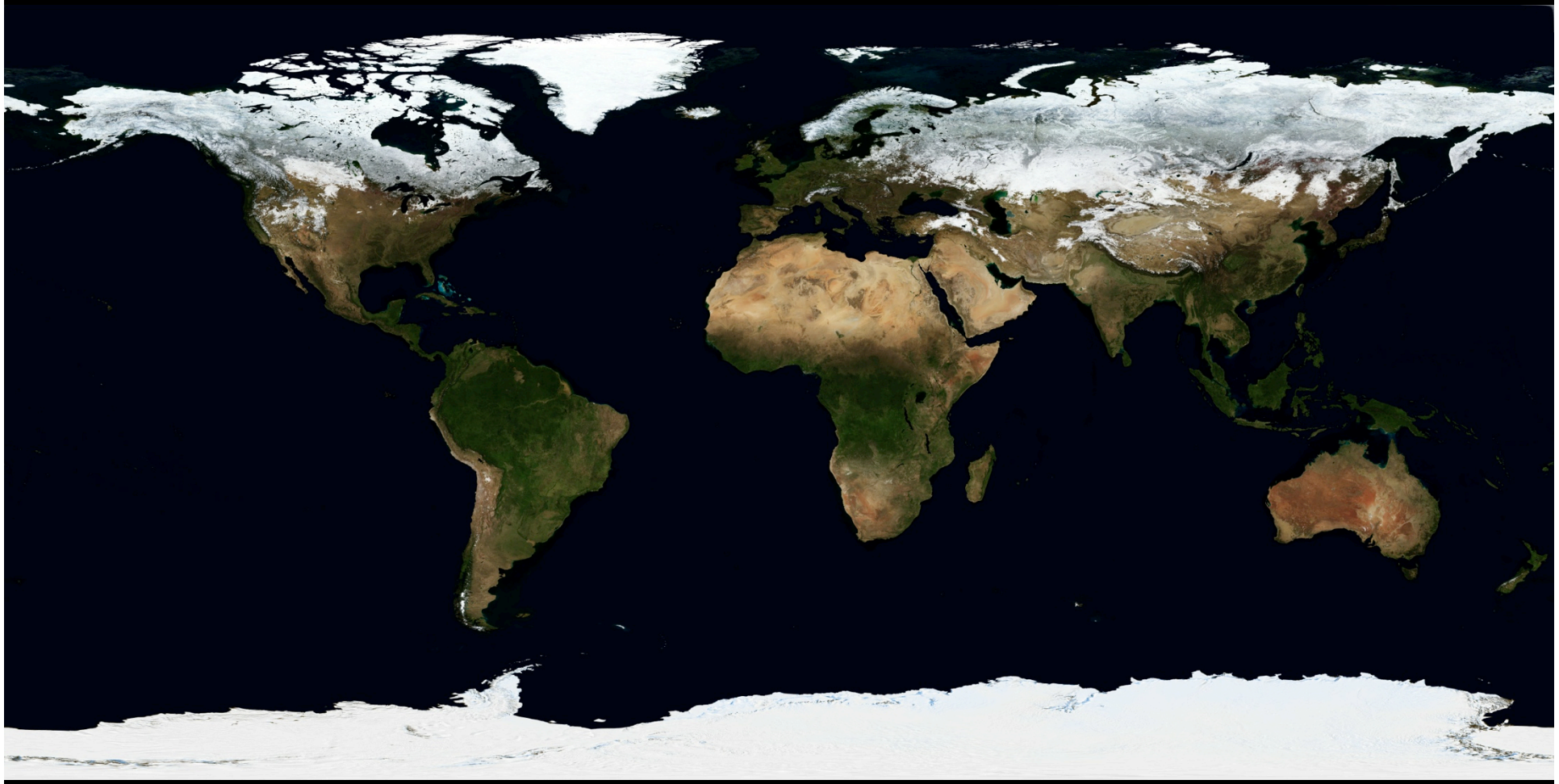
Discovering the Accelerating Universe

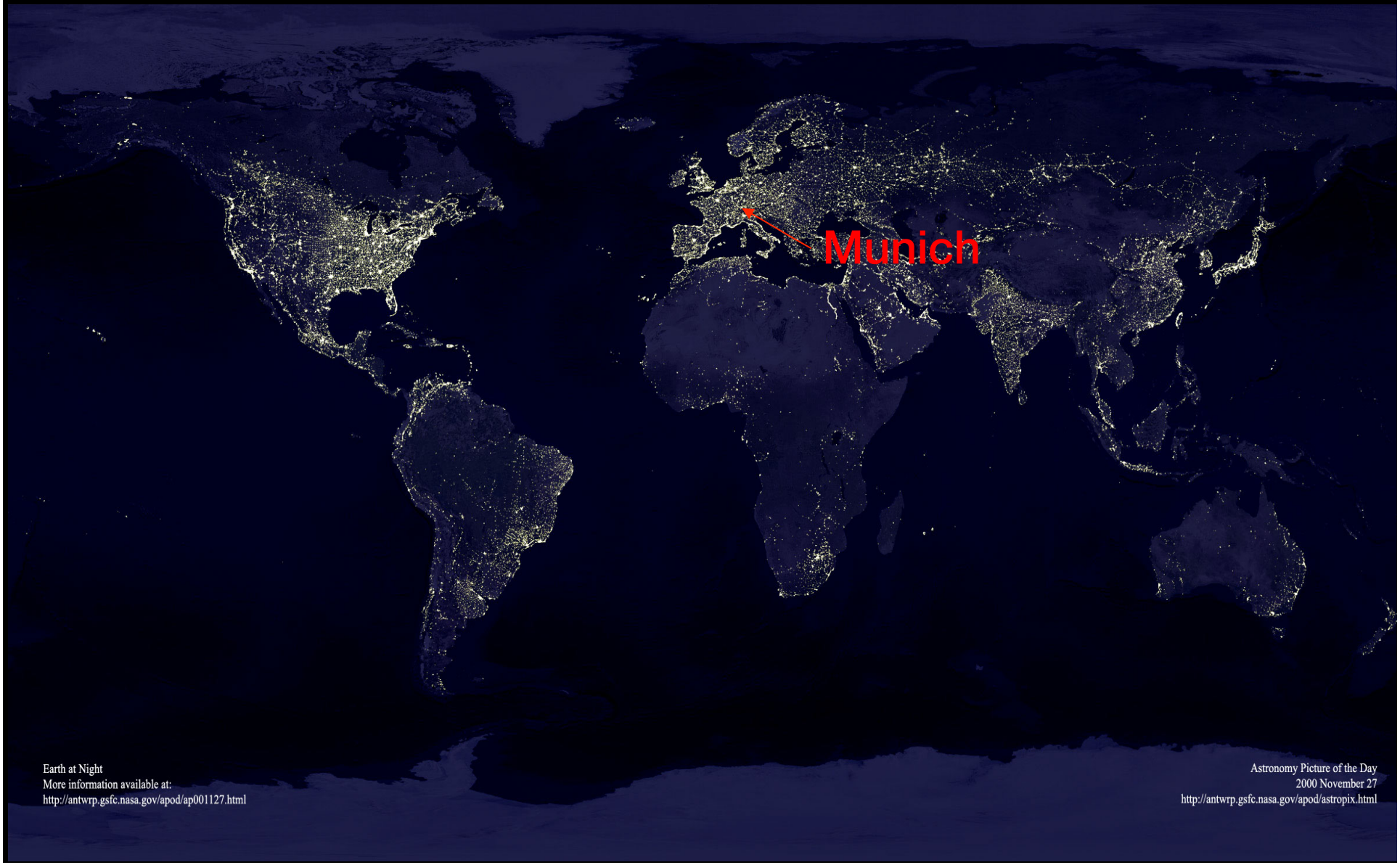
Bruno Leibundgut
European Southern Observatory (ESO)

How do we see our world?

