BIG UNIVERSE — LARGE TELESCOPES

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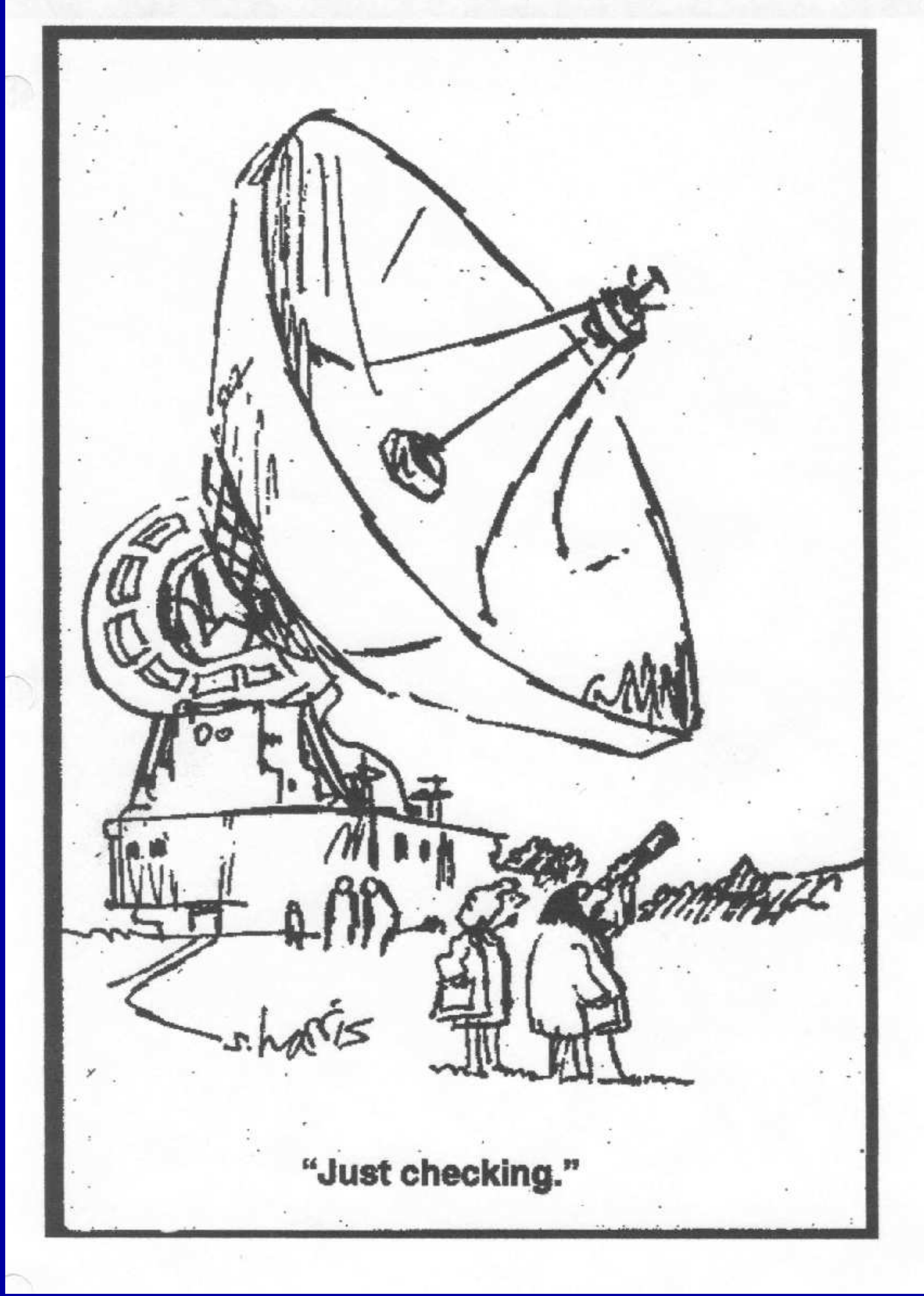
Dept. of Geological Sciences, Arizona State University, April 6, 2005



Why radio astronomers do optical identifications ...

How astronomy and telescopes may fit into SESE ...

Outline

(0) Brief Tutorial on Cosmology

(1) BIG UNIVERSE: Evidence for the "Hot Big Bang"

- (1a) Cosmological distance measurements
- (1b) The Hubble Expansion and Age of the Universe
- (1c) The Cosmic microwave Background Radiation (CBR)
- (1d) Light Element production predicted by Hot Big Bang

(2) LARGE TELESCOPES: Why needed, what do they do, and how?

- (2a) Large Optical–IR Telescopes
- (2b) Radio Telescopes and Radio Interferometers
- (2c) A Low-frequency Interferometer on the Moon's far-side

(3) Conclusions

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0. Simplified Summary of Quantities and Units Used

Property	Units Used	Range Used
Distance or Size	Gpc $= 3.26 \times 10^9$ ly	nearby—far
Angular Size	arcsec	apparently small–large
Luminosity	Watts/Hz or $L_\odot$	weak—luminous
Flux	nJy (10^{-35} W/Hz/m^2)	faint—bright
Surface Brightness	nanoJansky/arcsec^2	dim—bright
Mass	$M_\odot$	light—heavy
Density	Objects/Volume (or /Area)	few—many

0. Brief Tutorial on Cosmology

Property	Euclidean Univ.	Λ-Universe (H$_o$, Ω_m, Ω_Λ)= (71, 0.27, 0.73)
A. Cosmol. Redshift	—	$\lambda_{obs}=\lambda_{rest}.(1+z)$ [$\longrightarrow$ Bandpass-shifting]
B. Hubble's Law	— —	$z \lesssim 0.1$: $d=v/H_o=(c/H_o).z=R_o.z$ $z \gtrsim 0.1$: $d=(c/H_o).d(z)=R_o.d(z)$
C. Flux vs. Dist.	$F \propto d^{-2}$ Inv. square law	$F \propto d(z)^{-2} \,.\, (1+z)^{-2}$ [Relativistic. Inv. Square law]
D. Ang. size vs. Dist.	$\Theta \propto d^{-1}$ small Θ approx.	$z \lesssim 0.1$: $\Theta \propto z^{-1}$ $z \gtrsim 2.0$: $\Theta \propto d(z)^{-1}.(1+z)$ [Relativistic Θ-z relation]

0. Brief Tutorial on Cosmology (cont.)

Property	Euclidean Univ.	Λ-Universe (H_o, Ω_m, Ω_Λ)= (71, 0.27, 0.73)
E. SB vs. Dist. ($E \equiv C/D^2$)	$SB \equiv I \propto d^0$ ($SB=I=F/\Theta^2$)	$z \gtrsim 0.1$: $SB \equiv I \propto (1+z)^{-4}$ [Cosmic SB-dimming]
F. CBR-Temp. ($E = \sigma.F^4$)	T_o=2.735K	$\forall$ z: $T = T_o.(1+z)$ [Cosmic Stephan-Boltzmann]
G. Lookback Time	$t = d/c$	$t \simeq H_o^{-1}\ .\ z/(1+z)$

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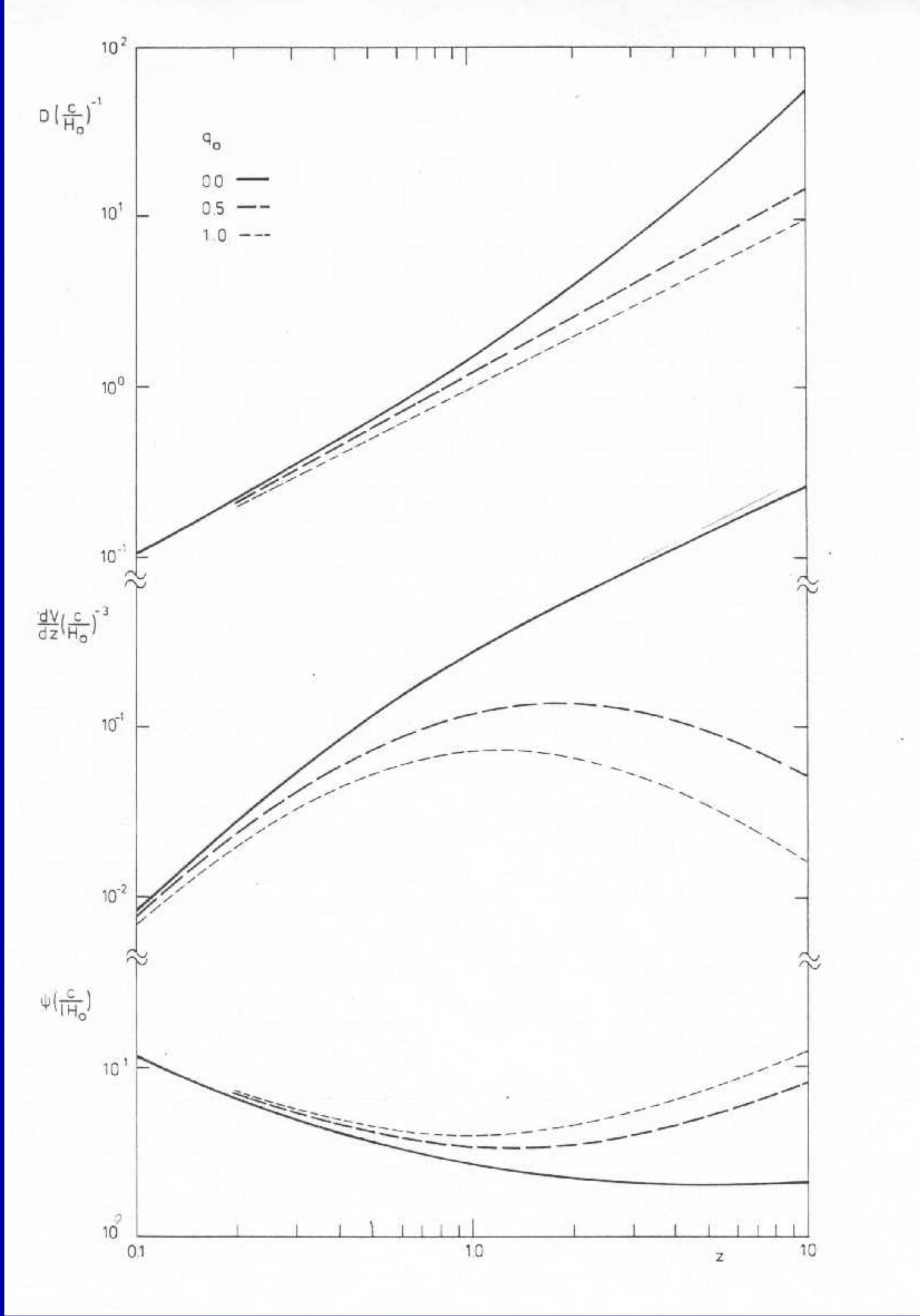
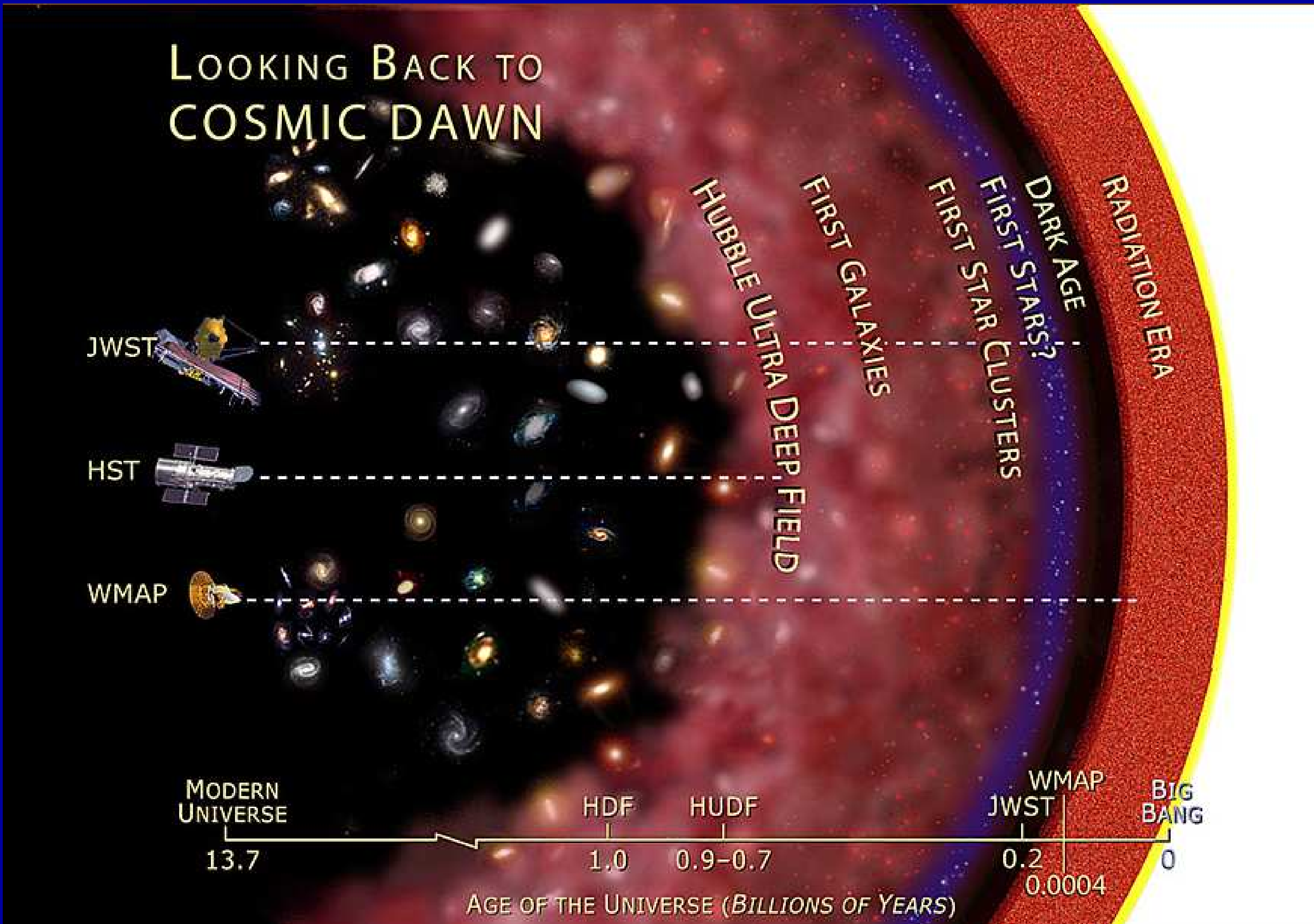
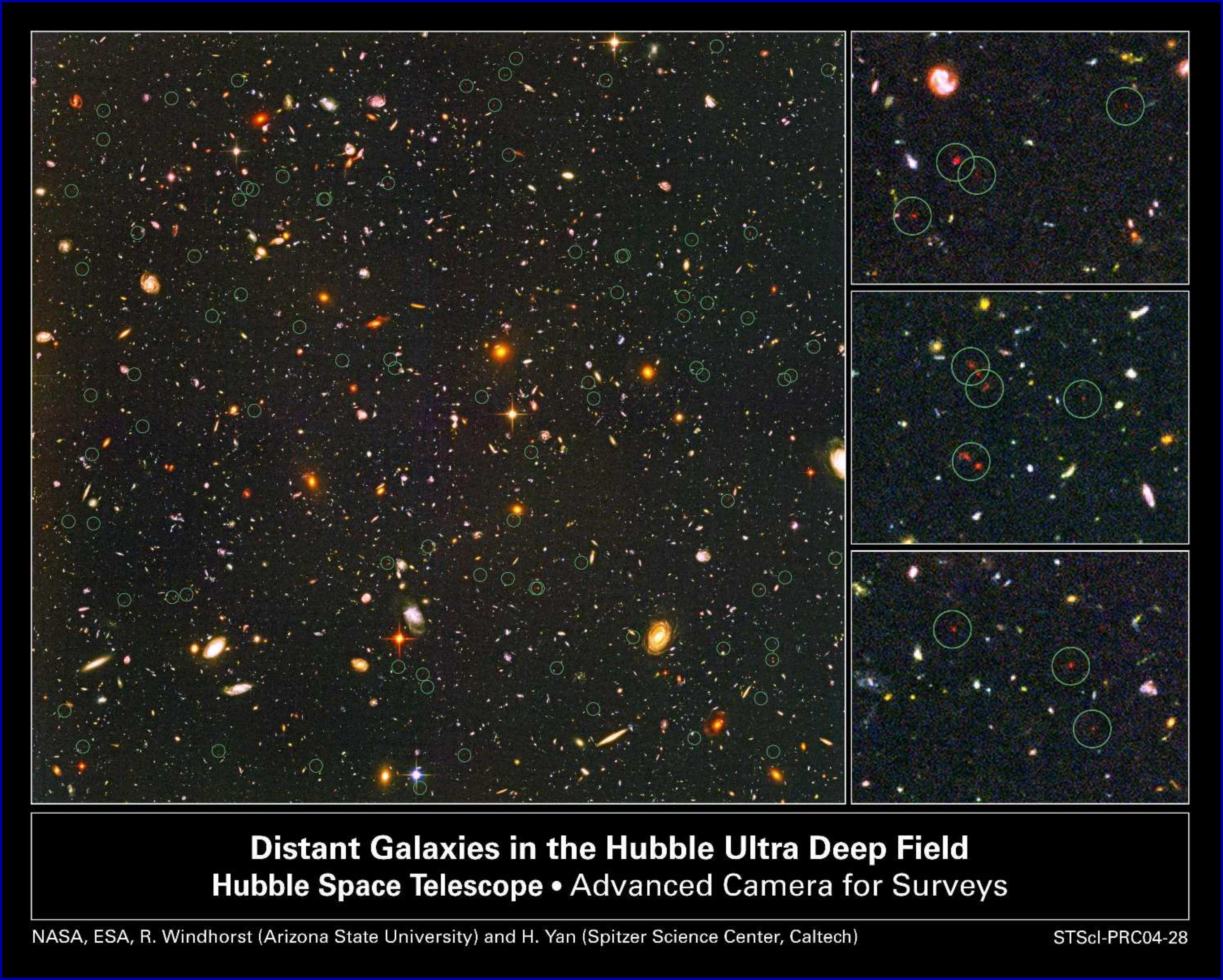


Relativistic Distance, Volume Element, and Angular Size vs. z.

(1) BIG UNIVERSE: Evidence for the "Hot Big Bang"



NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination

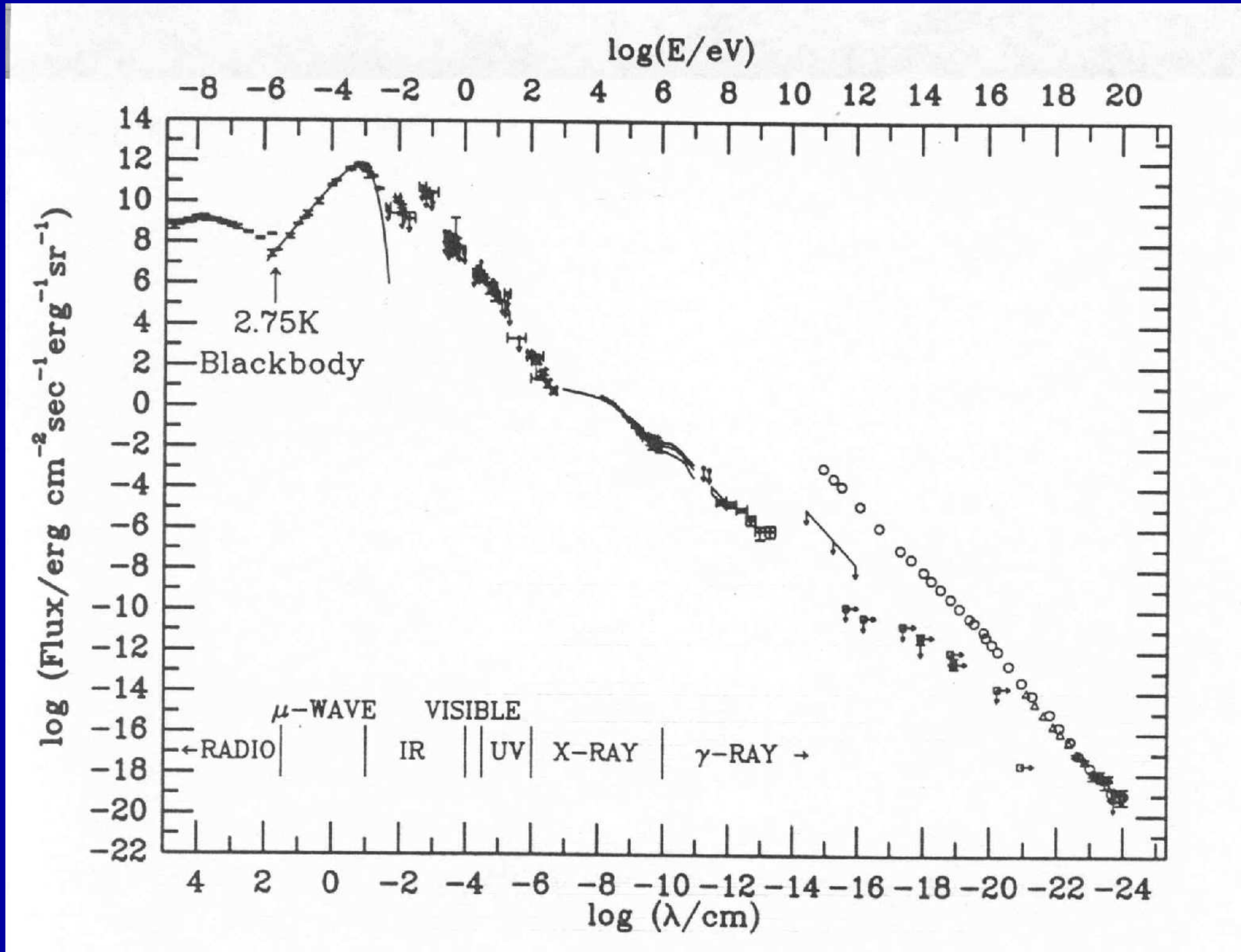


A Study of Comic Dawn with the Hubble Space Telescope

Contents and Energy Density of the Universe

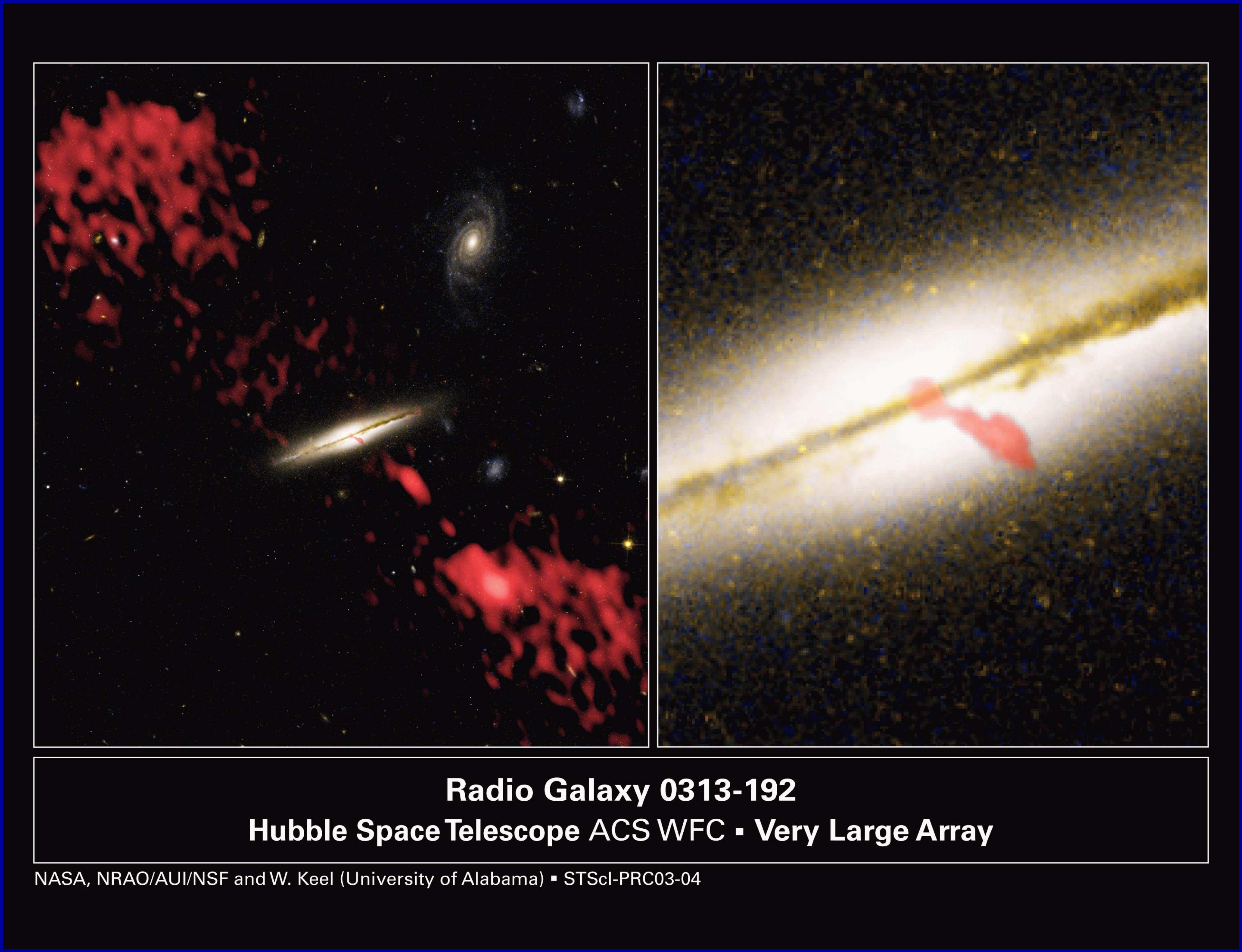
Item	Numbers inside R_0=c/Ho=13.7 Glyr
Baryons	$N_b \sim 10^{80}$
Photons	$N_{h\nu} \sim 10^{89}$
η=Photons/Baryons	$\eta \sim 10^9$
Energy Density	As fraction of critical closure density
Baryons	$\Omega_b = \rho_b/\rho_{crit} = 0.044$
Dark Matter	$\Omega_d = \rho_d/\rho_{crit} = 0.23$
Dark Energy	$\Omega_\Lambda = \rho_\Lambda/\rho_{crit} = 0.73$
Total	$\Omega_T = \rho_T/\rho_{crit} = 1.00 \pm 0.02$ $(\rho_{crit} = 10^{-29}$ gr/cm$^3)$

Integrated Background: nearly a power-law over 20 dex in λ!



In contrast with Cosmic Background, dust & stars in galaxies, Active Galactic Nuclei powered by supermassive black-holes dominate over 20 dex in λ.

$\Rightarrow$ Majority of power in Universe generated by $\lesssim$1% of mass!



- VLA image of 0313-192: Optical galaxy (color) and Radio source (red).

Active Galactic Nuclei: powered by supermassive black-holes (10^6–10^{10} $M_\odot$)

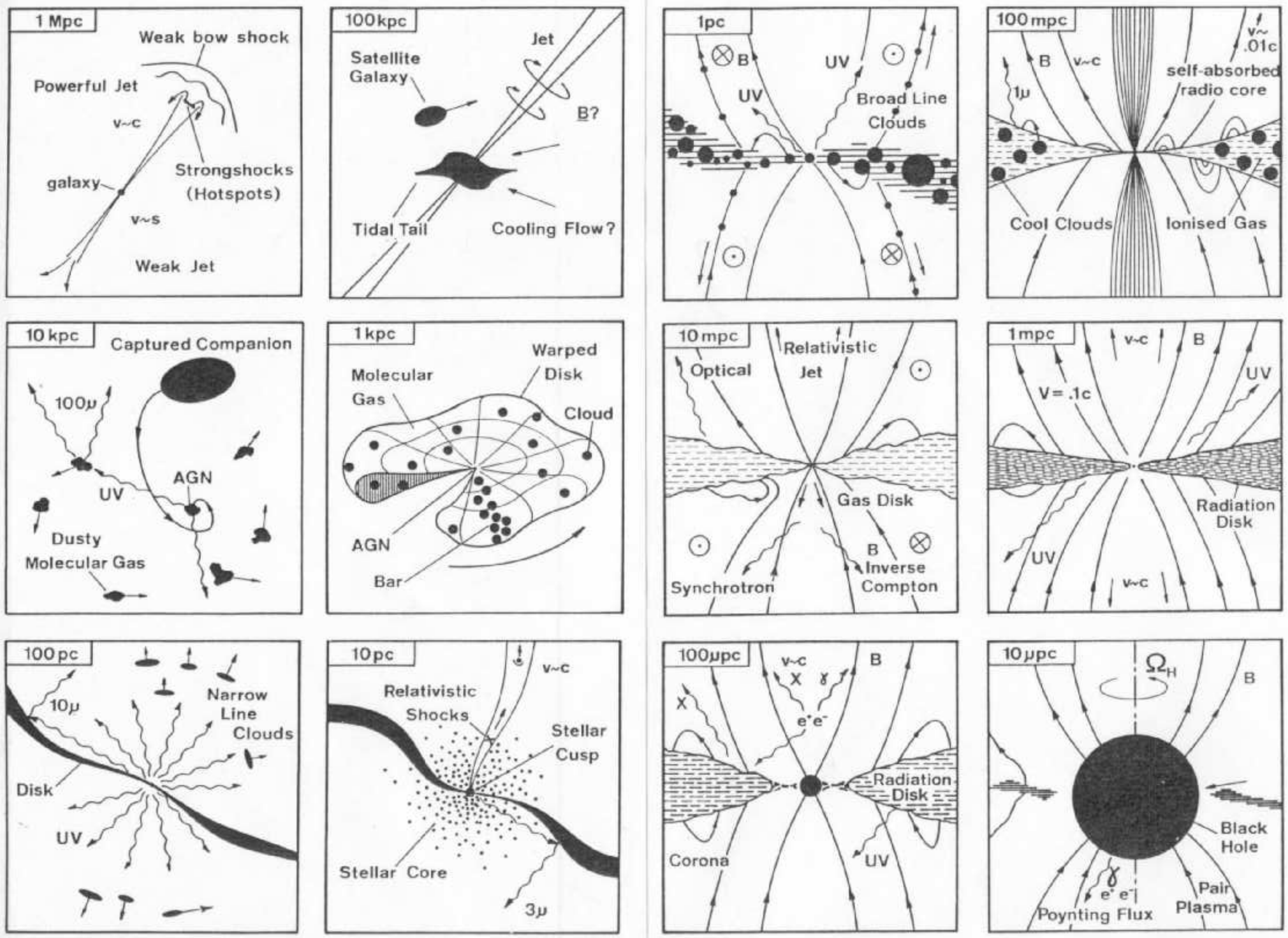
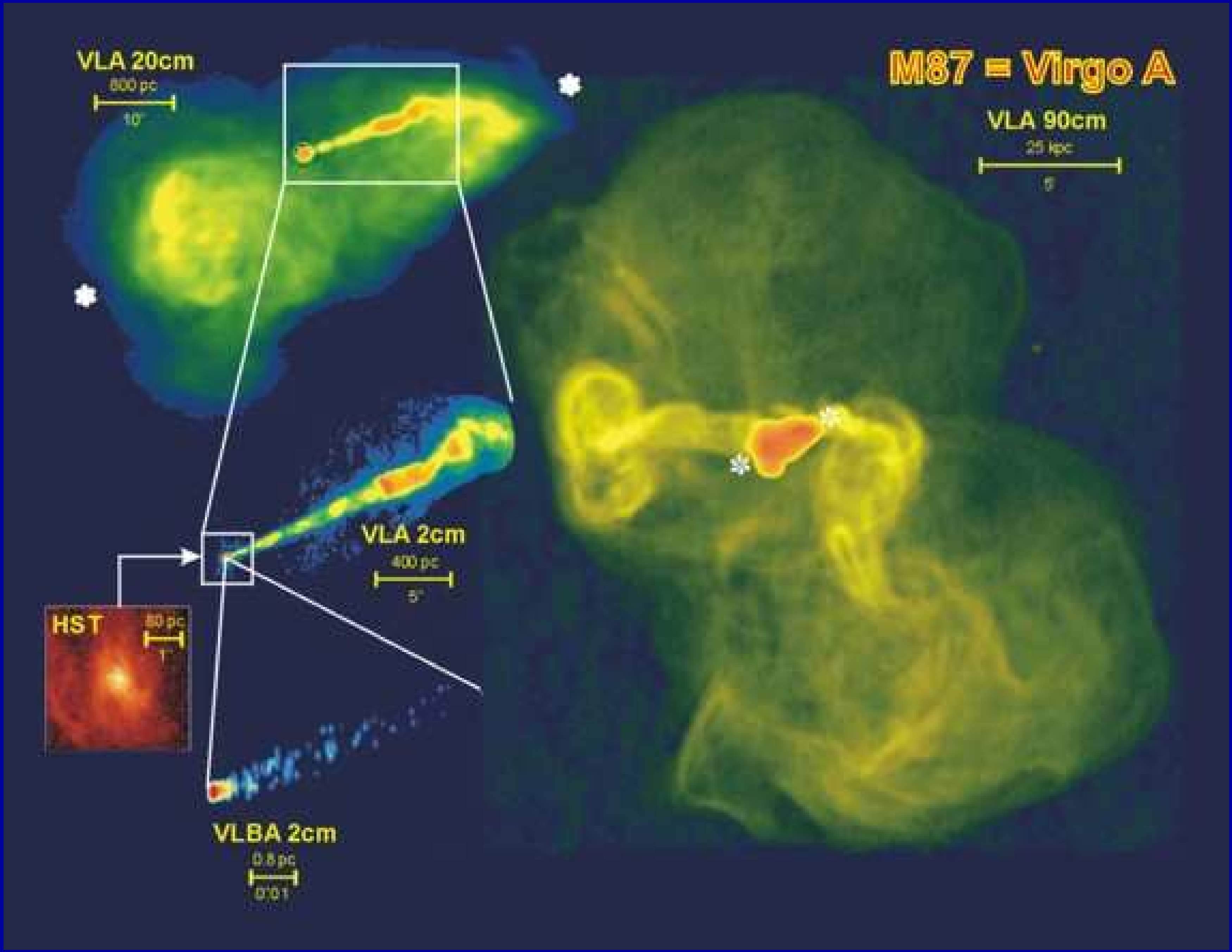


Fig. 7.1. Montage of scales exhibiting some effects of accretion onto a black hole over 12 successive decades of radius ranging from ~ 1Mpc to ~ 3×10^{13}cm. This is scaled to a black hole of mass ~ $10^8 M_\odot$. We comment upon the individual frames in the text.

