Introdução à Astronomia
Prof. Antônio Kanaan
Aula 13 – 11 junho 2018

A Expansão do Universo

referências:
http://www.pnas.org/cgi/content/full/101/1/8

http://www.astro.ucla.edu/~wright/cosmo_01.htm

Frank Shu, The Physical Universe
Andrew Liddle, An Introduction to Modern Cosmology
Sciama, Modern Cosmology
http://www.pnas.org/content/101/1/8.full


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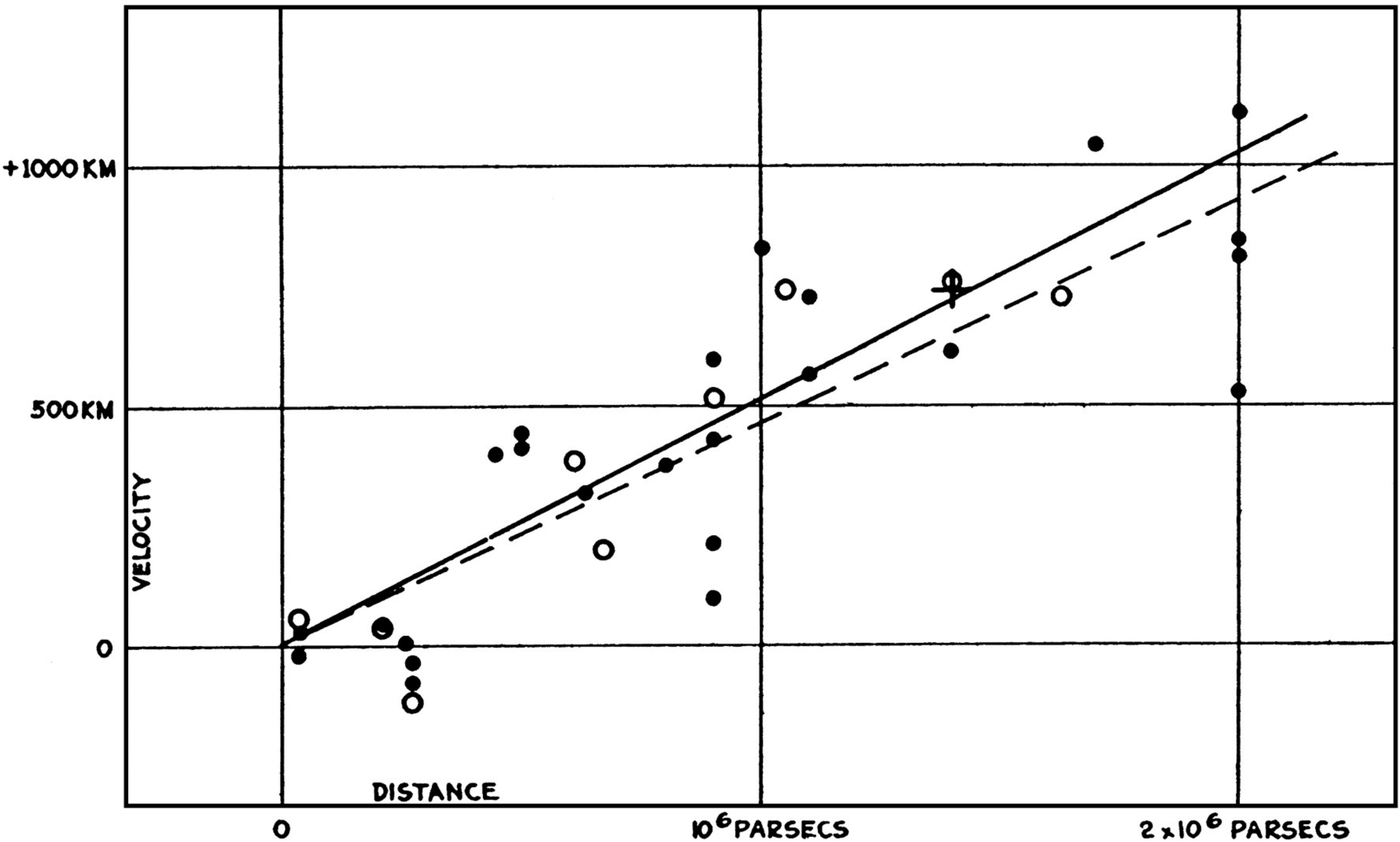
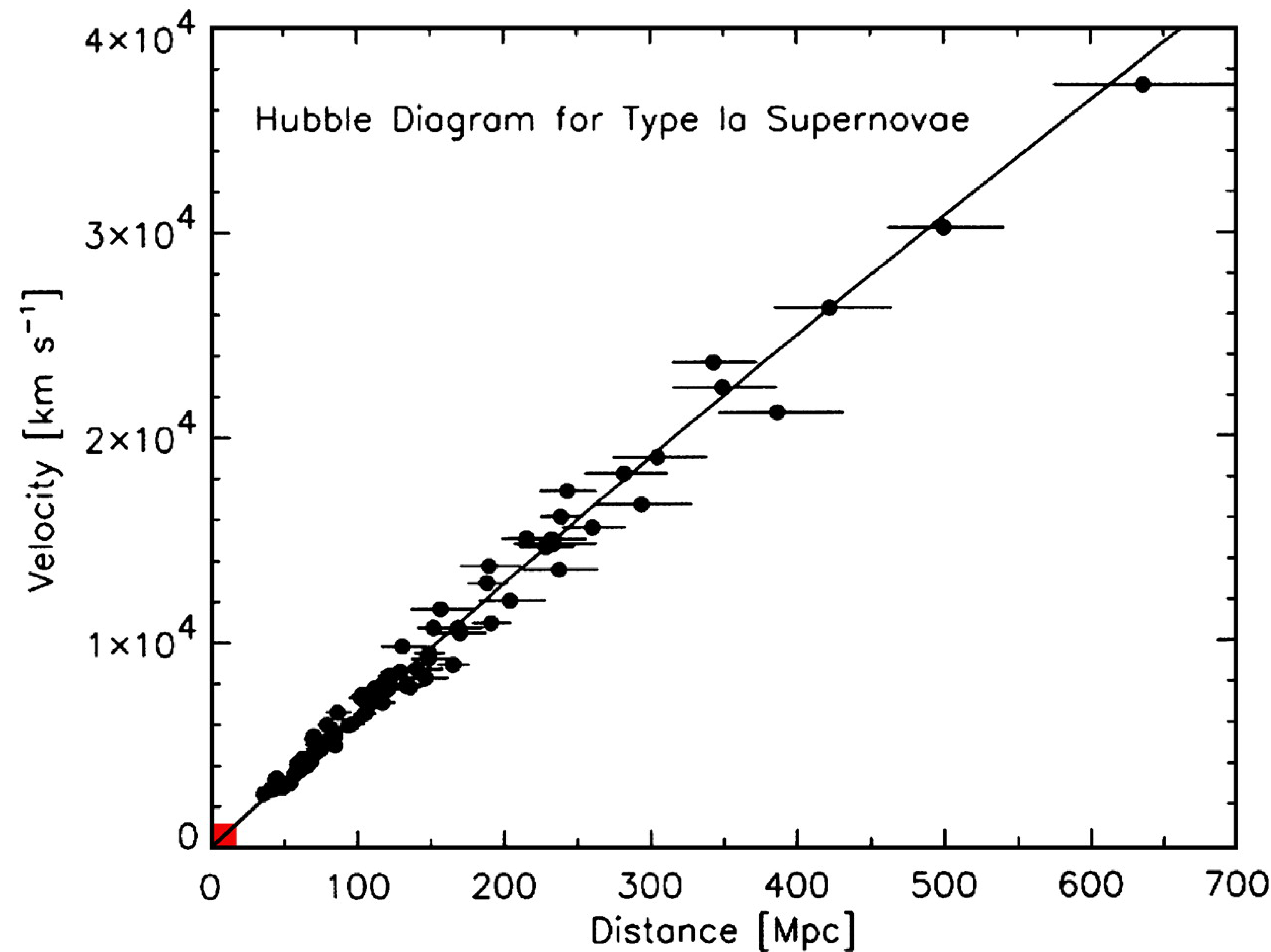
www.MrEclipse.com

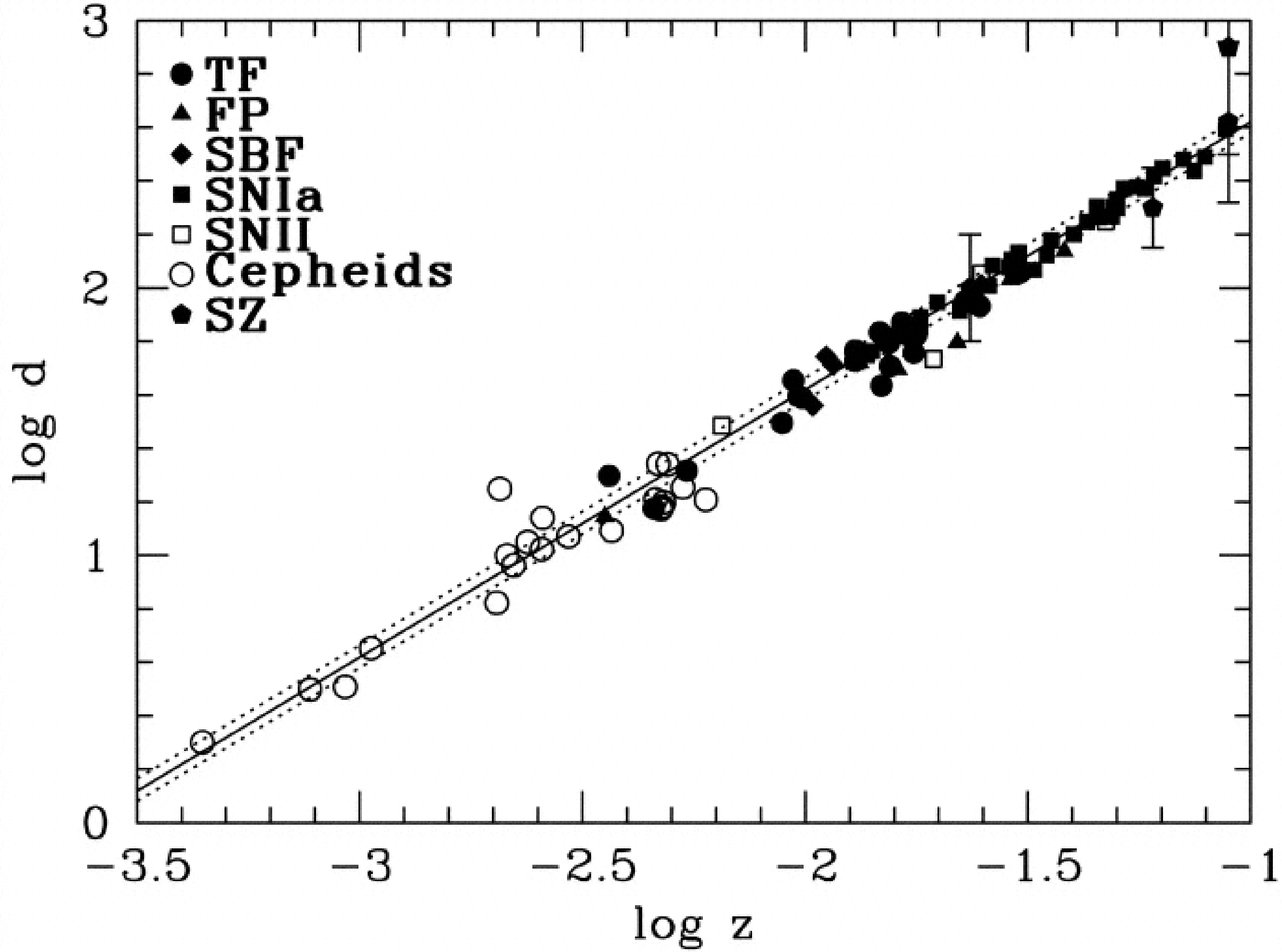
M100

Aglomerado da Virgem
Dist= 20Mpc=56AL


+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2 x 10⁶ PARSECS



Hubble Diagram for Type Ia Supernovae
Velocity [km s^{-1}]
Distance [Mpc]
0
1×10^4
2×10^4
3×10^4
4×10^4
0
100
200
300
400
500
600
700

