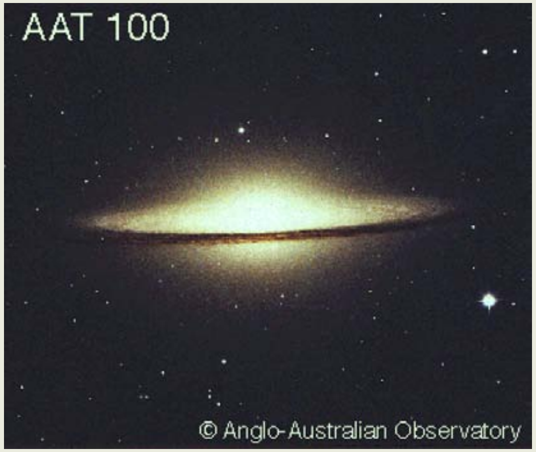
Physical Cosmology

Wolfgang Hillebrandt
MPI für Astrophysik
Garching

Lecture, TU Munich
WS 2011/12

The Hubble sequence of galaxies


M87 © Anglo-Australian Observatory
Photo by David Malin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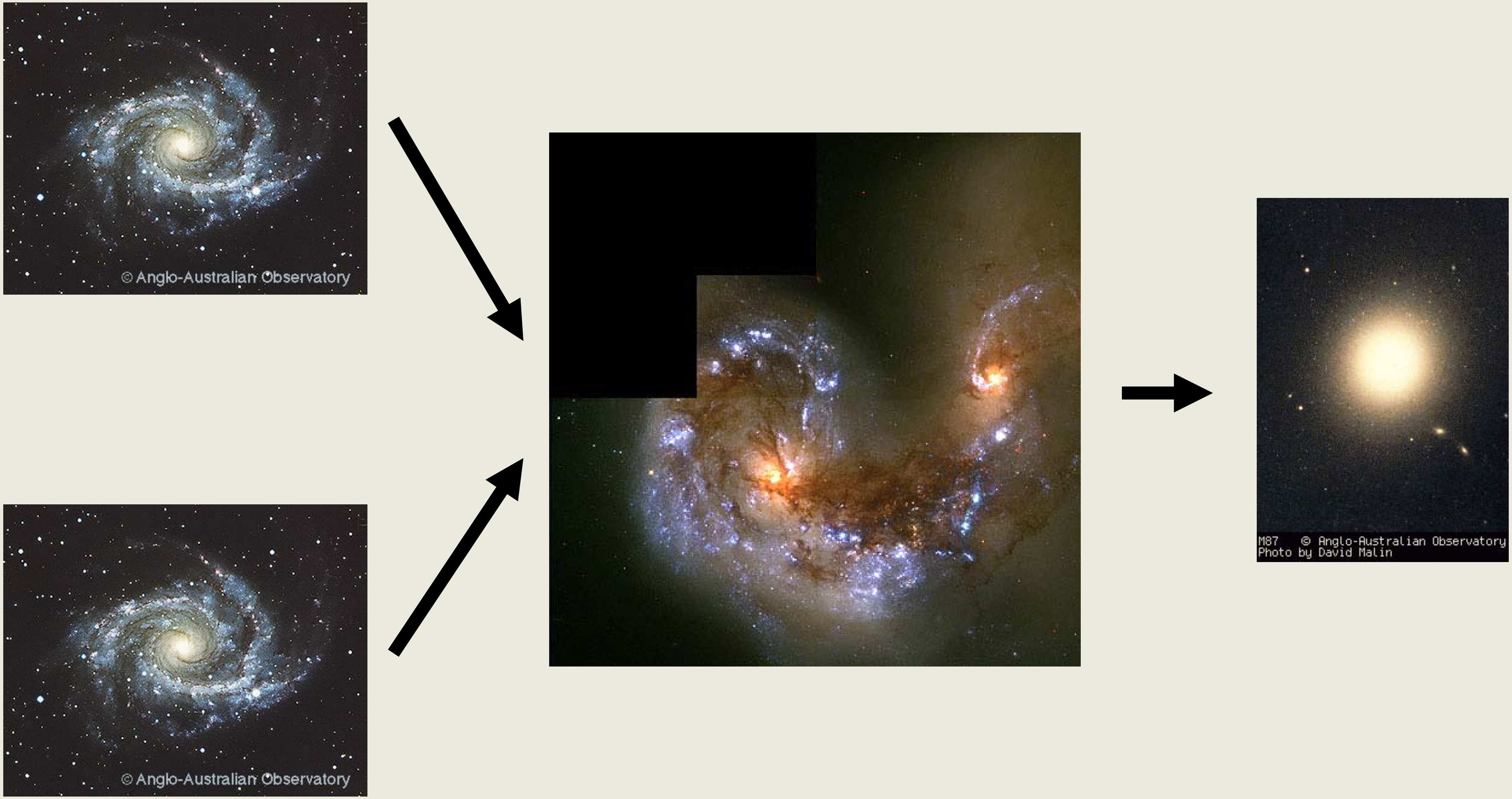
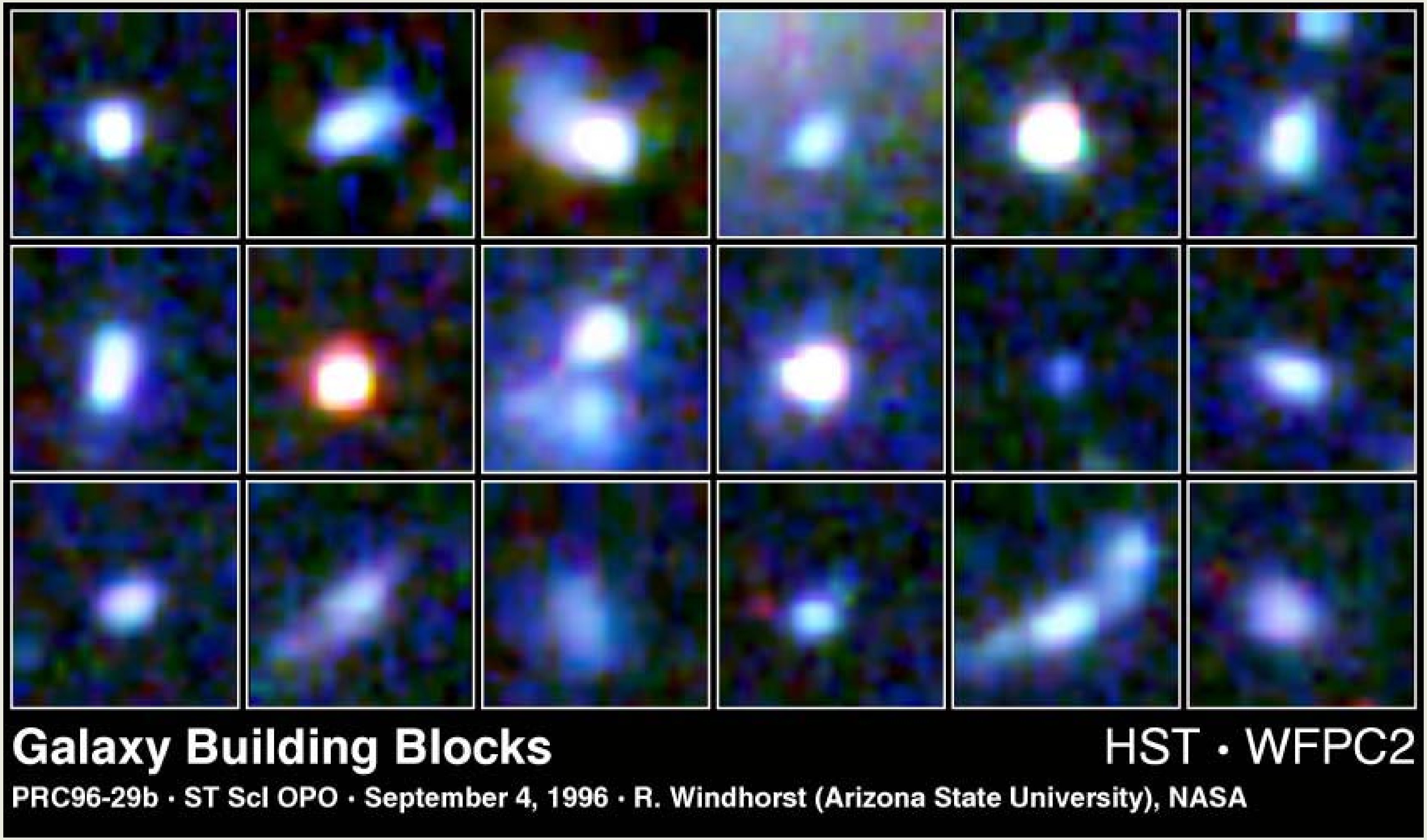
Do ellipticals form by merging spirals ?



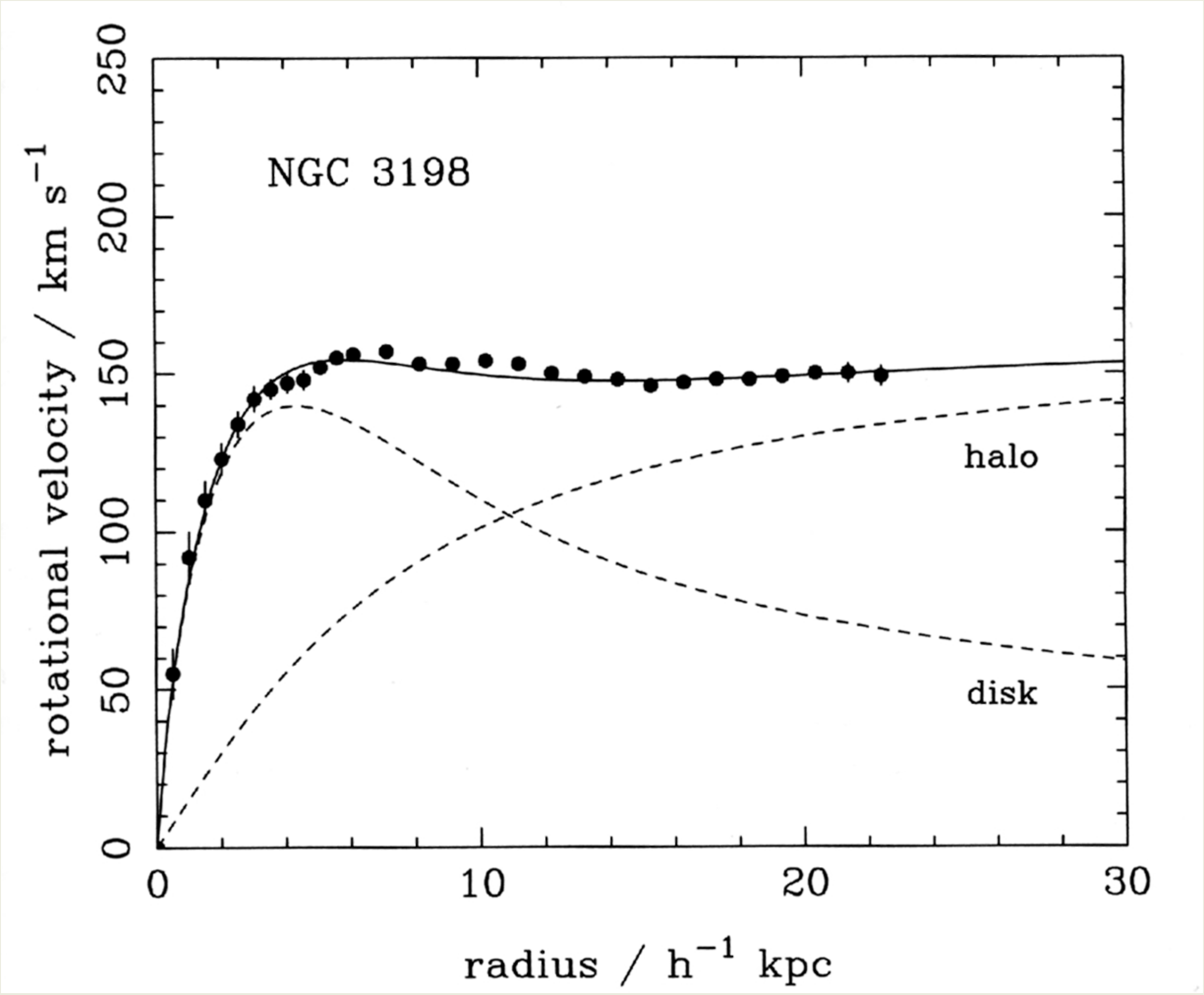
Younger galaxies should be smaller ...



Evidence of dark matter: Rotation curves of galaxies

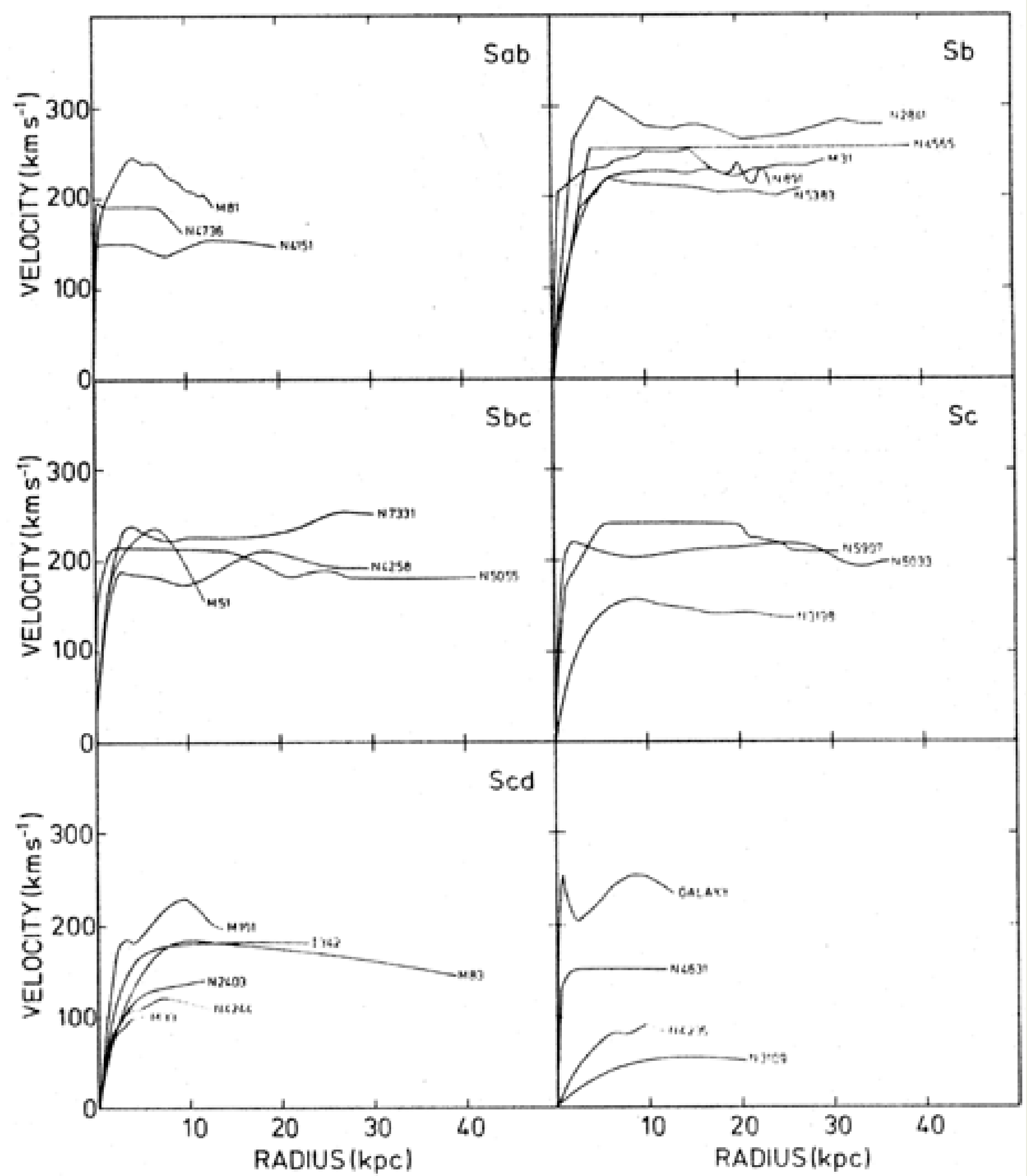
Outside a "point mass":

$V \sim R^{-1/2}$!



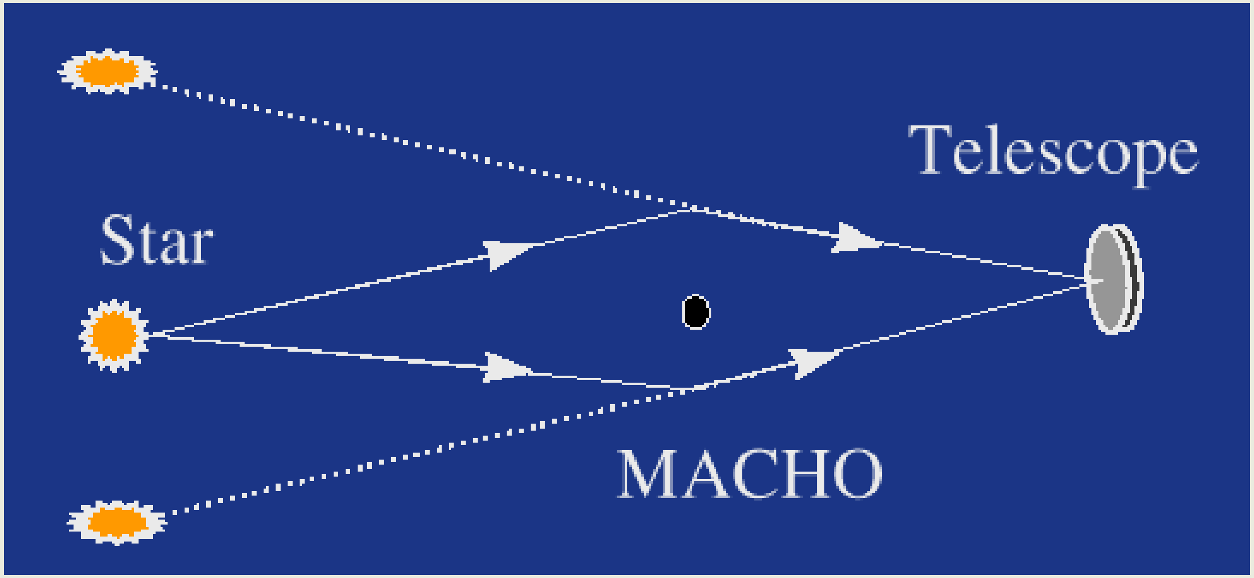
(van Albada, 1995)

Rotation curves of galaxies



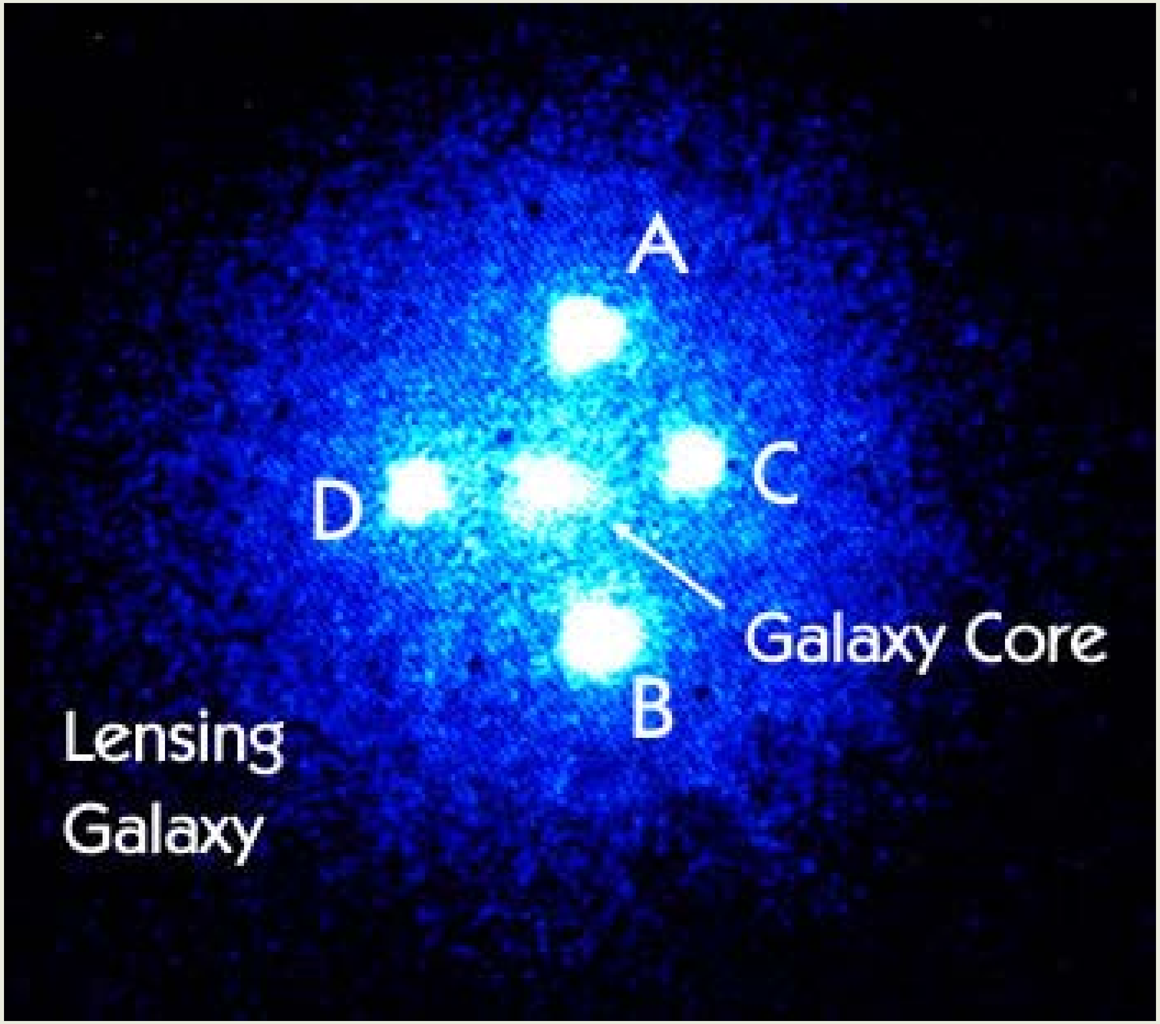
How can we see MACHOs ?

