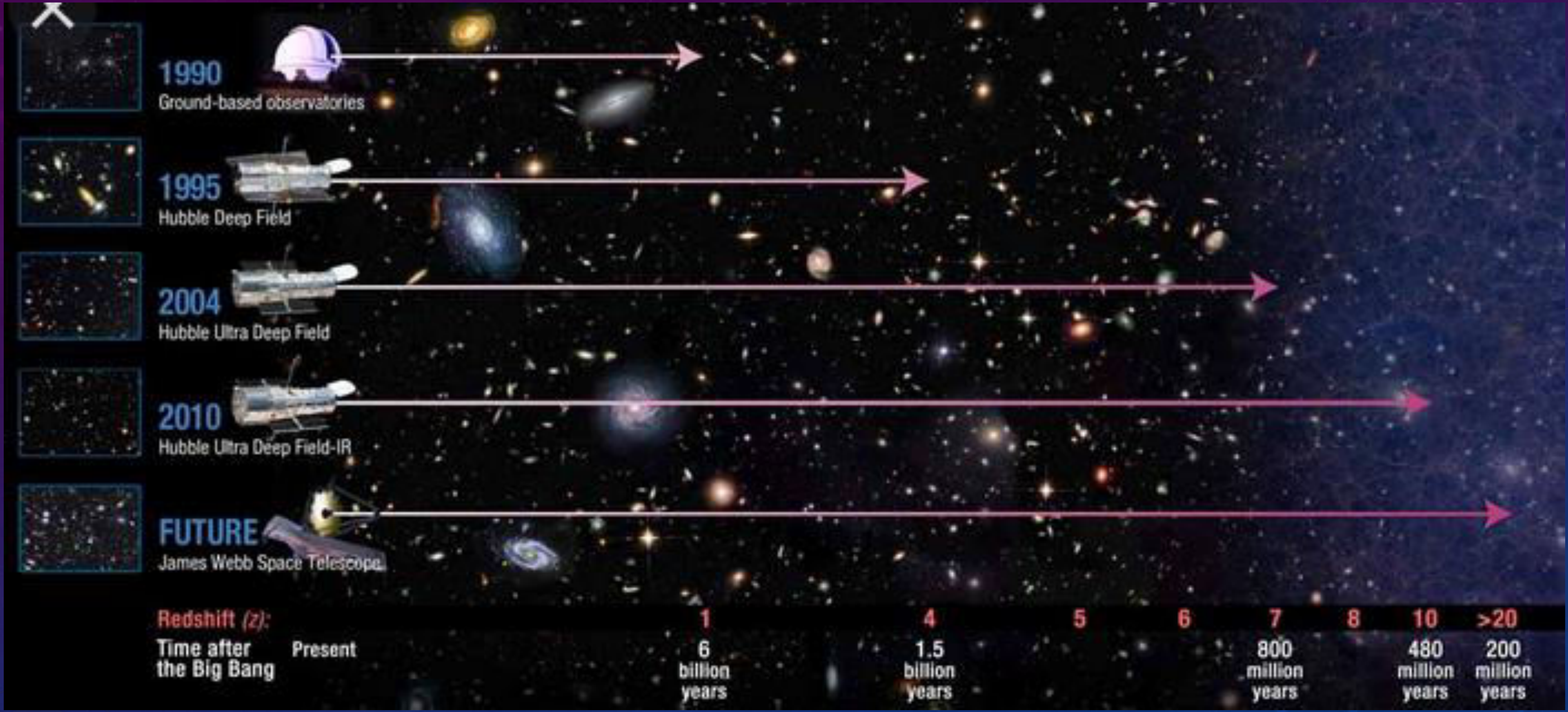
HUGE SIMPLIFICATION



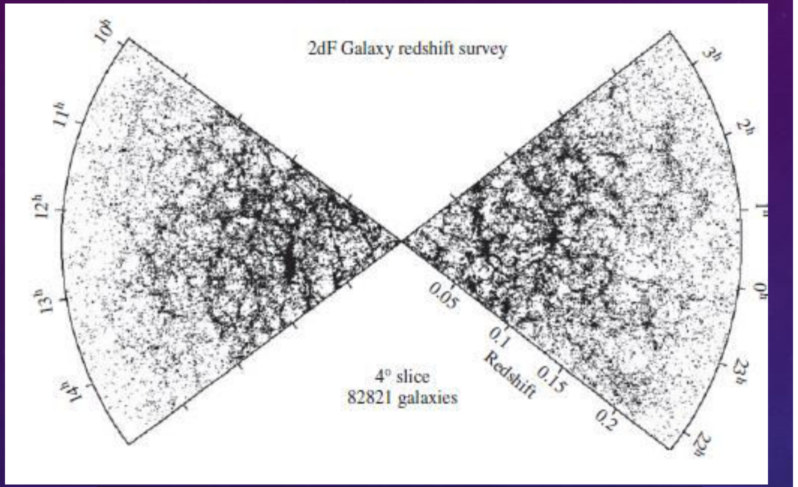


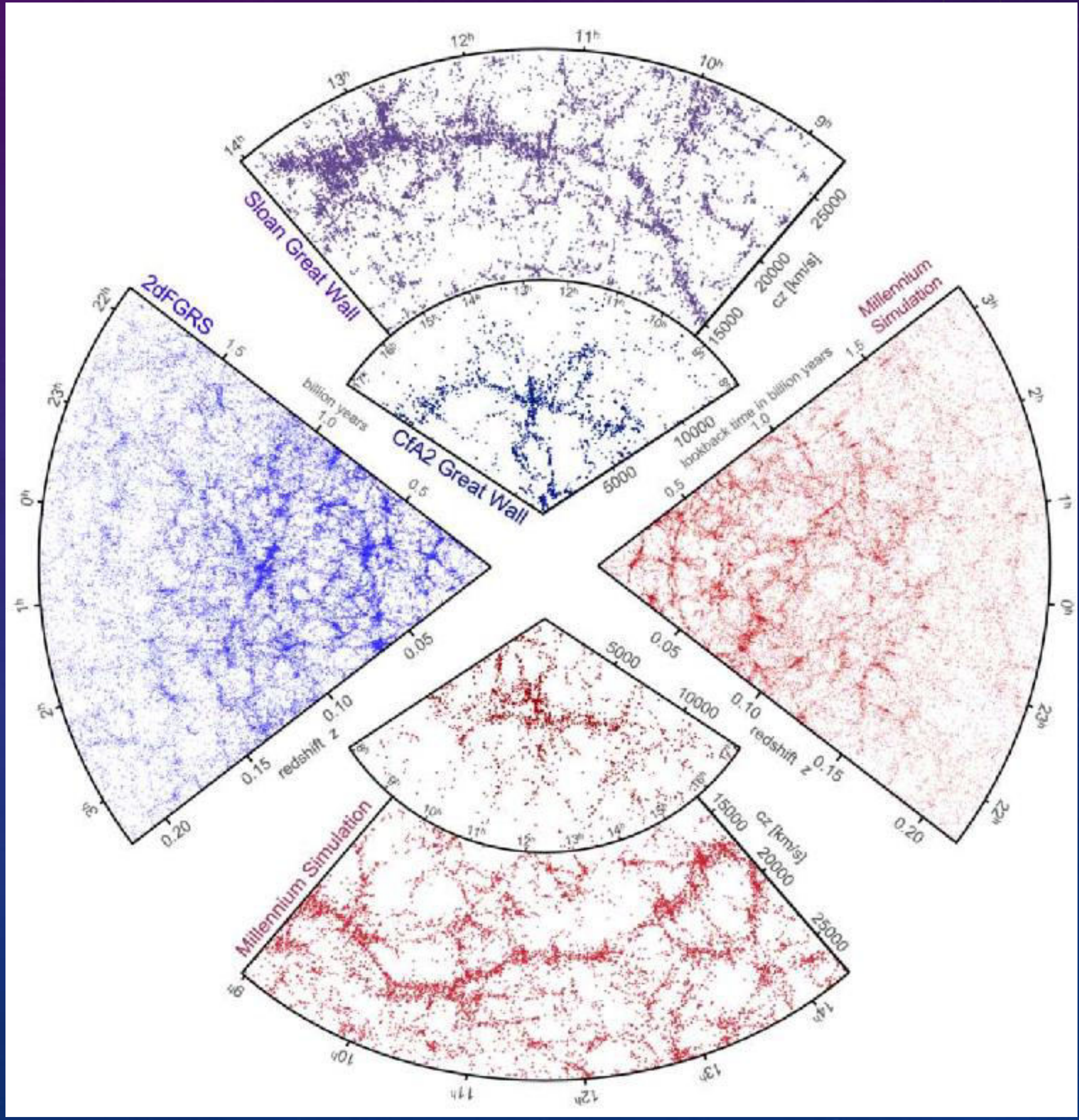


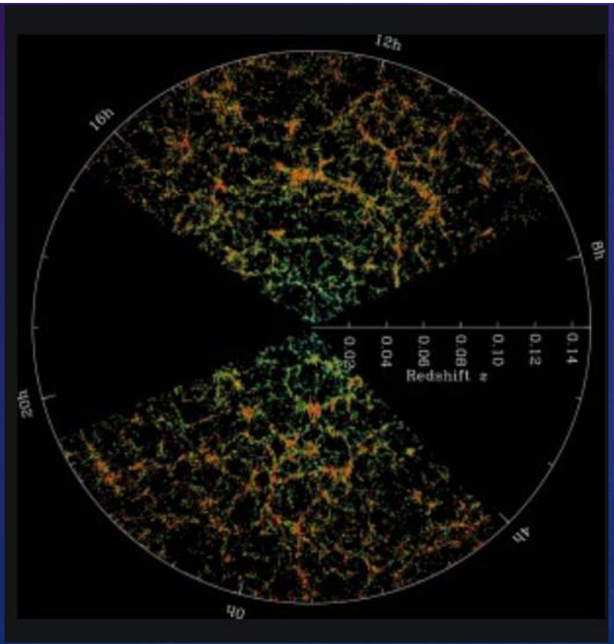
Solar System
1 Mpc
100 Mpc
10 kpc
3 Mpc
1000 Mpc
3000 Mpc
cosmology


1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

ESTRUTURA EM GRANDE ESCALA
LARGE SCALE STRUCTURE (LSS)

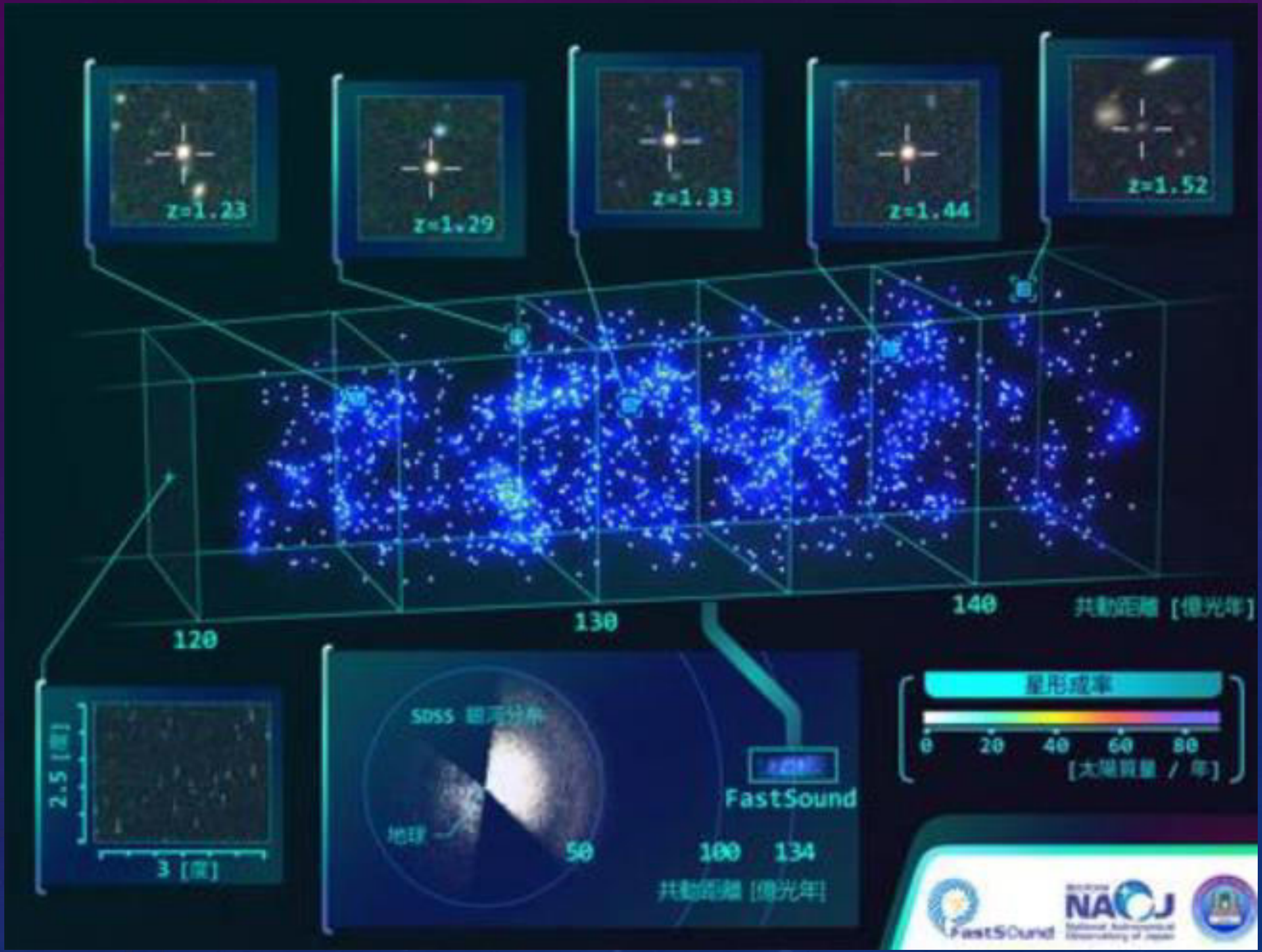


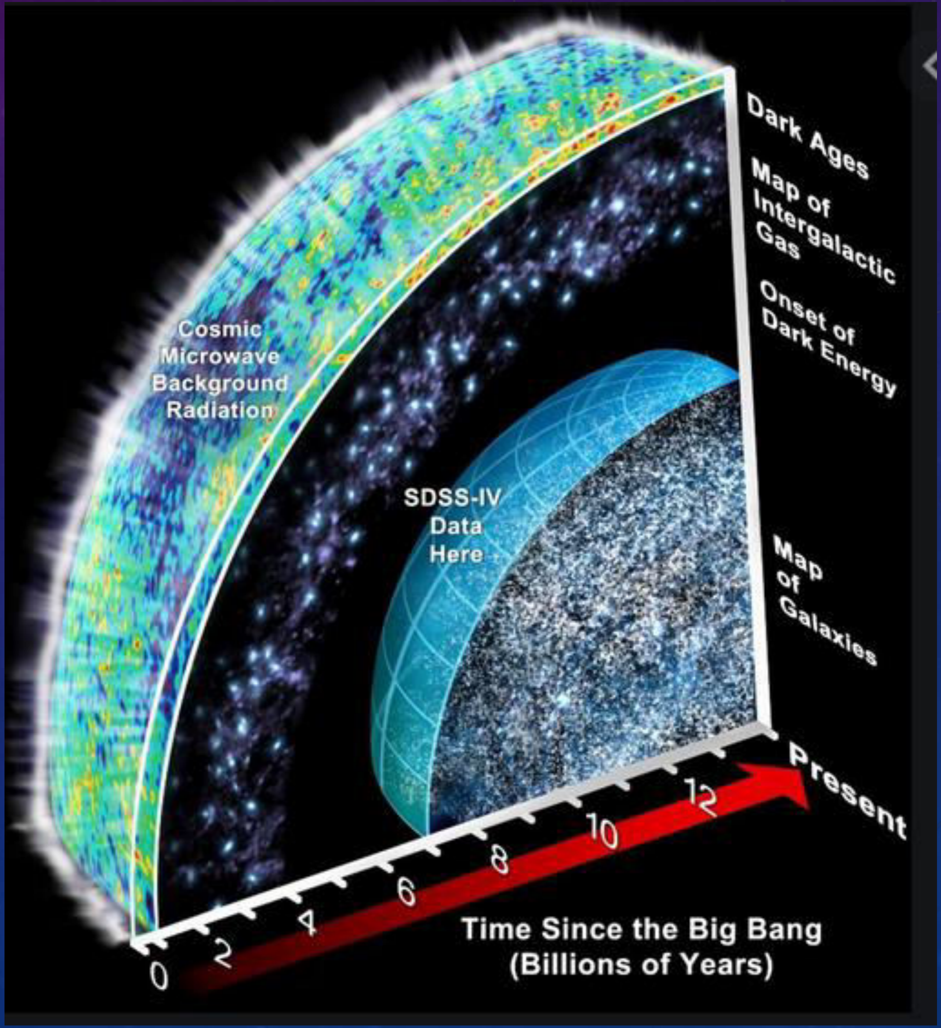




- https://www.youtube.com/watch?v=RAiPZ_oUPI4

GRANDES MAPEAMENTOS DE GALÁXIAS EM 3D





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

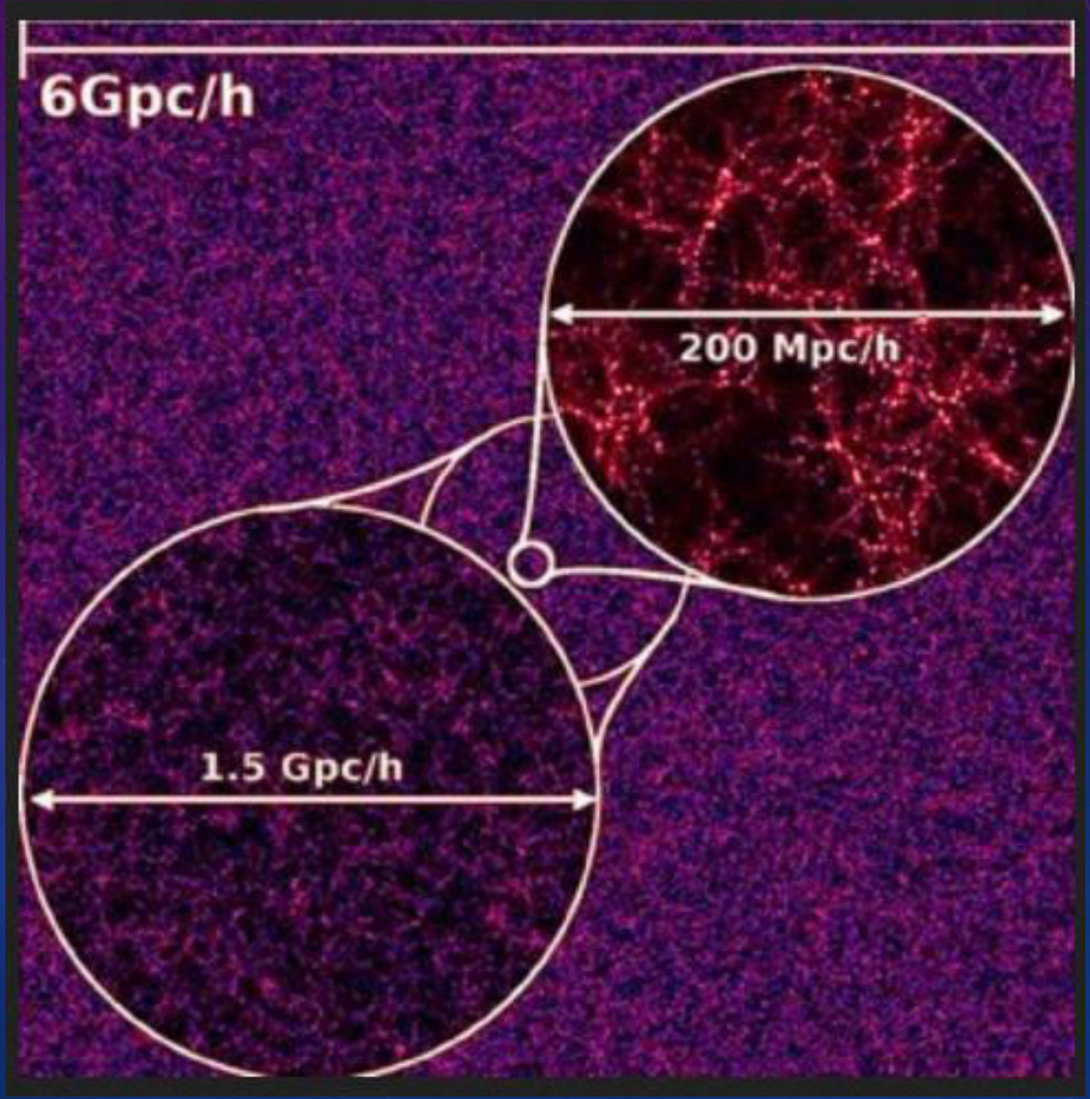
The fractal galaxy distribution

P.J.E. Peebles

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

Searching for the scale of homogeneity

Vicent J. Martínez,[1★] María-Jesús Pons-Bordería,[2★] Rana A. Moyeed[3★] and Matthew J. Graham[1,4★]
[1]*Departament d'Astronomia i Astrofísica, Universitat de València, E–46100 Burjassot, València, Spain*
[2]*Departamento de Física Teórica, Universidad Autónoma de Madrid, 28049 Cantoblanco, Madrid, Spain*
[3]*School of Mathematics and Statistics, University of Plymouth, Drake Circus, Plymouth PL4 8AA*
[4]*Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE*



PRINCÍPIO COSMOLÓGICO
VS
ESCALA DE HOMOGENEIDADE DO UNIVERSO

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

Roger G. Clowes,[1⋆] Kathryn A. Harris,[1] Srinivasan Raghunathan,[1,2†]
Luis E. Campusano,[2] Ilona K. Söchting[3] and Matthew J. Graham[4]
[1] *Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE*
[2] *Observatorio Astronómico Cerro Calán, Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*
[3] *Astrophysics, Denys Wilkinson Building, Keble Road, University of Oxford, Oxford OX1 3RH*
[4] *California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA*

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

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Largest structure challenges Einstein's smooth cosmos

SPACE 11 January 2013

By Jacob Aron

https://www.livescience.com/giant-arc-in-space.html

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Science News *from research organizations*

Biggest structure in universe: Large quasar group is 4 billion light years across

Date: January 11, 2013

Source: Royal Astronomical Society (RAS)

Summary: Astronomers have found the largest known structure in the universe. The large quasar

The Atlantic

TECHNOLOGY

The Largest Structure Ever Observed in the Universe

By Rebecca J. Rosen

JANUARY 14, 2013

SHARE

COSMOLOGICAL PRINCIPLE VS HOMOGENEITY SCALE IN THE UNIVERSE

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

Roger G. Clowes,[1⋆] Kathryn A. Harris,[1] Srinivasan Raghunathan,[1,2†]
Luis E. Campusano,[2] Ilona K. Söchting[3] and Matthew J. Graham[4]
[1] *Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE*
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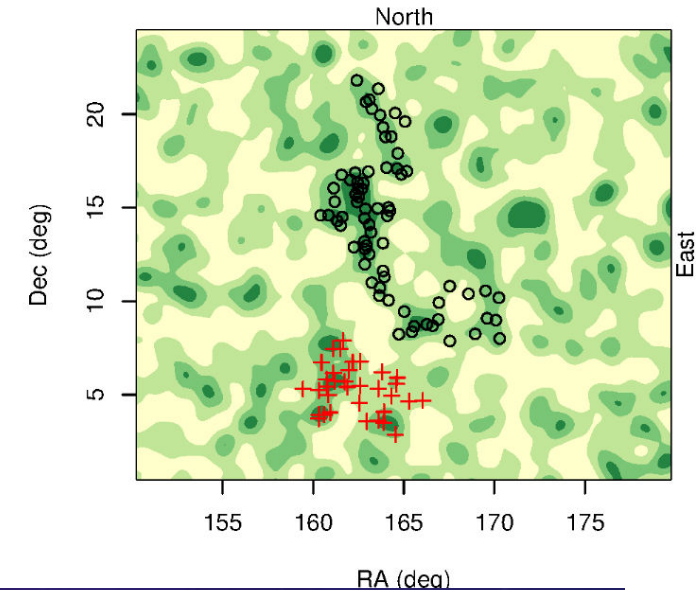
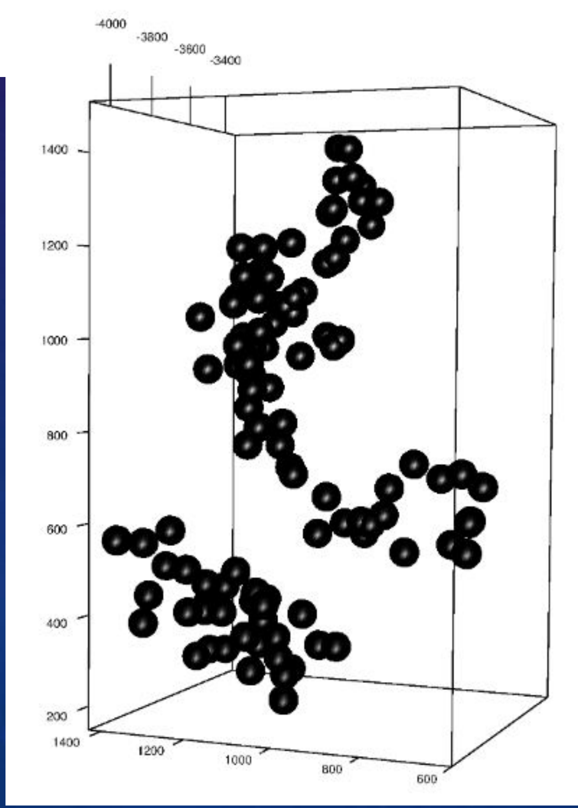
[3] *Astrophysics, Denys Wilkinson Building, Keble Road, University of Oxford, Oxford OX1 3RH*
[4] *California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA*

Clowes R. G., Harris K. A., Raghunathan S., Campusano L. E., Soechting 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 (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 $1.0 \leqslant z \leqslant 1.8$ of our current investigation. Its location on the sky is $\sim 8.8°$ 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 $\sim 2°$ (~ 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.



(STATISTISCAL) 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

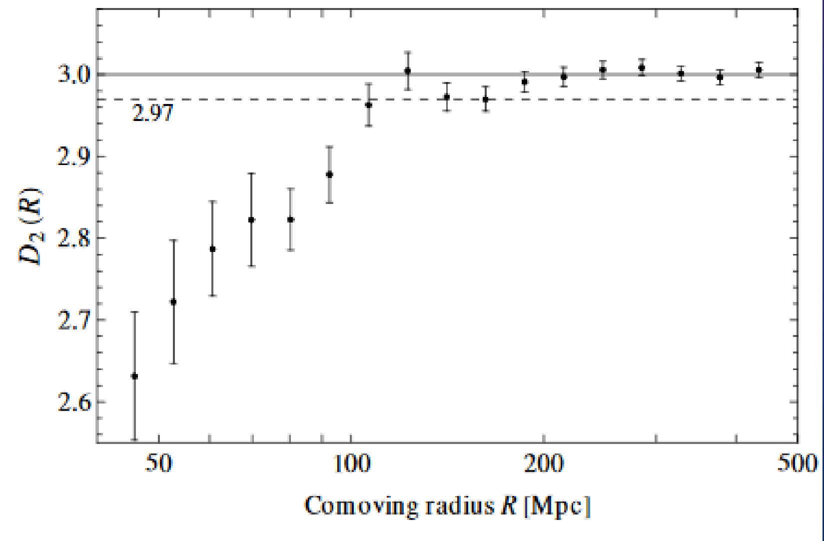
Seshadri Nadathur[1]

[1] *Fakultät für Physik, Universität Bielefeld, Postfach 100131, D-33501 Bielefeld, Germany*

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

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 ΛCDM. 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 ith member of the point set, with the requirement that the entire sphere lies within the distribution of points:

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

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

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

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

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

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

EXPANSION OF THE UNIVERSE (LEMAITRE-HUBBLE LAW)

Edwin Hubble (1889 - 1953)

First: the discovery of galaxies beyond the Milk Way

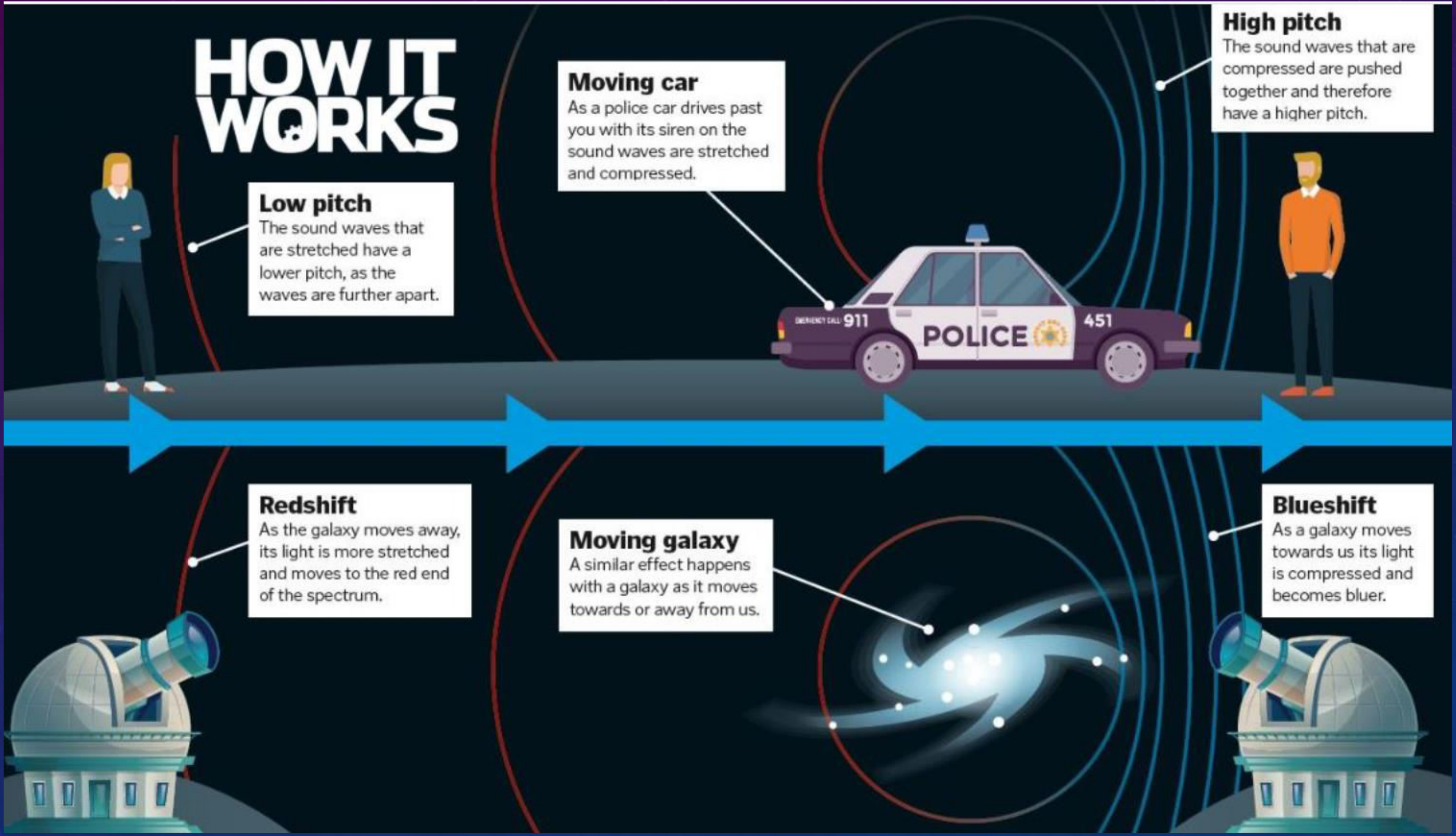
ANOTHER UNIVERSE SEEN BY ASTRONOMER

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

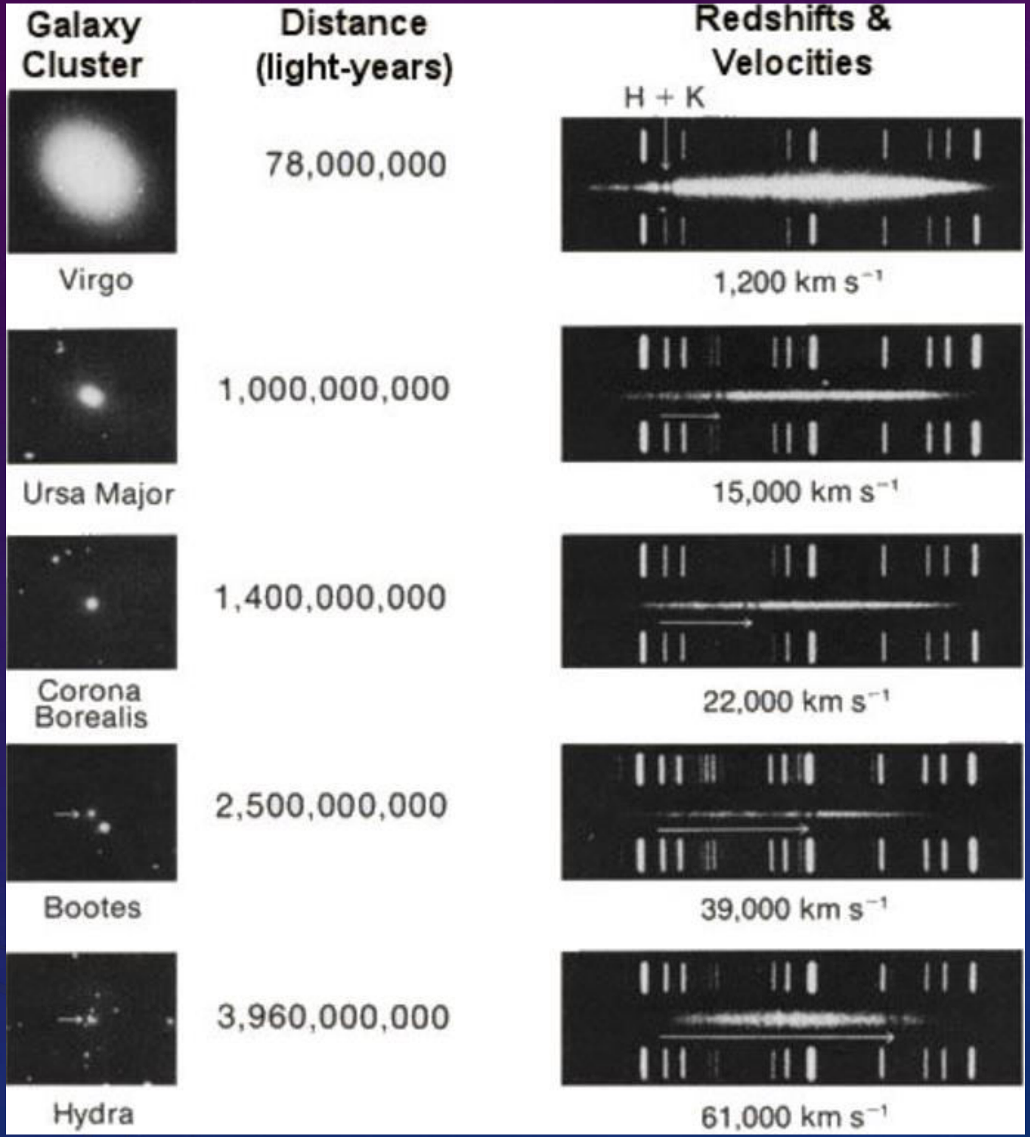
PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

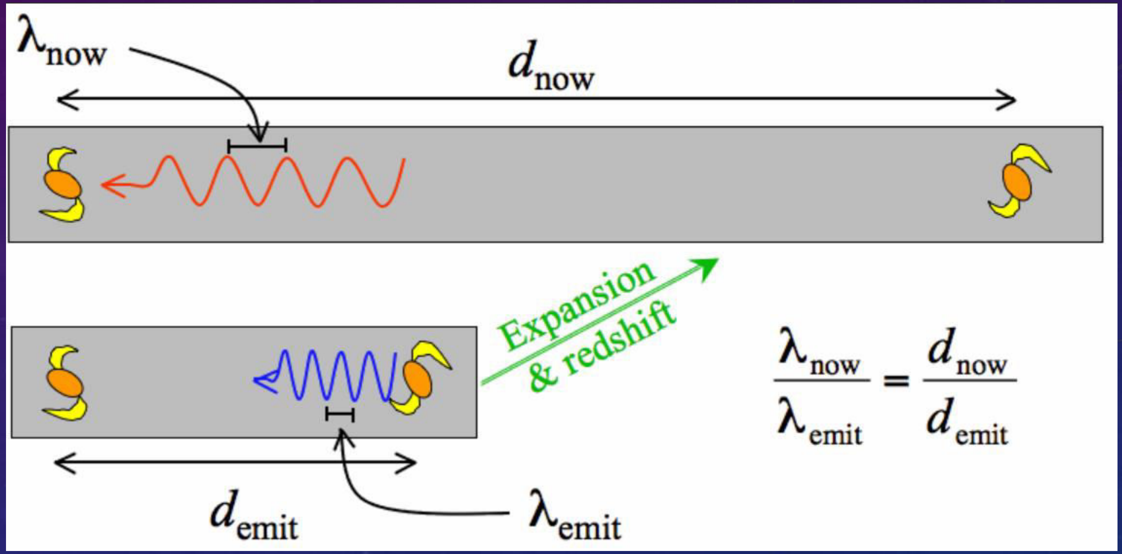
Redshift



PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Redshift is proportional to distance





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

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 Milk-way 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


September, 1922 — 37

Are There Other Universes than Ours?