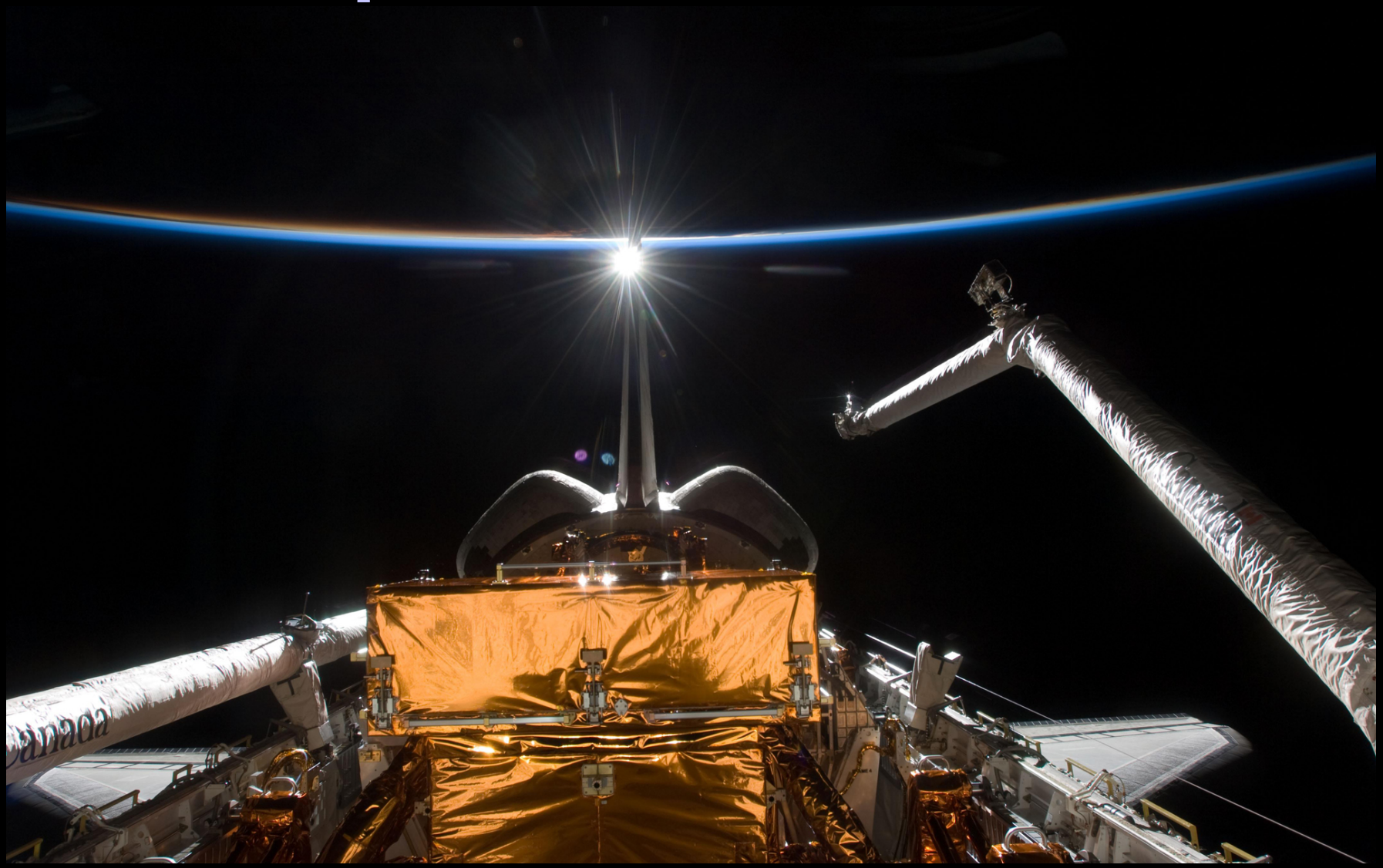
A changing world



The Earth at night



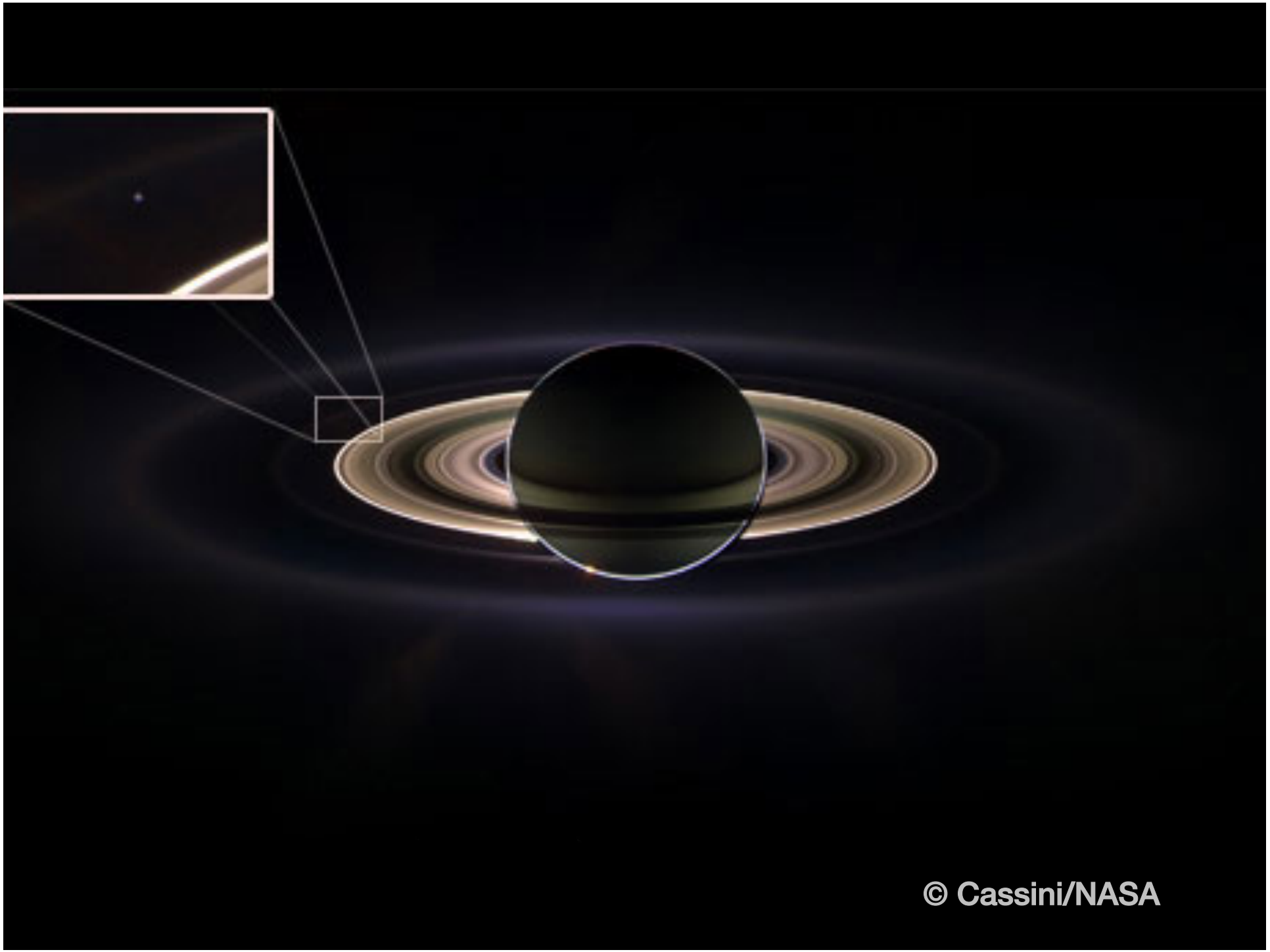
Our place in the universe



Our Home

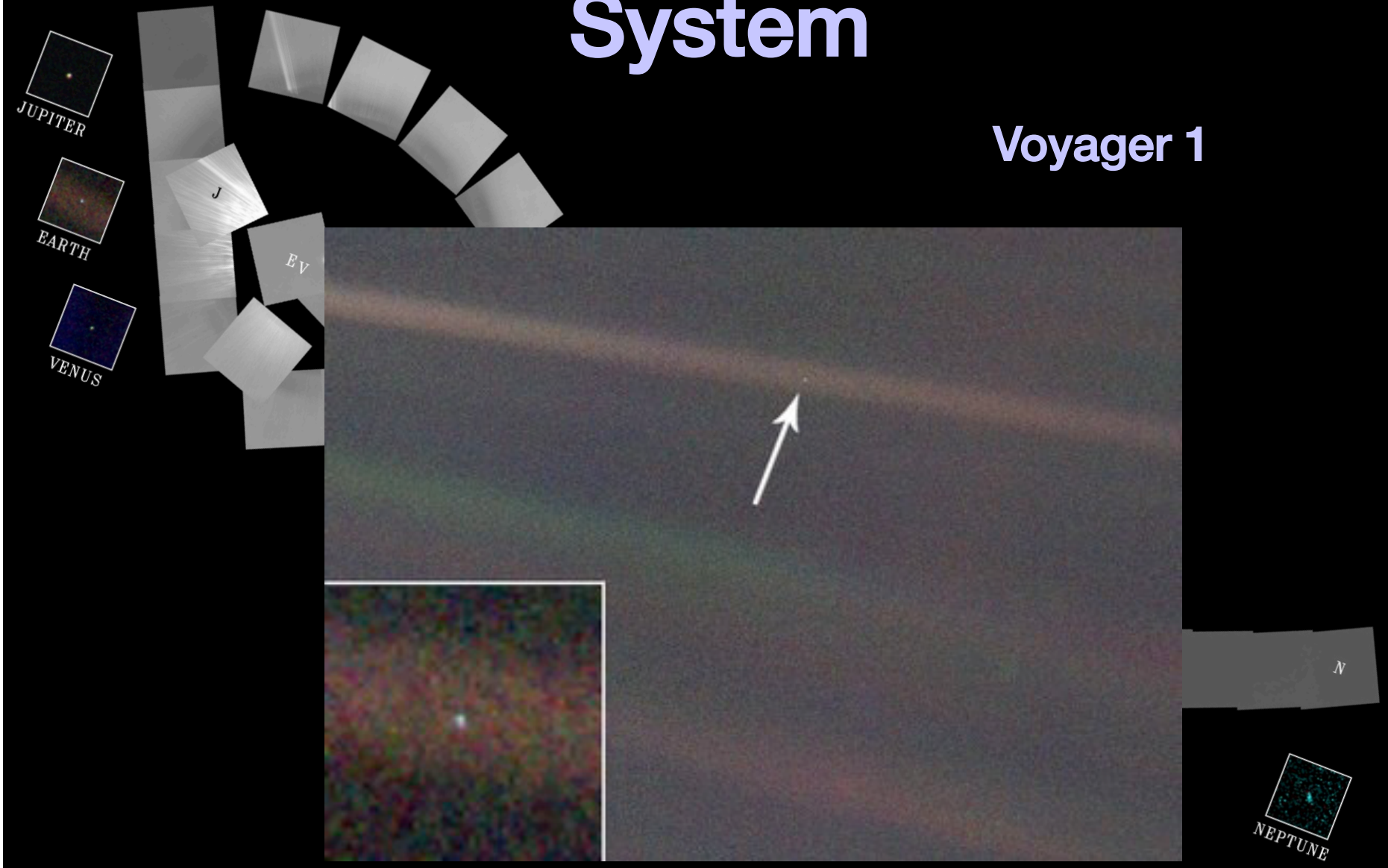
Our Home

MESSENGER (© NASA)