- Gravitational lensing:



- If foreground object has only little mass, the image split is too small to be observed
- But the amplification (brightening) is observable

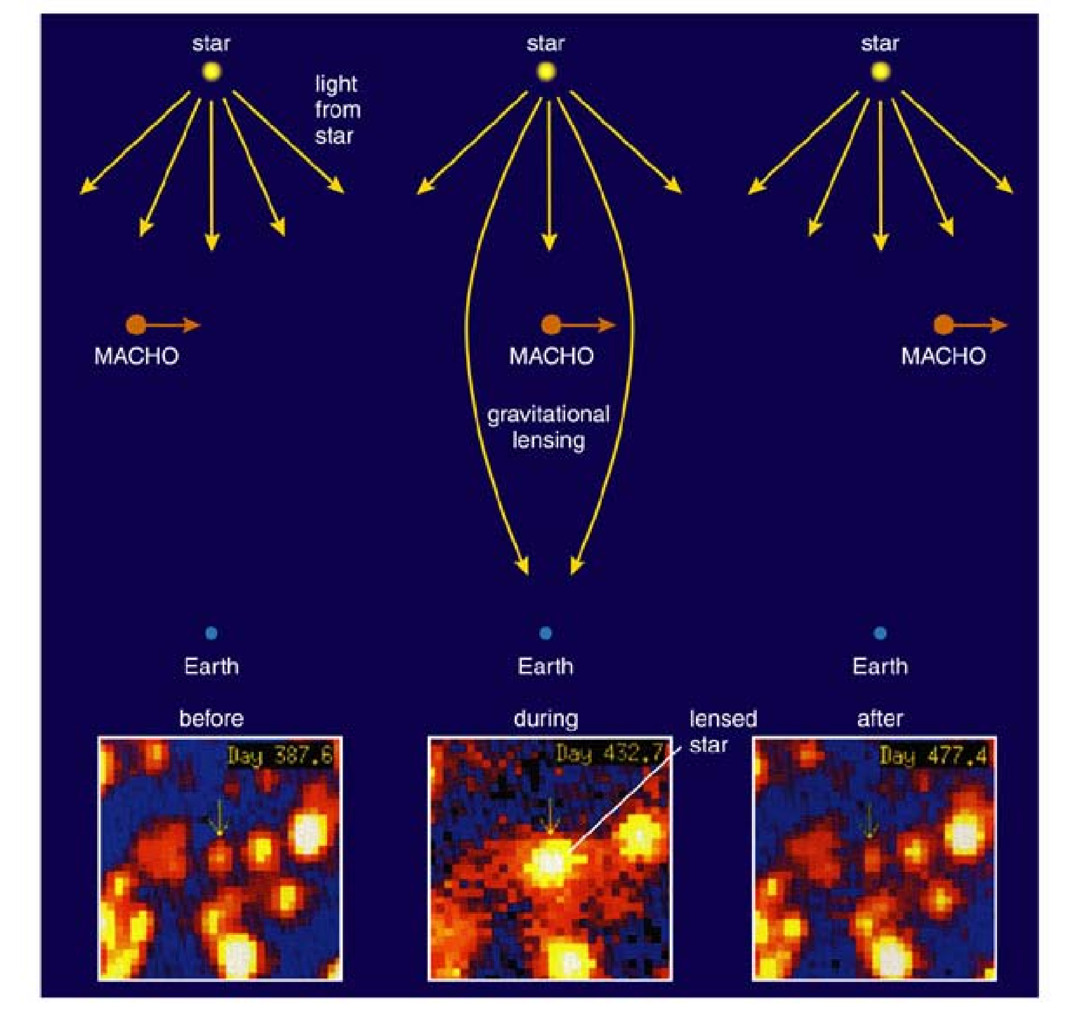
Example for light bending



“Einstein Cross” - G2237+0305

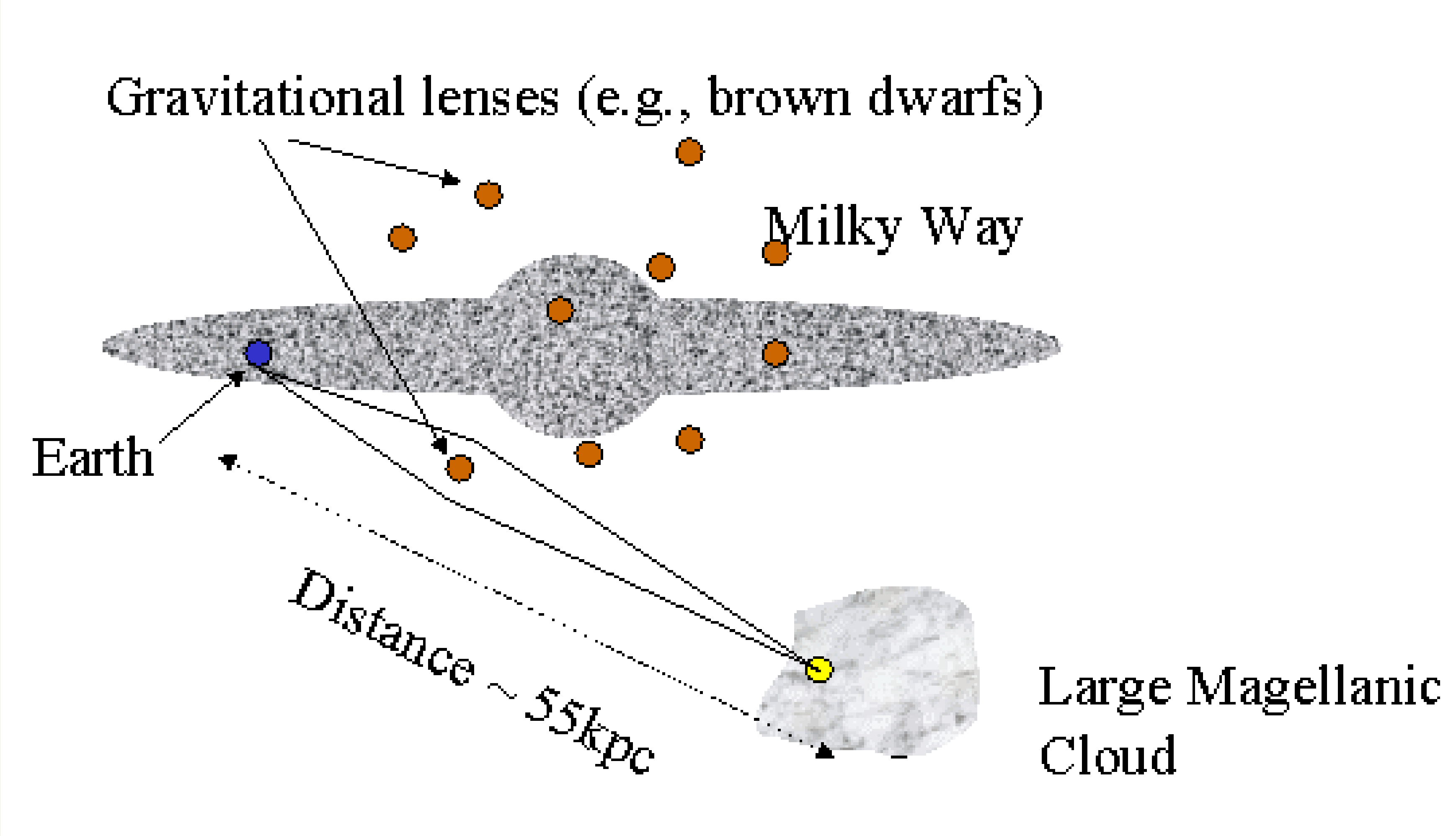
How can we see MACHOs ?

- How likely is it for a star in the Milky Way to get amplified ?
- Once every 10 million years !!!

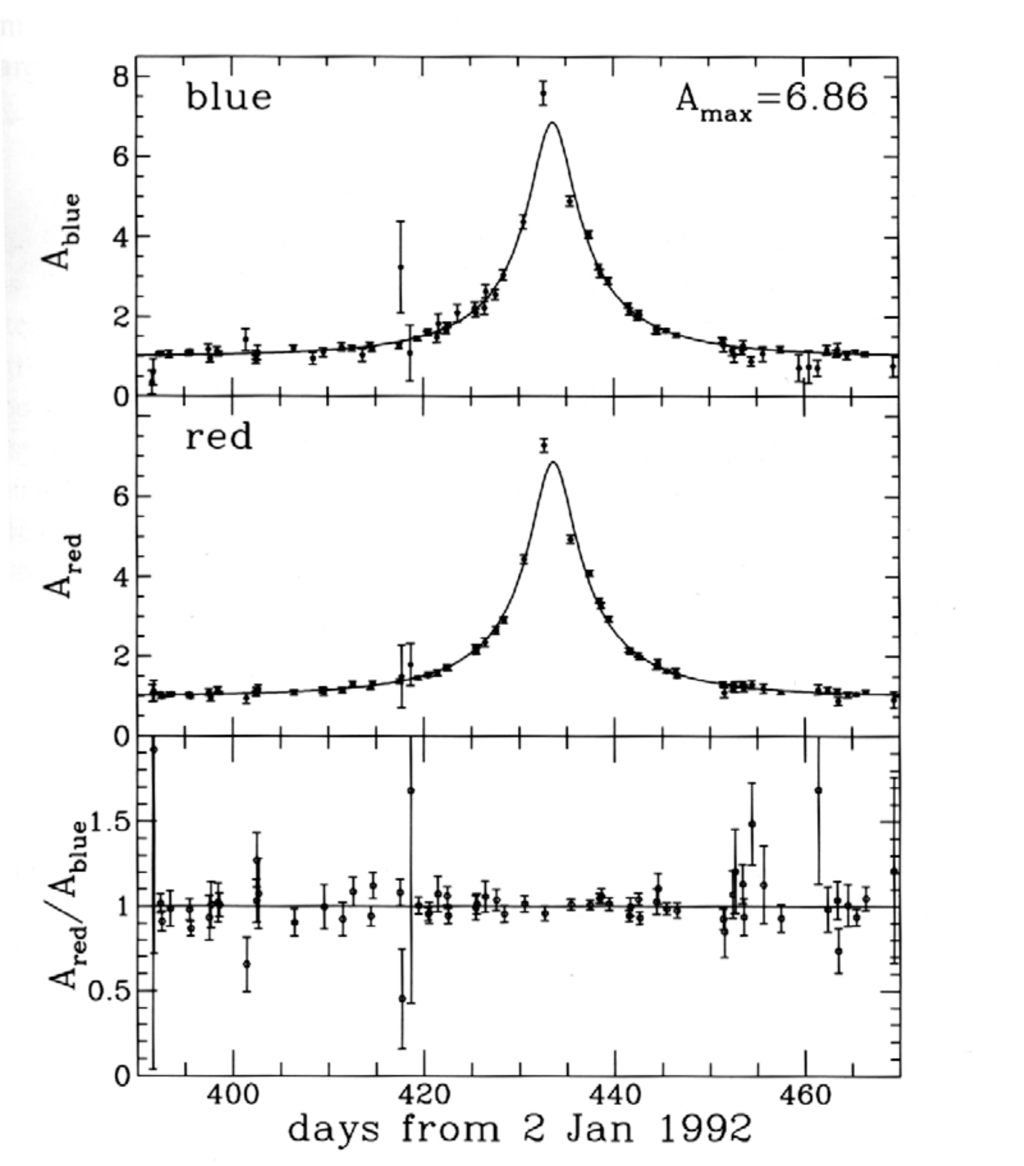


How did this work ?

- Monitor 10 million stars simultaneously !



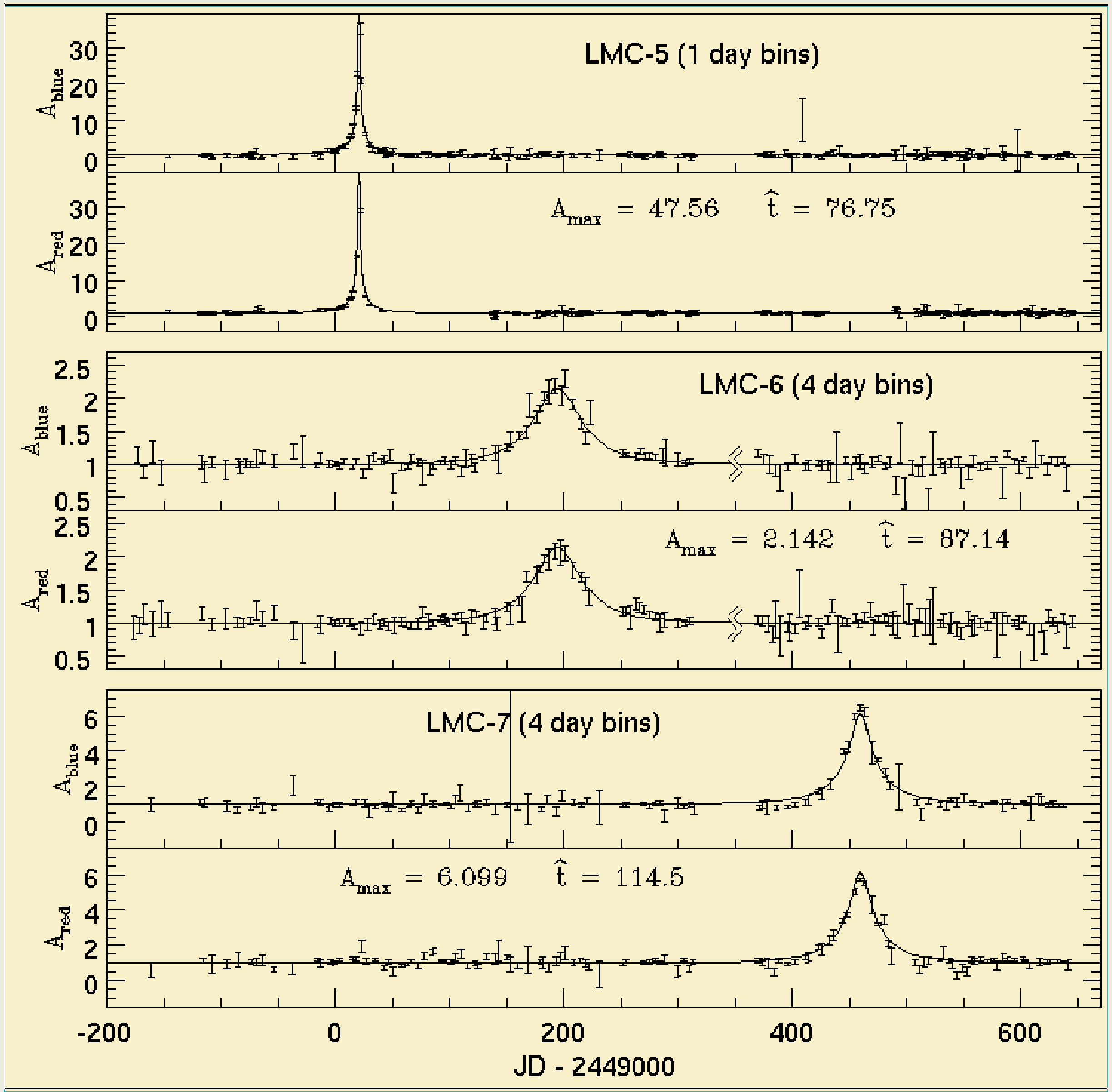
Light curve of a MACHO event



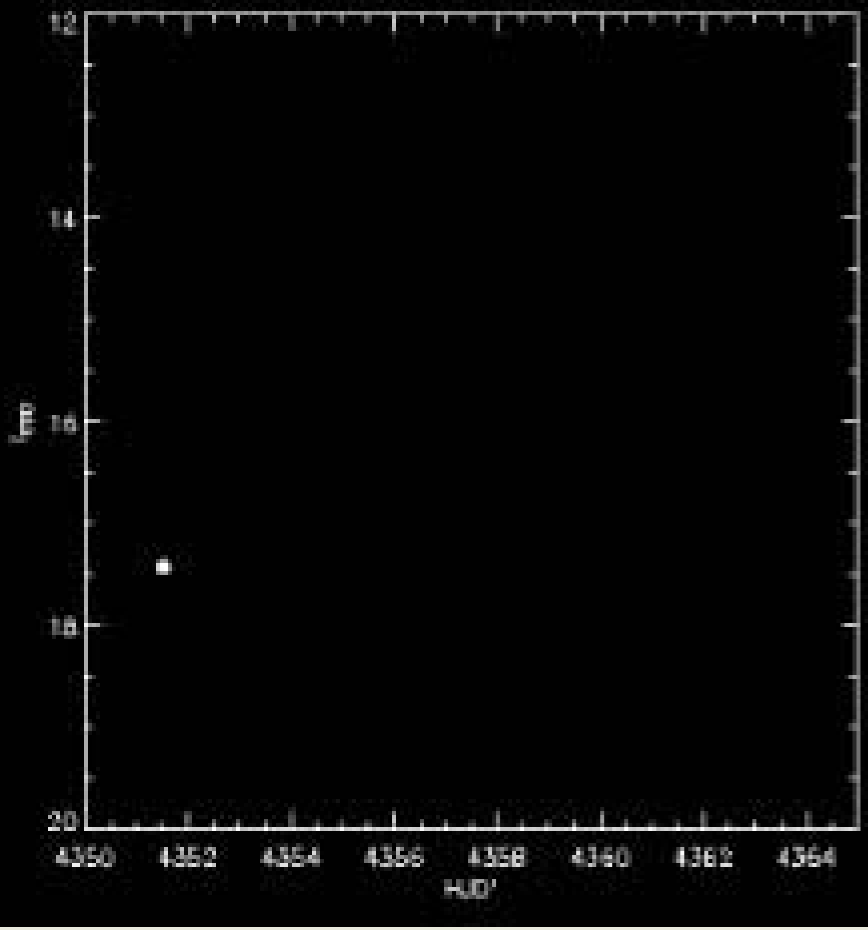
Achromatic (!) magnification due to gravitational lensing

There seem to be not enough brown dwarfs (or dark objects of similar mass) to account for the dark matter in the Milky Way !

