The Distance Ladder, Dark Energy, Dark Matter & other Flaws of the Universe

Peter Hoeflich

Dept. of Physics, Florida State University, Tallahassee, USA

Questions:

- What is the structure of 'Space and the Universe' ?

- How was the 'Past' and the 'Future' ?

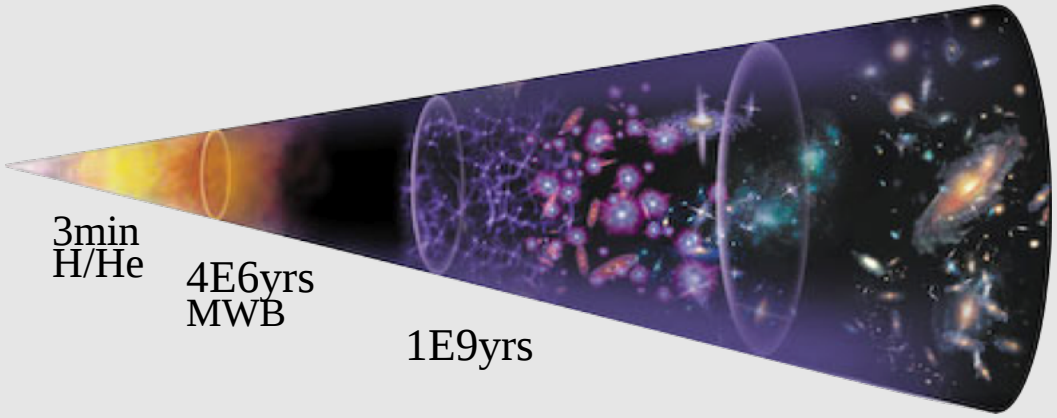
- Methods of Distance Measurements in the Universe

- Why does the Universe looks like it does,

or does is look like it does because we are looking?

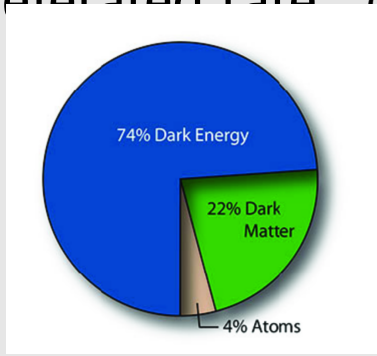
- Is our Universe unique ?

•Overall picture: Evolution of the Universe



- Distances are large, and we look back in time
- Universe is expanding, and at an accelerated rate ($E=m\,c^2$)

=> We do hardly know
what our Universe is made off



Tasks: Measure the dots, and connect them

The Earth

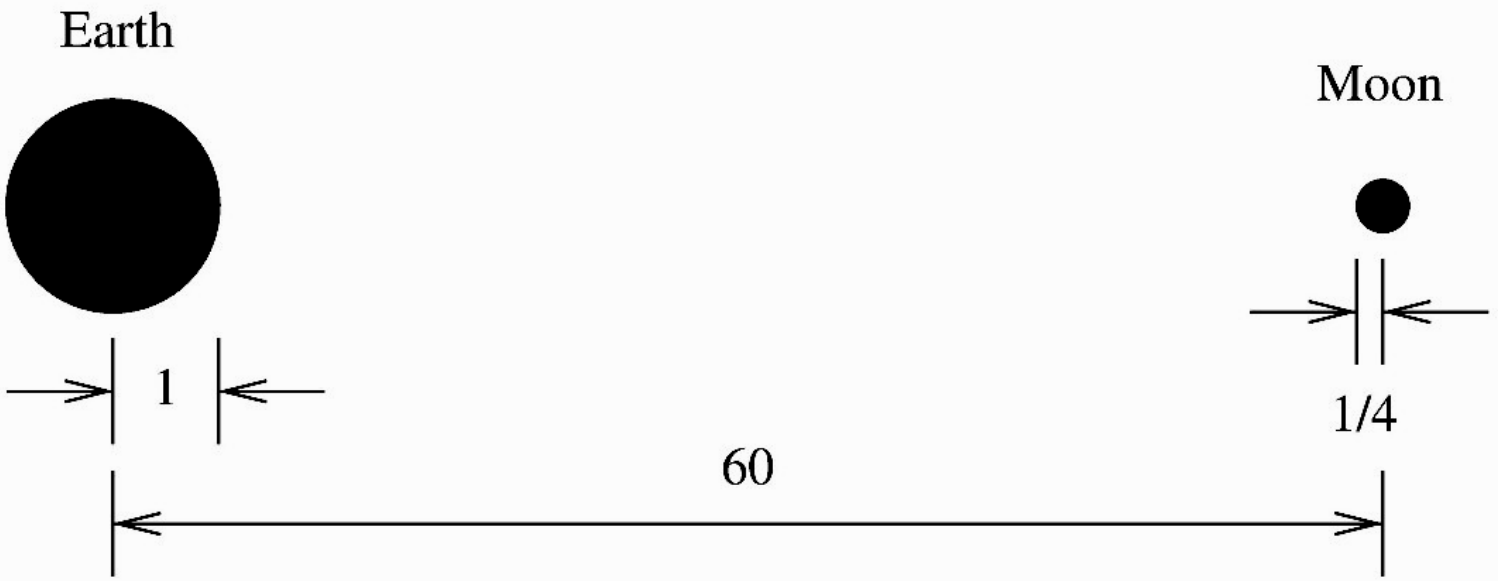
Spherical

Radius = 6400 km

Biosphere = 5km

Max light travel time = 0.02 sec

The Earth-Moon System



Earth Radius = 6400 km

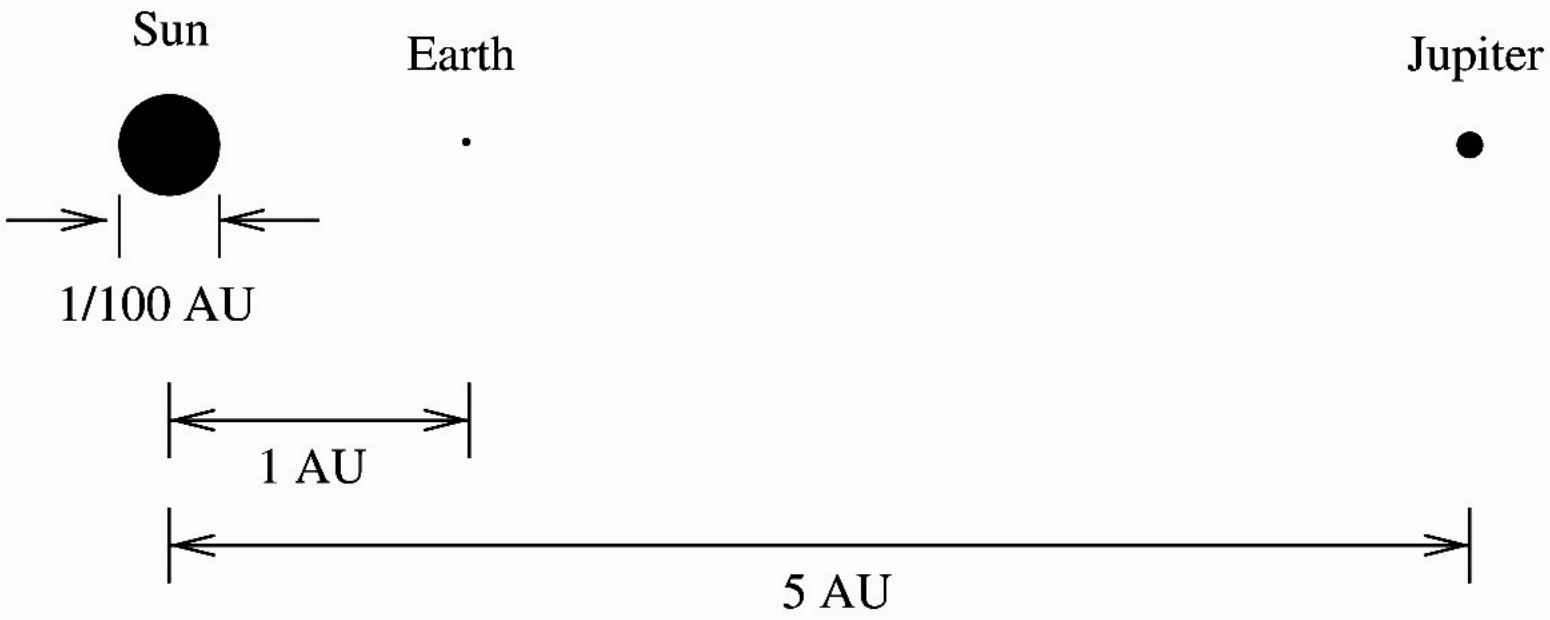
Moon Radius = 1700 km

Earth-Moon Distance = 3.8×10^{5} km

(Light travel time = 1.2sec)

Moon orbits the Earth in 27 days

The Size of the Solar System



1 AU = 1 Astronomical Unit

= The distance from the sun to the Earth

= 1.5×10^{8} km (light travel time = 8 min)

The Distance to the Nearest Star

250,000 AU = 4 Light Years

1 Light Year (Ly) = the distance light travels in one year

= (speed of light) x (length of a year)

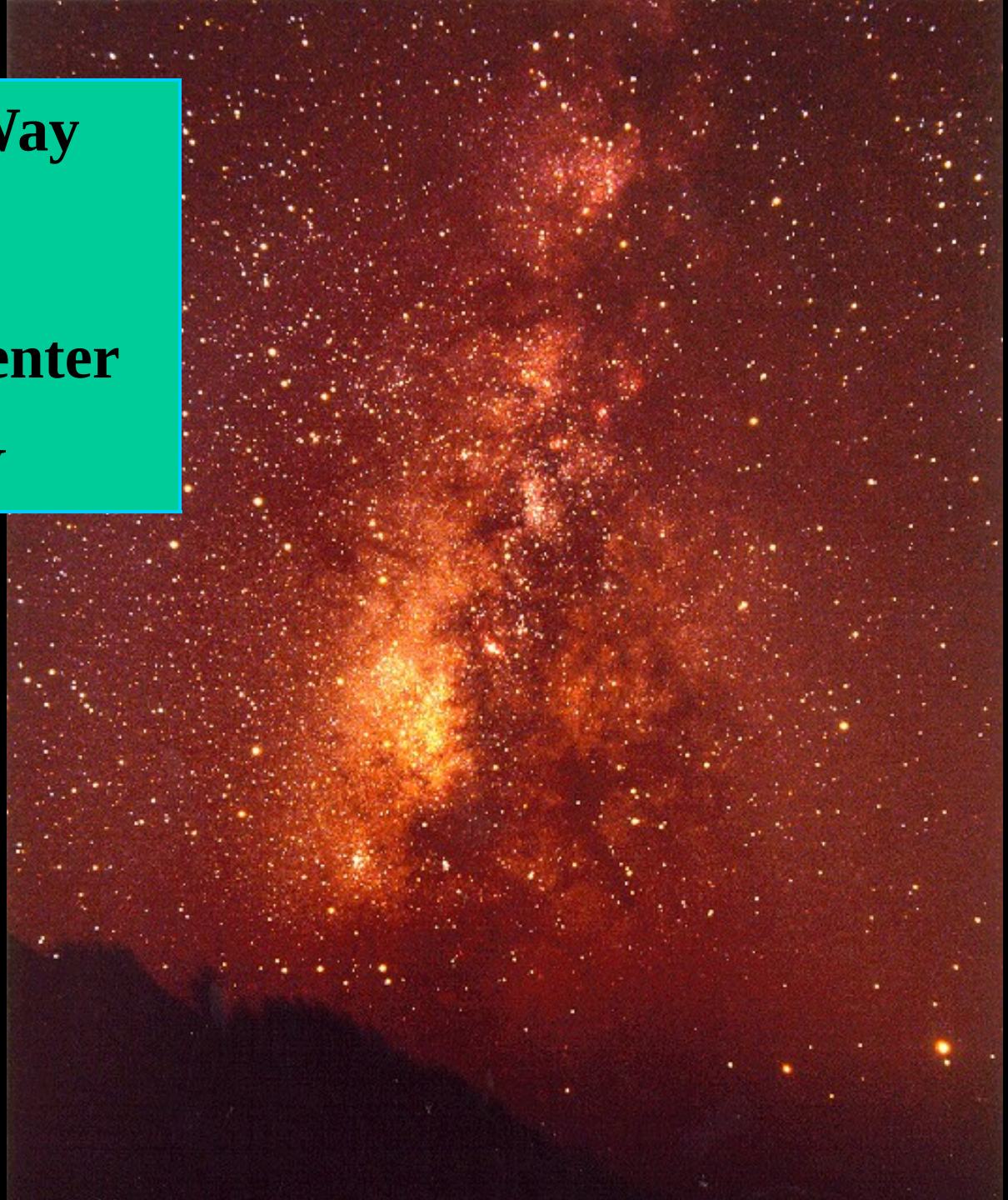
= $(3 \times 10^{10}$ cm/sec) x $(3.15 \times 10^{7}$ sec)