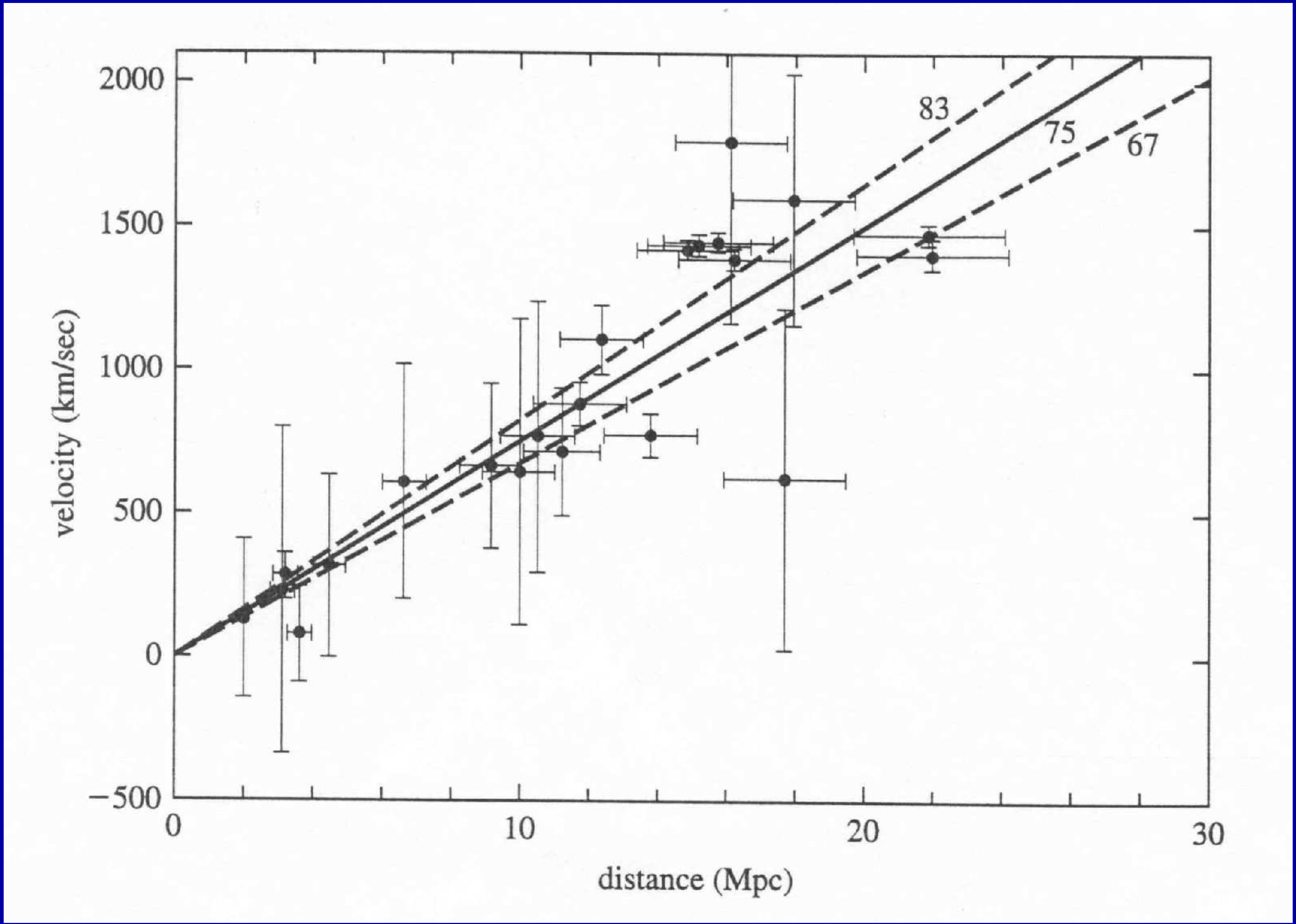
Affect surroundings over 12 dex in size: from AU to Mpc scales (300 Mlyr), or from General Relativistic Singularity (AU) to Relativistic Jets (Mpc).

If jet shines in face $\Rightarrow$ Quasars: $10^{15} L_\odot$ coming from several AU!



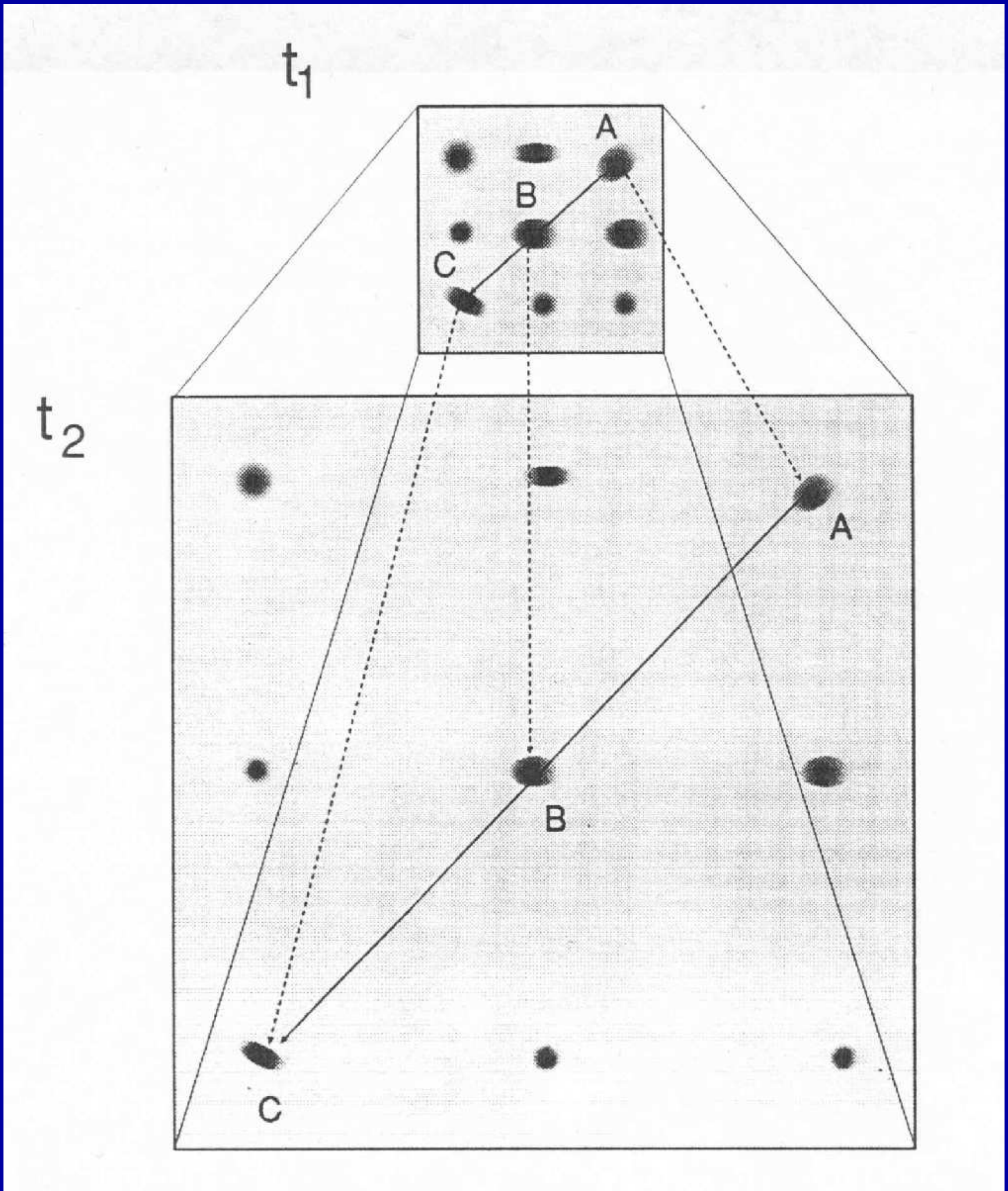
- VLA image of M87: Radio source stretches over a factor of 30,000 in size.
- Supermassive Black-Hole powered sources are brightest in the universe.

(1a,b) Cosmological distances, Hubble Expansion and Age of Universe



Hubble Cepheid Distances: v = $H_0 \times$ D (H_0 = 75 km/s/Mpc)

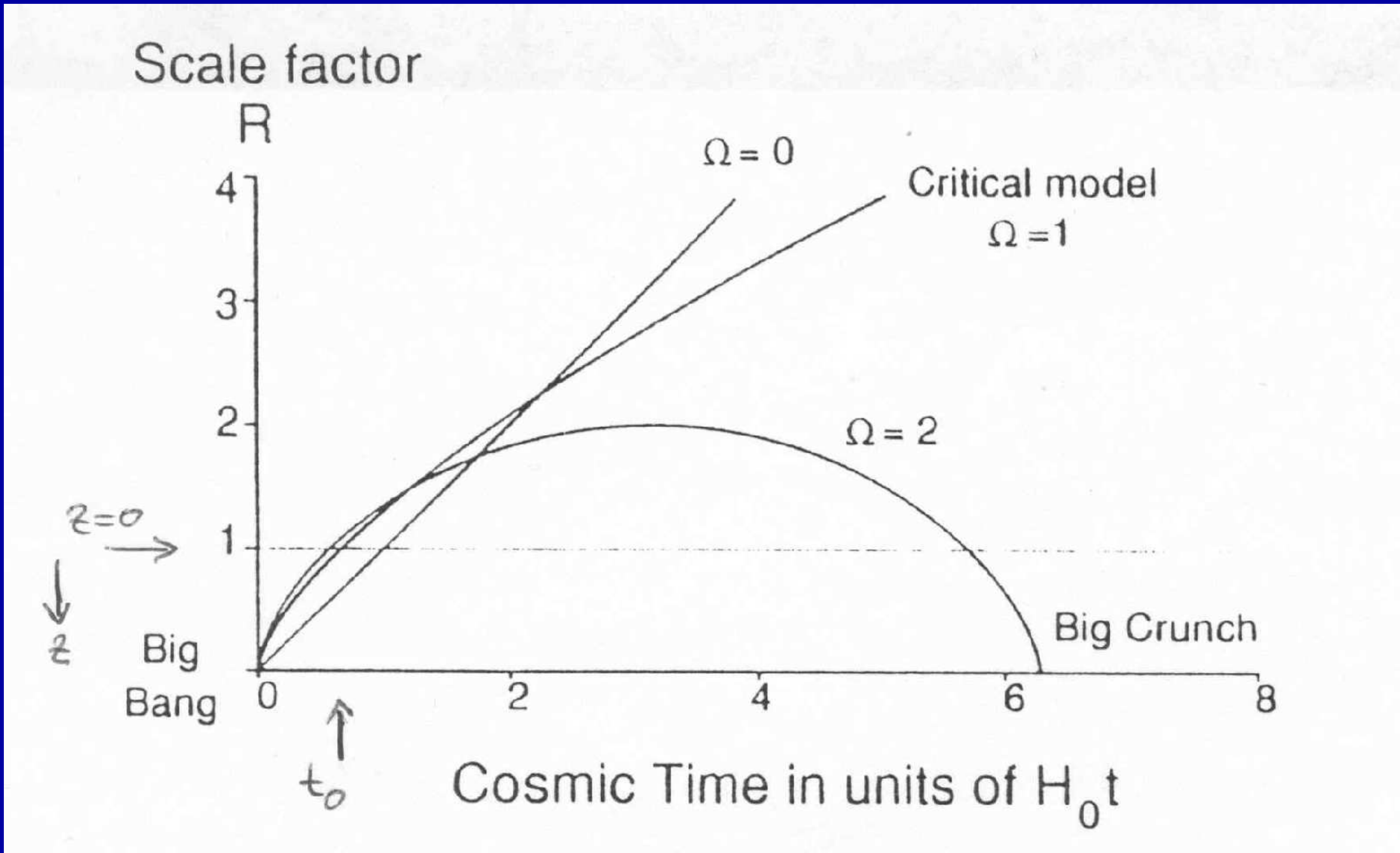
For H_0 = 71 km/s/Mpc, the Hubble time or Universe's Age = 13.7 Gyr.



All galaxies appear to move away from eachother with speed $\propto$ distance.

- Only the space *between* the galaxies expands, like raisins in bread.

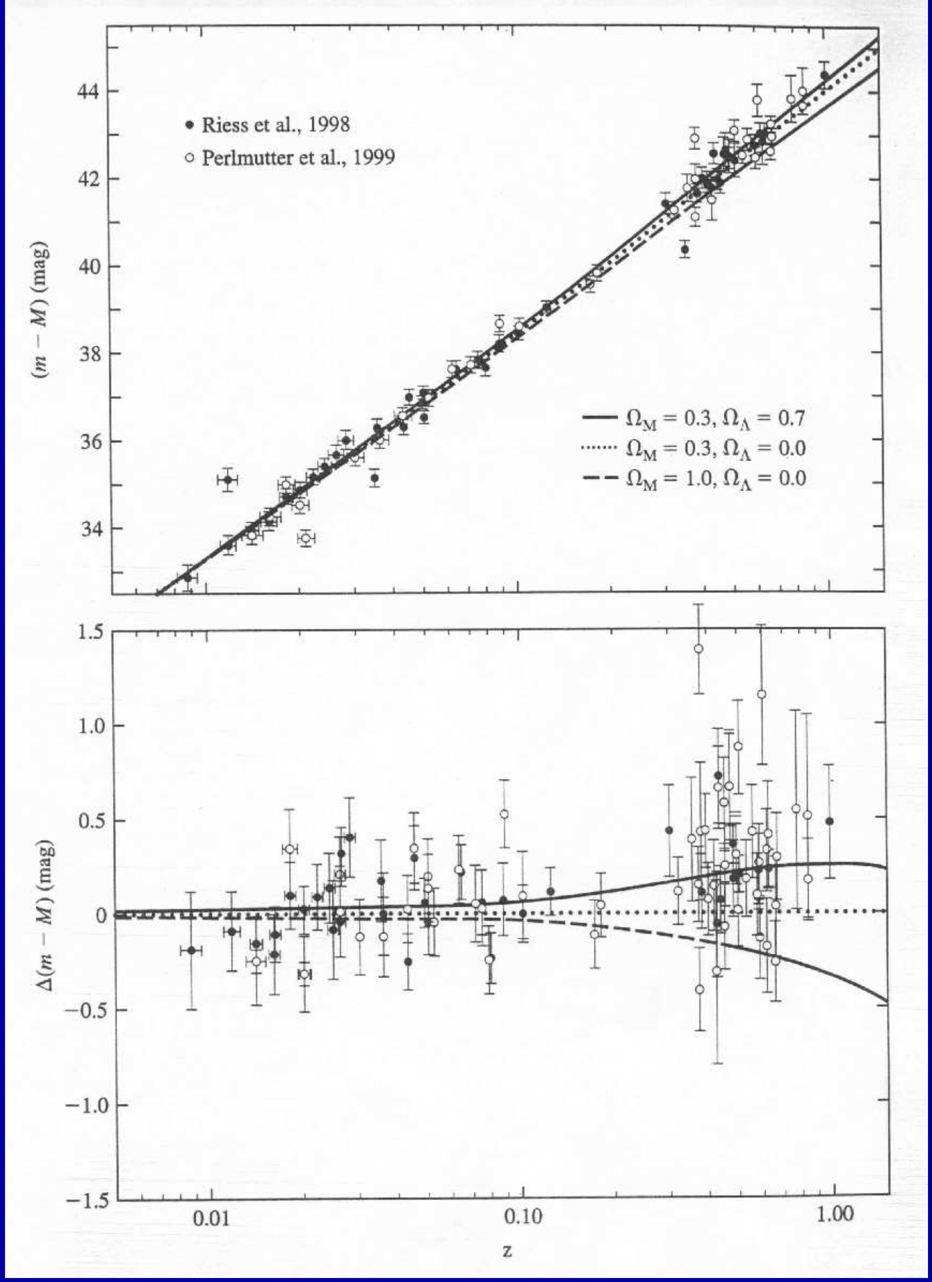
(1b) Hubble Expansion: Friedmann–Robertson-Walker models



Friedmann-Robertson-Walker models: Scale factor $\boldsymbol{R}$ vs. cosmic time t.

Scale-factor $\boldsymbol{R} = 1/(1+\mathrm{z})$ where redshift $\boldsymbol{z} = \boldsymbol{\Delta\lambda/\lambda} \simeq$ v/c.

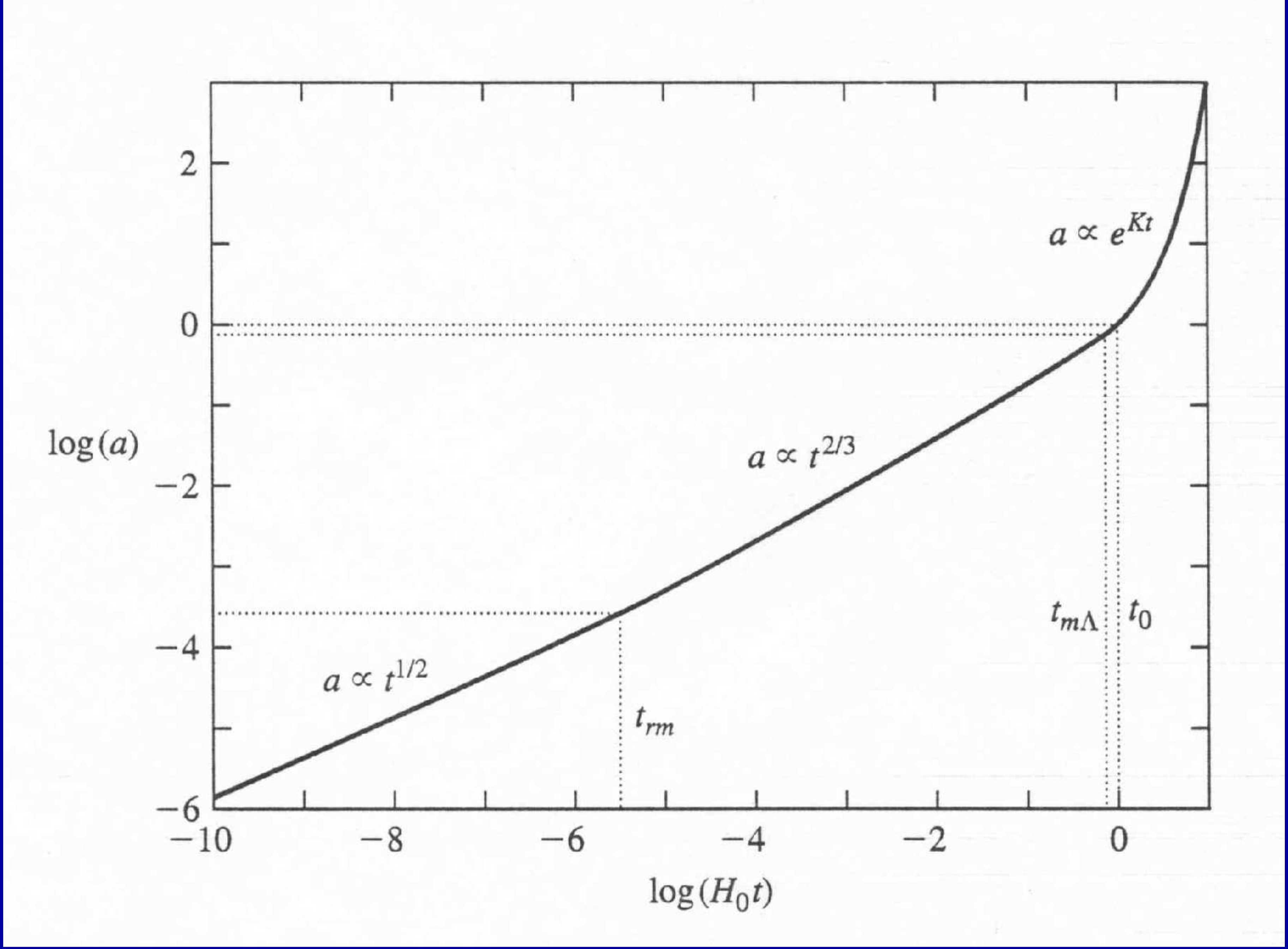
Mass-Energy density $\boldsymbol{\Omega} = \boldsymbol{\rho/\rho_{crit}}$ and $\boldsymbol{\rho_{crit}} = 10^{\boldsymbol{-29}}$ gr/cm$^{\boldsymbol{3}}$.



Type Ia Supernovae: Evidence for (exponentially) accelerated expansion:

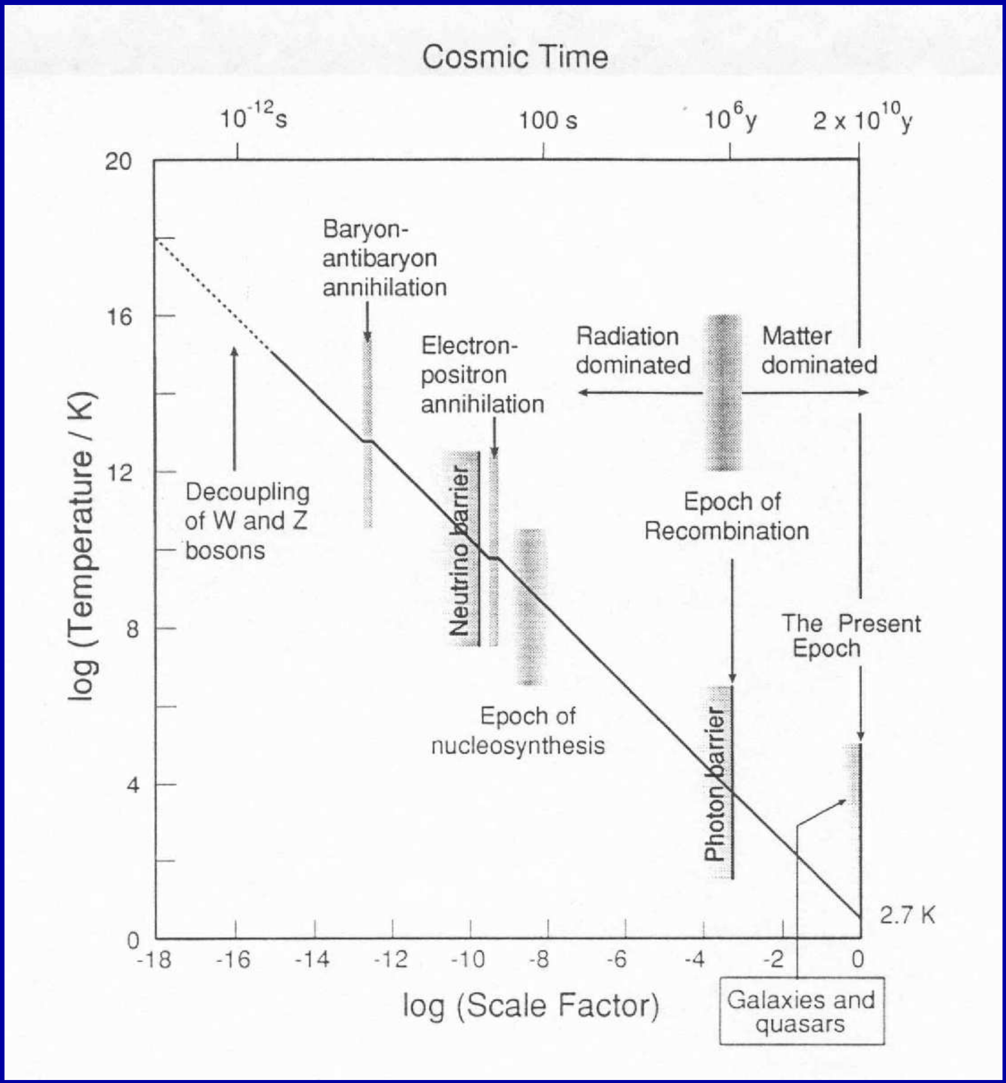
- Space has expanded exponentially for the last 4.2 Gyr — "Dark Energy"?

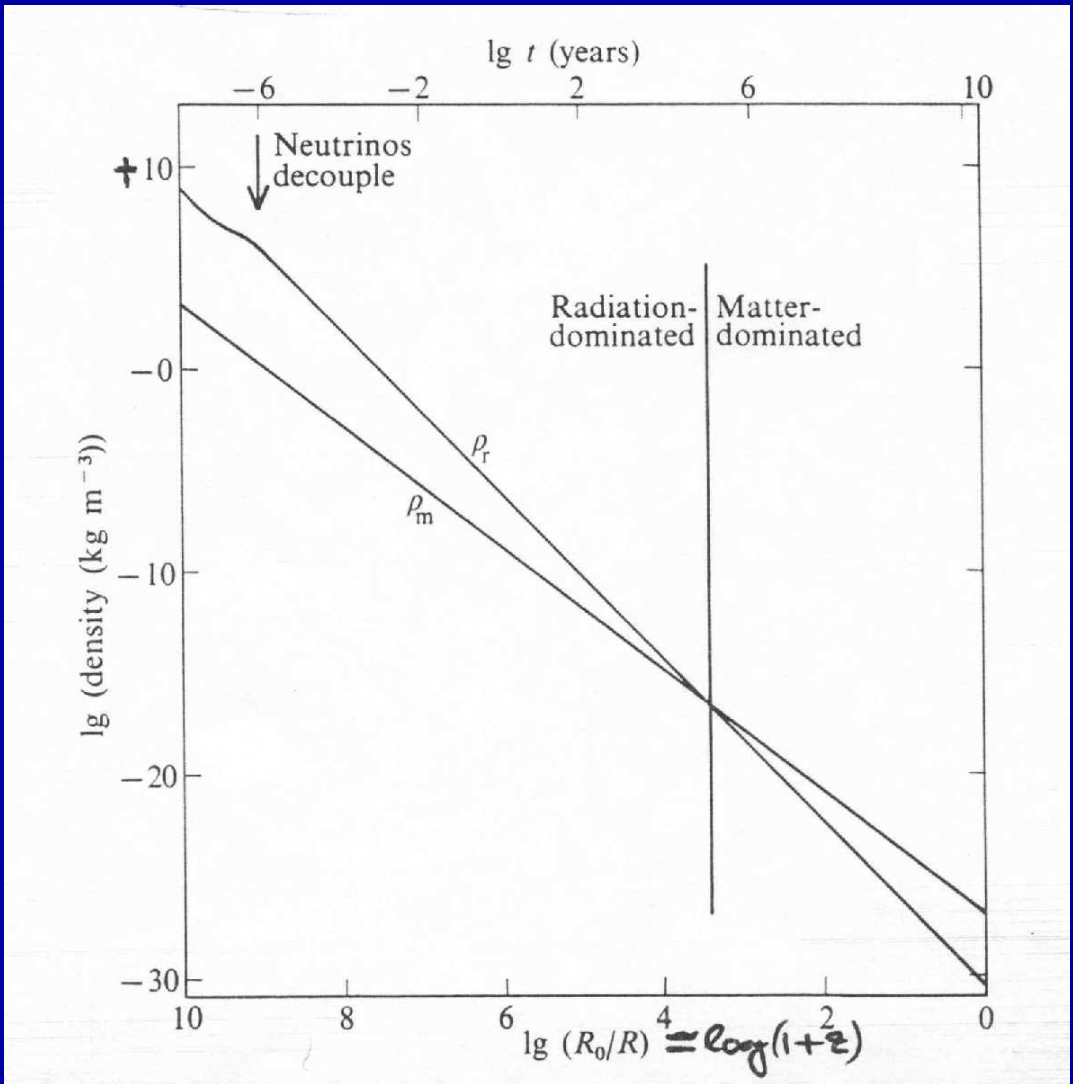
$\Longrightarrow$ Mary had a little Lambda (Einstein's Cosmological Constant $\mathbf{\Lambda}$).



The Cosmic Stock Market: A much better and safer bet than Wall Street!

Real Expansion R $\propto$ $t^{1/2}$ (Radiation era); $t^{2/3}$ (Matter era); e^{Kt} (Λ-era)





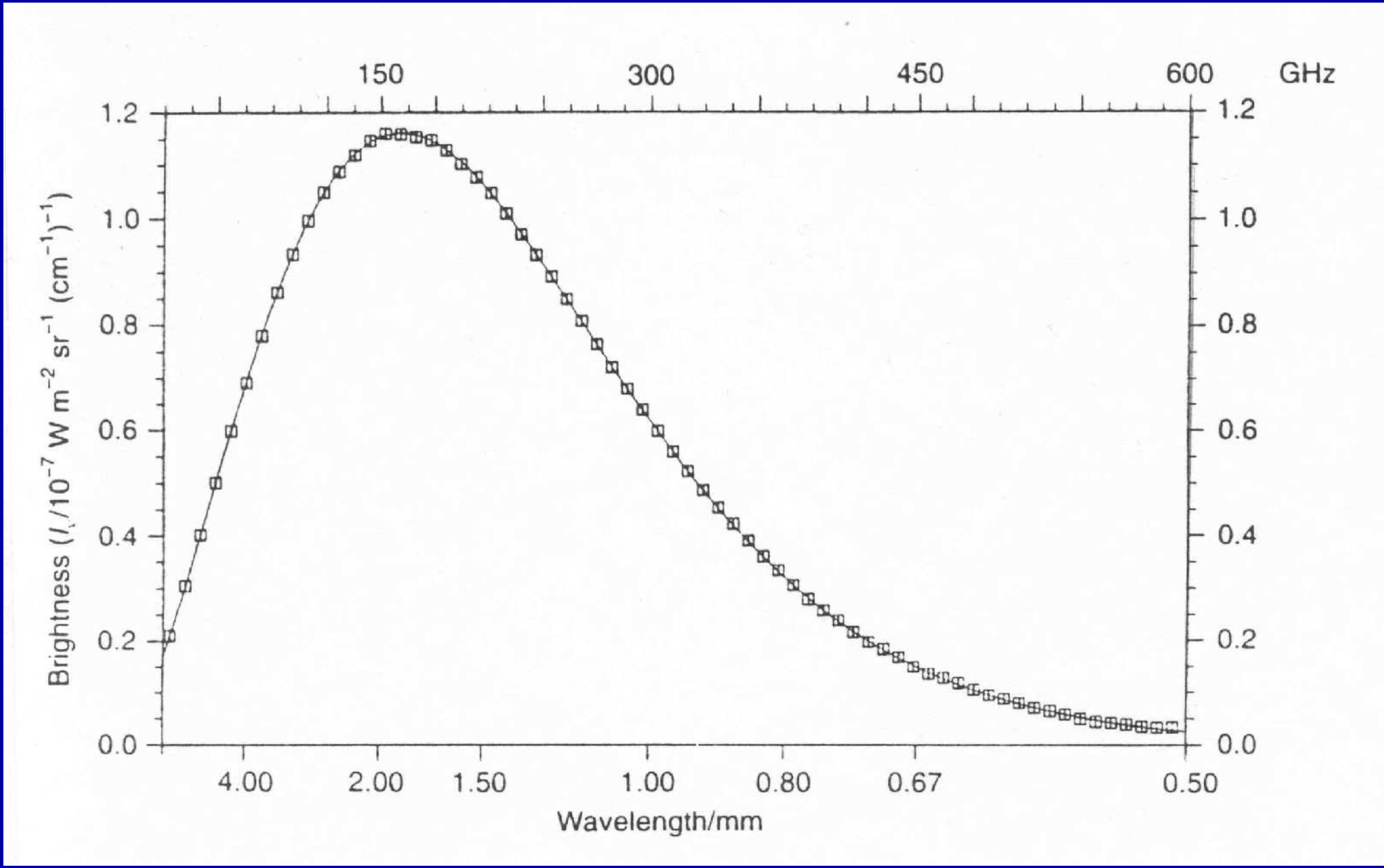
Thermal History of BB (Left): Temperature vs. Scale Factor R=1/(1+z).

Cosmic Background Temperature = T_0 (1+z) [T_0 = 2.7348 K today].

Hot Big Bang (Right): Radiation and Matter Density vs. Scale Factor.

Radiation density $\rho_r \propto (1+z)^4$; Matter density $\rho_m \propto (1+z)^3$.

