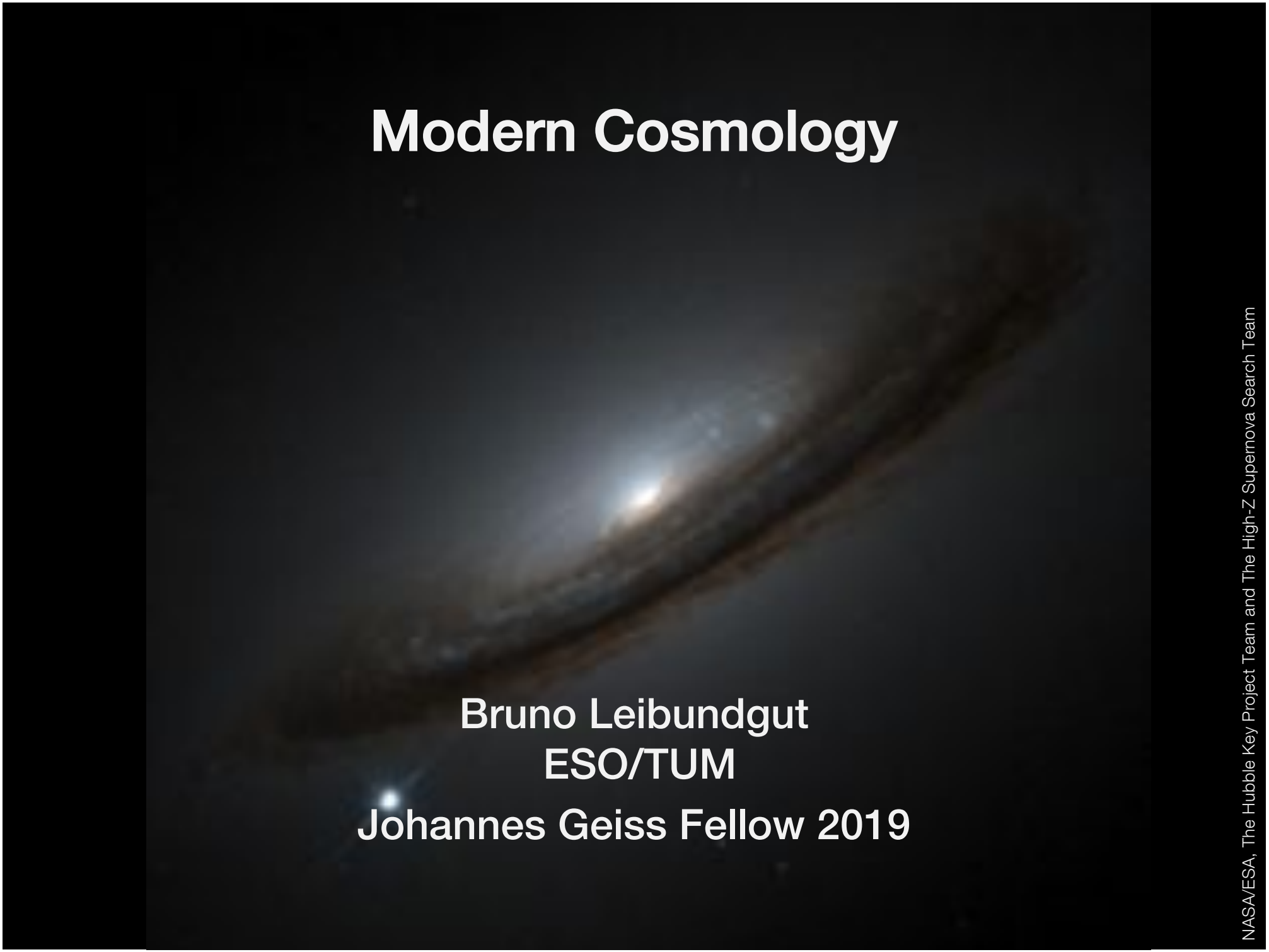
Modern Cosmology

Bruno Leibundgut
ESO/TUM

Johannes Geiss Fellow 2019



NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

Modern Cosmology

- **The Universe yesterday**
  - making elements
  - cosmic microwave background
  - universal expansion
- **The Universe today**
  - dark matter
  - dark energy
- **The Universe tomorrow**
  - detection of dark matter particle(s)
  - equation of state of dark energy
    - EUCLID
  - neutrinos
  - gravitational waves

INTERNATIONAL SPACE SCIENCE INSTITUTE
No. 1, April 1998

SPATIUM

Publikationsorgan des Vereins Pro ISSI

Entstehung des Universums

Faszination des Ursprungs: Die drei ersten Minuten vor rund 14 Milliarden Jahren waren bestimmend für unser Universum. Experimente der Weltraumwissenschaft ermöglichen uns Einblicke in die Tiefen von Raum und Zeit.

R. Wyttenbach

INTERNATIONAL SPACE SCIENCE INSTITUTE
No 3, May 1999

SPATIUM

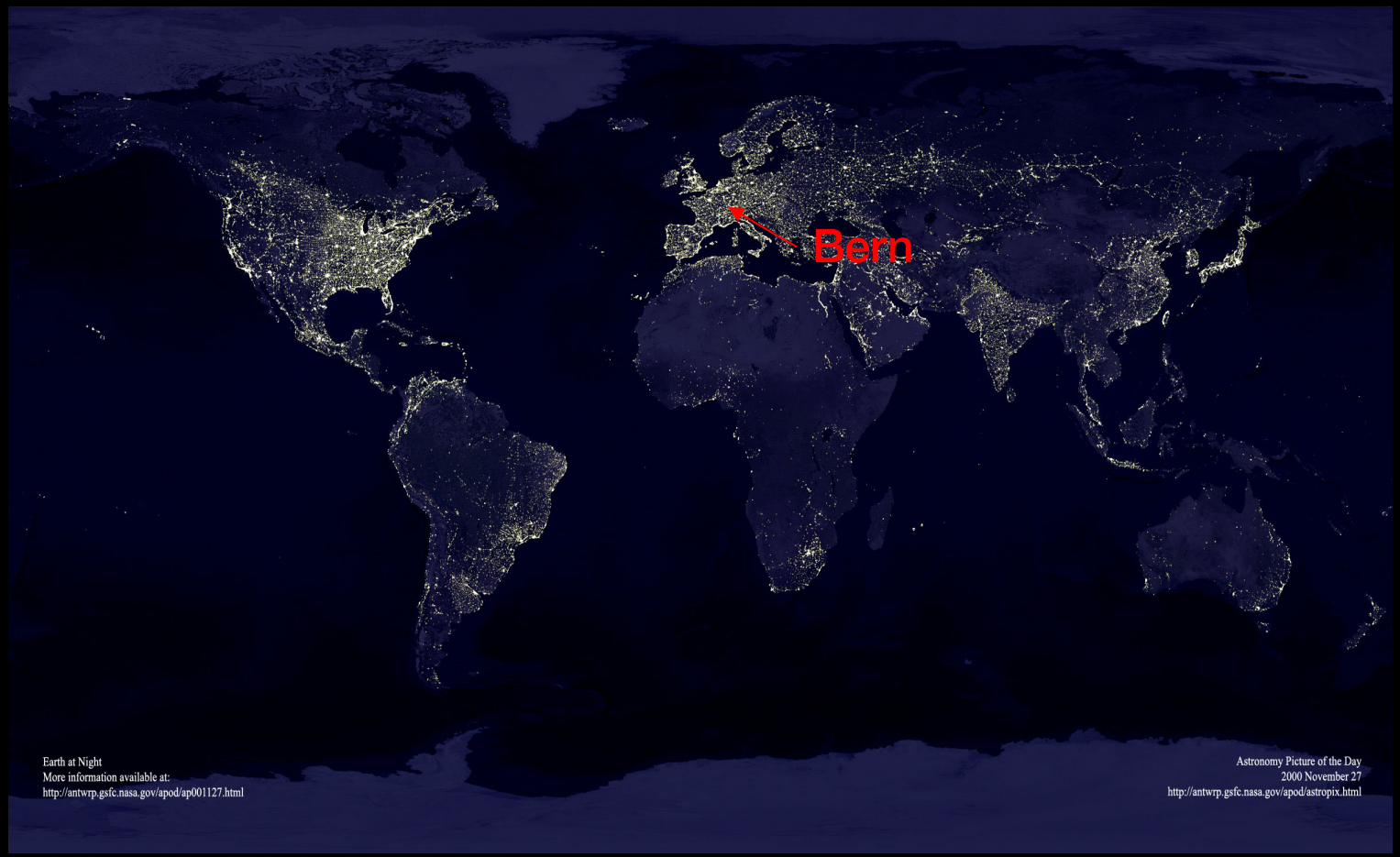
Published by the Association Pro ISSI

Birth, Age and the Future of the Universe

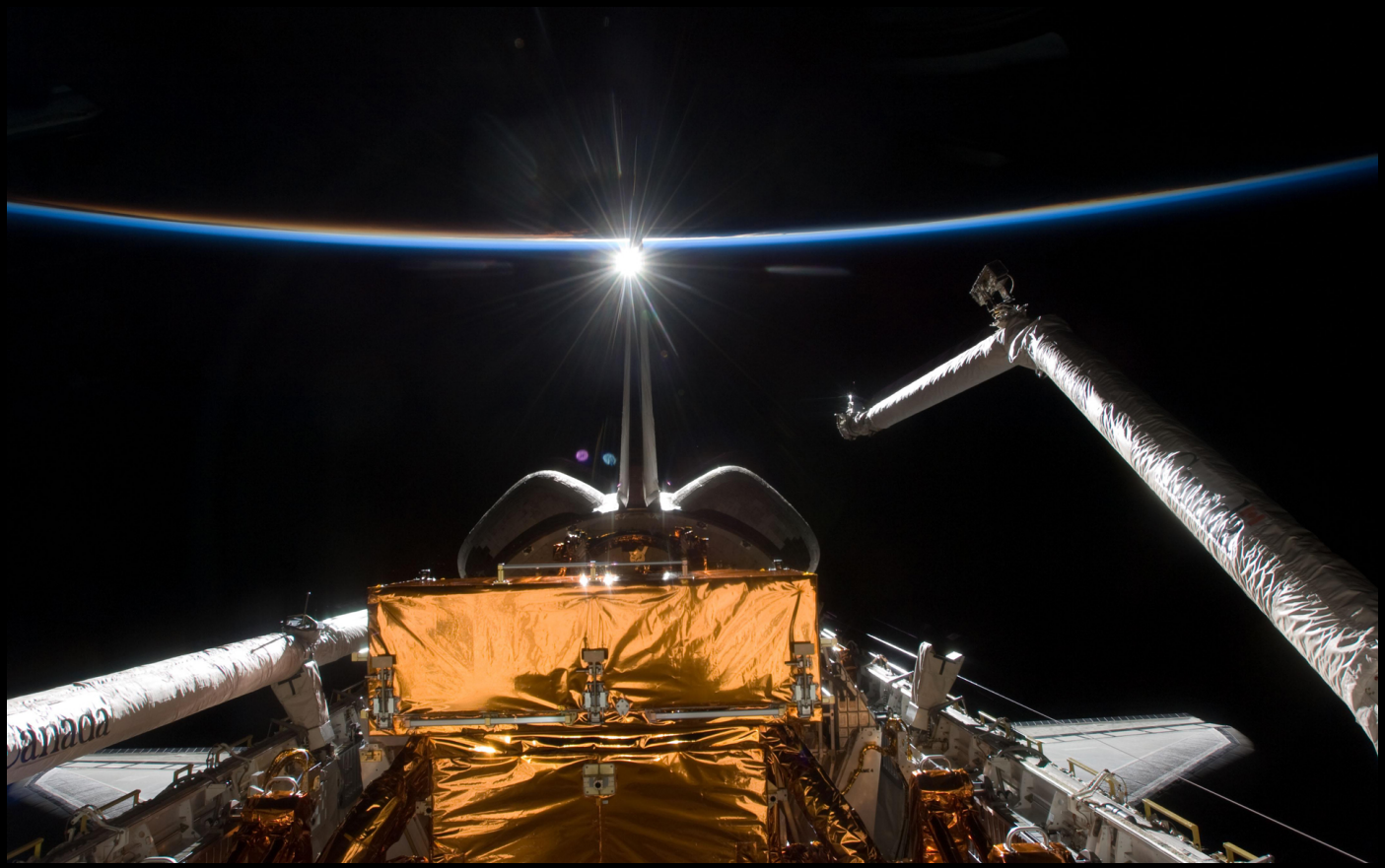
Recent results of space research tell us a story of unlikely events. Life emanating from the vaste of exploded stars is but one of them.

How do we observe the world?