= 9.5×10^{17} cm

The Milky Way

Distance to Center

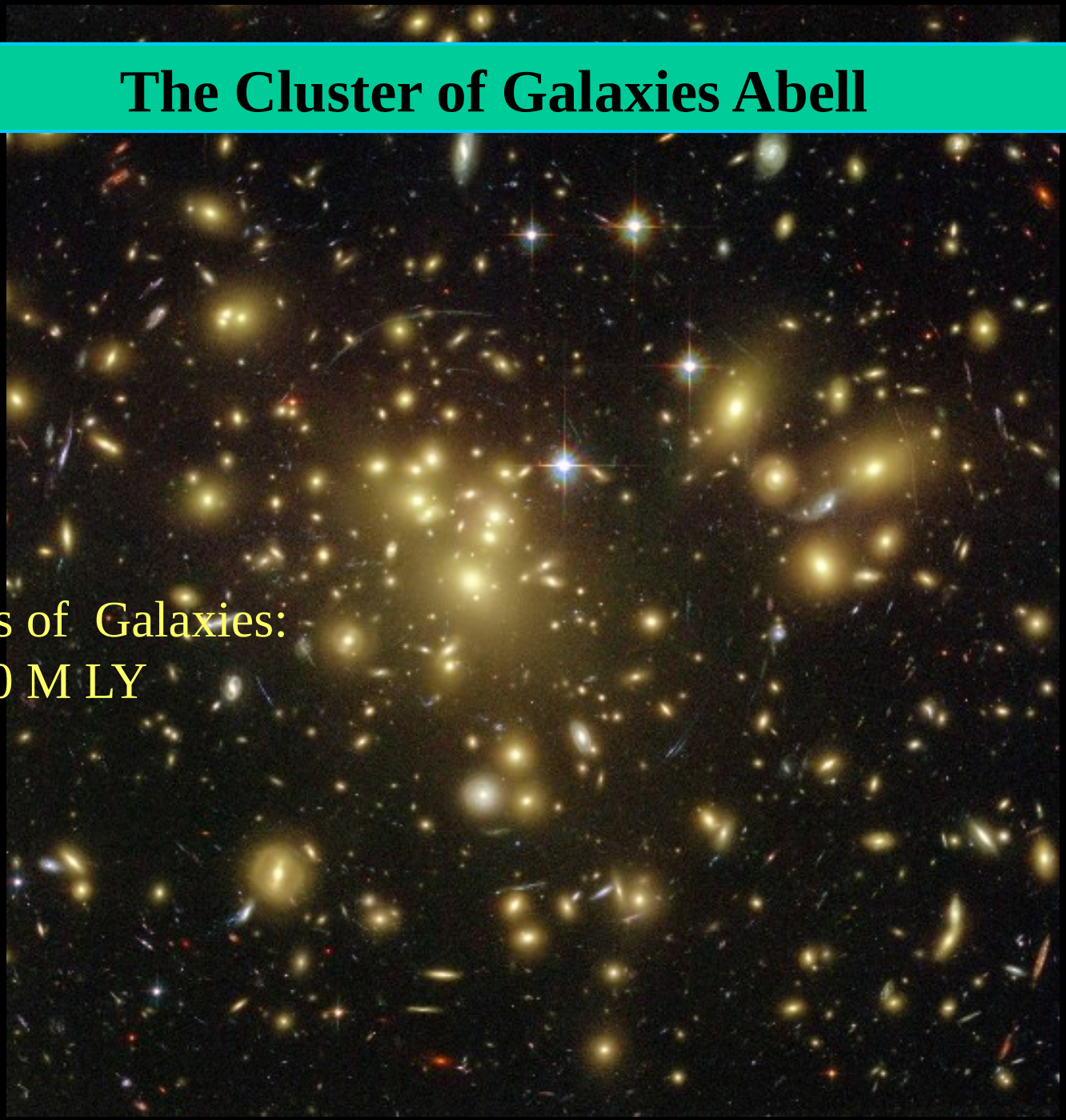
10,000 LY



The Nearby Galaxy M31 in Andromeda

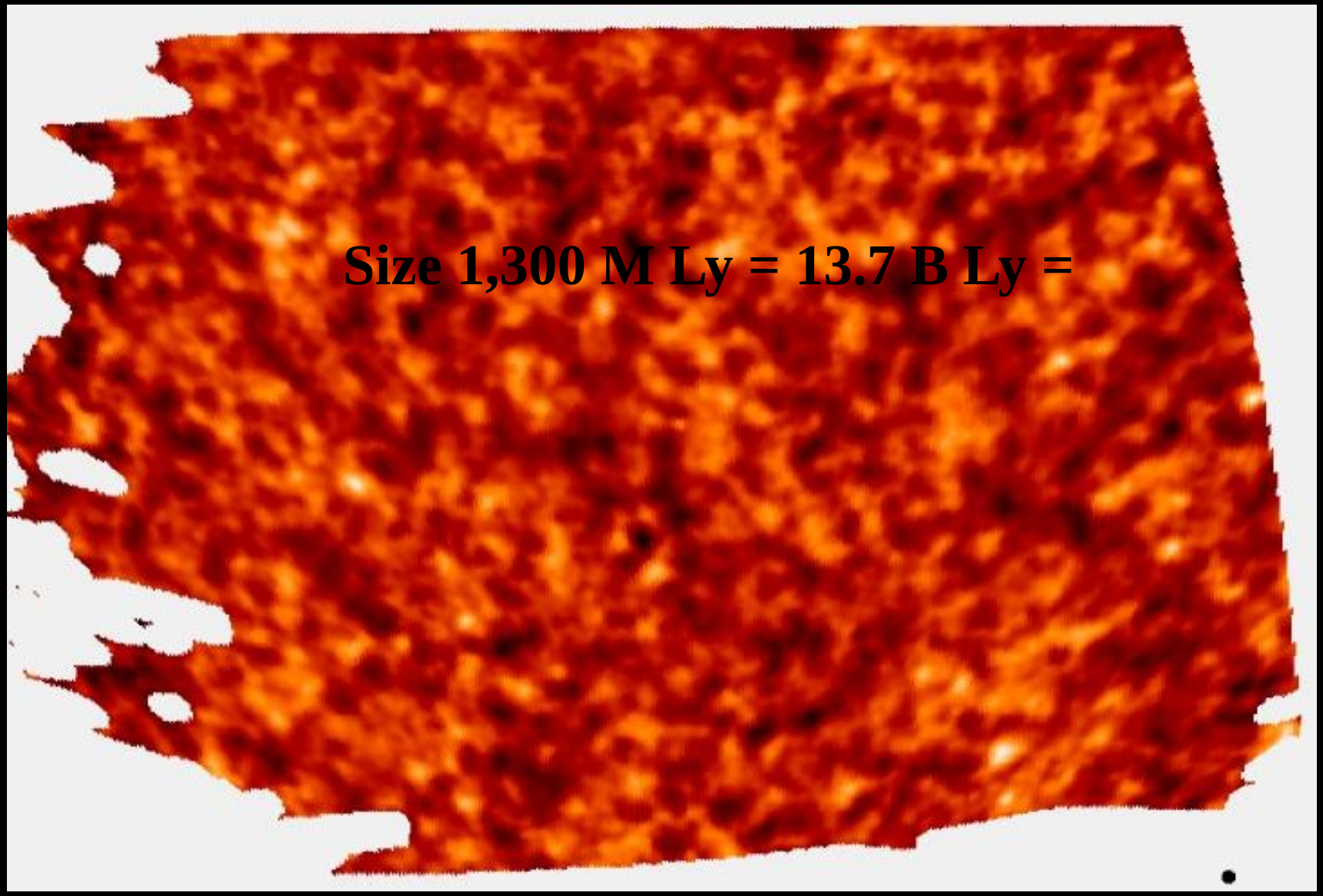
Distance to the nearest large Spiral Galaxy 2,000,000 Ly

The Cluster of Galaxies Abell



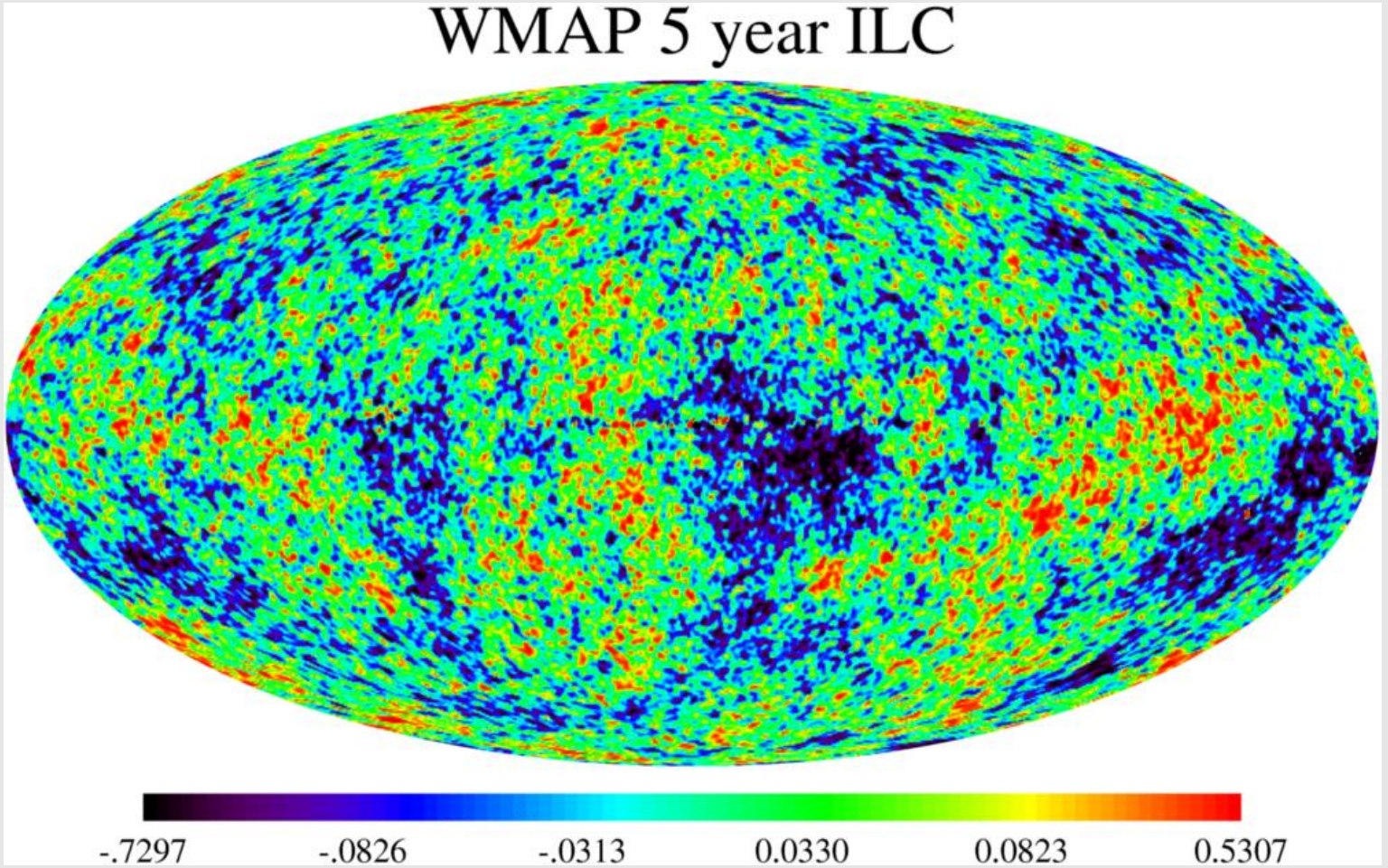
Clusters of Galaxies:
3 to 100 M LY

The Universe



Fluctuations in the MWB

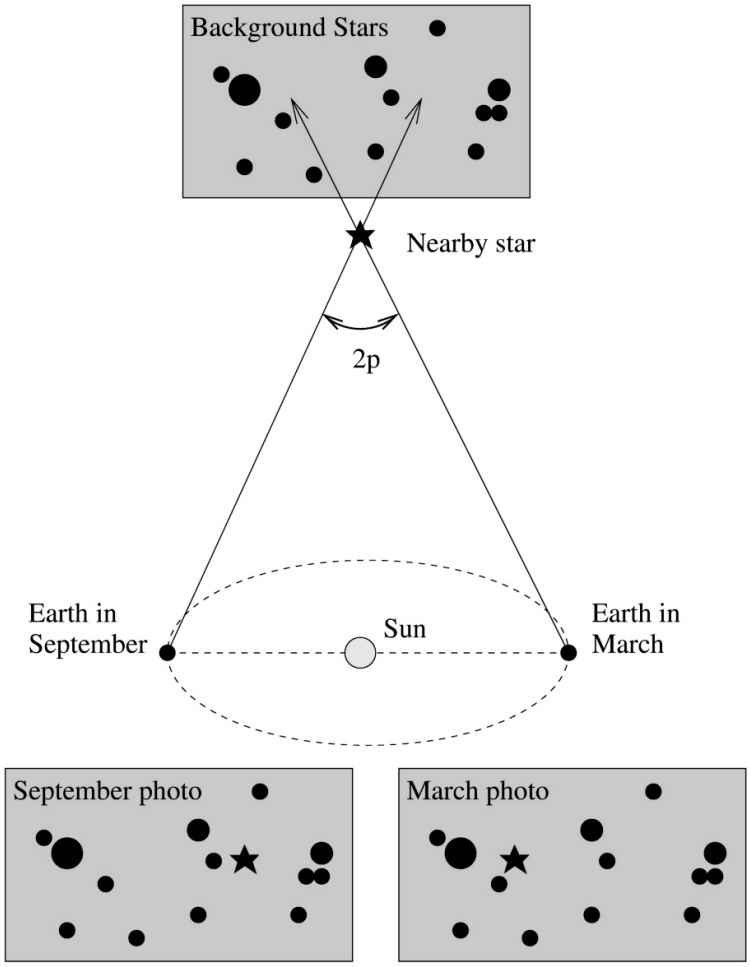
Does this look totally random to you?