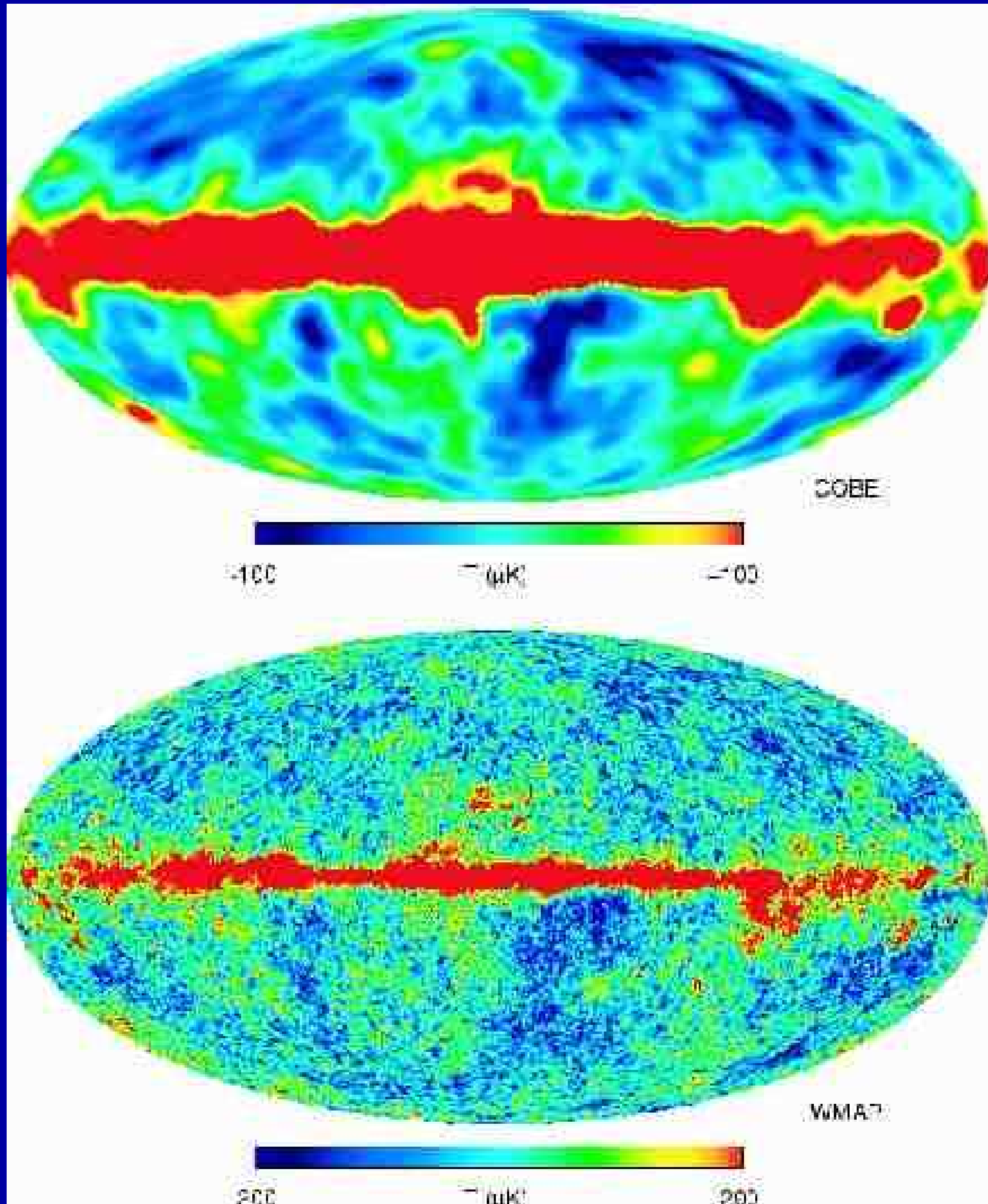
(1c) The Cosmic microwave Background Radiation (CBR)



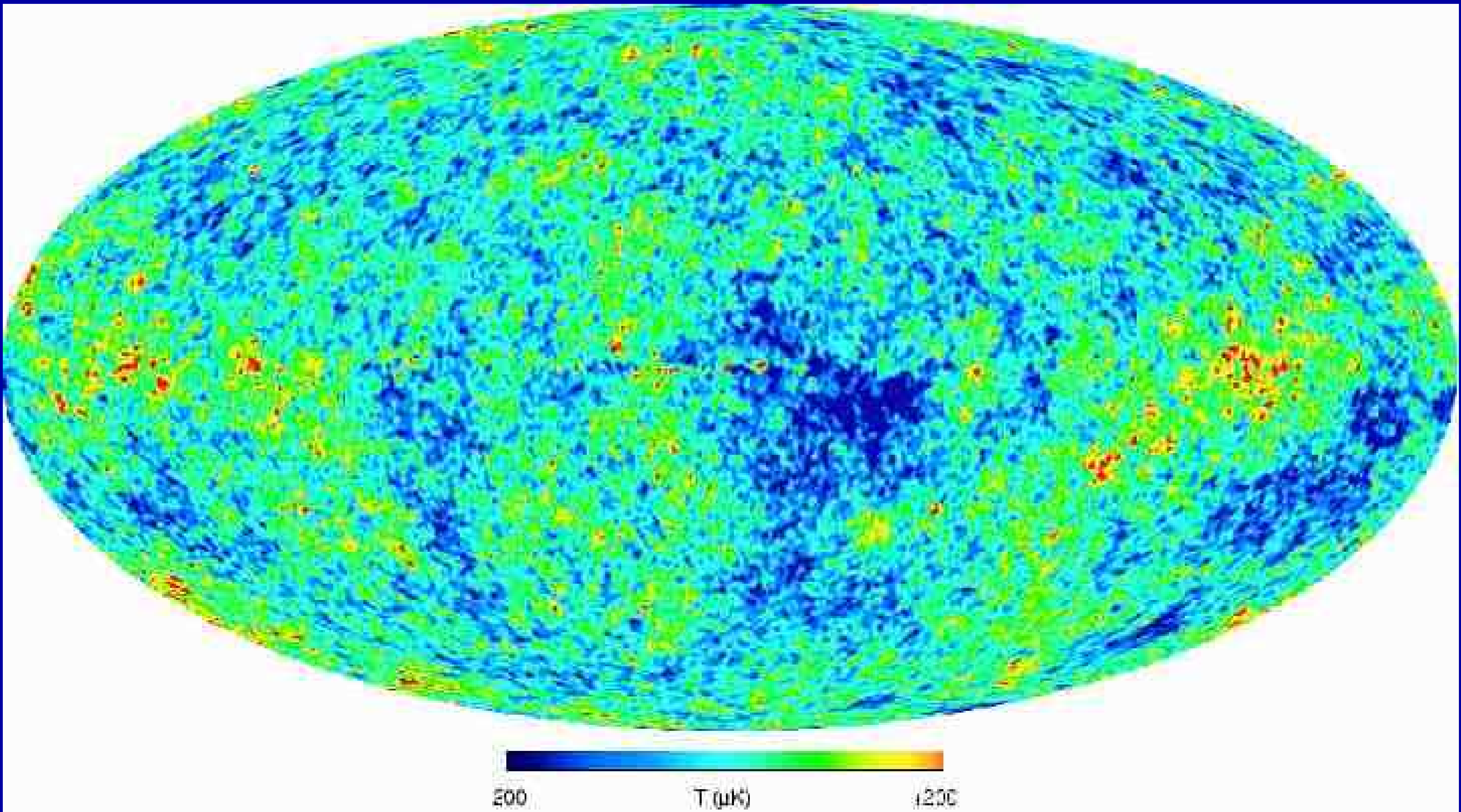
Hot Big Bang fits Cosmic Background Explorer data for T_o=2.7348... K

Errors<0.002%! – Likely the most precise measurement you will ever see.

$\Longrightarrow$ Best confirmation we have of the Hot Big Bang model!



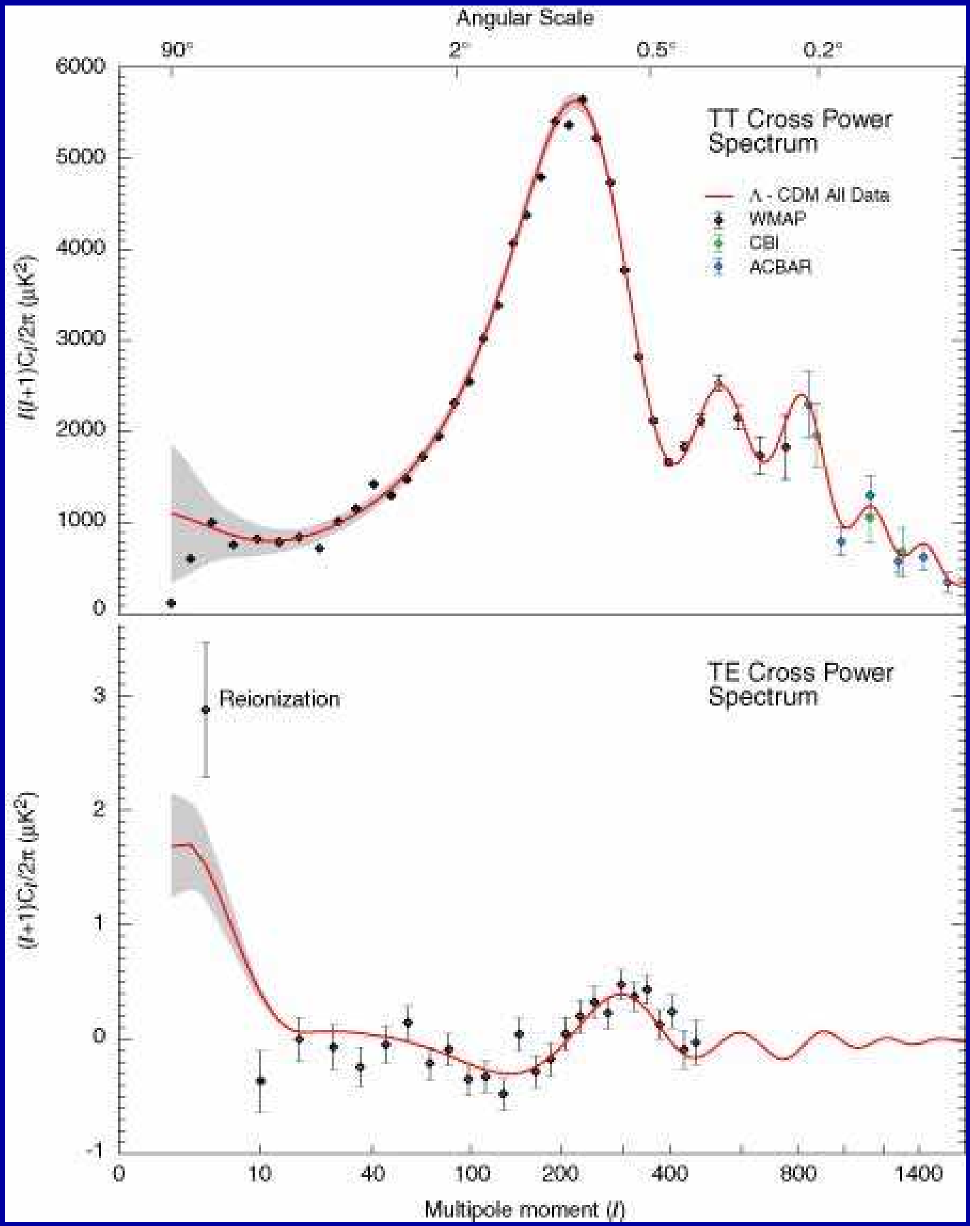
Microwave Background Radiation from COBE (1992) and WMAP (2003)



Microwave Background from Wilkinson Microwave Anisotropy Probe:

Foreground Galactic emission has been very carefully removed.

Remainder are structure-formation imprints at t=378,000 yrs (z=1089), causing temperature fluctuations of $\simeq 10^{-5}$ when H became neutral.



WMAP Power Spectrum: total light (top) & polarization (bottom).

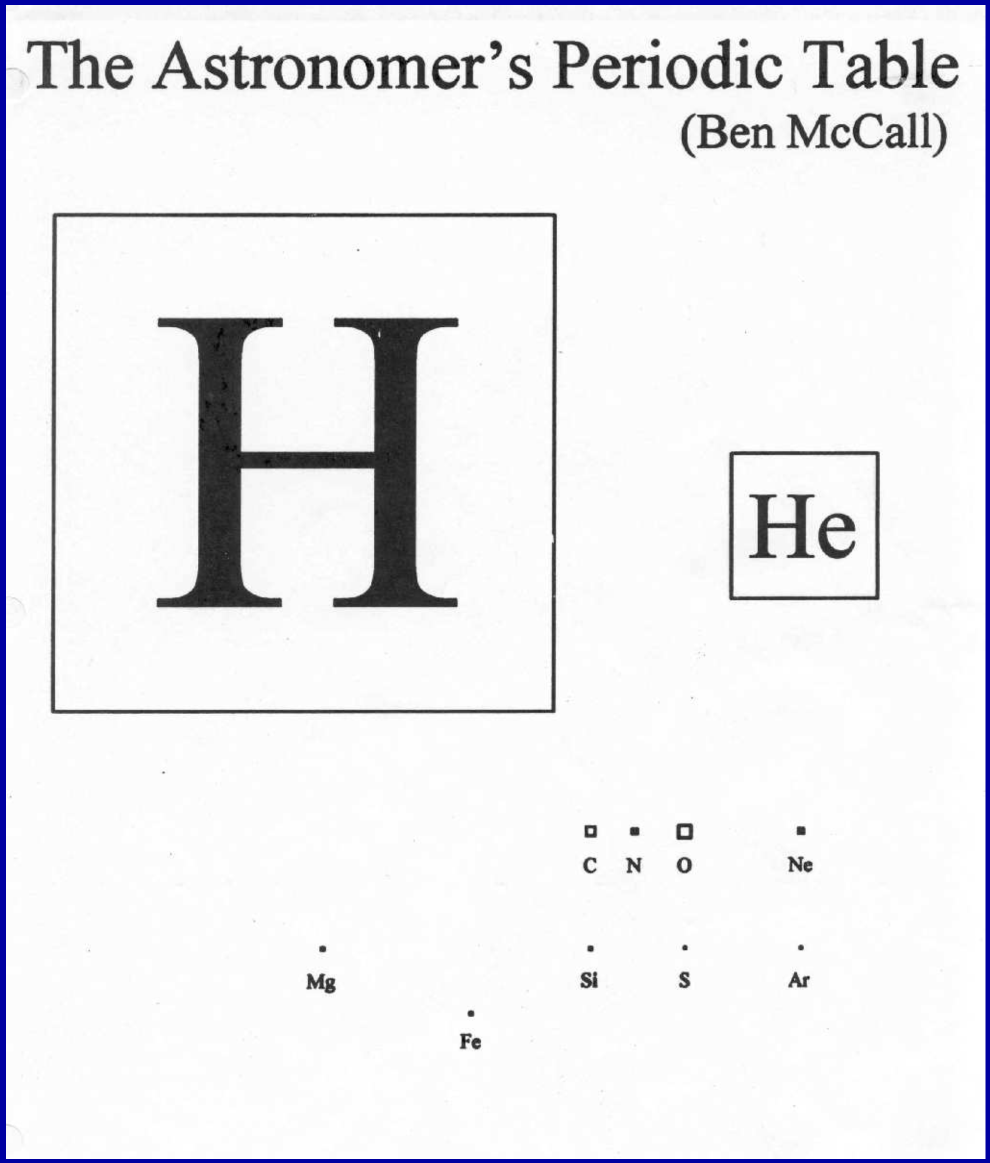
Best fit: H_0 =71±1 km/s/Mpc ⇒ Current Age=13.7±0.2 Gyr; AND:

Ω_{baryon}=0.044; Ω_{dark}=0.23; Ω_{Λ}=0.73; SUM=1.00±0.02 !!

Dark Matter: Cold, Non-relativistic (v$\simeq$0), and only interacts by gravity!

Microwave Background $\Rightarrow$ Cold Dark Matter is non-baryonic ($\neq$ cats)

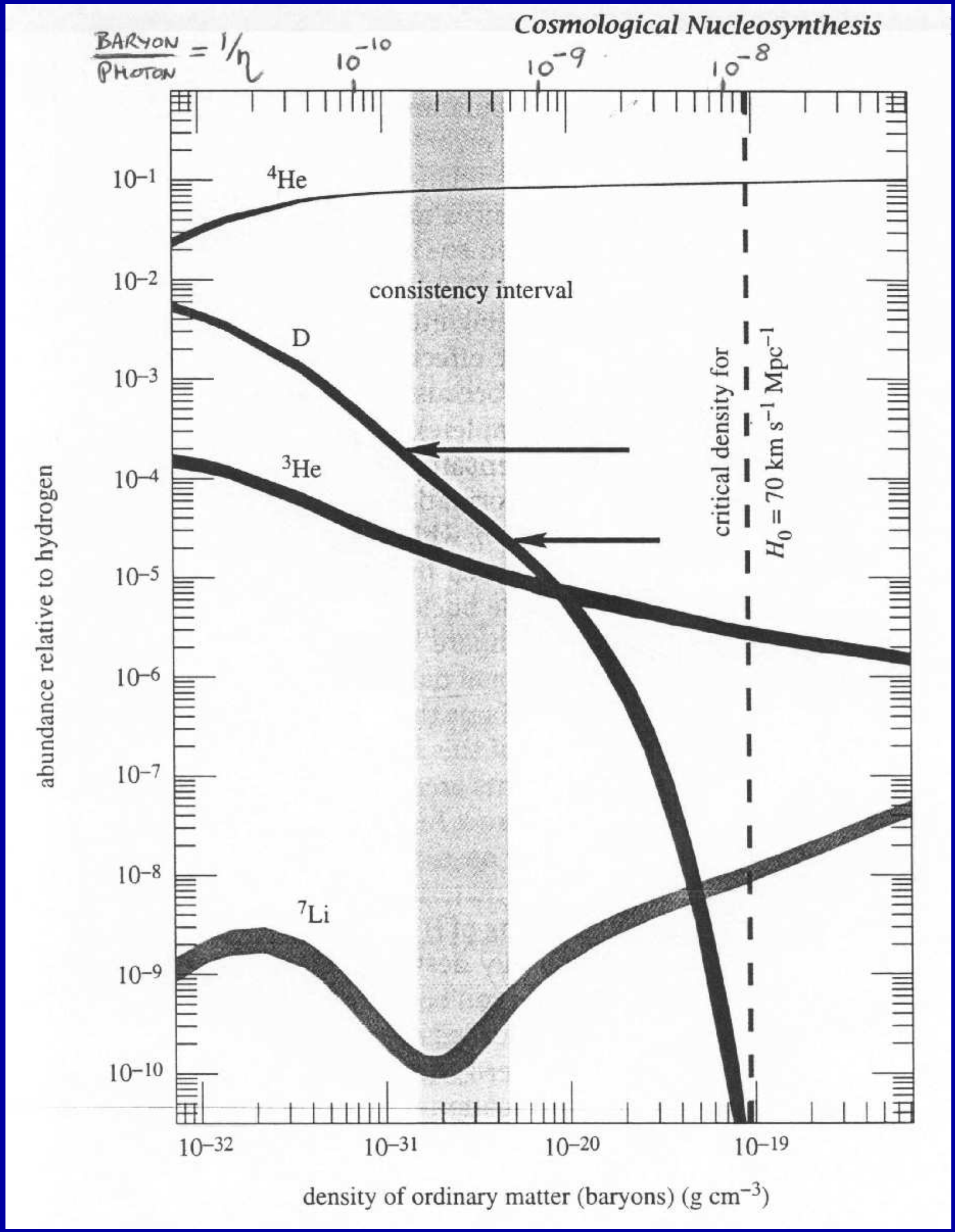
(1d) Light Element production predicted by Hot Big Bang



The astronomers periodic table is not quite what you learned in chemistry:

Cosmic abundances are universal: 75% H; 24% He; 1% rest (X).

The 1% has universally the same X/Fe ratios $\Longrightarrow$ X made in stars!



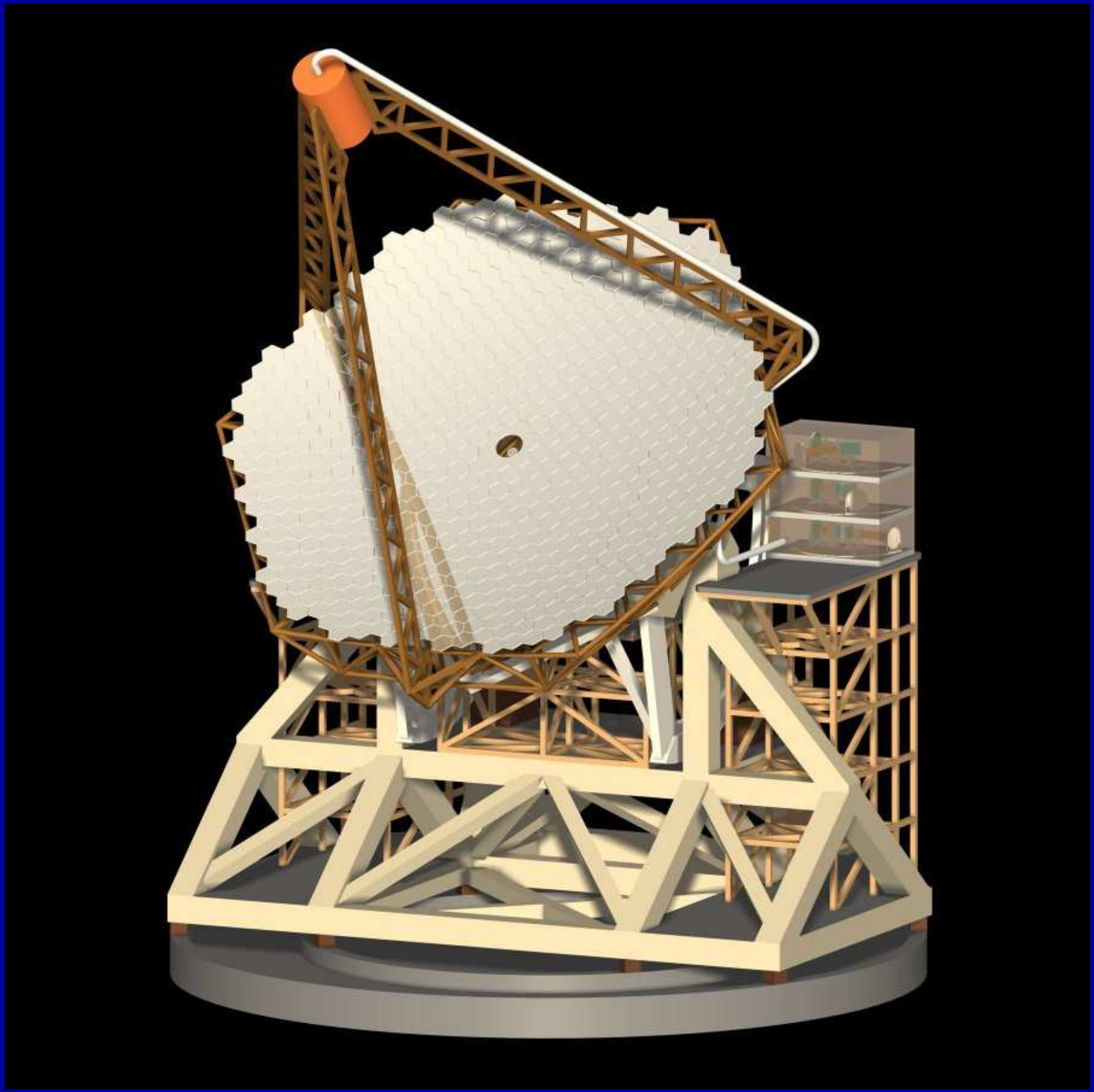
Light element production vs. Ω_{baryon} and baryon-to-photon ratio η.

Element production and CMB imply Ω_{baryon}=0.044, $1/\eta \simeq 4\times10^{-10}$

(2) LARGE TELESCOPES: Why needed, what do they do, and how?

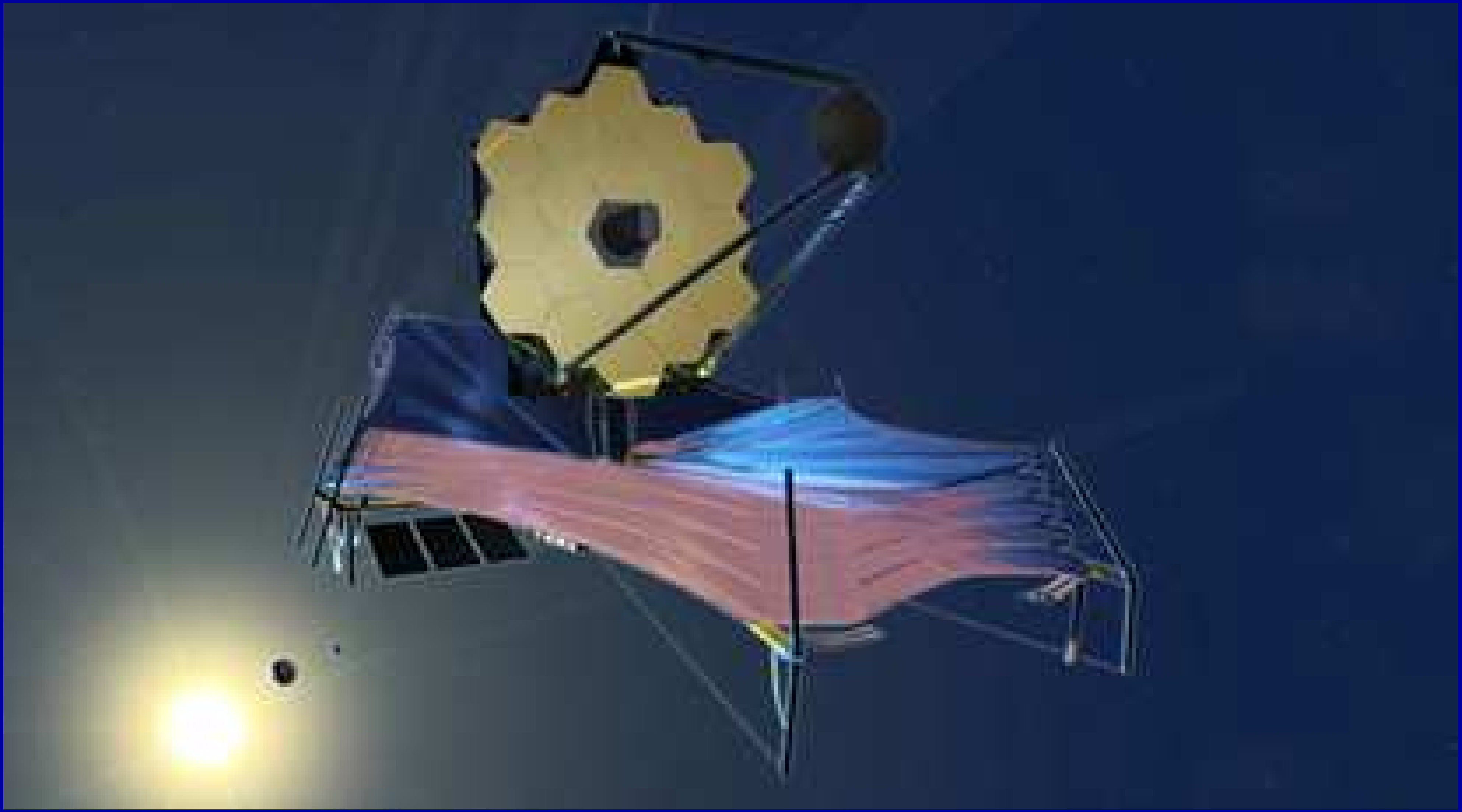
Telescope Property	How defined and used:
Mirror Diameter	D in meters
Field of View	Ω in Rad or deg^2
Resolution	$\Theta = 1.22 \times 206265 \times (\lambda / D)$ [arcsec]
Collecting Area	$A = \pi \, (D/2)^2$
Discovery Space	$DS = A \times \Omega \times \log(\lambda_{hi} / \lambda_{lo})$

• (2a) Large Optical–IR Telescopes

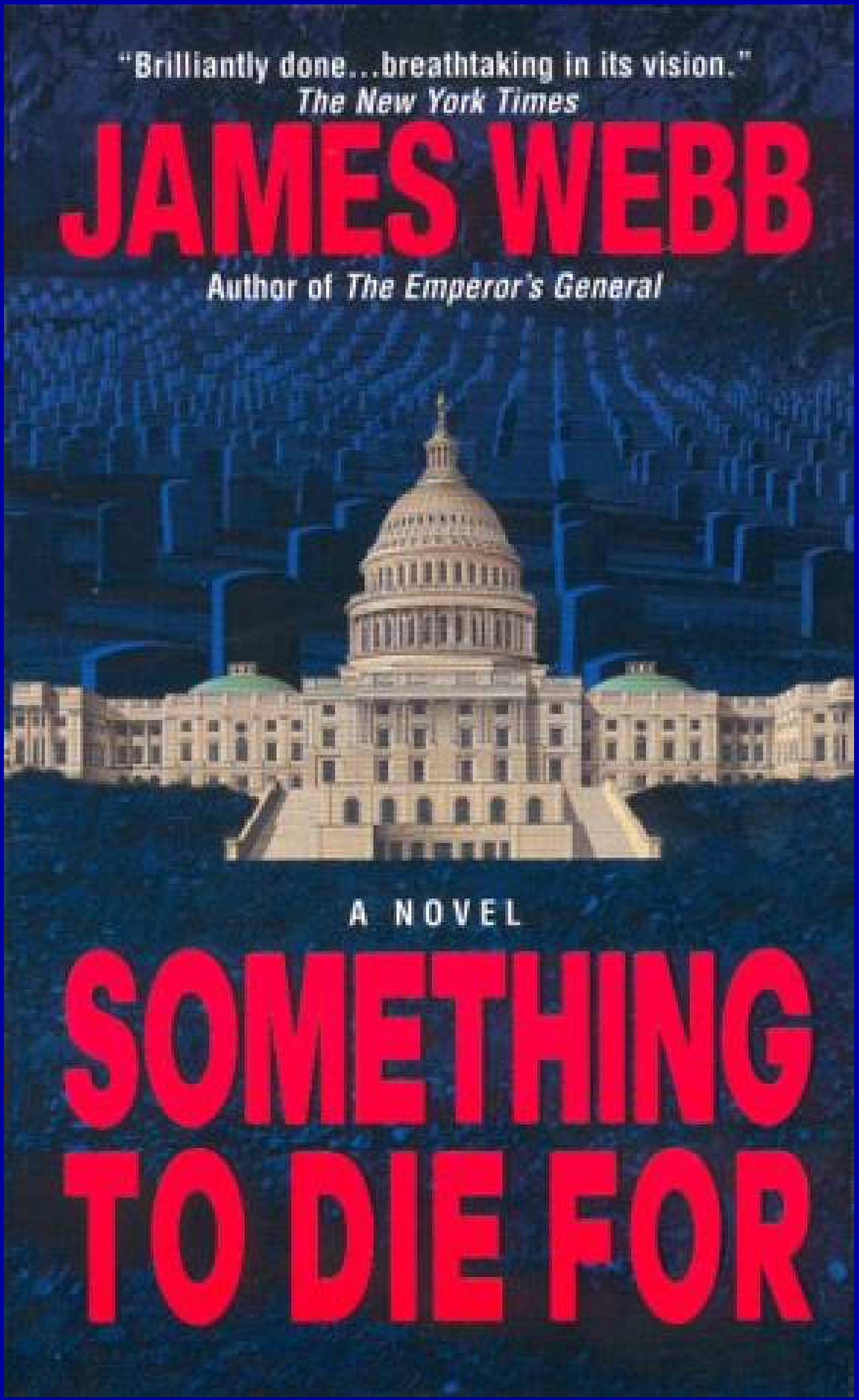


• Giant Segmented Mirror Telescope (GSMT): A segmented mirror with 30 m aperture and active optics correction of atmospheric phase fluctuations: $\Rightarrow$ FWHM(PSF)$\sim$0.025". Expected operational before 2020.

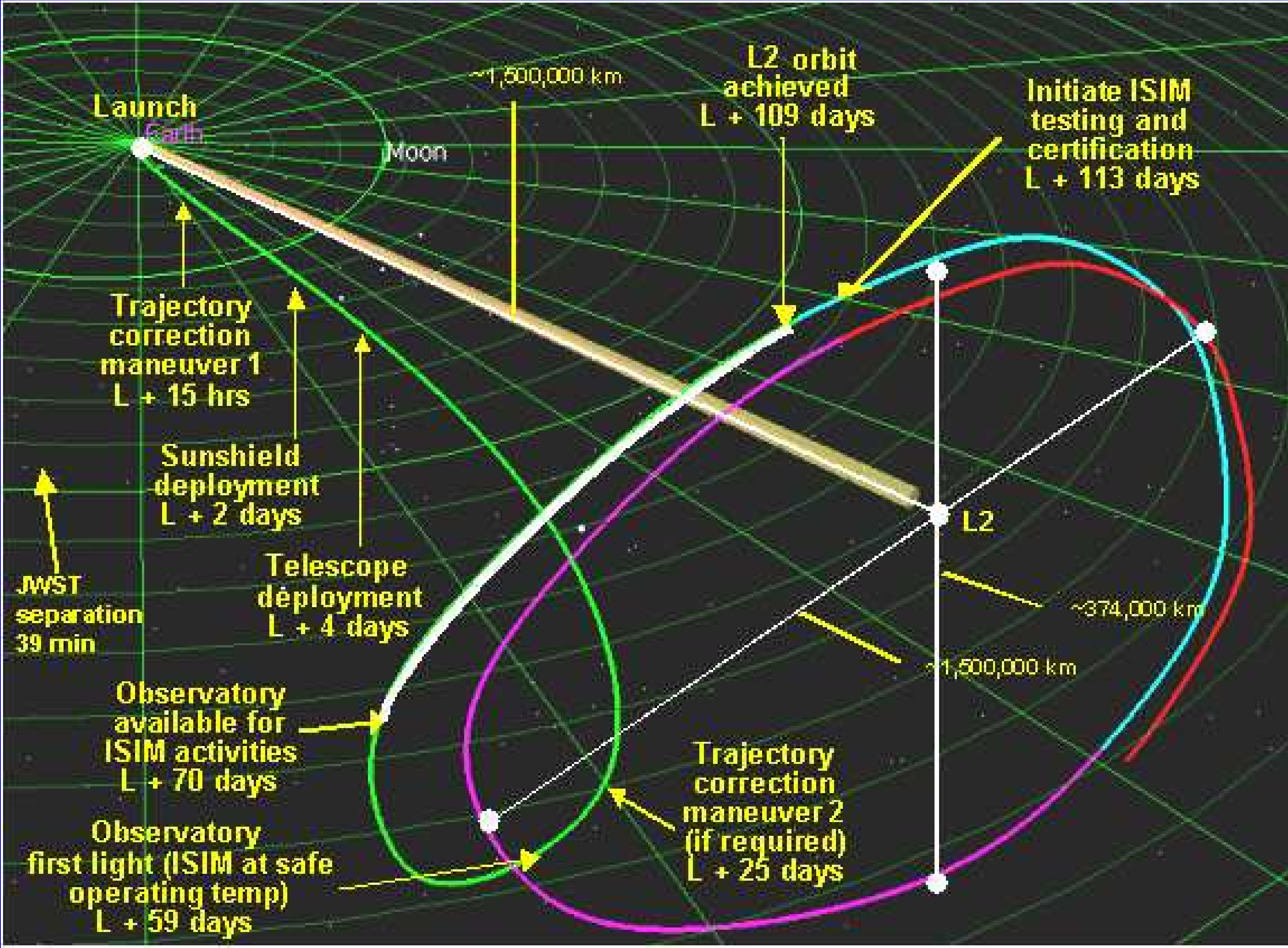
• (2a) The James Webb Space Telescope (JWST)



• JWST: A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6–28μm, to be launched Aug. 2011. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

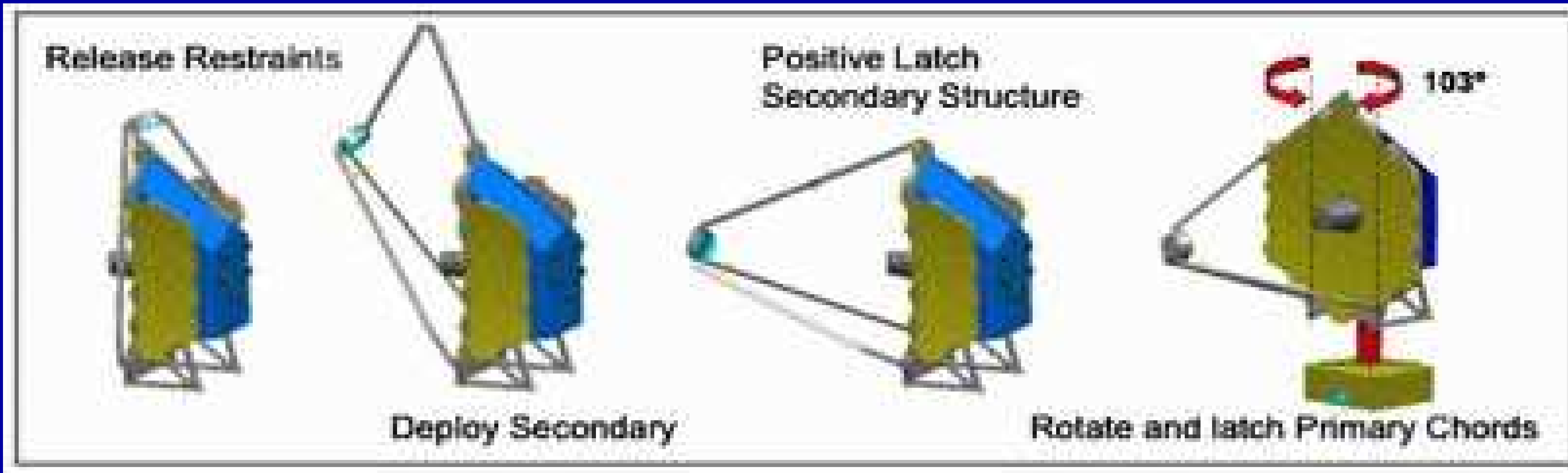


Need hard-working grad students & postdocs in 2011 ... It'll be worth it!



