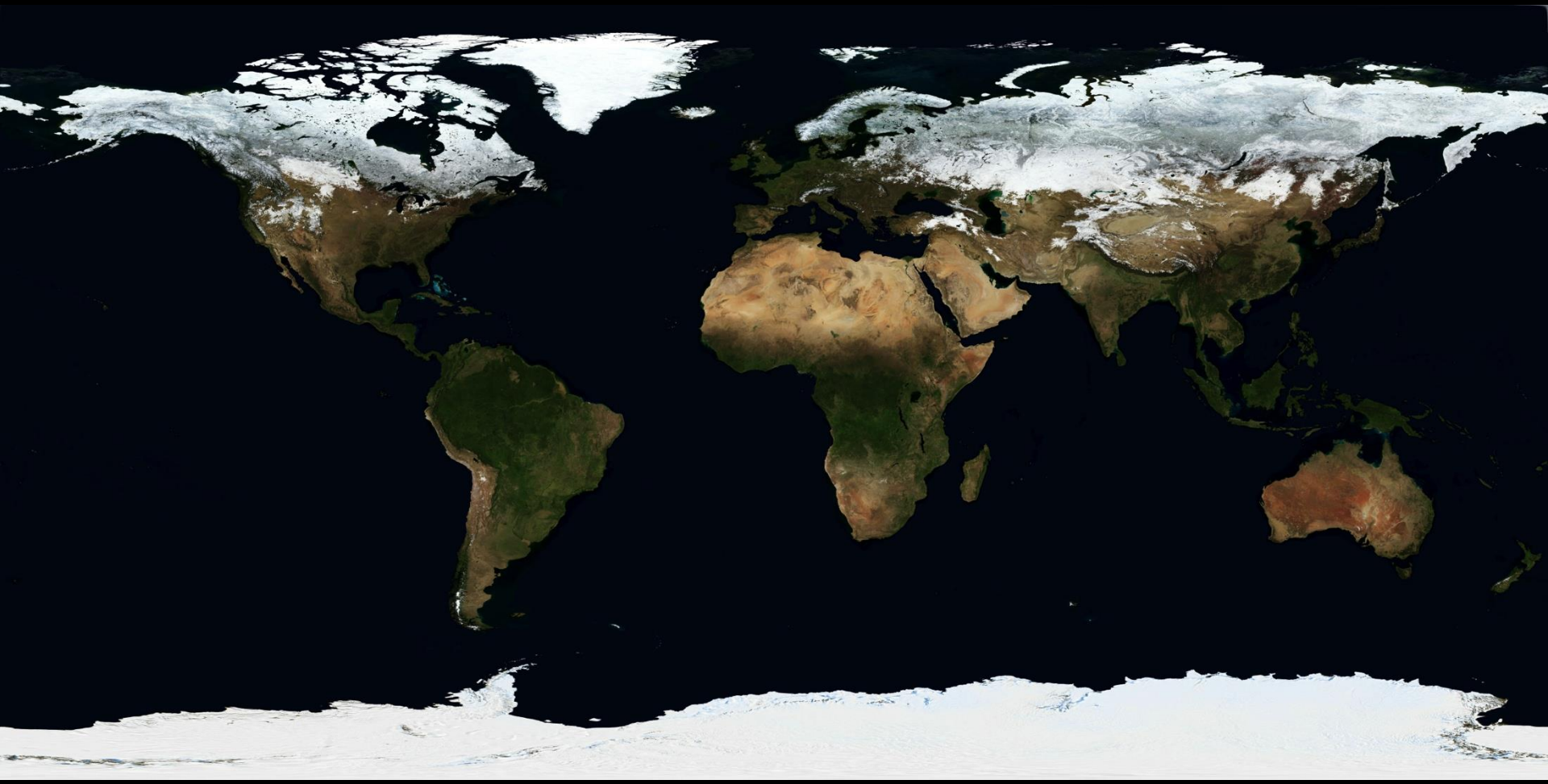
Discovering the Accelerating Universe

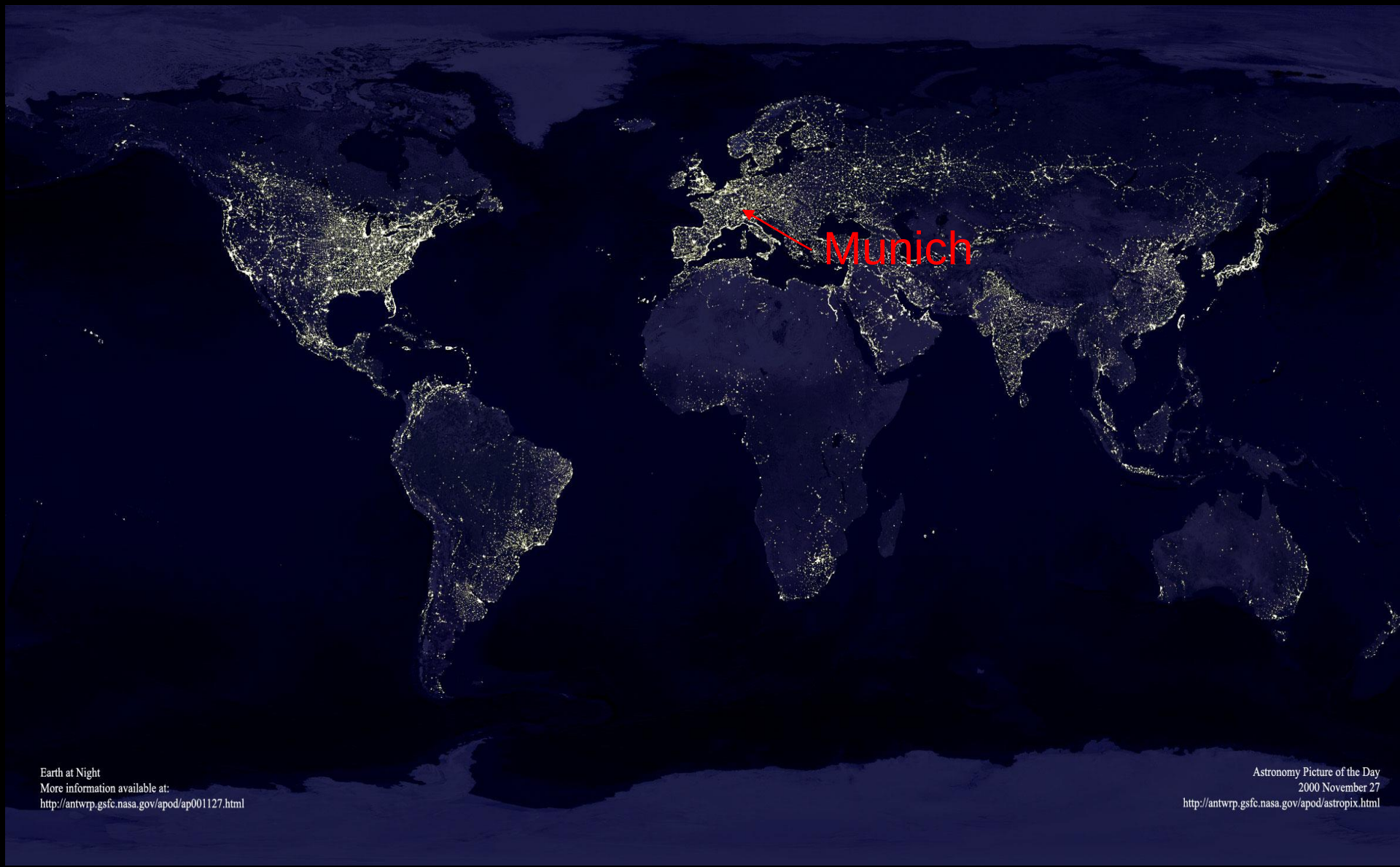
Bruno Leibundgut
European Southern Observatory (ESO)

How do we see our world?