Distances can be not measured in one step

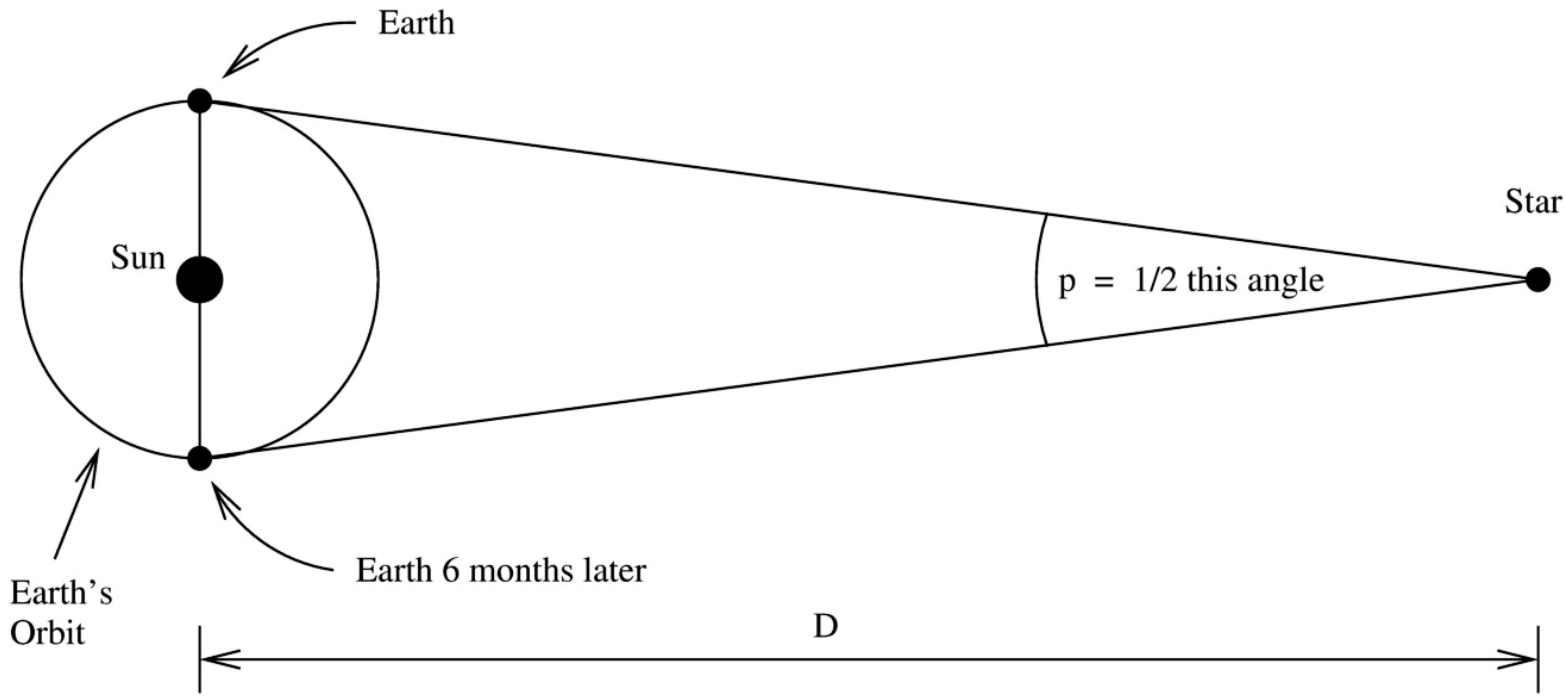
1. Annual parallax and the distances to stars
2. Distances on bright objects
3. Properties of the Micro-wave background
4. Nucleosynthesis
5. Physics of the early Universe and the imprint on later stages.

Nearby Stars Move Against Background Stars as the Earth Orbits the Sun



- The motion of the foreground star against the background stars is called the annual parallax.
- The angle p is called the parallax angle or just the parallax.

A Simple Approximate Formula for the Distance



PARSEC P: Triangulation in arc seconds

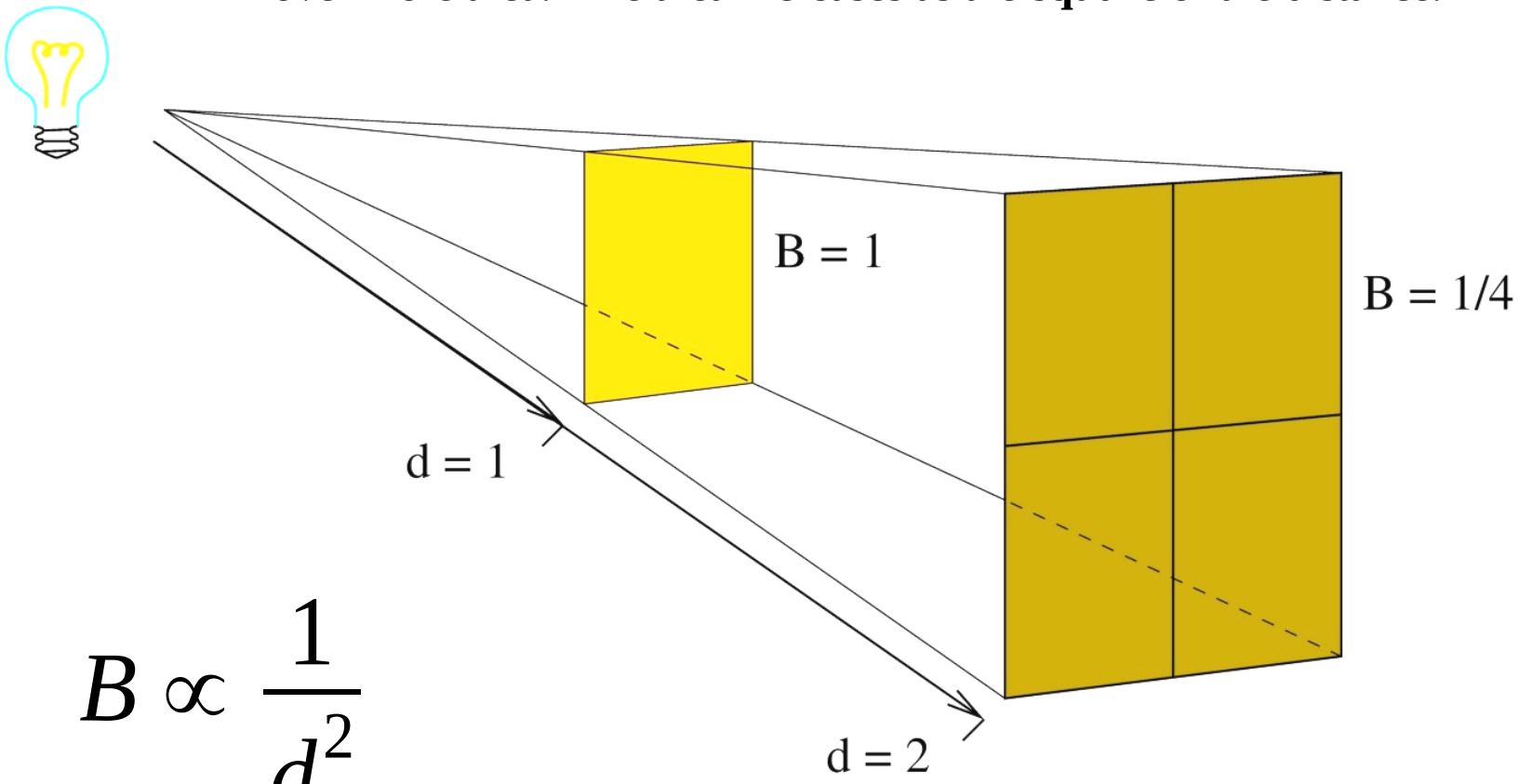
$$D = \frac{1}{p}$$

- P of the order of arc-sec

(reach of nearby stars)

Inverse Square Law for the Propagation of Light

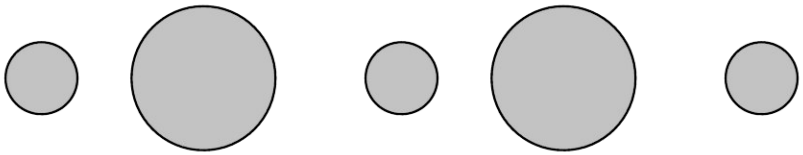
The bulb appears dimmer with distance because its light spreads out over more area. The area increases as the **square** of the distance.



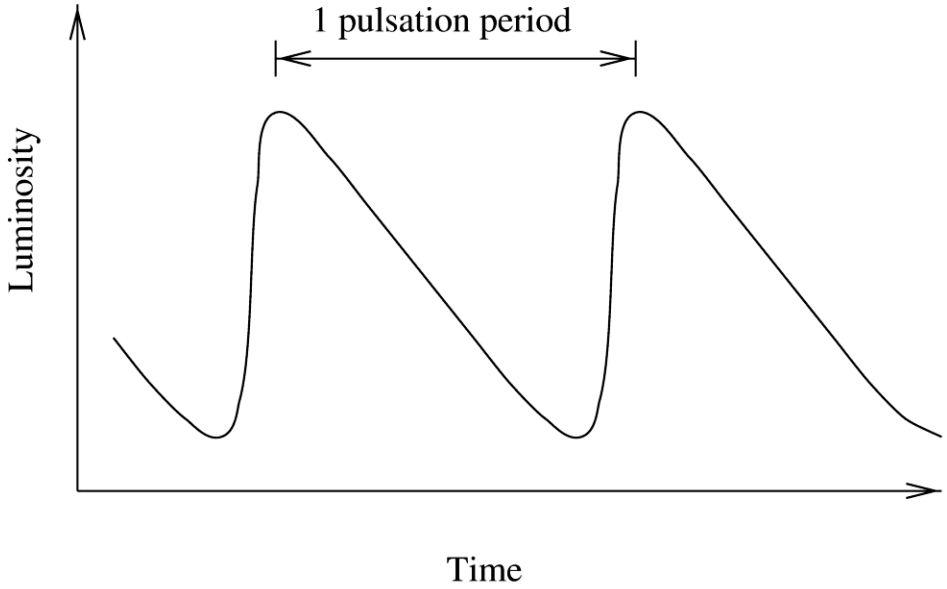
$$B \propto \frac{1}{d^2}$$

Pulsating Variable Stars

Size of the Star:



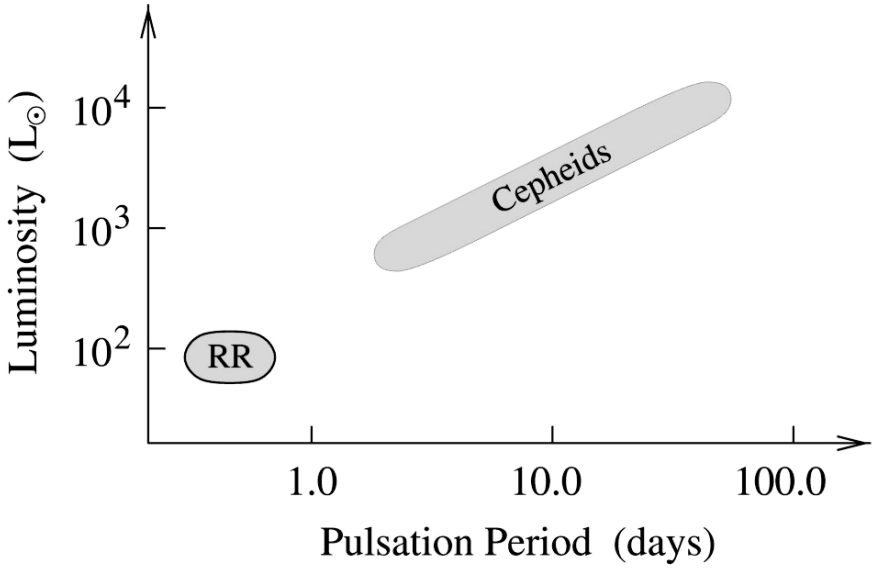
Light Curve:



Two Important Types of Pulsating Variable Stars

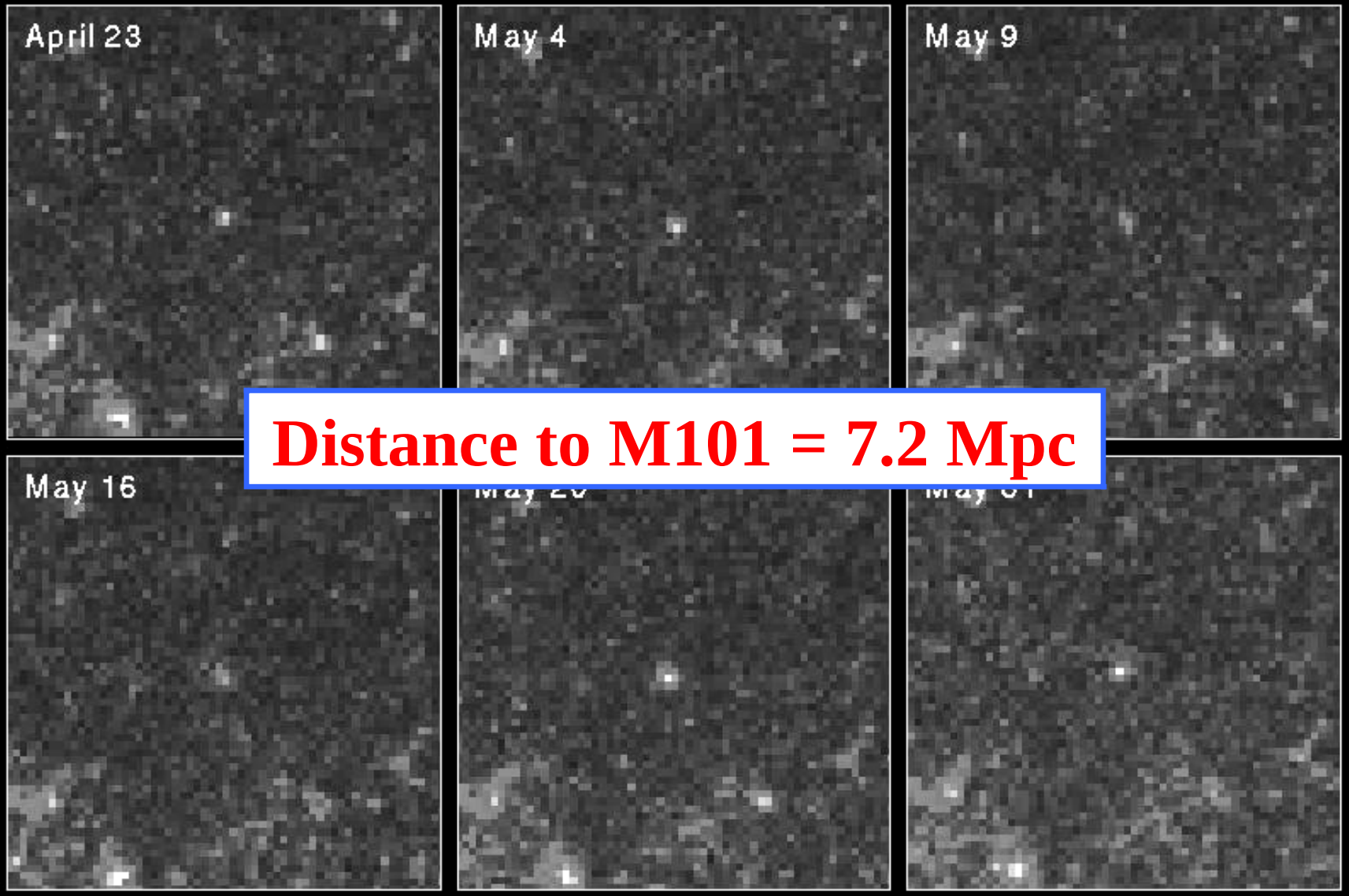
Type	Period (days)	Luminosity
RR Lyrae	0.3 - 0.7	10^2 $L_\odot$
Cepheid	3 - 50	10^3 to 10^4 $L_\odot$

The Period - Luminosity Relation:



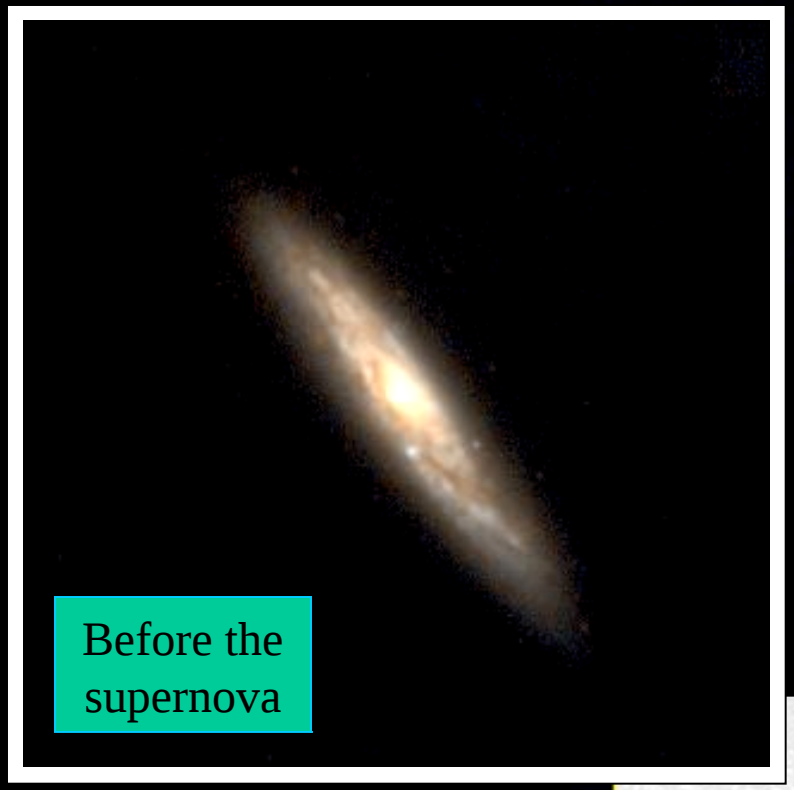
M101: The Pinwheel Galaxy

A Cepheid Variable in M101

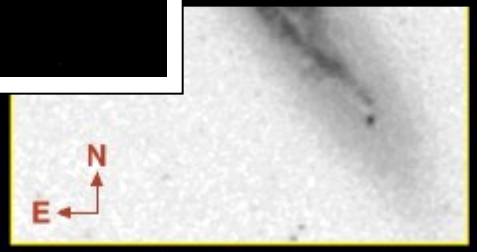


Distance to M101 = 7.2 Mpc

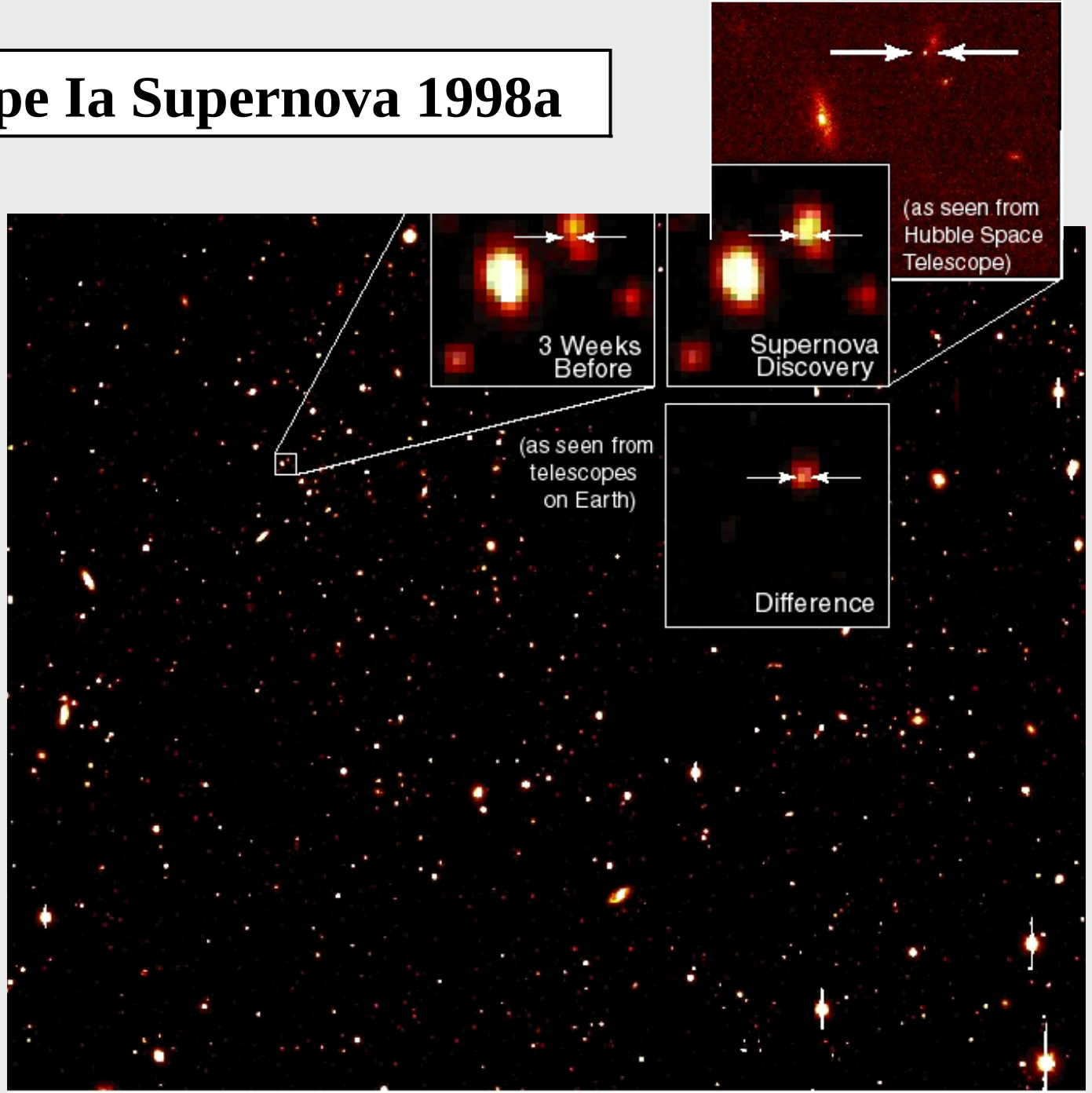
A Supernova in the Galaxy NGC 3877



Before the supernova



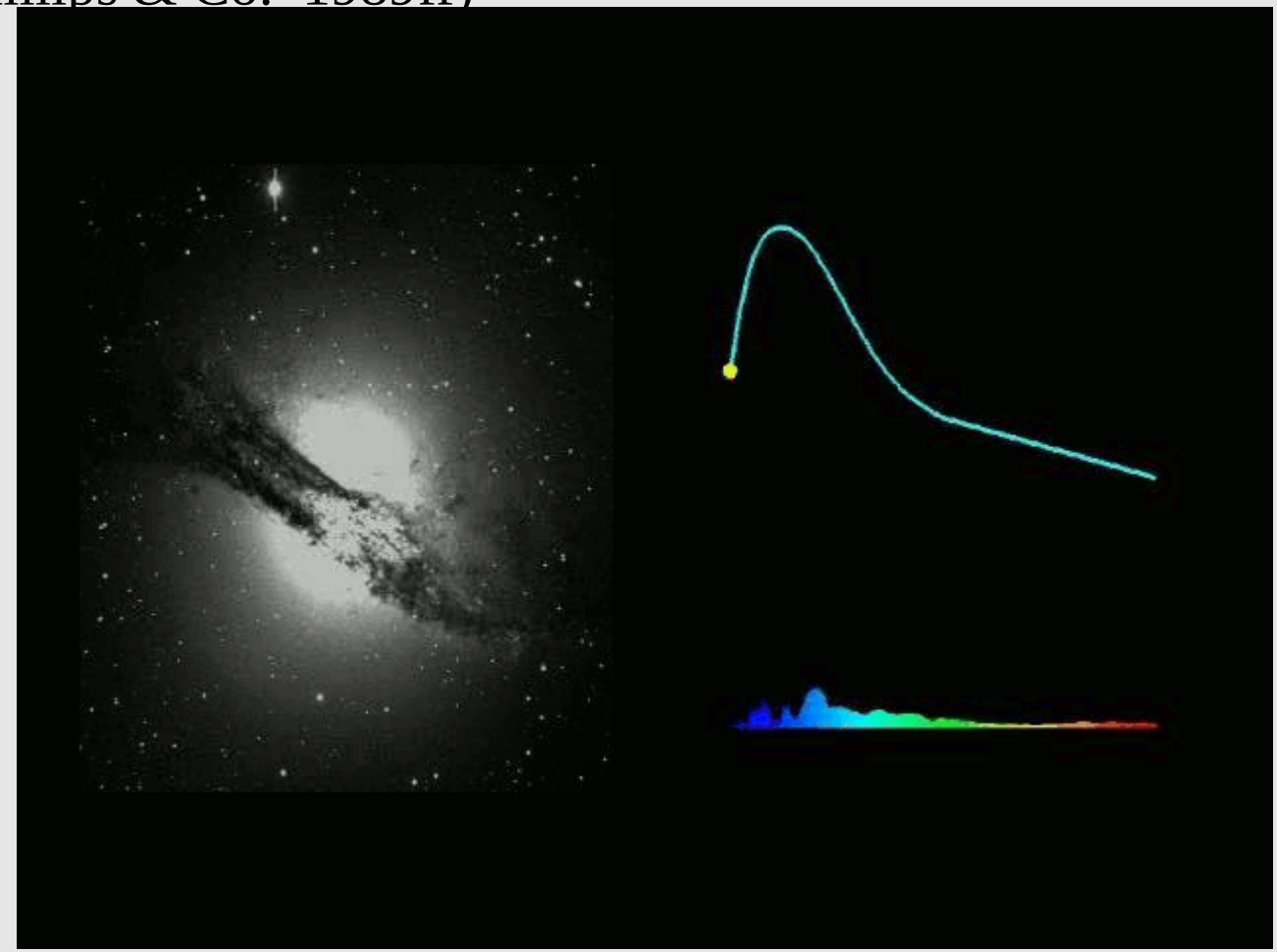
The Type Ia Supernova 1998a



TSome 80 yeaddfrs later: A Big Surprise:

Type Ia Supernovae as 'quasi'-standard Candles

(Phillips & Co. 1989ff)



(Animation from Saul's Webpage)

Edwin Hubble (1889 – 1953)

Hubble's Law

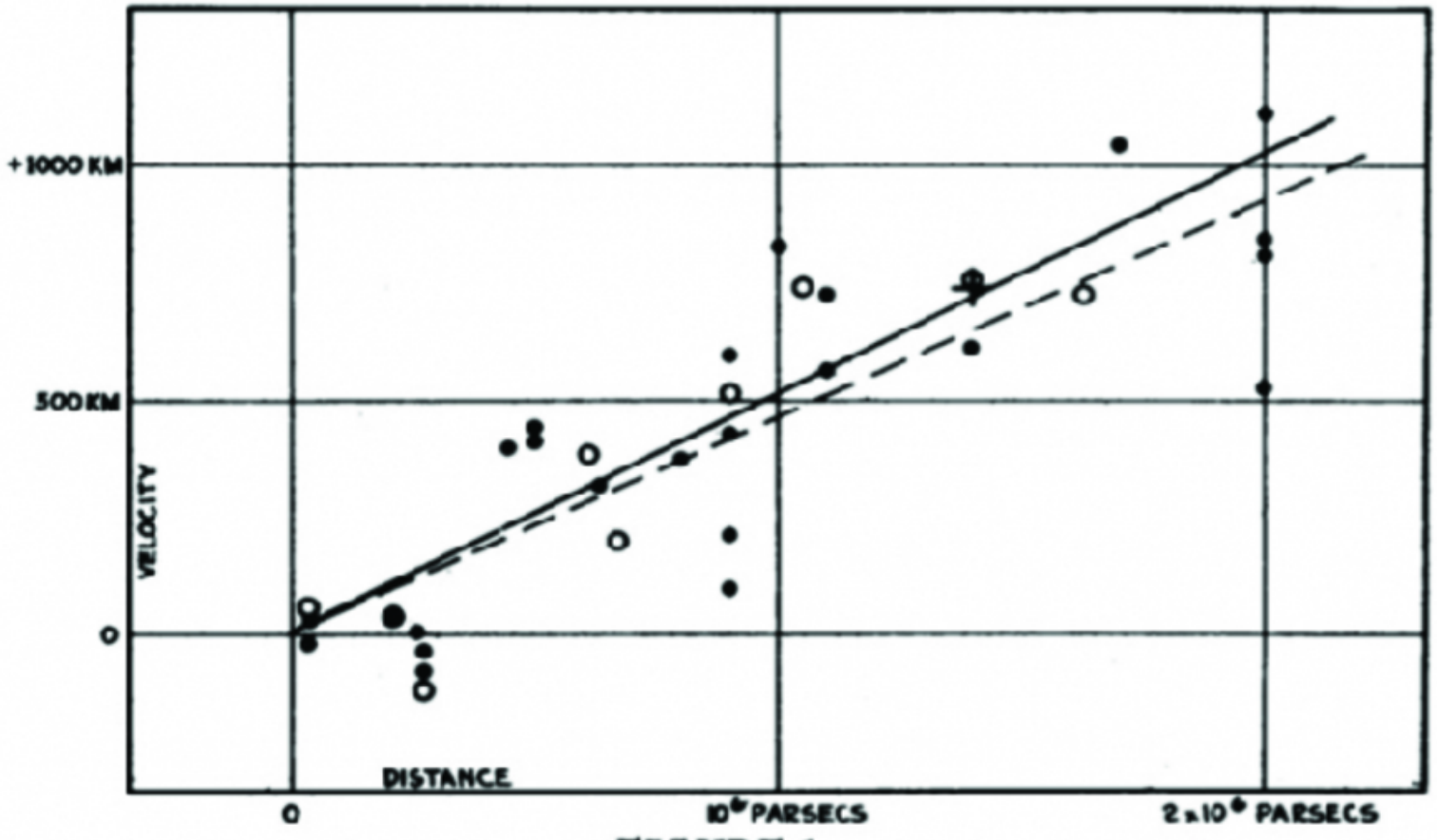
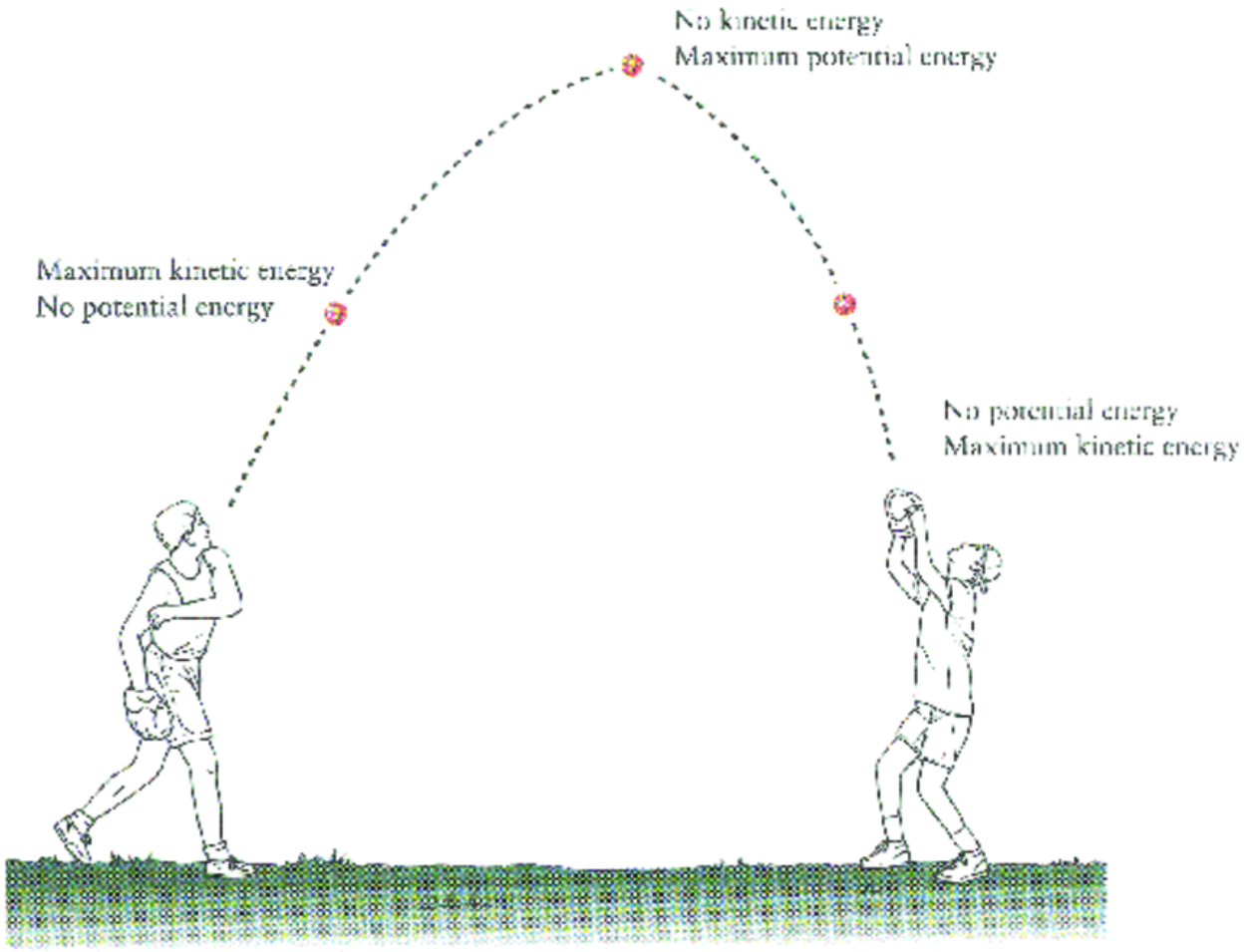


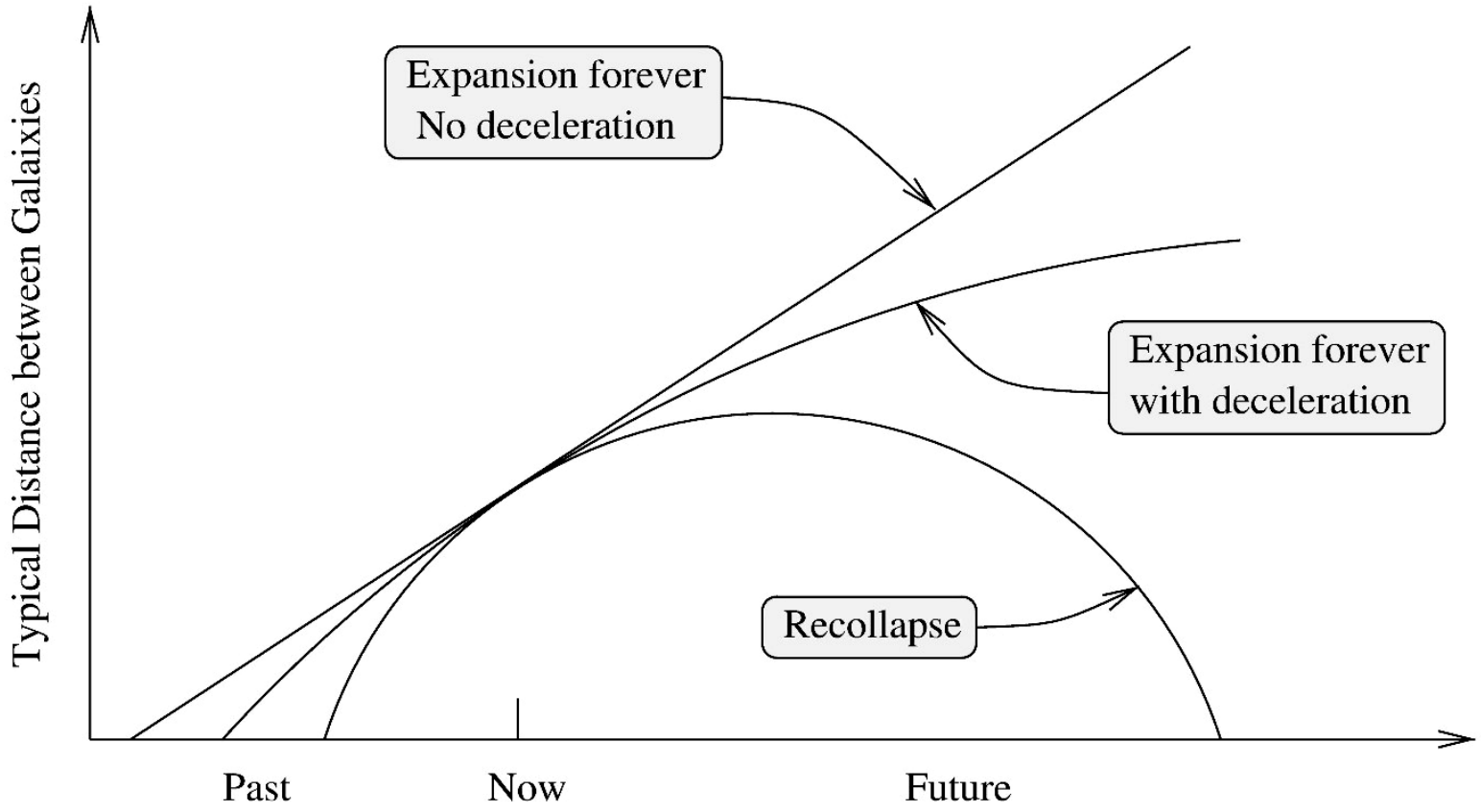
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

What is the Past and Future of the Universe ?