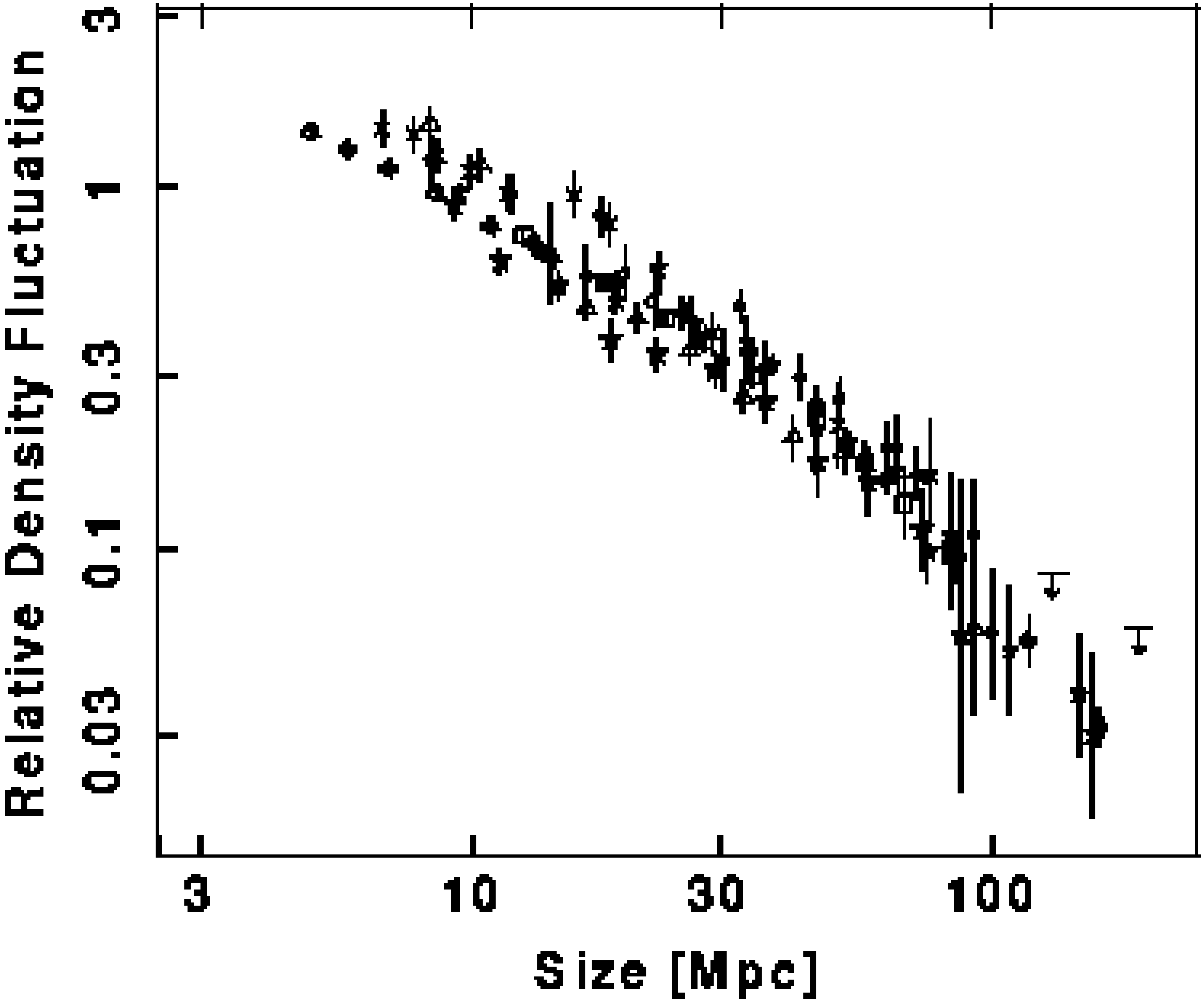


TF
FP
SBF
SNIa
SNII
Cepheids
SZ
log d
log z
0
1
2
3
−3.5
−3
−2.5
−2
−1.5
−1

Princípio cosmológico perfeito:
isotrópico
homogêneo
constante

Princípio cosmológico:
isotrópico
homegêneo

Figure 15.1. Deep galaxy map of a square section of the sky, 6° on a side, made from data supplied by Rudnicki and colleagues at the Jagellonian University in Cracow. The average galaxy among the more than 10,000 counted may be located between two and three billion light-years away in this map. Notice that the distribution on this scale is almost random, in contrast with Figure 14.6. (For details, see Groth, Peebles, Seldner, and Soneira, *Scientific American*, **237**, May 1977, 76.)



Relative Density Fluctuation
3
1
0.3
0.1
0.03
3
10
30
100
Size [Mpc]

SN Ia

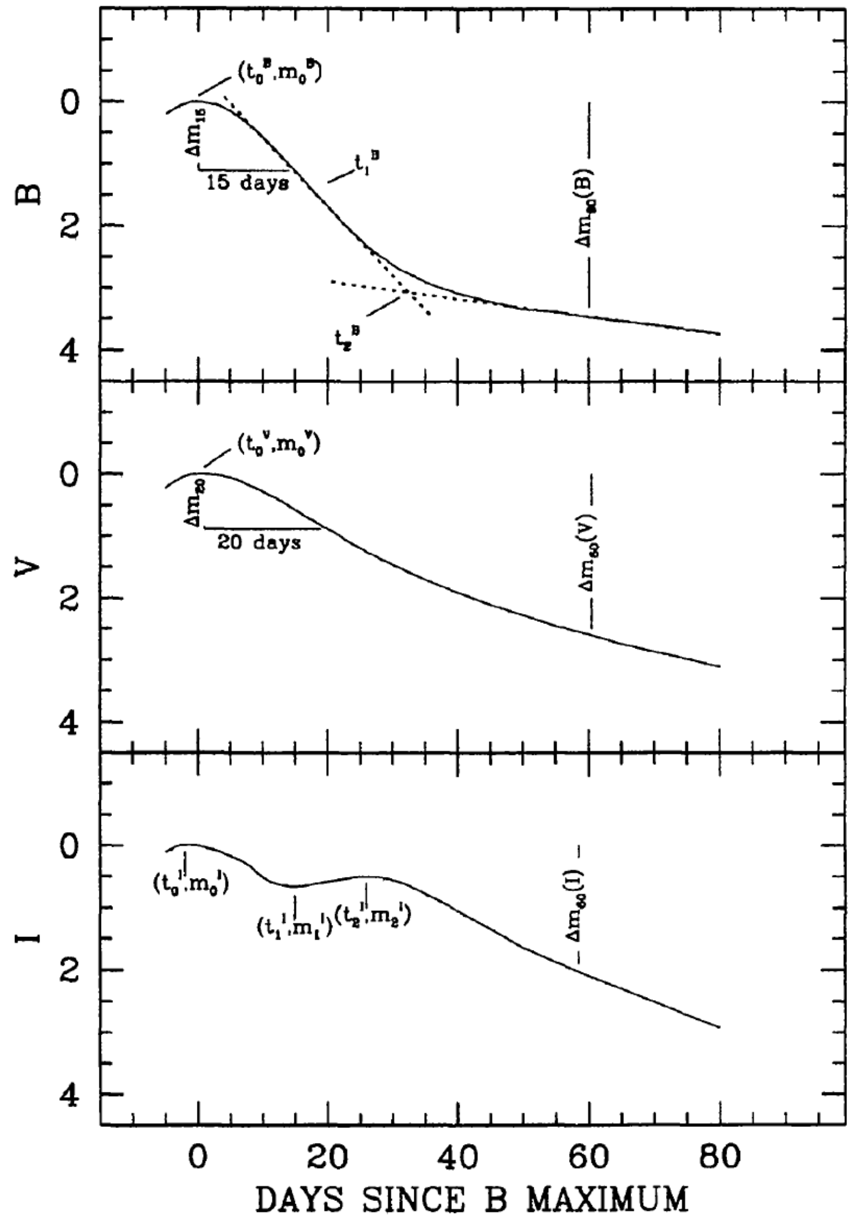


FIG. 8. The template B (top), V (middle), and I (bottom) light curves of SN 1992al. Also shown are the graphical representations of the key parameters defined here in order to characterize the shape of the individual templates.

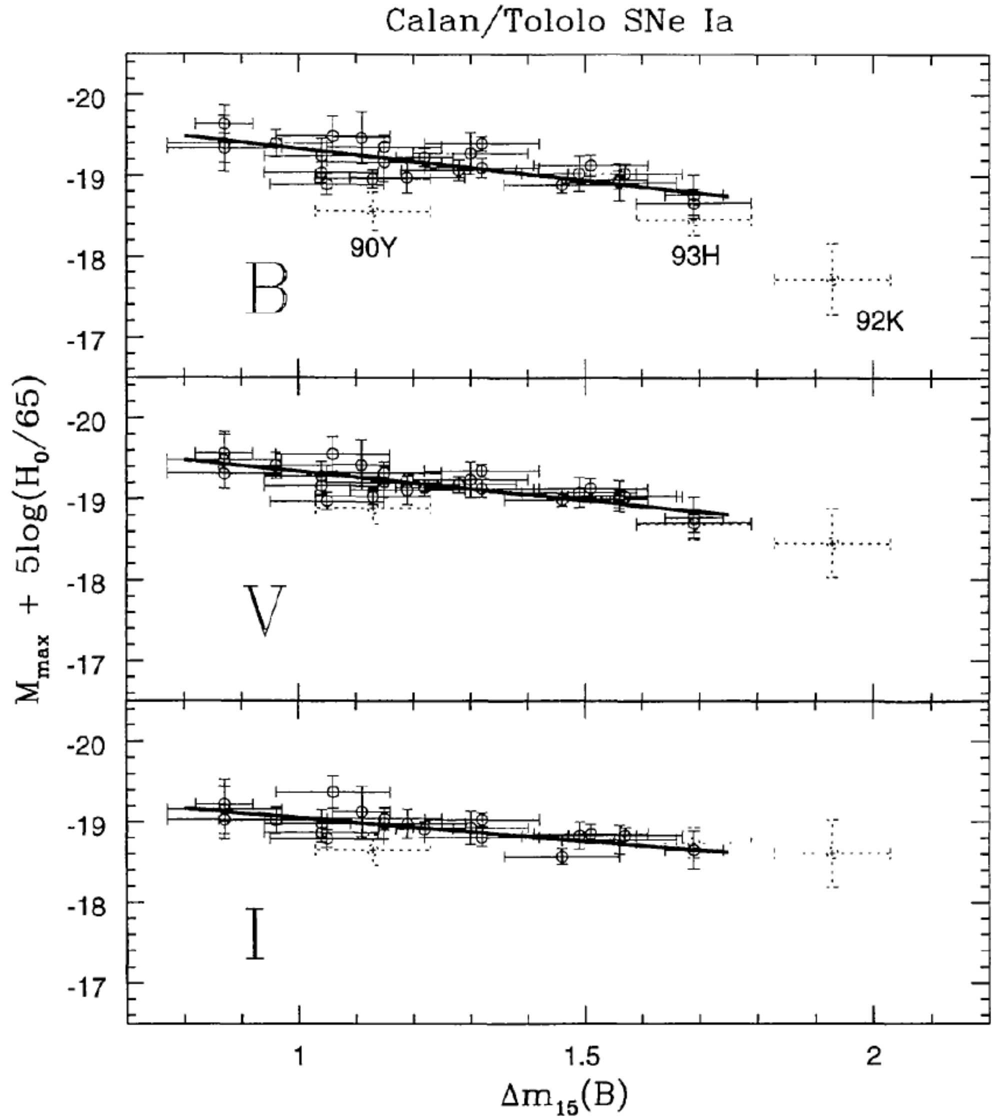
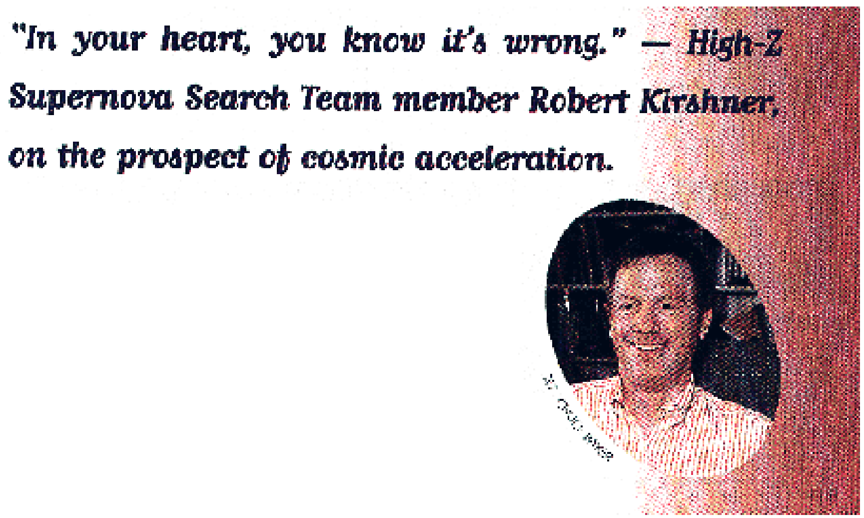


FIG. 1. The absolute B,V, and I magnitudes (from Table 1) of the 29 Calán/Tololo SNe Ia plotted as a function of $\Delta m_{15}(B)$. Points with dotted error bars correspond to the two SNe (90Y and 93H) suspected to be significantly reddened by dust and to the intrinsically red SN 1992K. The ridge lines correspond to weighted linear least-squares fits to the remaining 26 (B & V) and 22 (I) SNe with $0.87 \leqslant \Delta m_{15}(B) \leqslant 1.69$.


"In your heart, you know it's wrong." — High-Z Supernova Search Team member Robert Kirshner, on the prospect of cosmic acceleration.