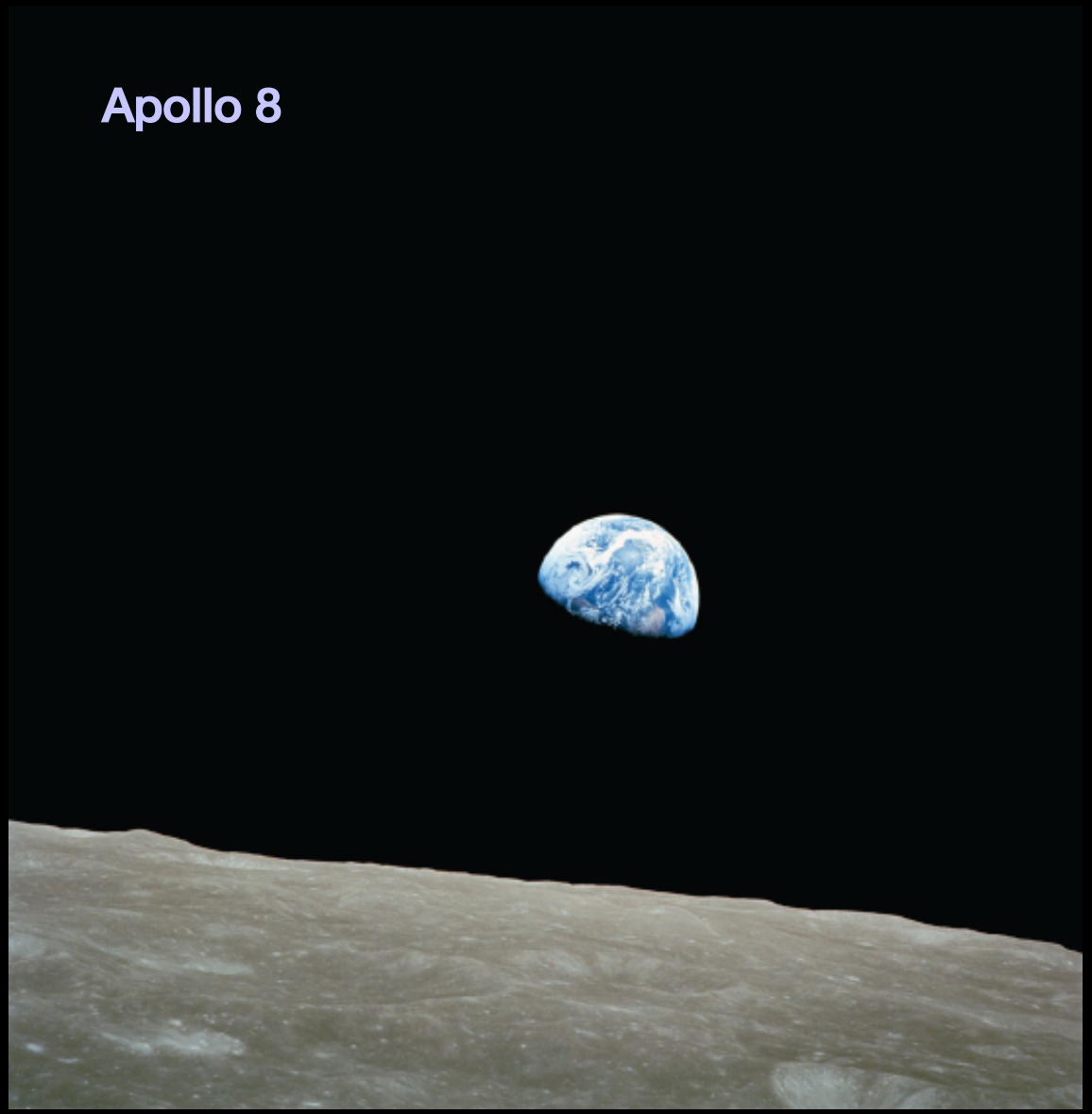
The Earth at night



Our place in the universe



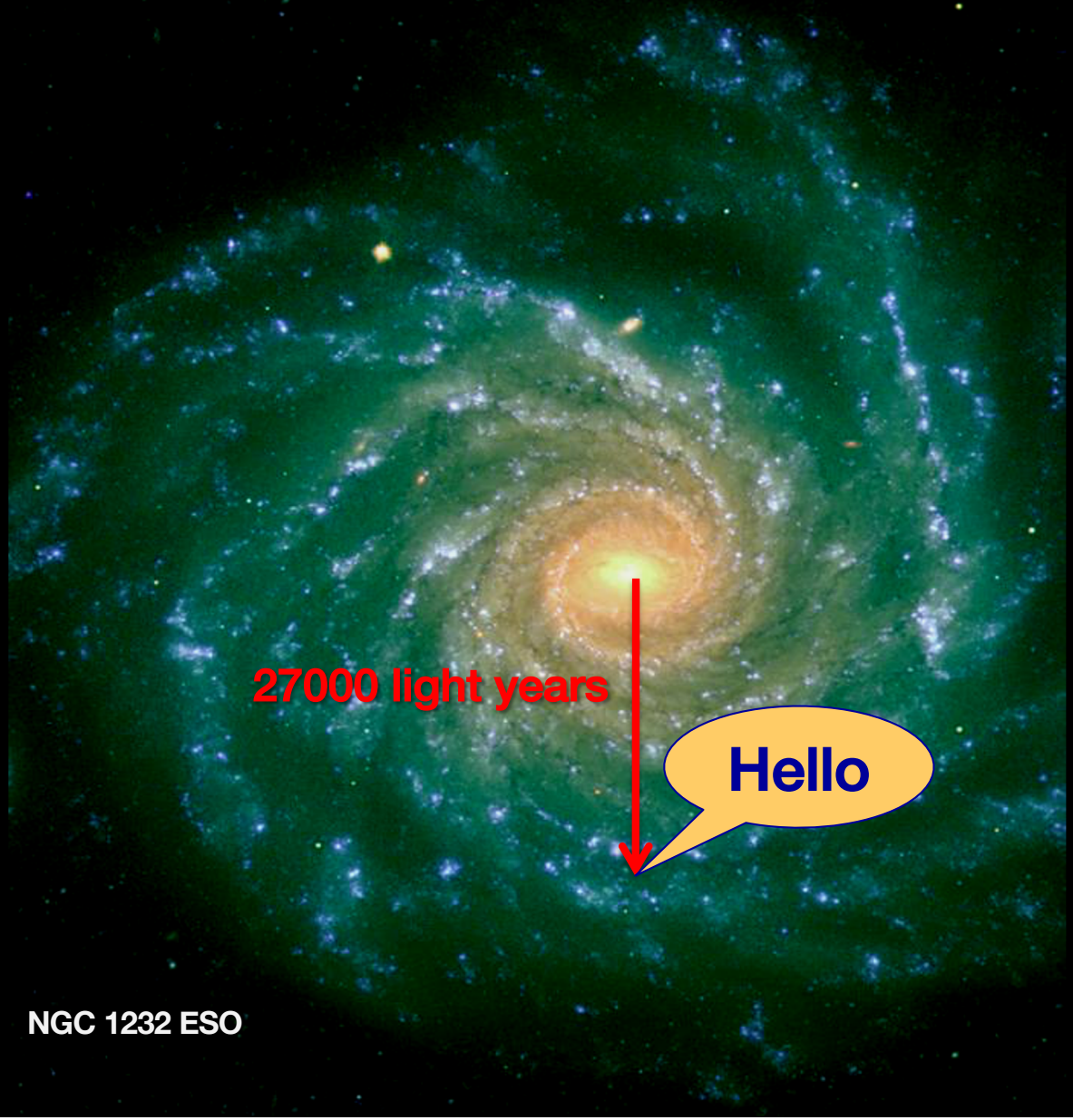
Our Home



Our place in the universe

© Cassini/NASA

Our place in the Milky Way



1. January: Big Bang

The Milky Way forms

Sun and planets form

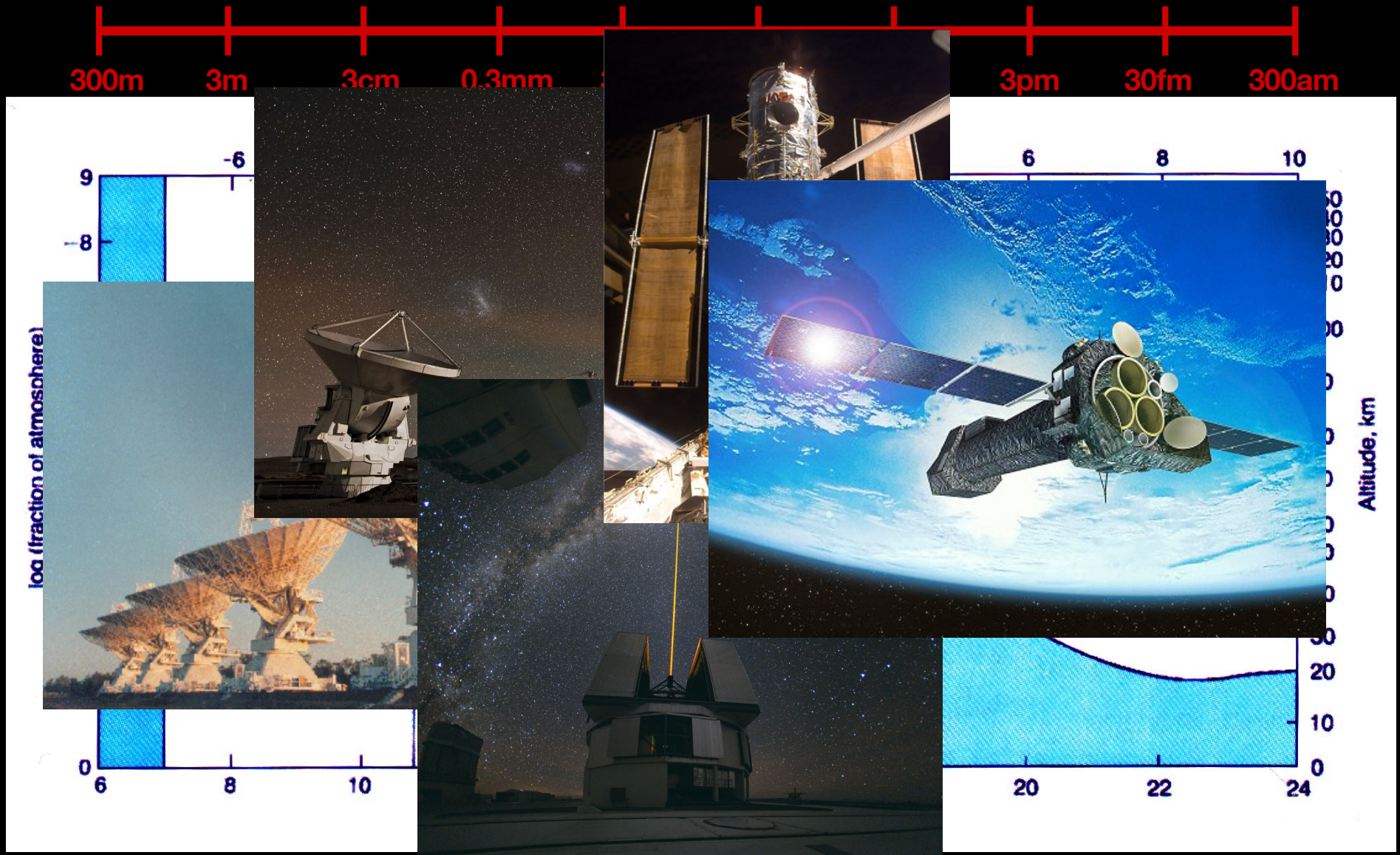
Oldest known life

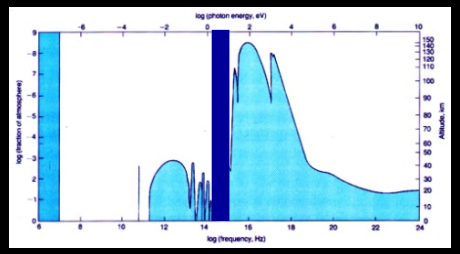
First multi-cellular organisms

January	February	March	April	May	June	July	August	September	October	November

December						
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15 Cambrian Explosion	16	17 Emergence of first vertebrates	18 Early land plants	19	20 First four-limbed animals	21 Variety of insects begins to flourish
22	23	24 First dinosaurs appear	25 First mammalian ancestors appear	26	27 First known birds	28
29 Dinosaurs wiped out by asteroid or comet	30	31 23:54 Modern humans (homo sapiens) appear 23:59:45 Invention of writing 23:59:50 Pyramids built in Egypt 23:59:59 Galileo observes the sky with a telescope				

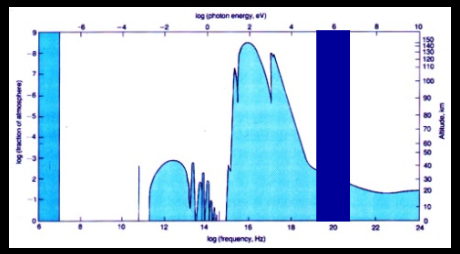
Earth‘s atmosphere
Shield and Window to the Universe




log (photon energy, eV)
log (frequency, Hz)
Altitude, km

“visible”

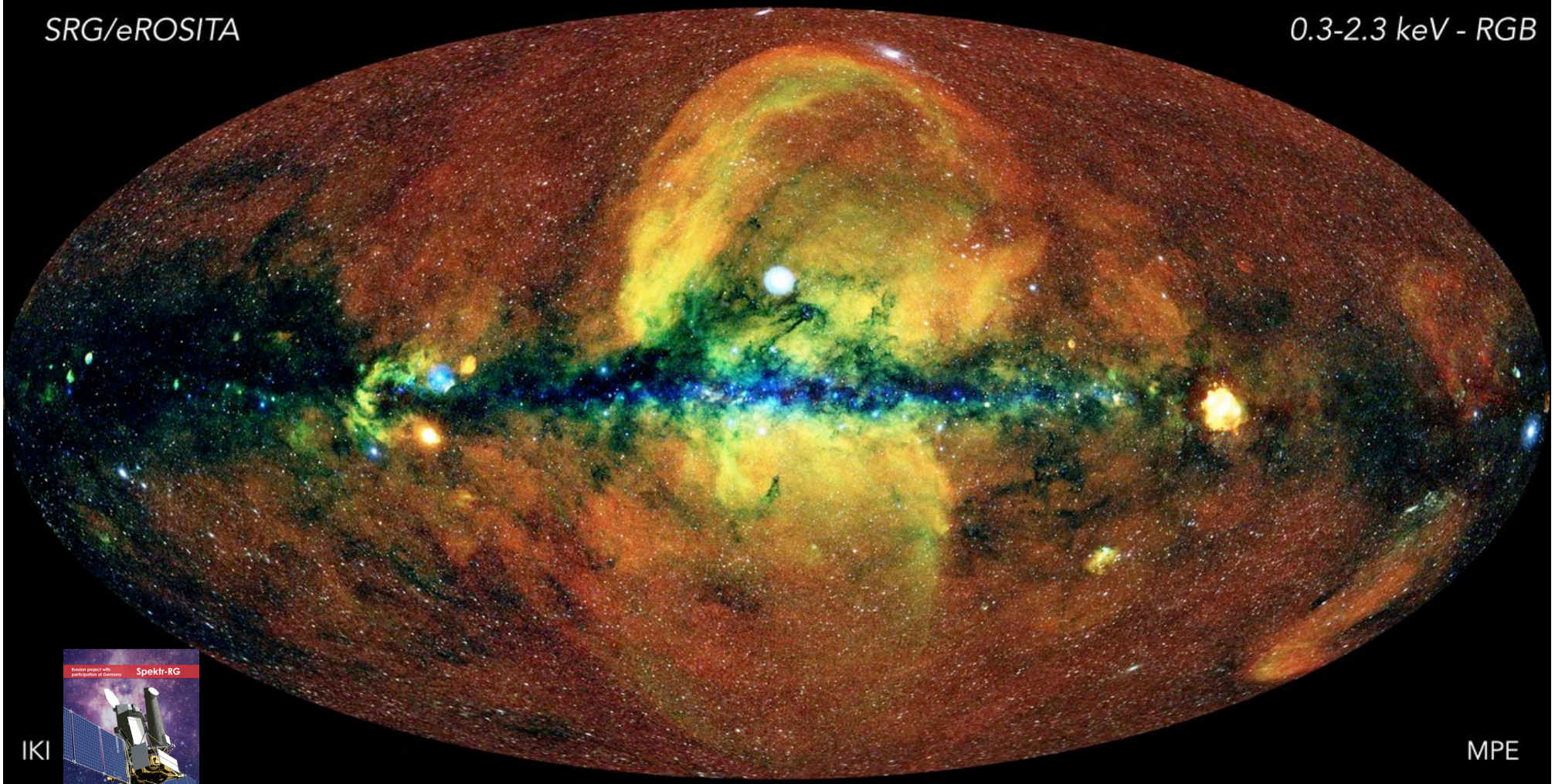

New Years Day: The Big Bang
Milky Way forms
Sun and planets form
Oldest known life (single celled)
First multi-cellular organism
January February April May June July August September October November
December
Cambrian explosion (burst of new life forms)
Emergence of first vertebrates
Early land plants
First four-limbed animals
Variety of insects begin to flourish
First dinosaurs appear
First mammal-like ancestors appear
First known birds
Dinosaurs wiped out by asteroid or comet
23:54 Anatomically modern humans appear
23:59:45 Invention of writing
23:59:50 Pyramids built in Egypt
23:59:59 Voyage of Christopher Columbus



“invisible”

SRG/eROSITA

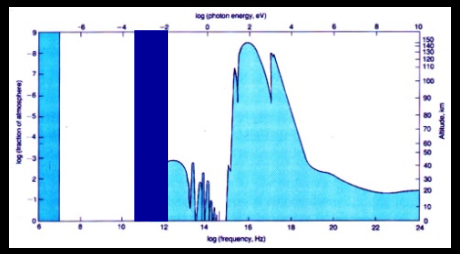
0.3-2.3 keV - RGB



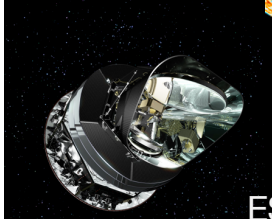
IKI

MPE

IKI/MPE/eROSITA



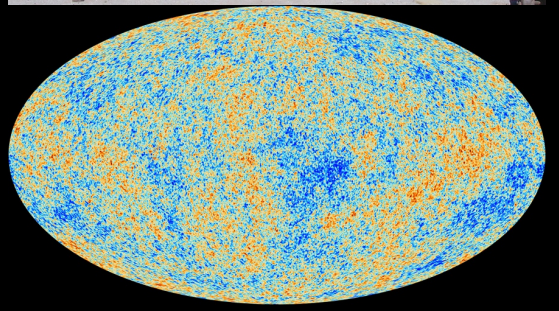
“invisible”



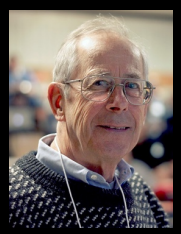
ESA/Planck

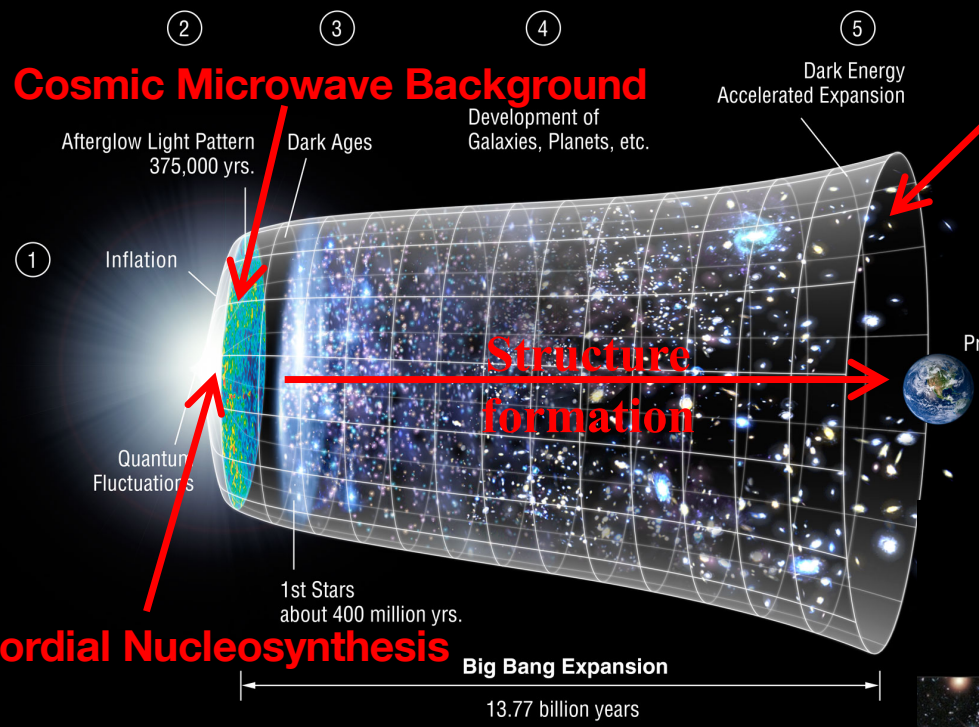
Basics of cosmology

- Theory of gravity
  - Einstein's General Relativity
- Isotropy
  - There is no preferred direction
- Homogeneity
  - There is no preferred region
  - (e.g. no centre of the universe)
- Anthropic principle
  - We are a product of this universe



Our current picture of (the history of) the Universe

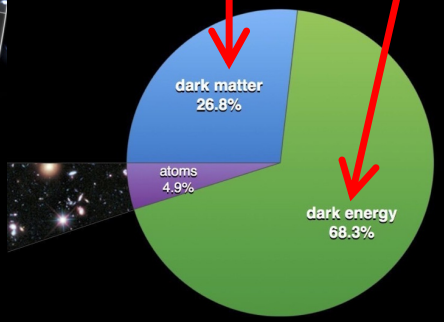




Late-time clustering
(of galaxies)