Astounding New Theory Pictures Ours as a Mere Pinwheel among Millions of Other World-Groups

Astronomy's Photographic Masterpiece—A Spiral Nebula

Are spiral nebulae such as this, photographed from the Mount Wilson Observatory, merely gaseous whirlpools close to the borders of our universe, or is each nebula a separate universe of solar systems as vast as the billion-starred system of suns in which we dwell? Many astronomers now believe that our universe is but one of countless "island universes," thousands of light-years apart

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

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

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

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

From a discussion of available data, we adopt

$$\frac{R'}{R} = 0{\cdot}68 \times 10^{-27} \text{ cm.}^{-1} \quad . \quad . \quad . \quad (24)$$

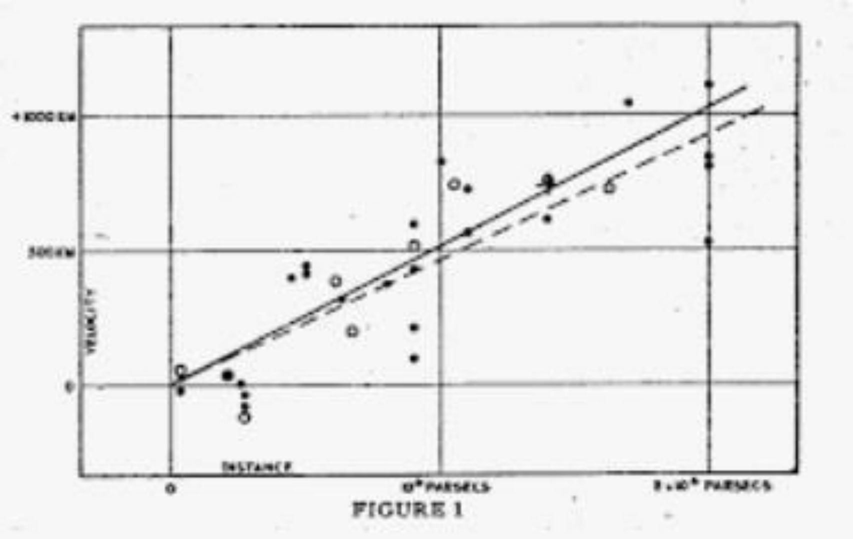
Text translated by Eddington

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 $\alpha = 315°$, $\delta = 62°$), 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

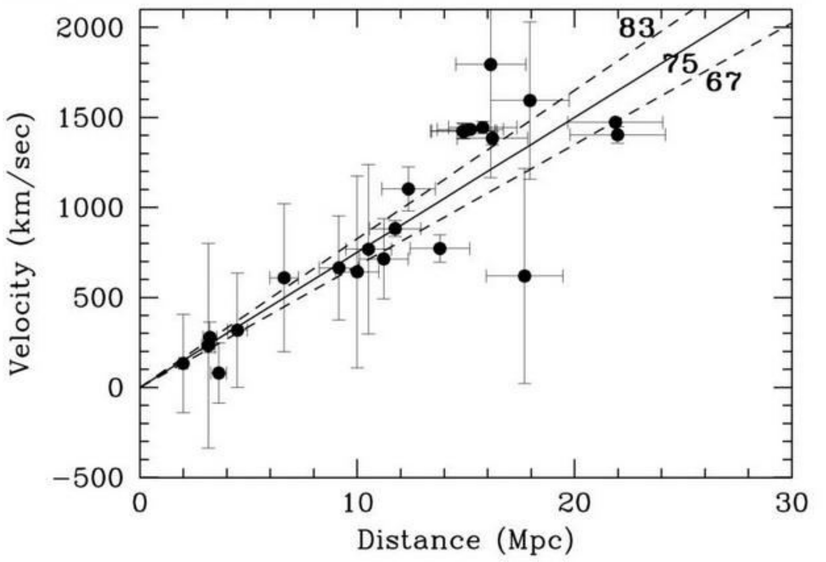
$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27} \text{ cm}^{-1} \quad (24)$$

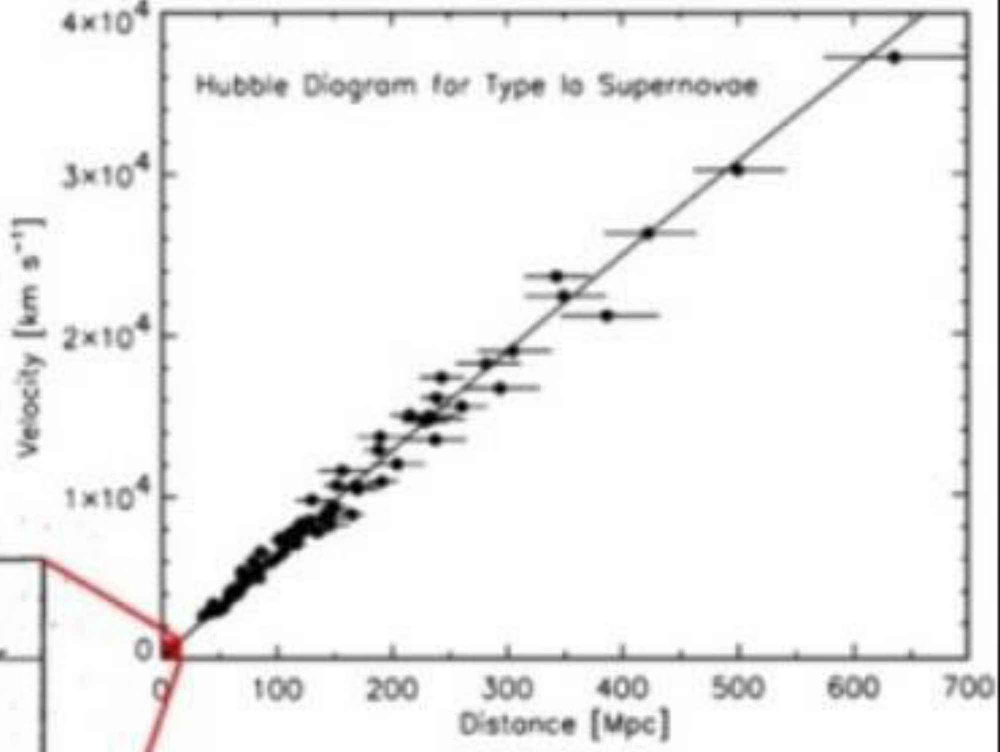
original ...

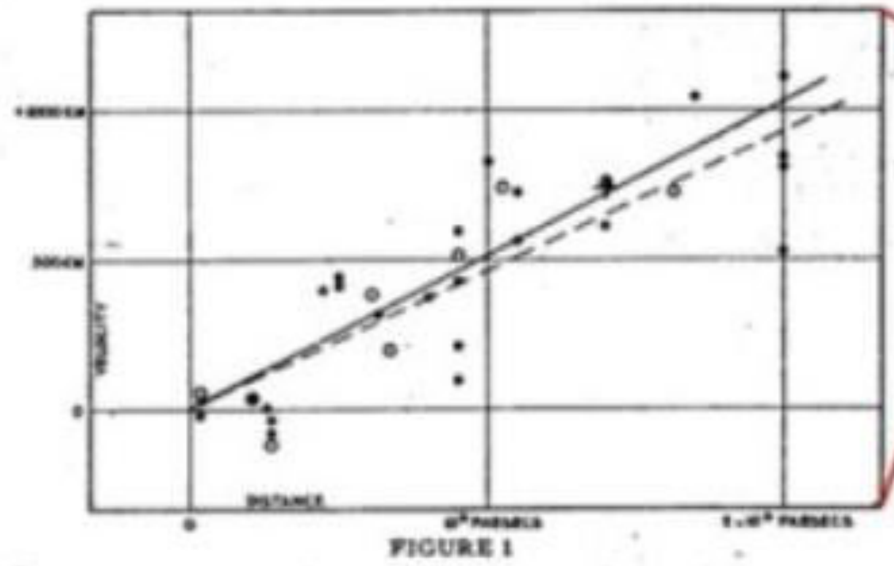


Edwin Hubble (left), Georges Lemaître (right)

Hubble's Law (modern data)







$$v = H_0 r$$

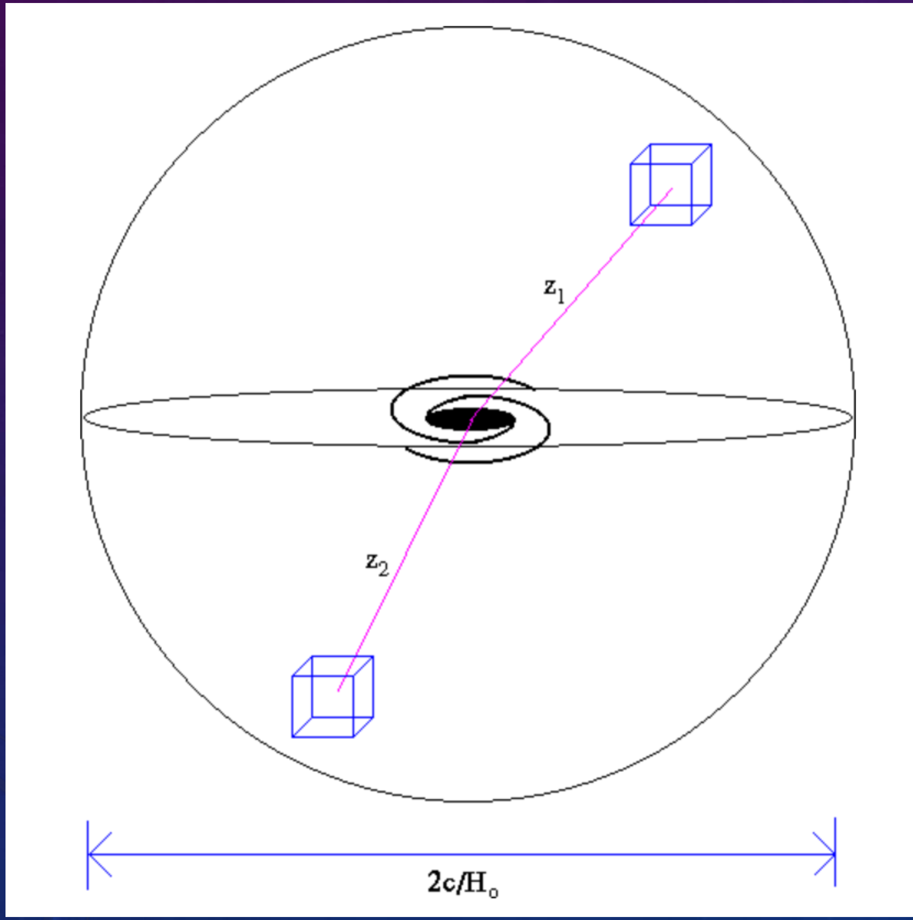
Hermano Velten

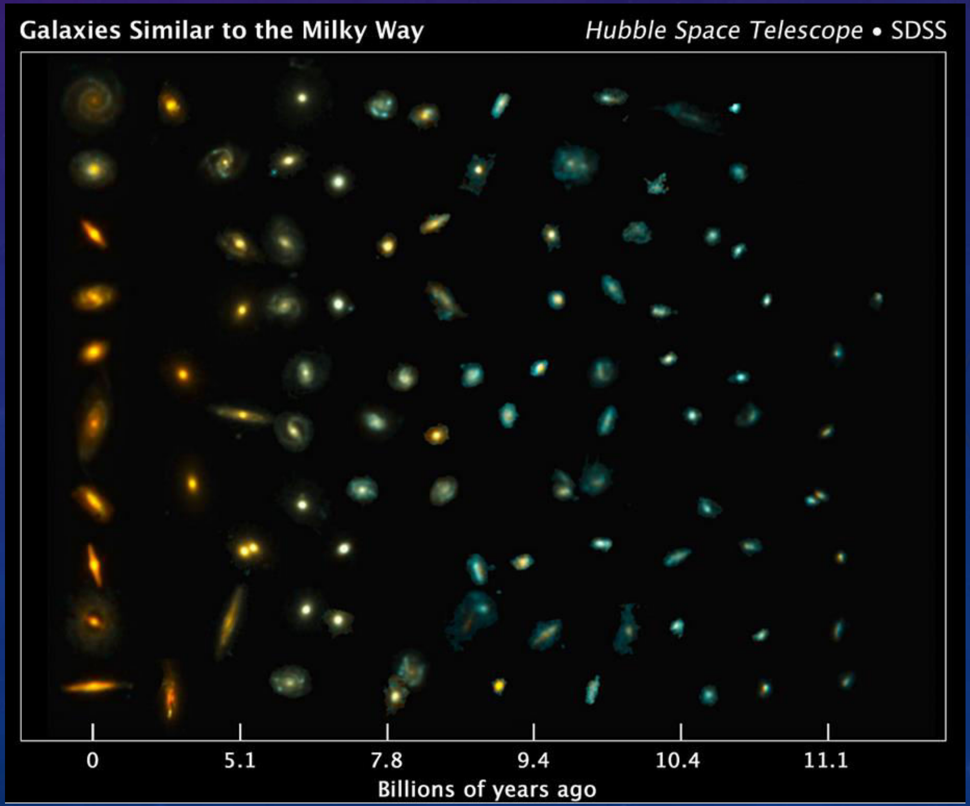
PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

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

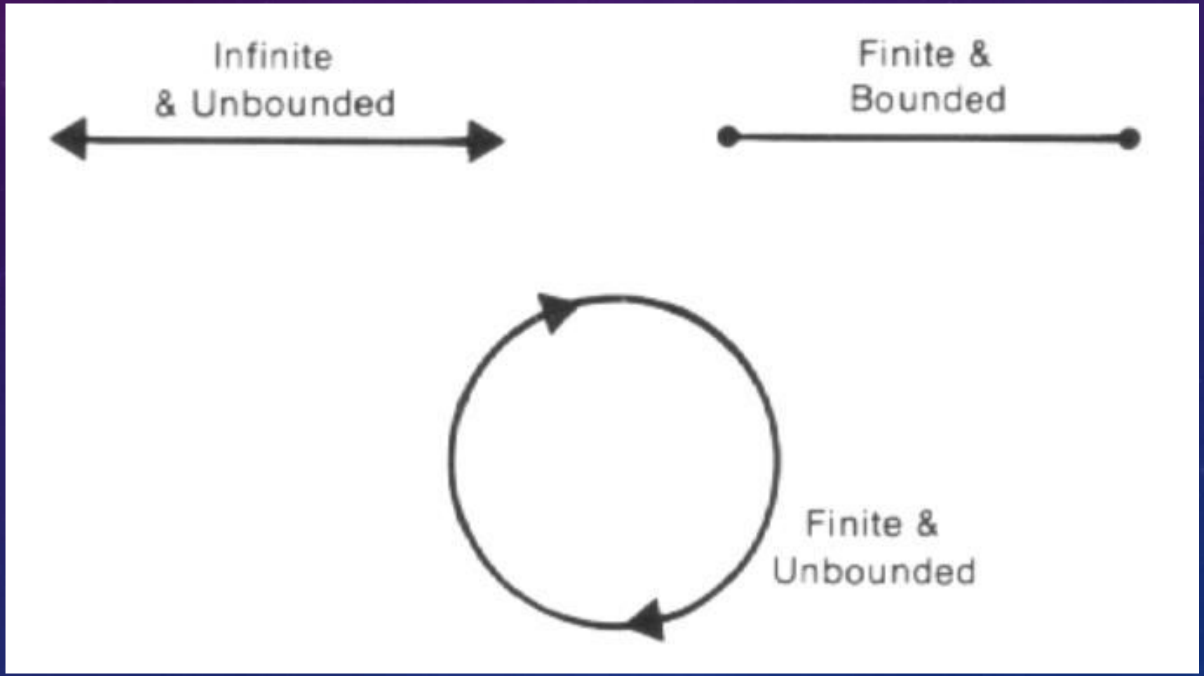




PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Cosmic Edge

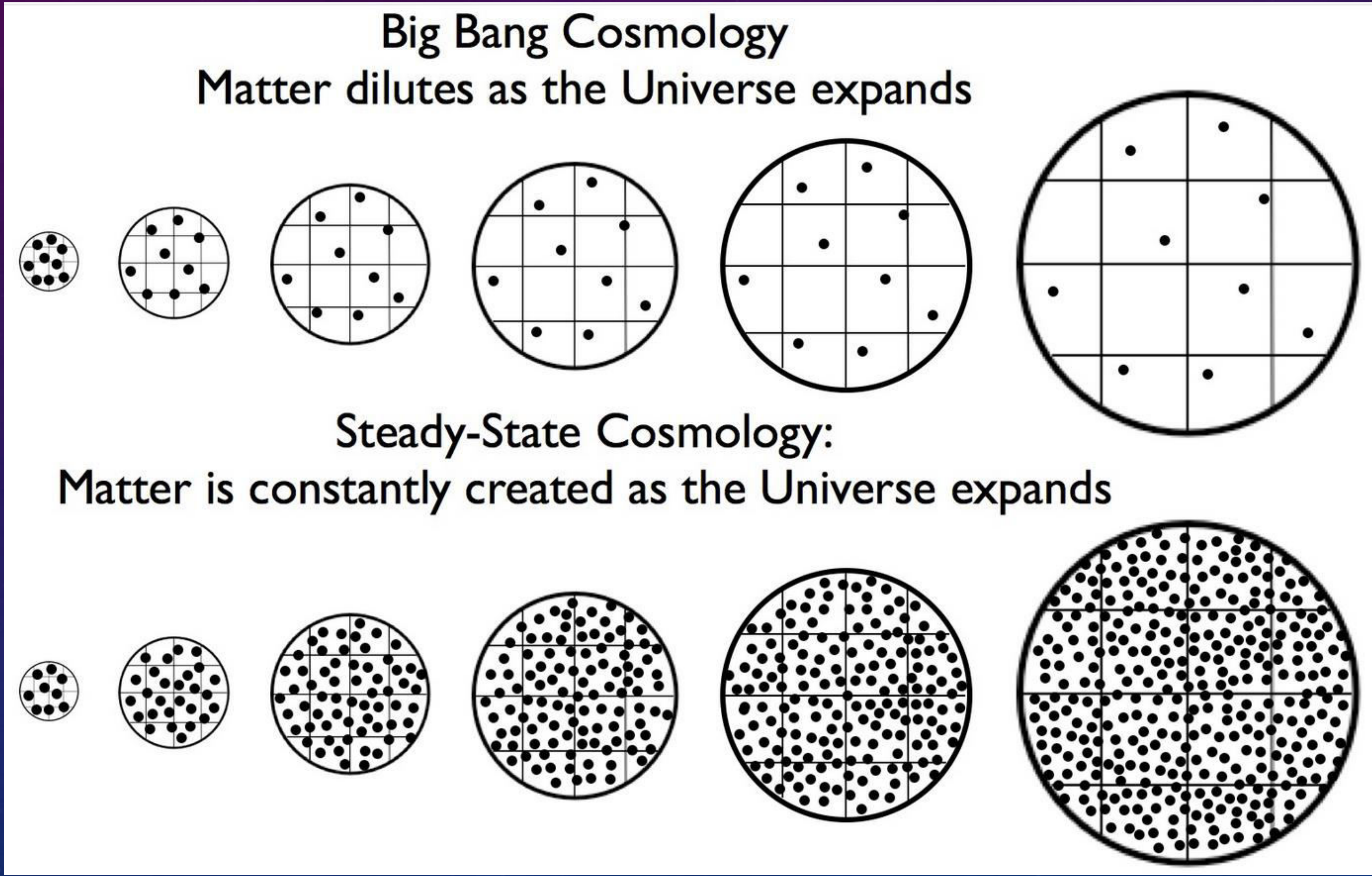
FAQ by students: Where is the border of the universe? What do we find beyond the border?
Answer: The Universe has to contain the properties of everything. Invoking an outside property of the Universe is logically inconsistent.



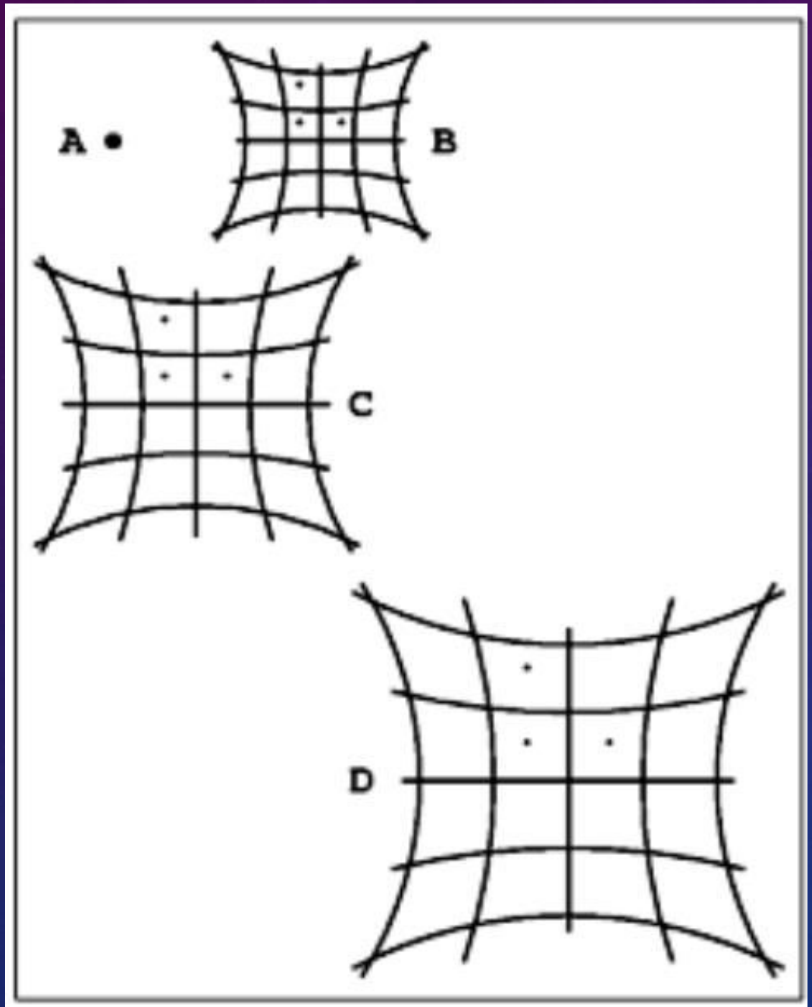
A corollary to this point is that the Universe must be boundless. This does not necessary mean that the Universe is infinite, although this is the simplest solution.

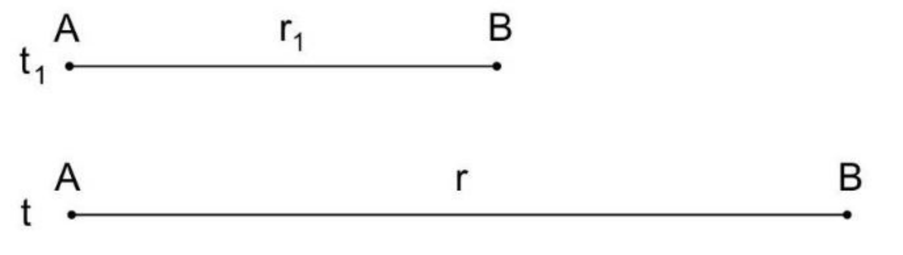
PRINCIPLES AND CONCEPTS USED IN COSMOLOGY

Expanding – diluting - universe



PARAMETERIZING THE EXPANDING UNIVERSE: THE SCALE FACTOR





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

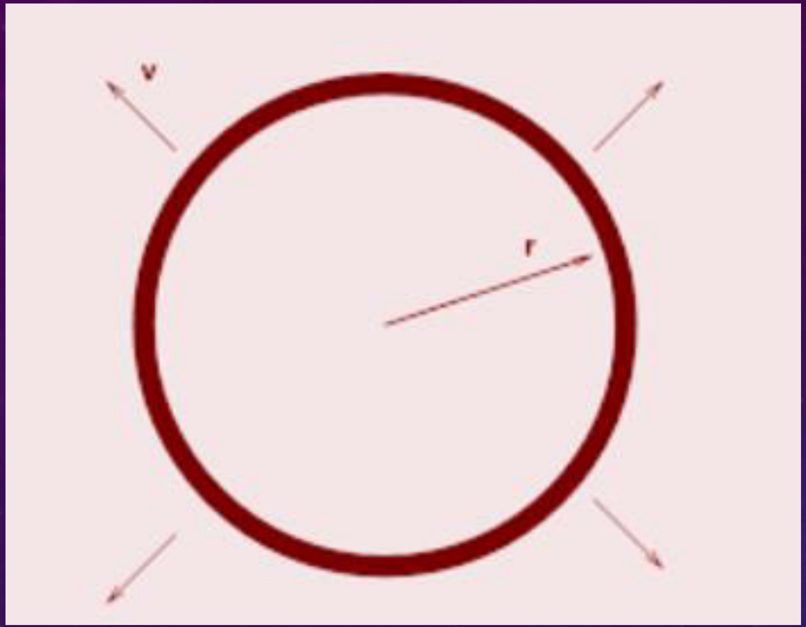
$$\mathbf{r} = \frac{R(t)}{R(t_1)} \mathbf{r}_1$$

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

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

http://www.astro.iag.usp.br/~laerte/form_ev_gal/cosmologia.pdf

UMA VISÃO NEWTONIANA PARA A COSMOLOGIA



$$E = \frac{1}{2}mv^2 - \frac{GMm}{r} = \text{constante}$$

$$\frac{v^2}{2} = \frac{GM}{r}$$

$$E = 0 \qquad v = (\dot{a}/a)r$$

$$\frac{H^2 r^2}{2} = \frac{G}{r}\rho_0 \frac{4}{3}\pi r^3$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho(t)a^2 - K$$

$$r = \frac{R(t)}{R_0} r_0 = a(t) r_0$$

$$\ddot{r} = \ddot{a}(t) r_0$$

$$\ddot{a} = -\frac{4\pi G}{3}\rho a$$

$$F = m\ddot{r} = -\frac{GmM(r)}{r^2} = -\frac{4\pi}{3}Gm\rho r$$

$$M(r) = \frac{4}{3}\pi r^3 \rho$$

EXERCÍCIO:

1: Energy continuity. Differentiate the first Friedmann equation to find

$$2\dot{a}/a(\ddot{a}/a - (\dot{a}/a)^2) = 8\pi G/3\dot{\rho} + 2K\dot{a}/a^3.$$

Use the first Friedmann equation again to get rid of K, and the second Friedmann equation to get rid of $\ddot{a}$, and it all reduces to

$$\dot{\rho} = -3(\rho + p)\frac{\dot{a}}{a}.$$

But this also comes from thermodynamics. If ρ is the energy per volume $= E/V$, we have

$$d\rho = dE/V - dV/V\rho$$

Then use that for adiabatic expansion (constant p), $dE = -pdV$ and that $dV/V = 3a^2da$, and we have

$$d\rho = -3(\rho + p)\frac{da}{a},$$

which is the same thing. Total energy is not conserved for the "gas", but it decreases as if it was an expanding gas, in accordance with thermodynamics. Note that for "matter", pressure p is zero, *total energy* is conserved, but the *energy density* decreases as a result of cosmological expansion.

AS COMPONENTES DO UNIVERSO DEVEM OBEDECER LEIS DE CONSERVAÇÃO DE MASSA/ENERGIA E MOMENTO

- Matéria sem pressão: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$
- Radiação/fótons e também neutrinos (!) $$P = \frac{\rho c^2}{3}$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{P}{c^2}\right) = 0$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}\rho = 0 \quad \Rightarrow \frac{1}{a^3}\frac{\partial}{\partial t}\left(\rho a^3\right) = 0 \quad \Rightarrow \rho \propto a^{-3}$$

$$\dot{\rho} + 4\frac{\dot{a}}{a}\rho = 0 \quad \Rightarrow \frac{1}{a^4}\frac{\partial}{\partial t}\left(\rho a^4\right) = 0 \quad \Rightarrow \rho \propto a^{-4}$$

acceleration

gravity

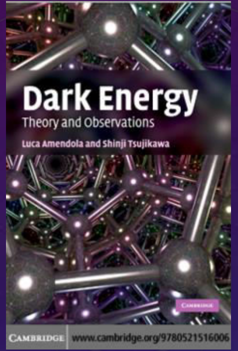
cosmological constant

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

slows down expansion

speeds up expansion

MODELLING THE EXPANDING UNIVERSE



The metric of an expanding space

Jargon: FLRW metric

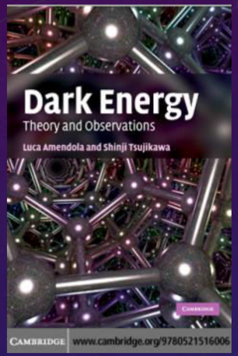
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a^2(t) d\sigma^2$$

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

$K = +1, -1, 0$ (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:

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

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

$$\frac{\partial T^{\mu}{}_{0}}{\partial x^{\mu}} + \Gamma^{\mu}{}_{\alpha\mu} T^{\alpha}{}_{0} - \Gamma^{\alpha}{}_{0\mu} T^{\mu}{}_{\alpha} = 0\,.$$

Conservation is assumed!

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

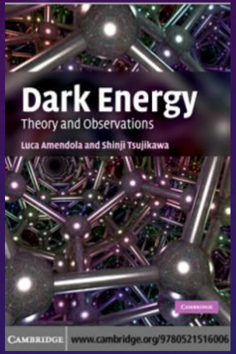
EOS

Equation of state parameter

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

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

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

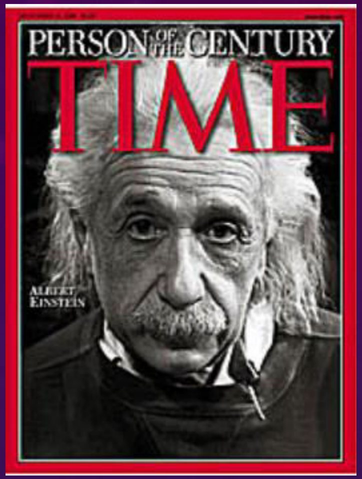
$$\rho = \begin{cases} (\pi^2/30) g_* T^4 , & \text{(Bosons)} \\ (7/8)(\pi^2/30) g_* T^4 , & \text{(Fermions)} \end{cases}$$

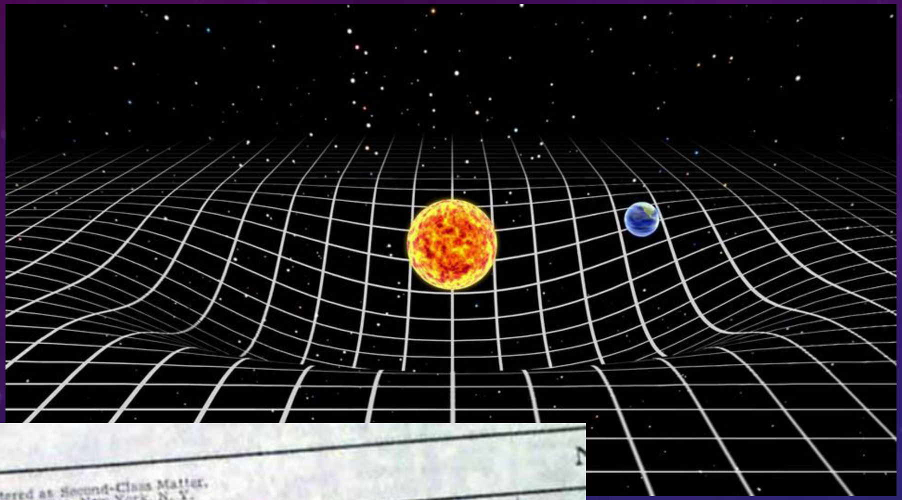
$$P = \rho/3 ,$$

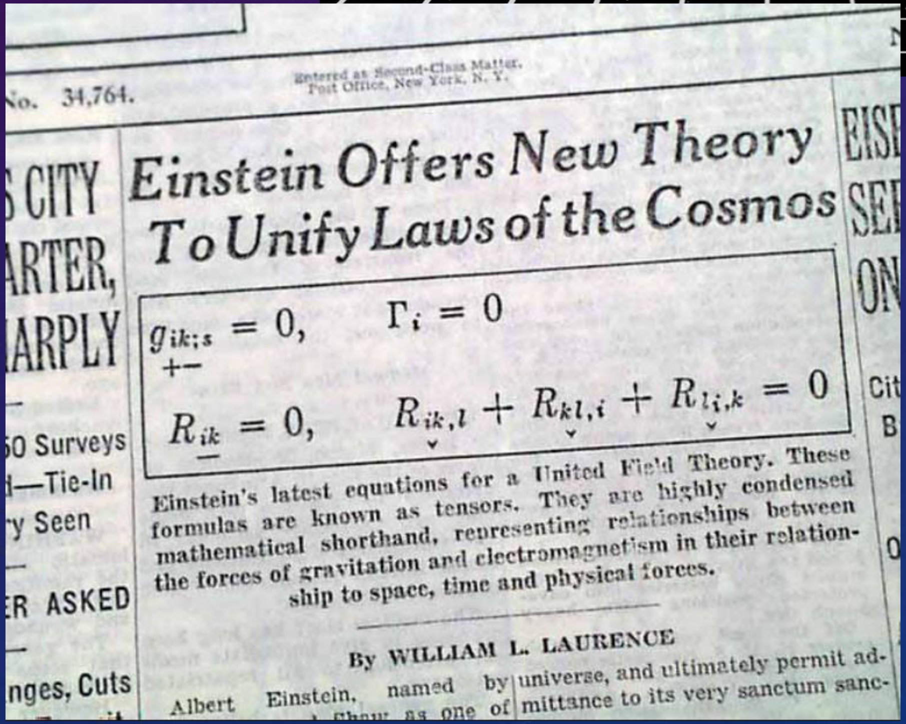
Dominant component	w	ρ	P	T
matter	0	a^{-3}	a^{-5}	a^{-2}
radiation	$1/3$	a^{-4}	a^{-4}	a^{-1}
vacuum energy	-1	a^0	a^0	

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

GENERAL RELATIVITY







No. 34,764.

Entered as Second-Class Matter, Post Office, New York, N. Y.

Einstein Offers New Theory To Unify Laws of the Cosmos

$$g_{ik;s} = 0, \qquad \Gamma_i = 0$$

$$R_{ik} = 0, \qquad R_{ik,l} + R_{kl,i} + R_{li,k} = 0$$

Einstein's latest equations for a Unified Field Theory. These formulas are known as tensors. They are highly condensed mathematical shorthand, representing relationships between the forces of gravitation and electromagnetism in their relationship to space, time and physical forces.

By WILLIAM L. LAURENCE

Albert Einstein, named by ... as one of ... universe, and ultimately permit admittance to its very sanctum sanc-

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

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

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

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 Príncipe and Brazil to photograph stars near the sun during a total eclipse. The results confirmed the predictions of GR.

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.

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.

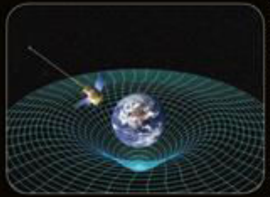
1979 Gravity's lens

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.

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.

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.

2016-2018 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.

2017-2020 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.

2025-2035 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.

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

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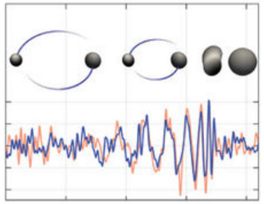


On the Cover

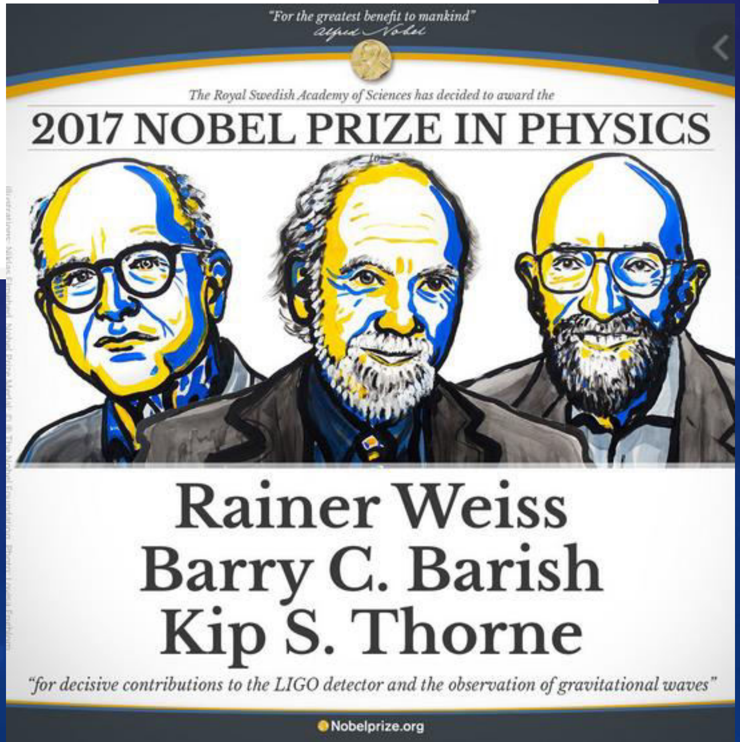
First direct detection of gravitational waves by the LIGO Hanford (Livingston) detectors in red (blue) from the inspiral of two large black holes. Selected for an Editors' Suggestion and a Viewpoint in *Physics*.