— *Sky & Telescope*, September 1998

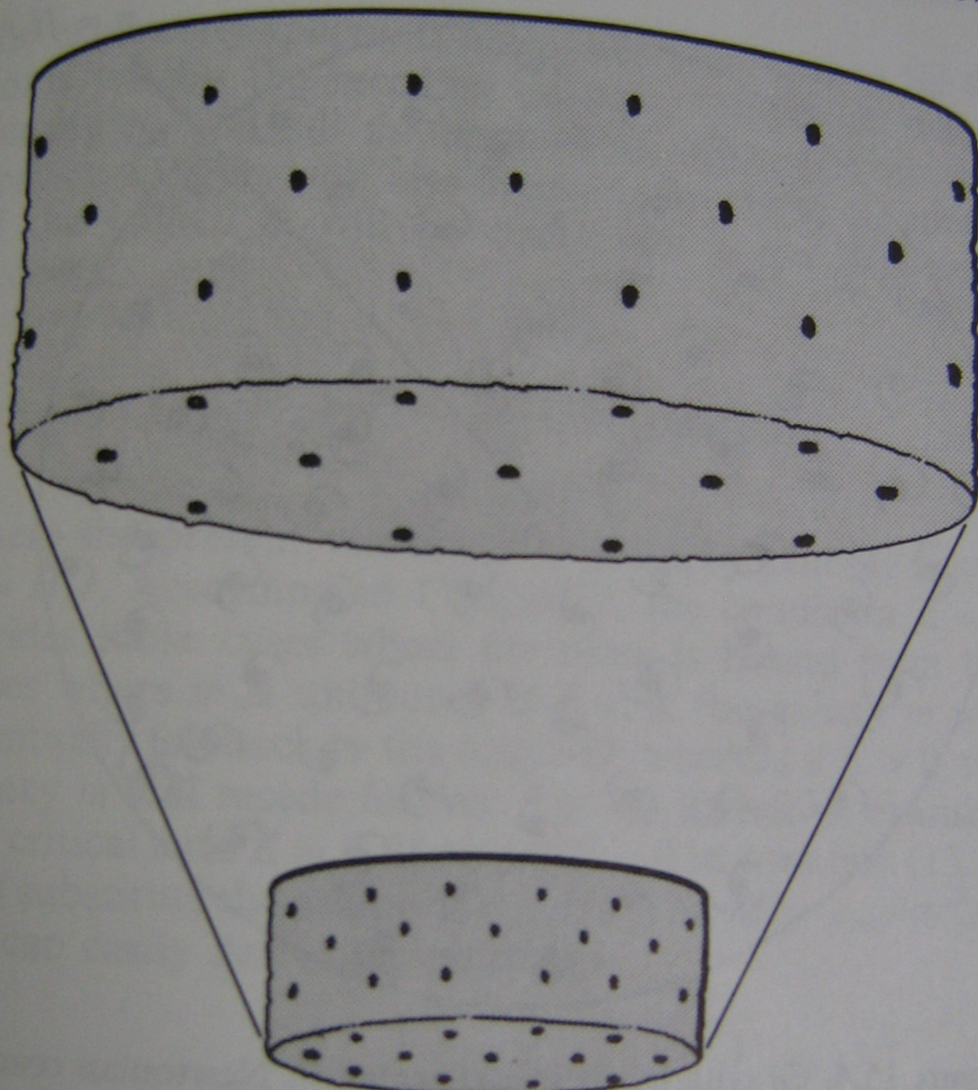


Figure 15.2. A rising raisin cake illustrates a recession of raisins from each other which occurs homogeneously and isotropically except for the raisins which are located at the surface of the cake. If the cake were infinite in extent, it would be a model of Hubble's law in Newtonian cosmology.

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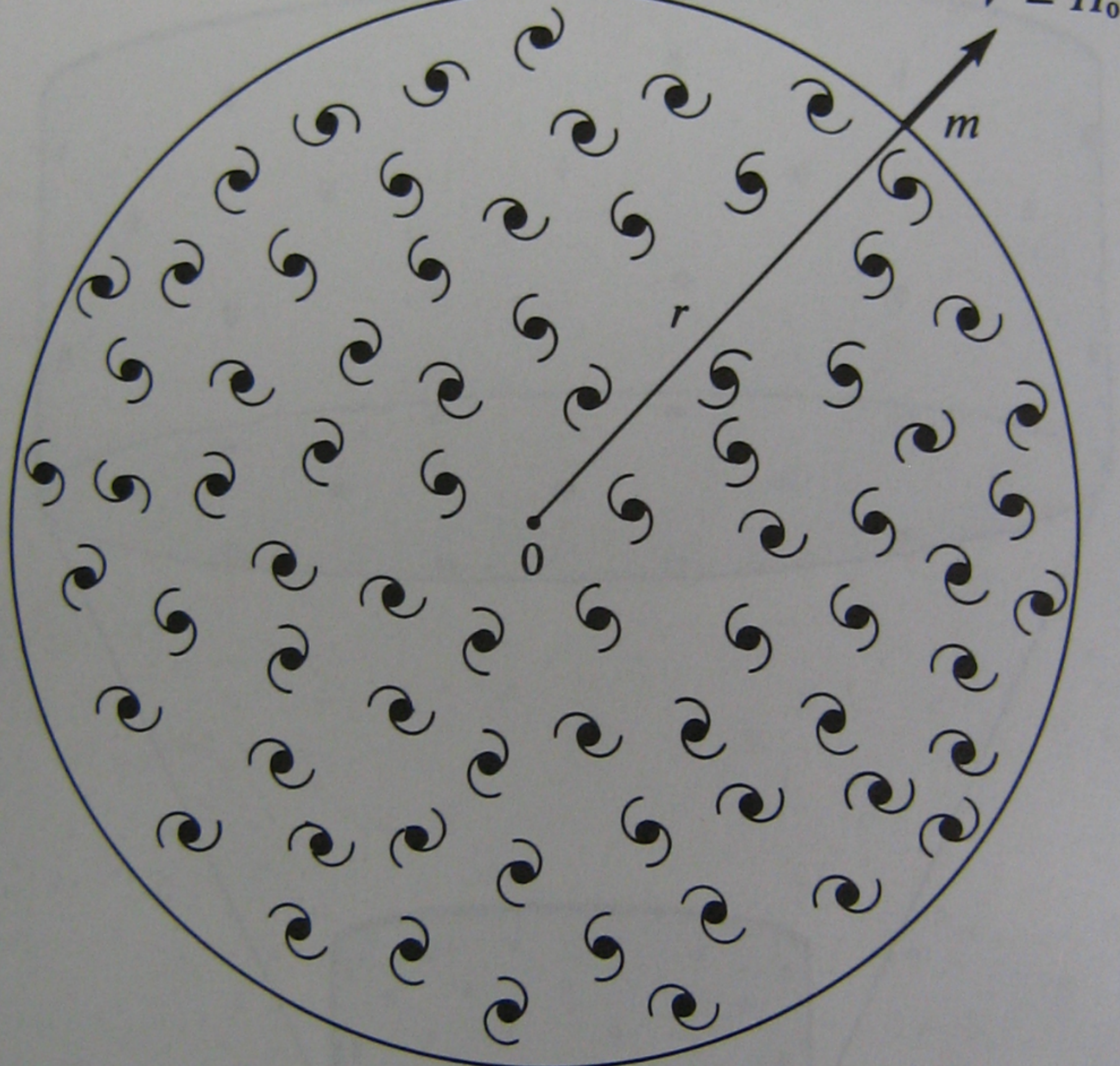


Figure 15.4. Gravitation is incorporated in Newtonian cosmology by adopting Birkhoff's rule that the motion *v* of a galaxy *m* located at distance *r* from an observer *O* is influenced only by all the matter which lies within a sphere of radius *r* centered on *O*.

ation
neces-
d do
view

gravitational pull of all the

A regra de Birkhoff é forćada, mas vamos brincar um pouco:

E = $mv^2 / 2 – Gmm / r$ = constante

assumindo $v = Ho * r$

se $E=0 \rightarrow \rho = 3 Ho^2 / 8 \pi G$

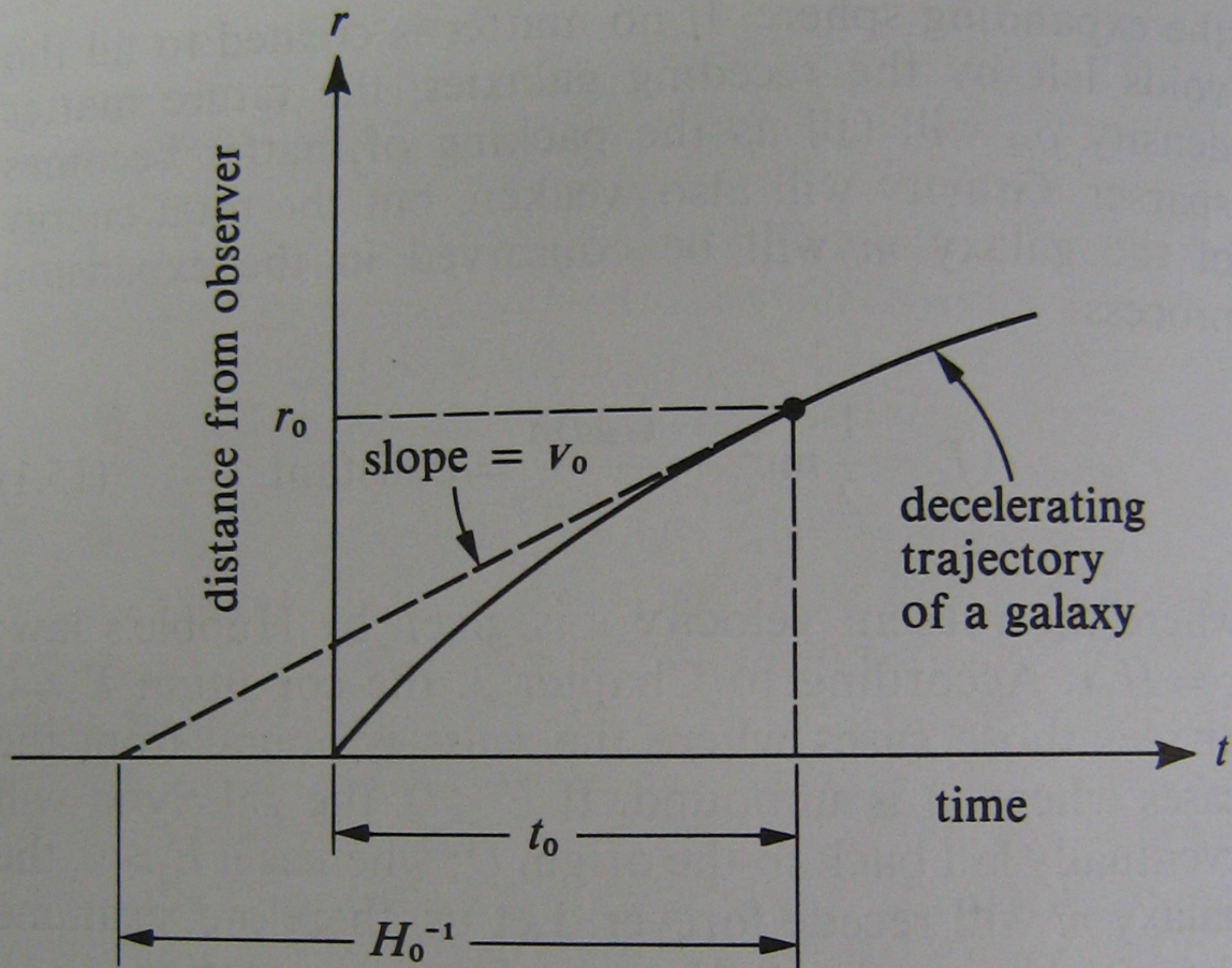


Figure 15.6. A galaxy at distance r_0 from us at the present time t_0 is observed to have a velocity of recession $v_0 = H_0 r_0$. If it is assumed that this galaxy has been moving at constant speed

Assumindo que
não há
desaceleraćão:

t = Ho ^(-1)

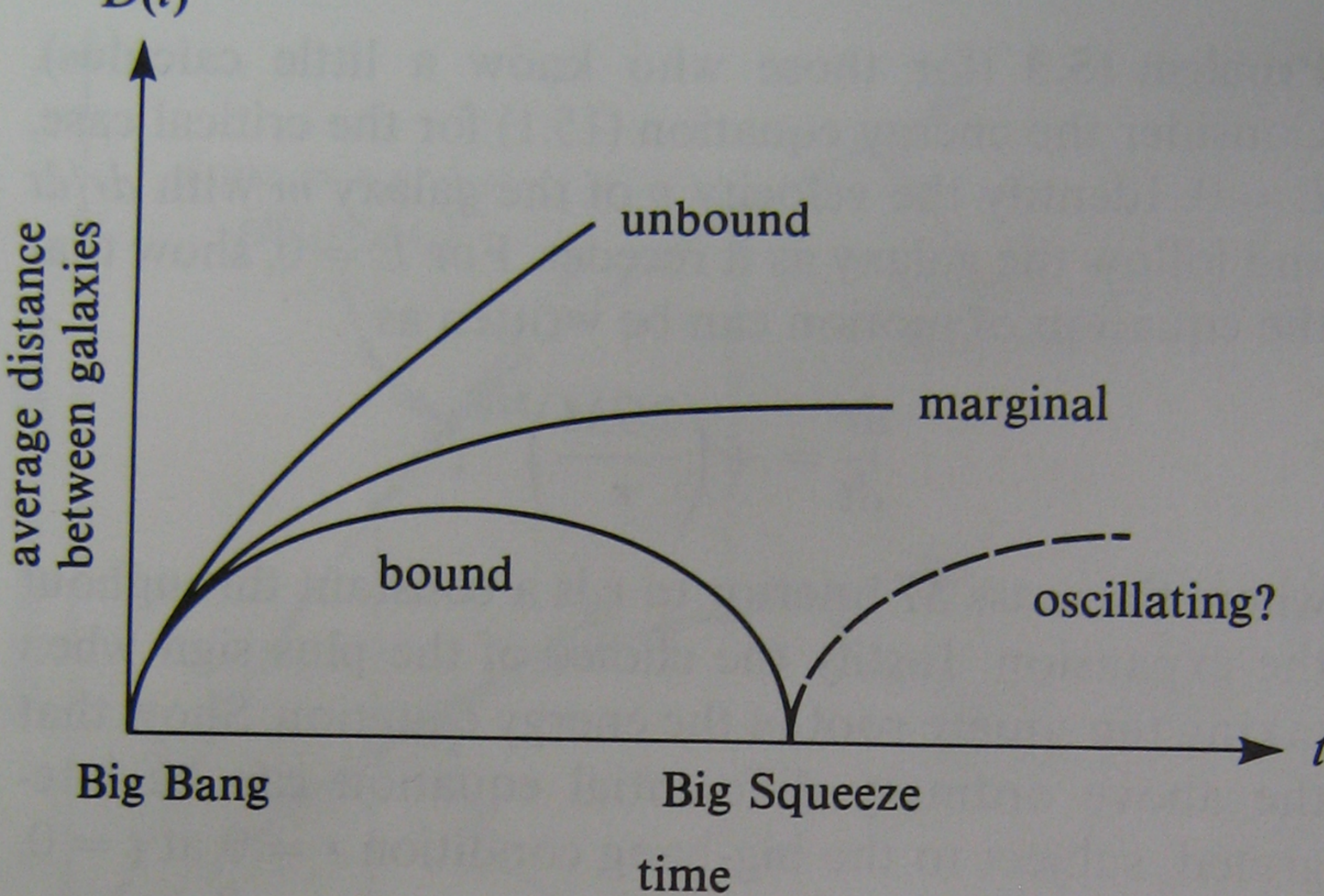


Figure 15.7. The history of the average separations of the galaxies if the universe is bound, marginally bound, or unbound. In an unbound universe, the galaxies will recede forever, with nonzero velocities even when they are infinitely separated. In a marginally bound universe, the recession velocities will exactly equal zero at infinite separations. In a bound universe, the galaxies will come together again after a time of finite duration. Some workers have speculated that after a period of superhigh compression (the Big Squeeze), a closed universe may rebound in another