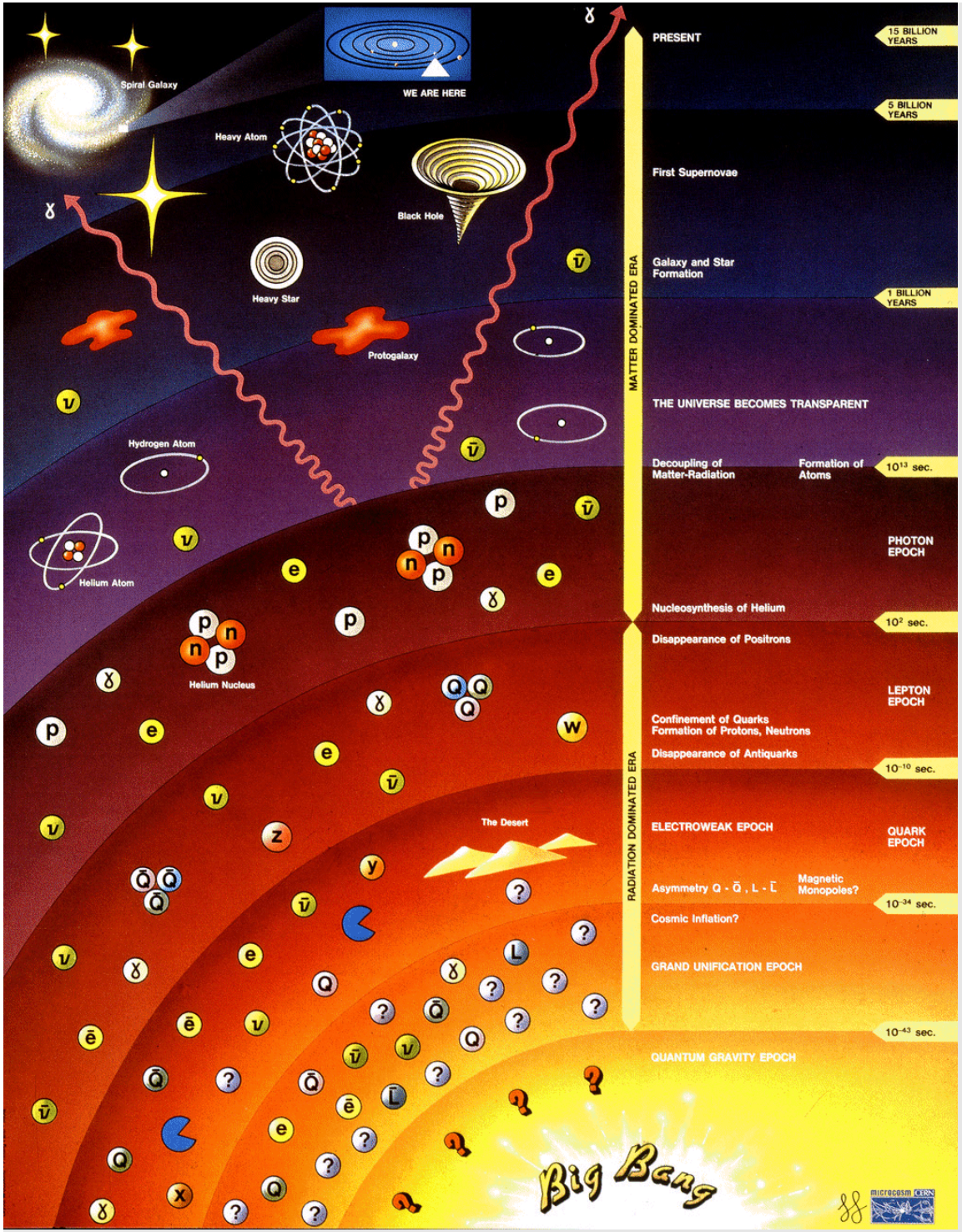
Cosmological
Constant

Dark Matter



If you want to make an apple pie from scratch, you must first create the universe.

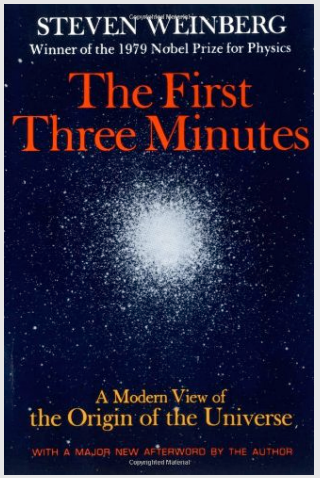
Carl Sagan
quoted in Big Bang
by Simon Singh (2004)



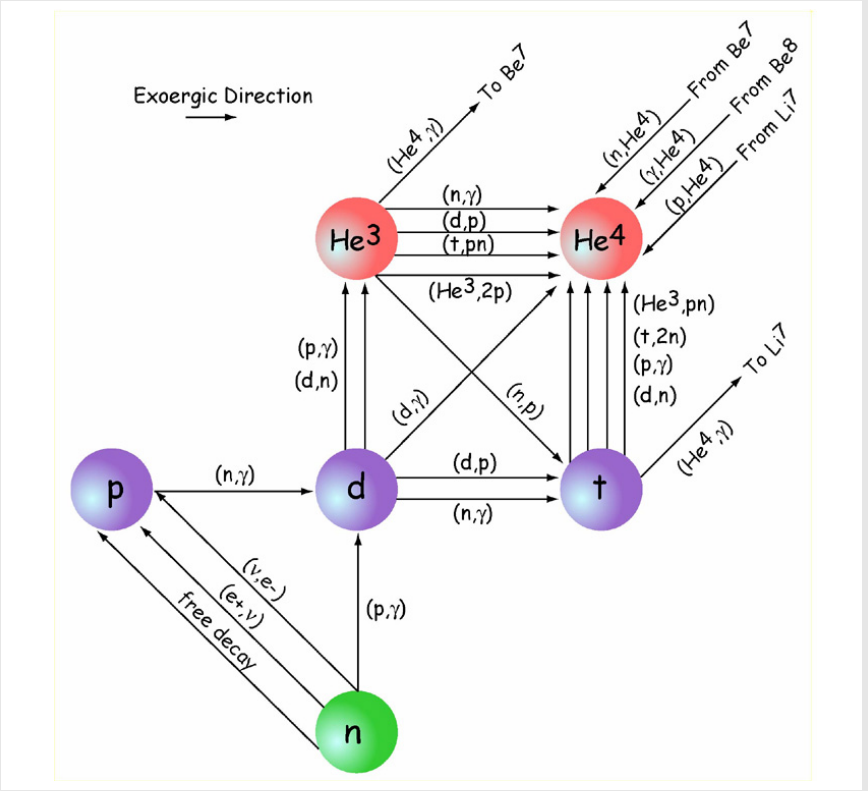
Why is this so?

- Elements form from elementary particles
- Quarks → protons and neutrons
- Electrons
- Protons and Neutrons form atomic nuclei
- Together with the electrons atomic nuclei become atoms

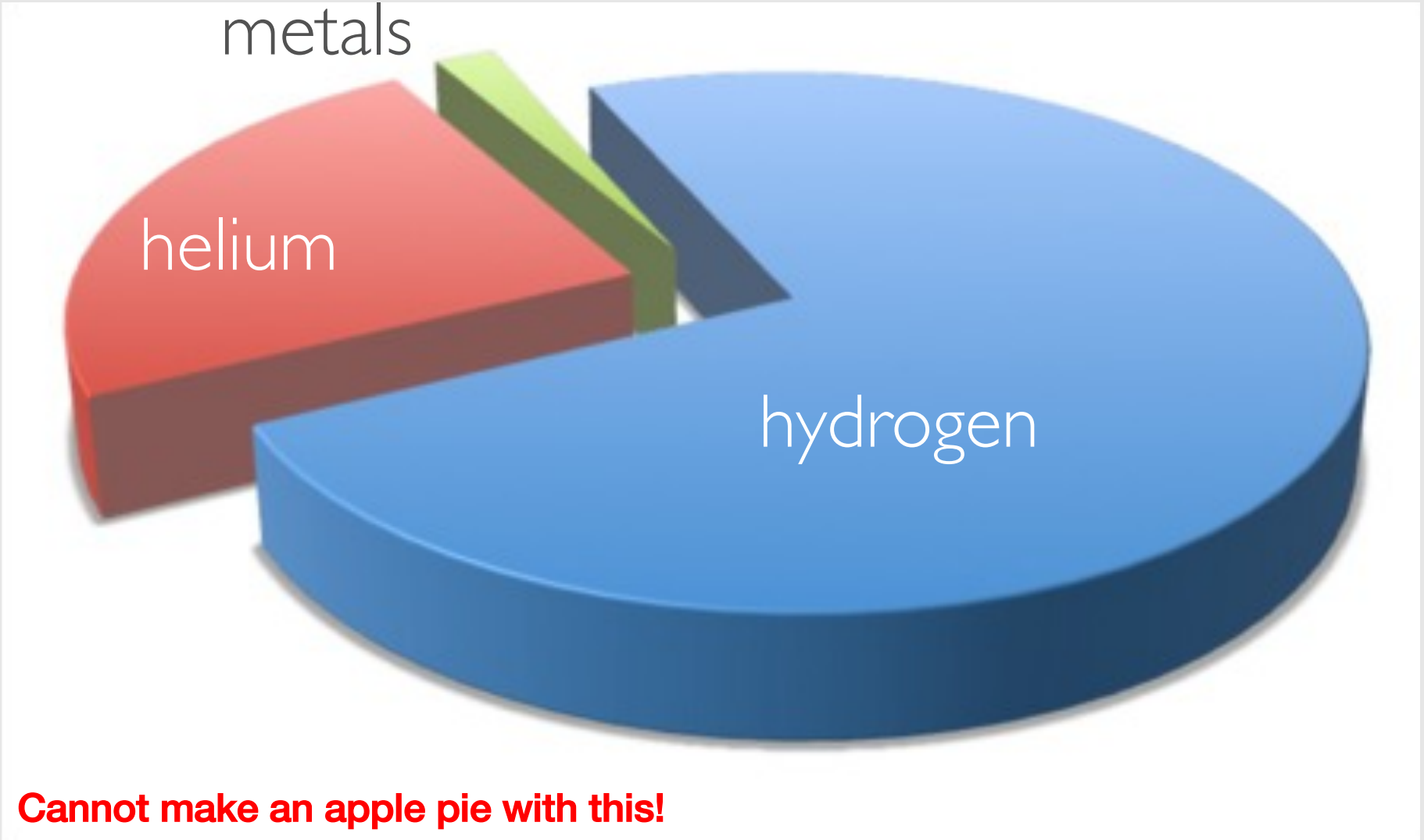
The First Three Minutes



- Creation of particles and first elements in the Big Bang
- Protons and neutrons form after 0.0001 seconds
- Electrons after 4 seconds
- Deuterium (proton + neutron) after 2 minutes
- Helium (2 protons and 2 neutrons) after 3 minutes



Composition of the Universe



Cannot make an apple pie with this!

Astron. & Astrophys. 18, 126–132 (1972)

Special Bern Contribution

Cosmic and Solar System Abundances of Deuterium and Helium-3

J. GEISS
Physical Institute, University of Bern

H. REEVES
S.E.P. Saclay and Institut d'Astrophysique de Paris

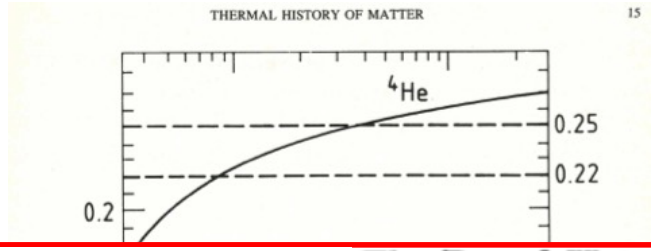
Received December 30, 1971

From analysis of solar and solar wind abundances it is concluded that the D/H ratio in the protosolar gas was much smaller than it is found in ocean water or carbonaceous chondrites. Best estimates for the protosolar gas are: $D/H = 2.5 \times 10^{-5}$ and $He/H \lesssim 10^{-5}$. Isotopic enrichment of deuterium is thought to have

The D and He^3 abundances in the protosolar gas are consistent with a Big Bang origin of these nuclei, corresponding to a universal baryonic density of 3×10^{-31} g/cm³ (deceleration parameter $q_0 \approx 10^{-2}$) and zero leptonic number.

Key words: D, He^3 — nucleosynthesis — solar wind — cosmology

Reeves Alpbach 1987



University of Bern

NASA images

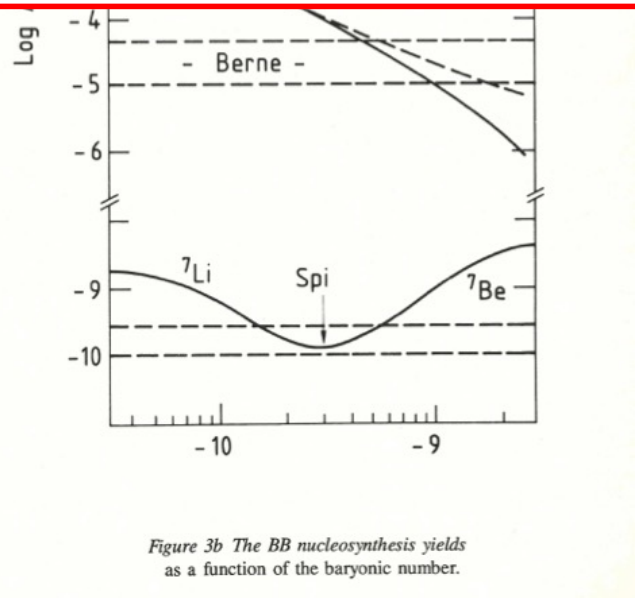


Figure 3b The BB nucleosynthesis yields as a function of the baryonic number.

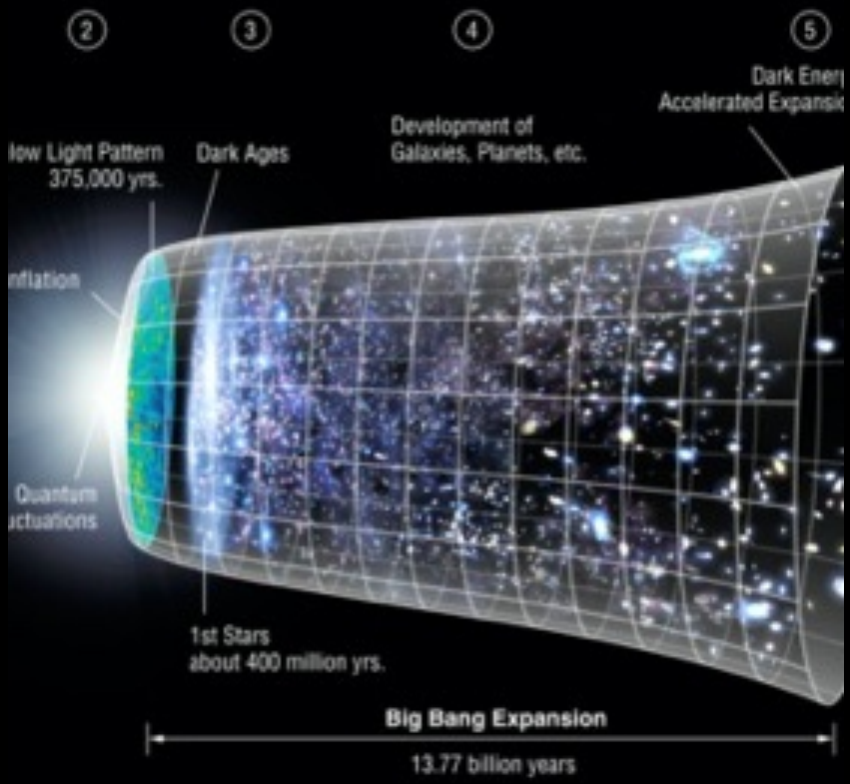
Fast forward 300000 years

First light in the universe

- photons decouple from the atoms

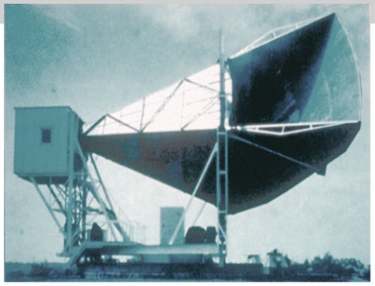
Why?

