The Accelerating Expanding Universe: Dark Matter, Dark Energy, and Einstein's Cosmological Constant

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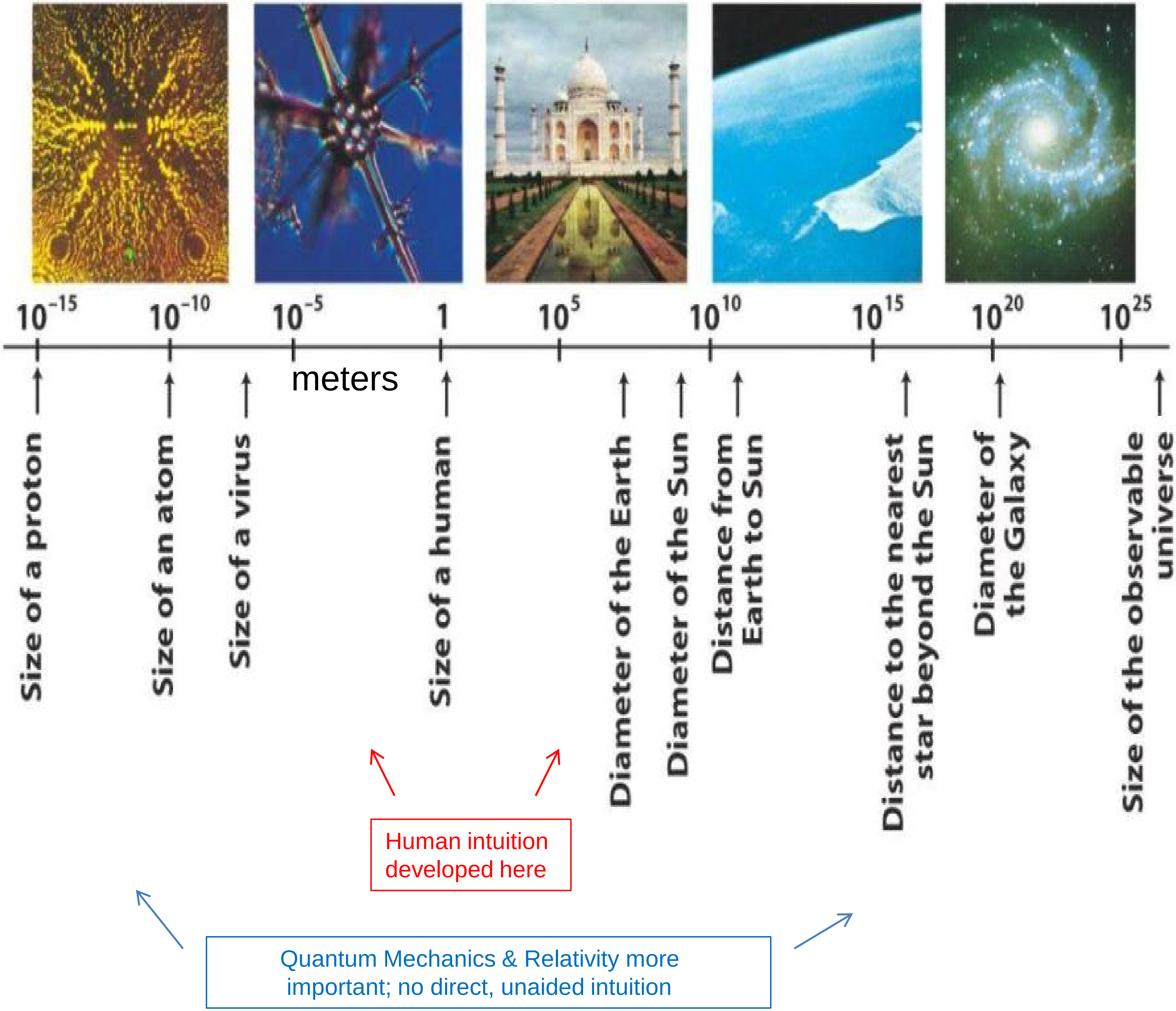
Indian Institute of Technology Madras Monday August 13, 2018

Please view & share: HowGlobalWarmingWorks.org (please forgive me for this PSA)

Yes, Dorothy, there are hills in Kansas!*

*See however M. Fonstad, W. Pugatch, & B. Vogt, "Kansas is flatter than a pancake", Ann. Improbable Res. 9, issue 3 (2003).



10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
meters
Size of a proton
Size of an atom
Size of a virus
Size of a human
Diameter of the Earth
Diameter of the Sun
Distance from Earth to Sun
Distance to the nearest star beyond the Sun
Diameter of the Galaxy
Size of the observable universe
Human intuition developed here
Quantum Mechanics & Relativity more important; no direct, unaided intuition

60 kg, 50 y

Typical human length scale

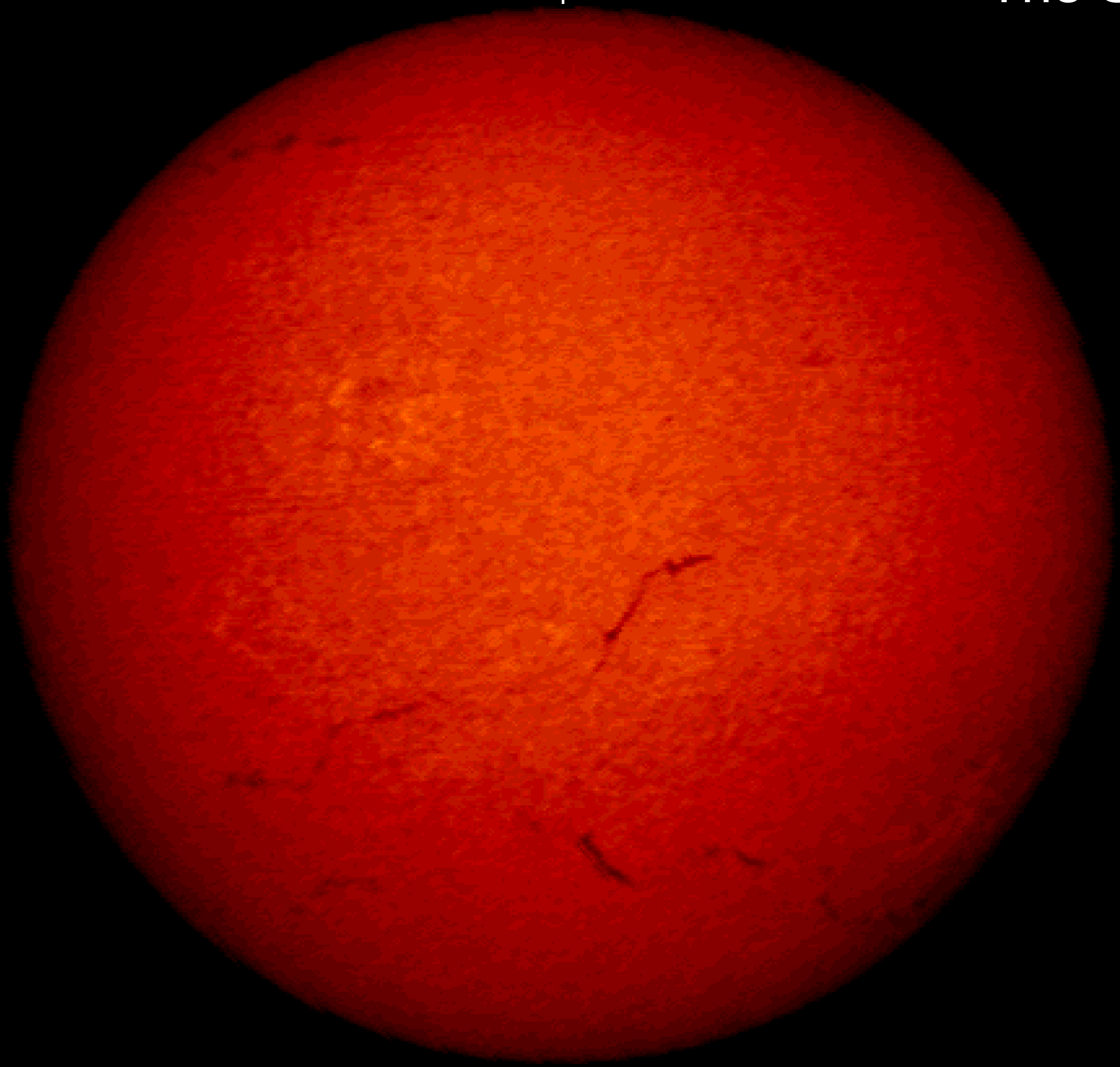
1 m = 0.5 einstein

6×10^{24} kg, 4.6×10^{9} y

13,000 km
= 1.3×10^{7} m

2×10^{30} kg = 1 $M_{\odot}$, 5×10^{9} y

The Sun, a typical star



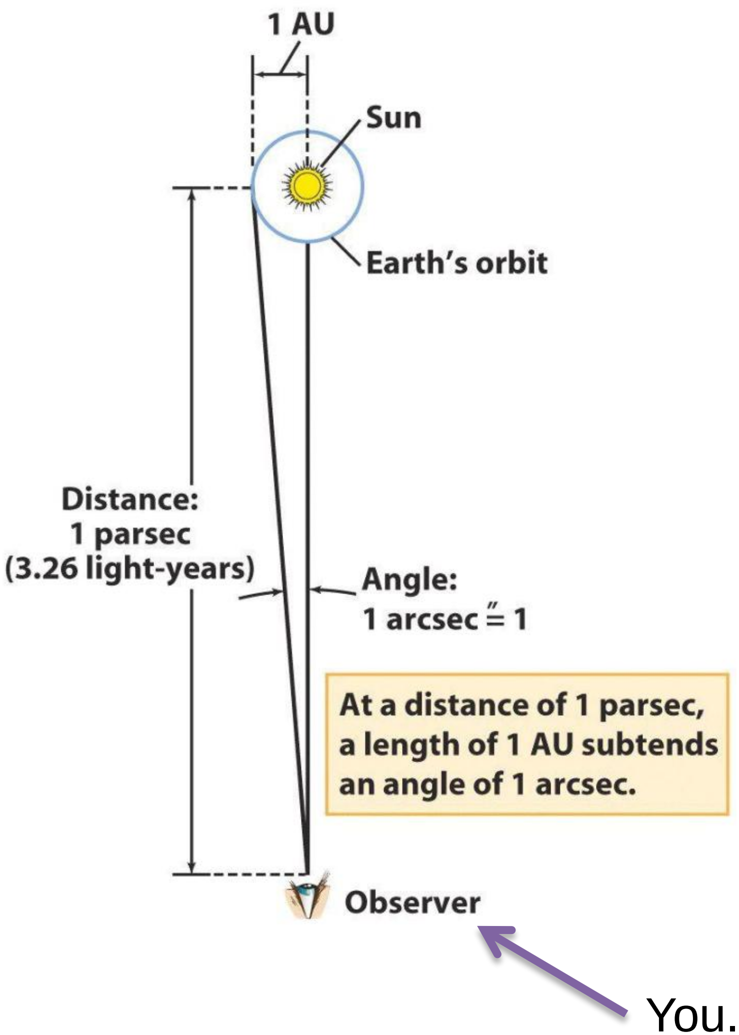
1,400,000 km
= 1.4×10^{9} m

Earth-Sun distance = 1 AU = 1.5 X 10^{11} m = 500 s (since speed of light is 3 X 10^{8} m/s)   AU is typical Solar System length scale

Nearest star, Proxima Centauri, is 4 X 10^{16} m = 4 y

= 2 X 10^{5} AU = 1 pc away

pc is typical galactic length scale



Earth-Moon distance = 4 X 10^{8} m = 1 s

(farthest humans have been!)