From the article:

Observation of Gravitational Waves from a Binary Black Hole Merger

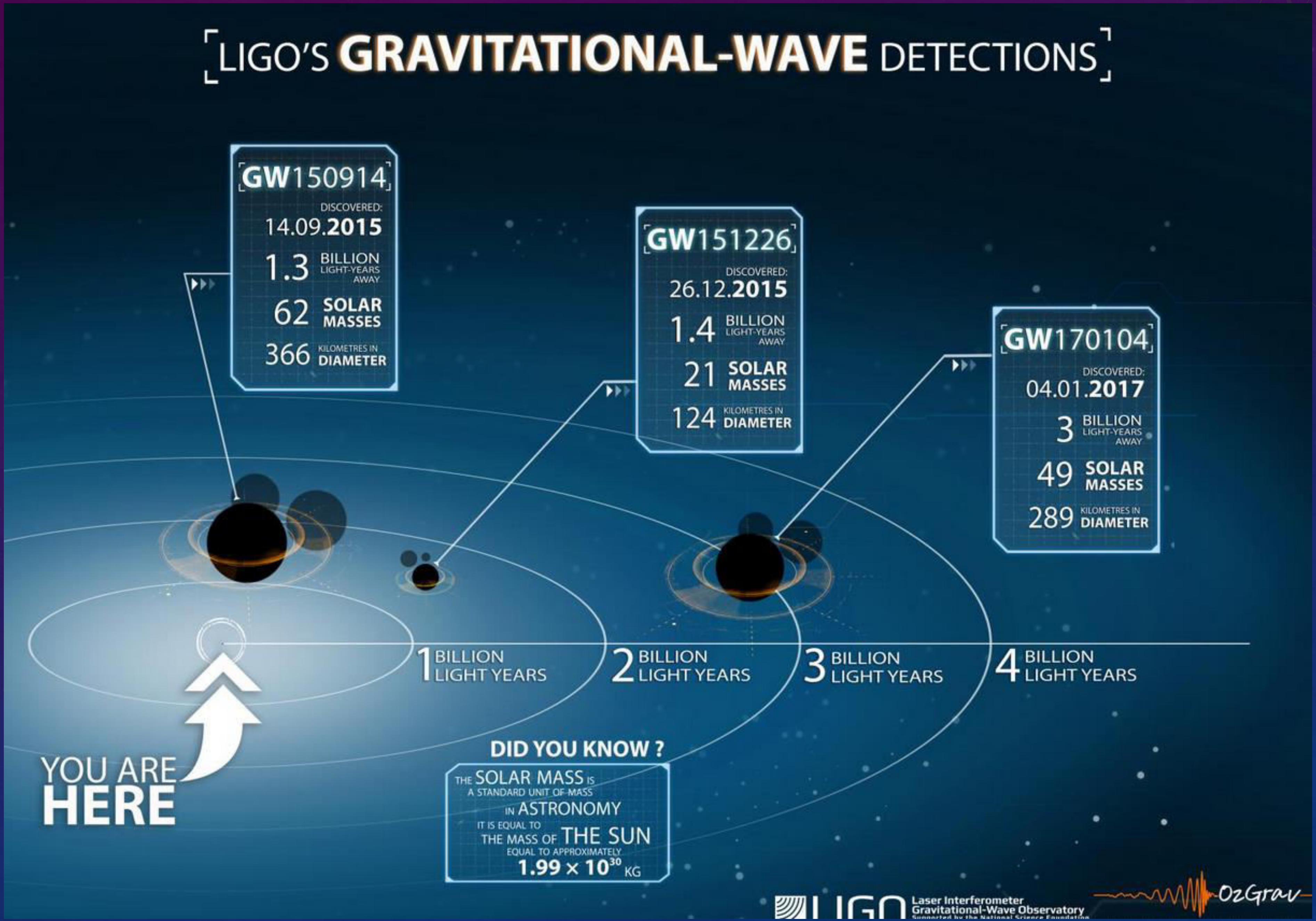
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

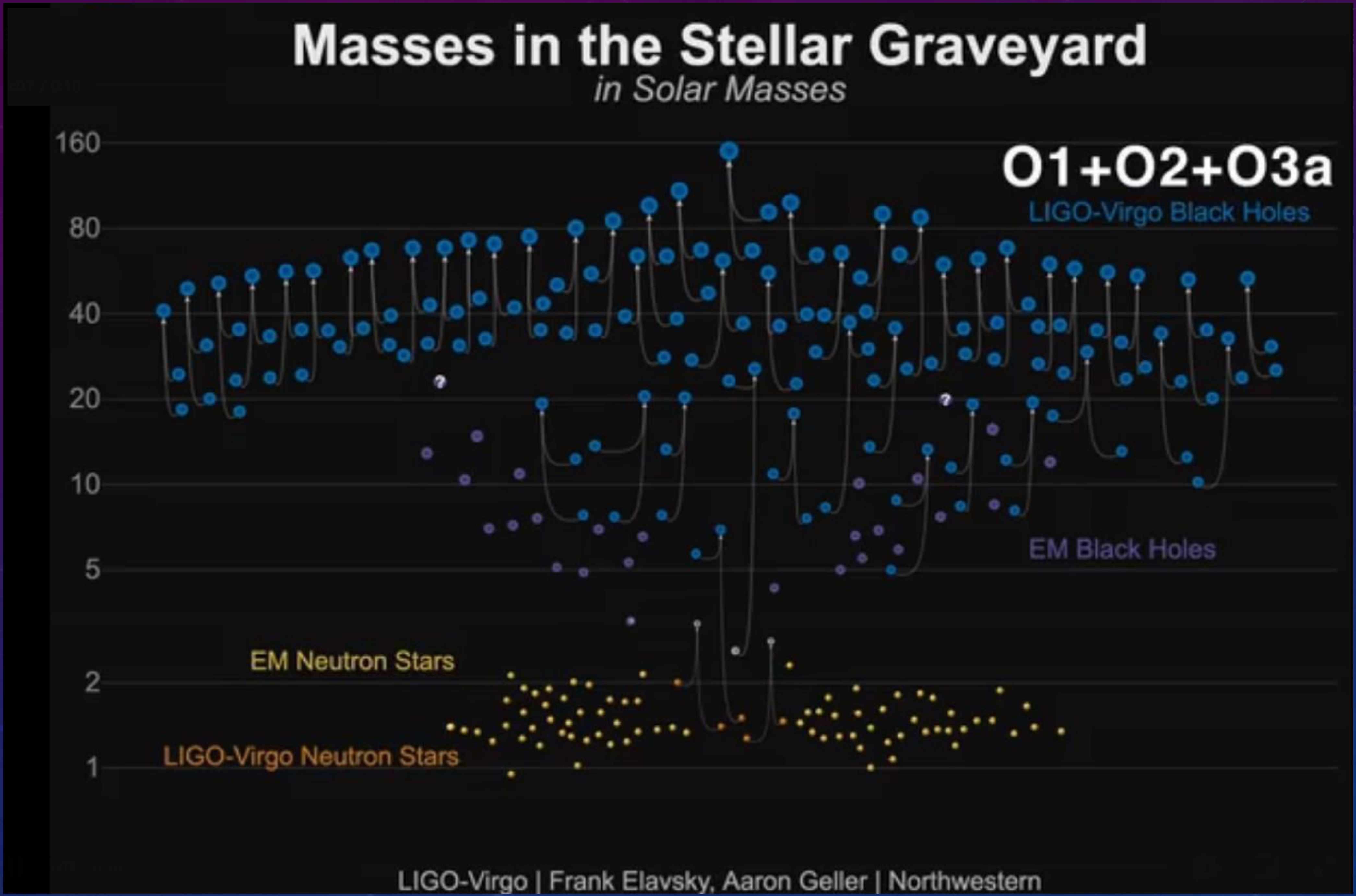
Phys. Rev. Lett. **116**, 061102 (2016)



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

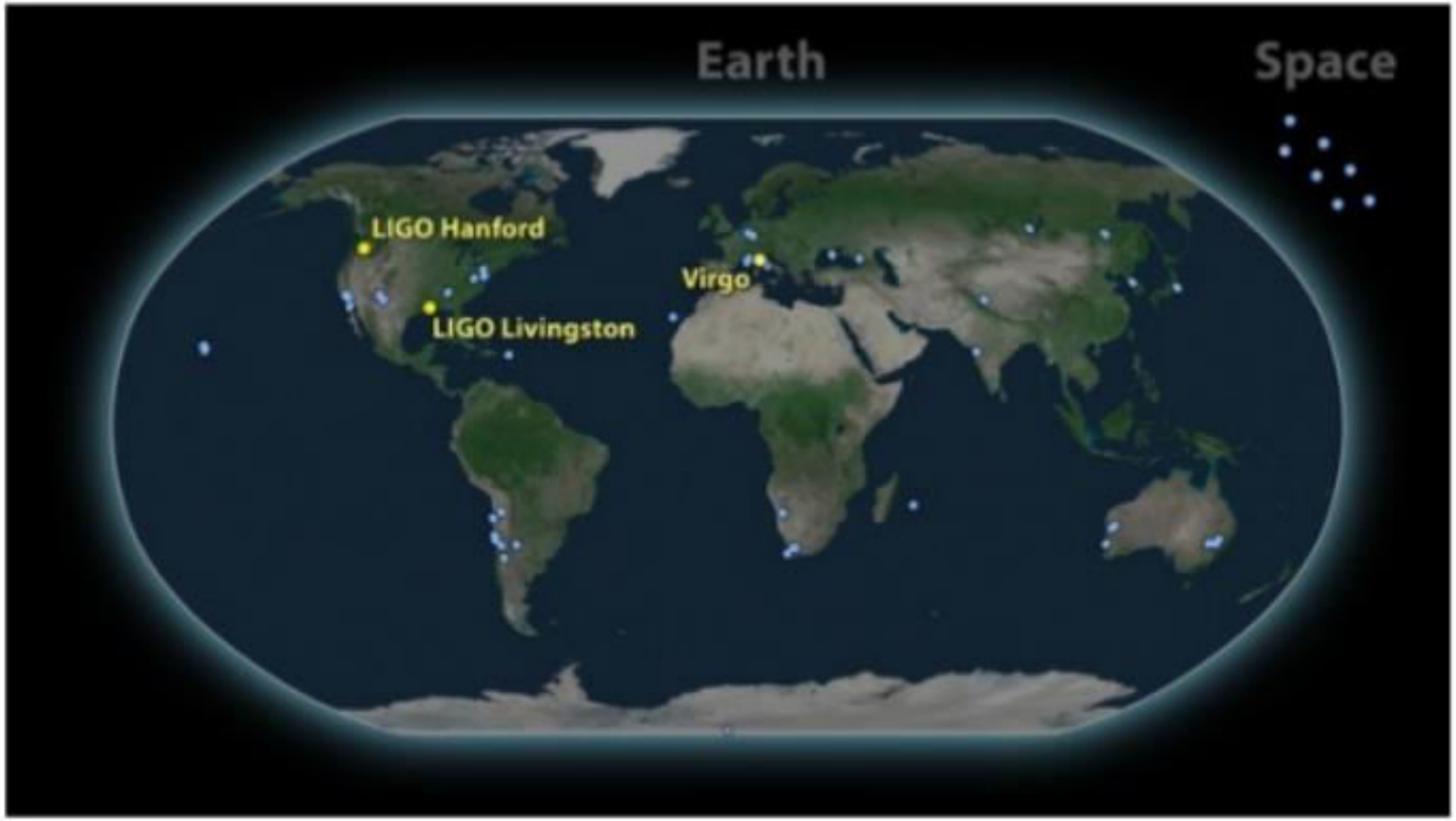
Aerial views showing the locations and extents of the LIGO Hanford and LIGO Livingston interferometers.


LIGO'S GRAVITATIONAL-WAVE DETECTIONS
GW150914
DISCOVERED: 14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
366 KILOMETRES IN DIAMETER
GW151226
DISCOVERED: 26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
124 KILOMETRES IN DIAMETER
GW170104
DISCOVERED: 04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
289 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY 1.99 × 10^30 KG
LIGO Laser Interferometer Gravitational-Wave Observatory
OzGrav

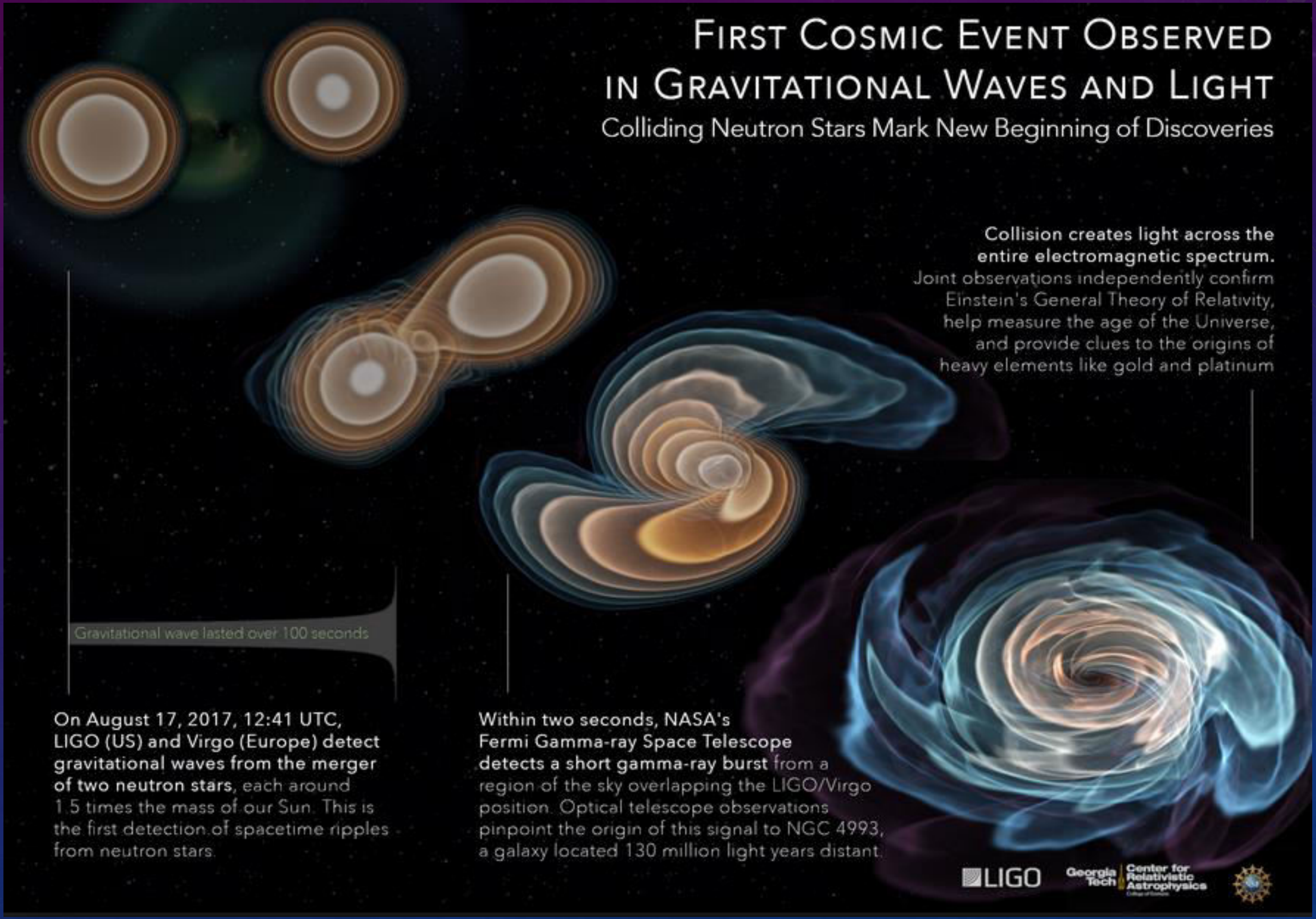


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
O1+O2+O3a
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW170817

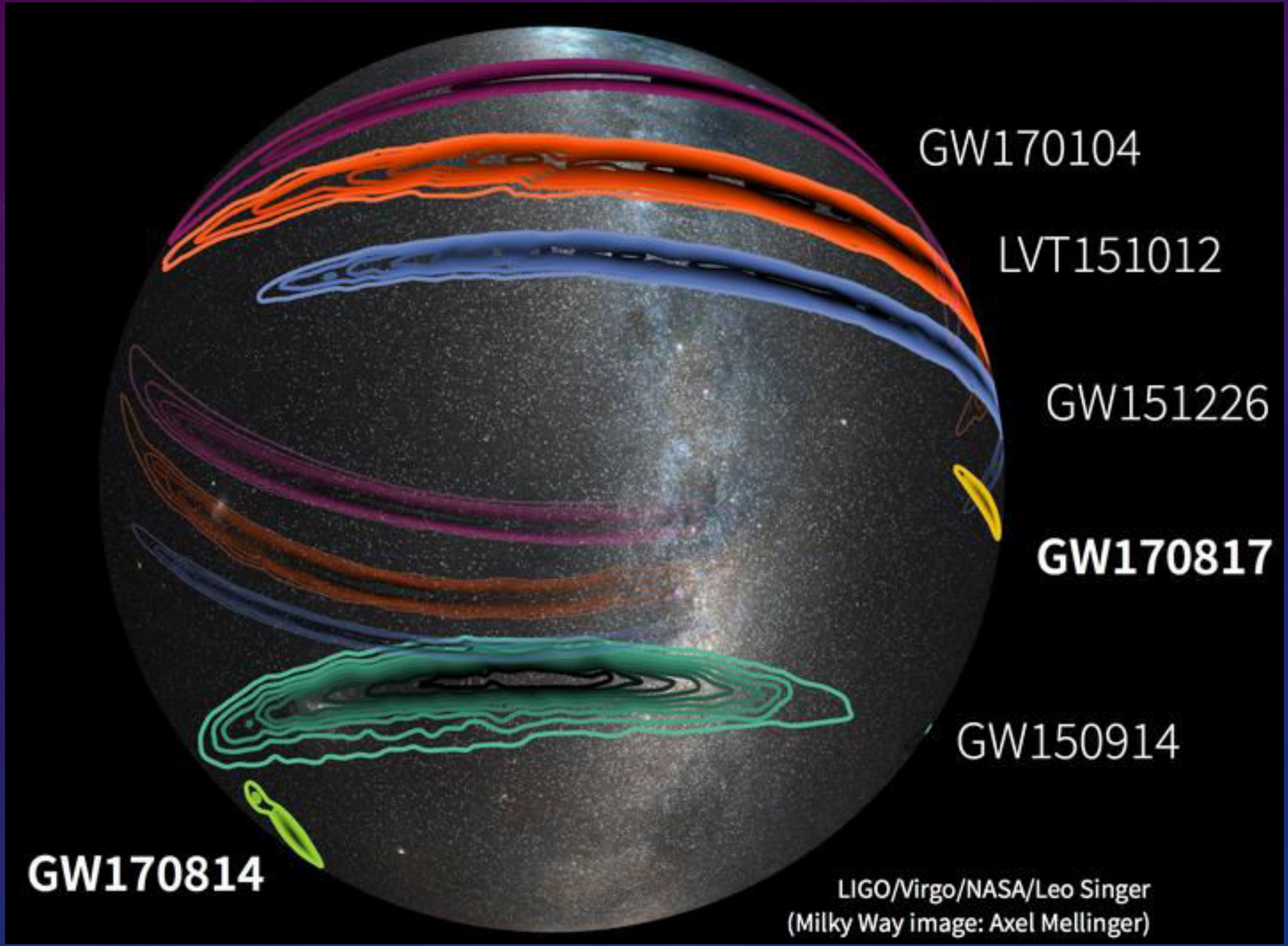


https://www.ligo.caltech.edu/image/ligo20171016e


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.
LIGO
Georgia Tech
Center for Relativistic Astrophysics

Hermano Velten

The speed of GWs is equal to c!



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

FRIEDMAN EQUATIONS AND BACKGROUND DYNAMICS

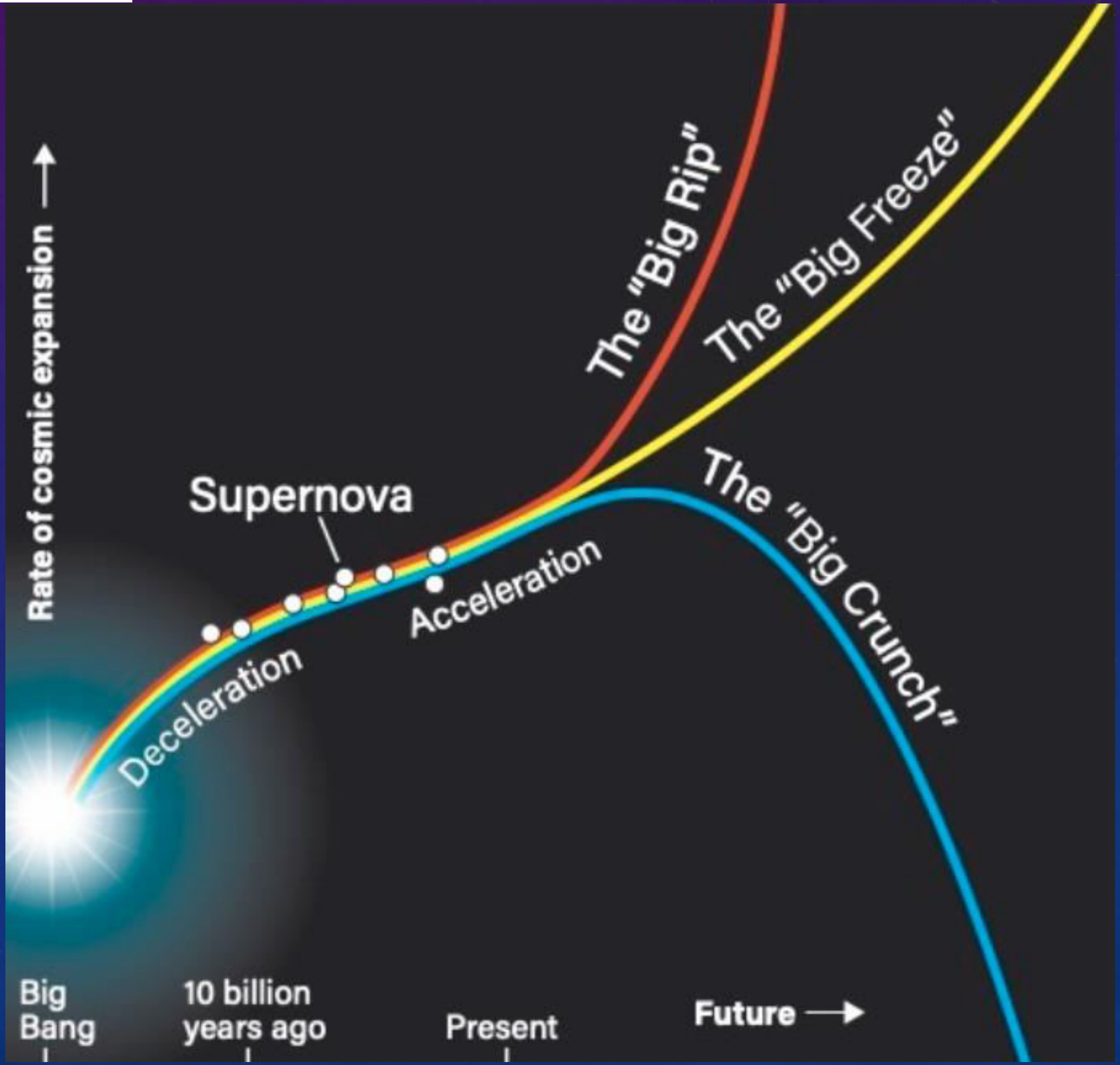
$$R_{00} = -3\left(H^2 + \dot{H}\right), \quad R_{0i} = R_{i0} = 0, \quad R_{ij} = a^2\left(3H^2 + \dot{H} + 2K/a^2\right)\gamma_{ij},$$
$$R = 6\left(2H^2 + \dot{H} + K/a^2\right).$$

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

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

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

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



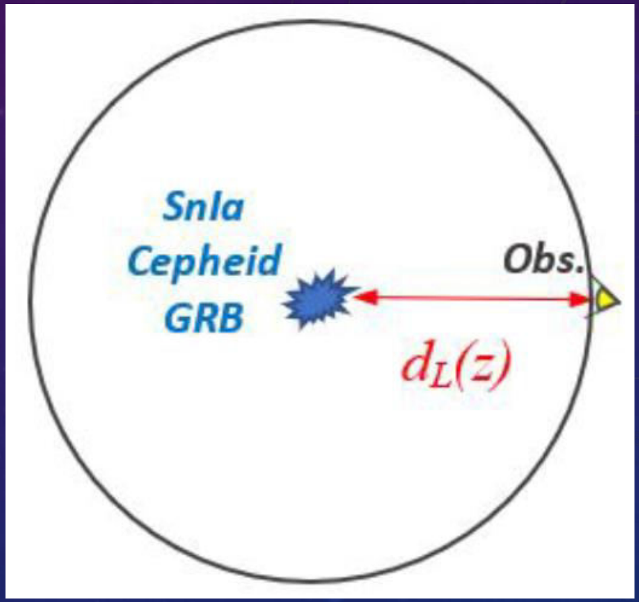
WHY IS IT INTERESTING TO MEASURE DISTANCES?

If we measure DISTANCES we can infer the EXPANSION RATE

Luminosity Distance

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

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



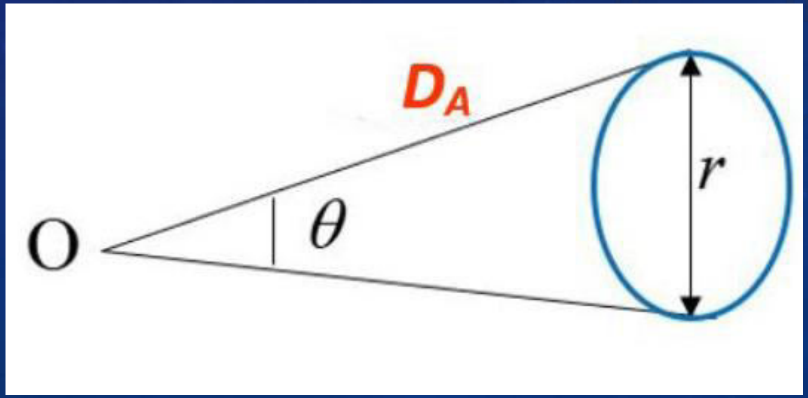
Apparent magnitude

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

Angular distance

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

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

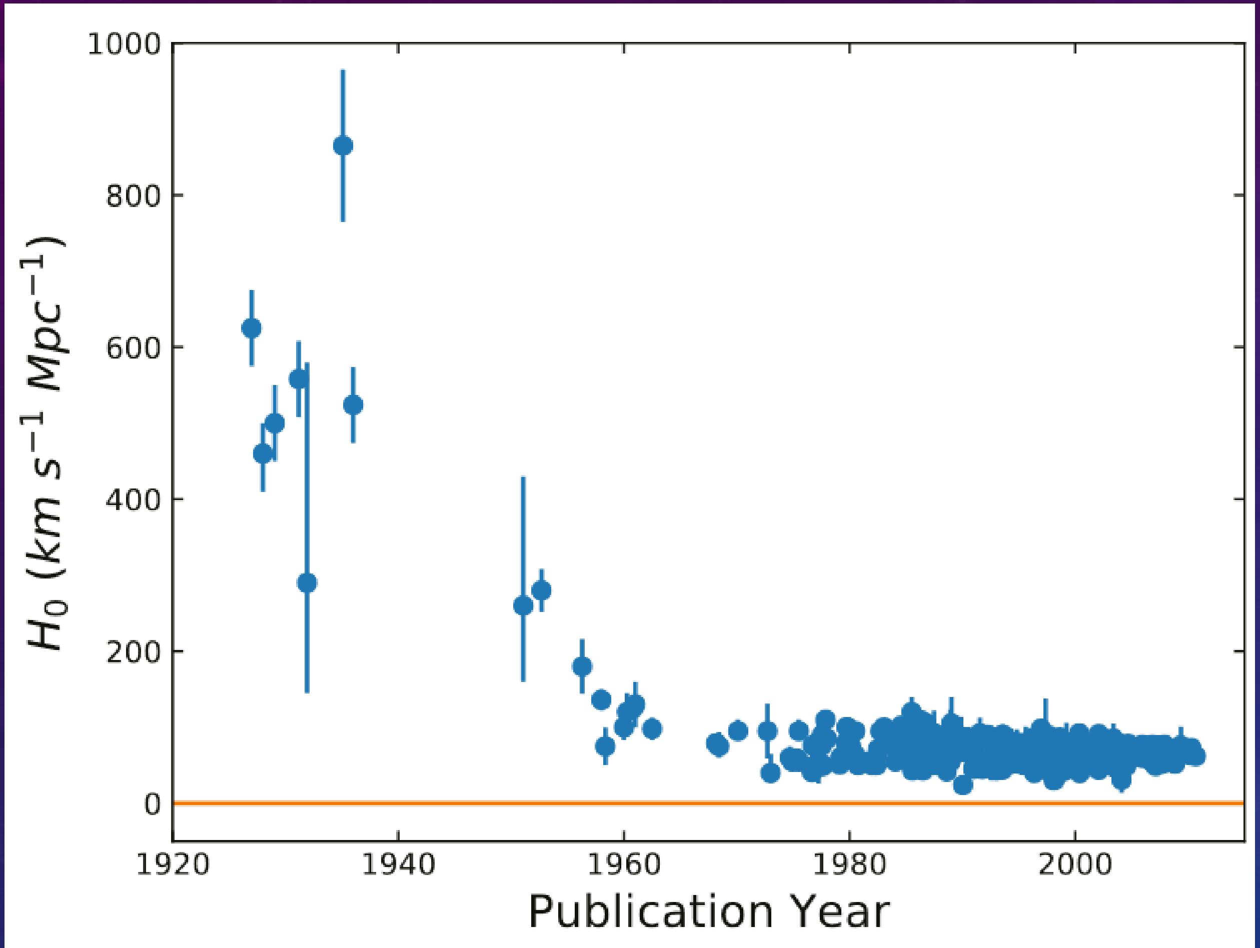


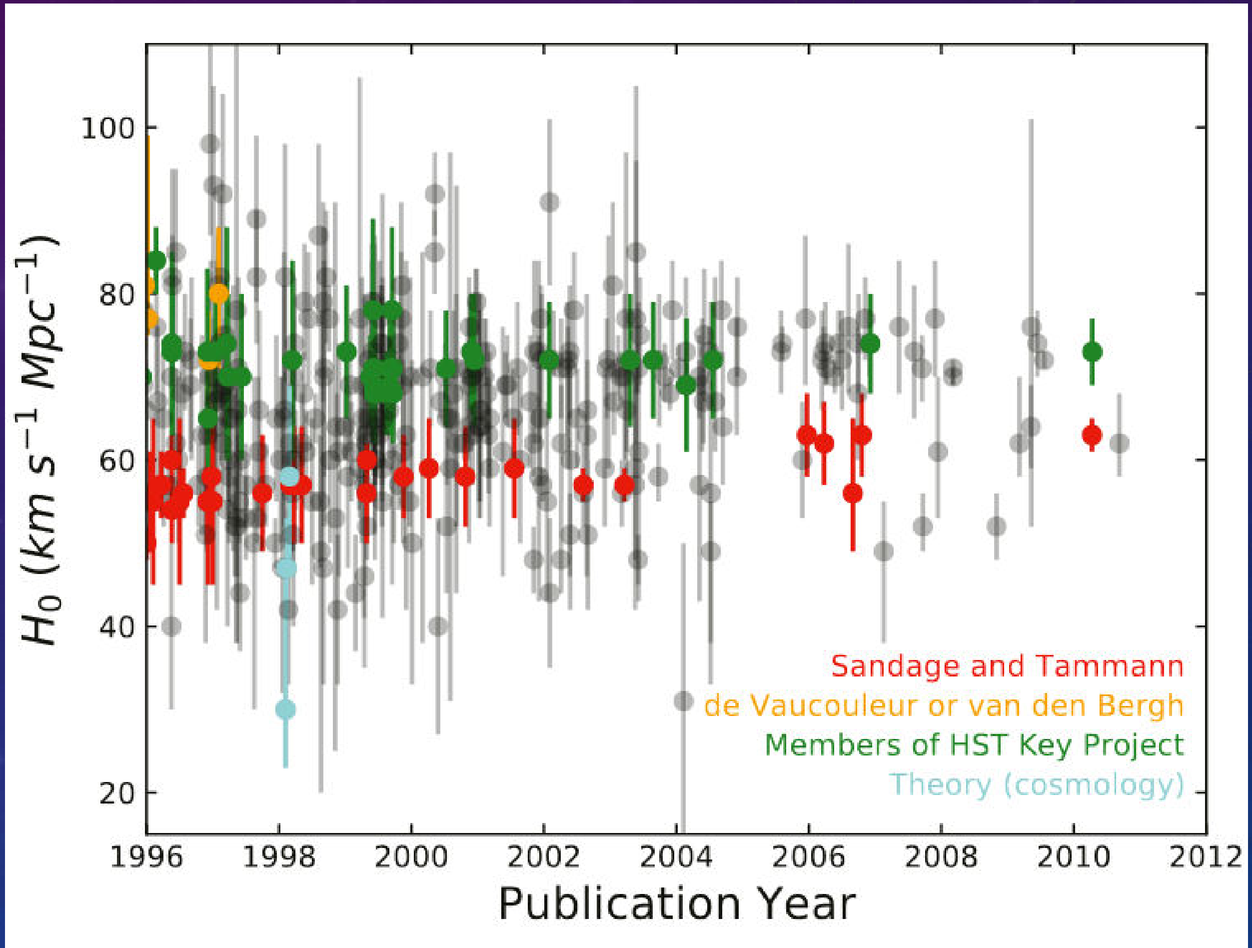
FOUR IMPORTANT EPOCHS WHICH ASTROPHYSICS CAN PROBE

- 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

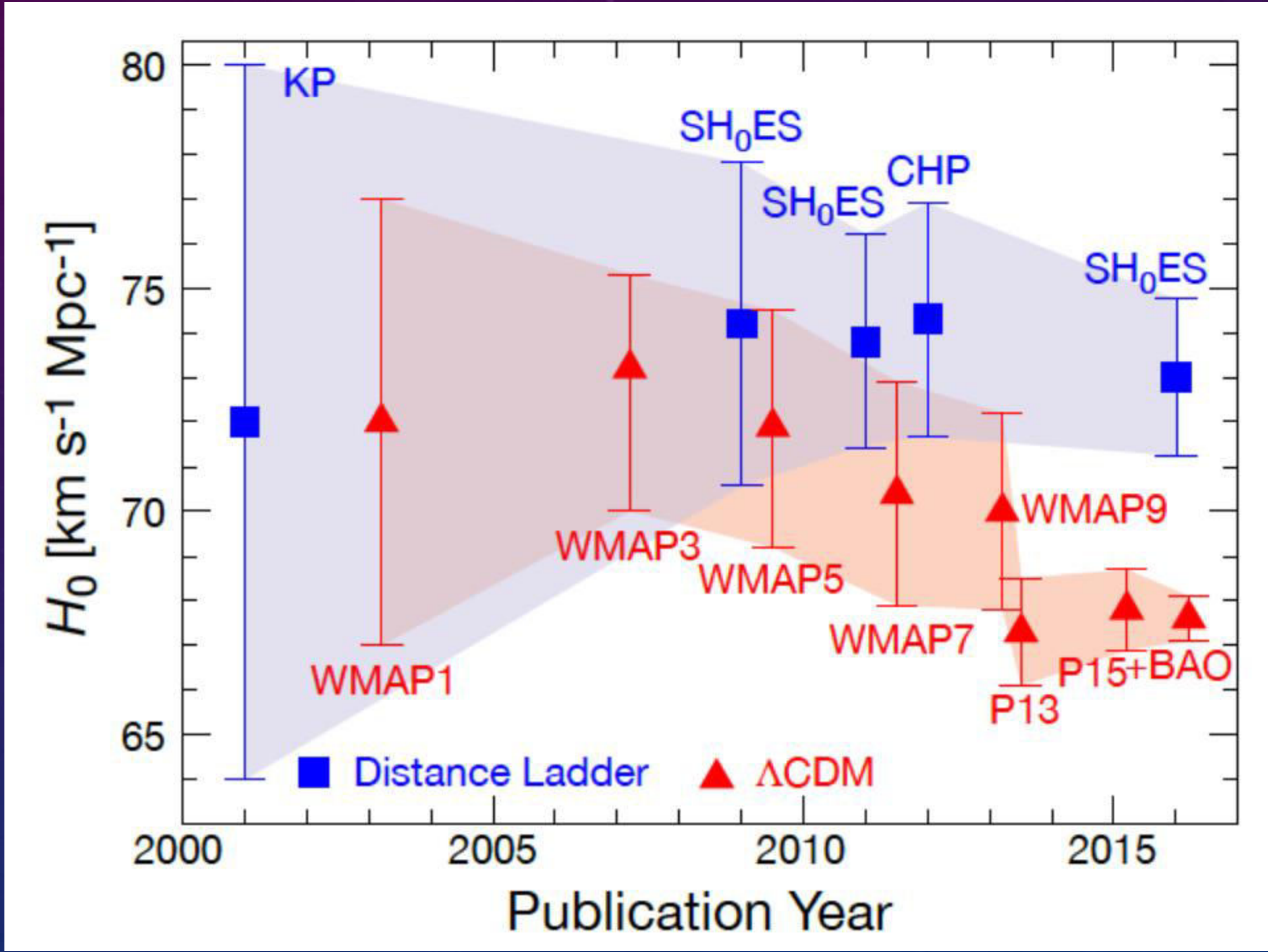




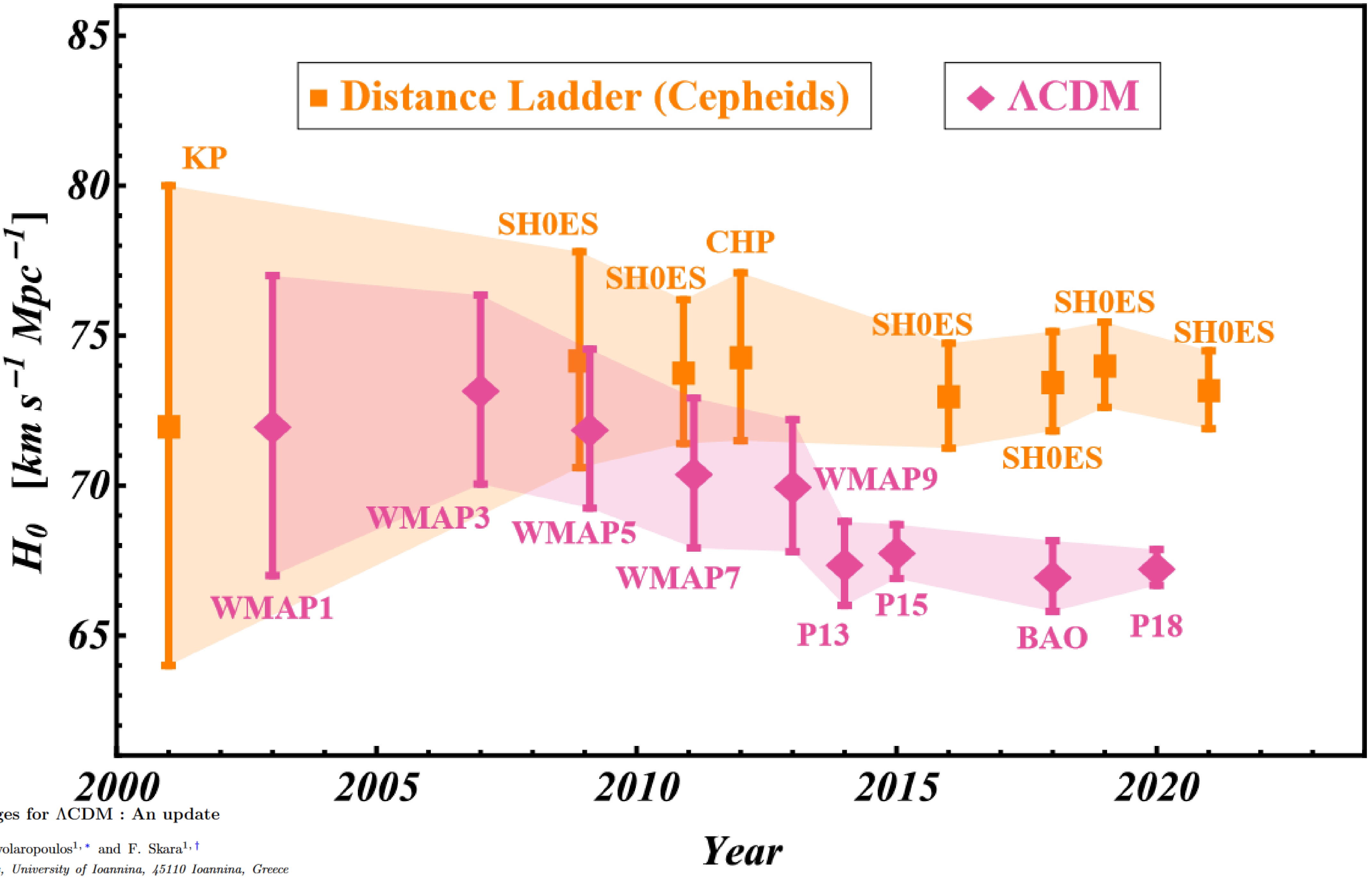
Bruno Leibundgut,

SPATIUM No. 47, May 2021

INTRODUCING THE COSMIC TENSION ON H0



Wendy L. Freedman *Nature Astronomy* **1**, Article number: 0121 (2017)