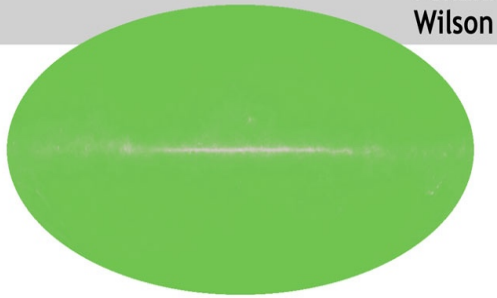
Free electrons are captured by the protons to form hydrogen atoms



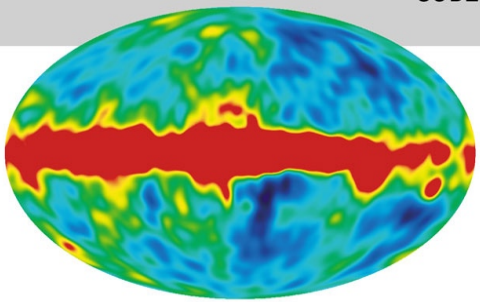
Uncovering the Cosmic Microwave Background

1965 Penzias and Wilson

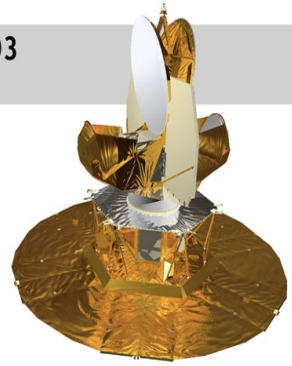


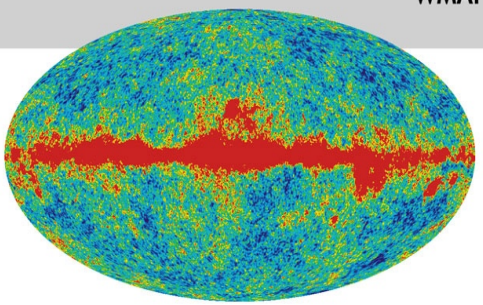


1992 COBE



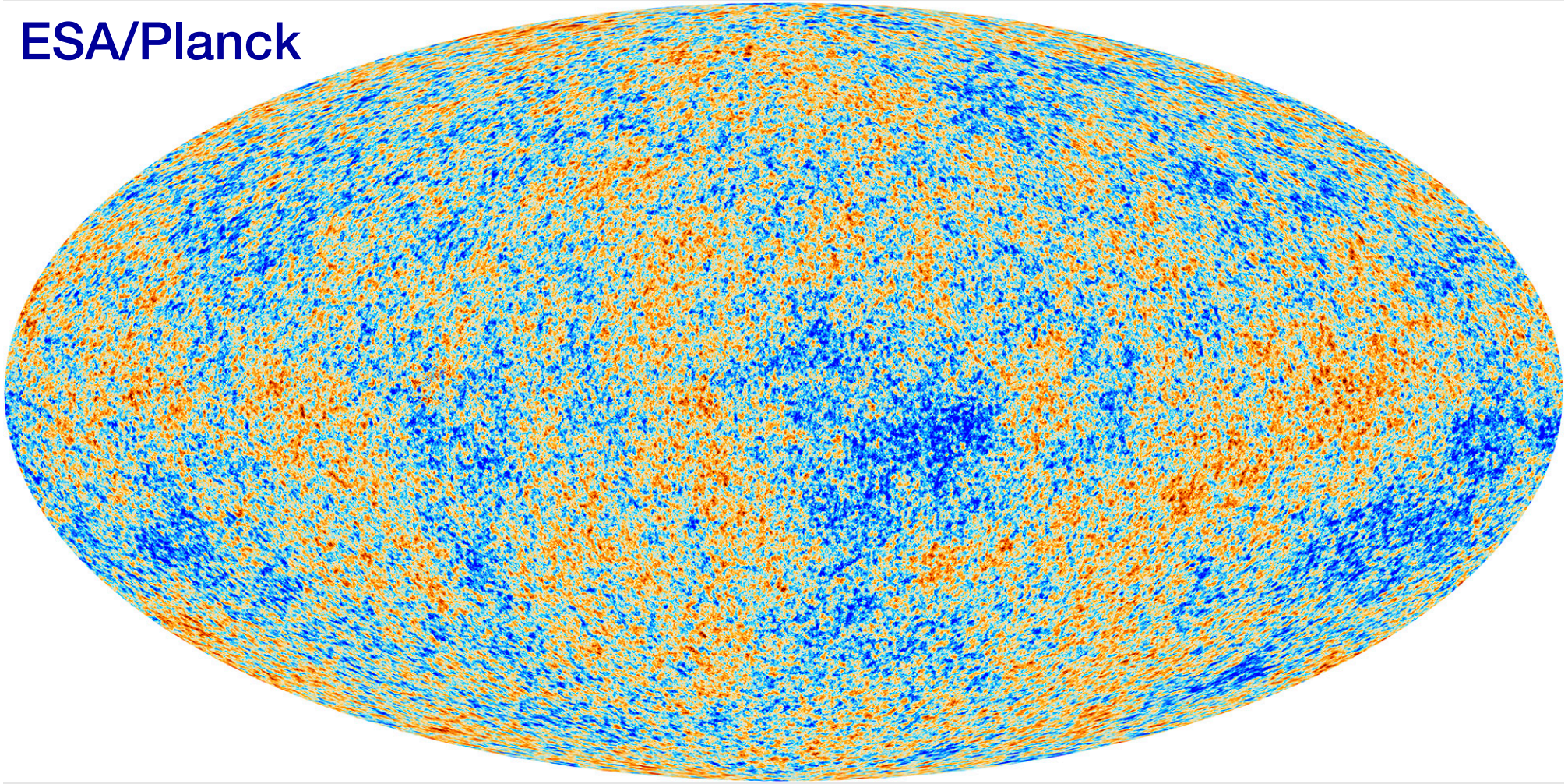
2003 WMAP



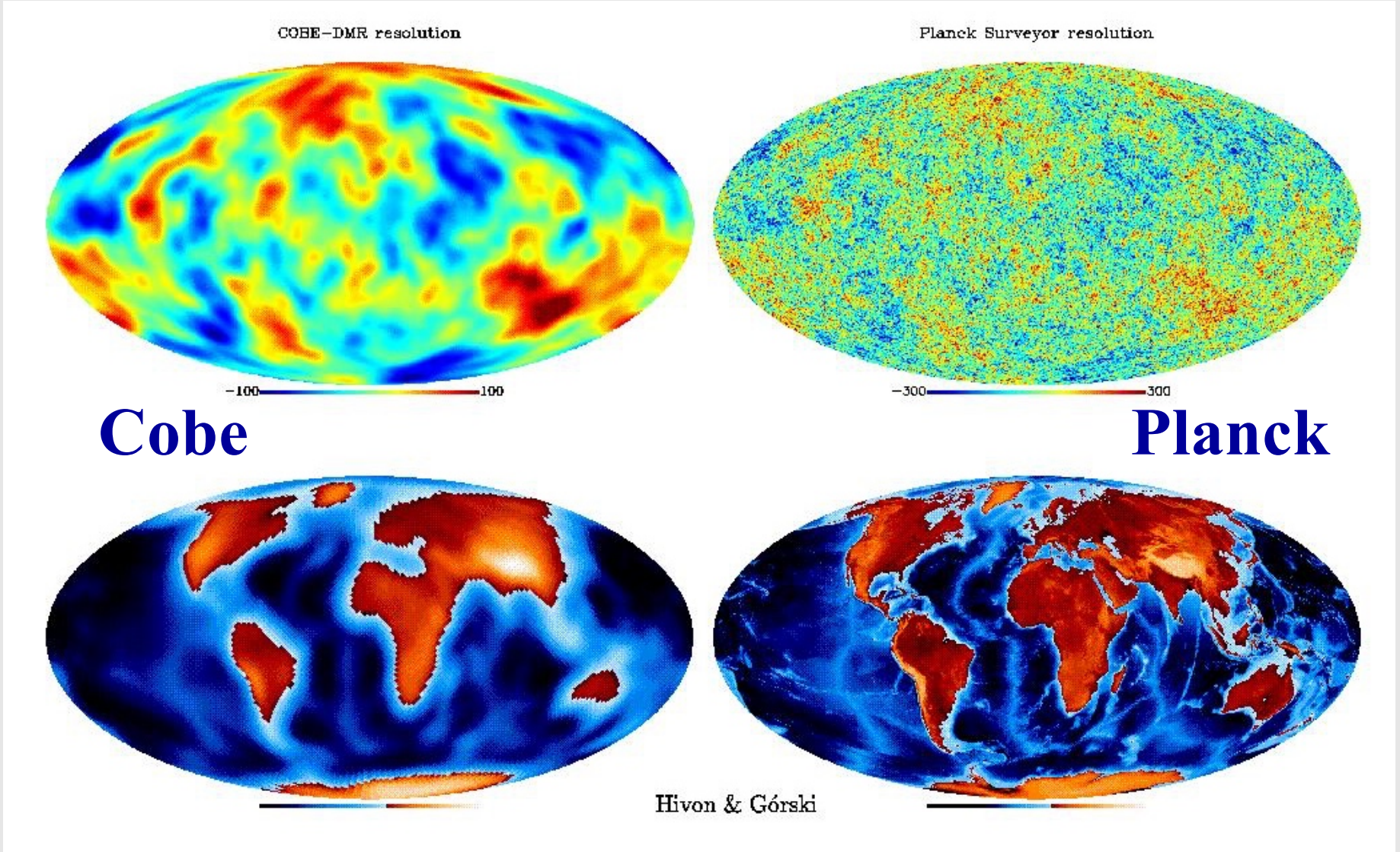


Uncovering the CMB

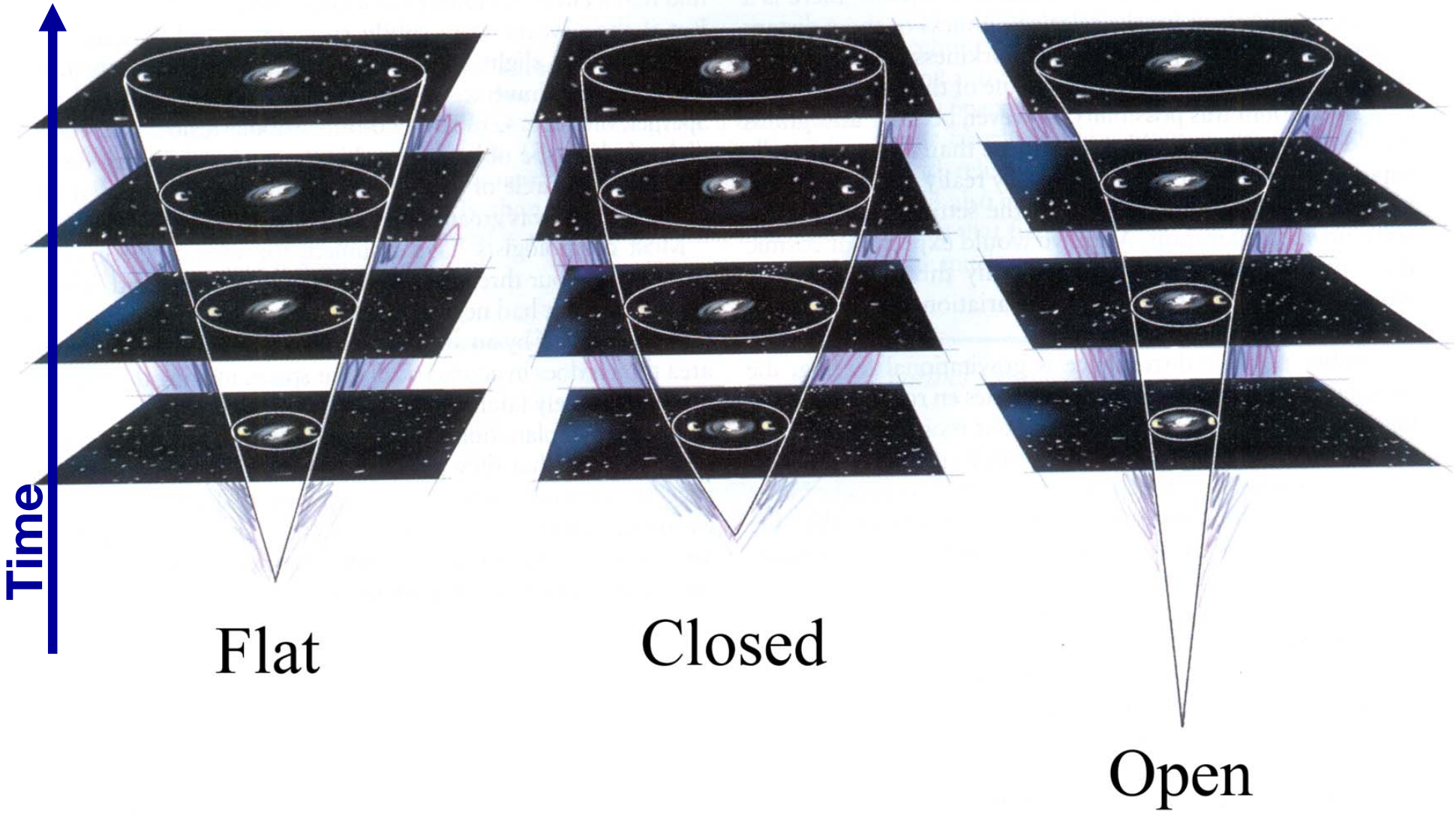
ESA/Planck

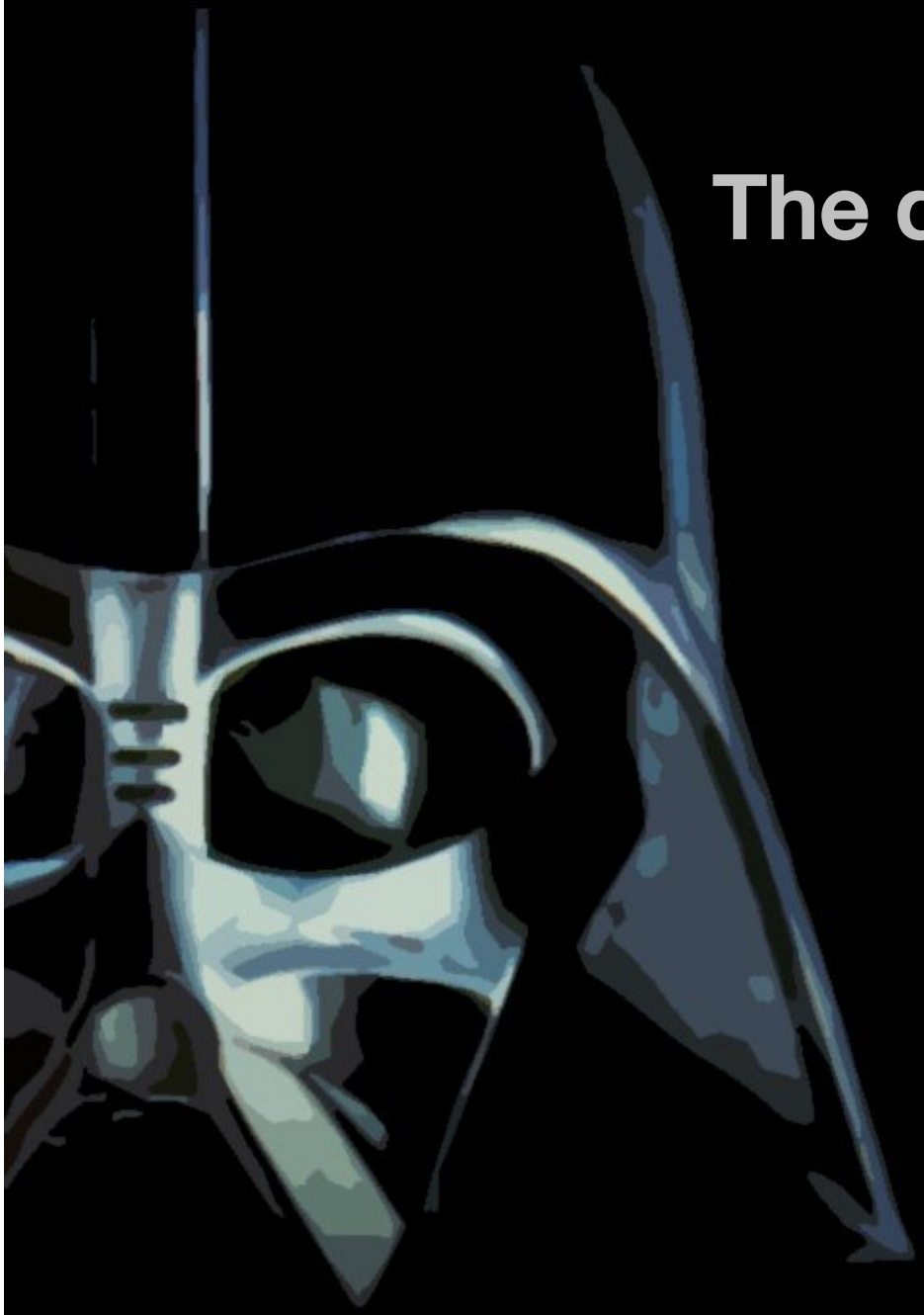


Comparison with a familiar surface



How to interpret the image





The dark side of the universe

What is the universe made of?

How do we understand the universe?

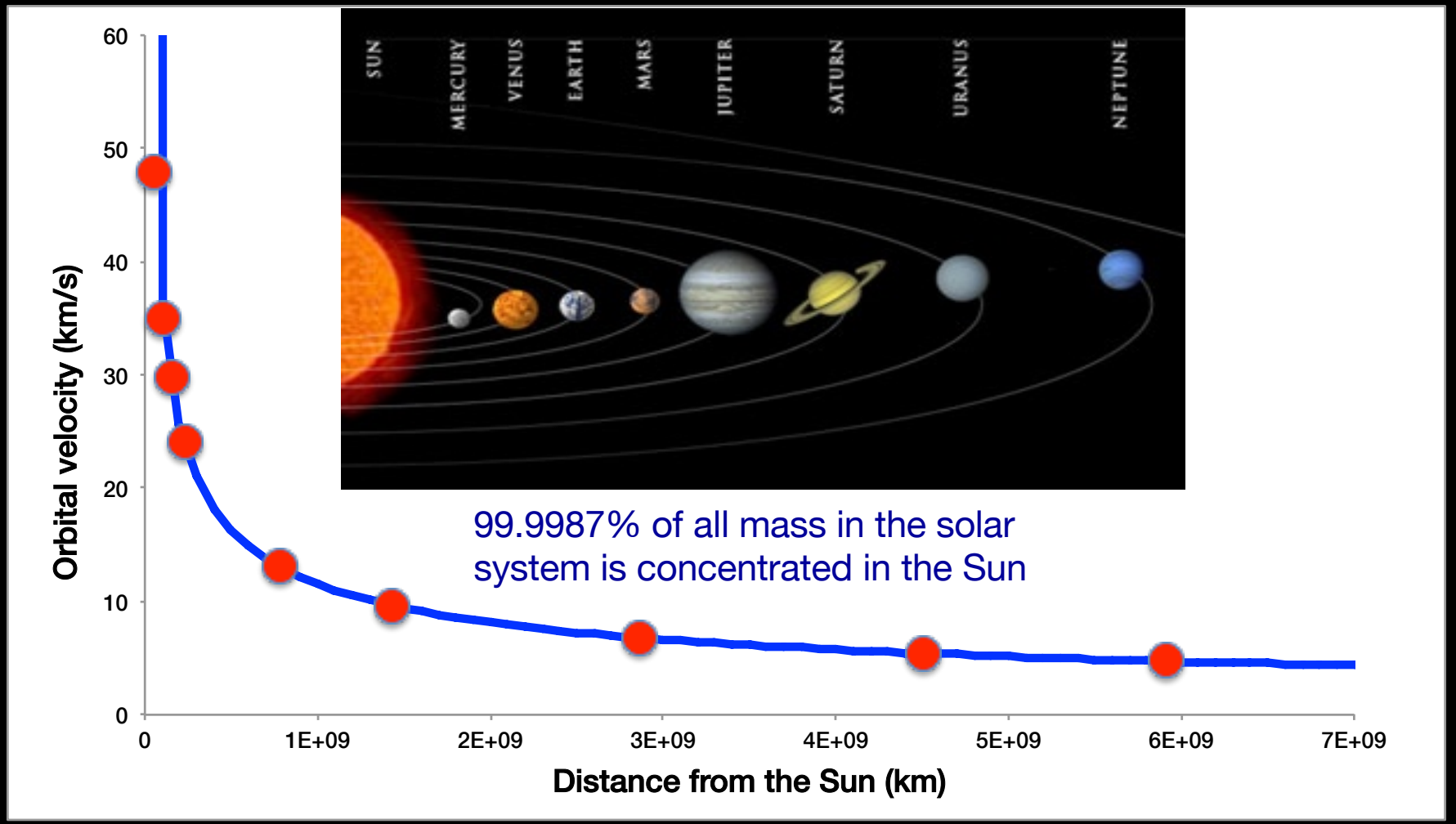
What are Dark Matter and Dark Energy?