Sun-Pluto* distance = 40 AU = 6 X 10^{12} m = 6 h

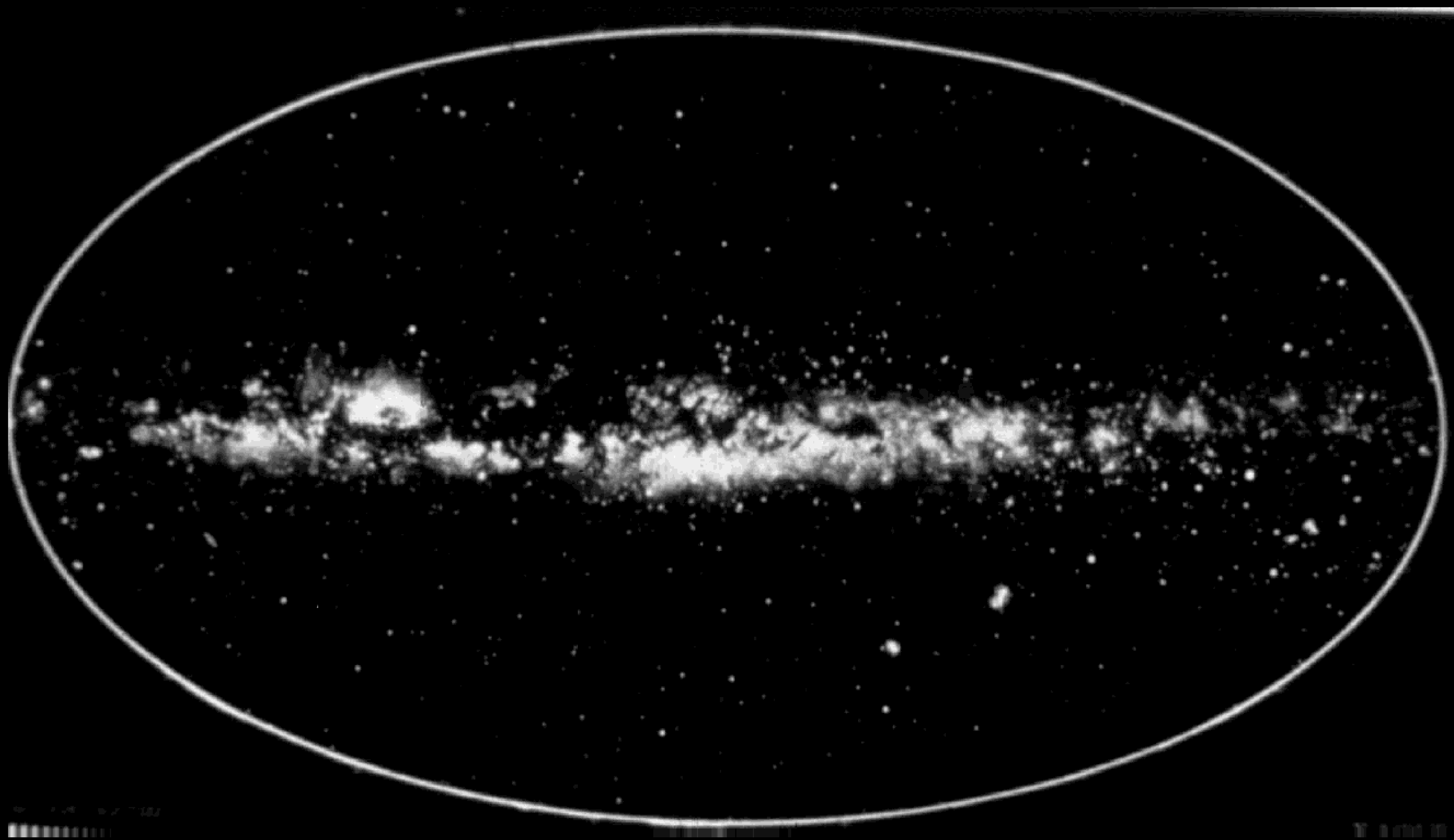
(size of Solar System)

Voyager I is 140 AU = 2.1 X 10^{13} m = 19 h 20 m

= 7 X 10^{-4} pc away from Sun, in 40 y

(farthest we have sent anything!)

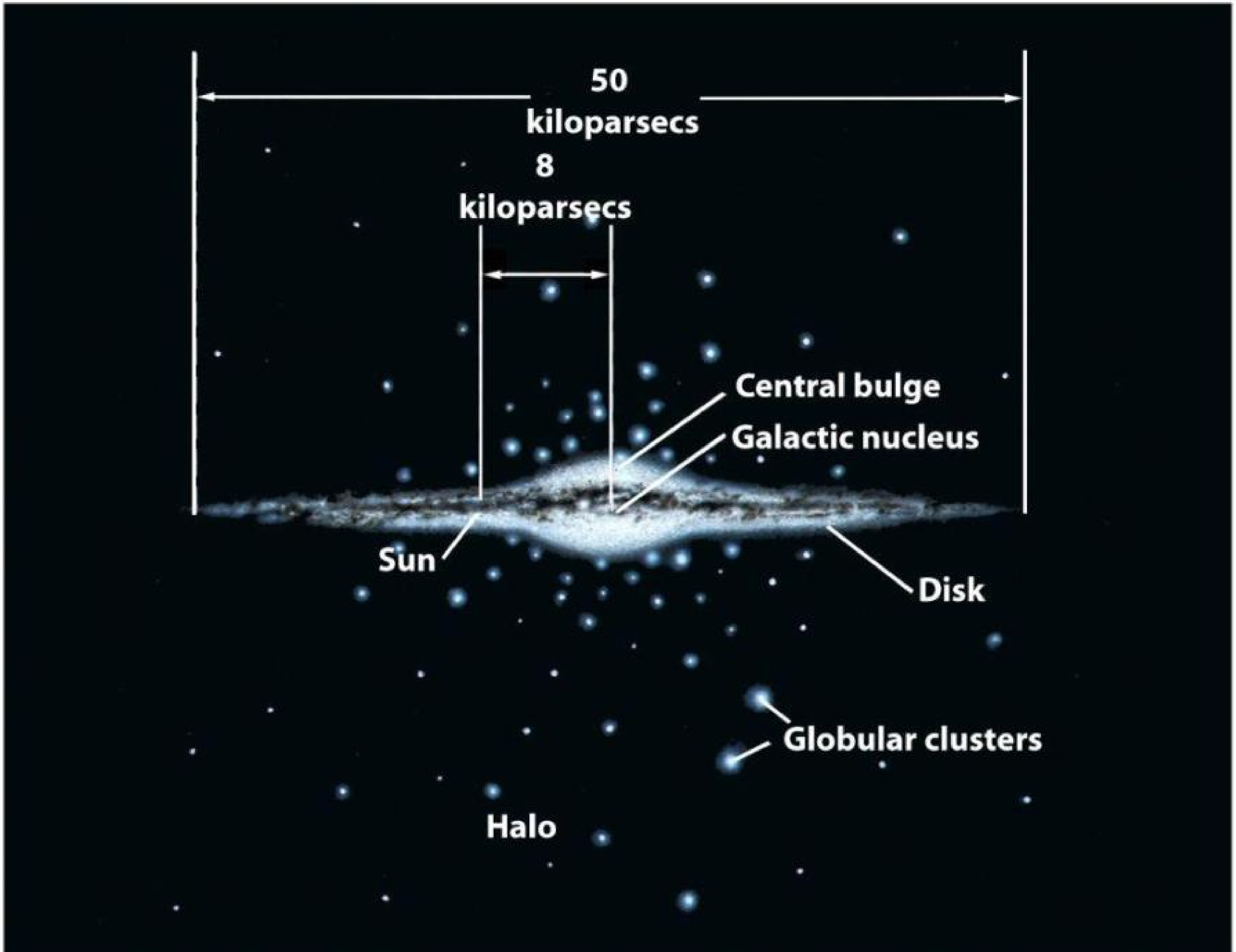
*Following his discovery of Pluto, Tombaugh earned bachelor's and master's degrees in astronomy from the University of Kansas ….. (Wikipedia).



2×10^{21} m = 50 kpc

Our Milky Way Galaxy, a few hundred billion stars…

4×10^{41} kg = $2 \times 10^{11} M_{\odot}$, 10^{10} y


50
kiloparsecs
8
kiloparsecs
Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo

There are a few different galaxy types, with a range of masses and sizes.

Nearest big galaxy, Andromeda, 2×10^{22} m = 2×10^{6} y = 700 kpc away

Some galaxies cluster. Center of nearby Virgo cluster. About16 Mpc = 7 X 10^{23} m away.
Possibly as many as 2000 galaxies. A few Mpc or a few X 10^{23} m across.

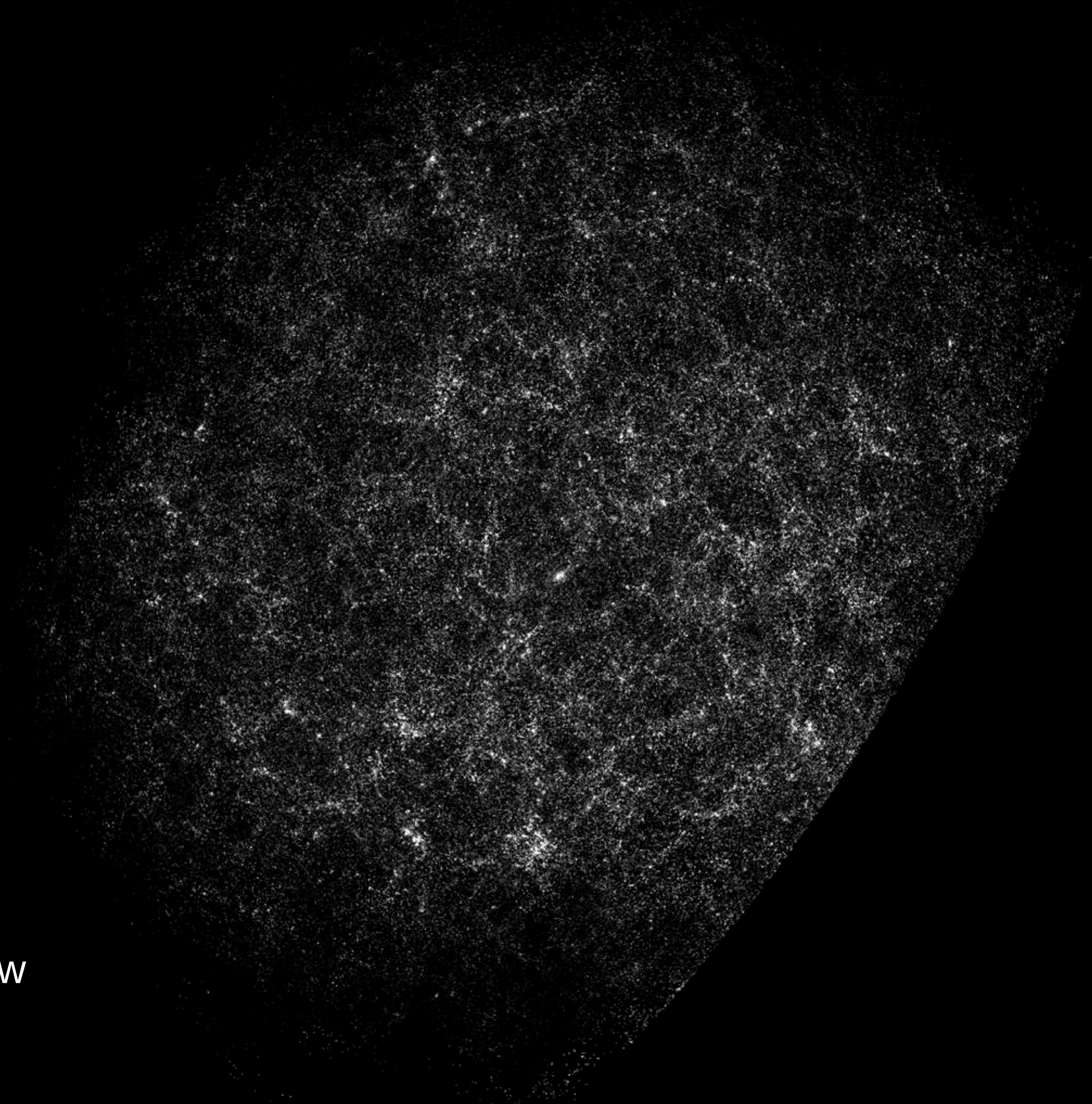
Largest and heaviest gravitationally bound systems. 10^{44} kg = 10^{14} $M_{\odot}$, >10^{10} y

Lick Observatory
(Shane & Wirtanen)
optical galaxy counts.