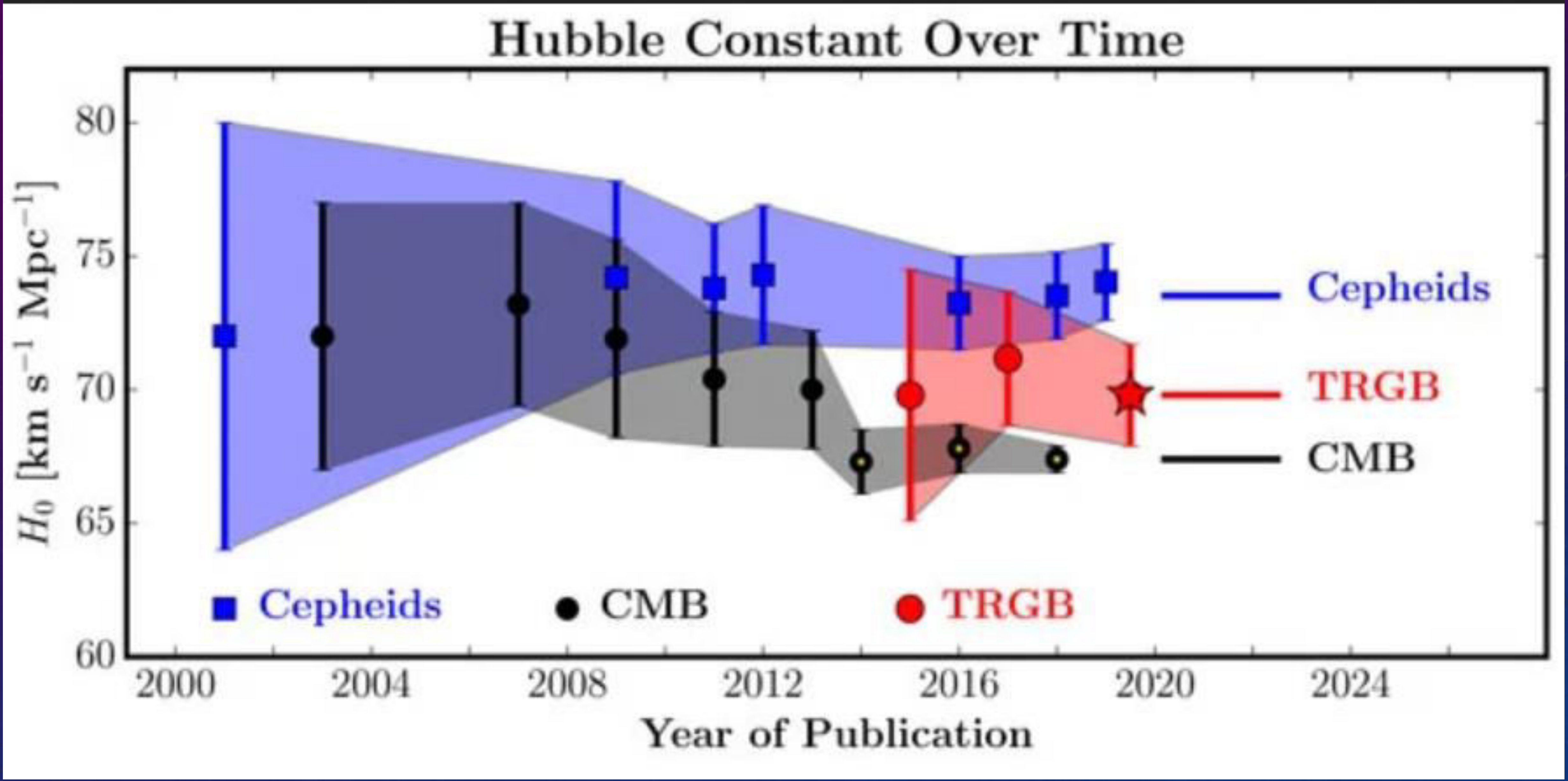


Challenges for ΛCDM : An update

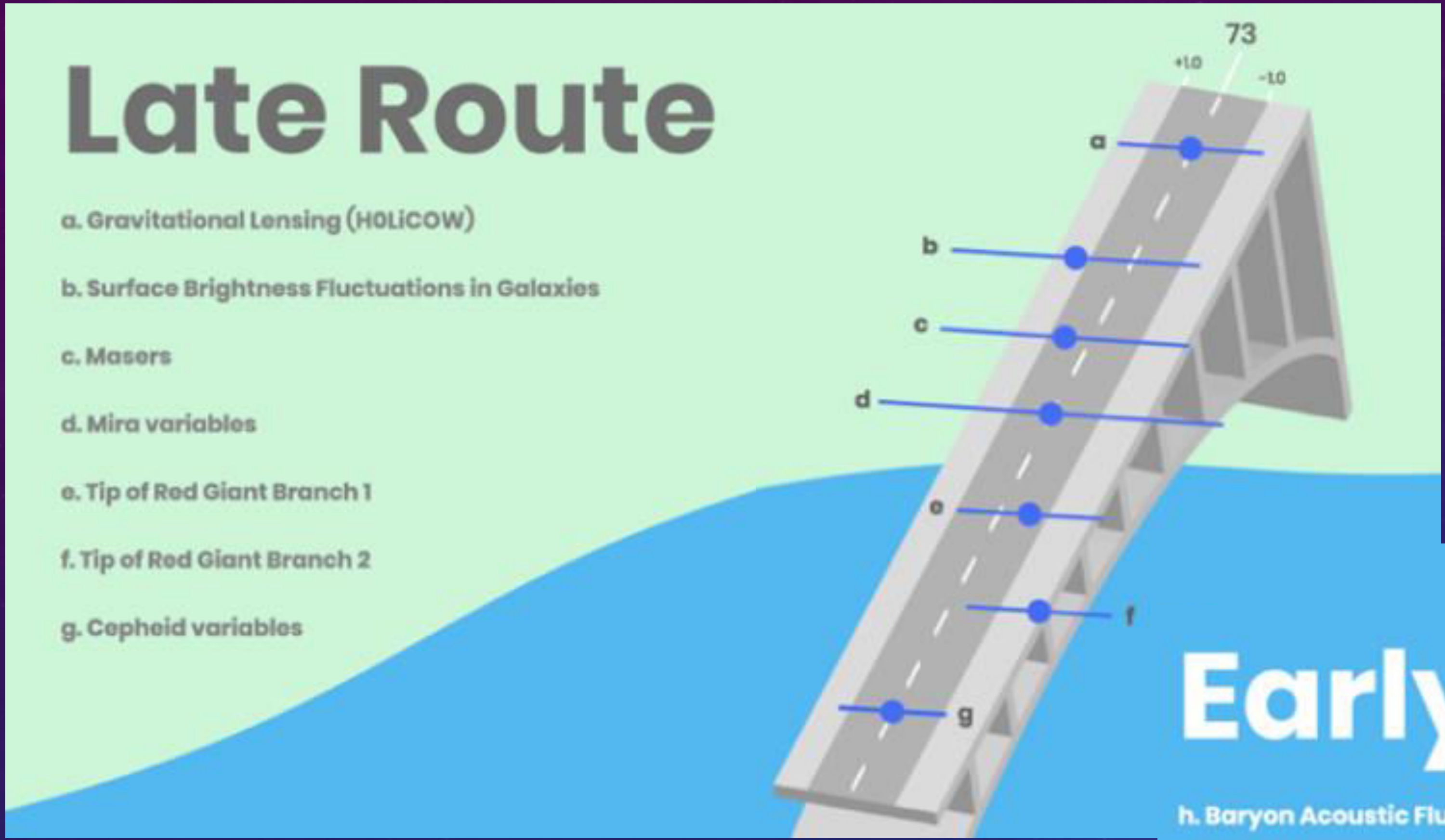
L. Perivolaropoulos[1,*] and F. Skara[1,†]

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

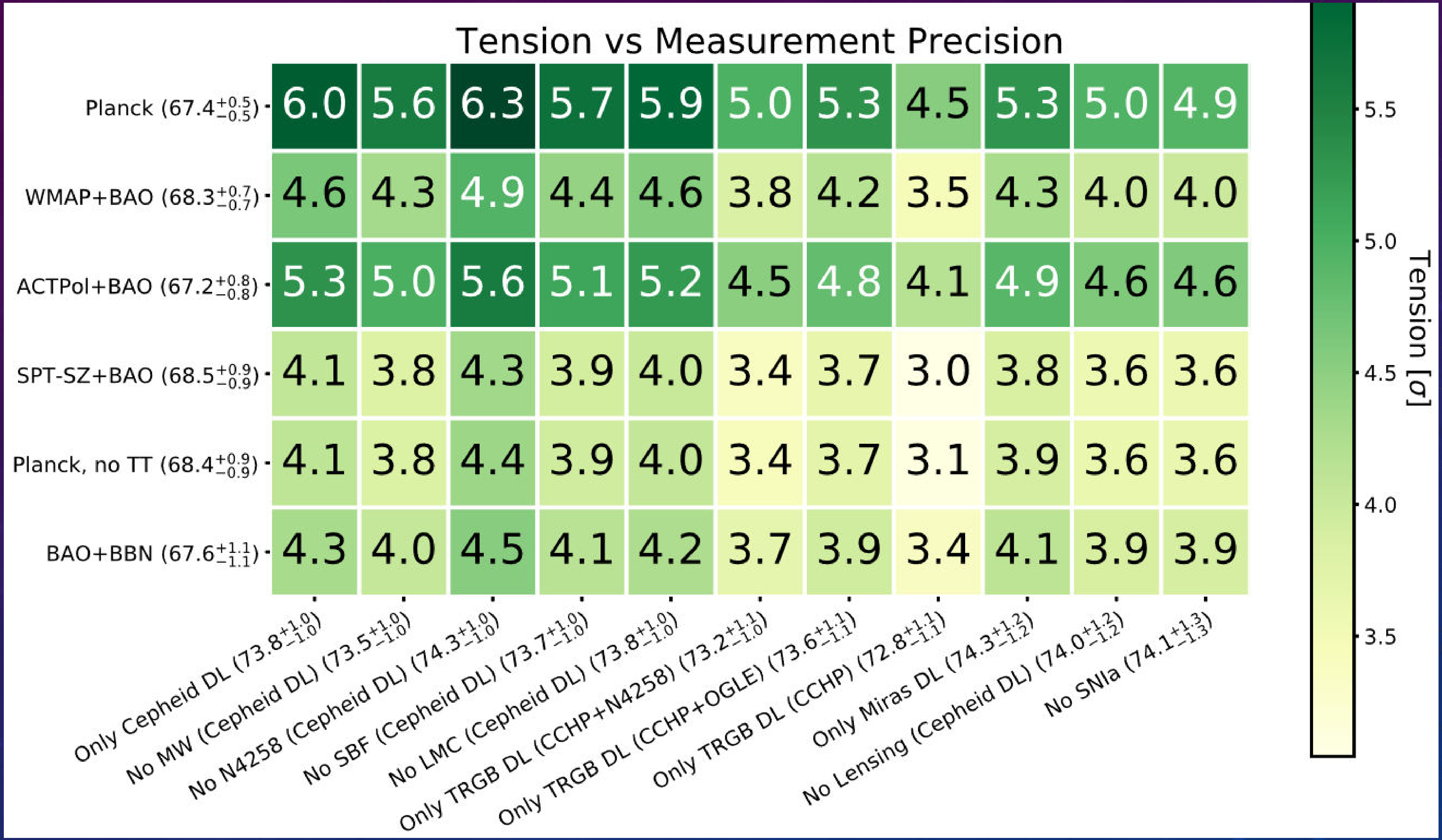
(Dated: May 20, 2021)


Hubble Constant Over Time
H_0 [km s^{-1} Mpc^{-1}]
80
75
70
65
60
2000
2004
2008
2012
2016
2020
2024
Year of Publication
Cepheids
TRGB
CMB
Cepheids
CMB
TRGB

INTRODUCING THE COSMIC TENSION ON H0



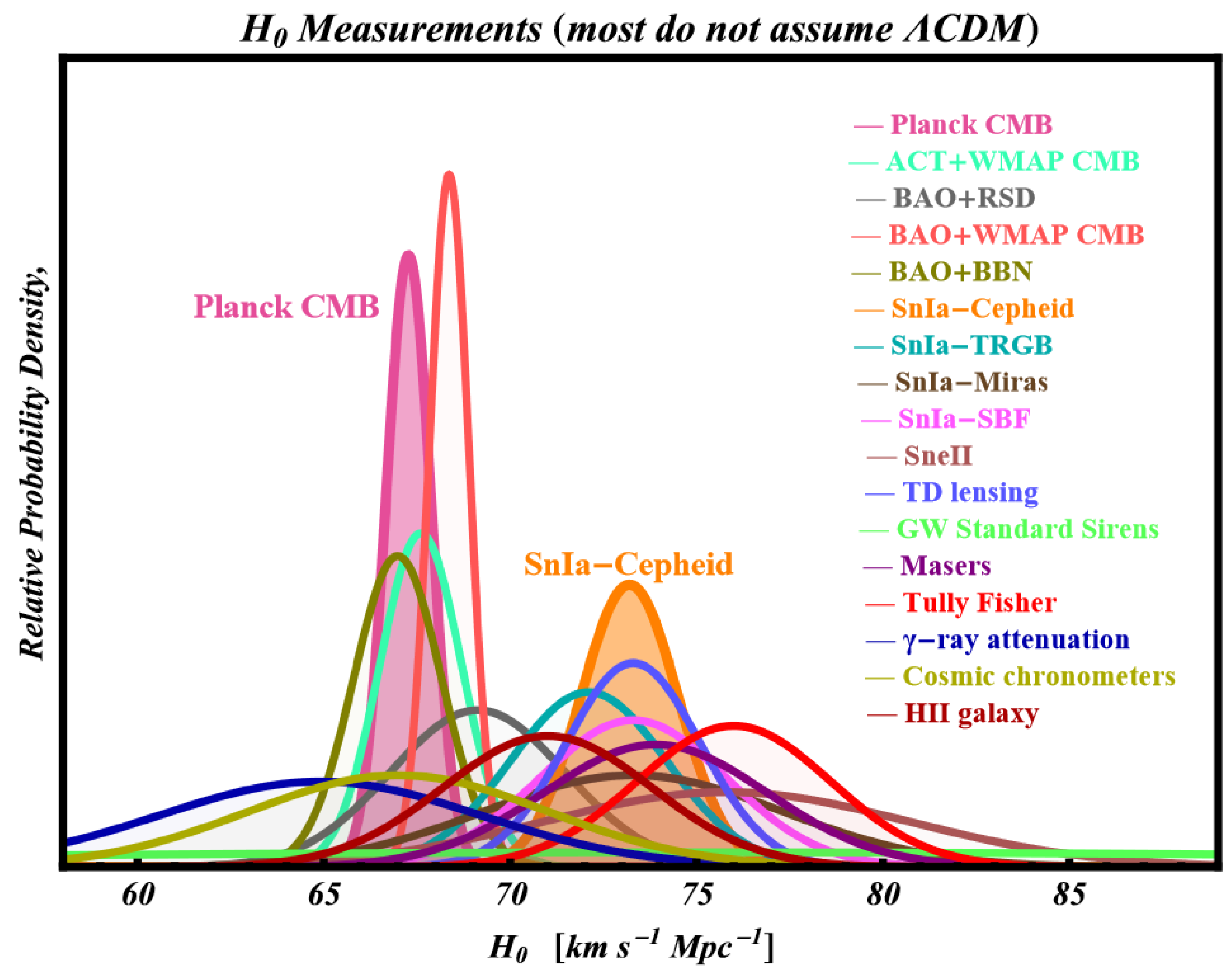
Credits: ADAM RIESS, Nature Review Physics 2019



Credits: ADAM RIESS, Nature Review Physics 2019

Challenges for ΛCDM : An update

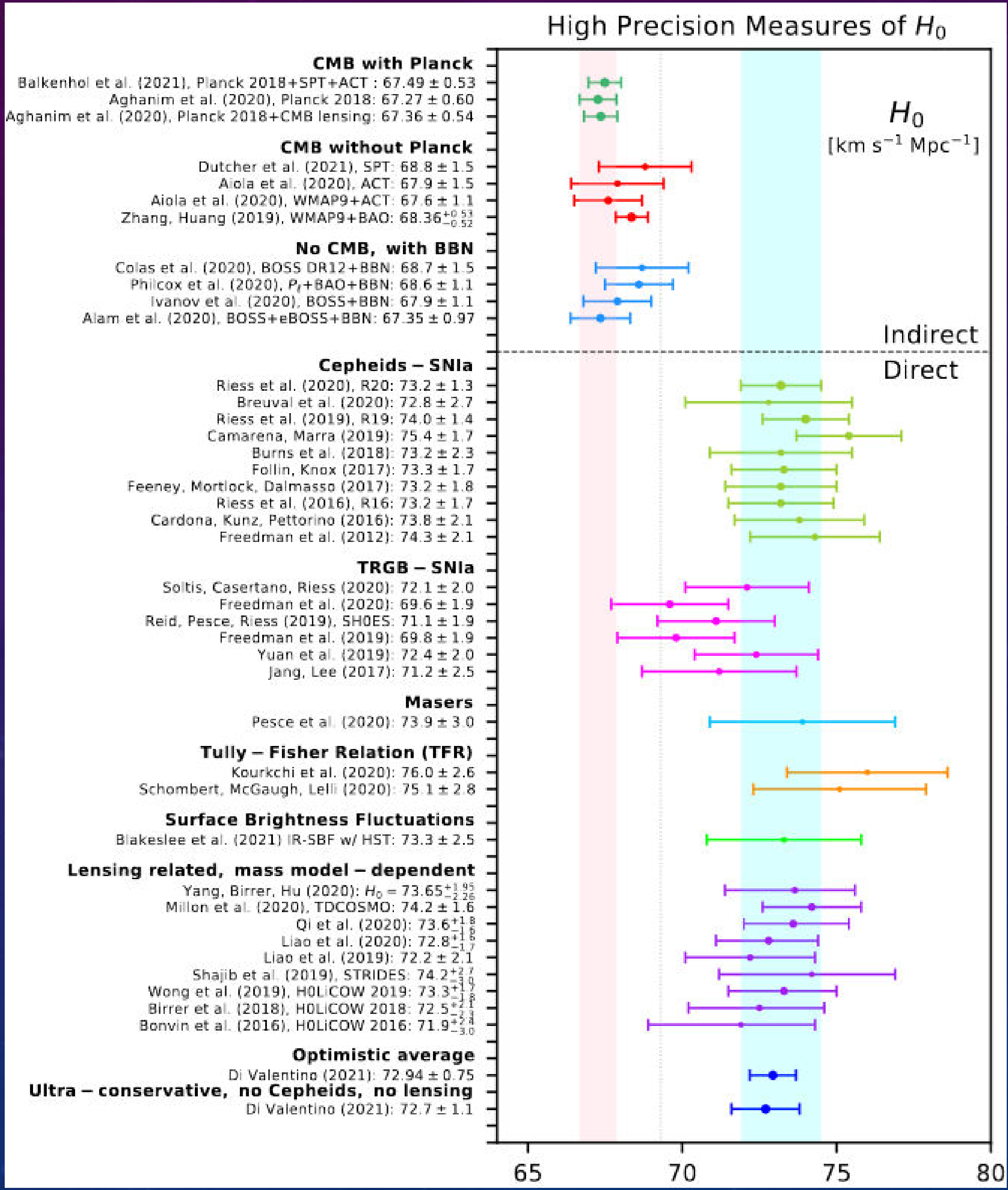
L. Perivolaropoulos[1,*] and F. Skara[1,†]
[1] *Department of Physics, University of Ioannina, 45110 Ioannina, Greece*
(Dated: May 20, 2021)

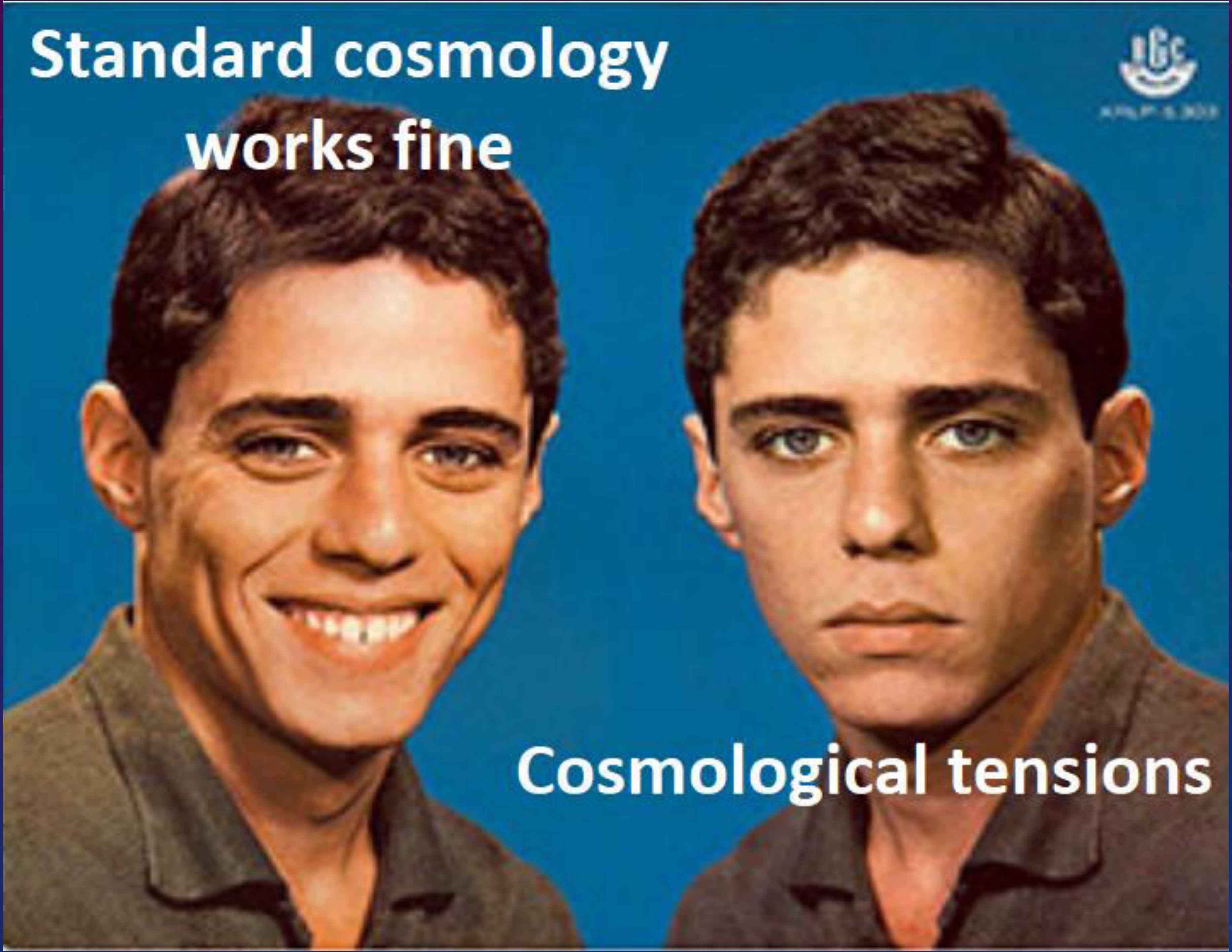


arXiv:2105.05208

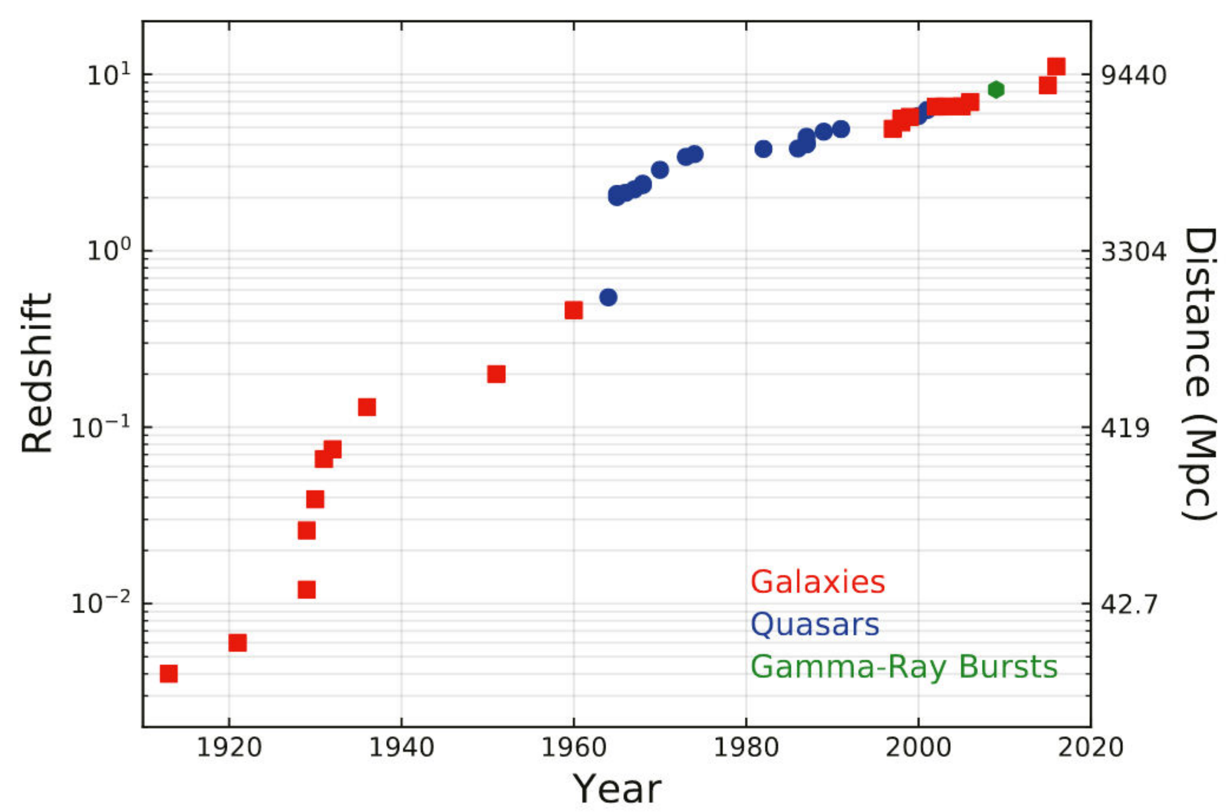
In the Realm of the Hubble tension – a Review of Solutions †

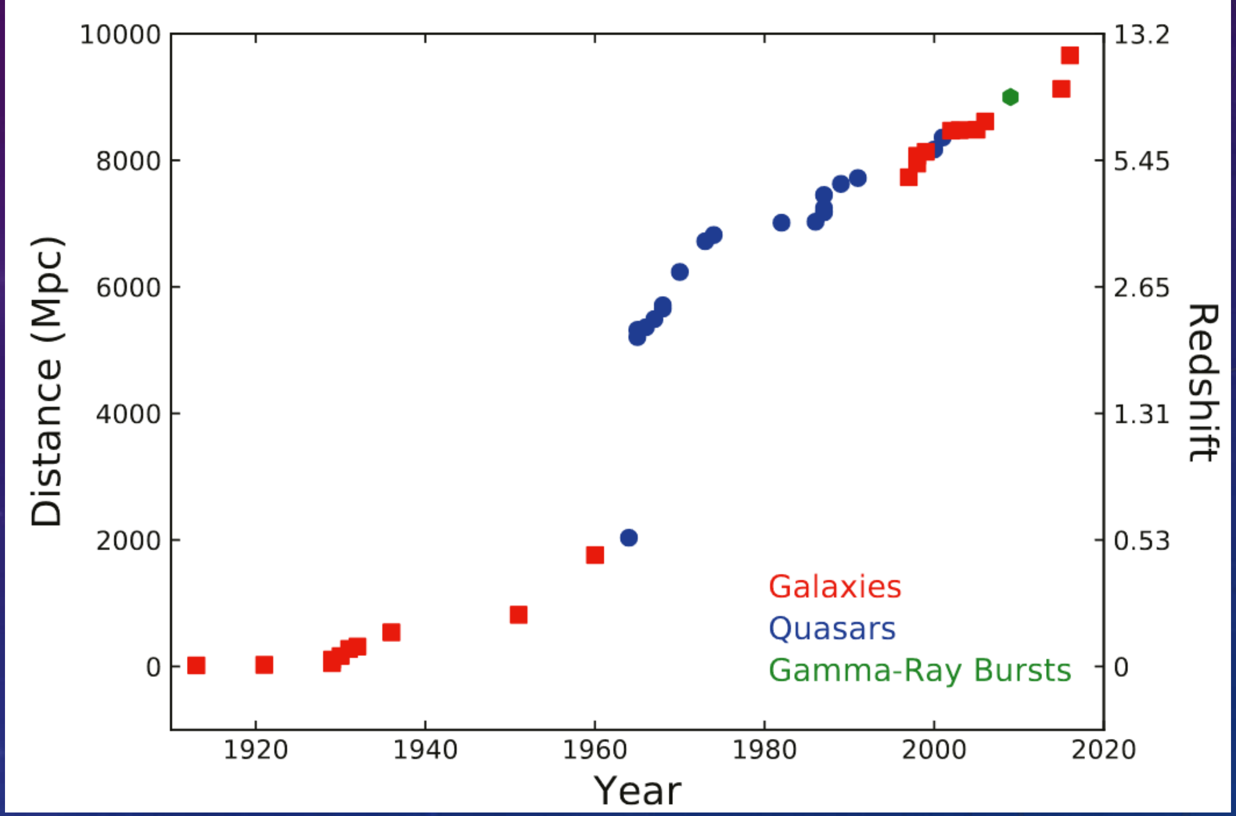
Eleonora Di Valentino[1*], Olga Mena[2], Supriya Pan[3], Luca Visinelli[4], Weiqiang Yang[5], Alessandro Melchiorri[6], David F. Mota[7], Adam G. Riess[8,9], Joseph Silk[8,10,11]




Standard cosmology
works fine
Cosmological tensions

2) THE UNIVERSE OVER THE PAST 12 BILLION YEARS





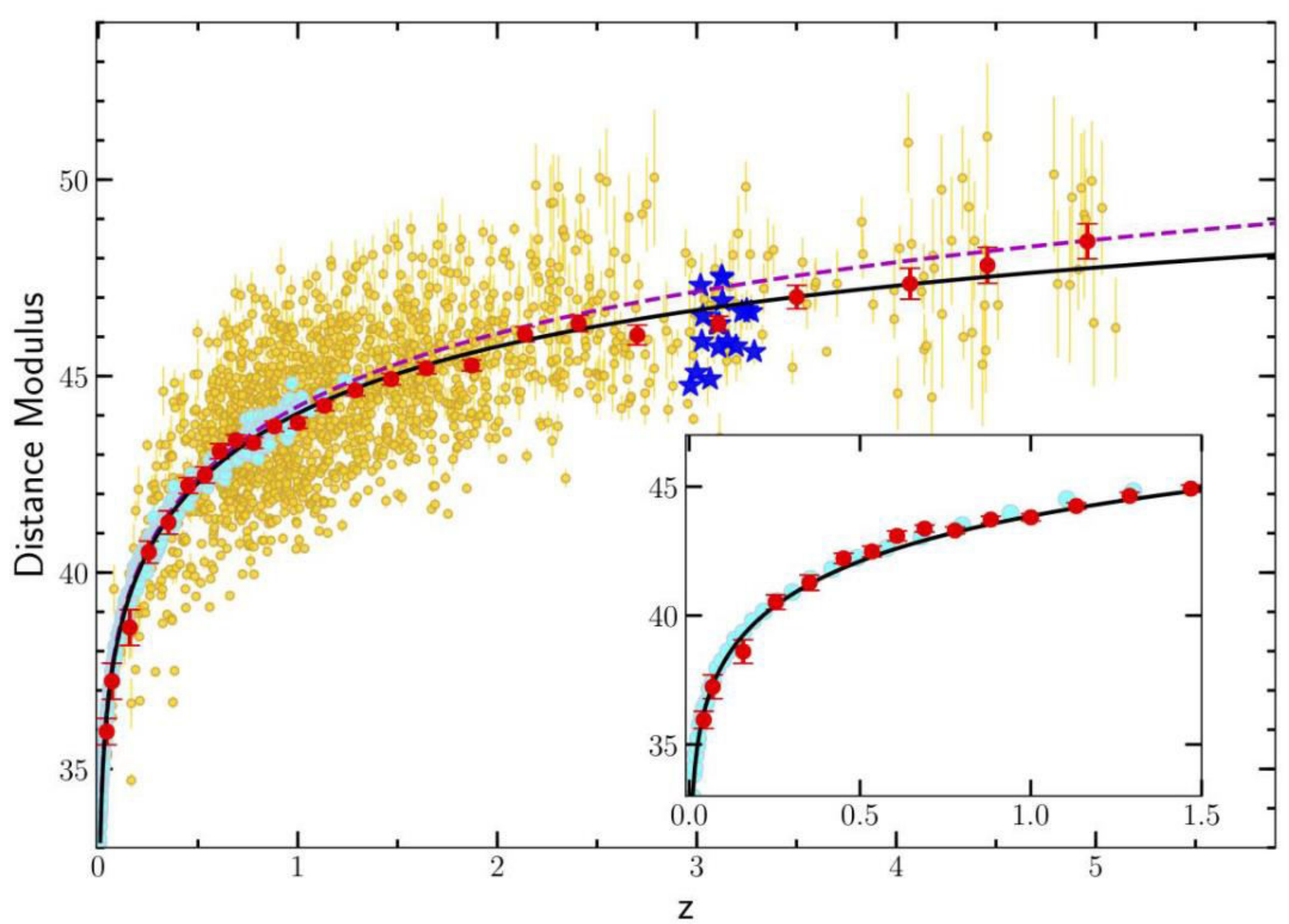
Bruno Leibundgut,

SPATIUM No. 47, May 2021

nature astronomy
Letter | Published: 28 January 2019

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 ~ 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 abundances[3] 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 universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. 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:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^5$ 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 $T \propto 1/l$ and $R_0 = 1\cdot9 \times 10^9 \sqrt{-1}$ light-years. The integrated values of $\rho_{mat.}$ and $\rho_{rad.}$ intersect at a reasonable time, namely, $3\cdot5 \times 10^{14}$ sec. $\cong 10^7$ years, and the masses and radii of condensations at this time become, according to the Jeans' criterion, $M_c = 3\cdot8 \times 10^7$ sun masses, and $R_c = 1\cdot1 \times 10^3$ 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 $2\cdot4 \times 10^9$ 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.

