Studying First Light and the Cosmic Dark Ages from beyond the Earth

Rogier Windhorst (Physics & Astronomy, ASU)

Earth Systems II meeting, Calgary, Canada, Aug. 10, 2005

The role of astronomers in the new NASA vision: Moon, Mars, Beyond ...

Outline

(0) Brief Summary of Big Bang, Dark Ages, and First Light

(1) The Hot Big Bang, Cosmic Dark Ages, and First Light

- (1a) NASA missions for Cosmic Dawn, First Light, & Recombination
- (1b) The Cosmic Expansion and Contents of the Universe
- (1c) The Cosmic microwave Background Radiation (CBR)
- (1d) Light Element production predicted by Hot Big Bang

(2) Telescopes beyond Earth: Why needed, what do they do, and how?

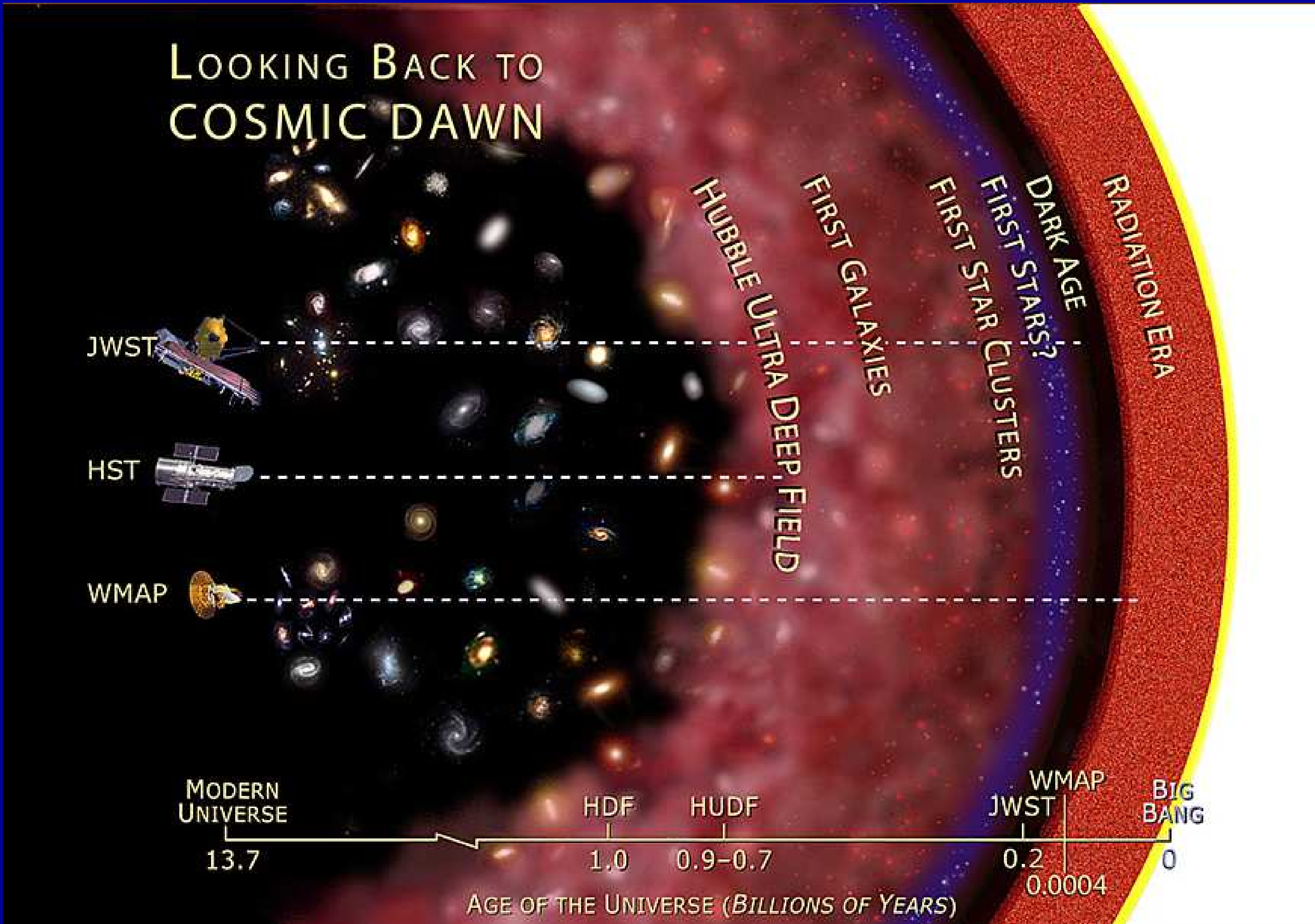
- (2a) Large Optical–IR Telescopes
- (2b) Large Radio Telescopes and Radio Interferometers
- (2c) A Low-frequency Interferometer on the Moon's far-side

(3) Conclusions

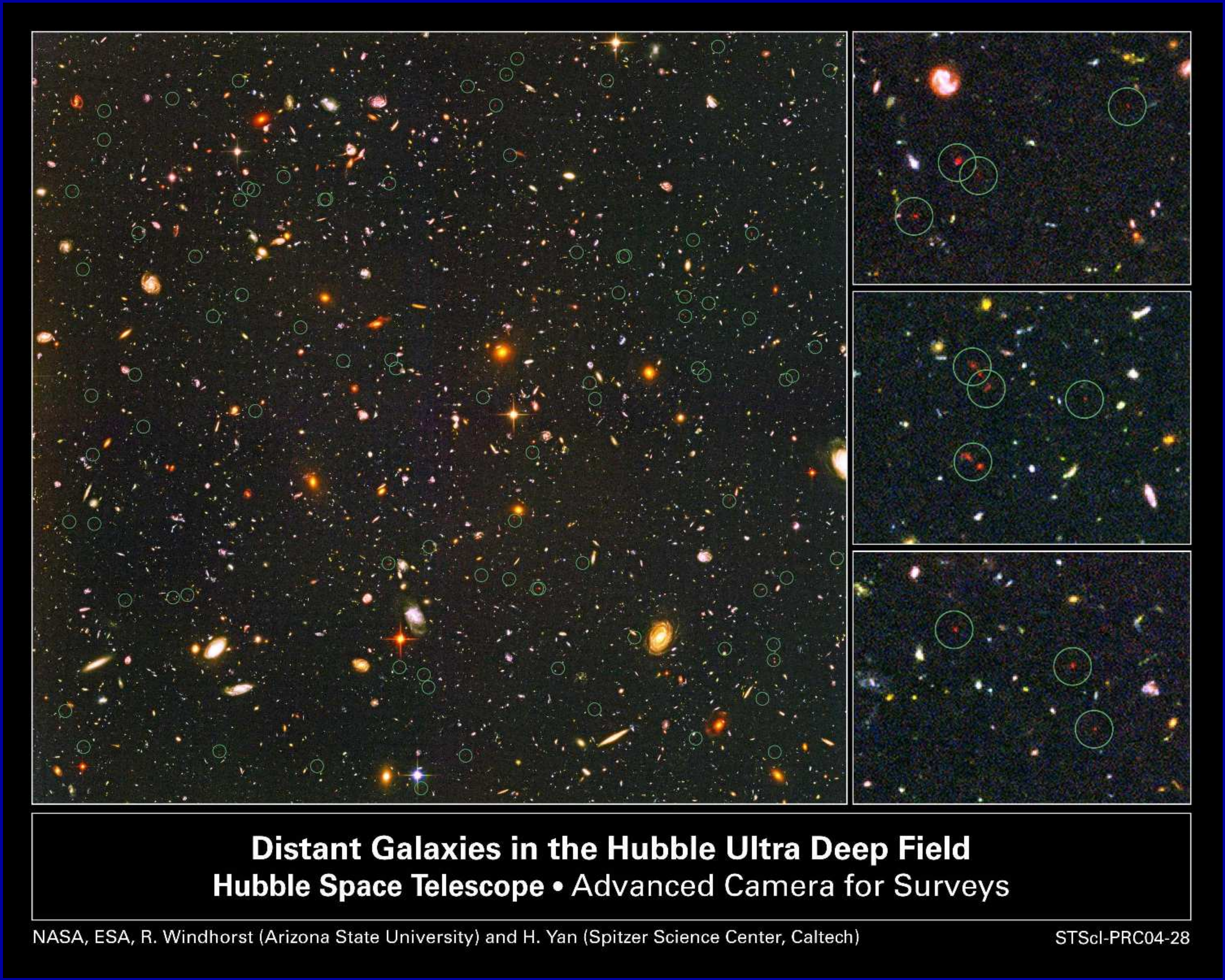
Sponsored by NASA

Arizona State University

(1) The Hot Big Bang, Cosmic Dark Ages, and First Light



(1a) NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination

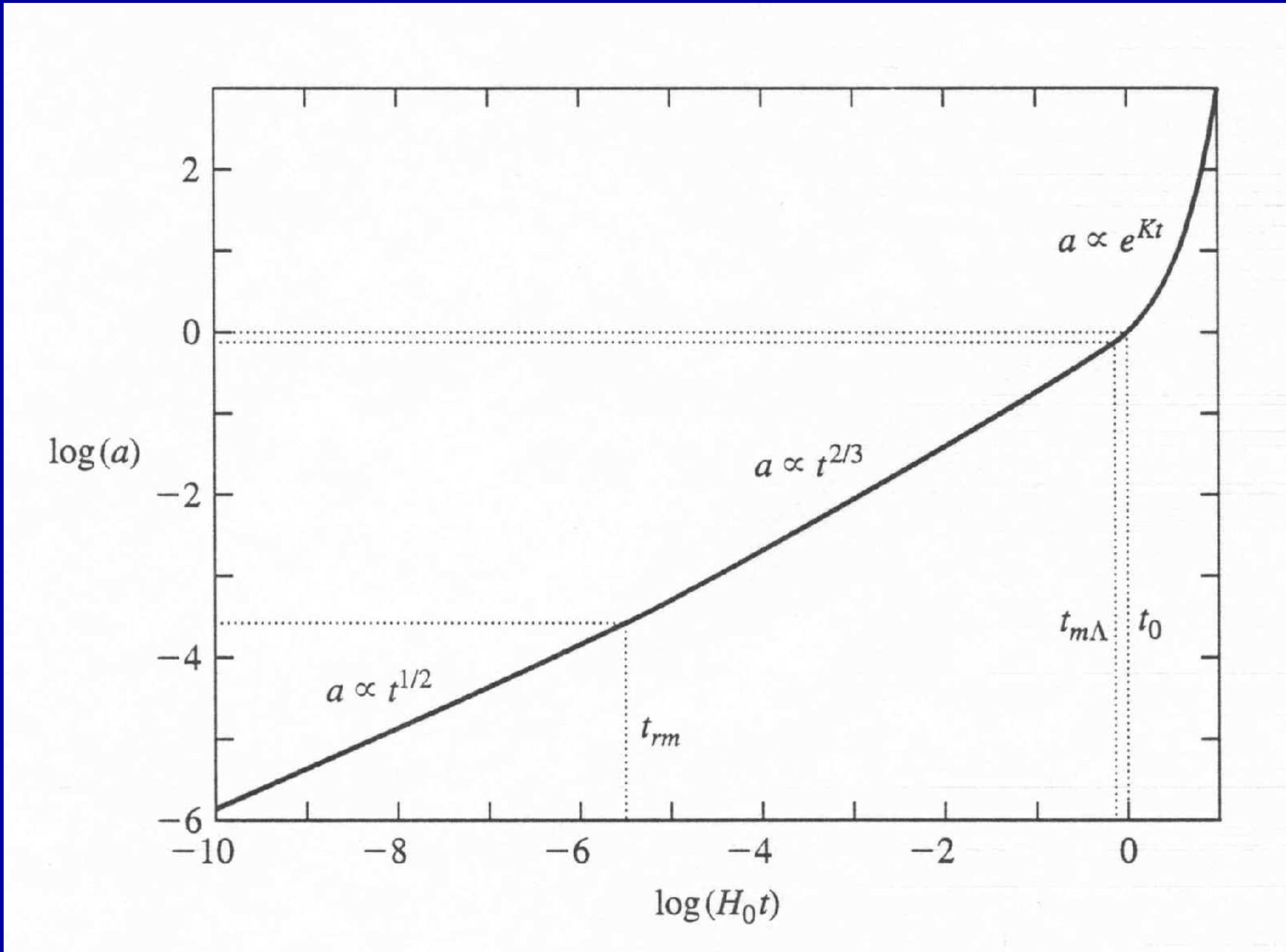


(1a) A Study of Comic Dawn with the Hubble Space Telescope

(1b) The Cosmic Expansion and Contents of the Universe

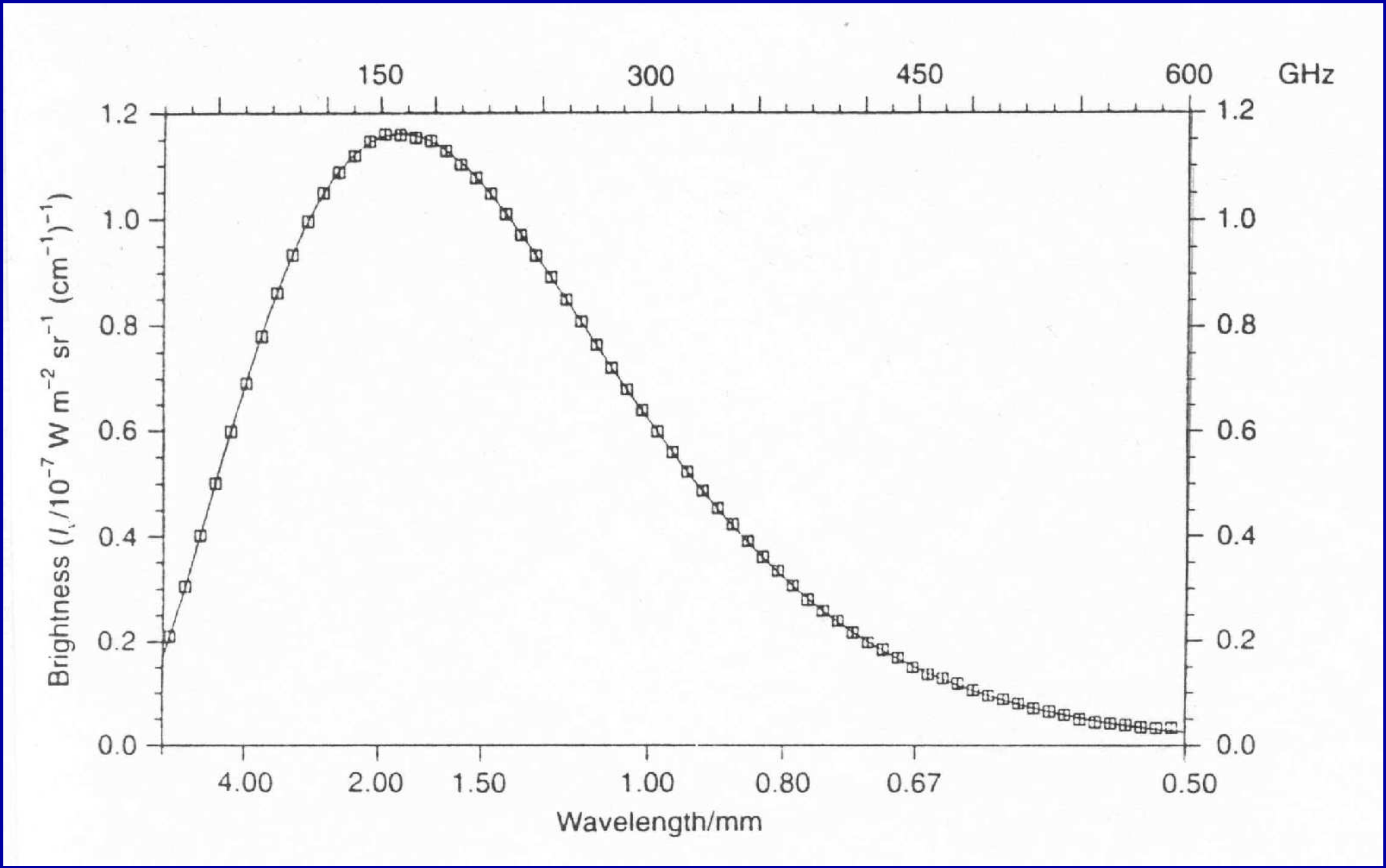
Expansion $\Longrightarrow$ redshift	$\lambda_{obs} = \lambda_{rest} \,.\, (1+z)$
Hubble's Law:	D = v / H_o = (c/H_o) . z = R_o . z
Item	Numbers inside R_0=c/Ho=13.7 Glyr
Baryons:	$N_b \sim 10^{80}$
Photons:	$N_{h\nu} \sim 10^{89}$
η=Photons/Baryons	$\eta \sim 10^9$
Energy Density	As fraction of critical 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)

(1b) The Cosmic Expansion: A much better & safer bet than Wall Street!



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

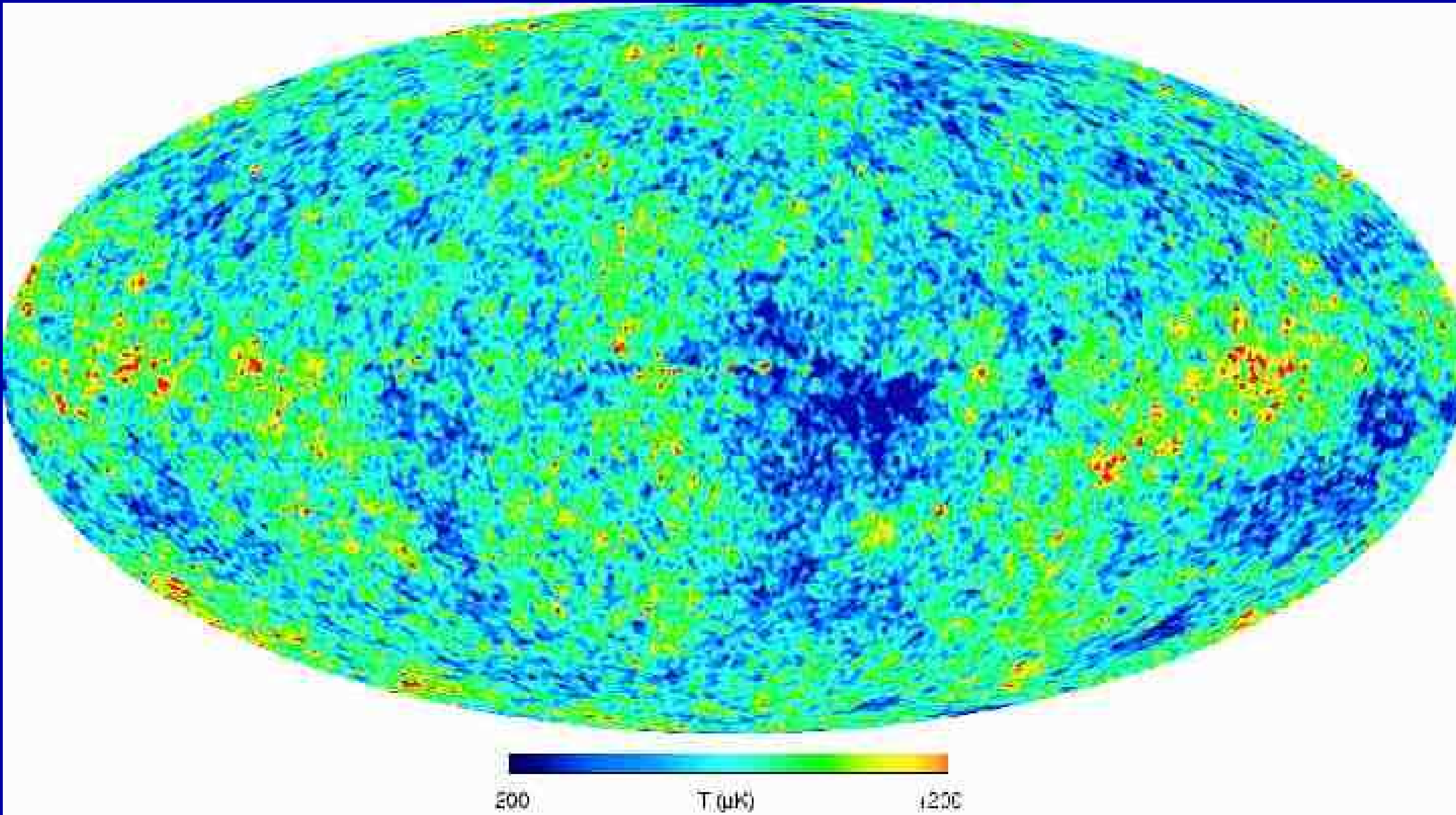
(1c) The Cosmic microwave Background Radiation (CBR)



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!