Curso relâmpago de relatividade geral 0

a curvatura do espaćo em um campo gravitacional

a equivalência entre gravidade e aceleraćão

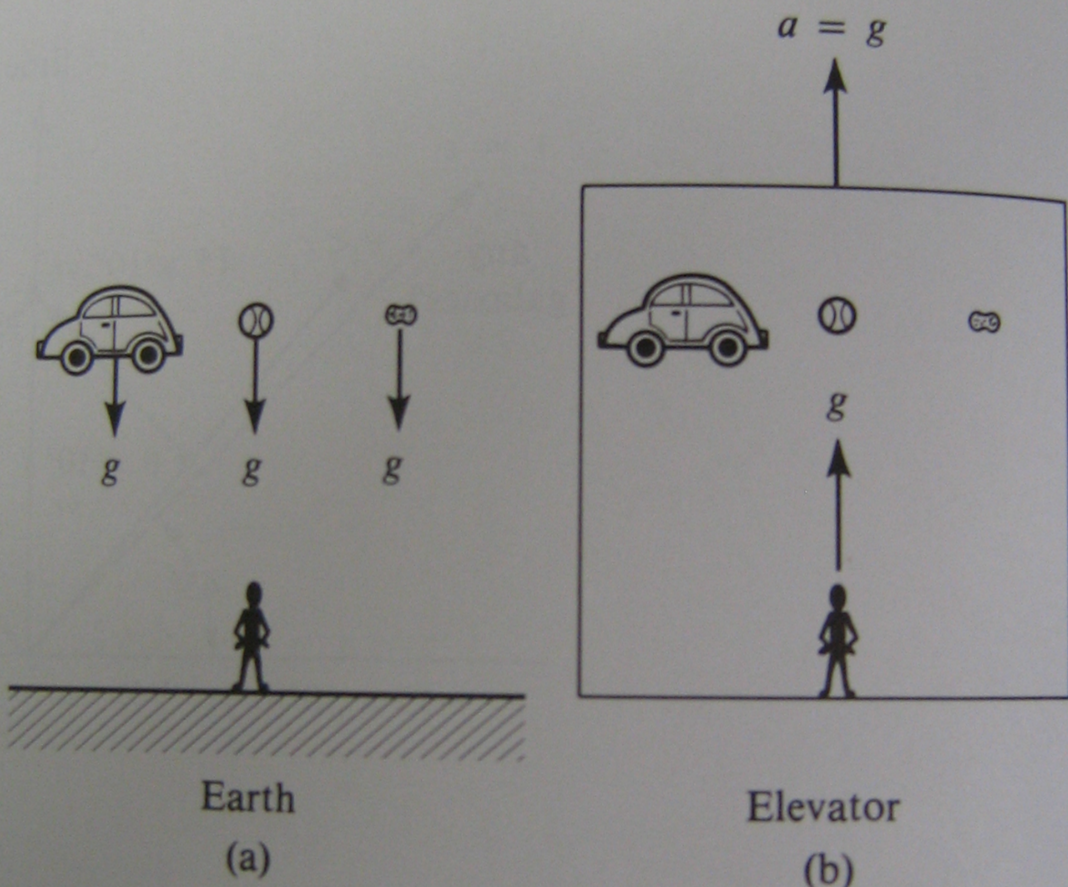


Figure 15.9. The principle of equivalence. According to this principle, an observer in space being accelerated upwards by an elevator with $\boldsymbol{a} = \boldsymbol{g}$, would feel the same physical effects as if he were back on Earth subjected to a gravitational field $\boldsymbol{g}$.

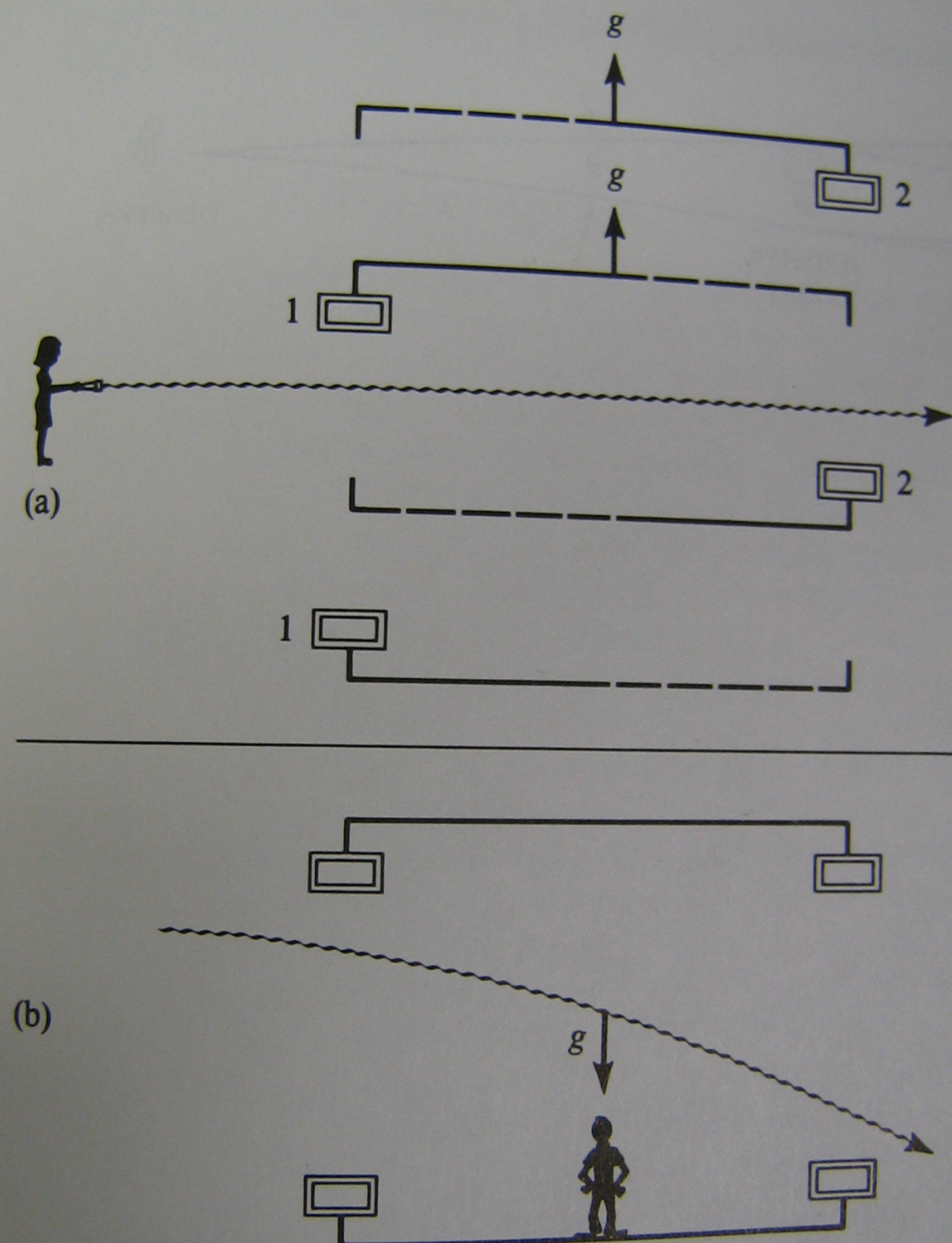


Figure 15.10. Two views of the same experiment involving the propagation of light: (a) according to an inertial observer, (b) according to an observer inside the accelerating elevator.

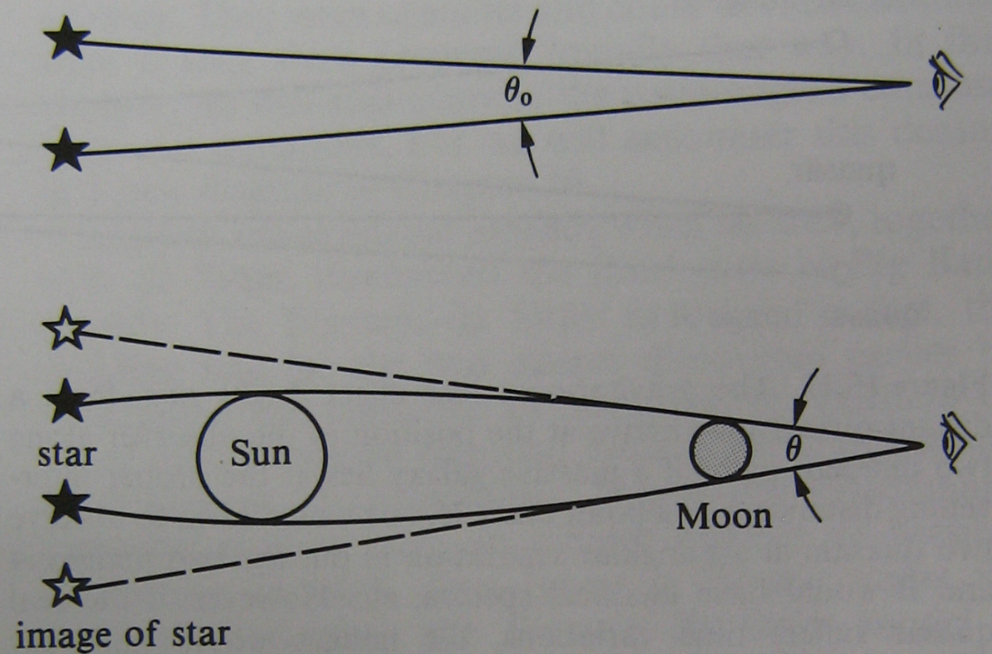


Figure 15.11. The bending of starlight by the gravitational field of a massive body. The angle θ subtended by two stars whose rays graze the limb of the Sun is larger than the angle θ_0 subtended when the Sun is not between the stars and the observer. For optical observations, this experiment must wait for an eclipse of the Sun by the Moon, so that the glare of sunlight does not interfere. For VLBI measurements of quasistellar radio sources, one does not need to wait for a solar eclipse.

If there is truly no way to tell the difference between the two situations depicted in Figure 15.9, then (Einstein

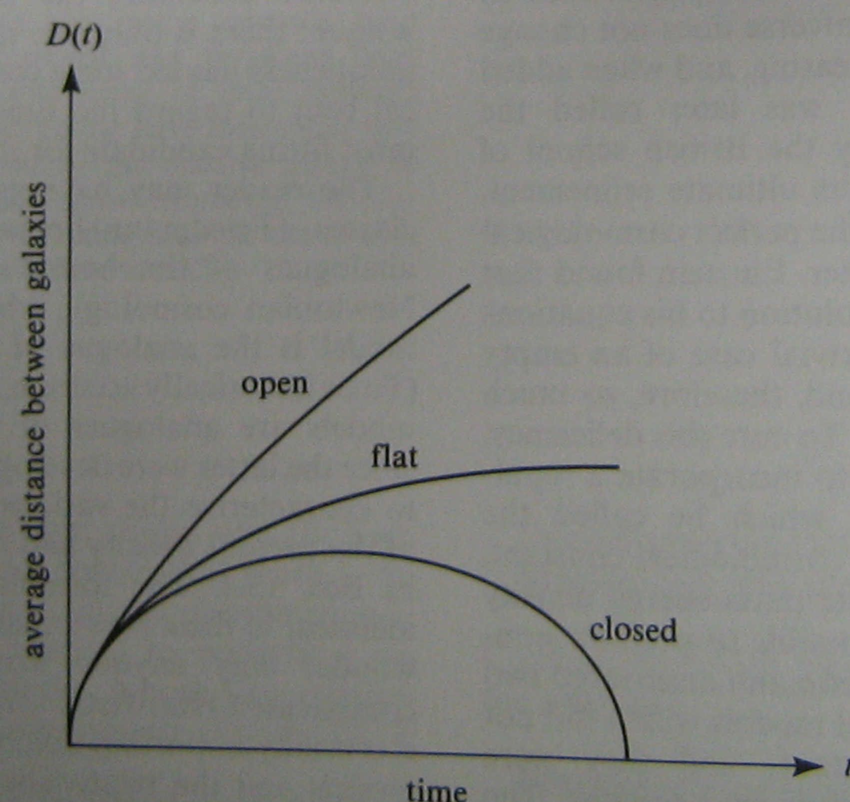
Fotos eclipse solar

BOX 15.4

Summary of Conventional Matter-Dominated Cosmological Models

Type	*Discoverers*	*Spatial curvature*	*Total volume*	*Present density*	*Present age*
Closed	Friedmann–Lemaitre	Positive	Finite	$\rho_{m0} > 3H_0^2/8\pi G$	$0 < t_0 < \frac{2}{3}H_0^{-1}$
Flat	Einstein–de Sitter	Zero	Infinite	$\rho_{m0} = 3H_0^2/8\pi G$	$t_0 = \frac{2}{3}H_0^{-1}$
Open	Friedmann–Lemaitre	Negative	Infinite	$\rho_{m0} < 3H_0^2/8\pi G$	$\frac{2}{3}H_0^{-1} < t_0 < H_0^{-1}$

Ultimate fate: Closed—will recontract; Flat—barely expands forever; Open—expands forever.