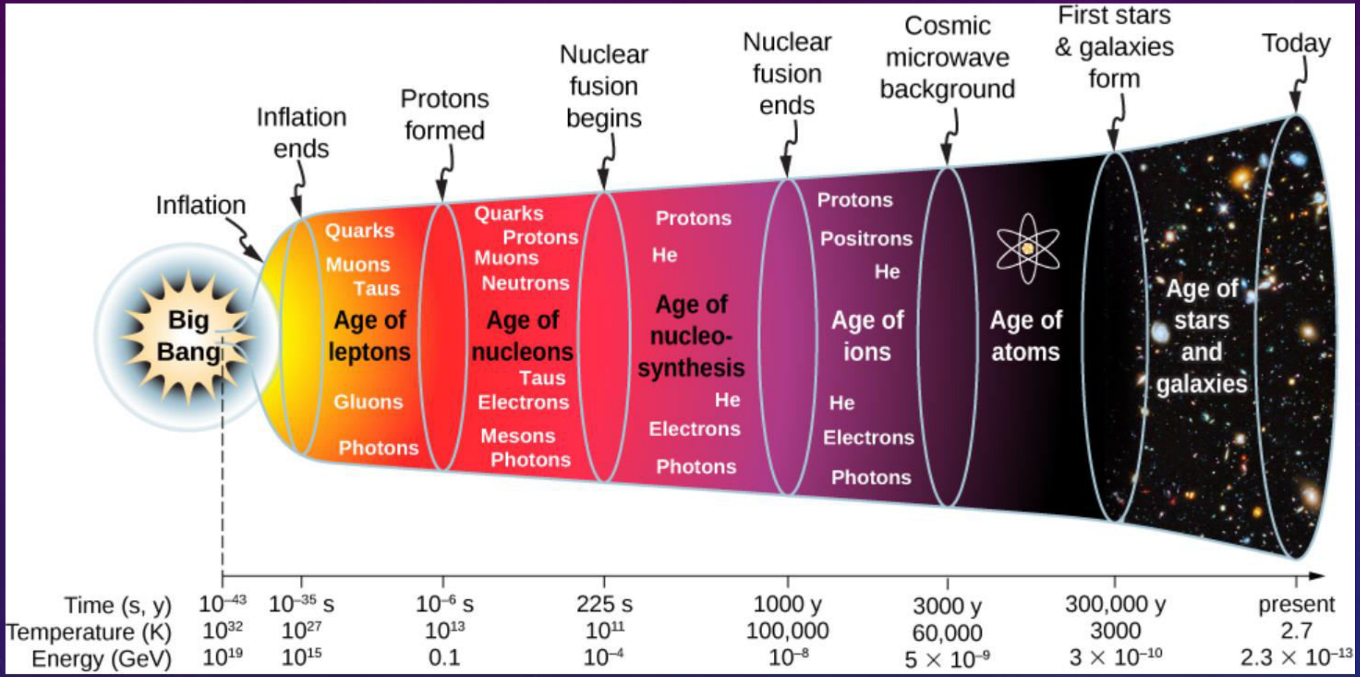
It might be assumed that the bulk of the argon generated in the solid crust was retained in the crust, but even this assumption will only reduce the discrepancy. From the quantity of sodium retained in the ocean, F. W. Clarke[5] estimates that an amount of solid material equal to about 5 per cent of 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 atmosphere[4], 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 $1\cdot3 \times 10^9$ 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.

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.

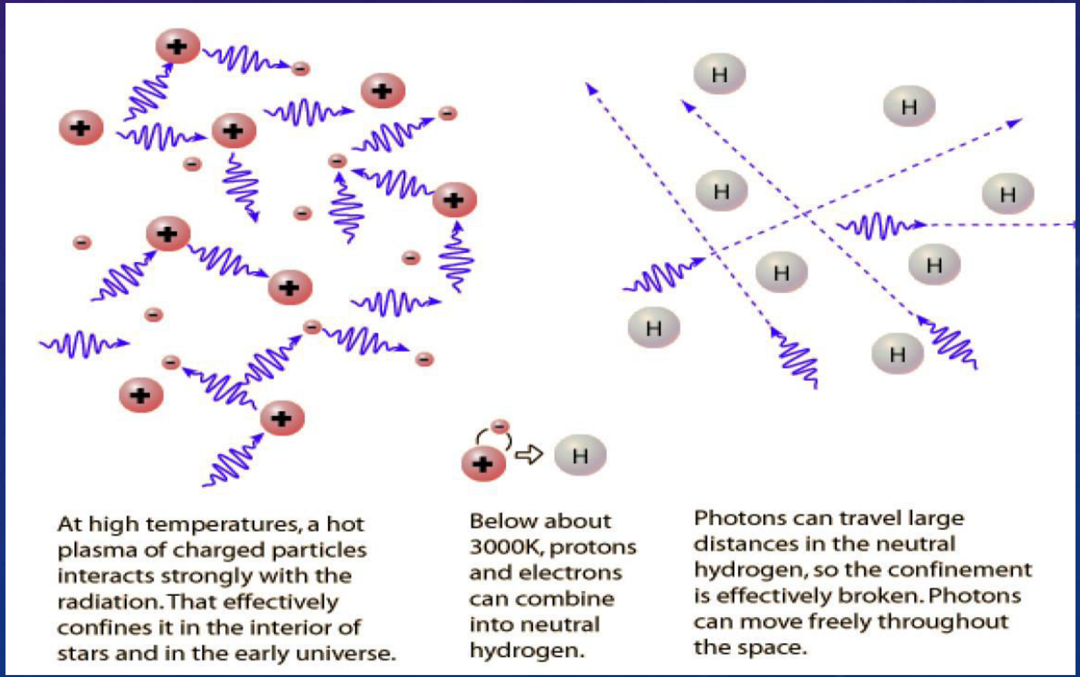
COSMIC MICROWAVE BACKGROUND (CMB)

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

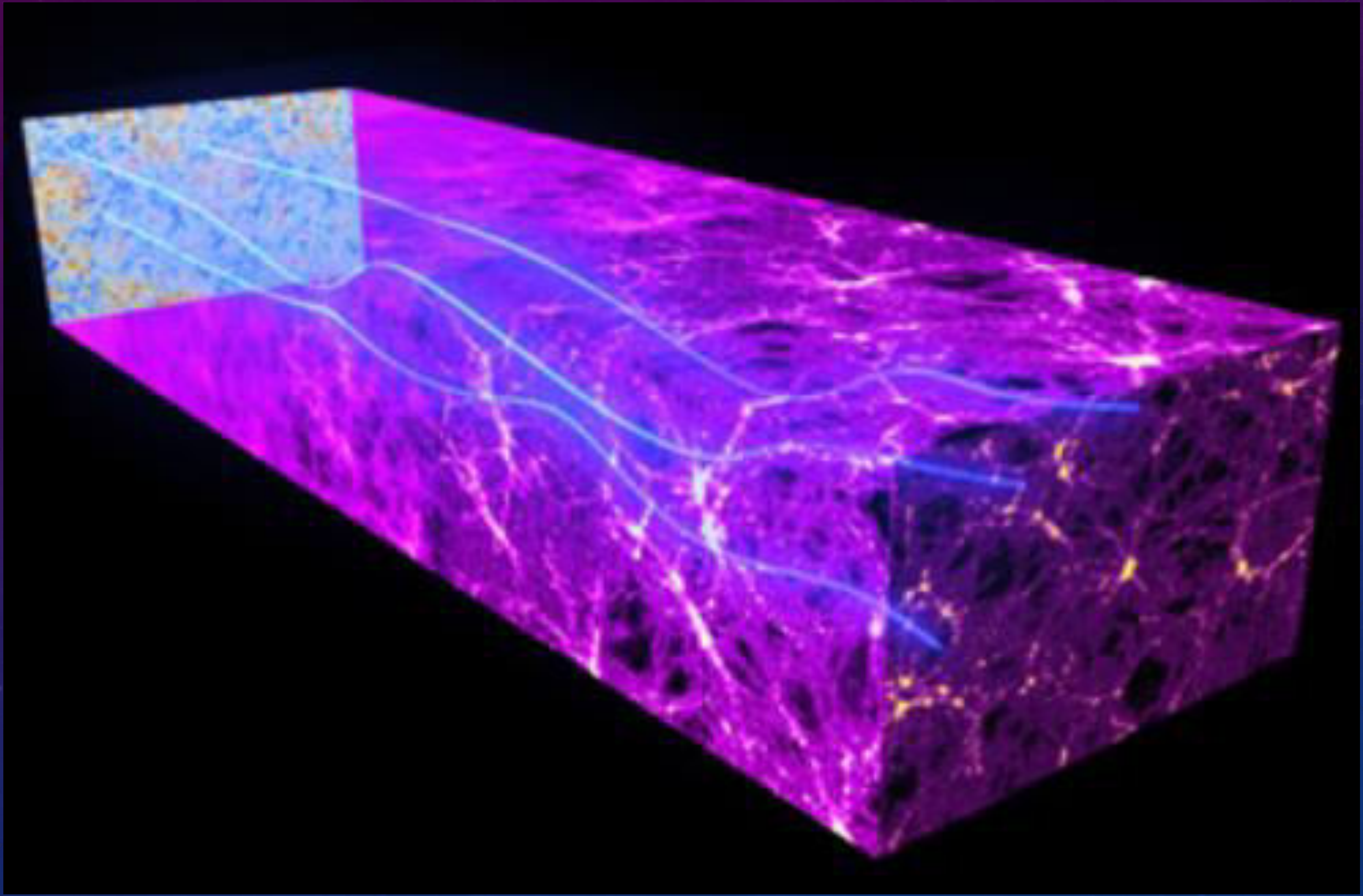
COSMIC MICROWAVE BACKGROUND (CMB)



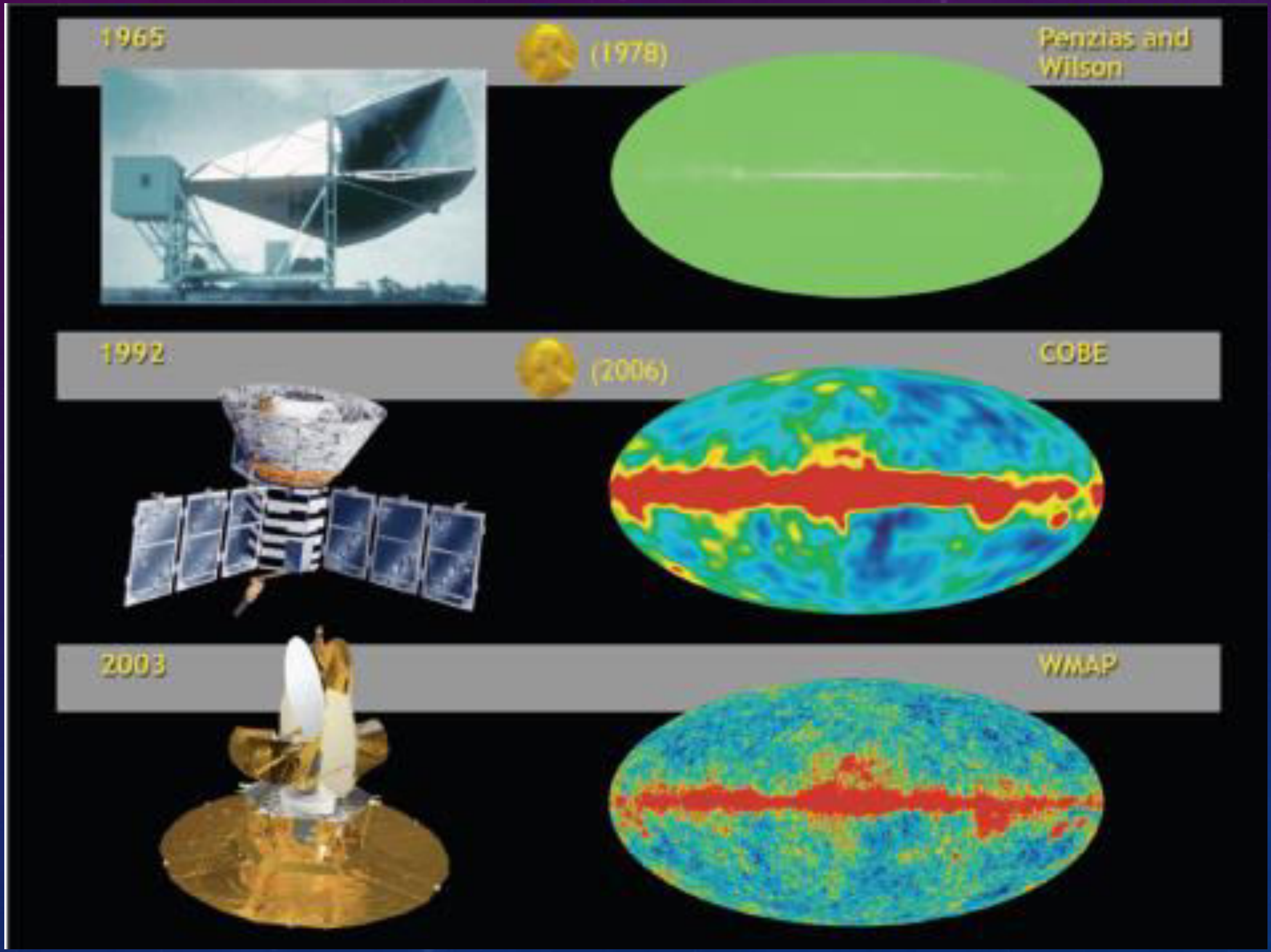
Radiation decoupled from charged particles

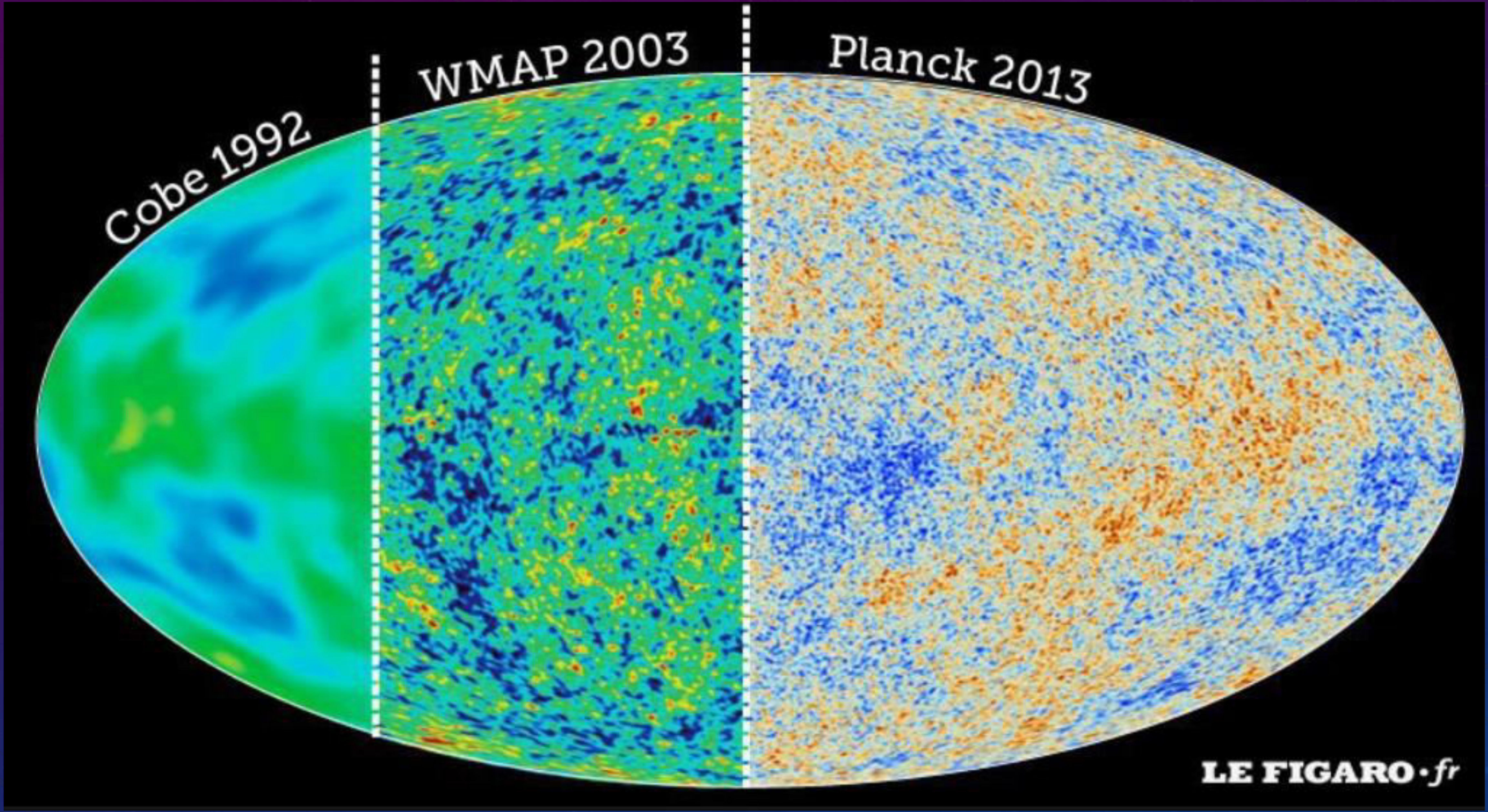


It is early to show this plot. But it shows the moment the CMB is released.



COSMIC MICROWAVE BACKGROUND (CMB)

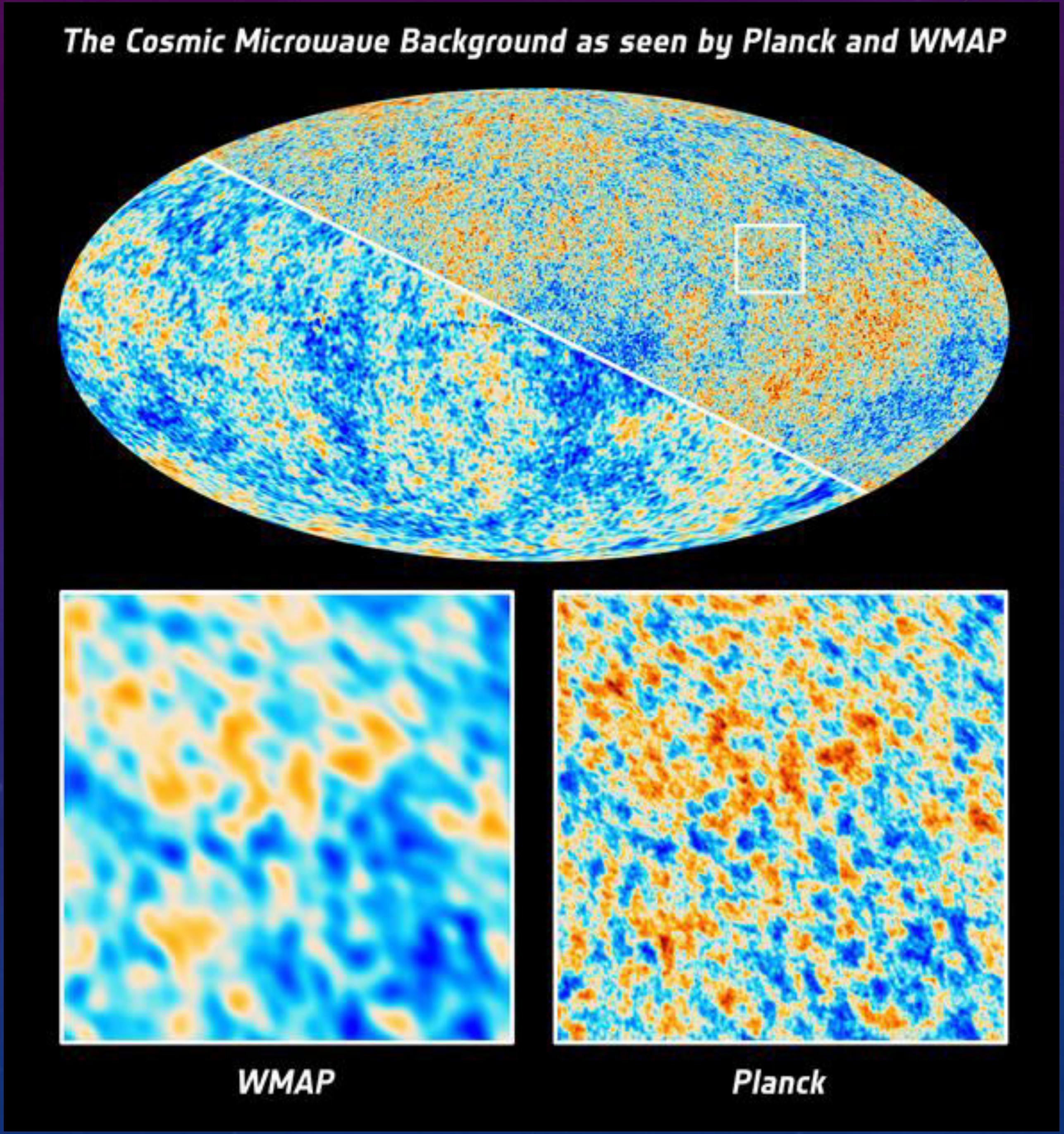



Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

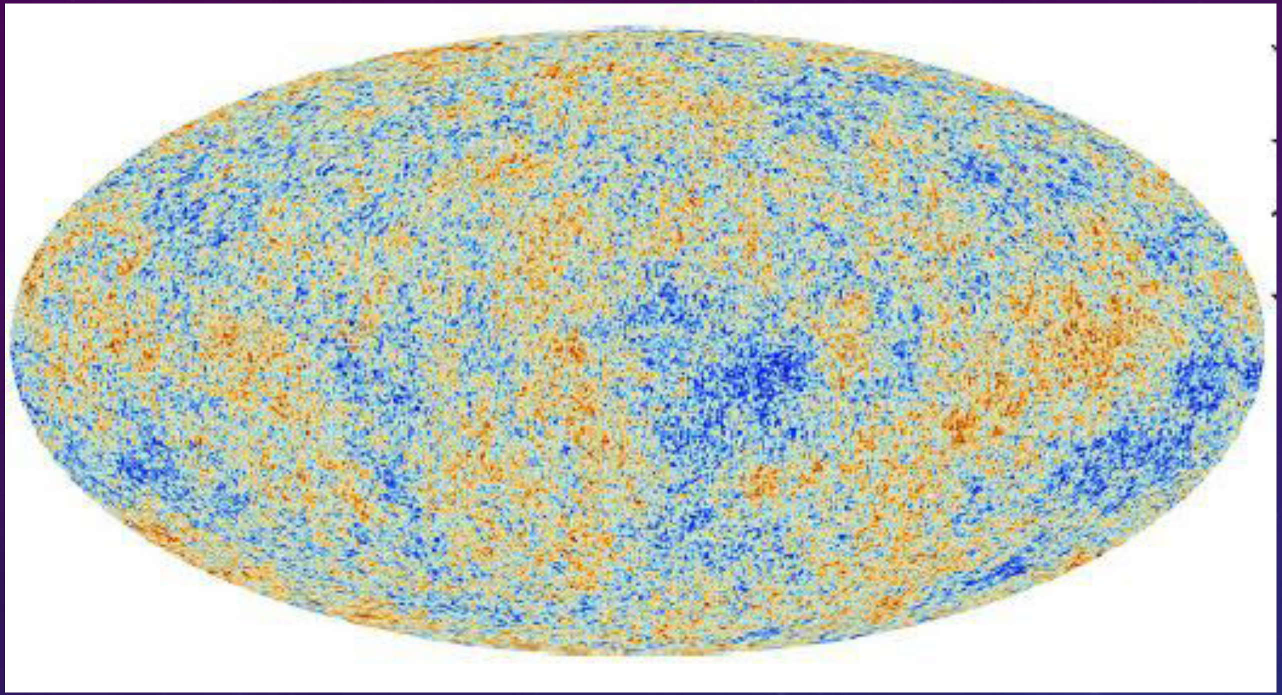
PLANCK satellite

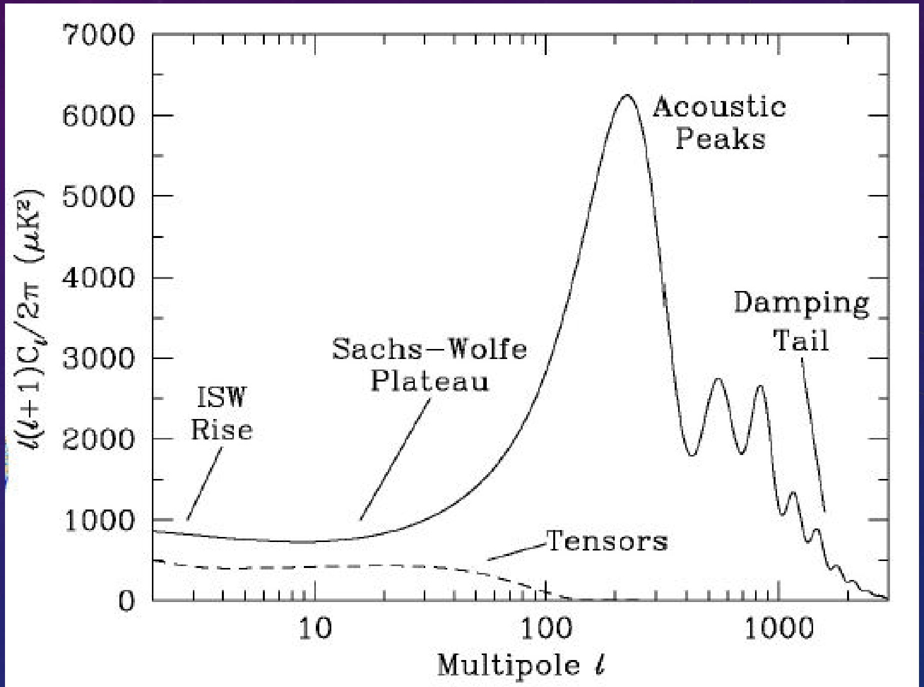
Lauch: 2009.
Took data until 2013.

Data releases: 2013, 2016, 2018



THE SACHS-WOLFE FORMULA





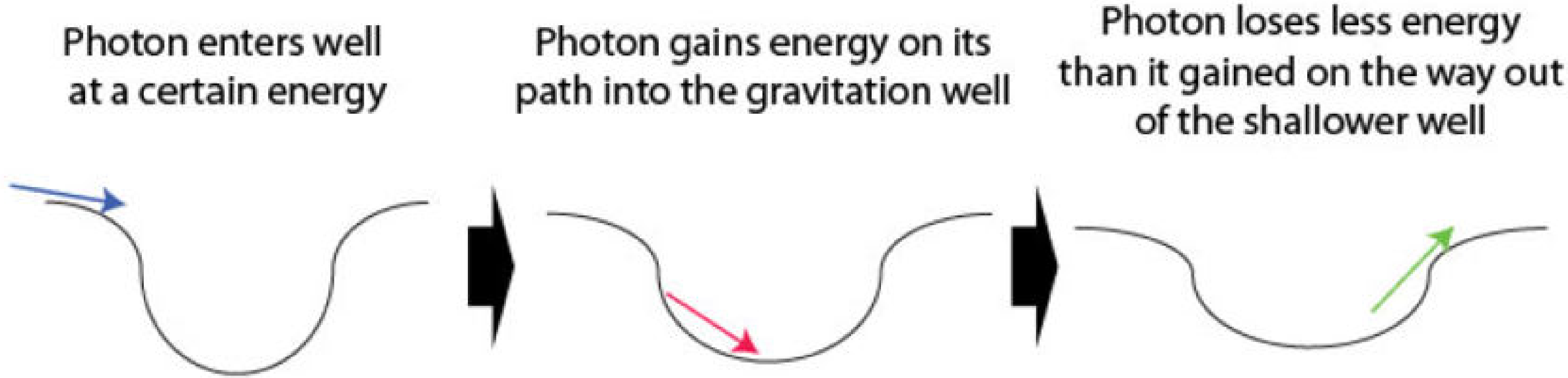
$$\frac{\delta T}{T}(\vec{e}) = \left[\frac{\delta T_\gamma}{T} + \phi - \vec{e}\cdot\vec{v_\gamma}\right]_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta \frac{\partial}{\partial\eta}(\phi + \psi)$$

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

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

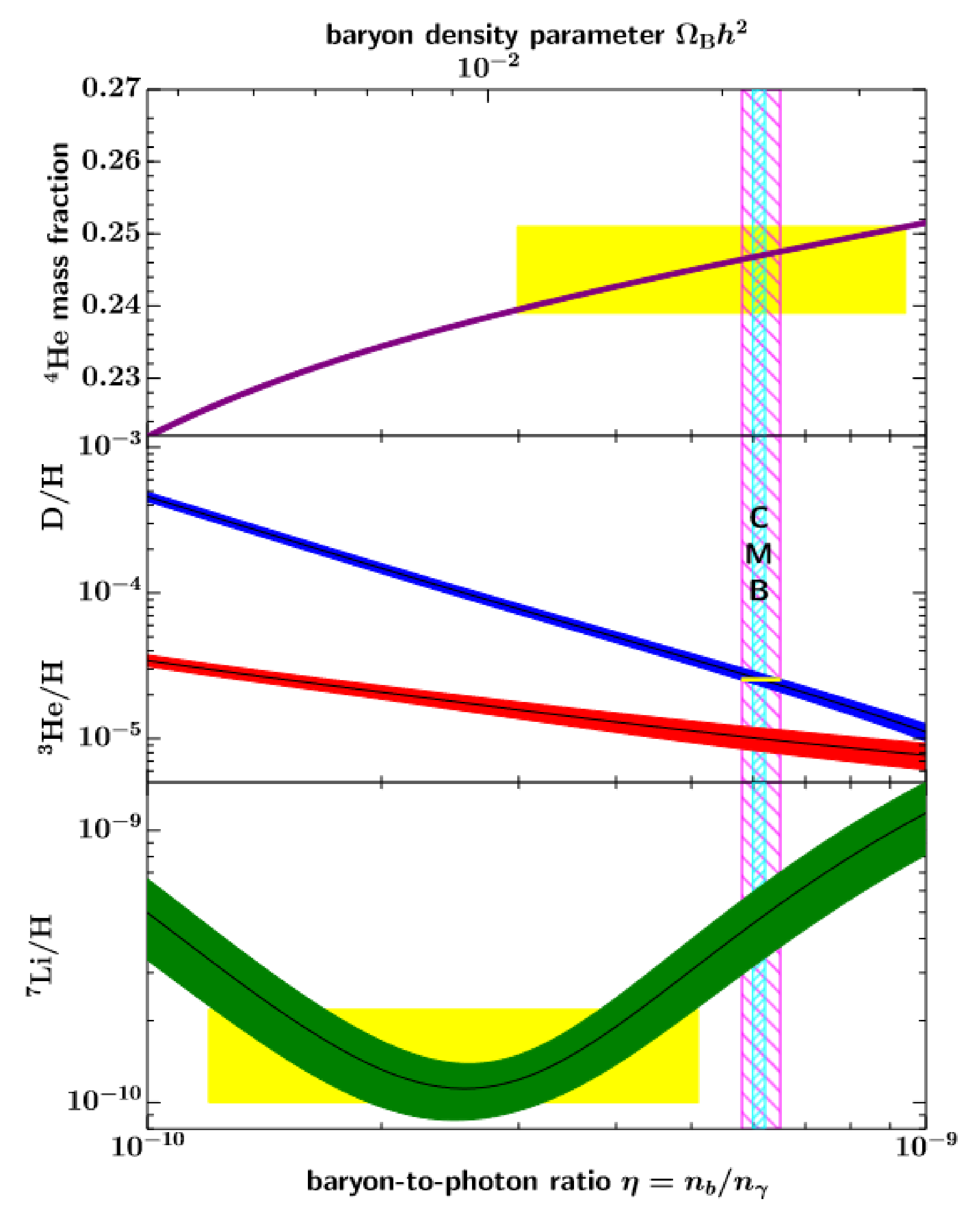


Gravitational well of galaxy supercluster - the depth shrinks as the universe (and cluster) expands

The Review of Particle Physics (2021)

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

4) PRIMORDIAL ABUNDANCES



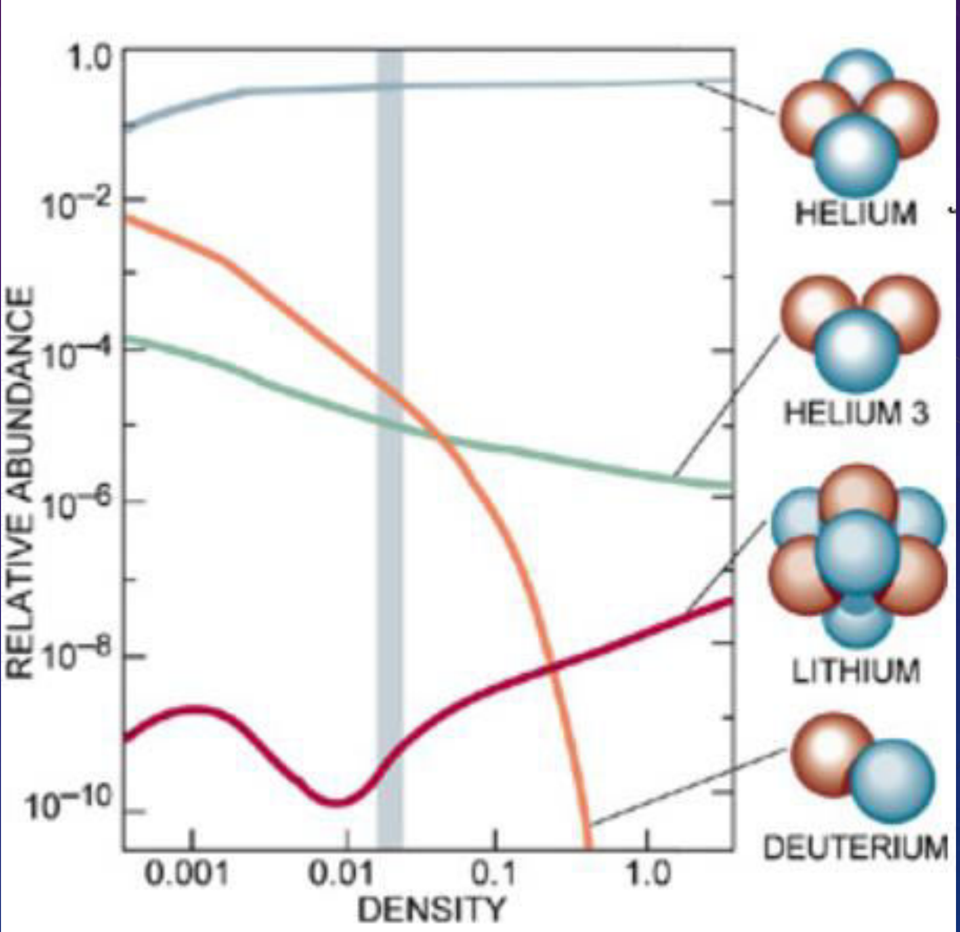


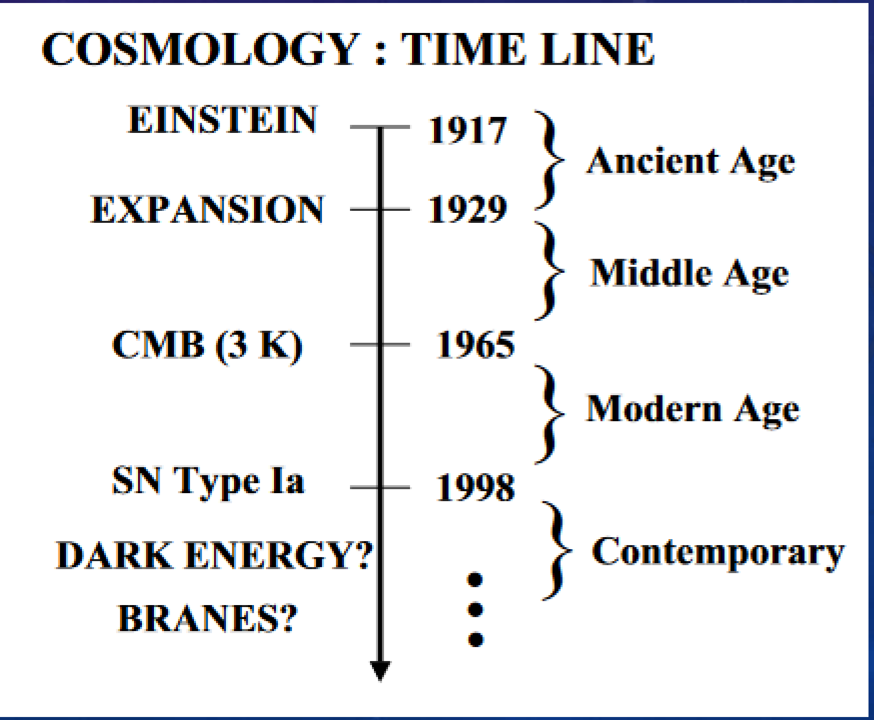
Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon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