After launch in 2011 with an Ariane V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

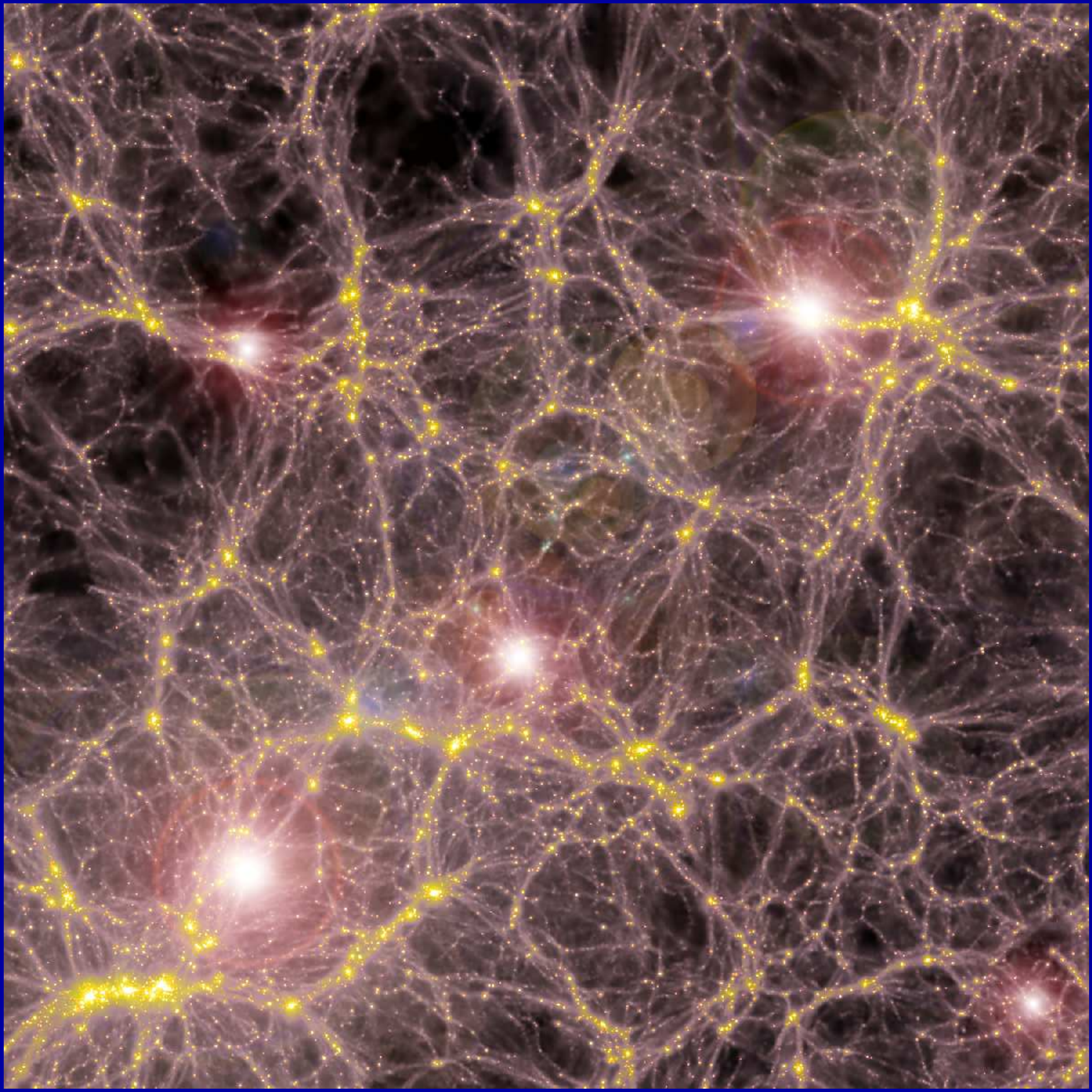
• (2a) How will the JWST be automatically deployed?



During its several month journey to L2 (shown on a previous page), JWST will be automatically deployed in phases (as shown here), its instruments will be tested, and it will then be inserted into an L2 halo orbit.

From an orbit around the the Earth–Sun Lagrange point L2, JWST can cover the whole sky in segments, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

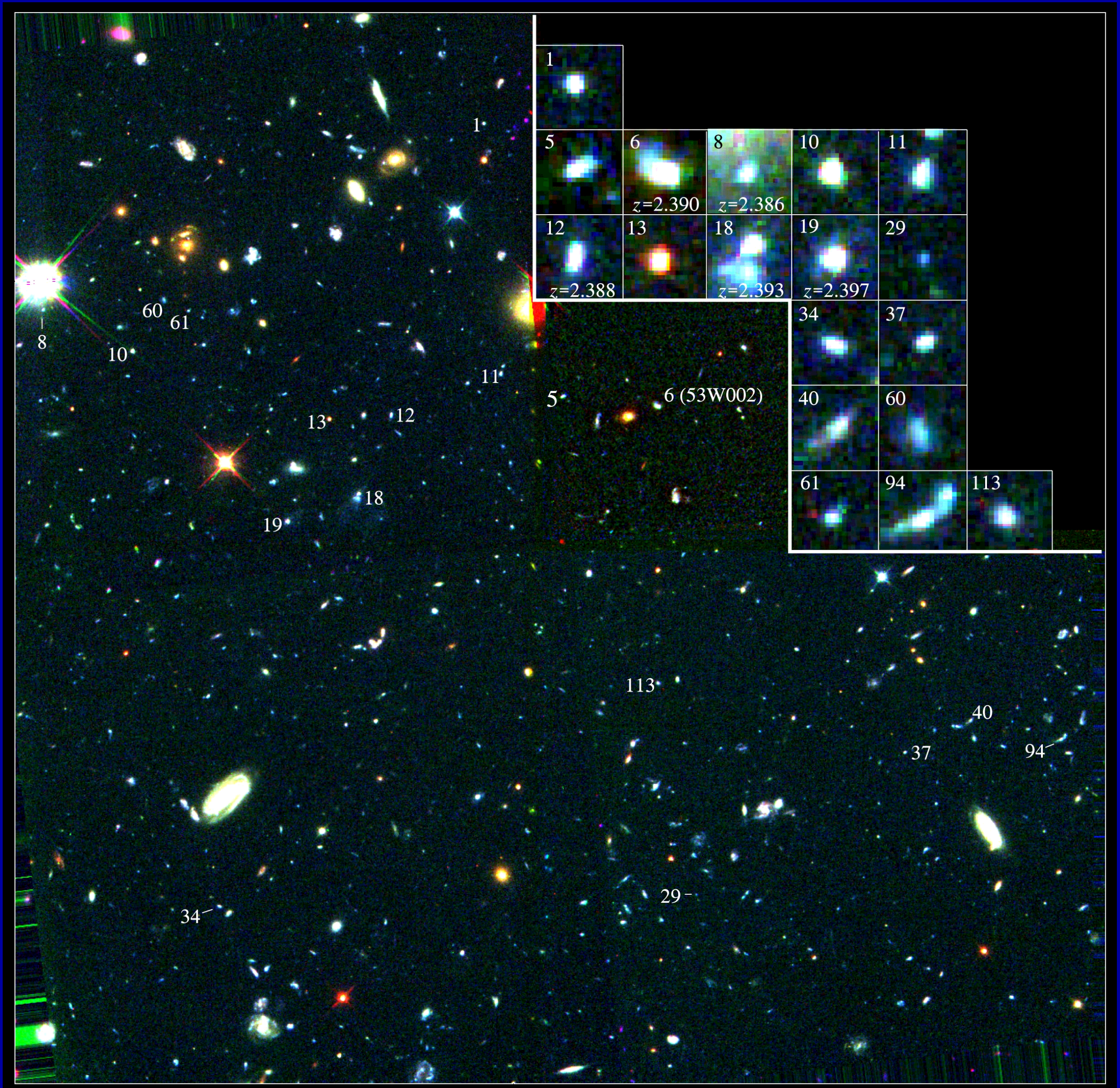
• (2a) How JWST can measure First Light and Reionization



• Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars reionized universe for the first time at z$\lesssim$25–30 (First Light).

• At least part of this should be visible to JWST as the first and extremely luminous supernovae of Pop III stars at z$\simeq$25$\rightarrow$15.

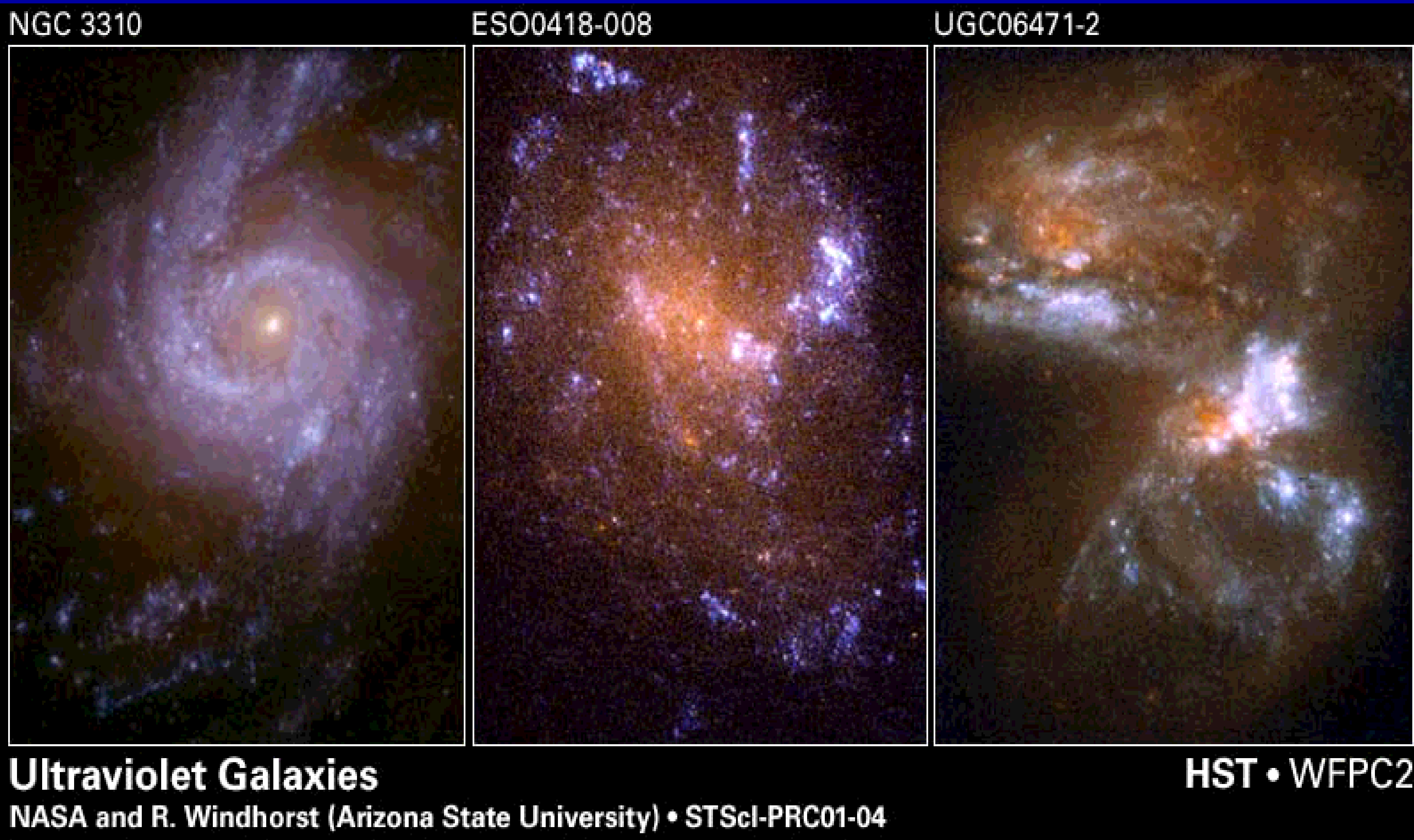
• (2a) How JWST can measure Galaxy Assembly



R. Windhorst (Arizona State University) and NASA

One of the remarkable discoveries of HST was how numerous and small faint galaxies are — the building blocks of the giant galaxies seen today.

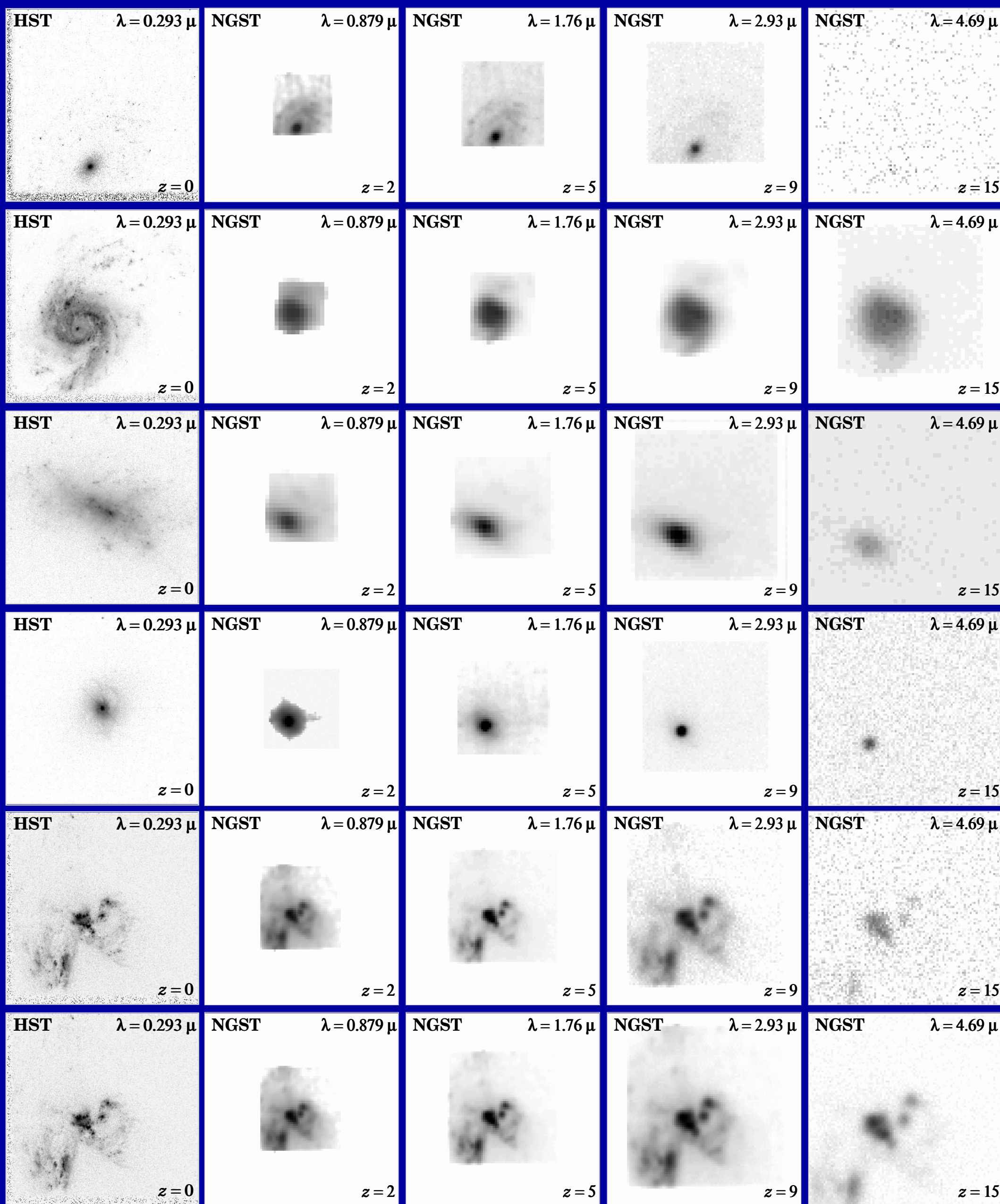
THE HUBBLE DEEP FIELD CORE SAMPLE ($I < 26.0$)



Ultraviolet Hubble images of nearby galaxies: Benchmarks for high redshifts

(2a) Predicted Galaxy Appearance for JWST at z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



With proper restframe-UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure over a wide range of cosmic time:

- (1) Most disks will SB-dim away at high z, but they formed at z$\lesssim z_{form} \simeq$1–2.
- (2) High SB structures are visible to very high z.
- (3) Point sources (AGN) are visible to very high z.
- (4) High SB-parts of mergers/train-wrecks are visible to very high z.

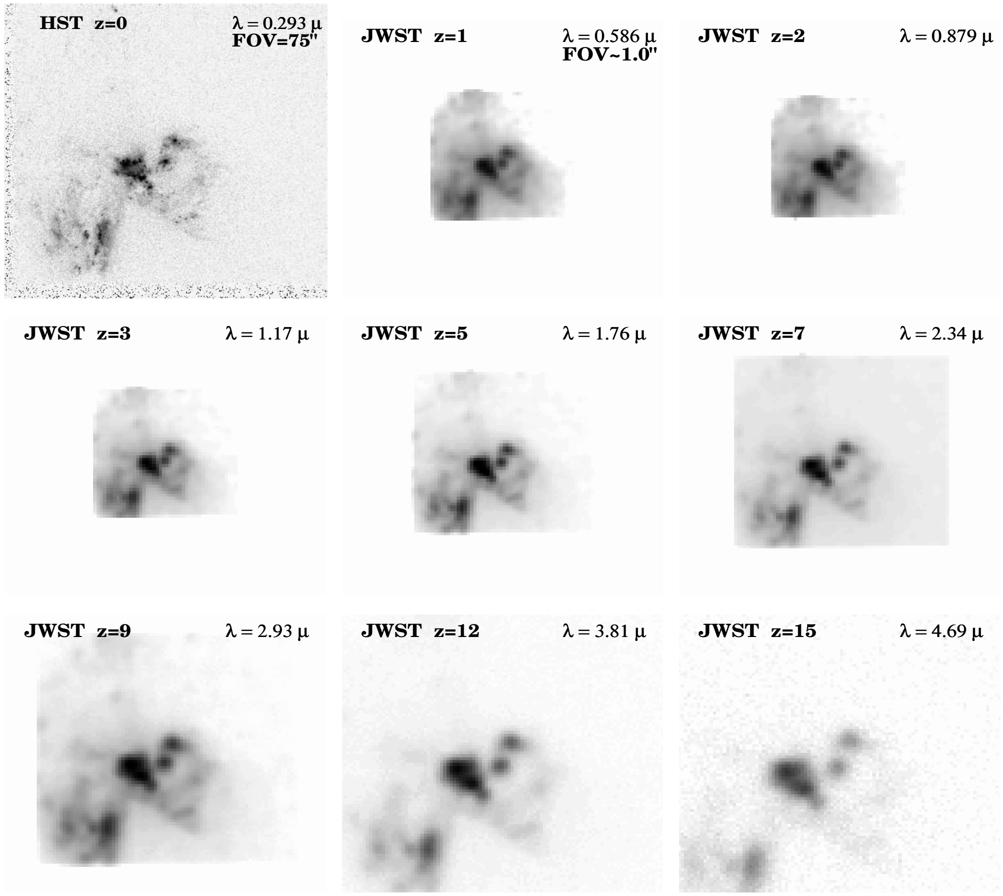


Fig. 4.06.c. JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). This is the BEST CASE JWST [meeting all GOALS, and t_{exp}=100 hrs]. The object is recognizable to z≃15.

ASSUMPTIONS: COSMOLOGY: H_0=71 km/s/Mpc, Ω_m=0.27, and Ω_Λ=0.73.

INSTRUMENT: 6.0 m effective aperture, JWST/NIR camera, 0.034″ /pix, RN=3.0 e^-, Dark=0.010 e^-/sec, NEP H-band Sky=21.7 mag/arcsec^2 in L2, Zodi spectrum, t_{exp}=100.0 hrs, read-out every 900 sec ("GOALS").

Row 1: z=0.0 (HST λ=0.293μm, FWHM=0.04″), z=1.0 (JWST λ=0.586μm, FWHM=0.084″), and z=2.0 (JWST λ=0.879μm, FWHM=0.084″). **Row 2:** z=3.0 (JWST λ=1.17μm, FWHM=0.084″), z=5.0 (JWST λ=1.76μm, FWHM=0.084″), and z=7.0 (JWST λ=2.34μm, FWHM=0.098″). **Row 3:** z=9.0 (JWST λ=2.93μm, FWHM=0.122″), z=12.0 (JWST λ=3.81μm, FWHM=0.160″), and z=15.0 (JWST λ=4.69μm, FWHM=0.197″)

The galaxy merger UGC06471-2 (z=0.0104).

This is the BEST CASE JWST. It assumes that all GOALS are met, and that t_{exp}=100 hrs. The whole object (including the two star-forming knots) is recognizable to z≃15.

This does not imply that observing galaxies at z=15 with JWST will be easy. On the contrary, since galaxies formed through hierarchical merging, real objects at z≃10–15 will be 10^1–$10^4\times$ less luminous, requiring to push JWST to its limits.

• (2a) Radio Telescopes — Movable Interferometers

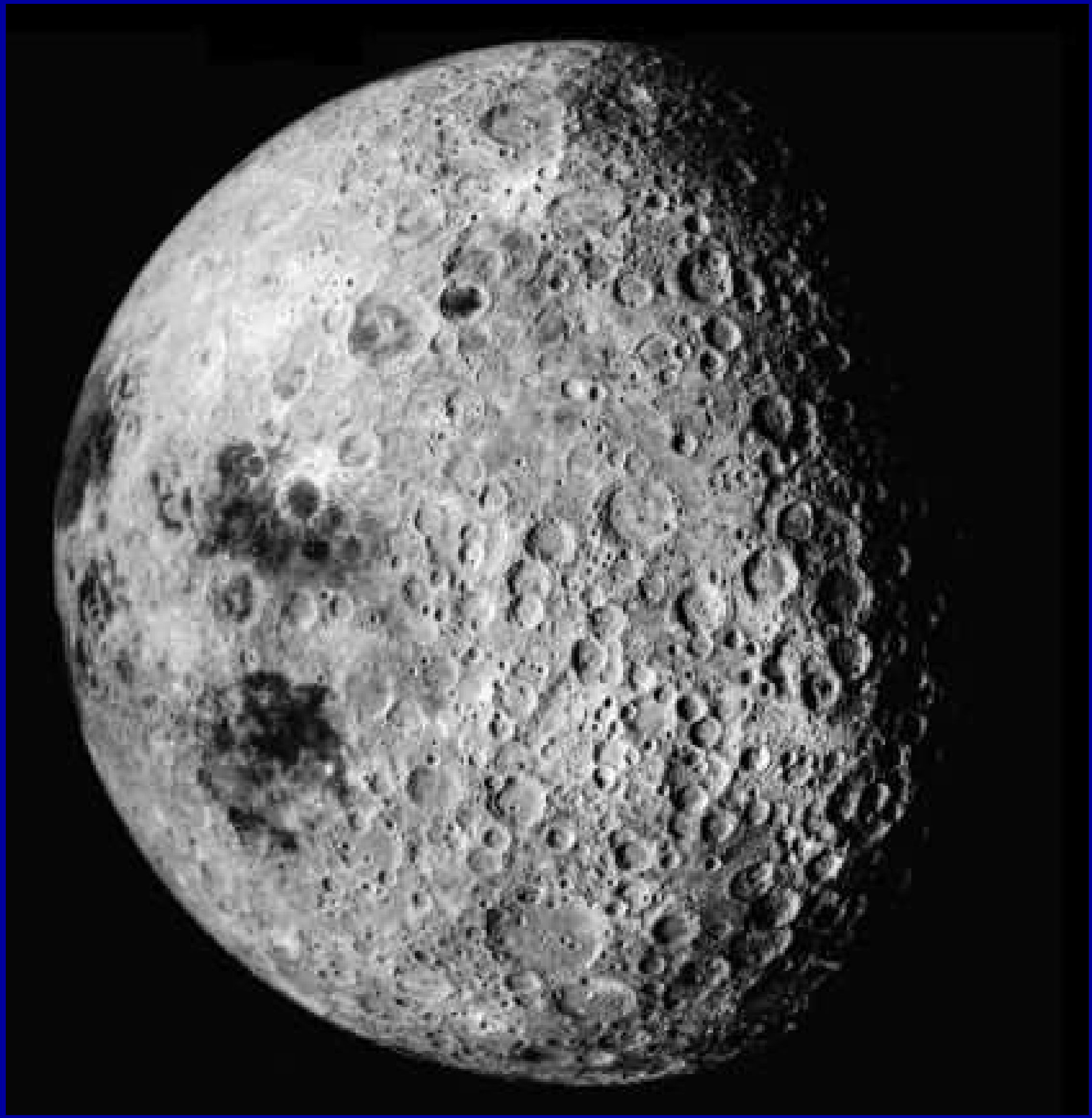
• Very Large Array (VLA, NM): 27 radio dishes (25-m) movable on railroad tracks over 1–27 km baselines $\Longrightarrow$ 1–30" resolution at $\nu \simeq$GHz.

• (2b) Radio Telescopes — Transcontinental Interferometers

• Very Long Baseline Array (VLBA): 10 fixed 25-m radio dishes across the US with 5000 km maximum baselines $\Longrightarrow \lesssim 0.01''$ resolution at $\nu \simeq$GHz.

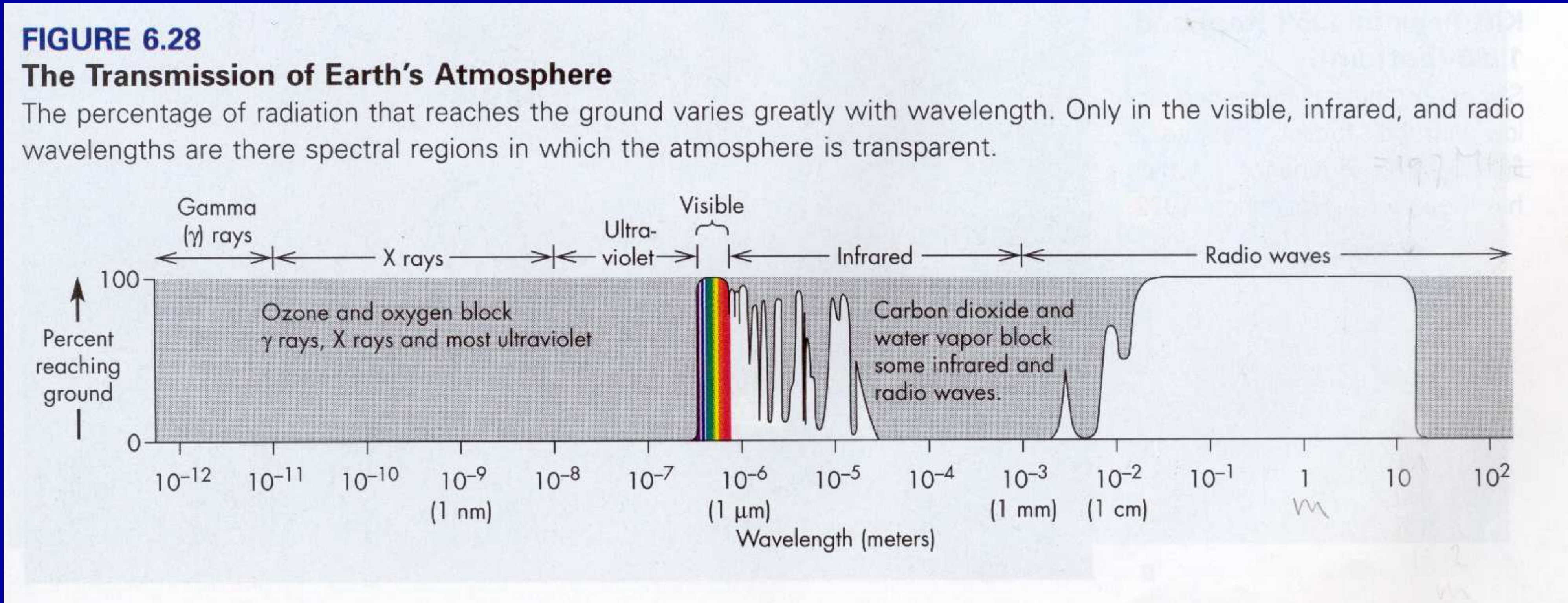
• (2c) A Low-frequency Interferometer on the Moon's far-side

Only place free of: (a) human ULF interference; (b) ionospheric absorption



• Moon's far-side has enough flat craters for interferometers of $\lesssim$3000 km baselines and hectare-collecting area $\Rightarrow$ FWHM$\lesssim$1" at $\nu\lesssim$30 MHz.

• (2c) Far-side of the Moon — only place to see H-I at z$\gtrsim$45



• Far-side of Moon only place free of human-made ULF interference and ionospheric absorption.

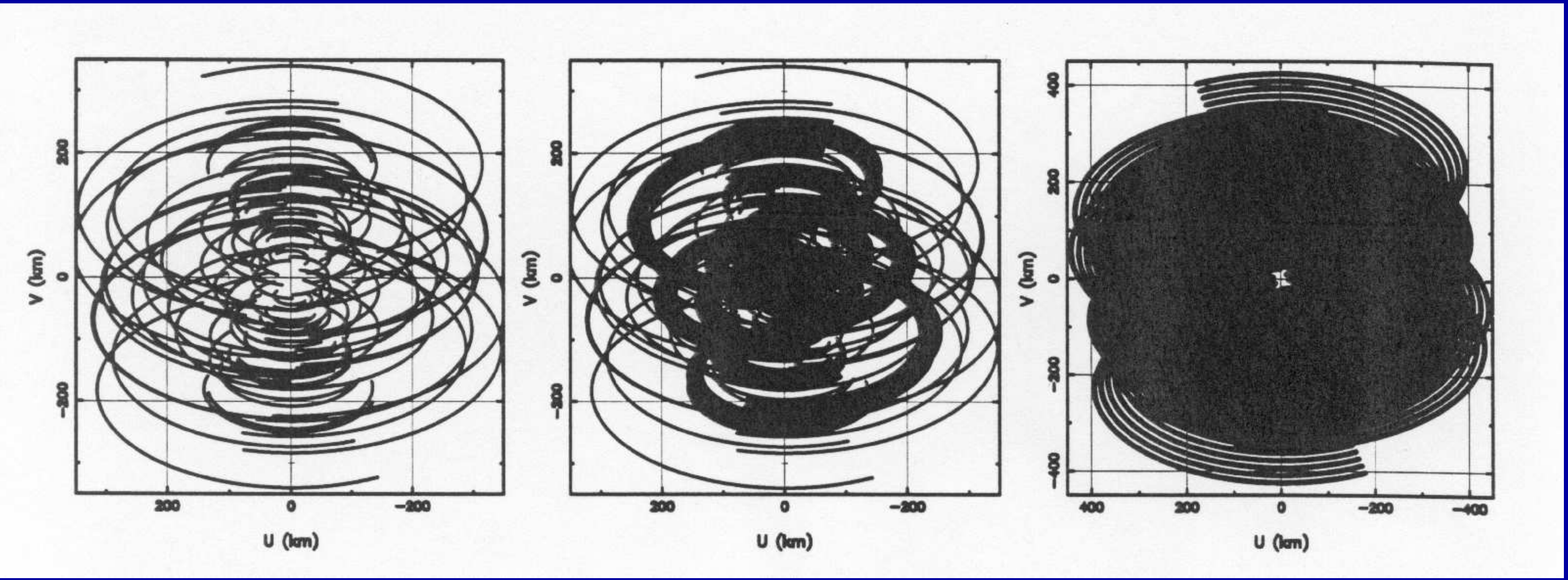
• $\Rightarrow$ H-I studies at $\nu \lesssim$30 MHz $\Leftrightarrow$ can see ν(H-I=1421 MHz) at z$\gtrsim$45 !

• $\Rightarrow$ Moon's far-side needed to penetrate first 55 Myr of the Universe's history: the Cosmic Dark Ages.

• (2c) Lunar Dark-Ages Array — How to build it?

- Use long-duration science rovers to lay down a fractal grid of foil and dipoles. Foil backs up as solar panels.
- Exact geometry is not important. Surface accuracy may be $\lesssim$50 cm!
- Use Ka-band to correlate data, Lunar TDRSS to send to Earth (Tb/day).
- Weeks–months to build. Then use rovers to explore interesting areas.

• (2c) Lunar Dark-Ages Array — How does it work?



• Use Lunar rotation to get 14-day integrations on large patches of sky.

• Fourier UV-tracks for 10 stations fill aperture fairly well (left).

• Multi-frequency UV-tracks will provide better aperture coverage (right).

• FFT of UV-coverage yields PSF, and FFT of (Ampl, ϕ) yields image.

• (Cannot do free floater, since need baselines $\gtrsim$few 100 km, and must rotate aperture to optimally fill UV-plane. Moon provides both).

(3) Conclusions

(1) BIG UNIVERSE: Solid evidence for "Hot Big Bang":

- (1a) Distance measurements are now secure to within a few %.
- (1b) Hubble expansion is a real expansion of space. Age=13.7±0.2 Gyr.
- (1c) (Ω_{baryon}=0.044) + (Ω_{dark}=0.23) + (Ω_{Λ}=0.73) = 1.00±0.02

⇒ Spatially flat, inflationary and now exponentially expanding universe.

⇒ We know very precisely that 96% of Ω_T is of unknown nature!

- (1d) Observed light element abundance exactly as predicted by Hot BB.

(2) LARGE TELESCOPES: Need them because of rapid expansion!

(2a) Golden age of space and ground-based telescopes is still ahead.

(2b) Need radio (+UV, X-ray, γ-ray) telescopes to trace GR singularities.

(2c) Penetrating Dark Ages may need Interferometer on Moon's far-side.