A changing world



The Earth at night



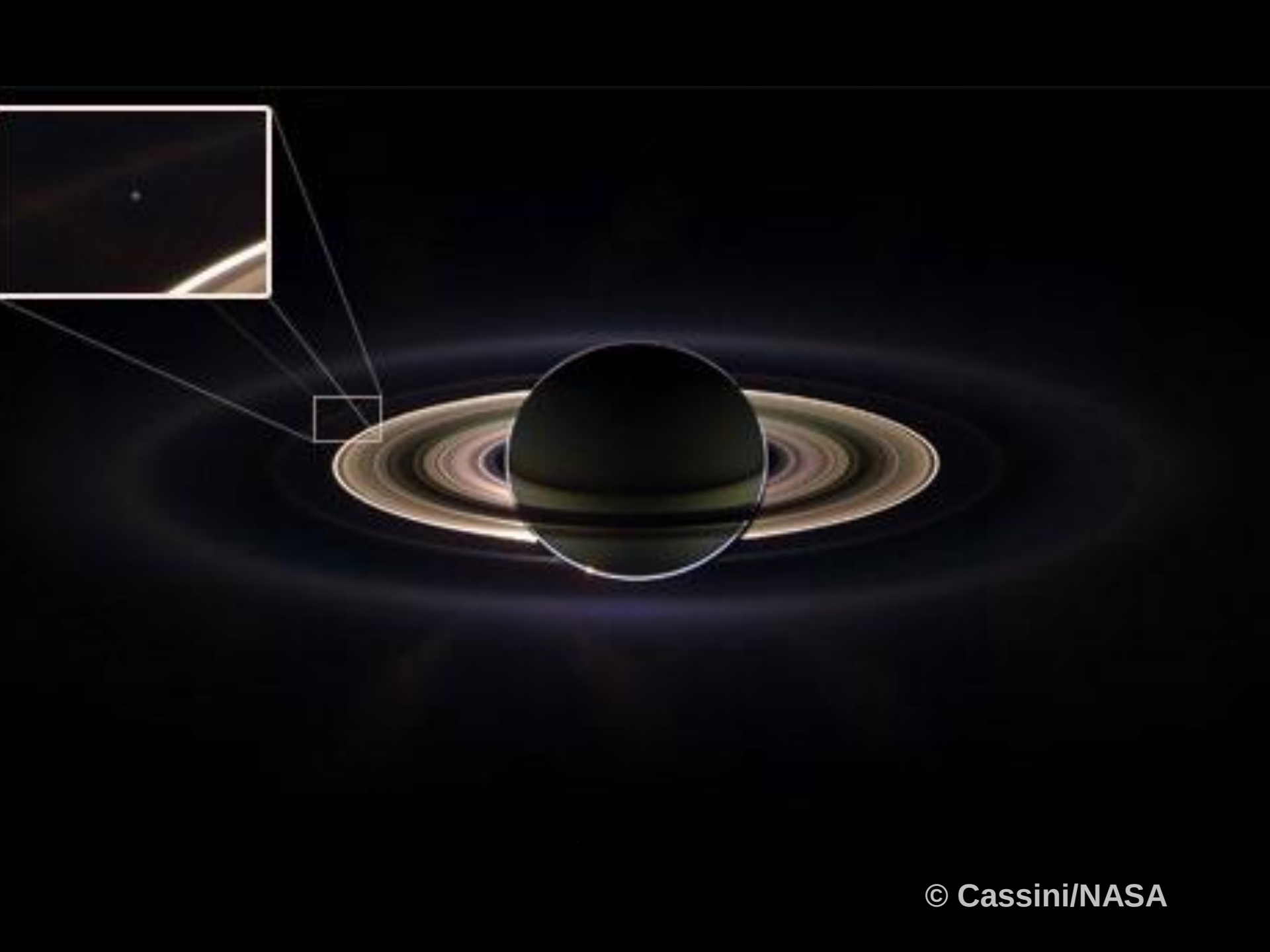
Our place in the universe

Our Home

Apollo 8

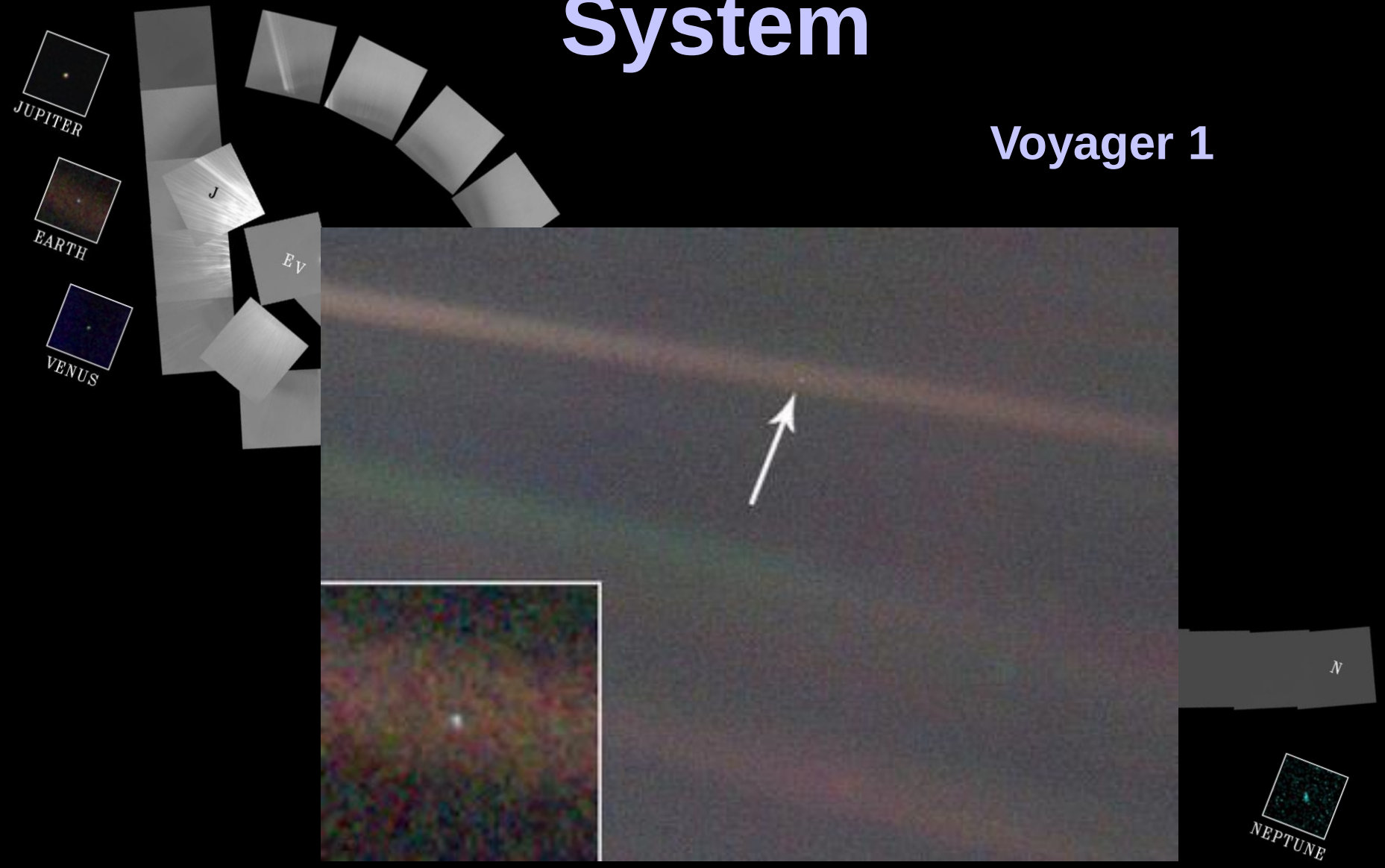
Our Home

MESSENGER (© NASA)

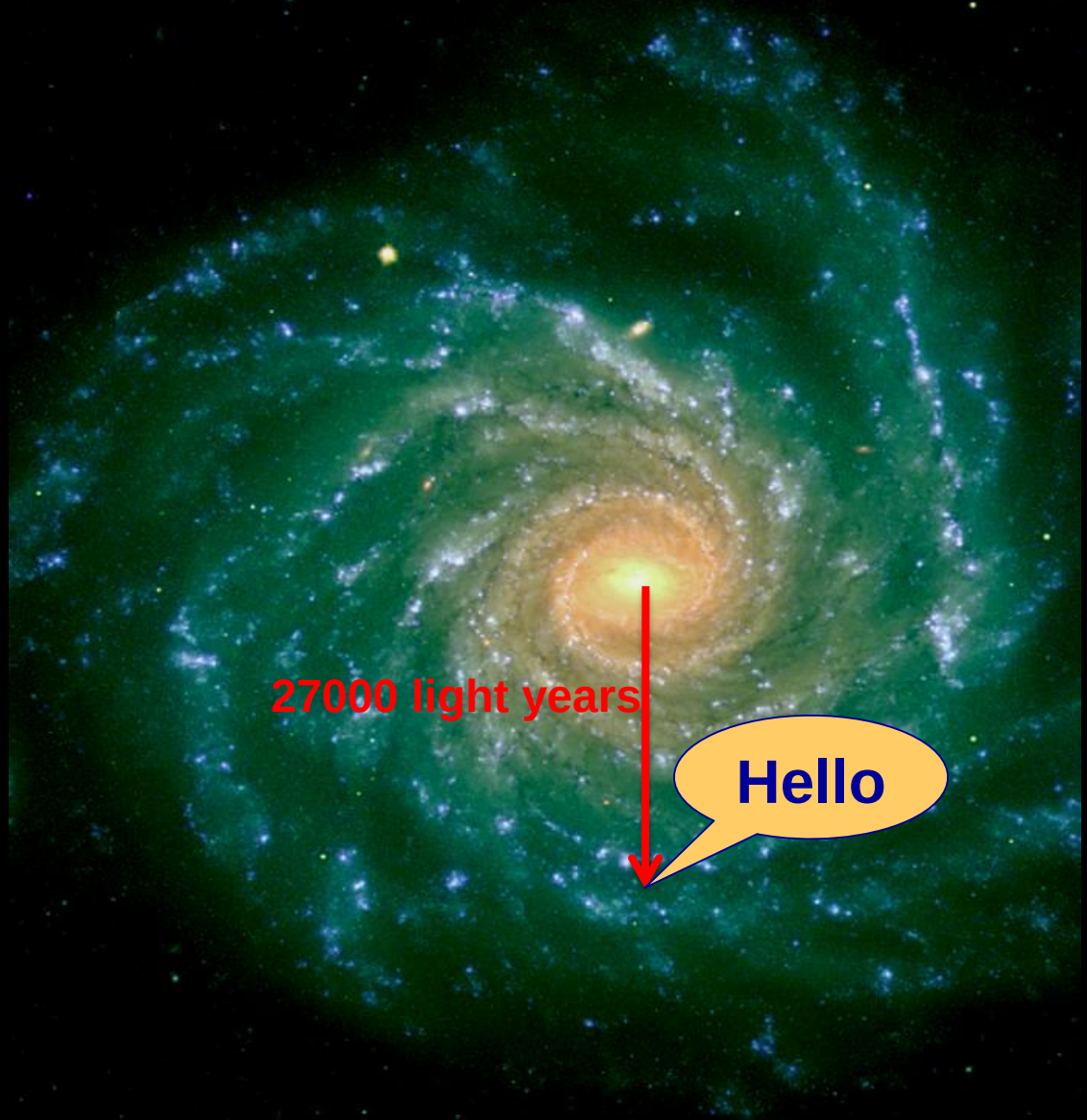

© Cassini/NASA

Family Portrait of the Solar System

Voyager 1



Our place in the Milky Way

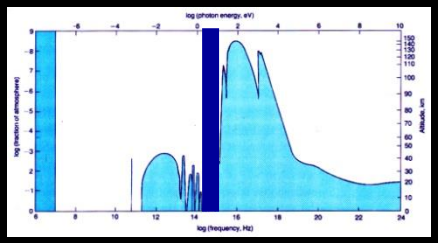


Place three grains of sand inside a vast cathedral, and the cathedral will be more closely packed with sand than space is with stars.