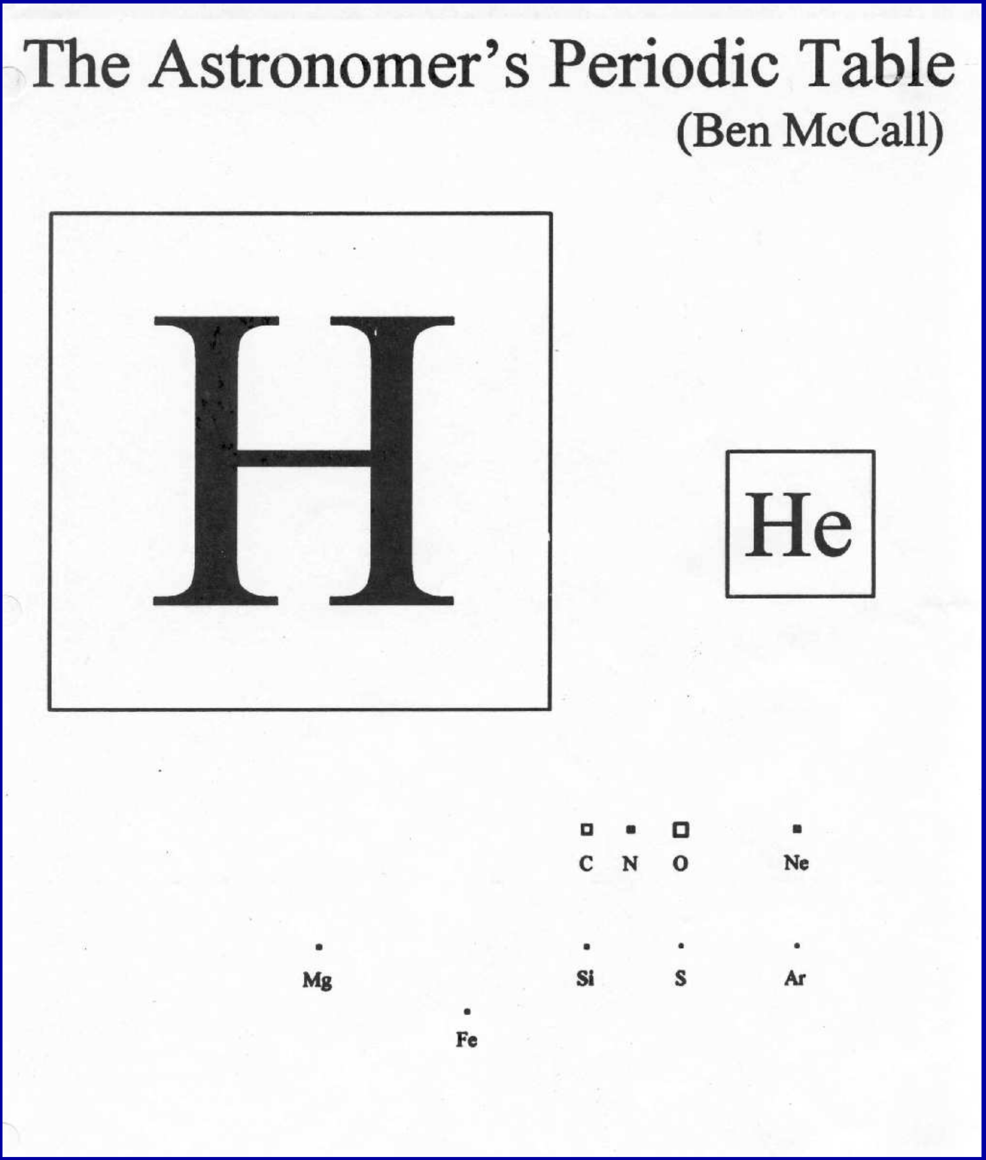


(1c) Microwave Background from Wilkinson Microwave Anisotropy Probe:

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.

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



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

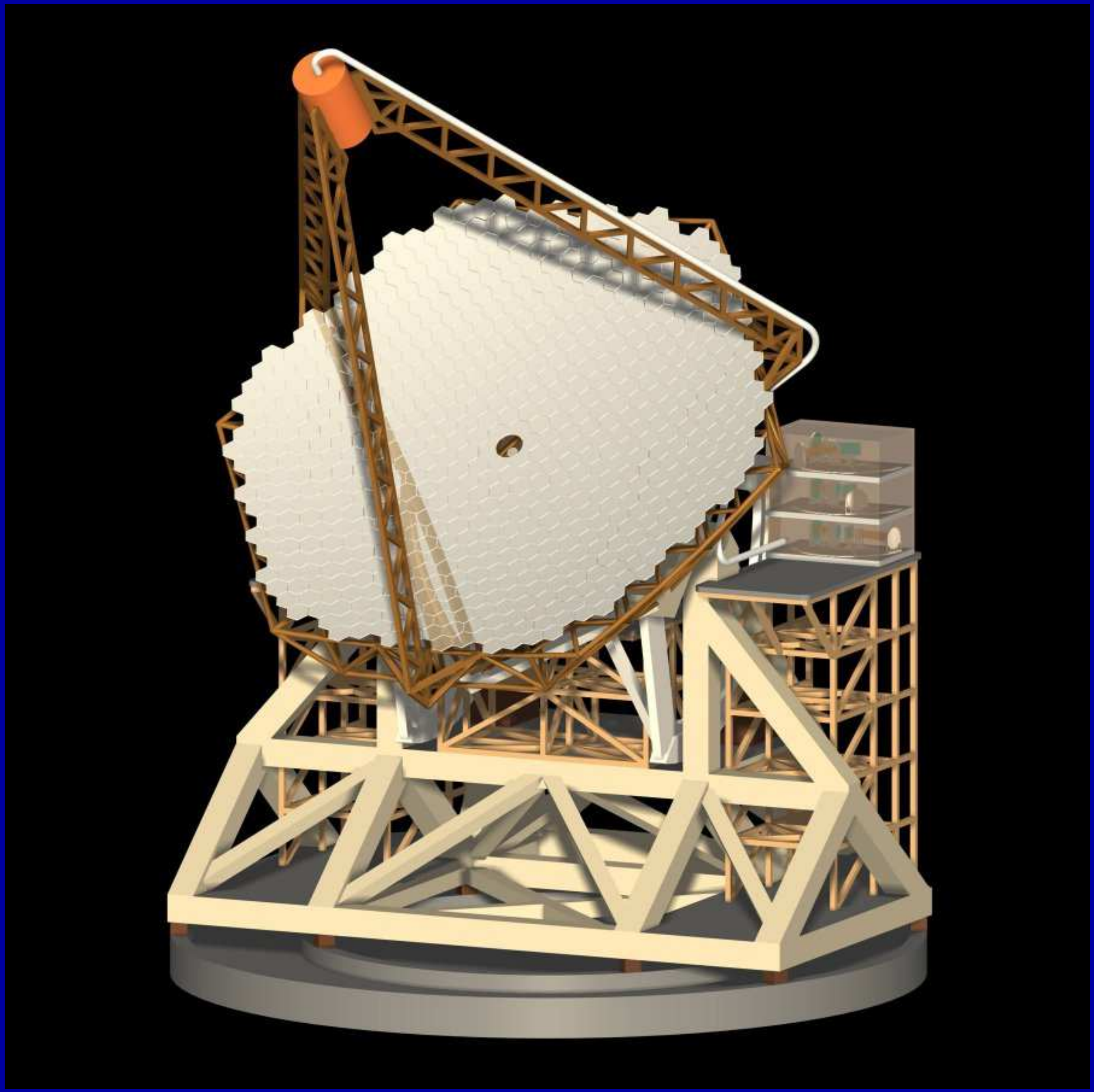
Cosmic abundances are universal: 75% H; 24% He; 1% rest (X).

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

(2) Telescopes beyond Earth: Why needed, what do they do, and how?

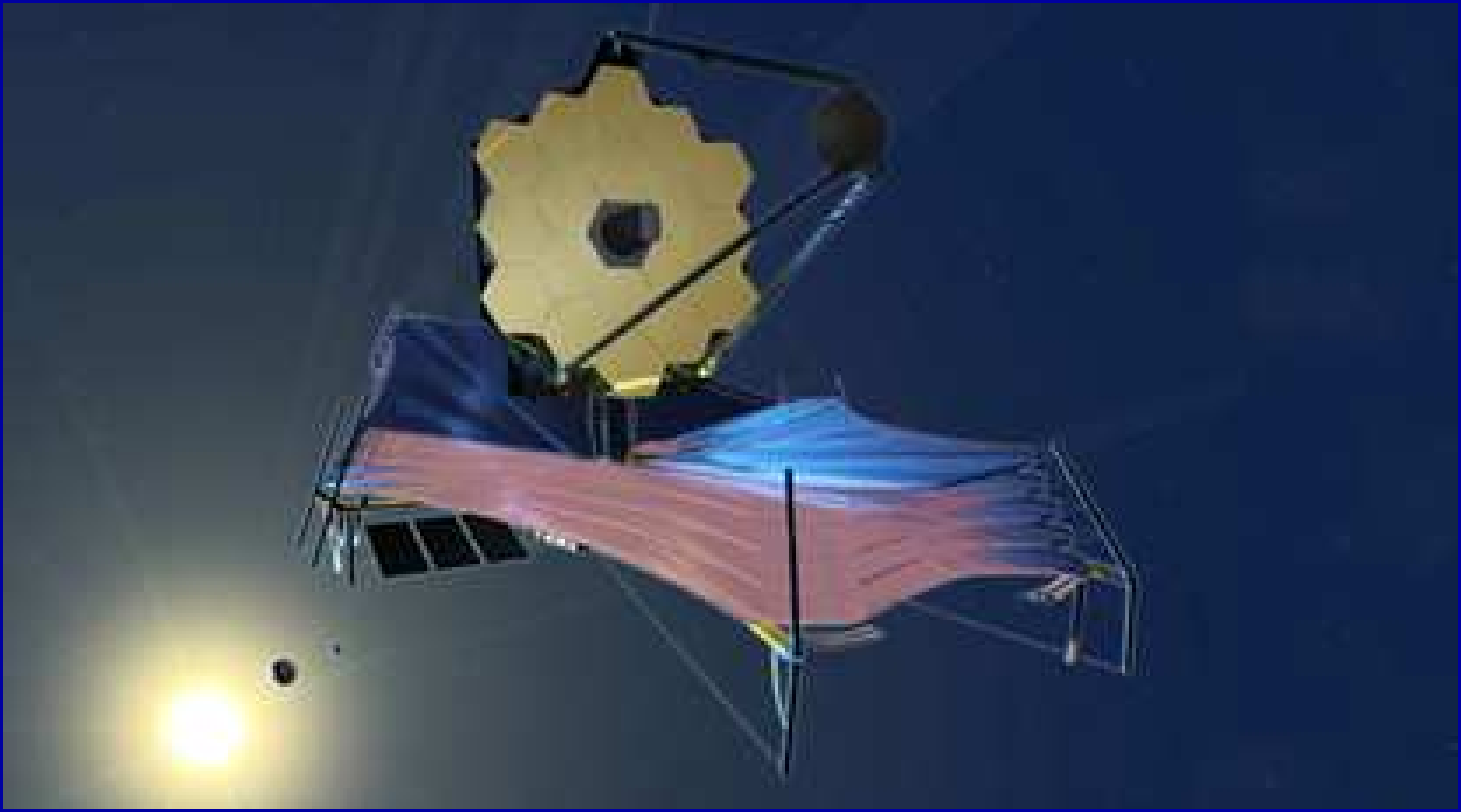
Telescope Property	How defined and used:
Mirror Diameter	D in meters
Field of View	Ω in Rad or deg^2
Resolution	$\Theta = 1.22 \times 206265 \times (\lambda/D)$ [arcsec]
Collecting Area	$A = \pi\ (D/2)^2$
Discovery Space	$DS = A \times \Omega \times \log(\lambda_{hi}/\lambda_{lo})$

• (2a) Large Optical–IR Telescopes (on Earth, but can also be on Moon)

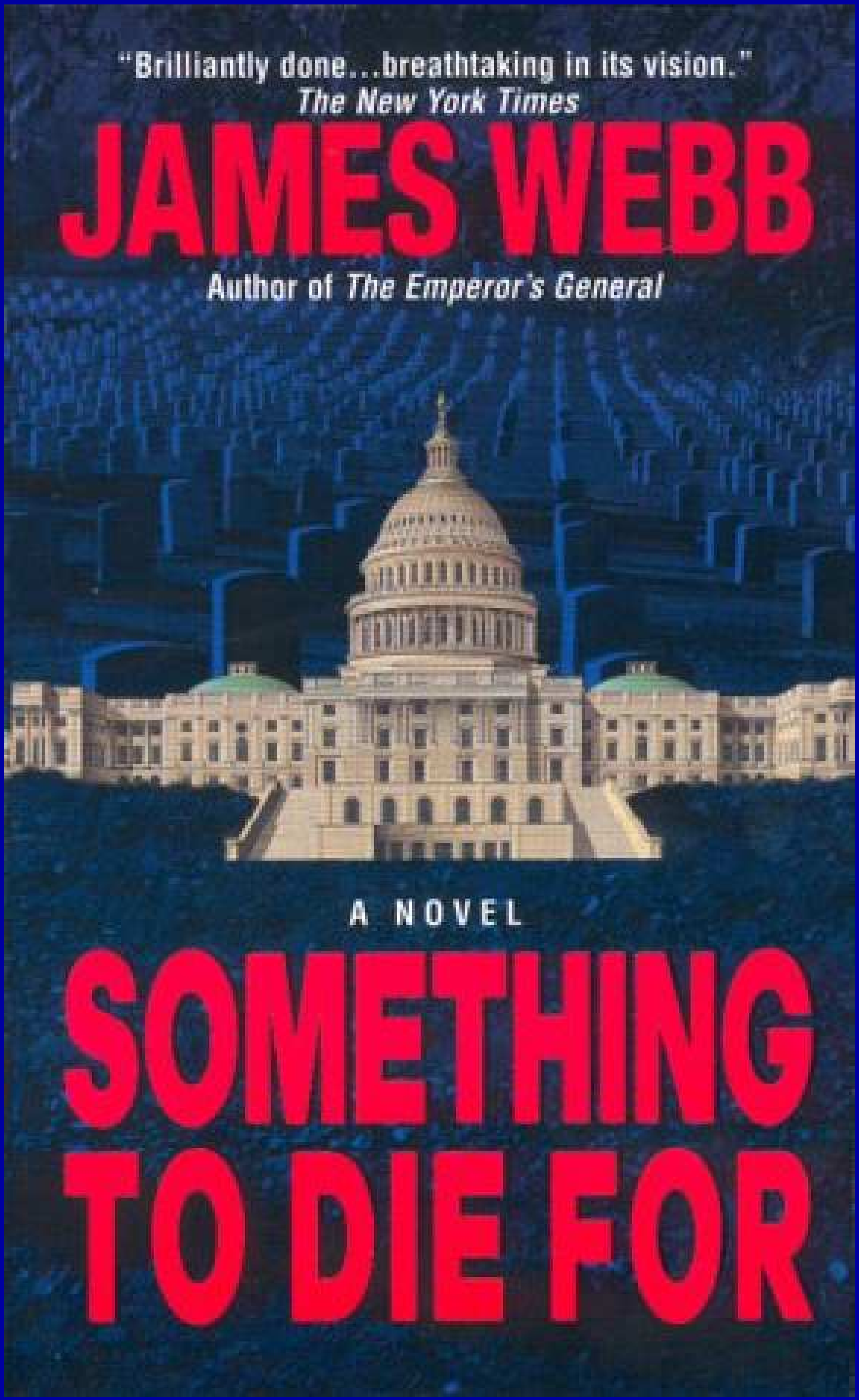


• Giant Segmented Mirror Telescope (GSMT): A segmented mirror with 30 m aperture and active optics correction of atmospheric phase fluctuations: ⇒ FWHM(PSF)∼0.025". Expected operational before 2020.

• (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. 2012. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K for faint imaging (1 nJy=10^{-35} W/Hz/m^2) & spectroscopy (10 nJy).



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

A life-sized model of JWST, used to test the deployment of its sun-shield.

● (2a) How will JWST travel to its L2 orbit?

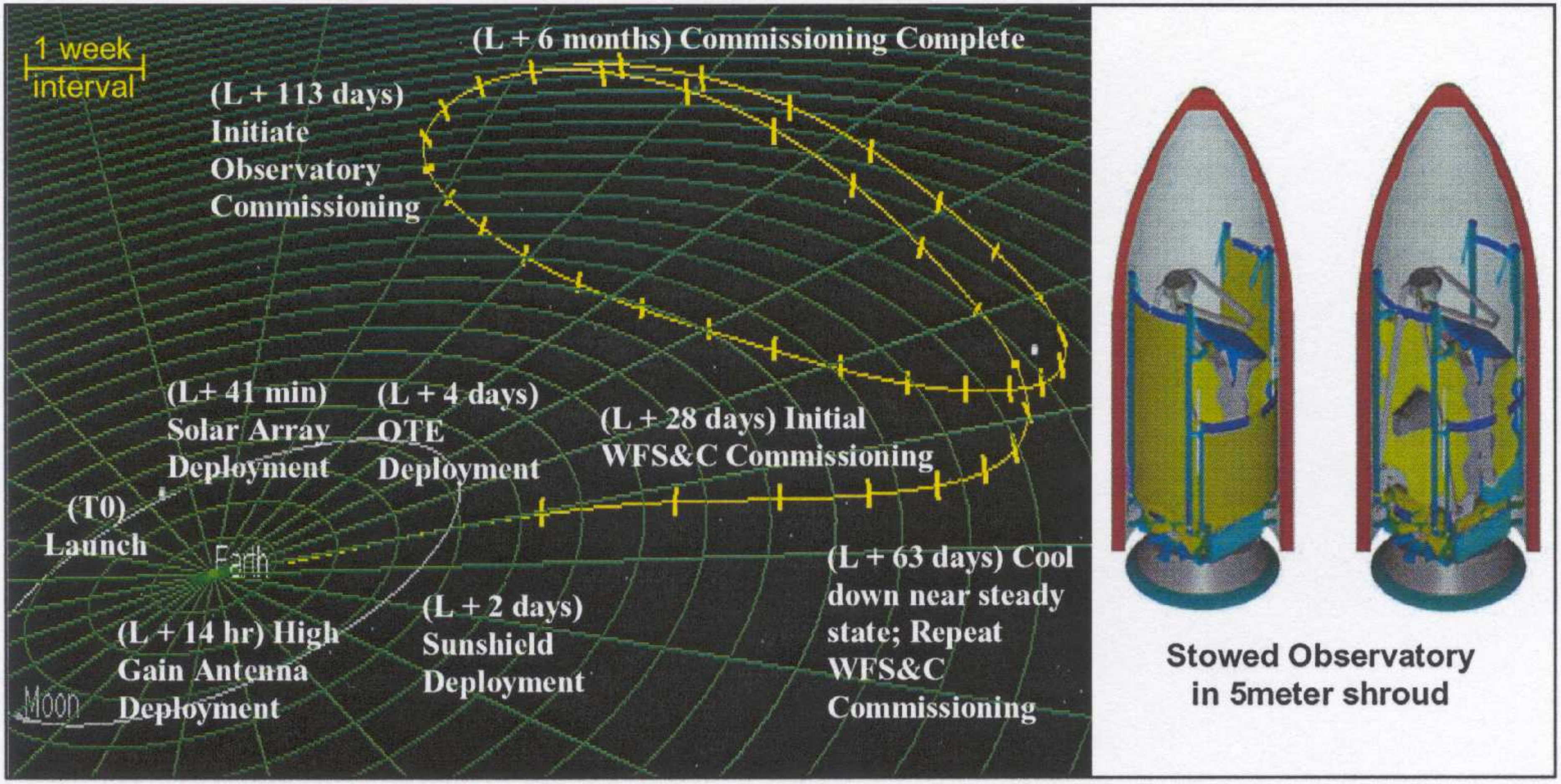


Figure 52. JWST orbit and trajectory to L2, and stowed view in 5 meter shroud.