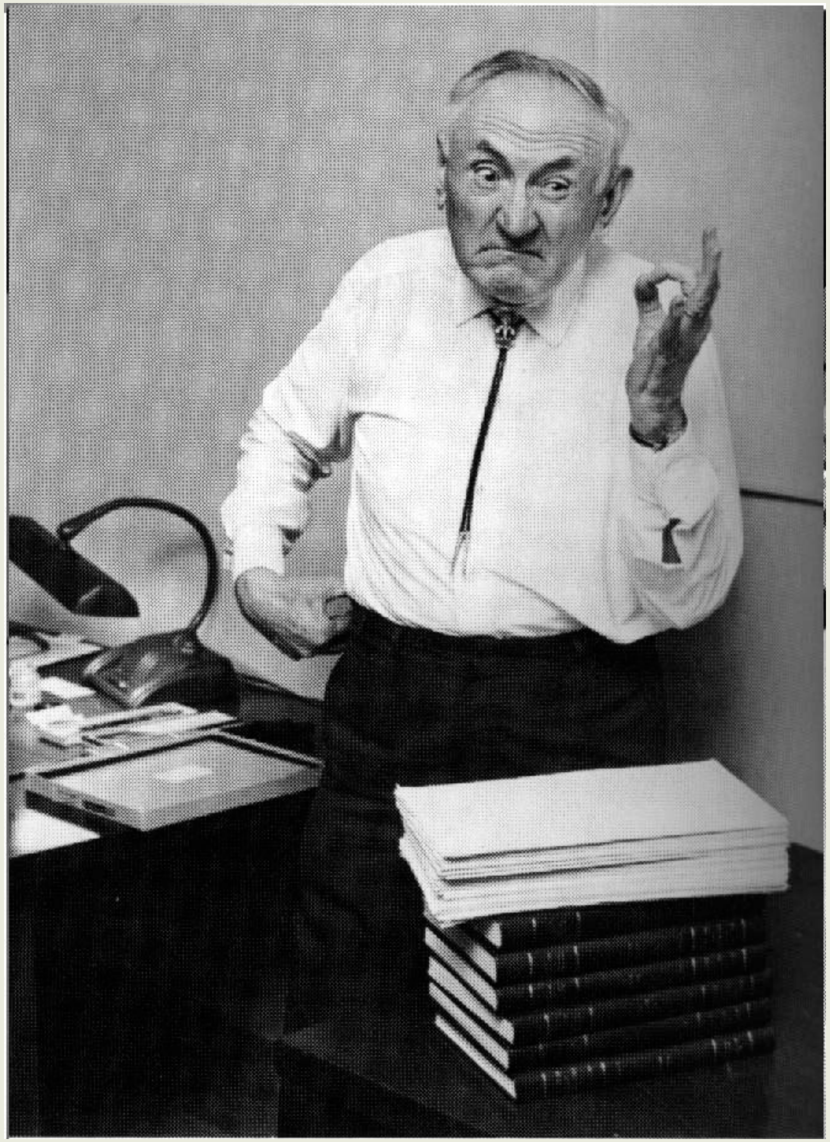
Other MACHO candidates



An OGLE MACHO candidate

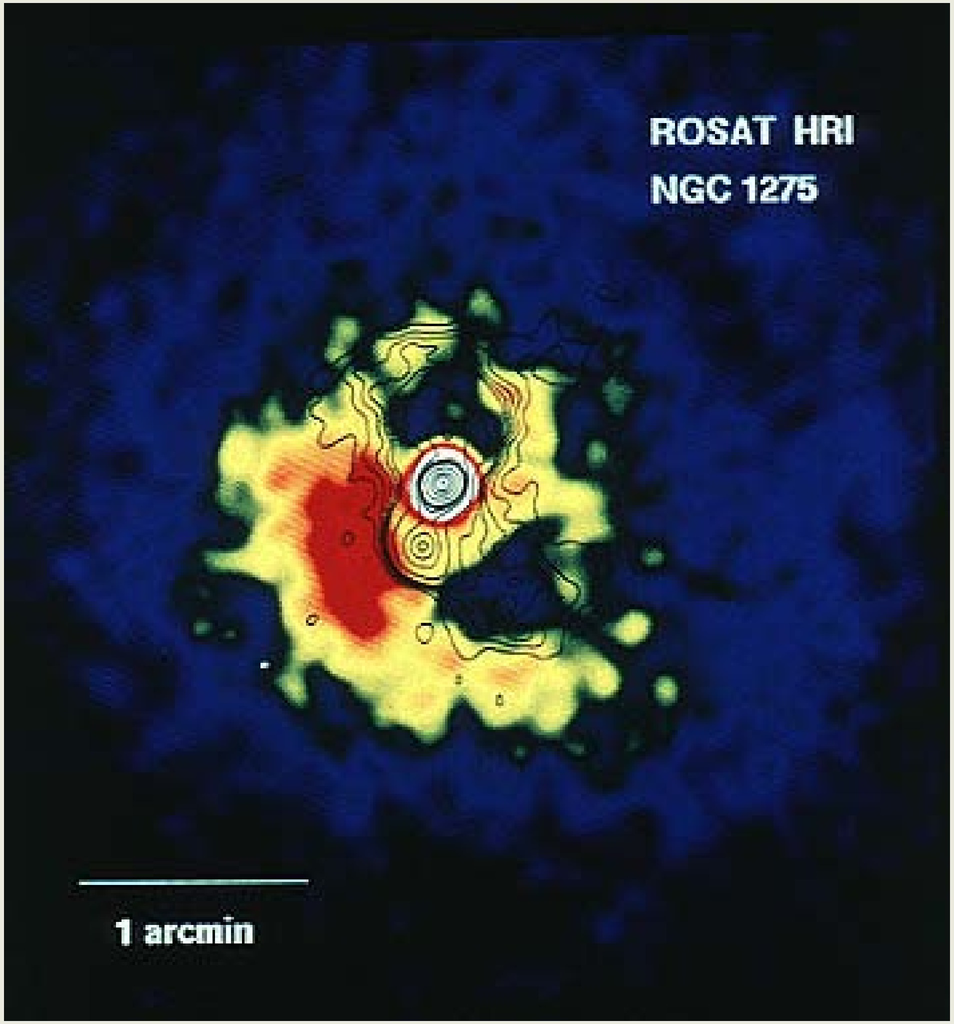


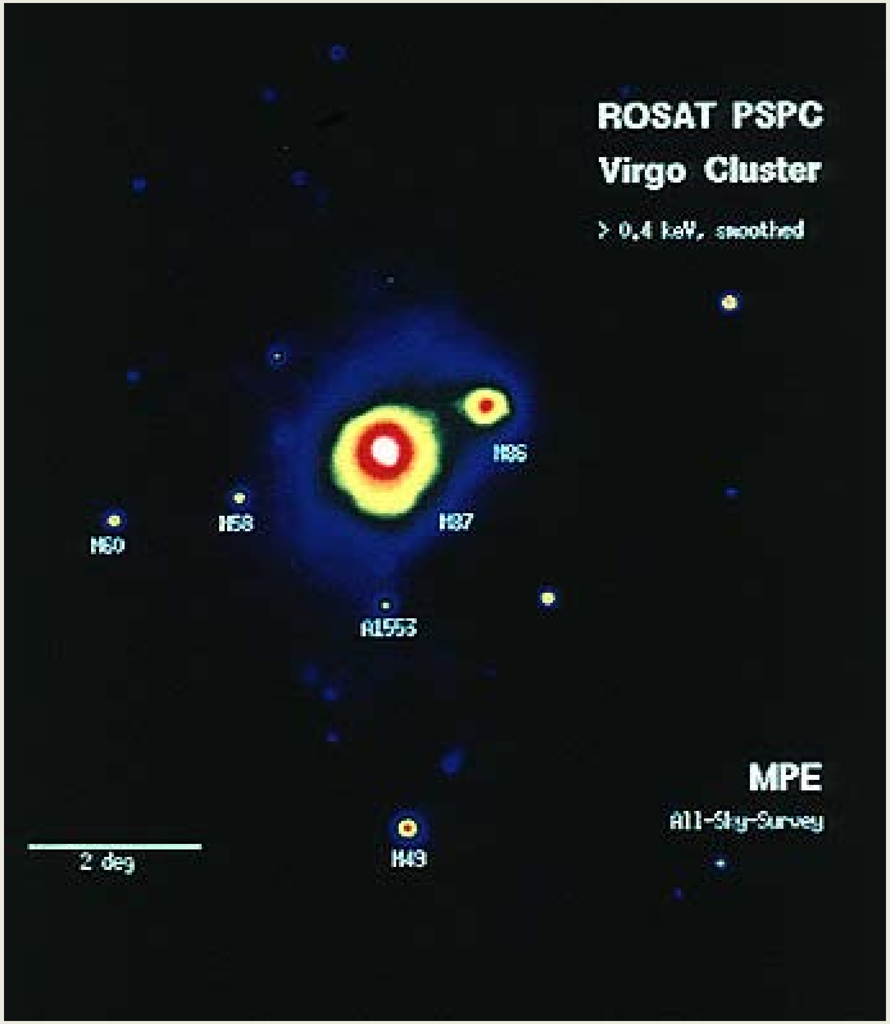
Fritz Zwicky



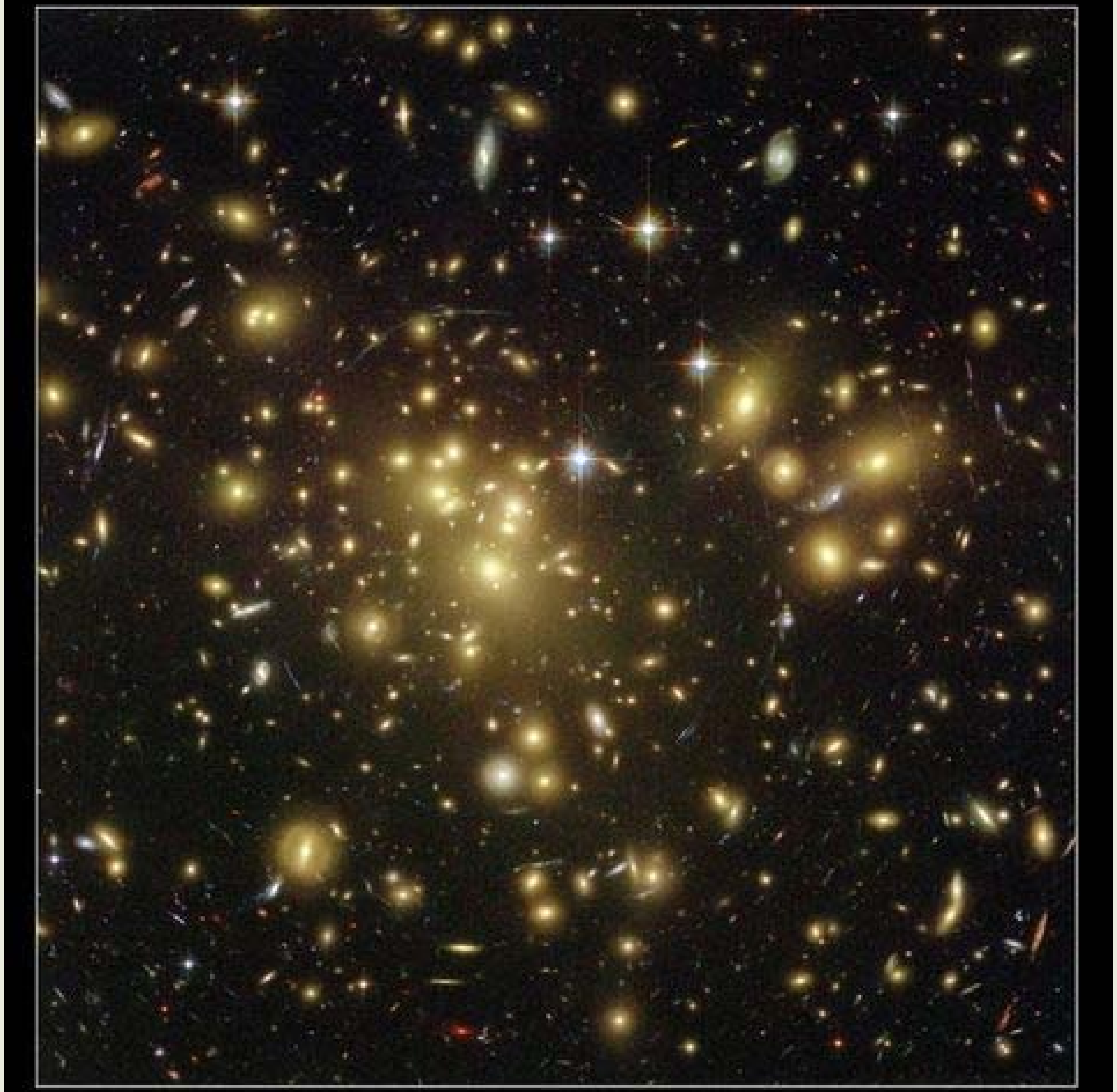
He measured the velocities of galaxies in galaxy clusters and concluded that most of the cluster's mass must be dark.

More evidence of dark matter: "X-ray clusters"





More evidence of dark matter: Galaxy clusters



Galaxy Cluster Abell 1689

Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Overall result:

$$\Omega_{matter} \approx 0.3$$

- Implications:
- Most of the mass in the Universe is dark
- Most of it is even of non-baryonic origin
- The perfect Copernican principle
  - The Earth is not at the center of the solar system
  - The Sun is not at the center of the Milky Way
  - The Milky Way is not at the center of the Universe
  - We may not even be made from the most abundant type of matter in the Universe

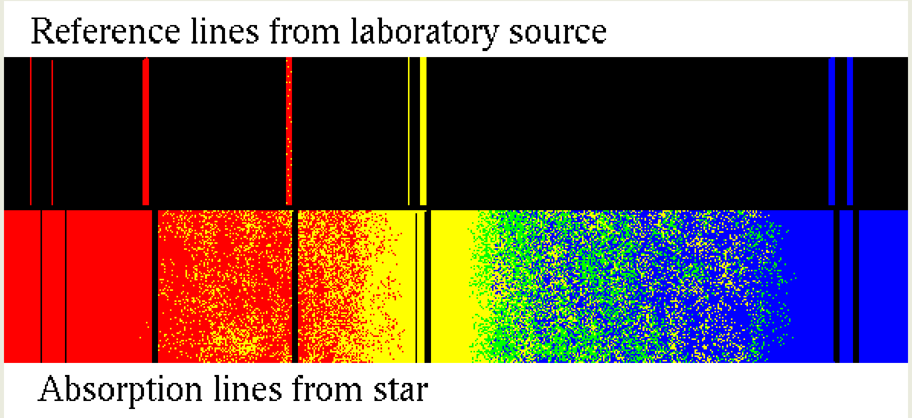
Edwin Hubble (1889-1953)

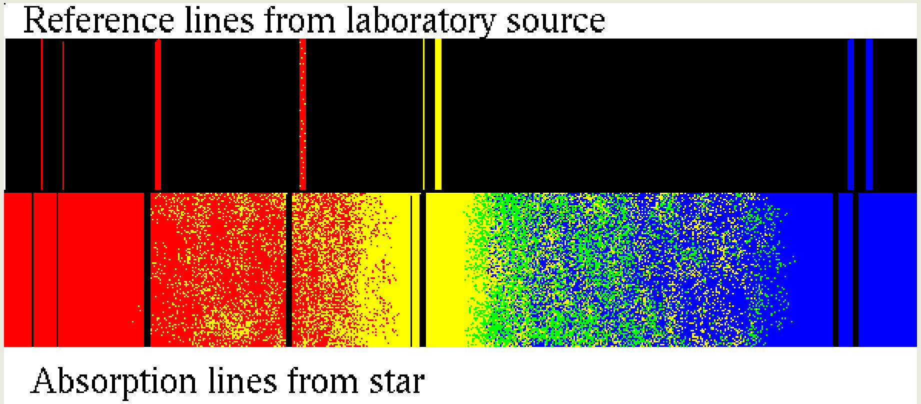
Four major accomplishments in extragalactic astronomy:

- The establishment of the Hubble classification scheme of galaxies
- The convincing proof that galaxies are island "universes"
- The distribution of galaxies in space
- The discovery that the universe is expanding

Doppler effect

The light of an approaching source is shifted to the blue, the light of a receding source is shifted to the red.





blue shift

red shift

Doppler effect

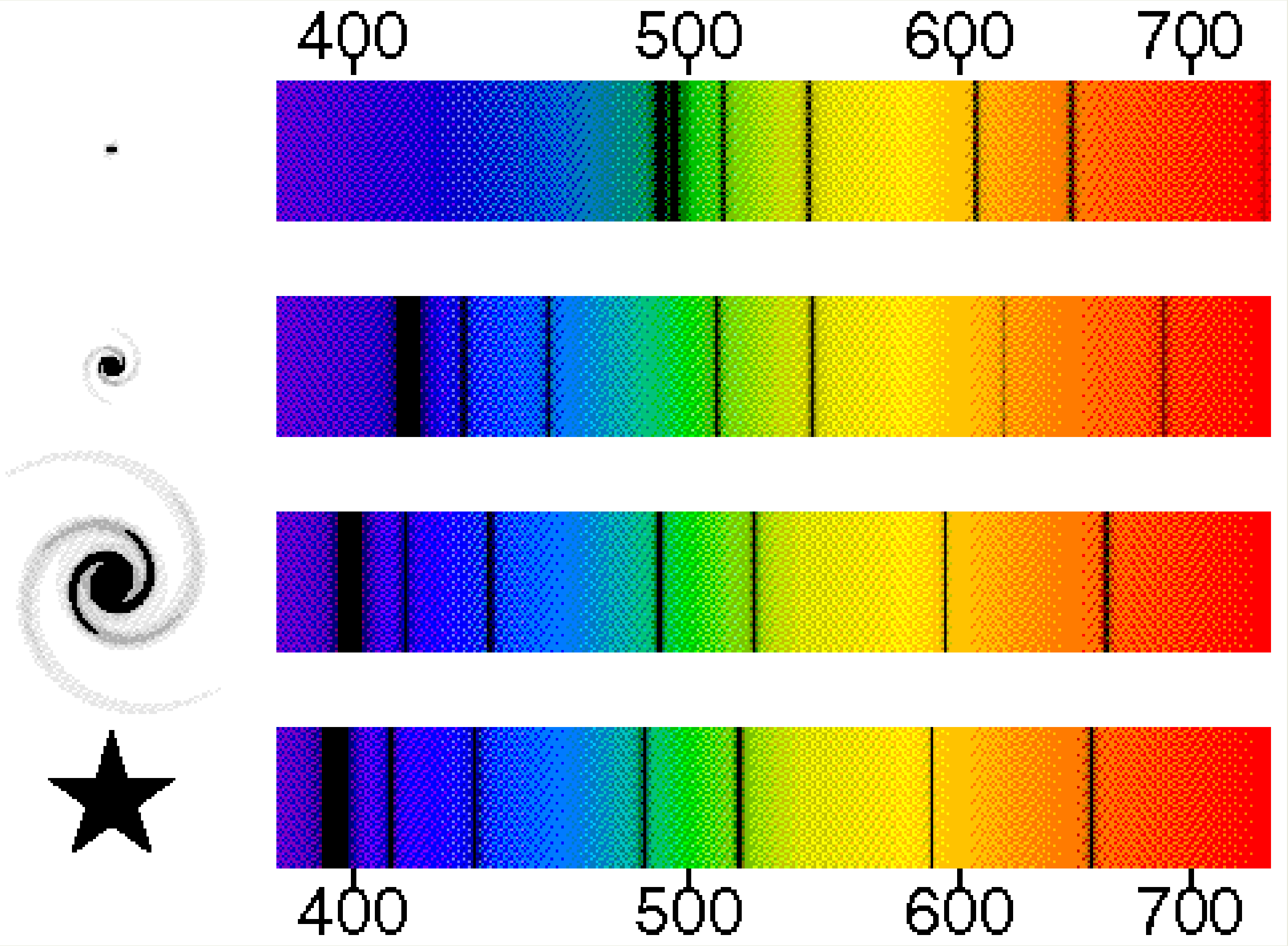
redshift:

$$1+z=\sqrt{\frac{1+v/c}{1-v/c}}$$

z=0: not moving

z=2: *v*=0.8*c*

z=∞: *v*=*c*



The redshift-distance relation

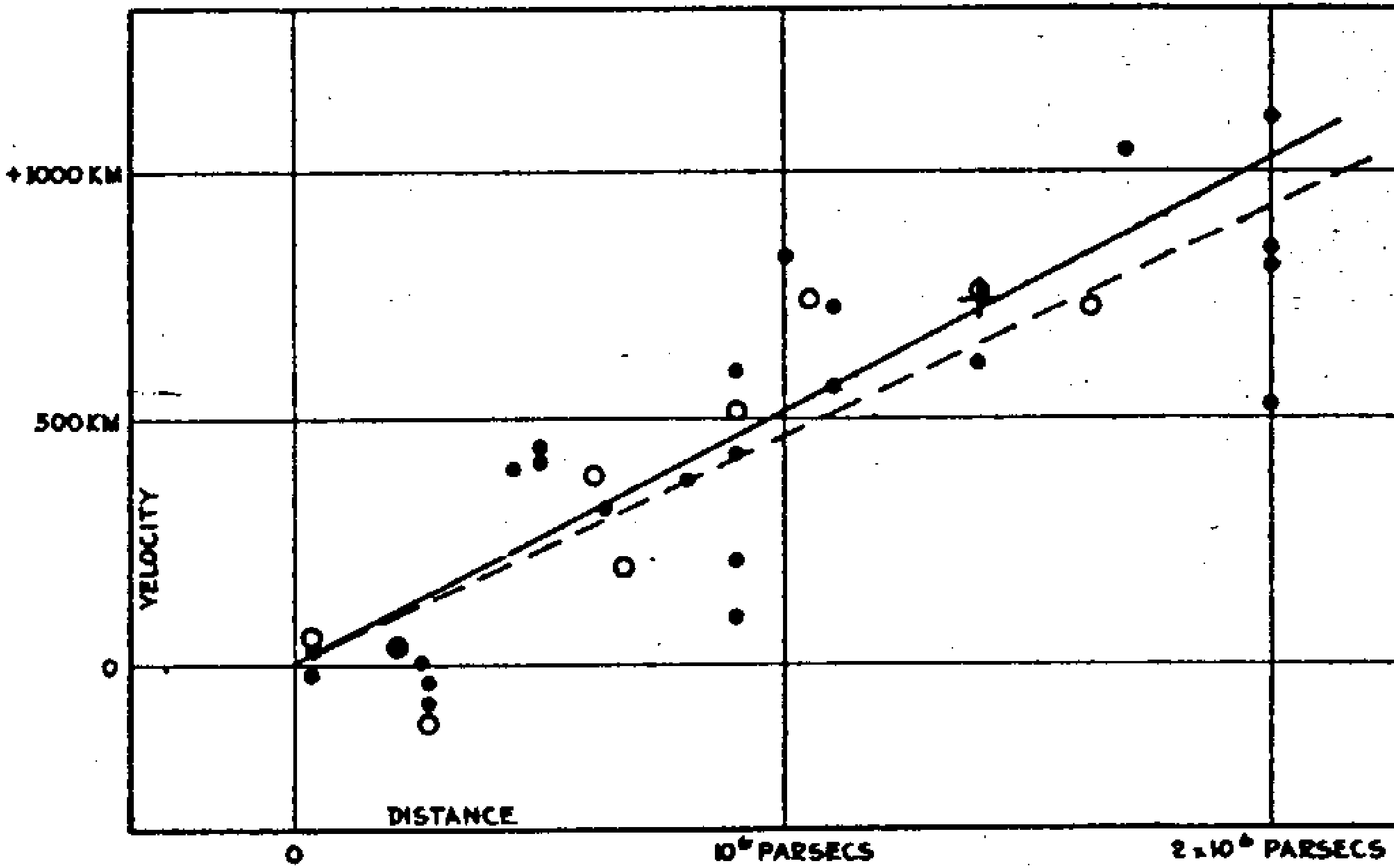
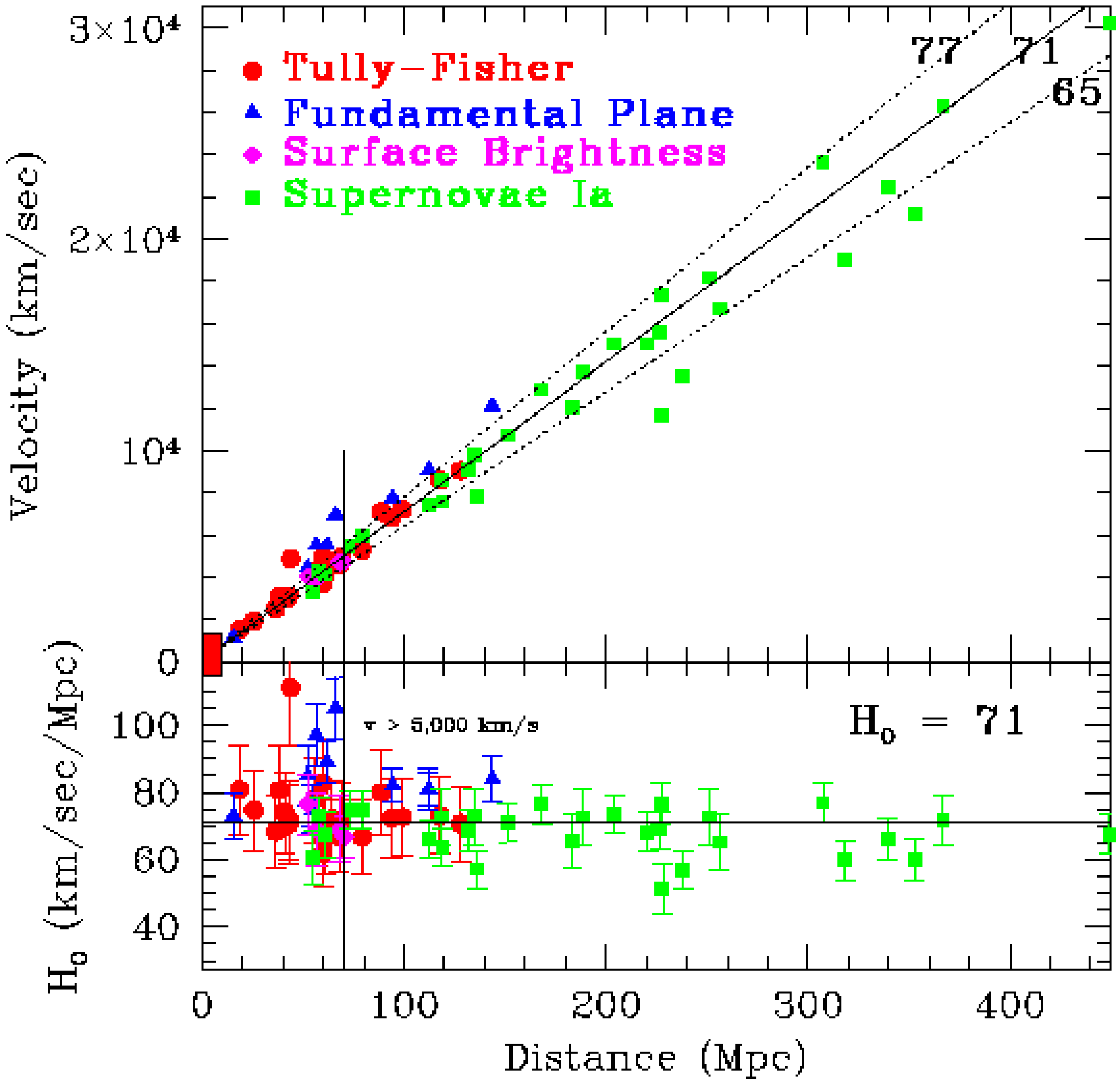