James Jeans
quoted in
Big Bang by Simon Singh (2004)

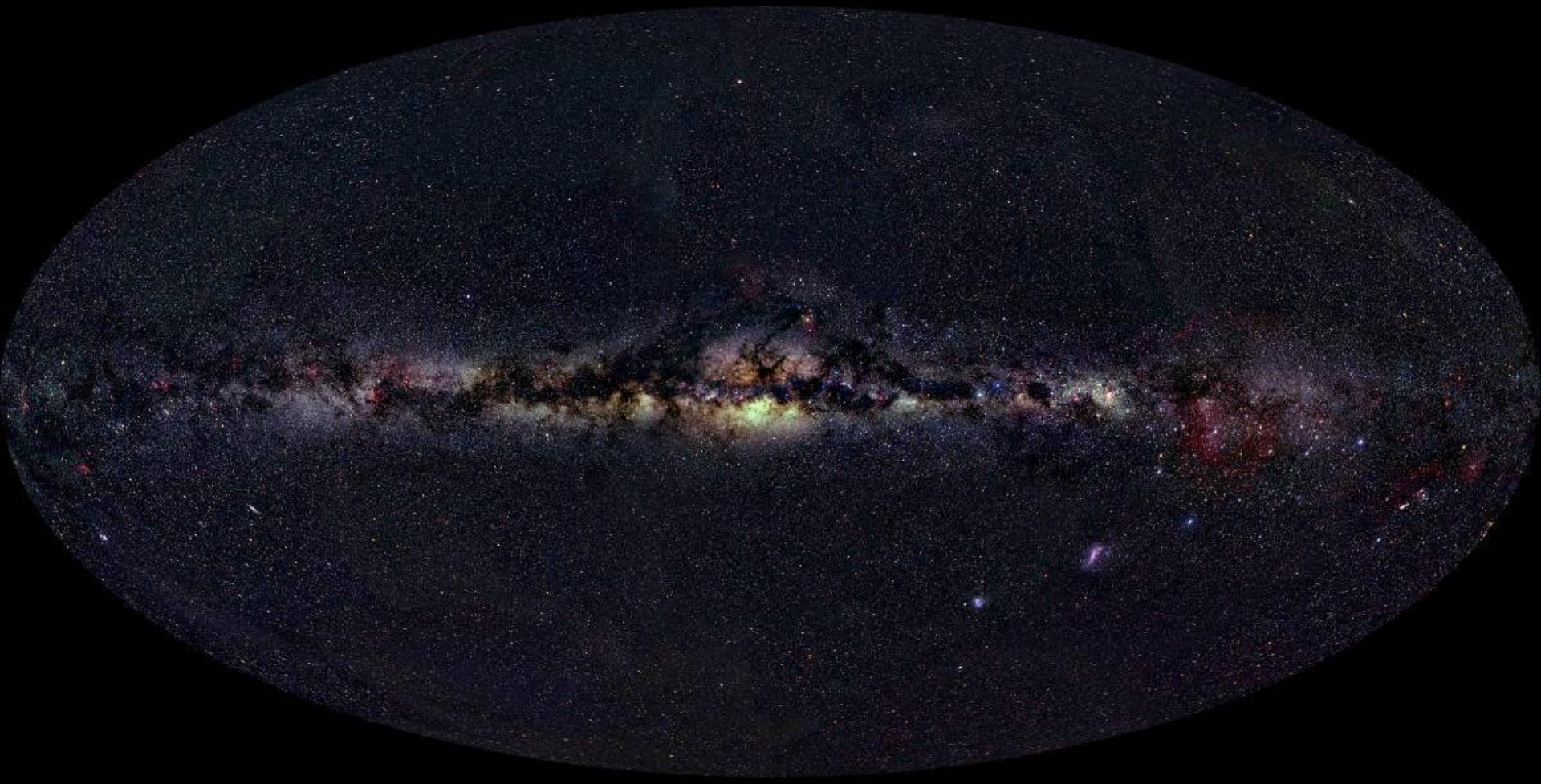
Earth's atmosphere

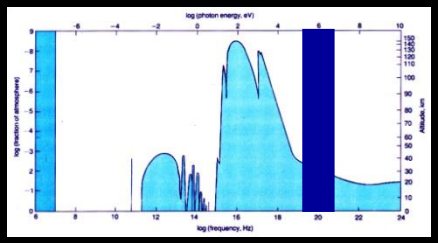
Shield and Window to the Universe


log (photon energy, eV)
log (fraction of atmosphere)
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
1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 Cambrian explosion (burst of new life forms)
16
17 Emergence of first vertebrates
18 Early land plants
19
20 First four-limbed animals
21 Variety of insects begin to flourish
22 23
24 First dinosaurs appear
25 First mammal-like ancestors appear
26
27 First known birds
28
29 Dinosaurs wiped out by asteroid or comet
30
31
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

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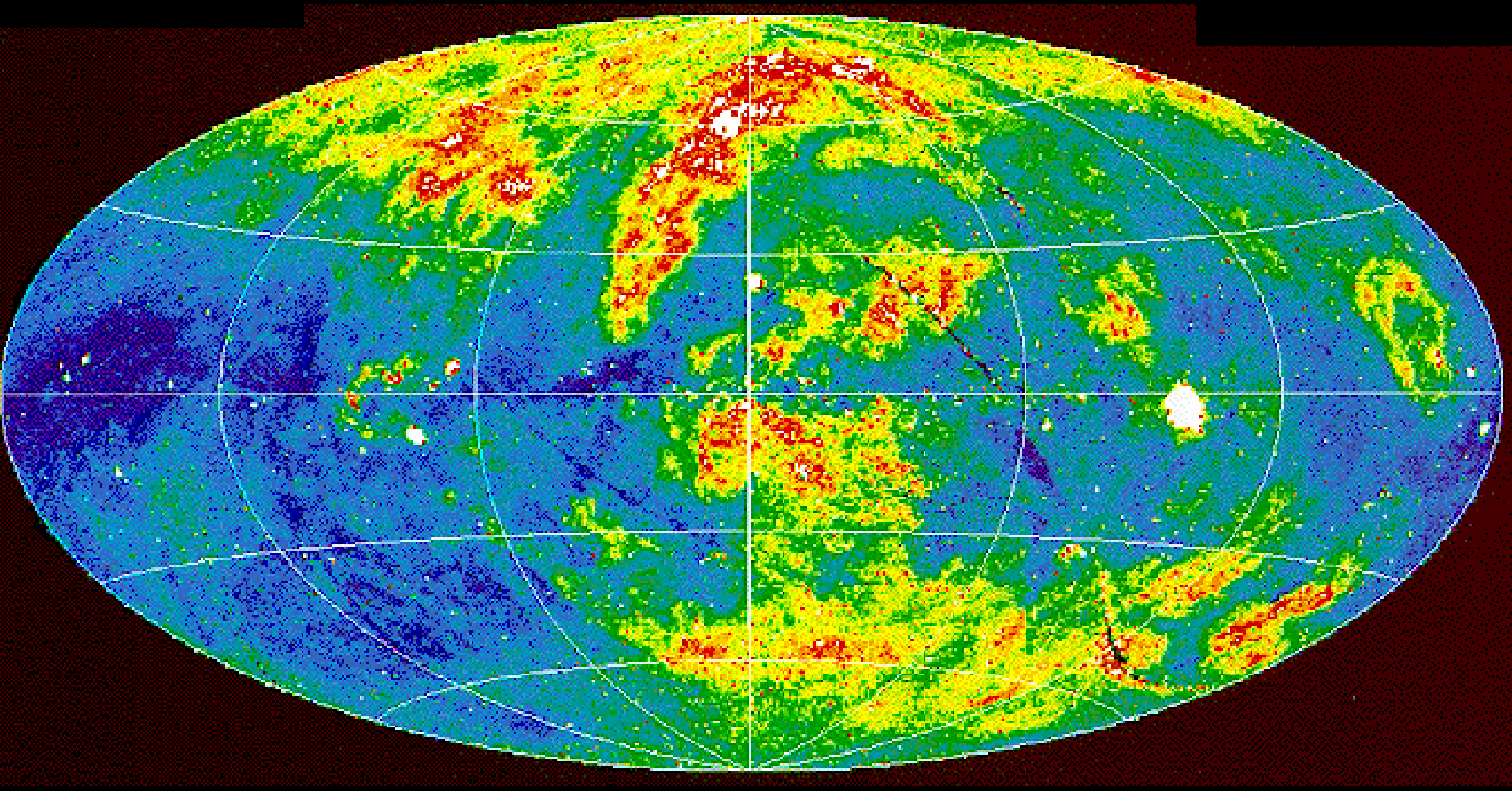