After launch in $\gtrsim$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 zodiacal longitude (Right Ascension) with the Earth's orbit around the Sun.

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

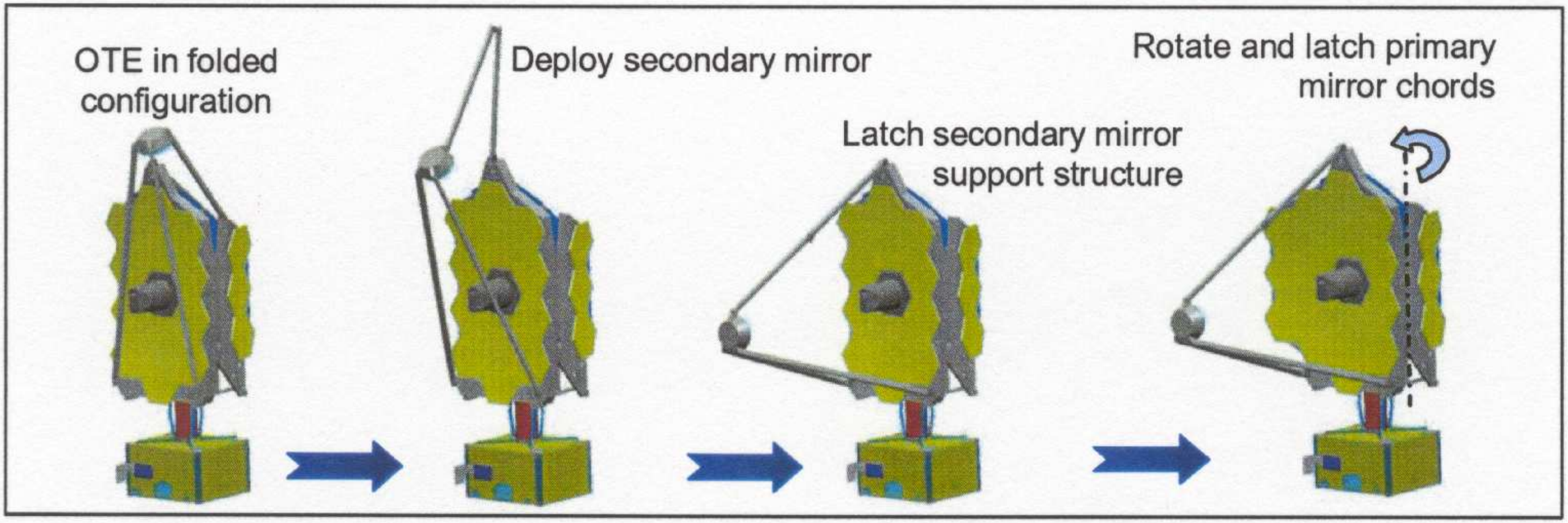
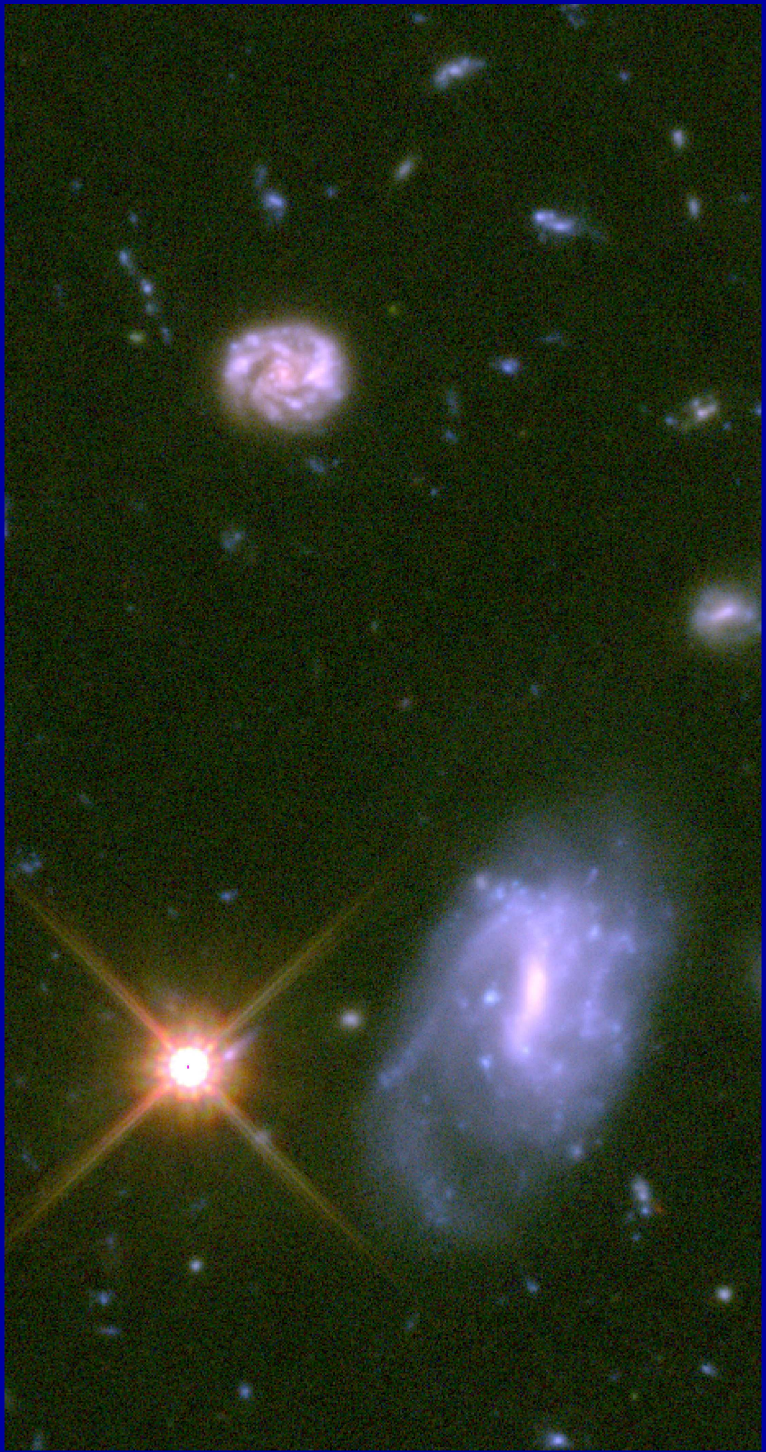


Figure 53. Telescope Deployment Sequence (Deployment steps 4 and 5)

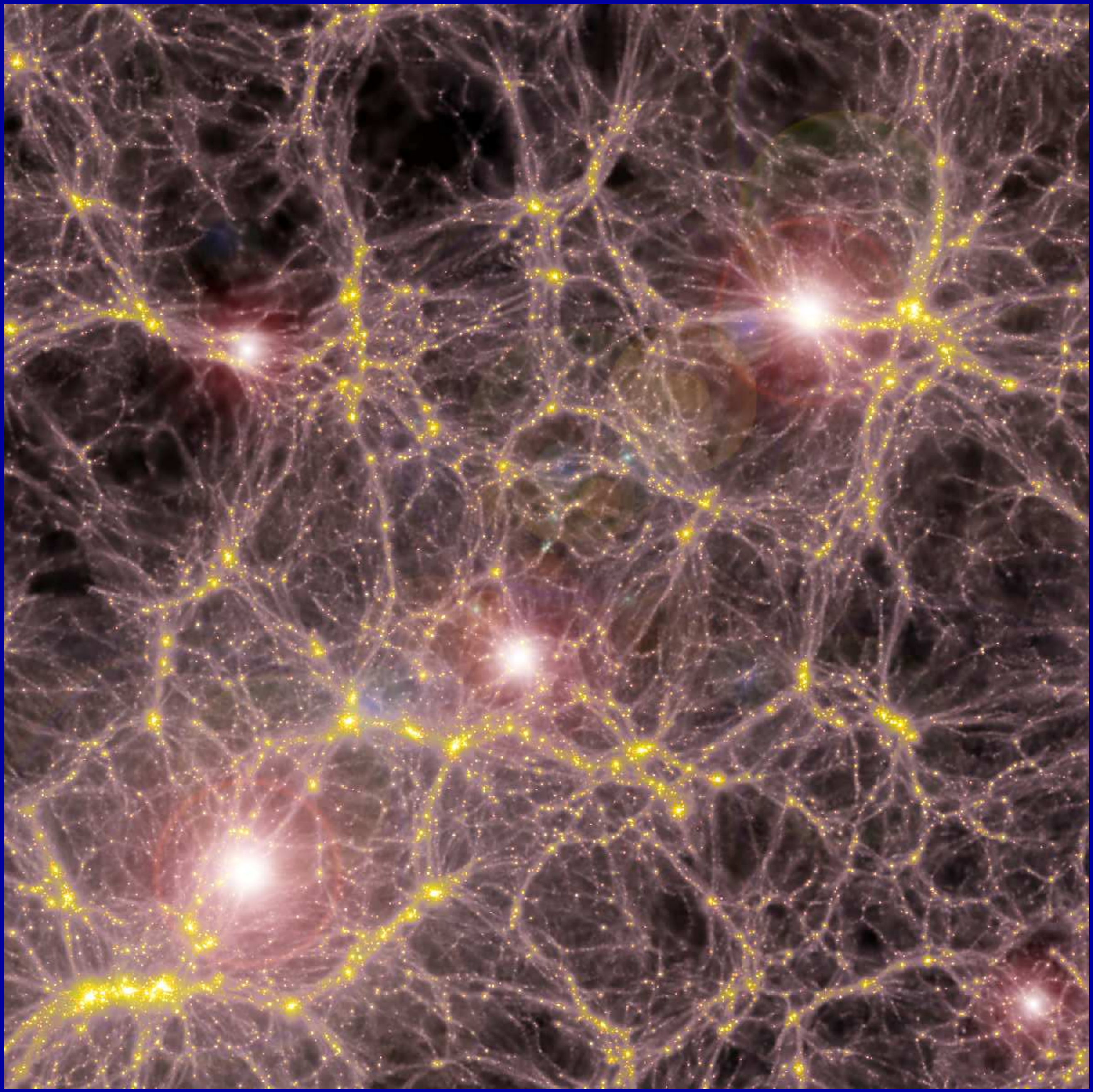
During its several month journey to L2 (shown on previous page), JWST will be automatically deployed in phases (as shown here), its instruments will be tested, and it will then be inserted into an L2 halo orbit.

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.



200 hr Hubble UltraDeep Field $\lesssim$20 hr JWST 0.7, 0.9, 2.0 μm

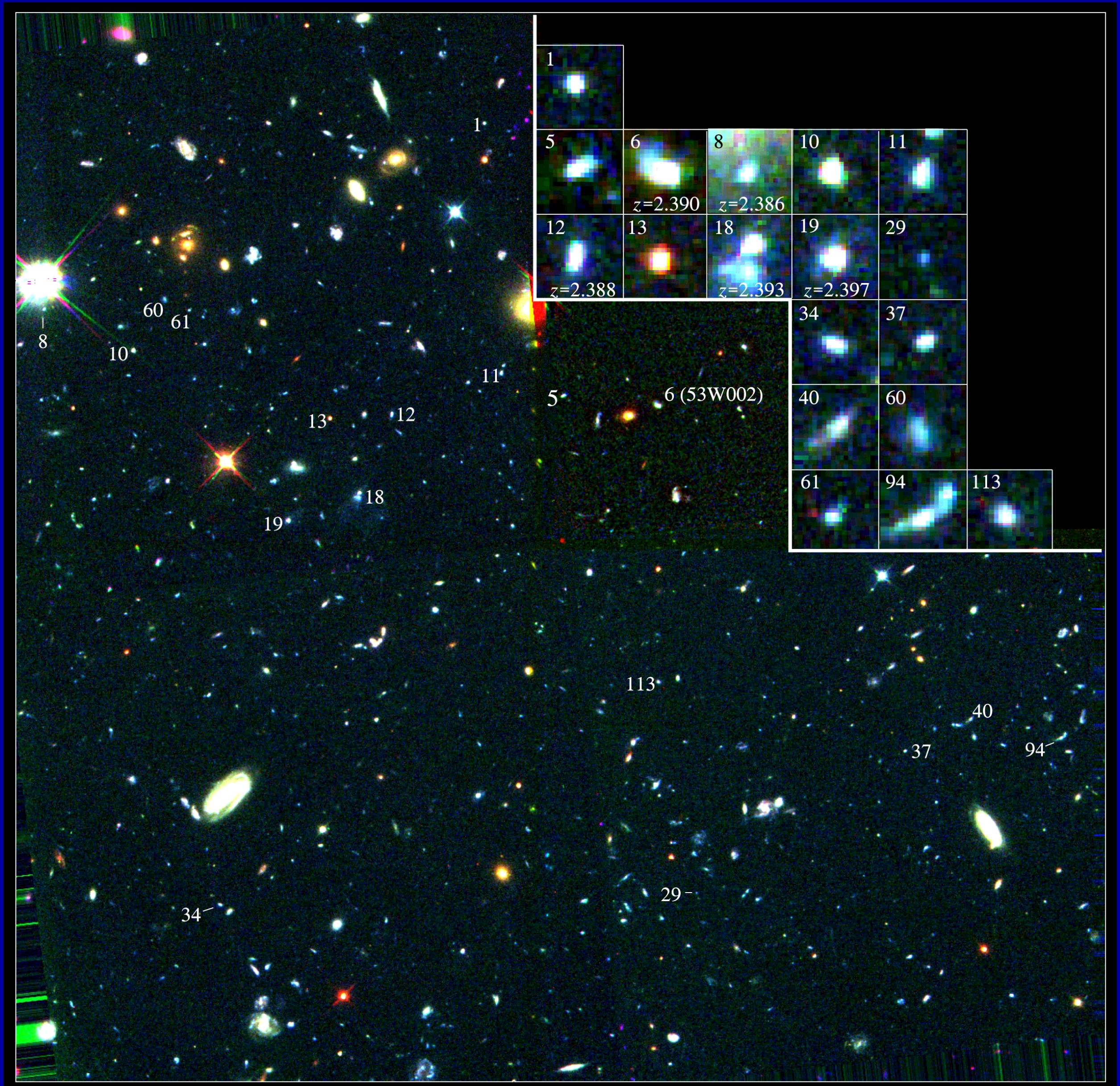
• (2a) How JWST can measure First Light and Reionization



• 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 $z \simeq 25 \rightarrow 15$.

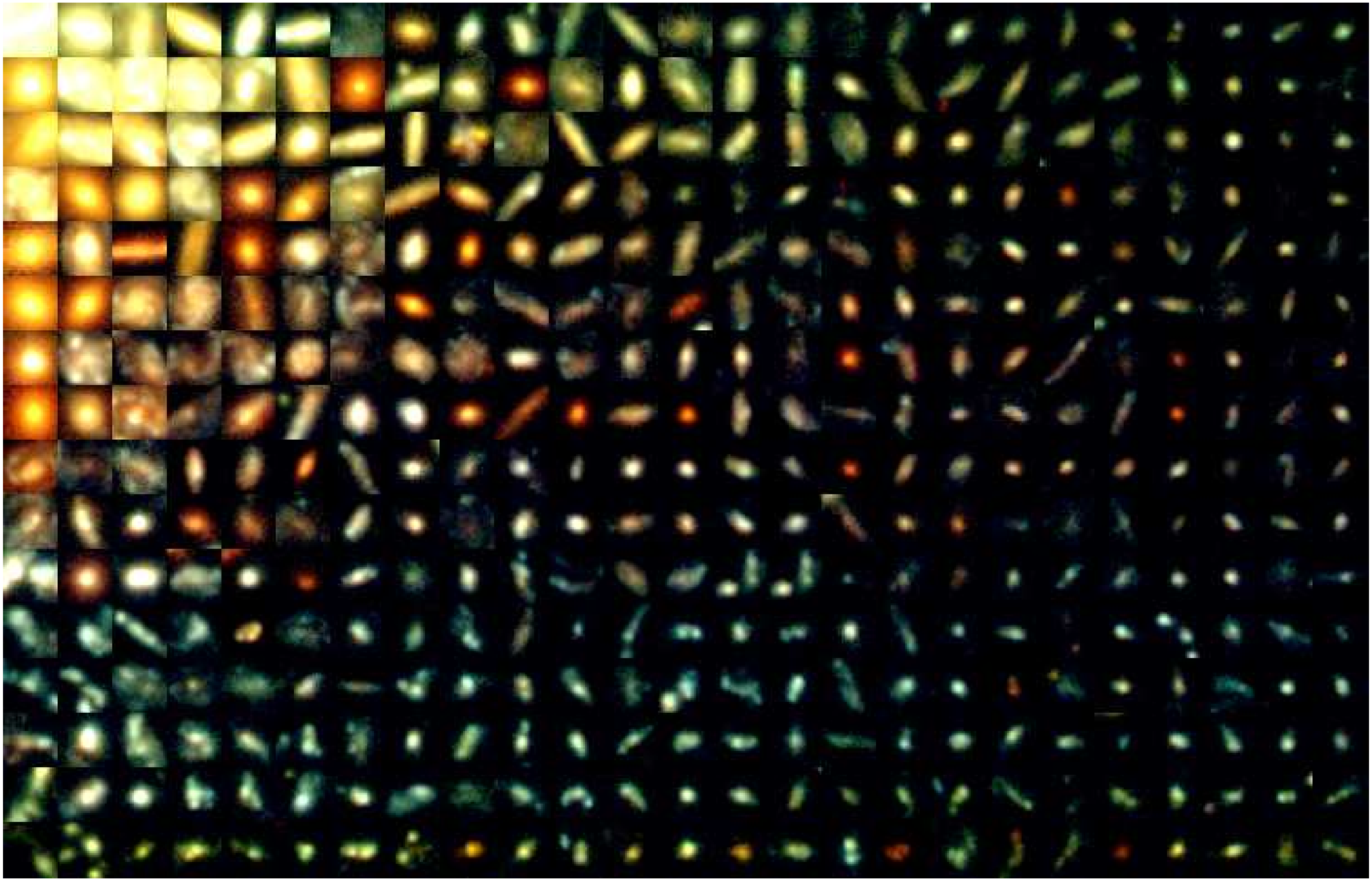
• (2a) How JWST can measure Galaxy Assembly