FIGURE 1

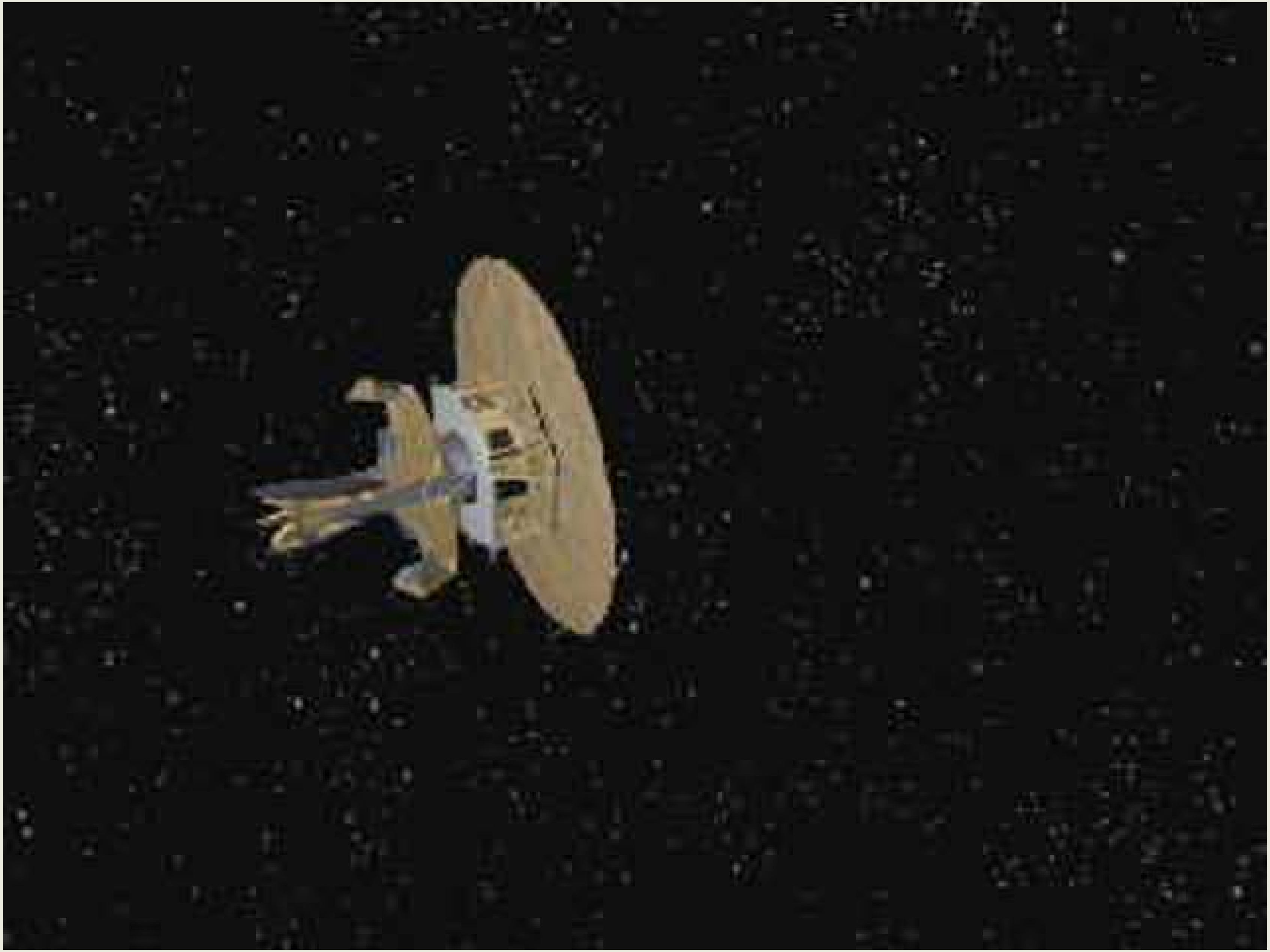
A “modern” Hubble diagram

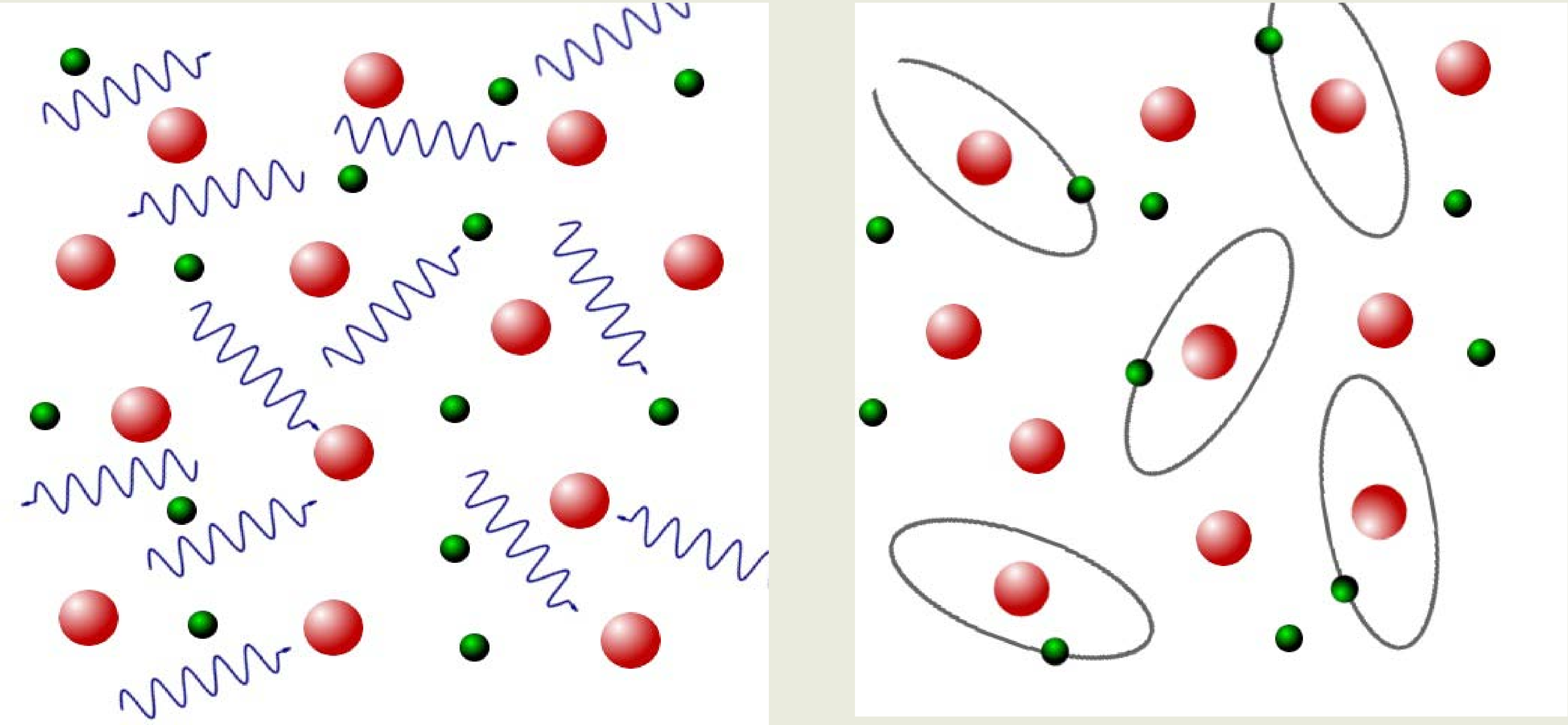


"HE HAD THE PRESENCE OF MIND THOSE DAYS TO TAKE A SNAP OF THE BIG BANG. HE STILL THINKS THAT IT'S RATHER IMPRESSIVE"

Georgy Gamov (1904-1968)

- If the universe is expanding, then there has been a big bang
- Therefore, the early universe must have been very dense and hot
- Optimum environment to breed the elements by nuclear fusion (Alpher, Bethe & Gamow, 1948)
  - success: predicted that helium abundance is 25%
  - failure: could not reproduce elements more massive than lithium and beryllium (⇒ formed in stars)

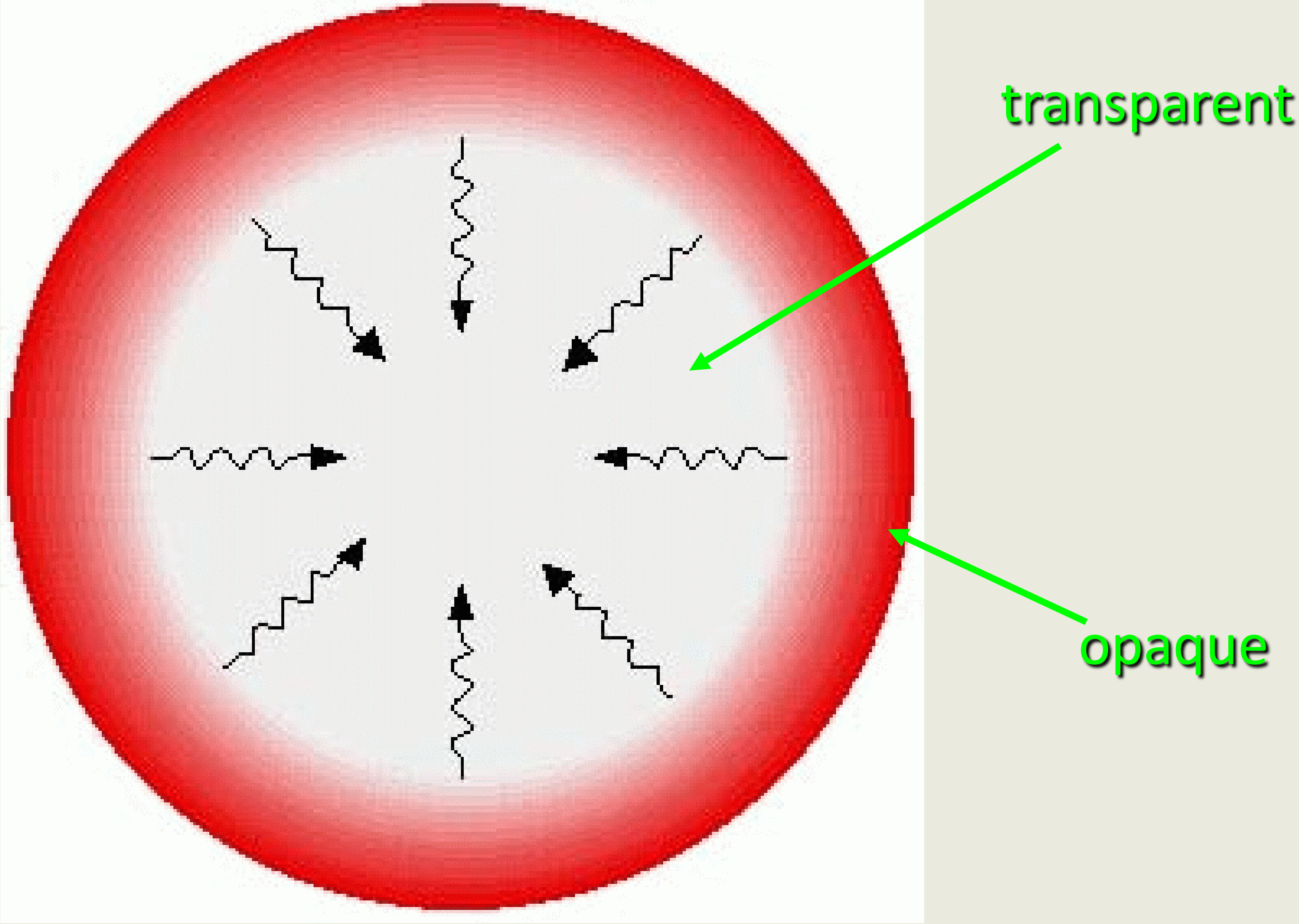




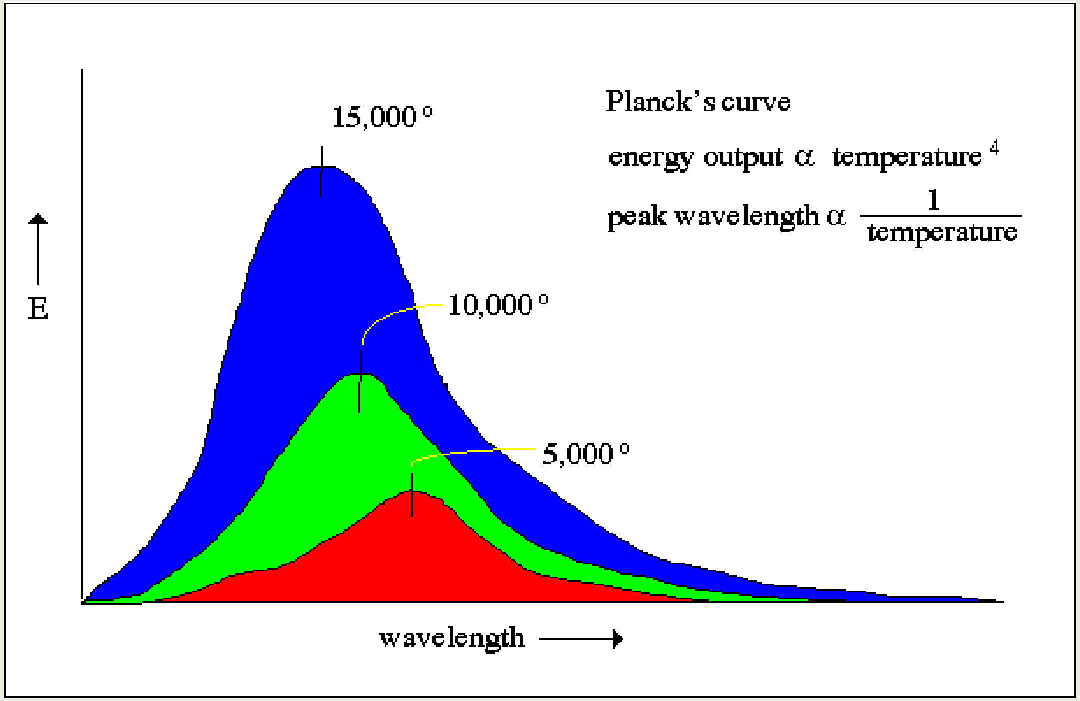
Before recombination: *The Universe is opaque*
After recombination: *The Universe is transparent*

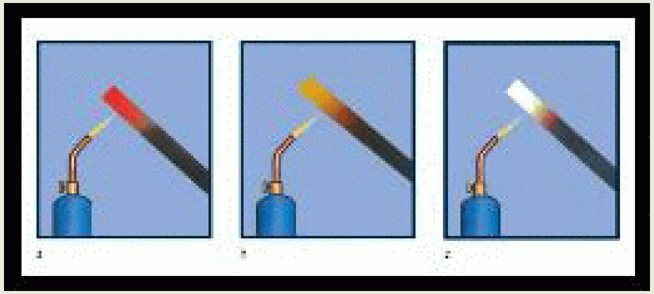
Transition ~ 300 000 years after the Big Bang

Last scattering surface



Black body radiation





- A hot body is brighter than a cool one ($L \propto T^4$, Stefan-Boltzmann's law)
- A hot body's spectrum is bluer than that of a cool one ($\lambda_{max} \propto 1/T$, Wien's law)

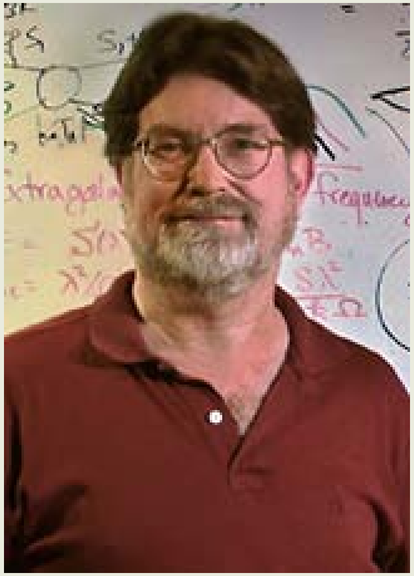
Penzias and Wilson 1965

- Working at Bell labs
- Used a satellite dish to measure radio emission of the Milky Way
- They found some extra noise in the receiver, but couldn’t explain it
  ⇒ discovery of the background radiation
- Most significant cosmological observation since Hubble
- Nobel prize for physics 1978

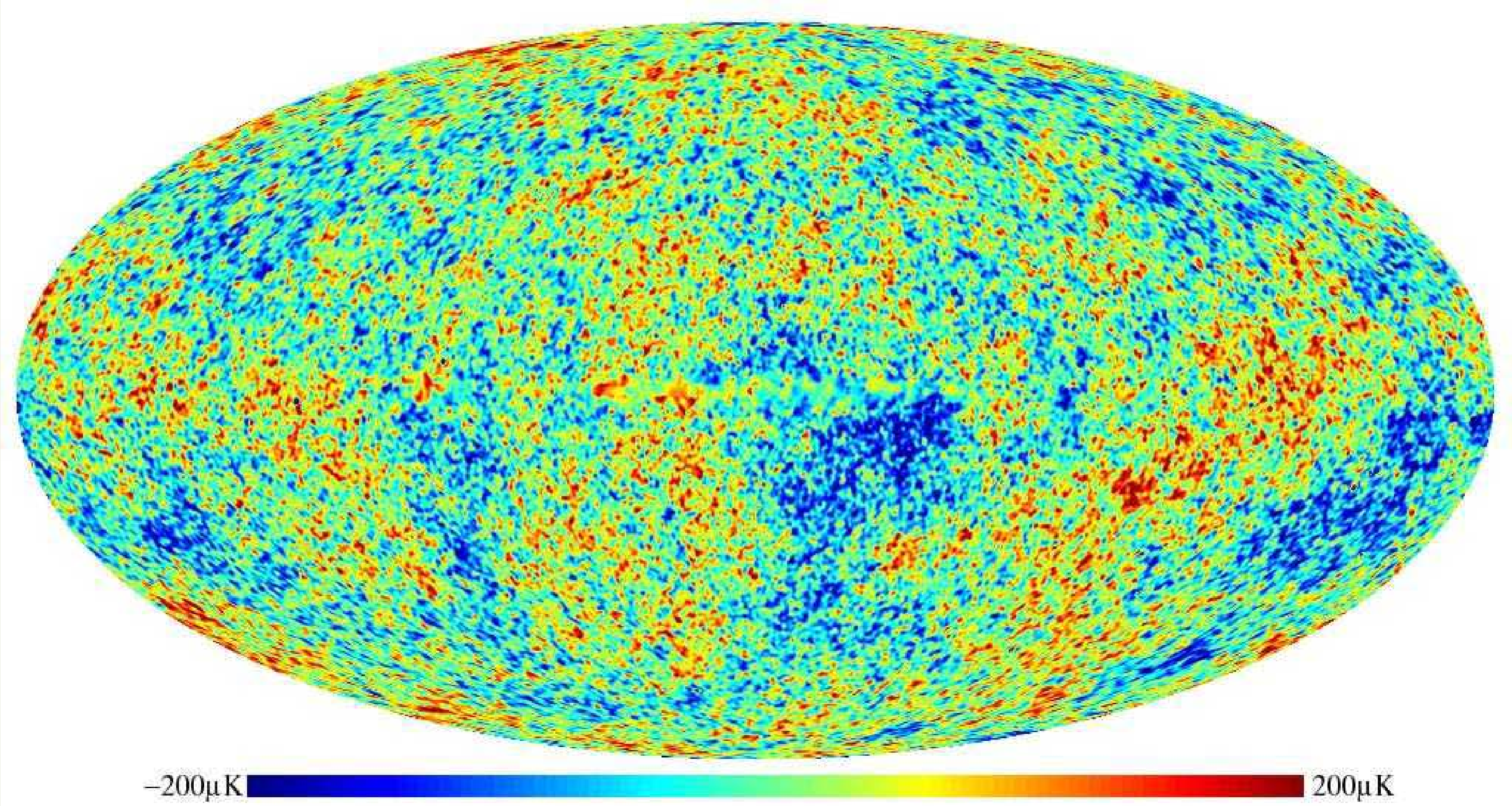
Nobel Price in Physics 2006 for COBE:

John Mather

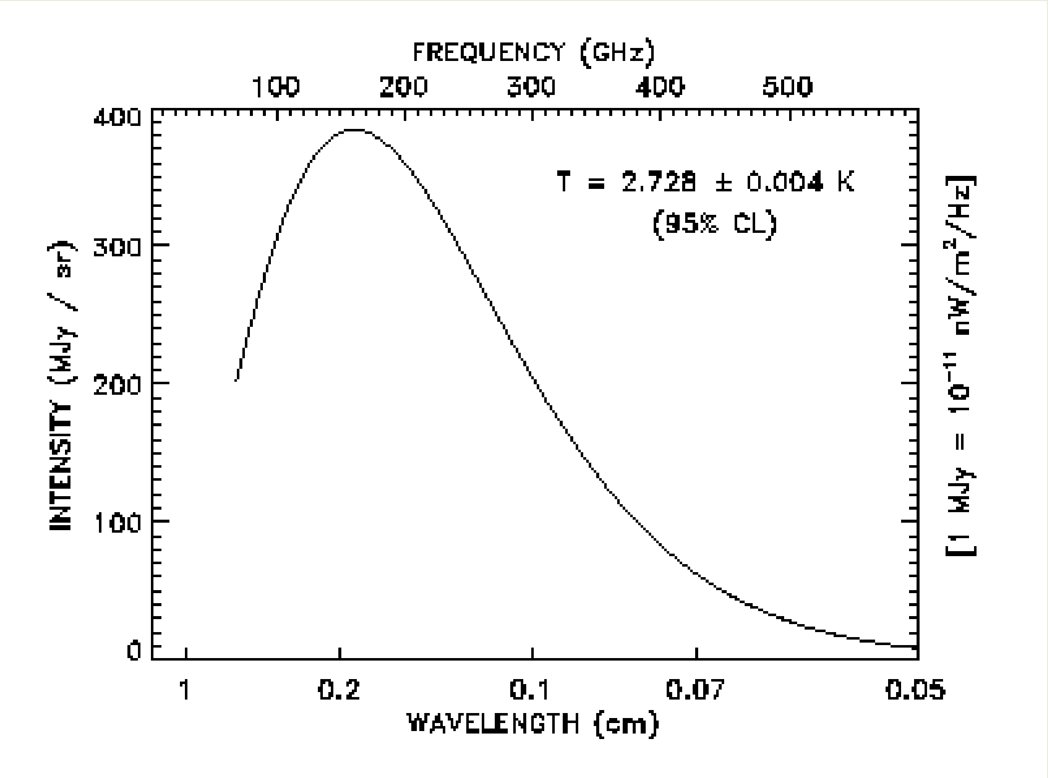
George Smoot



Results from WMAP



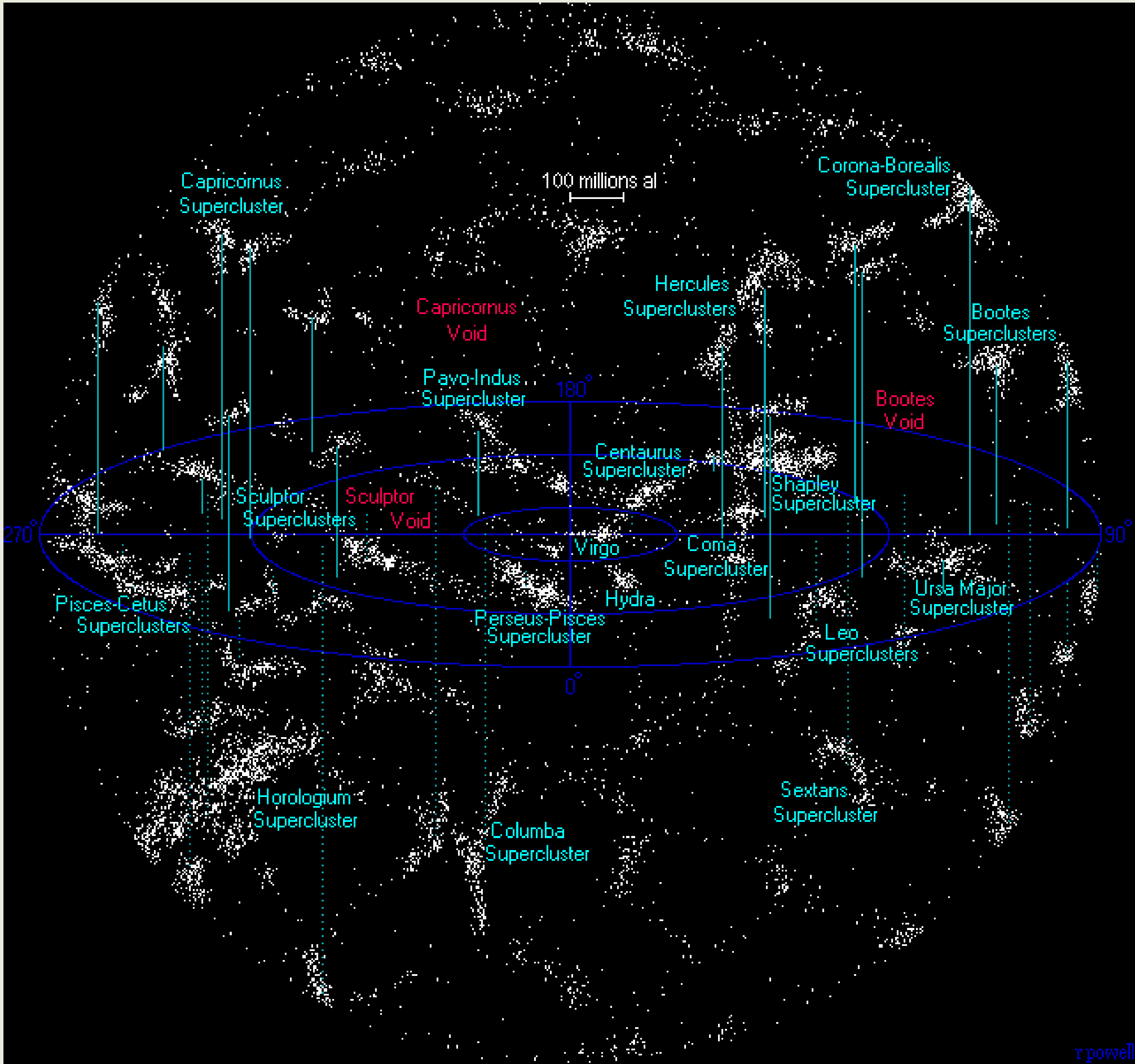
The cosmic microwave background radiation (CMB)



- Temperature of 2.728±0.004 K
- Isotropic to 1 part in 100 000
- Perfect black body
- 1990ies: CMB is one of the major tools to study cosmology
- Note: ~1% of the noise in your TV is from the big bang

How good is the assumption of isotropy?

- CMB: almost perfect
- But what about the closer neighbor-hood ?



How good is the assumption of isotropy?

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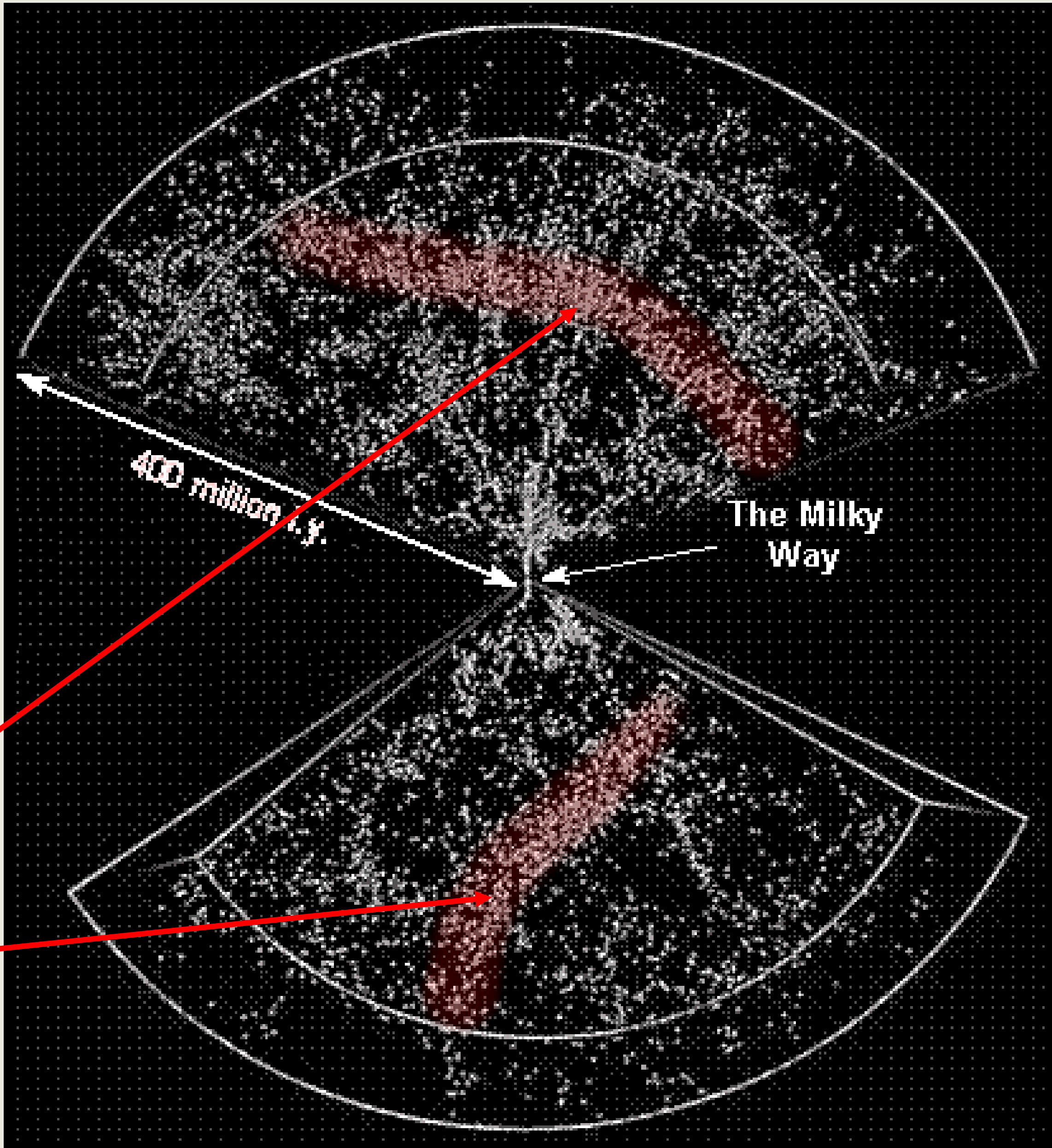
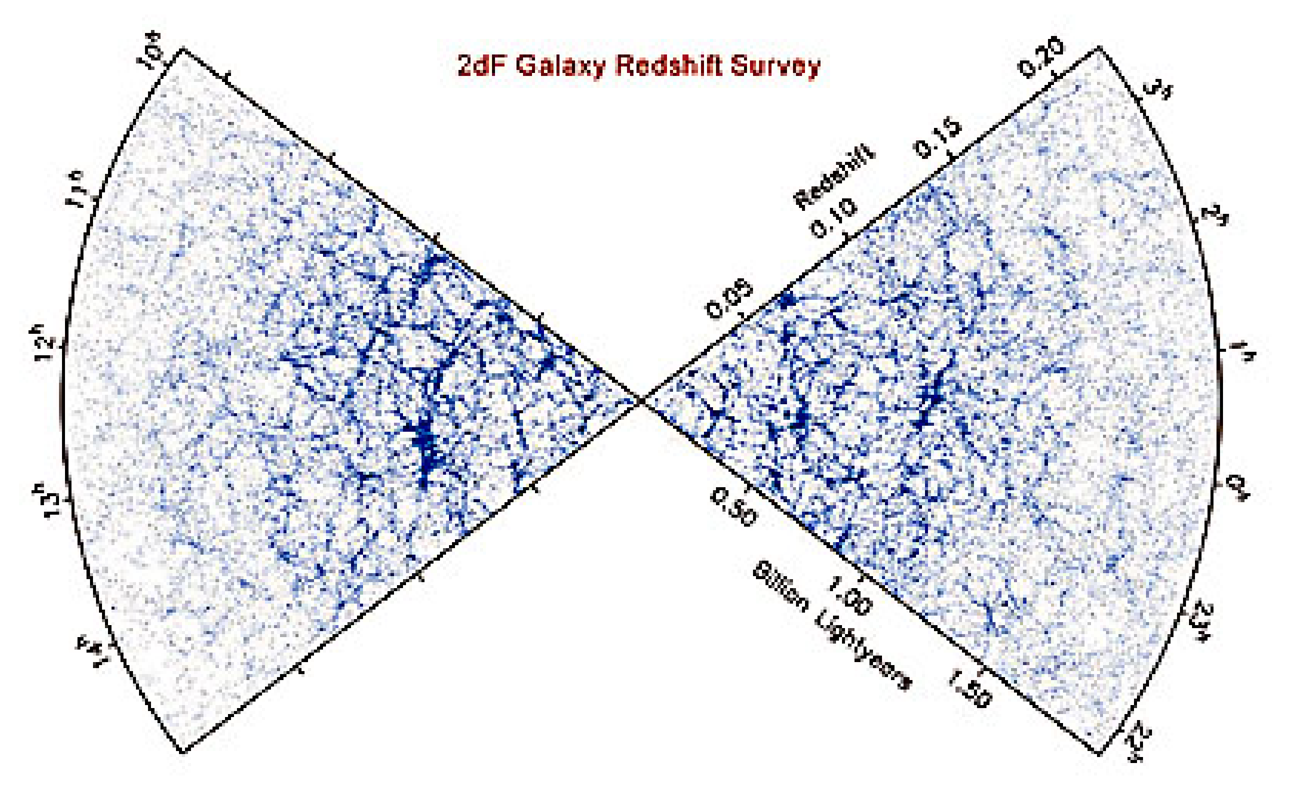


The "great wall"

The spatial distribution of galaxies

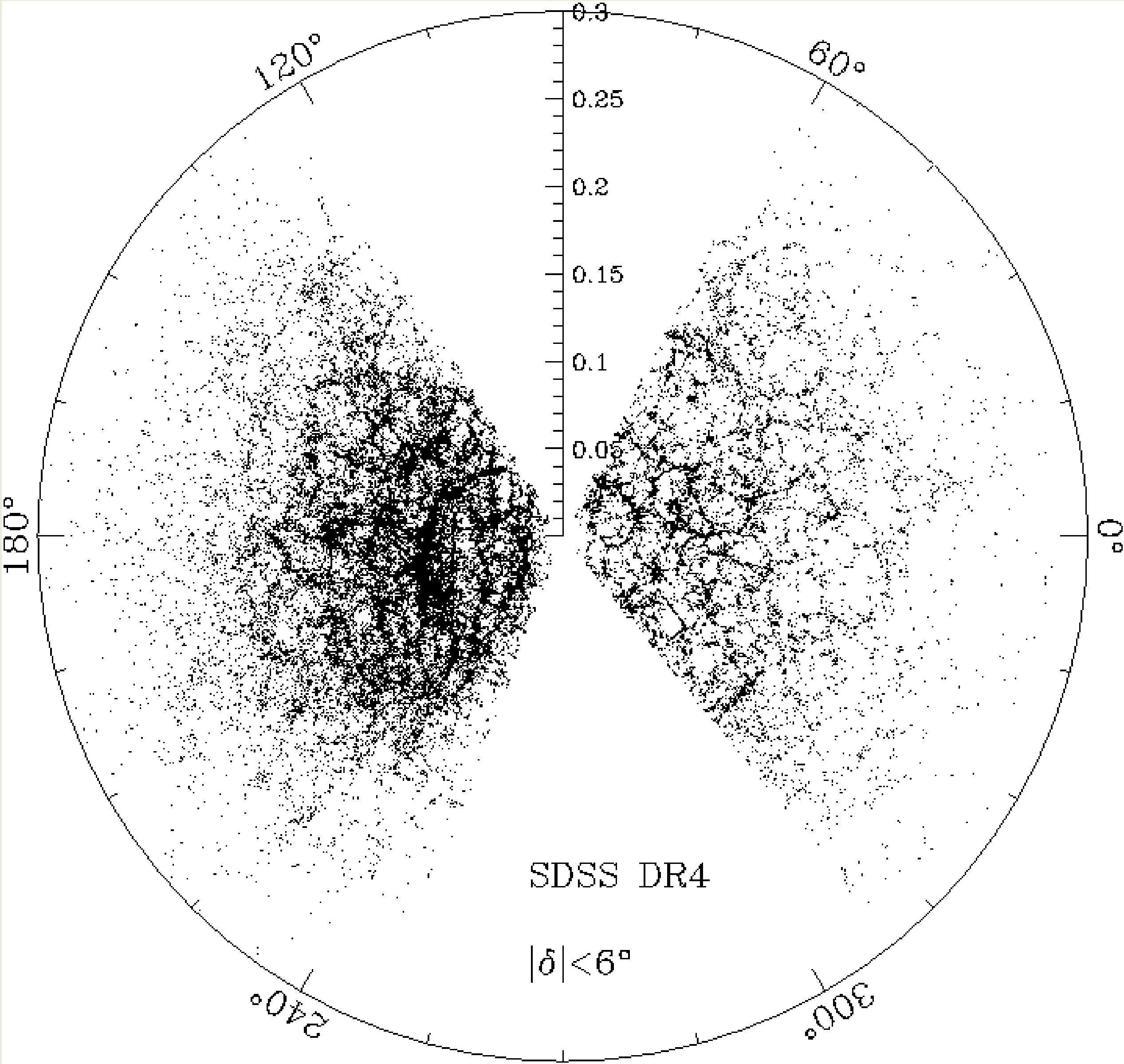
- Galaxies are not randomly distributed but correlated
- Network of structures (filaments, sheets, walls) ⇒ “cosmic web”



The spatial distribution of galaxies

- Data from the most recent survey:

  SDSS



The entire Universe in one line

$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

Geometry of
spacetime
(Einstein tensor)

Distribution of
mass and energy
in the universe
(stress-energy tensor)

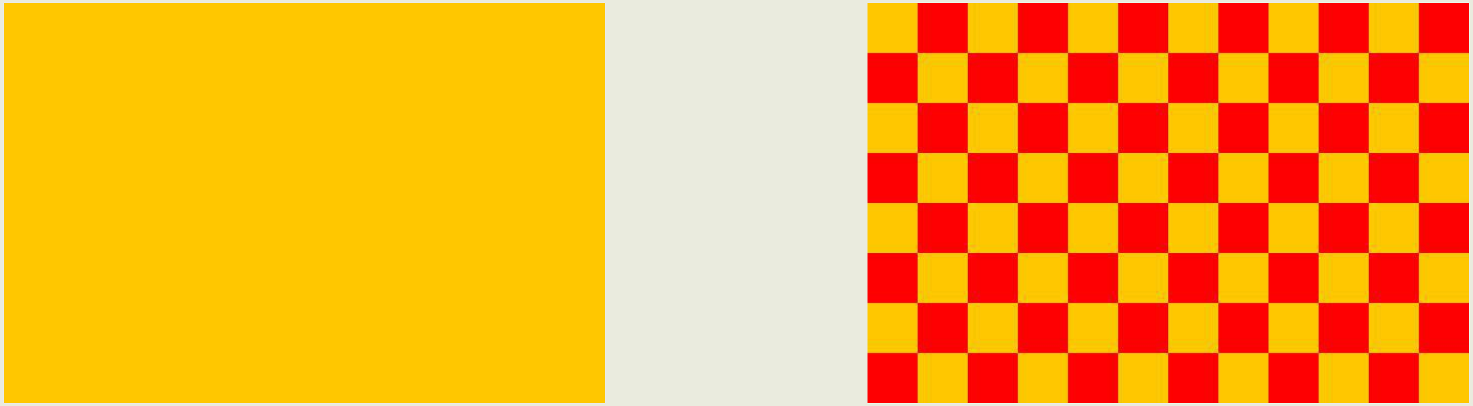
Some effects predicted by the theory of general relativity

- Gravity bends light
- Gravitational redshift
- Gravitational time dilation
- Gravitational length contraction

The cosmological principle

- Homogeneous: the universe looks the same everywhere on large scales
  $\Rightarrow$ there is no special place (center)
- Isotropic: the universe looks the same in all directions on the sky