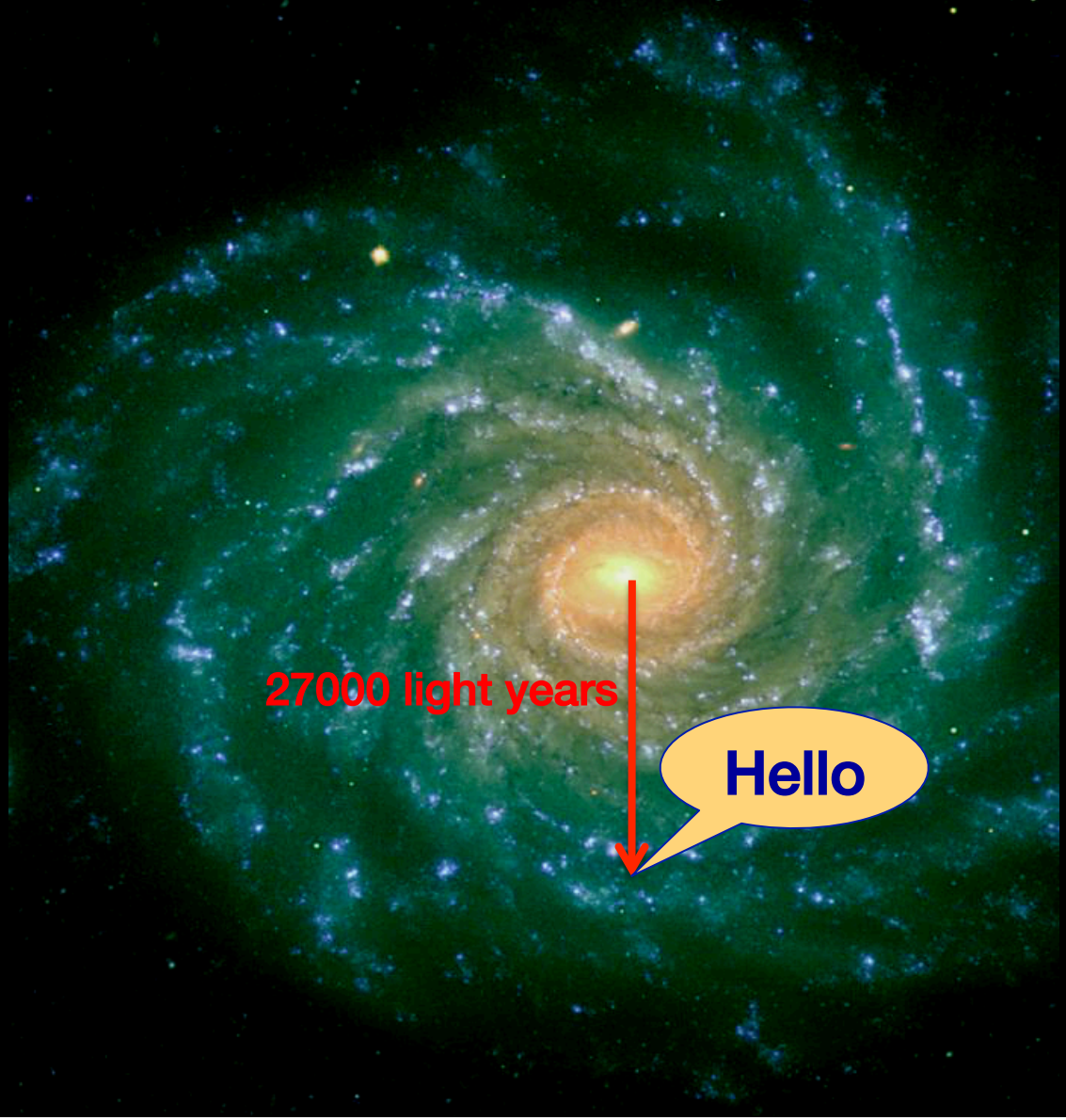

© Cassini/NASA

Family Portrait of the Solar System

Voyager 1

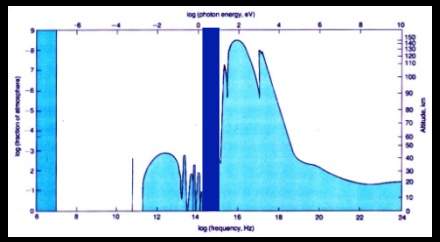


Our place in the Milky Way

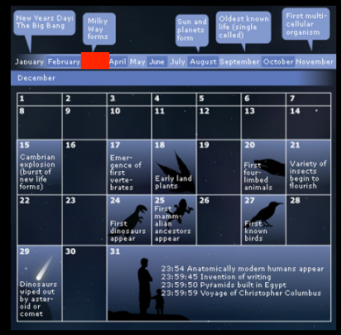


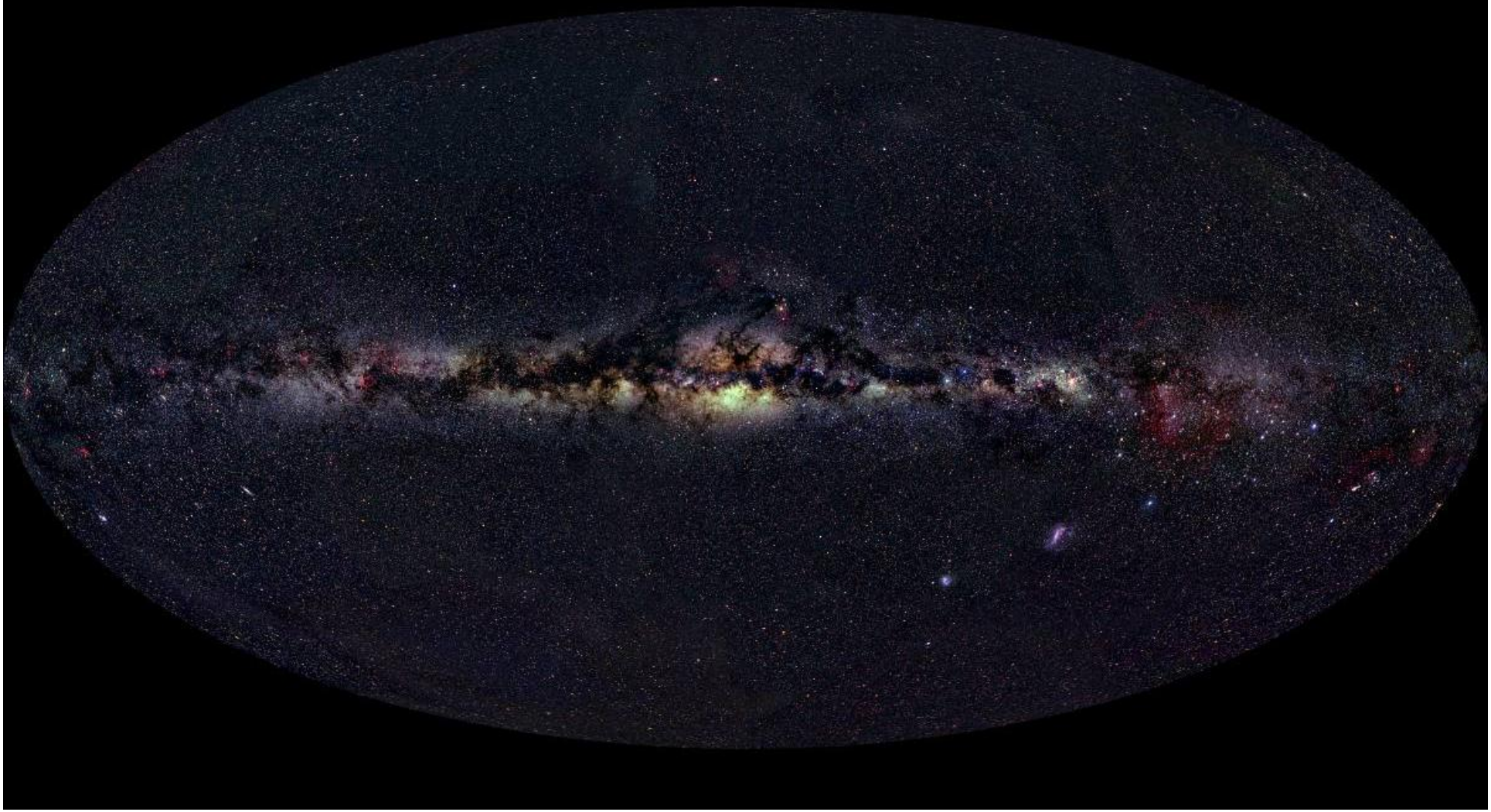
Earth‘s atmosphere

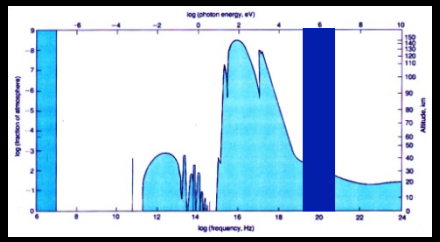
Shield and Window to the Universe


log (photon energy, eV)
log (fraction of atmosphere)
Altitude, km
log (frequency, Hz)

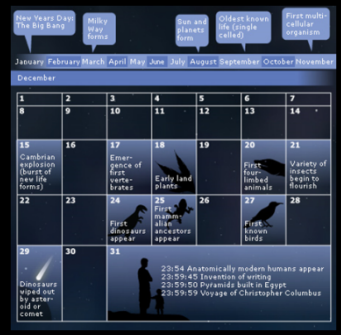
„visible“

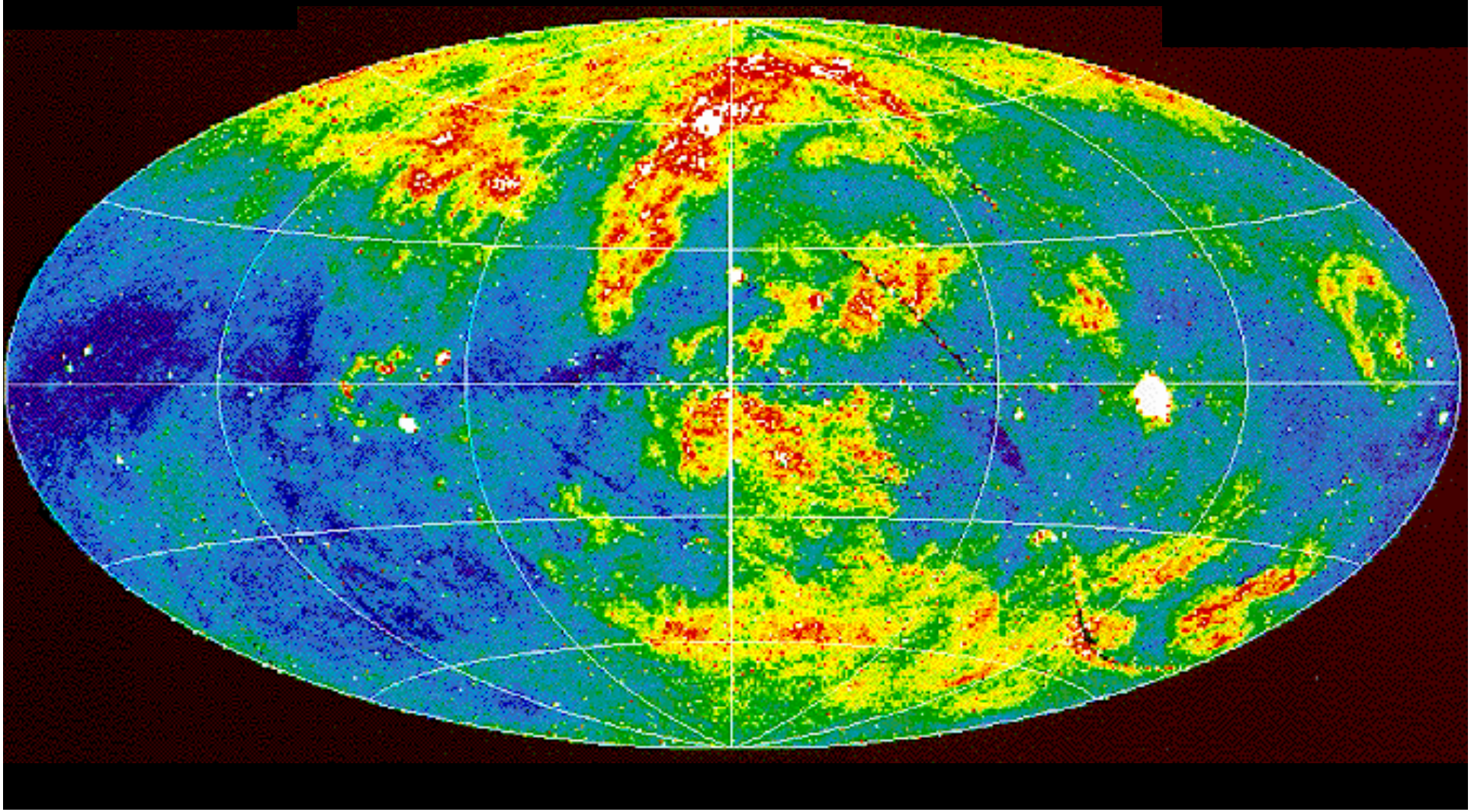

New Years Day! The Big Bang
Milky Way forms
Sun and planets form
Oldest known life (single celled)
First multi-cellular organism
January February April May June July August September October November December
Cambrian explosion (burst of new life forms)
Emergence of first vertebrates
Early land plants
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

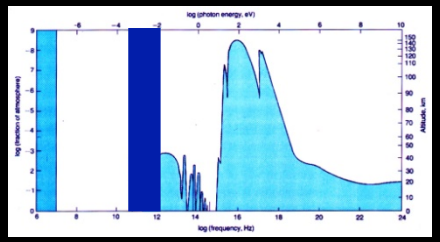



log (photon energy, eV)
log (fraction of atmosphere)
Altitude, km
log (frequency, Hz)