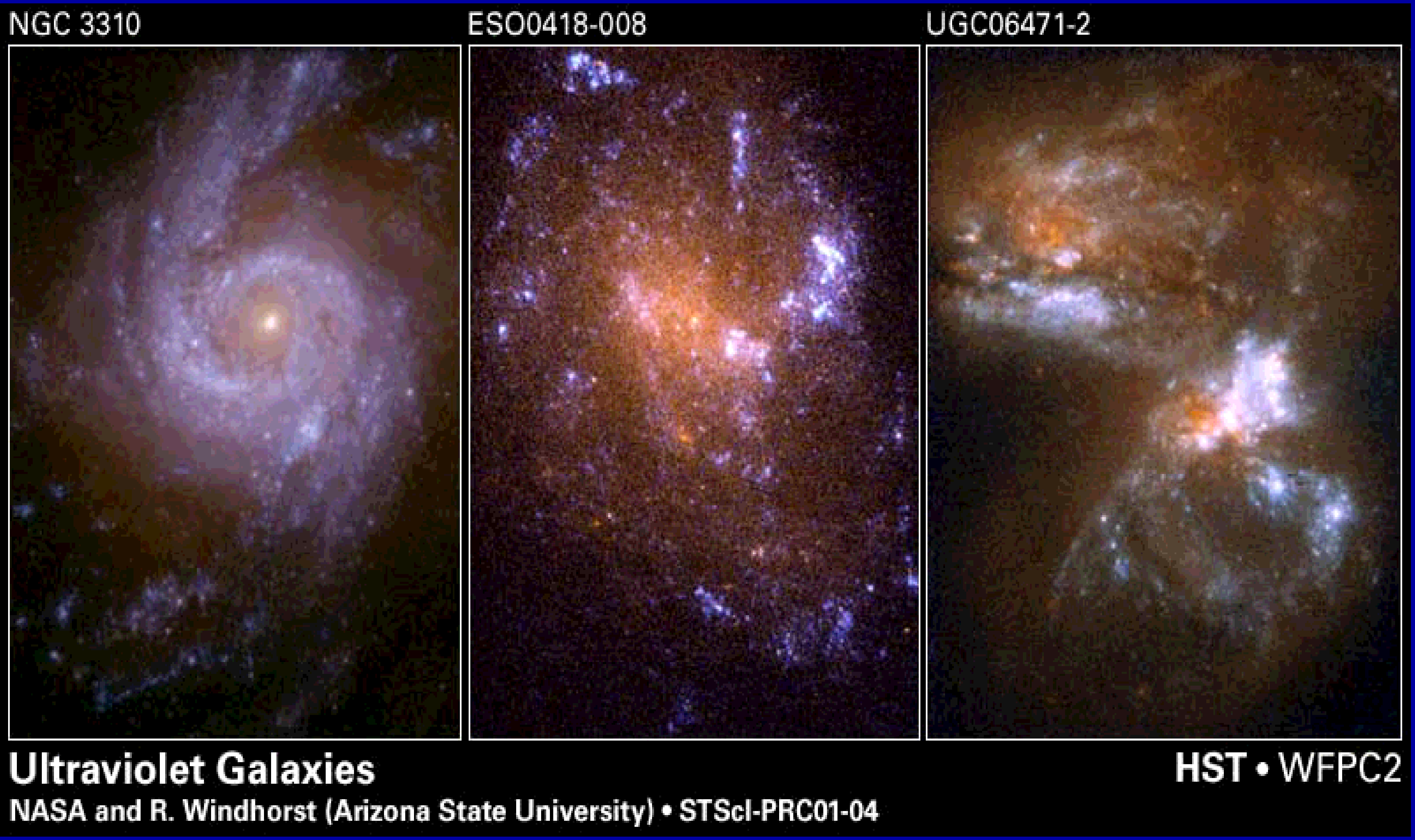
R. Windhorst (Arizona State University) and NASA

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 ($I < 26.0$)



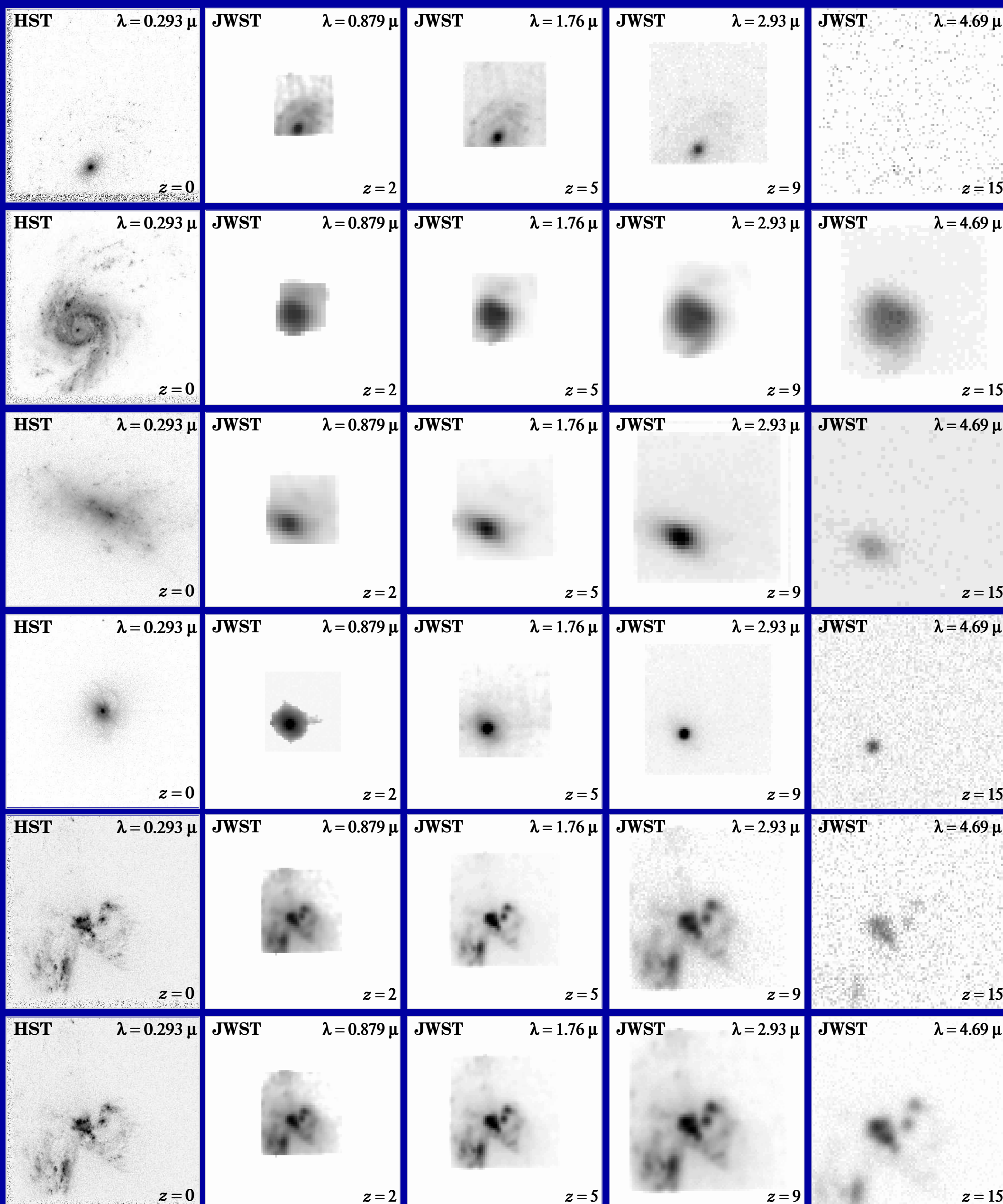
z	Age ($q_o = 0.5$)
0.19	77%
0.44	58%
0.54	52%
0.64	48%
0.74	44%
0.87	39%
0.97	36%
1.03	35%
1.14	32%
1.24	30%
1.41	27%
1.61	24%
1.76	22%
2.05	19%
2.57	15%
3.59	10%



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$\lesssim z_{form}$ ≃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.

• (2b) Radio Telescopes — Earth-based Movable Interferometers

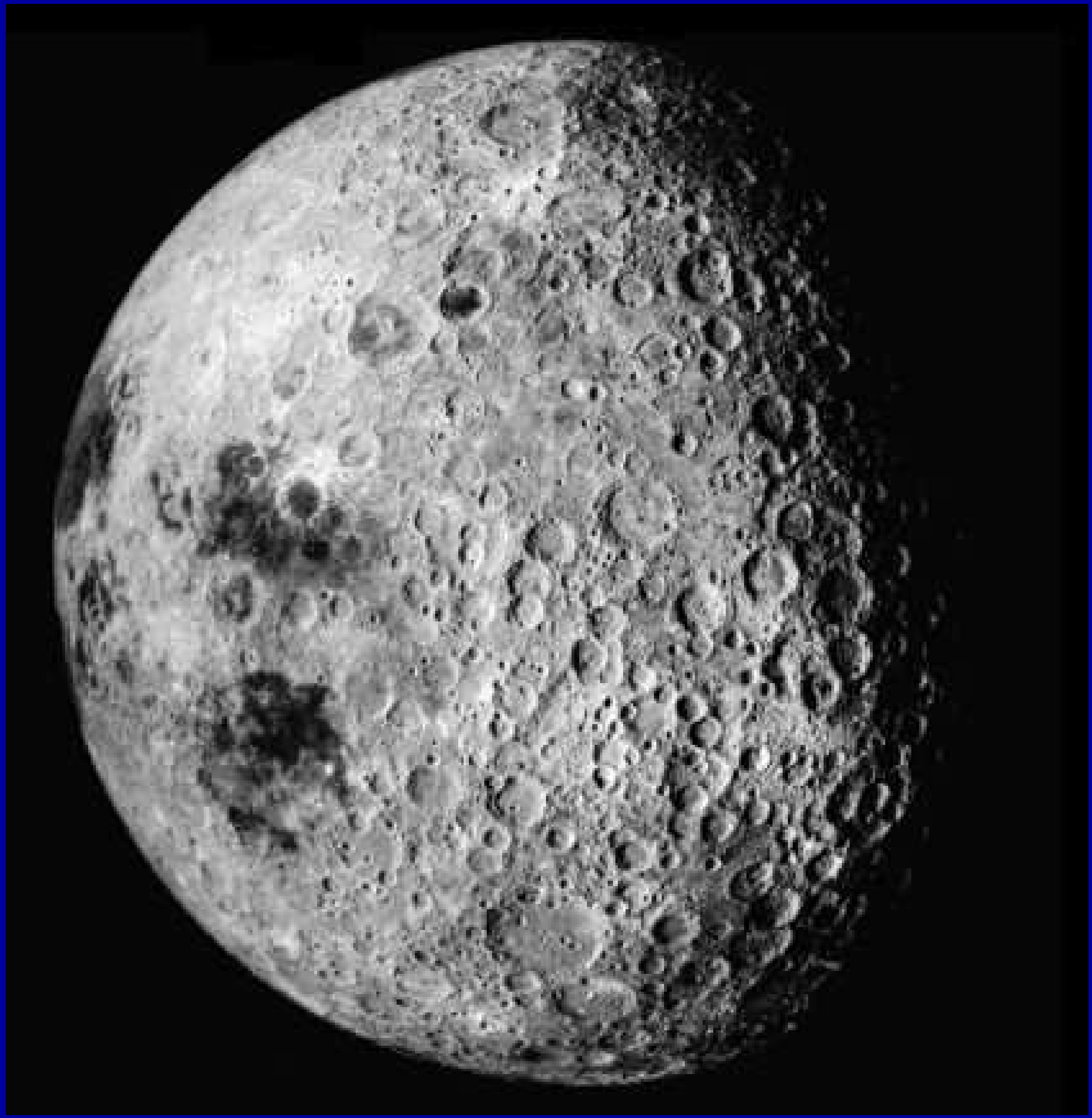
• Very Large Array (VLA, NM): 27 radio dishes (25-m) movable on railroad tracks over 1–27 km baselines $\Longrightarrow$ 1–30" resolution at $\nu \simeq$ GHz.

- (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

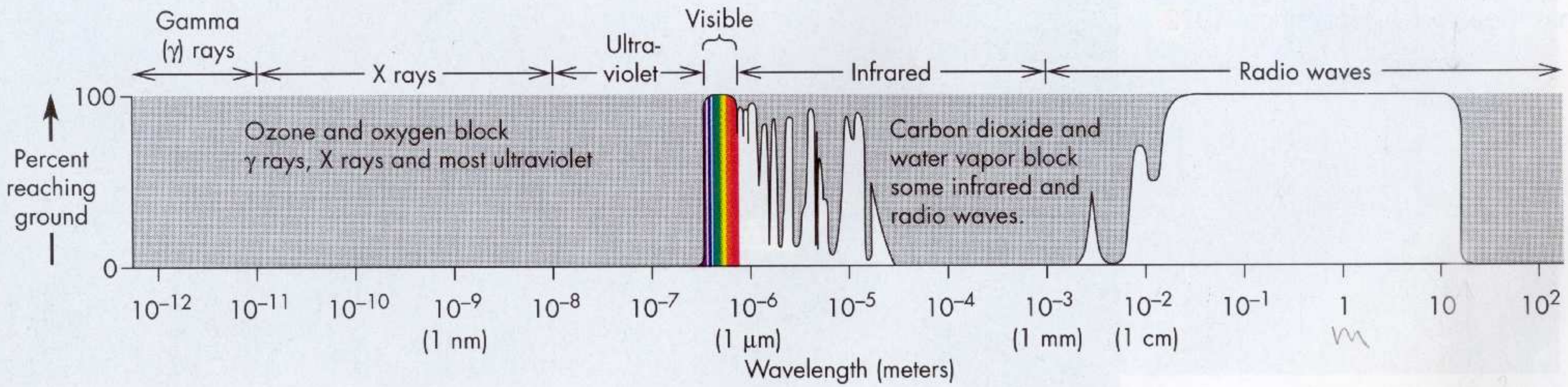
Only place free of: (a) human ULF interference; (b) ionospheric absorption



• 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

FIGURE 6.28
The Transmission of Earth's Atmosphere
The percentage of radiation that reaches the ground varies greatly with wavelength. Only in the visible, infrared, and radio wavelengths are there spectral regions in which the atmosphere is transparent.



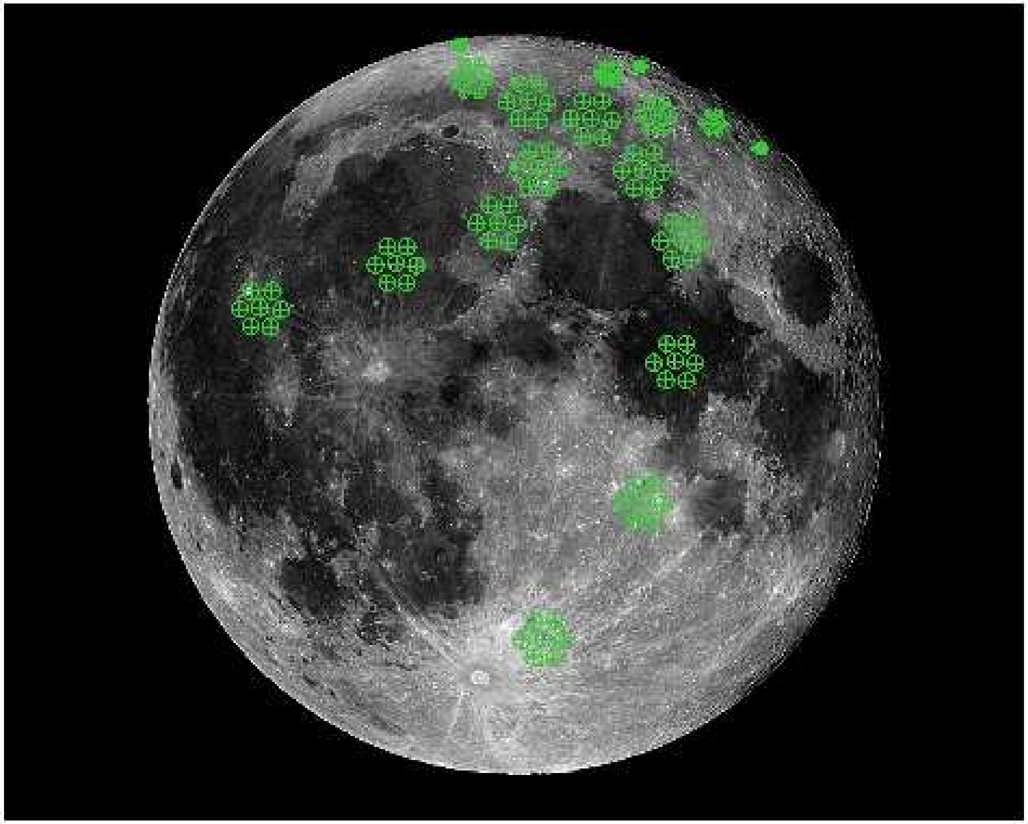
- Far-side of Moon only place free of human-made ULF interference and ionospheric absorption.
- $\Rightarrow$ H-I studies at $\nu \lesssim$30 MHz $\Leftrightarrow$ can see ν(H-I=1421 MHz) at z$\gtrsim$45 !
- $\Rightarrow$ Moon's far-side needed to penetrate first 55 Myr of the Universe's history: the Cosmic Dark Ages.

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

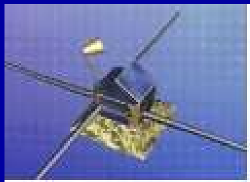
- Use long-duration science rovers to lay down a fractal grid of foil and dipoles. Foil backs up as solar panels.
- Exact geometry is not important. Surface accuracy may be $\lesssim$50 cm!
- Use Ka-band to correlate data, Lunar TDRSS to send to Earth (Tb/day).
- Weeks–months to build. Then use rovers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

Lunar LOFAR: Distributed array of radio sensors

- Number N of antennas: growing from 4 to 100 to 10000
- Collecting area A_{eff}:
  $N \times \lambda^2$ (10 MHz~λ30 m)
  A_{eff}~ 0.09 km^2, 9 km^2
  (N=10^2, N=10^4, =10 MHz)
  A_{eff}~ 9 km^2, 90 km^2
  (N=10^2, N=10^4, =1 MHz)
- Baselines D ~ 100-1000 km
  $\Rightarrow$ Resolution (λ/D):
  ~6'' (D/1000 km) @ 10 MHz
  ~ 1' (D/1000 km) @ 1 MHz
- Grouping in 100 stations with 100 antennas (alternative: 30×30)?
  - Minimum diameter of station ~3.3 km (densely packed for 1 MHz)
  - Average separation of dipoles ~ 300 Meter



European Lunar Low-Frequency Array (H. Falcke, Nijmegen & ASTRON)