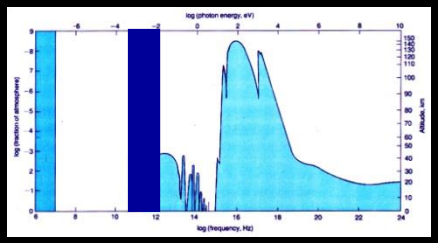
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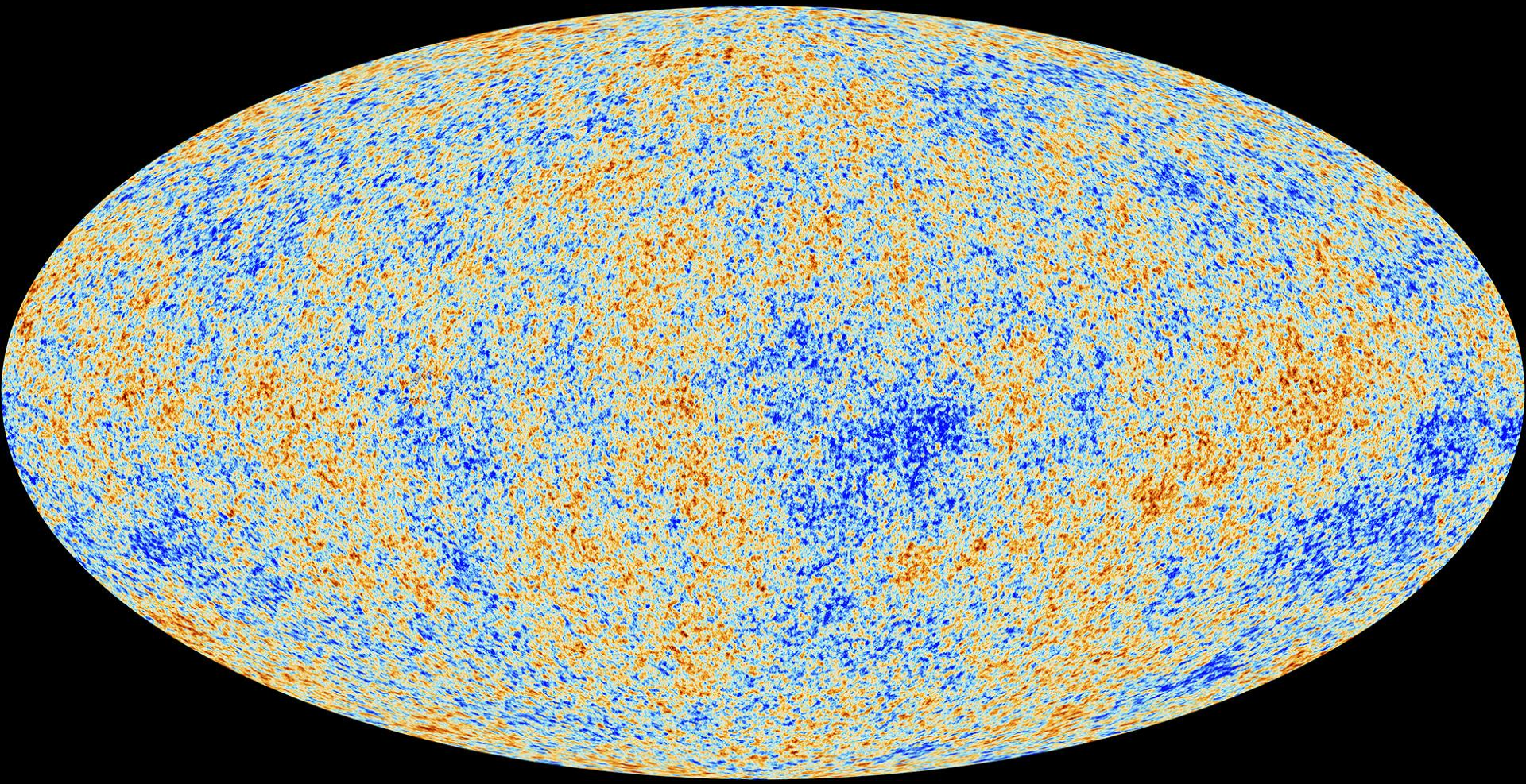


The dark side of the universe

- 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

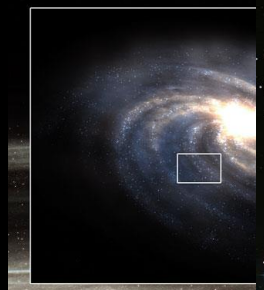
Gravitation!

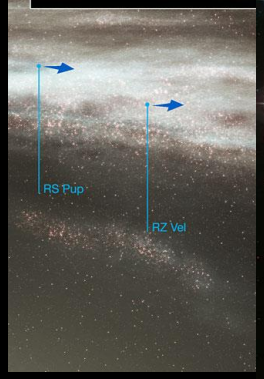
Of the four fundamental forces (Gravitation, Electromagnetism, Weak and Strong Forces) only gravitation determines the evolution of the universe.


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

What is in the Universe?

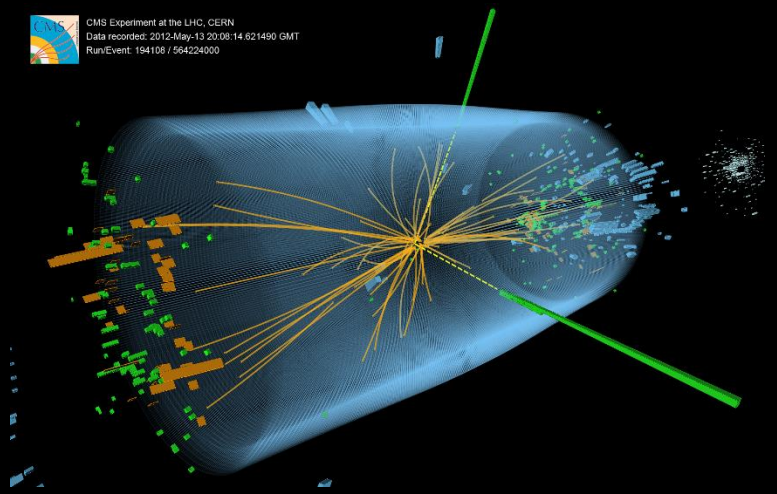
- We are!