„invisible“

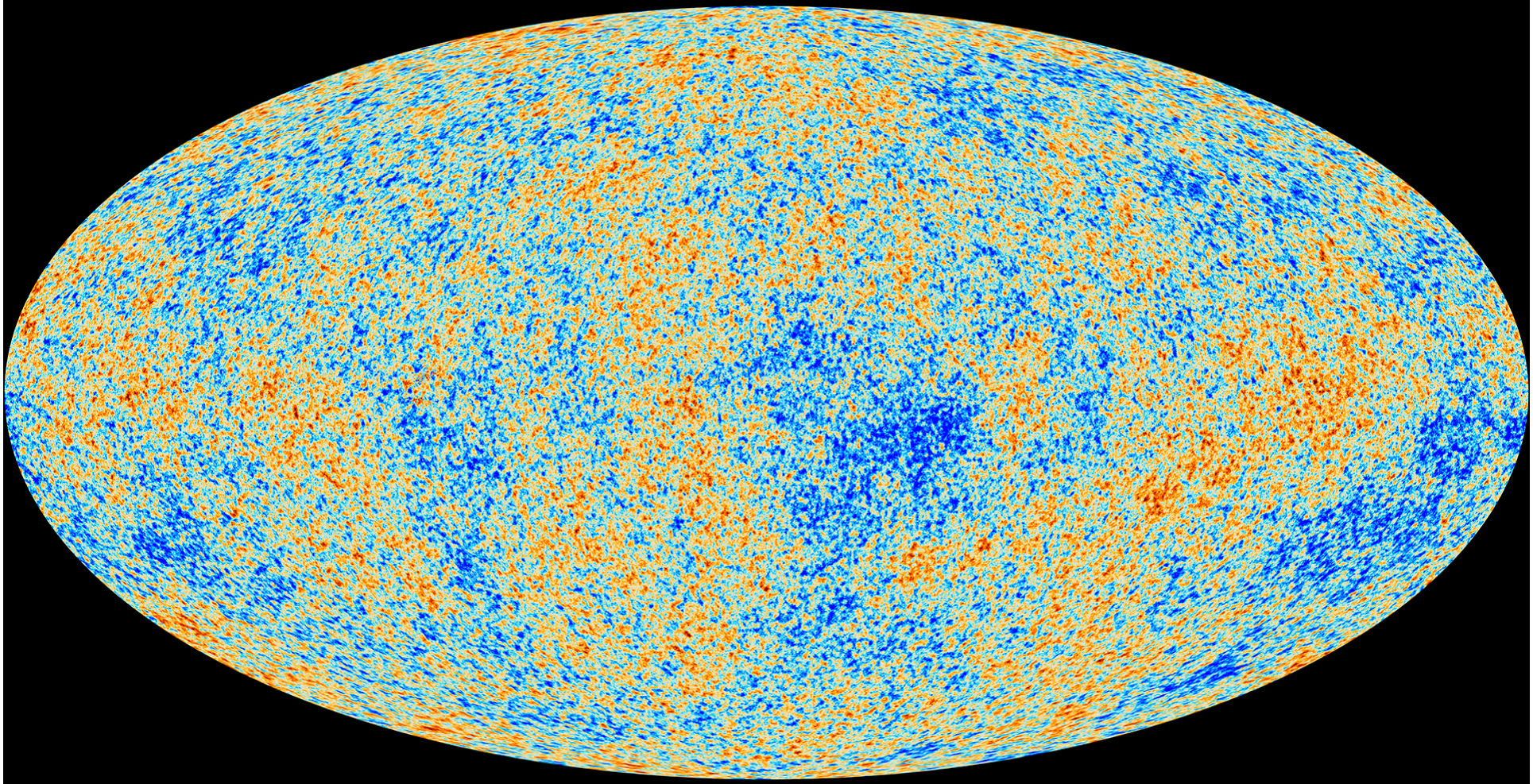

New Years Day! The Big Bang
Milky Way forms
Sun and planets form
Oldest known life (single celled)
First multi-cellular organism
January February March April May June July August September October November December
Cambrian explosion (burst of new life forms)
Emergence of first vertebrates
Early land plants
First four-limbed animals
Variety of insects begin to flourish
First dinosaurs appear
First mammalian 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

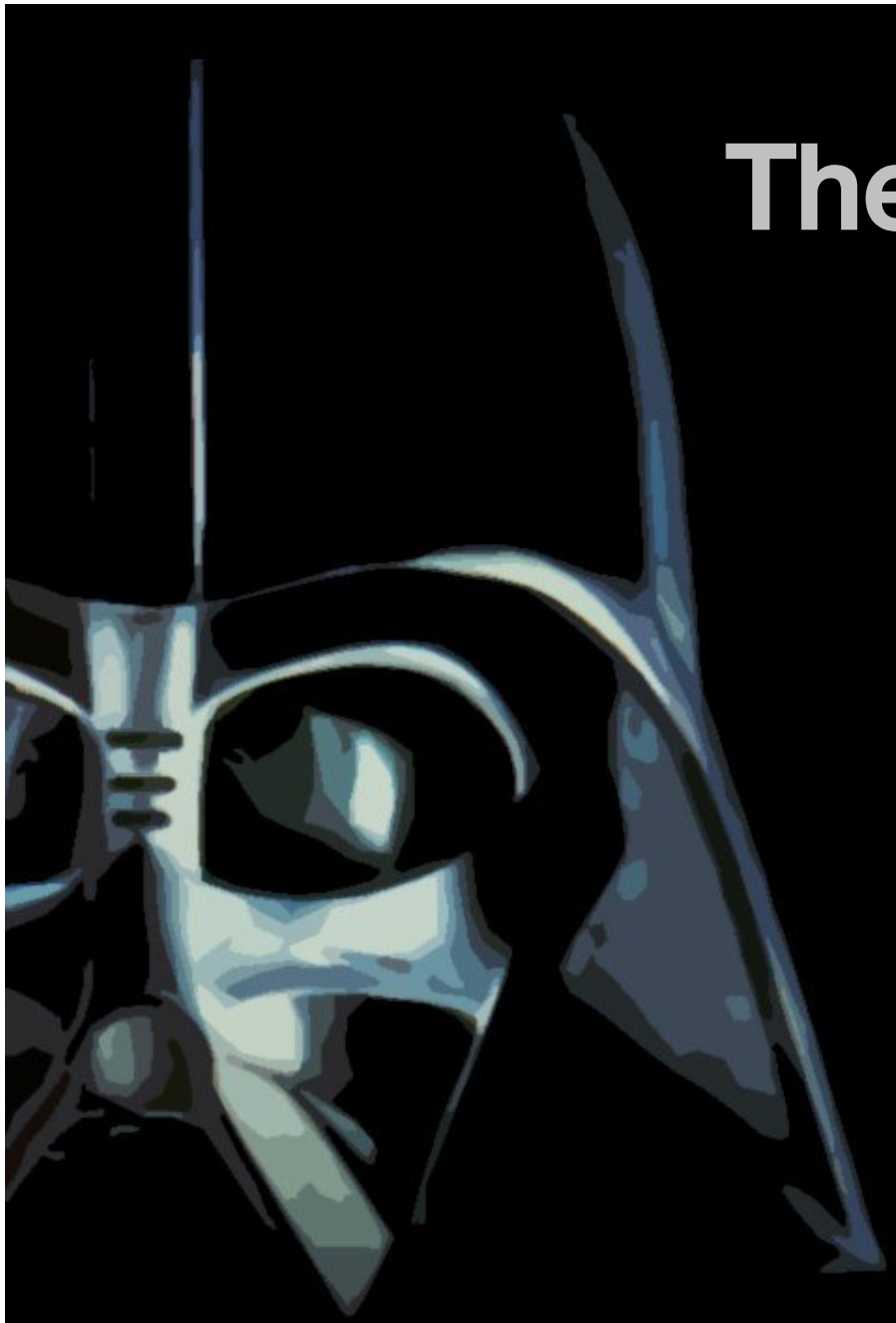



log (photon energy, eV)
log (fraction of atmosphere)
Altitude, km
log (frequency, Hz)

„invisible“


New Years Day! The Big Bang
Milky Way forms
Sun and planets form
Oldest known life (single celled)
First multi-cellular organism
February March 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 mammalian 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





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?

The „invisible” Universe

- Large parts of the Universe are dark
- „Dark“ (non-luminous matter) is everywhere
  - e.g. planets, molecules, dust, cool gas
- Measurements through indirect methods
  - Gravitation!
  - Model for the evolution of the Universe
    - Einstein’s Theory of Relativity

Basics of Cosmology

(our world view)

Theory of Gravity

Einstein's Theory of General Relativity

Isotropy

There are no preferred directions in the Universe

Homogeneity

No special region in the Universe

(e.g. no centre)

Anthropic Principle

The Universe created us

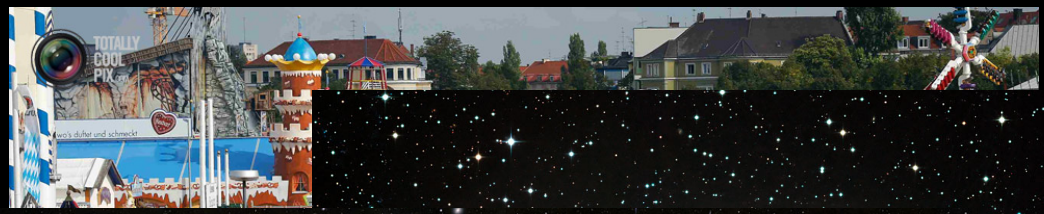
Gravitation!

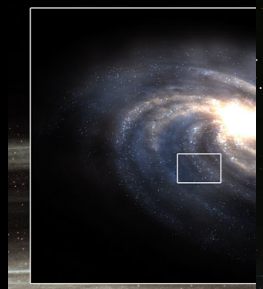
Of the four fundamental forces (Gravitation, Electromagnetism, Weak and Strong Forces) only gravitation determines the evolution of the universe.

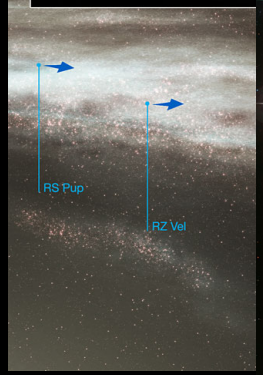

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$
A. EINSTEIN
FOR WORLD CUP
2003

What is in the Universe?

- We are!