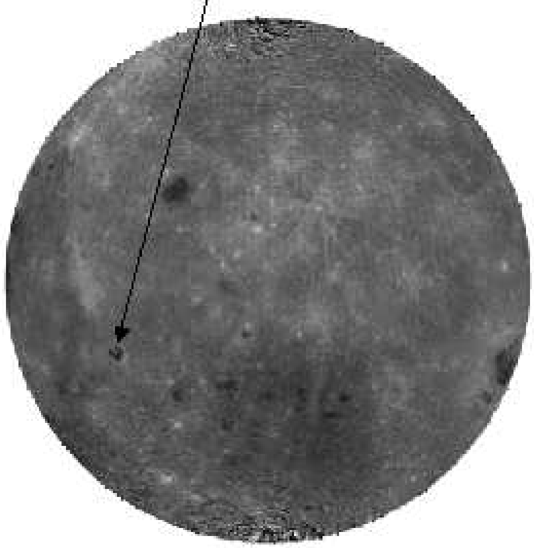


proposed site: Tsiolkovsky crater

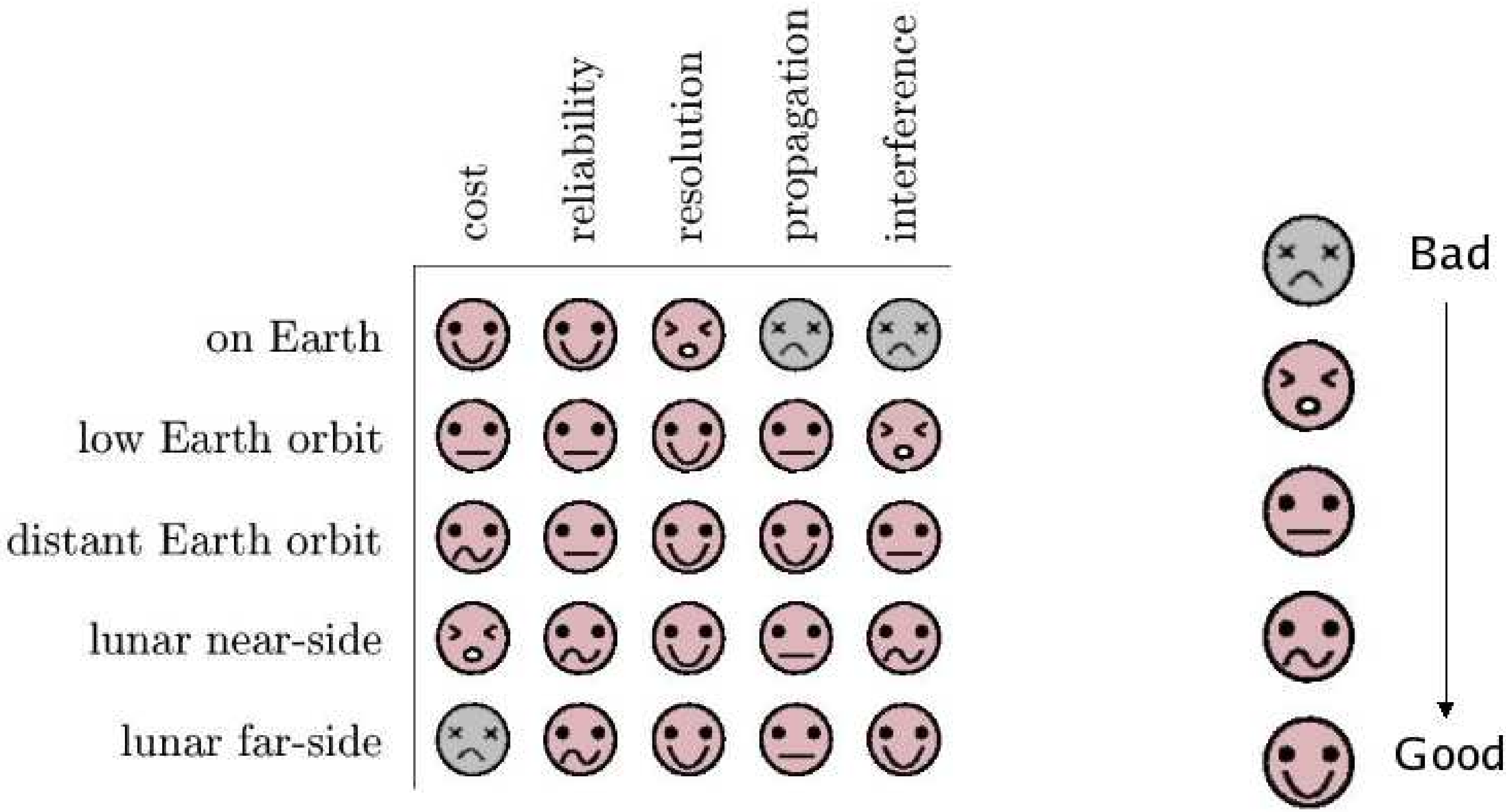
Tsiolkovsky crater

(100 km diameter)

20°S 129°E

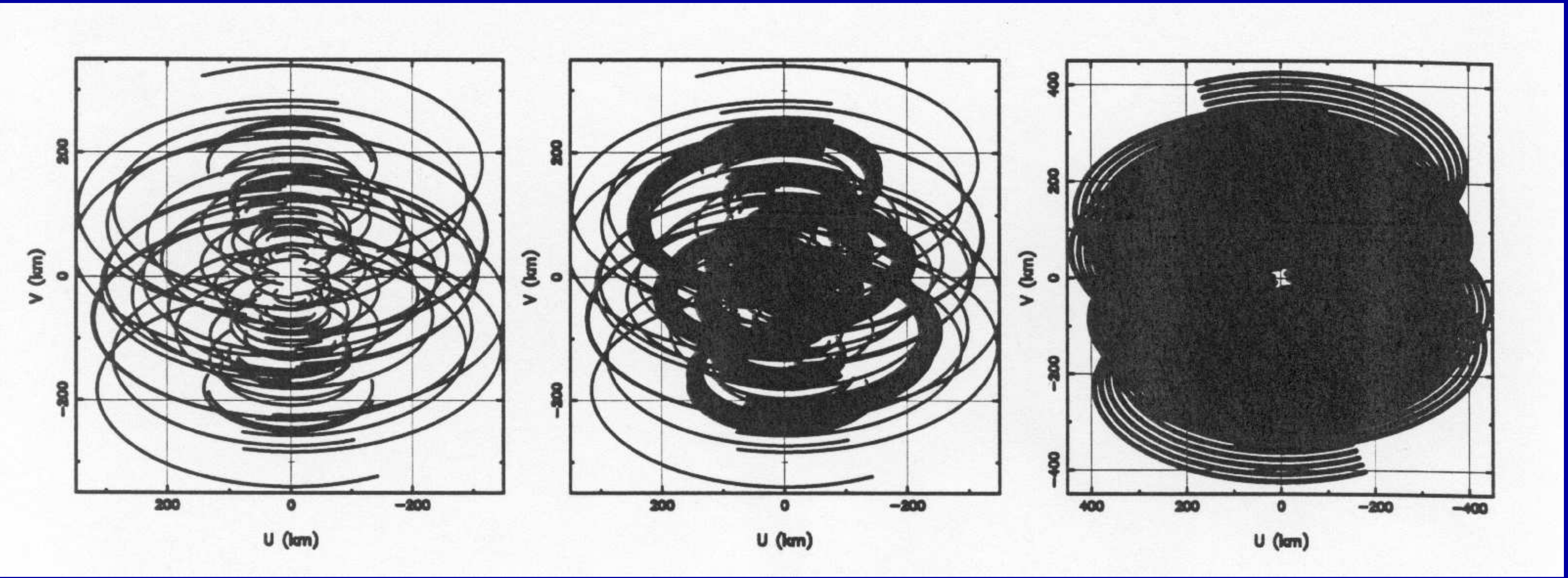


environments compared



Consumer's Report of Lunar LOFAR (G. Woan, U. Glasgow & ESA)

• (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) Solid evidence for "Hot Big Bang"

- (1a) Hubble expansion is a real expansion of space. Age=13.7±0.2 Gyr.
- (1b) $(\Omega_{baryon}$=0.044) + $(\Omega_{dark}$=0.23) + $(\Omega_{\Lambda}$=0.73) = 1.00±0.02

$\Rightarrow$ Spatially flat, inflationary and now exponentially expanding universe.

$\Rightarrow$ We know very precisely that 96% of Ω_T is of unknown nature!

- (1c) Observed light element abundance exactly as predicted by Hot BB.
- But Cosmic Dark Ages, First Light, & Reionization still a mystery.

(2) Telescopes beyond Earth: Need them because of rapid expansion!

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

- JWST will have major impact on First Light and Reionization.

(2b) Need Large Radio Interferometer to penetrate the Dark Ages.

- A Radio Interferometer on Moon's far-side will work best.

SPARE CHARTS

(3) Lessons to be learned for new NASA Vision:

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

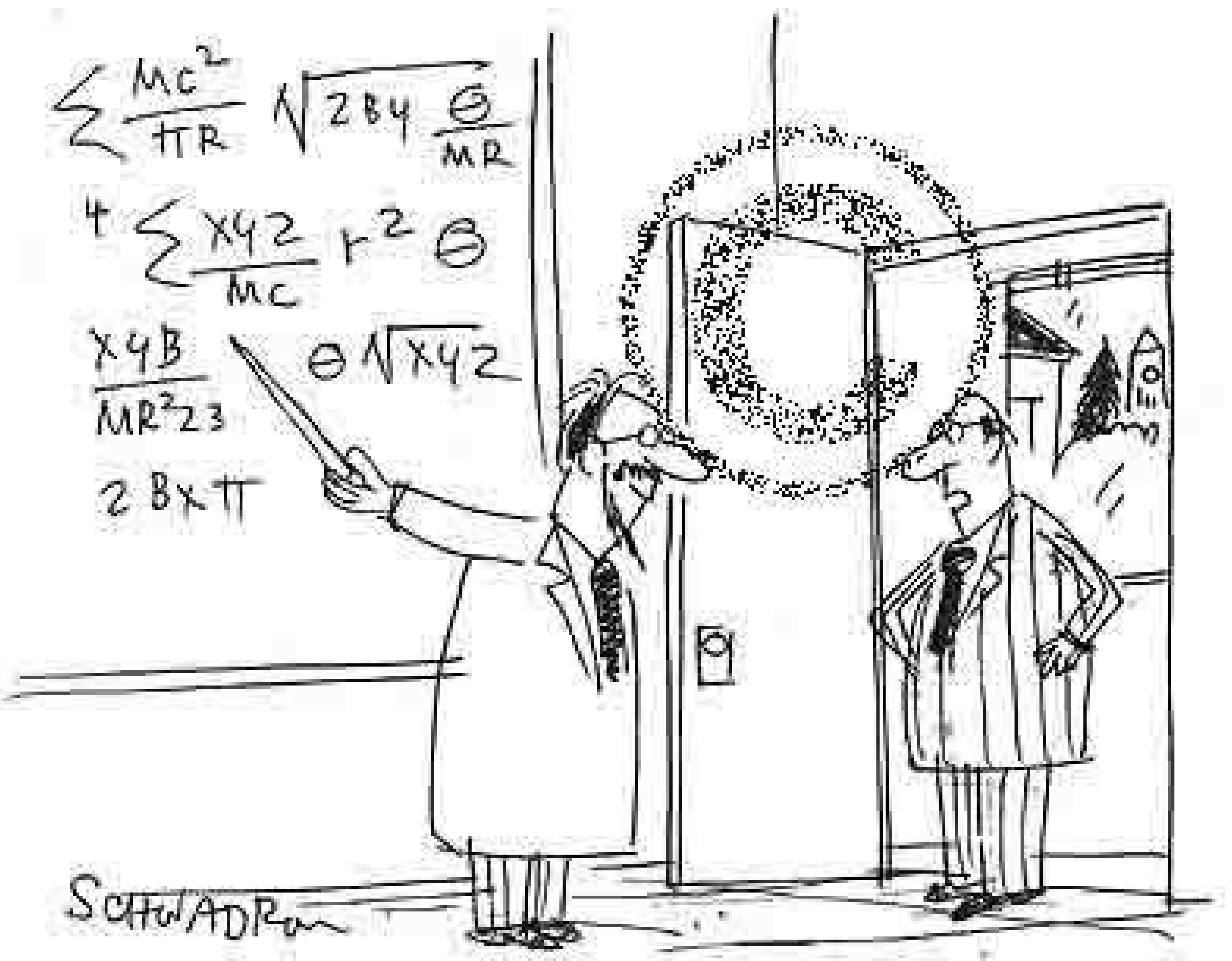
Earth/Moon/Mars/Beyond $\simeq 10^{51}/10^{49}/10^{50}/10^{80}$ baryons.

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

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

But, for the new NASA Vision 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.
- (5) Use L2 and the Moon to build the next generation of telescopes.



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

How to get tenure as cosmologist ...

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	—	$\lambda_{obs}=\lambda_{rest}.(1+z)$ [$\rightarrow$ 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.	$\Theta \propto d^{-1}$	$z \lesssim 0.1$: $\Theta \propto z^{-1}$
	small Θ approx.	$z \gtrsim 2.0$: $\Theta \propto d(z)^{-1}.(1+z)$ [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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carpet / details \ carpet

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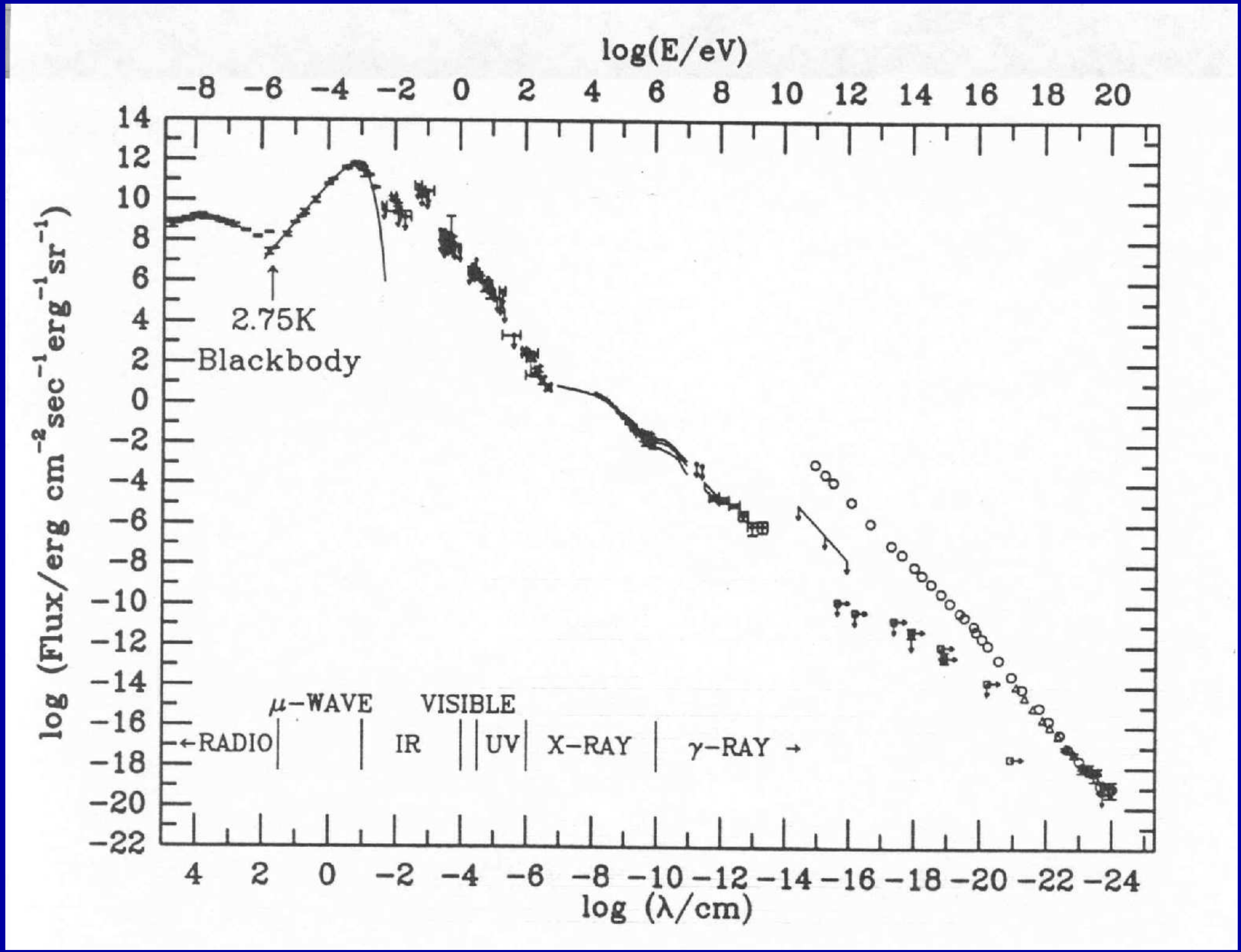
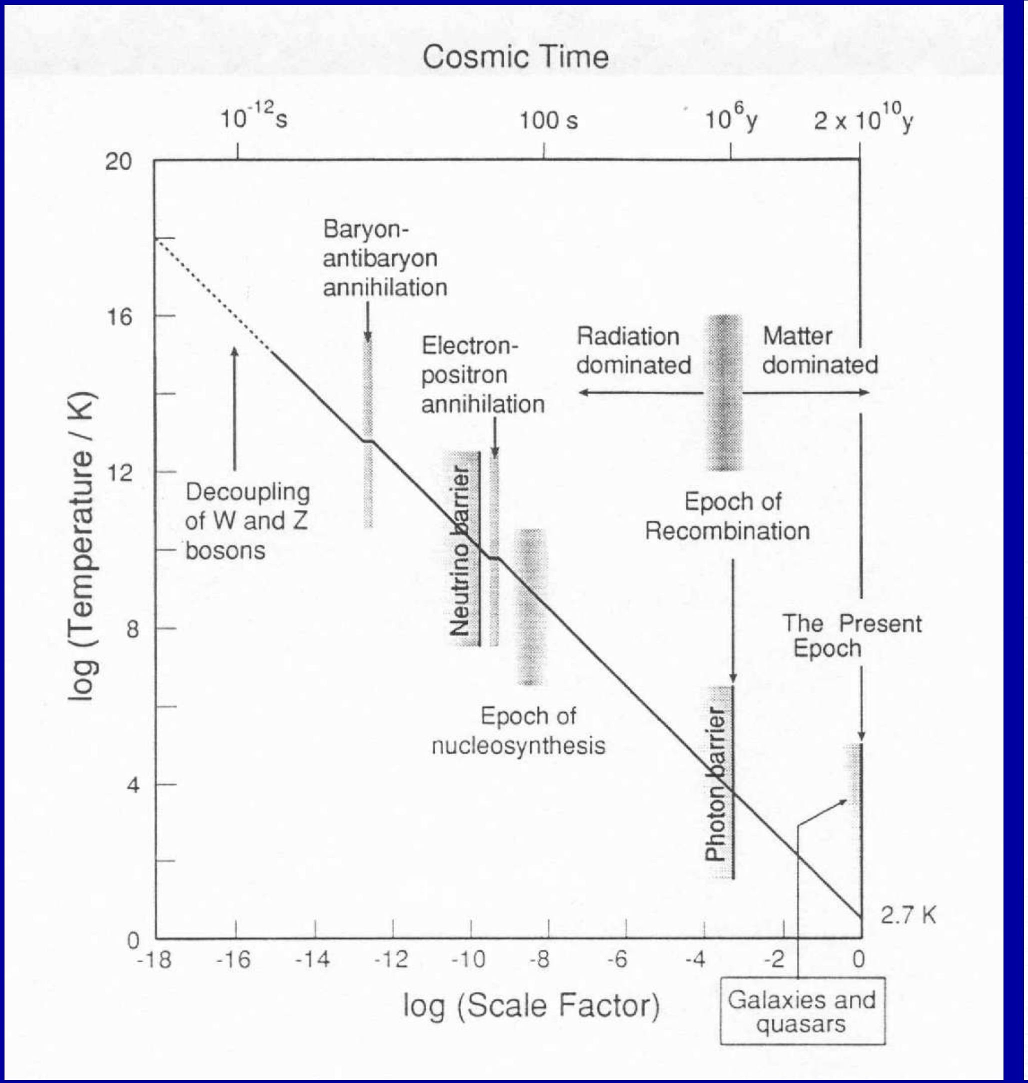
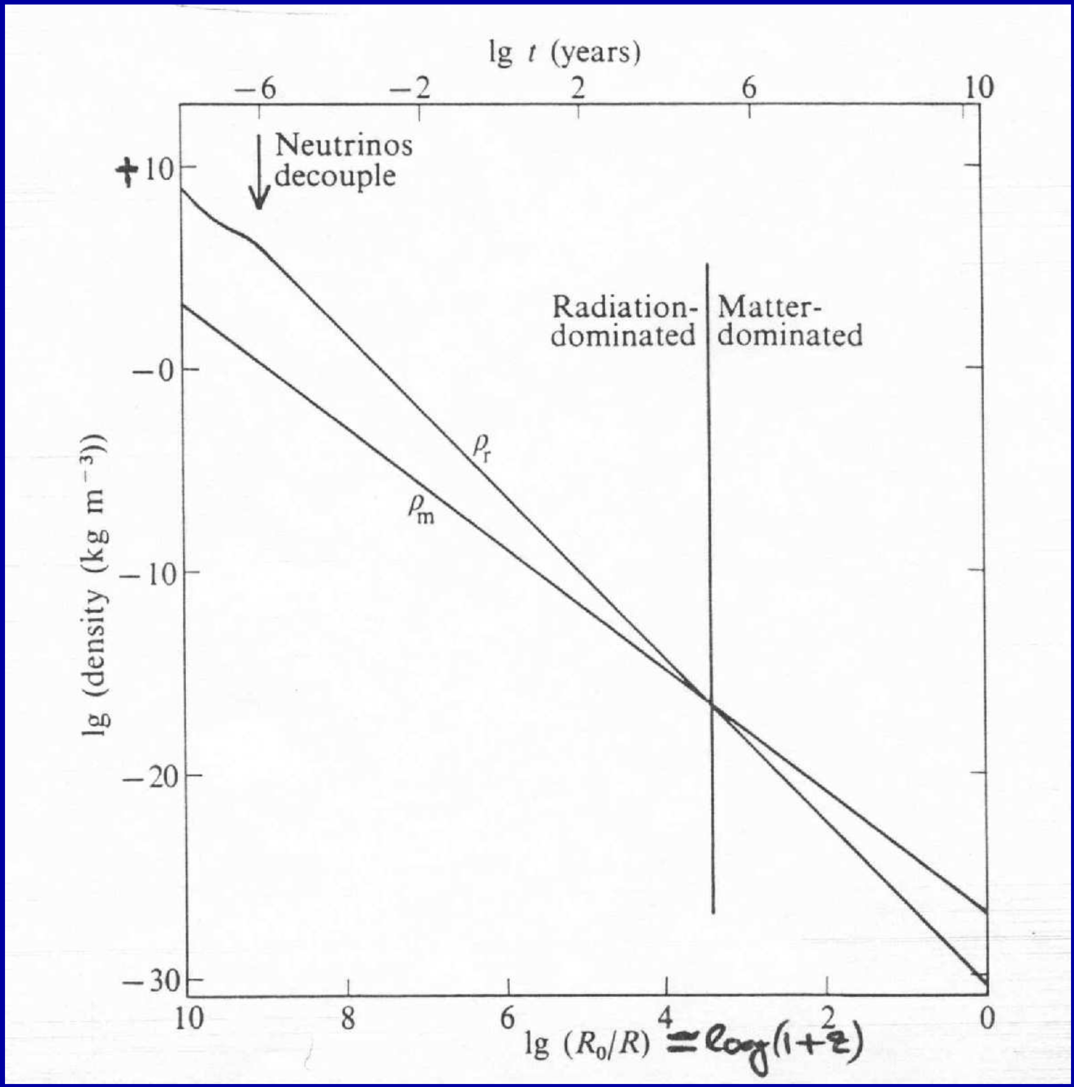
(1b) Integrated EM Background: nearly a power-law over 20 dex in λ!



