The "Standard" Model of Cosmology … and Open Questions

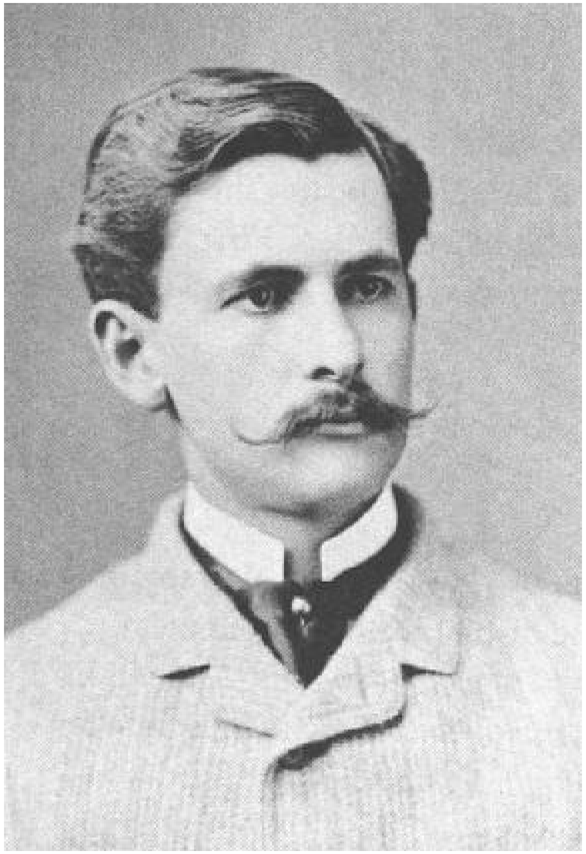
Bharat Ratra Kansas State University

Indian Institute of Technology Madras Monday August 13, 2018

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

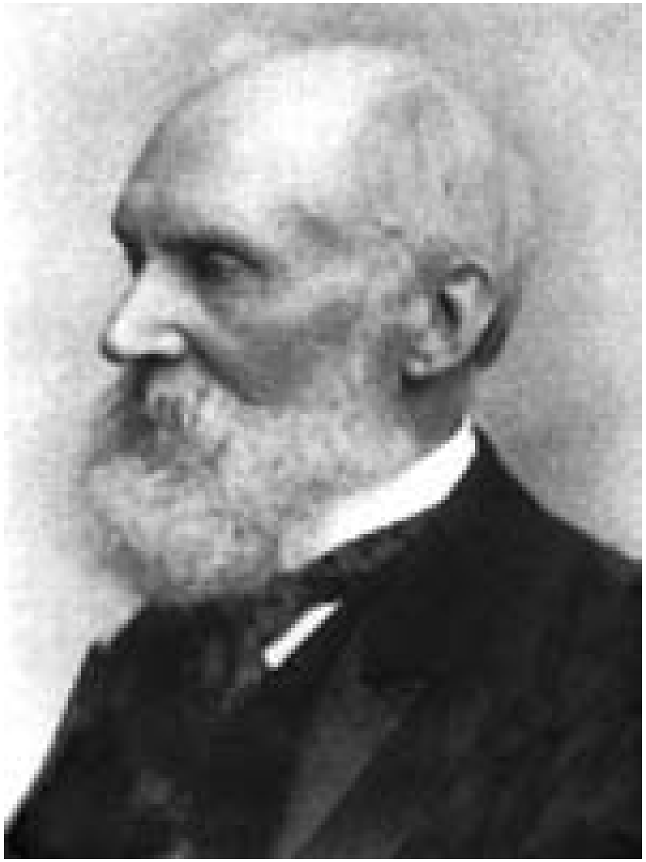
By no means is cosmology “solved”

…while not perfect, I do not think we are fooling ourselves about the gross validity of the “standard” model of cosmology, as has sometimes happened in the past …



The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote … Future discoveries must be looked for in the sixth place of decimals.

A. A. Michelson (1894)



There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.*

William Thomson,

Baron Kelvin (1900)

*He did discuss the aether and ultraviolet catastrophe issues.

meanwhile ….

Blackbody radiation, Planck (1900)

Photoelectric effect, Einstein (1905)

Atomic structure, Rutherford (1910), Bohr (1913)

Quantum mechanics, De Broglie, Bose, Pauli, Heisenberg, Born & Jordan, Uhlenbeck & Goudsmit, Dirac, Schrodinger, Fermi, Davisson & Germer (1923-1927)

Special relativity, Einstein (1905)

General relativity, Einstein (1916)

which led to …

Condensed matter physics, Einstein solid (1907)

AMO physics, Bohr atom (1913)

Astrophysics, Chandrasekhar white dwarf (1931)

Quantum electrodynamics (Tomonaga, Schwinger, Feynman 1940's)

Standard model of particle physics (1960's & 1970's)

… and now …

"Standard" hot big bang model of cosmology (2020's)

Main contributors to the present cosmological energy budget :

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

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

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

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

Outline

cosmology 101 (observations, theory)

inflation in the early universe

formation of structure in the radiation and matter fields

open questions

Hot Big Bang Cosmology: Late-Time, Large-Scale Dynamics of Spacetime, Matter and Radiation

1 pc = 3.26 ly = 3.1×10^{18} cm

Galaxies, radii ~ $10^{1\pm1}$ kpc ~ $10^{23\pm1}$ cm

Clusters of galaxies, radii ~ few Mpc

Superclusters, etc.

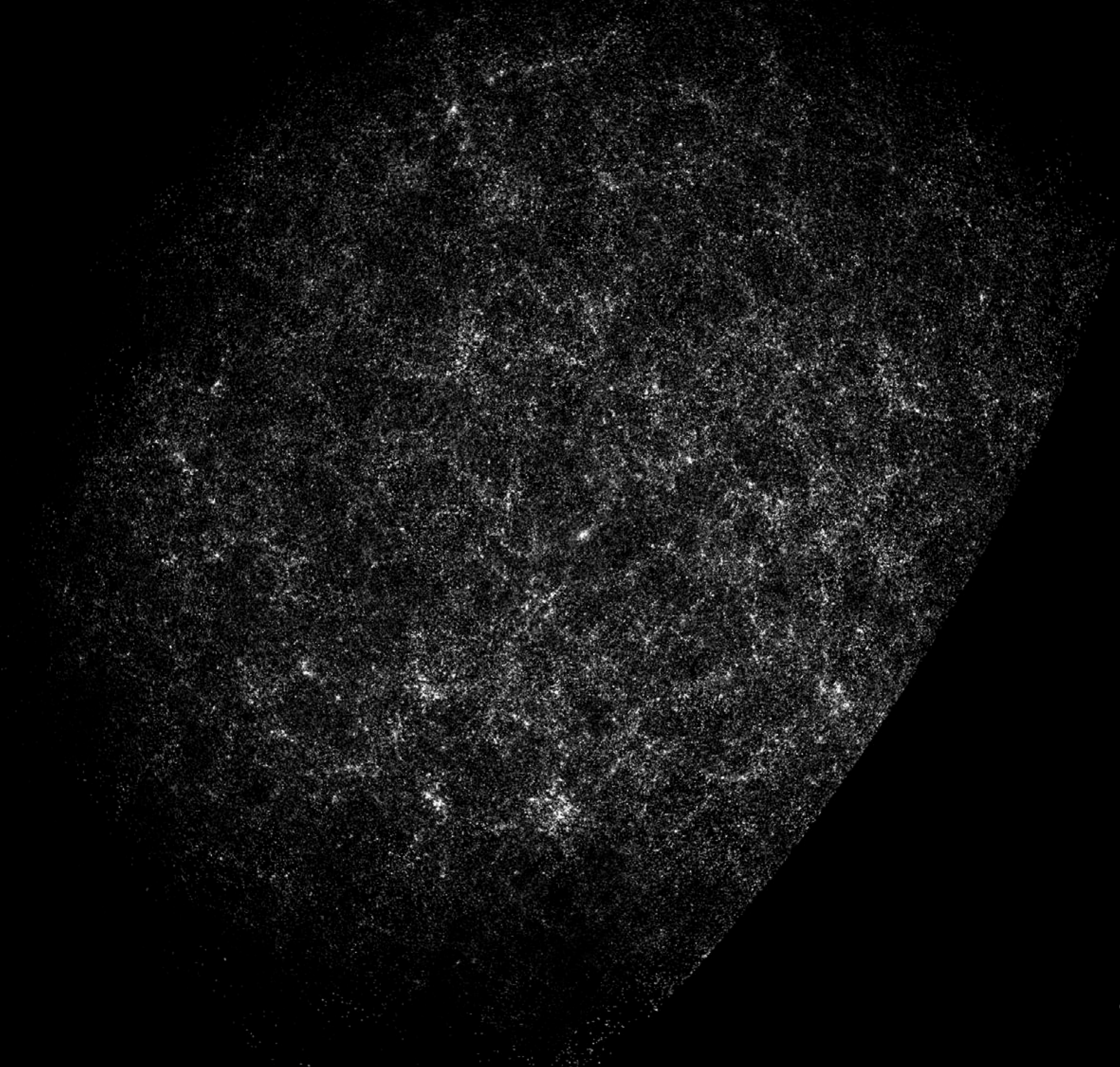
Hubble length ~ few Gpc

Lick Observat. (Shane & Wirtanen) optical galaxy counts.

400,000 galaxies, centered at NGP.

300 Mpc across.

Map is by Seldner et al.



Local distribution of matter is spatially anisotropic.

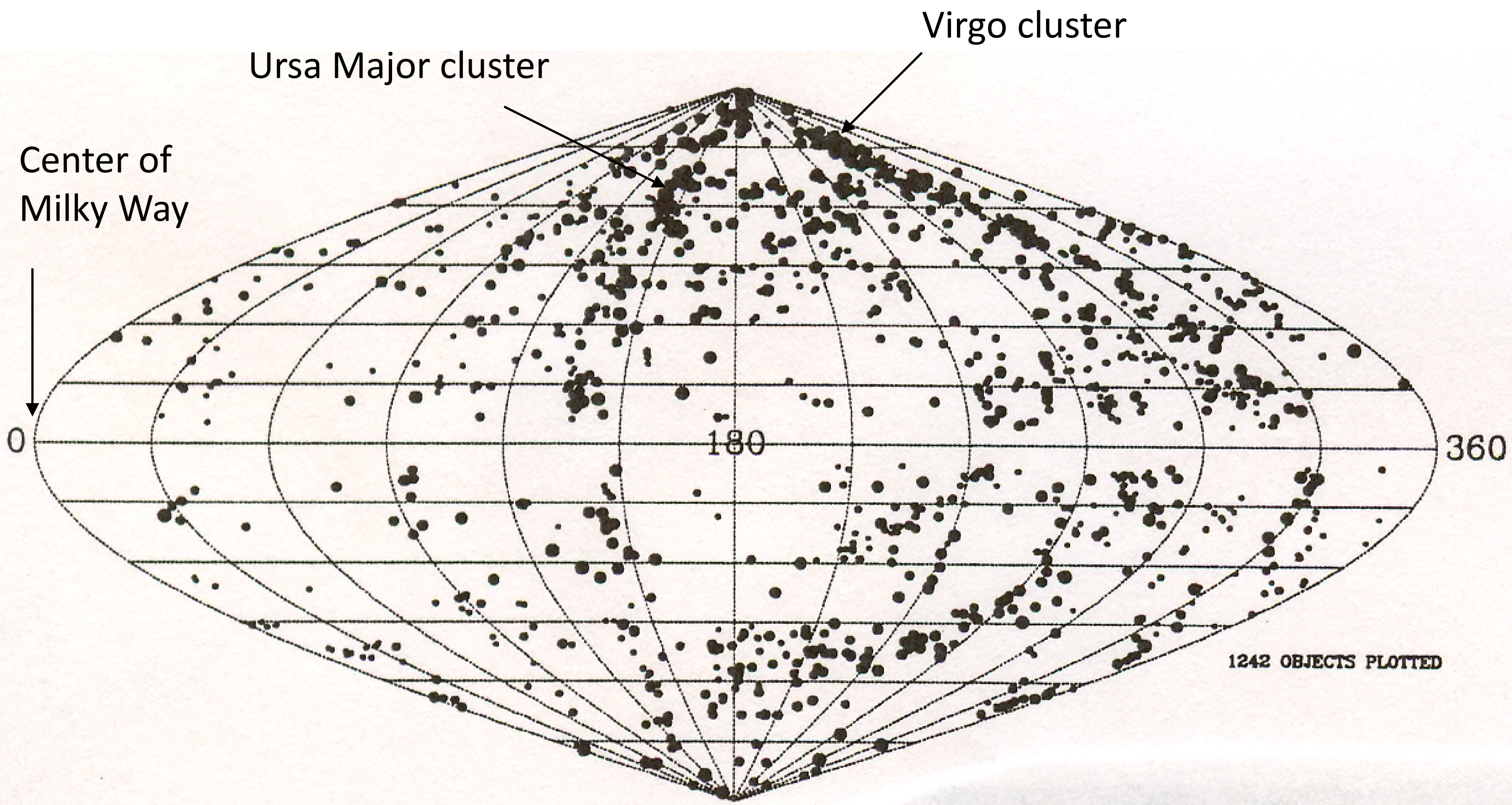
Averaged large-scale distribution of matter is (statistically) spatially isotropic.

Spatial anisotropy bounds:

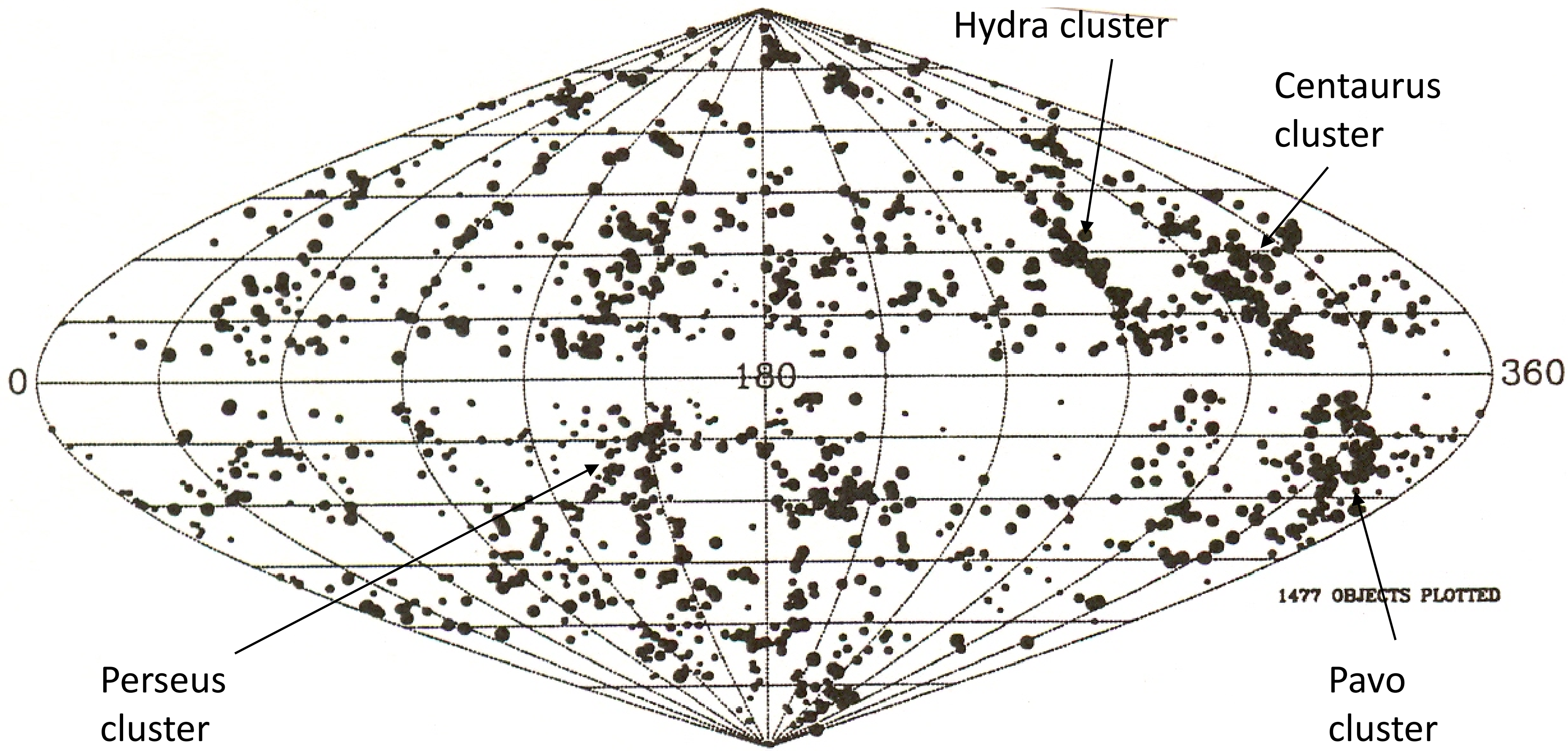
< 10% on ~ 50 – 100 Mpc from large-scale flows