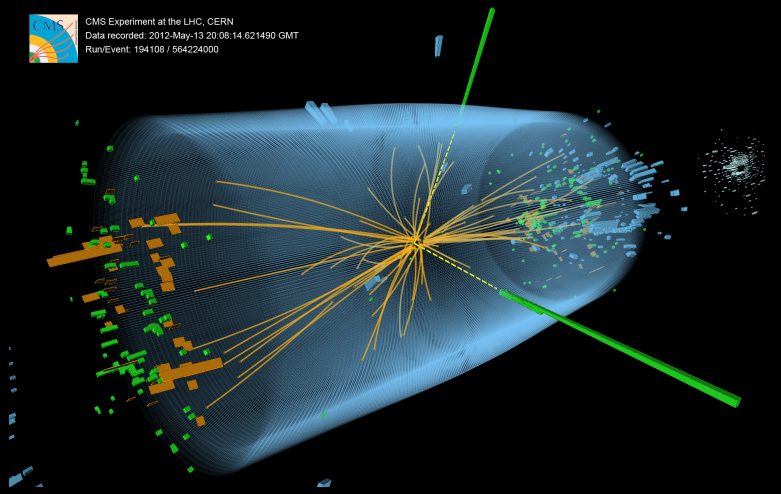


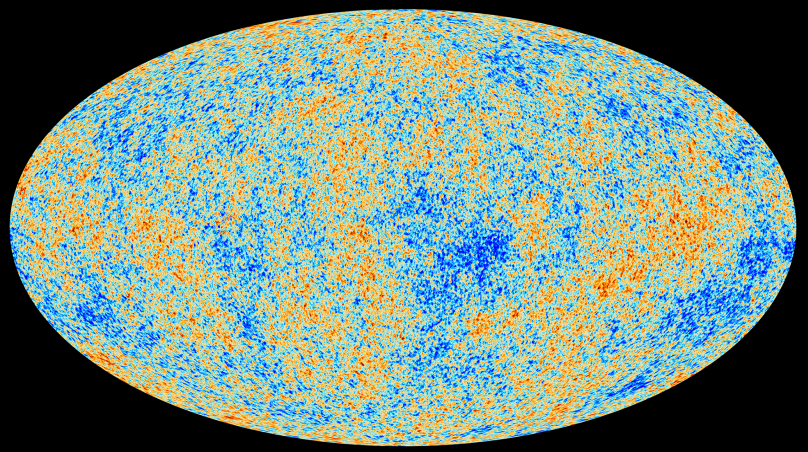




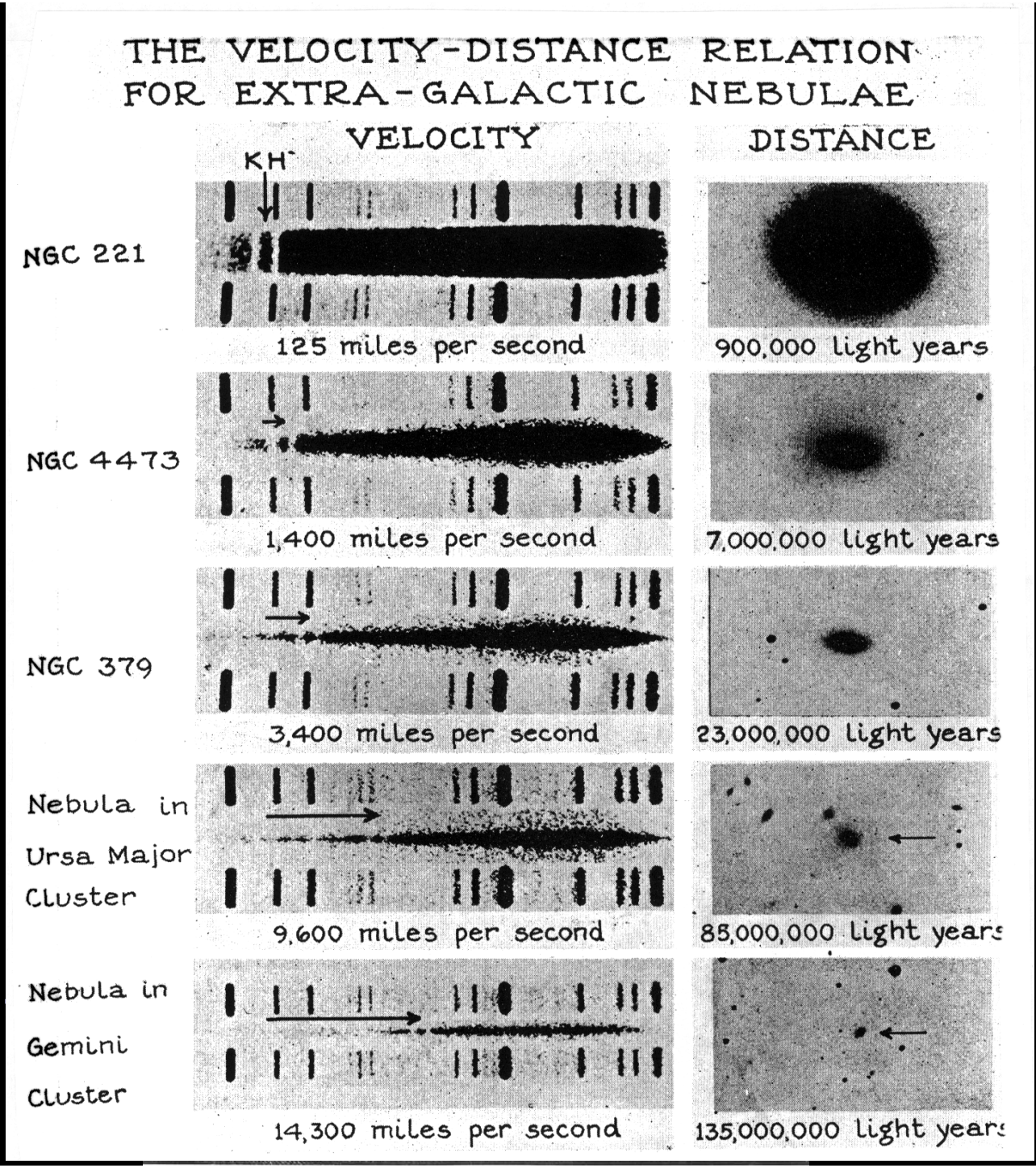
What is in the Universe?

- What else?
  - Elementary particles
    - Neutrinos
    - Higgs particle
    - yet unknown particles
  - Other forms of energy
    - radiation
    - ????





Hubble


THE VELOCITY-DISTANCE RELATION
FOR EXTRA-GALACTIC NEBULAE
VELOCITY
DISTANCE
K
H
NGC 221
125 miles per second
900,000 light years
NGC 4473
1,400 miles per second
7,000,000 light years
NGC 379
3,400 miles per second
23,000,000 light years
Nebula in
Ursa Major
Cluster
9,600 miles per second
85,000,000 light years
Nebula in
Gemini
Cluster
14,300 miles per second
135,000,000 light years

The original Hubble diagram

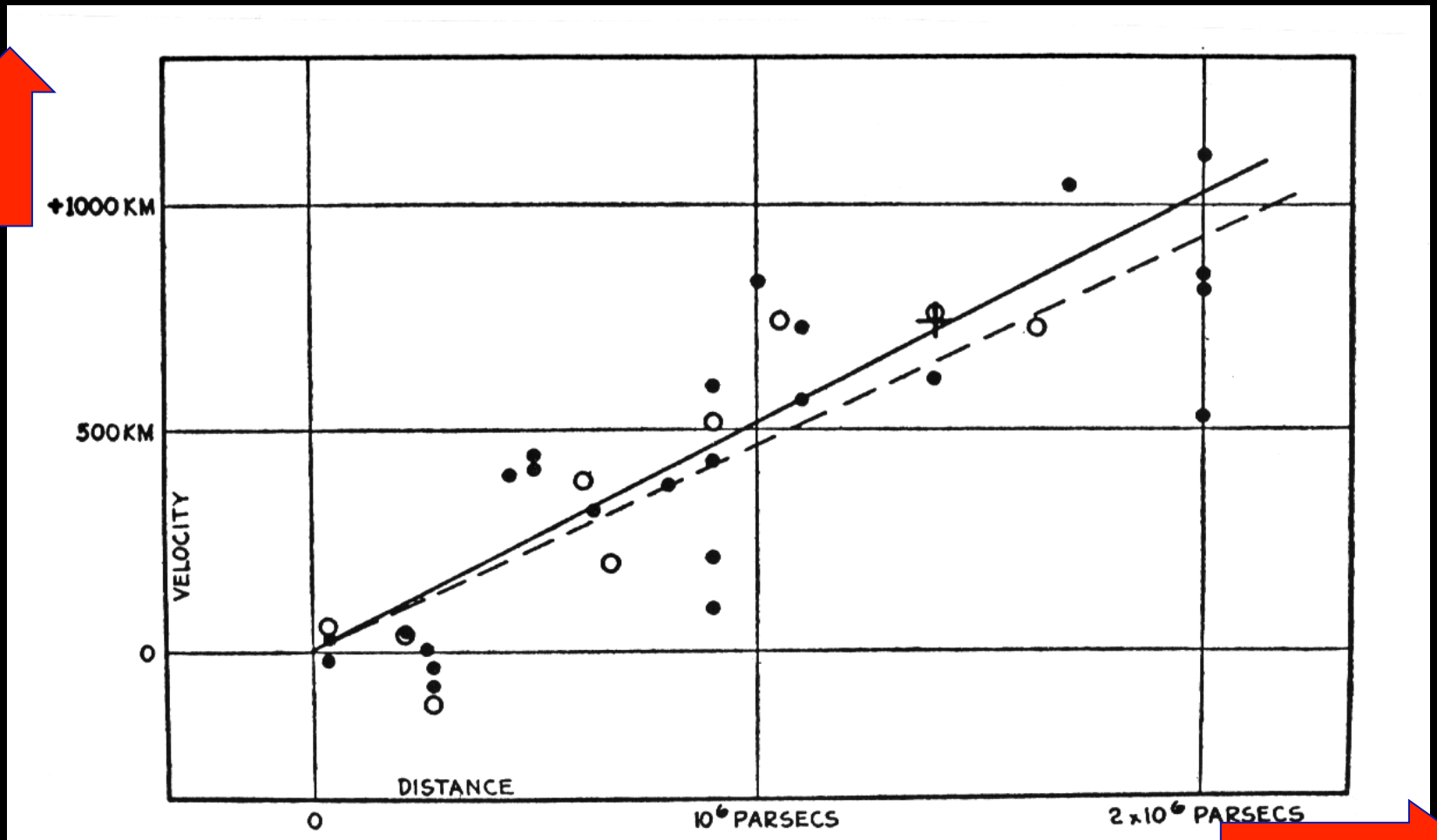
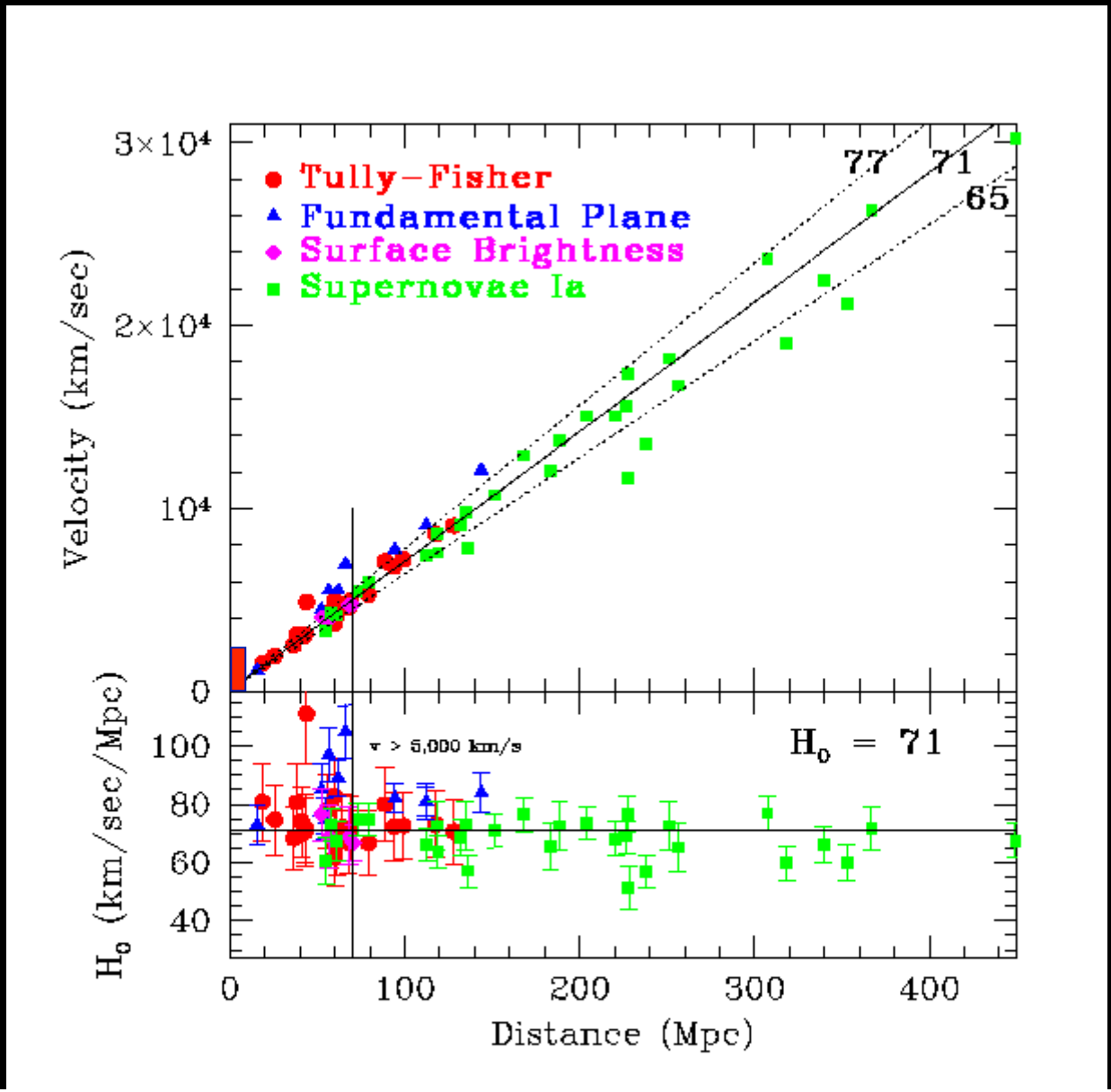


