Physics 129 LECTURE 10 February 6, 2014

- More Cosmology
  - Brief History of the Universe
  - The Backward Lightcone
  - Cosmic Particle and Event Horizons
  - Distances in the Expanding Universe
  - The Cosmic Particle and Event Horizons
  - Mapping the Universe
  - The Cosmic Spheres of Time
  - Three Pillars of the Big Bang: Expansion, CMB, BBN
  - Cosmic Radiation: Photons, Neutrinos, Particles

The in-class open-book Midterm Exam will be Thursday February 13.

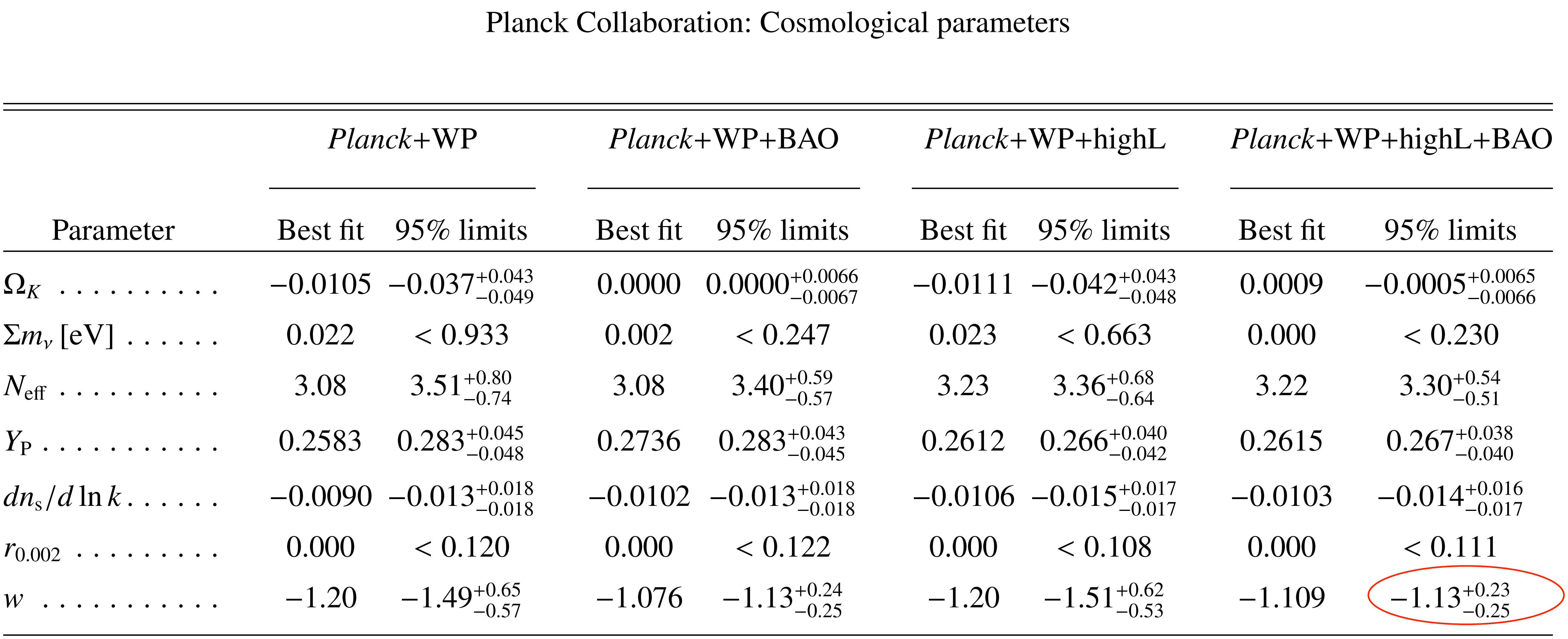
The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological constraints from the full shape of the clustering wedges

MNRAS **433,** 1202–1222 (2013)

Ariel G. Sánchez,[1]★ Eyal A. Kazin,[2,3] Florian Beutler,[4] Chia-Hsun Chuang,[5]

Table 2. The marginalized 68 per cent constraints on the most relevant cosmological parameters of the extensions of the ΛCDM model analysed in Sections 5.1.2–5.2.3, obtained using different combinations of the data sets described in Section 2. A complete list of the constrains obtained in each case can be found in Appendix .

	CMB	CMB+$\xi_0(s)$	CMB+$(\xi_{\perp}(s), \xi_{\parallel}(s))$	CMB+$(\xi_{\perp}(s), \xi_{\parallel}(s))$ +BAO+SN
Non-flat models				
Ω_k	-1.118 ± 0.021	$-0.0033^{+0.0046}_{-0.0044}$	-0.0040 ± 0.0045	-0.0041 ± 0.0039
$\Omega_{\rm DE}$	0.690 ± 0.072	0.715 ± 0.0145	0.715 ± 0.015	0.721 ± 0.011
$\Omega_{\rm m}$	0.321 ± 0.093	0.288 ± 0.016	0.288 ± -0.016	0.283 ± 0.010
Massive neutrinos				
f_ν	<0.12 (95 per cent CL)	<0.054 (95 per cent CL)	<0.051 (95 per cent CL)	<0.043 (95 per cent CL)
$\sum m_\nu$	<1.6 eV (95 per cent CL)	<0.68 eV (95 per cent CL)	<0.62 eV (95 per cent CL)	<0.50 eV (95 per cent CL)
$\Omega_{\rm m}$	$0.385^{+0.069}_{-0.072}$	$0.302^{+0.021}_{-0.020}$	0.302 ± 0.018	0.291 ± 0.012
Constant dark energy equation of state				
$w_{\rm DE}$	-1.14 ± 0.42	$-0.99^{+0.21}_{-0.20}$	-0.93 ± 0.11	-1.013 ± 0.064
$\Omega_{\rm m}$	0.26 ± 0.10	0.291 ± 0.042	0.299 ± 0.028	0.283 ± 0.012
Dark energy and curvature				
$w_{\rm DE}$	$-0.89^{+0.44}_{-0.45}$	$-0.96^{+29}_{-0.28}$	-0.97 ± 0.16	-1.042 ± 0.068
Ω_k	$-0.022^{+0.027}_{-0.031}$	$0.0012^{+0.0091}_{-0.0077}$	$-0.0023^{+0.0061}_{-0.0060}$	-0.0047 ± 0.0042
$\Omega_{\rm m}$	$0.265^{+0.097}_{-0.094}$	$0.280^{+0.093}_{-0.083}$	0.297 ± 0.046	0.278 ± 0.013
Time-dependent dark energy equation of state				
w_0	$-1.01^{+0.56}_{-0.53}$	$-1.11^{+0.63}_{-0.60}$	$-0.96^{+0.40}_{-0.39}$	$-1.10^{+0.12}_{-0.12}$
w_a	$-0.4^{+1.1}_{-1.5}$	0.2 ± 1.0	$0.03^{+0.96}_{-0.97}$	0.31 ± 0.40
$\Omega_{\rm m}$	0.285 ± 0.015	0.296 ± 0.037	0.284 ± 0.011	0.282 ± 0.012

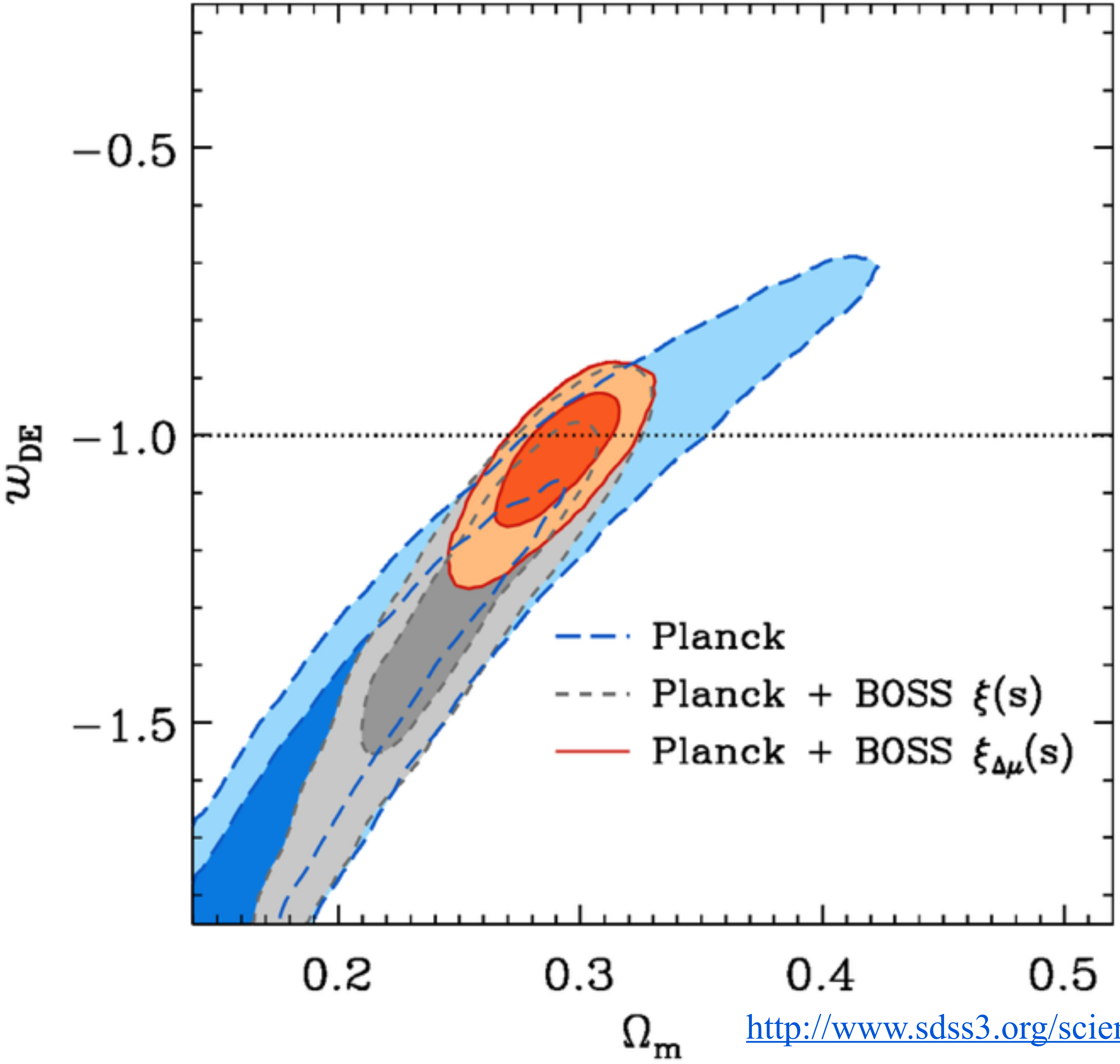


Planck Collaboration: Cosmological parameters

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include Planck combined with WMAP polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

Constraints in the Ω_m-*w* plane combining CMB data with BOSS clustering data

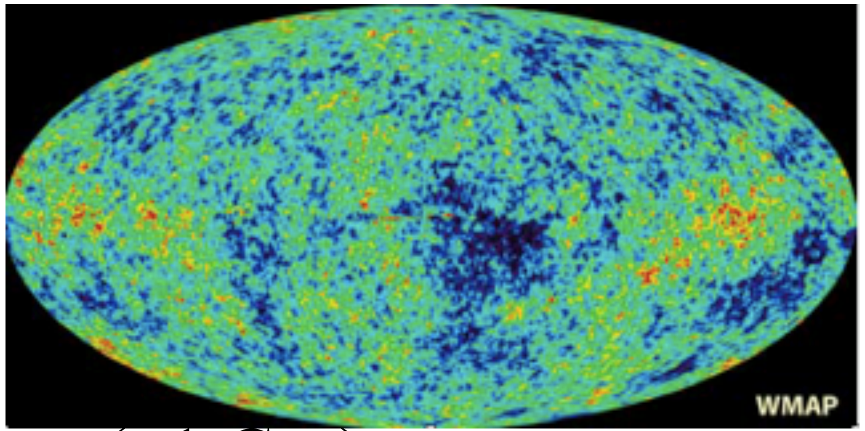


← Cosmological Constant

http://www.sdss3.org/science/boss_publications.php

Brief History of the Universe

- Cosmic Inflation generates density fluctuations
- Symmetry breaking: more matter than antimatter
- All antimatter annihilates with almost all the matter (1s)
- Big Bang Nucleosynthesis makes light nuclei (10 min)
- Electrons and light nuclei combine to form atoms, and the cosmic background radiation fills the newly transparent universe (380,000 yr)



- Galaxies and larger structures form (~1 Gyr)
- Carbon, oxygen, iron, ... are made in stars
- Earth-like planets form around 2nd generation stars
- Life somehow starts (~4 Gyr ago) and evolves on earth

Neutrino Decoupling and Big Bang Nucleosynthesis, Photon Decoupling, and WIMP Annihilation