400,000 galaxies,
centered at the North
Galactic Pole.

300 Mpc or 10^{25} m across.

Map is by Seldner et al.

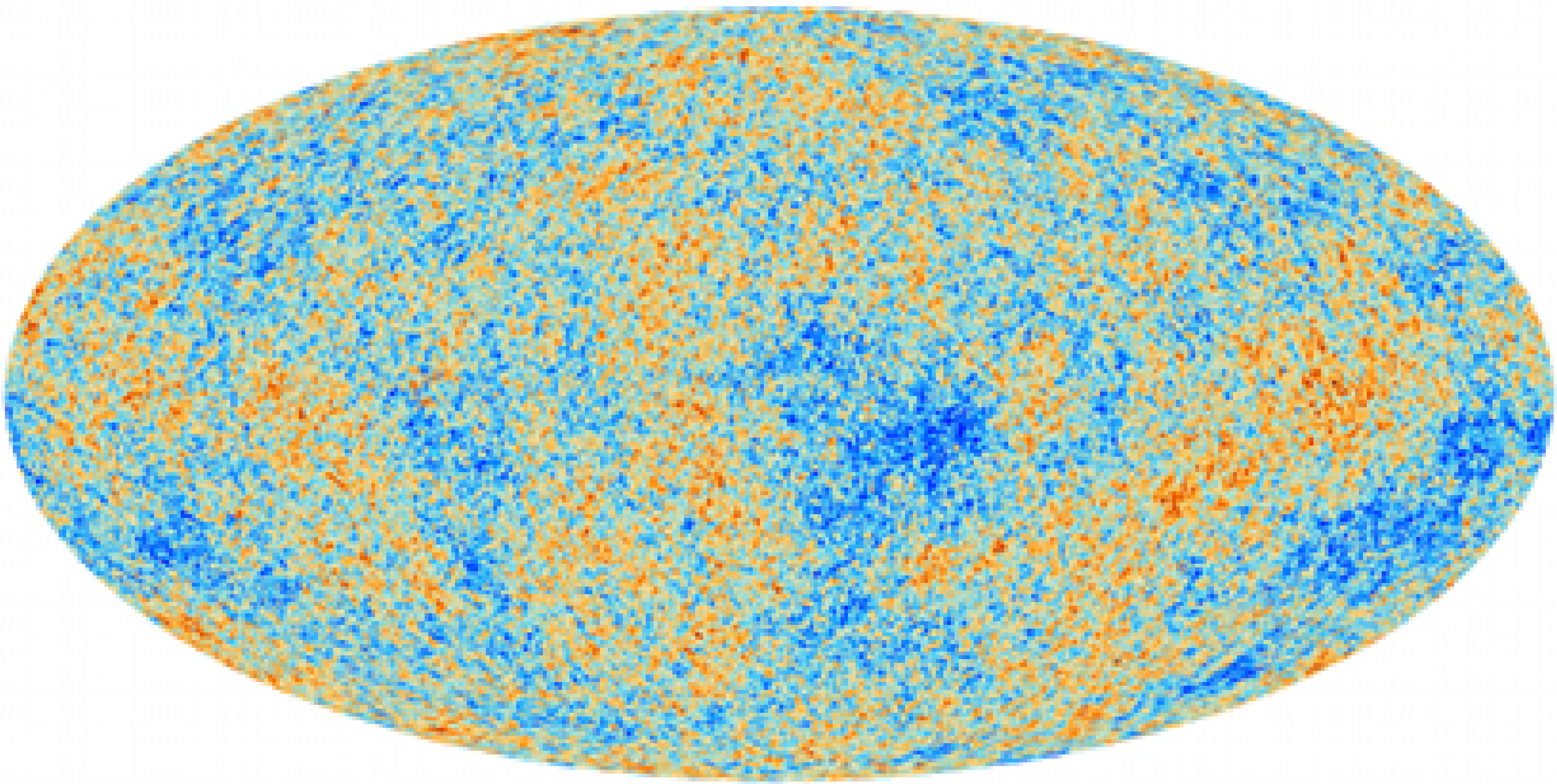


The observable Universe
is a few Gpc or 10^{26} m
across.

10^{52} kg = 10^{22} $M_{\odot}$ = a few
X 10^{11} galaxies,

>10^{10} y

Planck cosmic microwave background radiation anisotropy.



The Universe is isotropic to 0.001% or so on scales of 4000-5000 Mpc.

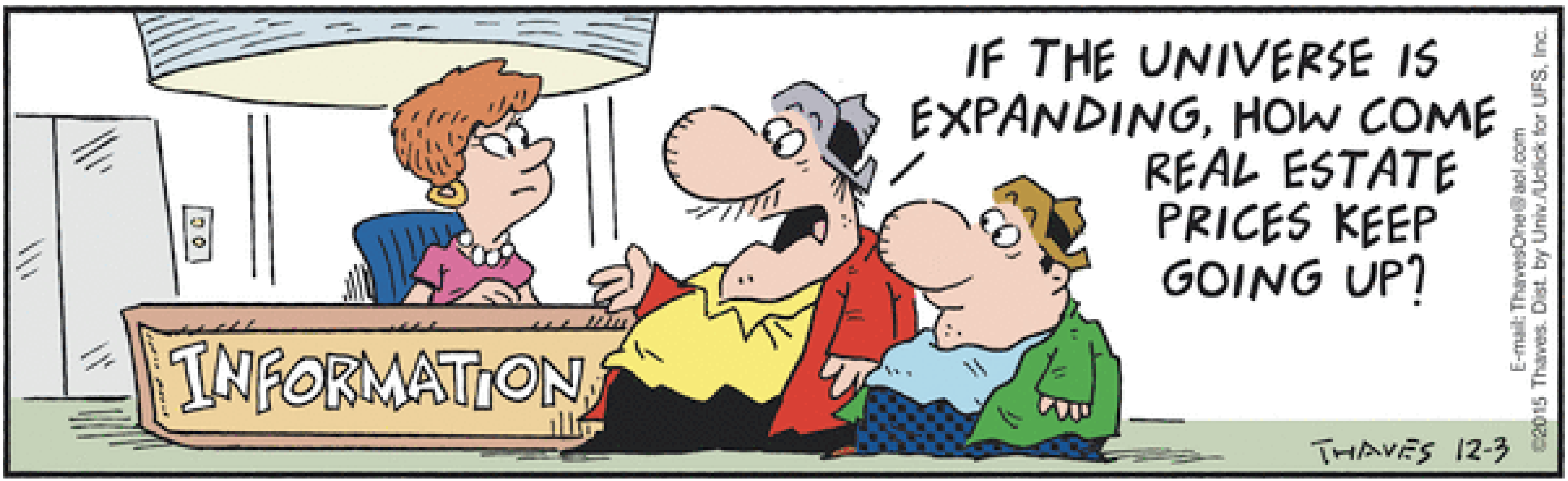
Two important facts:

Local distribution of matter and radiation is spatially anisotropic.

Averaged large-scale distribution of matter and radiation is (statistically) spatially isotropic.

How did these come about?

Fact: The universe expands.

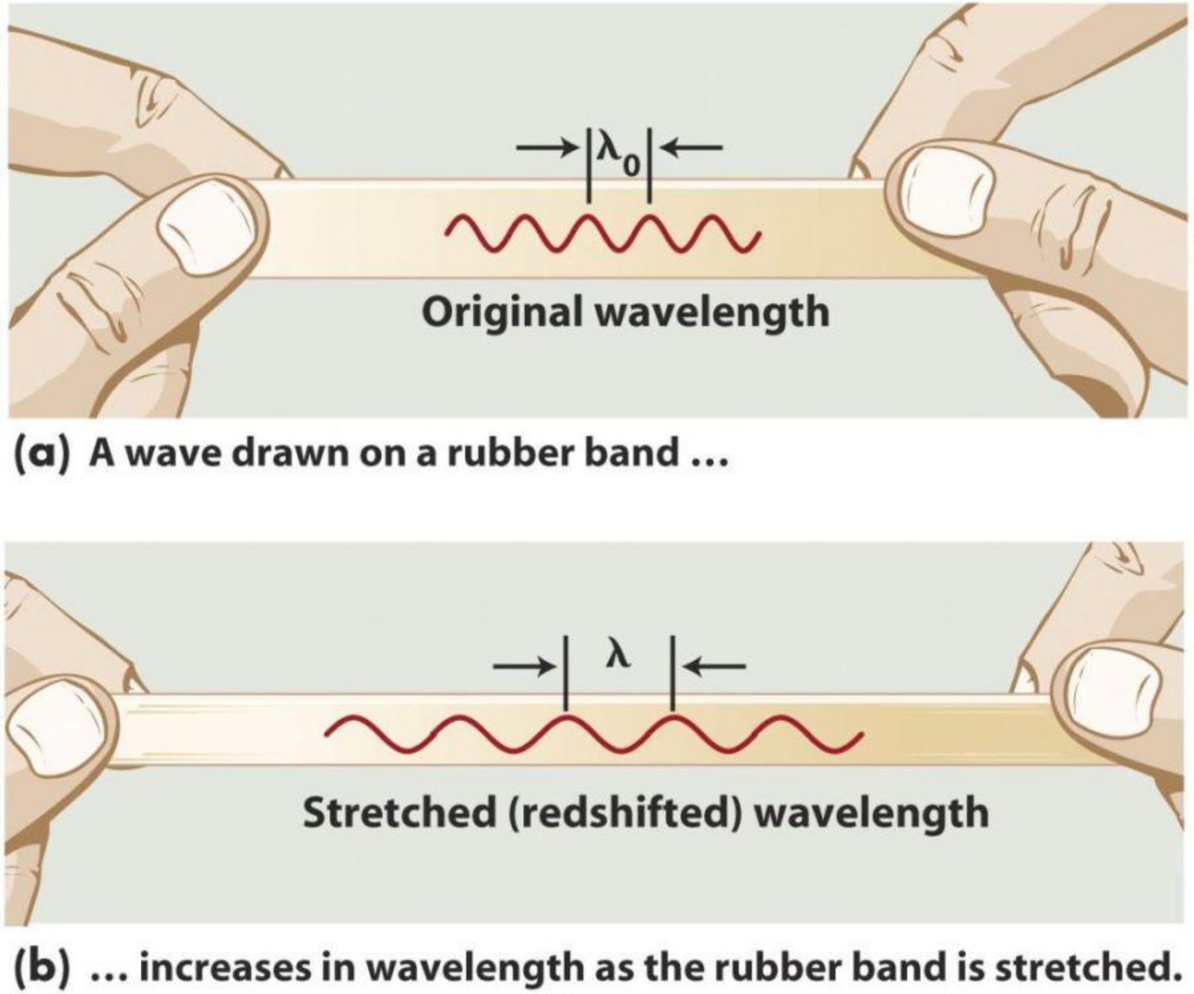


Fact: The universe expands.

Consider a wave propagating in a one-dimensional expanding universe. For adiabatic expansion the wavelength must expand with scale factor, $\lambda \sim a(t)$ (redshifting) .

Redshift z:

$1 + z = a_{now}/a(t)$.