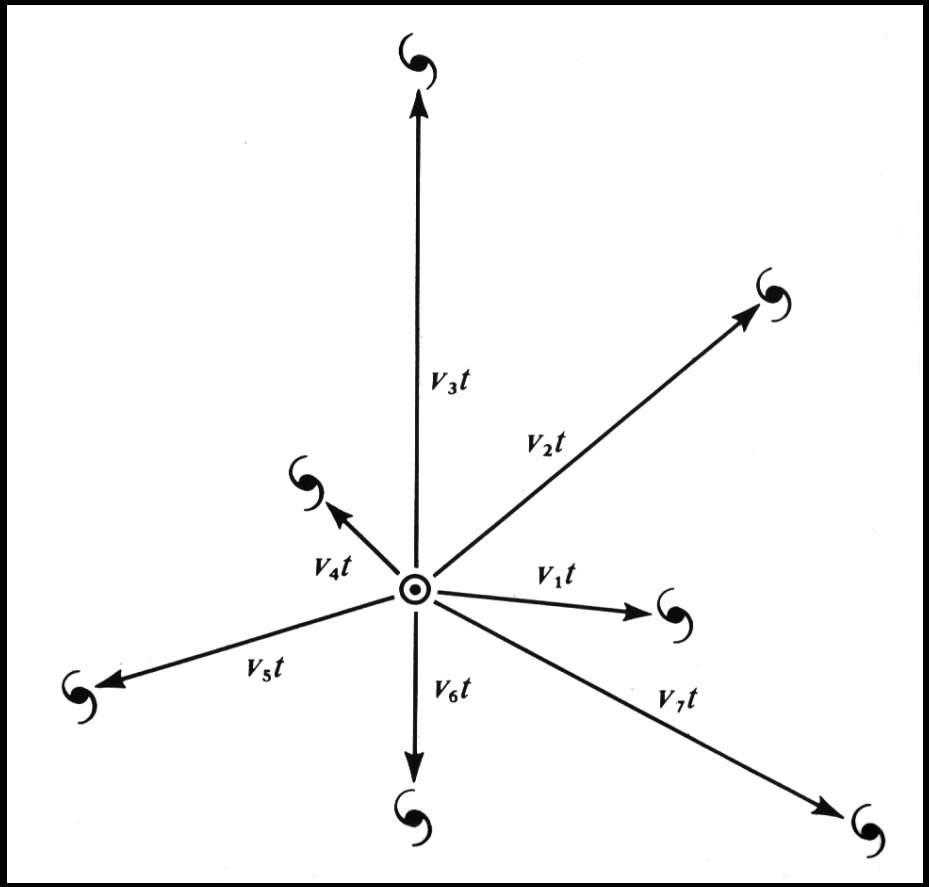
FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble diagram

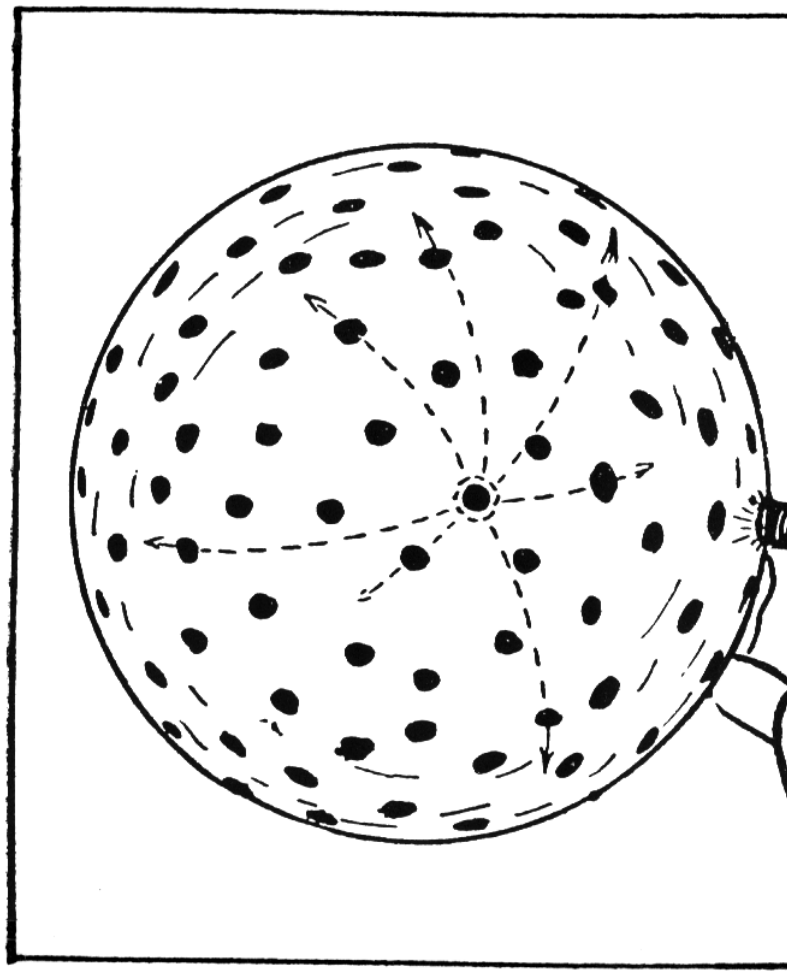


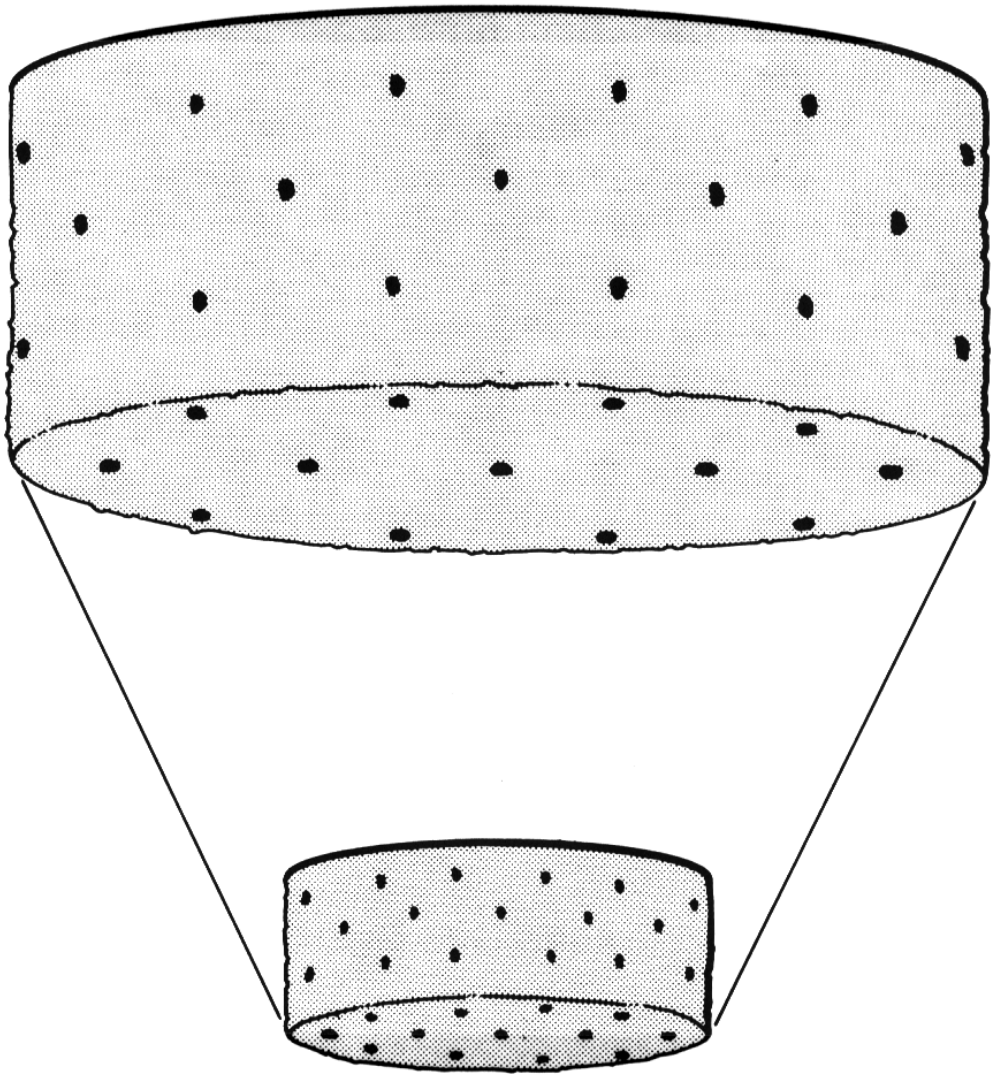
The age of the Universe

All galaxies start at the same point, which leads to the following picture



The expansion is the same for everybody (Isotropy)