O Universo das formigas,

ou como um ser bi-dimensional se sente em um mundo tri-dimensional

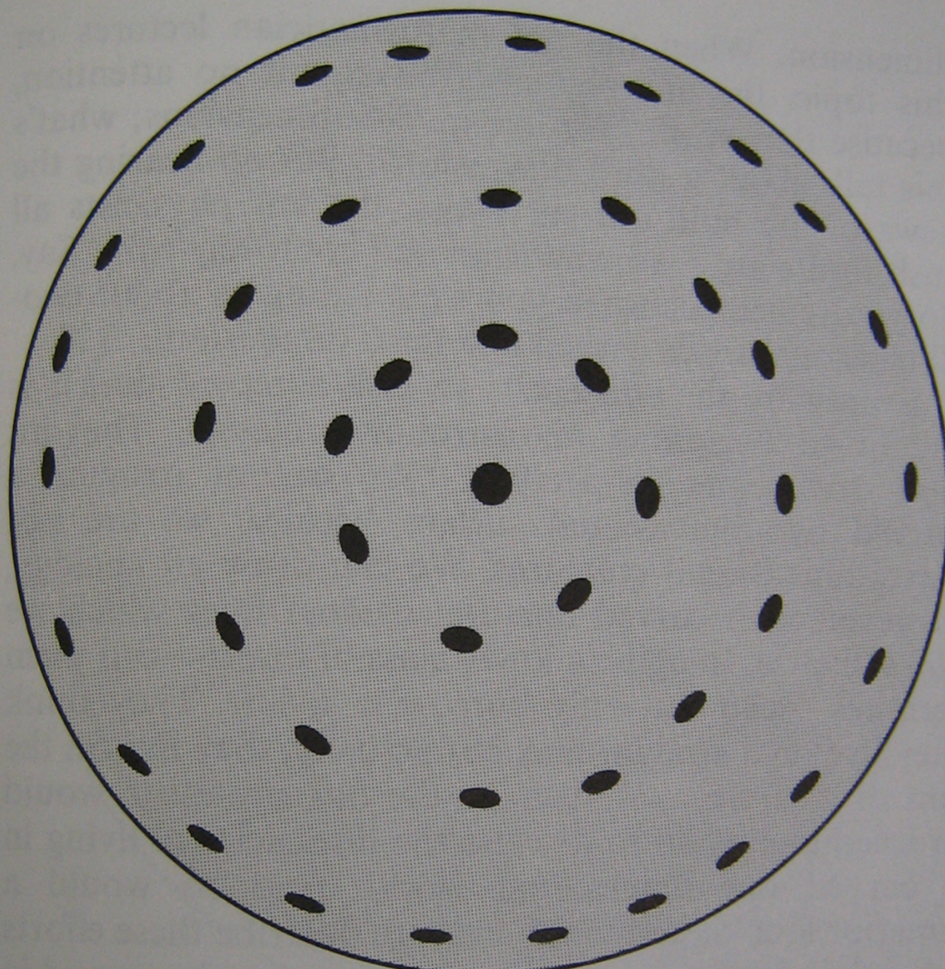


Figure 15.13. The distribution of ant cities on a spherical Earth. (We don't call them "anthills" because we wish to suppress the notion of a third dimension perpendicular to the surface of the world.) The distribution is homogeneous and isotropic on average, and there is a finite total number of ant cities on the finite surface area of the world.

fourth dimension here has nothing to do with time,

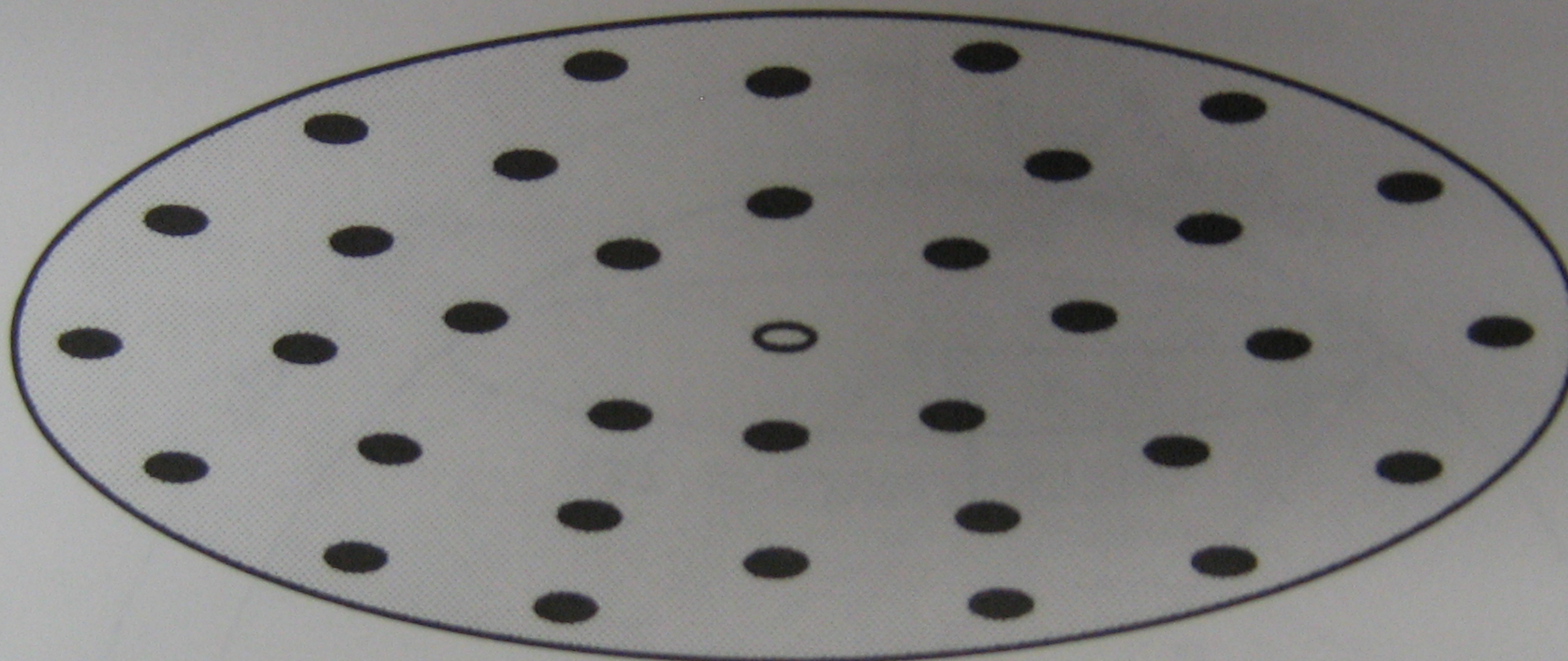


Figure 15.14. The common ant's view of its world with its city (white dot) being at the center of a flat circular plane containing many other ant cities (black dots).

on the average, the world is homogeneous and isotropic

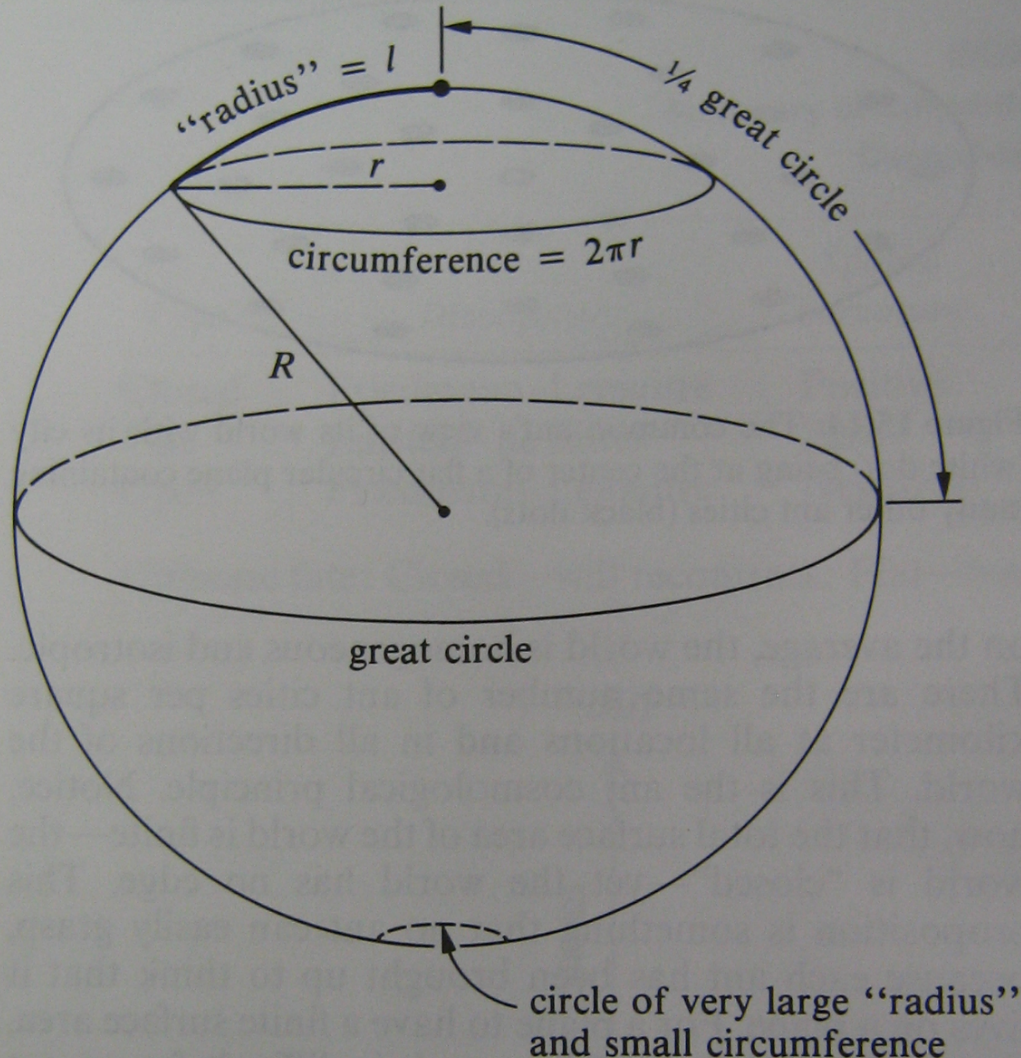


Figure 15.15. The geometric experiments of two bold ant surveyors who discover that the ratio of the circumference $2\pi r$ of a circle to its "radius" l does not equal 2π if the "radius" l is large. Notice that the quantity r is not the line of sight distance l that the ants can measure. Because r and R exist in the third unobservable dimension, ants can never measure r and R directly. They can, however, measure the circumference $2\pi r$, and by measuring the discrepancy between $2\pi r/l$ and 2π, the ants can indirectly calculate the radius of curvature R of their world.