GENERAL SPARE CHARTS ON BIG BANG

(3) Lessons to be learned for SESE:

In the New NASA Vision: Moon/Mars/Beyond, we must keep in mind:

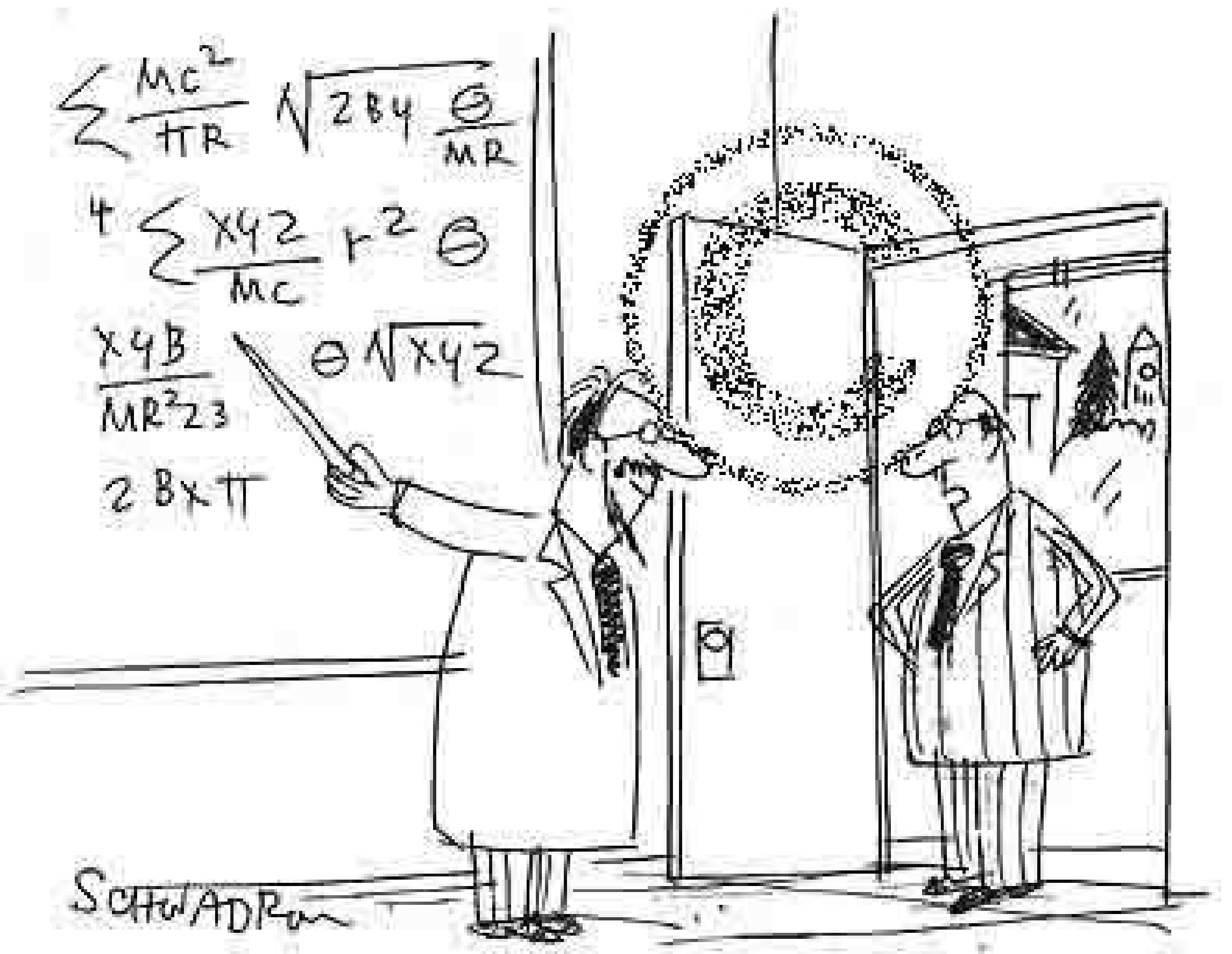
Earth/Moon/Mars/Beyond $\simeq 10^{51}/10^{49}/10^{50}/10^{80}$ baryons.

(and 96% of the Universe's energy density is not listed here!)

- This doesn't mean that funding should be proportional to these numbers.

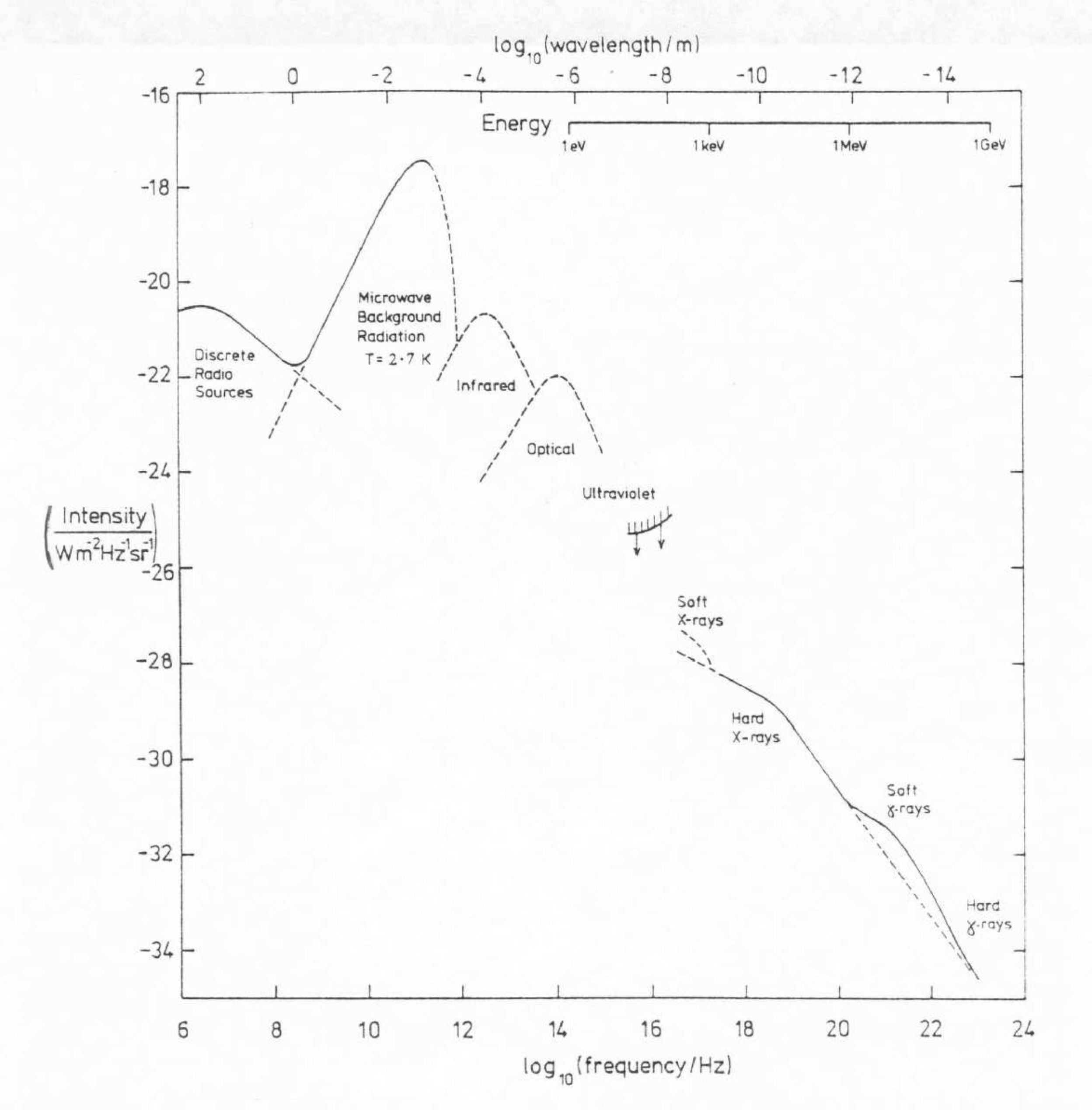
Hence, for SESE to be competitive and to succeed, we must not forget to:

- (1) Keep the overall picture in mind: Origins!
- (2) Have an open mind to other fields.
- (3) Build a balanced program that covers all relevant areas.
- (4) Build strong interdisciplinary ties between fields.



"The Big Bang Theory? I want you to come up with the Big Bucks Theory!"

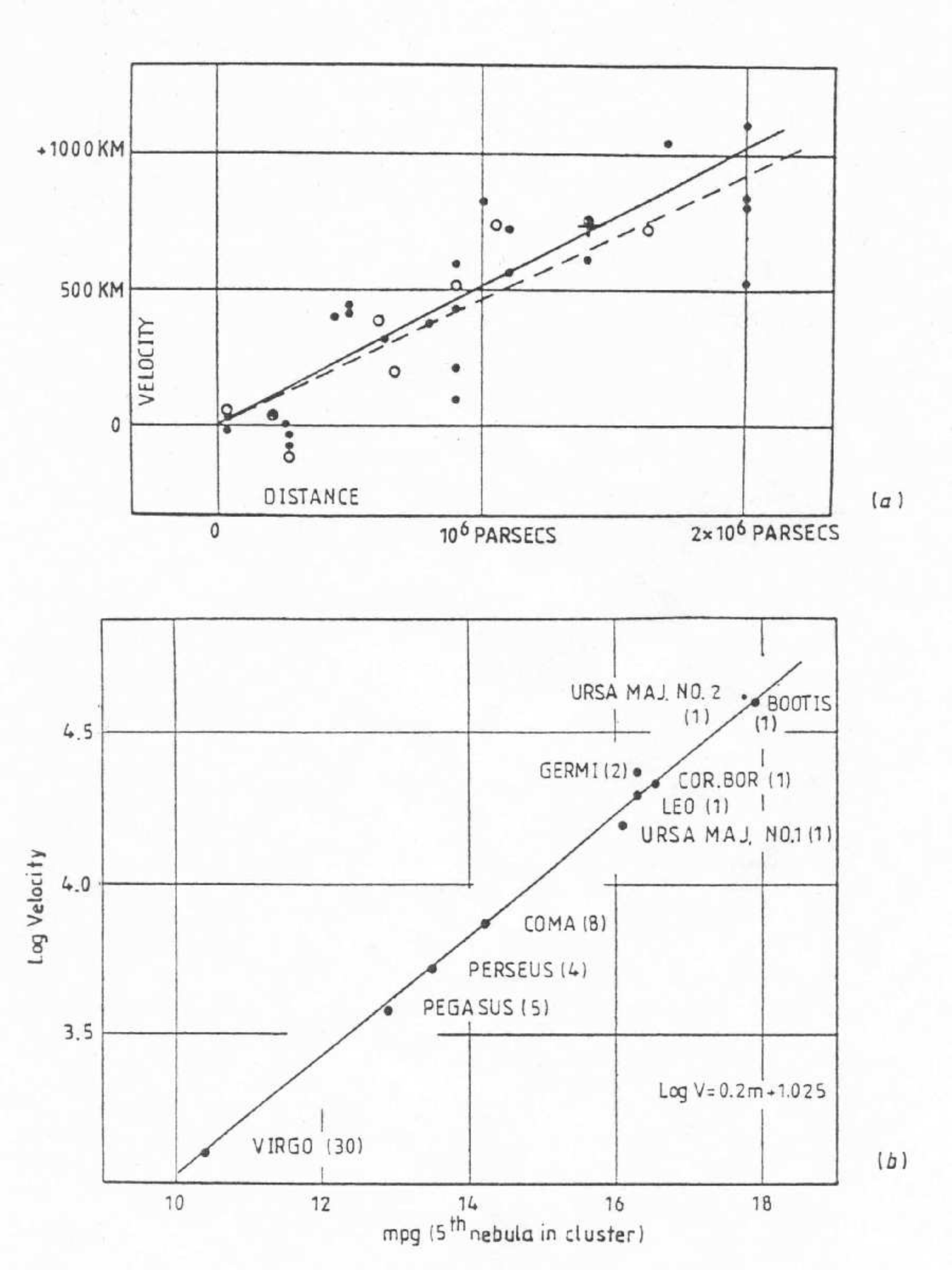
How to get tenure as cosmologist ...



Integrated Cosmic Background: nearly a power-law of 20 dex in wavelength!

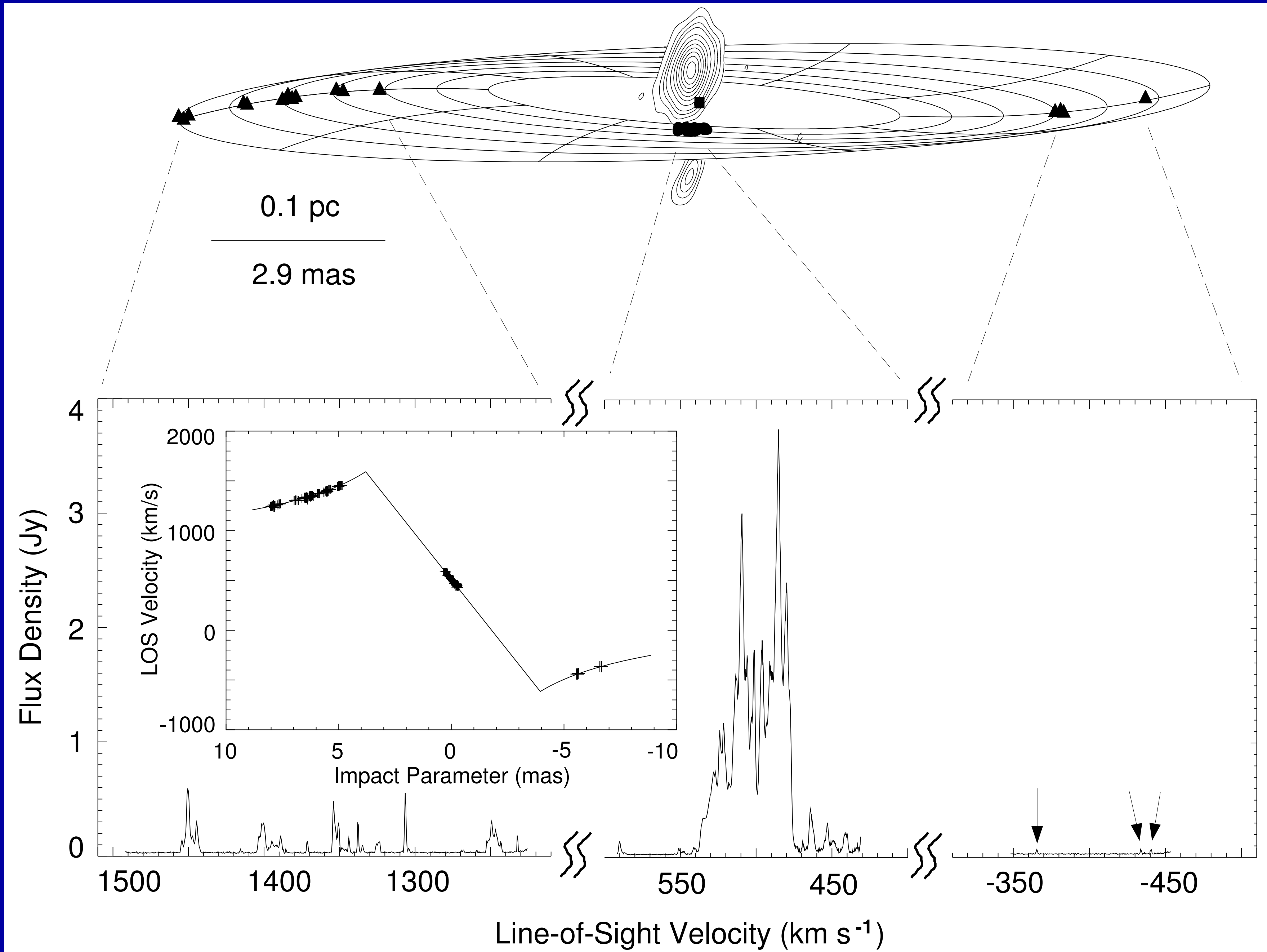
$\Rightarrow$ In addition to cosmic background, dust & stars in galaxies, there is another:

Power source: Active Galactic Nuclei powered by supermassive black-holes.



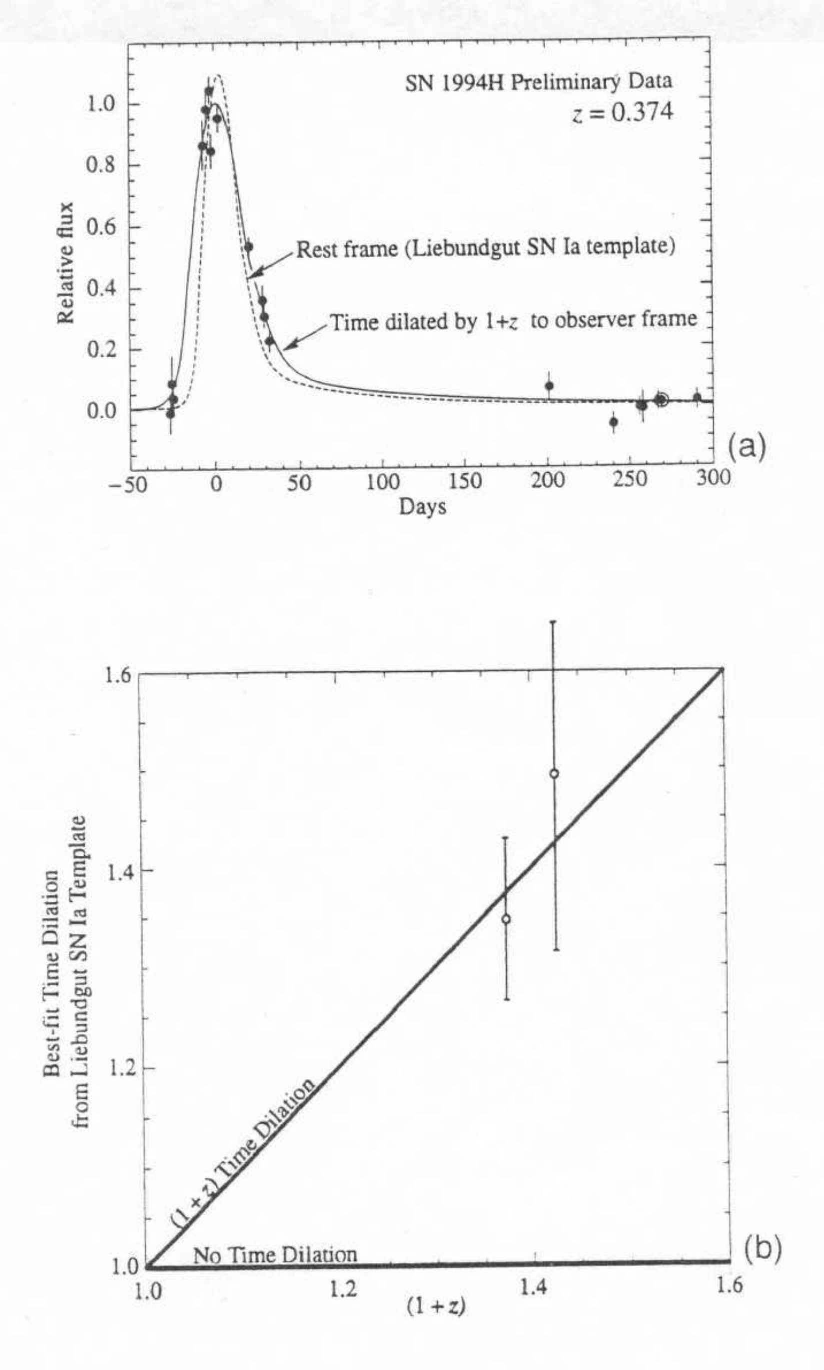
Hubble's original expansion data: v = H_0 ×D (H_0 =550 km/s/Mpc)

Hubble UV image of galaxy NGC 6782: spectacular star-forming rings



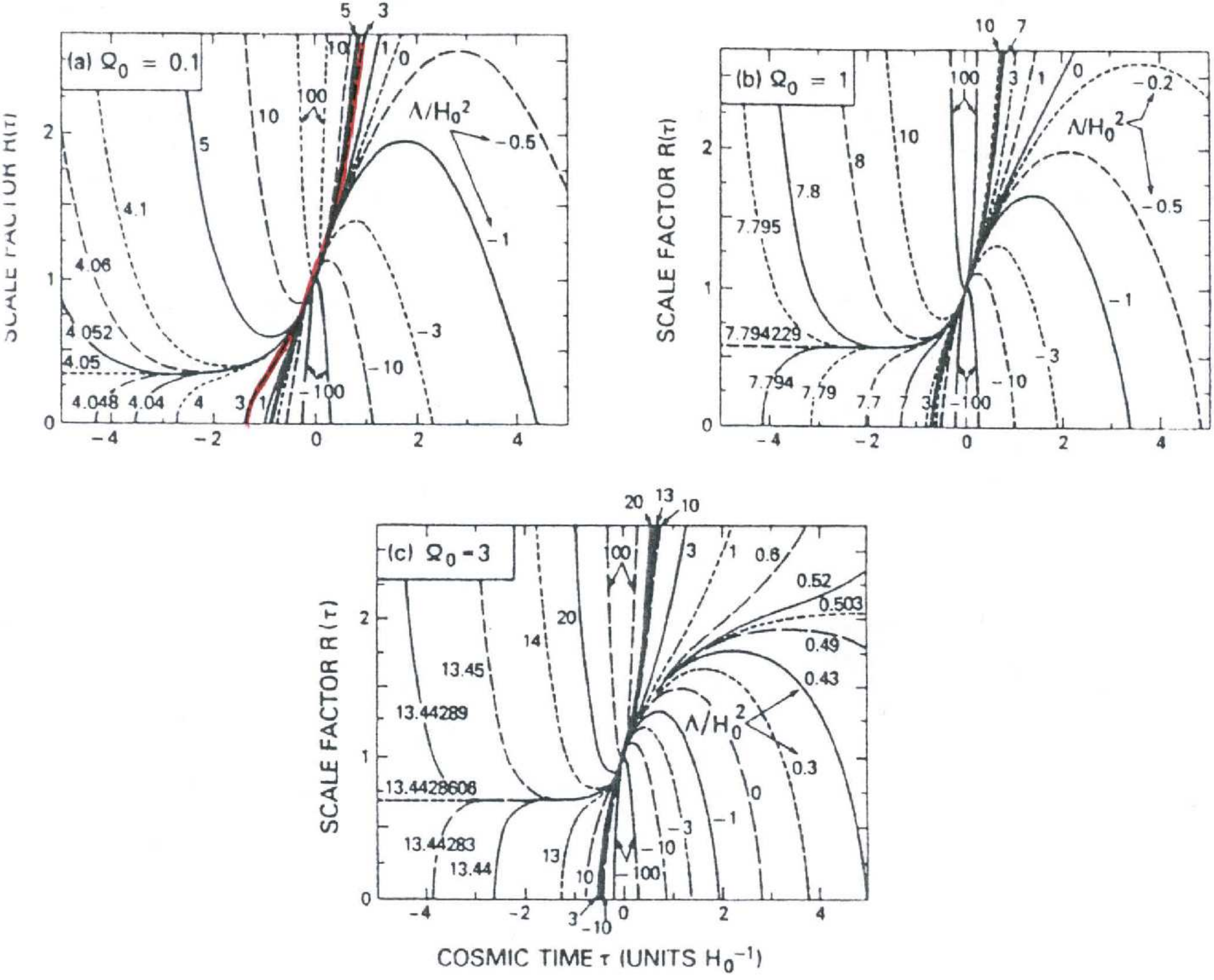
Geometric distance to NGC 4258 based on Kepler's 3rd law: 7.2±0.3 Mpc

The most precise distance known at 23.5±1.0 Mega-lightyear (Mlyr).

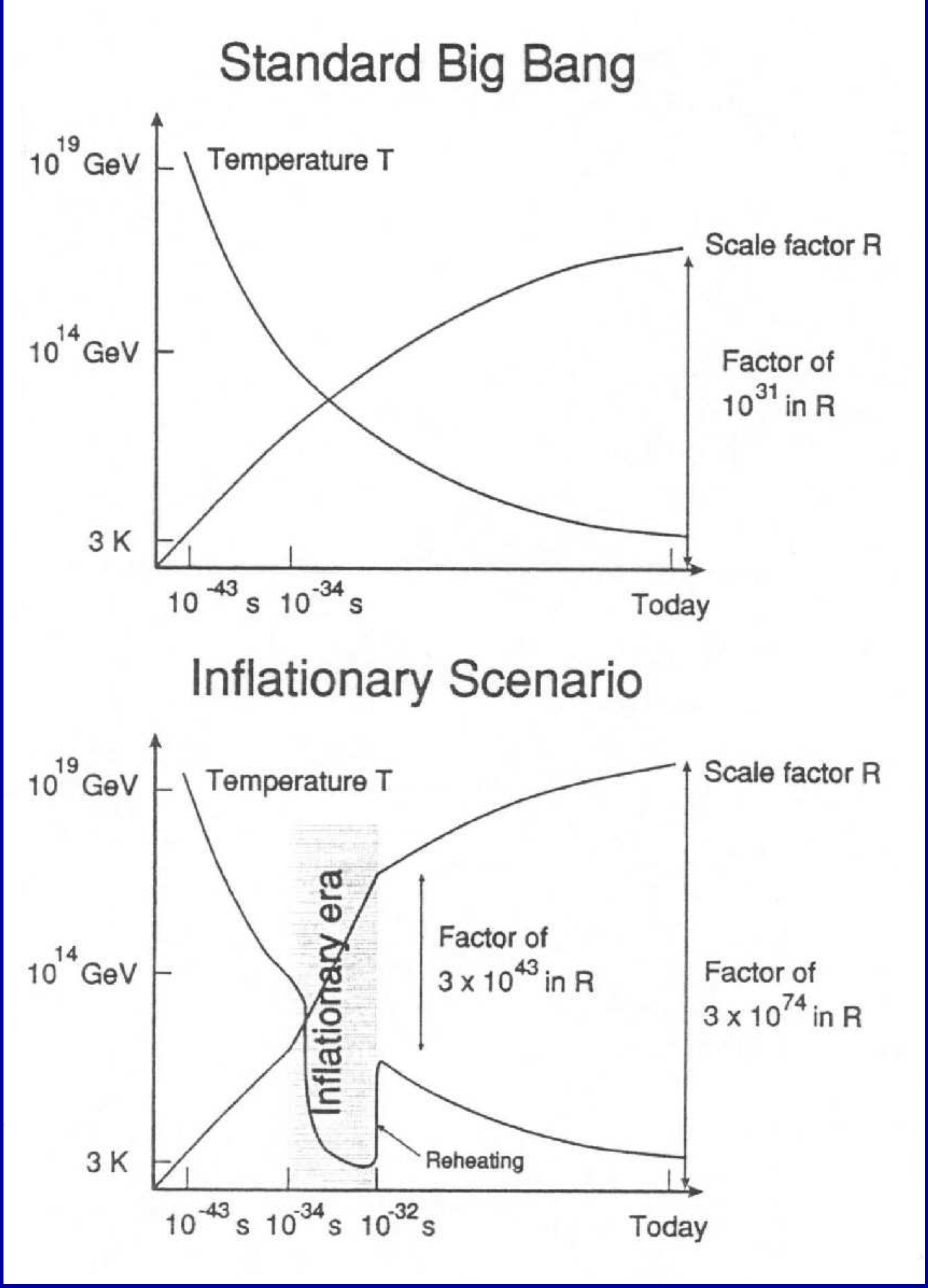


Supernovae Ia light-curves at z=0.37 show Relativistic time-dilation.

⇒ The expansion is therefore definitely real!



Lambda-dominated models: Scale Factor R vs. cosmic time t.



Cosmology with (top) and without (bottom) an inflationary epoch.

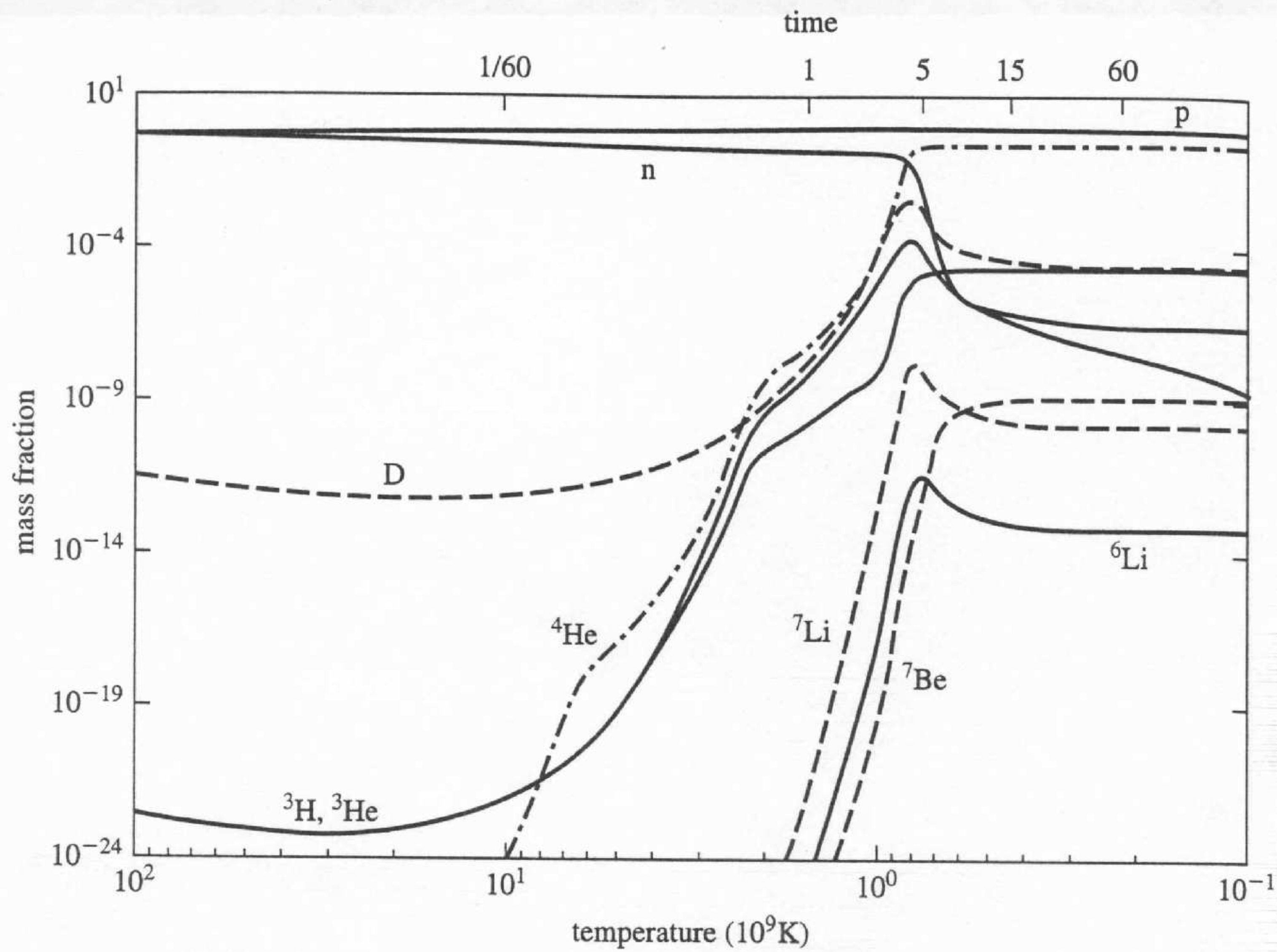
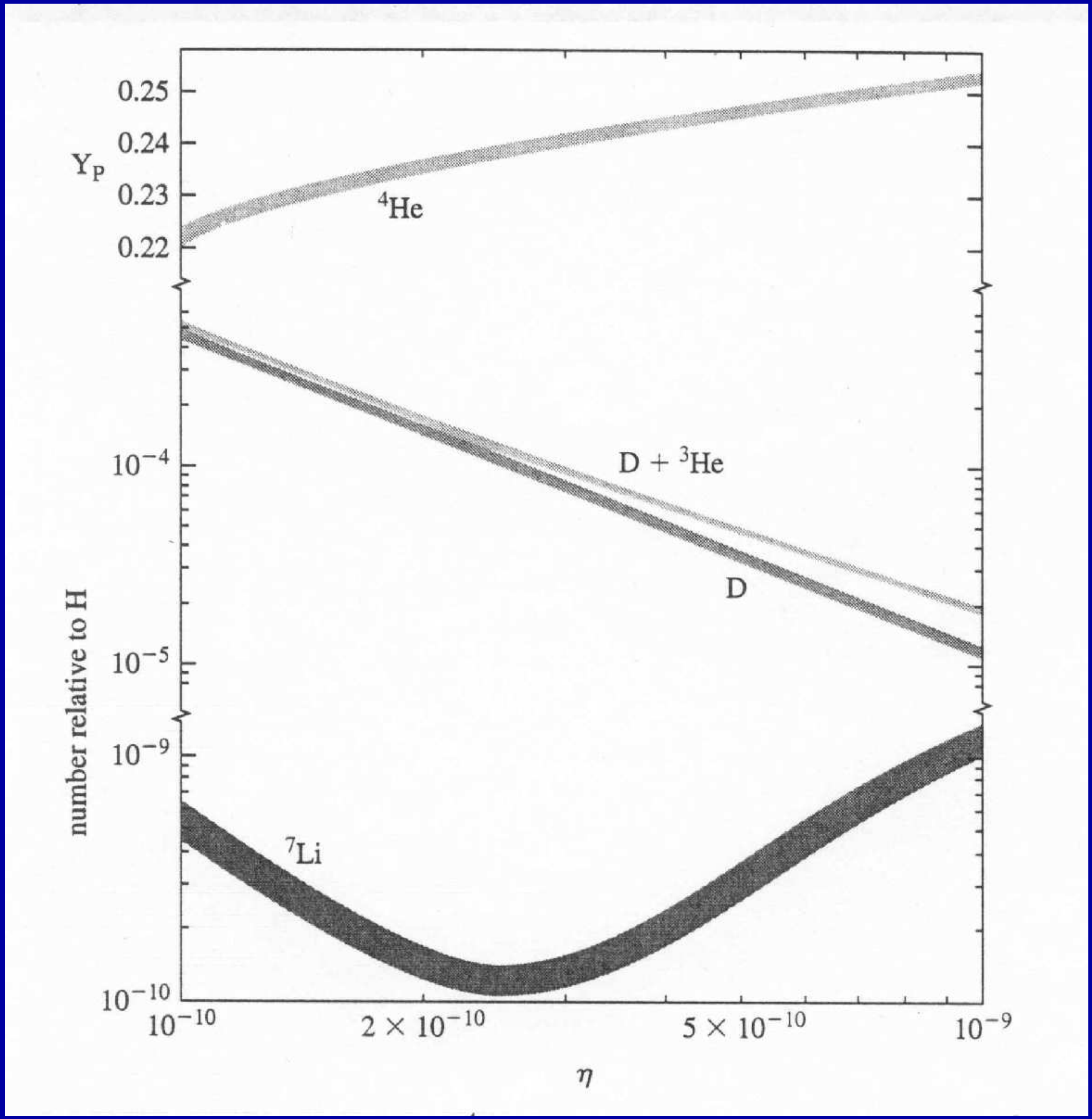


FIGURE 10.4 Mass fraction of nuclei as a function of time during the epoch of nucleosynthesis. A baryon-to-photon ratio of $\eta = 5.1 \times 10^{-10}$ is assumed.