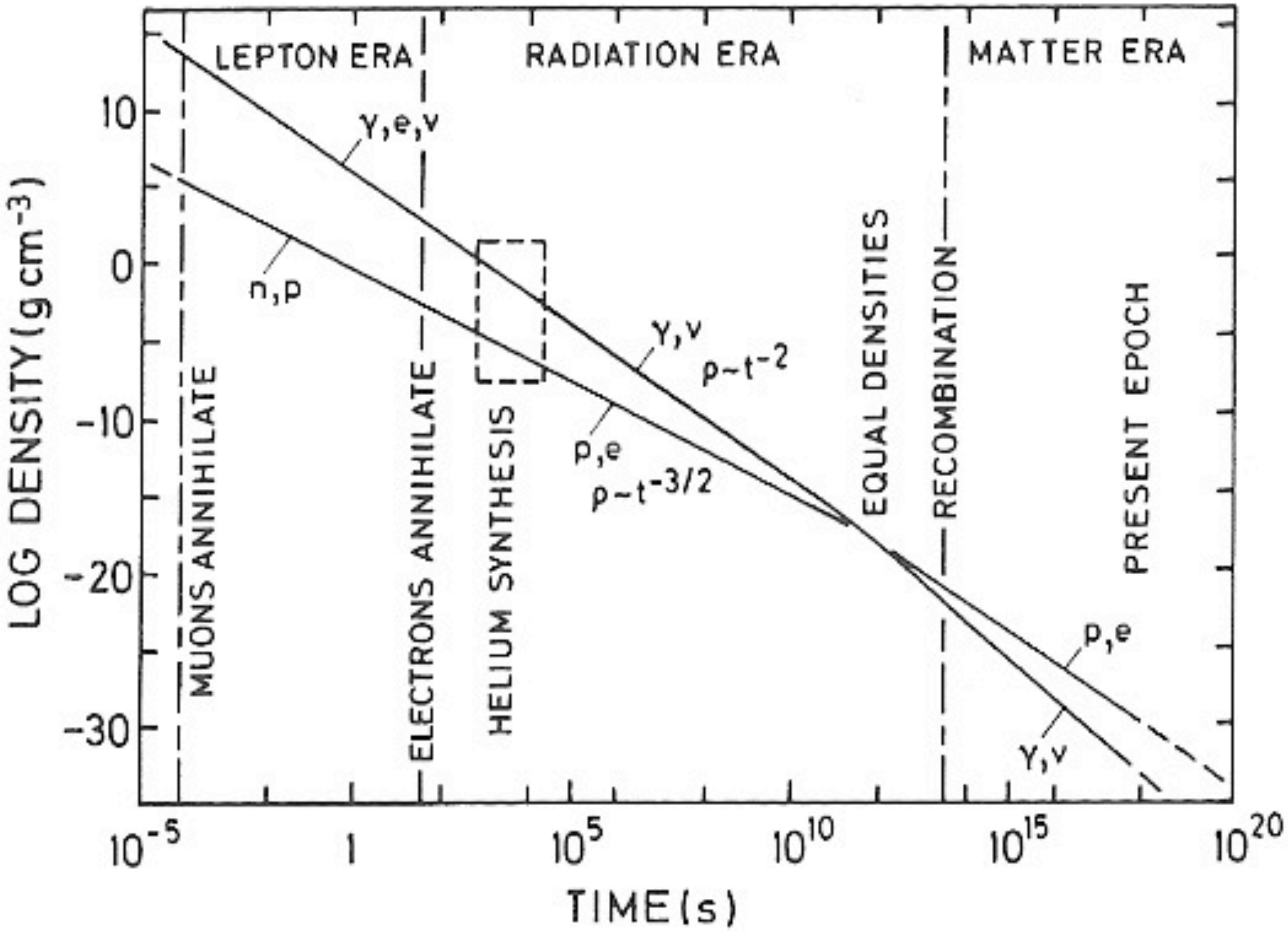
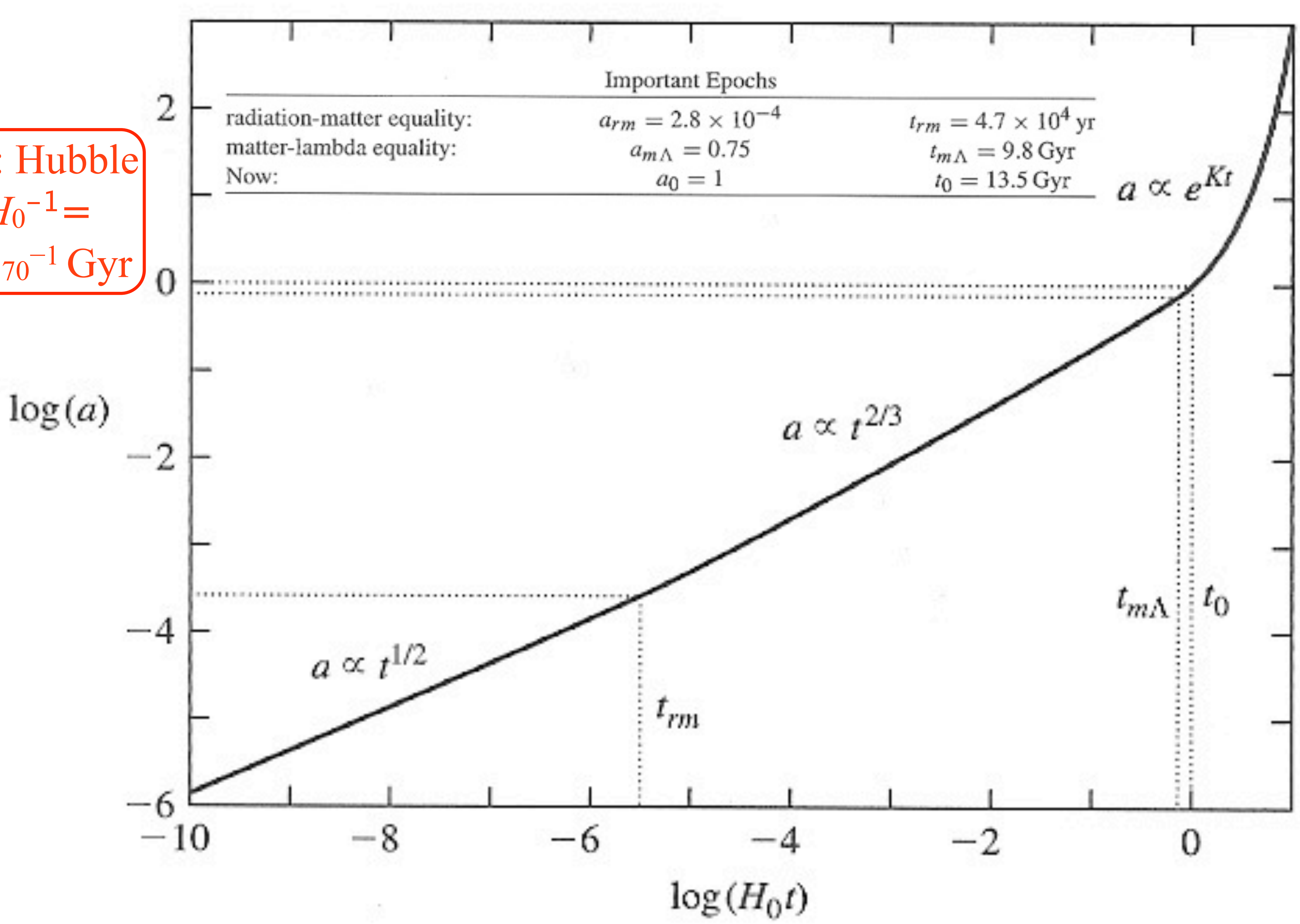


Fig. 3.1. The thermal history of the standard model. The densities of protons, electrons, photons, and neutrinos are shown at various stages of cosmological evolution [after Harrison (1973)]

Börner, *Early Universe* 4th Ed, p. 152

Benchmark Model: Scale Factor vs. Time

Recall: Hubble time $H_0^{-1} = 13.97 h_{70}^{-1}$ Gyr

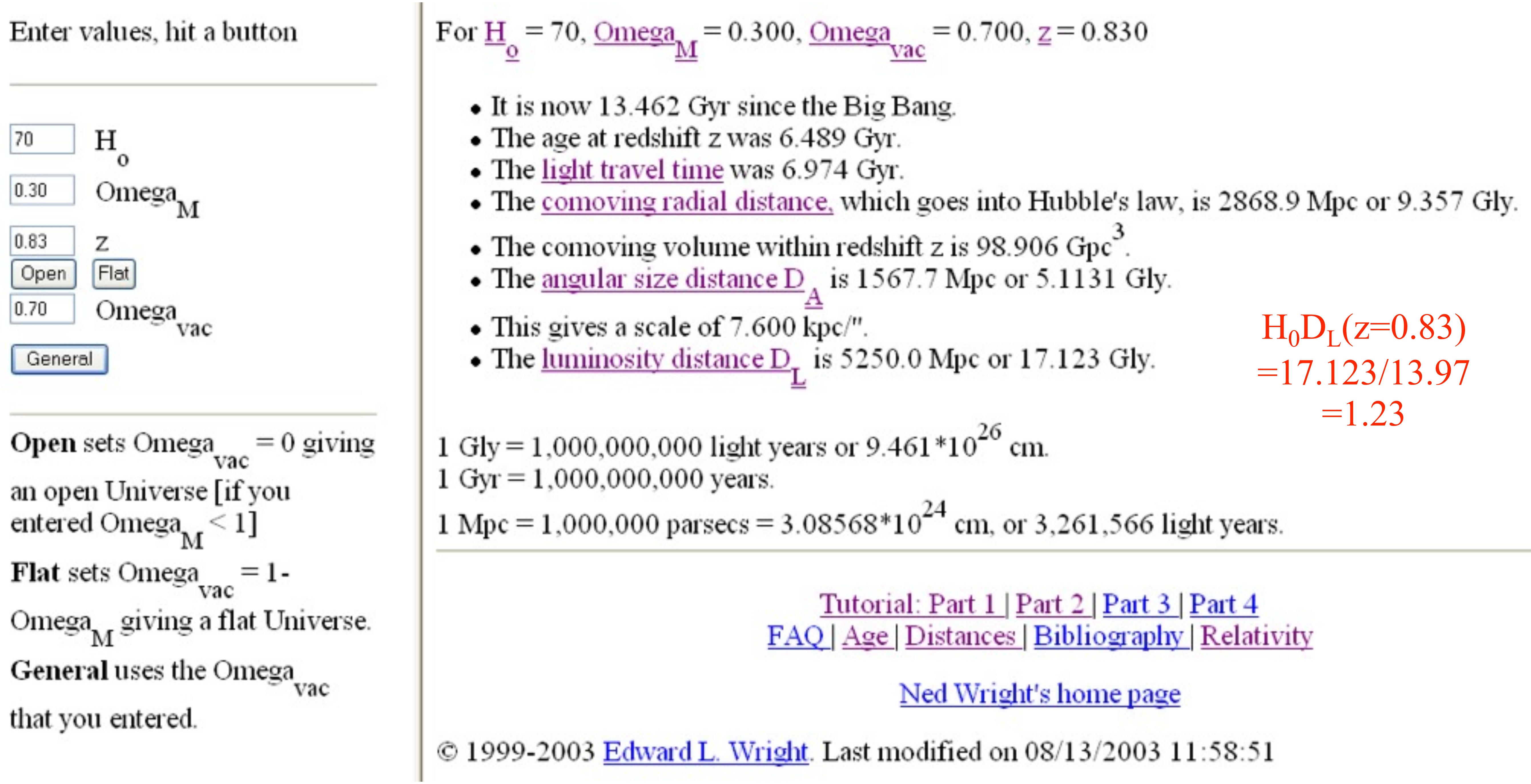


radiation-matter equality:	$a_{rm} = 2.8 \times 10^{-4}$	$t_{rm} = 4.7 \times 10^4$ yr
matter-lambda equality:	$a_{m\Lambda} = 0.75$	$t_{m\Lambda} = 9.8$ Gyr
Now:	$a_0 = 1$	$t_0 = 13.5$ Gyr

FIGURE 6.5 The scale factor a as a function of time t (measured in units of the Hubble time), computed for the Benchmark Model. The dotted lines indicate the time of radiation-matter equality, $a_{rm} = 2.8 \times 10^{-4}$, the time of matter-lambda equality, $a_{m\Lambda} = 0.75$, and the present moment, $a_0 = 1$.

Barbara Ryden, *Introduction to Cosmology* (Addison-Wesley, 2003)

Distances in the Expanding Universe:
Ned Wright's Javascript Calculator



Enter values, hit a button

70 H_o

0.30 Omega_M

0.83 z

0.70 Omega_{vac}

Open sets $\text{Omega}_{vac} = 0$ giving an open Universe [if you entered $\text{Omega}_M < 1$]

Flat sets $\text{Omega}_{vac} = 1 - \text{Omega}_M$ giving a flat Universe.

General uses the Omega_{vac} that you entered.

For $H_o = 70$, $\text{Omega}_M = 0.300$, $\text{Omega}_{vac} = 0.700$, $z = 0.830$

- It is now 13.462 Gyr since the Big Bang.
- The age at redshift z was 6.489 Gyr.
- The light travel time was 6.974 Gyr.
- The comoving radial distance, which goes into Hubble's law, is 2868.9 Mpc or 9.357 Gly.
- The comoving volume within redshift z is 98.906 Gpc^3.
- The angular size distance D_A is 1567.7 Mpc or 5.1131 Gly.
- This gives a scale of 7.600 kpc/".
- The luminosity distance D_L is 5250.0 Mpc or 17.123 Gly.