< 10^{-5} on ~ few Gpc from the CMB

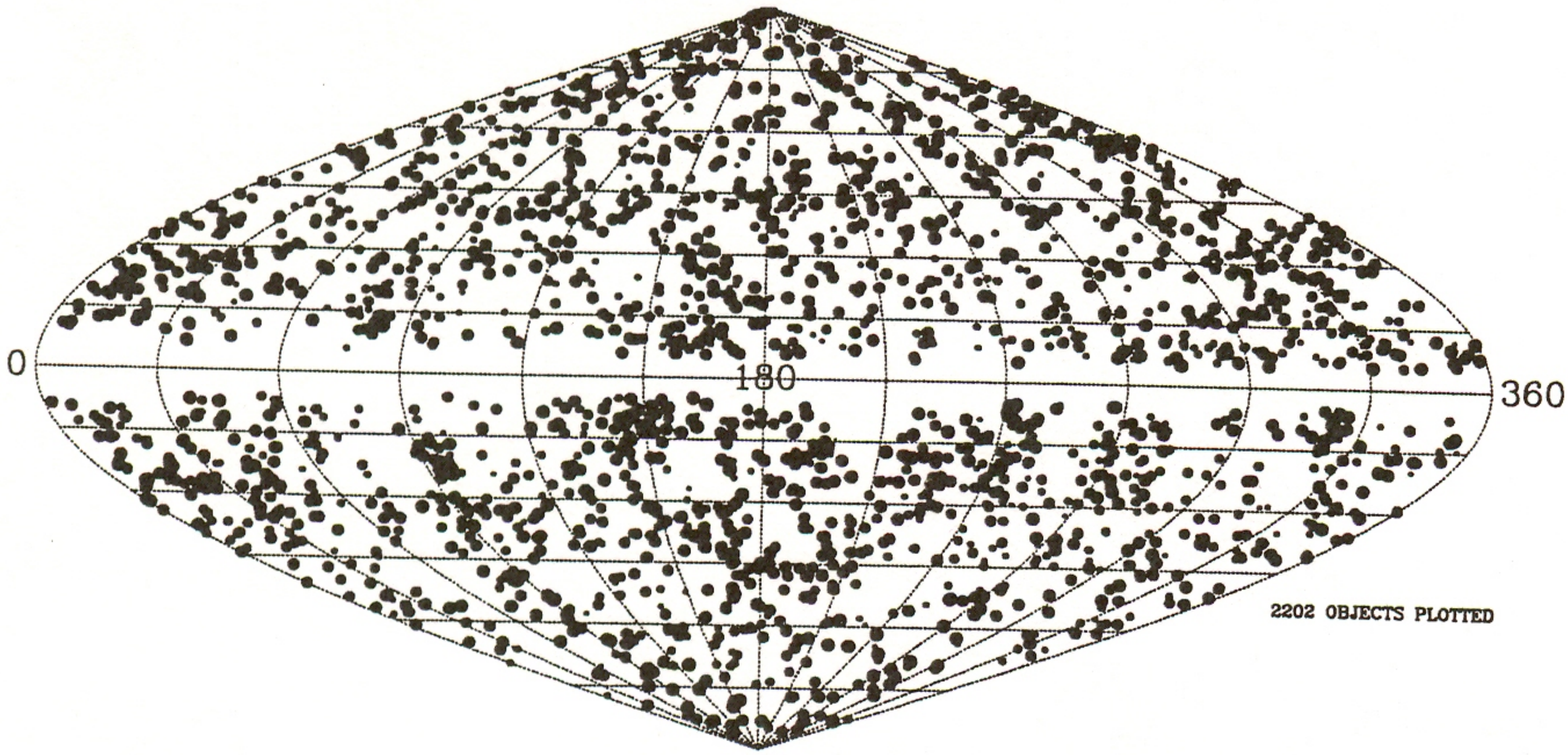
So, following Copernicus (our position is not special), we postulate that the averaged large-scale distribution of matter is (statistically) spatially homogeneous.



Infrared bright IRAS galaxies within ~45 Mpc of us.
Smaller symbols represent more distant galaxies.

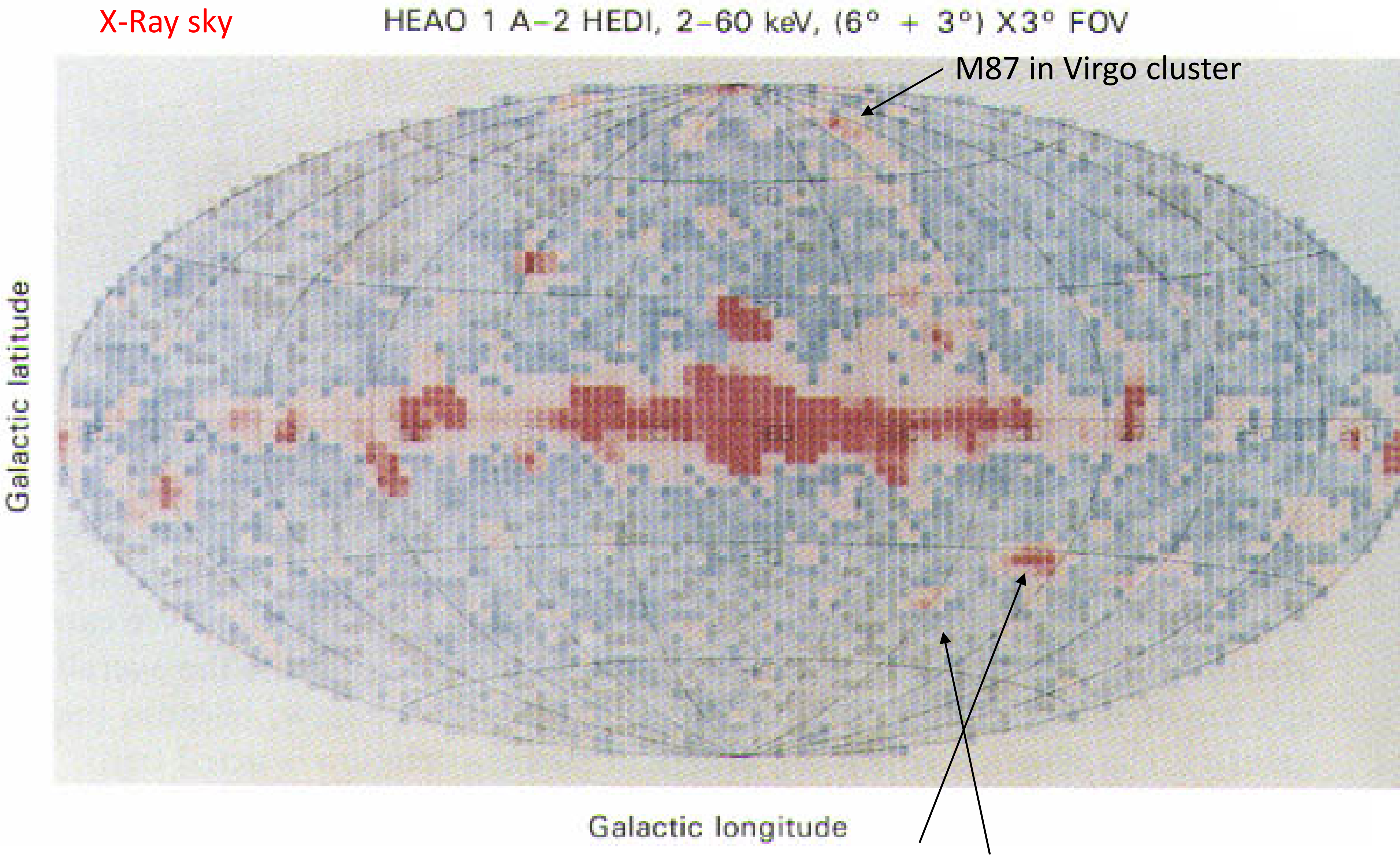


Infrared bright IRAS galaxies between ~45 Mpc and ~90 Mpc from us.



Infrared bright IRAS galaxies between ~90 Mpc and ~300 Mpc from us.

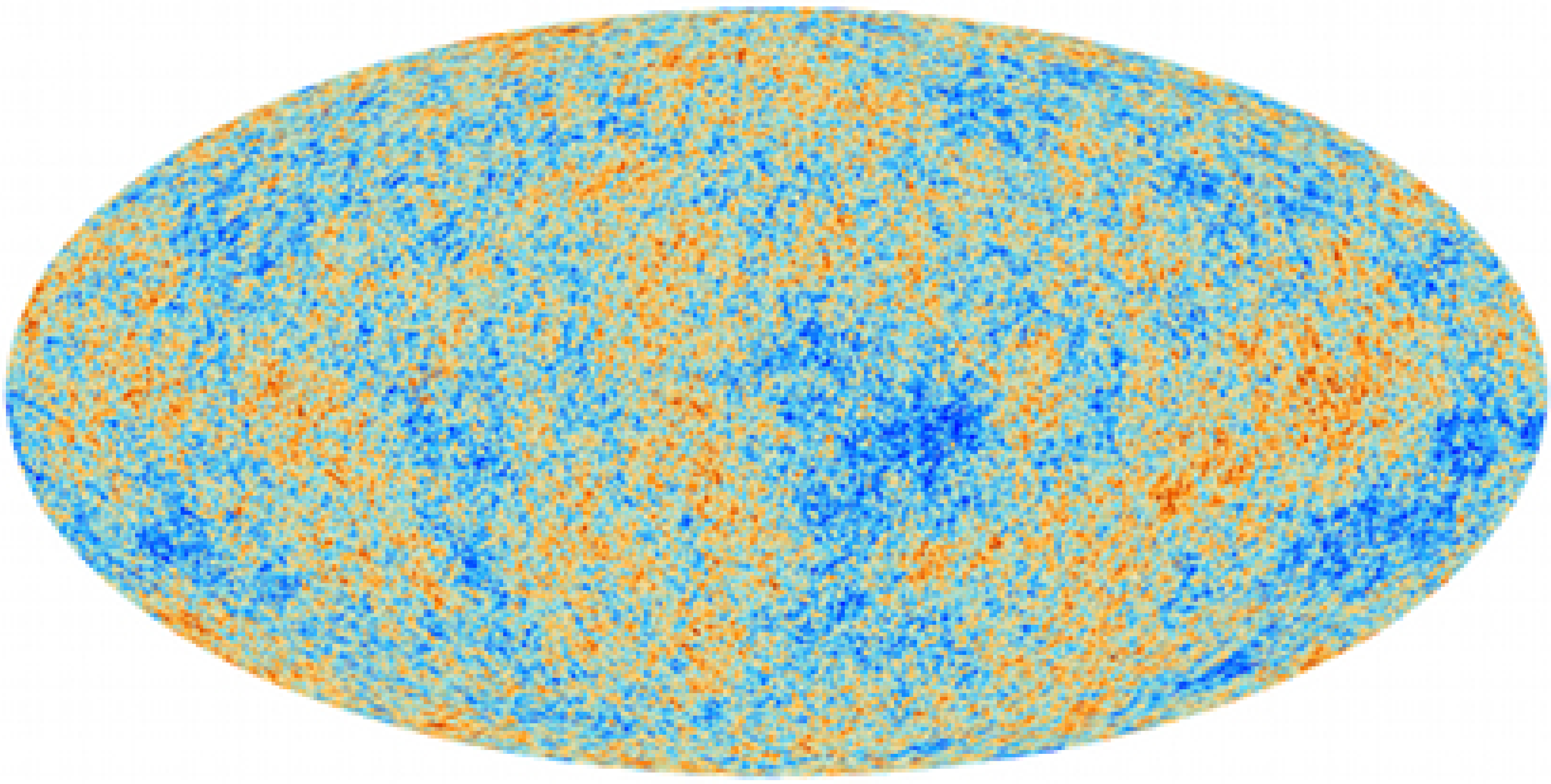
X-Ray sky



Local sources are in the plane of the Milky Way, and the LMC, SMC, M87 in Virgo.

Between the red patches, out to 4000 Mpc, the XRB is smooth to 0.1%.

Planck cosmic microwave background radiation anisotropy.



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

Fact: local distribution of matter and radiation is spatially anisotropic.

How did this come about?

Fact: averaged large-scale distribution of matter and radiation is (statistically) spatially isotropic.

How did this come about?

Fact: the universe expands.

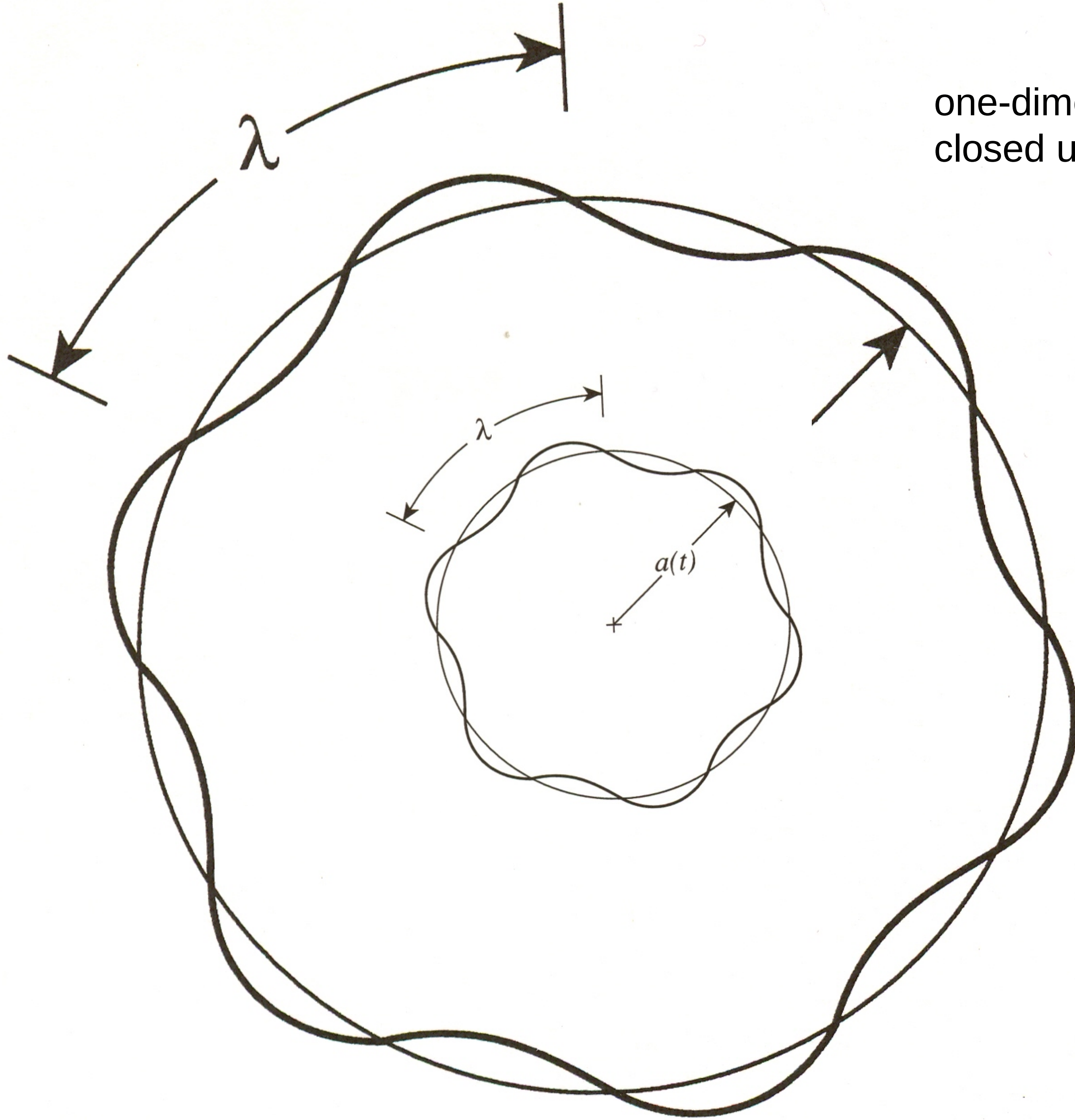
Consider a wave propagating in a one-dimensional expanding universe. For adiabatic expansion the wavelength must expand with scalefactor, $\lambda \sim a(t)$ (redshifting). Redshift z: $1 + z = a_{now}/a(t)$.

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

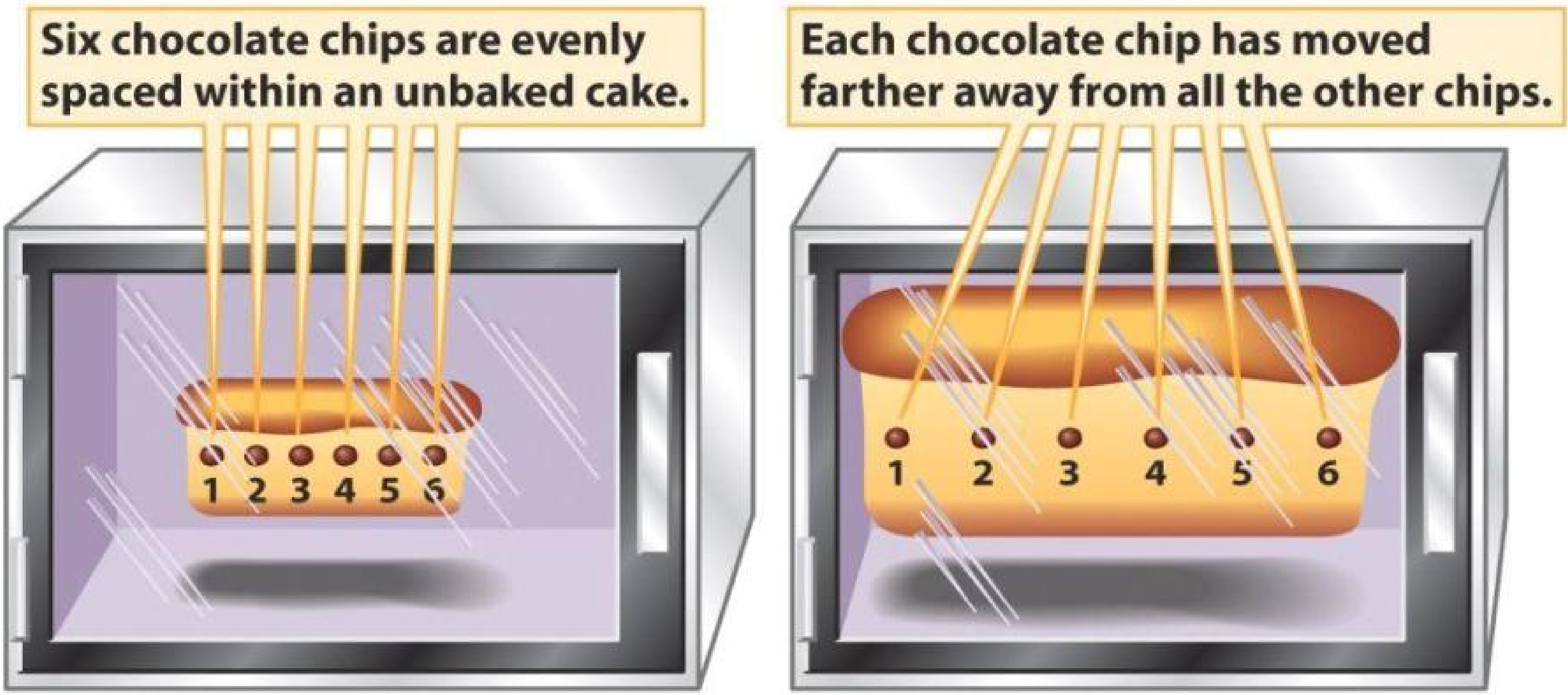
Slipher* discovered the redshifting in 1912.