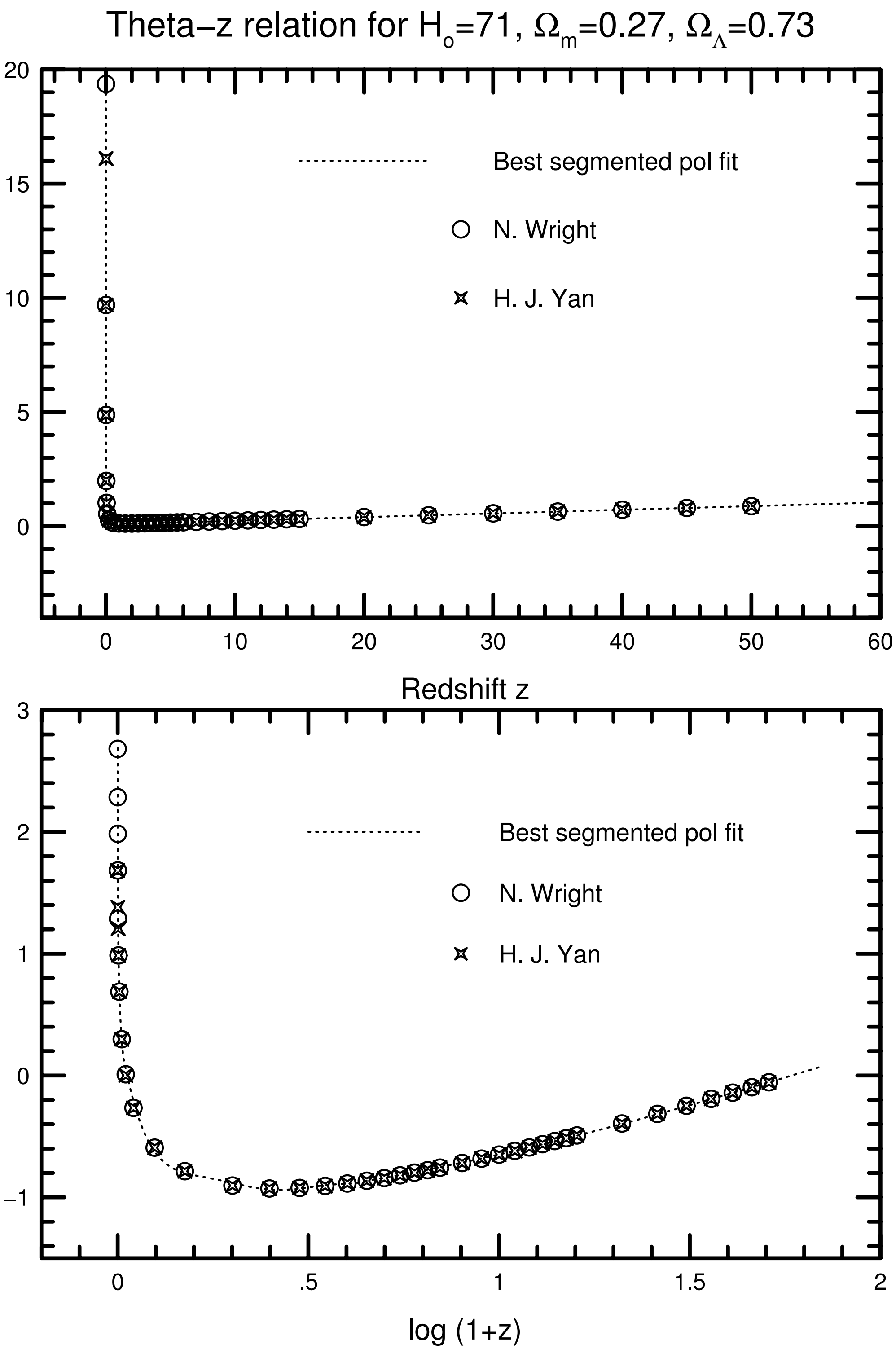
Hot Big Bang: Light element production vs. temperature and cosmic time.

$\Longrightarrow$ Explains 24% He (+some Li & Be). Need $\eta^{-1} \simeq 4 \times 10^{-10}$, Ω_{bar}=0.044.



Light element production vs. Baryon-to-Photon ratio $\eta \simeq 5\times10^{-10}$.

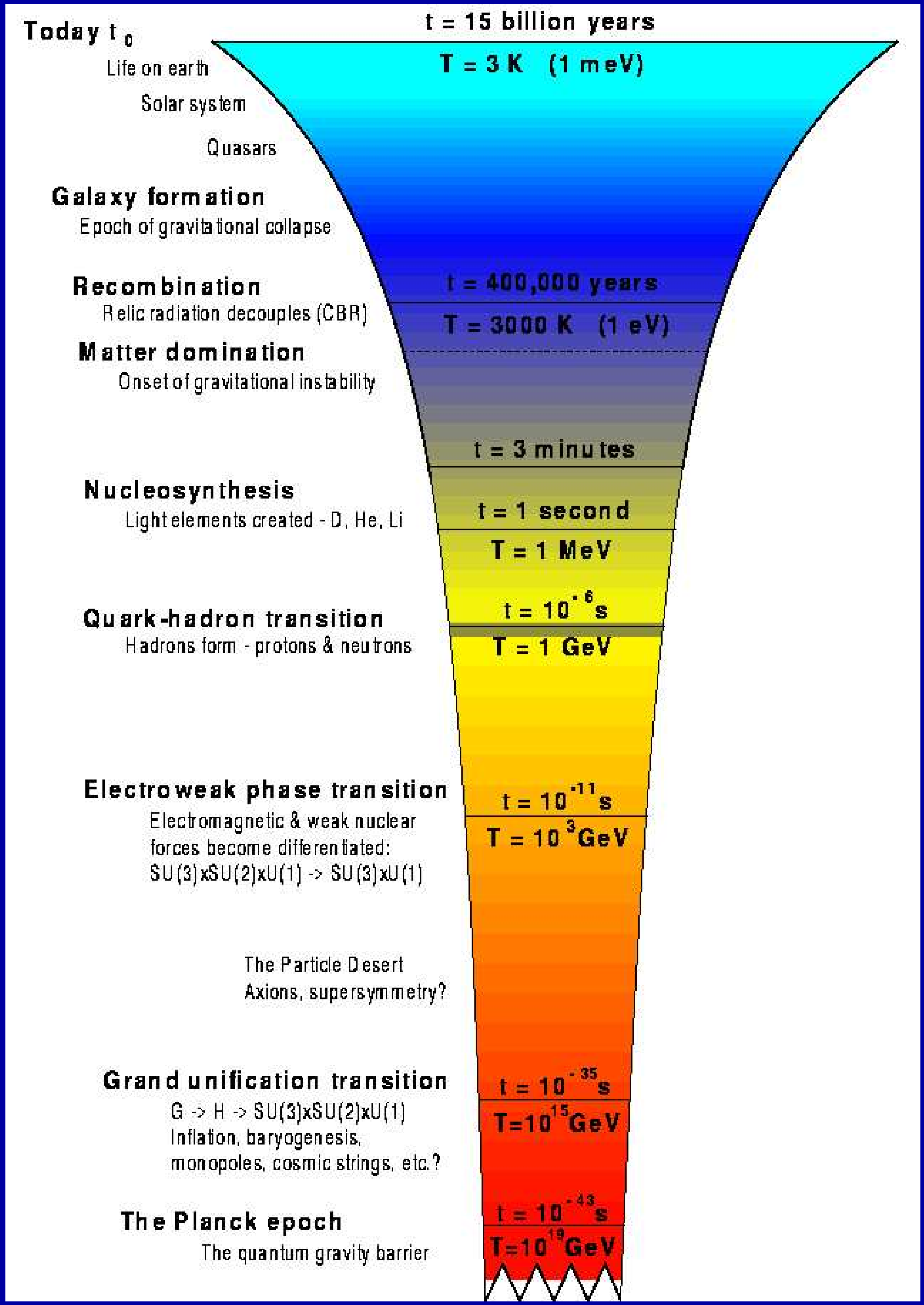
$\Longrightarrow$ Hot Big Bang and Microwave Background imply Ω_{baryon}=0.044.



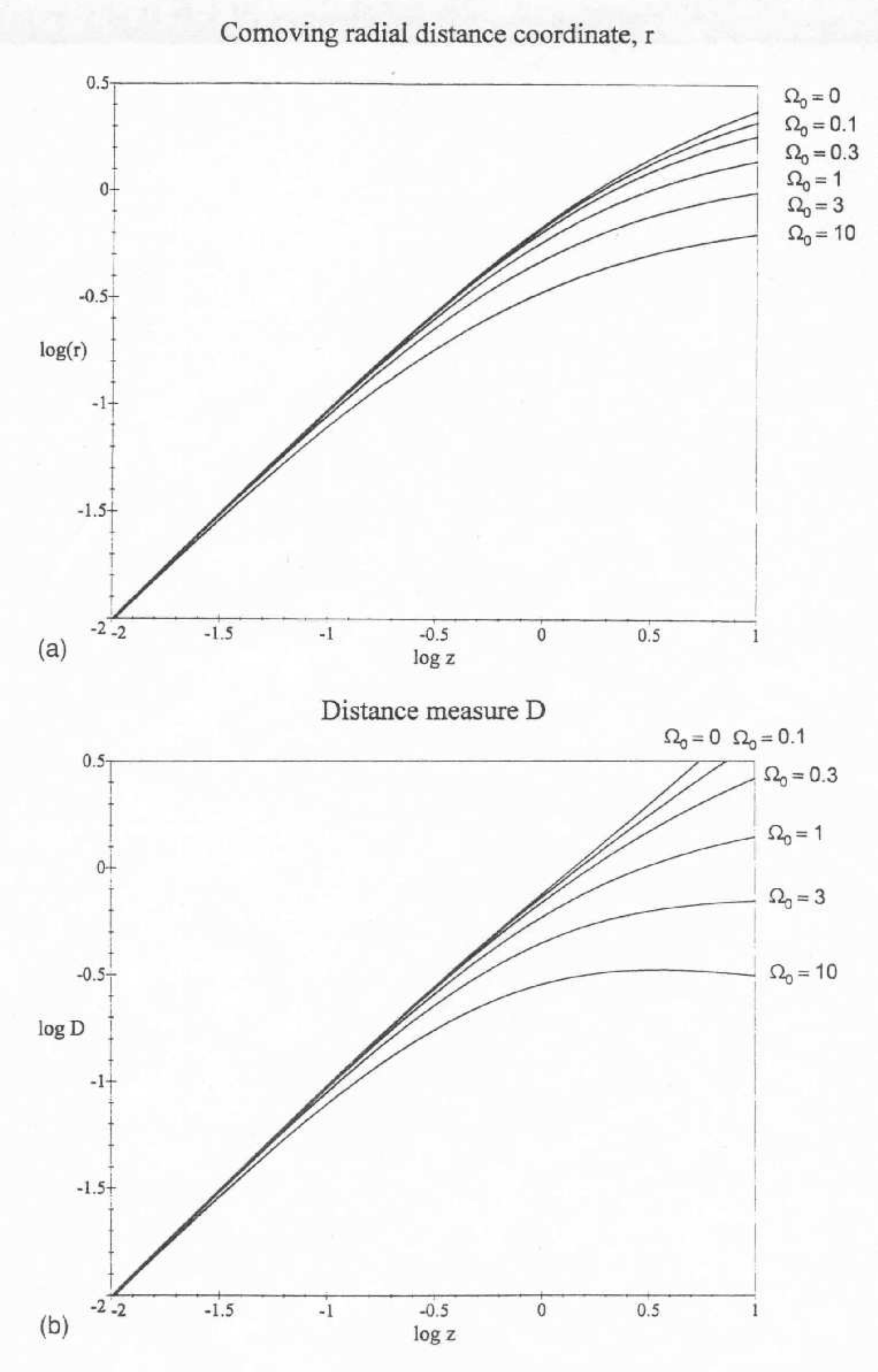
Angular size vs. redshift relation in a Lambda dominated cosmology of H_0 =71 km/s/Mpc, Ω_m=0.27, Ω_Λ=0.73.

In the top panel the relation is nearly linear in 1/z for z$\lesssim$0.05 (the small angle approximation) and linear in z for z$\gtrsim$3 (the Lambda dominated universe).

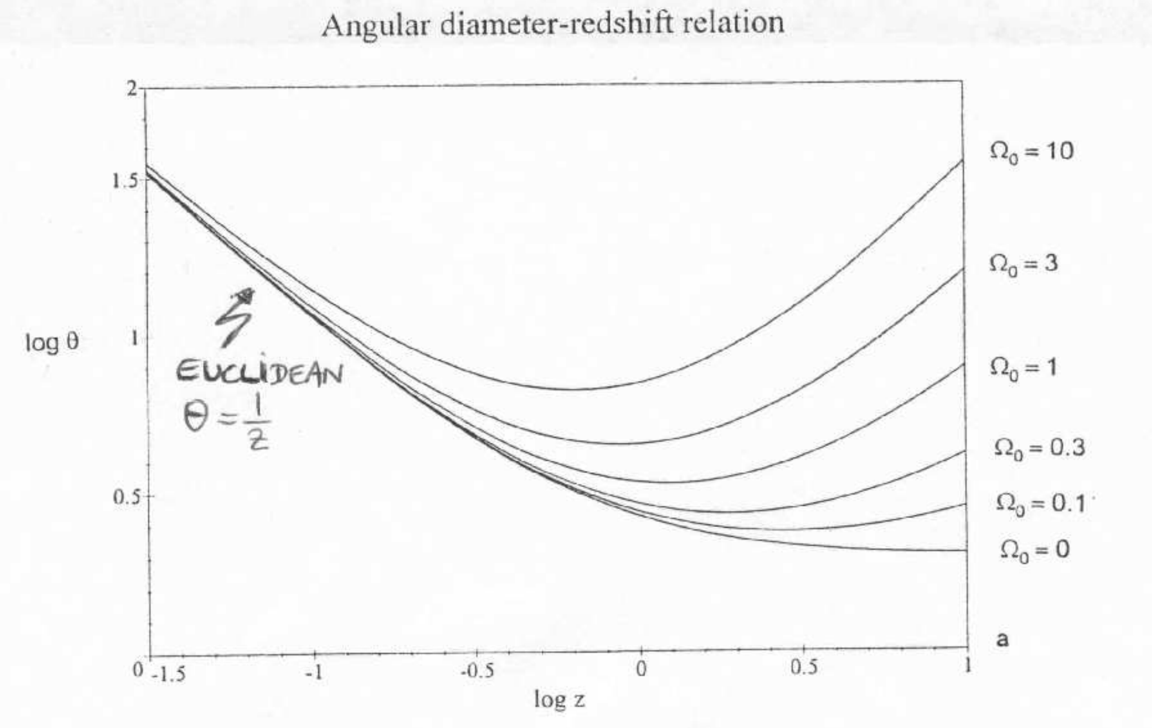
All curvature occurs in the range 0.05$\lesssim$z$\lesssim$3, which is coded up in the IRAF script that does the JWST simulations.

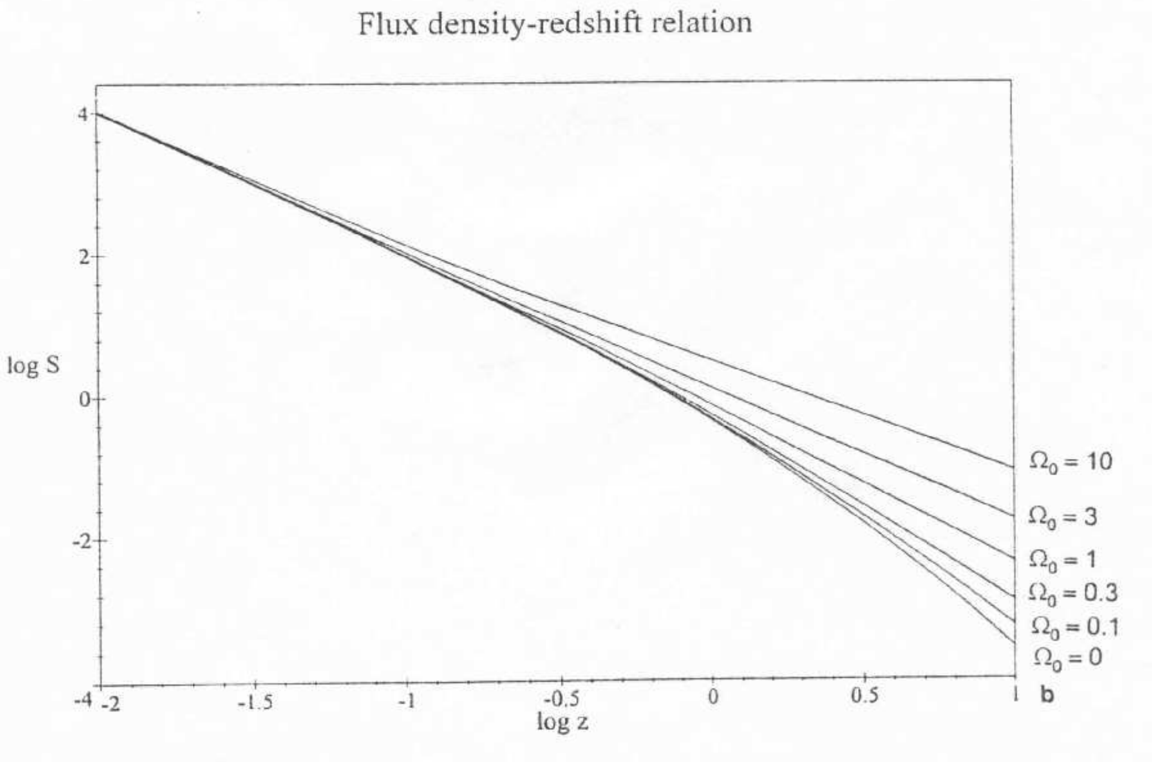


Brief History of the Hot Big Bang: Cosmic Soup vs. temperature & time.



Radial distance coordinate r and Distance measure D vs. redshift z.





Angular Size Θ and Flux S_ν vs. redshift z.

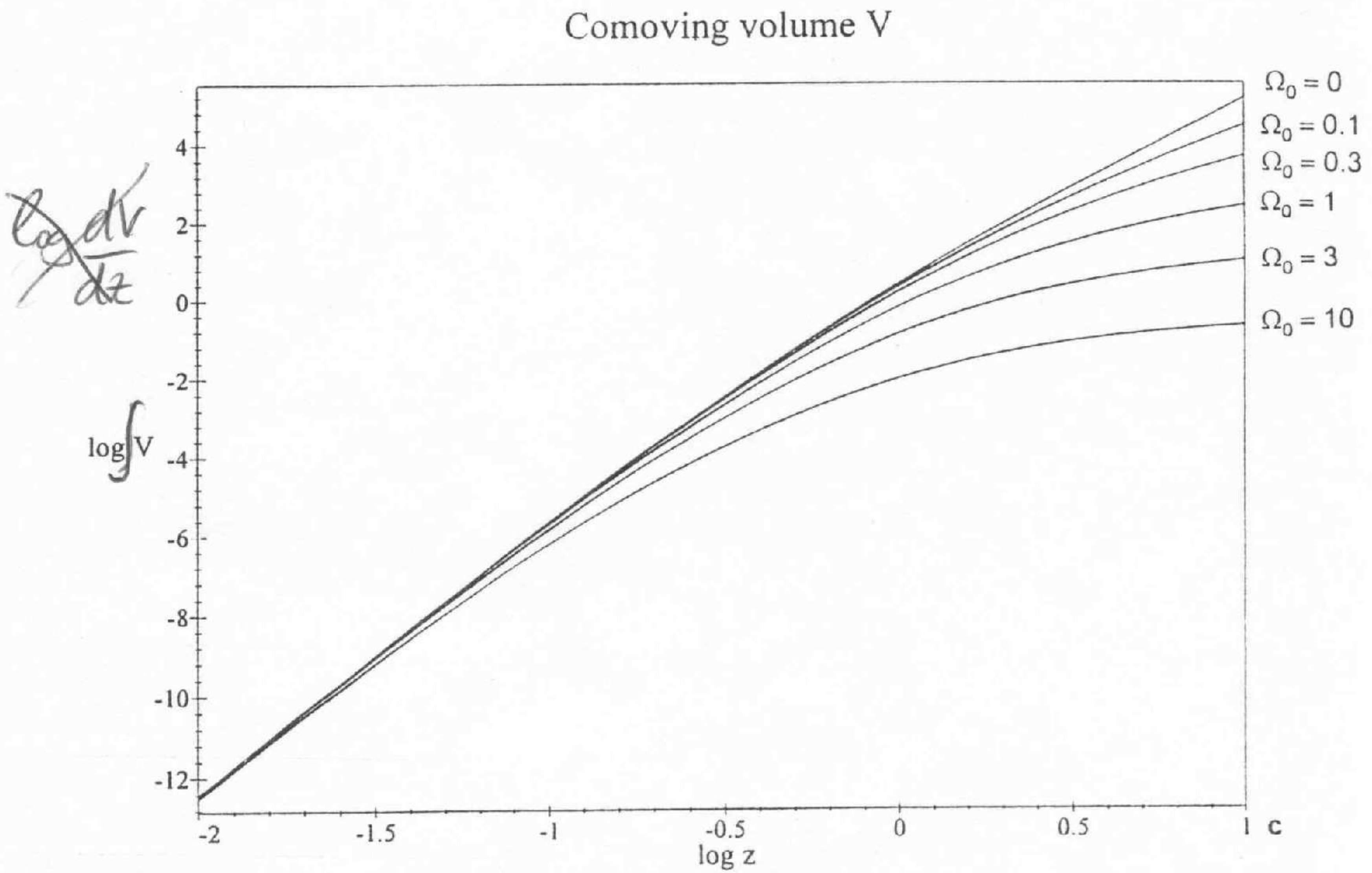
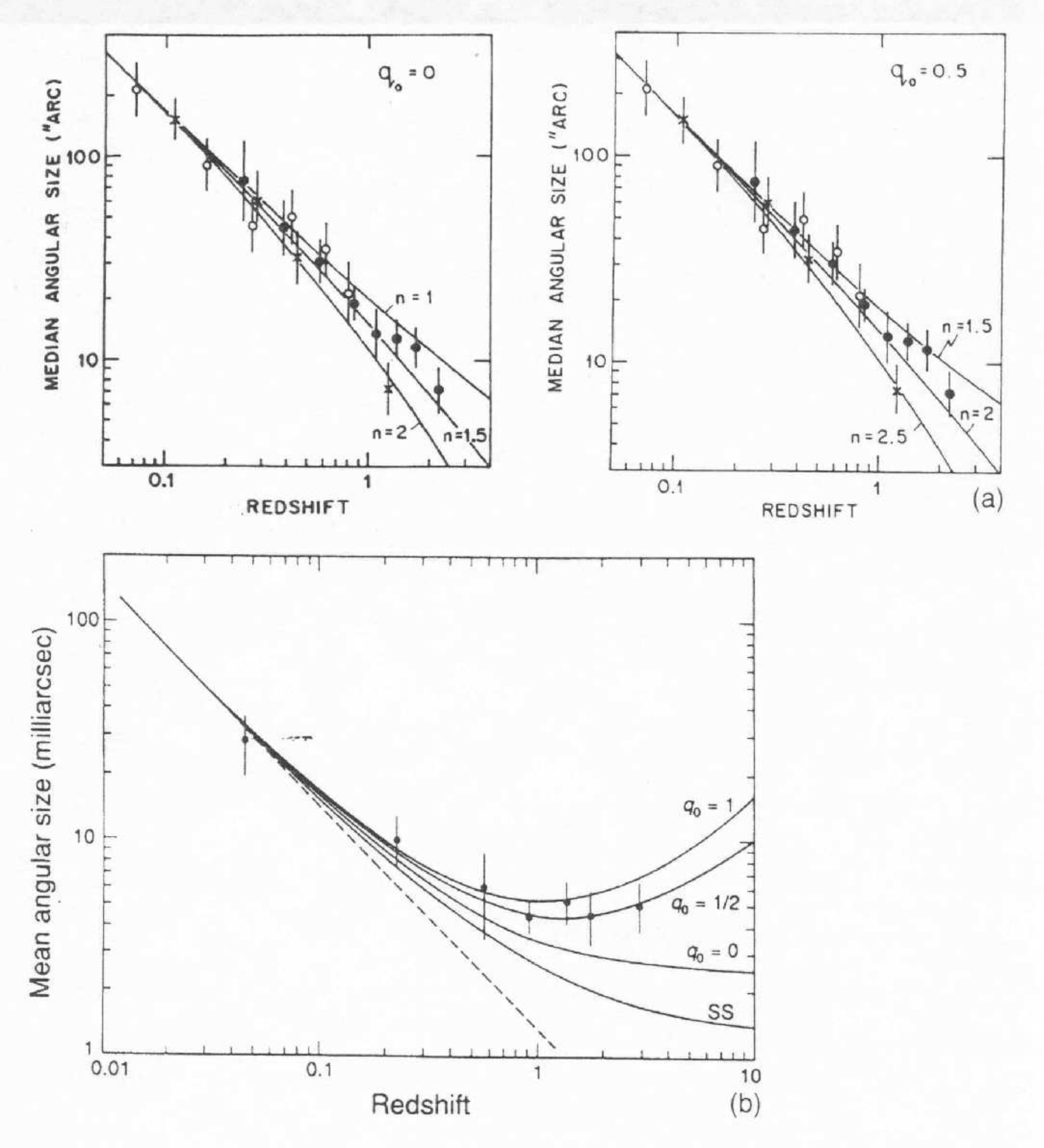


Fig. 7.4a-c. continued.

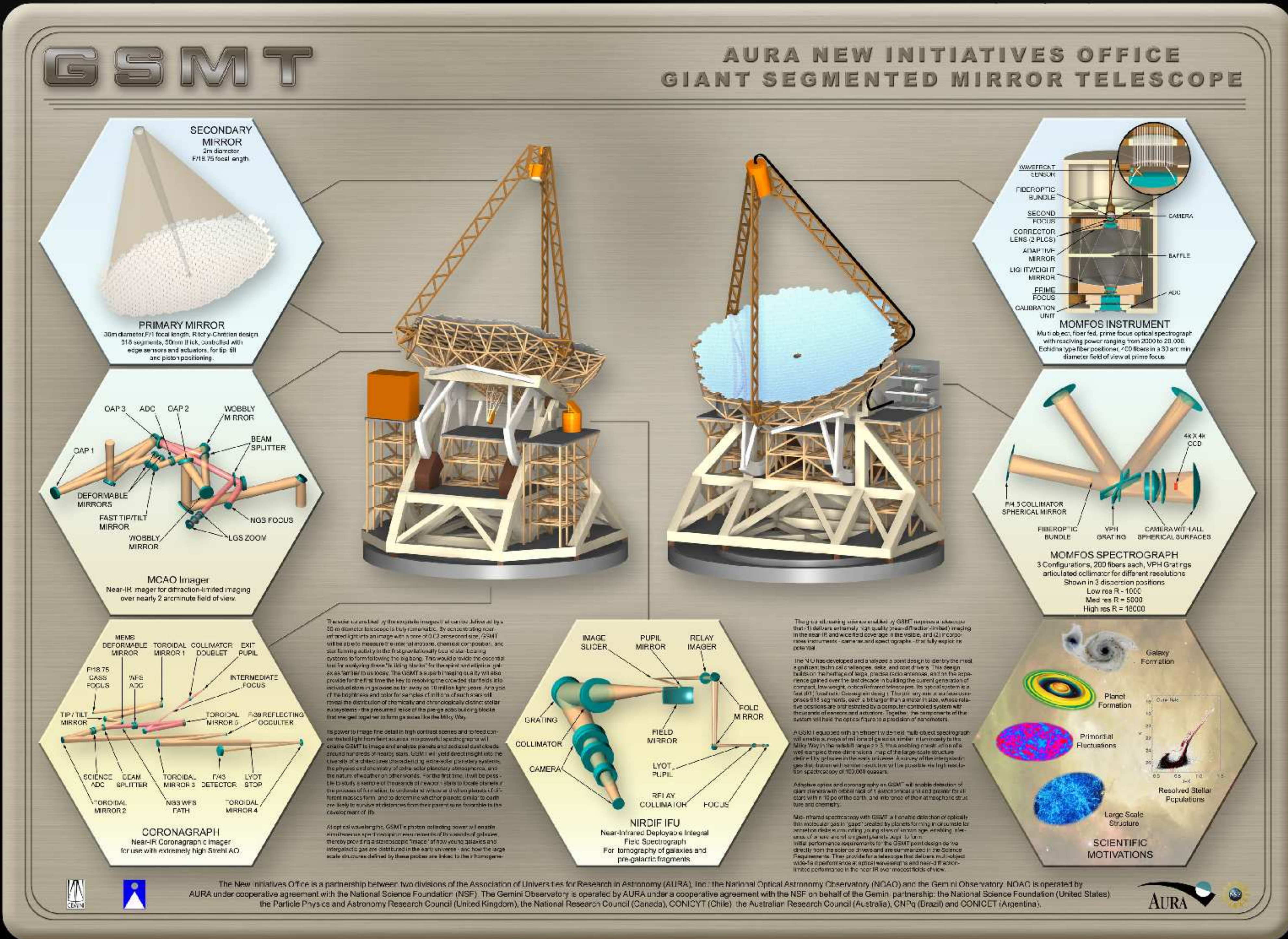
Co-moving Integrated Volume vs. redshift z. Corollary:

There exists very little differential volume at high redshifts $\Longrightarrow$

Must survey very large areas deeply to find rare faint very high z objects.

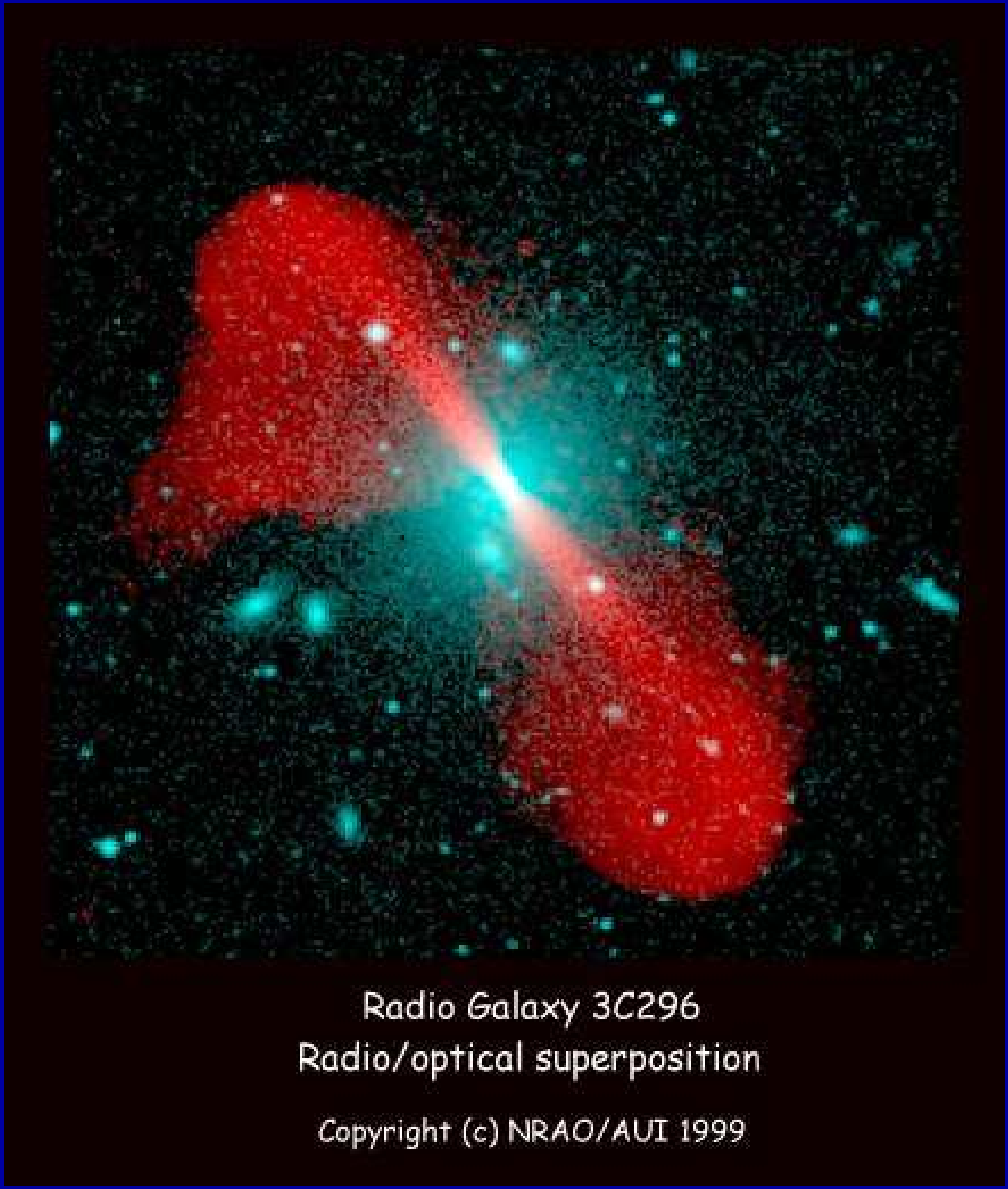


Angular Size Θ vs. z for double-lobed and VLBI radio sources.