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!



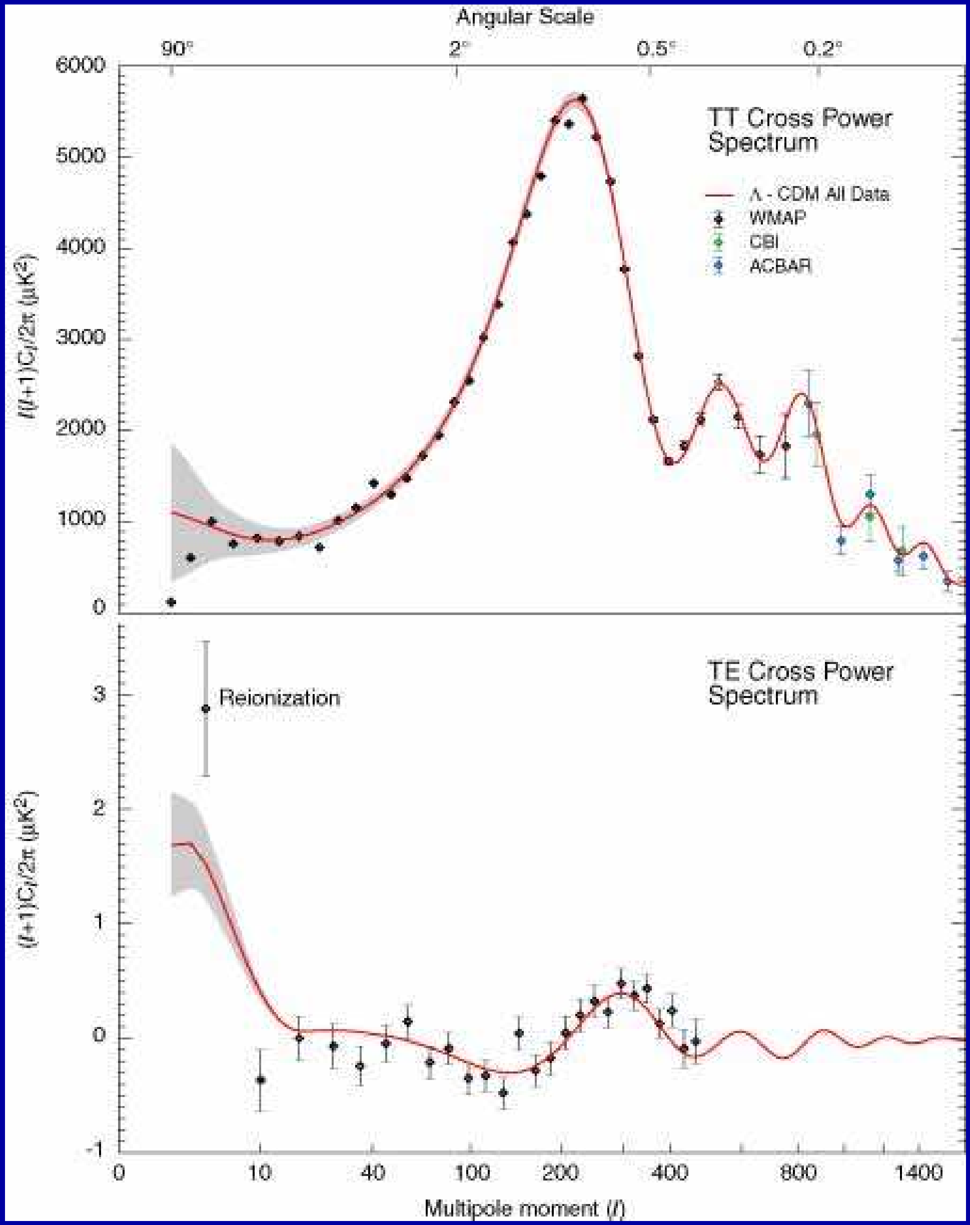


Thermal History of BB (Left): Temperature vs. Scale Factor R=1/(1+z).

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 $\rho_m \propto (1+z)^3$.



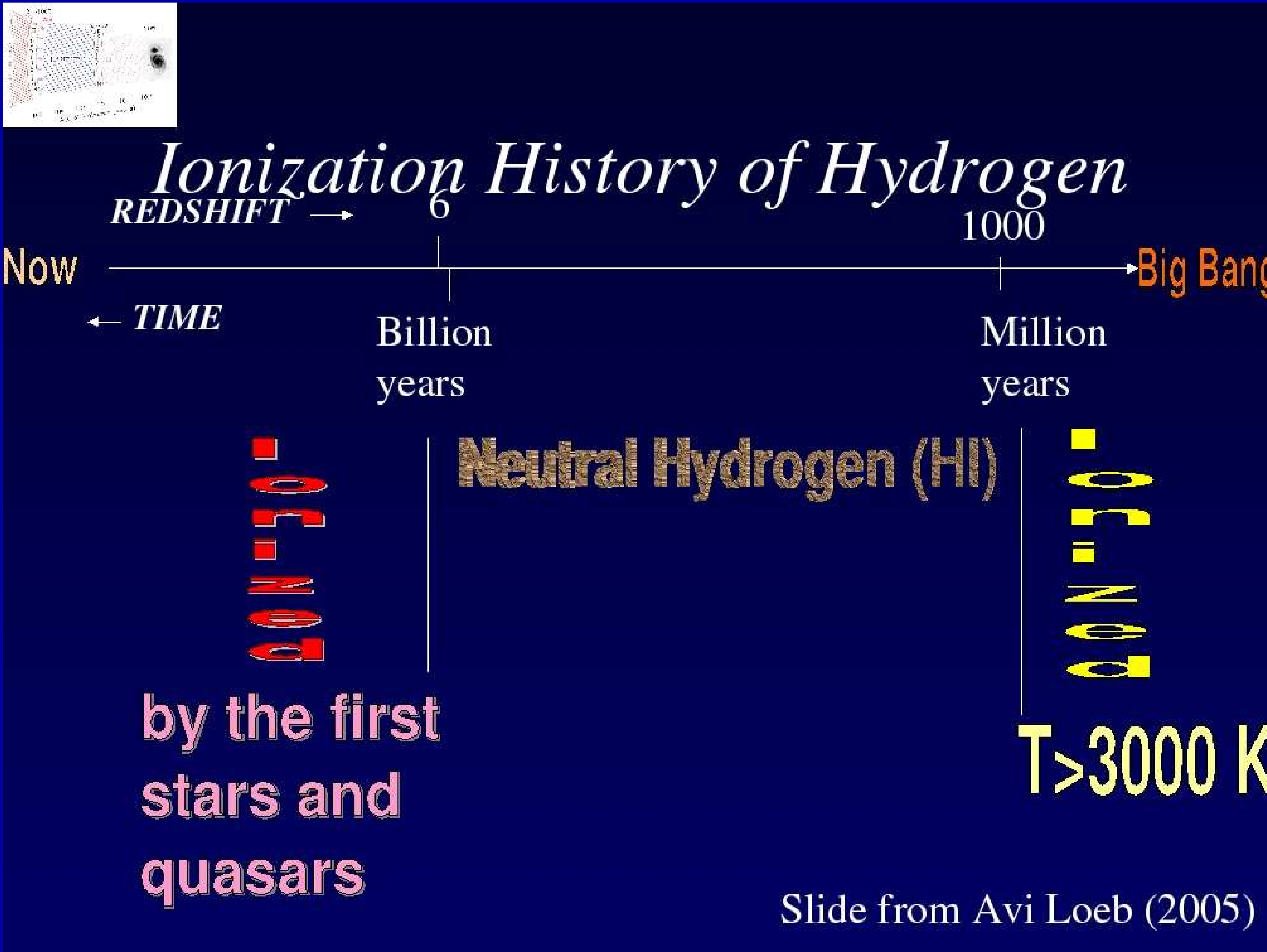
WMAP Power Spectrum: total light (top) & polarization (bottom).

Best fit: H_0 =71±3 km/s/Mpc ⇒ Current Age=13.7±0.2 Gyr; AND:

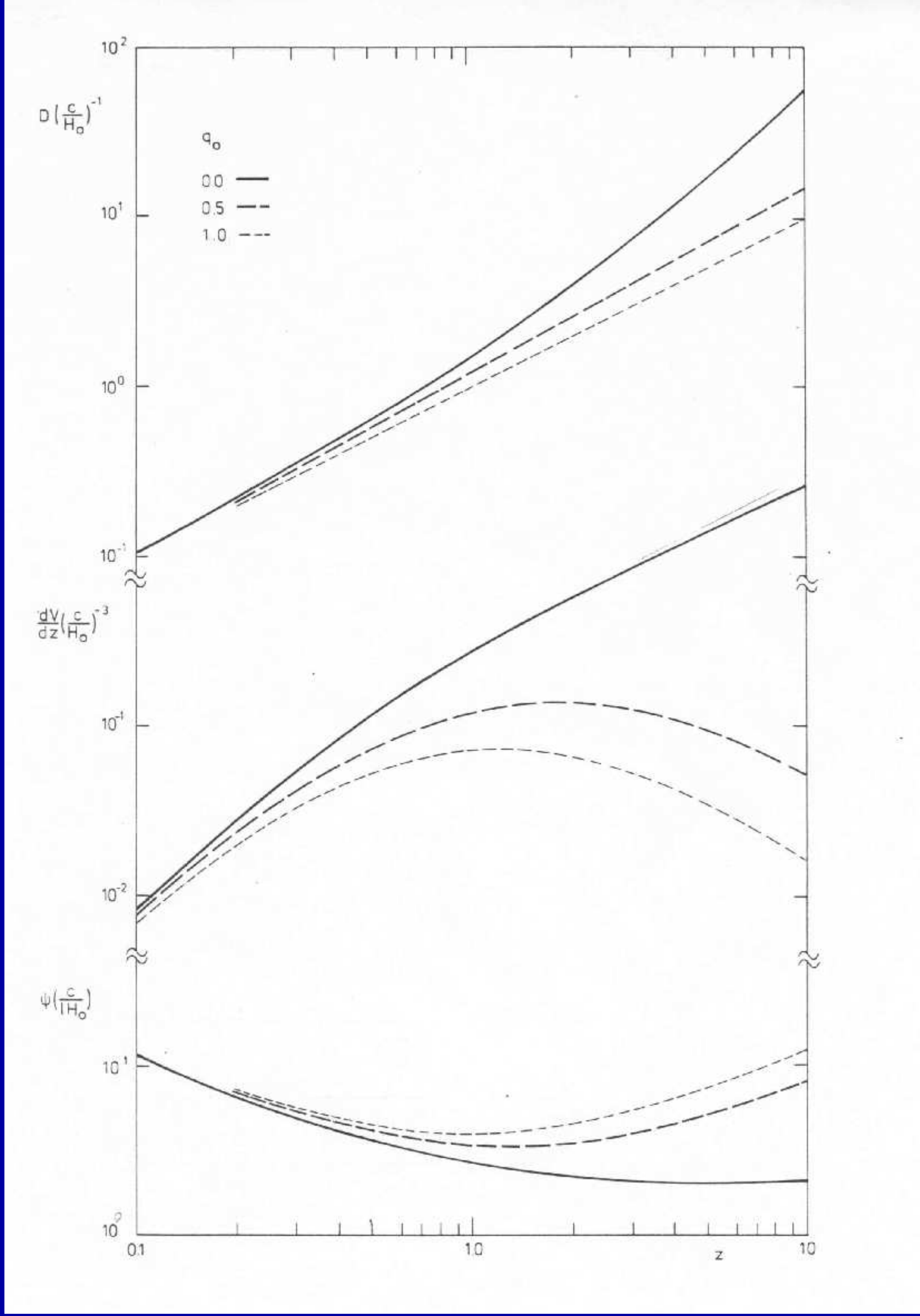
Ω_{baryon}=0.044; Ω_{dark}=0.23; Ω_Λ=0.73; SUM=1.00±0.02 !!

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

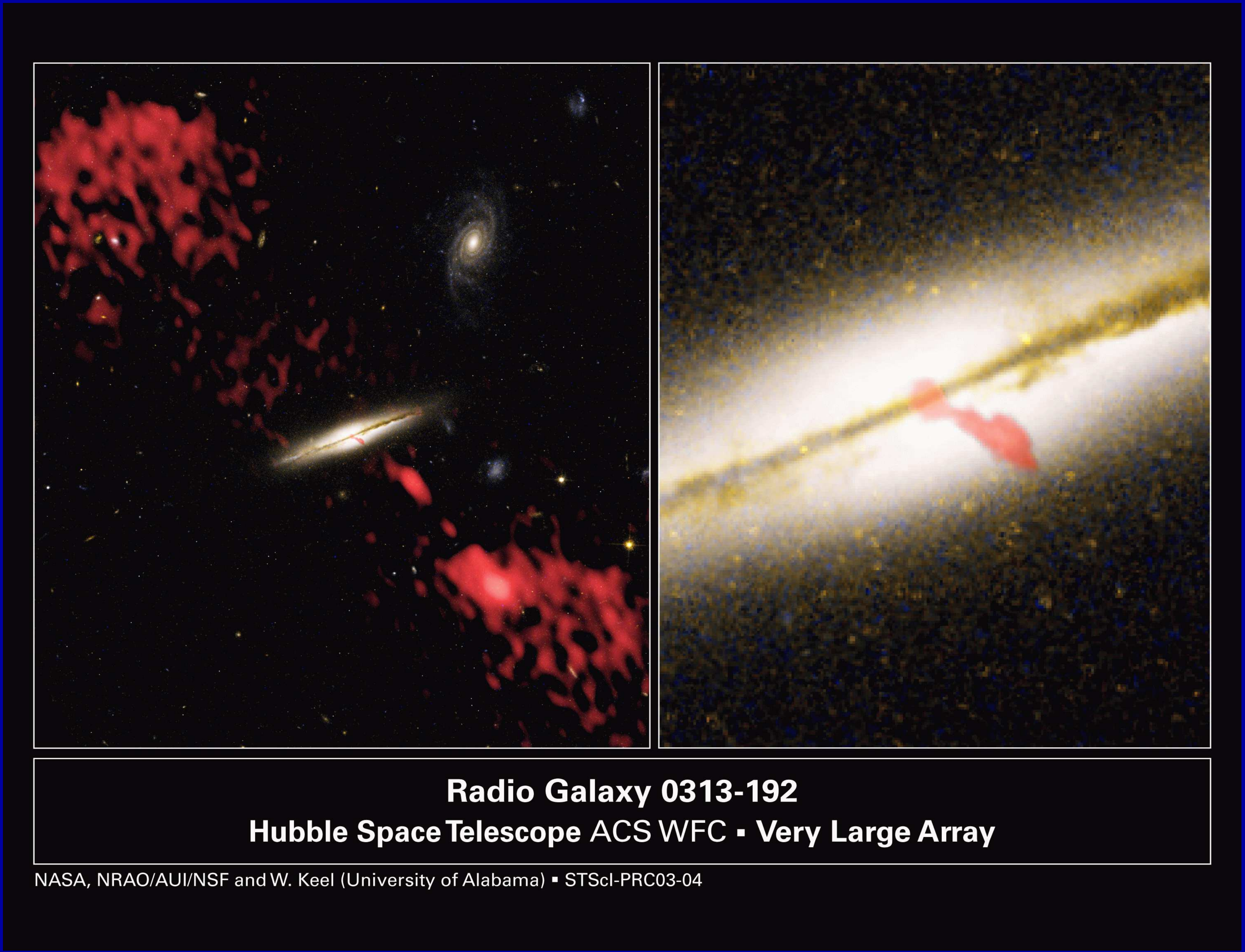
Microwave Background $\Rightarrow$ Cold Dark Matter is non-baryonic ($\neq$ cats)



The Hydrogen Reionization History of the Universe (Loeb 2005)