Supernova!
© Anglo-Australian Telescope

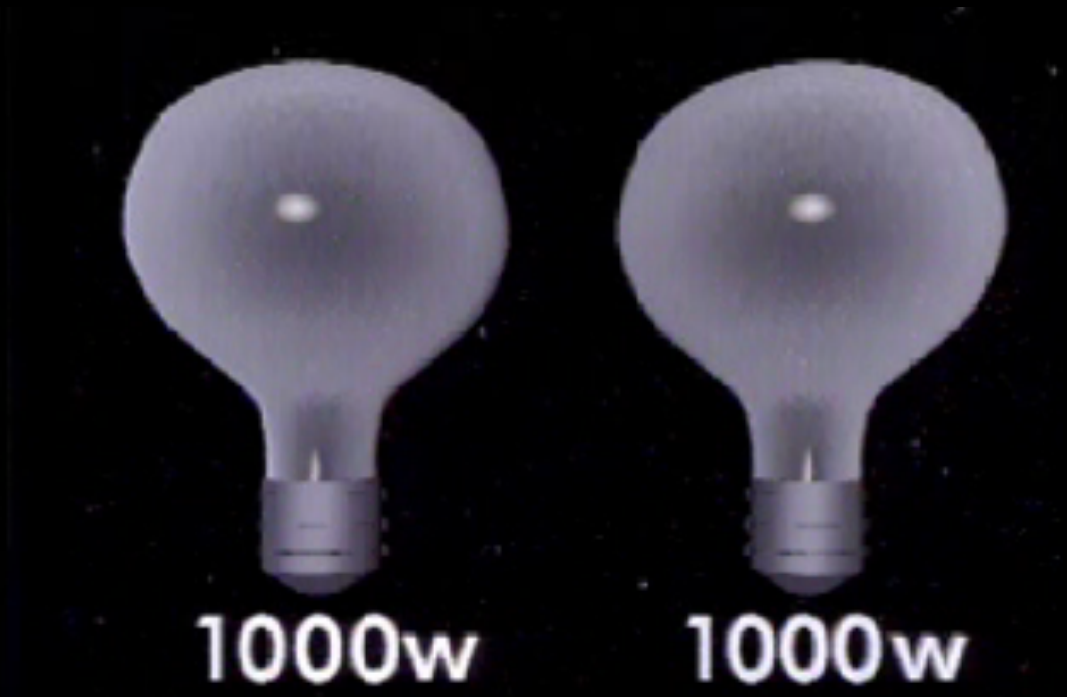
The Supernova of 1054

Cosmology with Supernovae

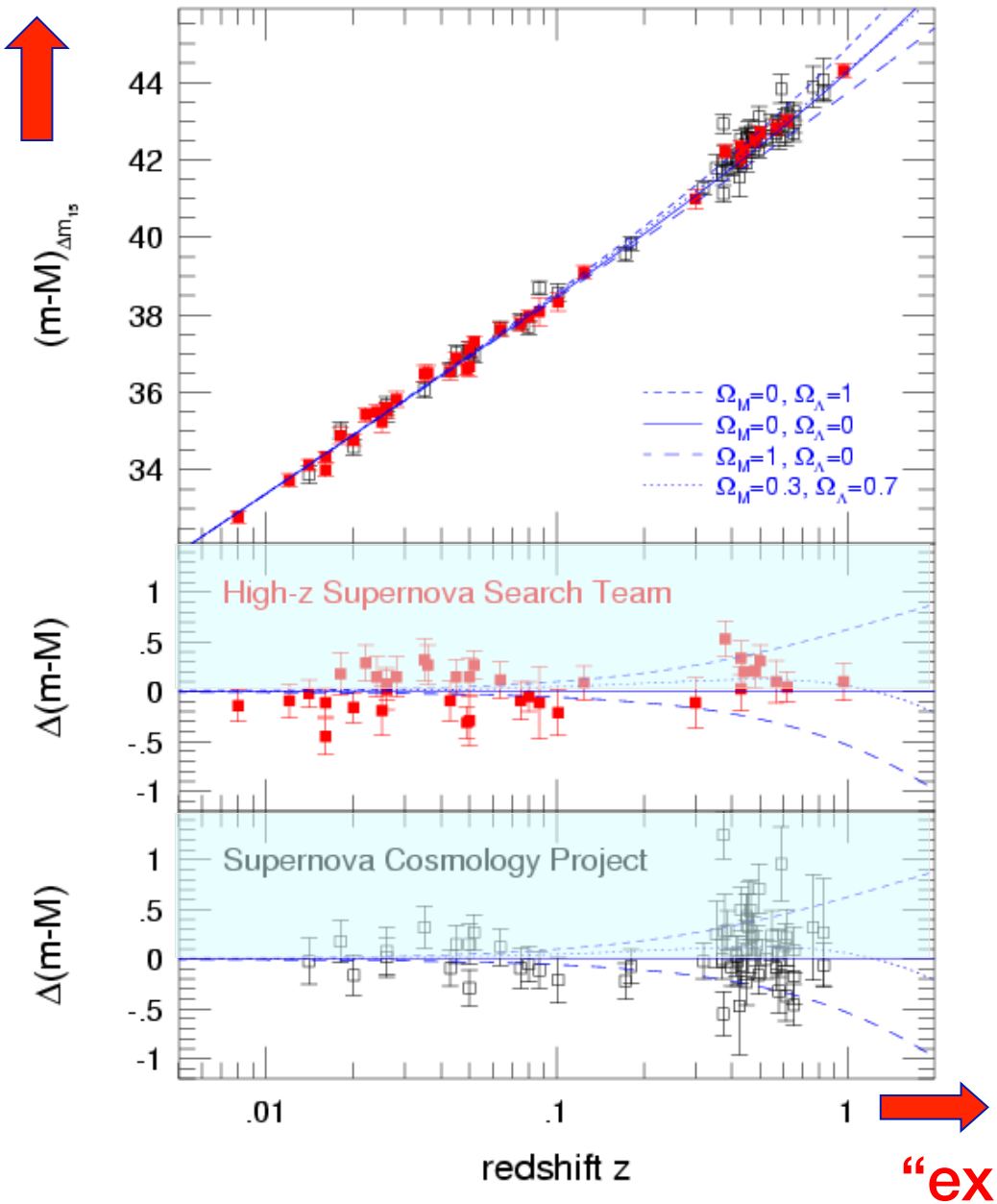
It is very difficult to measure distances in the universe. Supernovae are an essential tool to determine the expansion rate and its history.

Type Ia Supernovae are excellent distance indicators

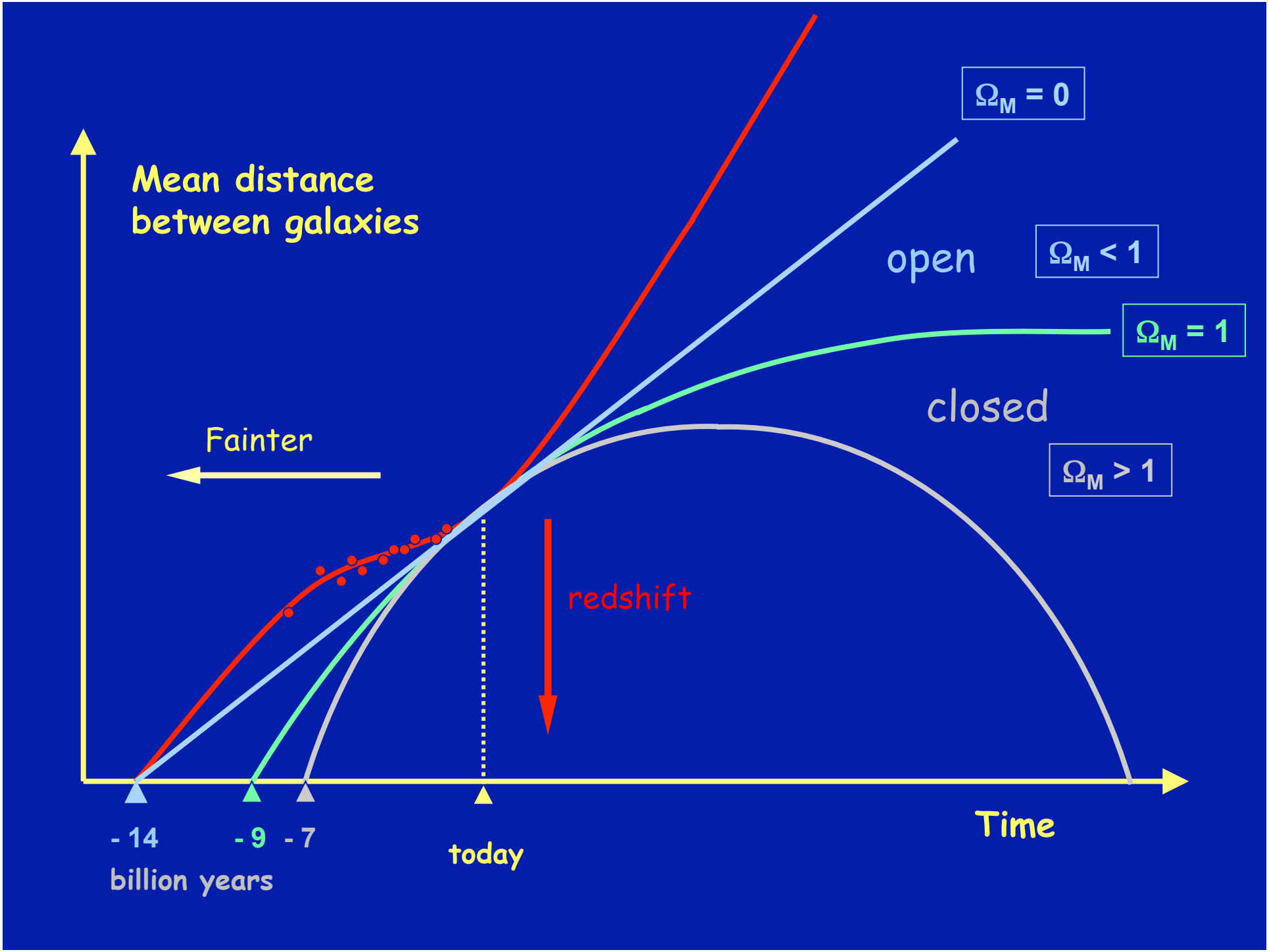
Distance measurement with a constant light source



The SN Hubble Diagram



"expansion"


Mean distance
between galaxies
$\Omega_M = 0$
open
$\Omega_M < 1$
$\Omega_M = 1$
closed
$\Omega_M > 1$
Fainter
redshift
- 14
- 9
- 7
billion years
today
Time

This is a very interesting paper that makes me very nervous. Ultimately the solution is to publish it and let the world take its shots.

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[1] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

Received 1998 March 13; revised 1998 May 6

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 3.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_T = \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

[1] Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720-3411.
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[3] Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica, Casilla 104, Santiago 22, Chile.
[4] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195.
[5] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[6] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany.
[7] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, Casilla 603, La Serena, Chile. NOAO is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
[8] Mount Stromlo and Siding Spring Observatories, Private Bag, Weston Creek, ACT 2611, Australia.
[9] Visiting Astronomer, Cerro Tololo Inter-American Observatory.
[10] Department of Astronomy, University of Michigan, 834 Dennison Building, Ann Arbor, MI 48109.
[11] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

1. INTRODUCTION

This paper reports observations of 10 new high-redshift Type Ia supernovae (SNe Ia) and the values of the cosmological parameters derived from them. Together with the four high-redshift supernovae previously reported by our High-z Supernova Search Team (Schmidt et al. 1998; Garnavich et al. 1998a) and two others (Riess et al. 1998b), the sample of 16 is now large enough to yield interesting cosmological results of high statistical significance. Confidence in these results depends not on increasing the sample size but on improving our understanding of systematic uncertainties.