*Indirectly motivated by the idea of a Martian civilization!

one-dimensional
closed universe



three-dimensional flat universe



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

Freedman and Kaufmann

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

$$v = H_0 \, r$$

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

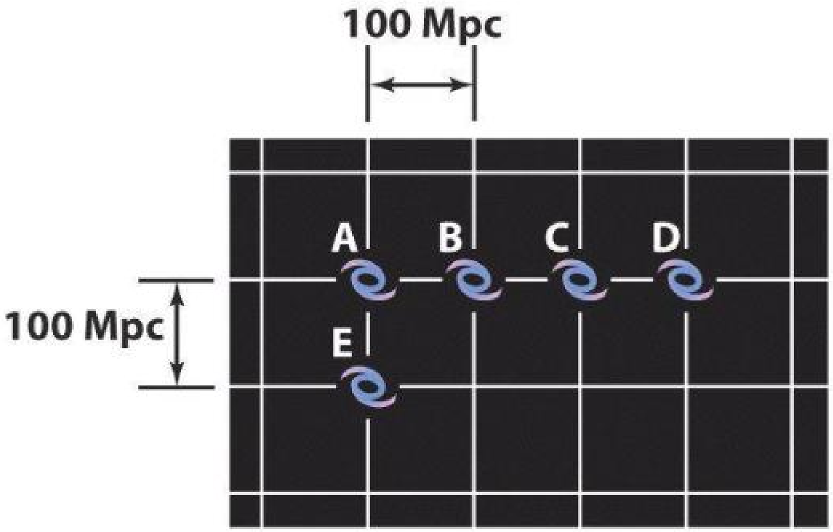
H_0 = Hubble constant = (68 ± 2.8) km s^{-1} Mpc^{-1}

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

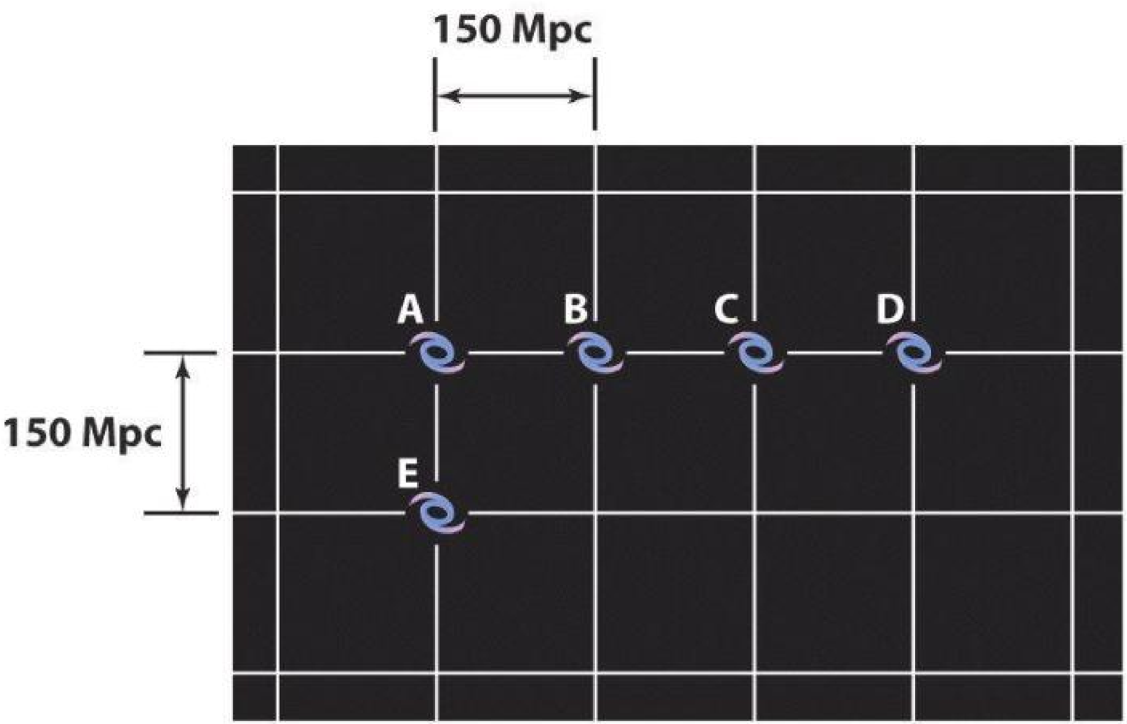
H_0 is the present value of the Hubble parameter.

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

*Middle school dropout and one time muleskinner and janitor.



(a) Five galaxies spaced 100 Mpc apart



(b) The expansion of the universe spreads the galaxies apart

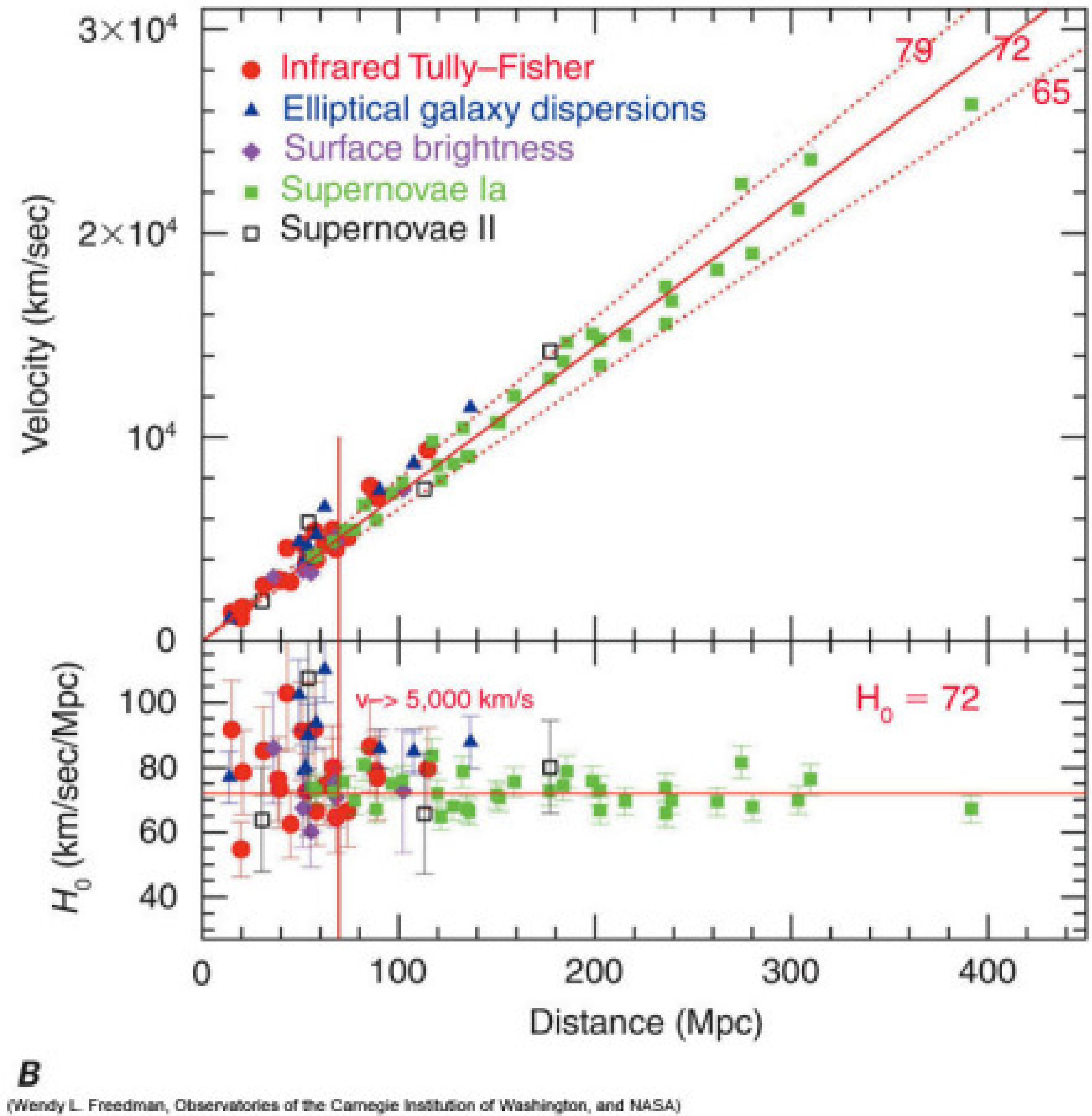
two-dimensional flat universe

	original	final	change
A-B	100	150	50
A-C	200	300	100
A-D	300	450	150
A-E	100	150	50

all distances in Mpc

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

Freedman and Kaufmann



Hubble law

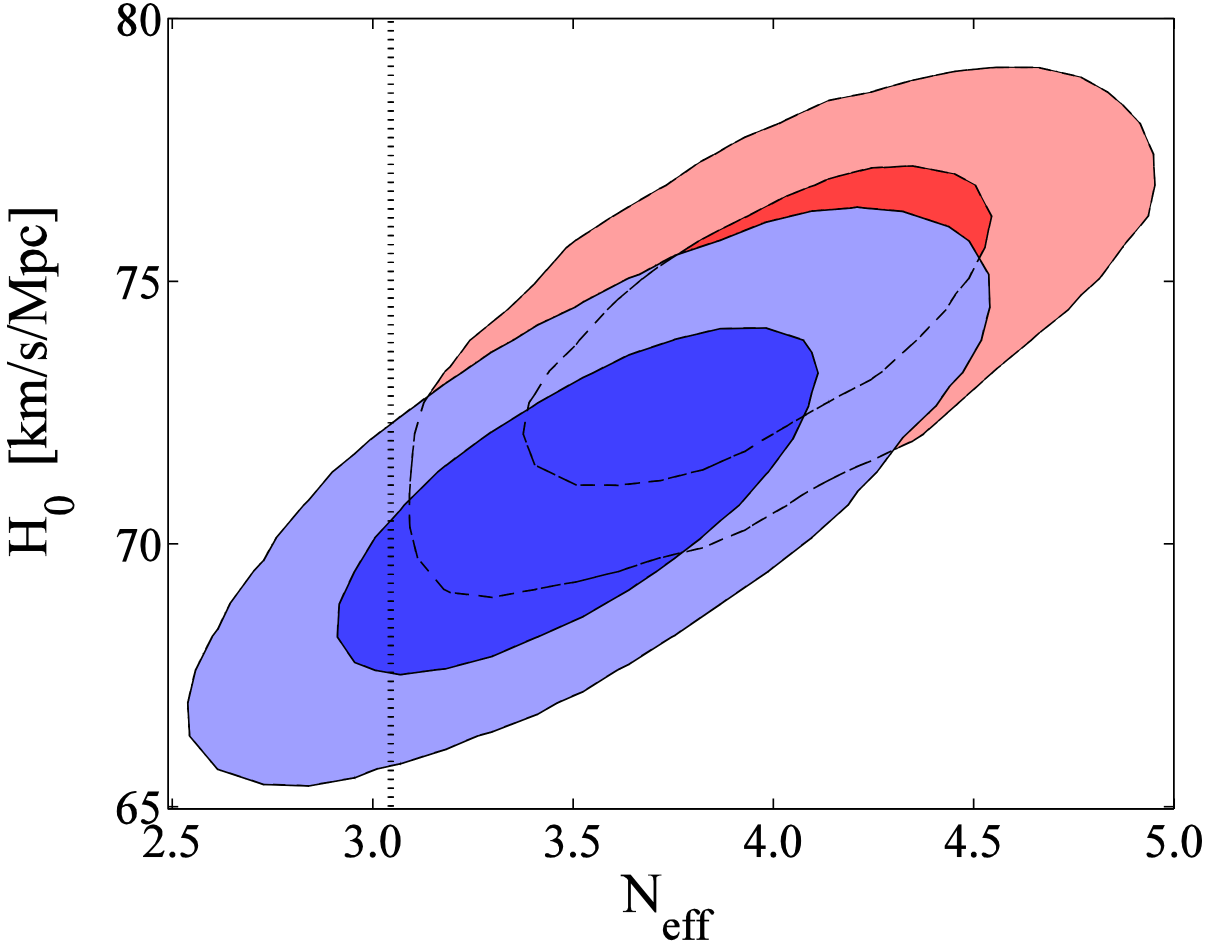
H_0 = Hubble constant

= (68 ± 2.8) km s^{-1} Mpc^{-1}

= 100 h km s^{-1} Mpc^{-1}

Chen & Ratra PASP123,1127 (2011)

An aside: Large H_0 value forces consideration of dark radiation



Red contours
H_0 = (73.8 ± 2.4) km s^{-1} Mpc^{-1}
require dark radiation
Riess et al. ApJ730,119 (2011)

Blue contours
H_0 = (68 ± 2.8) km s^{-1} Mpc^{-1}
do not require dark radiation
Chen & Ratra PASP123,1127 (2011)

From WMAP7, ACBAR, ACT, SPT & SDSS-DR7

Calabrese et al. PRD86, 043520 (2012)

Cosmology thus re-introduces preferred observers, cosmological observers, locally at rest w.r.t. the expansion.

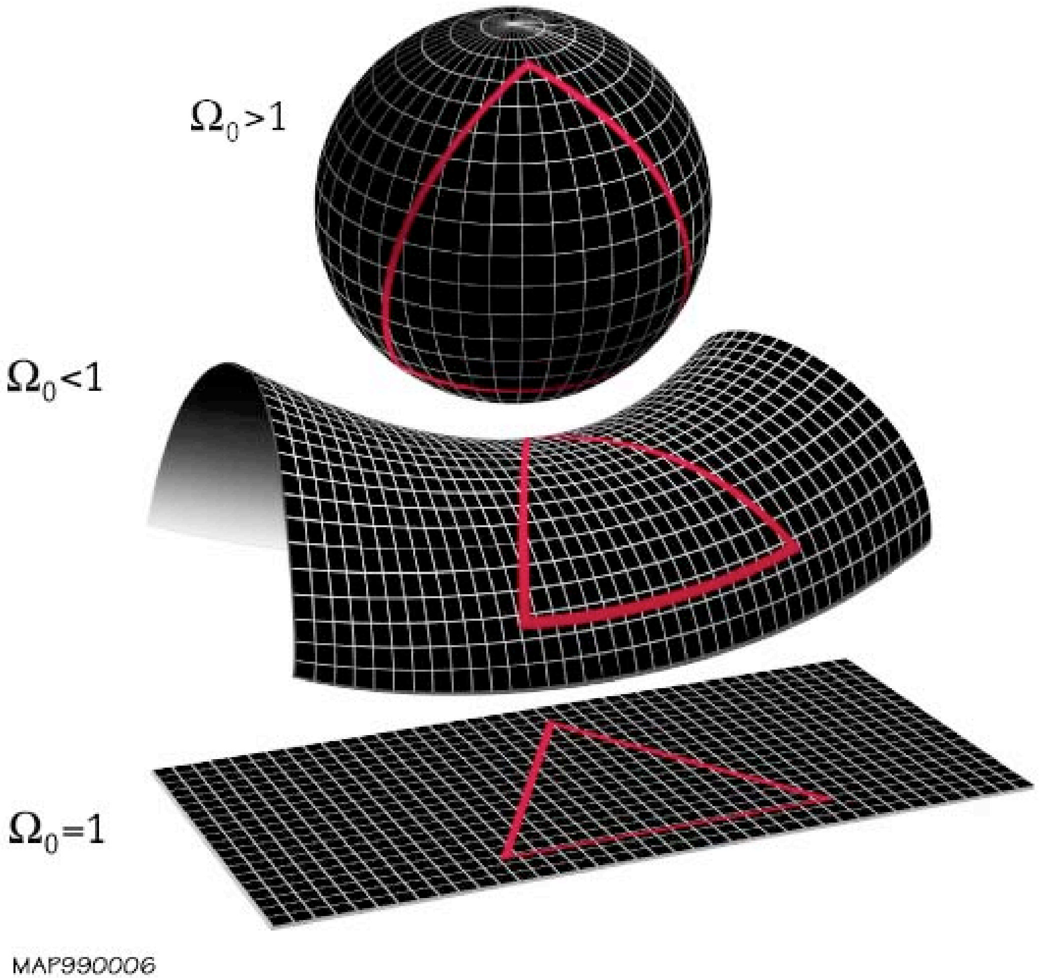
Cosmological Principle (assumption): the universe is (statistically) spatially isotropic for all cosmological observers.

This implies (statistical) spatial homogeneity.