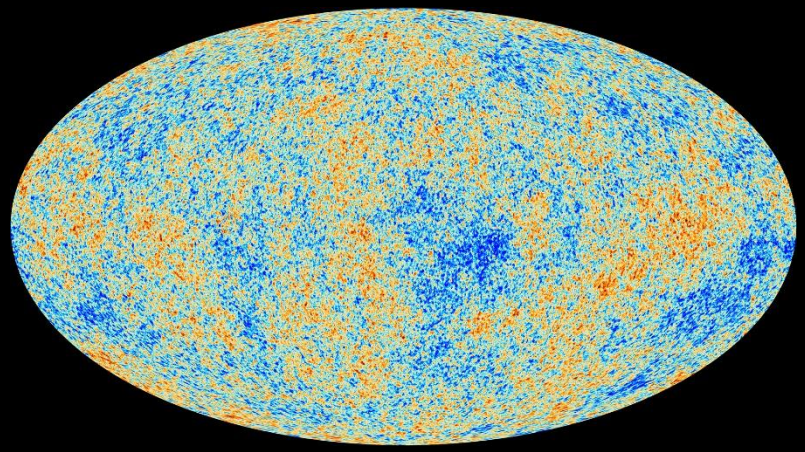


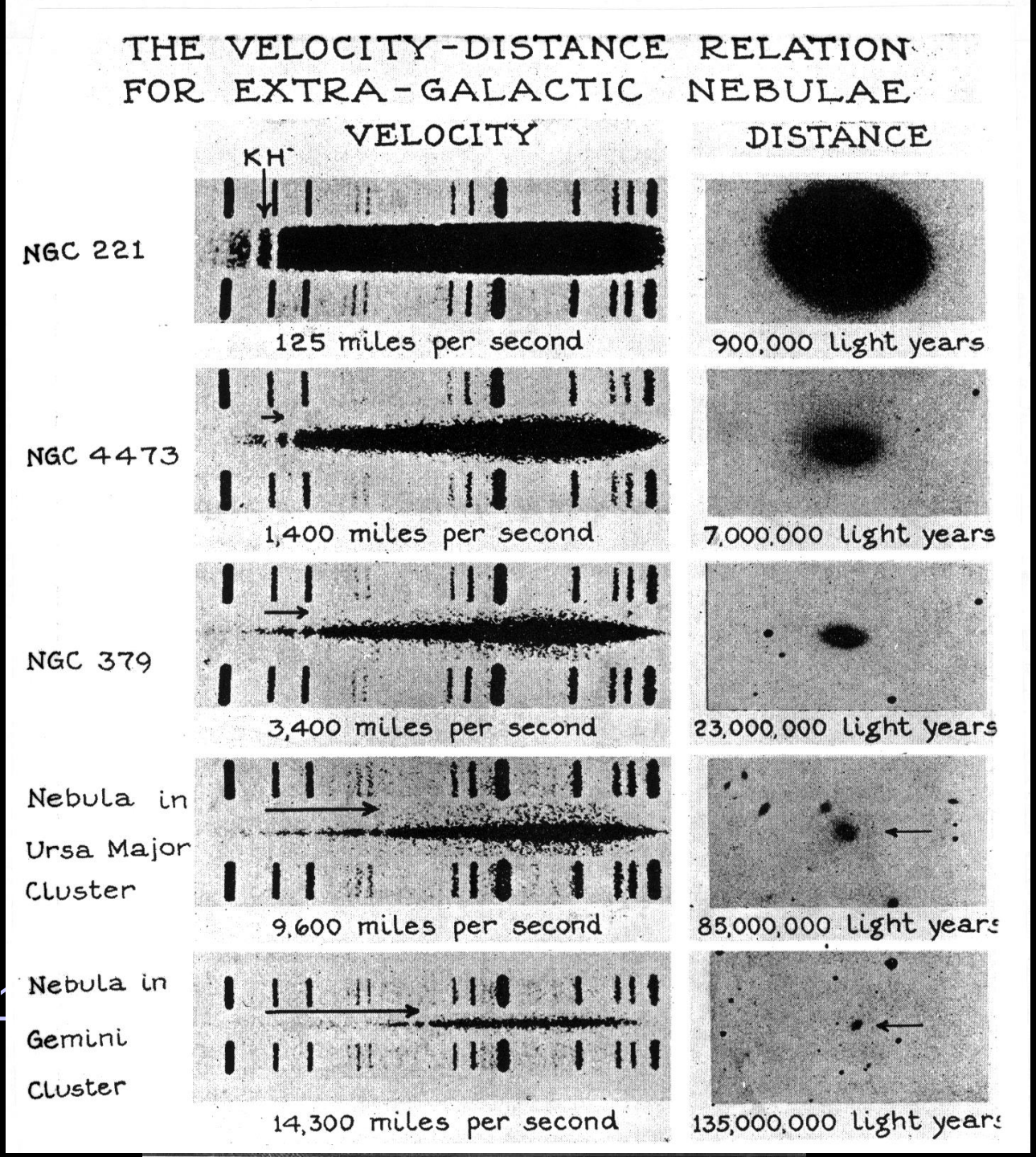


What is in the Universe?

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






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

Hubble 1

The original Hubble diagram

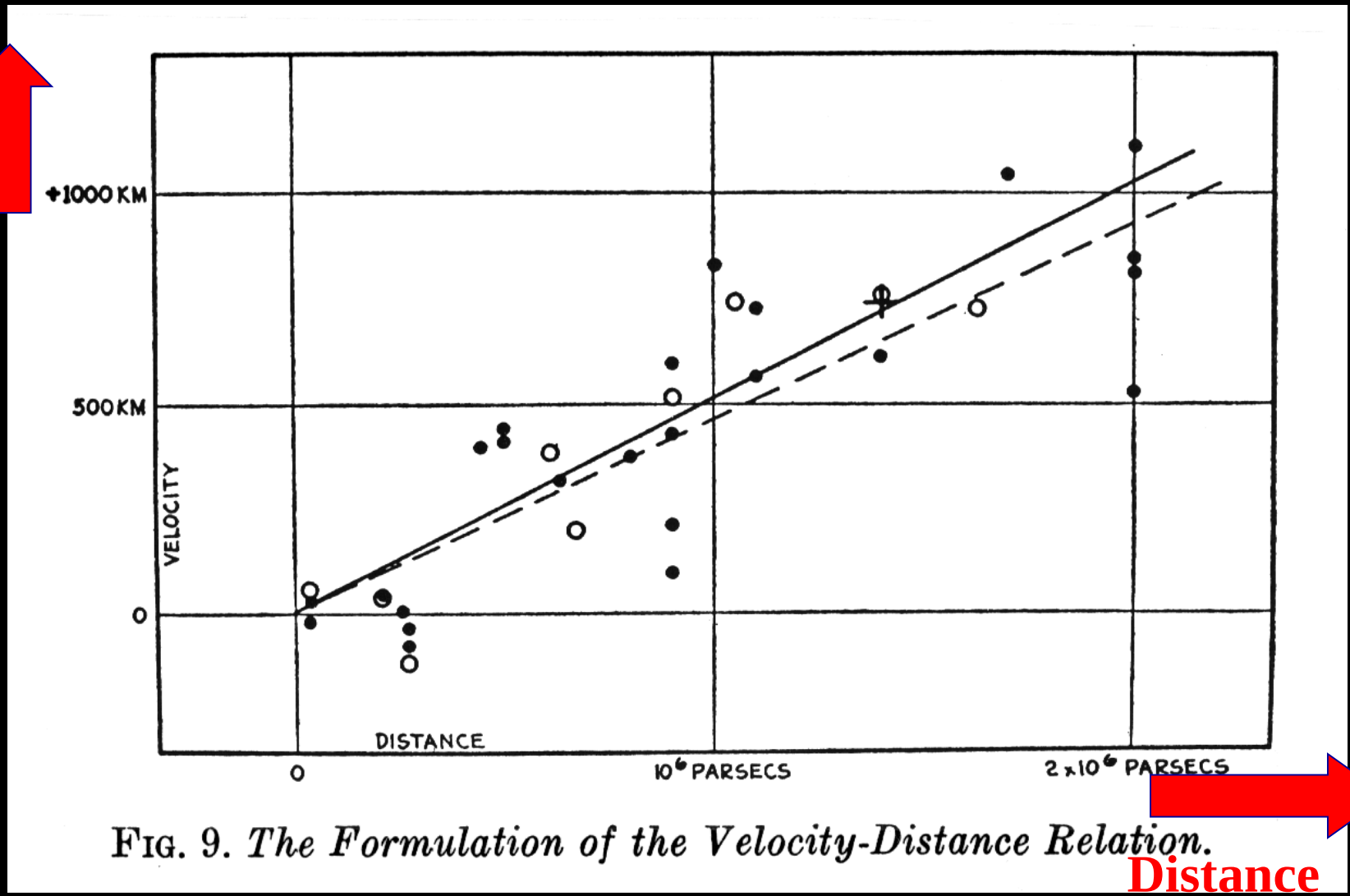
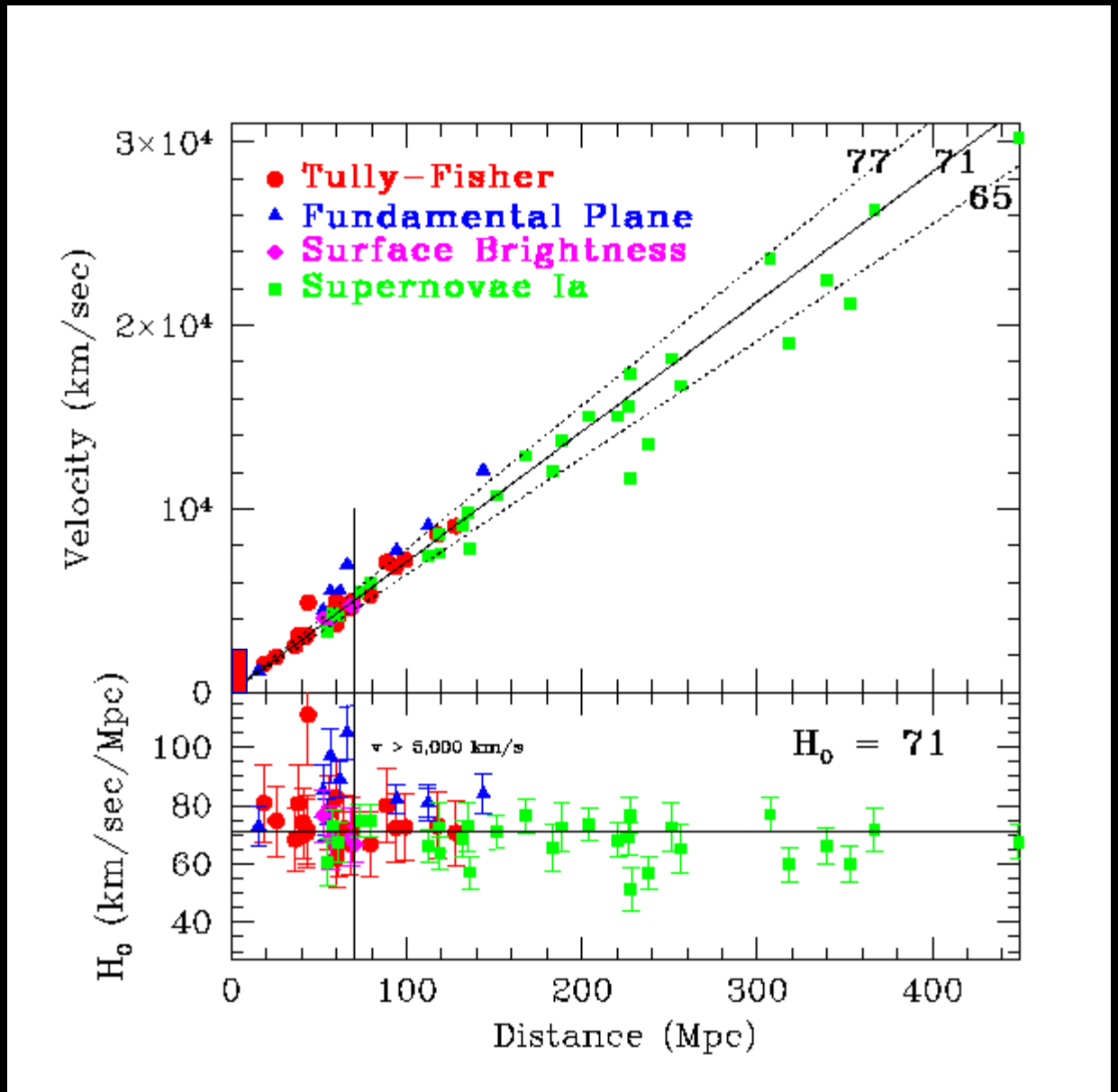