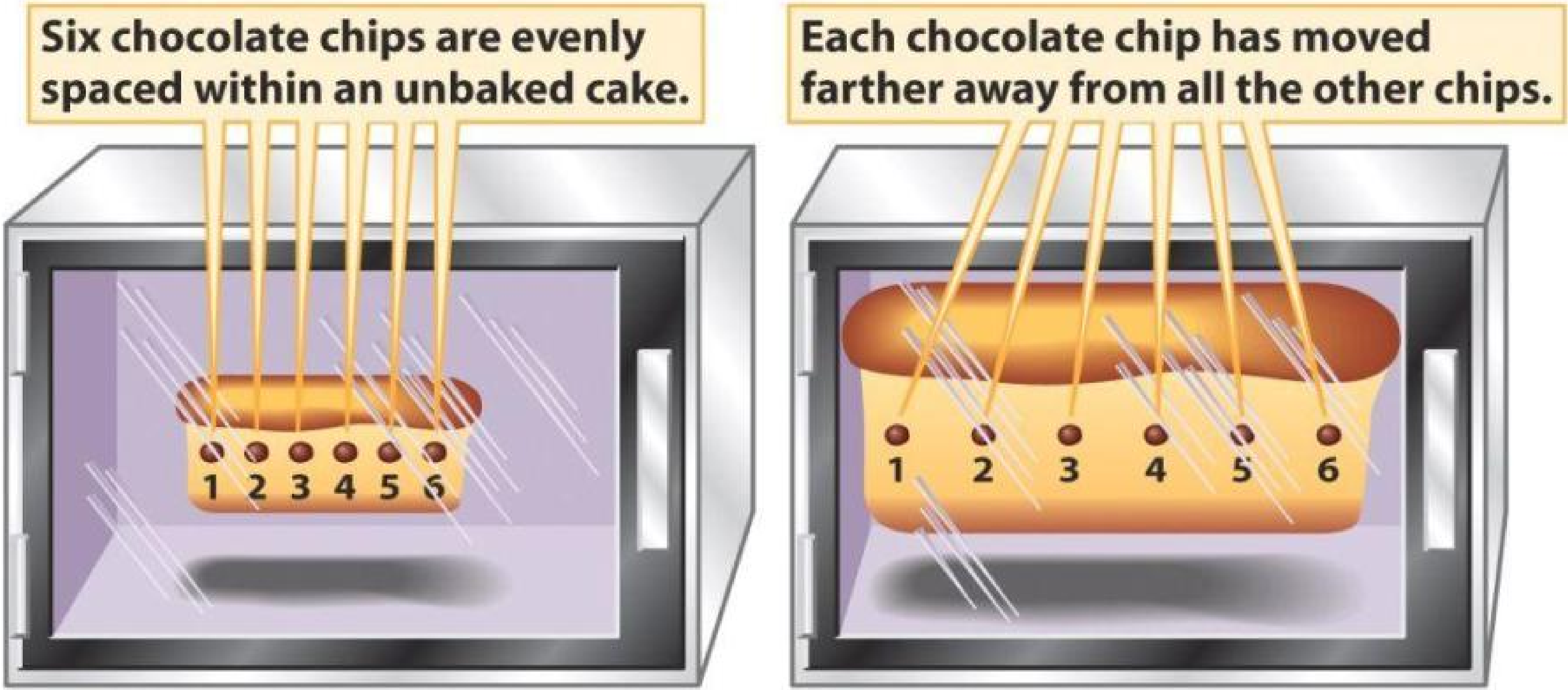


There is no preferred center. Galaxies separate and the light from them redshifts.

Slipher* discovered the redshifting in 1912.

*Indirectly motivated by the idea of a Martian civilization!

three-dimensional flat universe



Proper lengths and wavelengths expand in proportion to the scale factor a.
Proper volumes expand in proportion to a^3.

Uniform expansion: Increase in distance is proportional to the initial distance. This is just Hubble's Law.

Freedman and Kauffmann

Fact: farther apart the galaxies, the greater the redshift, and the faster the separation.

$$v = H_0\, r$$

v = recession speed of galaxy, r = distance to galaxy

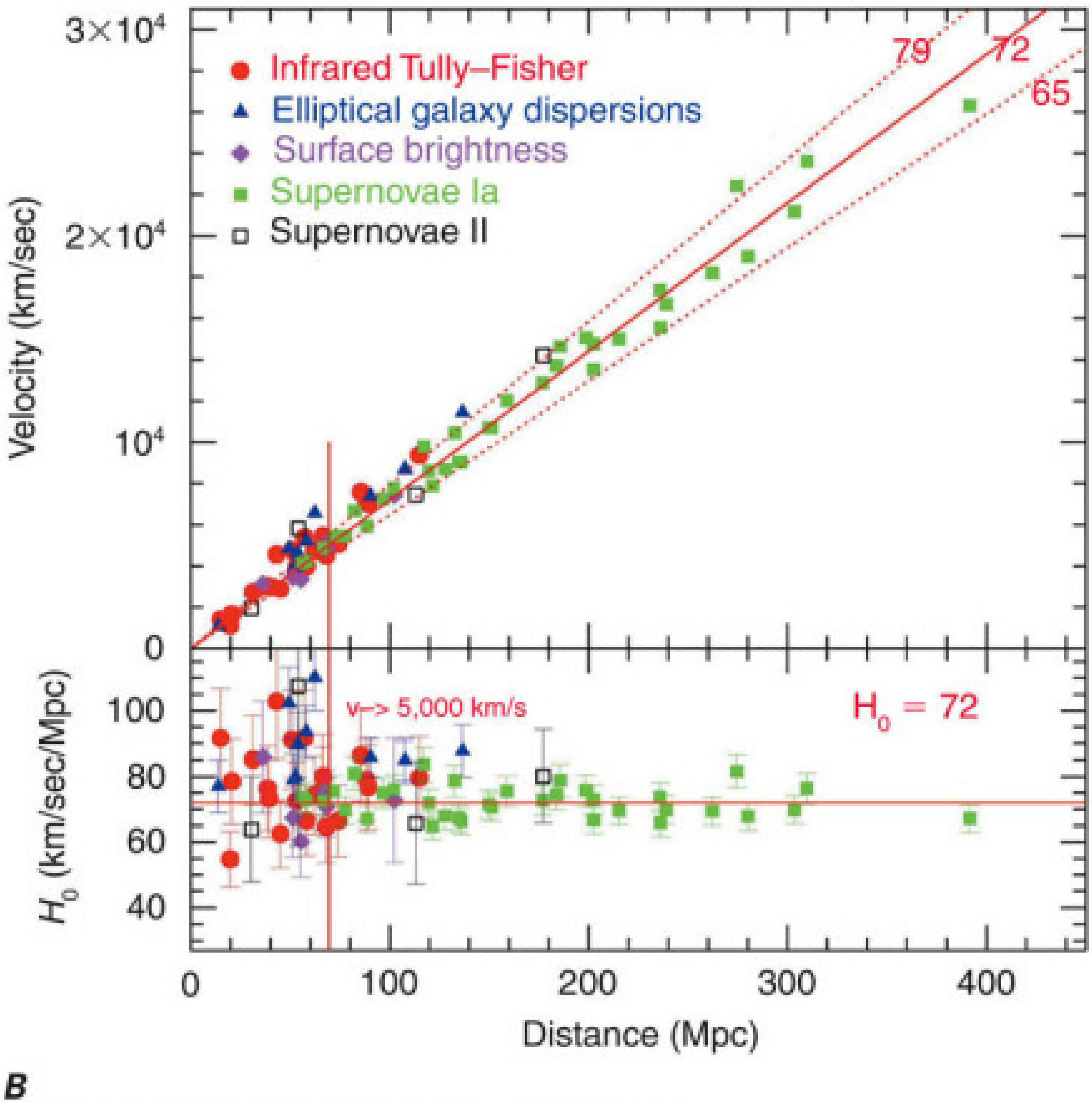
H_0 = Hubble constant = (68 ± 2.8) km s^{-1} Mpc^{-1}

= 100 h km s^{-1} Mpc^{-1} Chen & Ratra PASP123,1127 (2011)

This is the Hubble law (1929), discovered by Hubble & Humason*.

H_0 is the present value of the Hubble parameter.

*Middle school dropout and one time muleskinner and janitor.



(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

Hubble law

H_0 = Hubble constant
= (68 ± 2.8) km s^{-1} Mpc^{-1}
= 100 h km s^{-1} Mpc^{-1}

Chen & Ratra PASP123,1127 (2011)

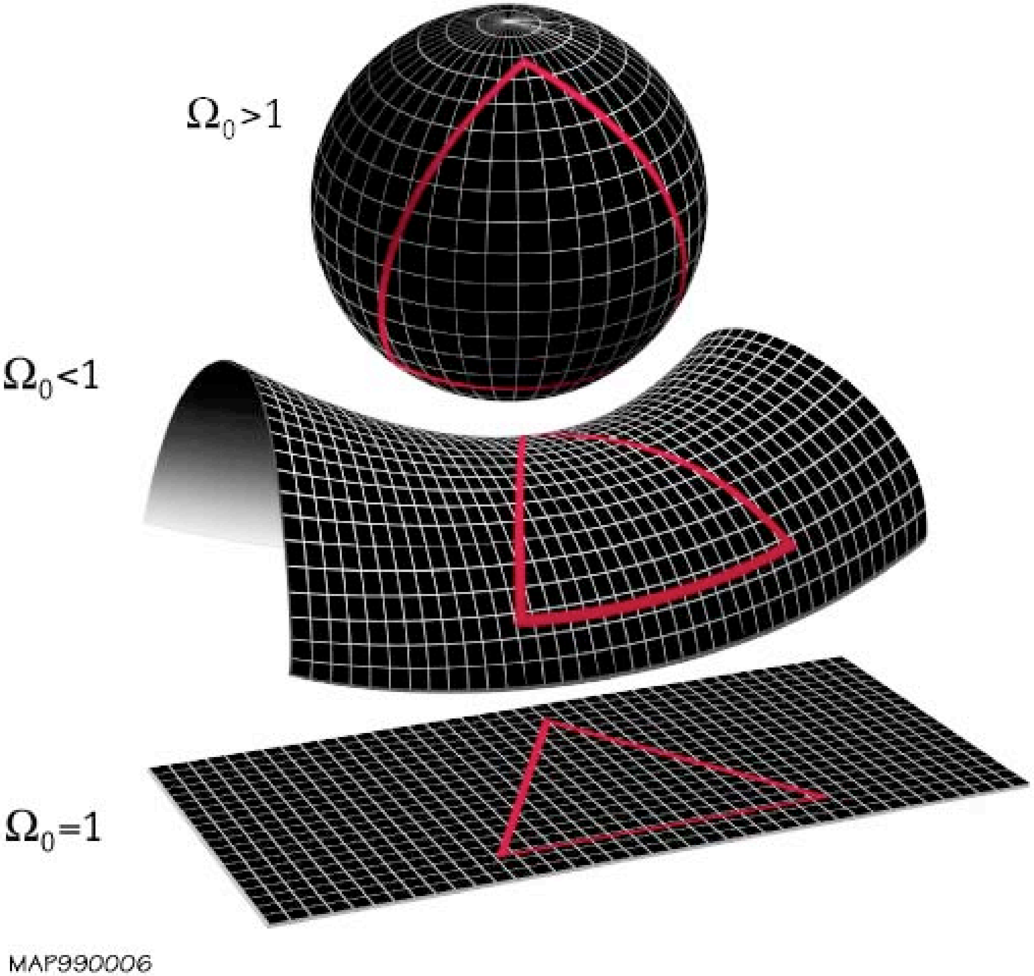
Most recent H_0 estimates agree with this 2011 measurement.

Cosmological Principle: the universe is (statistically) spatially isotropic for all cosmological observers.

This implies (statistical) spatial homogeneity.

There are then only three possible spatial geometries: the flat, open and closed Friedmann-Lemaitre-Robertson-Walker models.

(2 dimensional analogs)



	K^2
closed	>0
open	<0
flat	=0

Scale factor a(t) describes how the geometry expands with time.