1 Gly = 1,000,000,000 light years or 9.461×10^{26} cm.

1 Gyr = 1,000,000,000 years.

1 Mpc = 1,000,000 parsecs = 3.08568×10^{24} cm, or 3,261,566 light years.

Tutorial: Part 1 | Part 2 | Part 3 | Part 4
FAQ | Age | Distances | Bibliography | Relativity

Ned Wright's home page

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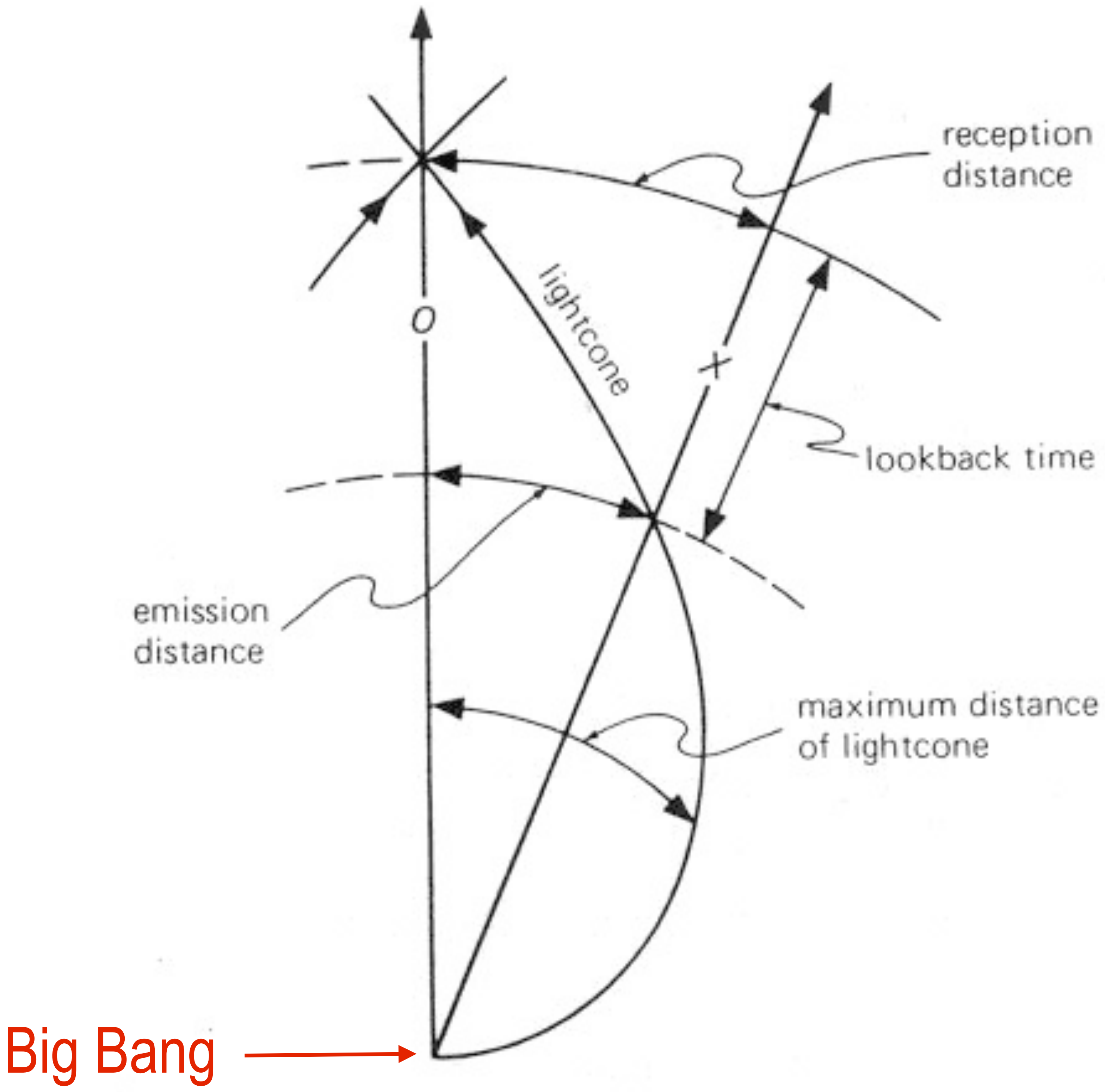
$H_0D_L(z=0.83)$
$=17.123/13.97$
$=1.23$

Web app http://www.astro.ucla.edu/~wright/CosmoCalc.html

iPhone app http://itunes.apple.com/us/app/cosmocalc/id334569654?mt=8

Picturing the History of the Universe: The Backward Lightcone



From E. Harrison, *Cosmology* (Cambridge UP, 2000).

Our Particle Horizon

FRW: $ds^2 = -c^2\, dt^2 + a(t)^2\, [dr^2 + r^2\, d\theta^2 + r^2 \sin^2\theta\ \ d\phi^2]$ for curvature $k=0$ so $\sqrt{g_{rr}} = a(t)$

Particle Horizon

$$\mathbf{d_p}(\text{horizon}) = (\text{physical distance at time } t_0) = a(t_0)\, r_p = r_p$$

$$\mathbf{d_p}(\text{horizon}) = \int_0^{r_{horizon}} dr = r_{horizon} = c\int_0^{t_0} dt/a = c\int_0^{1} da/(a^2H)$$

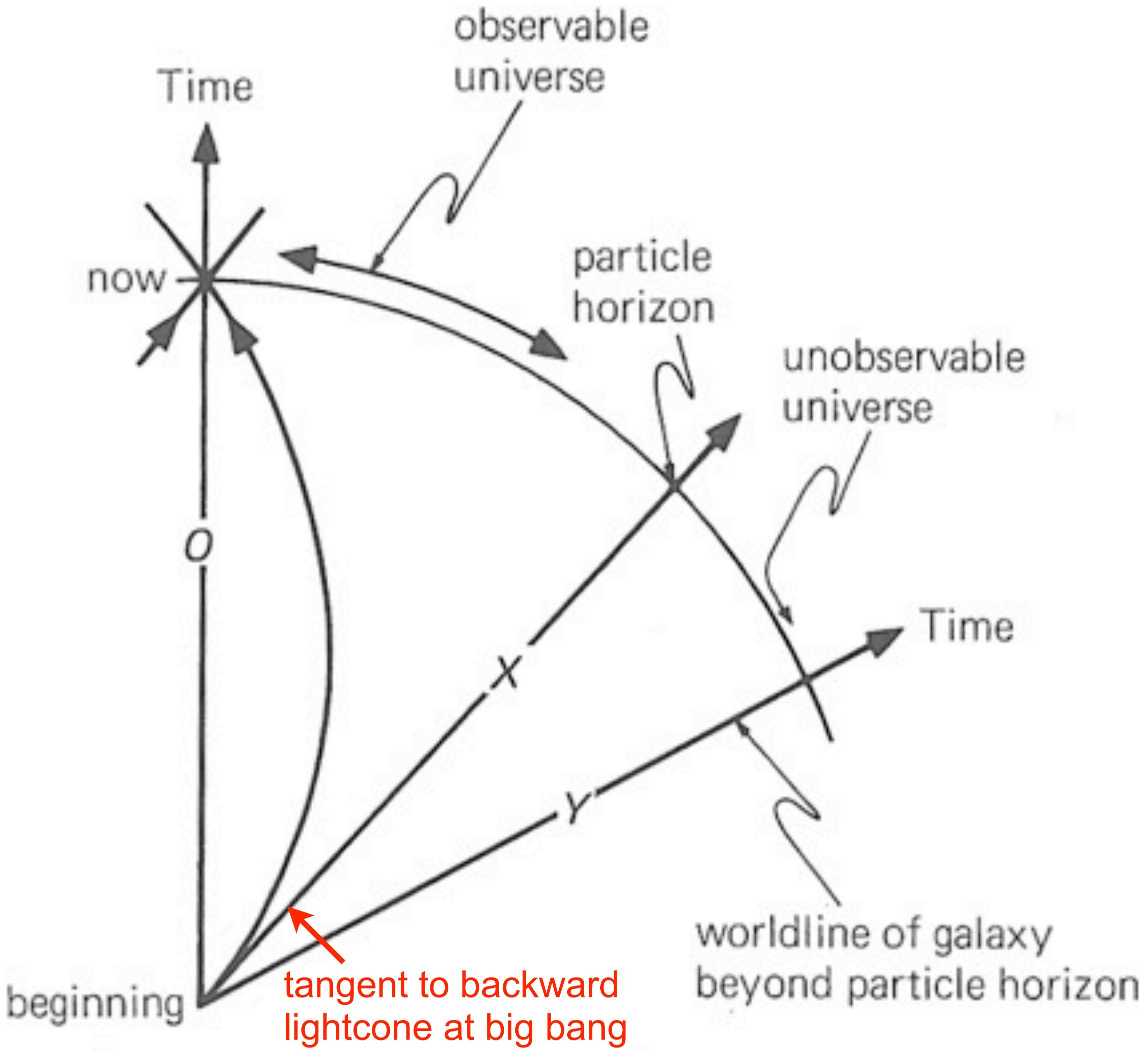
For E-dS, where $H = H_0\, a^{-3/2}$,

$$r_{horizon} = \lim_{a_e \to 0} 2d_H\,(1-a_e^{1/2}) = 2d_H =$$

$$= 8.58\ h_{70}^{-1}\ \text{Gpc} = 27.94\ h_{70}^{-1}\ \text{Glyr}$$

For the Benchmark Model with h=0.70,

$r_{horizon}$ = 13.9 Gpc = 45.2 Glyr.



tangent to backward lightcone at big bang

Figure 21.11. At the instant labeled "now" the particle horizon is at worldline X. In a big bang universe, all galaxies at the particle horizon have infinite redshift.

For the parameters of
WMAP5 h = 0.70, Ω_m = 0.28, k = 0, t_0 = 13.7 Gyr, $r_{horizon}$ = 14.3 Gpc = 46.5 Glyr.
WMAP7 h = 0.70, Ω_m = 0.27, k = 0, t_0 = 13.9 Gyr, $r_{horizon}$ = 14.5 Gpc = 47.1 Glyr.
Planck h = 0.67.8, Ω_m = 0.308, k = 0, t_0 = 13.8 Gyr, $r_{horizon}$ = 14.2 Gpc = 46.2 Glyr.

Distances in an Expanding Universe

Proper distance = physical distance = d_p

$d_p(t_0)$ = (physical distance at t_0) = $a(t_0)\, r_e = r_e$

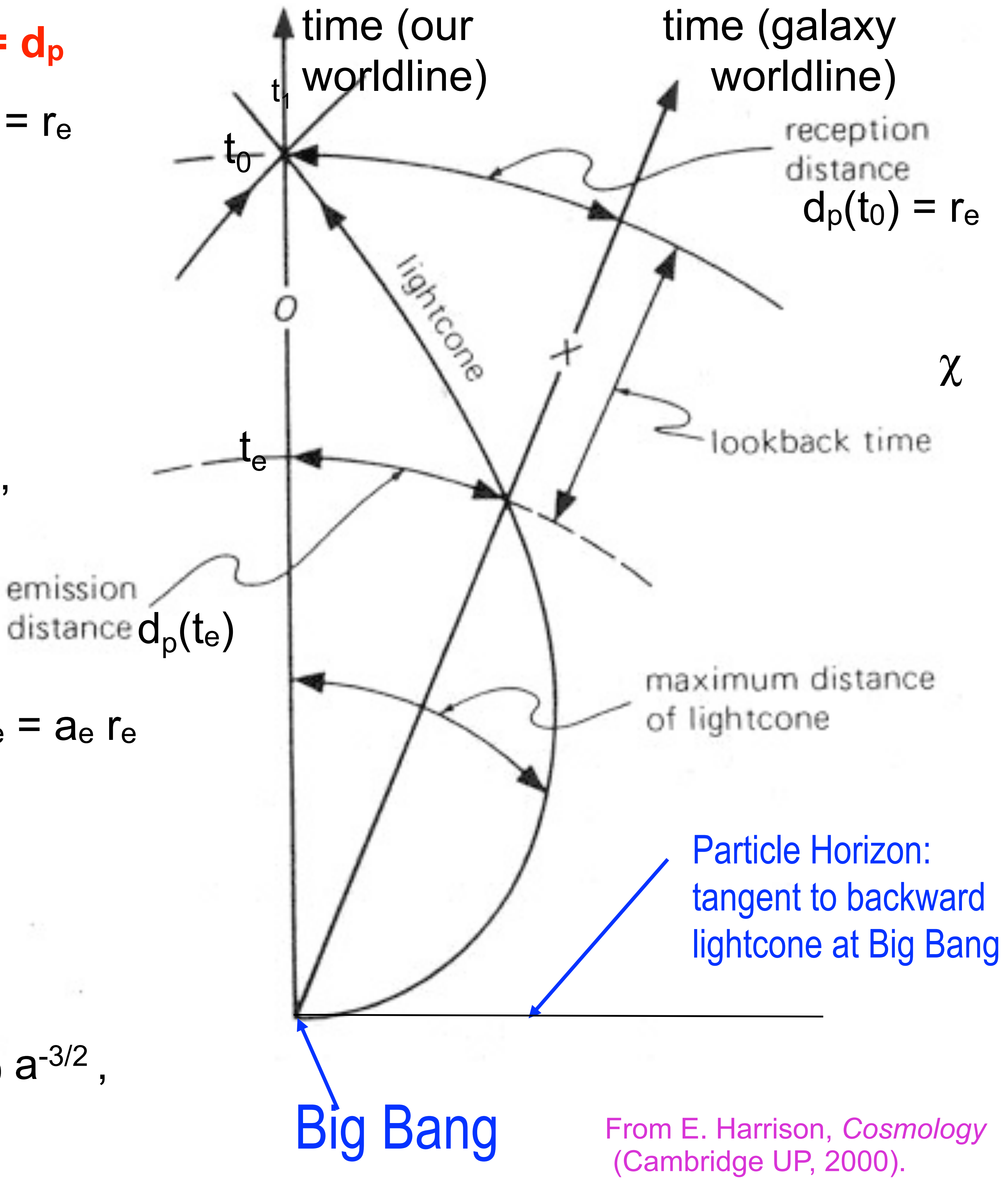
$\chi(t_e)$ = (comoving distance of galaxy emitting at time t_e) = r_e

$$\chi(t_e) = \int_0^{r_e} dr = r_e = c\int_{t_e}^{t_0} dt/a = c\int_{a_e}^{1} da/(a^2H)$$

because for light $a\,dr = c\,dt$, so $dr = c\,dt/a$,

$$dt = (dt/da)\, da = (a\, dt/da)\, da/a = da/(aH)$$

$d_p(t_e)$ = (physical distance at t_e) = $a(t_e)\, r_e = a_e\, r_e$



Particle Horizon: tangent to backward lightcone at Big Bang

From E. Harrison, *Cosmology* (Cambridge UP, 2000).