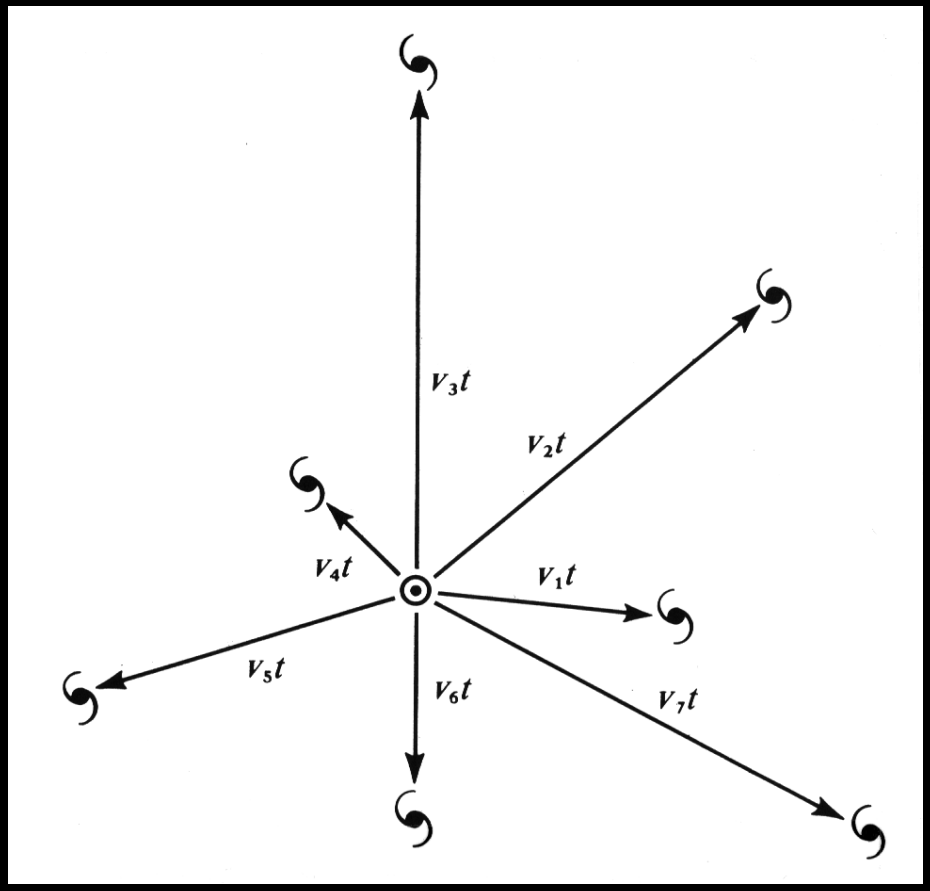
FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble diagram