Einstein's general relativity equations of motion say scale factor a(t) evolution is powered by mass-energy density ρ

(digression for those who know some calculus)

$H(t) = \dot{a}/a$ is the expansion rate

Is this increasing or decreasing with time?

also, $\ddot{a}/a = -(4\pi G/3)(\rho + 3p)$ (ρ includes Λ or add +Λ/3)

matter and radiation with pressure $p > 0$

=> $\ddot{a} < 0$ decelerated expansion

Einstein-de Sitter (simplest cosmological model) mass density

$\rho_c = 3H^2/8\pi G = 1.9 \times 10^{-29}\ h^2\ \mathrm{g\ cm^{-3}}$

Density parameter $\Omega = \rho/\rho_c$

Einstein-de Sitter model has $\Omega = 1$

Main contributors to the present cosmological energy budget :

about 5% baryonic matter (mostly atoms in gas clouds, stars, planets, dust , …), first clearly measured in the 1960's (Gamow, Alpher, Herman, Penzias & Wilson, Dicke et al.)

about 20% non-baryonic non-relativistic cold dark matter (probably a WIMP), first seen in the 1930's (Zwicky, Smith, Babcock,…) and first clearly measured in the 1970's (Rubin & Ford, Ostriker & Peebles, Einasto et al., Ostriker et al.)

about 70% non-baryonic relativistic dark energy (not clear what this is), first real suggestion in the 1980's (Peebles, Peebles & Ratra) and first clearly measured in the 1990's (Riess et al., Perlmutter et al.)

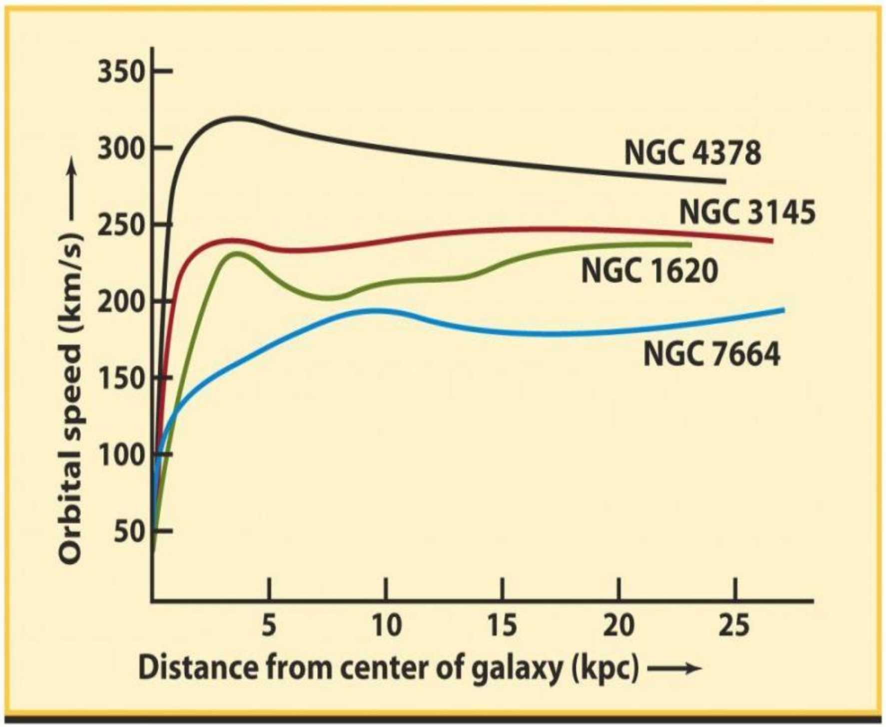
We do not understand 95% of the current cosmological energy budget, but we do have a "standard" model of cosmology!

Contents of the universe

Optically visible, luminous matter $\Omega_{lum} \leq 0.005$ (stars)

Force balance (mass from dynamics) $v^2(r) = GM(r)/r$;

on large scales where there is no optical light use 21cm hydrogen radiation: $0.20 \leq \Omega_{dyn} \leq 0.35$ (2σ)



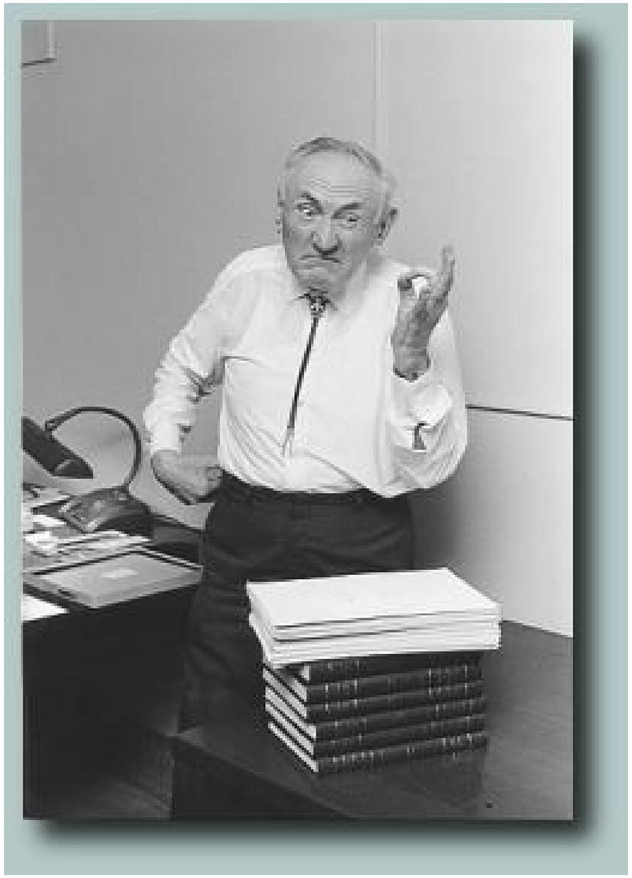
(on few kpc to 10's of Mpc)

Dark matter! Pressureless like luminous matter, so $\rho_{dyn} = M/V \sim 1/a^3$ which decreases with time.

ρ_{dyn} = few X 10^{-30} g cm^{-3}

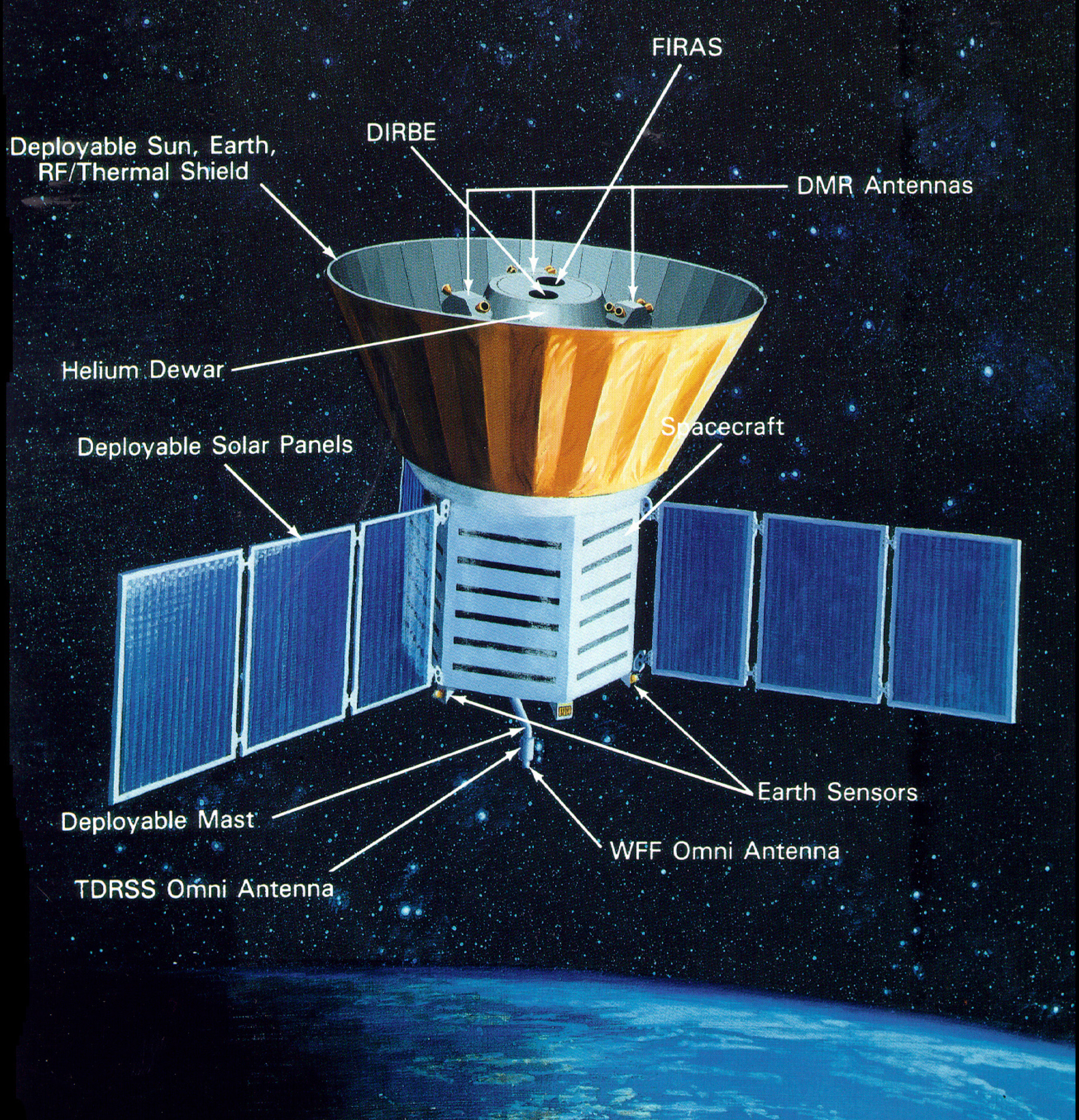
The universe was denser at earlier times.

Zwicky in the 1930’s determined that the “large” velocities of galaxies in the Coma cluster required a “large” Coma gravitational field, significantly larger than could be produced by the material that was shining in the Coma cluster.

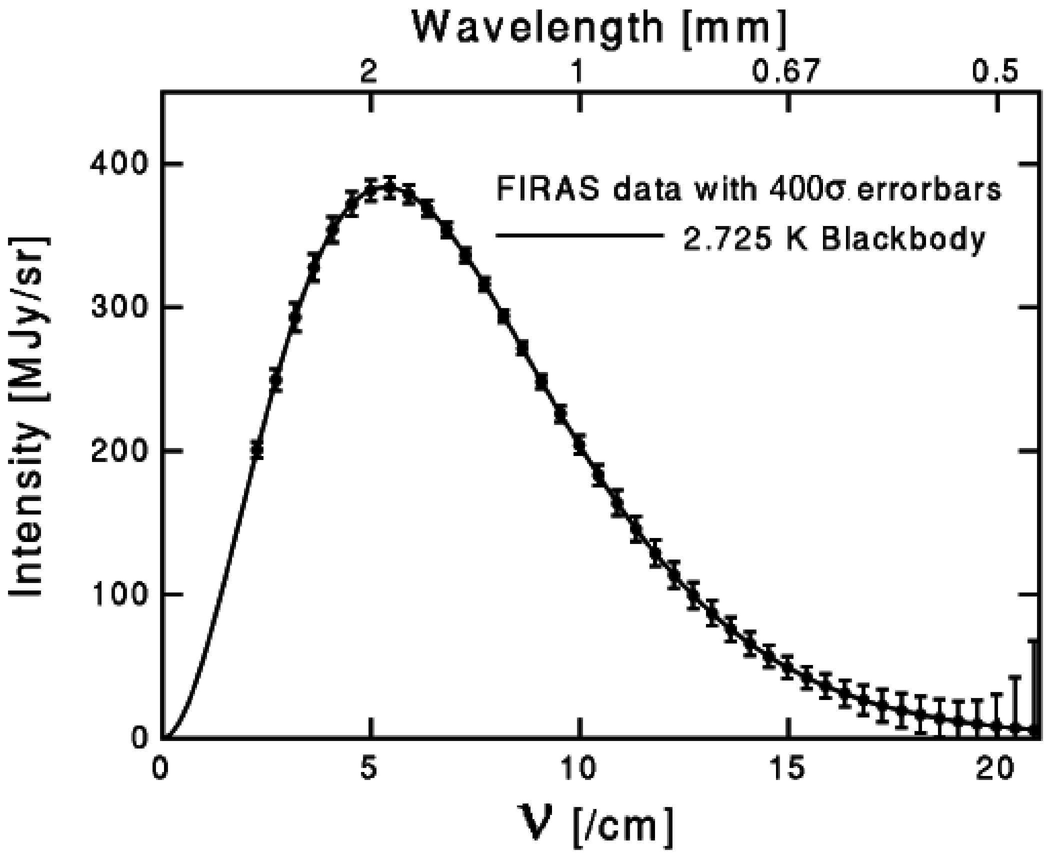


Dark matter!