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



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

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

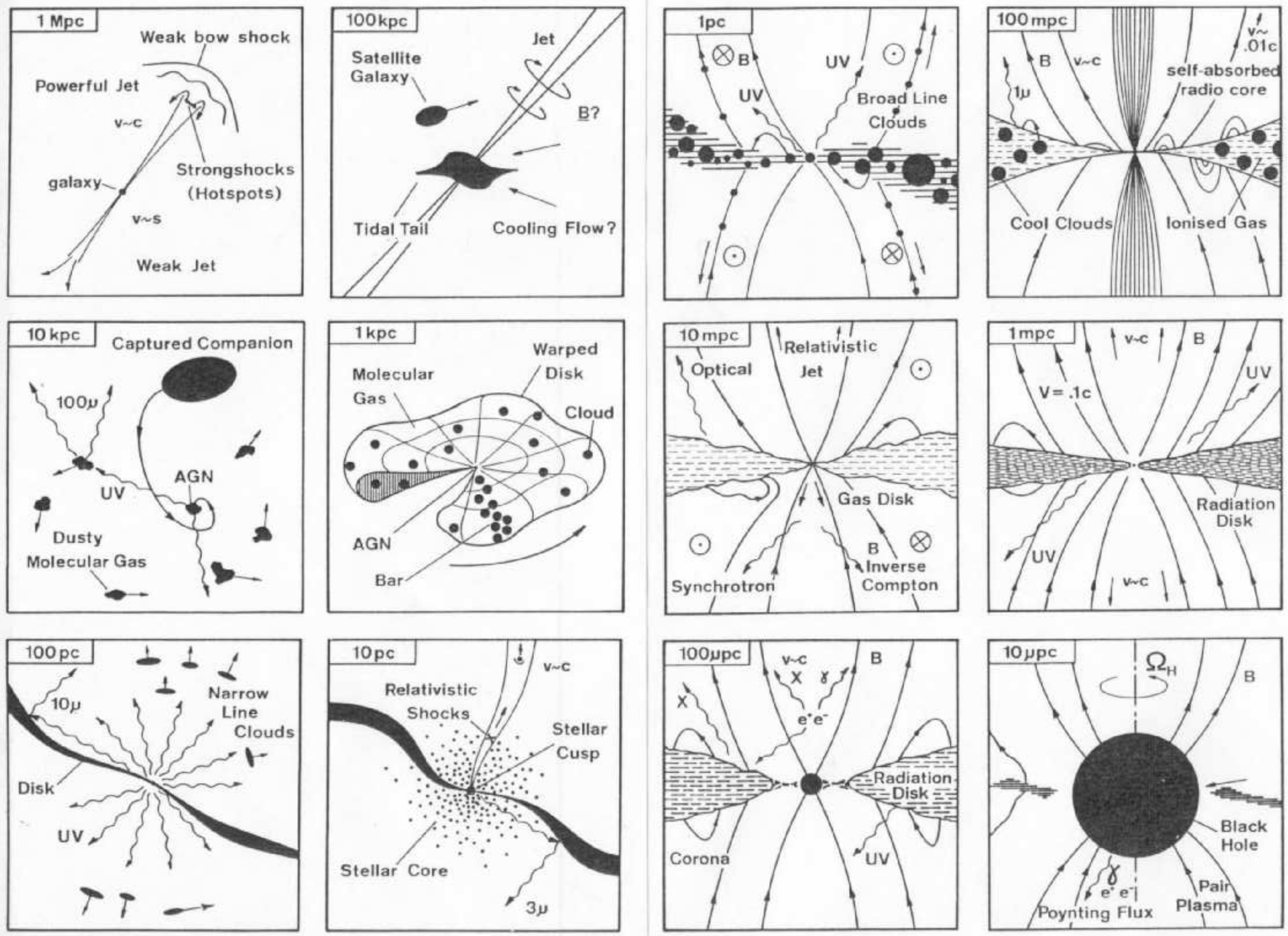
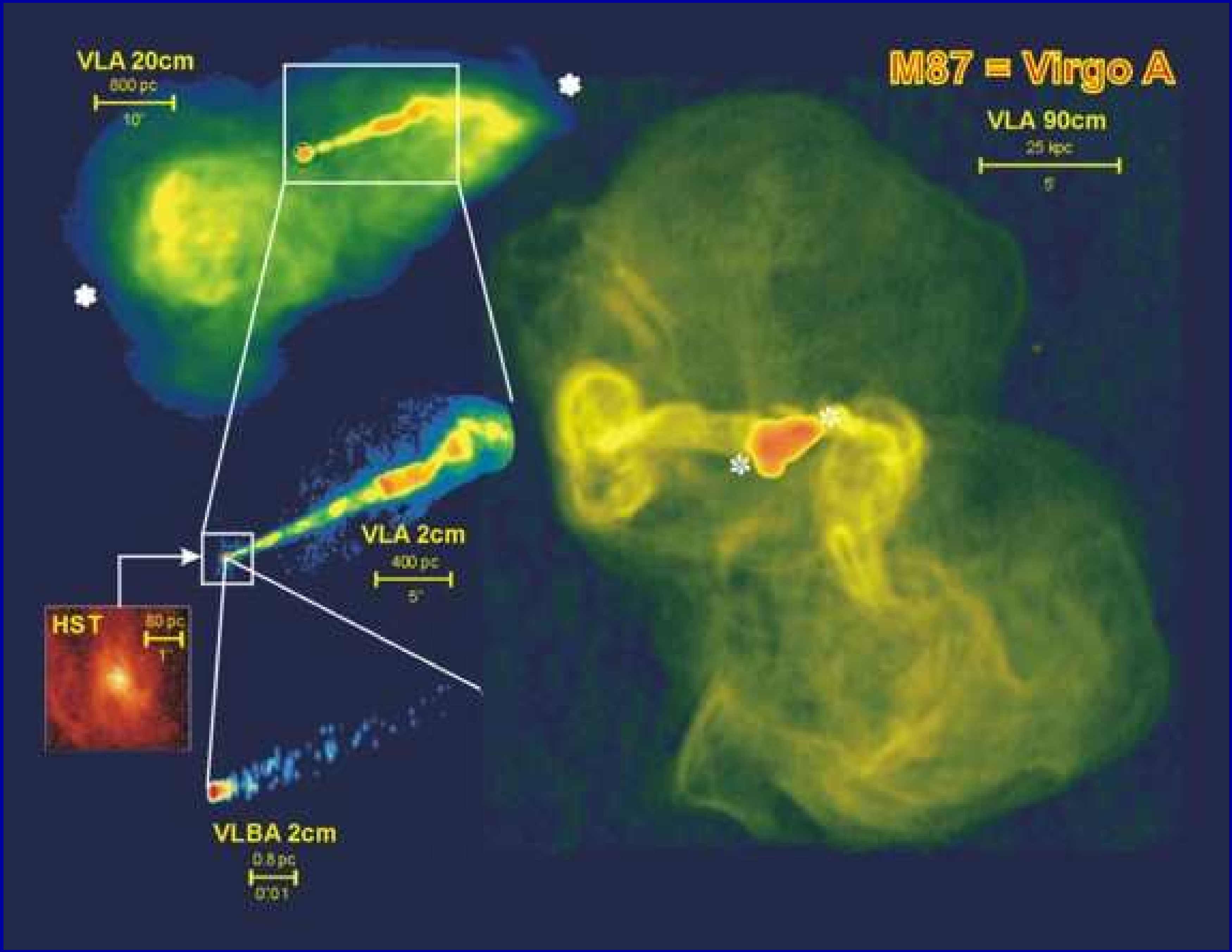


Fig. 7.1. Montage of scales exhibiting some effects of accretion onto a black hole over 12 successive decades of radius ranging from ~ 1Mpc to ~ 3×10^{13}cm. This is scaled to a black hole of mass ~ $10^8 M_\odot$. We comment upon the individual frames in the text.

Affect surroundings over 12 dex in size: from AU to Mpc scales (300 Mlyr),

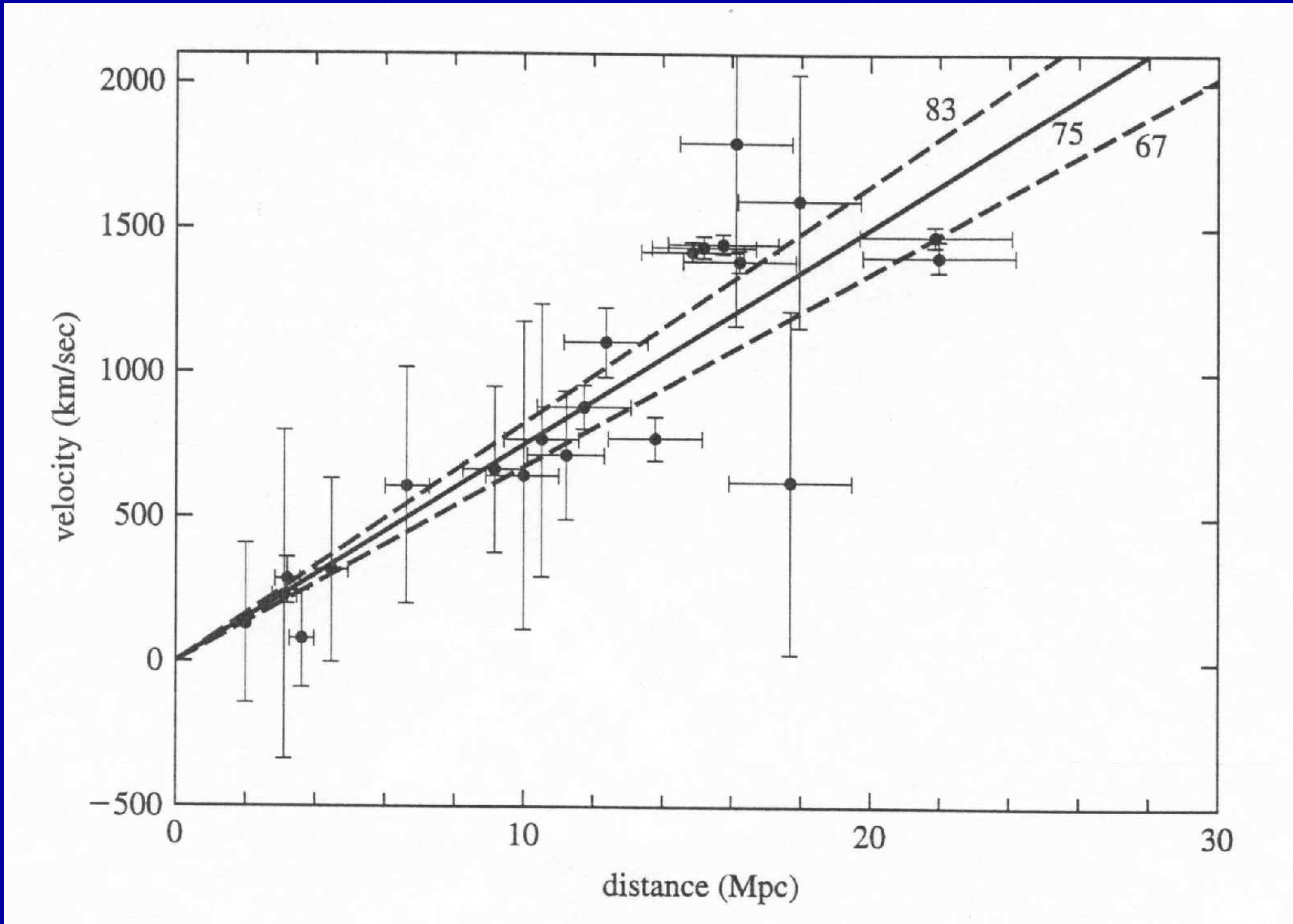
or from General Relativistic Singularity (AU) to Relativistic Jets (Mpc).

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



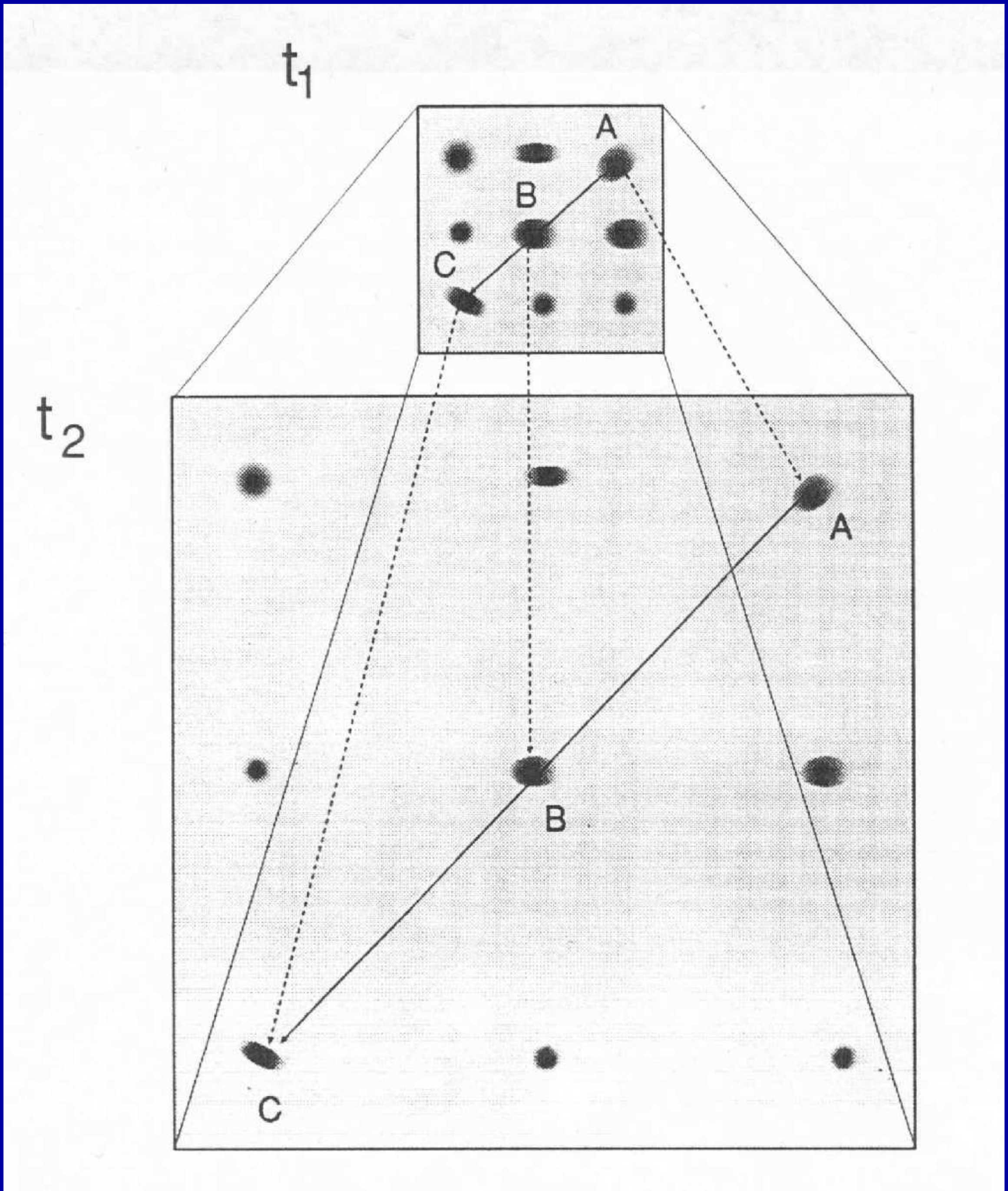
- VLA image of M87: Radio source stretches over a factor of 30,000 in size.
  - Supermassive Black-Hole powered sources are brightest in the universe.

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



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

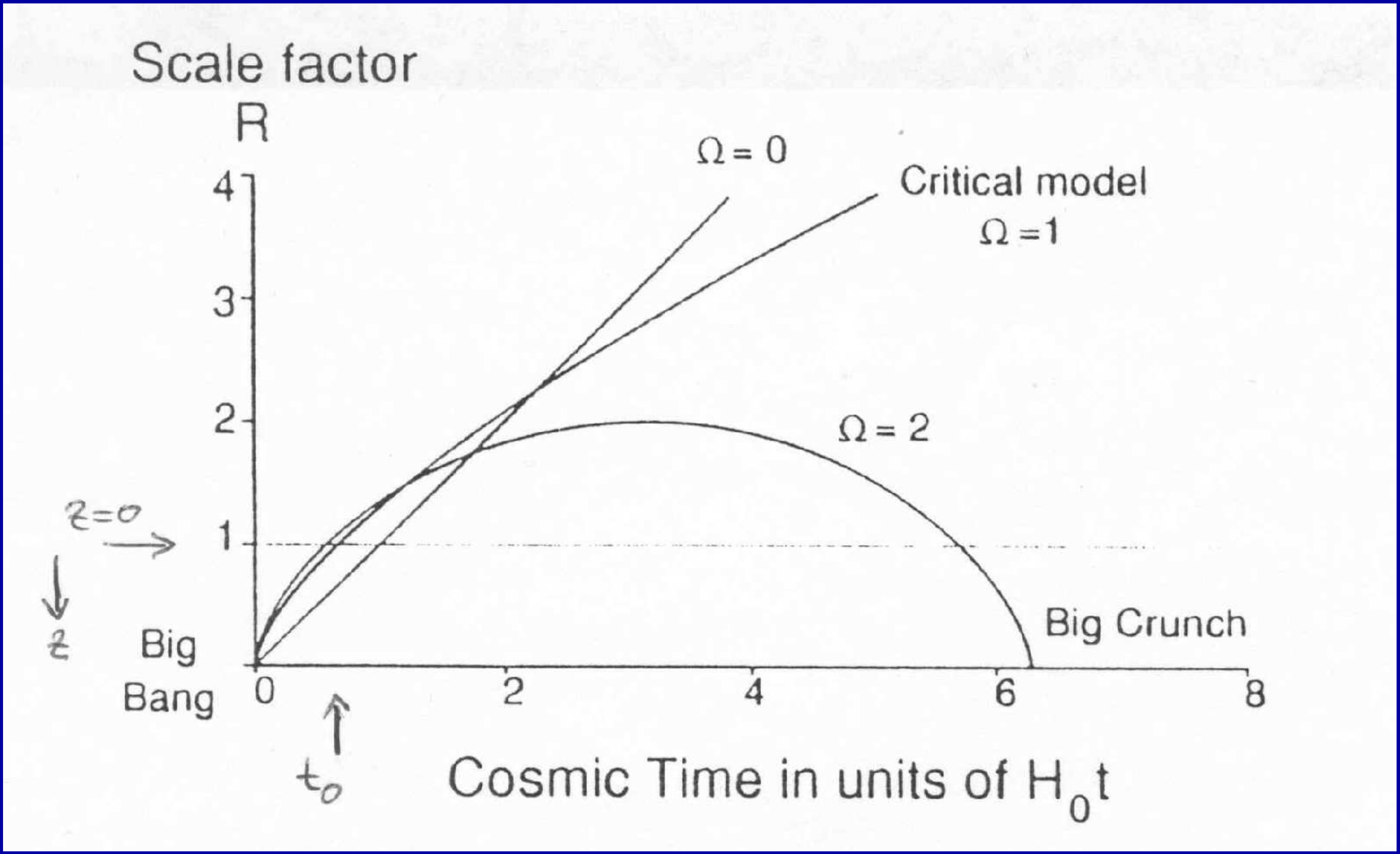
For H_0 = 71 km/s/Mpc, the Hubble time or Universe's Age = 13.7 Gyr.