The Hubble radius $d_H \equiv c\, H_0^{-1}$=

$= 4.29\, h_{70}^{-1}$ Gpc $= 13.97 h_{70}^{-1}$ Glyr

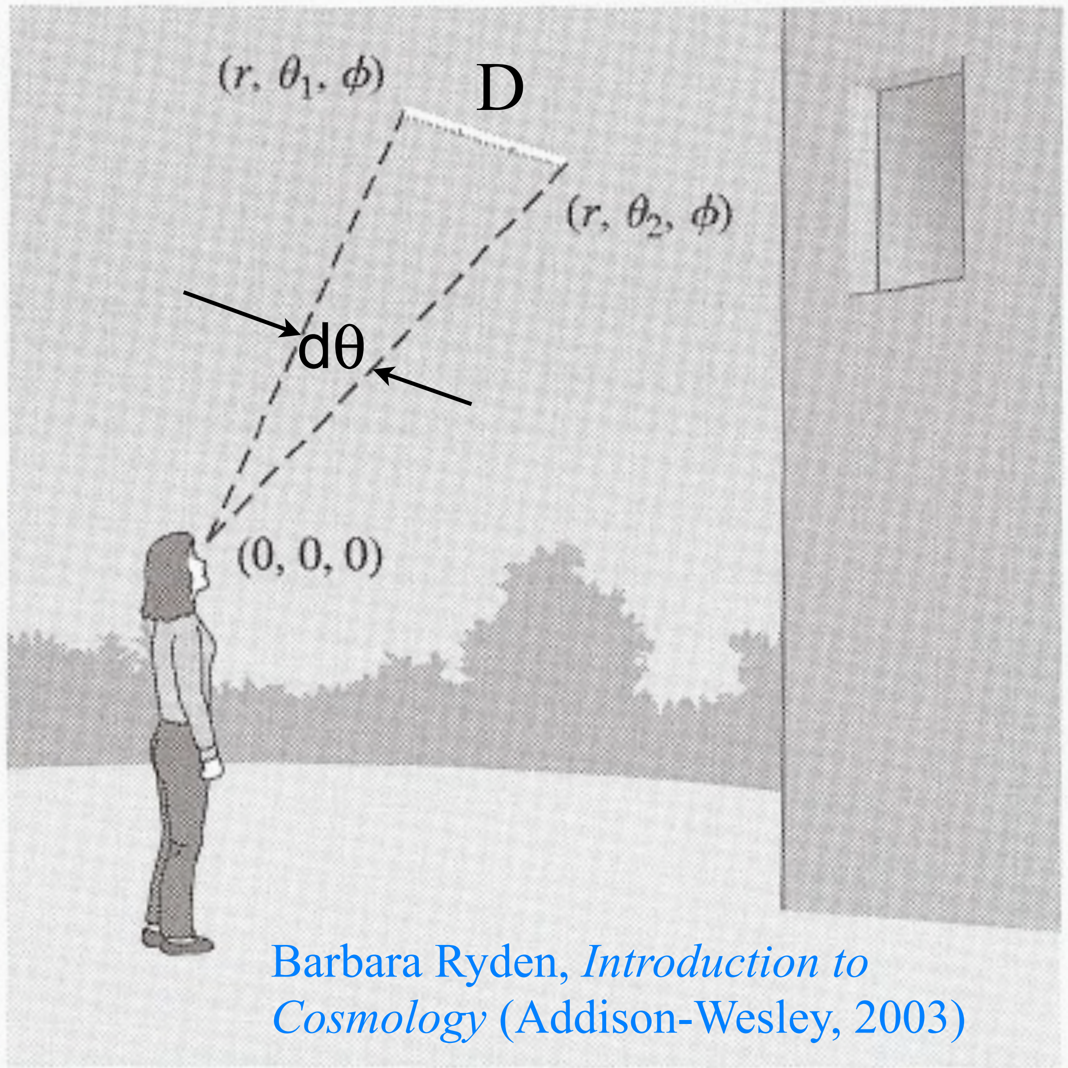
For E-dS ($\Omega_m = 1$, $\Omega_\Lambda = 0$), where $H = H_0\, a^{-3/2}$,

$$\chi(t_e) = r_e = d_p(t_0) = 2d_H\,(1 - a_e^{1/2})$$

$$d_p(t_e) = 2d_H\, a_e\,(1 - a_e^{1/2})$$

Distances in an Expanding Universe

Angular Diameter Distance



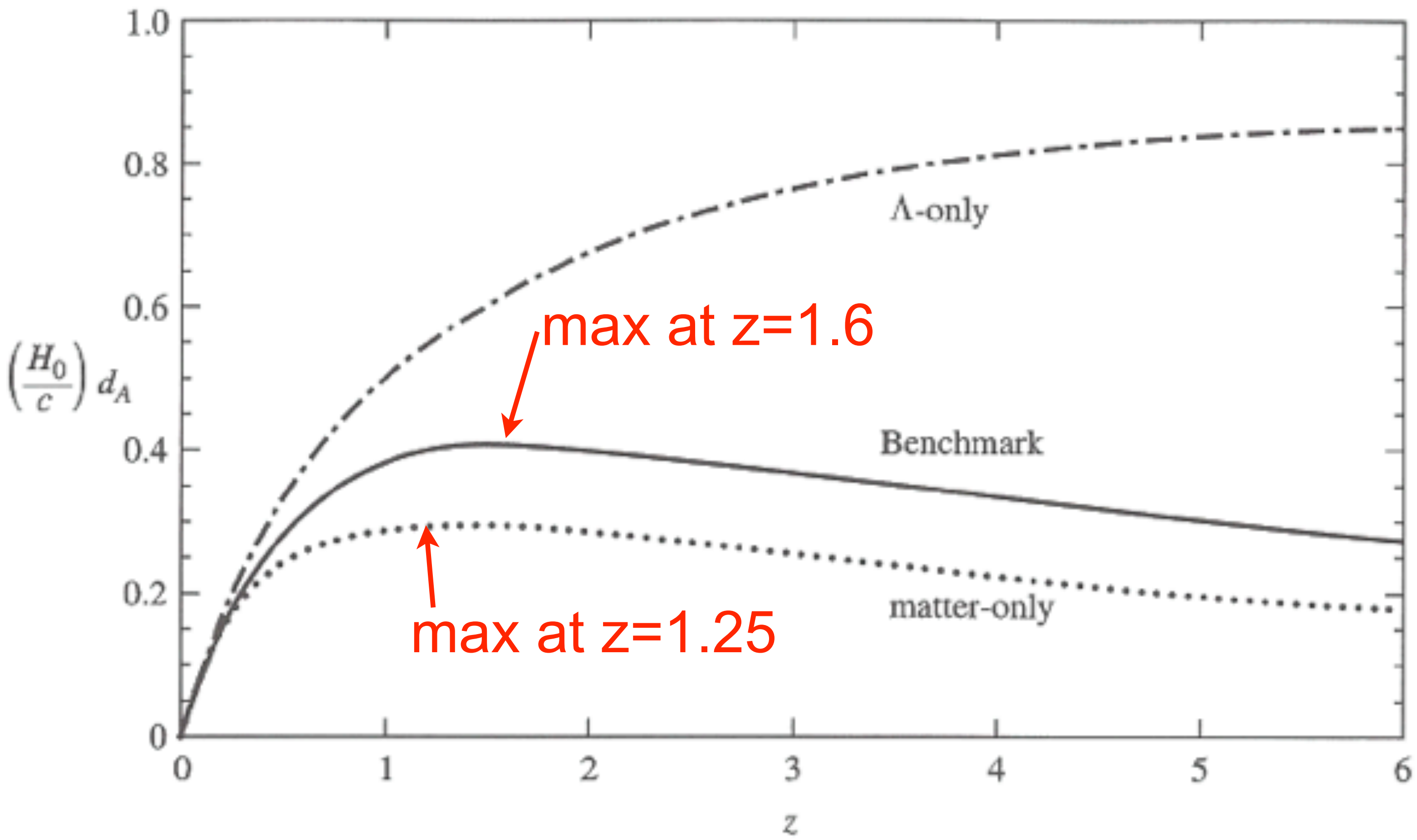
Barbara Ryden, *Introduction to Cosmology* (Addison-Wesley, 2003)

From the FRW metric, the distance D across a source at comoving distance r = r_e which subtends an angle $d\theta = \theta_1 - \theta_2$ is $D = a(t)\, r\, d\theta$, or $d\theta = D/[a(t)\, r]$.

The **angular diameter distance d_A** is defined by $d_A = D/d\theta$, so

$$\mathbf{d_A = a(t_e)\, r_e = r_e/(1+z_e) = d_p(t_e)}\ .$$

This has a maximum, and $d\theta$ a minimum.



max at z=1.6

max at z=1.25

For the Benchmark Model

redshift z	D↔1 arcsec
0.1	1.8 kpc
0.2	3.3
0.5	6.1
1	8.0
2	8.4
3	7.7
4	7.0
6	5.7

Distances in an Expanding Universe

In Euclidean space, the **luminosity** L of a source at distance d is related to the **apparent luminosity** ℓ by ℓ = Power / Area = $L / 4\pi d^2$

The **luminosity distance** $\mathbf{d_L}$ is defined by

$$d_L = (L / 4\pi\ell)^{1/2} .$$

Weinberg, *Cosmology*, pp. 31-32, shows that in FRW

$$\ell = \text{Power/Area} = L / 4\pi d_L^2$$

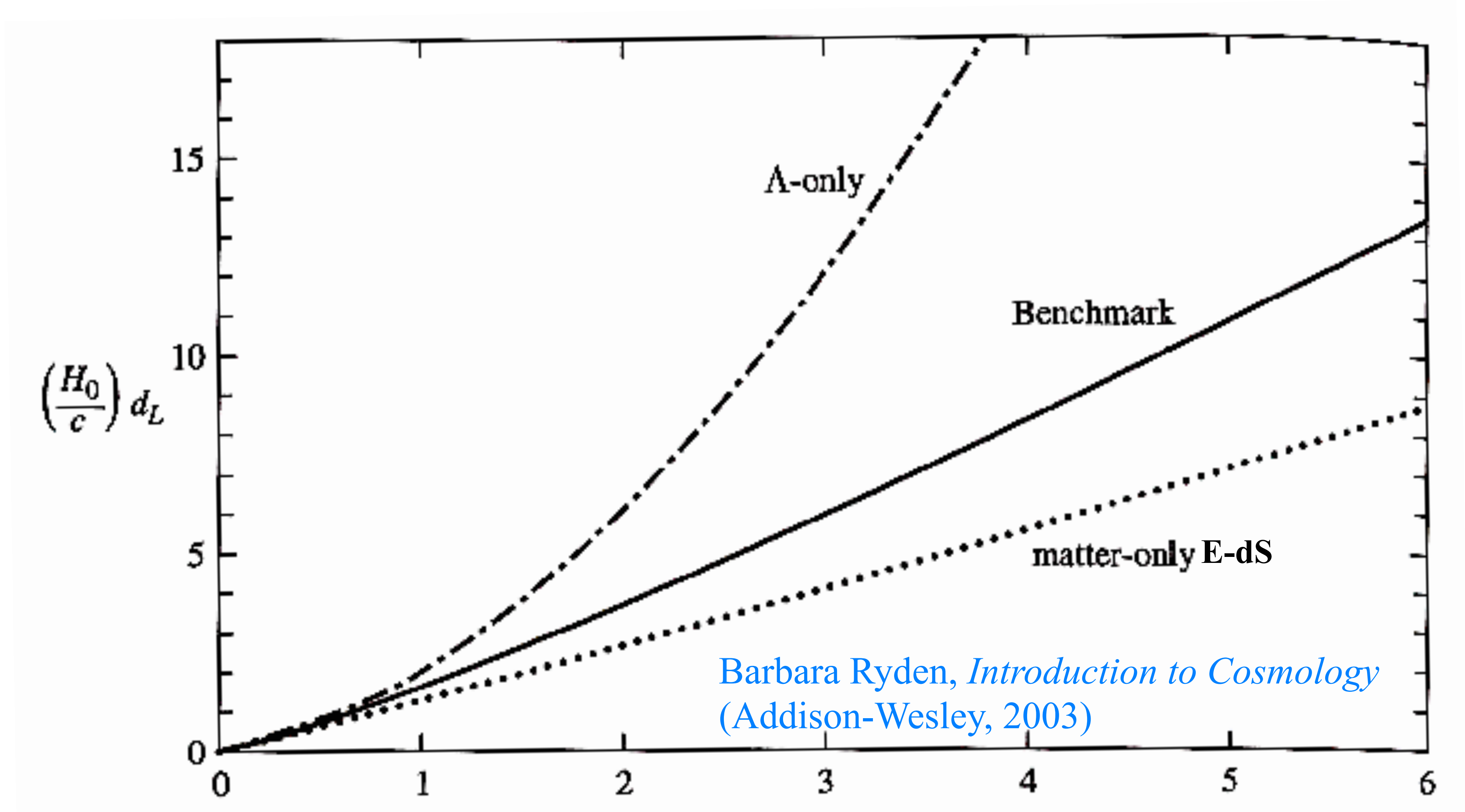
fraction of photons reaching unit area at t_0

$$= L\,[a(t_1)/a(t_0)]^2 / [4\pi d_p(t_0)^2] = L\,a(t_1)^2 / 4\pi r_1^2 = L / 4\pi r_1^2 (1+z_1)^2$$

(redshift of each photon)(delay in arrival)

Thus

$$\mathbf{d_L = r_1/a(t_1) = r_1\,(1+z_1) = d_p(t_0)\,(1+z_1) = d_A\,(1+z_1)^2}$$



Barbara Ryden, *Introduction to Cosmology* (Addison-Wesley, 2003)

Astronomers measure luminosity in magnitudes *m* or *M*, where *m*(*z*) is the apparent (measured) magnitude of a source at redshift *z* and *M* is its absolute magnitude (what it would be at a distance of 10 pc). They quote distances using the *distance modulus*

$$m(z) - M = 5 \log_{10} d_L(z) + 25$$

redshift *z* →

Summary: Distances in an Expanding Universe

FRW: $ds^2 = -c^2\,dt^2 + a(t)^2\,[dr^2 + r^2\,d\theta^2 + r^2 \sin^2\theta\ \ d\phi^2]$ for curvature $k=0$ so $\sqrt{g_{rr}} = a(t)$