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

$$ds^2 = dt^2 - a^2(t)\,[dr^2 + S_K{}^2(r)\,\{d\theta^2 + \sin^2(\theta)d\phi^2\}]$$

(2 dimensional analogs)



	$S_K(r)$	K^2
closed	sin(r)	>0
open	sinh(r)	<0
flat	r	=0

equations of motion (ideal fluid matter):

$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + \Lambda/3$ Einstein-Friedmann

$\dot{\rho} = -3\,(\dot{a}/a)\,(\rho + p)$ stress-energy conservation

$p = p(\rho)$ equation of state

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

Is this increasing or decreasing with time?

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

matter and radiation with $p > 0$ (Λ e.o.s. is $p = -\rho$)

$\Rightarrow \ddot{a} < 0$ decelerated expansion

Einstein-de Sitter mass density

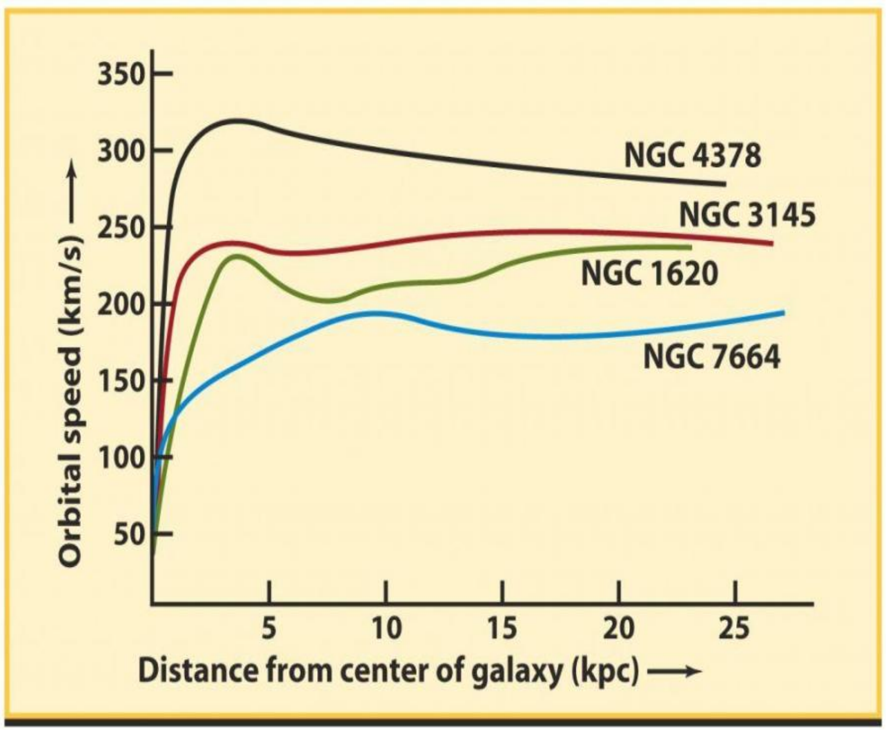
$$\rho_c = 3H^2/8\pi G = 1.9 \times 10^{-29}\, h^2\ \mathrm{g\ cm^{-3}}$$

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

Contents of the universe

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

Force balance (mass from dynamics) $v^2(r) = GM(r)/r$; on large scales where there is no optical light use 21cm hydrogen radiation: $0.20 \leq \Omega_{dyn} \leq 0.35$ (2σ)



(on few kpc to 10's of Mpc)

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

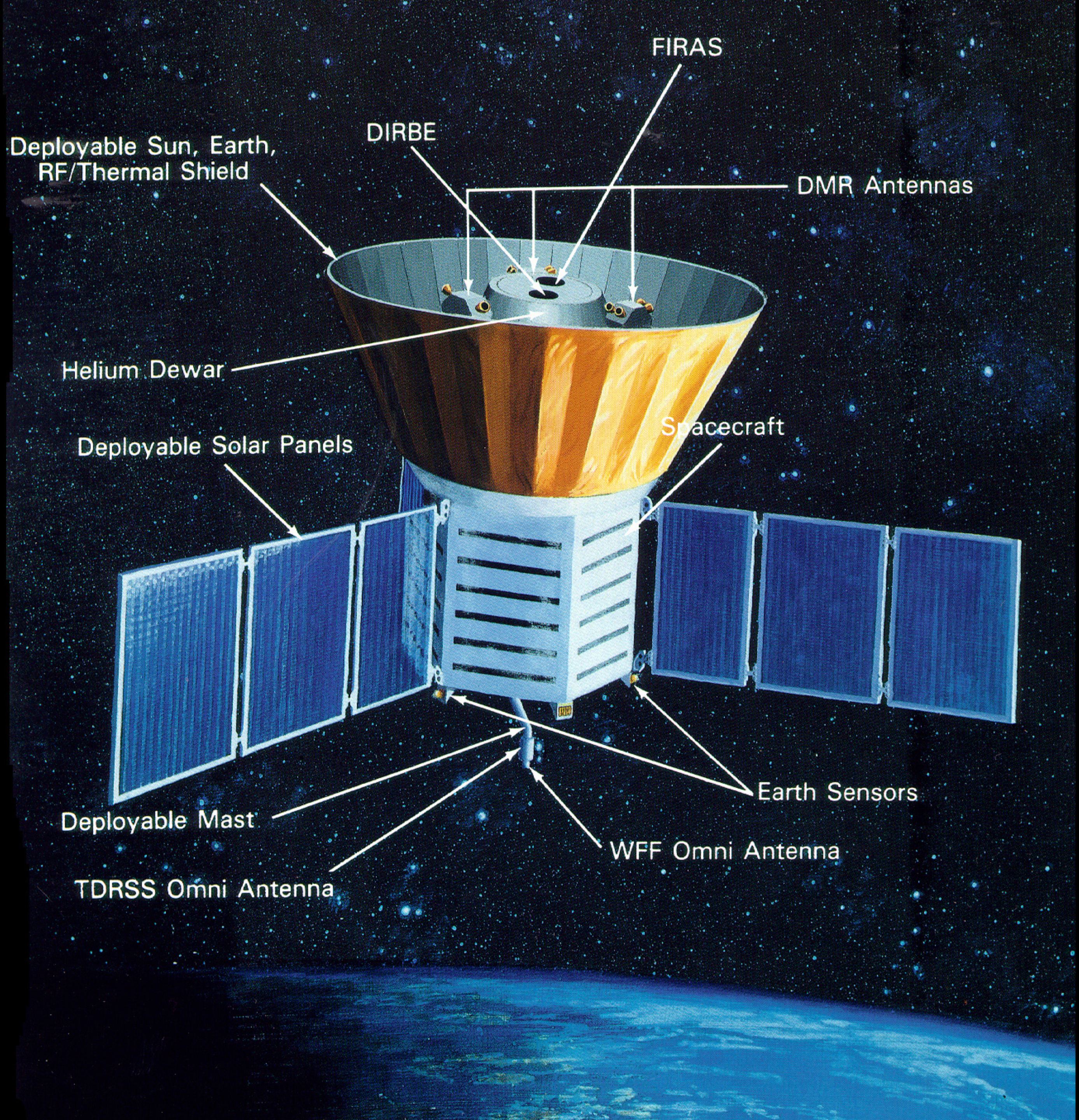
ρ_{dyn} = few X 10^{-30} g cm^{-3}

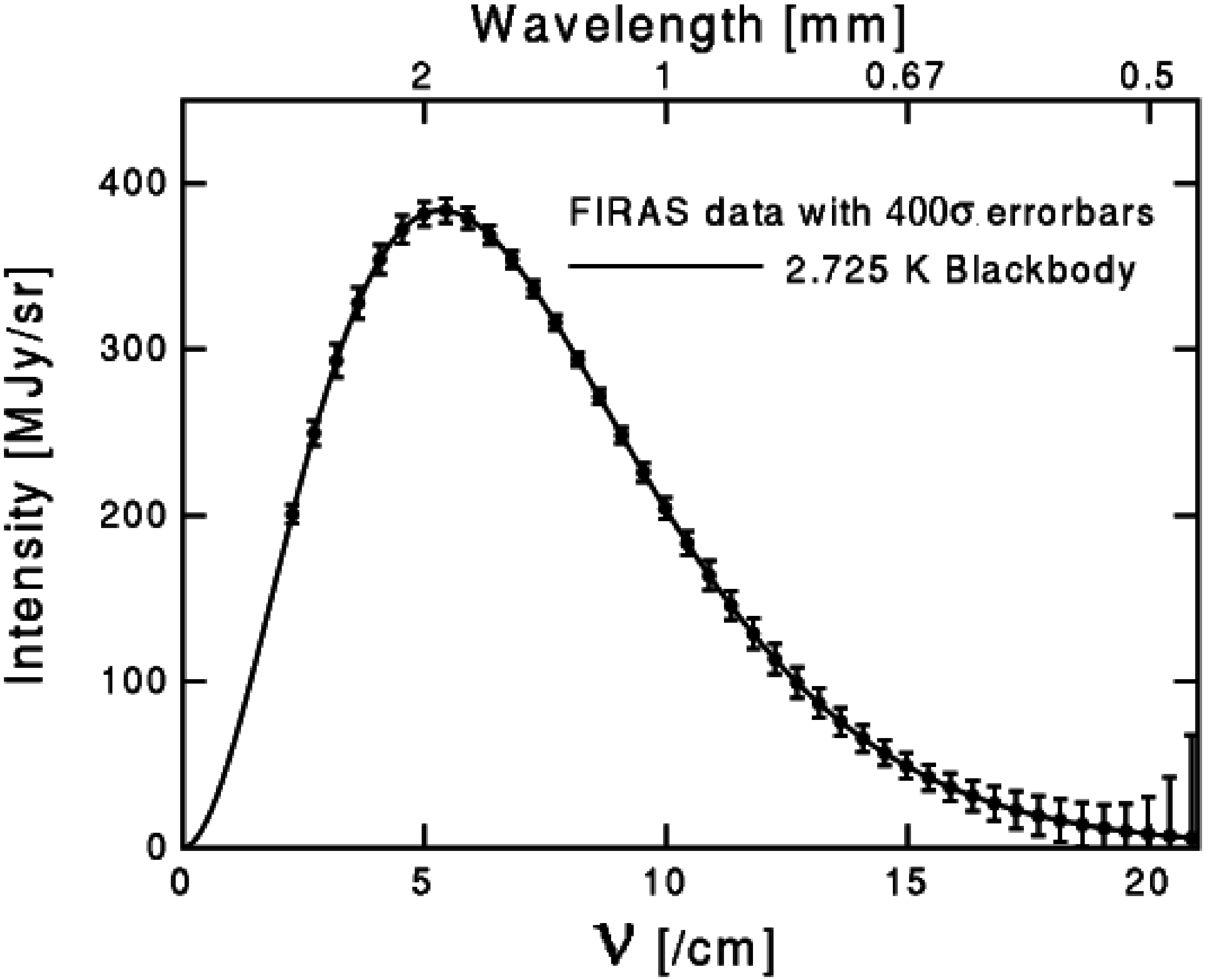
The universe was denser at earlier times.

Cosmic microwave black-body radiation background

Bell Labs horn antenna (for Echo satellite project) that resulted in the discovery of the cosmic microwave background radiation.

COBE


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



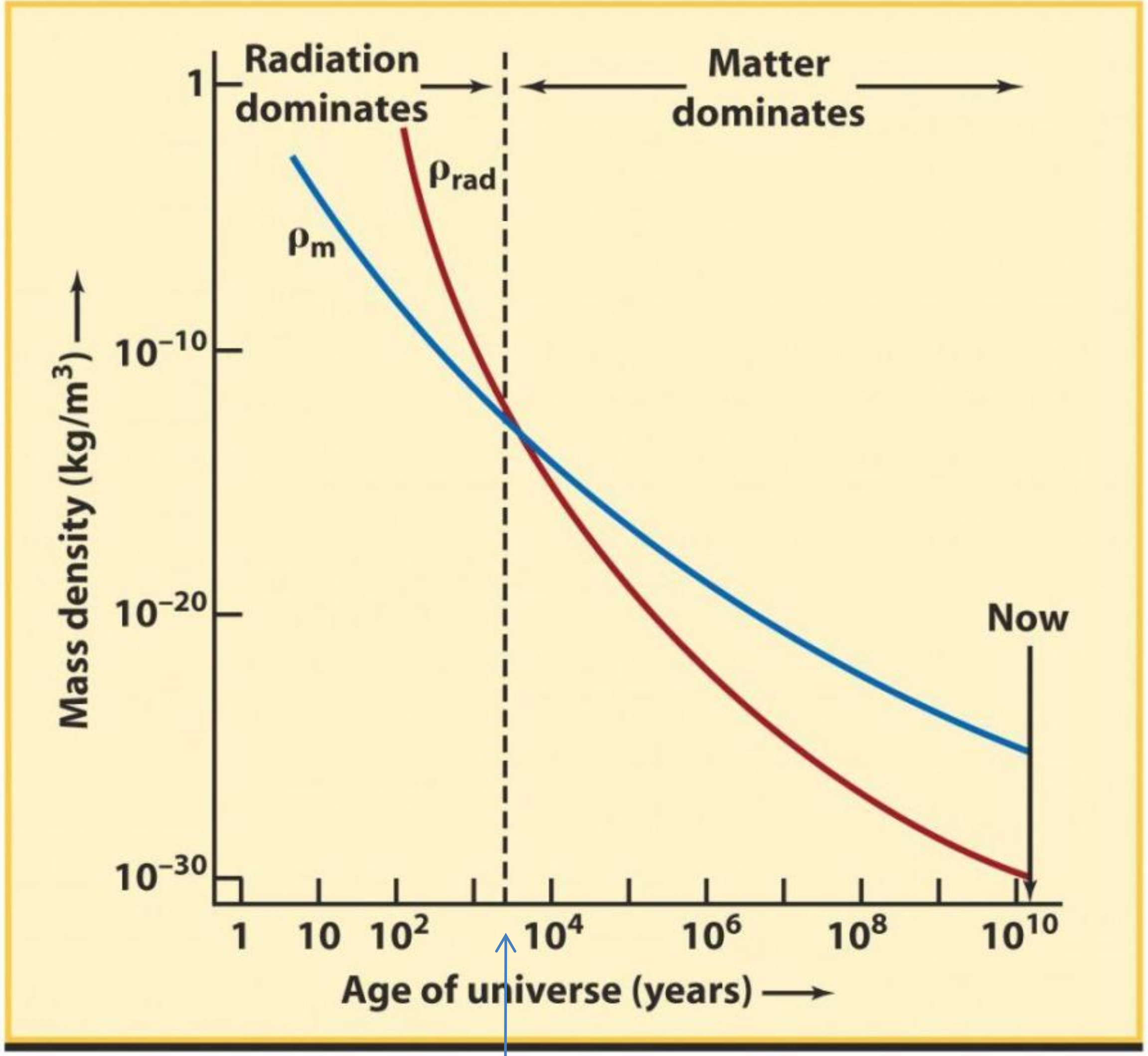
$\Omega_{rad} \sim 0.00005$

$\Omega_\nu \sim 0.001$ (massive ν's)

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

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

The universe was hotter at earlier times.



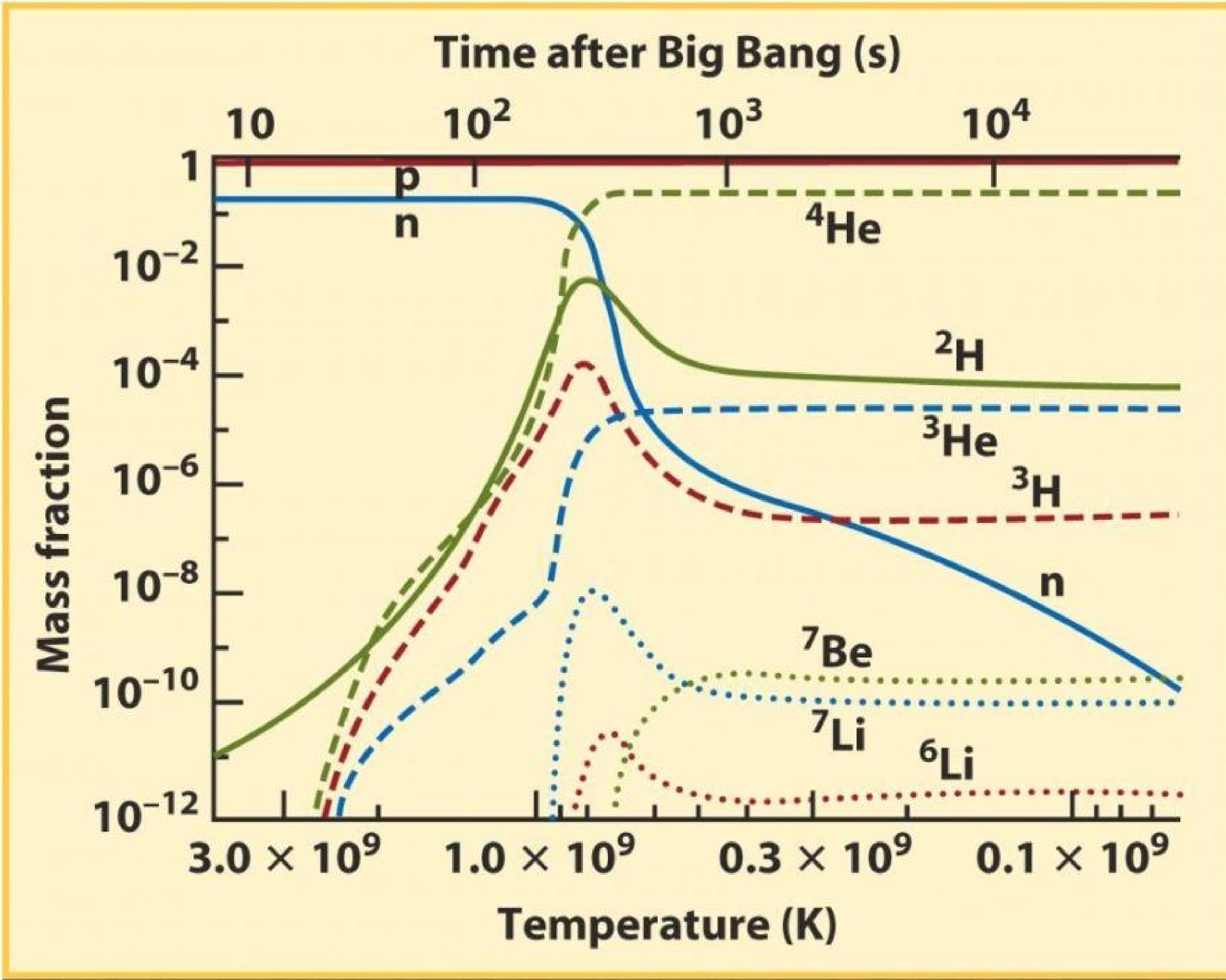
Ignoring dark energy for now, at earlier times radiation dominated and the universe was hot.