  $\Rightarrow$ there is no special direction (axis)



The perfect cosmological principle

- Homogeneous: the universe looks the same everywhere on large scales
  ⇒ there is no special place (center)
- Isotropic: the universe looks the same in all directions on the sky
  ⇒ there is no special direction (axis)
- Unchanging: The universe looks the same at all times
  ⇒ there is no special epoch

Homogeneity and Isotropy

Isotropy + Copernican Principle ⇒ Homogeneity

Isotropy + Isotropy around another point ⇒ Homogeneity

A metric of an expanding Universe

- Recall: flat space

$$\Delta s^2 = (c\Delta t)^2 - \Delta x^2 - \Delta y^2 - \Delta z^2$$

- better: using spherical coordinates (r, θ, ϕ)

$$\Delta s^2 = (c\Delta t)^2 - (\Delta r^2 + r^2 \Delta\theta^2 + r^2 \sin^2\theta \, \Delta\phi^2)$$

A metric of an expanding Universe

- But, this was for a static (flat) space. How does this expression change if we consider an expanding space ?

$$\Delta s^2 = (c\Delta t)^2 - a^2(t)\left(\Delta r^2 + r^2\Delta\theta^2 + r^2\sin^2\theta\,\Delta\phi^2\right)$$

- *a(t)* is the so-called scale factor

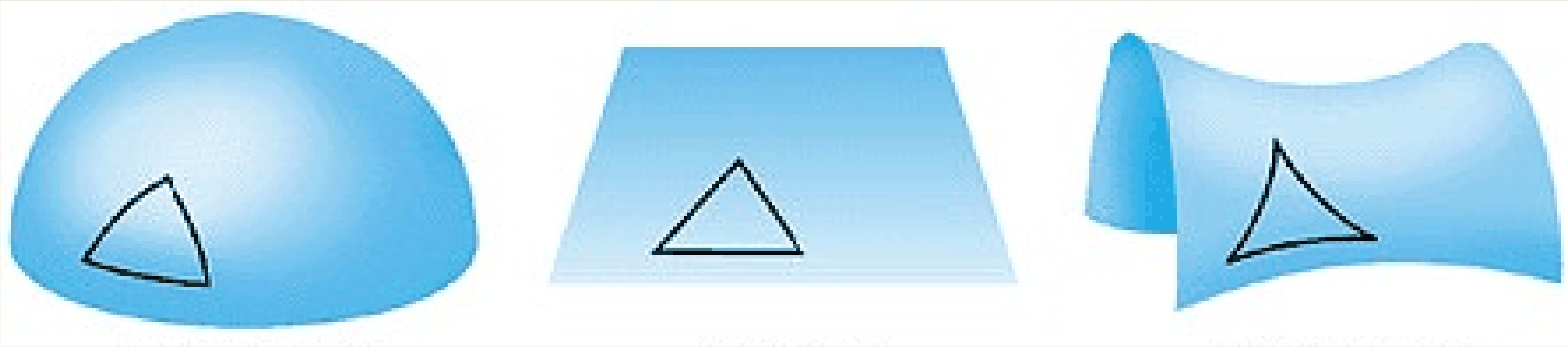
A metric of an expanding Universe

- Robertson-Walker metric

$$\Delta s^2 = (c\Delta t)^2 - a^2(t)\left(\frac{\Delta r^2}{1-kr^2} + r^2\Delta\theta^2 + r^2\sin^2\theta\,\Delta\phi^2\right)$$

- *a(t)* is the scale factor
- *k* is the curvature constant
  - *k=0*: flat space
  - *k>0*: spherical geometry
  - *k<0*: hyperbolic geometry

A metric of an expanding Universe



$k>0$ **$k=0$** **$k<0$**

- k is the curvature constant
  - $k=0$: flat space
  - $k>0$: spherical geometry
  - $k<0$: hyperbolic geometry

Euclidean (flat) geometry:

- Given a line and a point not on the line, only one line can be drawn through that point that will be parallel to the first line
- The circumference of a circle of radius r is $2\pi r$
- The three angles of a triangle sum up to 180°

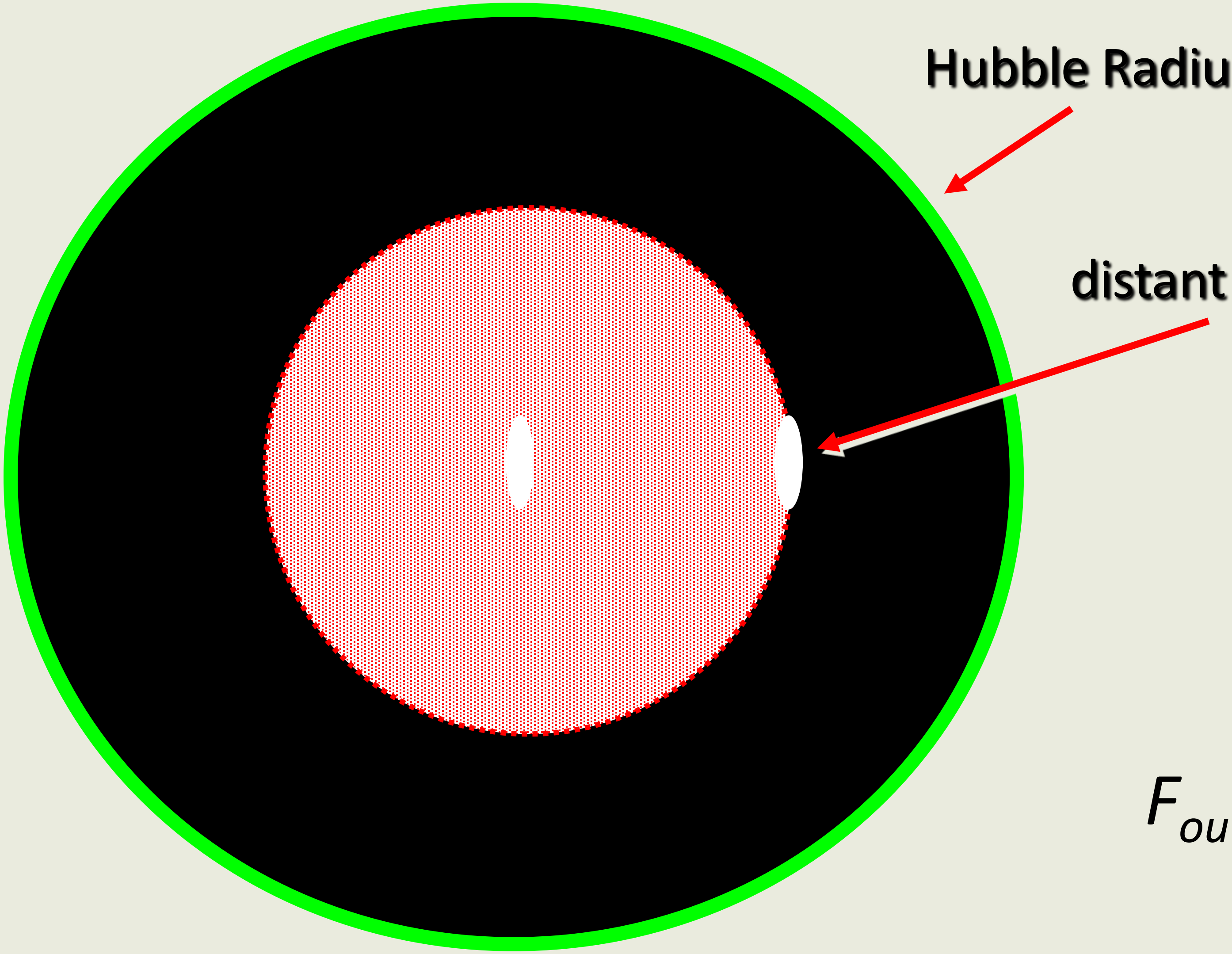
Spherical geometry:

- Given a line and a point not on the line, no line can be drawn through that point that will be parallel to the first line
- The circumference of a circle of radius r is smaller than $2\pi r$
- The three angles of a triangle sum up to more than 180°

Hyperbolic geometry:

- Given a line and a point not on the line, an infinite number of lines can be drawn through that point that will be parallel to the first line
- The circumference of a circle of radius r is larger than $2\pi r$
- The three angles of a triangle sum up to less than 180°

Can we calculate a(t) ?

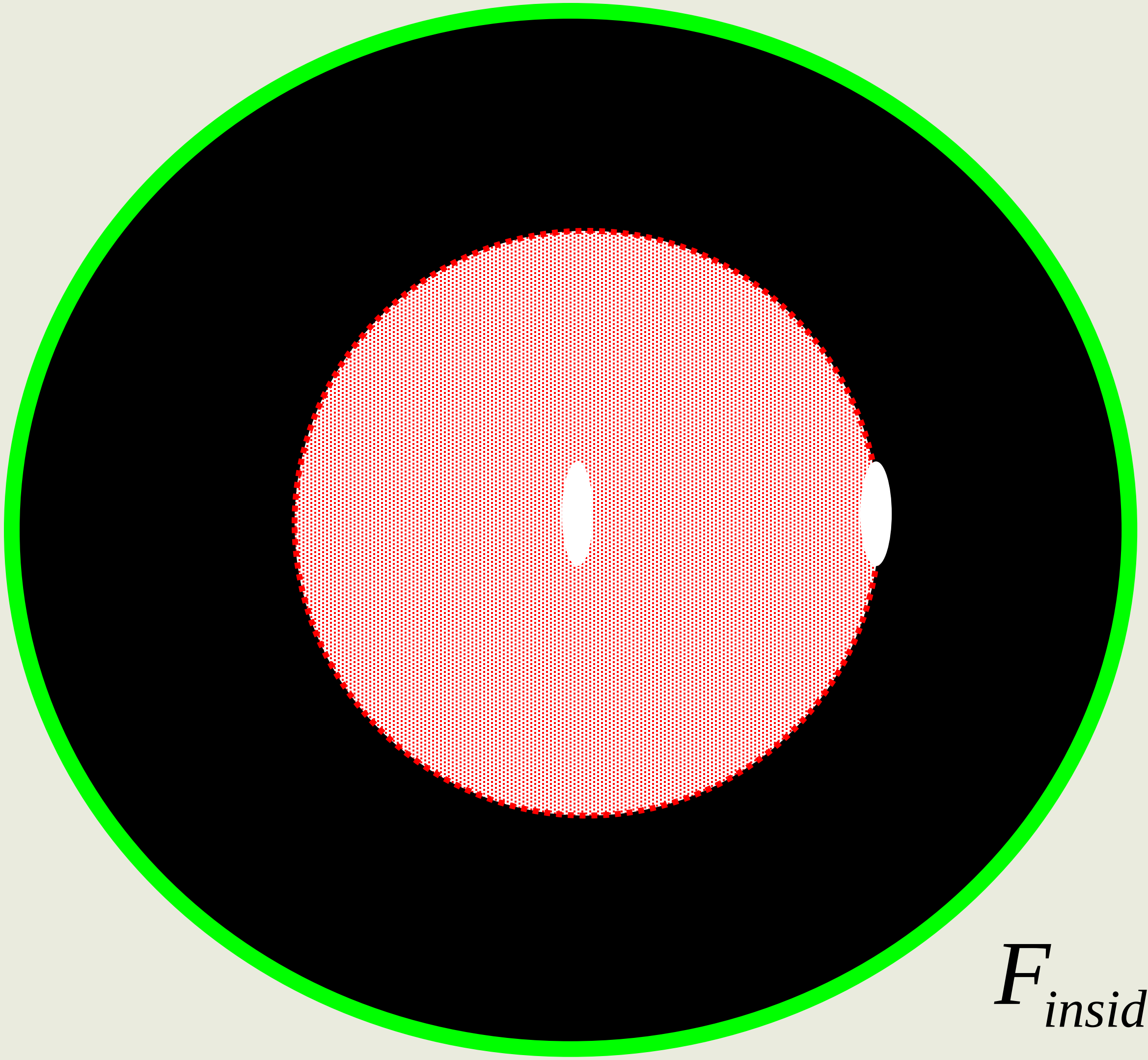


Hubble Radius

distant galaxy

$$F_{outside} = 0$$

Can we calculate a(t) ?



$$F_{inside} = -G\frac{M_{inside}m_{gal}}{R^2}$$

What is the future of that galaxy ?

- Critical velocity: escape speed

$$v_{esc} = \sqrt{\frac{2GM_{inside}}{a}}$$

- $v<v_{esc}$: galaxy eventually stops and falls back
- $v>v_{esc}$: galaxy will move away forever

Let’s rewrite that a bit ...

$$v^2 = \frac{2GM_{inside}}{a} + 2\varepsilon_\infty$$

- $\varepsilon_\infty < 0 \Rightarrow v < v_{esc}$: galaxy eventually stops and falls back
- $\varepsilon_\infty > 0 \Rightarrow v > v_{esc}$: galaxy will move away forever

Let’s rewrite that a bit ...

- Homogeneous sphere of density ρ :

$$M_{inside} = \frac{4\pi}{3} \rho\, a^3$$

- so for the velocity:

$$v^2 = \frac{8\pi G}{3} \rho a^2 + 2\varepsilon_\infty$$

- but what is ε_∞ ?

Let’s switch to general relativity

- Friedmann equation

$$v^2 = \frac{8\pi G}{3}\rho a^2 - kc^2$$

- same *k* as in the Robertson-Walker metric

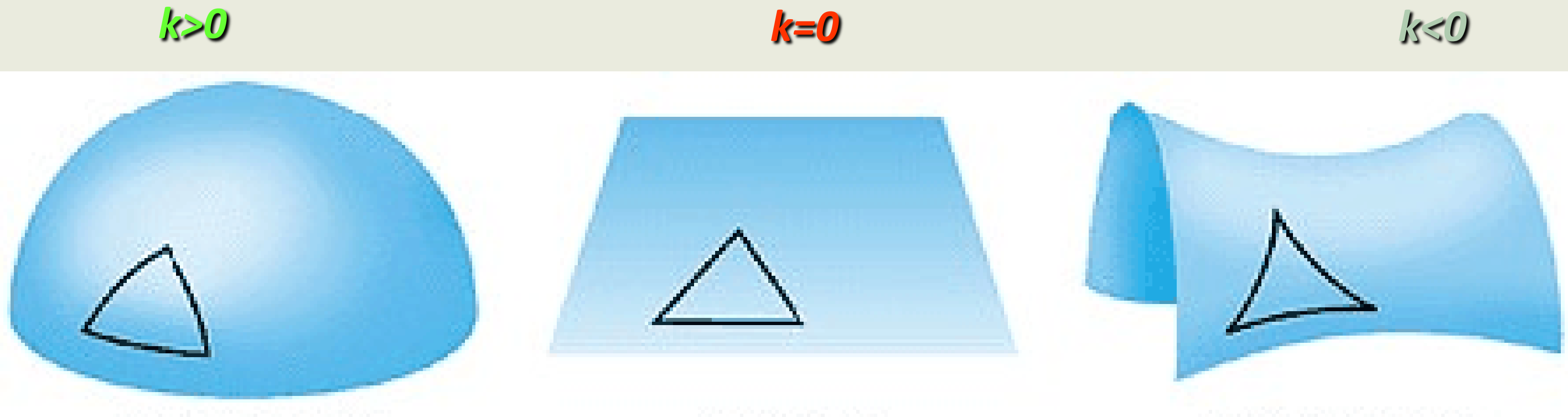
$$\Delta s^2 = (c\Delta t)^2 - a^2(t)\left(\frac{\Delta r^2}{1-kr^2} + r^2\Delta\theta^2 + r^2\sin^2\theta\,\Delta\phi^2\right)$$

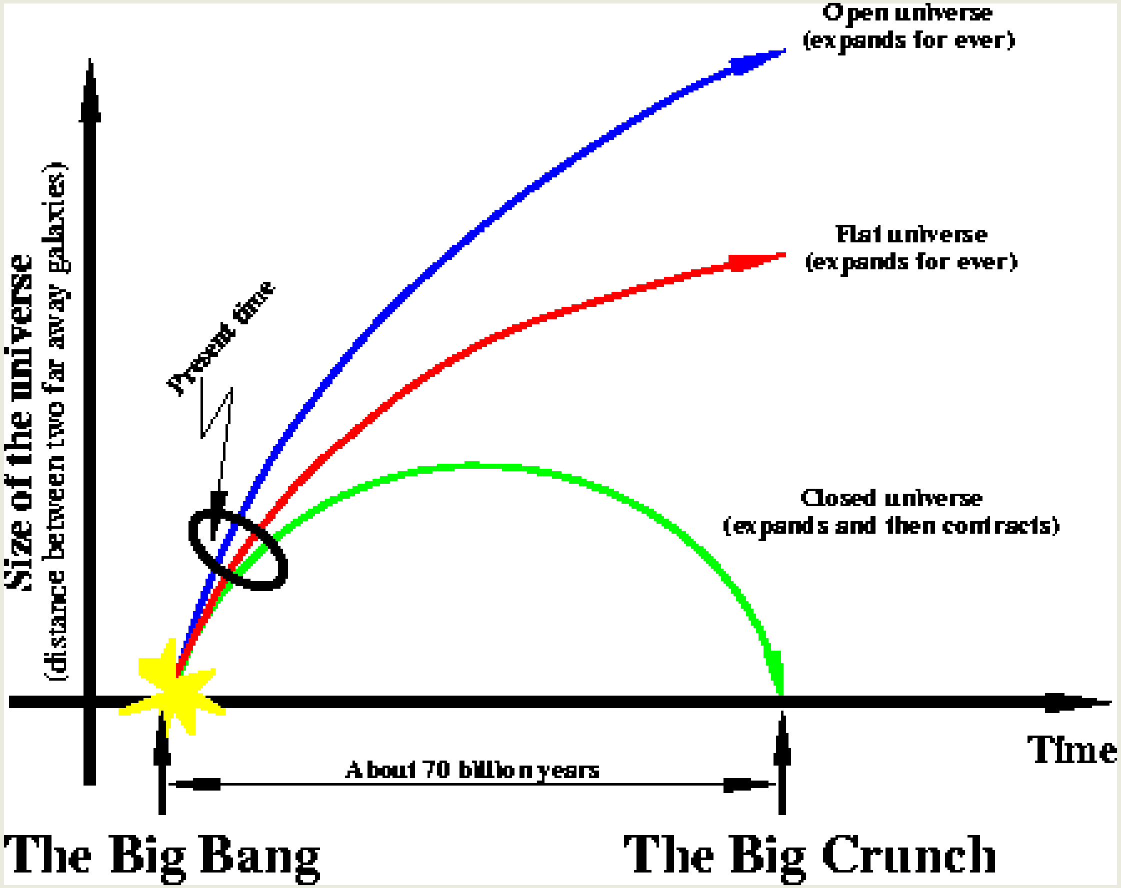
Let’s switch to general relativity

- Friedmann equation

$$v^2 = \frac{8\pi G}{3}\rho a^2 - kc^2$$

- *k* is the curvature constant
  - *k=0*: flat space, forever expanding
  - *k>0*: spherical geometry, eventually recollapsing
  - *k<0*: hyperbolic geometry, forever expanding


k>0
k=0
k<0


Open universe
(expands for ever)
Flat universe
(expands for ever)
Closed universe
(expands and then contracts)
Present time
Size of the universe
(distance between two far away galaxies)
Time
About 70 billion years
The Big Bang
The Big Crunch

Cosmological redshift

- While a photon travels from a distance source to an observer on Earth, the Universe expands in size from a_{then} to a_{now}.
- Not only the Universe itself expands, but also the wavelength of the photon λ.

$$\lambda_{received} = \frac{a_{now}}{a_{then}} \lambda_{emitted}$$

Cosmological redshift

- General definition of redshift:

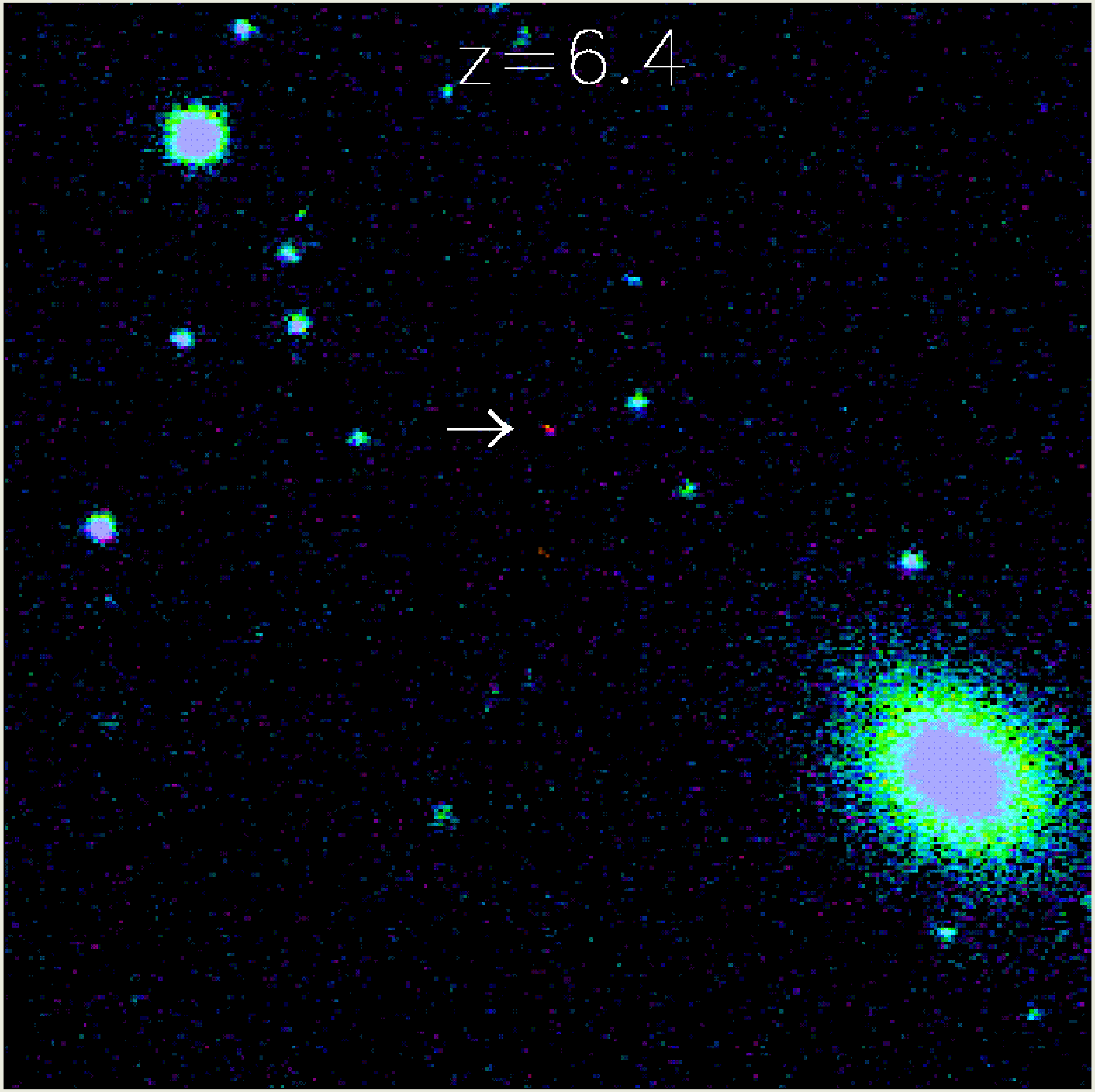
$$z = \frac{\lambda_{received} - \lambda_{emitted}}{\lambda_{emitted}}$$