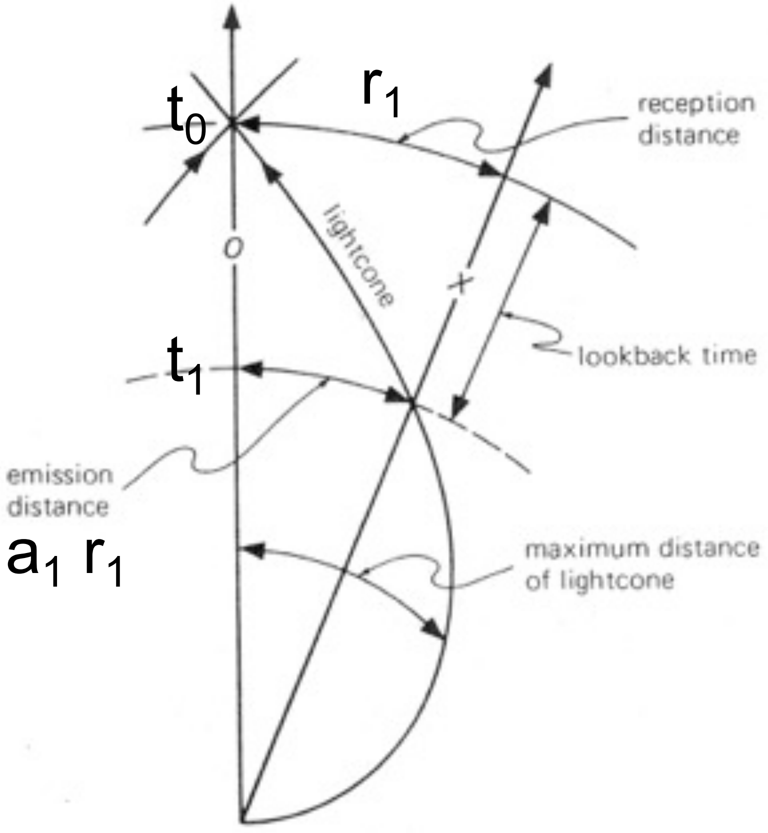
$\chi(t_1)$ = (comoving distance at time t_1) = $\int_0^{r_1} dr = r_1 = \int_{t_1}^{t_0} dt/a$

adding distances at time t_1

$d(t_1)$ = (physical distance at t_1) = $a(t_1)\,\chi(t_1) = a_1\,r_1$

$\chi(t_1)$ = (comoving distance at time t_0) = r_1 (since $a(t_0) = 1$)

$\mathbf{d_p}$ = (physical distance at time t_0) = $a(t_0)\,r_p = r_p$



From the FRW metric above, the distance D across a source at comoving distance r_1 which subtends an angle $d\theta$ is $D = a(t_1)\,r_1\,d\theta$. The **angular diameter distance $\mathbf{d_A}$** is defined by $d_A = D/d\theta$, so

$$\boxed{\mathbf{d_A = a(t_1)\,r_1 = r_1/(1+z_1)}}$$

In Euclidean space, the **luminosity** L of a source at distance d is related to the **apparent luminosity** ℓ by

$$\ell = \text{Power/Area} = L/4\pi d^2$$

$\chi(t_1)$ = (comoving distance at time t_0) = r_p

so the **luminosity distance $\mathbf{d_L}$** is defined by $d_L = (L/4\pi\ell)^{1/2}$.

Weinberg, *Cosmology*, pp. 31-32, shows that in FRW

$$\ell = \text{Power/Area} = L\,[a(t_1)/a(t_0)]^2\,[4\pi a(t_0)^2\,r_1^2]^{-1} = L/4\pi d_L^2$$

fraction of photons reaching unit area at t_0

(redshift of each photon)(delay in arrival)

Thus

$$\boxed{\mathbf{d_L = r_1/a(t_1) = r_1\,(1+z_1)}}$$

Horizons

$$ds^2 = dt^2 - dX^2 = dt^2 - R^2 dx^2 = R^2(d\eta^2 - dx^2)$$

conformal time $d\eta = dt/R$ comoving coord. $dx = dX/R$

PARTICLE HORIZON

Spherical surface that at time t separates ***worldlines*** into observed vs. unobserved

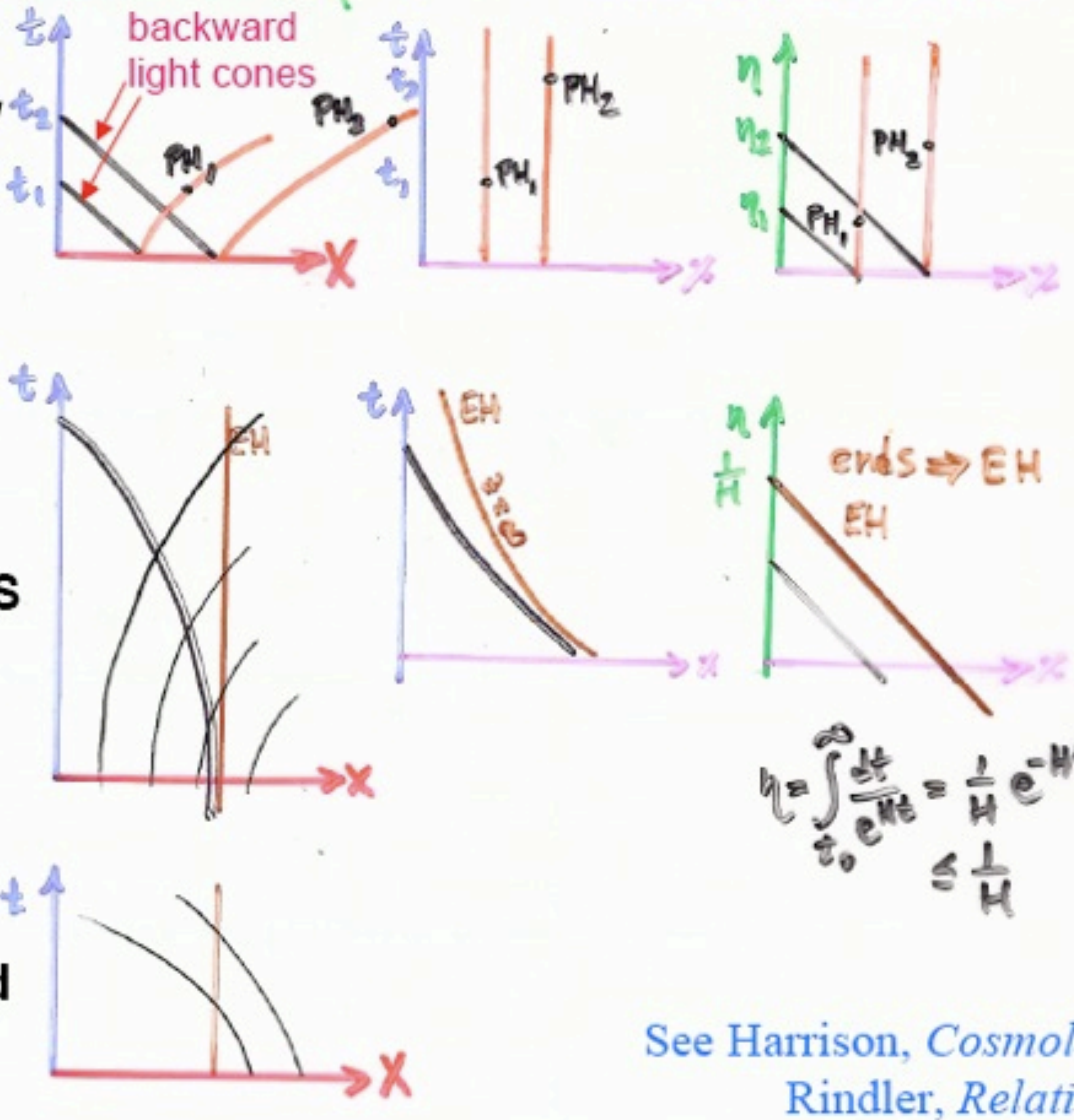
EVENT HORIZON

Backward lightcone that separates *events* that will someday be observed from those never observed

FRW

deS

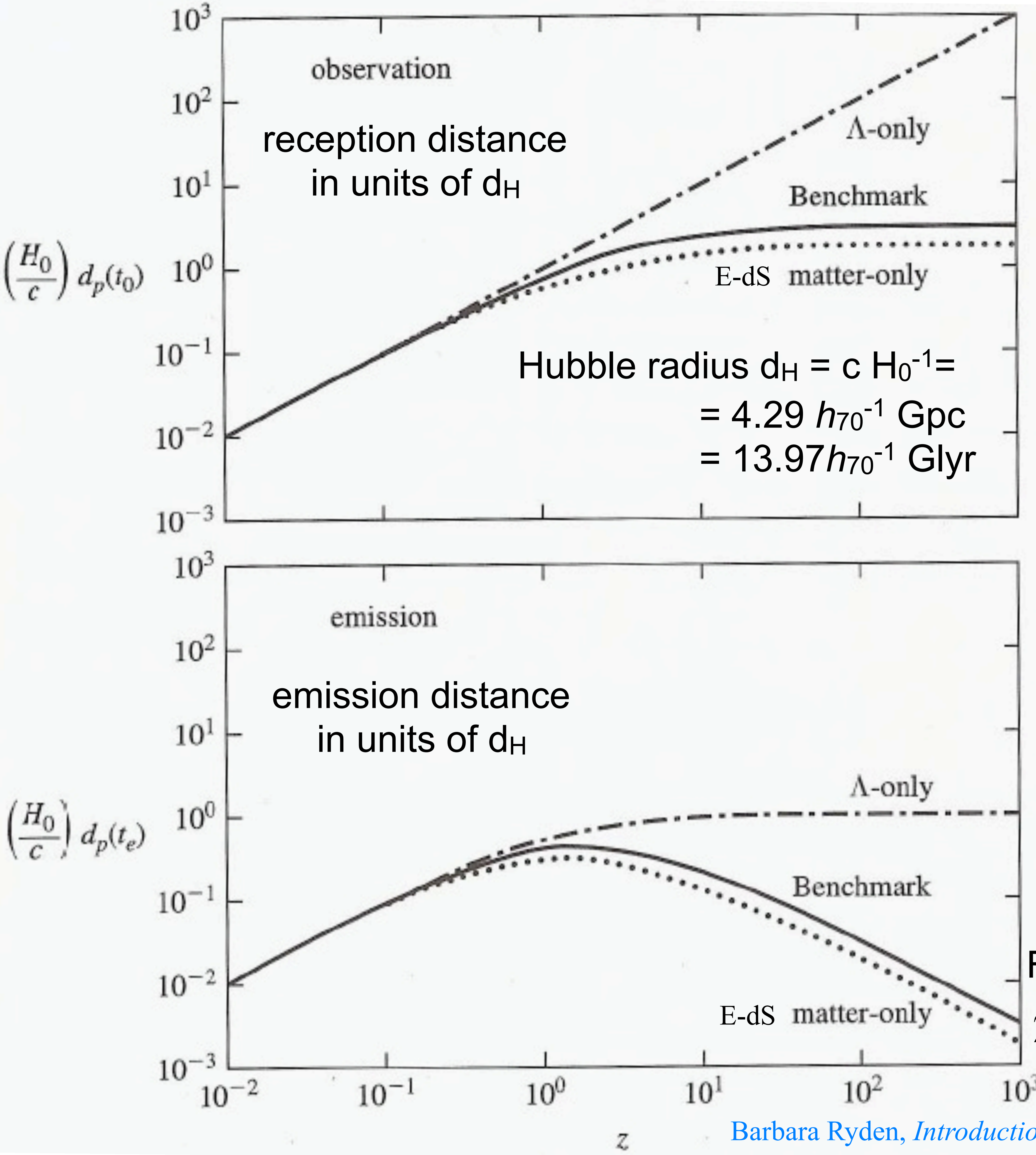
Schwarzschild



$$\eta = \int_{t_0}^{\infty} \frac{dt}{e^{Ht}} = \frac{1}{H} e^{-Ht_0} \leq \frac{1}{H}$$