Fast weak interactions built up a thermal abundance of neutrons and protons at T ~ 1 MeV ~ 10^{10} K…..

Redshift of equal matter and radiation z_{eq} ~ 3000

Freedman and Kaufmann

...then the strong interactions built up the light nuclei.



$n + p \rightarrow {}^2H + \gamma$

${}^2H + n \rightarrow {}^3H + \gamma$

${}^2H + {}^2H \rightarrow {}^3H + p$

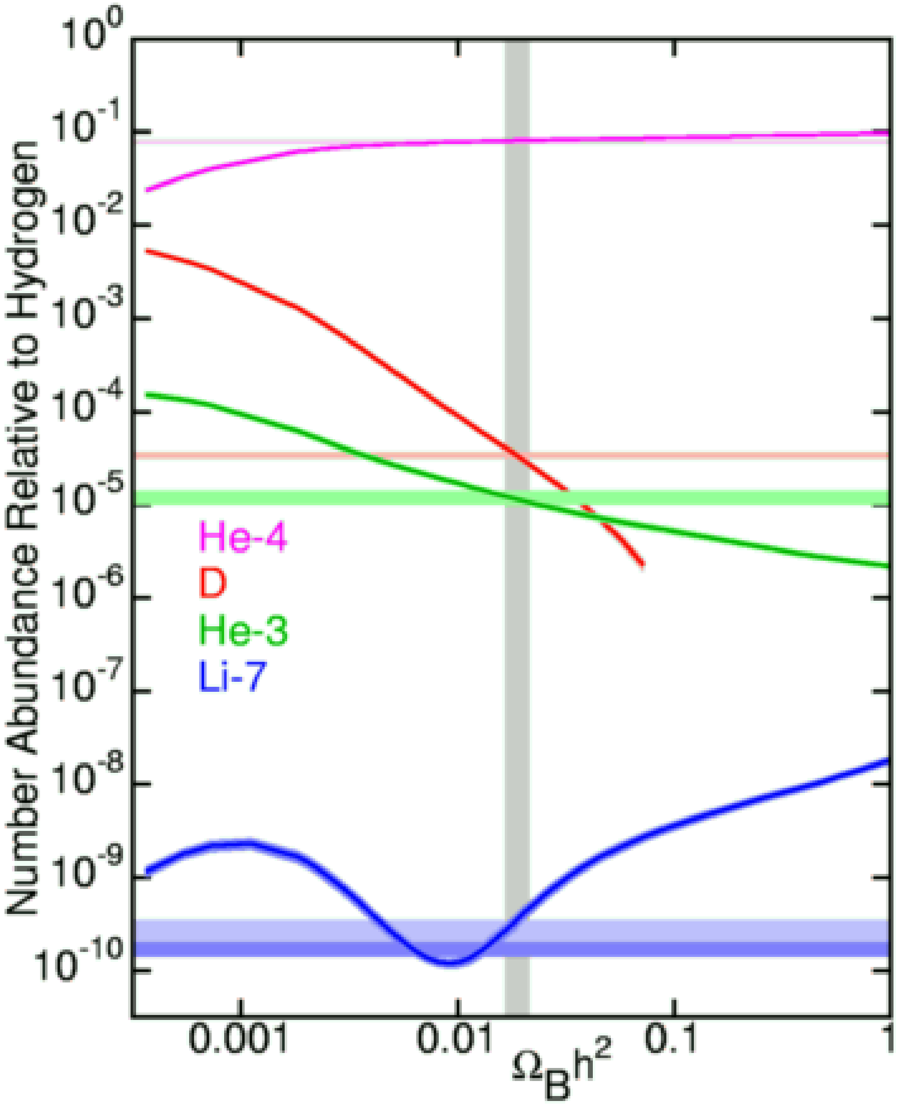
${}^2H + p \rightarrow {}^3He + \gamma$

etc.

The predicted abundances depend only on the baryonic matter density $\Omega_{bar} h^2$ ....

Freedman and Kaufmann

… so the observed abundances constrain $\Omega_{bar}\, h^2$ …



^{4}He and ^{7}Li favor lower $\Omega_{bar}\, h^2$ while D favors higher $\Omega_{bar}\, h^2$ (consistent with the CMB anisotropy). Compromise with $0.017 \leq \Omega_{bar}\, h^2 \leq 0.024$ (2σ) as the BBN bounds.

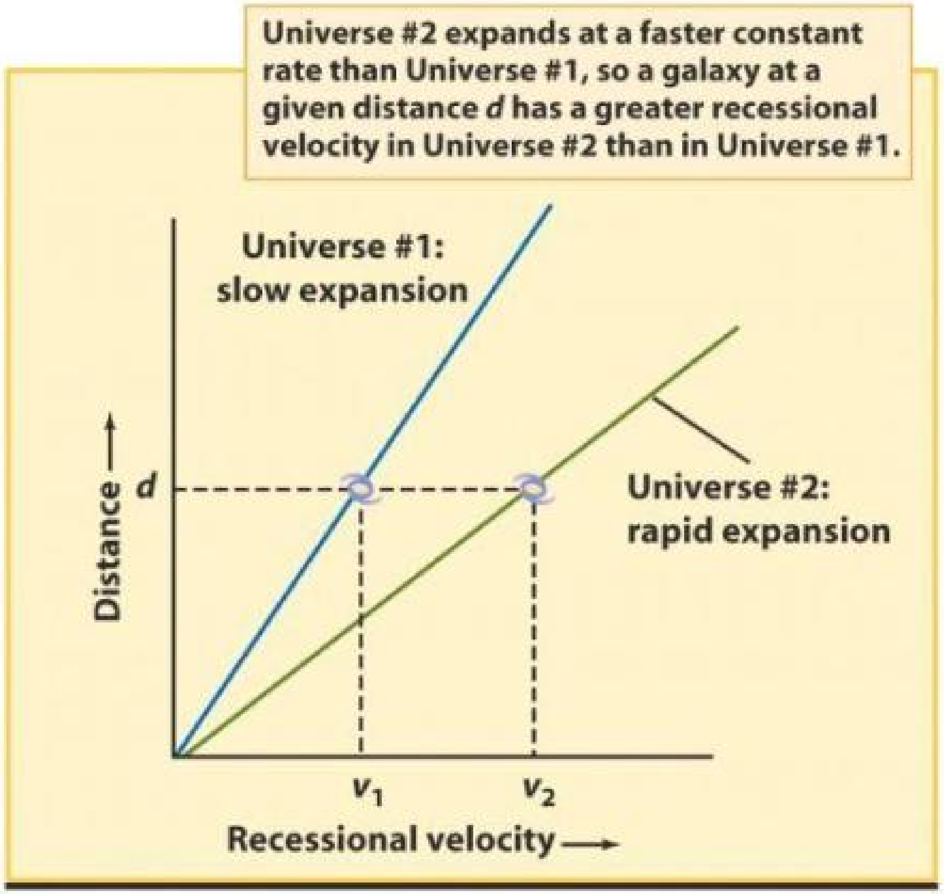
So, $0.03 \leq \Omega_{bar} \leq 0.06$ (2σ)
and, $0.20 \leq \Omega_{dyn} \leq 0.35$ (2σ)
and $\Omega_{lum} \leq 0.005$ (stars, etc.)

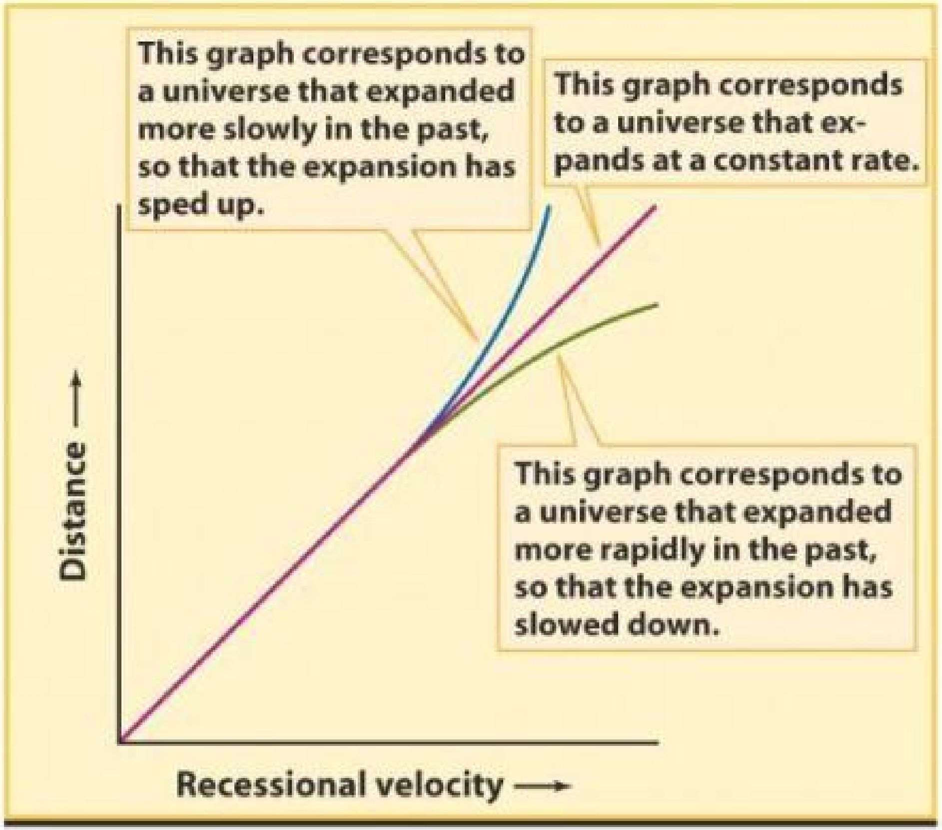
$\Rightarrow$there are dark baryons
and non-baryonic dark matter

This is cold dark matter, non-relativistic, maybe axions or from supersymmetry.