Gravitation!

Of the four fundamental forces (Gravitation, Electromagnetism, Weak and Strong Forces) only gravitation determines the evolution of the universe.

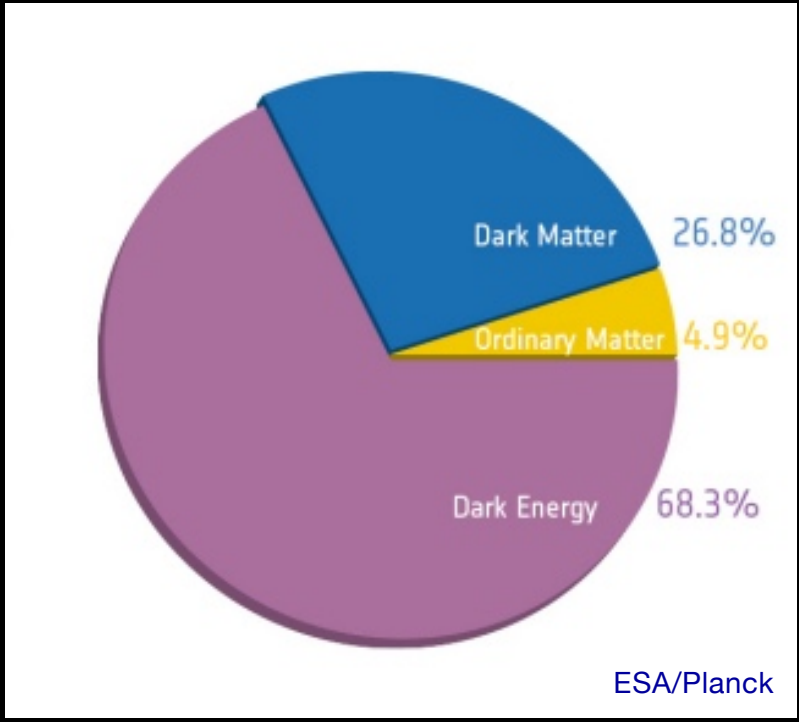
Measure gravitational influence

Orbits!



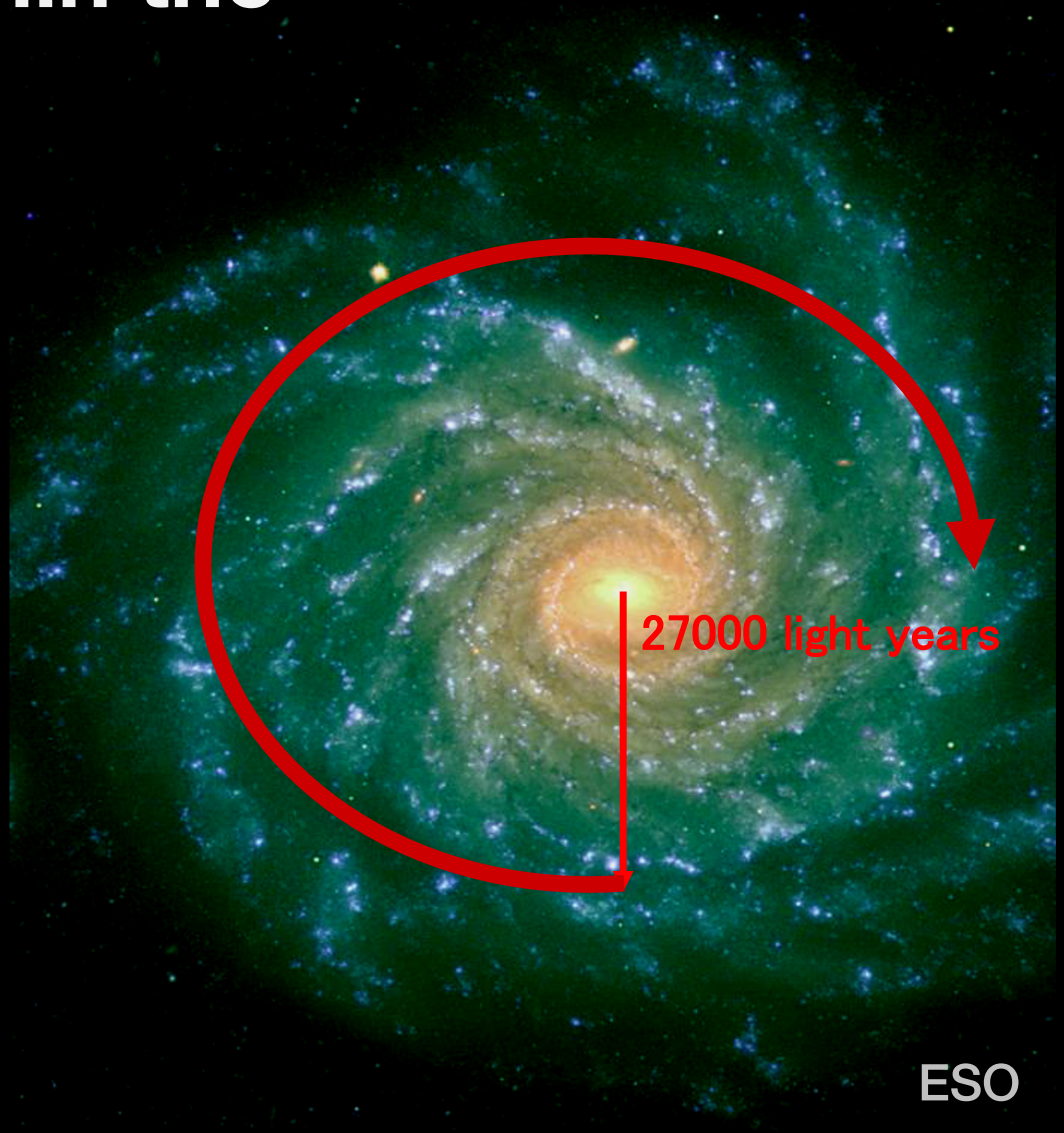
Why Dark Matter?

- The solar system can be fully understood with gravitation of a point source – the Sun.
- Where does Dark Matter come into the game?
  - Clusters of galaxies
  - Rotation of galaxies
  - Gravitational lenses
  - Contents of the universe

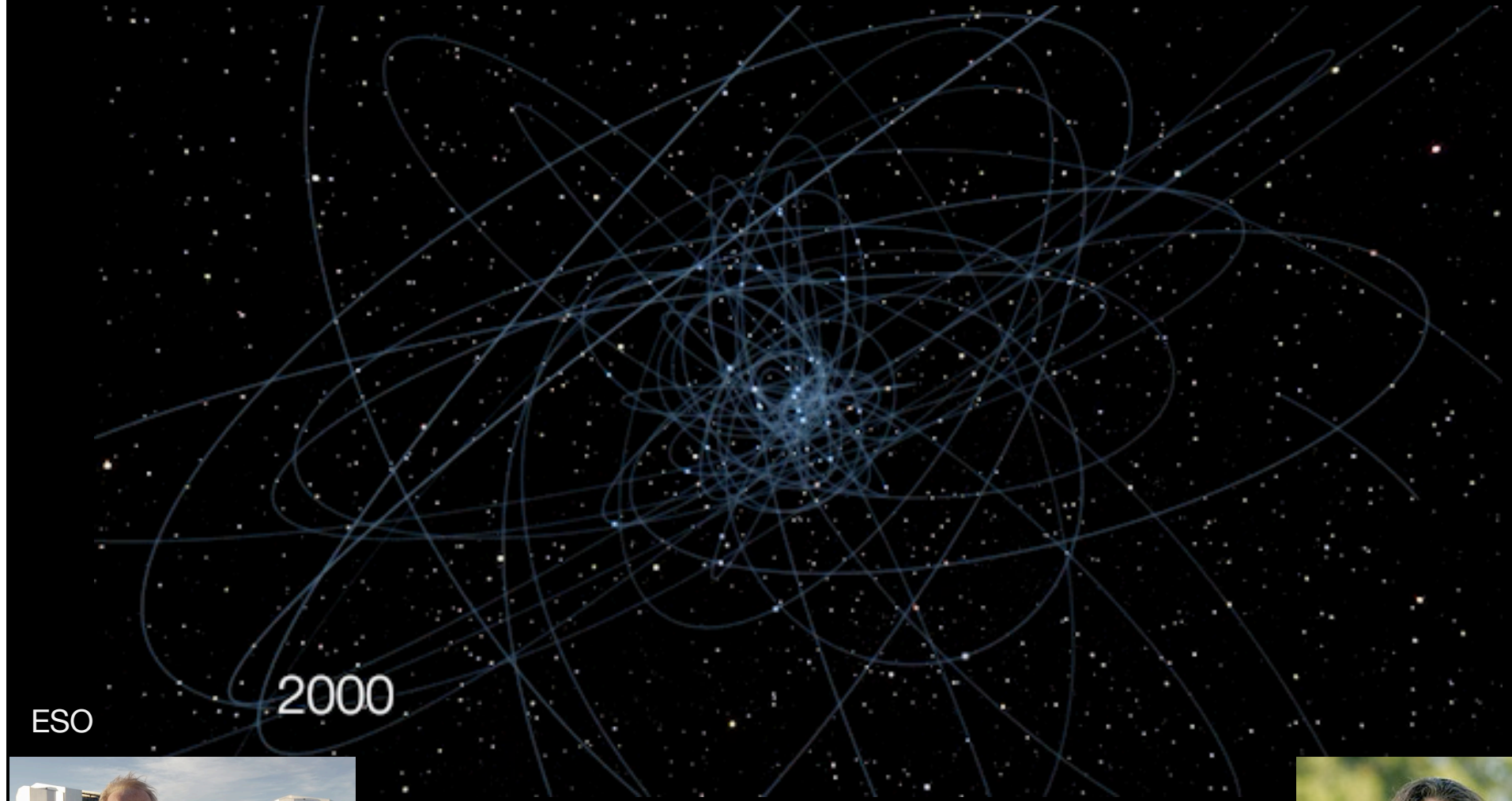


The Sun within the Milky Way

The Sun orbits the centre of the Milky Way in about 220 million years.



Example: Galactic Centre



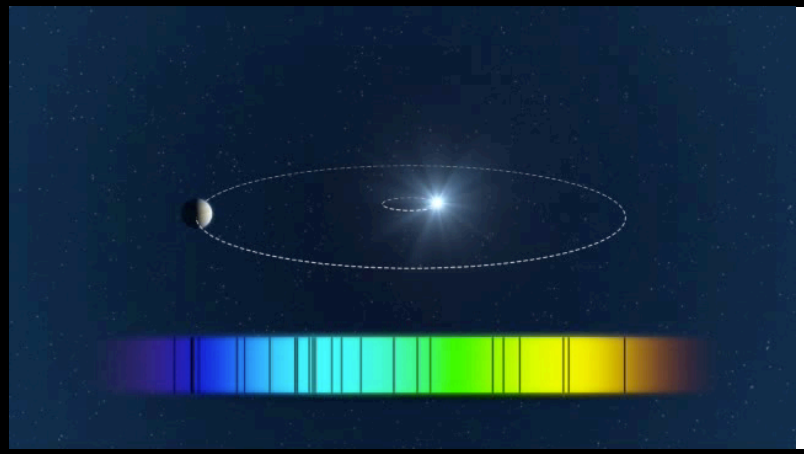
ESO

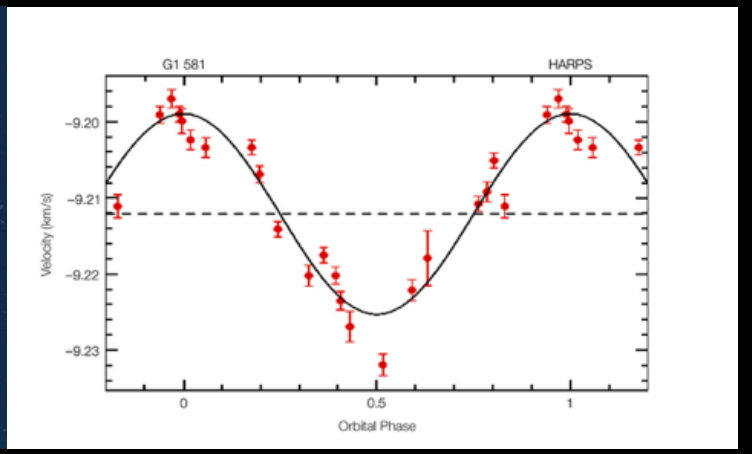
Physics Nobel Prize 2020

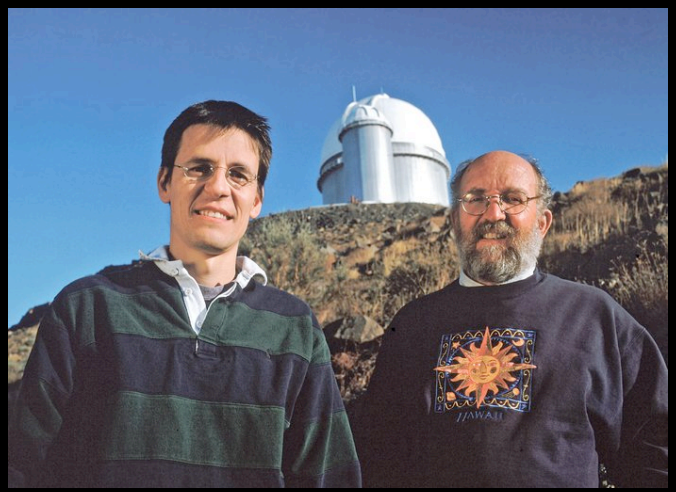
Discovery of Exoplanets

Radial velocities

– gravitational pull of a planet on the host star

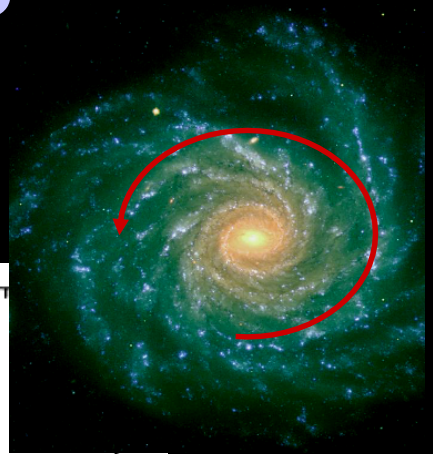


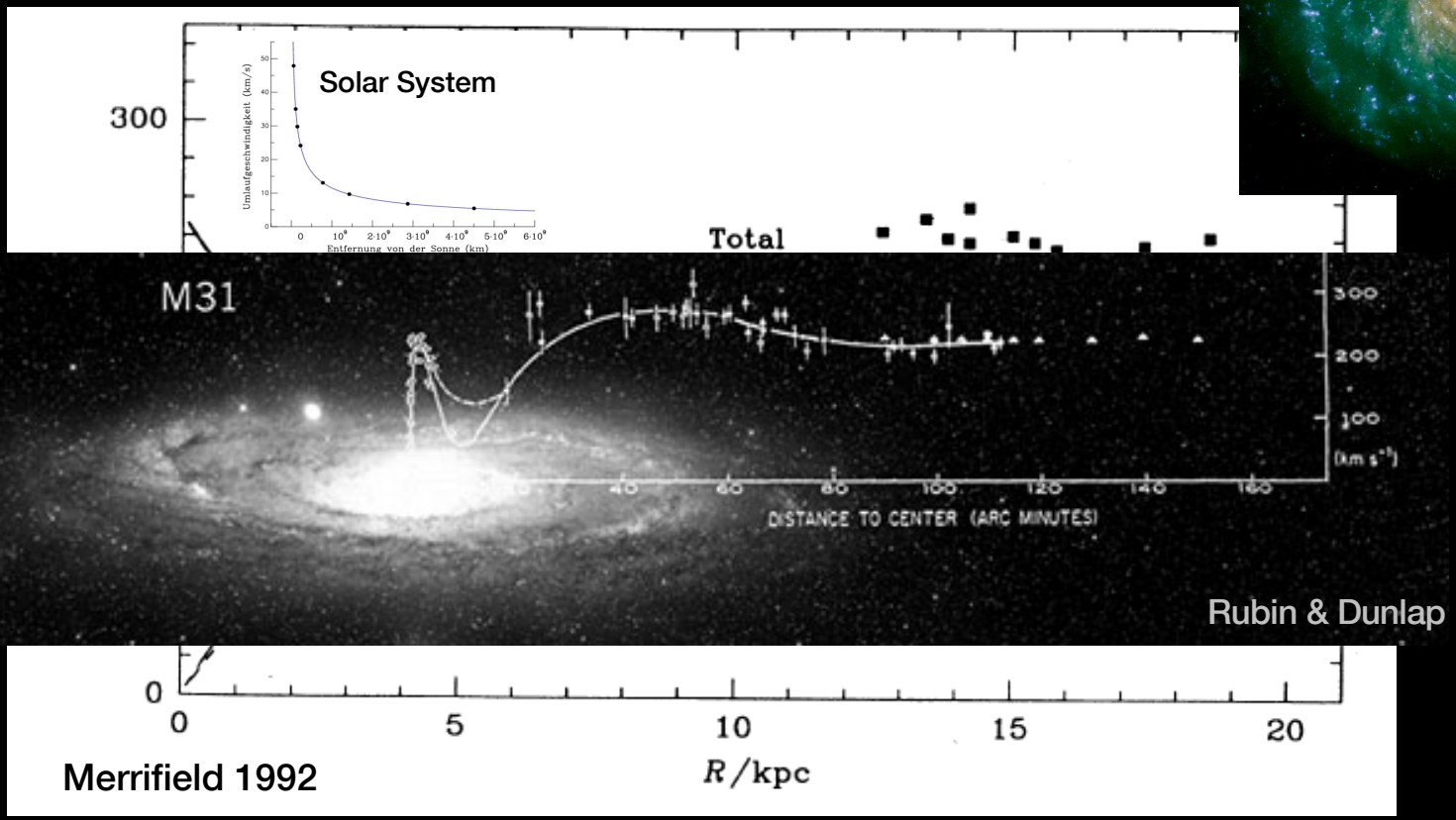




Physics Nobel Prize 2019

Milky Way Rotation Curve





HELVETICA
PHYSICA ACTA

EDITA A SOCIETATE PHYSICA HELVETICA

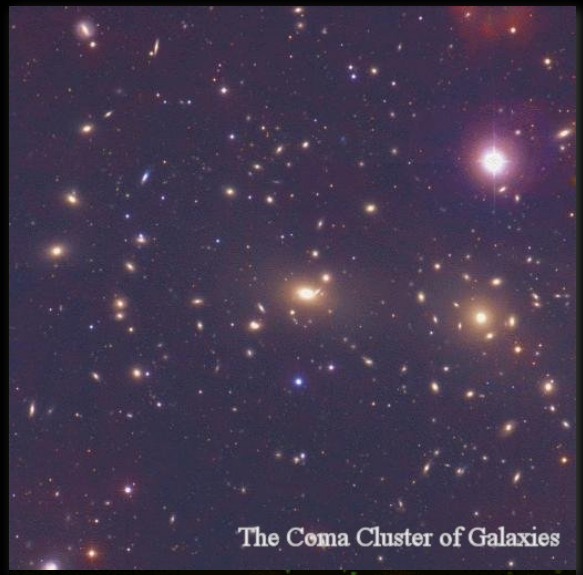
Die Rotverschiebung von extragalaktischen Nebeln