THE STANDARD COSMOLOGICAL MODEL CHRONOLOGY

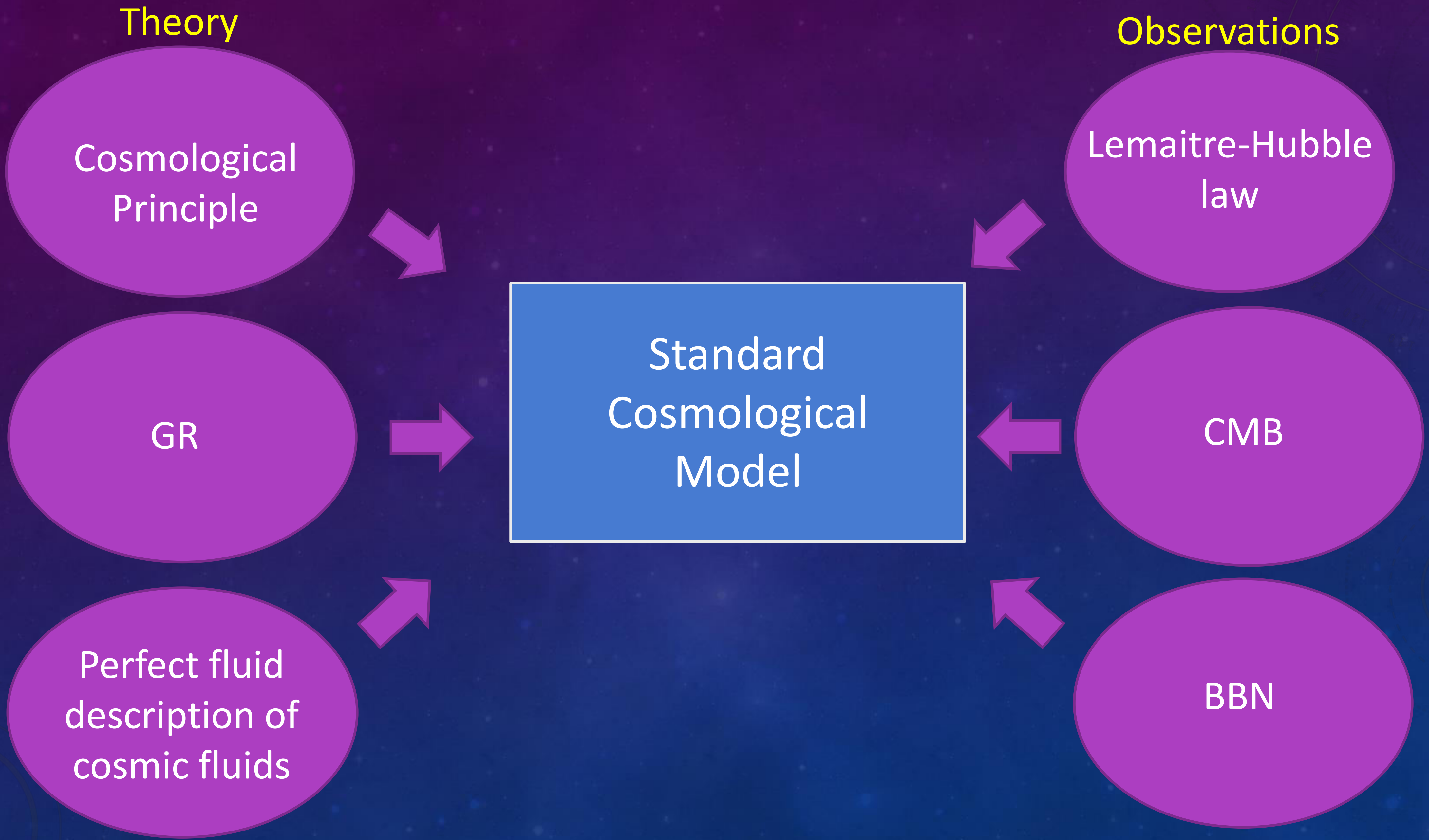
- 1915: Einstein has formulated GR
- 1917: Einstein, De Sitter try to build the first cosmological models (Prejudice: Static/Stationary universe)
- 1922: A. Friedmann
- 1927: G. Lemaitre
- 1933: Robertson, Walker

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

- 1929 Hubble's law (first confirmation)
- 1930-1965: Accumulation of proofs in favour of FLRW
- 1965: CMB Discovery (full confirmation)
- 1992: COBE measures CMB anisotrpy
- 1998: Sne studies reveal that expansion is accelerating
- 2003: WMAP observes several peaks in CMB anisotropy
- 2013: PLANCK: Density content revision



SUMMARY: PILLARS OF THE STANDARD COSMOLOGY



DARK MATTER

DARK MATTER EVIDENCES

- Astrophysical evidences

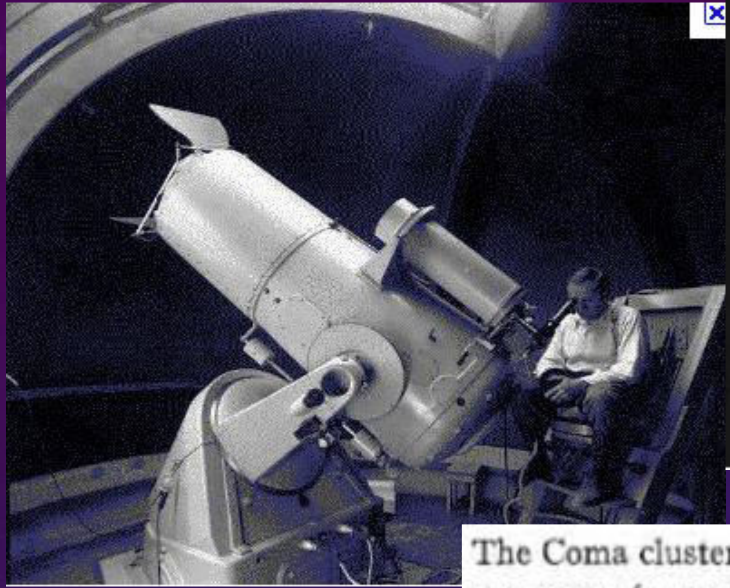
Isolated systems like galaxies and galaxy clusters.

- 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

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

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

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

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

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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 rotations* 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 rotations 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 $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

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

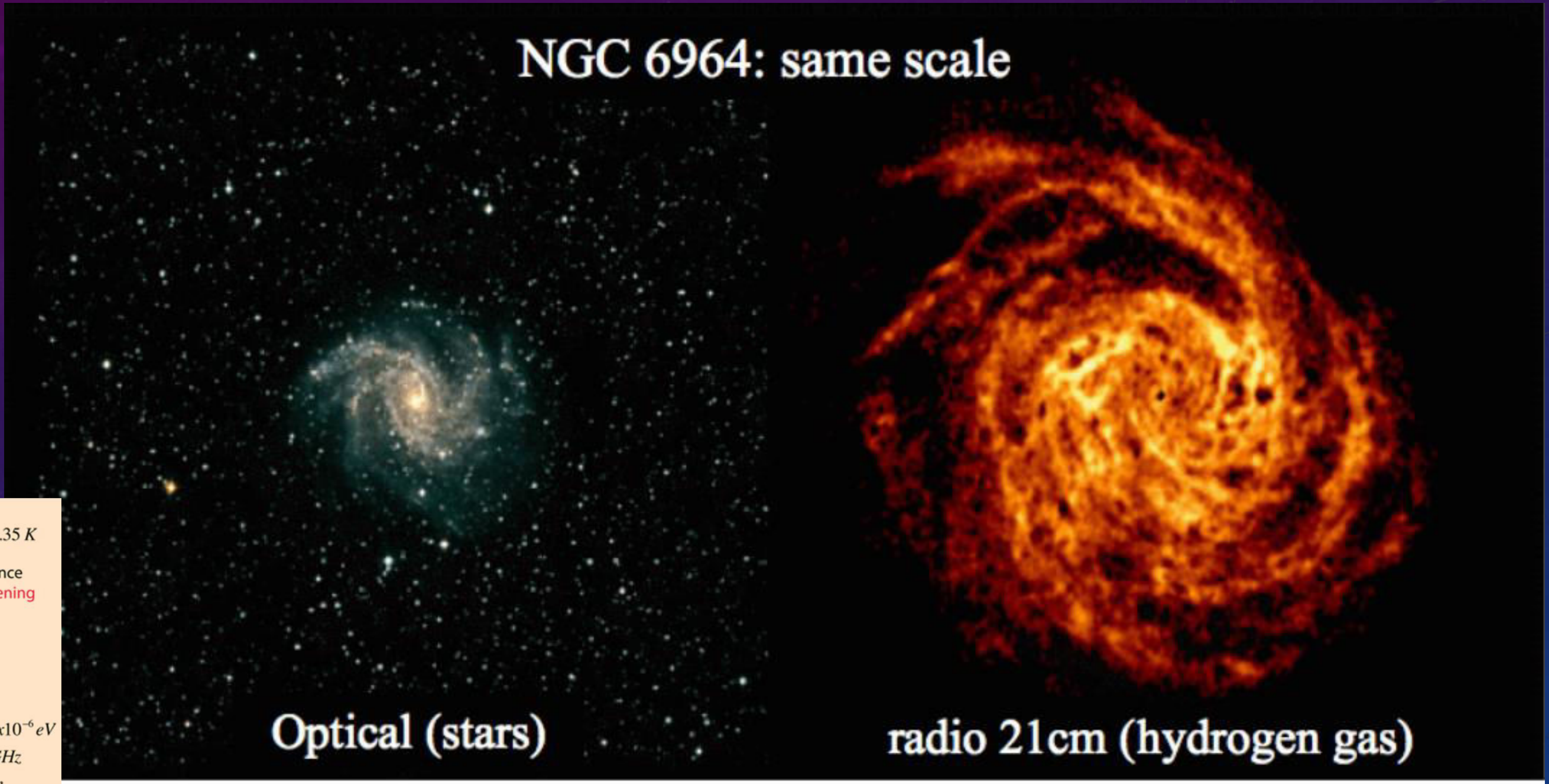
Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes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

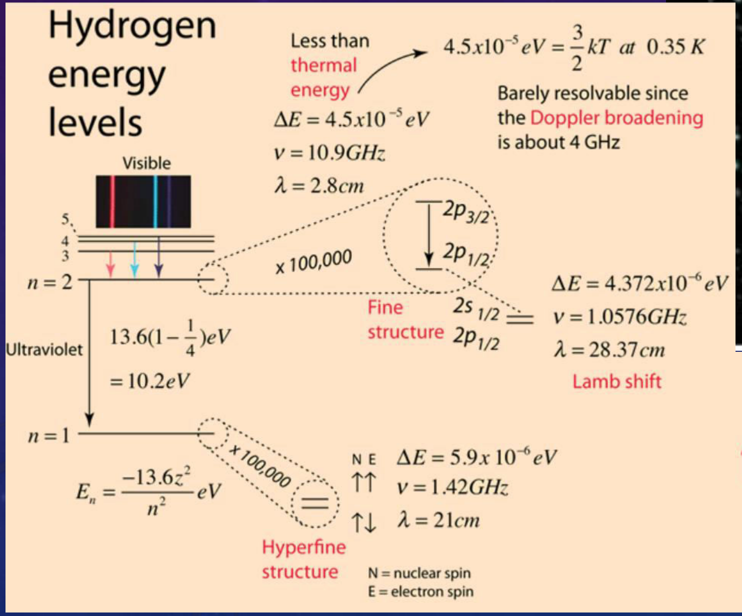
As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in 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

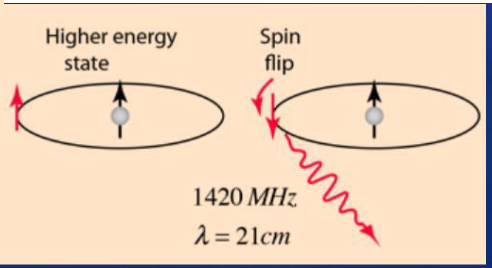
VERA RUBIN 1980

GALAXY ROTATION CURVES

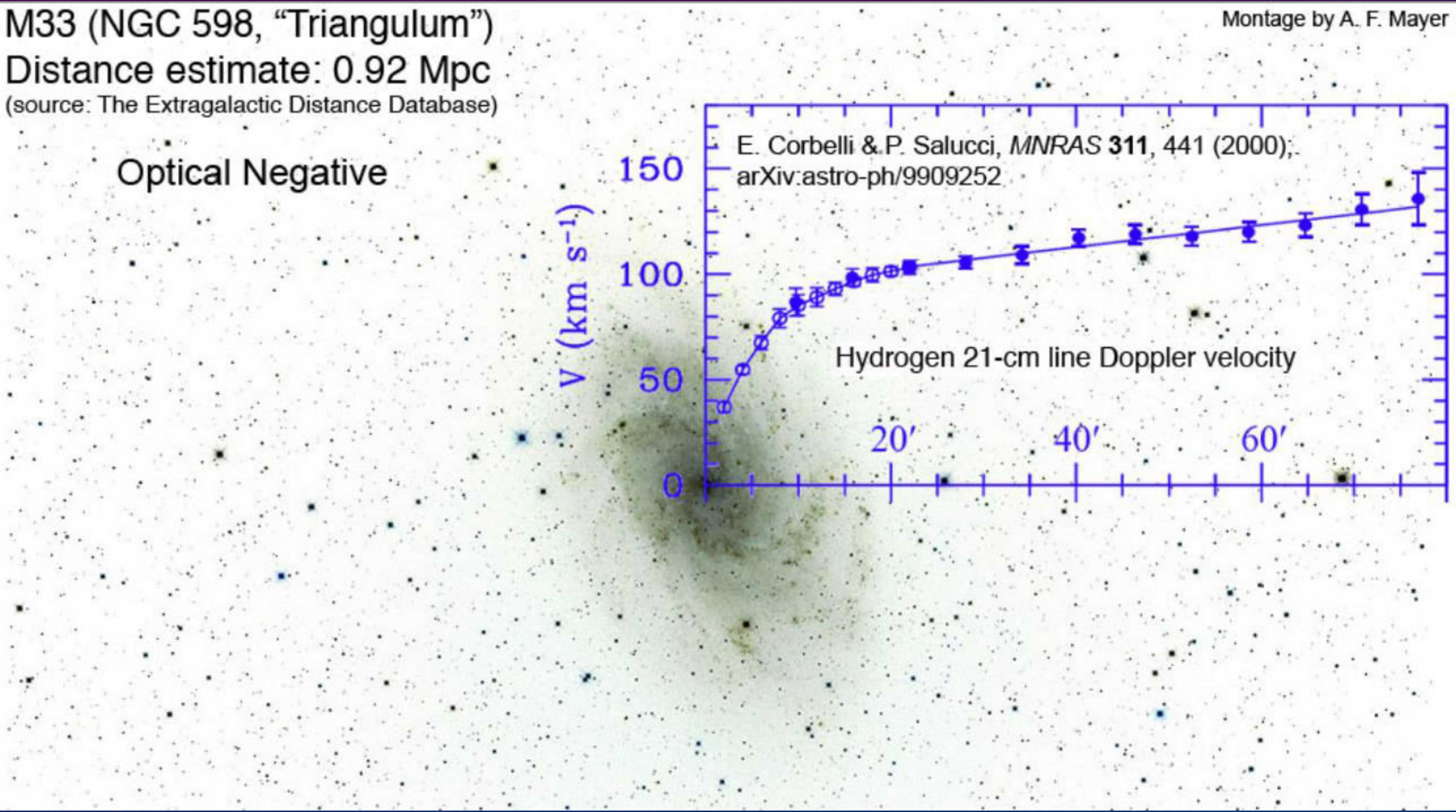
Multi-wavelength observations allows to see beyond the luminous disk







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


M33 (NGC 598, "Triangulum")
Distance estimate: 0.92 Mpc
(source: The Extragalactic Distance Database)
Montage by A. F. Mayer
Optical Negative
E. Corbelli & P. Salucci, *MNRAS* **311**, 441 (2000);
arXiv:astro-ph/9909252
Hydrogen 21-cm line Doppler velocity
V (km s^{-1})
150
100
50
0
20′
40′
60′

DISTANT GALAXIES LACK DARK MATTER

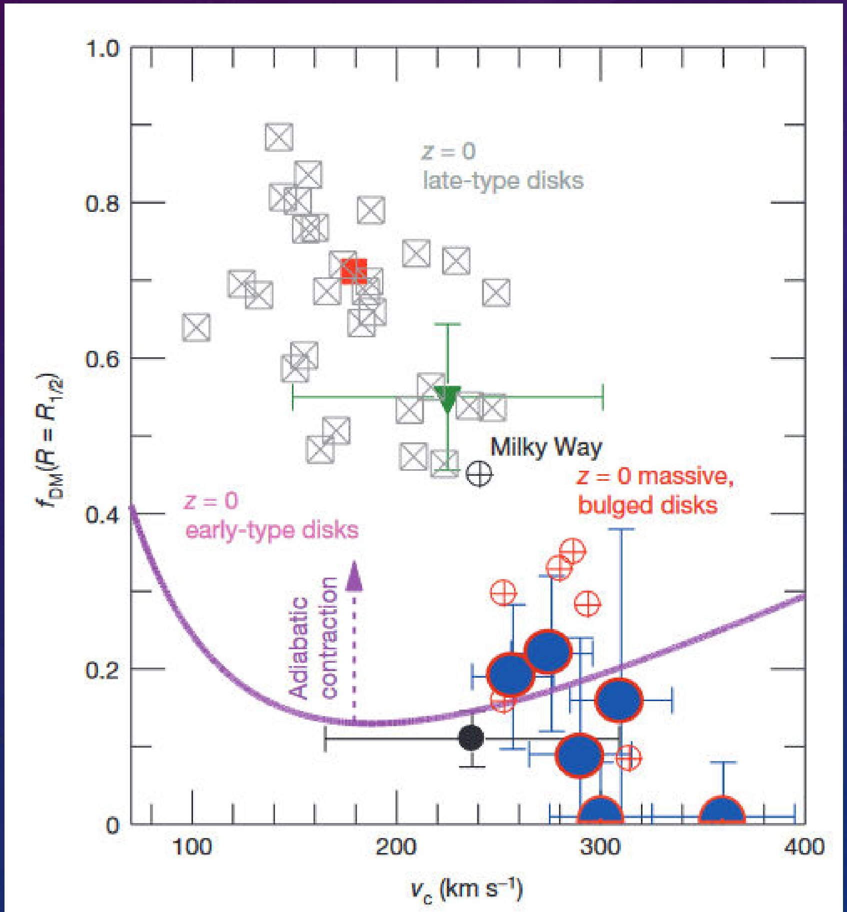
Sample in the redshift range 0.9<z<2.4

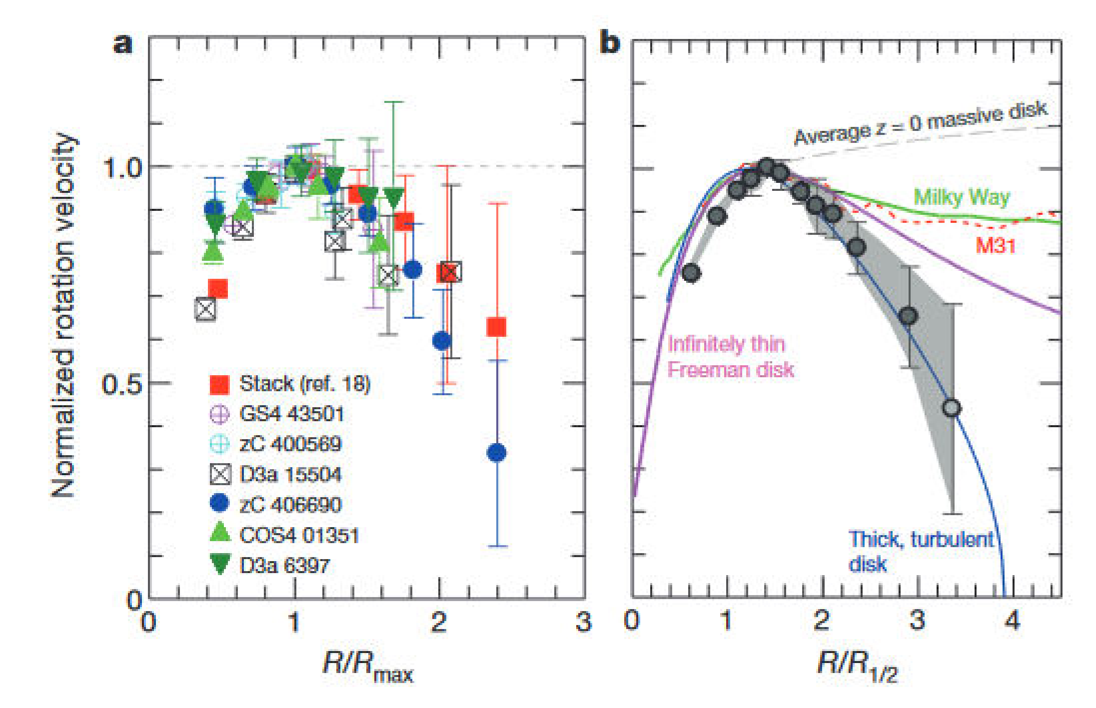
Published: 16 March 2017

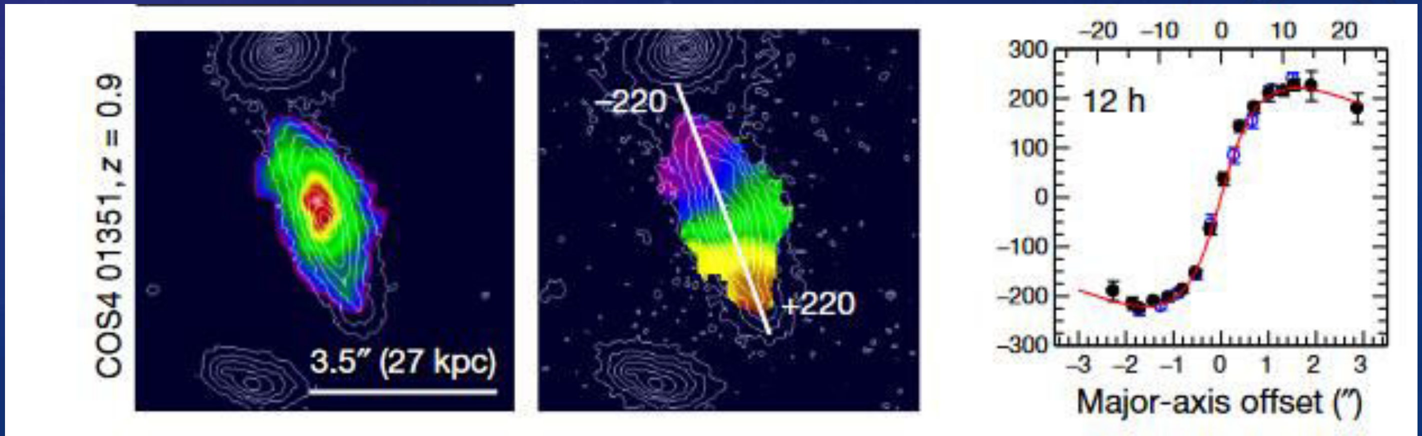
Strongly baryon-dominated disk galaxies at the peak of galaxy formation ten billion years ago

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

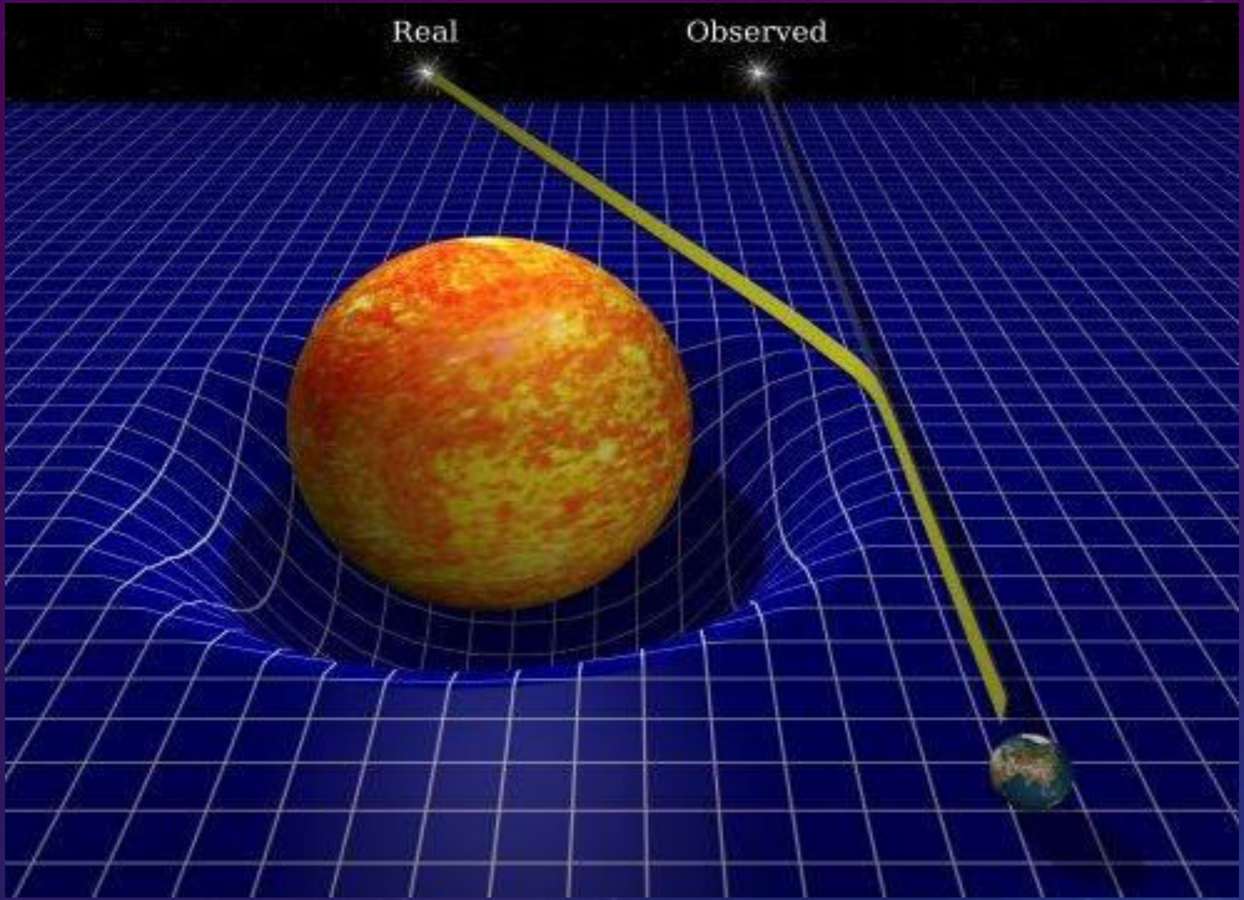
Nature **543**, 397–401 (2017) | Cite this article