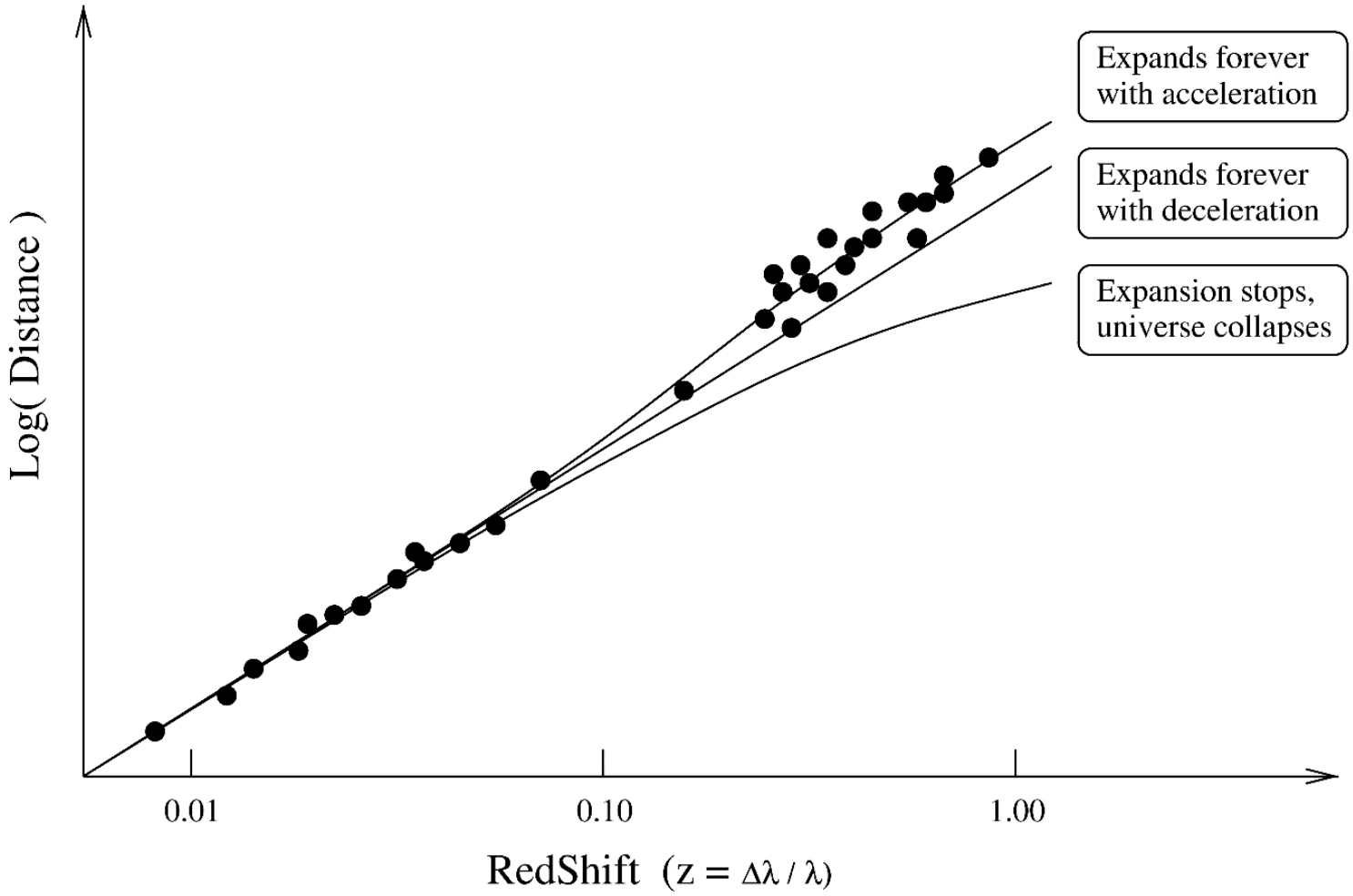


The Newtonian View of the Expansion of the Universe



The Hubble Diagram for Type Ia Supernovae

The distances to the supernovae are measured from their brightness



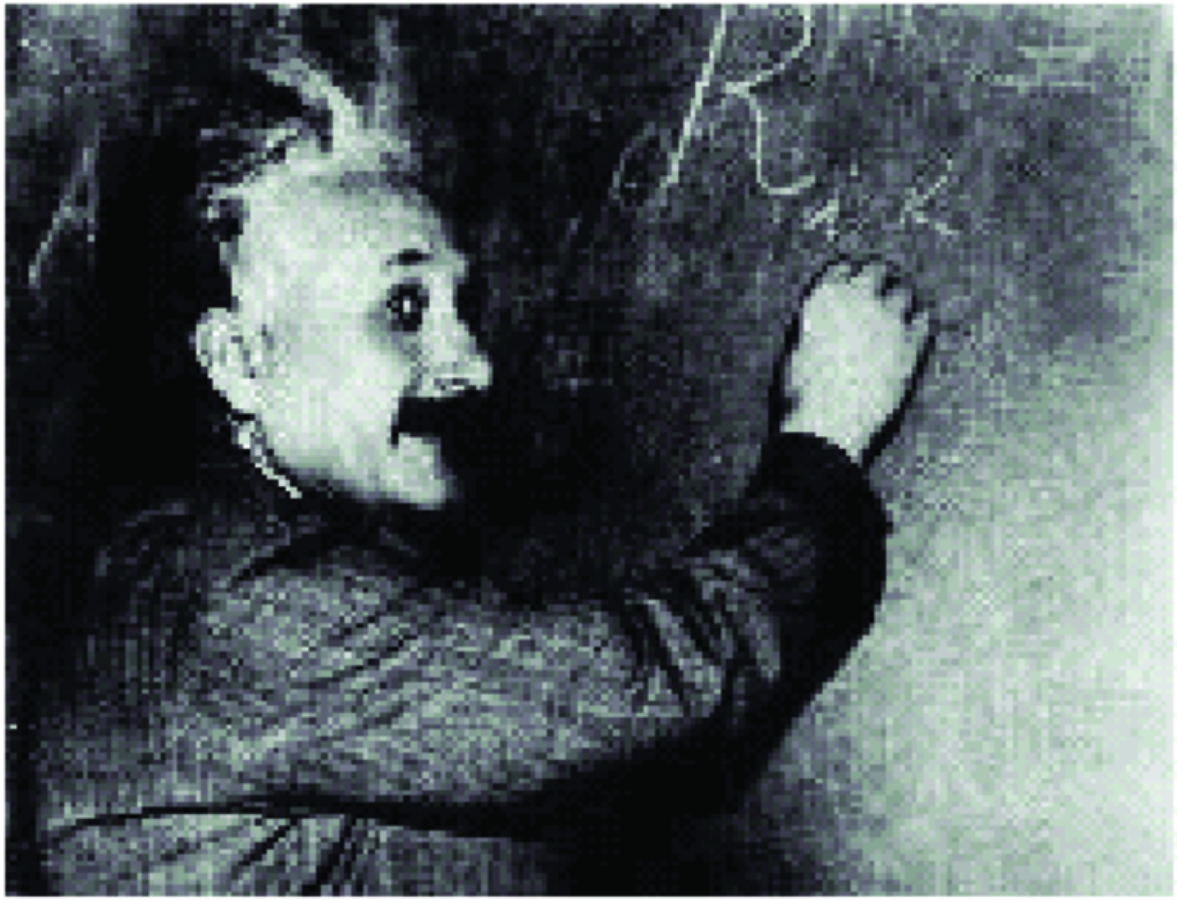
Nobel Price 2011: Perlmutter, Riess & Schmidt

What is Space, Time and Gravitation ?

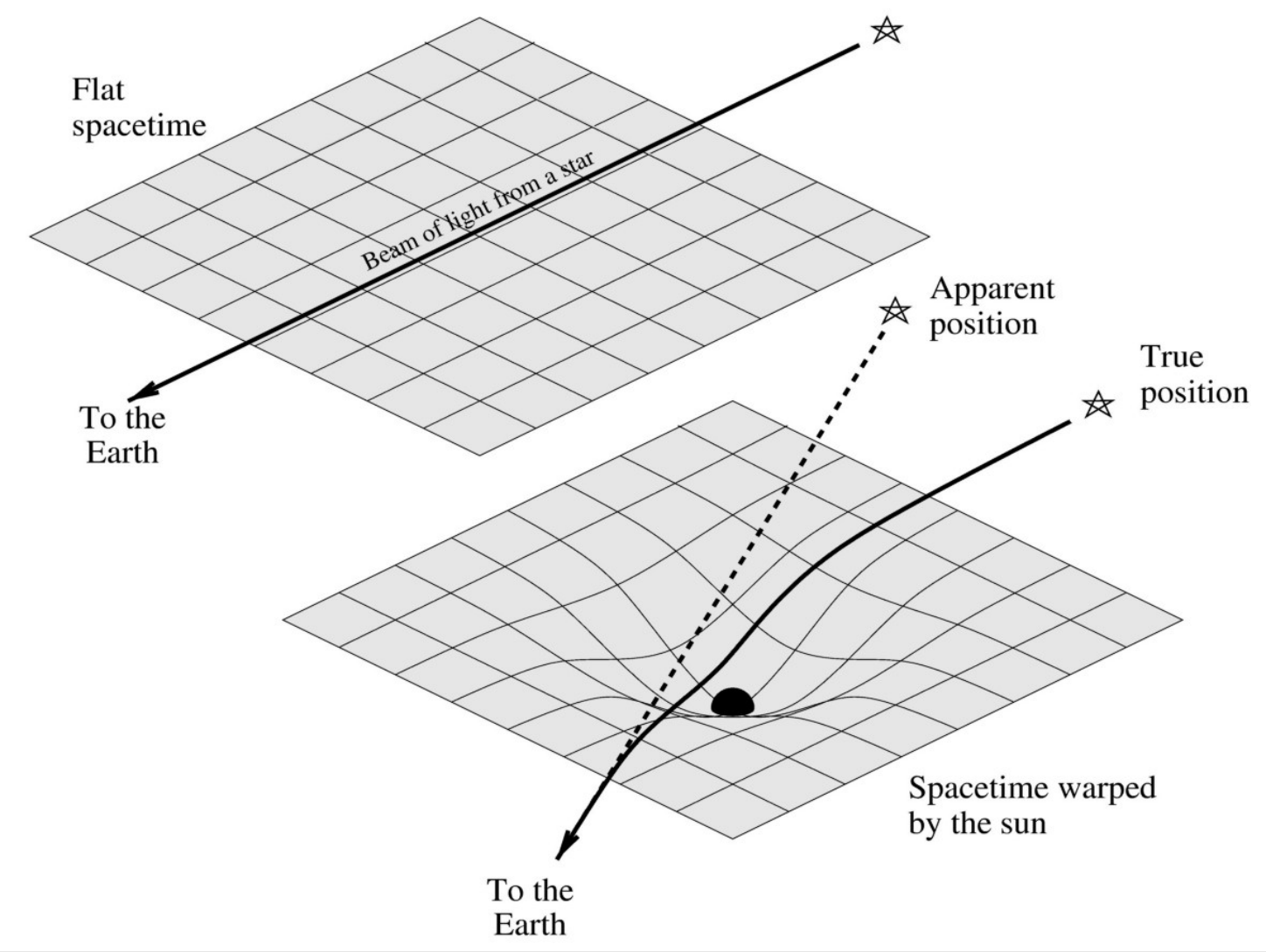
Big Al has a great idea!!!

In 1915 Albert Einstein proposed his theory of gravity.

He believed that space and time were parts of one spacetime continuum.



The Rubber Sheet Picture of Gravity

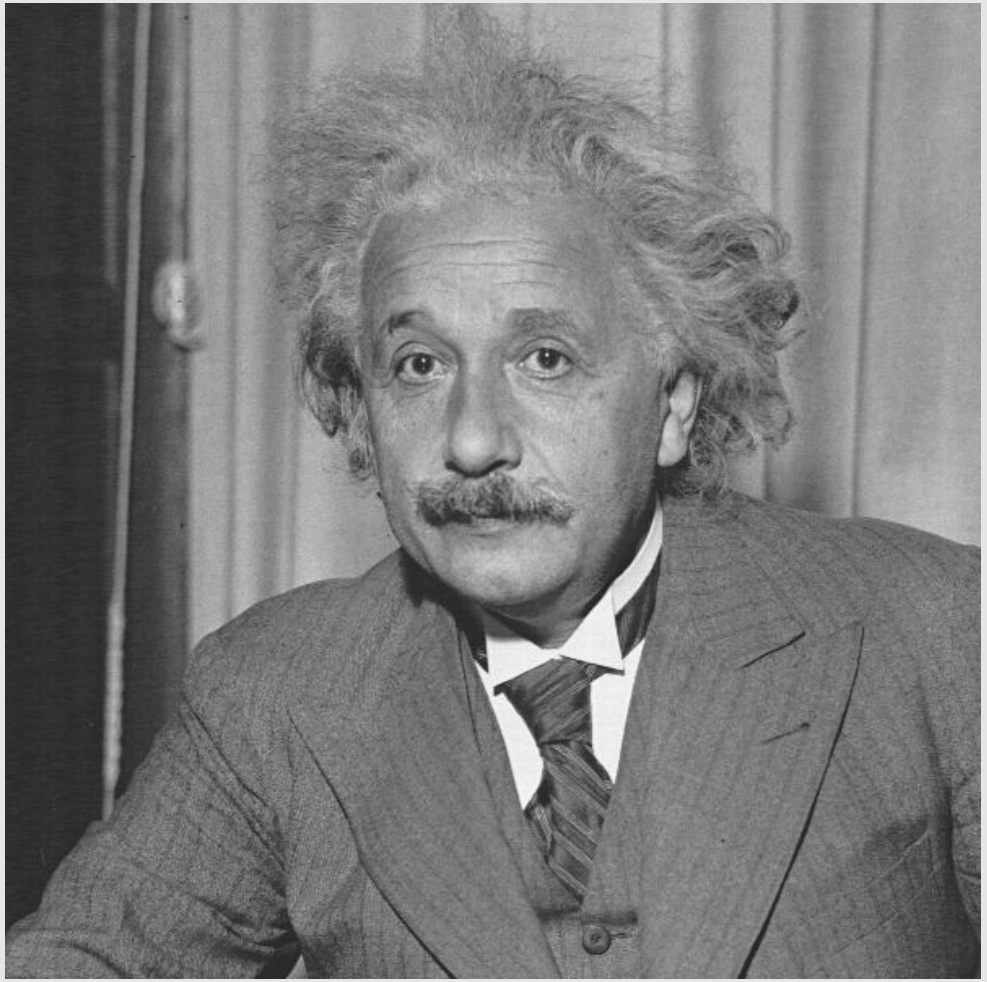


“The Worst Mistake of My Life.” (Part 1)

1) The original version of Einstein’s equations of general relativity demanded that the universe expand or contract.