$\Rightarrow$ for cosmological redshift:

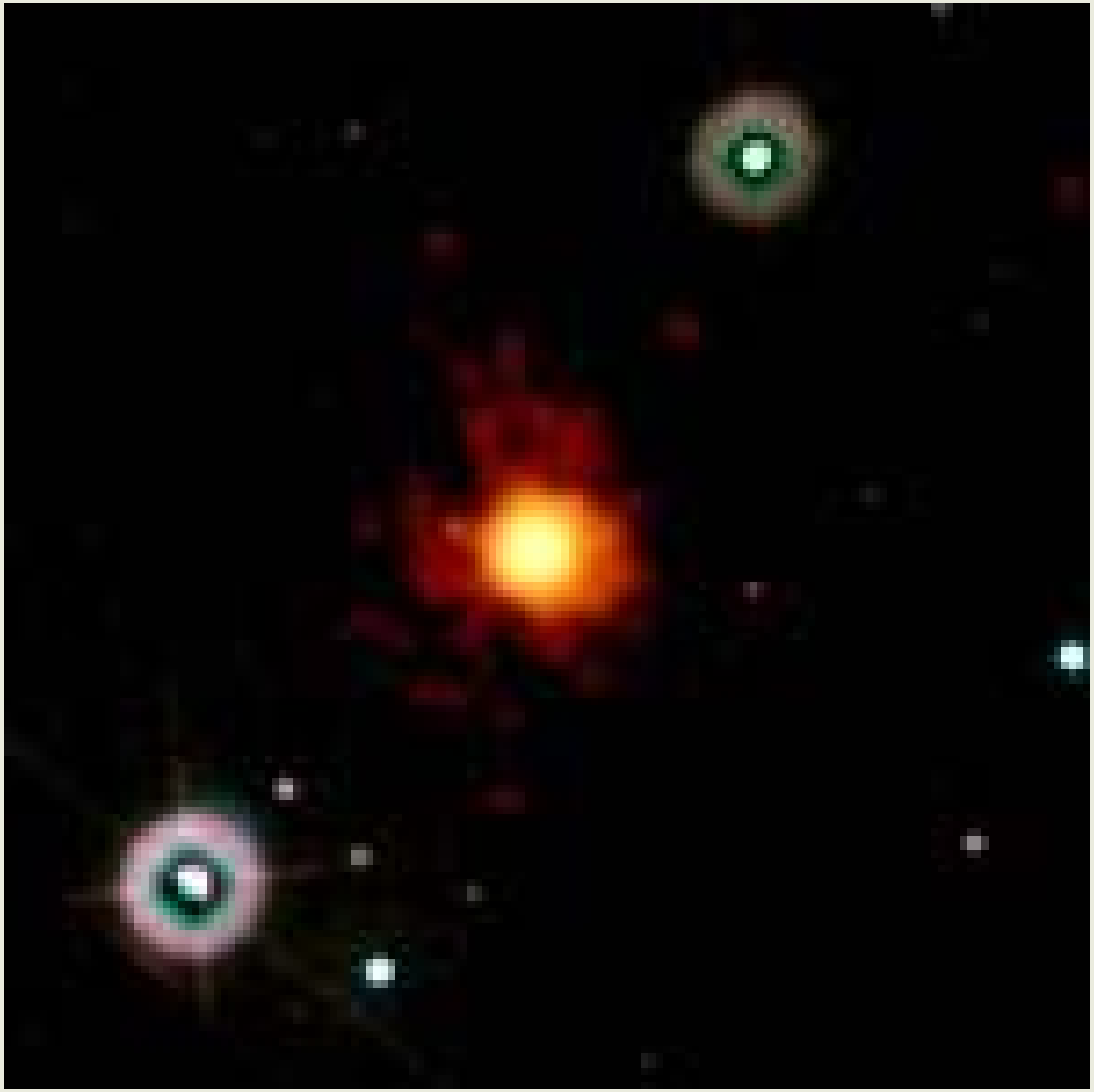
$$1 + z = \frac{\lambda_{received}}{\lambda_{emitted}} = \frac{a_{now}}{a_{then}}$$

Cosmological redshift

- Examples:
  - $z=1 \Rightarrow a_{then}/a_{now} = 0.5$
    - at z=1, the universe had 50% of its present day size
    - emitted blue light (400 nm) is shifted all the way through the optical spectrum and is received as red light (800 nm)
  - $z=4 \Rightarrow a_{then}/a_{now} = 0.2$
    - at z=4, the universe had 20% of its present day size
    - emitted blue light (400 nm) is shifted deep into the infrared and is received at 2000 nm
  - most distant astrophysical object discovered so far: Quasars ($z\approx6.4$) and GRBs ($z\approx8.2$)

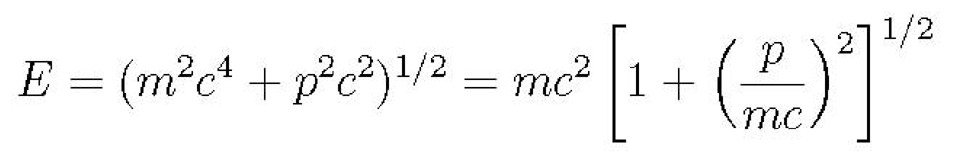


(SDSS image; taken in October 2003)

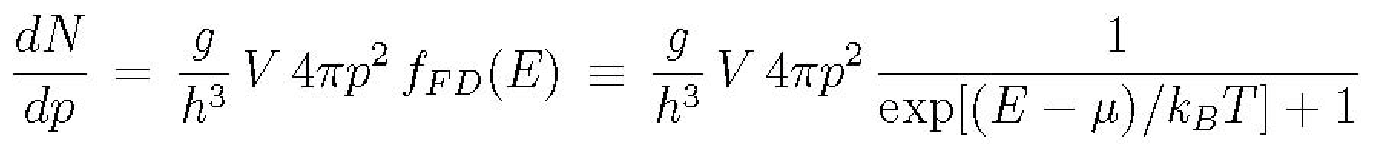


(Swift image; GRB 090423A)

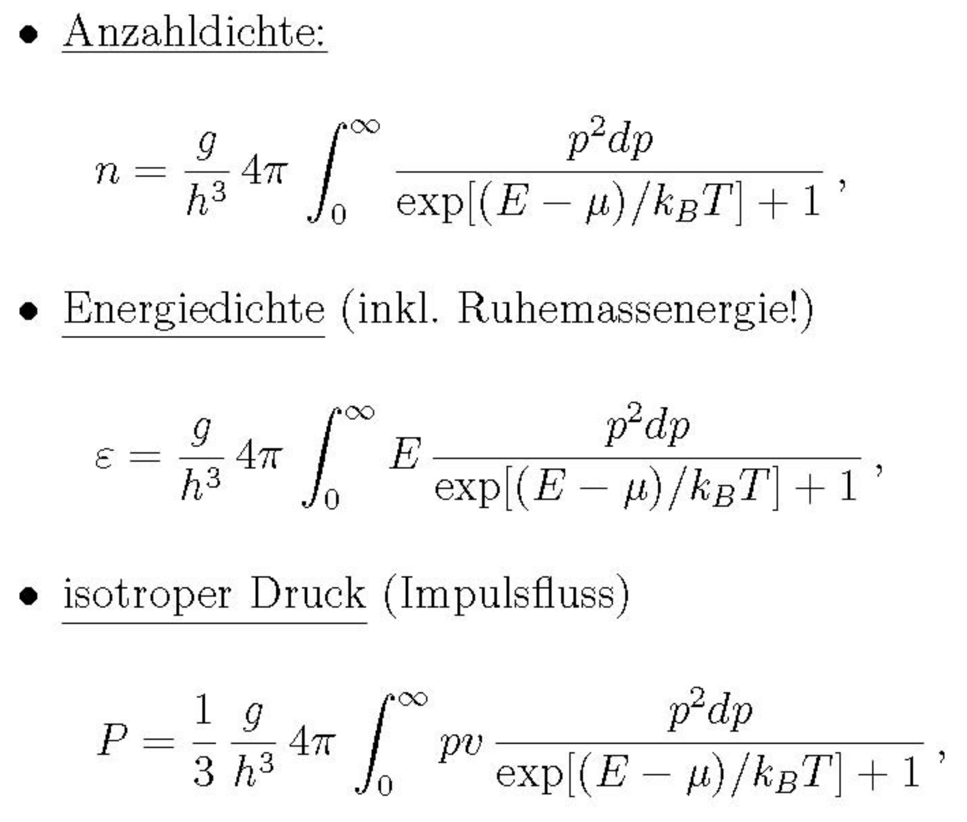
The equation of state of cosmic matter: Fermi gas



$$E = (m^2c^4 + p^2c^2)^{1/2} = mc^2 \left[1 + \left(\frac{p}{mc}\right)^2\right]^{1/2}$$



$$\frac{dN}{dp} = \frac{g}{h^3} V\, 4\pi p^2\, f_{FD}(E) \equiv \frac{g}{h^3} V\, 4\pi p^2 \frac{1}{\exp[(E-\mu)/k_BT] + 1}$$



- Anzahldichte:

$$n = \frac{g}{h^3} 4\pi \int_0^\infty \frac{p^2 dp}{\exp[(E-\mu)/k_BT] + 1} \,,$$

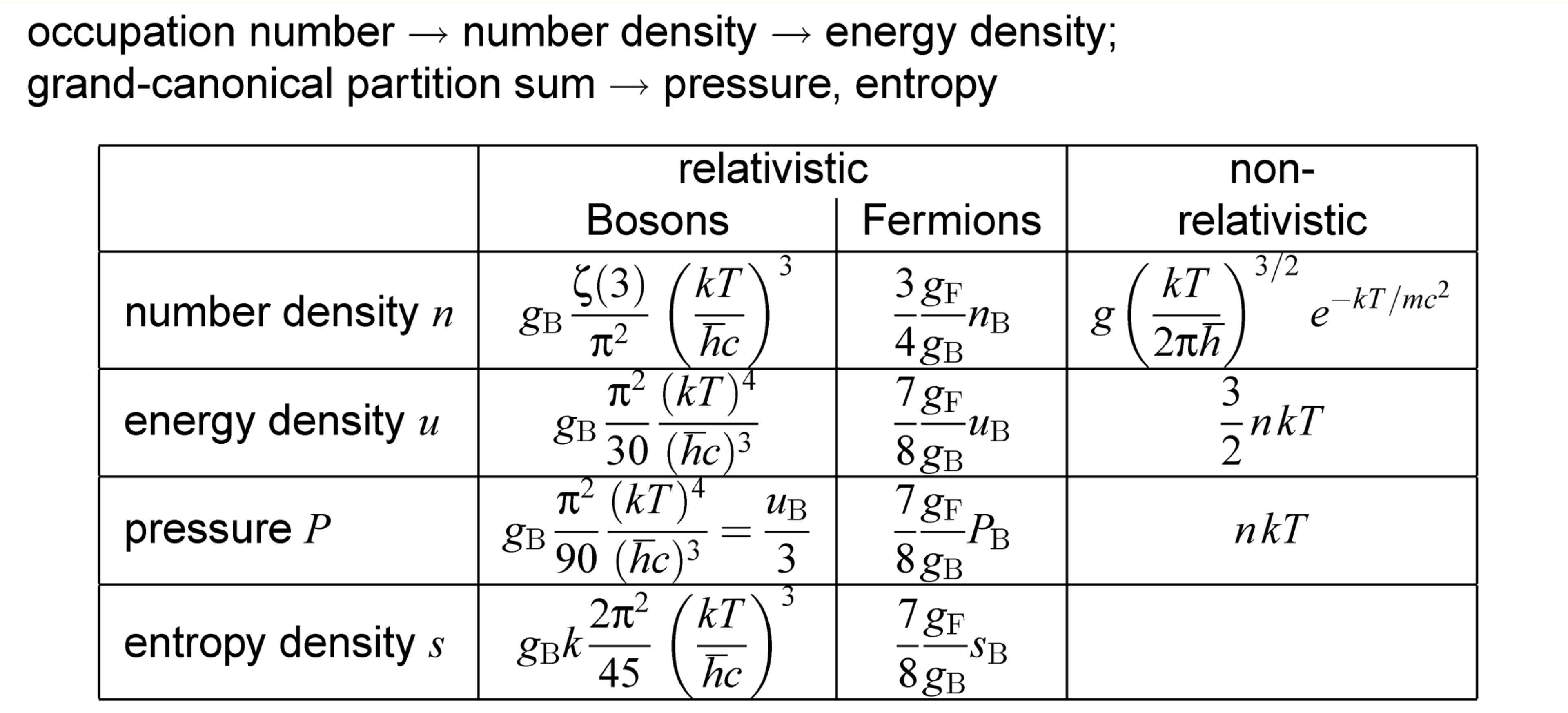
- Energiedichte (inkl. Ruhemassenergie!)

$$\varepsilon = \frac{g}{h^3} 4\pi \int_0^\infty E \frac{p^2 dp}{\exp[(E-\mu)/k_BT] + 1} \,,$$

- isotroper Druck (Impulsfluss)

$$P = \frac{1}{3} \frac{g}{h^3} 4\pi \int_0^\infty pv \frac{p^2 dp}{\exp[(E-\mu)/k_BT] + 1} \,,$$

The equation of state of cosmic matter: general

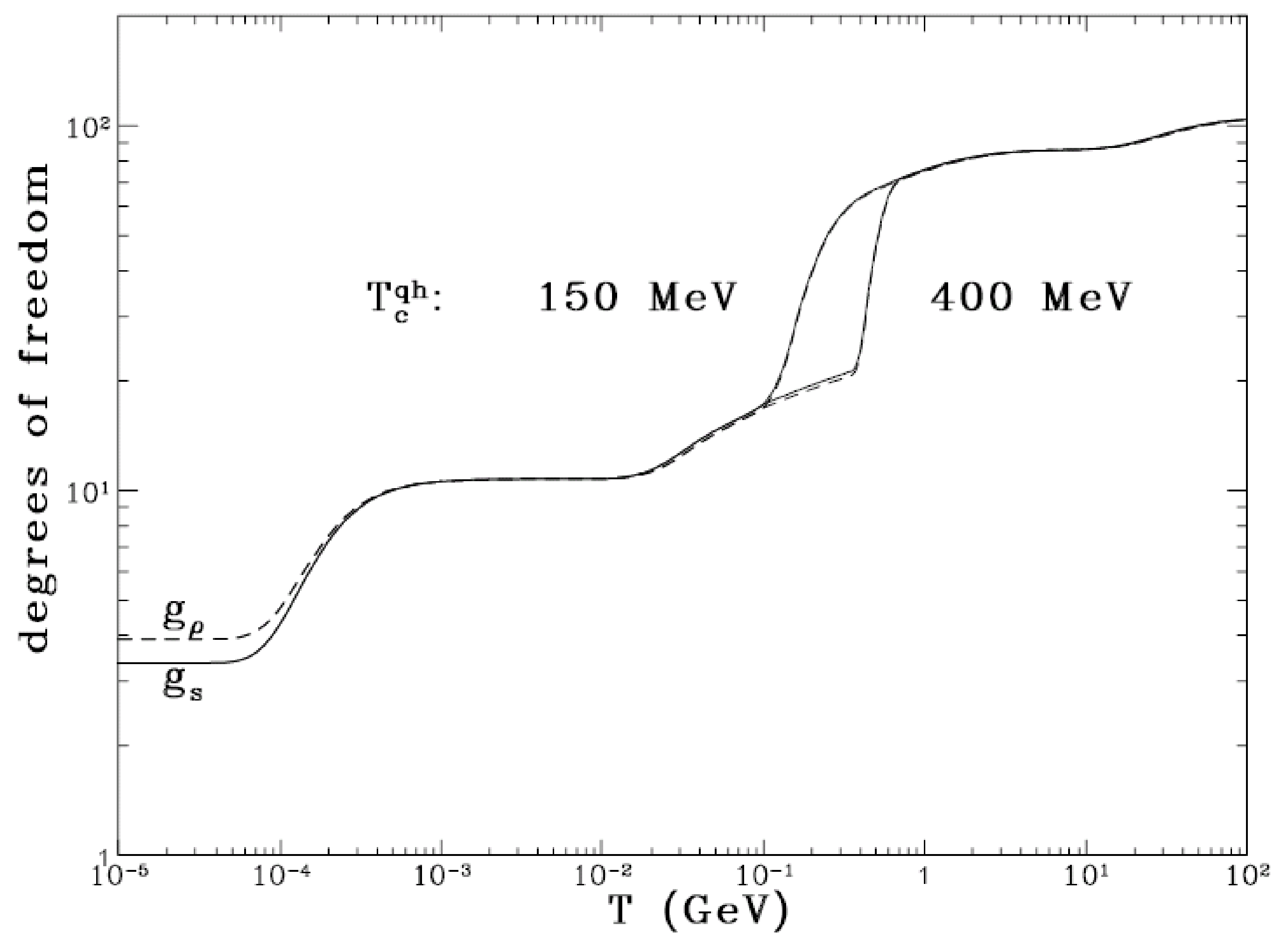


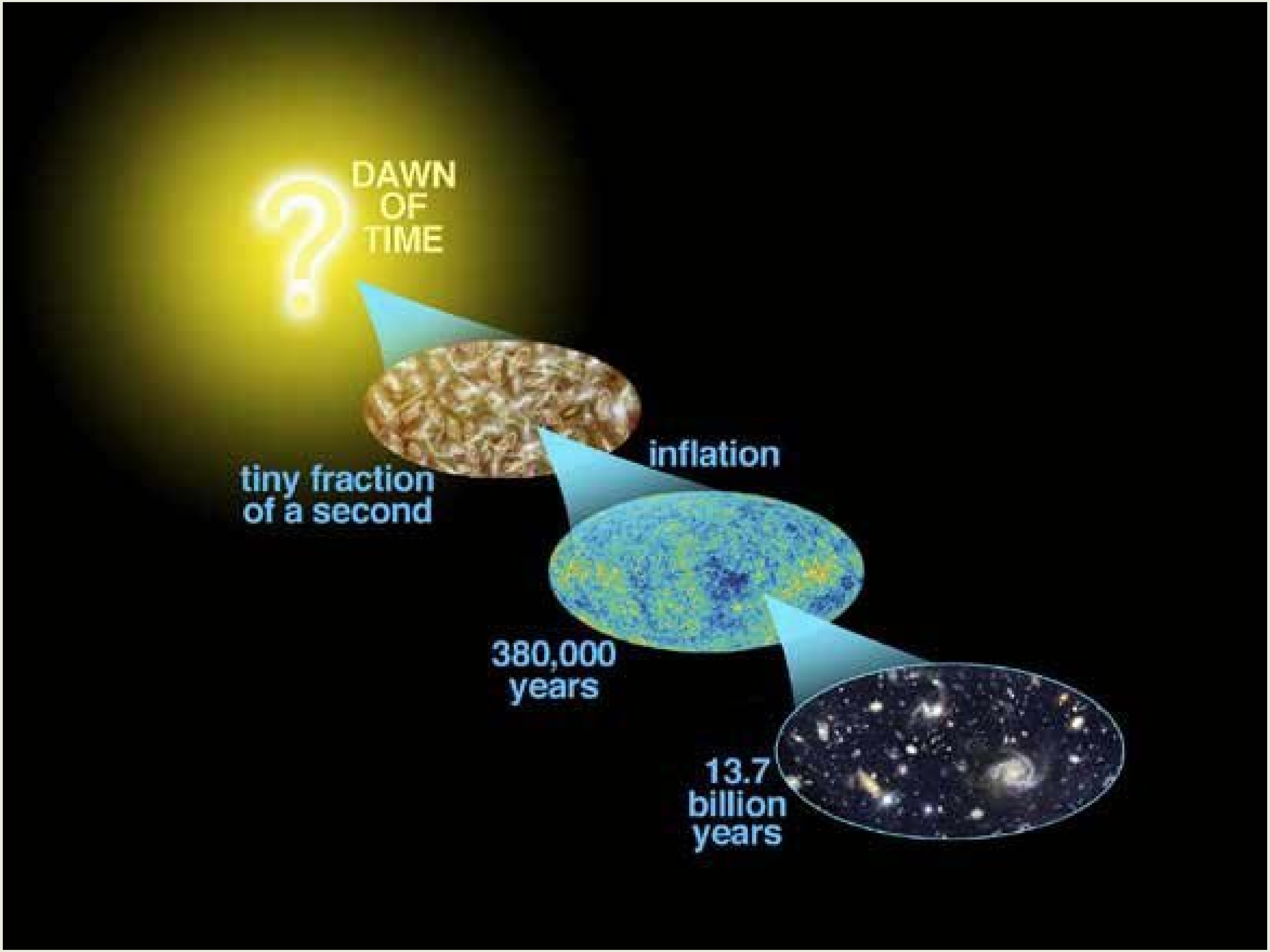
occupation number → number density → energy density;
grand-canonical partition sum → pressure, entropy

	relativistic		non-relativistic
	Bosons	Fermions	
number density n	$g_{\mathrm{B}} \frac{\zeta(3)}{\pi^2} \left(\frac{kT}{\hbar c}\right)^3$	$\frac{3}{4}\frac{g_{\mathrm{F}}}{g_{\mathrm{B}}} n_{\mathrm{B}}$	$g \left(\frac{kT}{2\pi\hbar}\right)^{3/2} e^{-kT/mc^2}$
energy density u	$g_{\mathrm{B}} \frac{\pi^2}{30} \frac{(kT)^4}{(\hbar c)^3}$	$\frac{7}{8}\frac{g_{\mathrm{F}}}{g_{\mathrm{B}}} u_{\mathrm{B}}$	$\frac{3}{2} n kT$
pressure P	$g_{\mathrm{B}} \frac{\pi^2}{90} \frac{(kT)^4}{(\hbar c)^3} = \frac{u_{\mathrm{B}}}{3}$	$\frac{7}{8}\frac{g_{\mathrm{F}}}{g_{\mathrm{B}}} P_{\mathrm{B}}$	$n kT$
entropy density s	$g_{\mathrm{B}} k \frac{2\pi^2}{45} \left(\frac{kT}{\hbar c}\right)^3$	$\frac{7}{8}\frac{g_{\mathrm{F}}}{g_{\mathrm{B}}} s_{\mathrm{B}}$	