The time evolution of the cosmic scale factor depends on the composition of mass-energy in the universe. While the universe is known to contain a significant amount of ordinary matter, Ω_M, which decelerates the expansion, its dynamics may also be significantly affected by more exotic forms of energy. Prominent among these is a possible energy of the vacuum (Ω_Λ), Einstein's "cosmological con-

Physics Nobelprize 2011

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

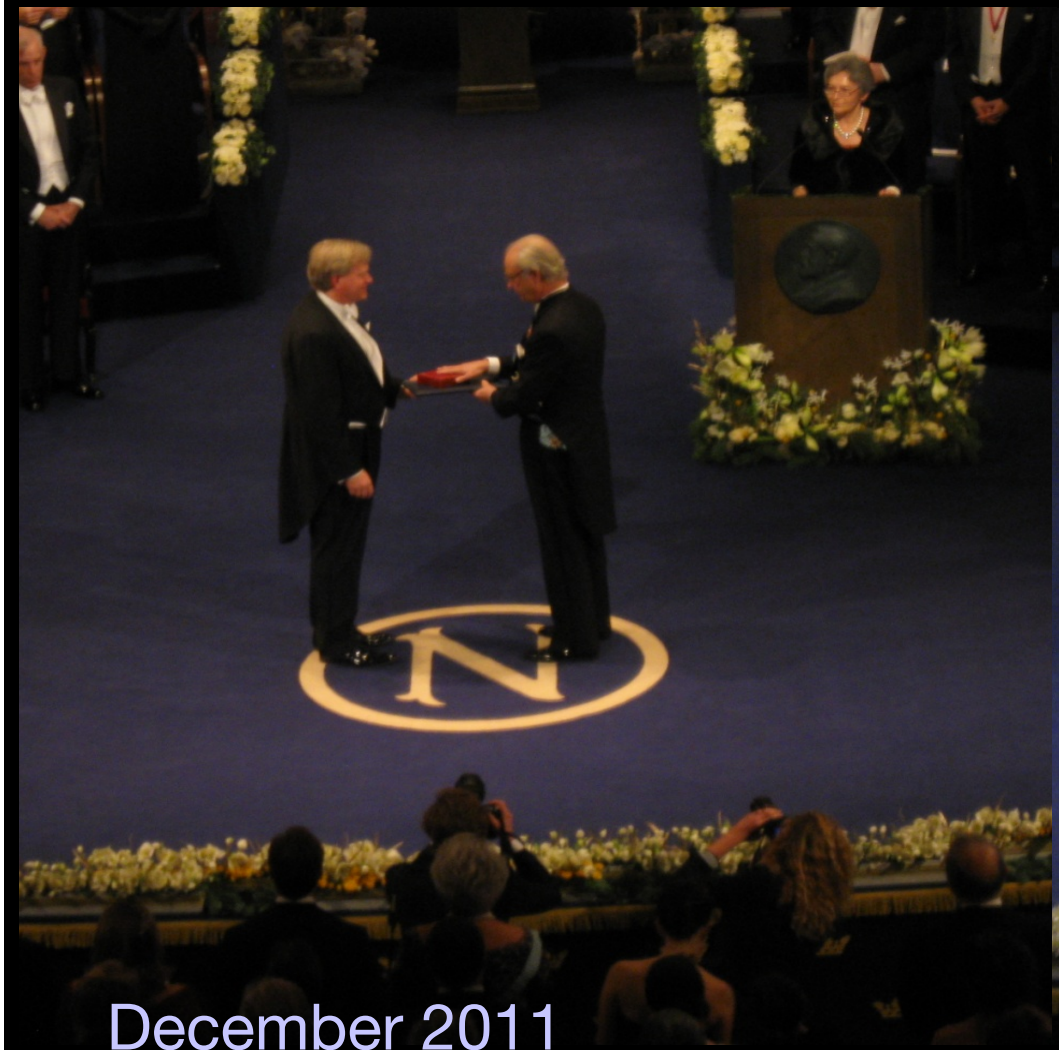
Saul Perlmutter

Brian Schmidt

Adam Riess

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

You need to dress up for this



December 2011

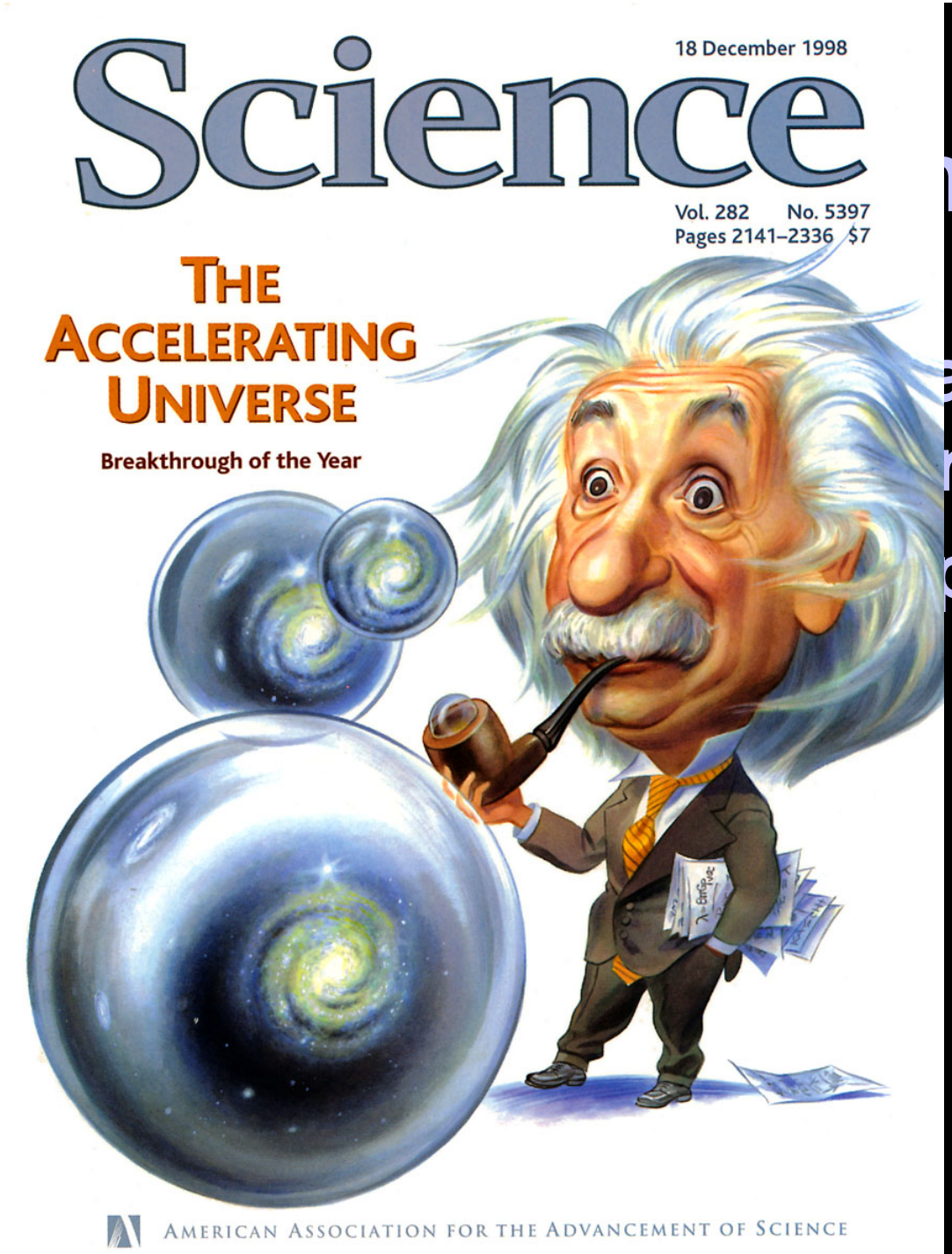

The High-z Supernova Search Team
December 2011

W

Distant

in a fre

This re



n?

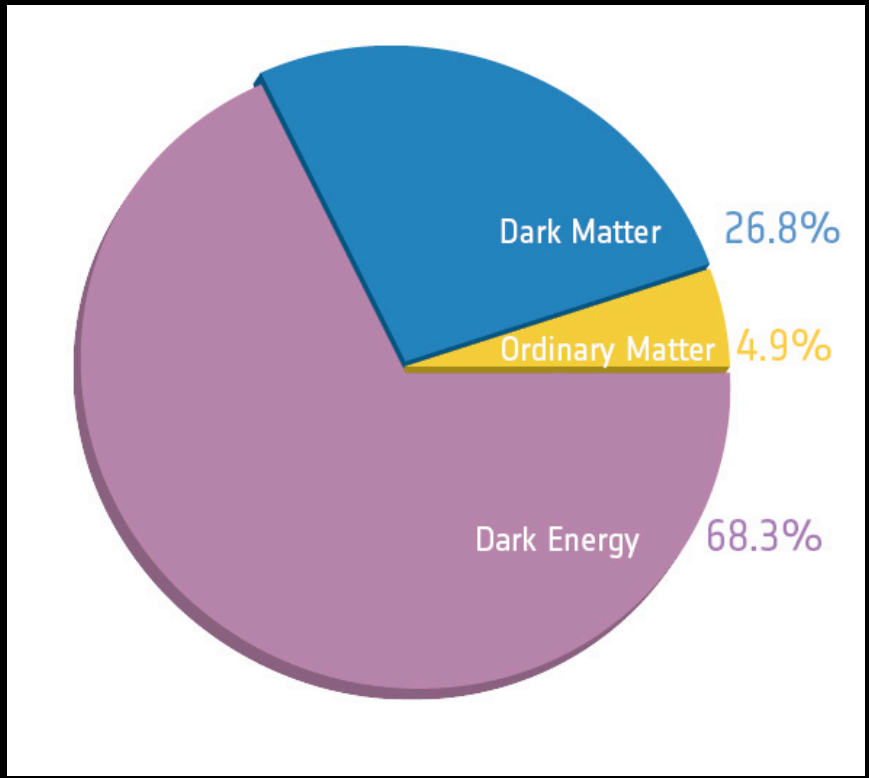
ay than

rse

ponent

Contents of the universe

Dark Matter and Dark Energy are the dominant energy components in the universe.



What does this mean?

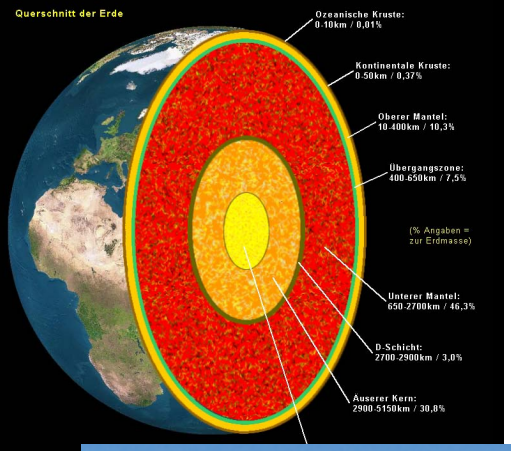
The universe is essentially

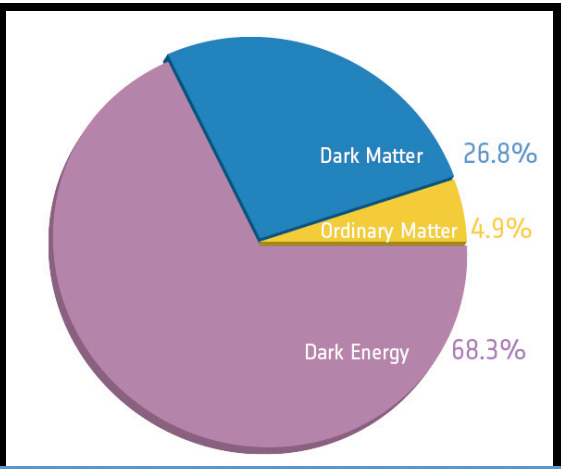
empty

The universe expands forever

No convincing physical interpretation of the cosmological constant or the vacuum energy (Dark Energy)

Only 4% of the universe are of the same matter as we are (and that we know)





Our universe
Our world