COBE


FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

Cosmic microwave black-body radiation background



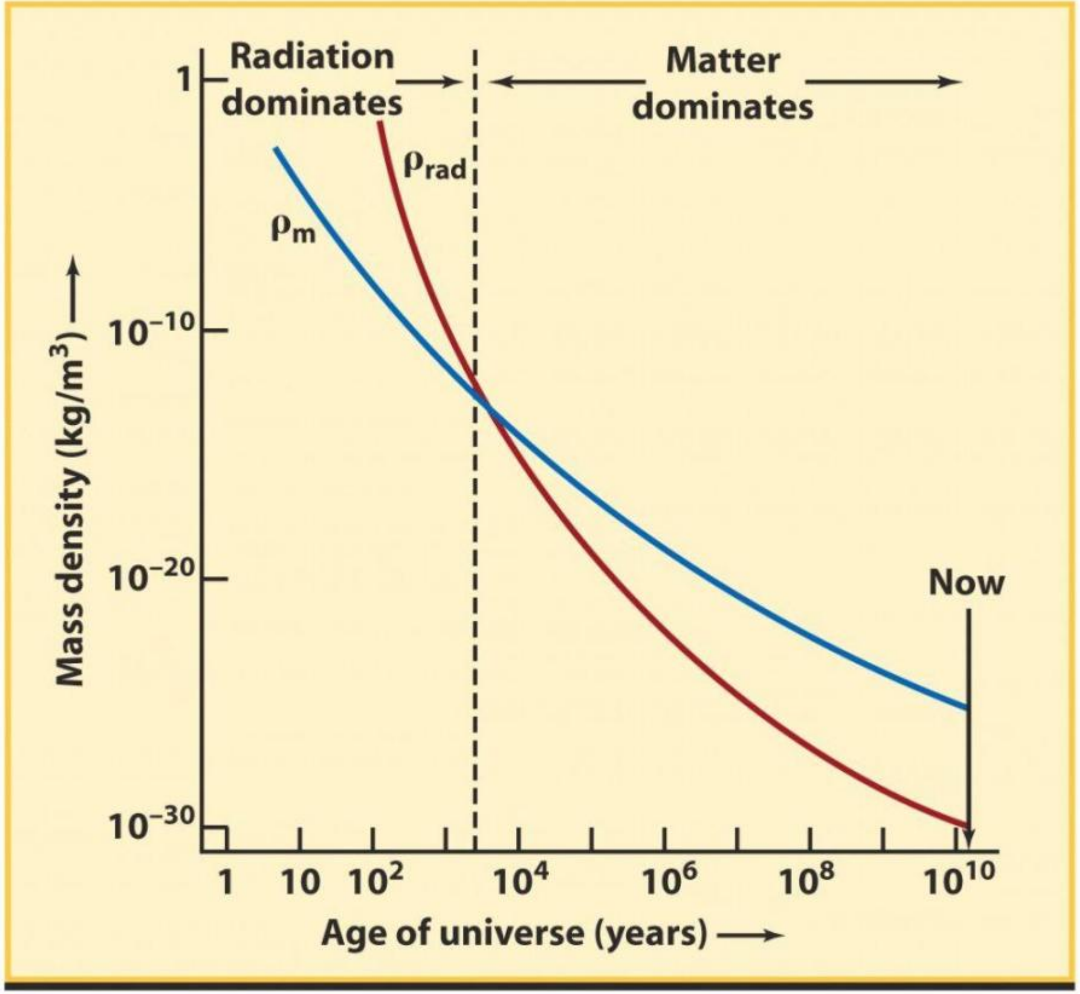
$\Omega_{rad} \sim 0.00005$

$\rho_{rad} = a_{SB} T^4 = 4.7 \times 10^{-34}$ g cm^{-3} $\ll \rho_{dyn}$. $k_B T = hc/\lambda \sim 1/a$

$\Rightarrow \rho_{rad} \sim (E/c^2)/V \sim 1/a^4$ which decreases faster than ρ_{dyn}

The universe was hotter at earlier times.

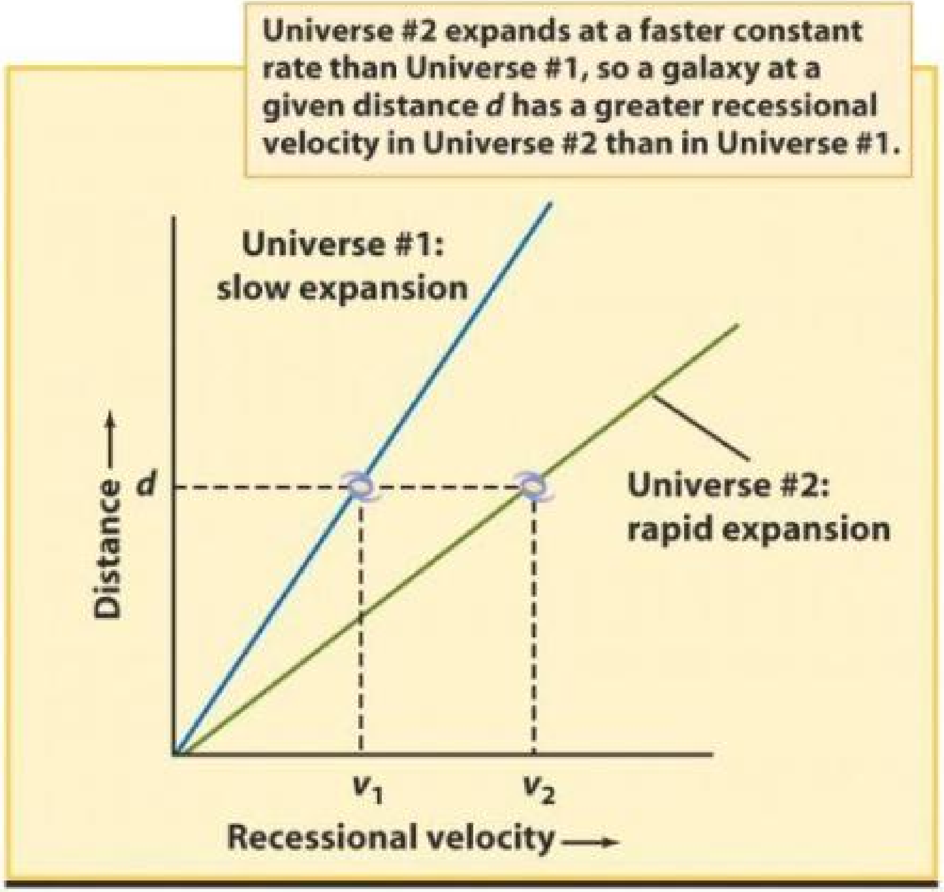
Ignoring dark energy for now, at earlier times radiation dominated and the universe was hot.

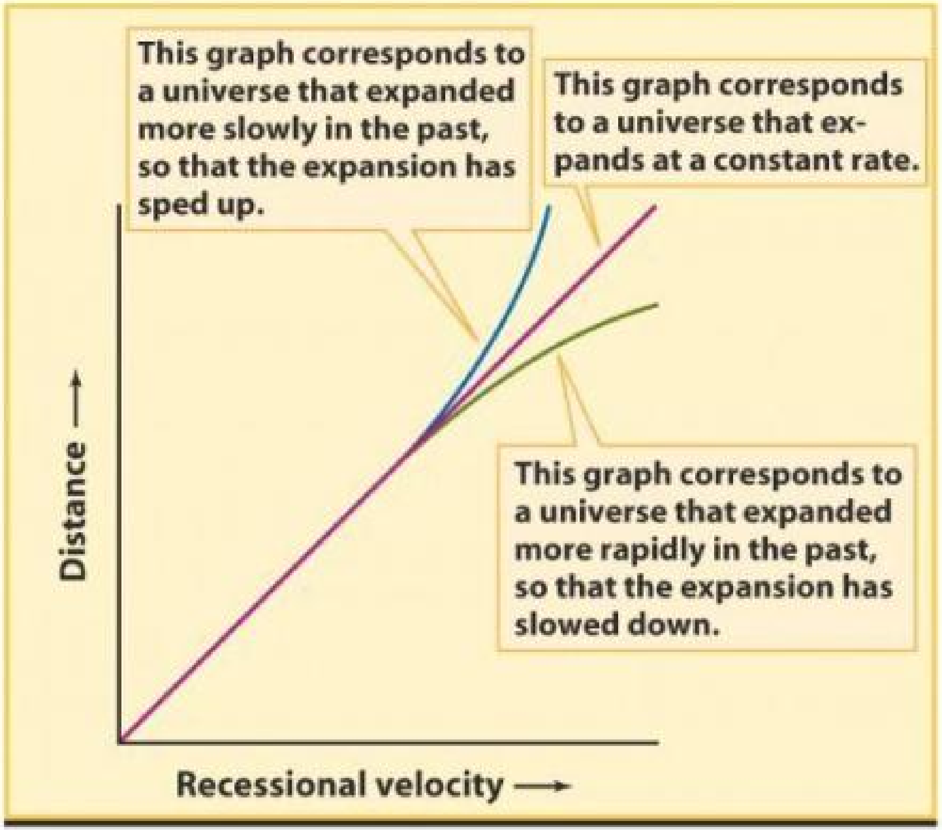


Freedman and Kaufmann

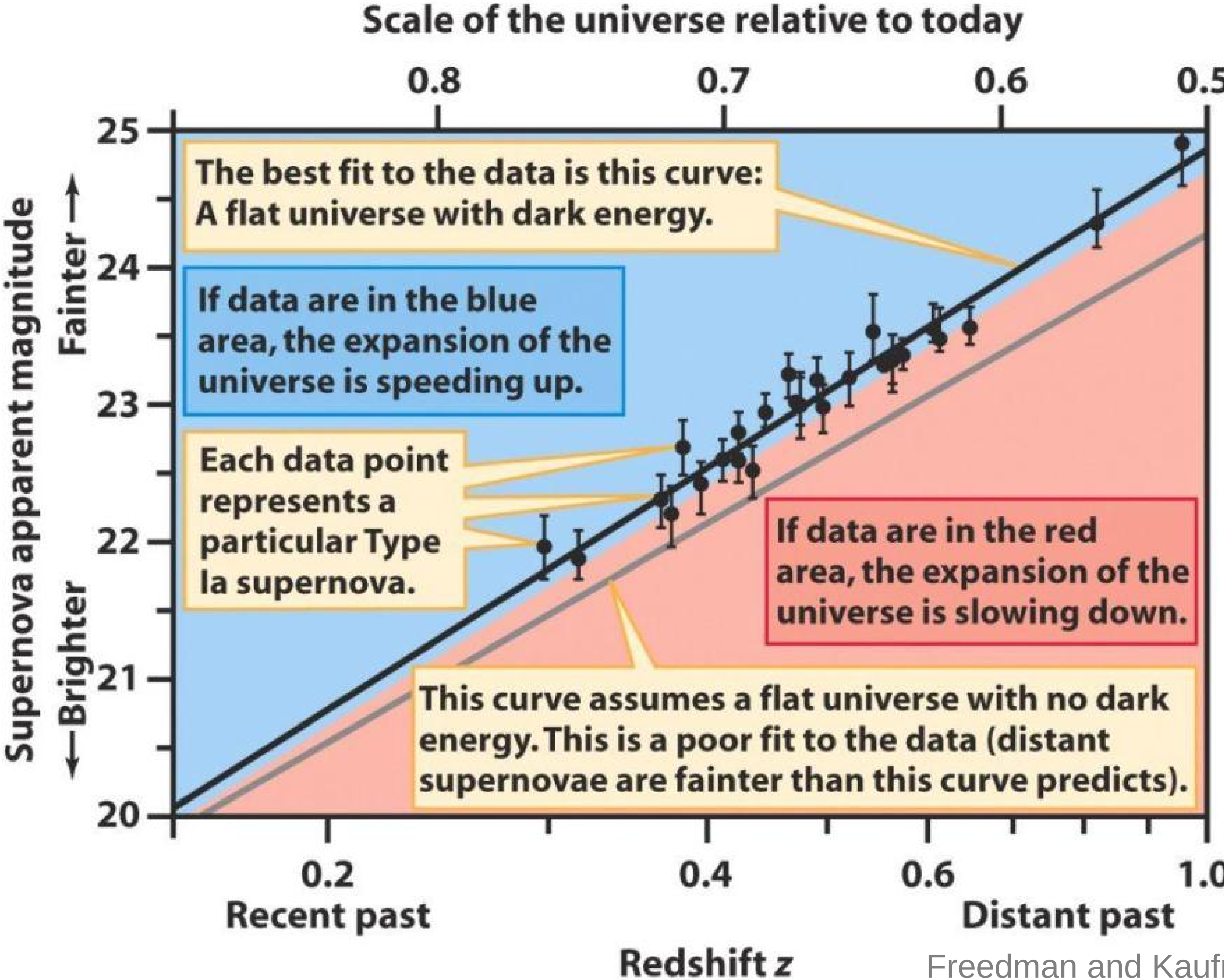
Dark Energy

The general idea (more correctly discussed in terms of the m-z diagram).