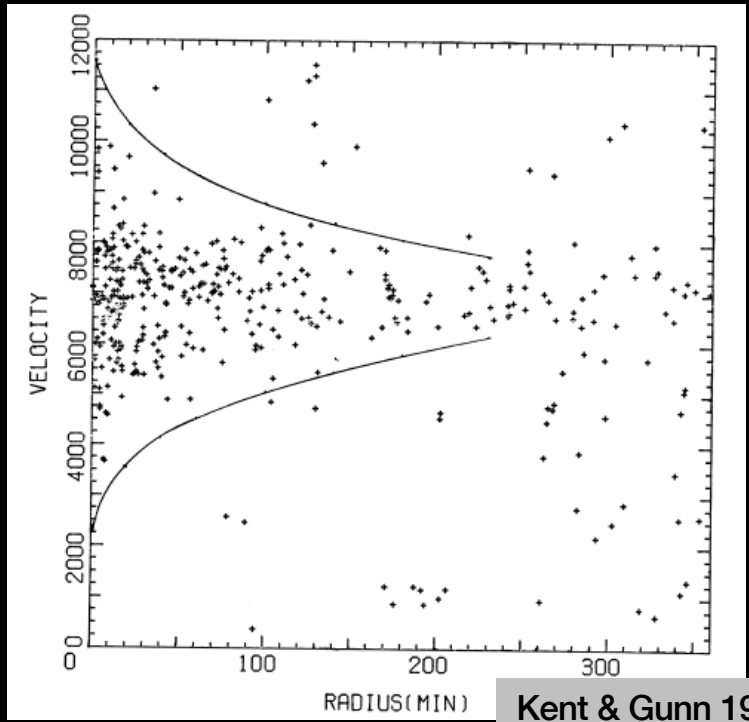
von F. Zwicky.

(16. II. 33.)

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

The Coma Cluster





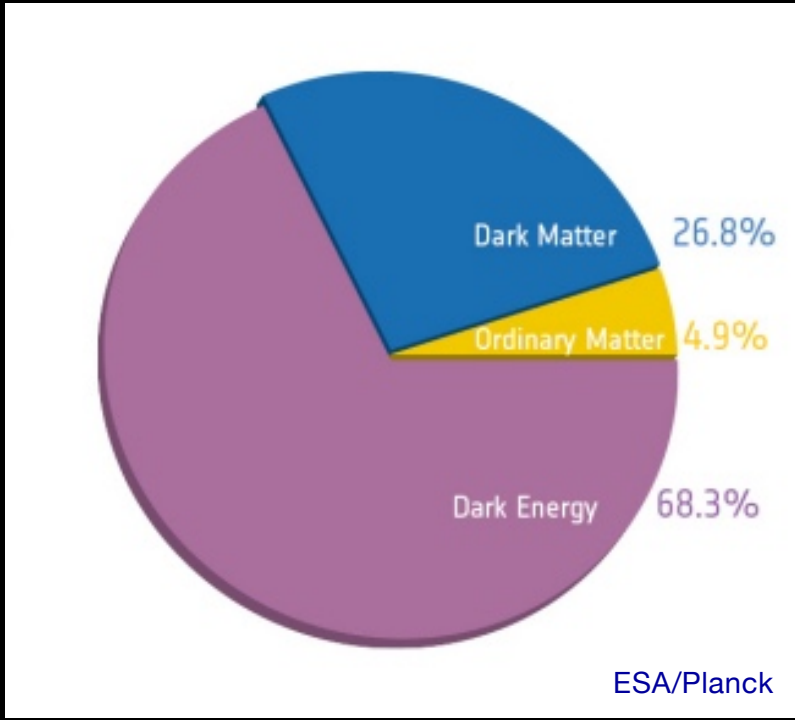
Kent & Gunn 1982

Summary on Dark Matter

- Not measured in the solar system
- Dominates galaxy clusters (velocities, hot gas and gravitational lenses)
- Contributes significantly to the outer regions of galaxies
- Determines the evolution of large scale structure
- Is a possible explanation for the discrepancy between the nucleosynthesis in the Big Bang and the deceleration of the cosmic expansion

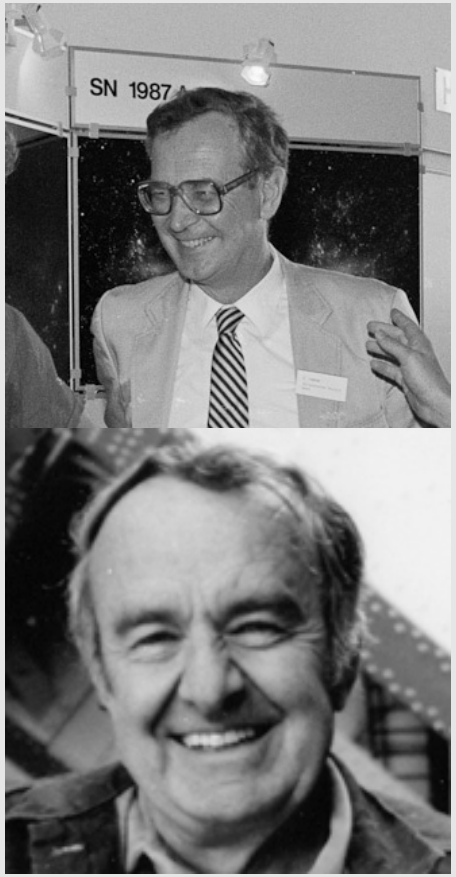
Why Dark Energy?

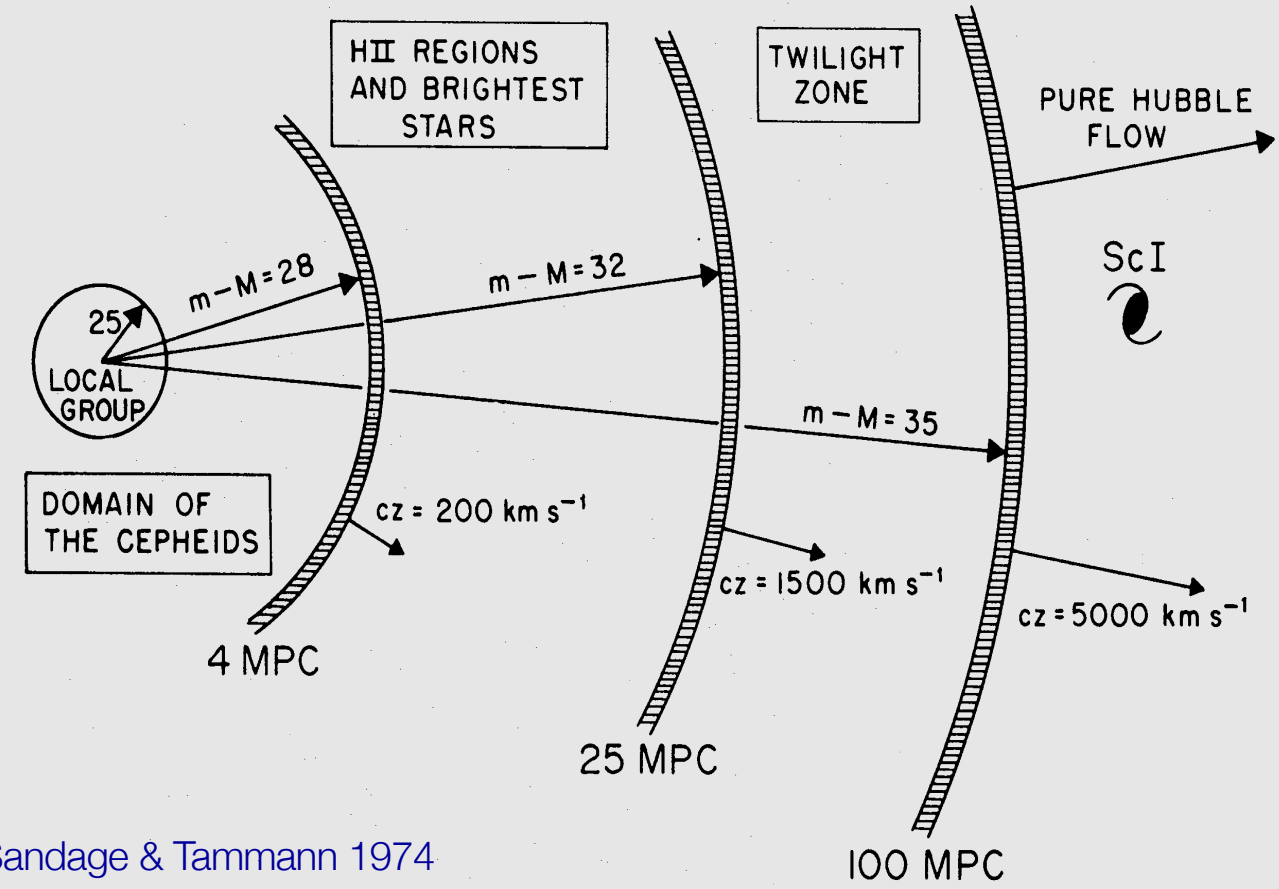
- The expansion of the universe should be slowed down by the gravitational attraction of matter
- Where does Dark Energy come into the game?
  - Expansion history of the universe
  - Curvature of the space compared to the measured matter density
  - Structure formation slowed down



Measuring the Hubble Constant H_0

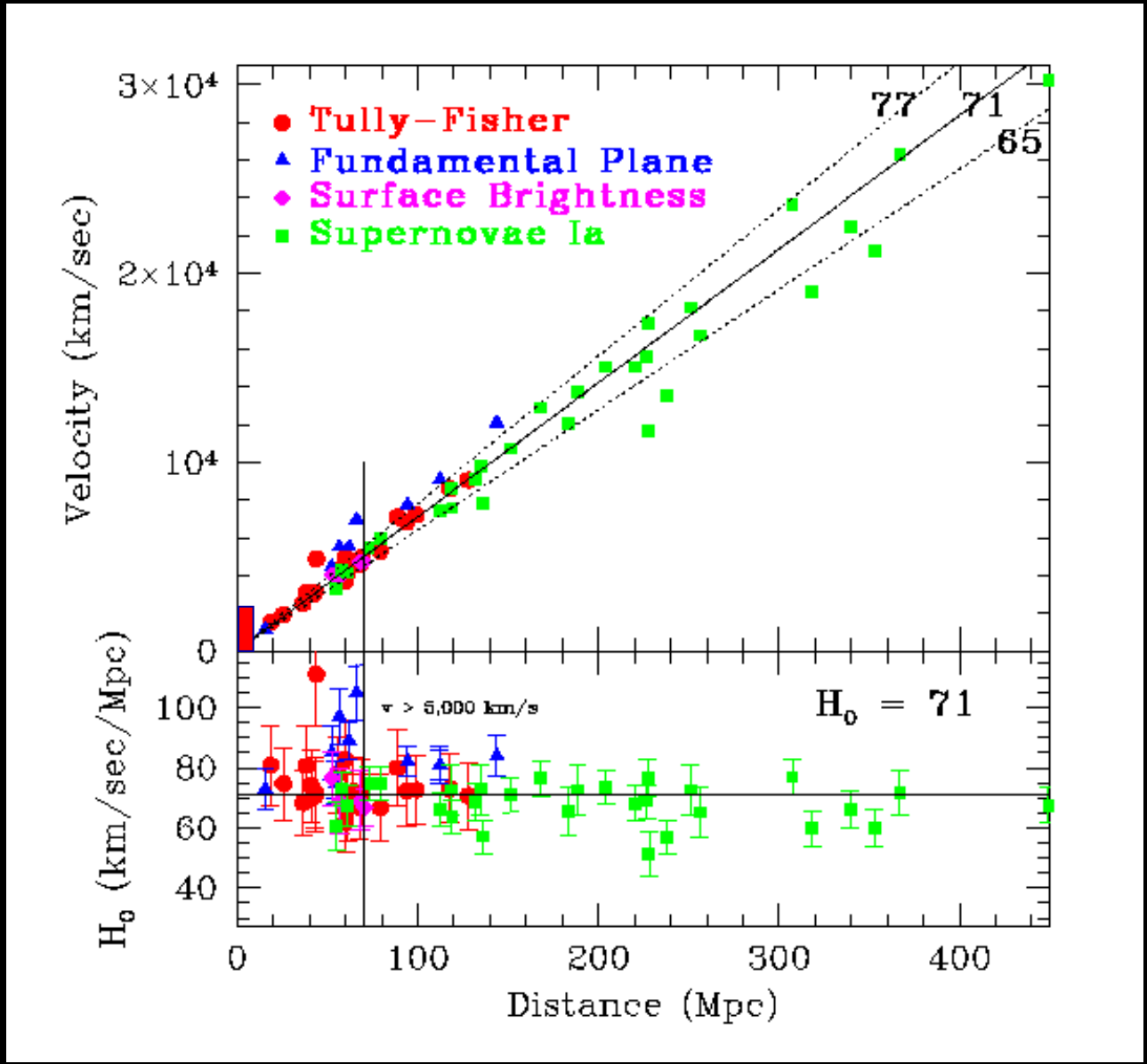
Distance ladder to reach out into the Hubble flow





Sandage & Tammann 1974

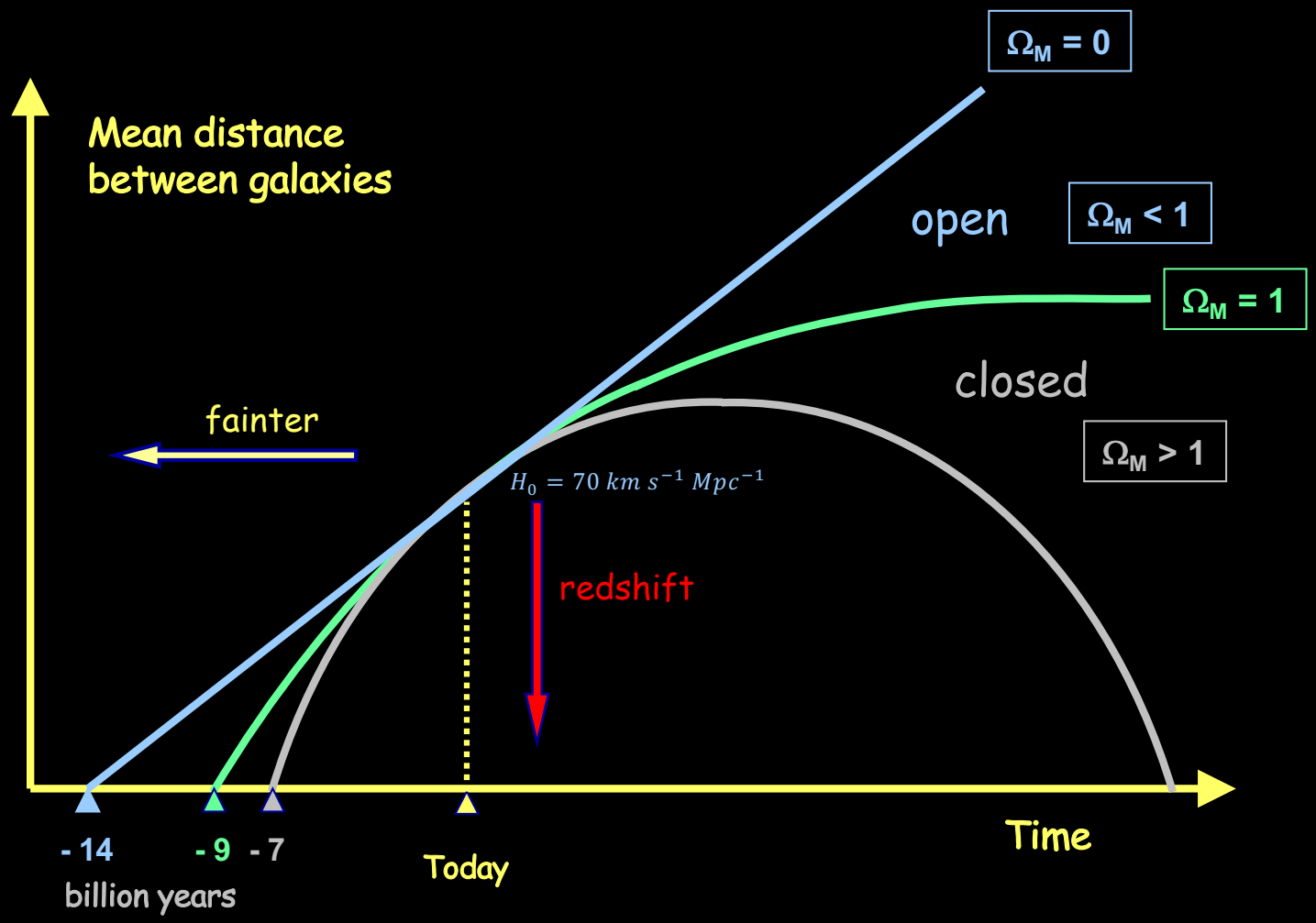
A modern Hubble diagram



The expansion is the same for all (Isotropy)

Gamow

Tammann (SPATIUM 3, 1999)

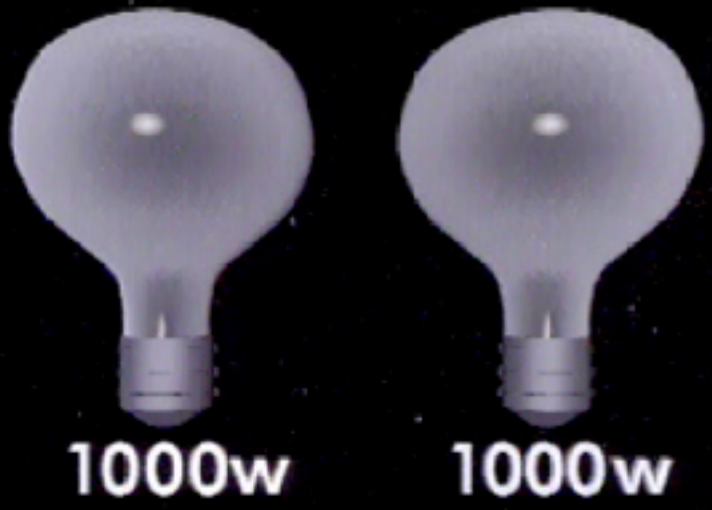

Mean distance
between galaxies
$\Omega_M = 0$
open
$\Omega_M < 1$
$\Omega_M = 1$
closed
$\Omega_M > 1$
fainter
$H_0 = 70\ km\ s^{-1}\ Mpc^{-1}$
redshift
- 14
- 9
- 7
billion years
Today
Time

Supernova!