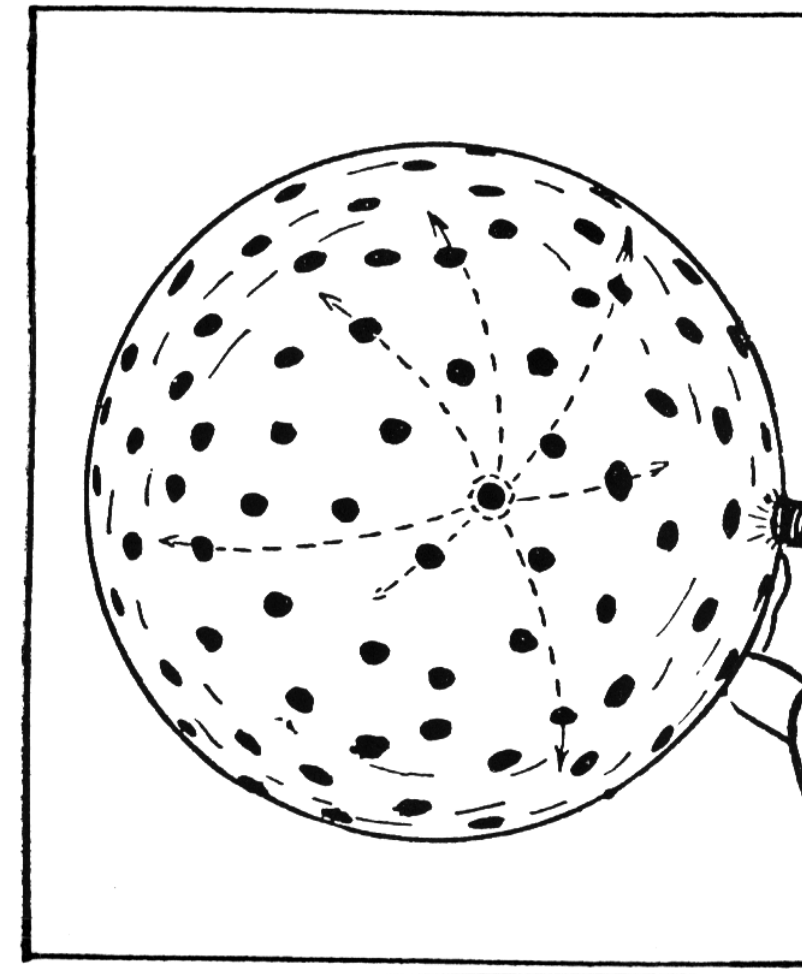


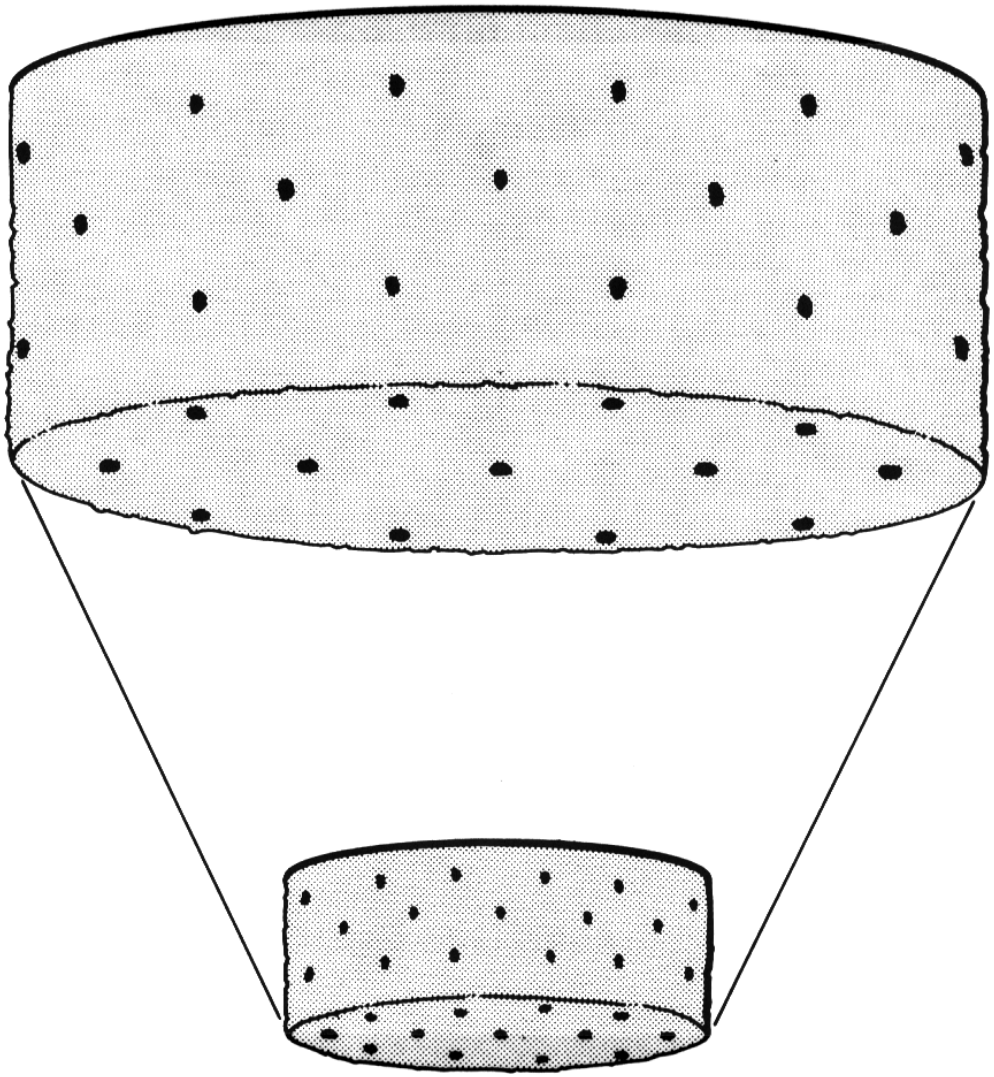
The age of the Universe

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

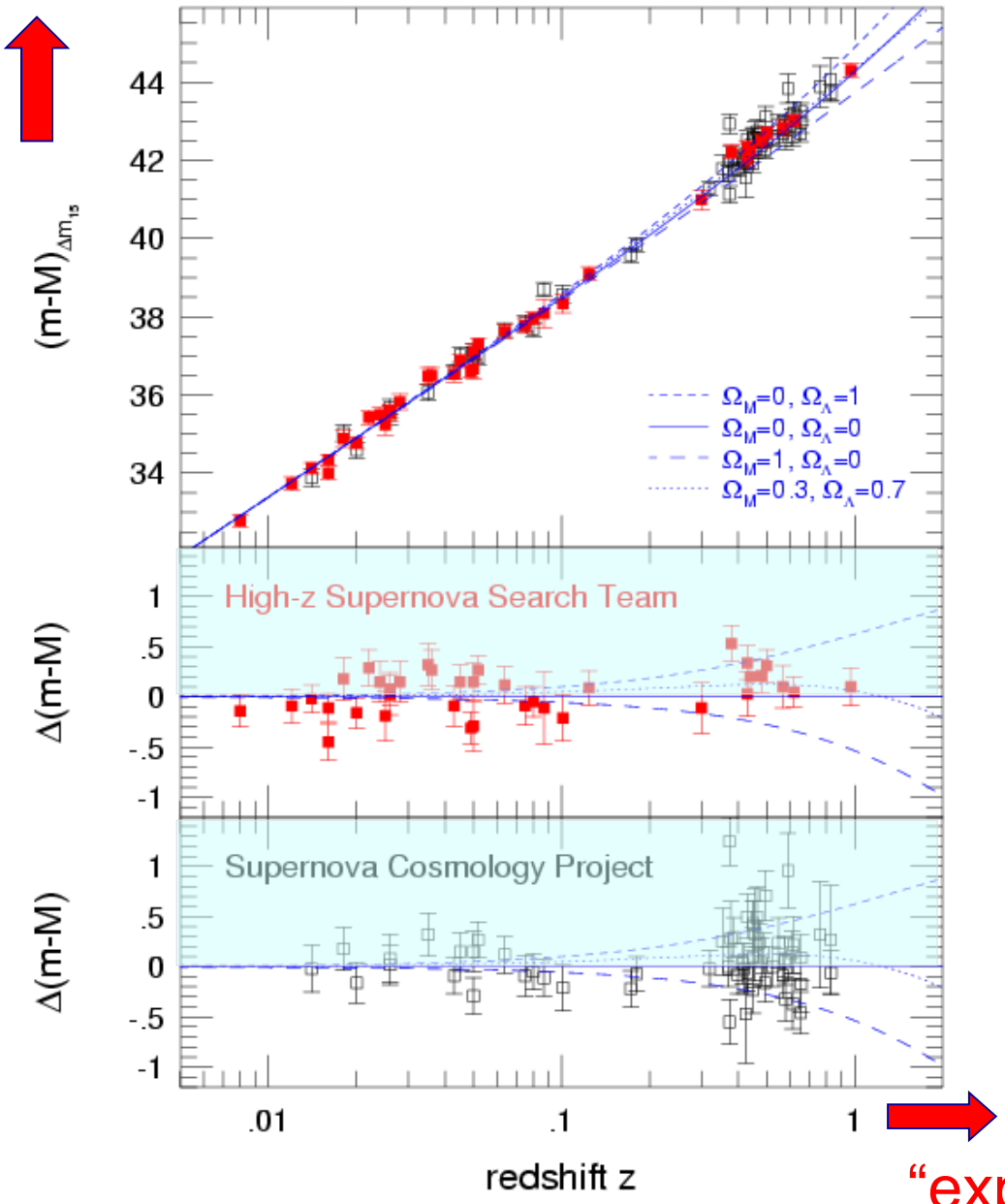
Cosmology with Supernovae

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

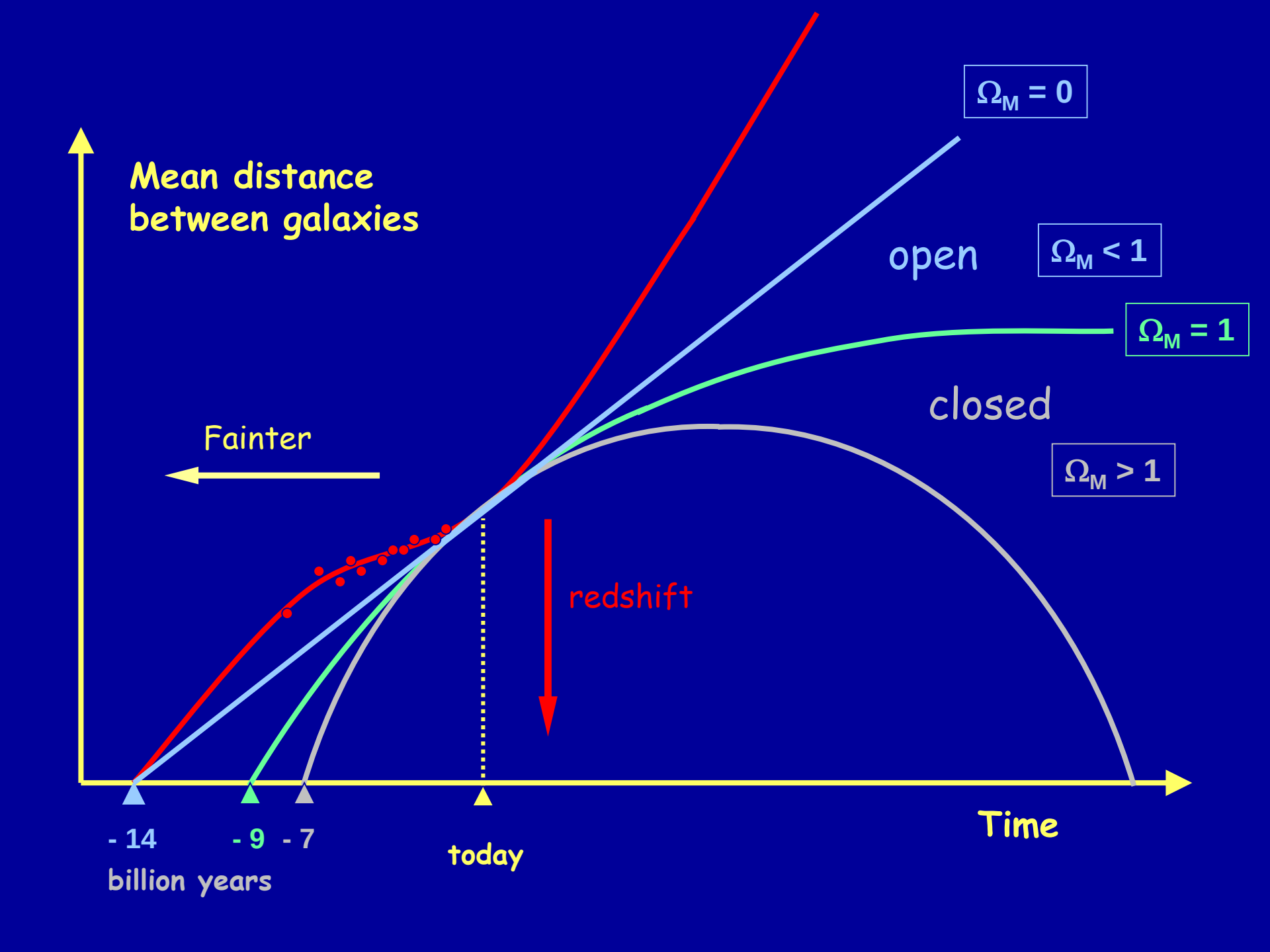
Type Ia Supernovae are excellent distance indicators

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
Time
- 14
billion years
- 9
- 7
today

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

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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 2.8 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 ($\Omega_M + \Omega_\Lambda = 1$), 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

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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-

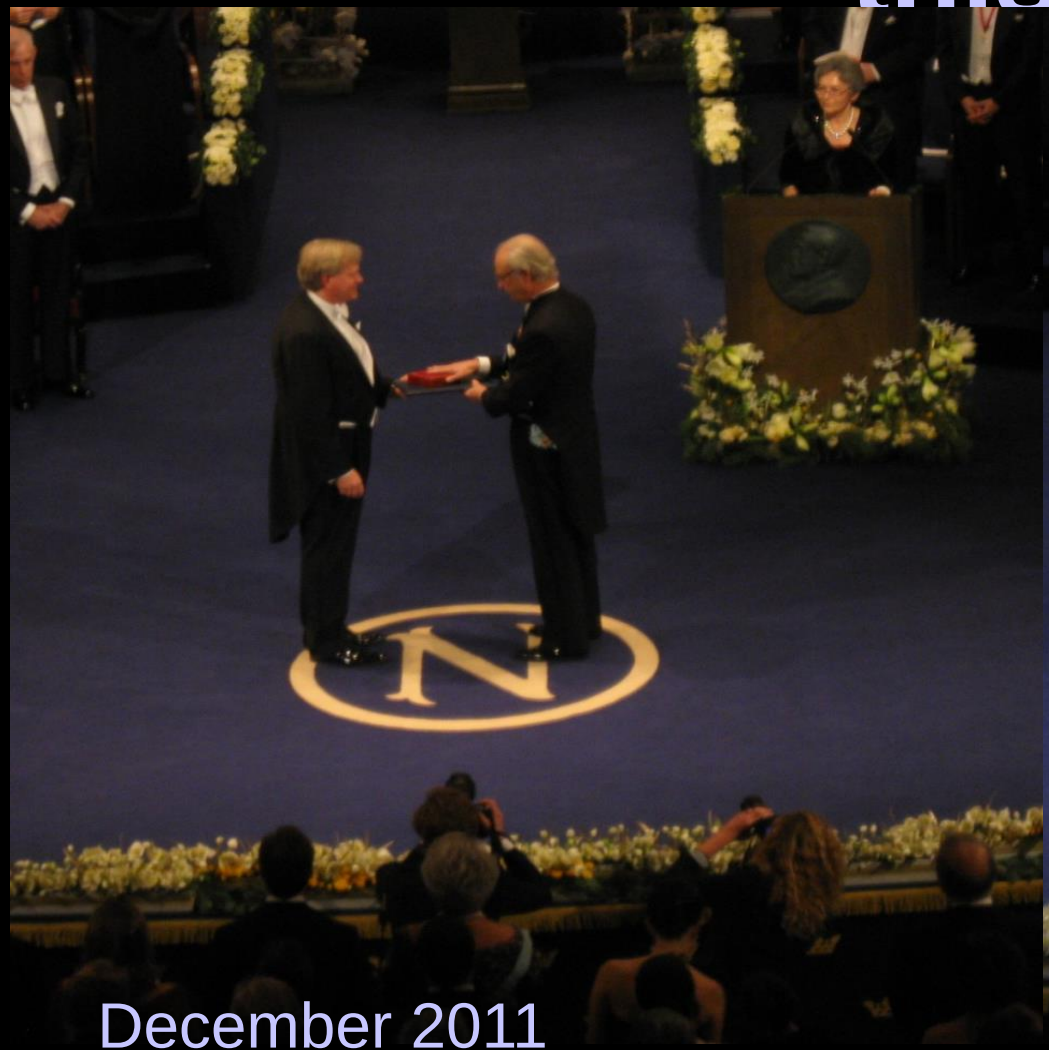
Physics Nobelprize 2011

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Saul Perlmutter Brian Schmidt Adam Riess