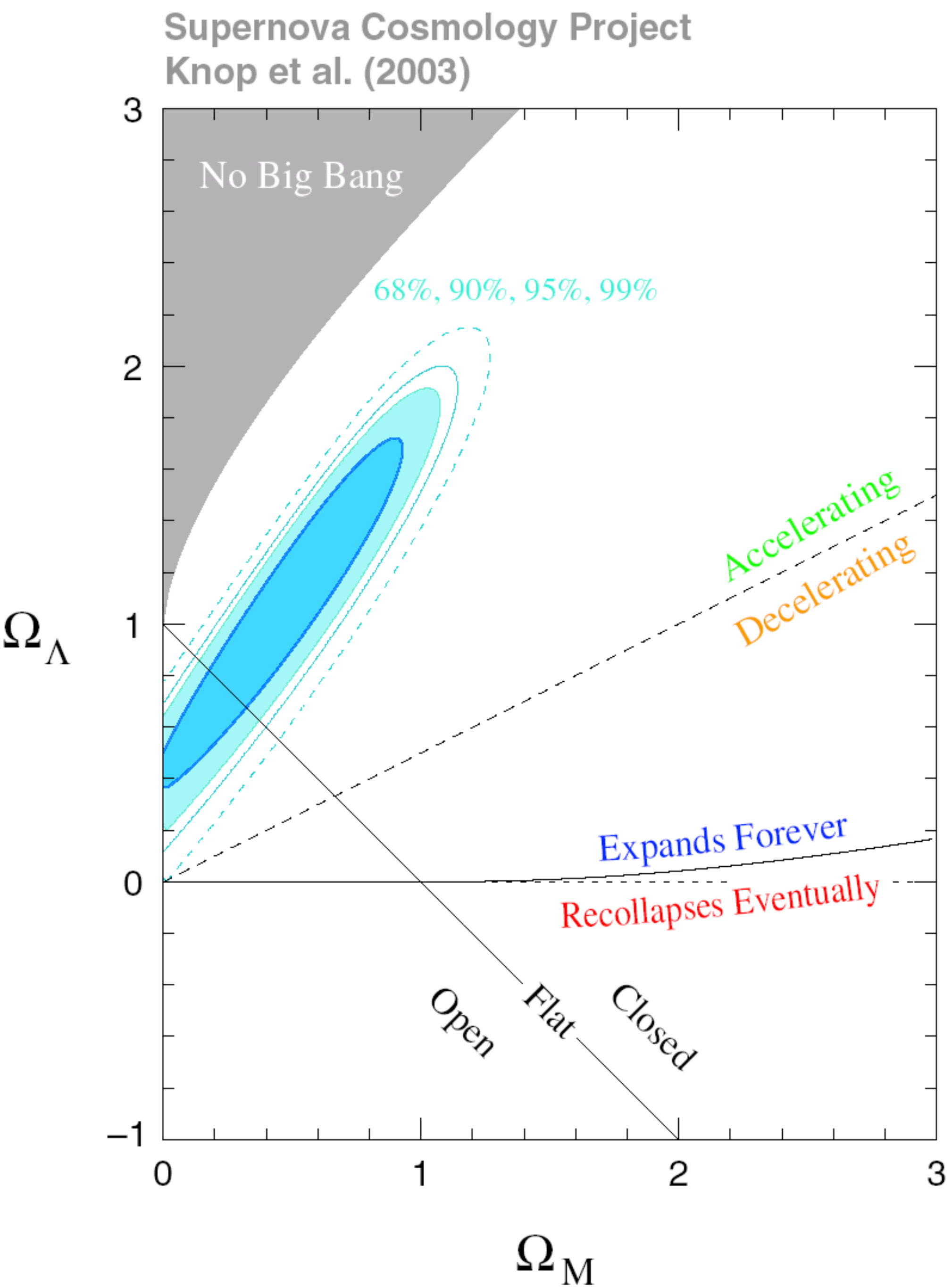




Freedman and Kaufmann



Freedman and Kaufman



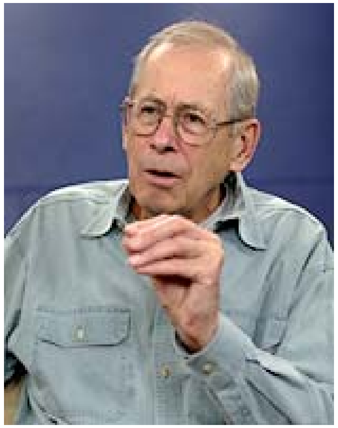
accelerated expansion

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

$p \leq -\rho/3$

dark energy

behaves like negative pressure



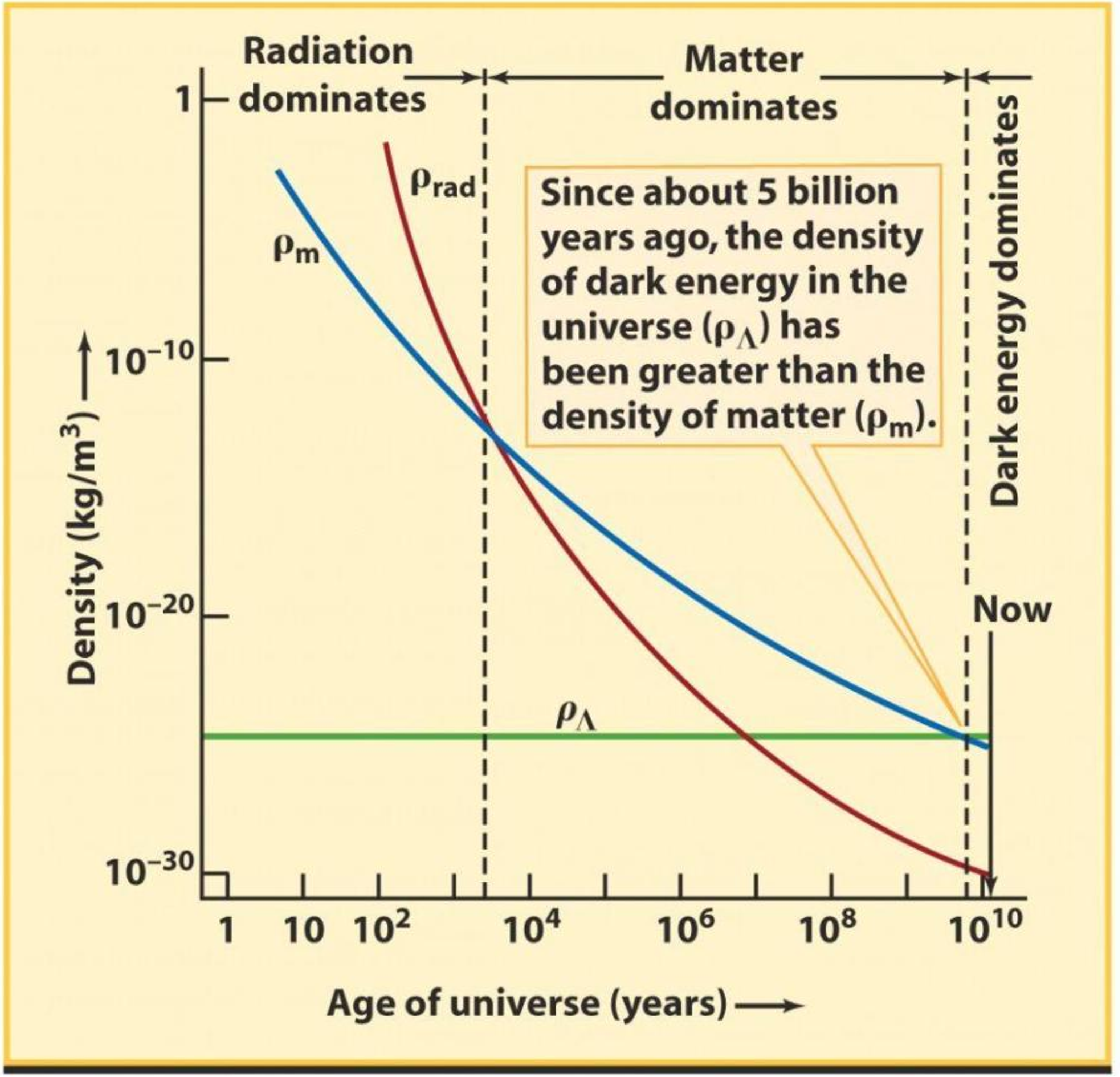
Peebles

Flat ΛCDM

In this simple model, dark energy will soon be completely dominant.

It's not dark yet, but it's getting there.