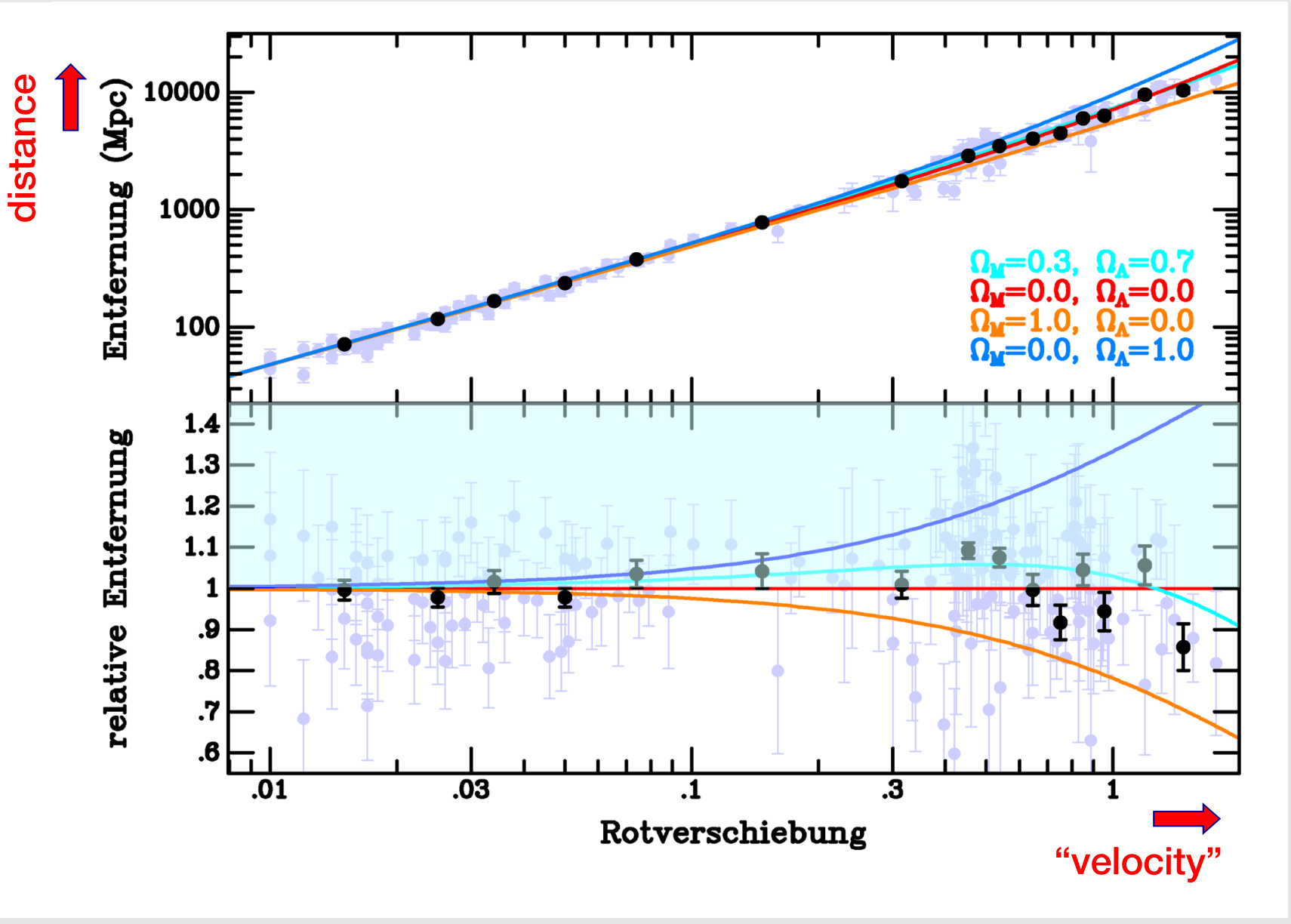
Cosmology with Supernovae

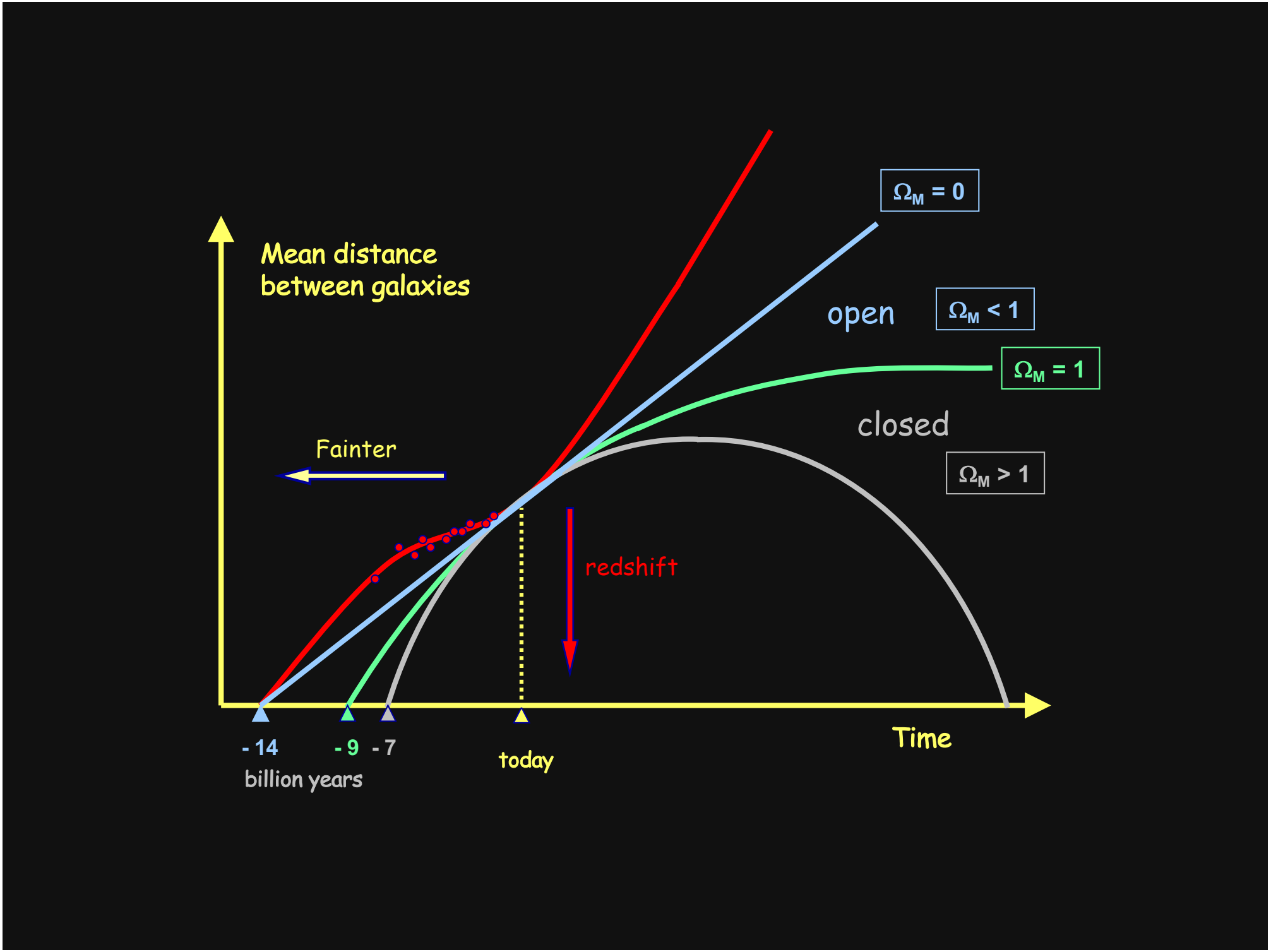
It is very difficult to measure distances in the universe. Supernovae are an essential tool to determine the expansion rate and its history

Typ Ia Supernovae are excellent distance indicators calibrated in the nearby universe



The supernova Hubble diagram

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billion years
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Physics Nobelprize 2011

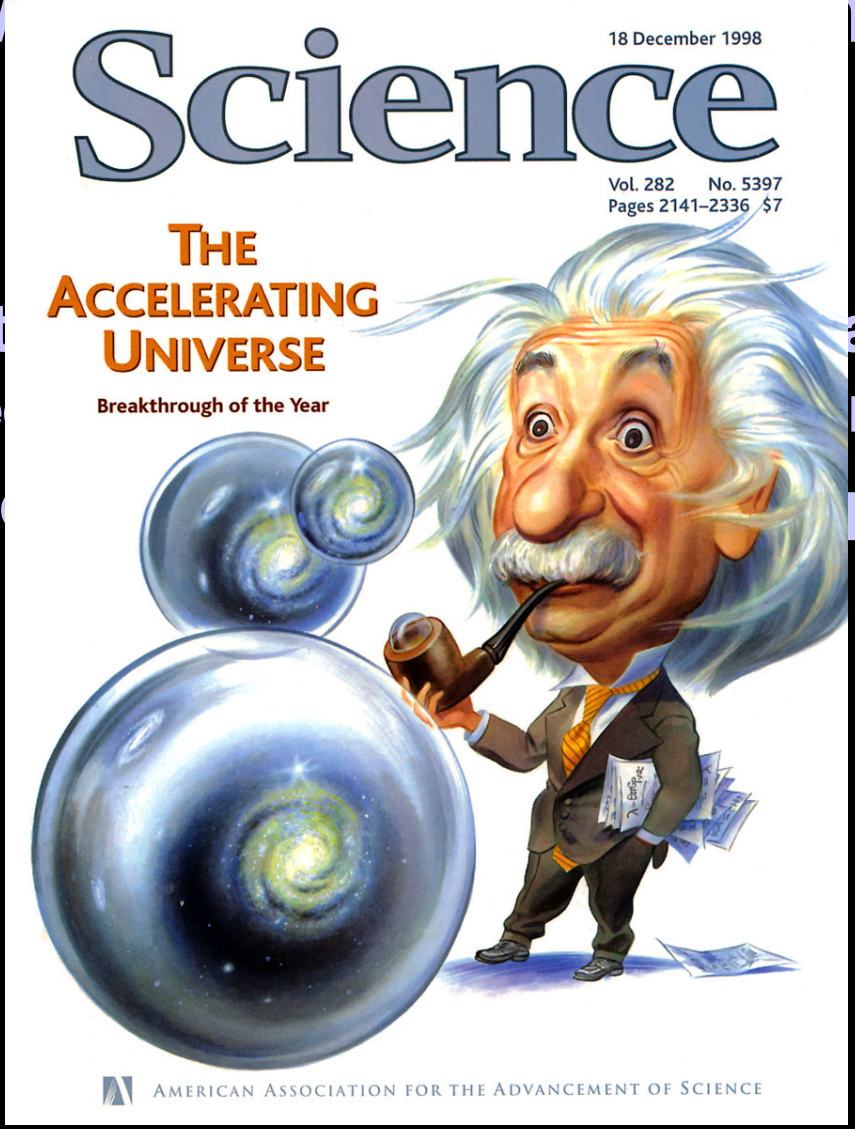
KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Saul Perlmutter Brian Schmidt Adam Riess

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

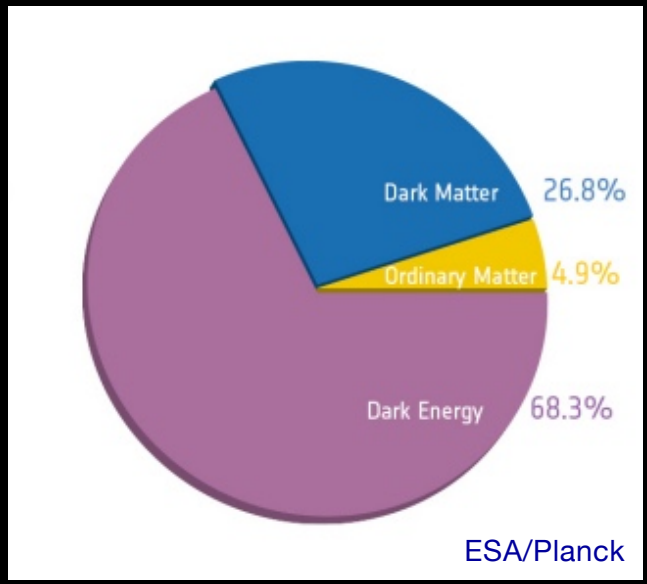
What does this mean?

Distant ay than
in a fre rse
This re ponent



Summary

- Dark Matter and Dark Energy are part of the theory of gravity (Relativity) with opposite signs.
- Dark Matter is attractive like baryons (“us”) and increases the gravitational potential.
- Dark Energy is a characteristic of space and acts as a repulsive force.