See Harrison, *Cosmology*
Rindler, *Relativity*

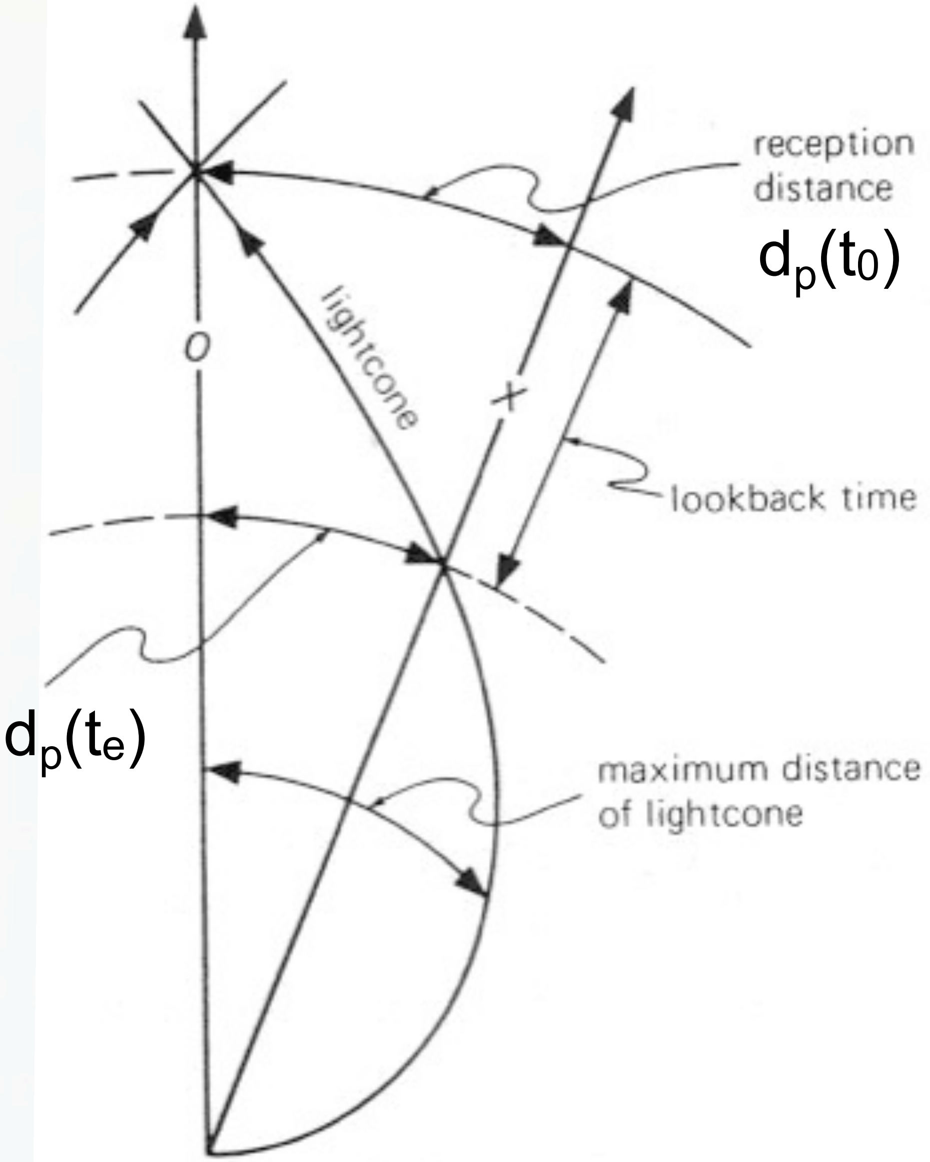
Distances in an Expanding Universe



reception distance
in units of d_H

Hubble radius $d_H = c\, H_0^{-1} =$
$= 4.29\ h_{70}^{-1}$ Gpc
$= 13.97 h_{70}^{-1}$ Glyr

emission distance
in units of d_H



For E-dS, where $H = H_0\ a^{-3/2}$,

$$\chi(t_e) = r_e = d_p(t_0) = 2 d_H\ (1 - a_e^{1/2})$$

$$d_p(t_e) = 2 d_H\ a_e\ (1 - a_e^{1/2})$$

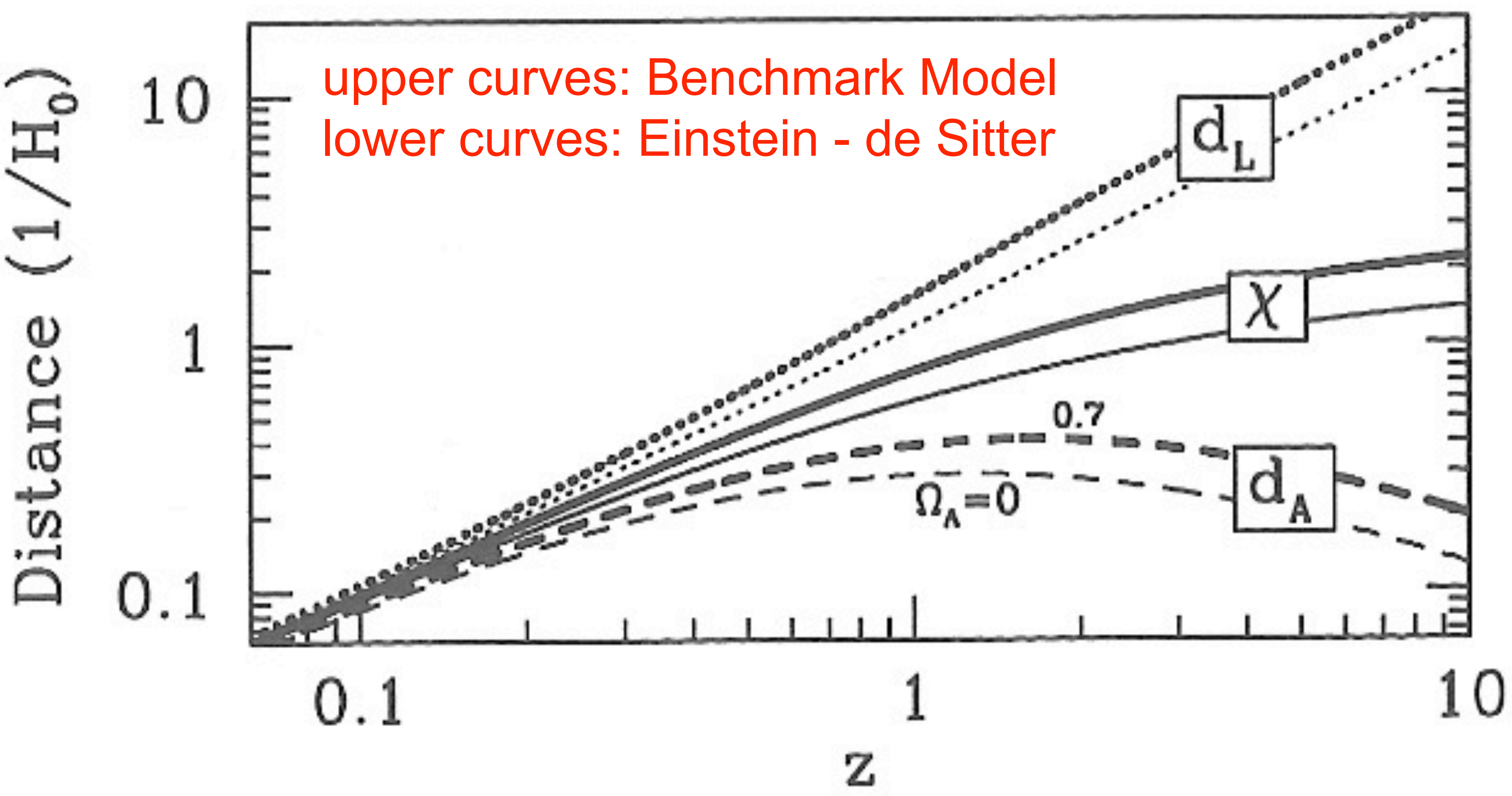
Barbara Ryden, *Introduction to Cosmology* (Addison-Wesley, 2003)

Distances in a Flat (k=0) Expanding Universe

$\chi(t_1)$ = (comoving distance at time t_1) = r_1

$d_A = a(t_1)\, r_1 = r_1/(1+z_1)$

$d_L = r_1/a(t_1) = r_1\,(1+z_1)$



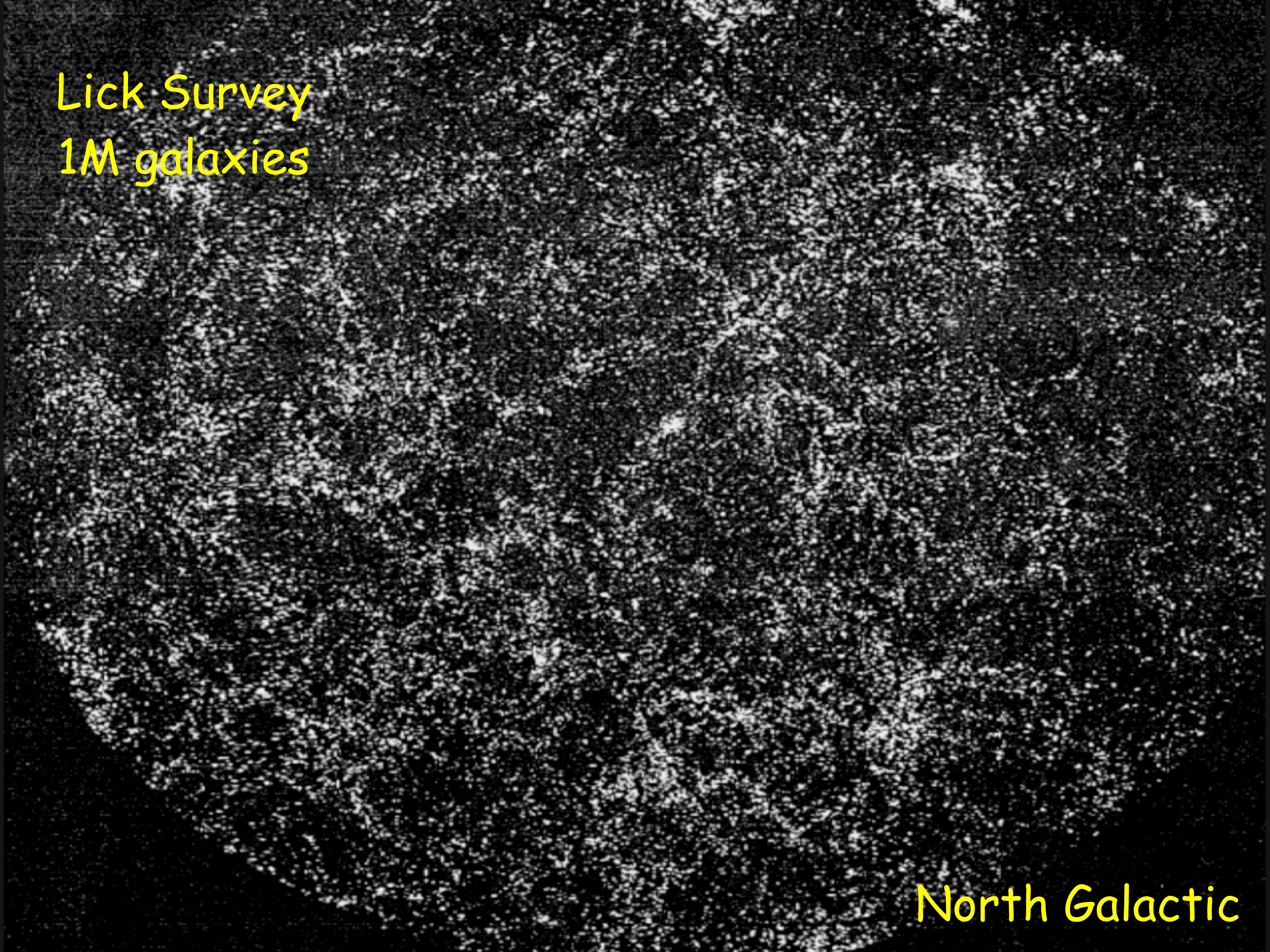
upper curves: Benchmark Model
lower curves: Einstein - de Sitter

Figure 2.3. Three distance measures in a flat expanding universe. From top to bottom, the luminosity distance, the comoving distance, and the angular diameter distance. The pair of lines in each case is for a flat universe with matter only (light curves) and 70% cosmological constant Λ (heavy curves). In a Λ-dominated universe, distances out to fixed redshift are larger than in a matter-dominated universe.

Scott Dodelson, *Modern Cosmology* (Academic Press, 2003)

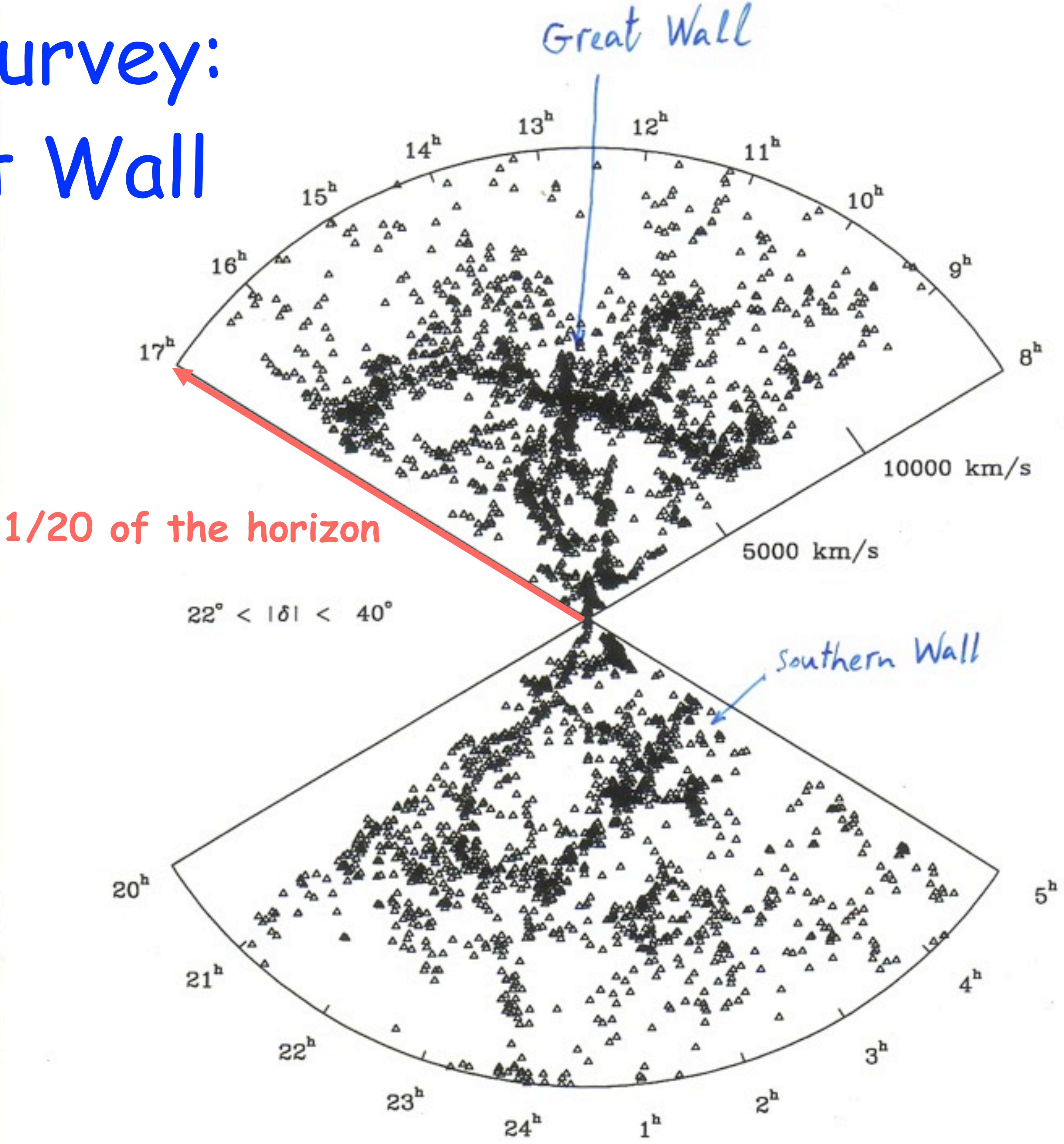
Mapping the large scale structure of the universe ...