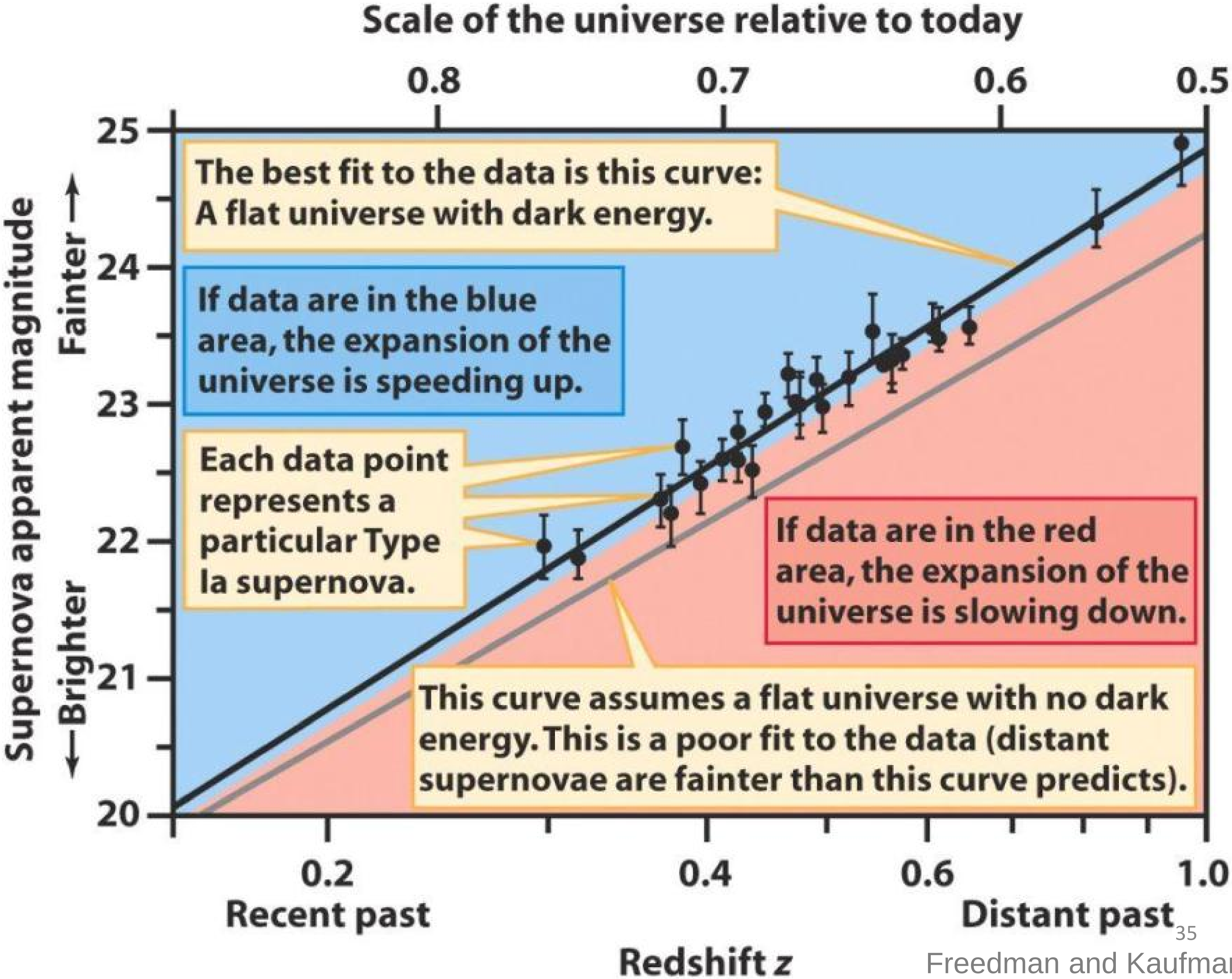
Dark Energy

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

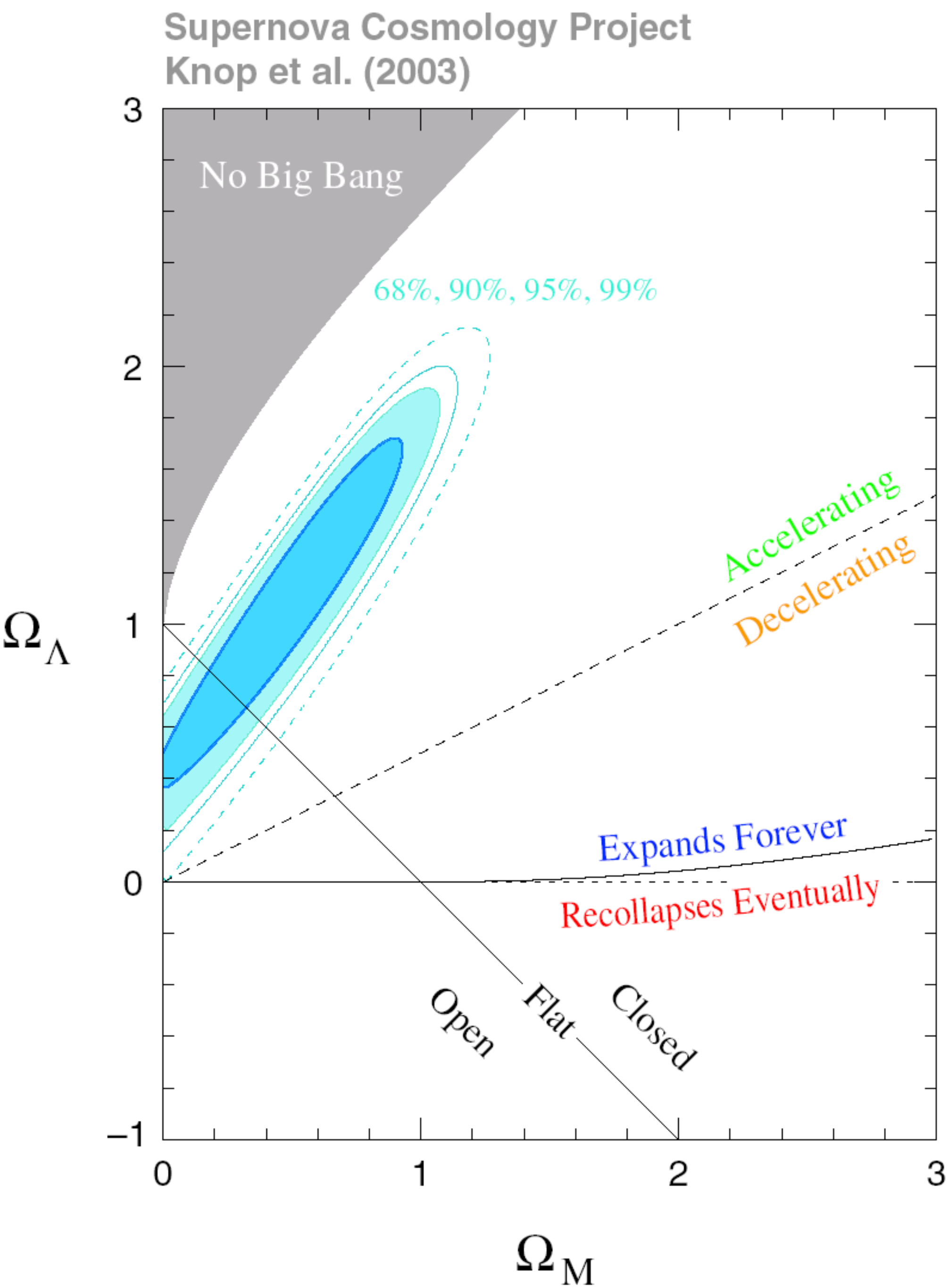




Freedman and Kaufmann



Freedman and Kaufmann



accelerated expansion

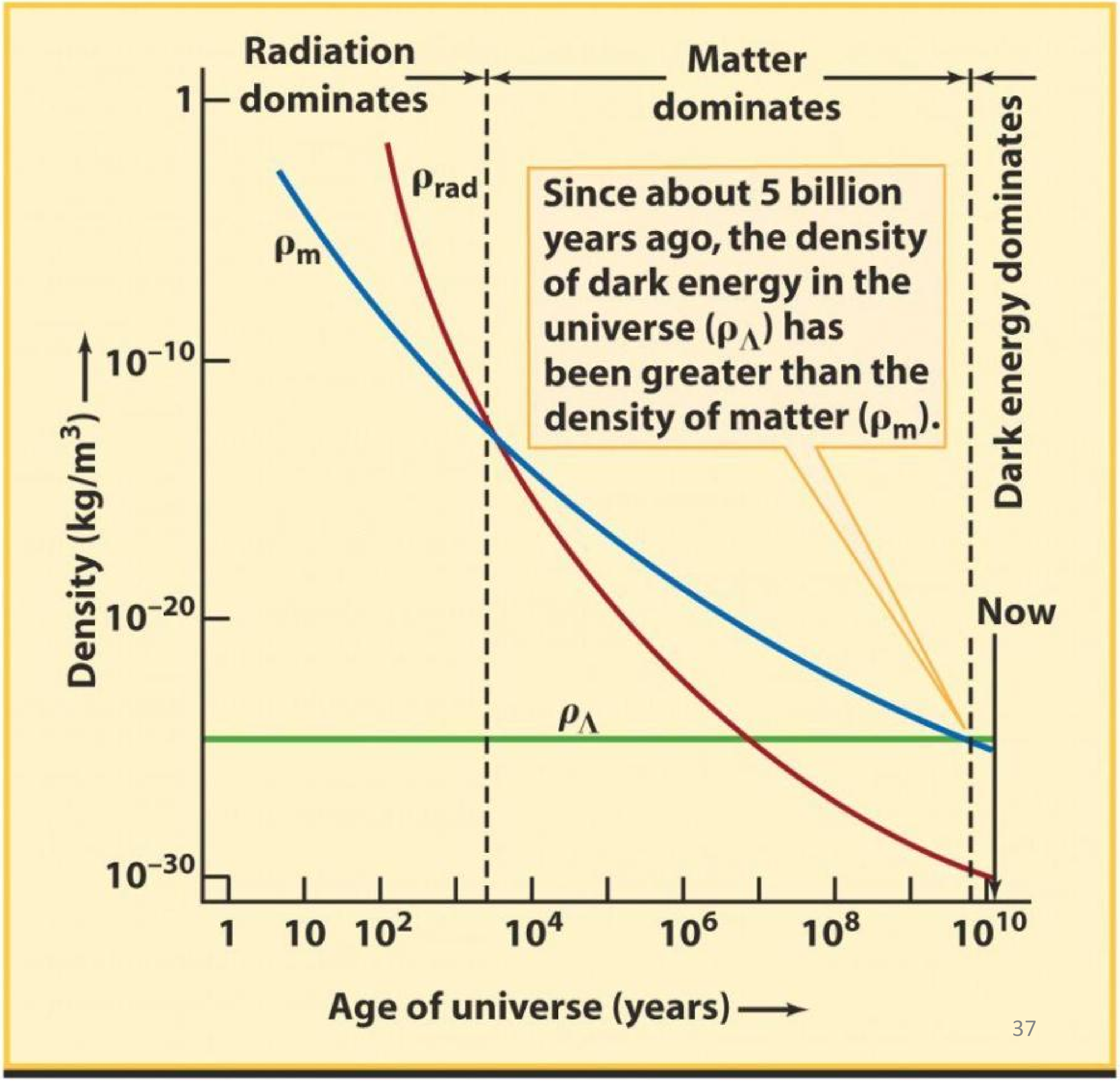
$\ddot{a}/a = -(4\pi G/3)(\rho + 3p)$

$p \leq -\rho/3$

dark energy

behaves like negative pressure

Flat ΛCDM

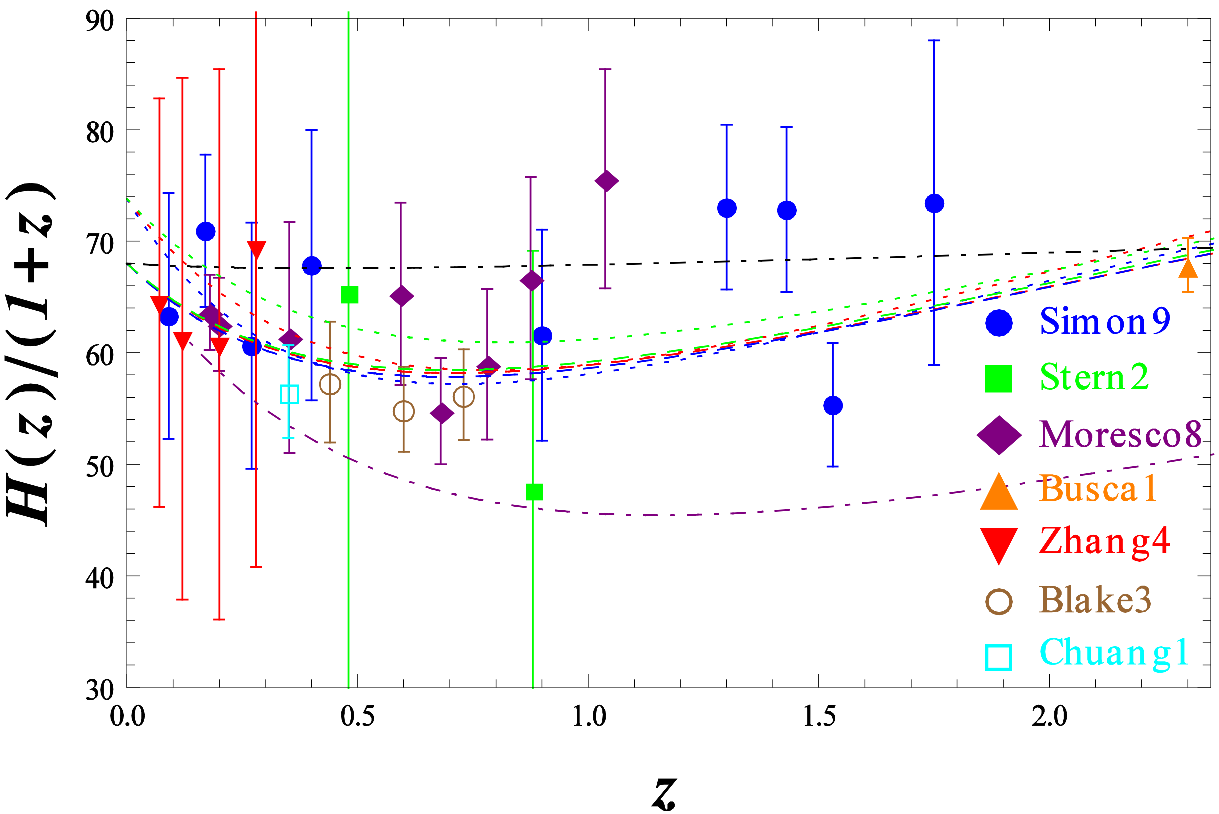


Freedman and Kaufmann

H(z) data & deceleration-acceleration transition

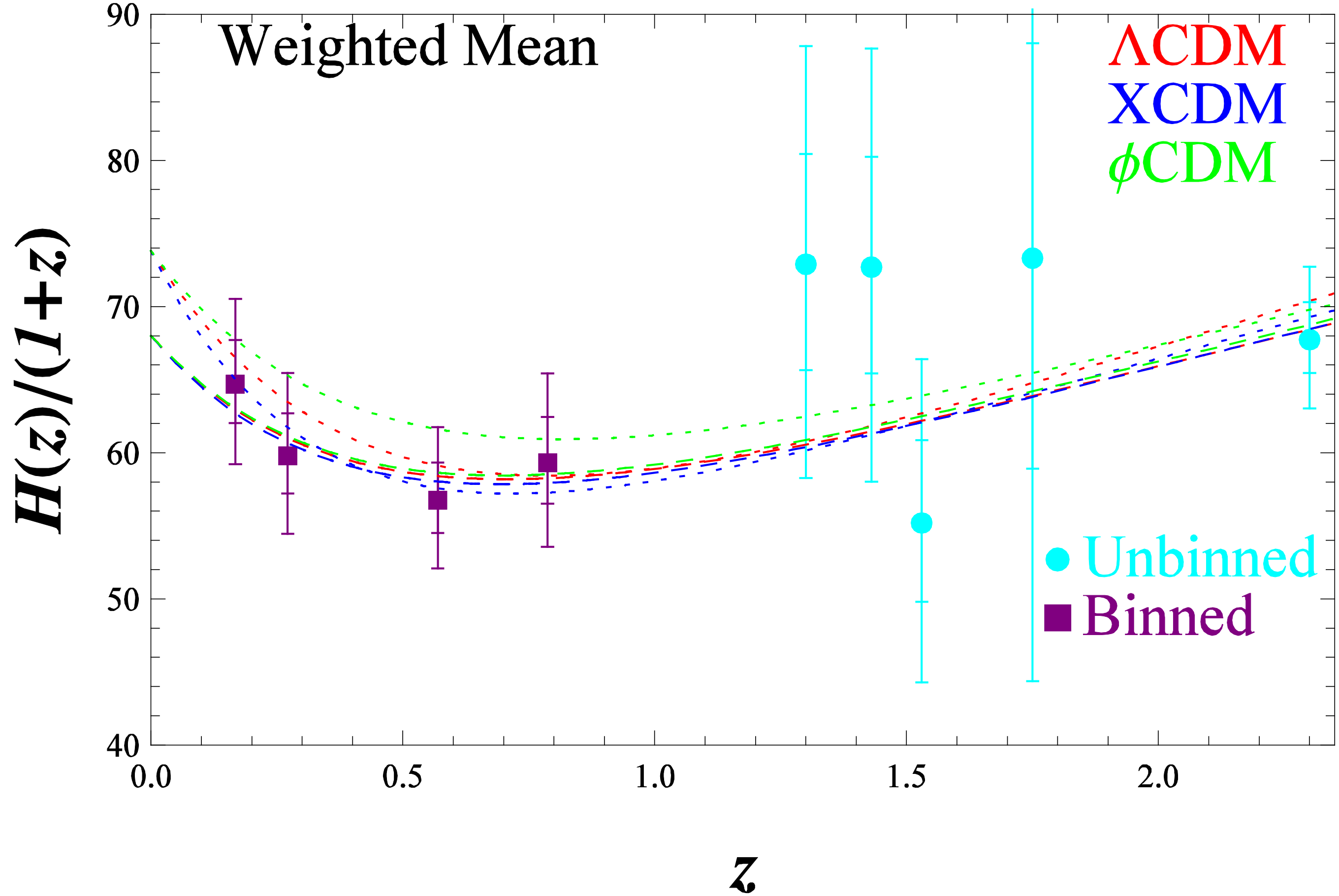
It is now possible to measure H(z) by using cosmic chronometers or radial BAO data (e.g., Moresco JCAP1208, 006; Busca A&A552, A96 (2013))

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



Six best-fit models and two 3σ deviant models

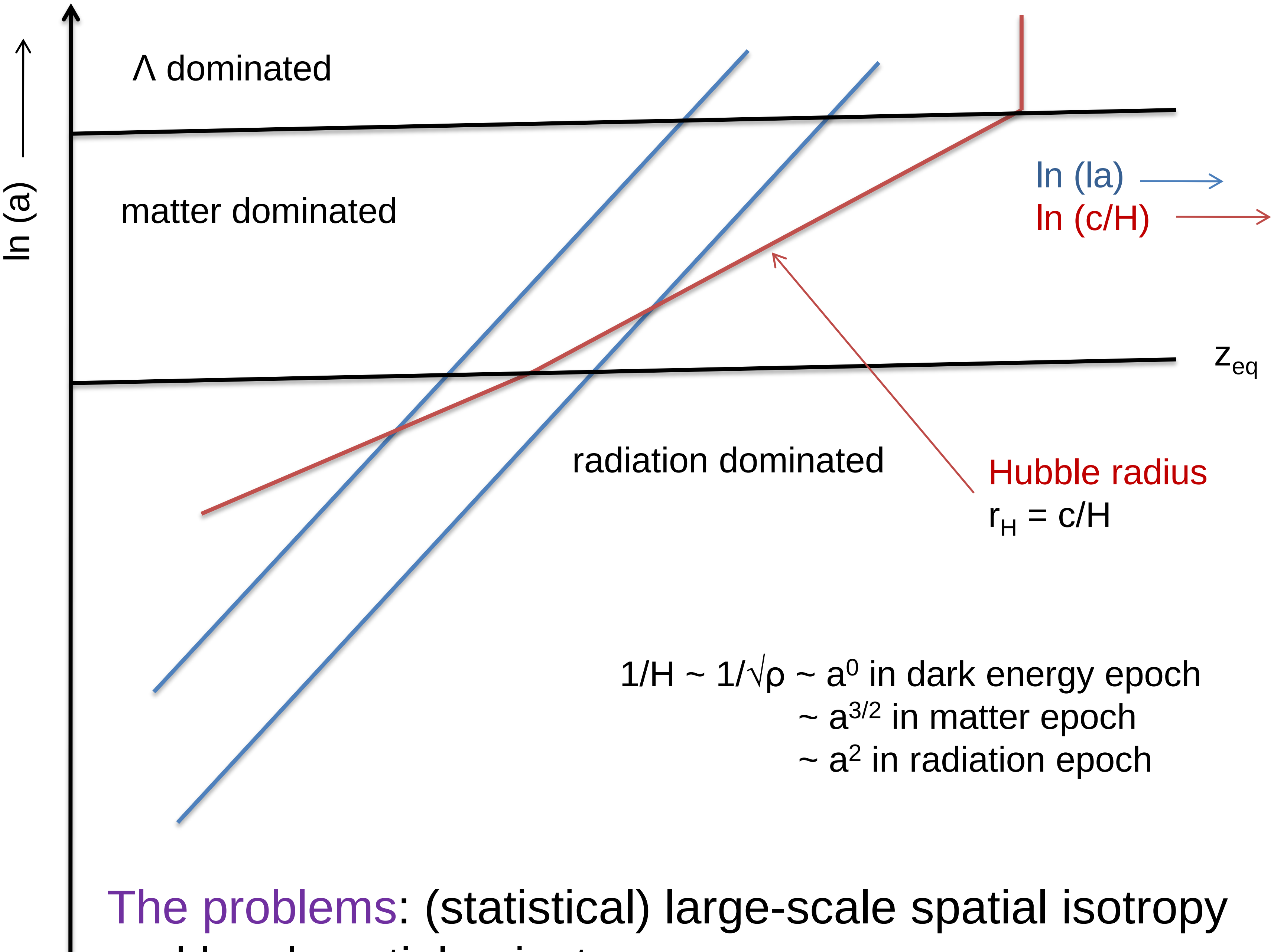
Data are noisy, so lets bin them



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

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

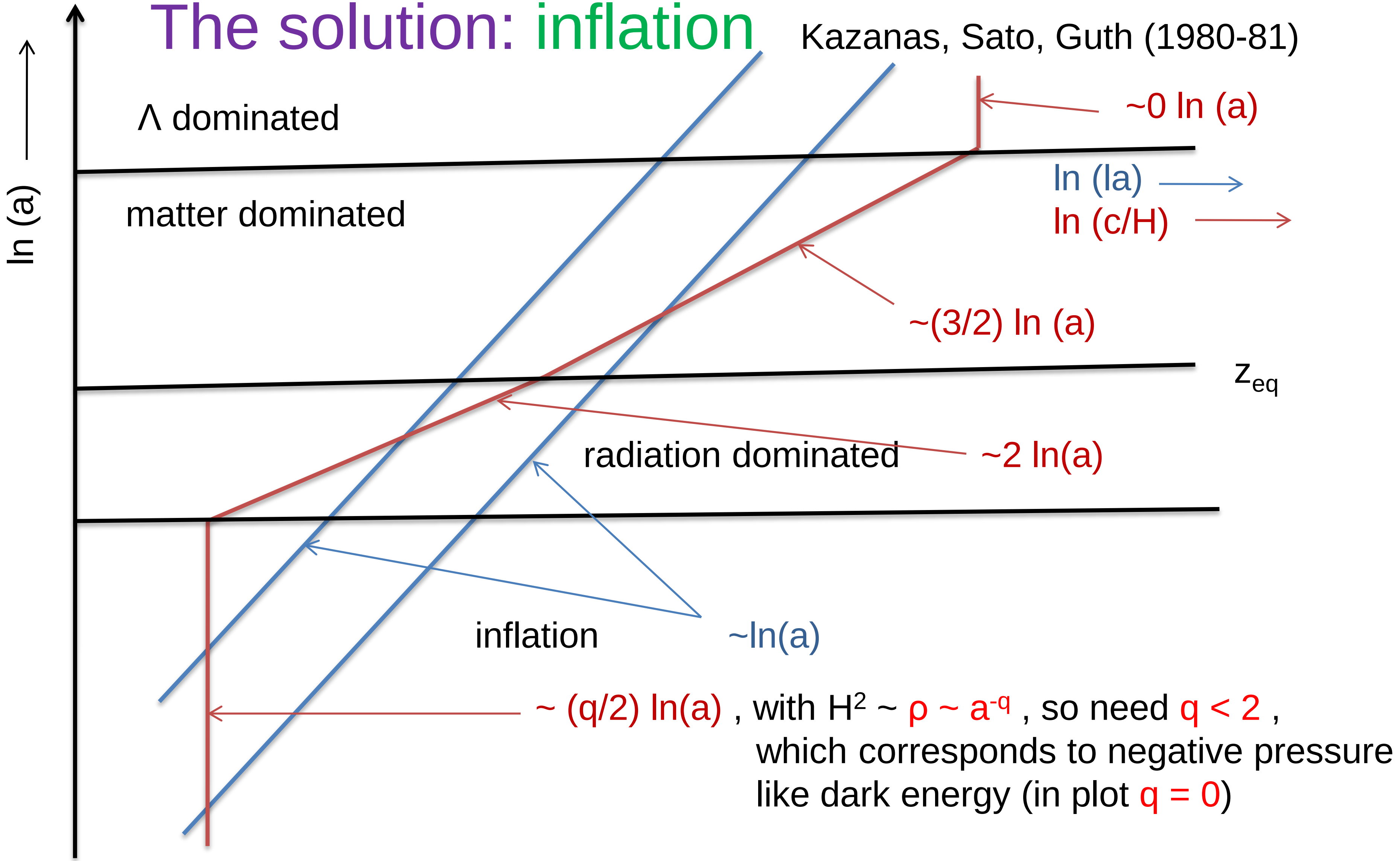
(This is the first real measurement of the deceleration-acceleration transition redshift.)