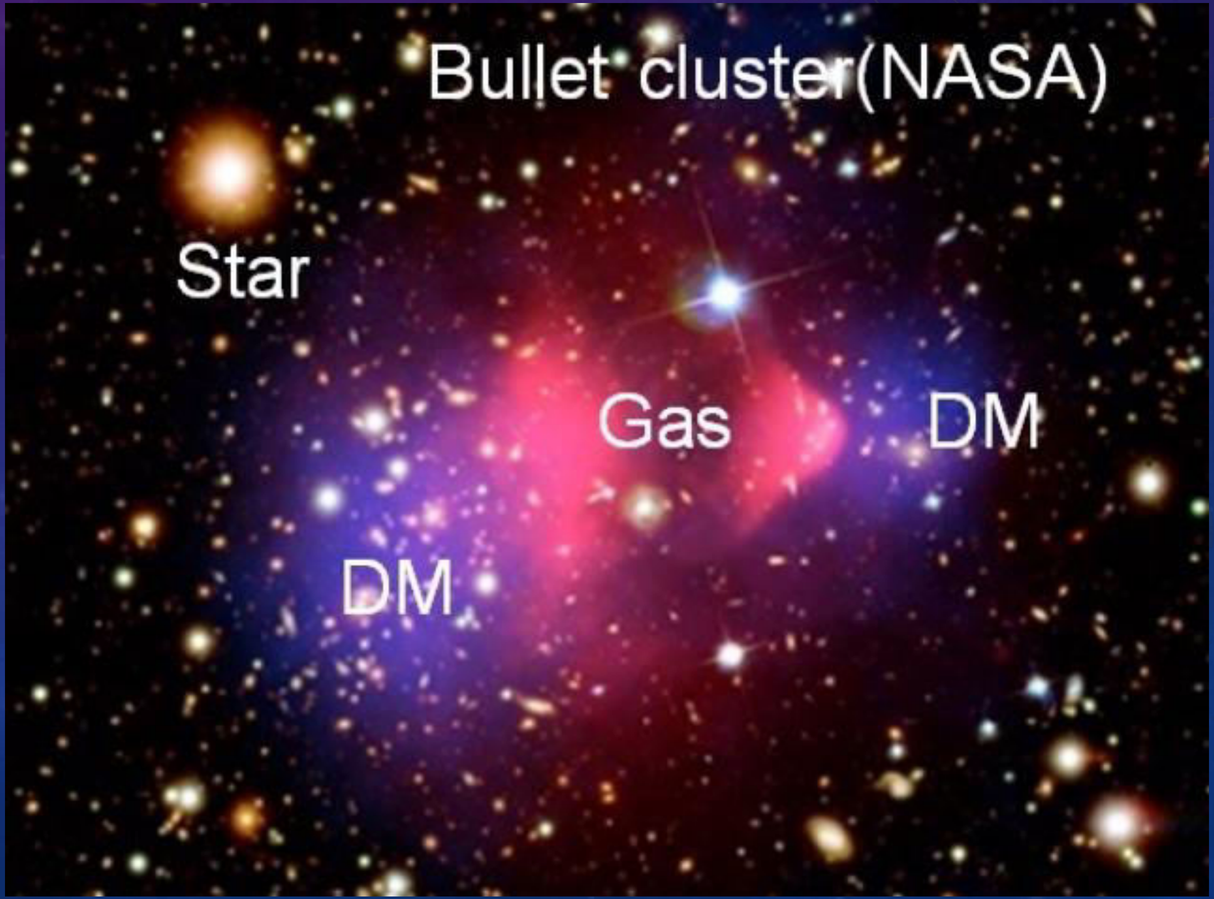




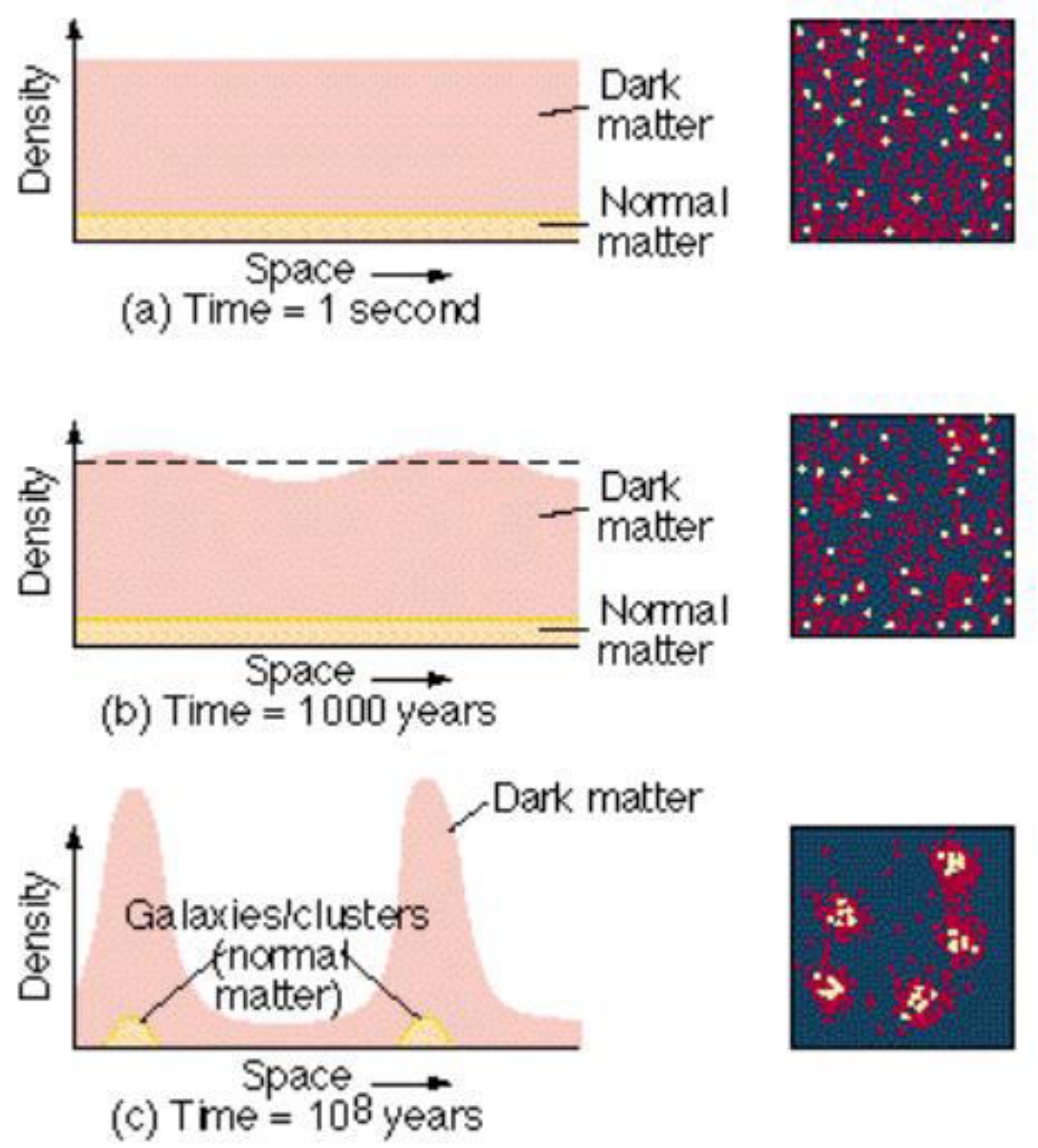
GRAVITATIONAL LENSING



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



LARGE SCALE STRUCTURE FORMATION



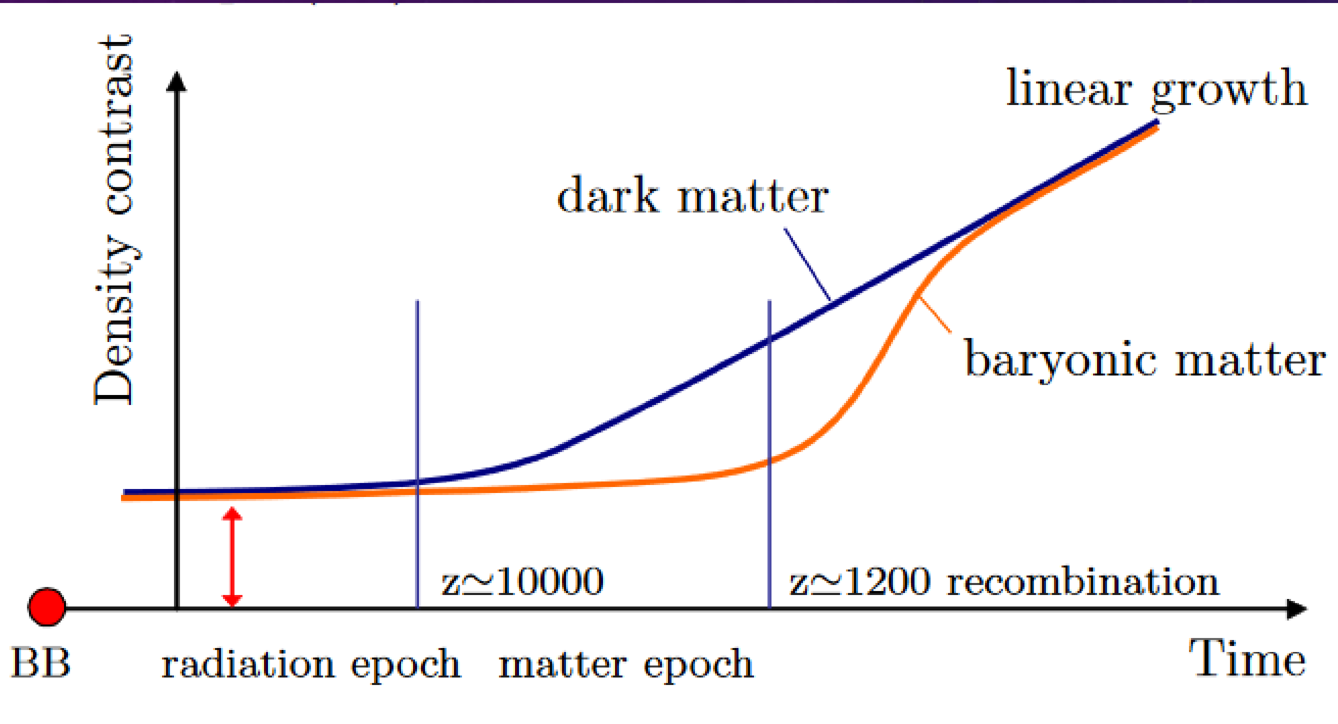
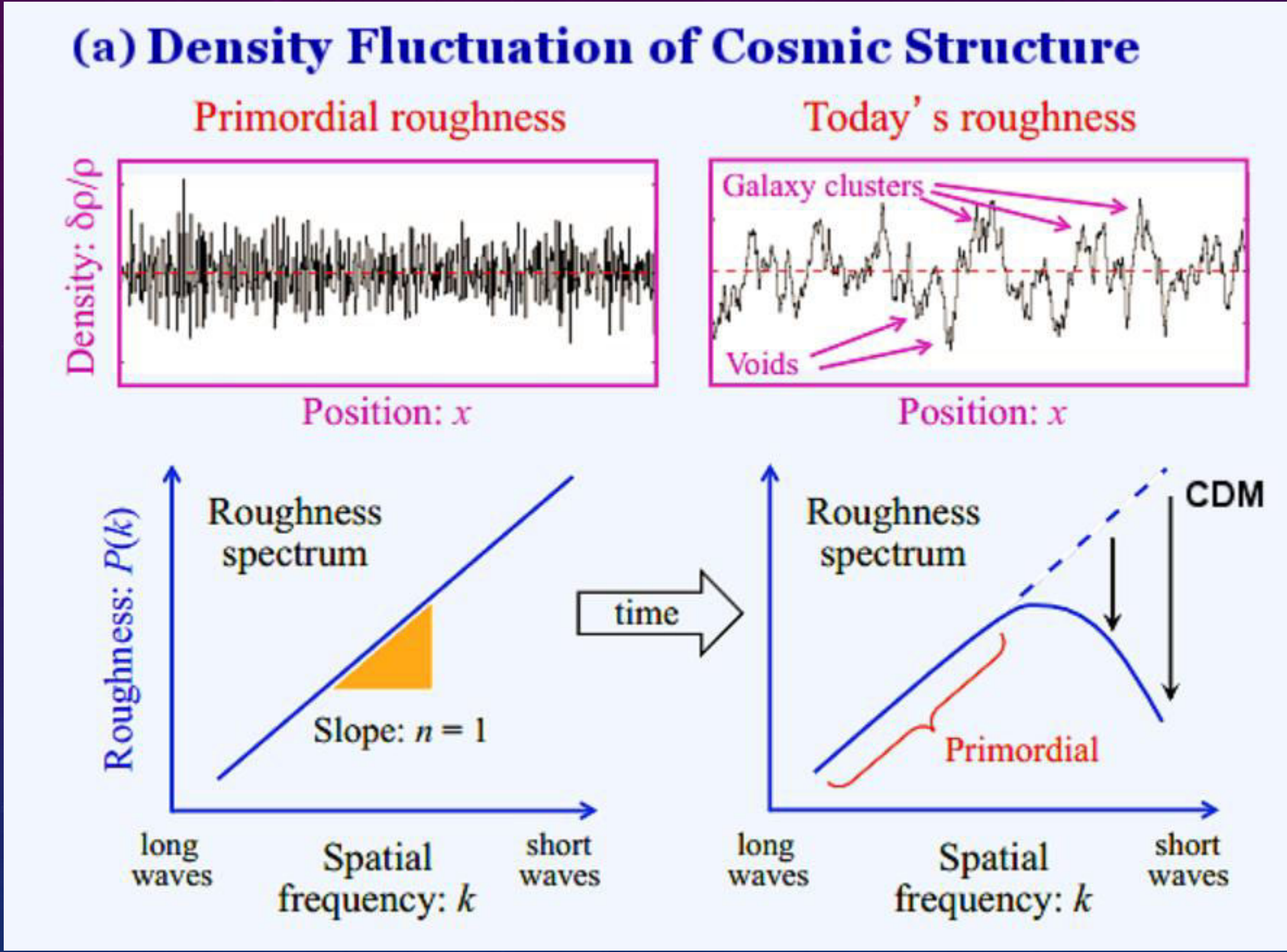
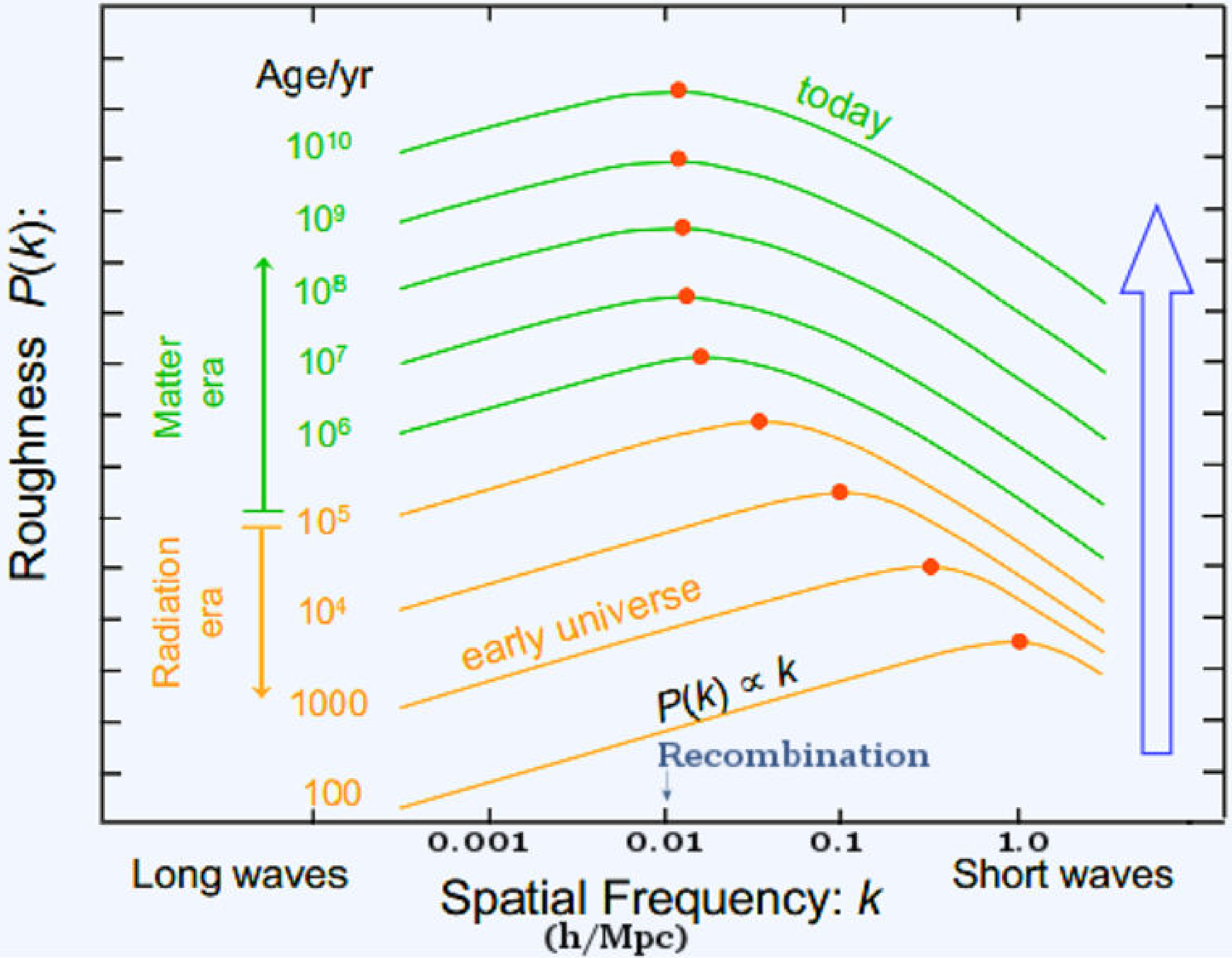


Figure 2.4: Growth of matter density contrast. After the recombination the baryonic is free to evolve and fall into the dark mater halos which formed earlier. Afterward both matter grow together.

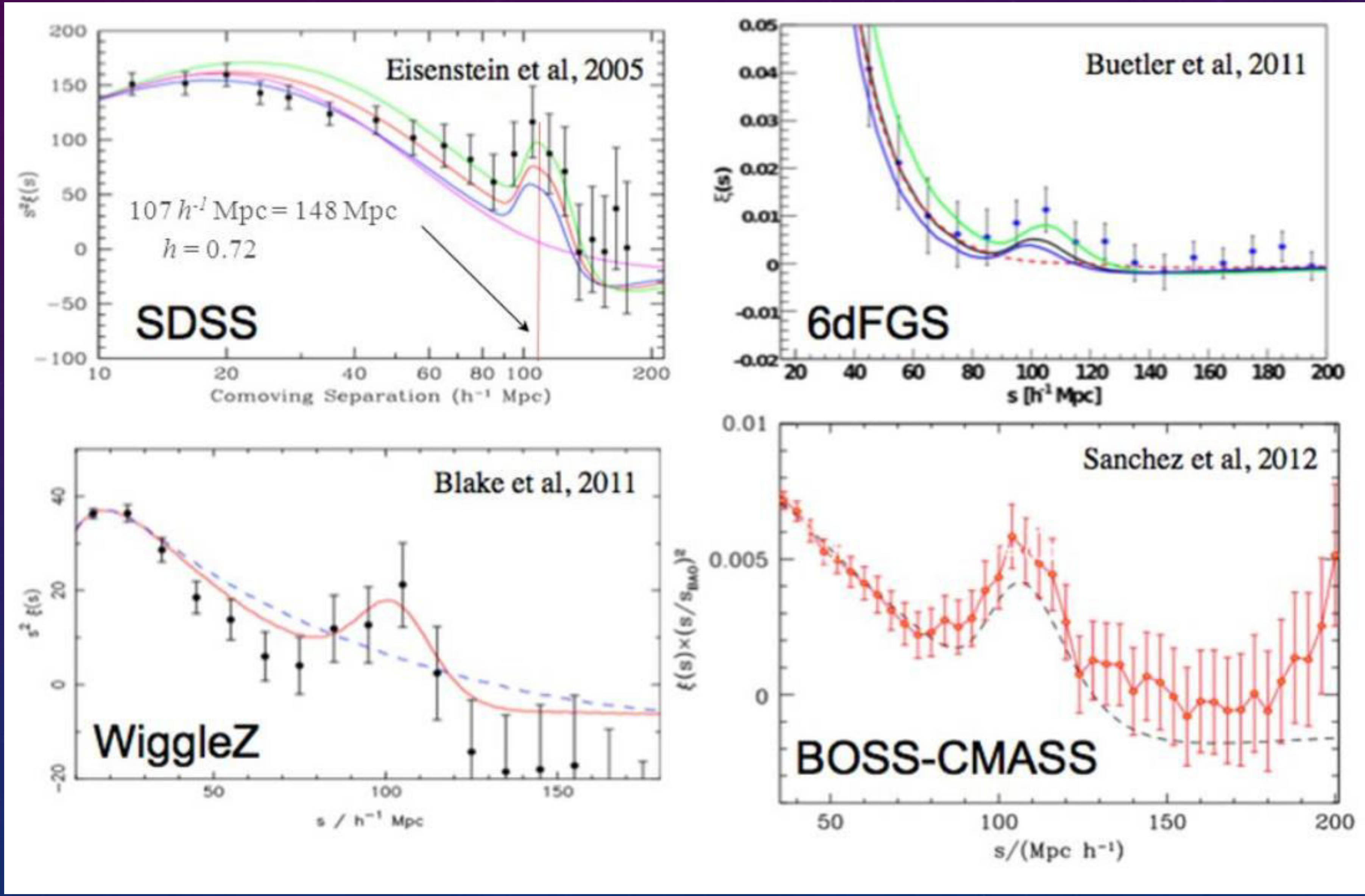


(a) Density Fluctuation of Cosmic Structure
Primordial roughness
Today's roughness
Density: δρ/ρ
Galaxy clusters
Voids
Position: x
Position: x
Roughness: P(k)
Roughness spectrum
Slope: n = 1
time
Roughness spectrum
CDM
Primordial
long waves
Spatial frequency: k
short waves
long waves
Spatial frequency: k
short waves

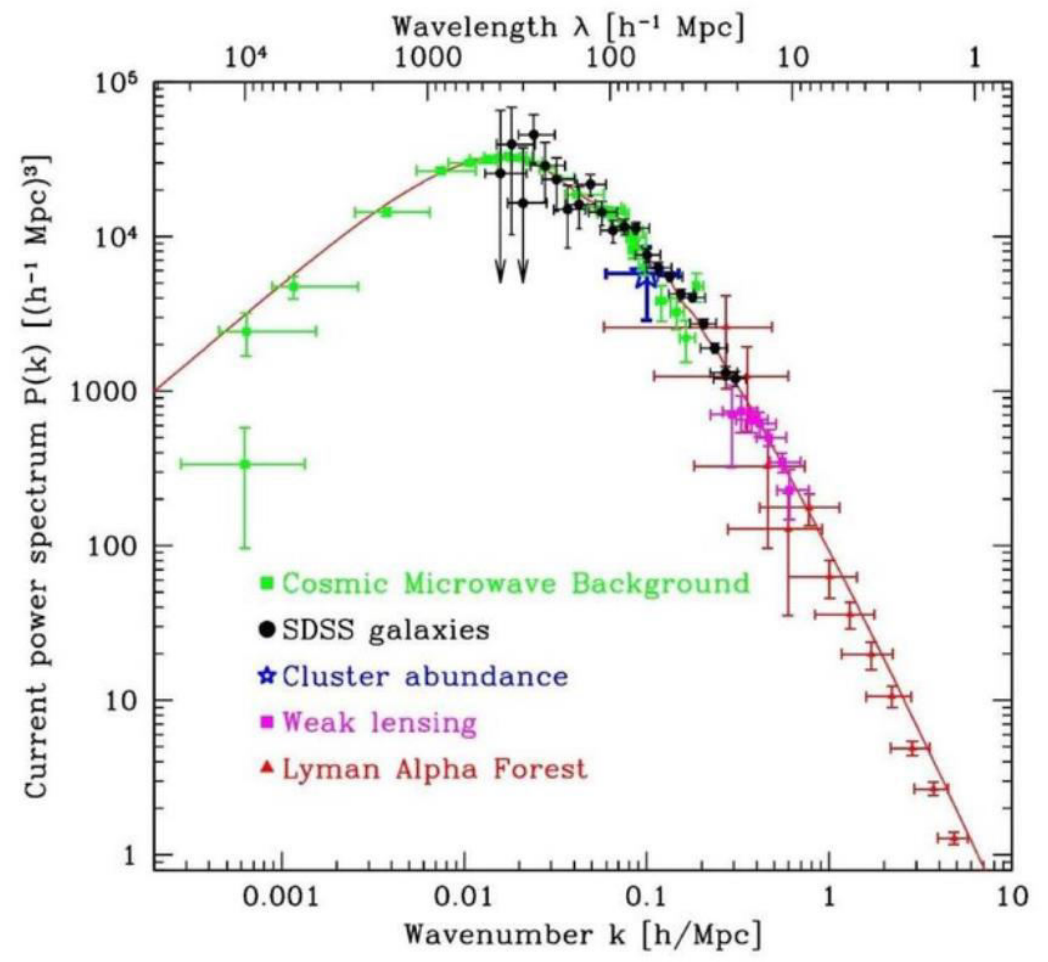
(b) Evolution of the power spectrum



BARYON ACOUSTIC OSCILATIONS



COSMOLOGICAL EVIDENCES FOR CDM



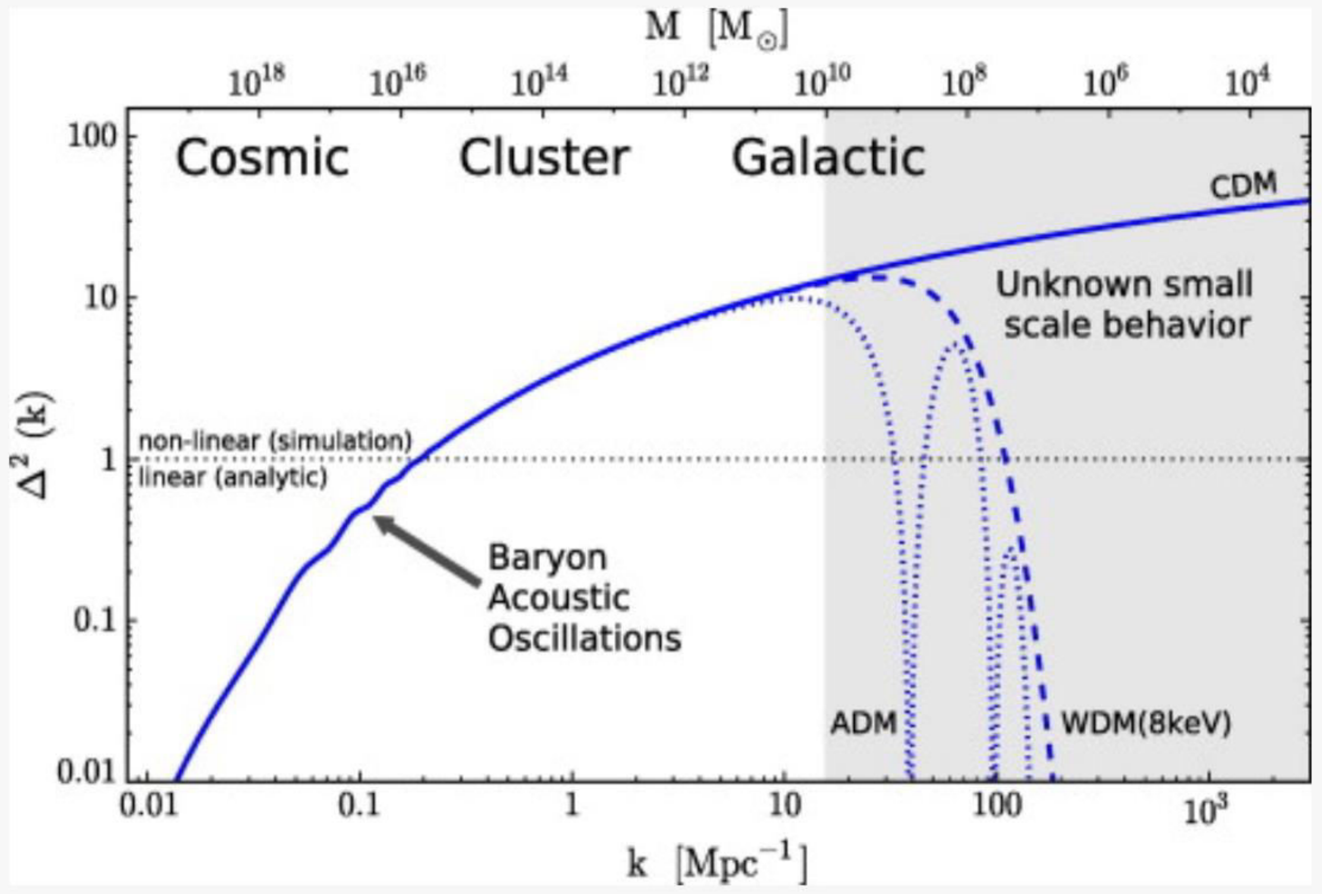


Image credit: Michael Kuhlen, Mark Vogelsberger, and Raul Angulo.

The dark matter particle?

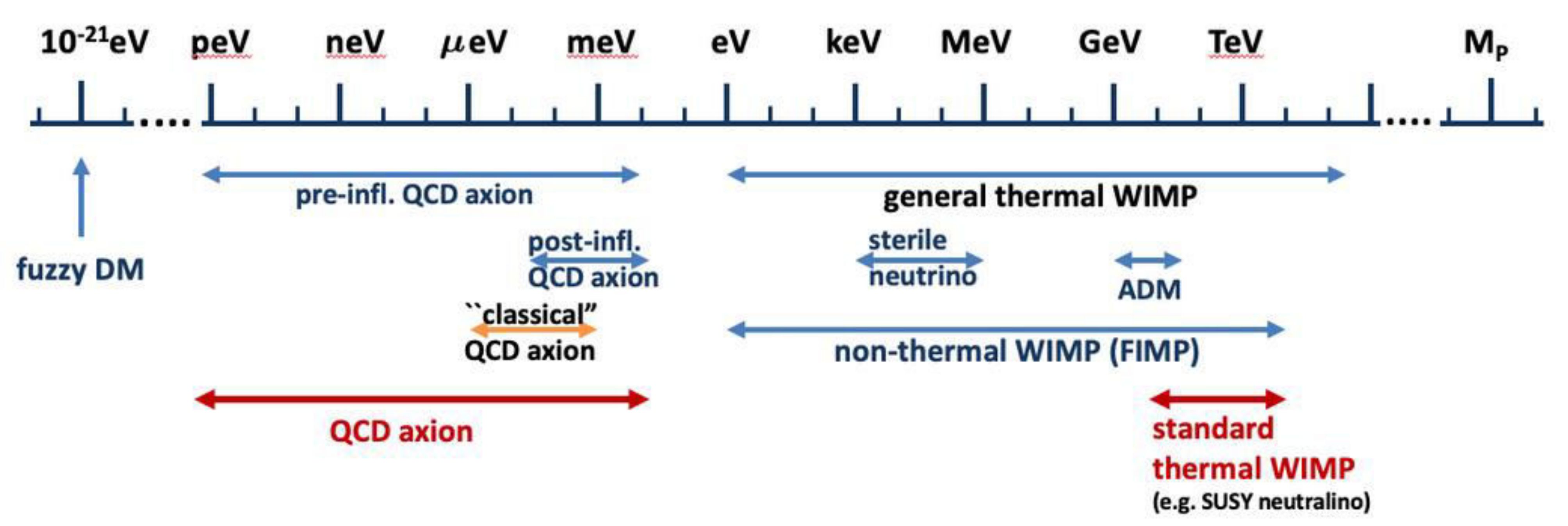
Minimum requirements for such particle candidate

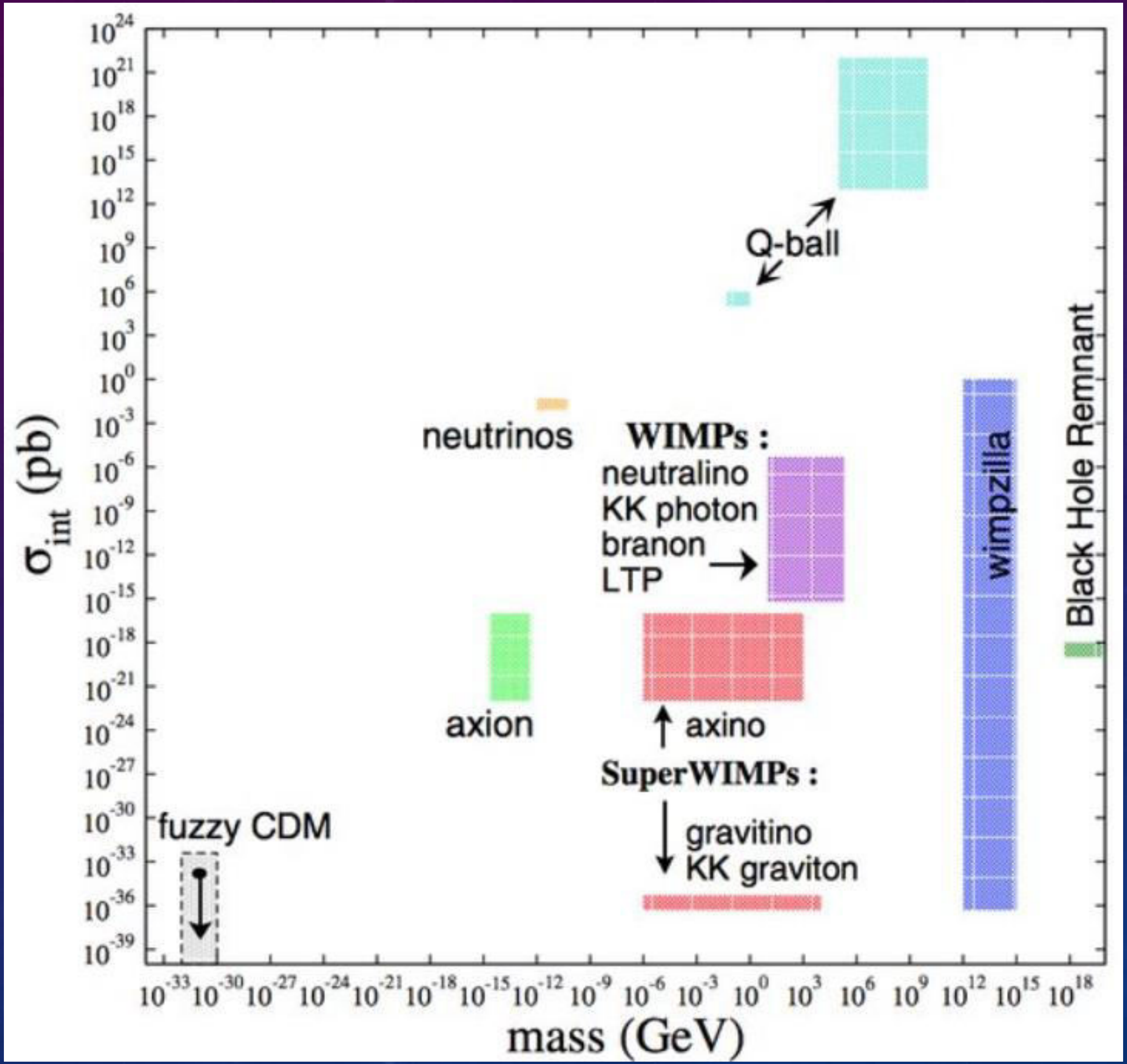
1) To Interact gravitationally;
2) Electrically neutral, otherwise it had already been detected;
3) Very small cross section (explains the lack of positive direct detection results);

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

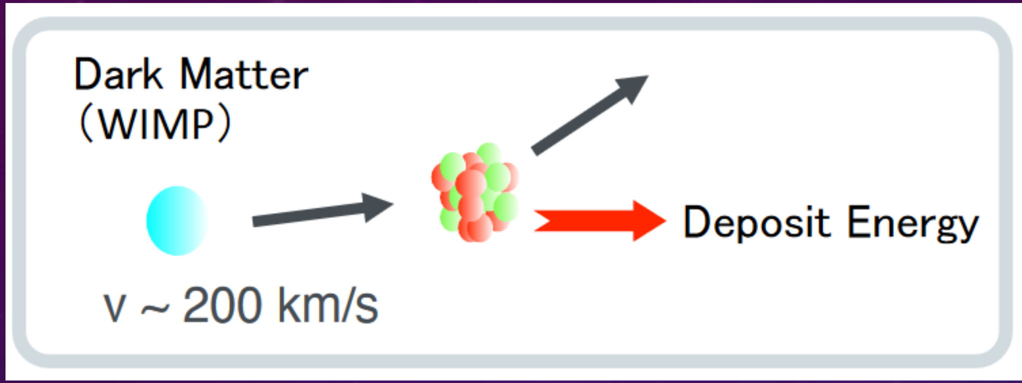
Cold dark matter: heaky and slow (prevailing view)

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



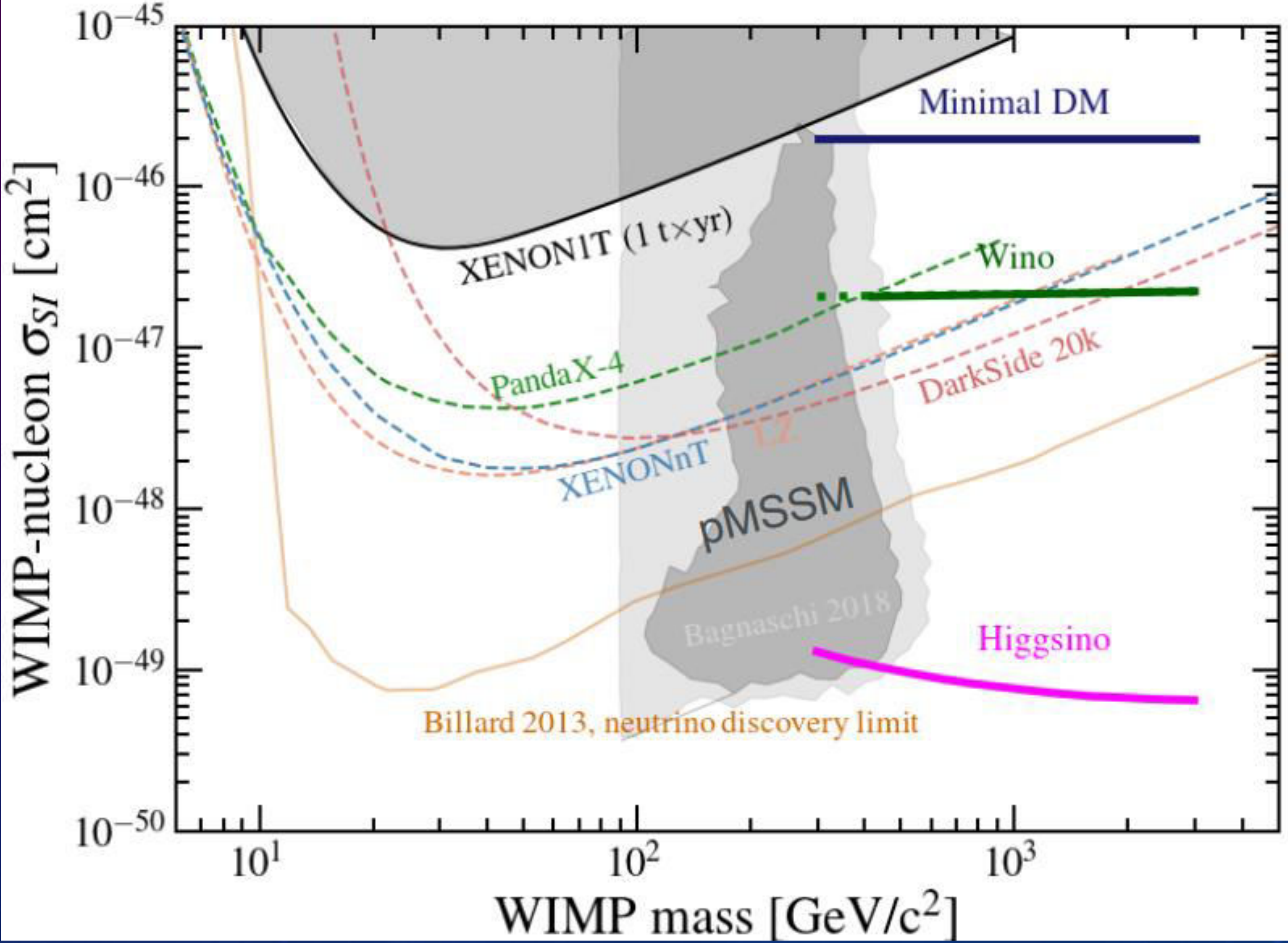


Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
σ_int (pb)
mass (GeV)

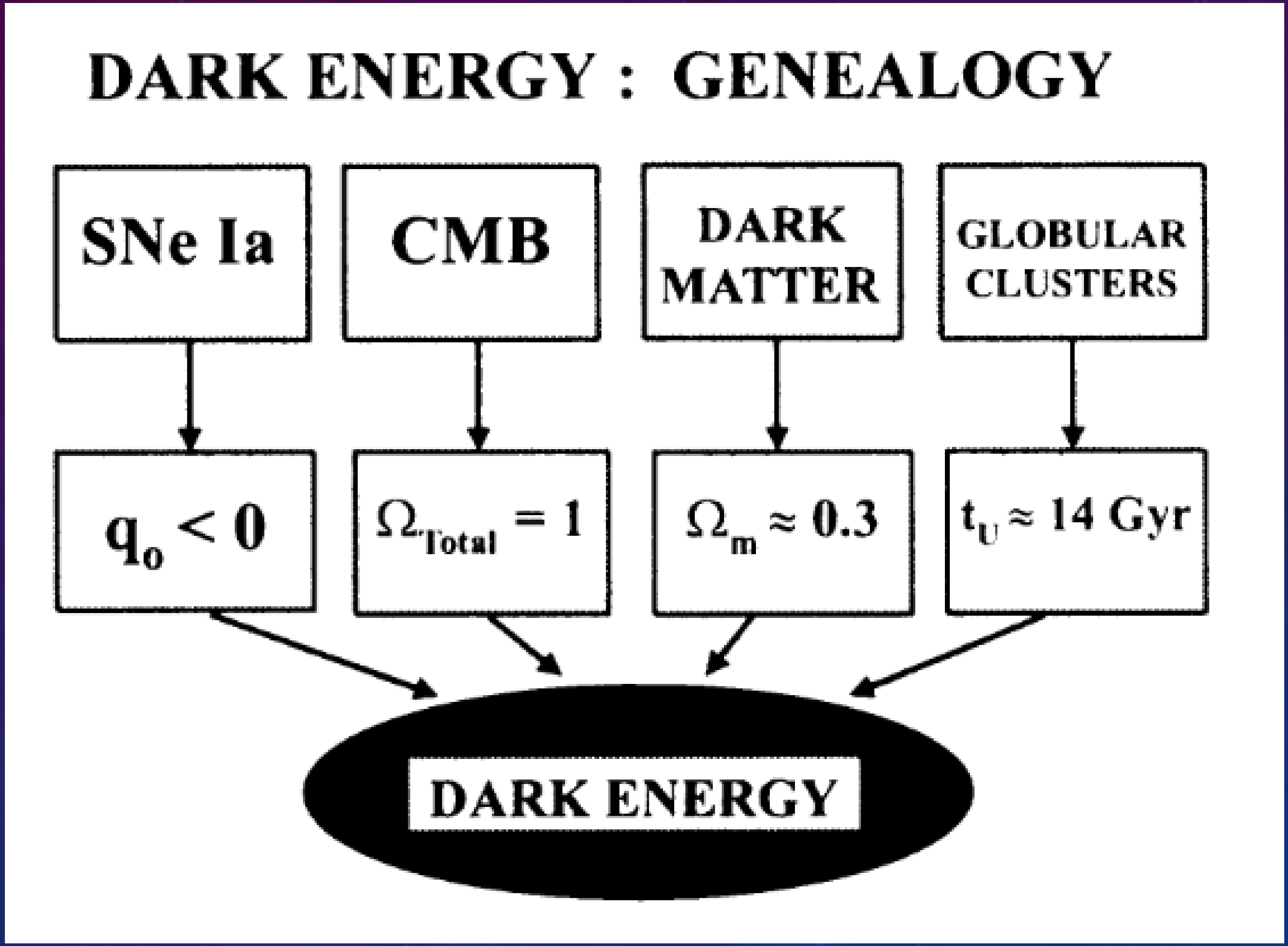

Dark Matter
(WIMP)
v ~ 200 km/s
Deposit Energy


SNOLAB
DEAP
CLEAN
PICO
NEWS-G
Boulby
NaIAD
ZEPLIN I/II/III
DRIFT I/II
Frejus
EDELWEISS
Soudan
CDMS II
CoGENT
CanFranc
IGEX
ROSEBUD
ANAIS
ArDM
Gran Sasso
DAMA/LIBRA
CRESST
XENON
DarkSide
NEWS
YangYang
KIMS, COSINE
Kamioka
XMASS
NEWAGE
PICOLON
JINPING
PANDA-X
CDEX
South Pole
DM-Ice
Finland
Sweden
Norway
Russia
United Kingdom
Poland
Germany
Ukraine
France
Italy
Kazakhstan
Mongolia
Turkey
China
South Korea
Afghanistan
Iran
Pakistan
India
Algeria
Mali
Thailand
North Atlantic
Venezuela
Colombia
Brazil
Perú
Bolivia
Chile
Argentina
México
South Atlantic Ocean
Angola
Namibia
Botswana
South Africa
Madagascar
Indian Ocean
Papua New Guinea
Australia
New Zealand

Generation2 : 2020-2025



DARK ENERGY



DARK ENERGY : GENEALOGY
SNe Ia
CMB
DARK MATTER
GLOBULAR CLUSTERS
$q_o < 0$
$\Omega_{Total} = 1$
$\Omega_m \approx 0.3$
$t_U \approx 14$ Gyr
DARK ENERGY

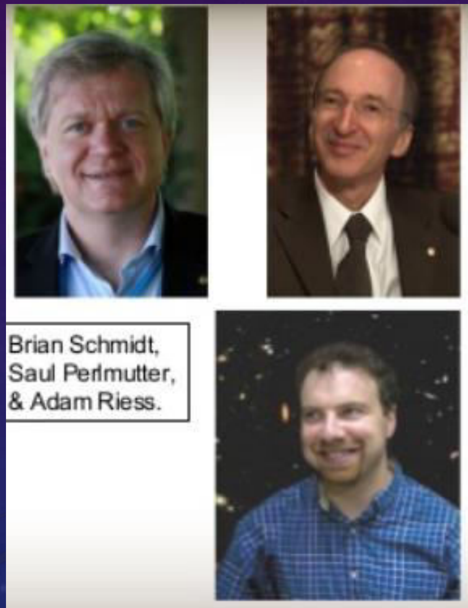
SUPERNOVAE AND THE ACCELERATED EXPANSION OF THE UNIVERSE: THE DARK ENERGY PHENOMENA

Hermano Velten

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"



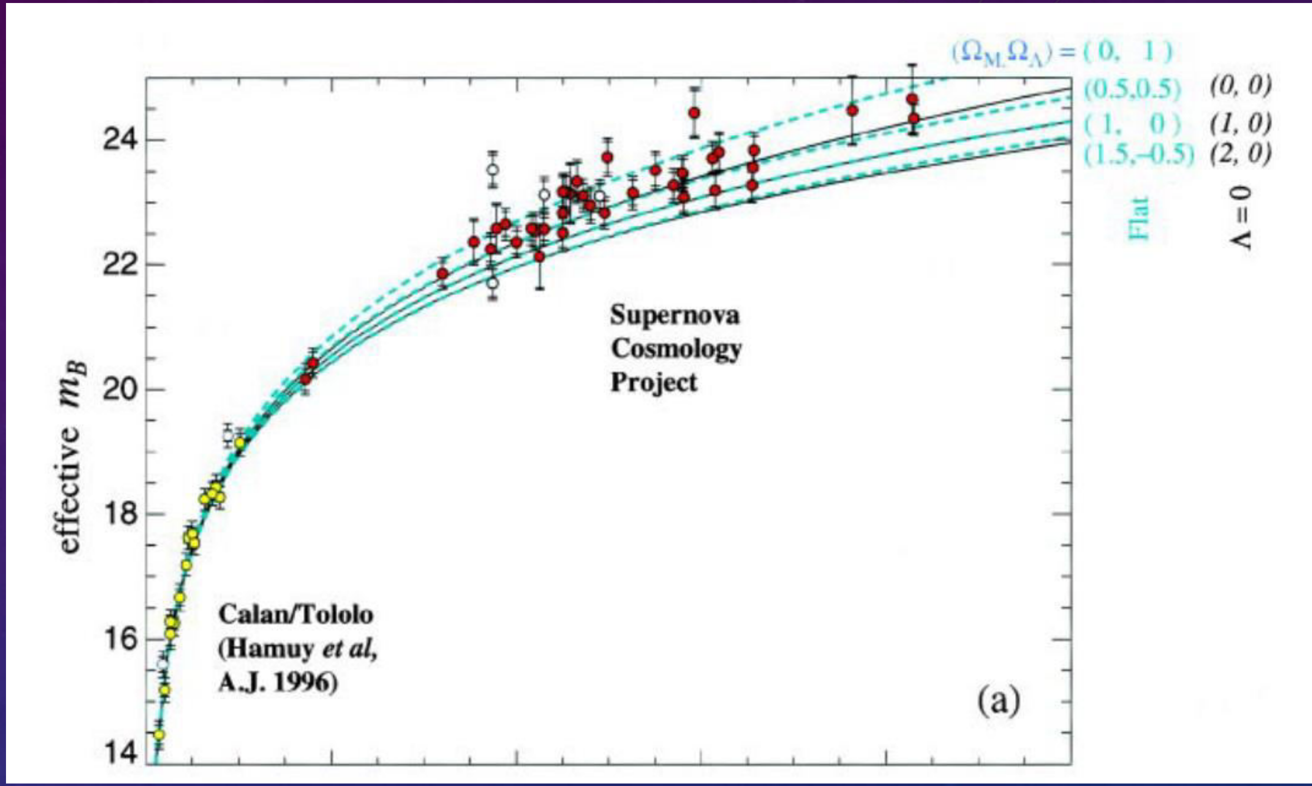
Brian Schmidt, Saul Perlmutter, & Adam Riess.