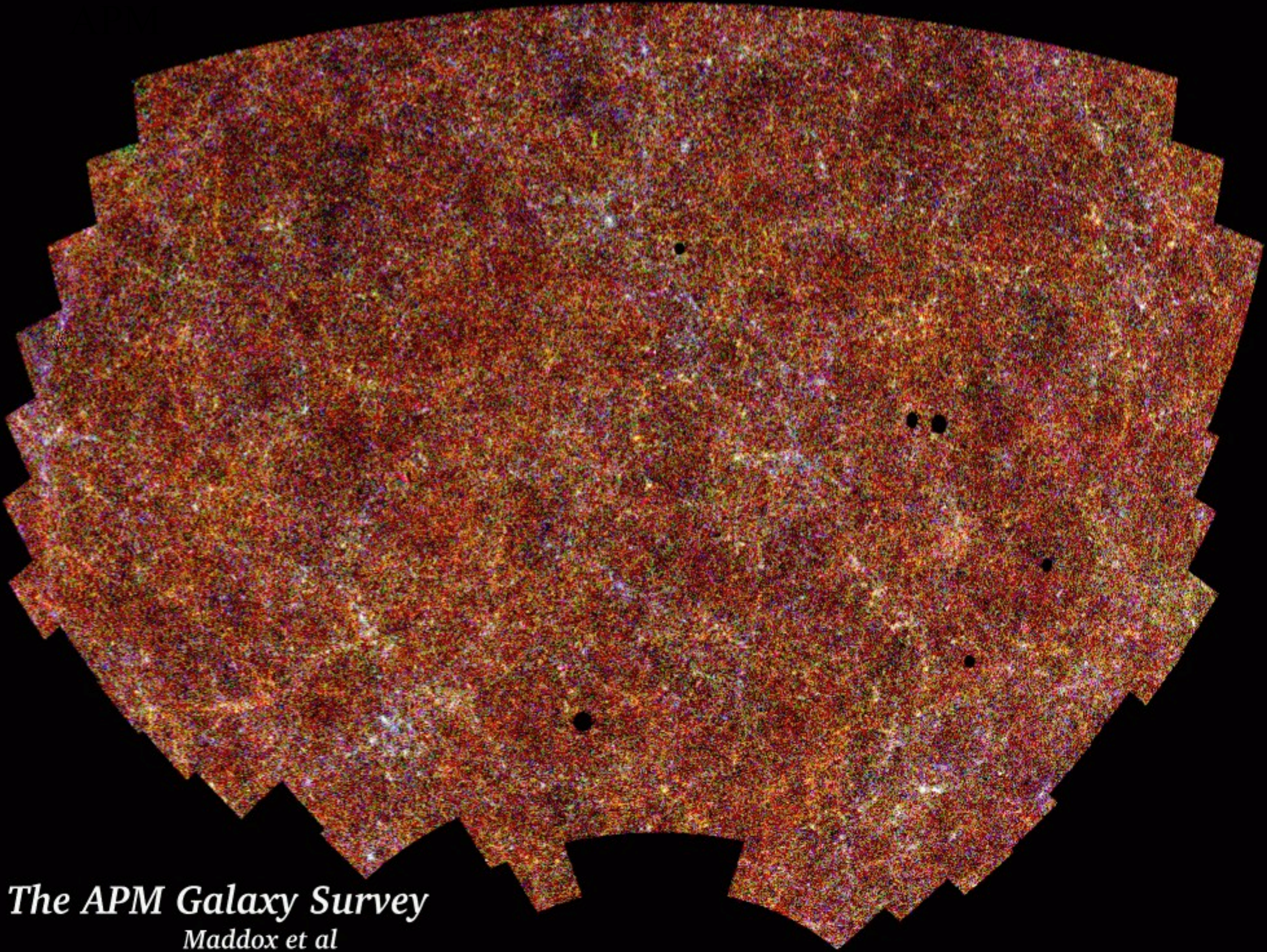
Lick Survey
1M galaxies



North Galactic

CfA survey: Great Wall

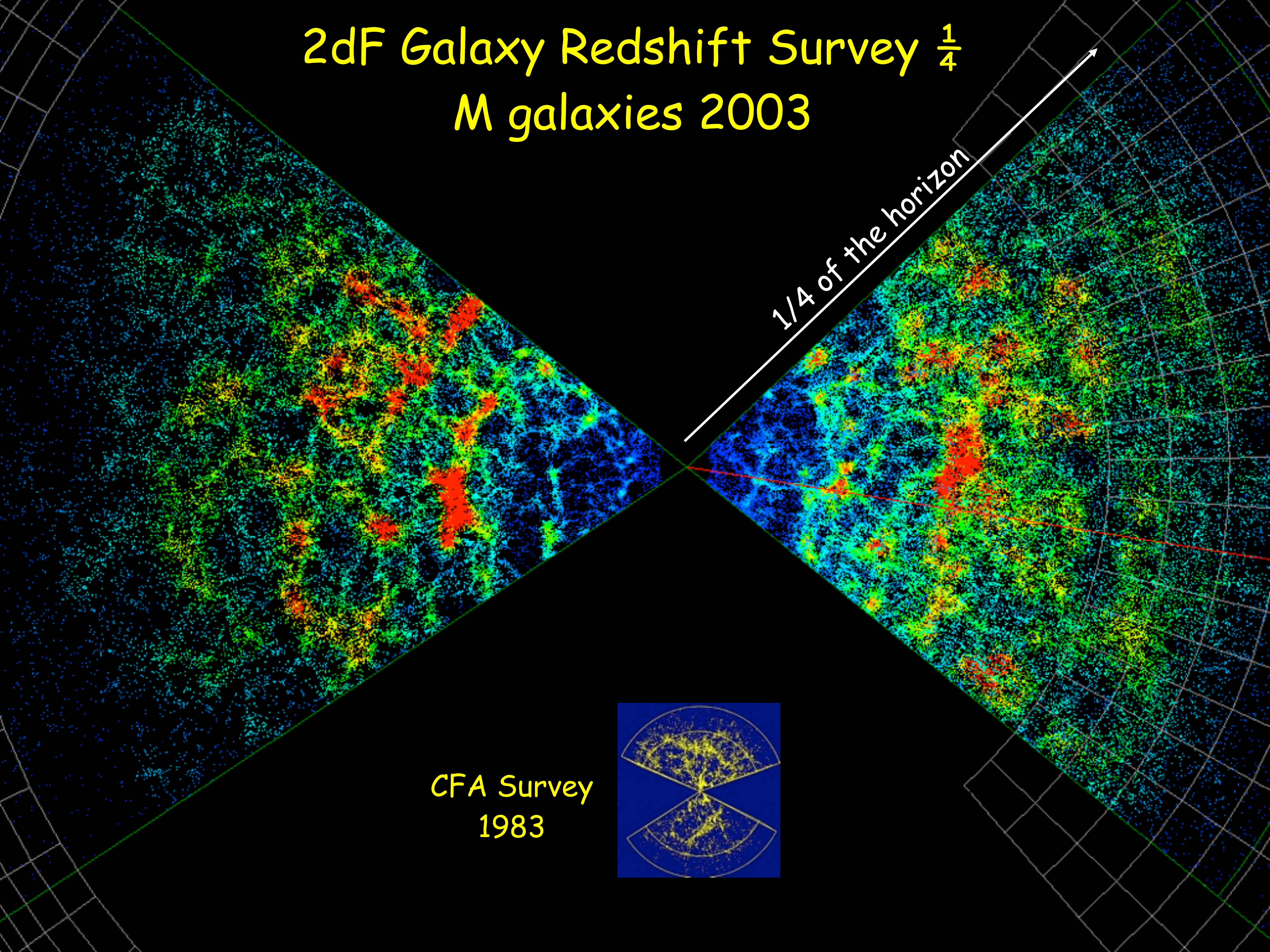




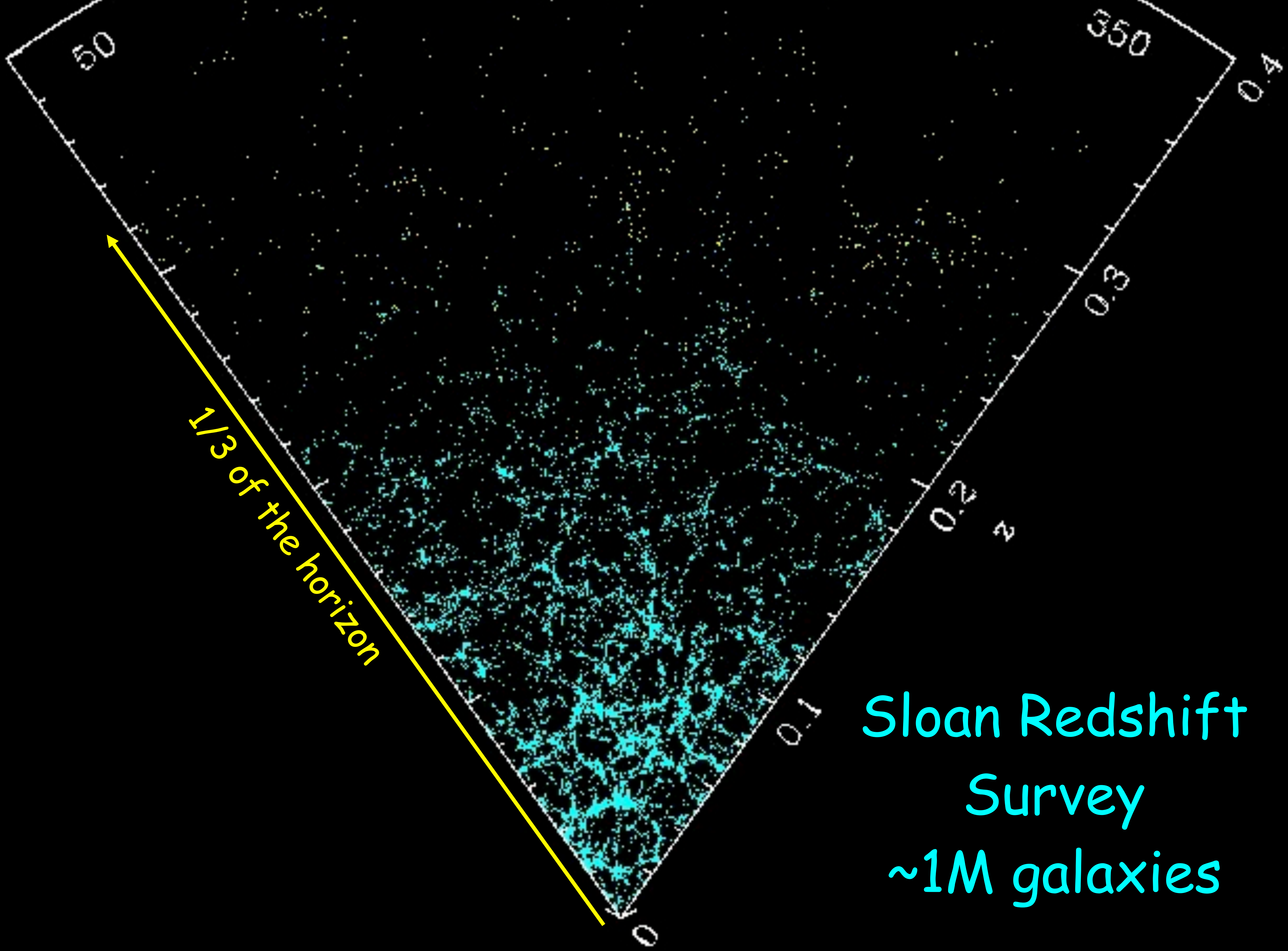
The APM Galaxy Survey

Maddox et al

2dF Galaxy Redshift Survey ¼ M galaxies 2003



CFA Survey
1983

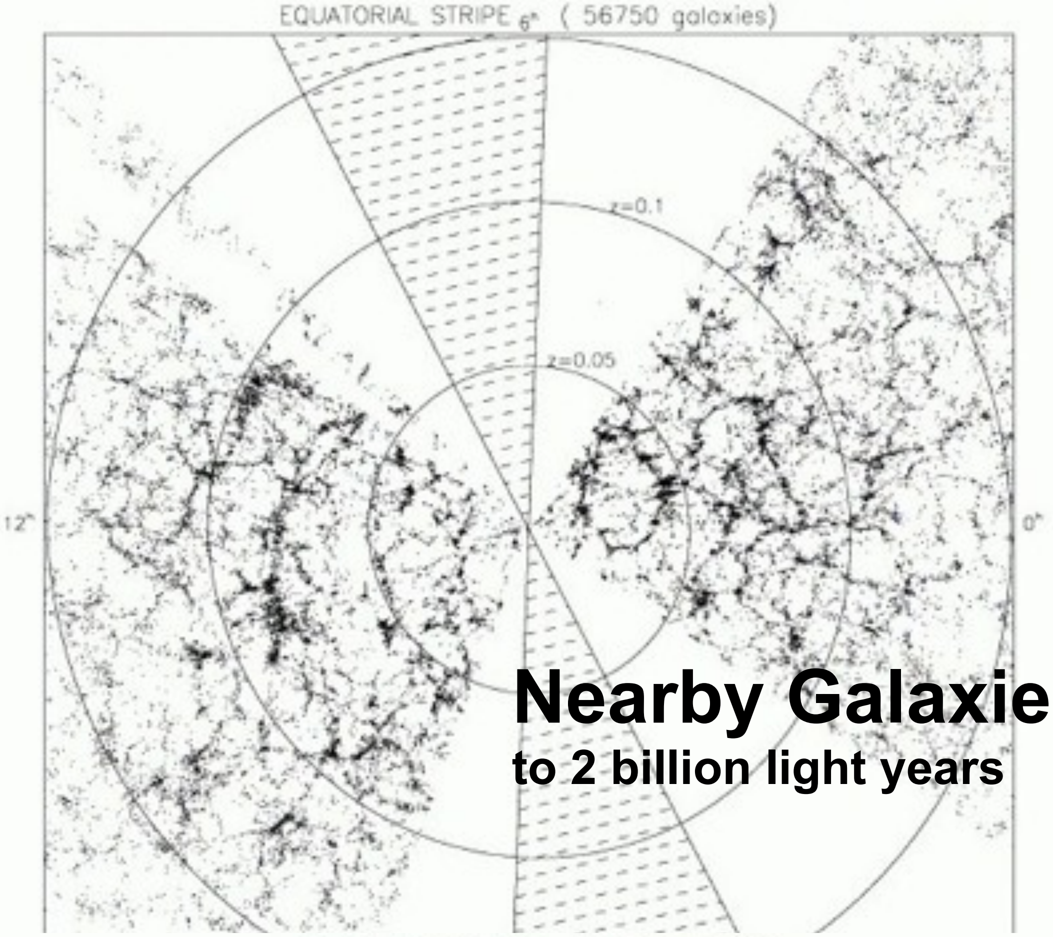


1/3 of the horizon

Sloan Redshift Survey

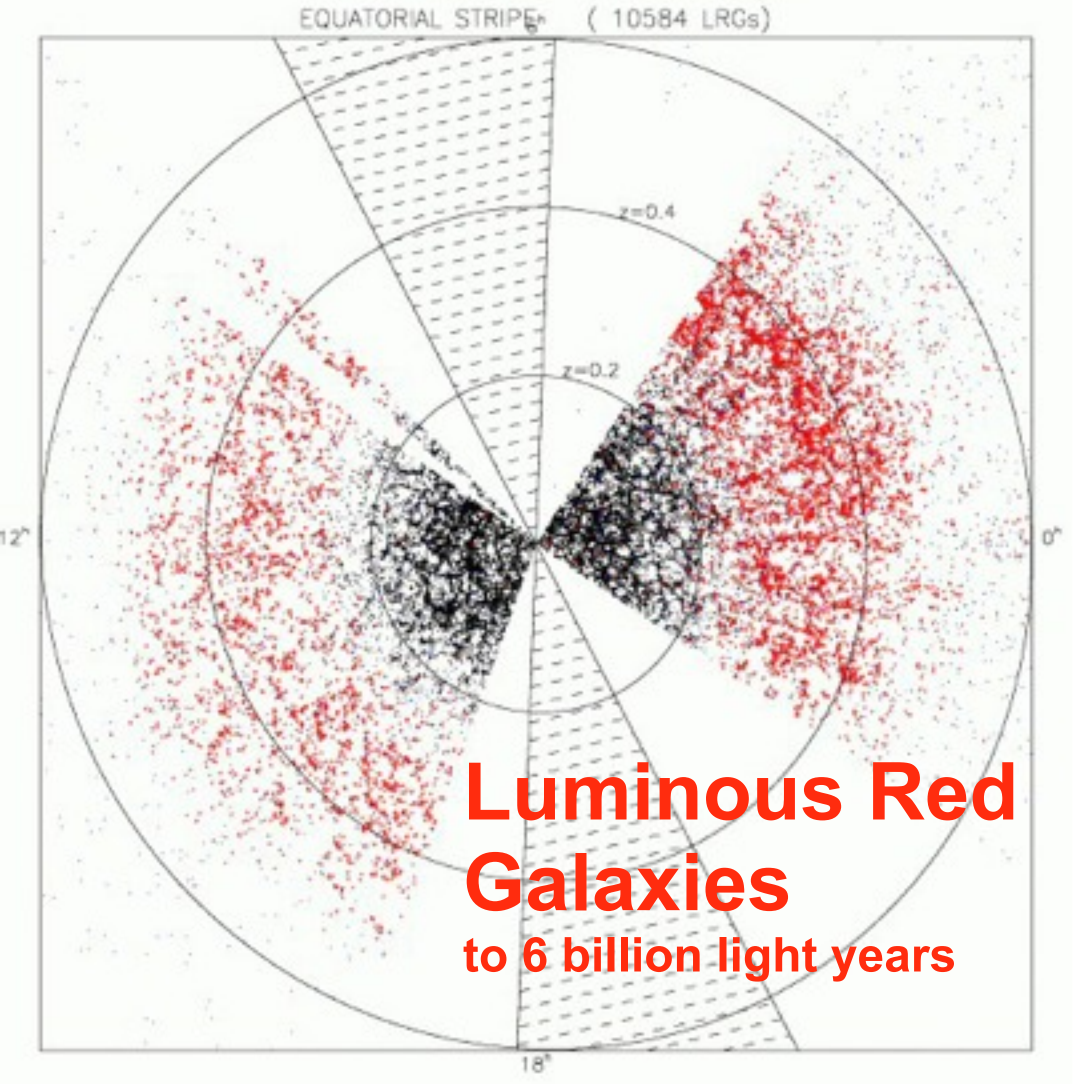
~1M galaxies

Mapping the Galaxies
Sloan Digital Sky Survey