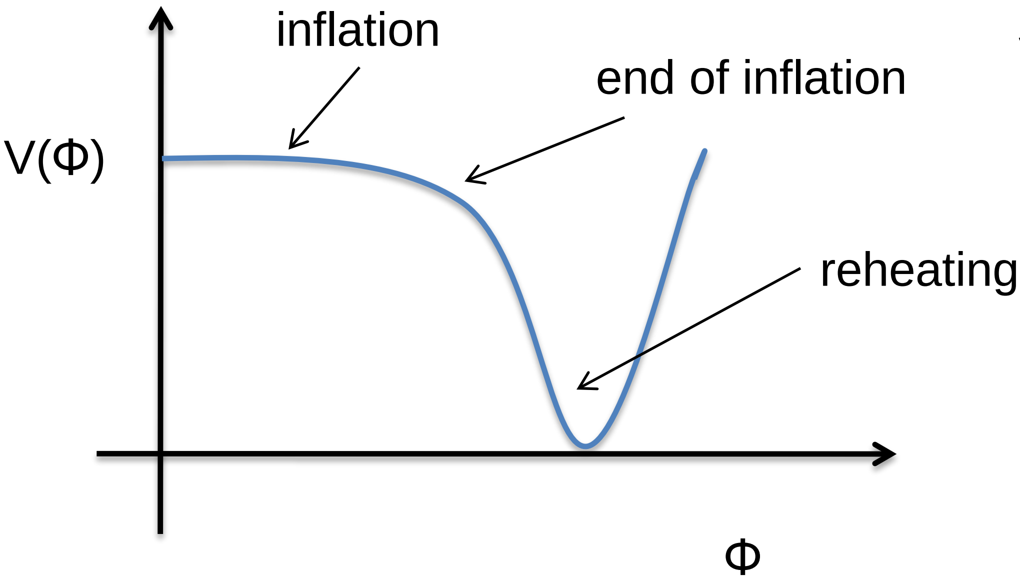
$1/H \sim 1/\sqrt{\rho} \sim a^0$ in dark energy epoch
$\sim a^{3/2}$ in matter epoch
$\sim a^2$ in radiation epoch

The problems: (statistical) large-scale spatial isotropy and local spatial anisotropy

The solution: inflation



So, to model inflation (and dark energy) use a scalar field ….



Spatially homogeneous background $\Phi(t)$

$$\rho_\Phi \sim 1/2(d\Phi/dt)^2 + V \sim V$$
$$p_\Phi \sim 1/2(d\Phi/dt)^2 - V \sim - V$$

$\Rightarrow p_\Phi = - \rho_\Phi$ (negative pressure)

$$\dot{\rho} = -3\,(\dot{a}/a)\,(\rho + p)$$
$\Rightarrow \rho_\Phi = \text{constant}$

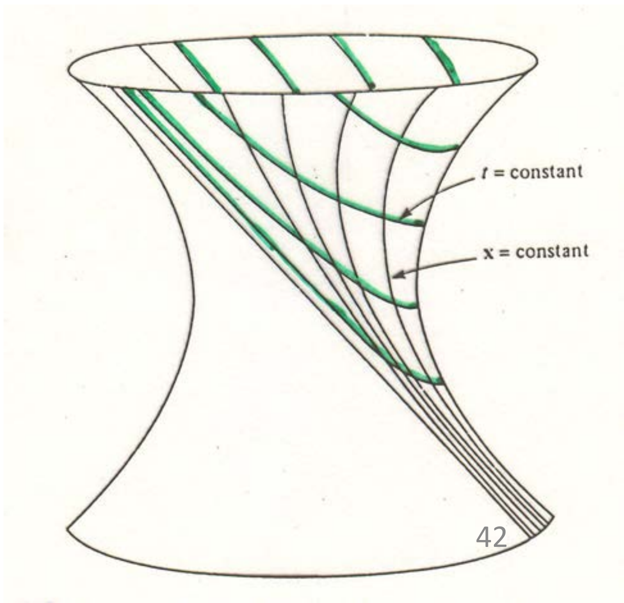
$\Rightarrow H = \text{constant}$

$\ddot{a}/a = -(4\pi G/3)(\rho + 3p) > 0$

$\Rightarrow$ accelerated expansion, like dark energy

Simplest solution is spatially-flat de Sitter with $a(t) \sim \exp(Ht)$. Length scales tremendously stretched

$\Rightarrow$ (statistical) large-scale spatial isotropy



No direct evidence for the inflaton scalar field, however there is persuasive indirect evidence.

Spatial irregularities

During inflation, quantum mechanics generates small-scale zero-point fluctuations (gravity modifies the usual ground state in a manner similar to what happens for the Casimir effect).

These are stretched by the expansion to cosmological length scales in the late time universe.

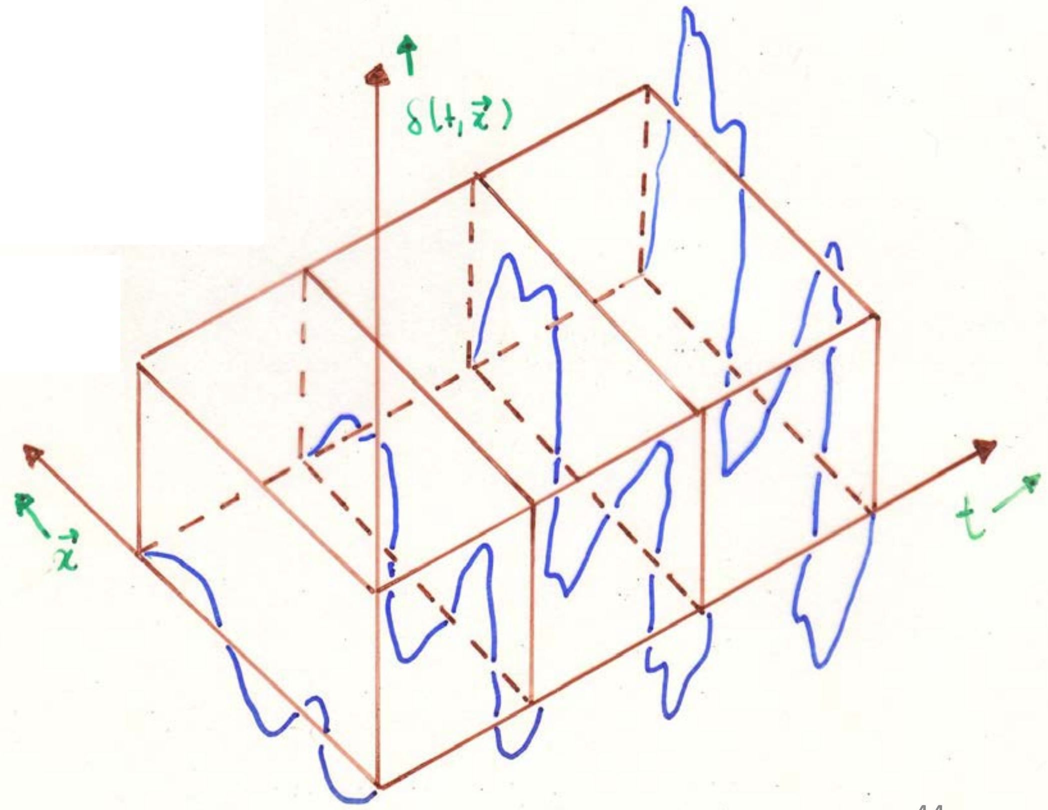
$\Rightarrow$Inflation can explain small-scale anisotropy.

$\rho(t,x) = \rho_b(t)[1 + \delta(t,x)]$ with $|\delta(t,x)| << 1$

Fourier modes power spectrum $P(t,k) = |\delta(t,k)|^2$

In a spatially-flat model there is only one scale, 1/H, so a reasonable guess is $P(k) \sim (k/aH)^n$. n=1 is the Harrison-Peebles-Yu-Zeldovich scale-invariant case predicted by simple inflation models.

Gravity is unstable so spatial irregularities grow in the radiation and matter epochs.

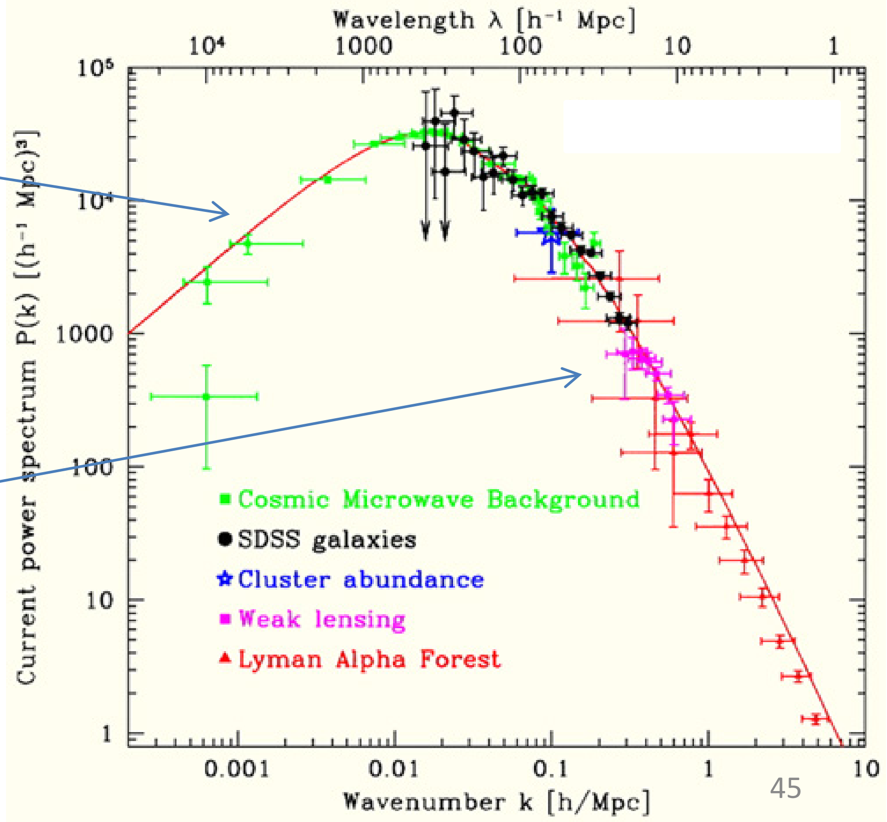


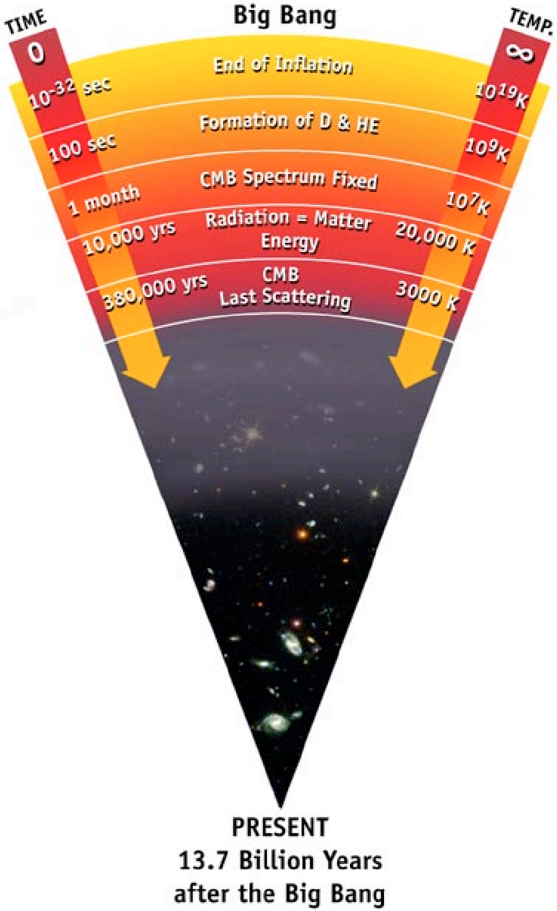
Small length scales enter the Hubble radius before z_{eq}; radiation pressure prevents growth until z_{eq}: transfer function T(k).

Observable matter $P_{mat}(k) = T^2(k)\ P(k)$

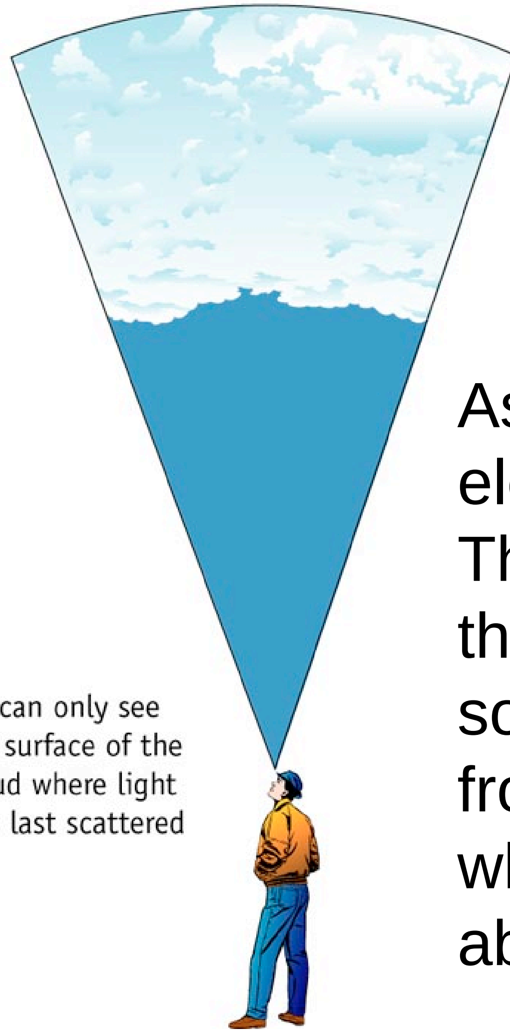
Primordial n=1 spectrum

Less growth on small scales





The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

As T drops nuclei capture electrons and form atoms. This results in a big drop in the ionization fraction and so the photons decouple from the matter at this time when the universe was about 400,000 years old.

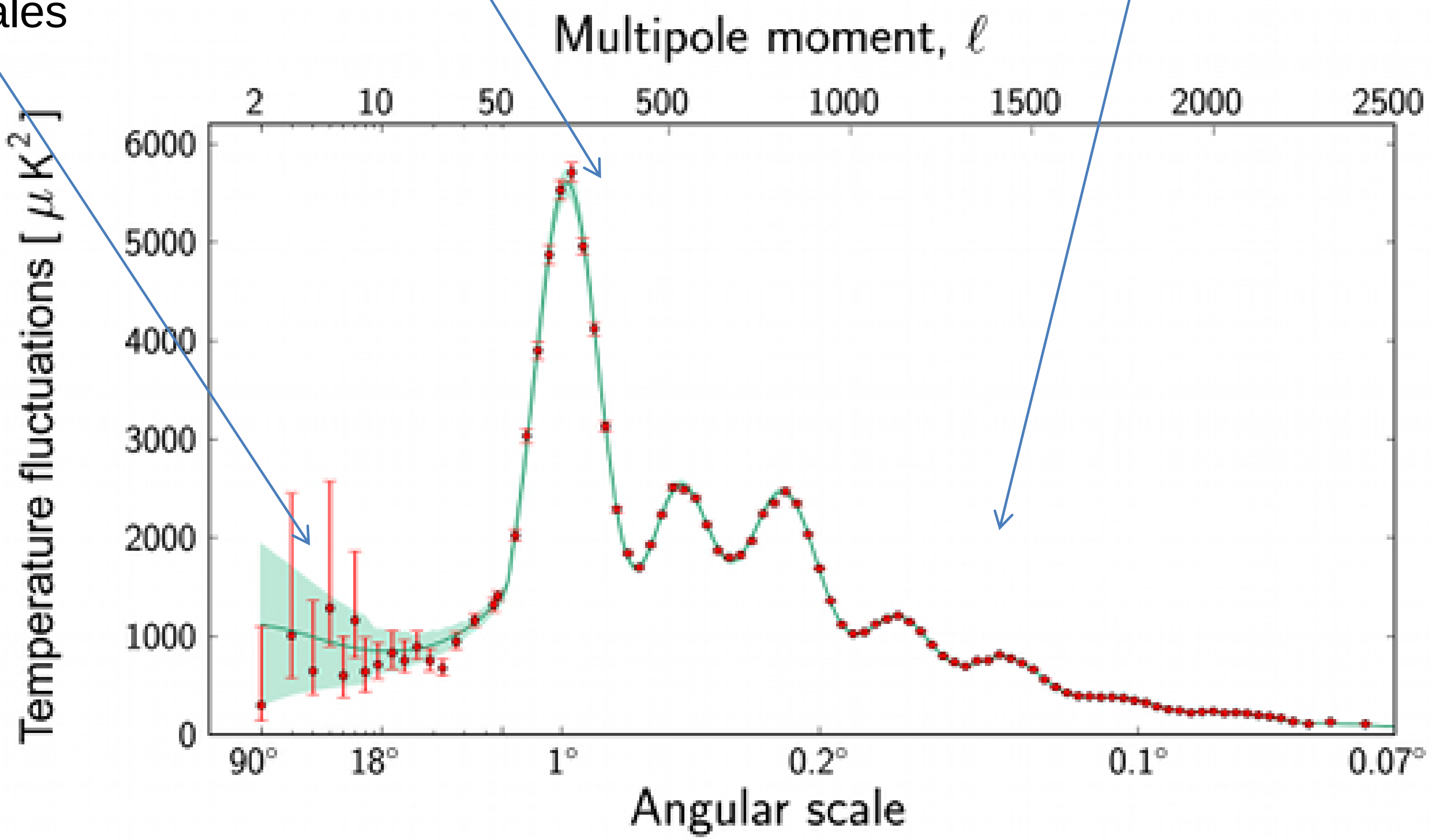
CMB anisotropy: Along with initial last-scattering surface irregularities, as the CMB propagates to us, metric irregularities along the line of sight make it more anisotropic.