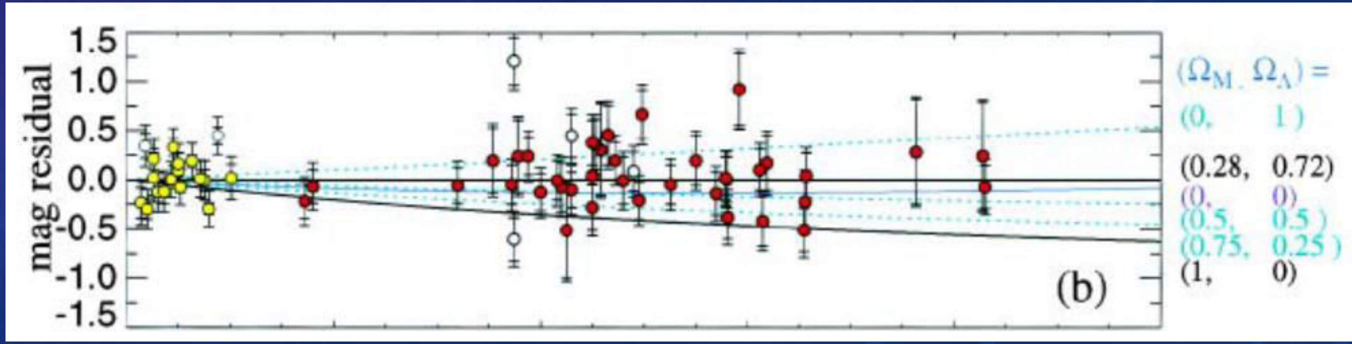
In 1998/9, published observations of ***Type Ia supernovae*** by

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

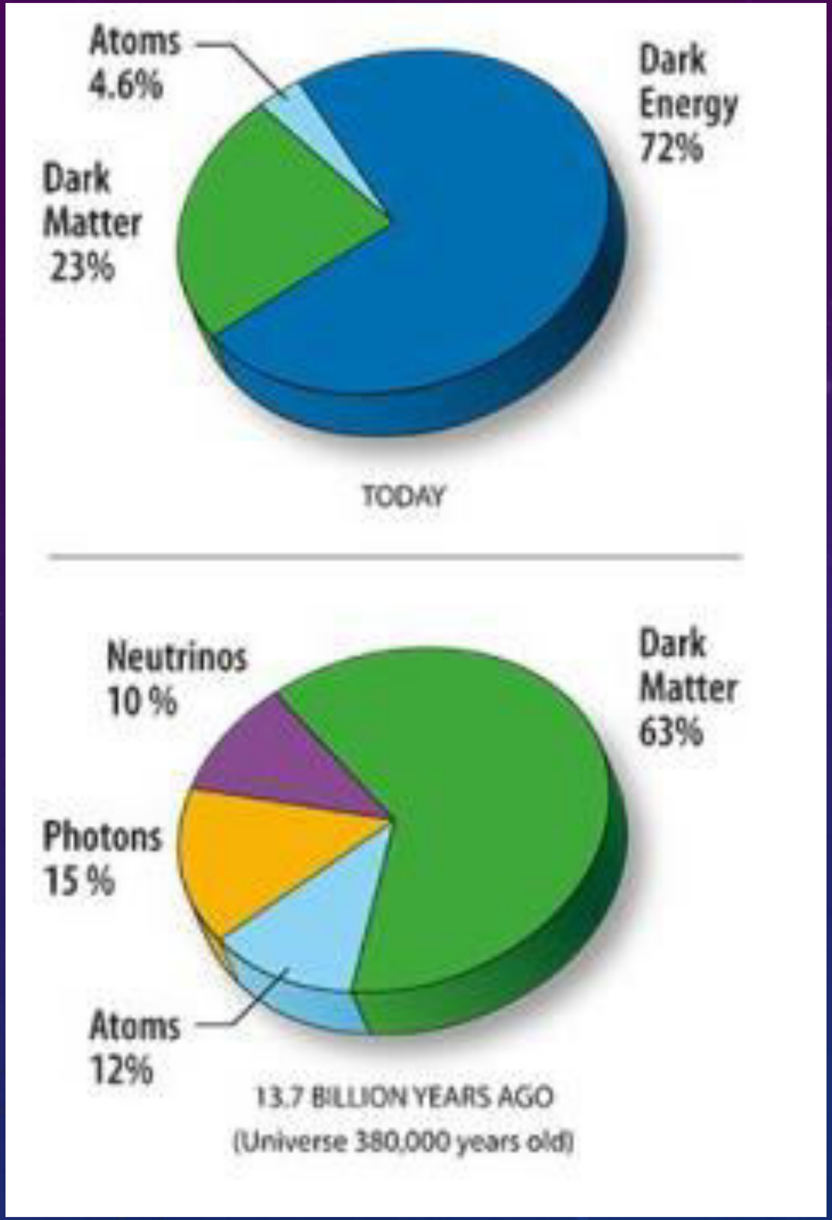
suggested that the expansion of the universe is *actually accelerating* – a total surprise to everyone.

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





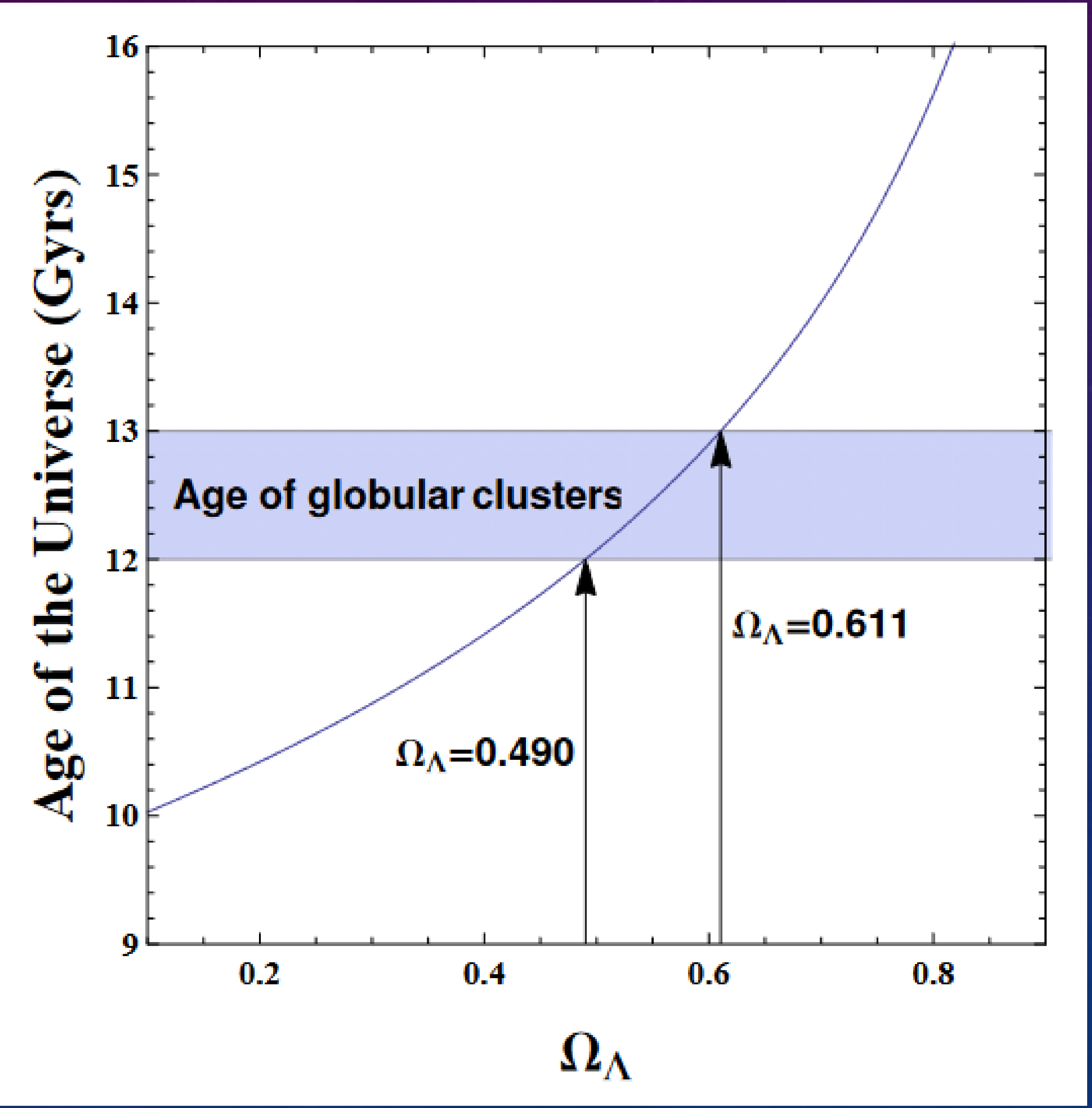
COSMIC ENERGY BUDGET



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

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

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 •

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

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.

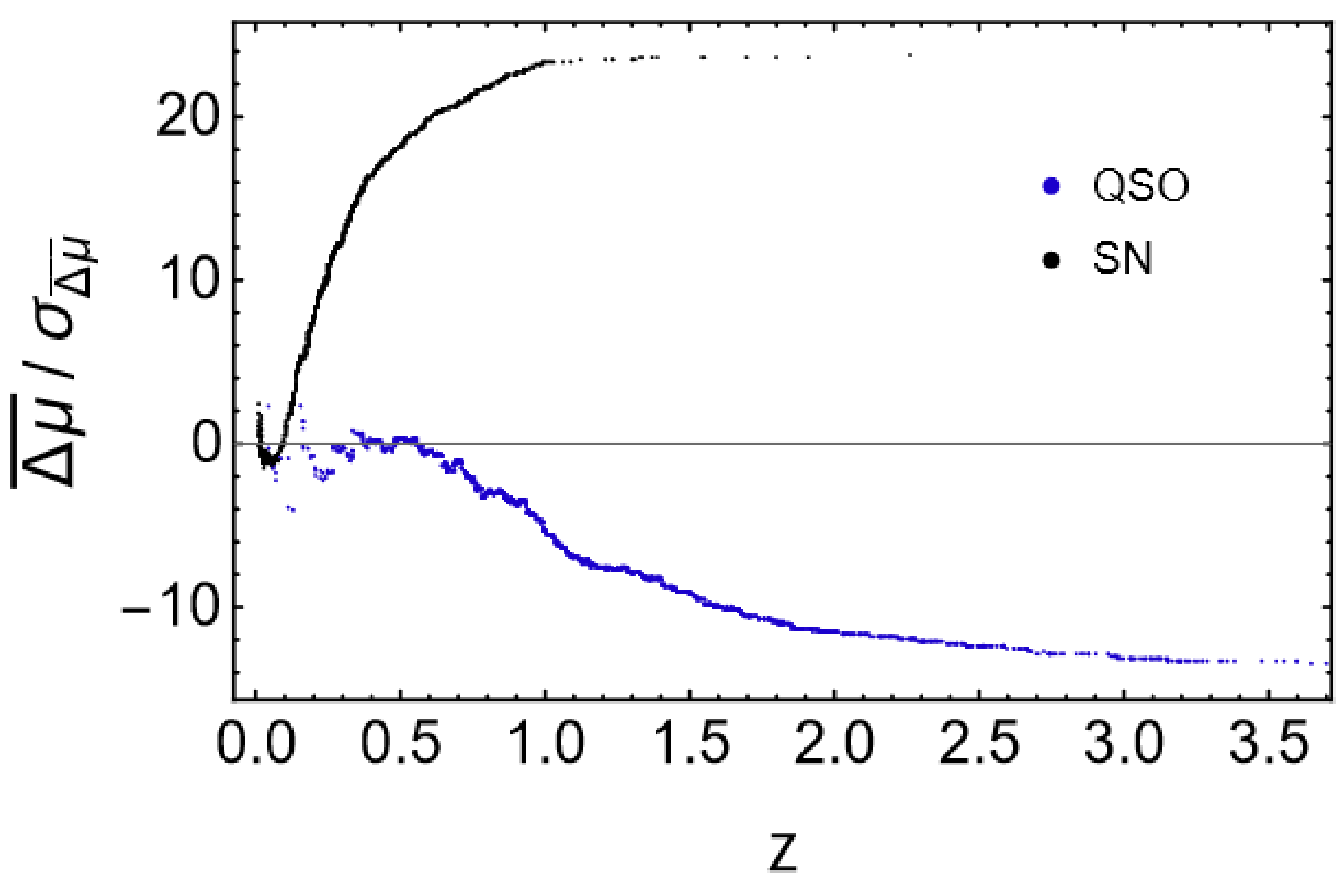
Sample	$\overline{\Delta\mu}$ / $\sigma_{\overline{\Delta\mu}}$ Evidence	# of Objects	Mean redshift
FULL JLA	+20.40	740	0.32
JLA no low-z	+22.33	588	0.40
Pantheon ΛCDM	+23.73	1048	0.32
Pantheon ΛCDM no low-z	+28.25	837	0.39
Pantheon wCDM	+24.23	1048	0.32
Pantheon wCDM no low-z	+28.73	837	0.39
Pantheon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

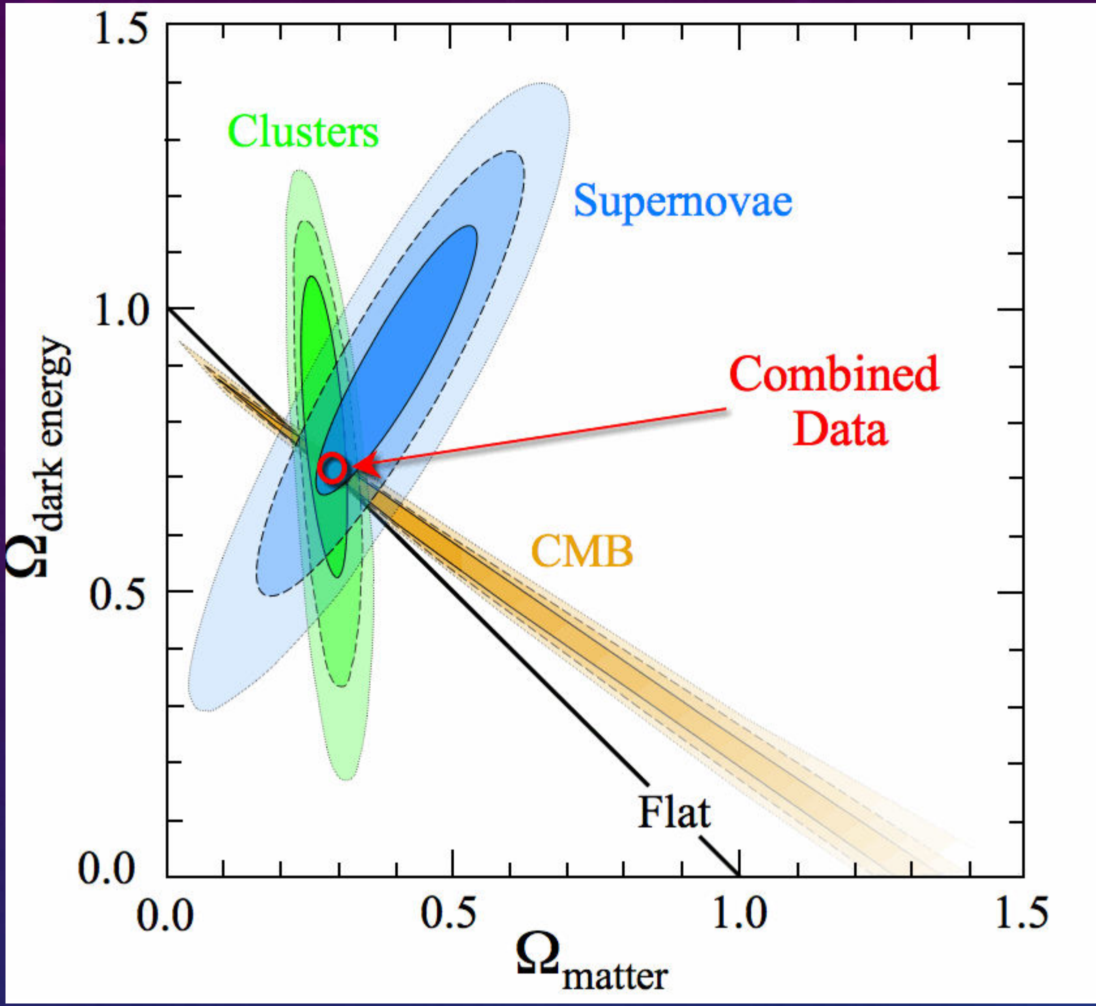
Hermano Velten, Syrios Gomes (Nov 26, 2019)

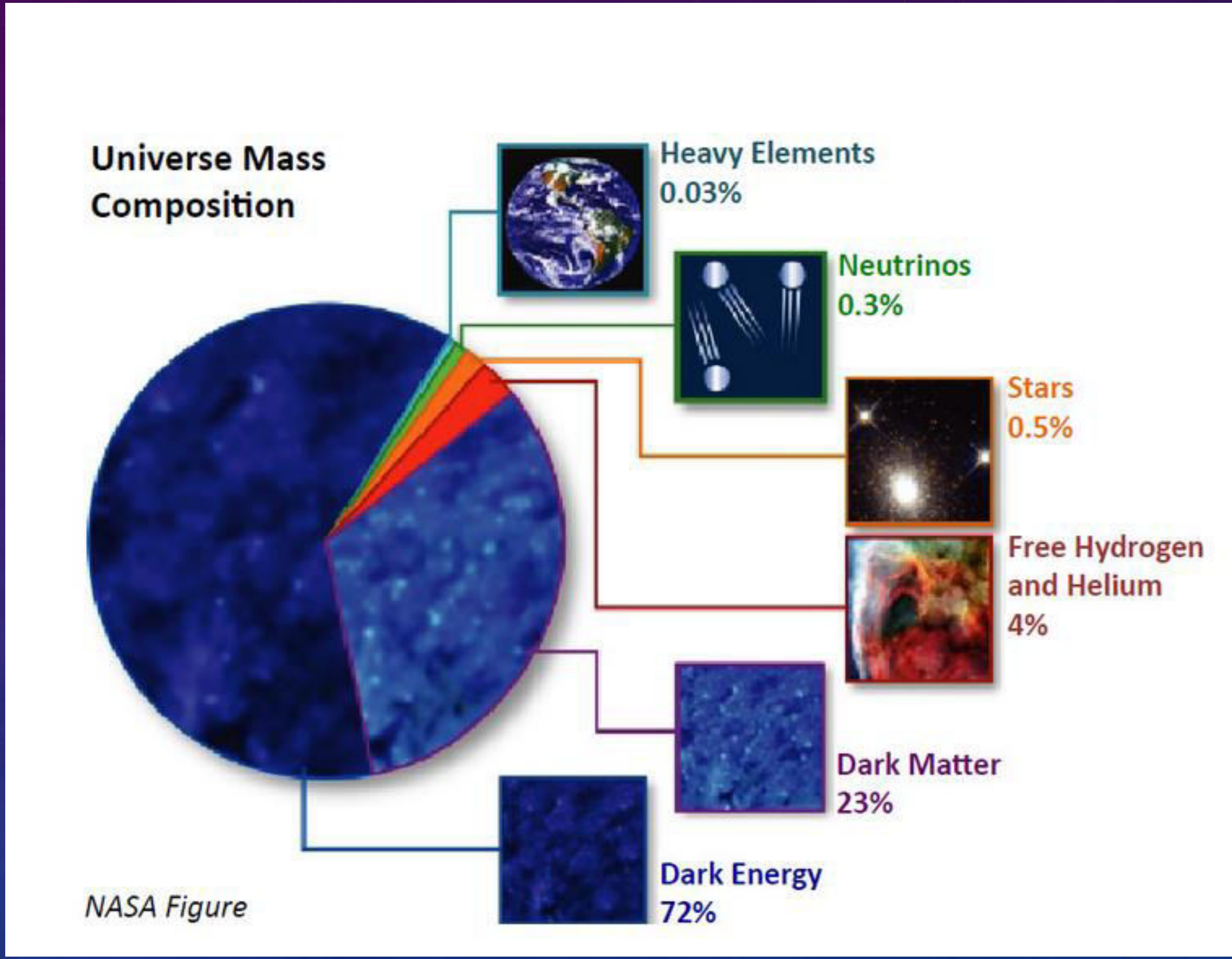
Published in: *Phys.Rev.D* 101 (2020) 4, 043502



Hermano Velten

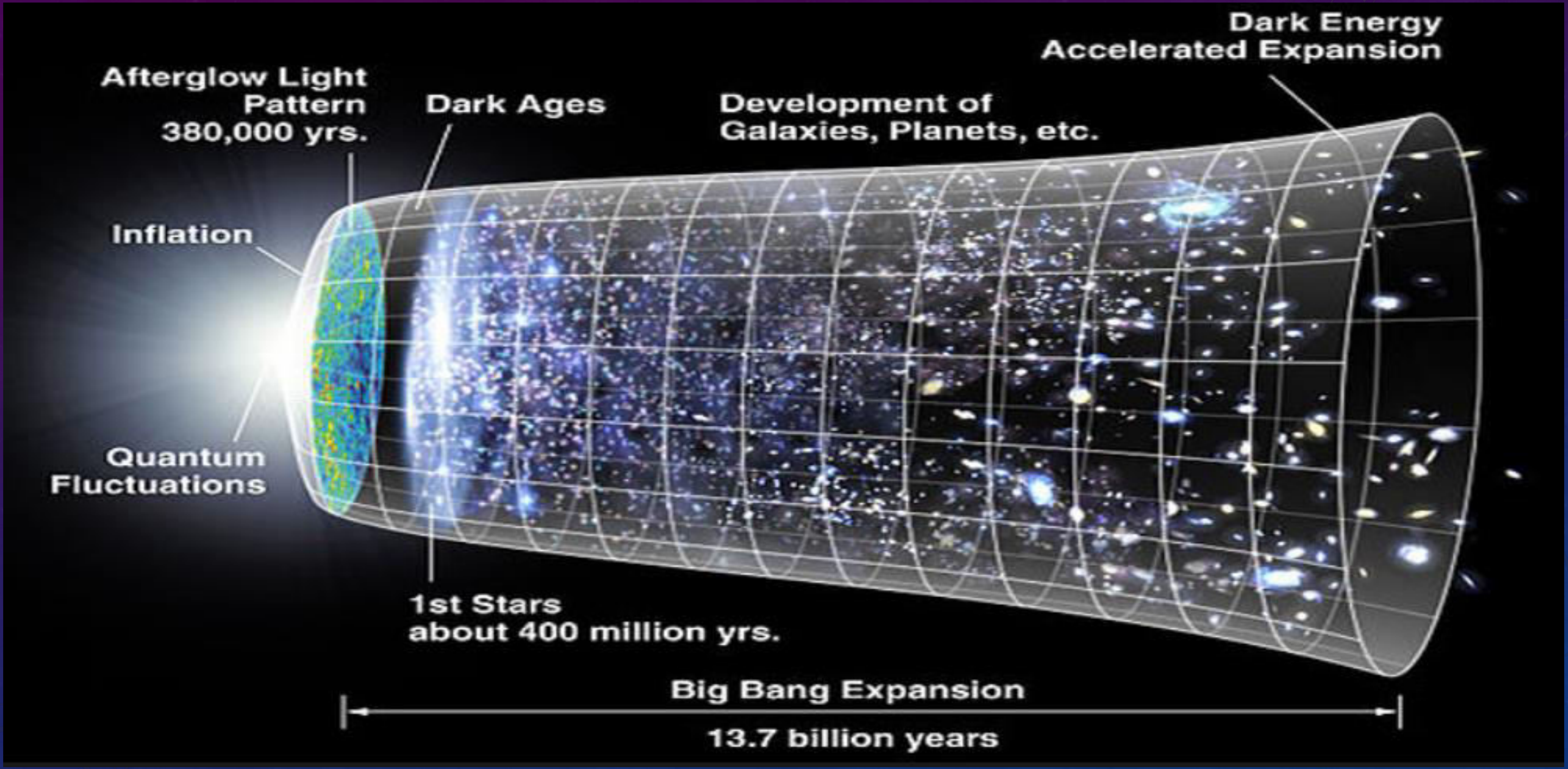
CONCORDANCE COSMOLOGICAL MODEL





DM AND DE CORRESPOND TO 95% OF THE COSMIC ENERGY BUDGET

WE HAVE NO DIRECT EVIDENCES FOR THESE PARTICLES/FIELDS


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

SIMPLE DARK ENERGY MODELS

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

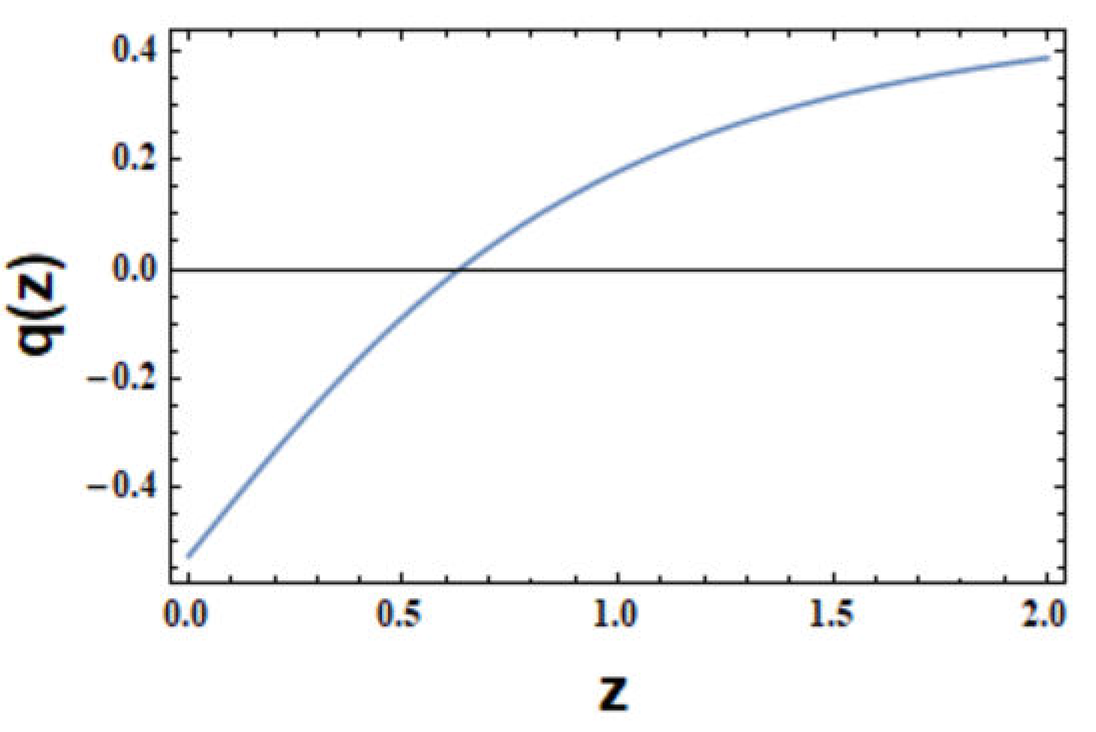
$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho_{\rm tot}$$

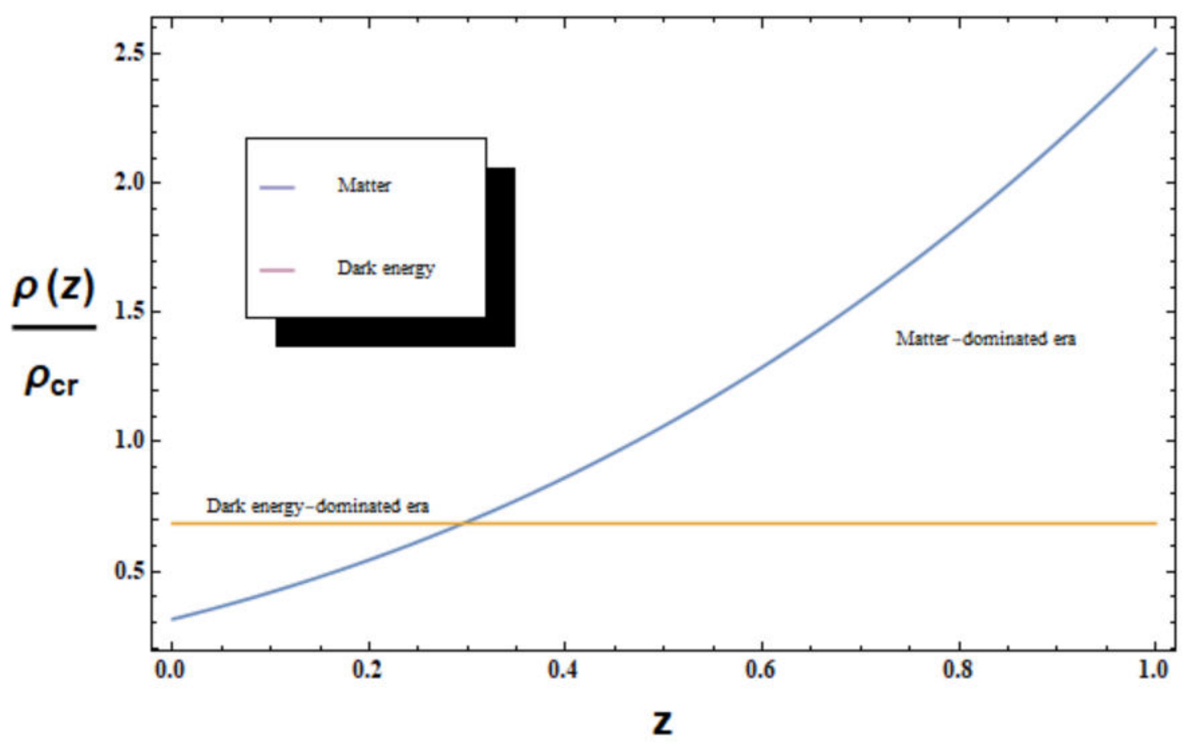
Simplest evolution of the late time cosmological background

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_{\rm m0}}{a^3} + (1-\Omega_{\rm m0})\, e^{-\int da \frac{1+w_{\rm DE}}{a}}$$

DECELERATION PARAMETER

$$q(z) = \frac{H'(z)}{H(z)}(1+z) - 1$$





2.6 Gyrs between acceleration starts and DE dominates

DARK ENERGY EQUATIONS OF STATE

- The constant EoS

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

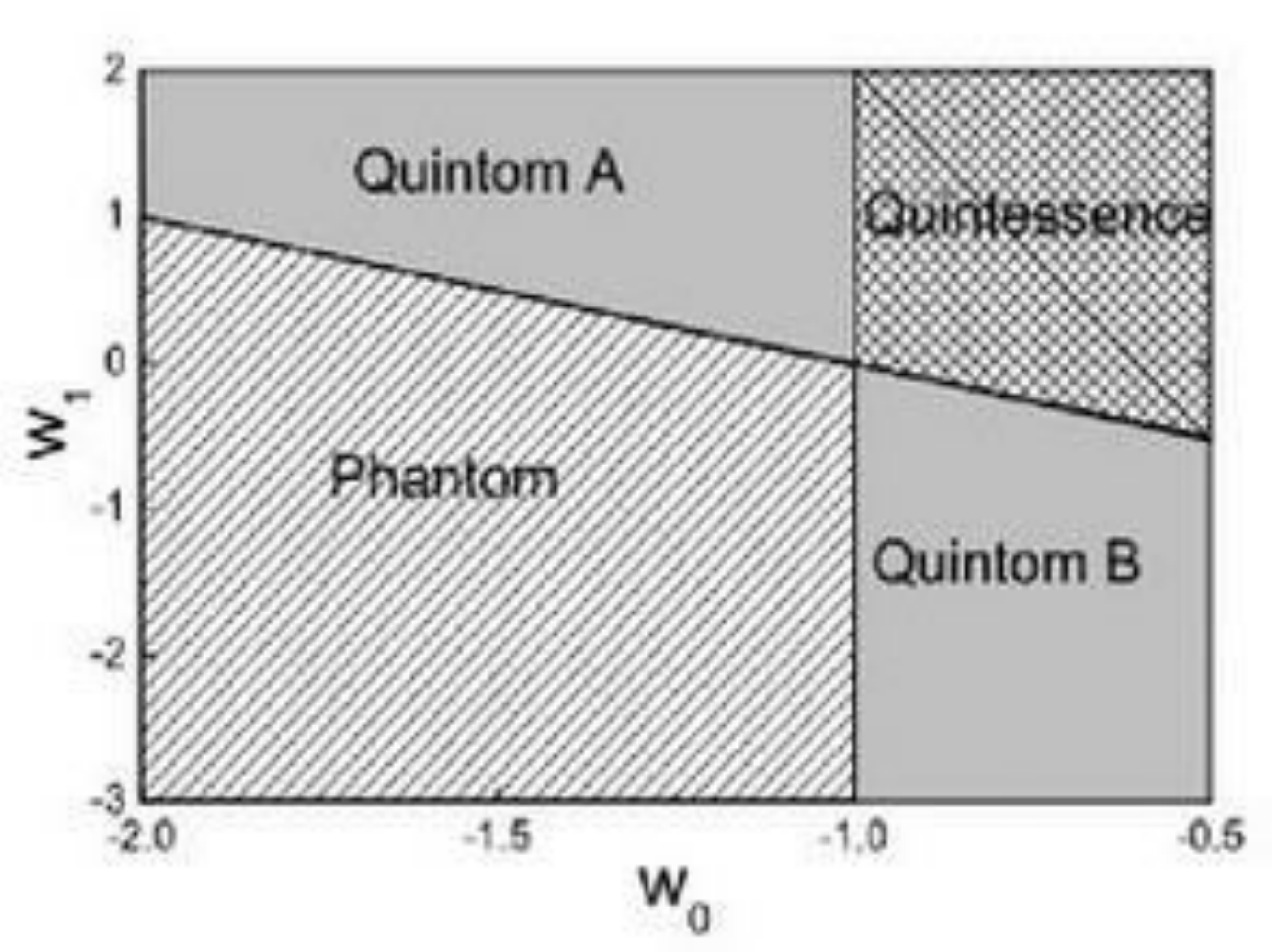
- The Chevallier-Polarski-Linder (CPL) [19, 20]

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

- The Wetterich-logarithmic one [21]

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

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



FIM!
OBRIGADO!