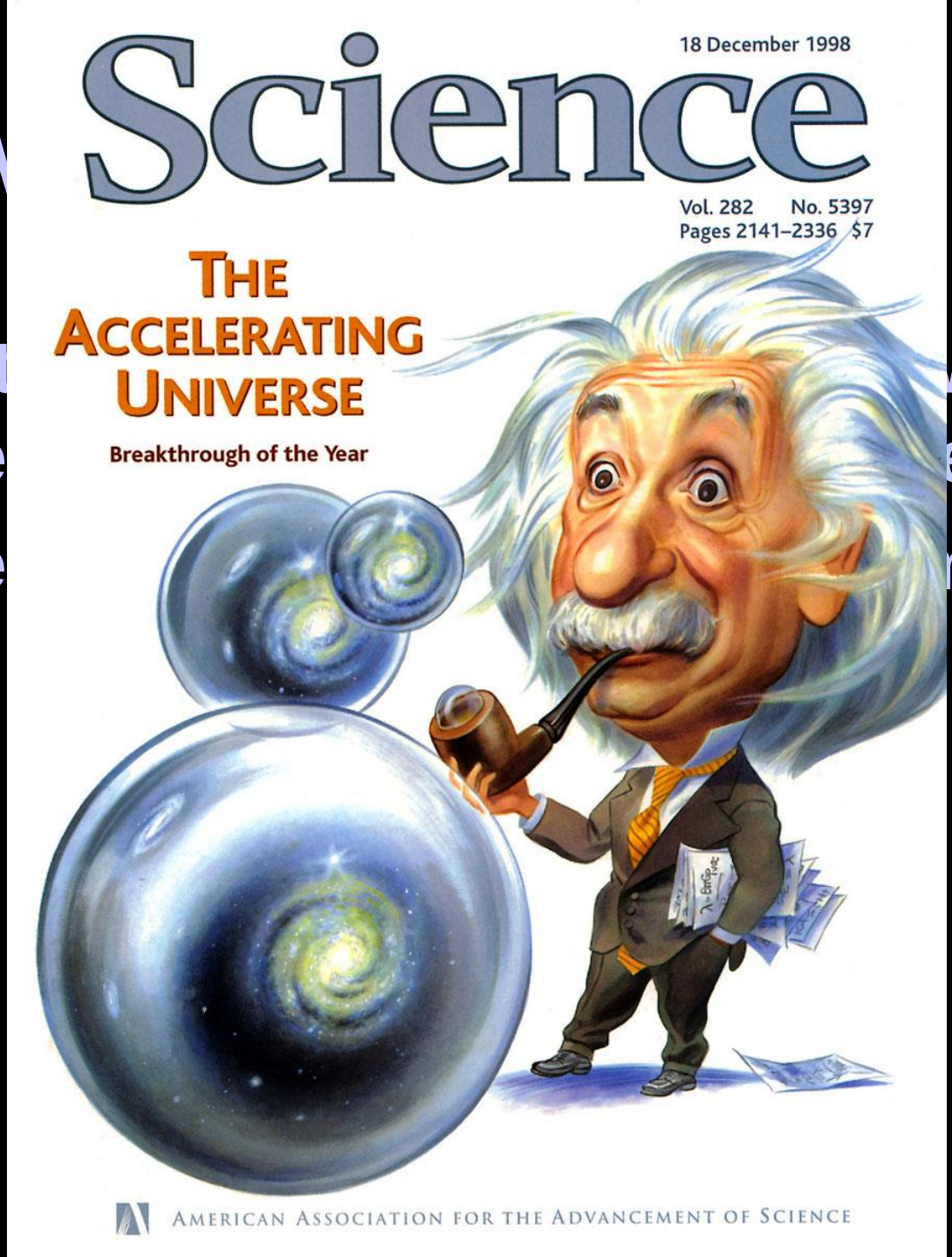
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

You need to dress up for this



December 2011

The High-z Supernova Search Team
December 2011

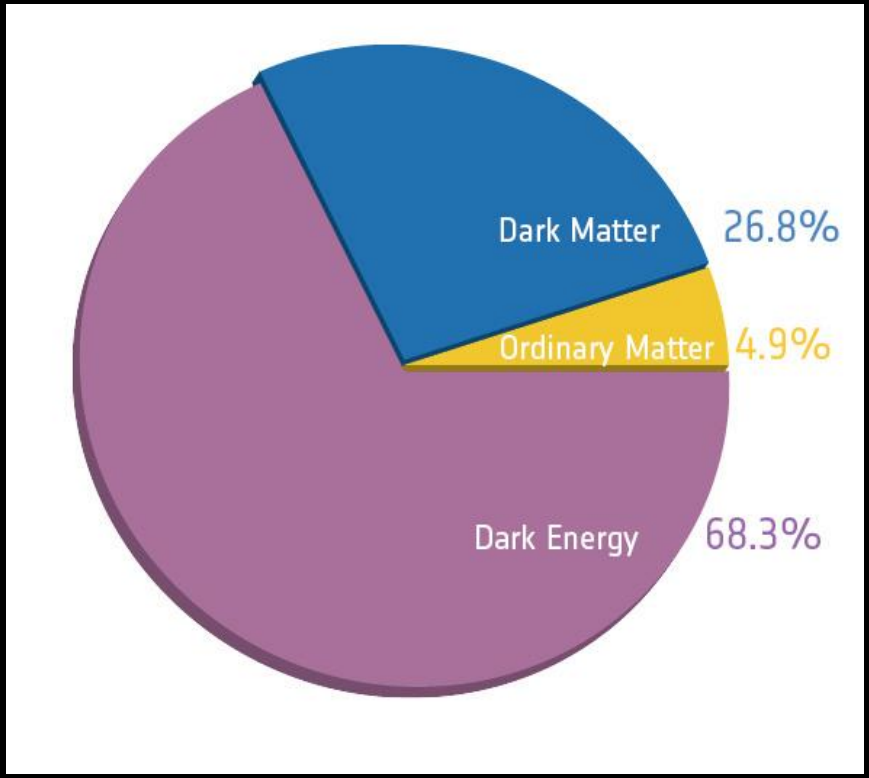


V ?

Distant way than
in a fre erse
This re nponent

Contents of the universe

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



What does this mean?

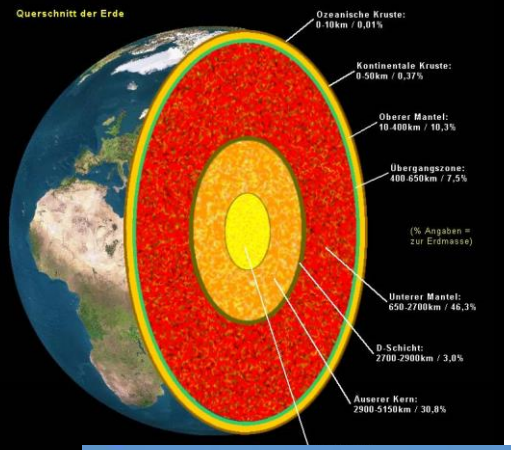
The universe is essentially

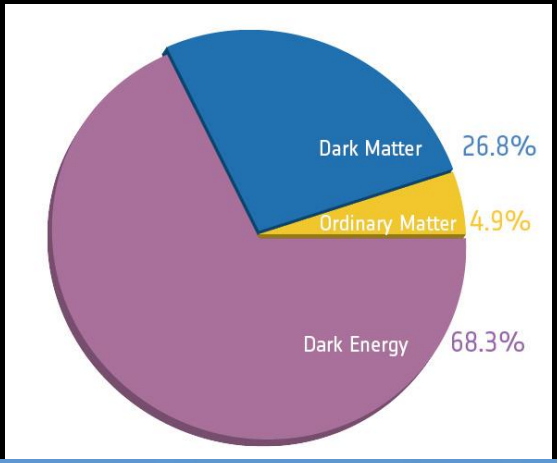
empty

The universe expands forever

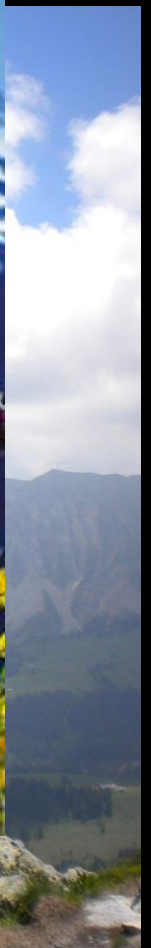
No convincing physical interpretation of the cosmological constant or the vacuum energy (Dark Energy)

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





Our universe
Our world



The true age of discovery in astronomy is only just starting.

F. Zwicky