Bob Dylan

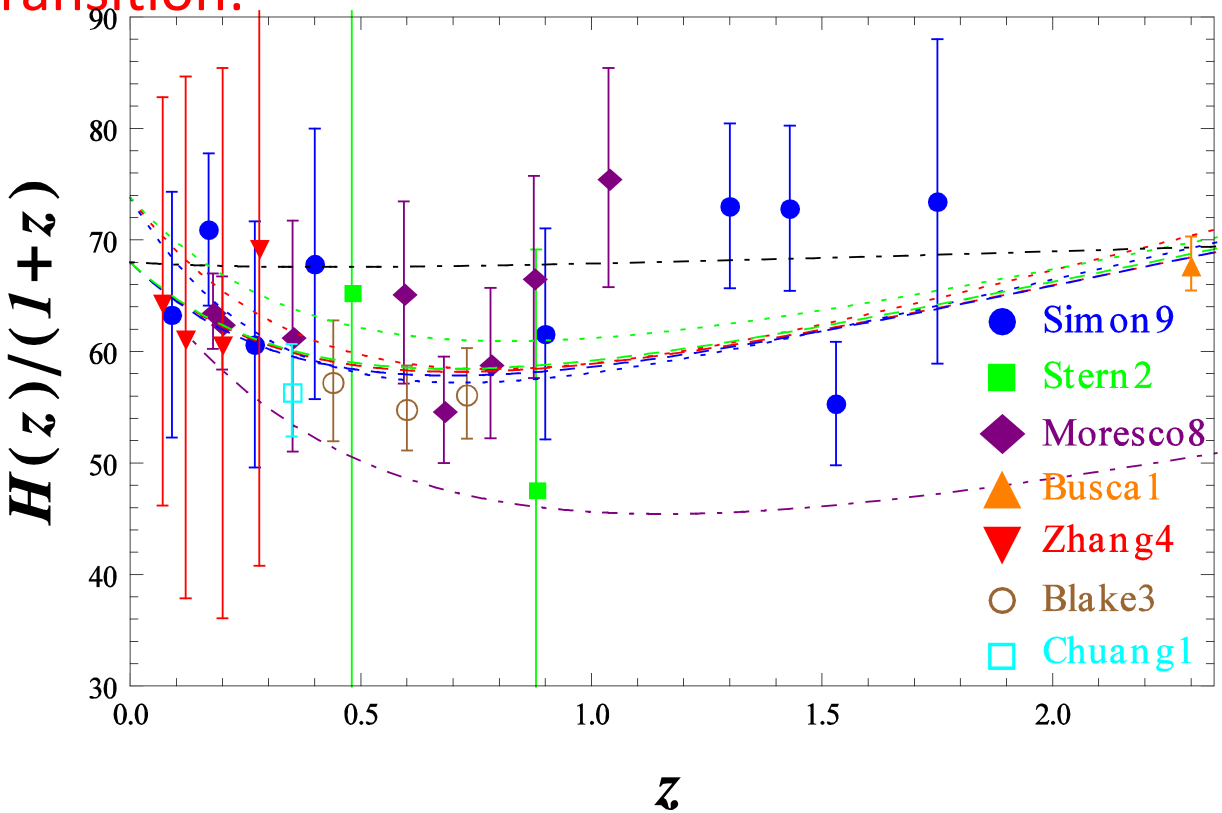


Freedman and Kaufmann

H(z) data & deceleration-acceleration transition

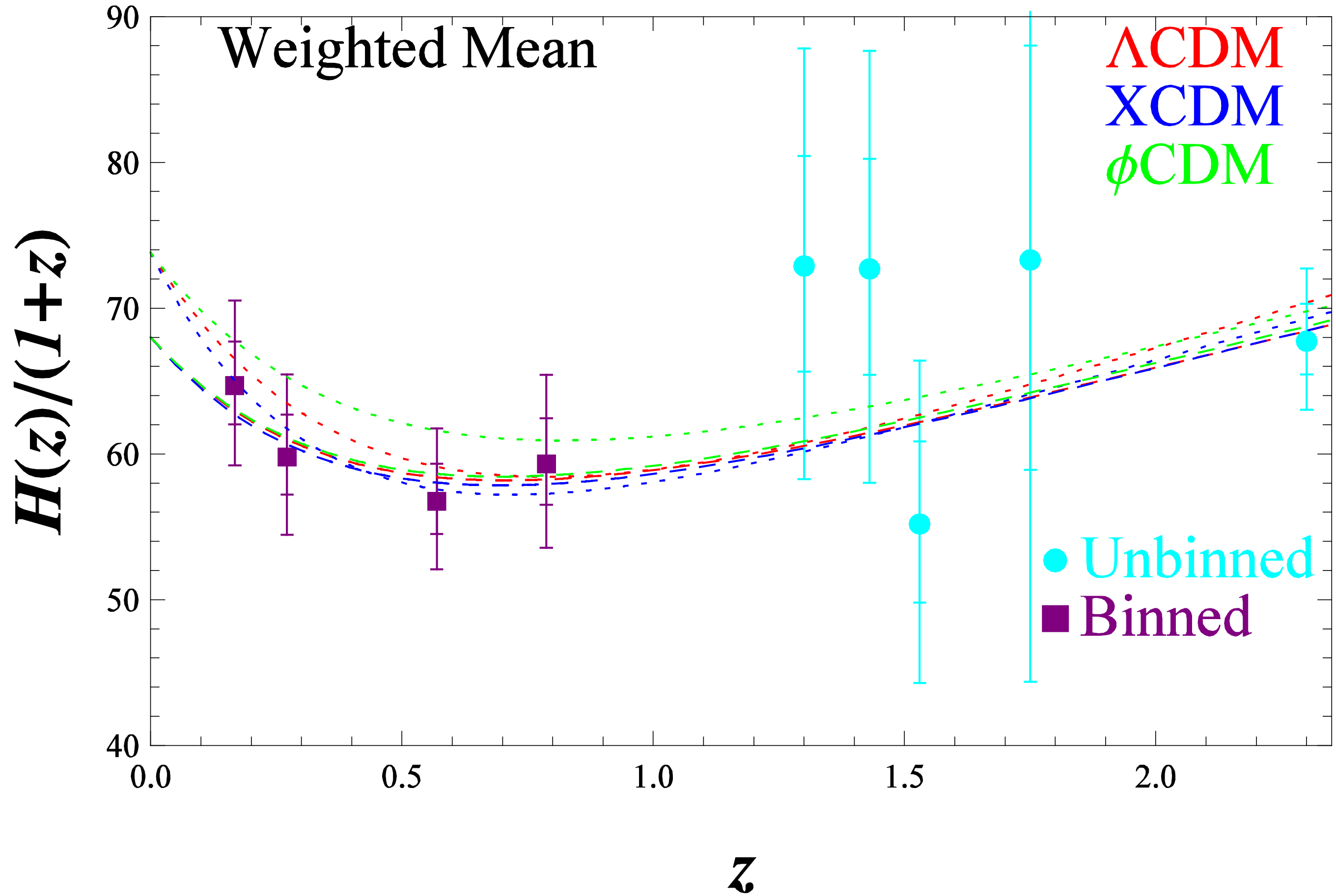
It is now possible to measure H(z) by using cosmic chronometers or radial BAO data (e.g., Moresco JCAP1208, 006; Busca A&A552, A96 (2013))

Combining 28 independent measurements over 0.07 < z < 2.3 (Farooq & BR ApJ766, L7 (2013); Farooq , Crandall & BR PLB726, 72 (2013)) shows a transition:



Six best-fit models and two 3σ deviant models

Data are noisy, so lets bin them

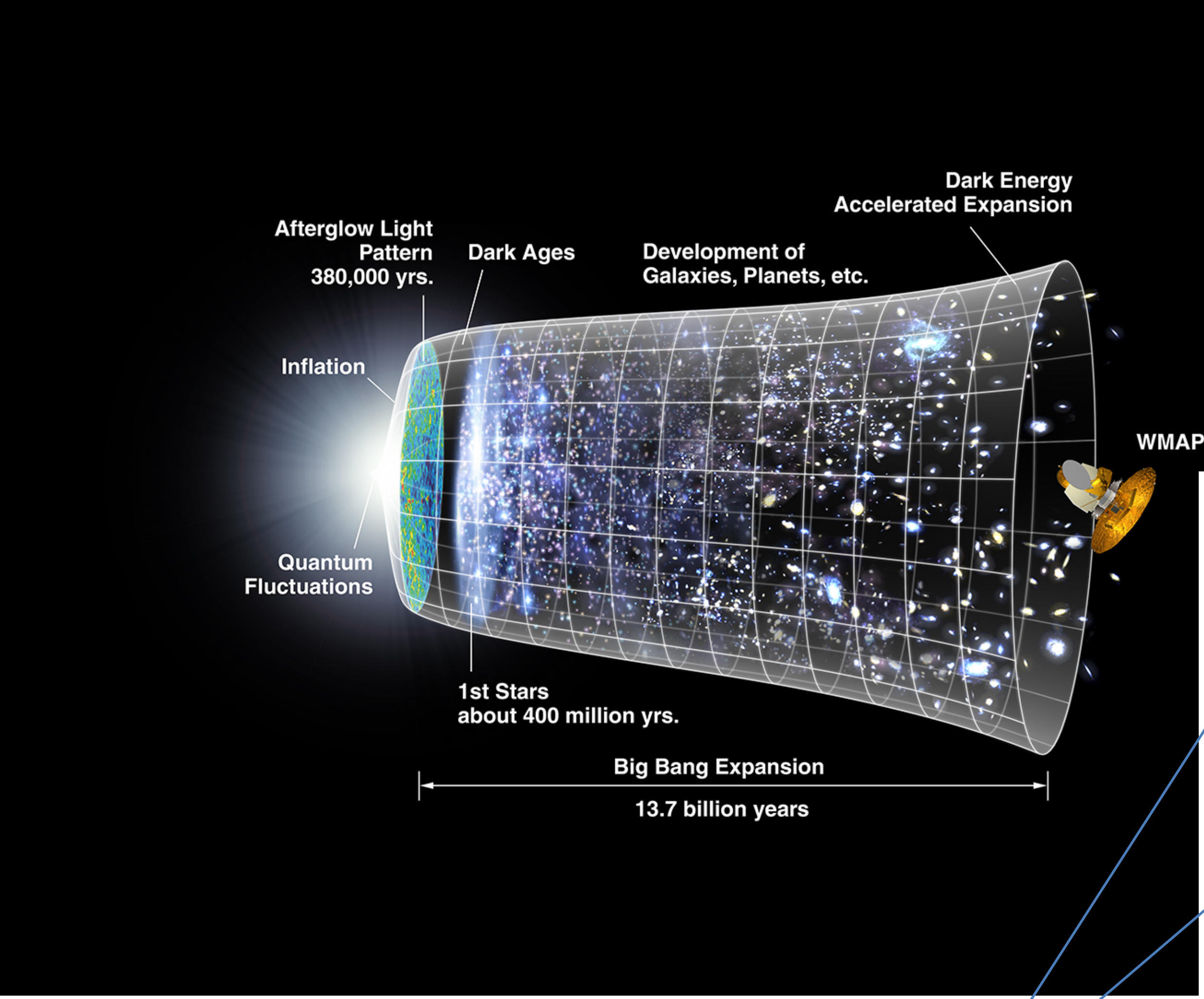


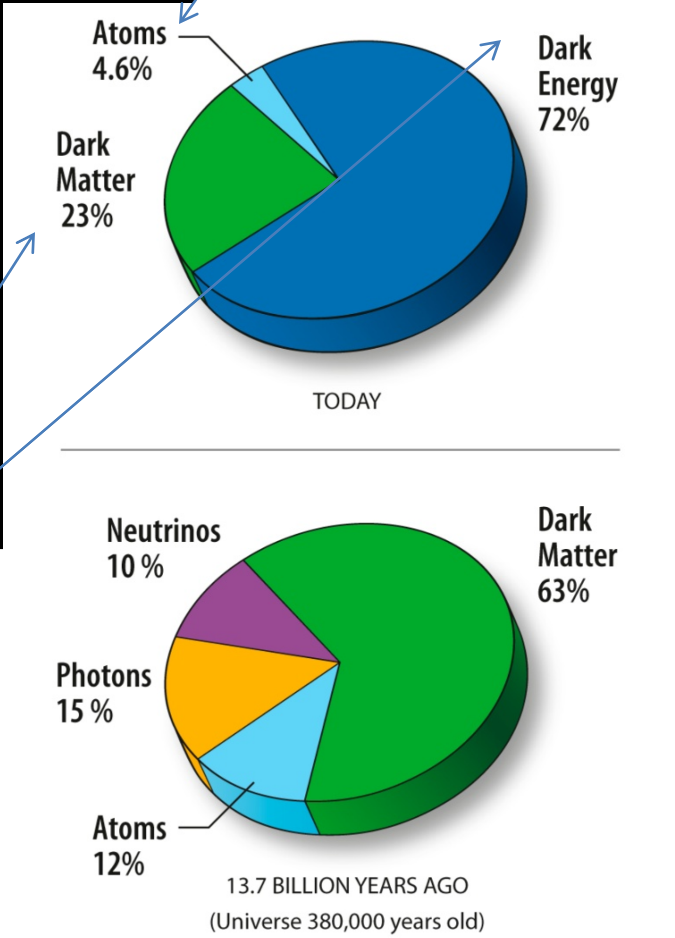
For ΛCDM: $H/(1+z) = H_0[\Omega_{M0}(1+z) + \Omega_{K0} + \Omega_\Lambda/(1+z)]^{1/2}$

Averaging over models and H_0 priors, transition redshift $z = 0.74 \pm 0.04$

(This is the first real measurement of the deceleration-acceleration transition redshift.)

We almost understand < 5% of the current energy budget.





We do not understand > 95% of the current energy budget.

But we do have a good “standard” model of cosmology, flat ΛCDM.

Summary of the current state of cosmology?

There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another (theory) which states that this has already happened.

Douglas Adams

This is an exciting time to be a cosmologist! Many puzzles remain!

Me