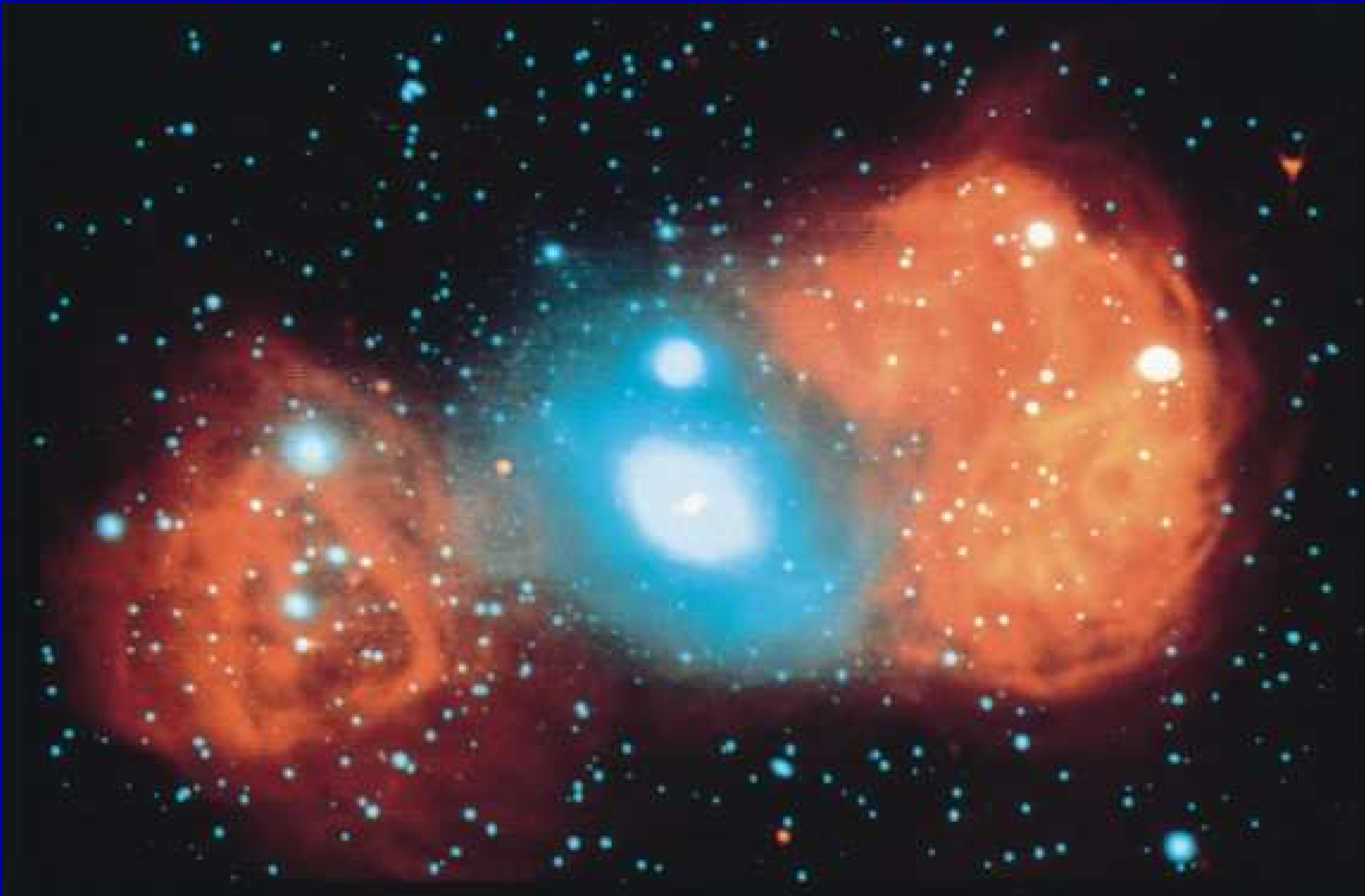
- Giant Segmented Mirror Telescope: segmented mirror, 30 m aperture.

• (1) Radio Telescope — Images

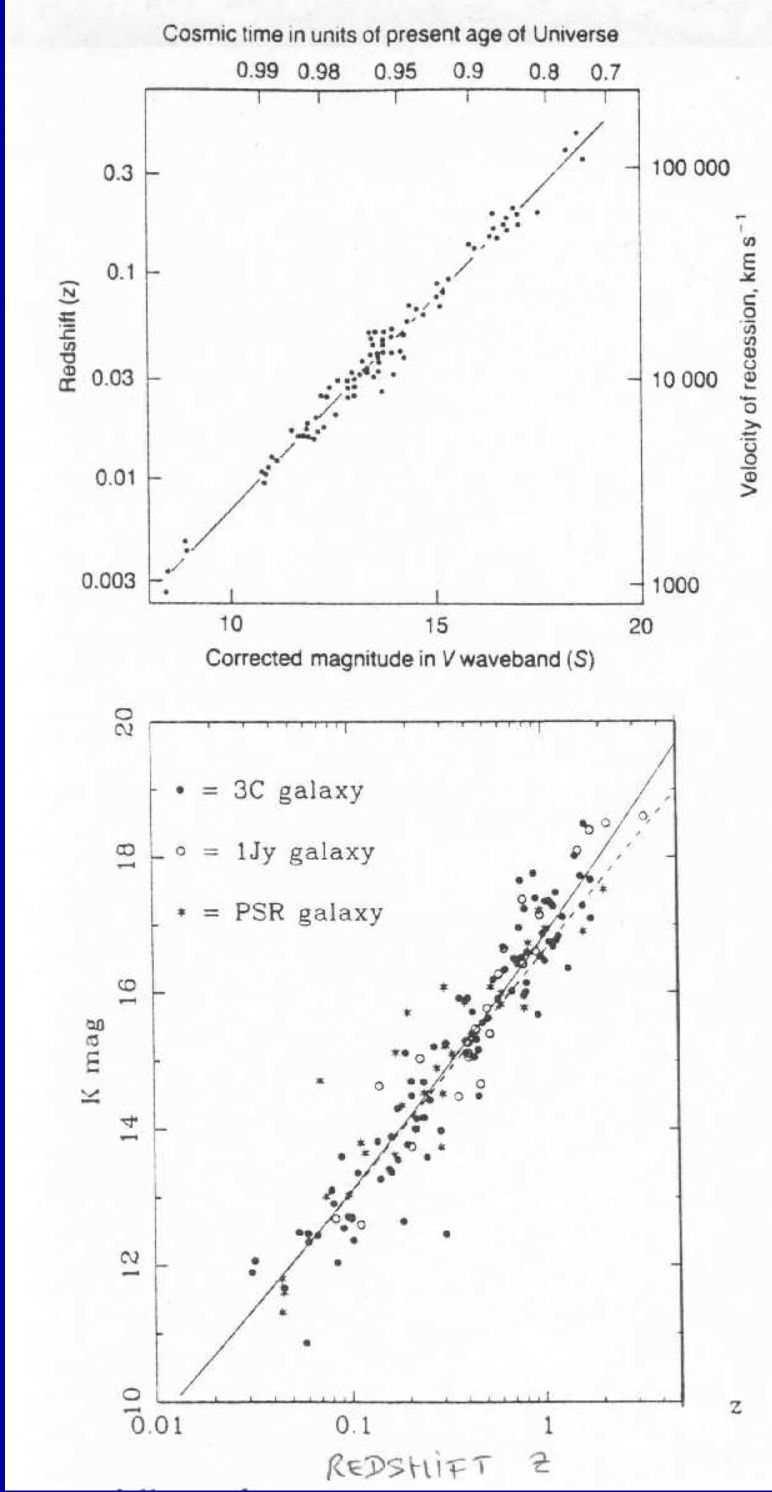


• VLA image of 3C296: Optical galaxy (blue) and Radio source (red).

• (1) Radio Telescope — Images



• VLA image of Fornax A: Optical galaxy (blue) and Radio source (red).



Expansion: Elliptical and Radio galaxy standard candle mag–z diagram.

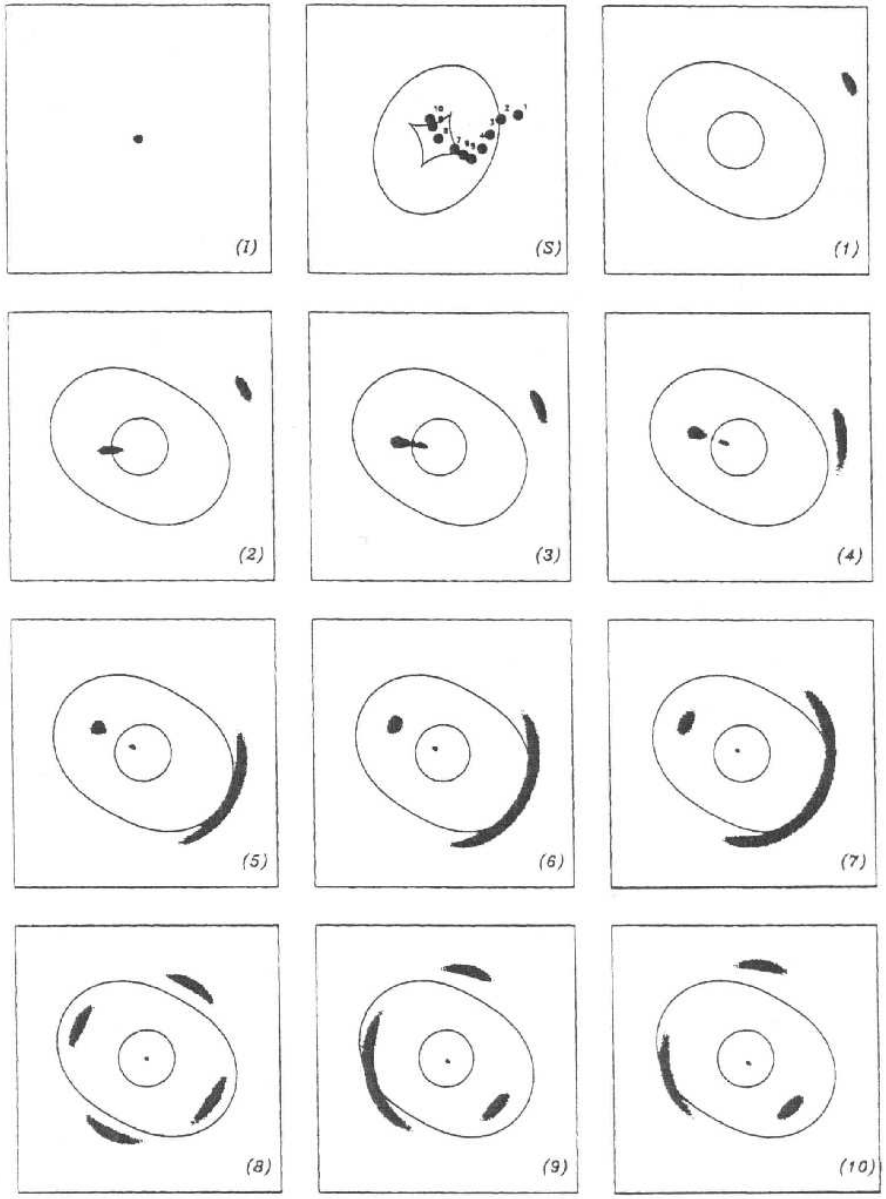
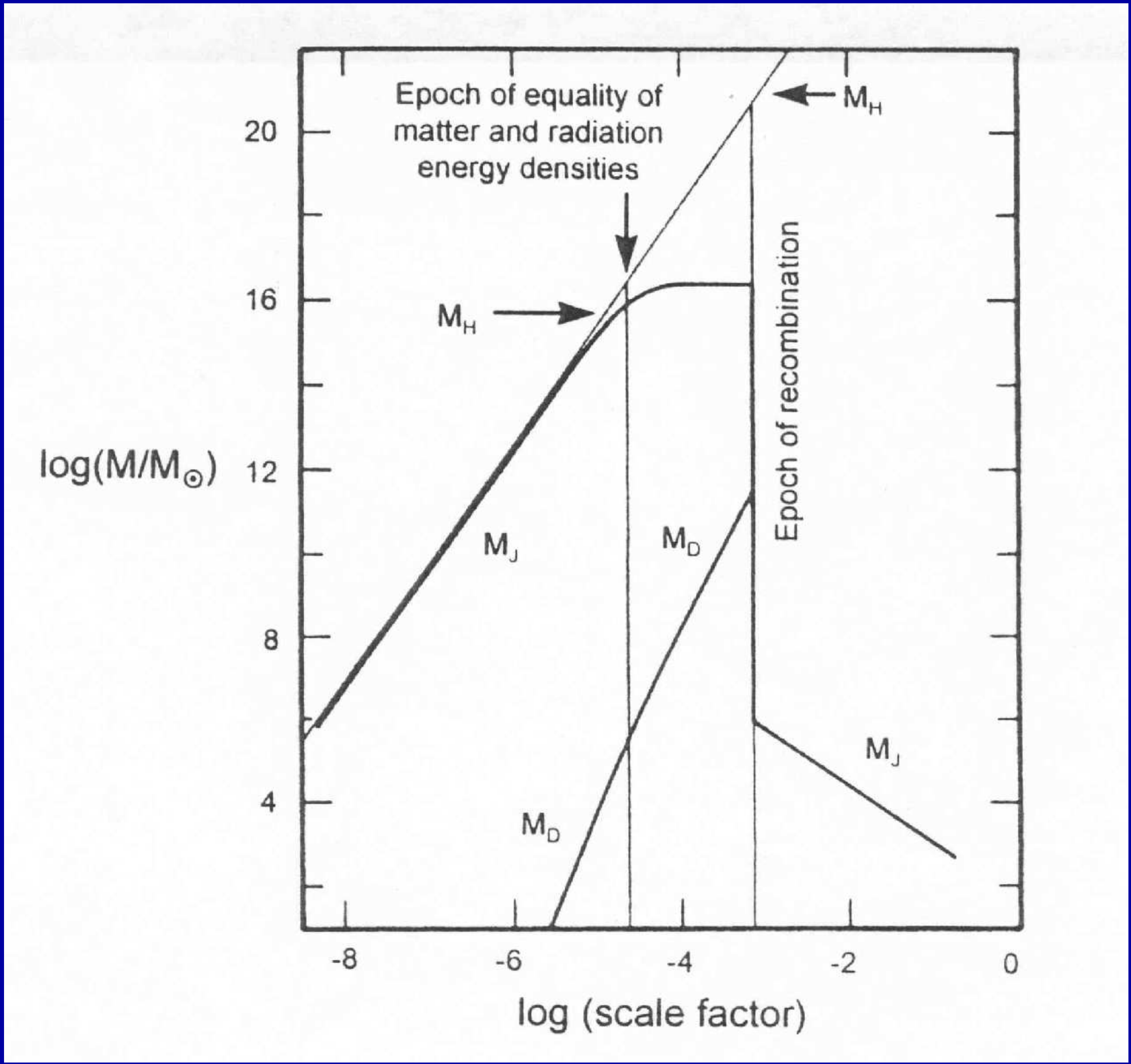
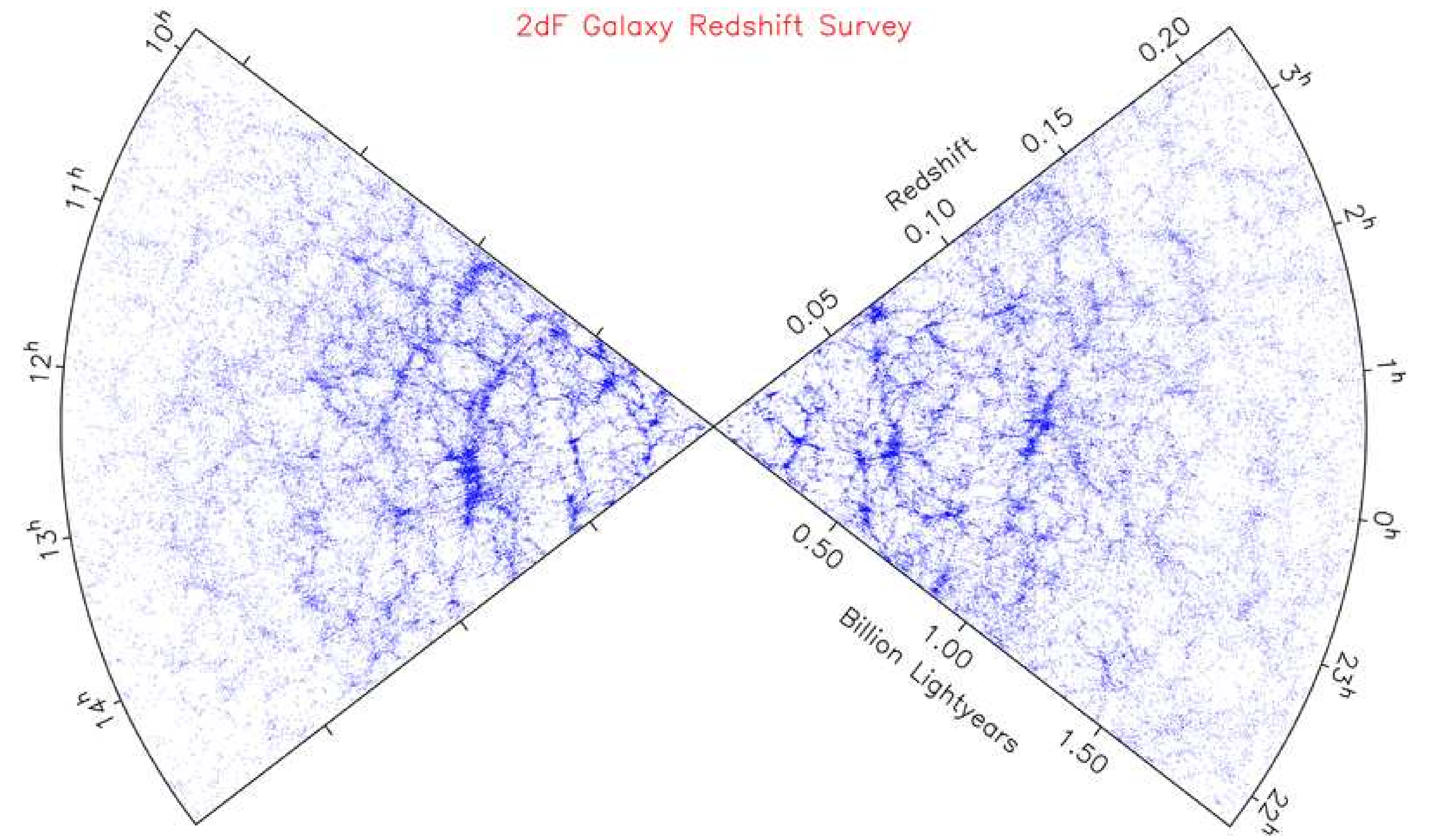


Fig. 4.10. The gravitational distortions of a background source (Panel I) when it is located at different positions with respect to the axis of the gravitational lens. In this example, the lens is an ellipsoidal non-singular squeezed isothermal sphere. The ten positions of the source with respect to the critical inner and outer caustics are shown in the panel (S). The panels labelled (1) to (10) show the shapes of the images of the lensed source (from J.-P. Kneib, Ph.D. Thesis (1993)). Note the

Objects gravitationally lensed by foreground galaxy: D $\propto$ z !

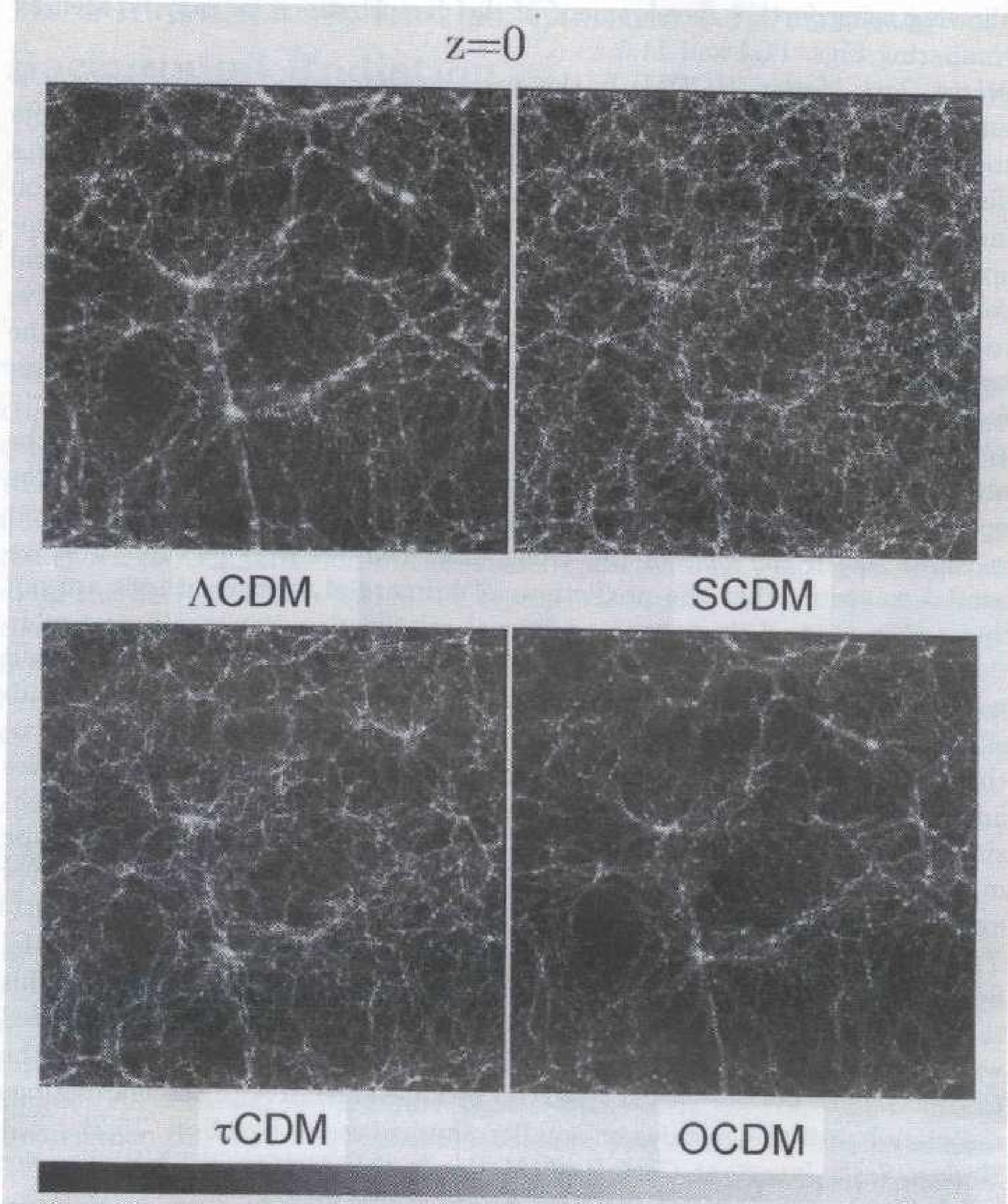


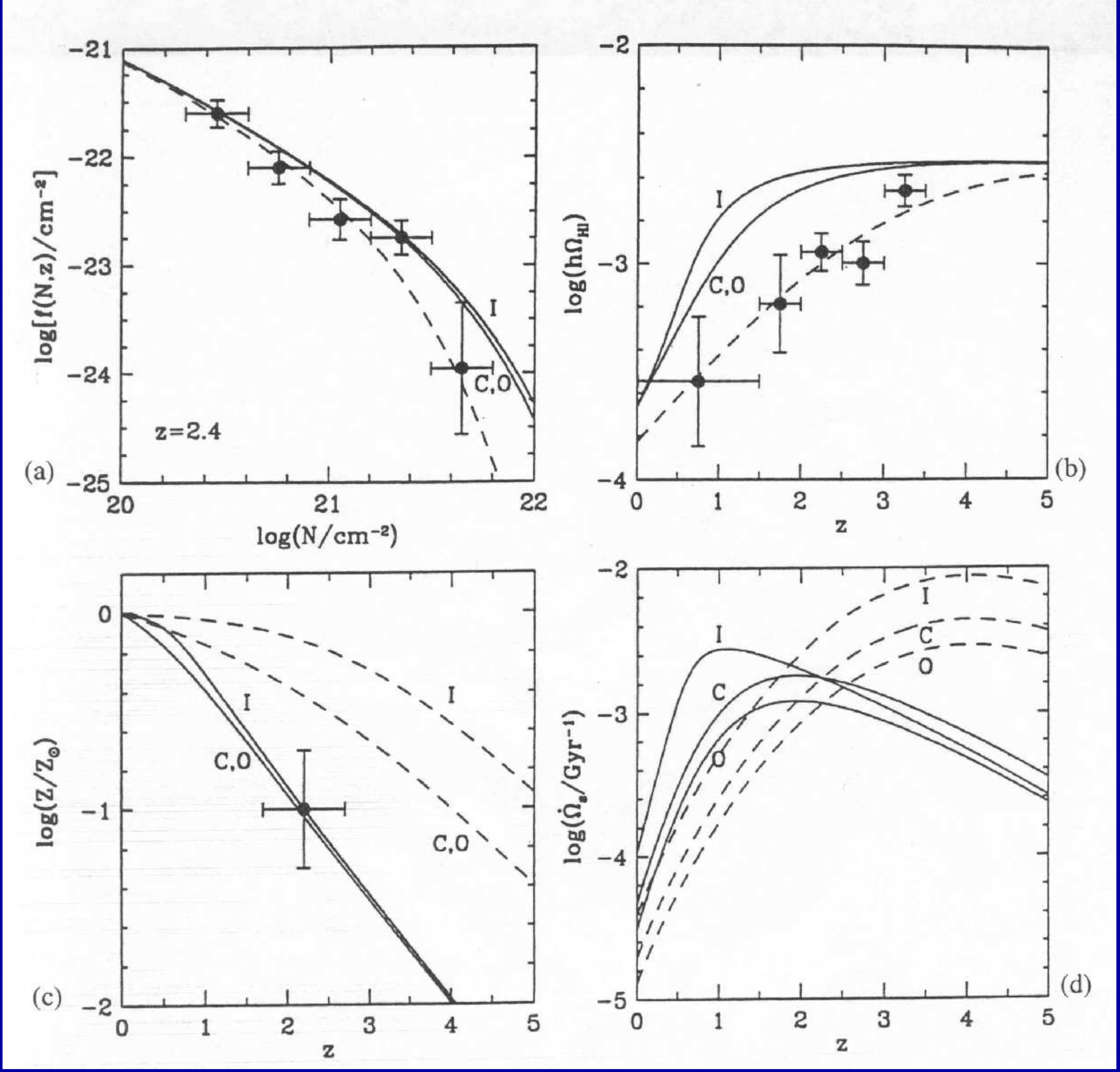
Structures that can form: bigger than Jeans mass vs. scale factor 1/(1+z).



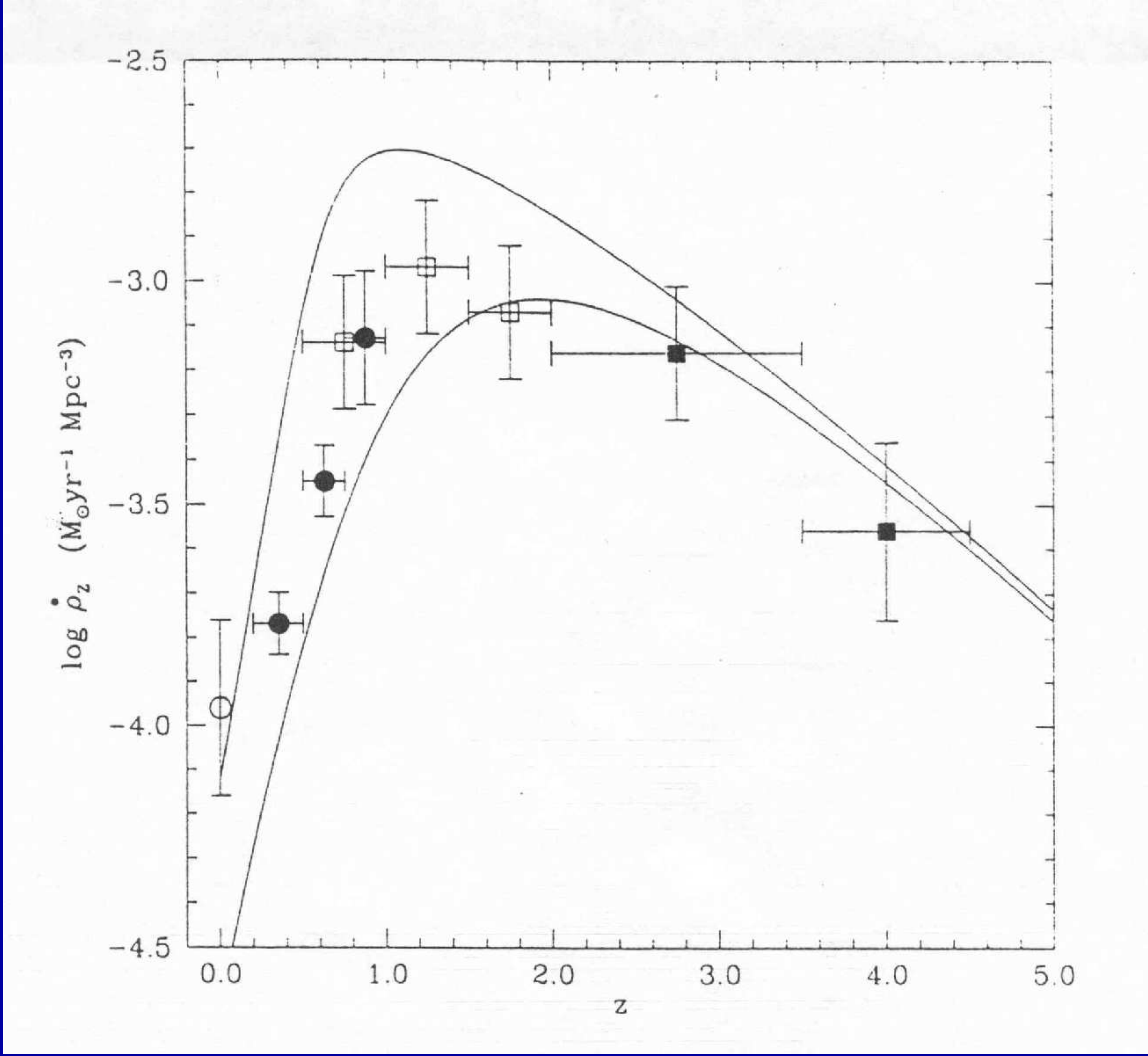
Large Scale Structure on 100's of Mpc scales from 2dF Redshift Survey.

$\Longrightarrow$ Hot Big Bang seeded galaxy distribution on $\gtrsim$300 Mlyr scales.


z=0
ΛCDM
SCDM
τCDM
OCDM



Cosmic HI-density, metallicity Fe/H, and Star-Formation Rate vs. z.

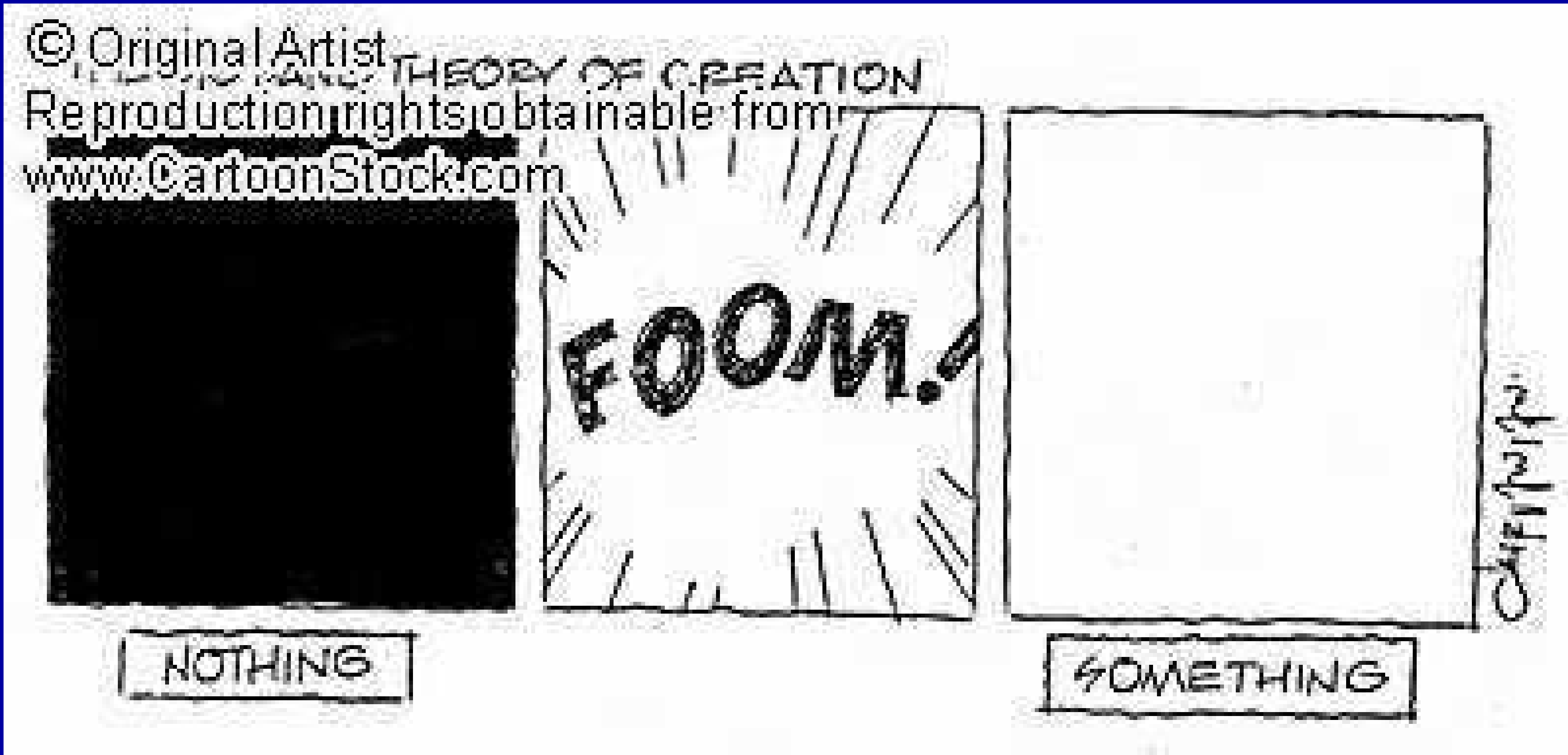


Cosmic Star-Formation Rate (SFR in $M_\odot$ /yr/Mpc^3) vs. redshift z.