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

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

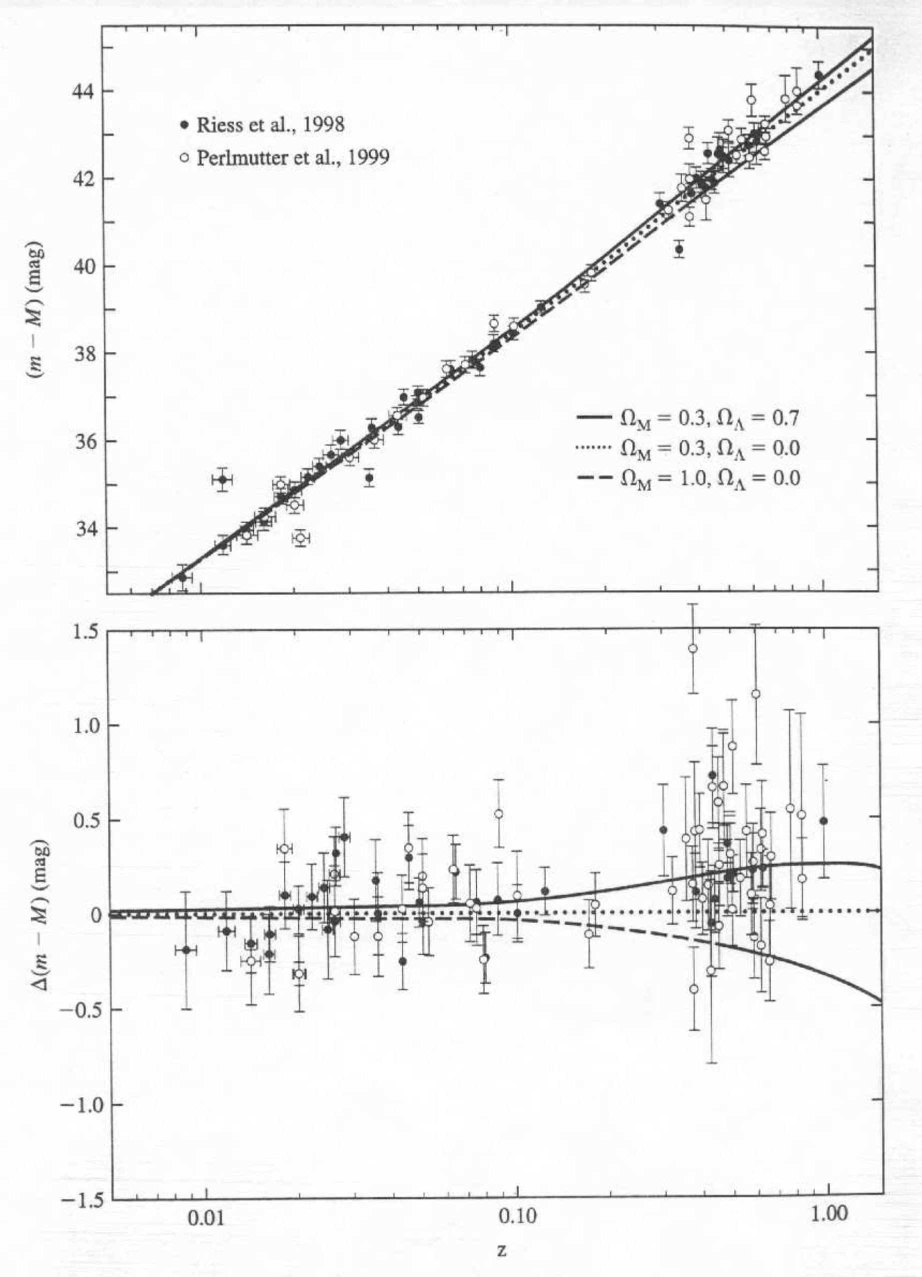
(1b) Hubble Expansion: Friedmann–Robertson-Walker models



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

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

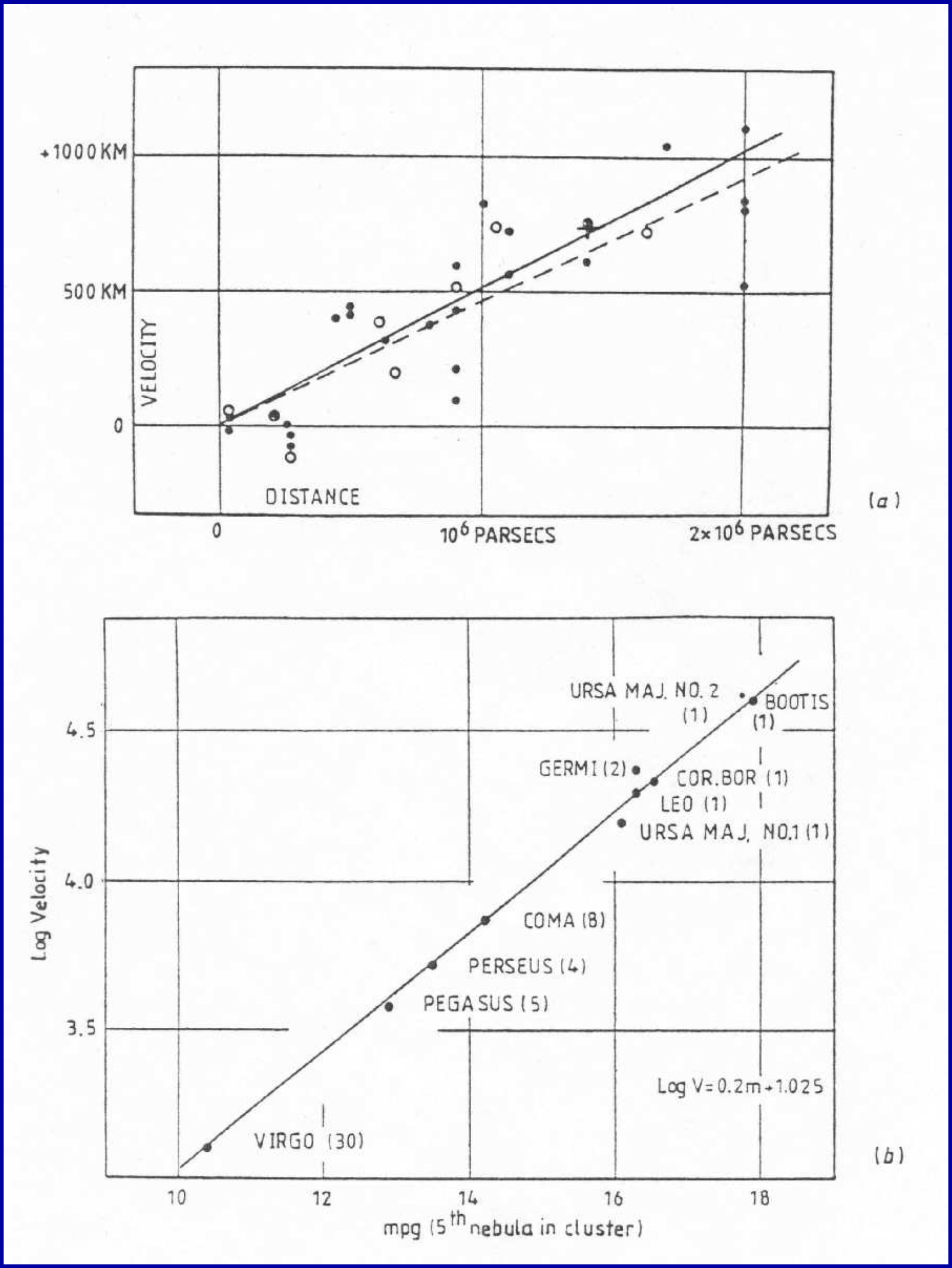
Mass-Energy density $\boldsymbol{\Omega} = \boldsymbol{\rho/\rho_{crit}}$ and $\boldsymbol{\rho_{crit}} = 10^{-29}$ gr/cm^3.



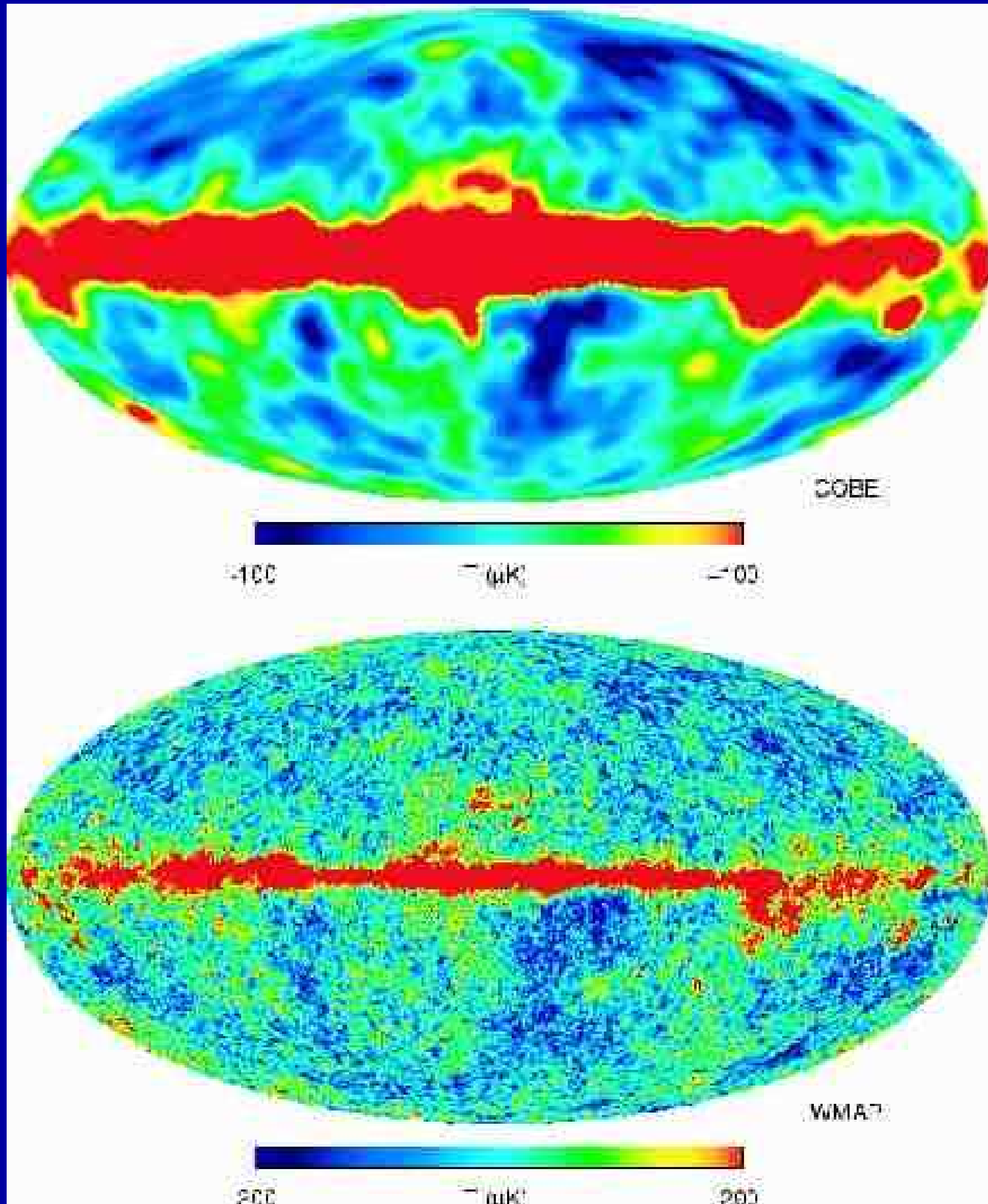
Type Ia Supernovae: Evidence for (exponentially) accelerated expansion:

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

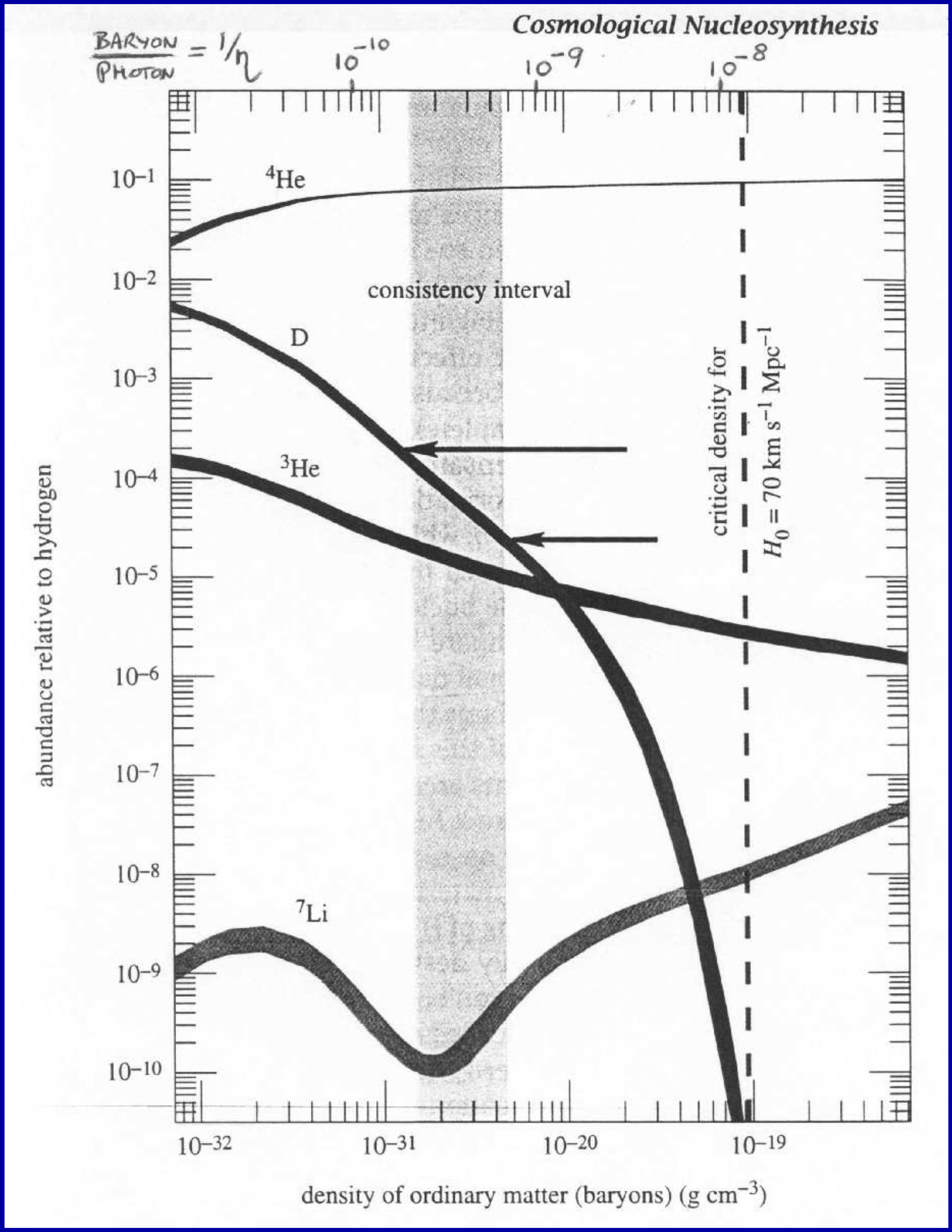
$\Longrightarrow$ Mary had a little Lambda (Einstein's Cosmological Constant Λ).



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



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



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

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

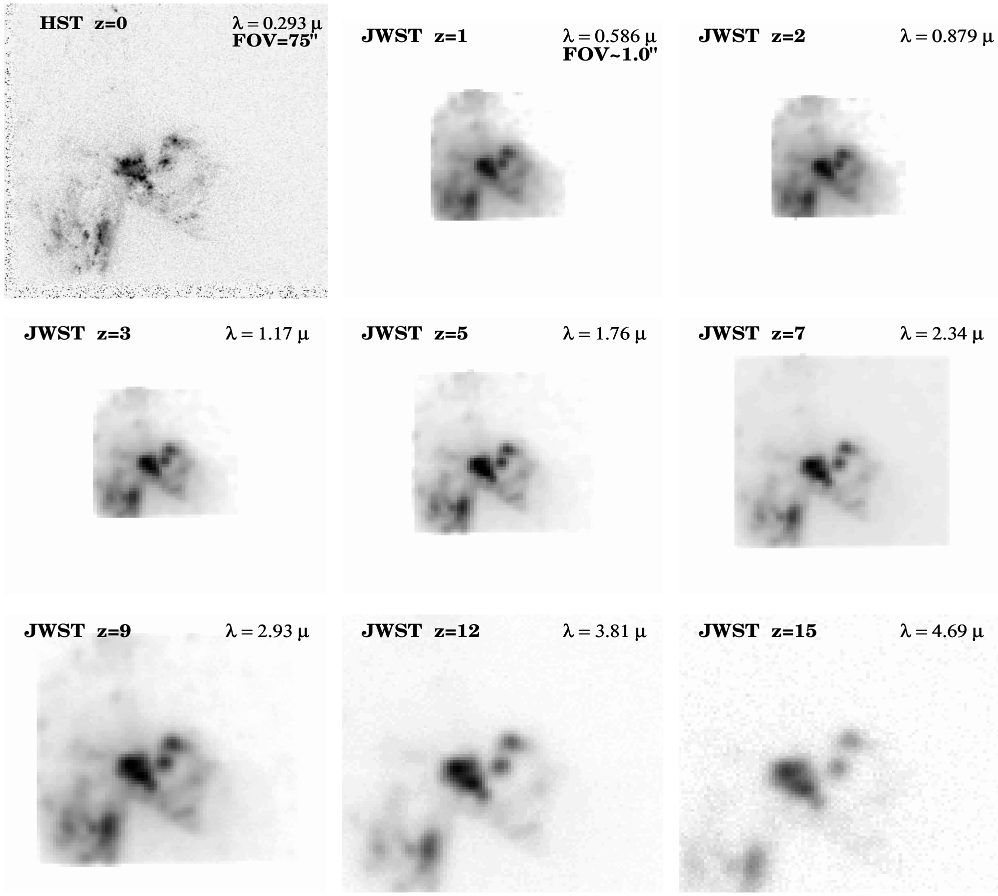


Fig. 4.06.c. JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). This is the BEST CASE JWST [meeting all GOALS, and t_{exp}=100 hrs]. The object is recognizable to z≃15.

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").

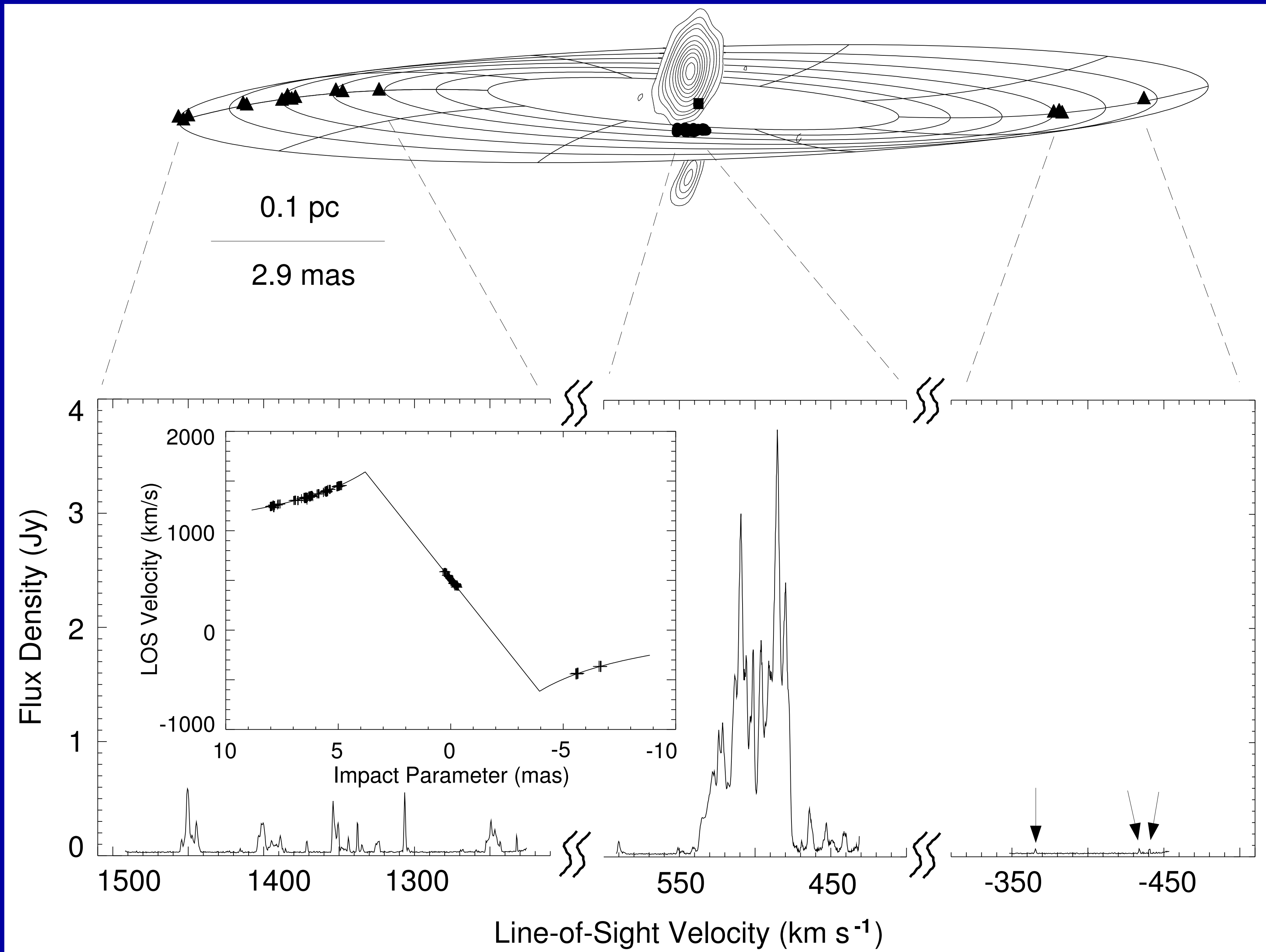
Row 1: z=0.0 (HST λ=0.293μm, FWHM=0.04″), z=1.0 (JWST λ=0.586μm, FWHM=0.084″), and z=2.0 (JWST λ=0.879μm, FWHM=0.084″). **Row 2:** z=3.0 (JWST λ=1.17μm, FWHM=0.084″), z=5.0 (JWST λ=1.76μm, FWHM=0.084″), and z=7.0 (JWST λ=2.34μm, FWHM=0.098″). **Row 3:** z=9.0 (JWST λ=2.93μm, FWHM=0.122″), z=12.0 (JWST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

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).