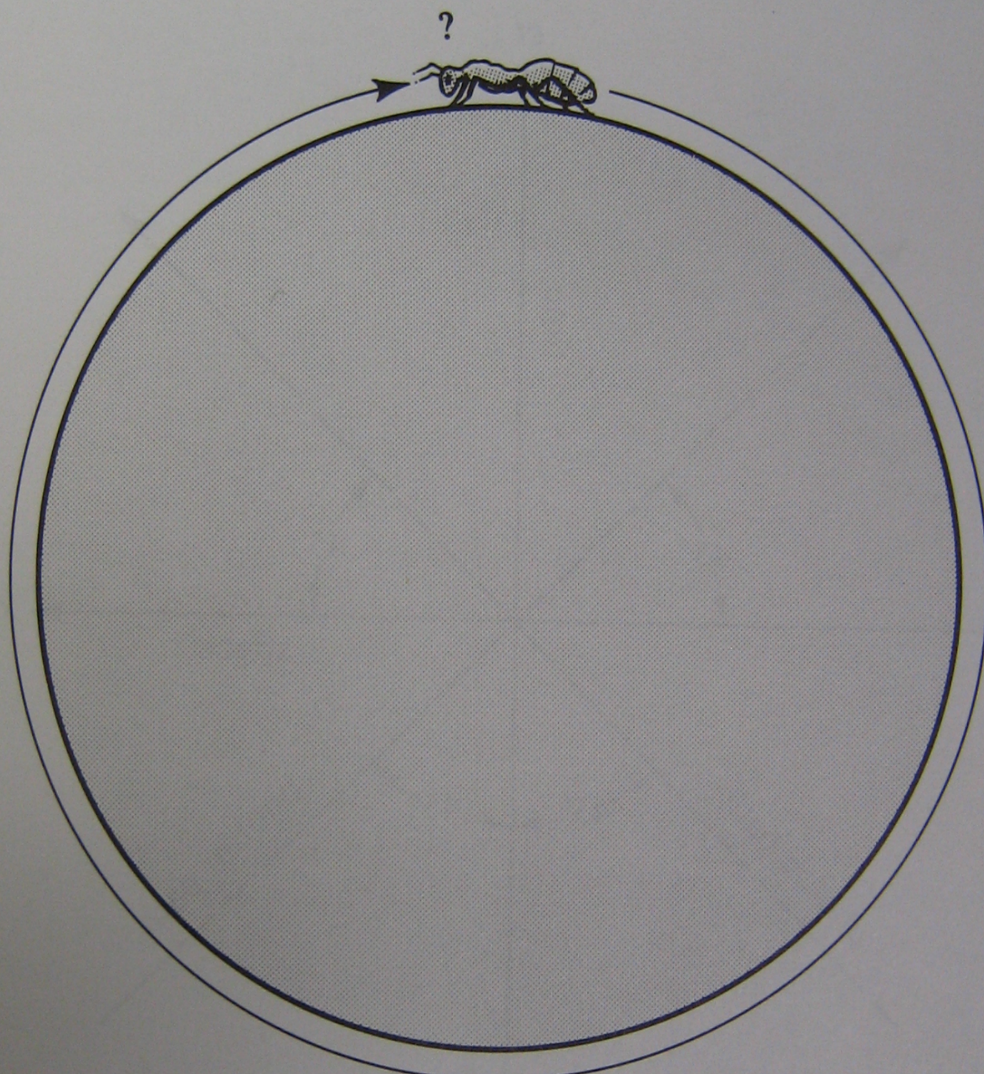


Figure 15.16. Ant light travels on a geodesic in the ant world (the shortest distance between two points, which is the arc of a great circle on a spherical world). Can ants make use of this property to see the back of their rear ends?

only in those two dimensions when they are told the

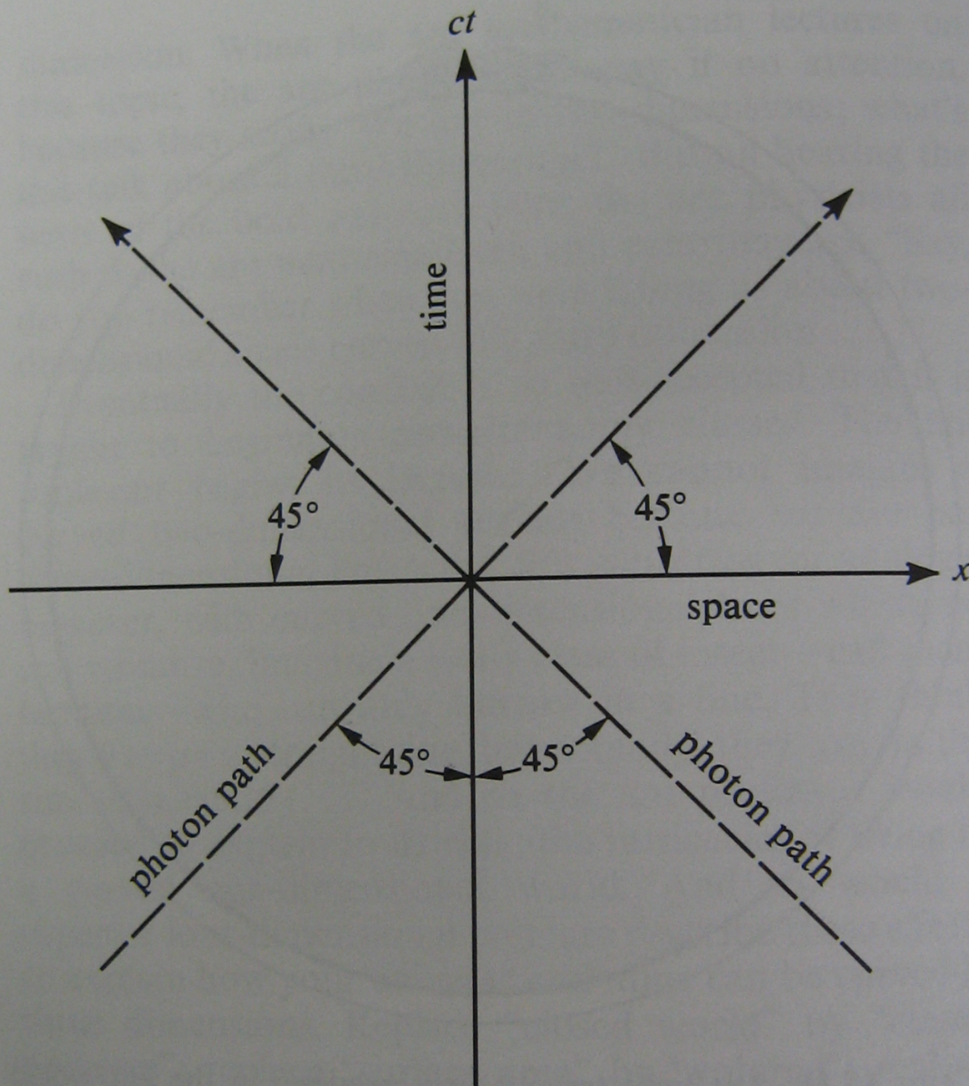


Figure 15.18. The trajectories of photons in flat spacetime are at angles of 45° to the coordinate axes.

trajectory of a photon is at 45° relative to the axes, be-

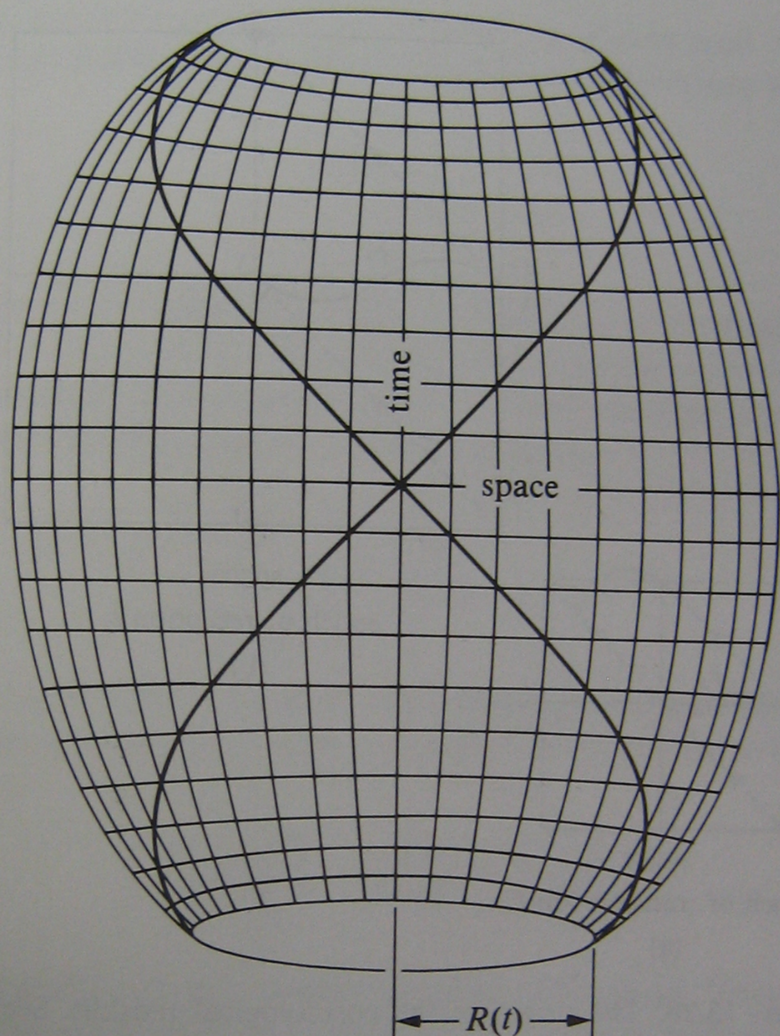


Figure 15.19. Curved spacetime in a closed, matter-dominated universe during the middle half of its existence. Galaxies on average travel upward along the time axis without moving with respect to the spatial grid. Photons travel along trajectories which are at 45° angles to the local spacetime axes ("corner to corner" if we construct little square grid markers). The space axis, at each instant of time t, forms a closed loop with radius $R(t)$ in an artificial "fourth" dimension. During the expansional phase, when $R(t)$ is an increasing function of t, notice that the individual square grids become larger. This is the expansion of spacetime that is the essence of relativistic cosmologies in the present epoch.

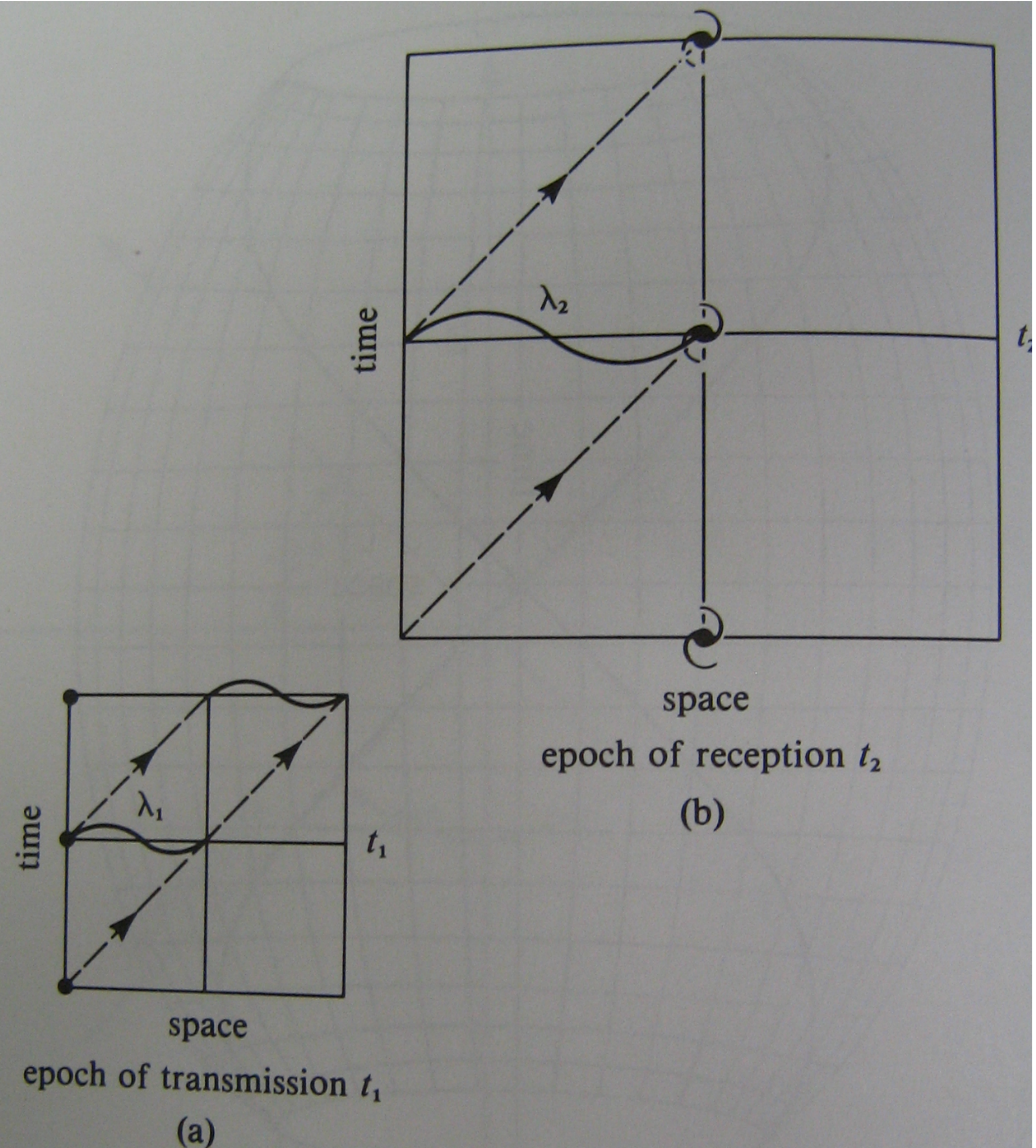


Figure 15.20. The origin of the cosmological redshift. See th
text and Figure 15.19 for explanations.