2) In those days (1917) the universe was thought to be static, so Einstein added an extra term to the equations so they gave a static universe.

3) Ten years later the expansion of the universe was discovered and the extra term was removed.



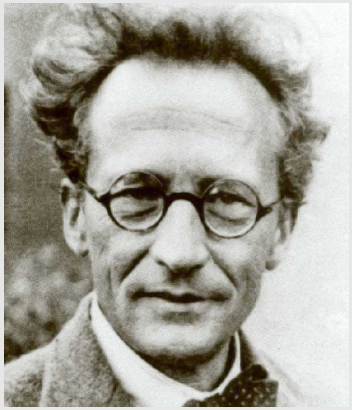
“The Worst Mistake of My Life.” (Part 2/post)

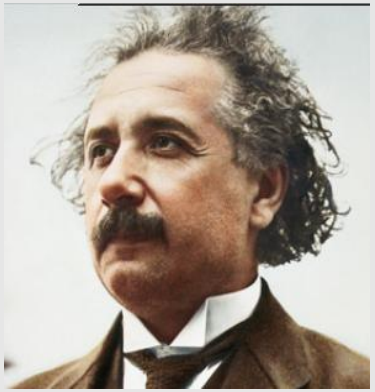
Exchange between **Einstein & Schroedinger (1917ff)** (from Harvey, astro-ph Nov 12, 2012)

1) *Schroedinger* suggests that a cosmological constant cannot be dismissed in an expanding universe and the GR-equations have still a solution.

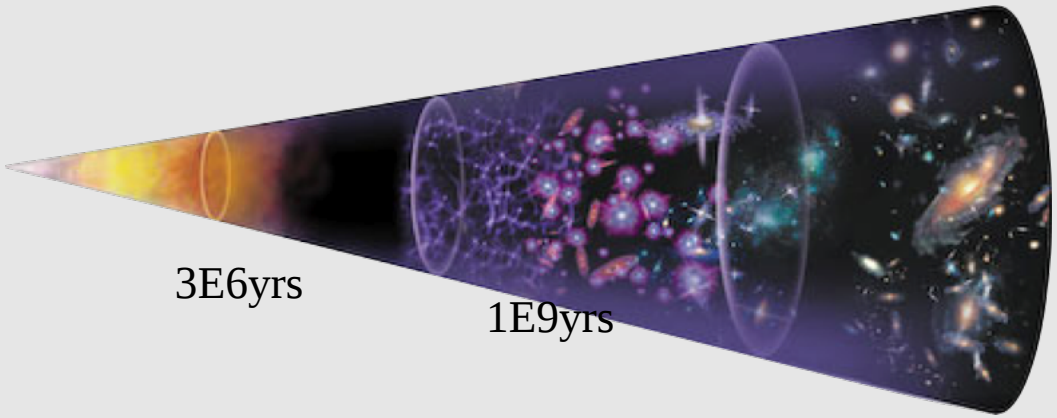
2) Einstein responds: “*This means, one not only has to start from the existence of a non-observable, dominant negative energy density in the interstellar space but also has to postulate a hypothetical law about space time distribution of this mass density.*”

Convinced all, and the dialogue was forgotten for some 80 years.





•Evolution of the Universe



- $T \sim 10^{15}\ K, t \sim 10^{-12}$ sec: Primordial soup of fundamental part
- $T \sim 10^{13}\ K, t \sim 10^{-6}$ sec: Protons and neutrons form.
- $T \sim 10^{10}\ K, t \sim 3$ min: Nucleosynthesis: nuclei form.
- $T \sim 3000\ K, t \sim 300,000$ years: Atoms form.
- $T \sim 10\ K, t \sim 10^{9}$ years: Galaxies form.
- $T \sim 3\ K, t \sim 10^{10}$ years: Today.

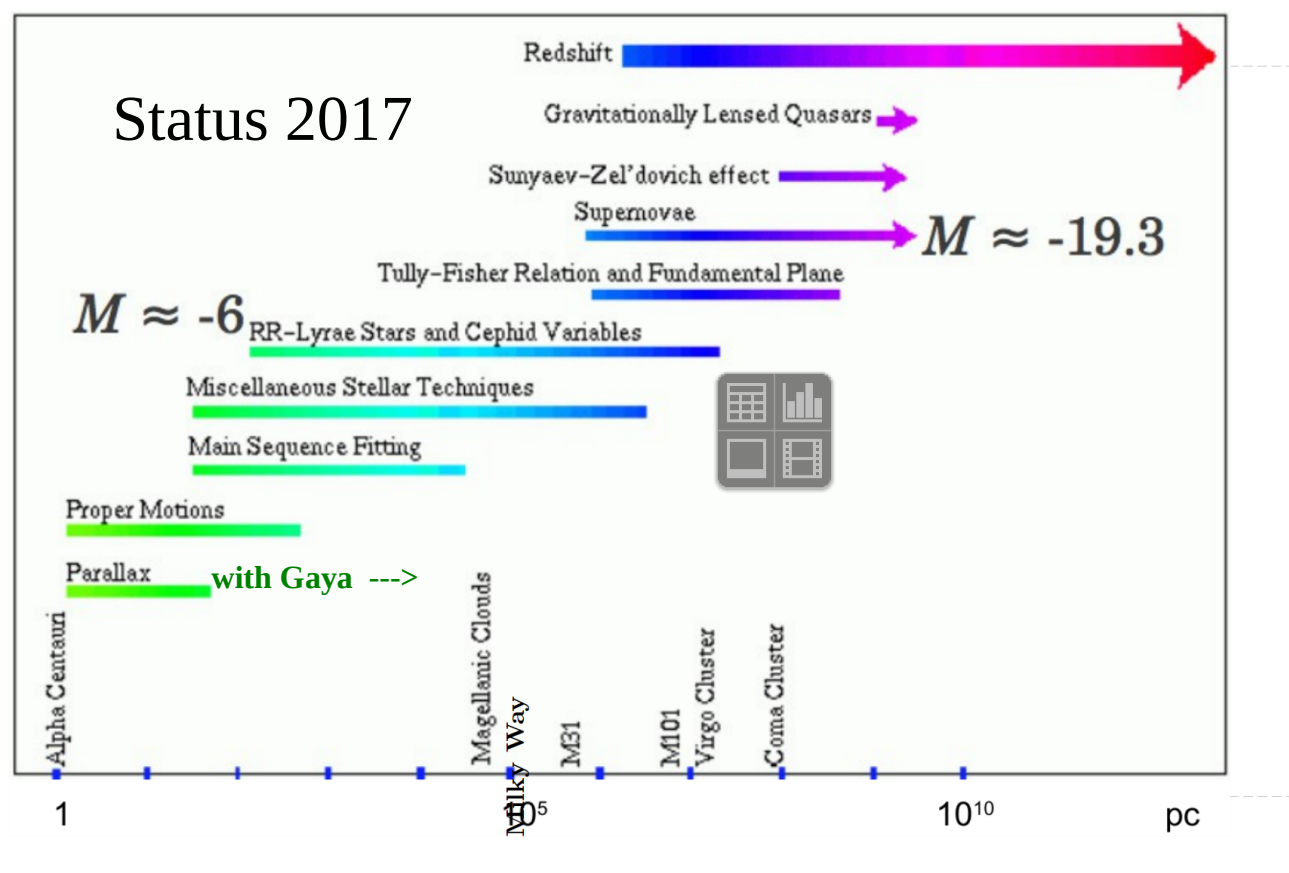
Cosmology, Distance Ladder & Big Bang Nucleosynthesis

H_o [km/s/Mpc] = 73.24 ±1.74 (SNIa, z(SN)<1.6 & local δ-Cepheii , Riess et al., 2016),

= 73.2 ± 2.3 (SNIa, local SN(CSPII), Burns et al. 2018)

= 66.93 ± 0.62 (MWB, assumptions: flat & 3 neutrino flavors, Planck-Collaboration et al. 2016)

= 69.3 ± 0.7 (MWB, " , WMAP+ACT+SPT+BAO, Bennet et al. 2013)



=> e.g. Δ H(^{7}Li/H) = 7- 30 %

Potential of BBN + SNe

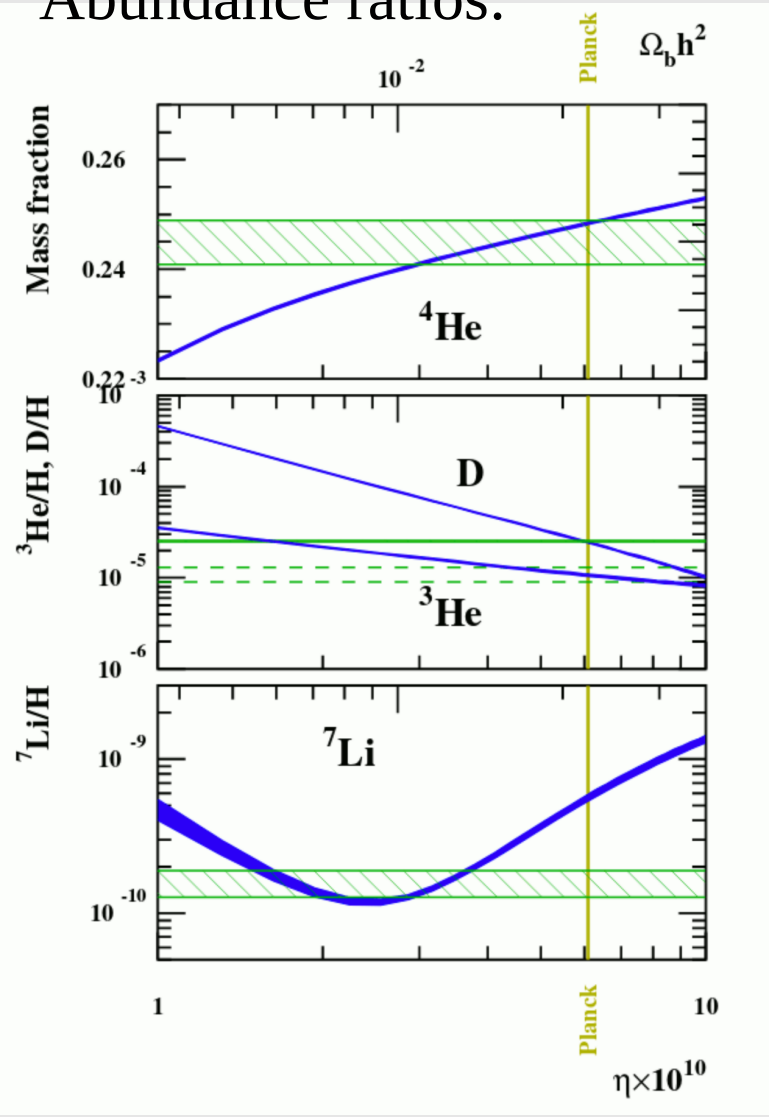
- confirm current physics*
- cosmology (e.g. flatness?)
- Dark matter (early black holes?)
- new physics beyond HEP-standard model
- Astrophyical solution
  a) Li-burning
  b) 1st future improvement of Distance ladder by **Gaya**

Remark: SN(models & SN-observations) = 68 ± 4 [km/s/Mpc] (Hoeflich & Khokhlov, 1996, H. et al. 2017)
→ ***Models identify*** systematics but *do not improve absolute calibration* !!!

* see Ingo Wiedenhoever's talk, or astrophysical abundances.

The first 1sec till 3-4 minutes: BB-Nucleosynthesis

Abundance ratios:



- initial H/He/D/Li are produced

(consistent with observations)

- Determination of excess of normal to antimatter

Agreement with ‘connecting the dots’

High-energy-standard model → nucleophysics → Microwave background → structure of galaxies → Explosion physics of supernovae

Problems:

Li- problem

Local vs. early Expansion Rate

Nature of Dark energy and matter

Why are the natural constants as they are ?