Expanded in multipole moments on the sky, the CMB temperature anisotropy power spectrum has damped acoustic peaks.

from gravity and pressure on intermediate scales …

… with dissipative damping on small scales

from gravity on large scales

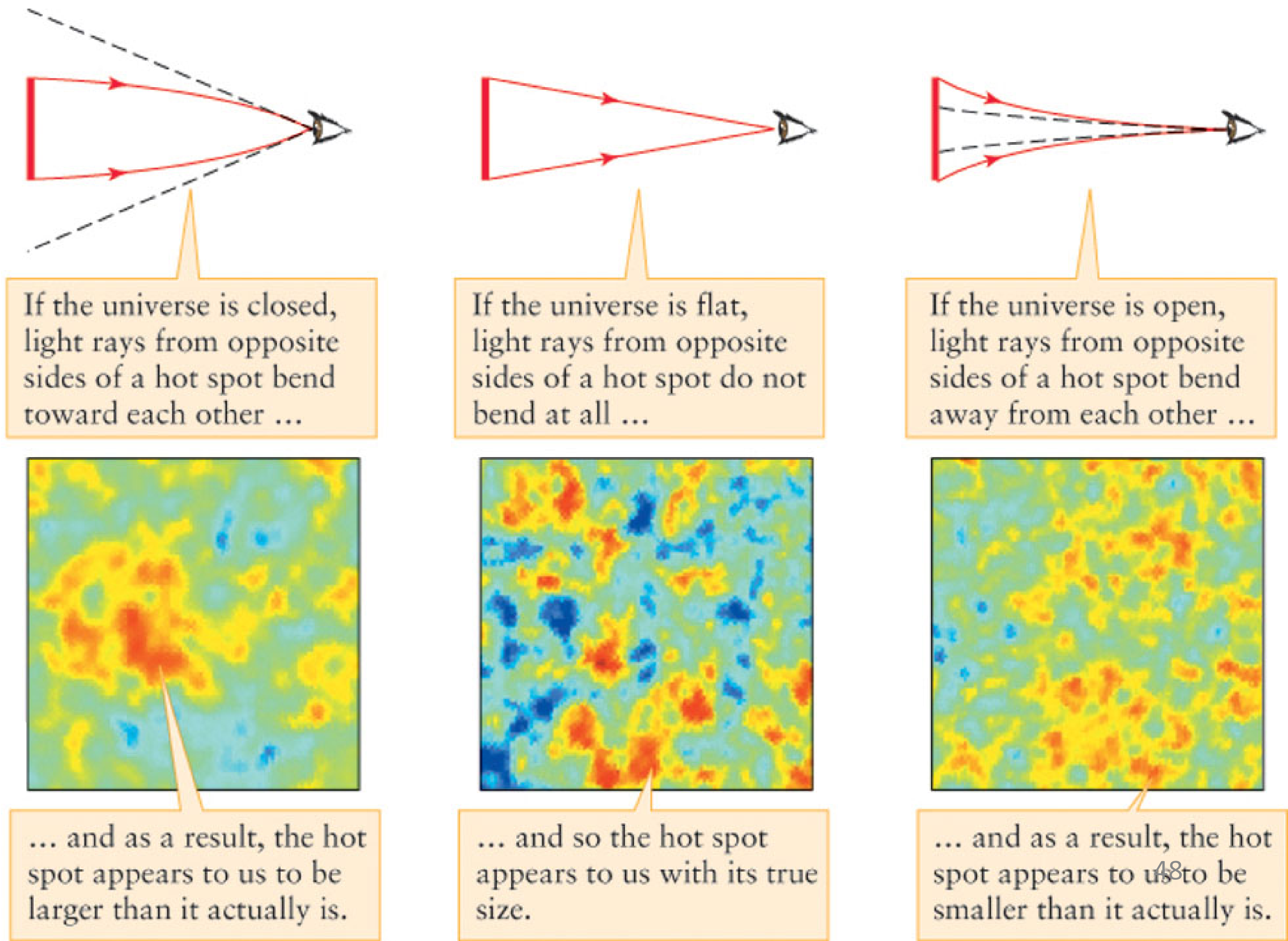


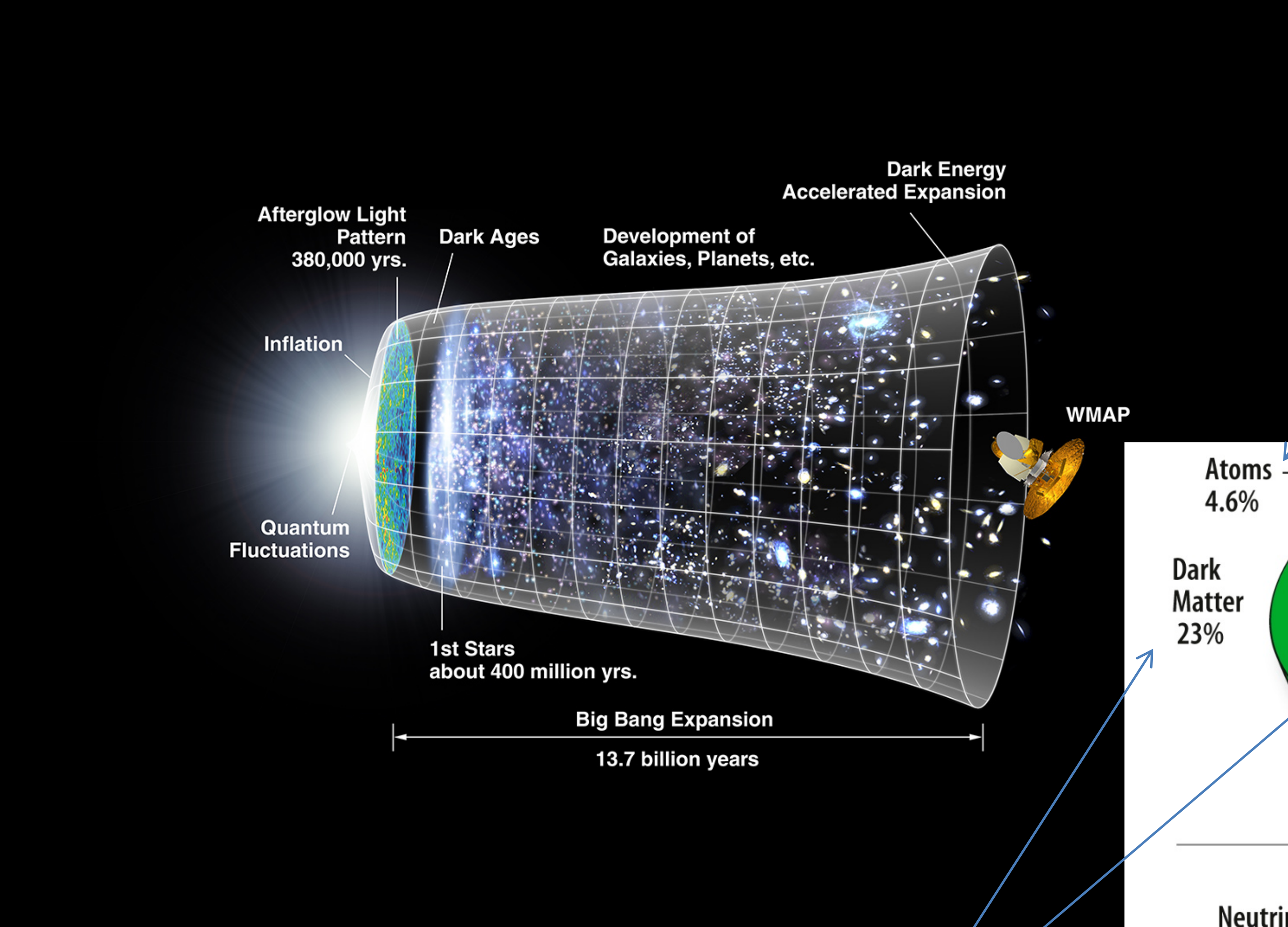
Planck 1.3 year

The acoustic peak angular scale directly measures curvature of space if dark energy does not evolve. The acoustic Hubble radius $r_{H,s} = c_s / H$ sets a new model-independent length scale at $z >> 1$. This corresponds to a multipole moment $l \sim 1/\theta \sim$ (angular size distance) now. The angular size distance is smaller for more positive curvature and larger for more negative curvature.

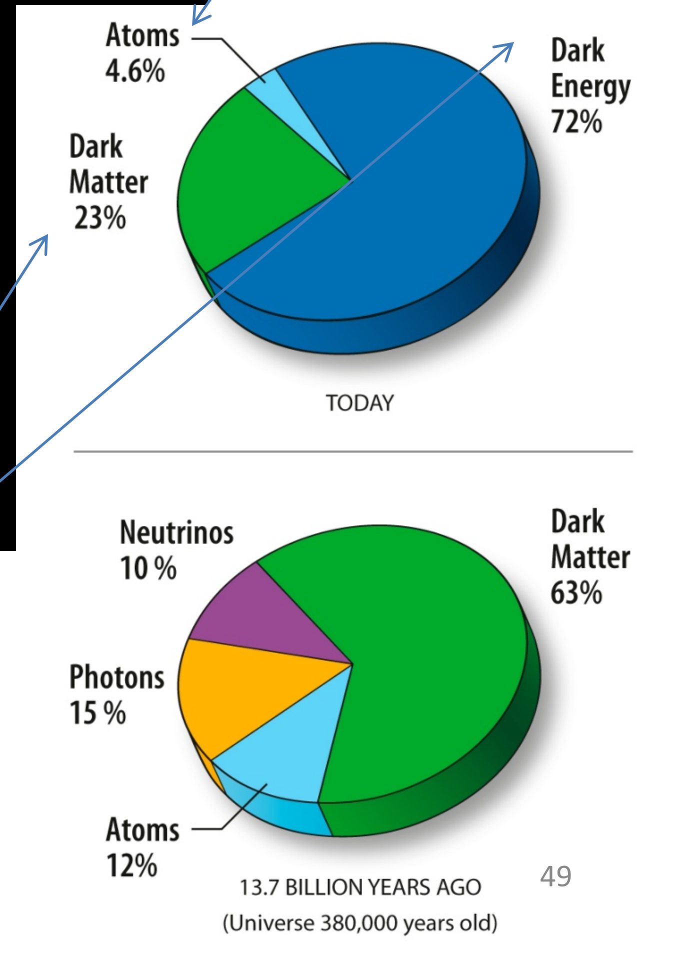
CMB data shows space is close to flat.

The low measured Ω_{dyn} then requires dark energy at the level seen by the SNeIa.



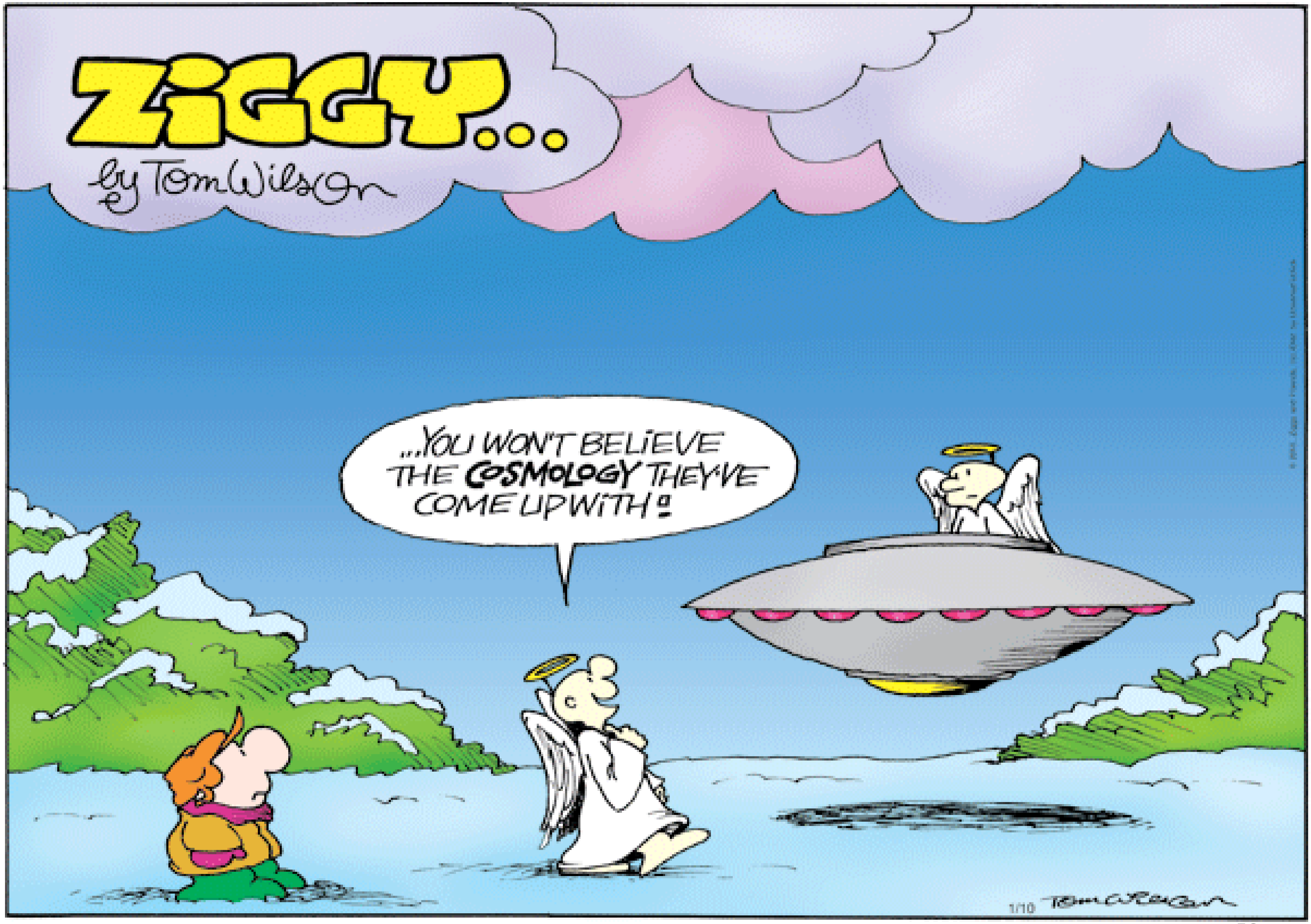


We almost understand < 5% of the current energy budget.



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

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


ZIGGY...
by Tom Wilson
...YOU WON'T BELIEVE THE COSMOLOGY THEY'VE COME UP WITH!
1/10
Tom Wilson

Open questions, missing links

B.R. & M. Vogeley, PASP120,235 (2008)

What is dark energy?

Is it a cosmological constant, or does it vary with space and in time?

Is the general theory of relativity correct on large scales?

Are the astronomy observations for dark energy secure?

Is it really decoupled (except gravitationally) from everything else?

What is dark matter?

(At least) two light neutrino species behave like HDM.

Supersymmetry? Axions?

Will the Large Hadron Collider at CERN tell us?

Laboratory searches for dark matter.

Dwarf galaxy abundances, galactic nuclear profiles might be problems for "pure" CDM.

What are the masses of neutrinos?

Are the constraints on baryon density consistent?

When and how was the baryon excess generated?

What is the geometry of space?

What is the topology of space?

What are the initial seeds for structure formation?

Did the early universe inflate and reheat?

When, how, and what were the first structures formed?

How do baryons light up galaxies and what is their connection to mass?

How do galaxies and black holes co-evolve?

Does the Gaussian, adiabatic CDM structure formation model have a real flaw?

Is the low quadrupole moment of the CMB anisotropy a problem for flat ΛCDM?

Are the largest observed structures a problem for flat ΛCDM?

Is there a cosmological magnetic field and what effects does it have?

...when you have eliminated the impossible, whatever remains, however improbable, must be the truth.

Sherlock Holmes (Arthur Conan Ignatius Doyle)