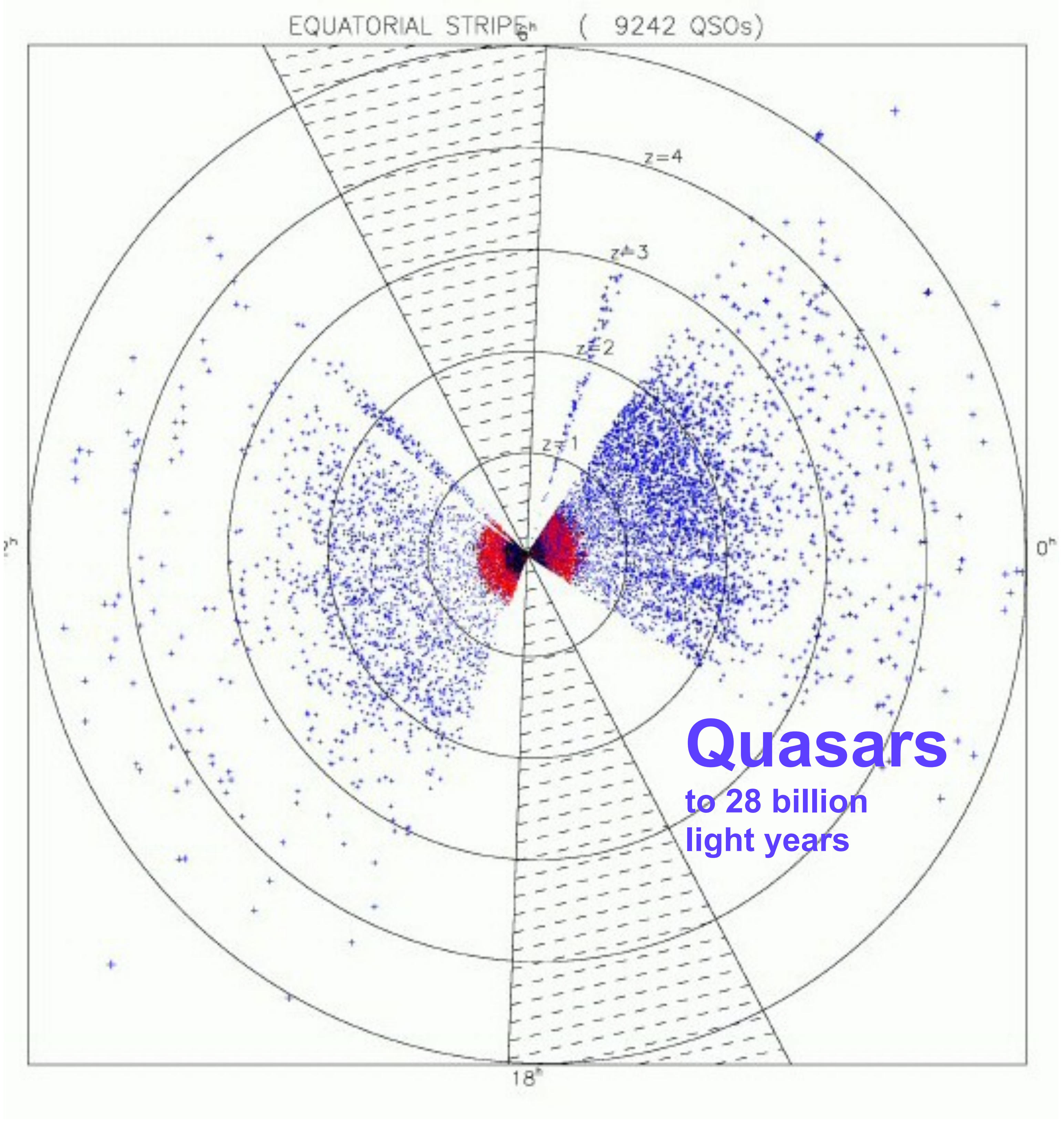
Nearby Galaxies

to 2 billion light years



Luminous Red Galaxies

to 6 billion light years



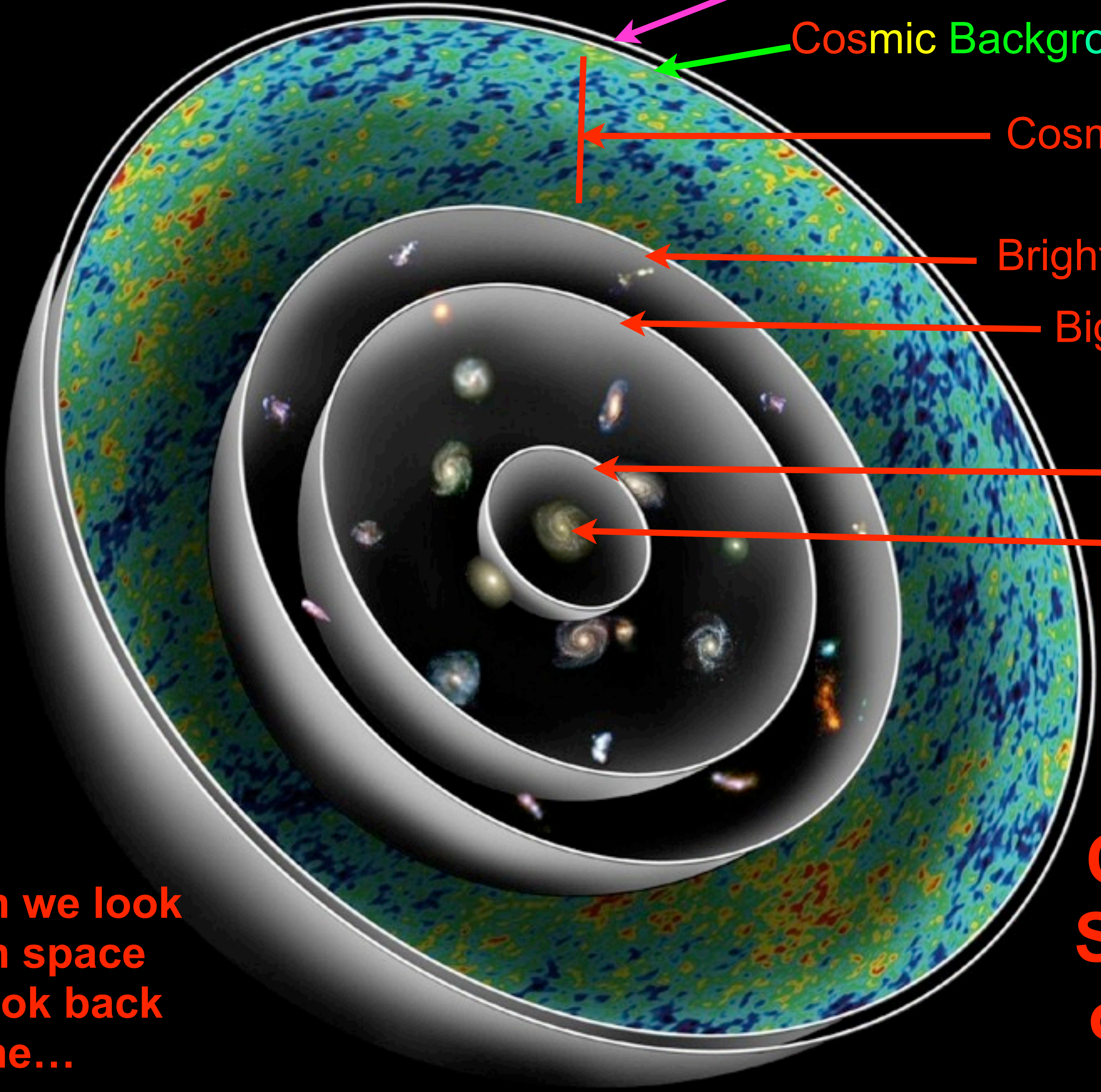
Quasars

to 28 billion light years

GALAXIES MAPPED BY THE SLOAN SURVEY

Data Release 4:
565,715 Galaxies & 76,403 Quasars

Cosmic Spheres of Time



Cosmic Horizon (The Big Bang)

Cosmic Background Radiation

Cosmic Dark Ages

Bright Galaxies Form

Big Galaxies Form

Earth Forms

Milky Way

When we look out in space we look back in time…