Hubble Constant

Calibration of the luminosity of *SN Ia @ max)*

PAST DISTANCE LADDER (100 Mpc)

11% error

1% # Modern, distant SNe Ia

3% # Modern, local hosts

3.5% SN Ia hosts,
Metallicity change

4% long to short Period Cepheids

4.5% Ground to HST

5% Anchor: LMC

NEW LADDER (100 Mpc)

4 % error

1%

2%

Calibrator

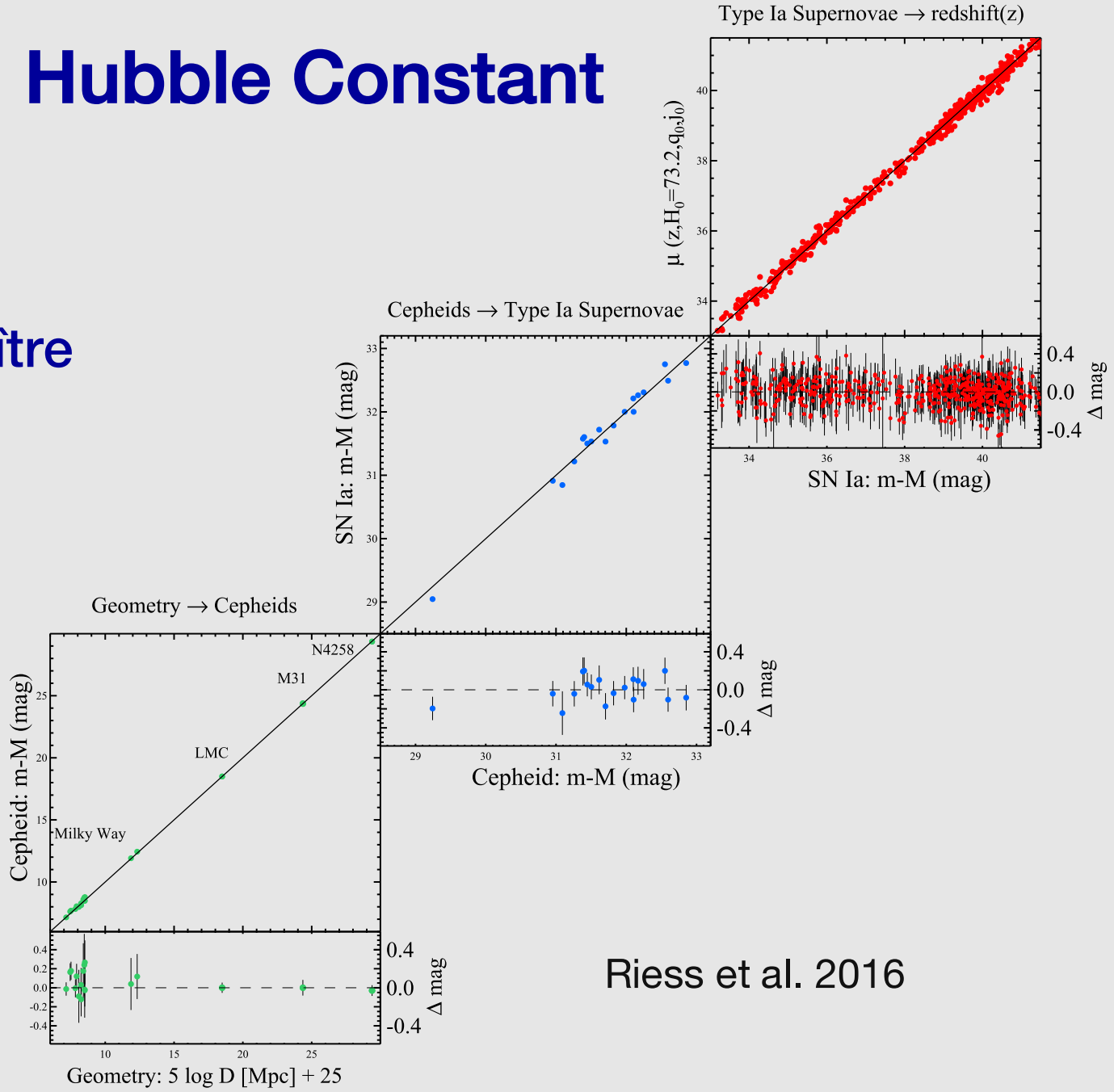
NA

3% Anchor:
NGC4258

Adam Riess

Hubble Constant

Supernova Ia Hubble-Lemaître Diagramm

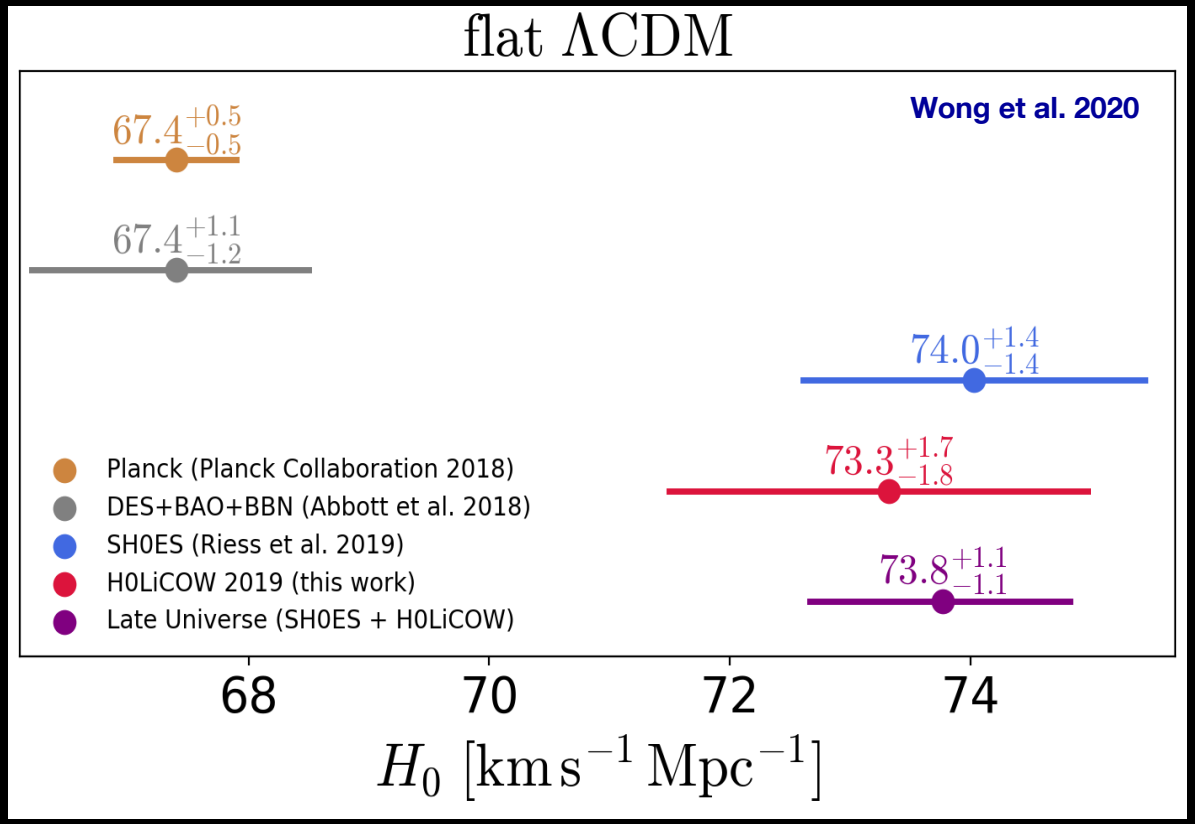


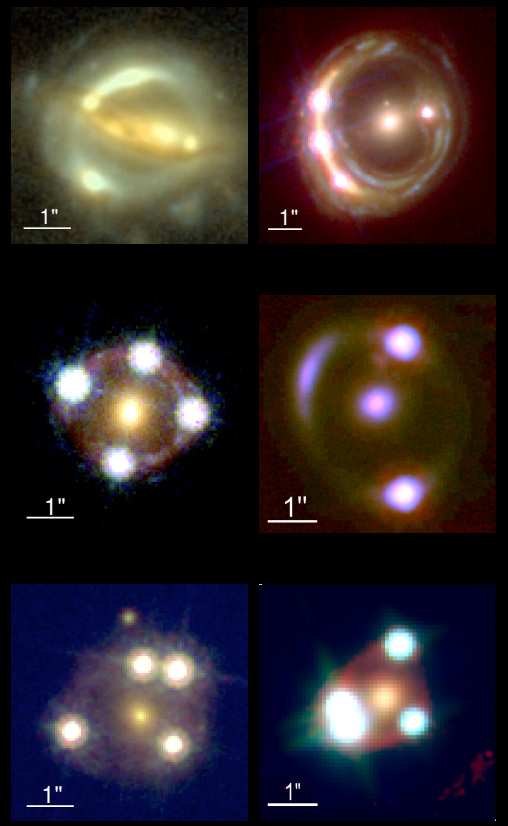
Riess et al. 2016

Sherry Suyu (J. Wiedersich / TUM)

Gravitational Lenses

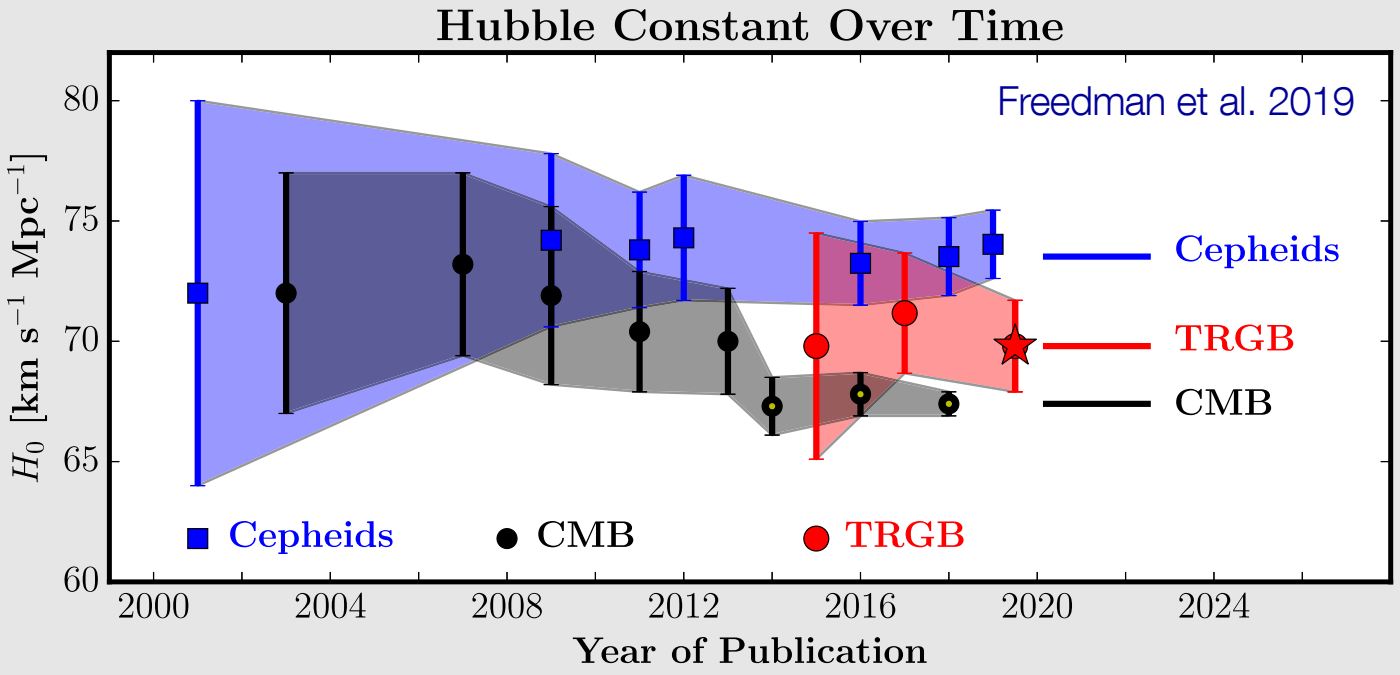
H0LICOW collaboration





Problem solved?

New discrepancy between the near (distance ladder) and distant (microwave background) determinations of H_0

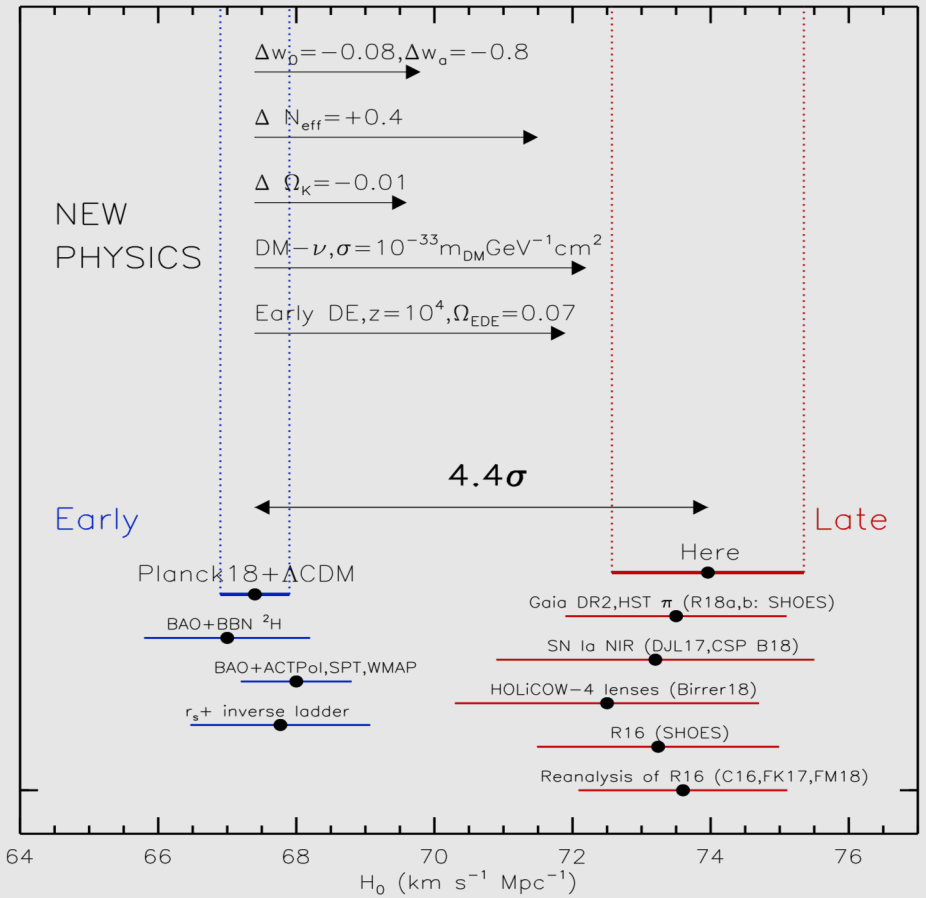


Summary

If the measurements are correct

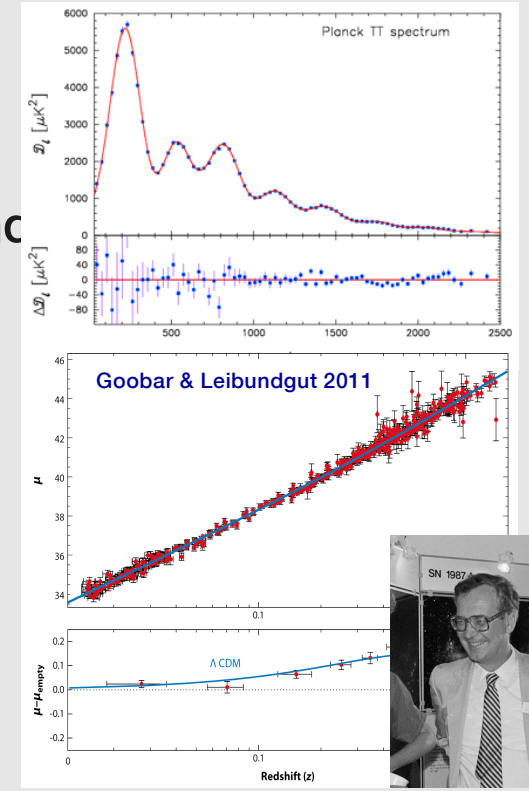
- is either the cosmological model incomplete or
- it is wrong

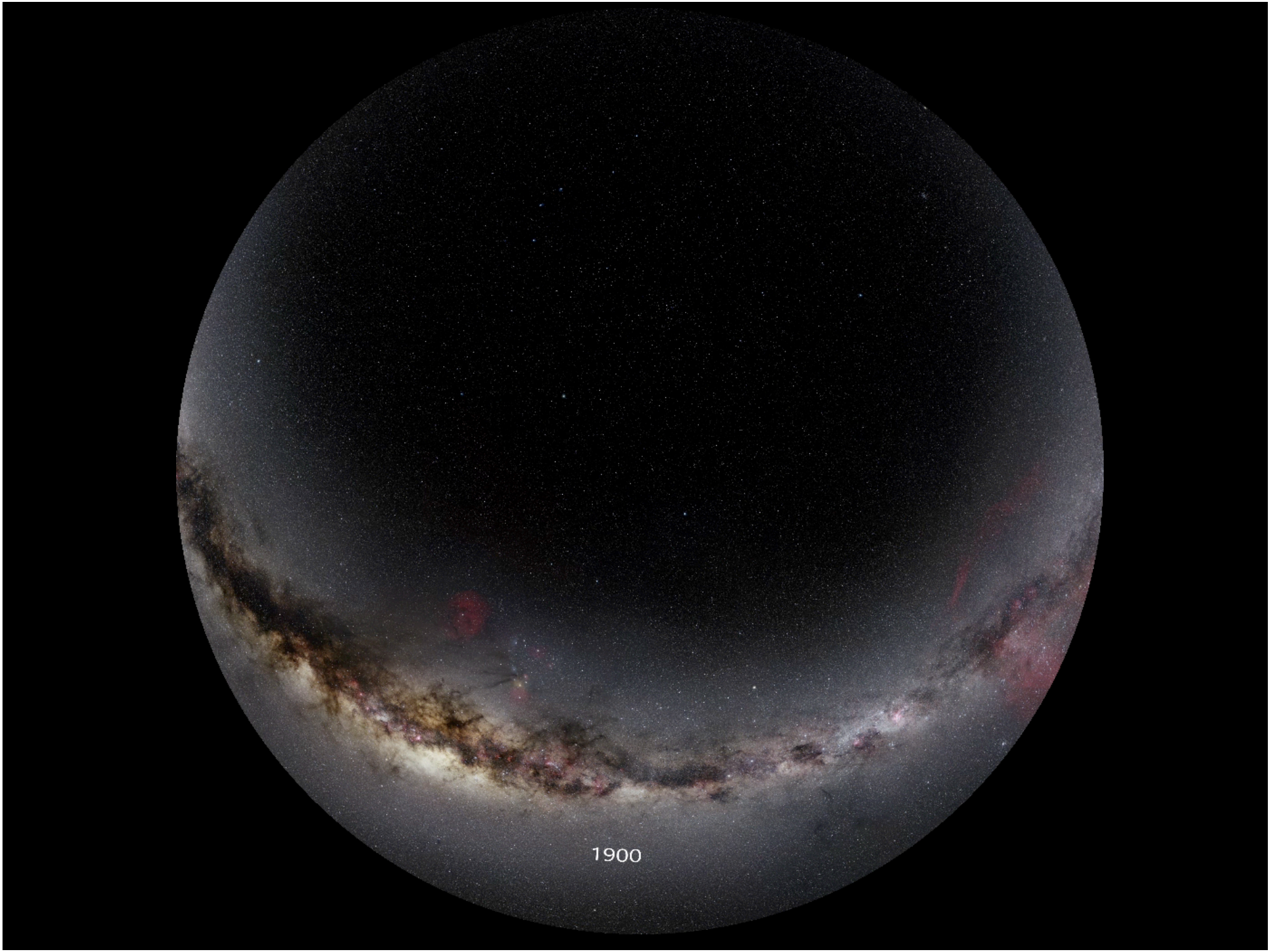
Riess et al. 2019



Summary

- Big Bang Theory
  - explains
    - early nucleosynthesis (deuterium, helium)
    - early radiation (cosmic microwave backgrounc
    - age of the universe
      - universe is older than the oldest stars
    - expansion
  - does not explain
    - Inflation (”before the Big Bang”)
    - Dark Matter
    - Dark Energy
    - problem with the Hubble Constant




1900