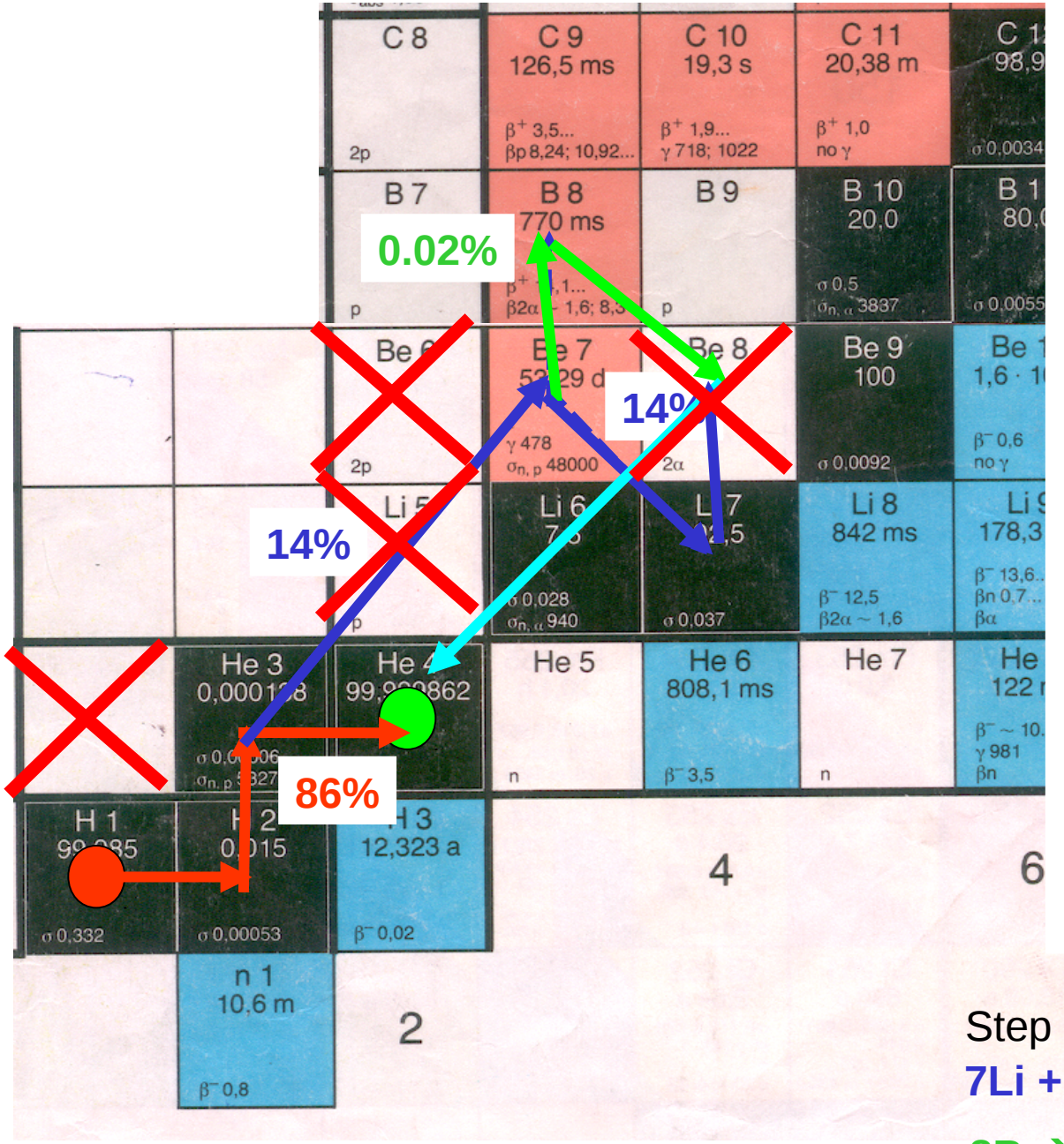
The sun shines with a power of 3.85e33 erg/s = 3.85e26 Watts
It has done so for 4.7 Bio. years (d: Milliarden)

Stars and Star explosions have created the chemical elements our world (and we) are made from

A little “Light Matter”

Only nuclear reactions can convert the chemical elements

- The big bang only created Hydrogen and Helium
- We are made of Hydrogen, Carbon, Oxygen, Calcium, etc.
- The heavier elements (>He) around us were created in stars and star explosions
- Is this just another curious coincidence of the Universe ?



pp-chains: 1H → 4He

Step 1:

- available: ^{1}H, some ^{4}He

$$p+p \rightarrow d + e^{+} + \nu_e$$

Step 2:

- available: p, some d,^{4}He

$$d+p \rightarrow {}^{3}He$$

Step 3:

- available: p, some 3He,4He
  little d (rapid destruction)

86% $^{3}He+{}^{3}He \rightarrow 2p + {}^{4}He$

14% $^{3}He+{}^{4}He \rightarrow {}^{7}Be$

Step 4:

14% $^{7}Be + e^{-} \rightarrow {}^{7}Li+\nu_e$

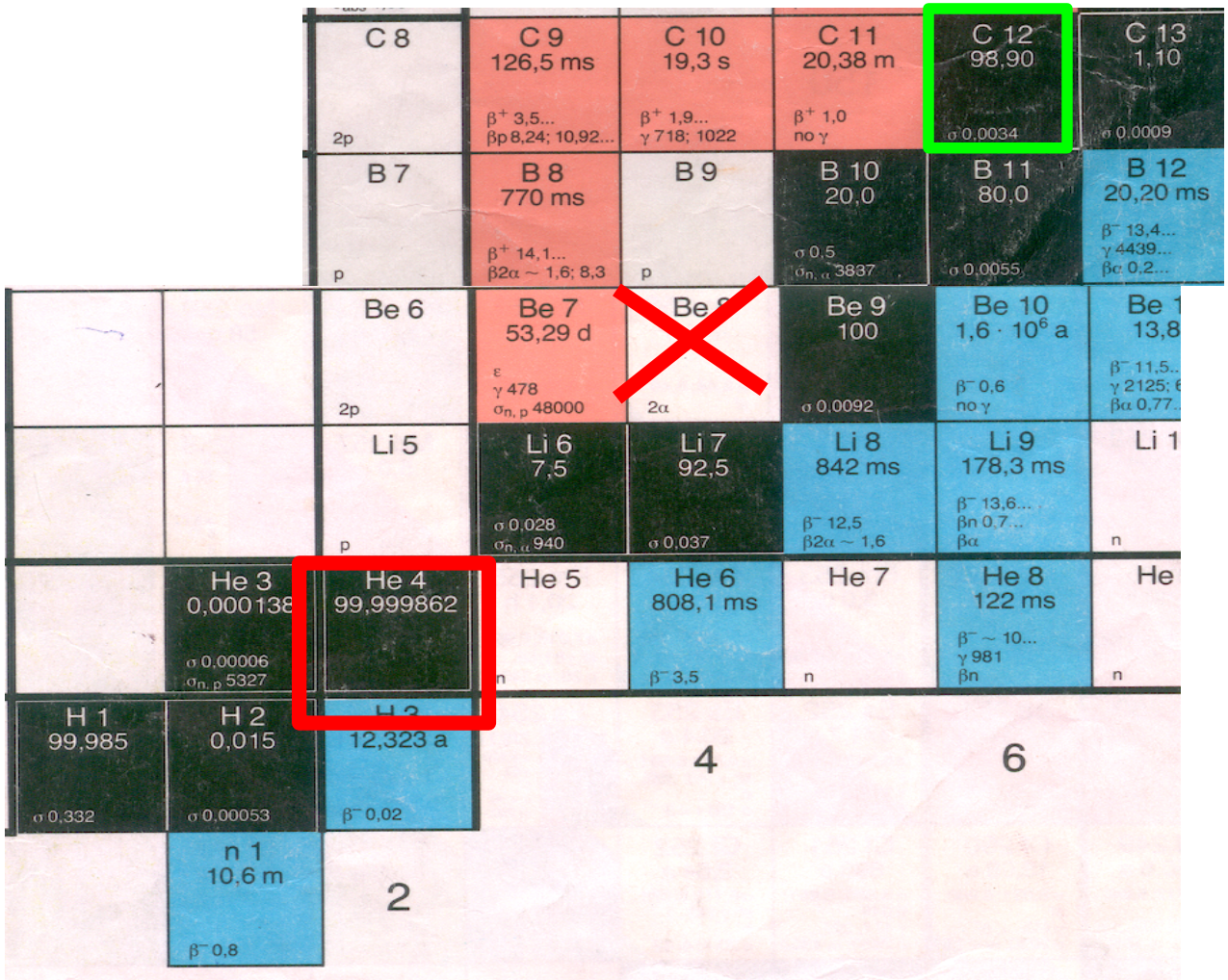
0.02% $^{7}Be + p \rightarrow {}^{8}B$

Step 5:

$^{7}Li + p \rightarrow {}^{8}Be$

$^{8}B \rightarrow e^{+} + \nu_e + {}^{8}Be$ } 2 x ^{4}He

When stars run out of Hydrogen, they burn Helium

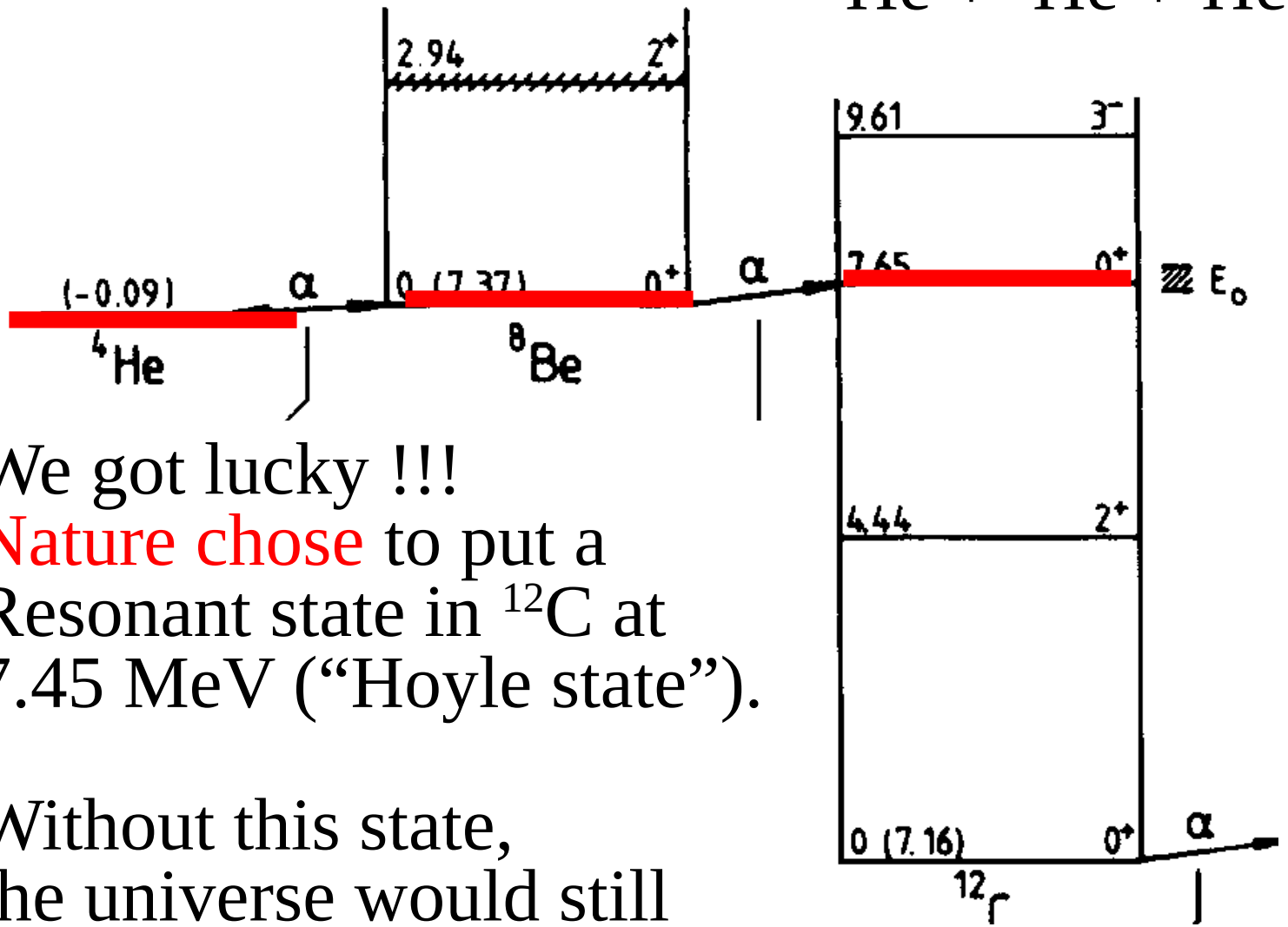


That is easier said than done !

^{12}C can not be made “step by step”.

Nature needs to collide three Helium-nuclei within 10^{-15} seconds !

$^4He + {}^4He + {}^4He = {}^{12}C$



We got lucky !!!
Nature chose to put a Resonant state in ^{12}C at 7.45 MeV (“Hoyle state”).

Without this state, the universe would still be made of Hydrogen and Helium.

The State of the Cosmos

The Universe is expanding at an accelerate rate.

(but we need an early phase of inflation).

The origin of elements can be understood but the Li-problem.

Thermodynamics, GR and QM work but the “HEP Standard Model” still rules HEP.

The laws of physics contain “Constants of Nature”, which seem carefully balanced to produce a universe we can live in.

We don't know why, but we keep trying and maybe succeed.

Some of the attempts predict a multitude of “parallel” universes, each with different “Constants of Nature”.

Progress is rapid, and driven by observations

Static Universe (1920) → Expanding Universe (1930) → acceleration Universe (2000)

We start to understand the origin of elements from H to Au.

We start to understand the structure of the Universe

(small → large fluctuations in density).