Web-sites and books used:

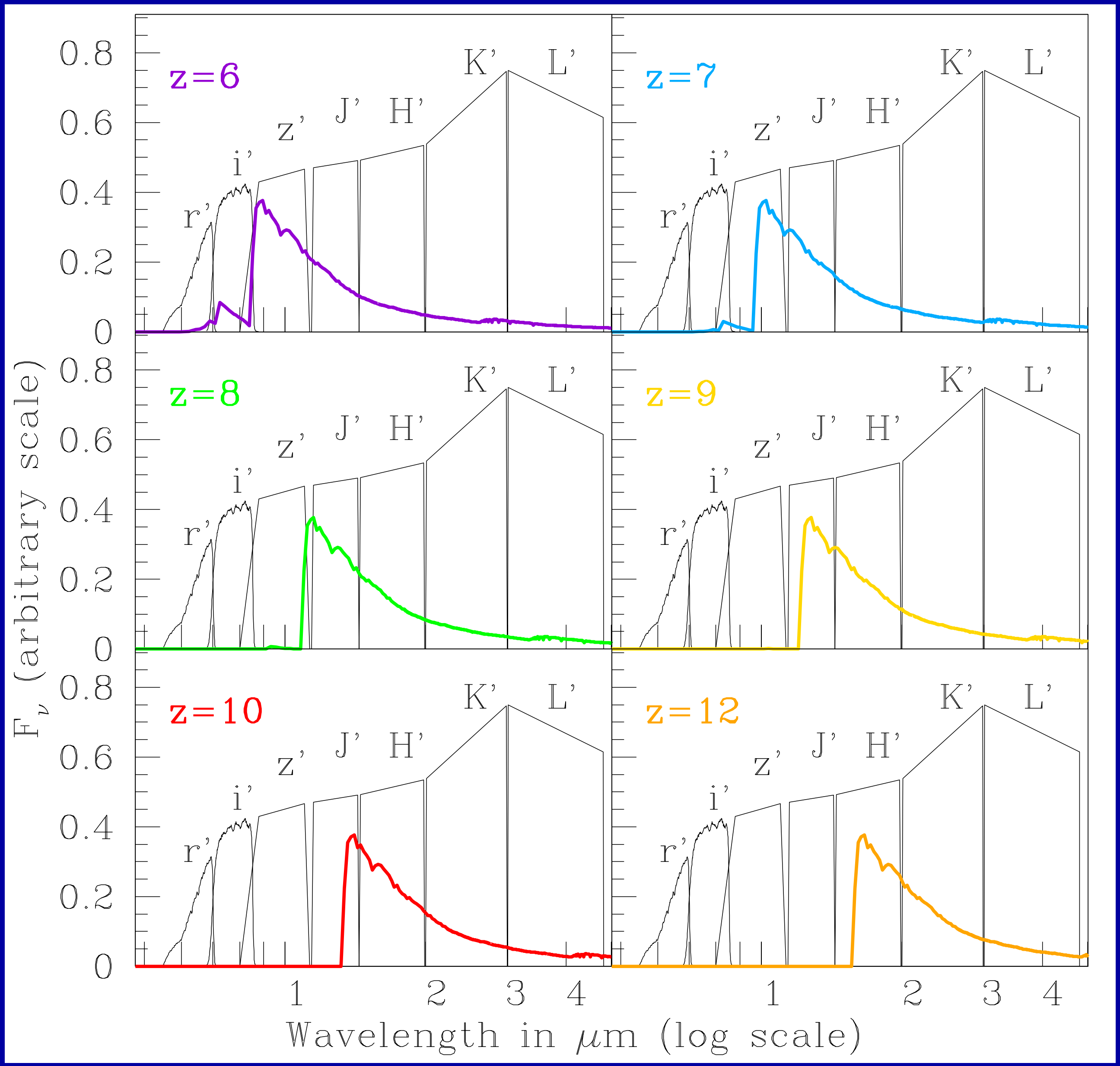
URL	WEB-SITE TOPIC
www.stsci.edu	NASA's Hubble Space Telescope
hubblesite.org/newscenter	Best of Hubble Space Telescope
hubblesite.org/news/2004/28	Cosmic Dawn seen by Hubble
hubblesite.org/news/2001/04	Ultraviolet galaxies with Hubble
hubblesite.org/news/2001/37	Star-forming rings seen by Hubble
hubblesite.org/news/1996/29	Hubble finds Galaxy Building Blocks
hubblesite.org/news/1995/08	Hubble unravels Faint Blue Galaxies
www.jwst.nasa.gov/	NASA's James Web Space Telescope
clavius.as.arizona.edu/vo	Vatican Observatory

BOOK TITLE	AUTHOR
Galaxy Formation	Dr. M. S. Longair (Springer Verlag)
Introduction to Cosmology	Dr. B. Ryden (Addison Wesley)



A simplified model of the Big Bang ...

MORE TECHNICAL SPARE CHARTS ON JWST



- Can't beat redshift: to see First Light, must observe near–mid IR.

$\Rightarrow$ This is why we need NIRCam at 0.8–5 μm and MIRI at 5–28μm .

• (2a) How JWST can measure Galaxy Assembly

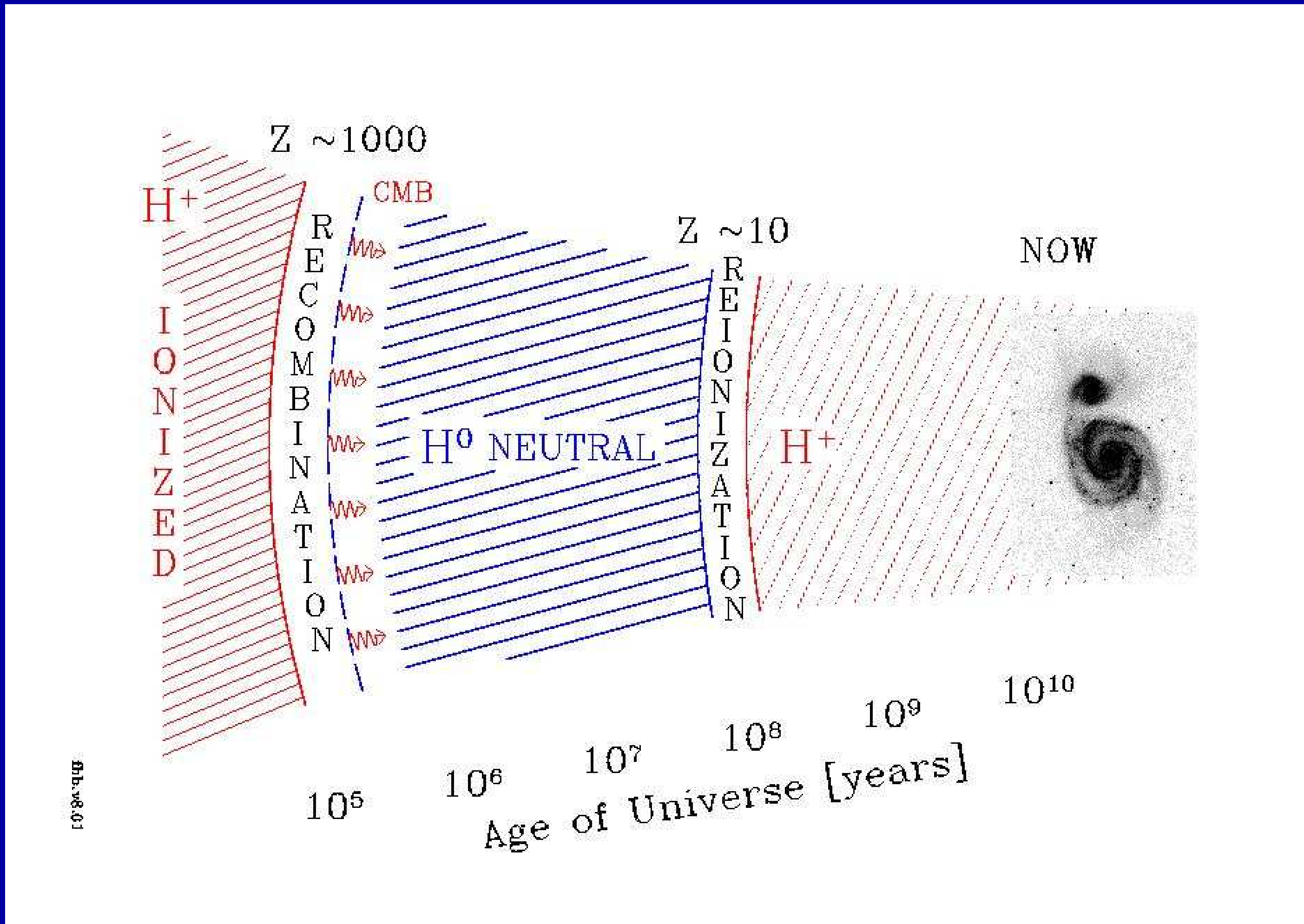
• Galaxies of Hubble types formed over a wide range of cosmic time, but with a notable phase transition around $z \simeq 0.5$–1.0:

(1) Subgalactic units rapidly merge from $z \simeq 7 \rightarrow 1$ to grow bigger units.

(2) Merger products start to settle as galaxies with giant bulges or large disks around $z \simeq 1$. These evolved passively since then, resulting in the giant galaxies that we see today.

• JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame type as a function of redshift or cosmic epoch.

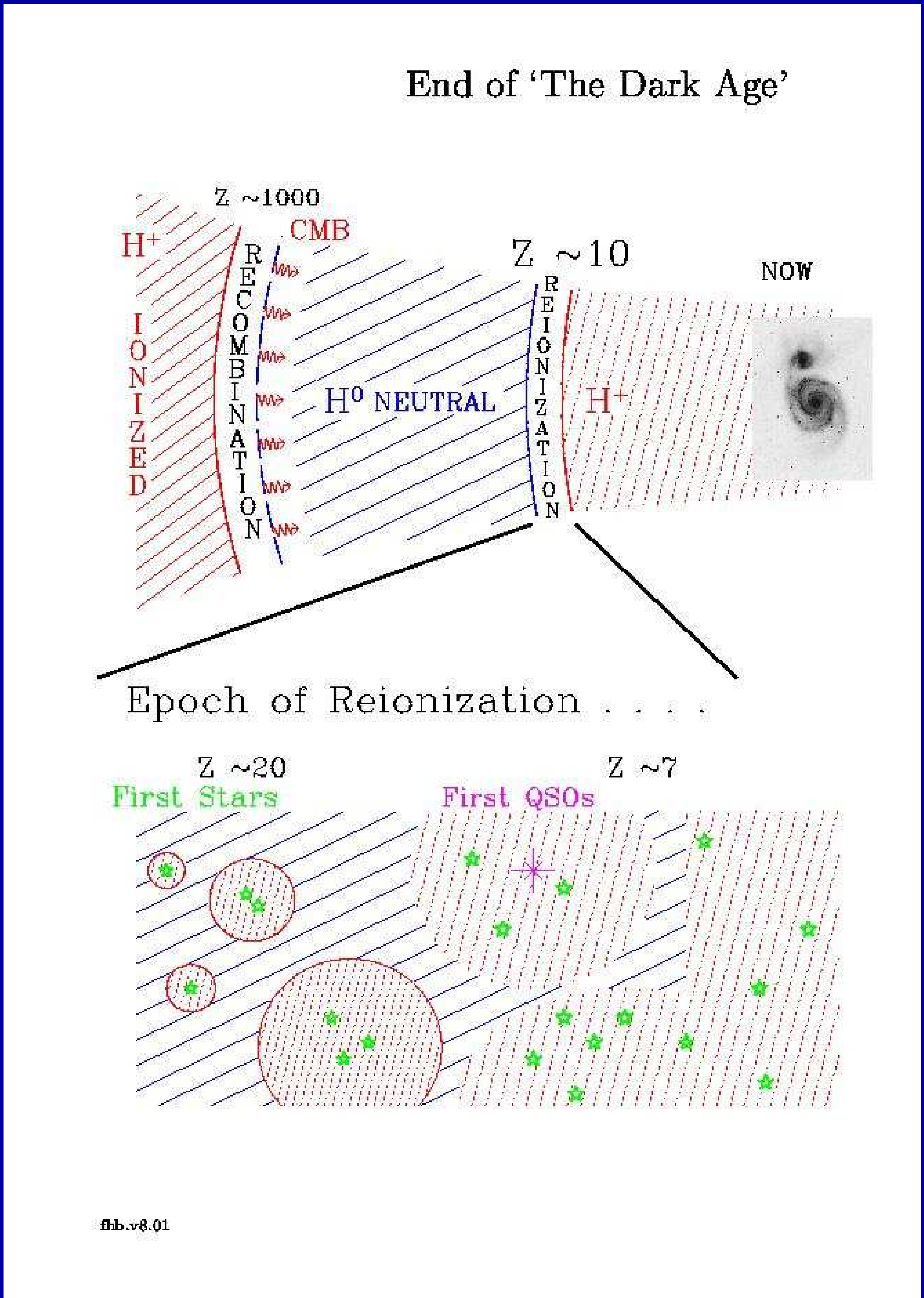
- (3) How JWST can measure First Light and Reionization



WMAP: First light may have happened in two epochs (Cen 2003):

- (1) Population III stars with 200-1000 $M_\odot$ at z≃15–25 (First Light).
- (2) Population II stars (halo stars) form in dwarf galaxies of mass=10^6 to 10^9 $M_\odot$ at z≃6–10 ("Second" or "Main" Light; Briggs 2002).

⇒ need NIRCam at 0.8–5 μm and MIRI at 5–28μm .



WMAP: First Light may have happened as following:

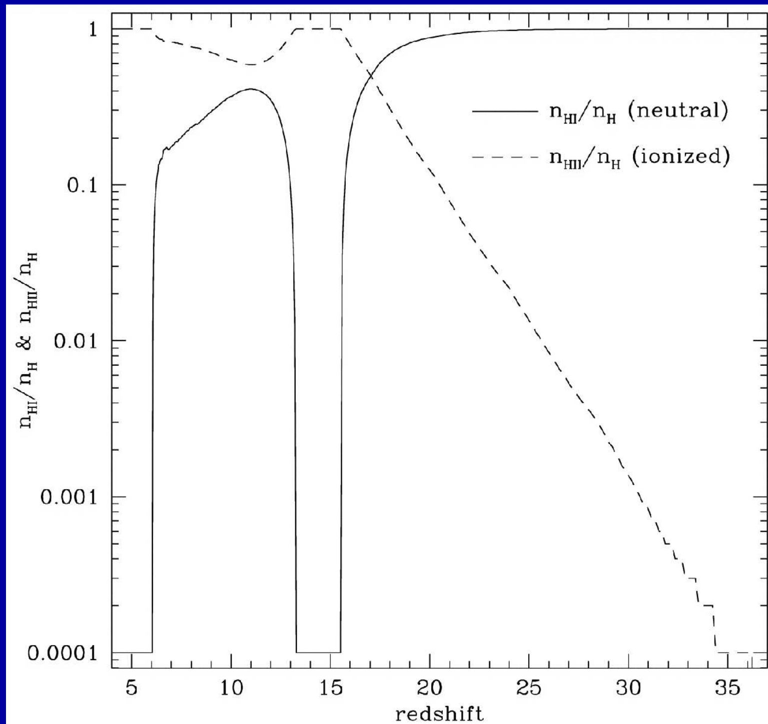
- (0) First Dark Ages since recombination (z=1089) until first light or reionization occurred (z=25–30)

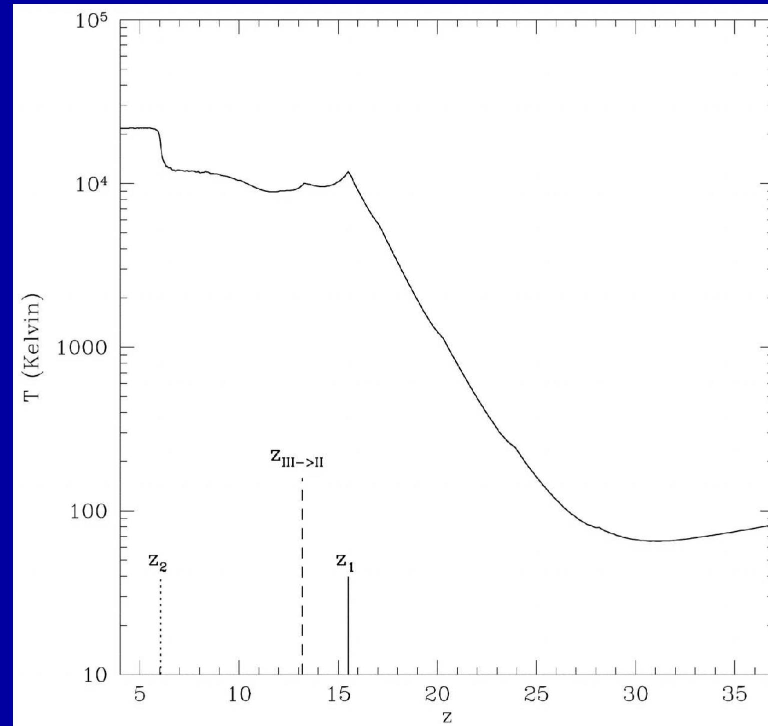
- (1) First Light when Population III stars start shining with mass=200-1000 $M_{\odot}$ at z$\simeq$15–25

- (2) Second Dark Ages since Pop III supernovae heated gas which could not cool and form normal Pop II halo stars until z$\simeq$15$\rightarrow$10.

- (3) "Second" or "Main Light" when Population II stars (halo stars) form in dwarf galaxies of mass=10^6–10^9 $M_{\odot}$ at z$\simeq$6–10.

(Fig. courtesy of Dr. F. Briggs)





WMAP and detailed Hydrodynamical models (Cen 2003) suggest that:

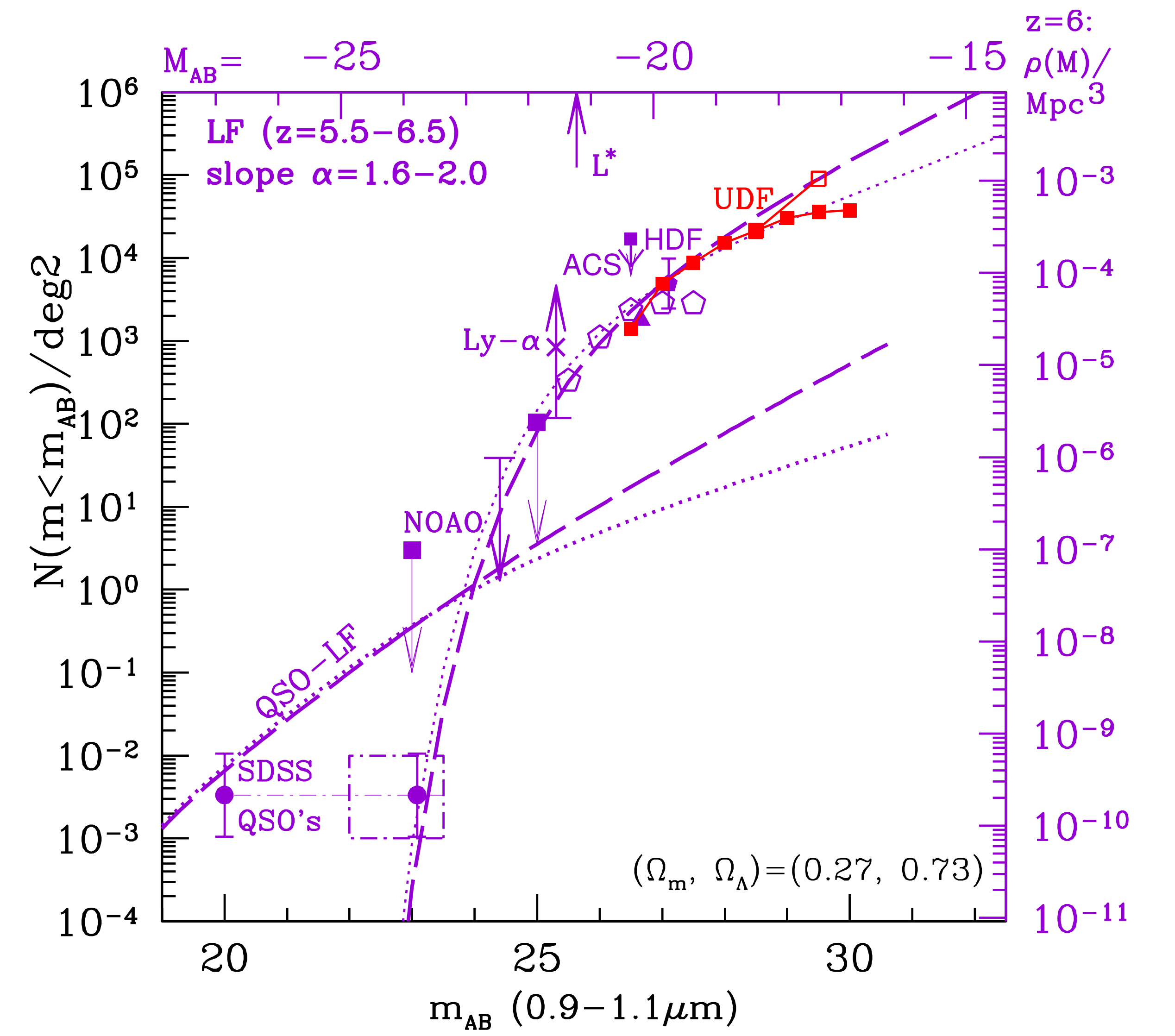
- (1) Population III stars caused epoch of First Light at z$\simeq$15–25.

- (2) Pop III supernovae may have caused the Second Dark Ages at z=15$\longrightarrow$10, since they heated the IGM, which could not cool until:

- (3) Second or "Main" Light when a prolonged burst of star-formation ("SF") made Pop II stars in dwarf galaxies with 10^6–10^9 $M_\odot$ at z$\simeq$6–10.

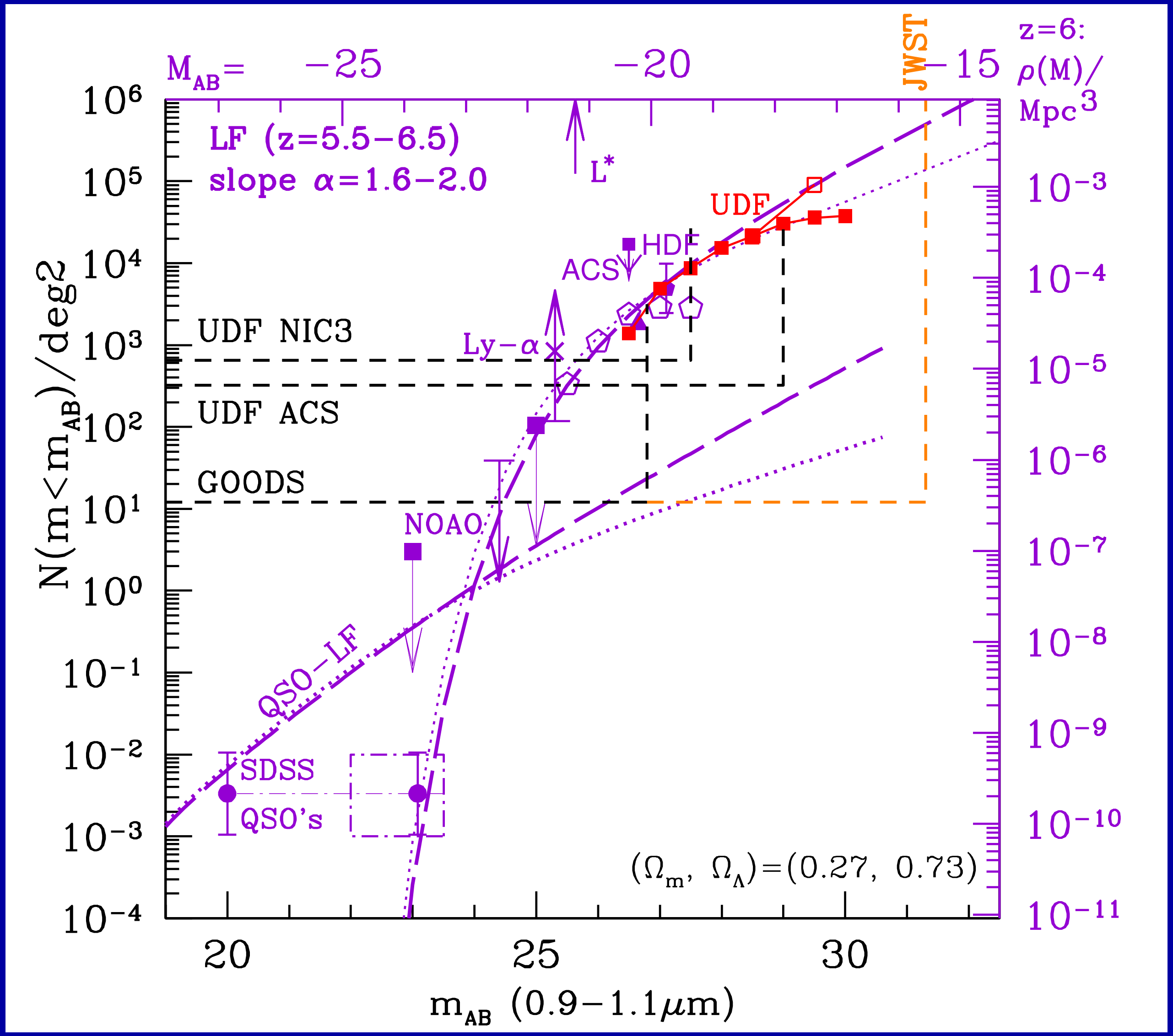
$\Longrightarrow$ This will be visible to JWST in the luminosity function (LF) of the first star-forming galaxies at z$\simeq$10$\longrightarrow$6.

• (3) How JWST can measure First Light and Reionization

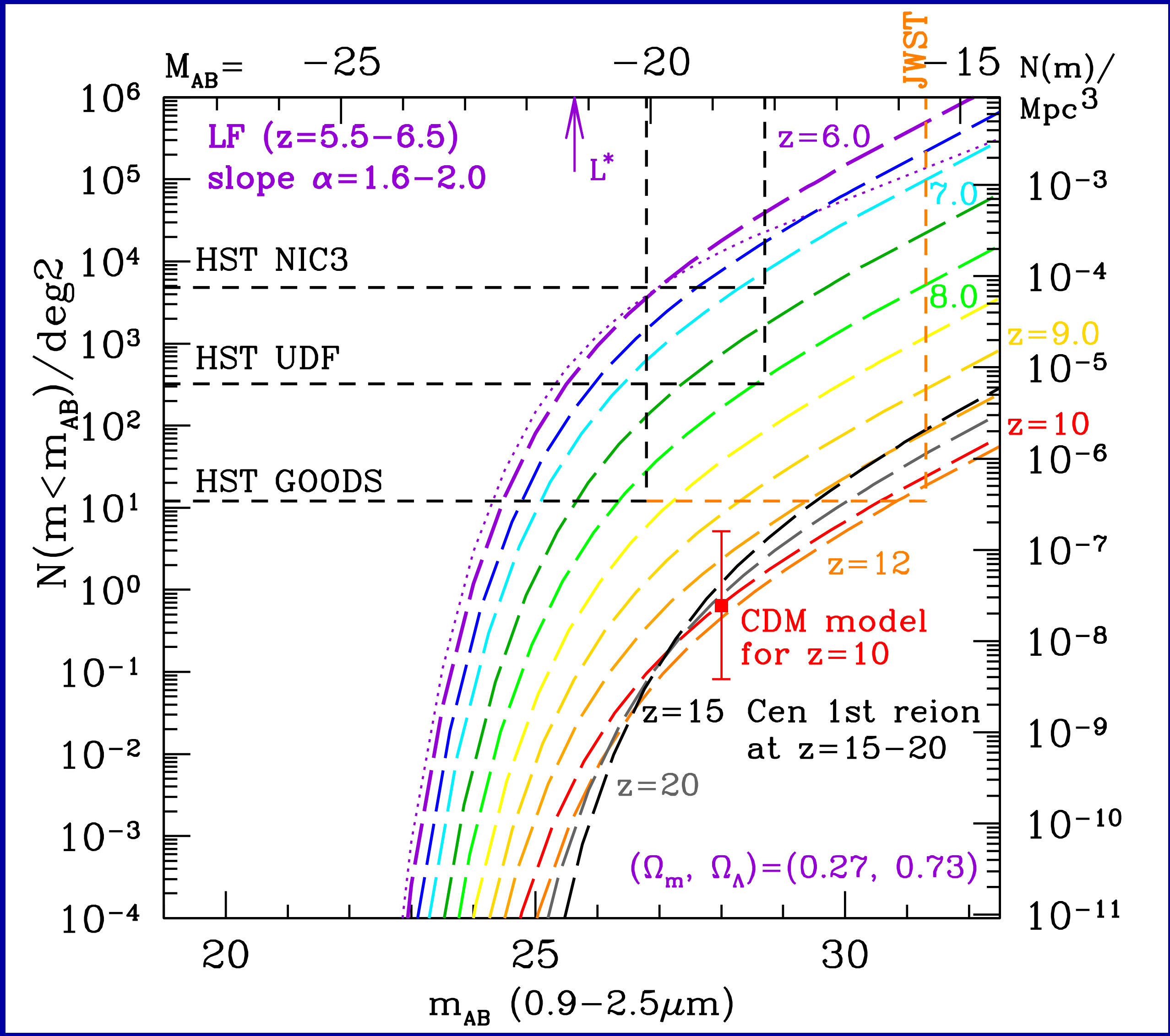


UDF shows that luminosity function of z≃6 objects (Yan et al. 2003, 2004) is very steep, with faint-end Schechter slope $|\alpha|\simeq$1.6–2.0.

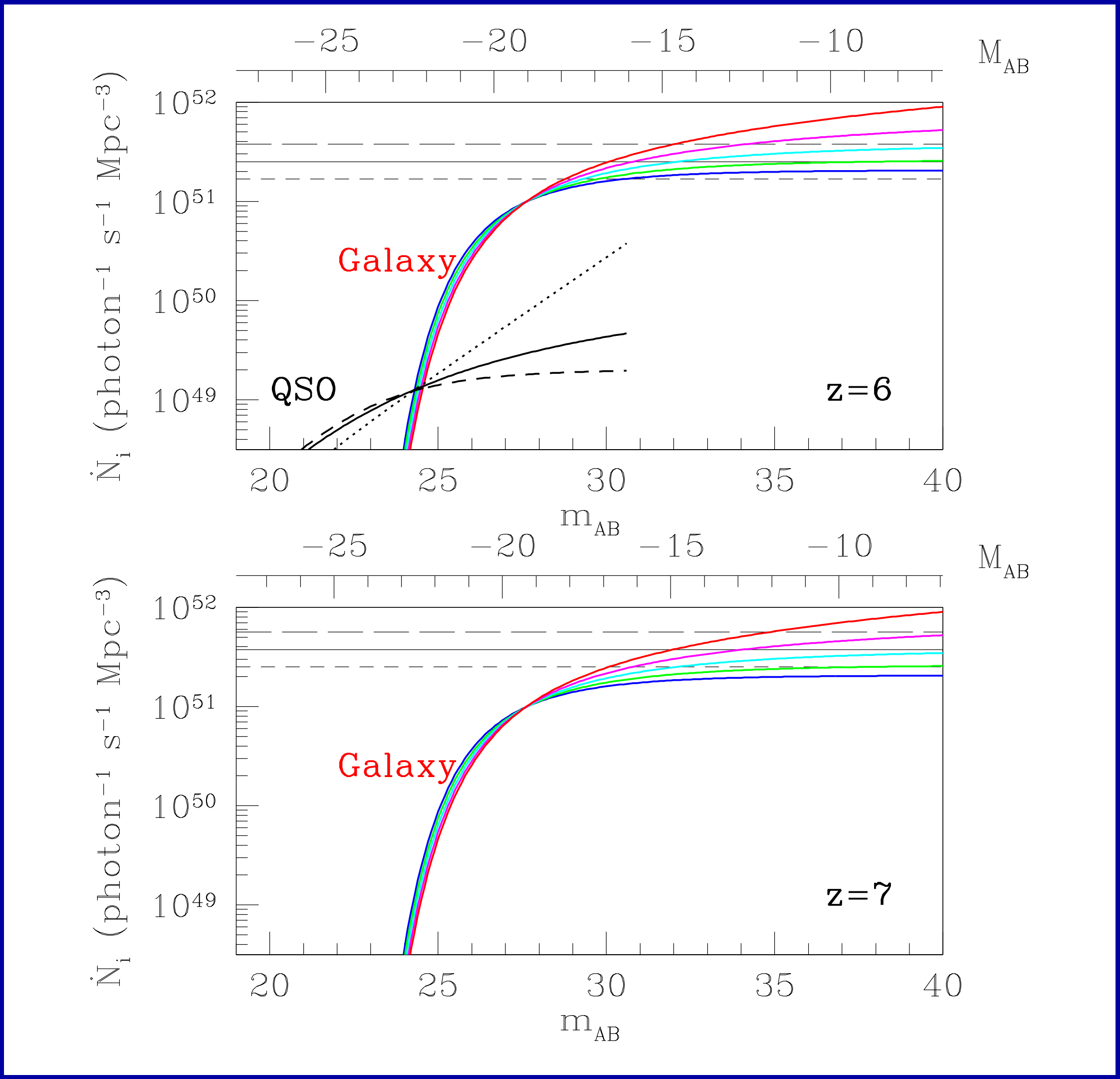
⇒ Dwarf galaxies and not quasars likely completed the second reionization epoch at z≃6. This is what JWST likely will observe in detail.



• HST/ACS has made significant progress at z≃6, surveying very large areas (GOODS, GEMS, COSMOS), or using very long integrations (UDF). ACS can detect objects at z≲6.5, but its discovery space A.**Ω**.**Δ**log(**λ**) cannot map the entire reionization epoch. NICMOS similarly is limited to z≲8–10. JWST will be able to trace the entire reionization epoch.



- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch, i.e. detect some of the first star-forming objects.
- For this to be successful in realistic or conservative model scenarios, JWST needs the quoted sensitivity/aperture (A), field-of-view (FOV=Ω), and wavelength range (0.7-28μm).



- The steep LF of z$\simeq$6 objects (Yan & Windhorst 2004) provides enough UV-photons to complete the second reionization epoch at z$\simeq$6.

- Pop II dwarf galaxies cannot have started shining much before z$\simeq$6–8, or no neutral H-I would be seen in the foreground of z$\gtrsim$6 quasars.

- JWST will measure this extremely numerous population of dwarf galaxies from the start of the second and main reionization epoch at z$\simeq$10 ("Second" Light) and beyond, into the epoch of First Light (Pop III stars).

(5) Details on JWST image simulations:

- All based on HST/WFPC2 F300W images from the HST mid-UV survey of nearby galaxies (Windhorst et al. 2002,ApJ Suppl. 143, 113).

- WMAP COSMOLOGY: H_0=71 km/s/Mpc, Ω_m=0.27, Ω_Λ=0.73.

- INSTRUMENT: 6.0 m effective aperture, diffraction limited at $\lambda \gtrsim 2.0 \mu$m, JWST/NIRCam, $0\farcs034$/pix, read-noise=5.0 e^-, dark-current=0.02 e^-/s, NEP-Sky(1.6 μm)=21.7 mag/($''^2$) in L2, Zodi spectrum, t_{exp}=4×900s.

Row	Telesc.	Redshift	λ (μm)	FWHM ($''$)
1	HST	z∼0	0.293μm	$0\farcs04$
	JWST	z=1.0	0.586μm	$0\farcs084$
	JWST	z=2.0	0.879μm	$0\farcs084$
2	JWST	z=3.0	1.17 μm	$0\farcs084$
	JWST	z=5.0	1.76 μm	$0\farcs084$
	JWST	z=7.0	2.34 μm	$0\farcs098$
3	JWST	z=09.0	2.93 μm	$0\farcs122$
	JWST	z=12.0	3.81 μm	$0\farcs160$
	JWST	z=15.0	4.69 μm	$0\farcs197$