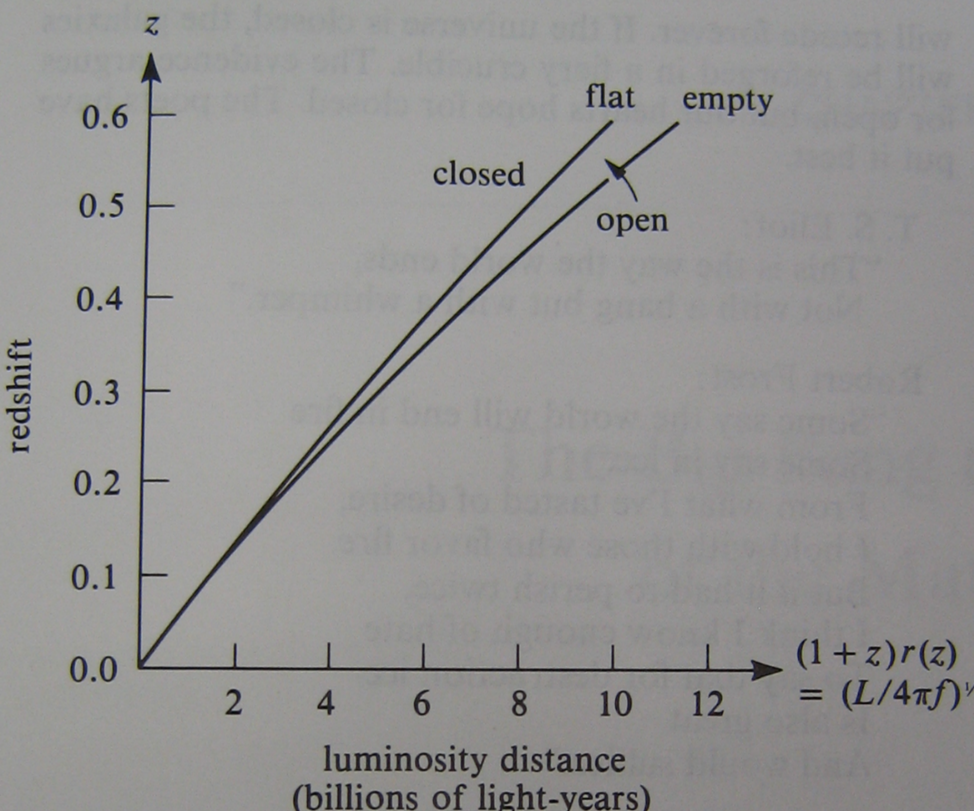
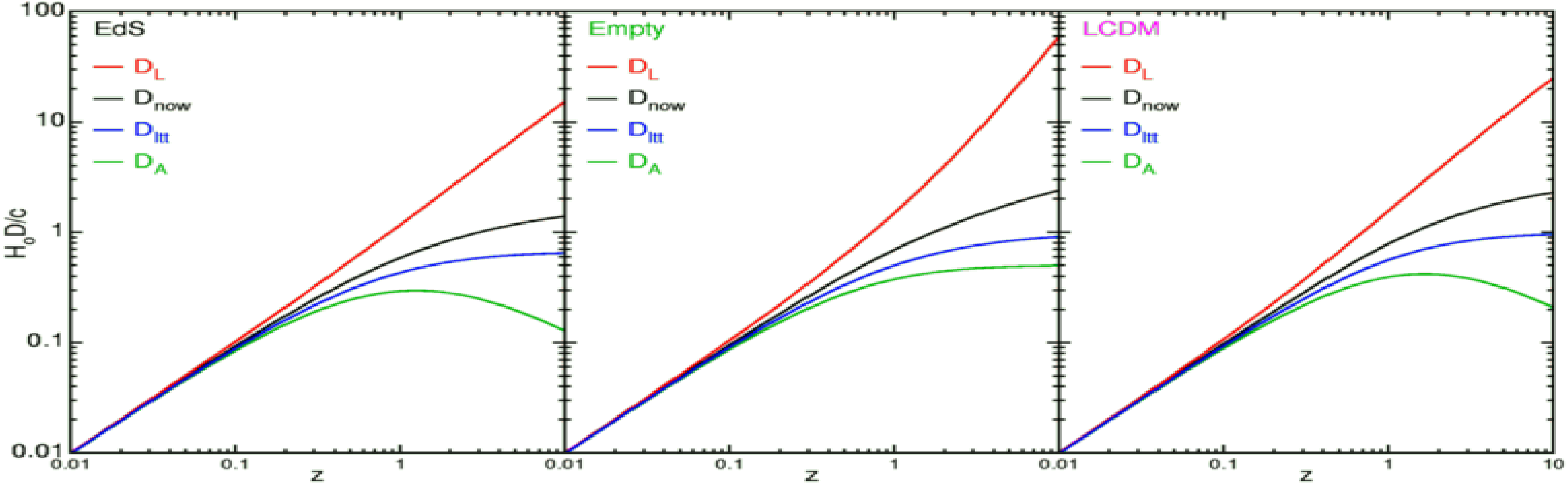


Figure 15.23. Theoretical Hubble diagram in which galaxies of a given luminosity L but of different apparent brightness f and redshift z in an open universe would lie between the curves labelled "flat" and "empty," while galaxies in a closed universe would lie above and to the left of "flat." All conventional cosmological models exhibit a linear relationship between redshift and luminosity distance at low z (Hubble's law), so only observations of the curvature in this relationship at high z can reveal whether the universe is open or closed. Unfortunately, as is discussed in the text, the interpretation of the observational Hubble diagram at high z is complicated by evolutionary and cannibalism effects.

why many astronomers believe that the universe is open. If they are correct, evolution is more important than



De:
http://www.astro.ucla.edu/~wright/cosmo_02.htm

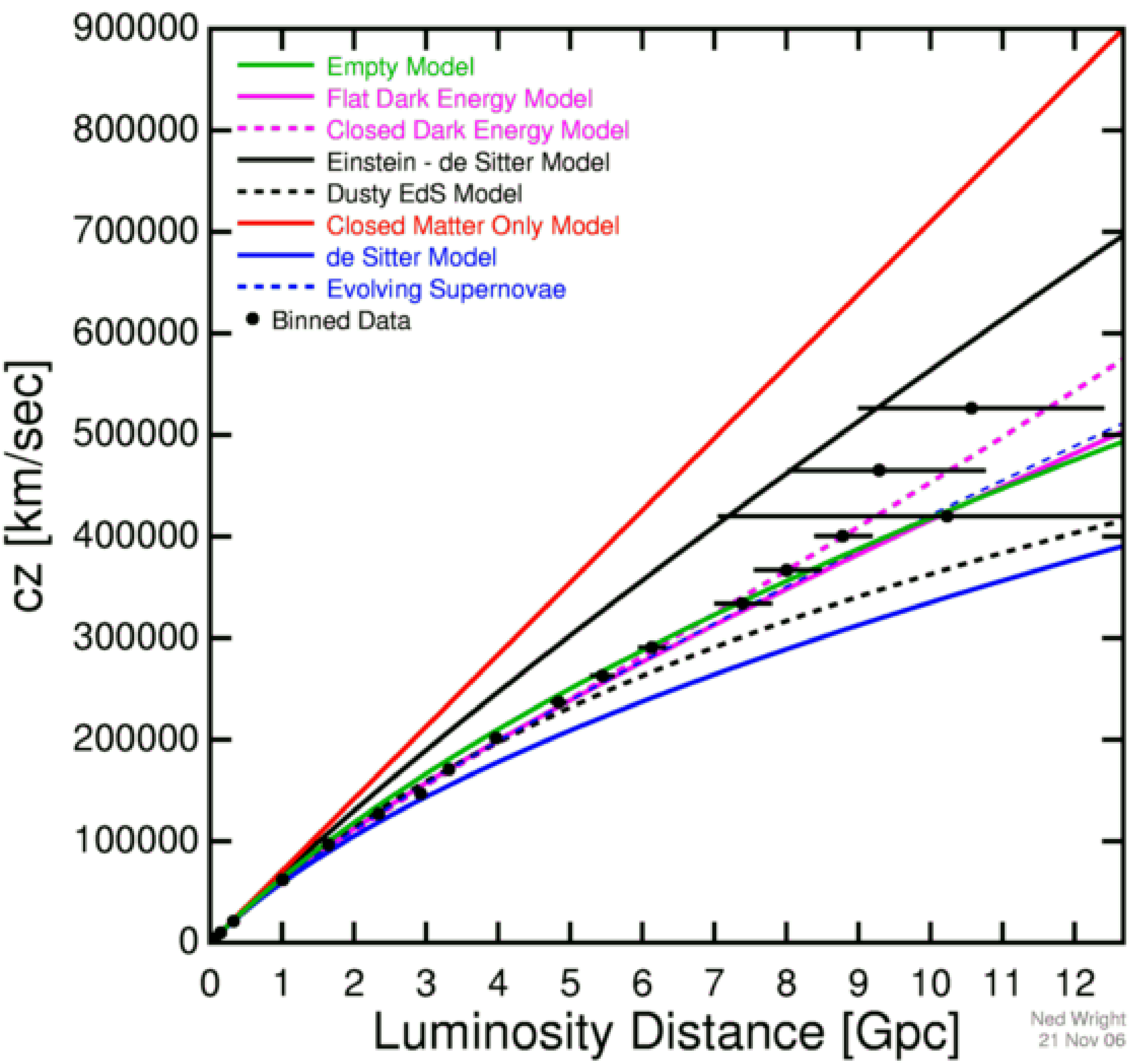
Testes cosmológicos através do diagrama de Hubble

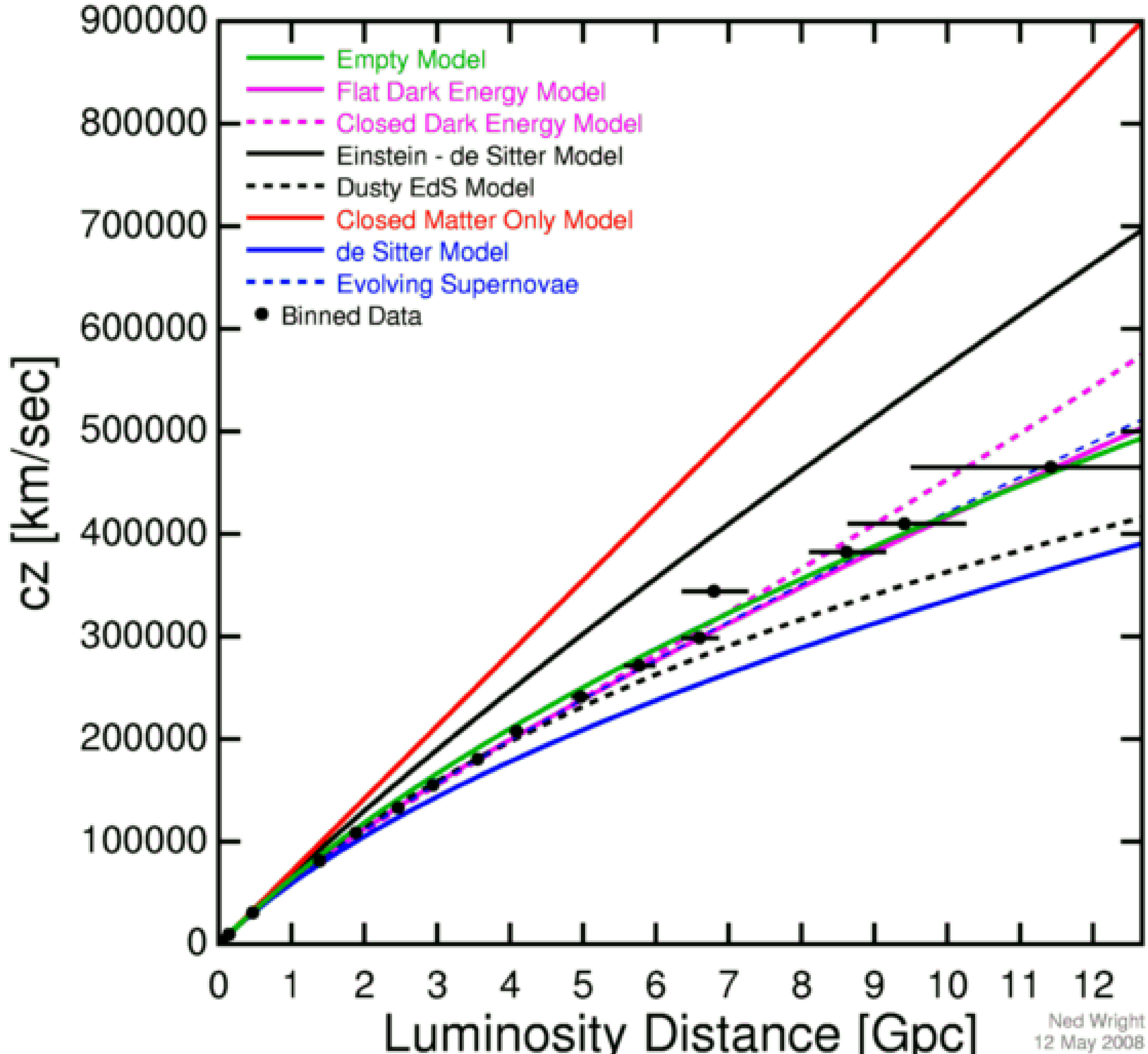
fontes padrão

f = L / 4 pi r^2 * 1/(1+z) * 1/(1+z)

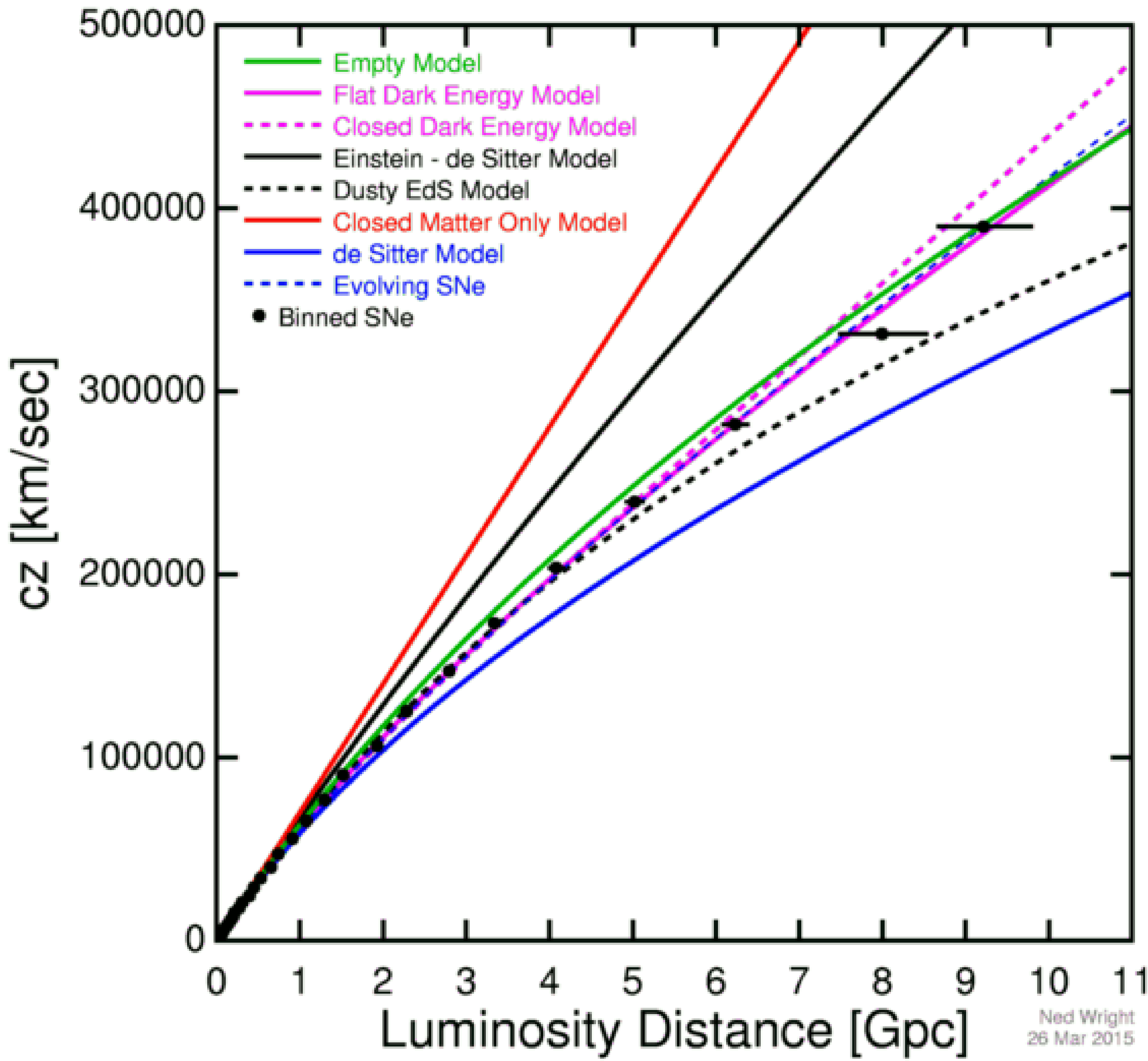
hc/λ   tempo

réguas padrão

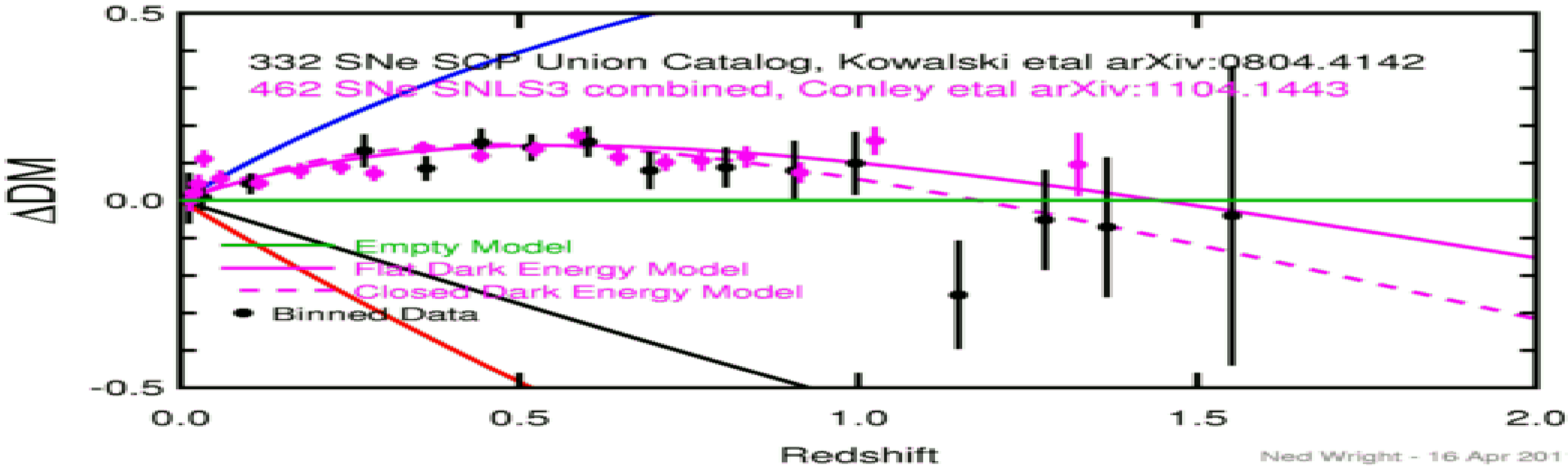

Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned Data
cz [km/sec]
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Luminosity Distance [Gpc]
Ned Wright
21 Nov 06



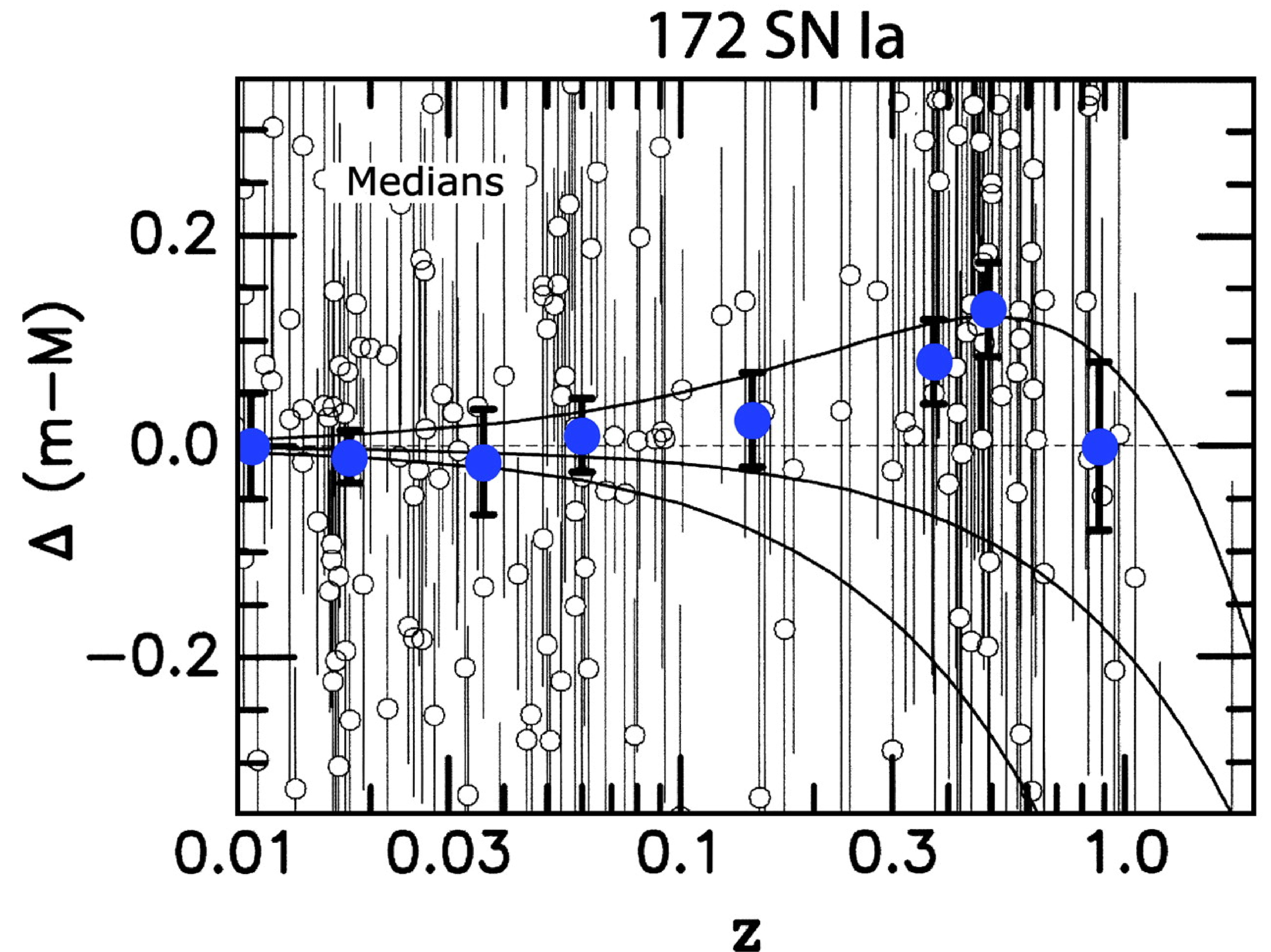
Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned Data
cz [km/sec]
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Luminosity Distance [Gpc]
Ned Wright
12 May 2008



Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving SNe
Binned SNe
cz [km/sec]
0
100000
200000
300000
400000
500000
0
1
2
3
4
5
6
7
8
9
10
11
Luminosity Distance [Gpc]
Ned Wright
26 Mar 2015



332 SNe SCP Union Catalog, Kowalski etal arXiv:0804.4142
462 SNe SNLS3 combined, Conley etal arXiv:1104.1443
ΔDM
0.5
0.0
-0.5
Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Binned Data
0.0
0.5
1.0
1.5
2.0
Redshift
Ned Wright - 16 Apr 2011



172 SN Ia
Medians
Δ (m−M)
0.2
0.0
−0.2
0.01
0.03
0.1
0.3
1.0
z

Fig. 6. Deviations in the Hubble diagram. Each point in this plot shows the difference at each redshift between the measured apparent brightness and the expected location in the Hubble diagram in a universe that is expanding without any acceleration or deceleration. The blue points correspond to median values in eight redshift bins. The upward bulge at z {approx} 0.5 is the signature of cosmic acceleration. The hint of a turnover in the data at the highest redshifts, near z = 1, suggests that we may be seeing past the era of acceleration driven by dark energy back to the era of deceleration dominated by dark matter. From top to bottom, the plotted lines correspond to the favored solution, with 30% dark matter and 70% dark energy, the observed amount of dark matter (30%) but no dark energy, and a universe with 100% dark matter (from ref. 18).

Hubble diagram at high z is complicated by evolutionary and cannibalism effects.

why many astronomers believe that the universe is open. If they are correct, evolution is more important than cannibalism.

Problem 15.12. Another observational cosmological test involves the use of "standard rulers." Suppose we have a galaxy of fixed length l_0 in its rest frame, and suppose this length is oriented perpendicular to our line of

Define $\alpha_0 = H_0 l_0/c$, and calculate its numerical value for a large galaxy. Convert your answer to seconds of arc. With the functions $r(z)$ given in Problem 15.11, plot $\Delta\theta$ versus z as expected theoretically for a flat and an empty universe. Can you explain why $\Delta\theta$ *increases* with large z for a flat universe? *Hint*: consider whether the universe as a whole can act as a gravitational lens. Construct the two-dimensional analogue of the effect (for a closed universe) by considering rulers on an expanding sphere. (See figures below.)

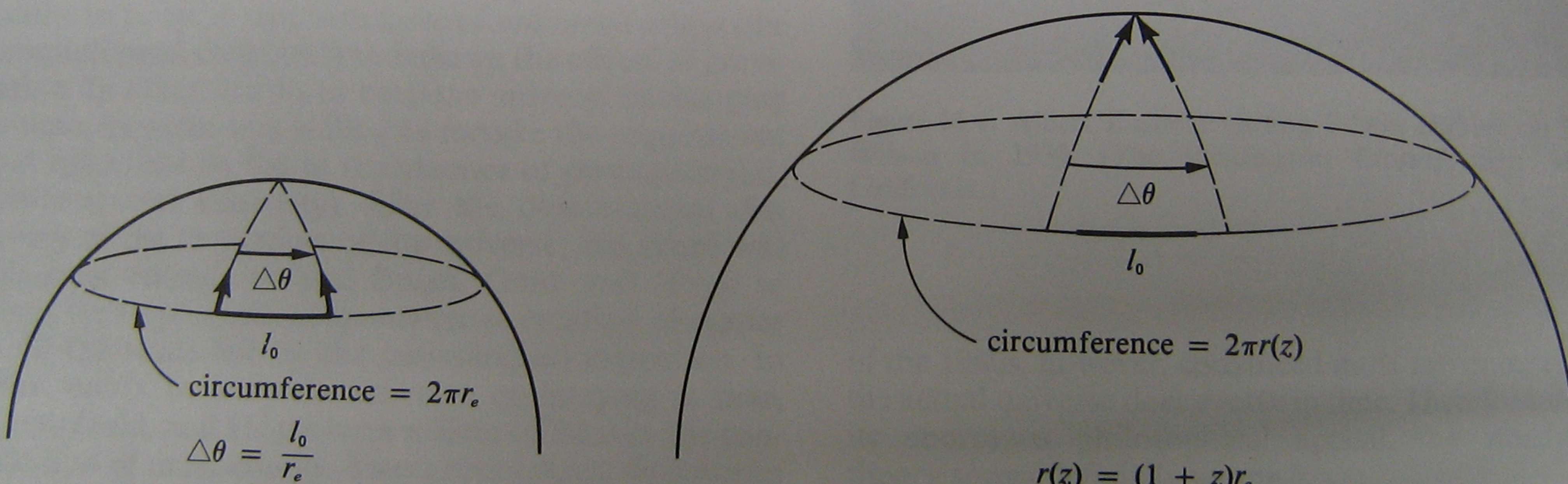


Figure P15.12