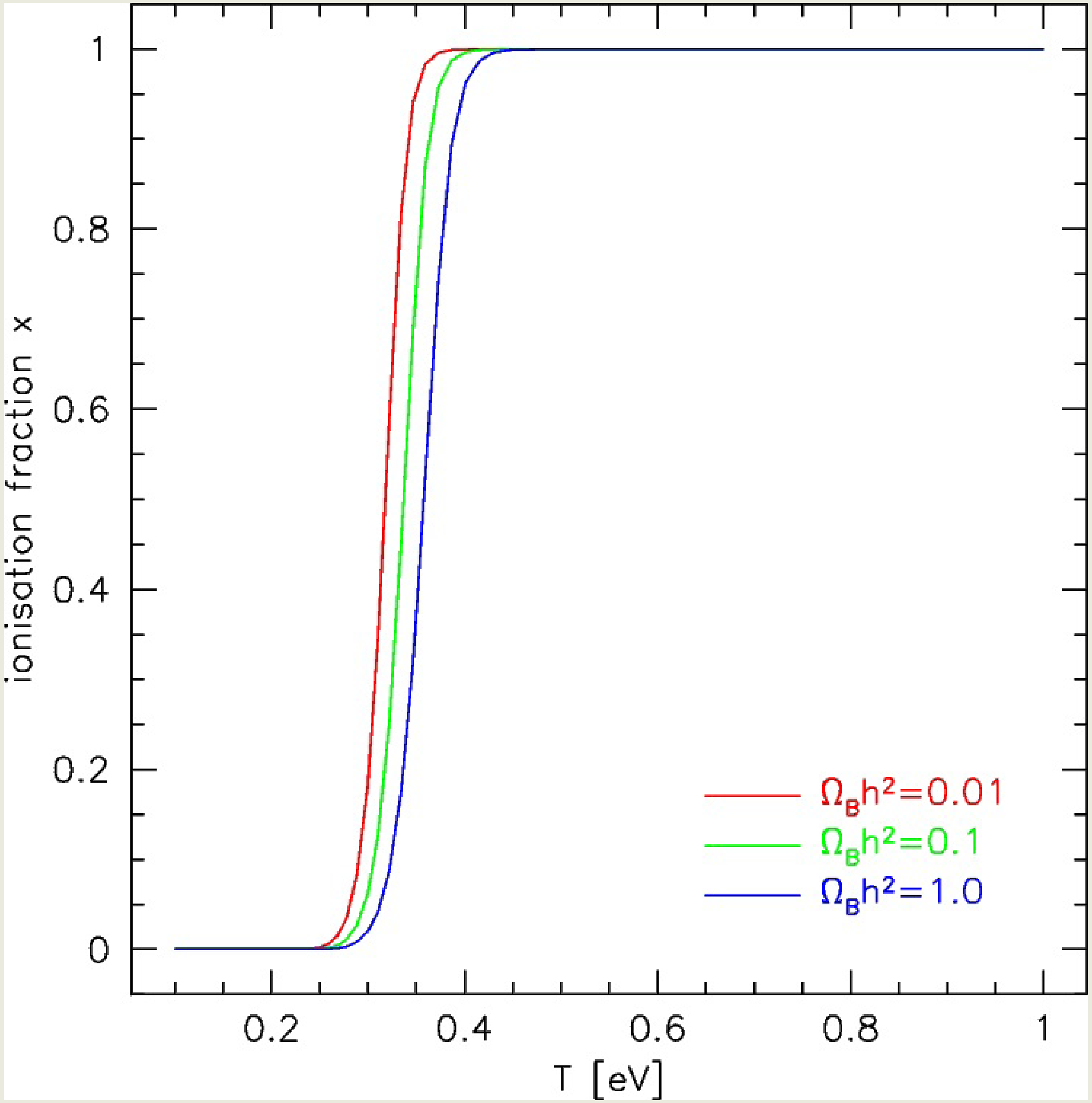
Relativistiv dgrees of freedom g_{eff}

$$g_{eff} = \Sigma_B \, g_B \left(\frac{T_B}{T_\gamma}\right)^4 + \frac{7}{8} \Sigma_F \, g_F \left(\frac{T_F}{T_\gamma}\right)^4 .$$

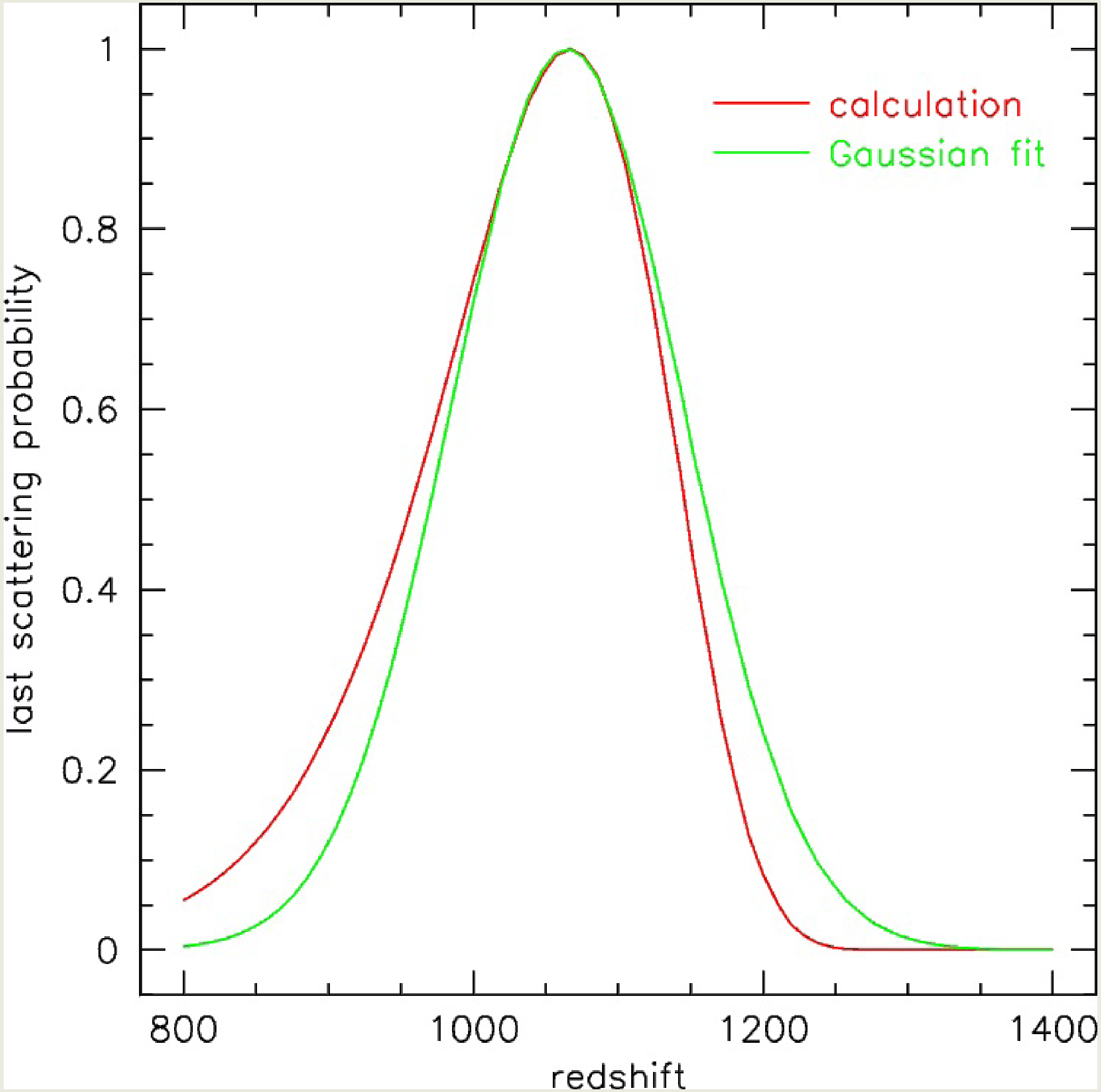



?
DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

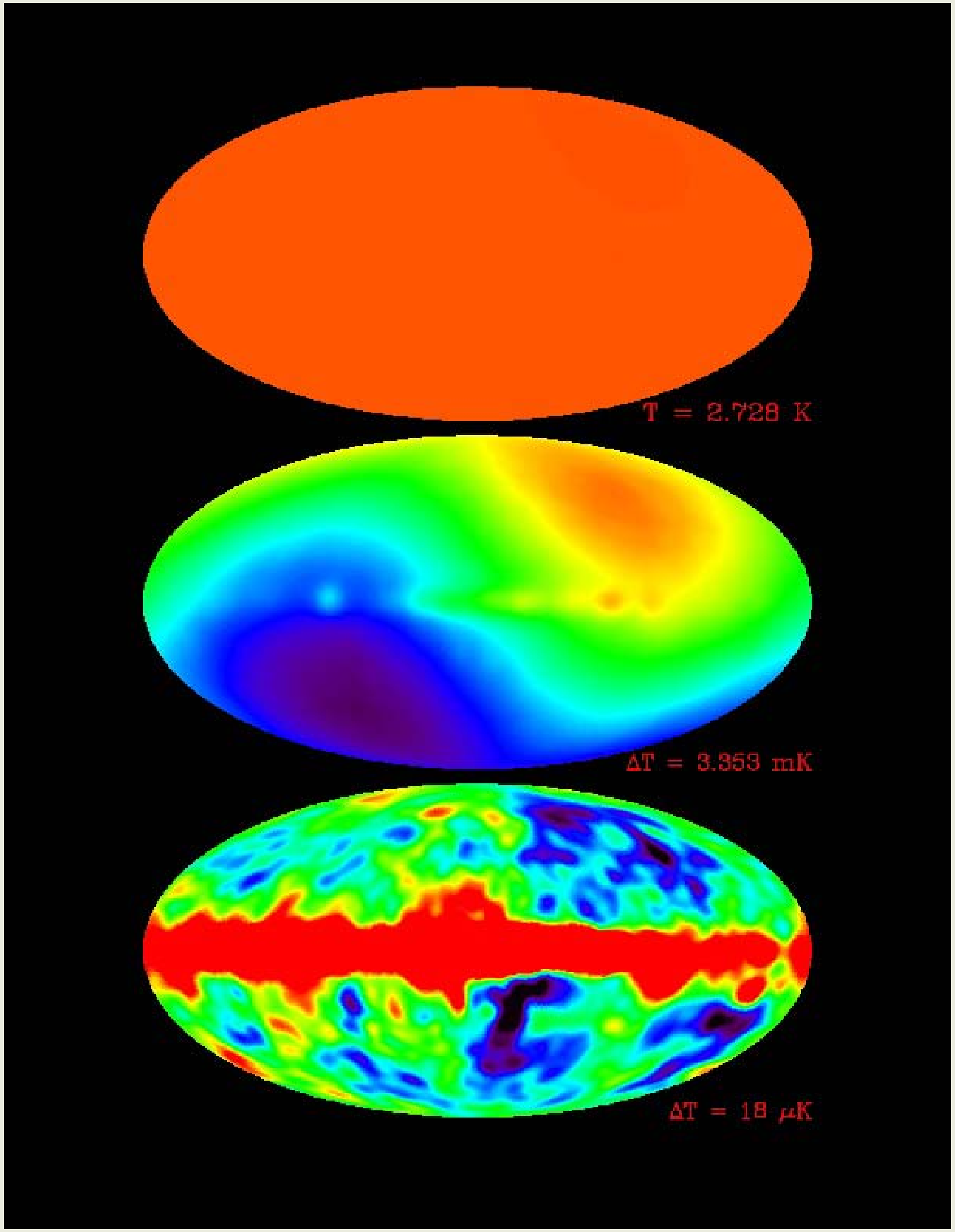
The physics of recombination: $T_{\text{recombination}}$



The physics of recombination: recombination shell



CMB: ‘foreground’ subtraction



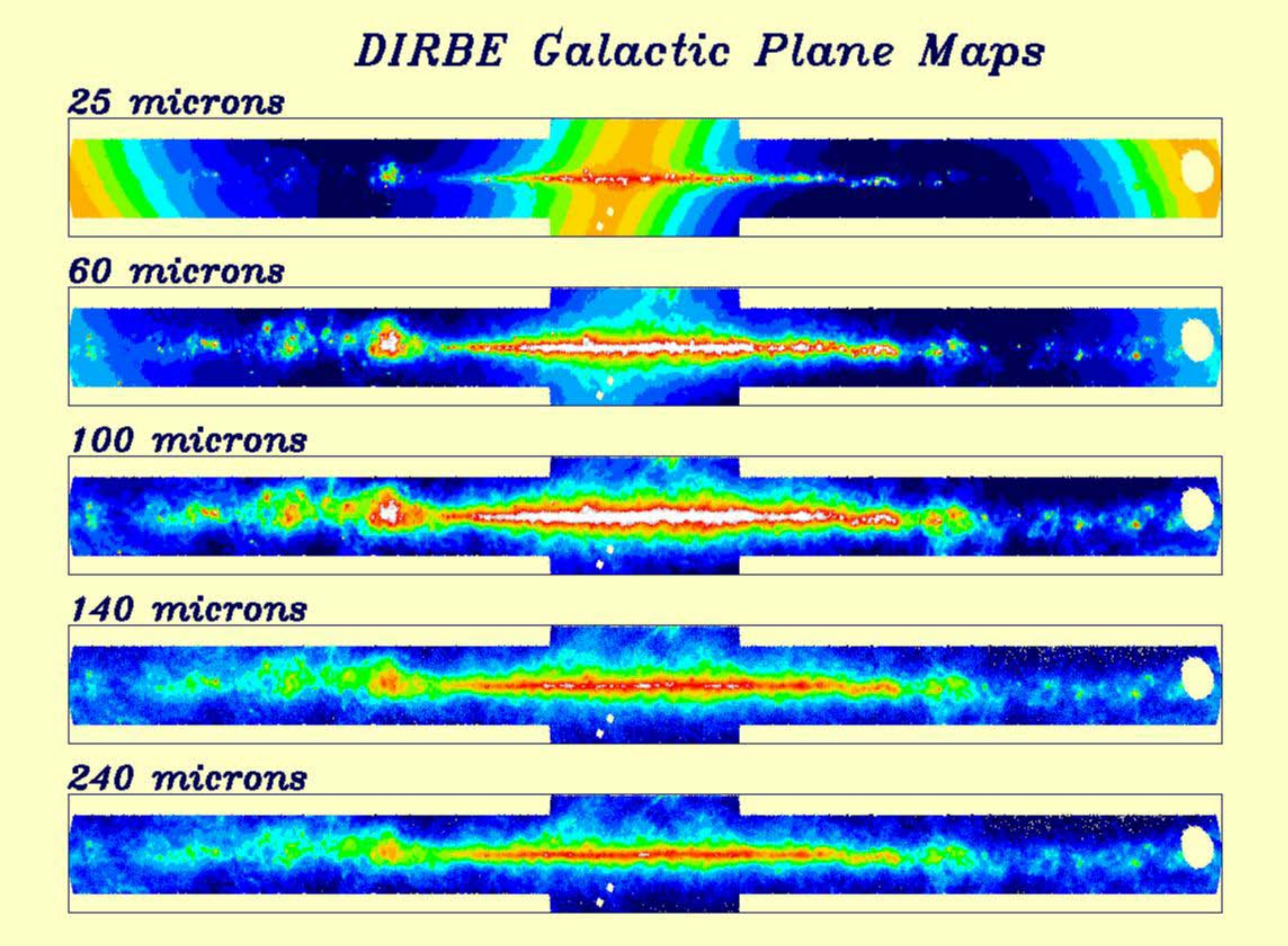
ΔT=2.728 K

ΔT=3.353 mK

ΔT=18 μK

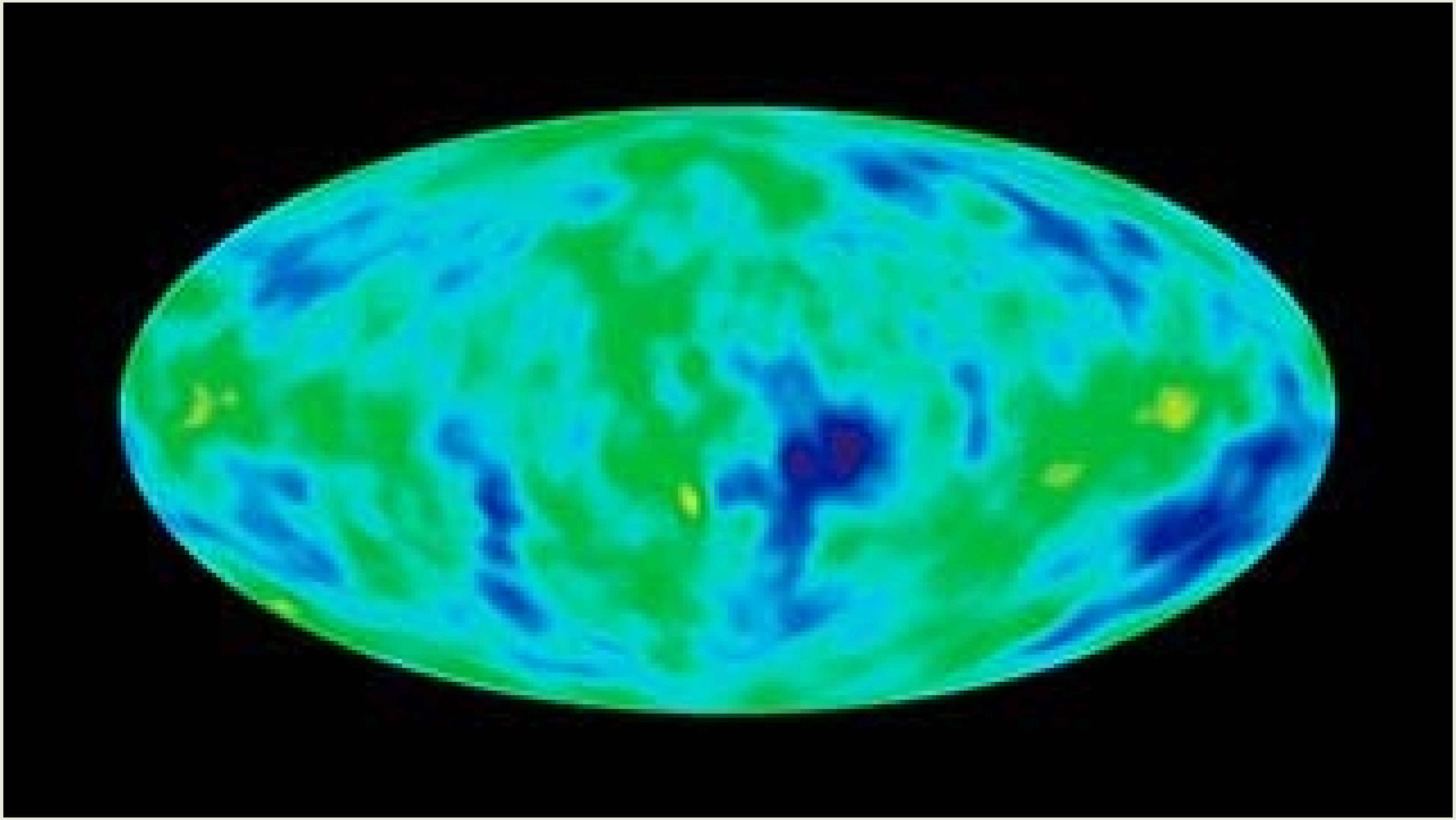
COBE maps

Milky Way contribution



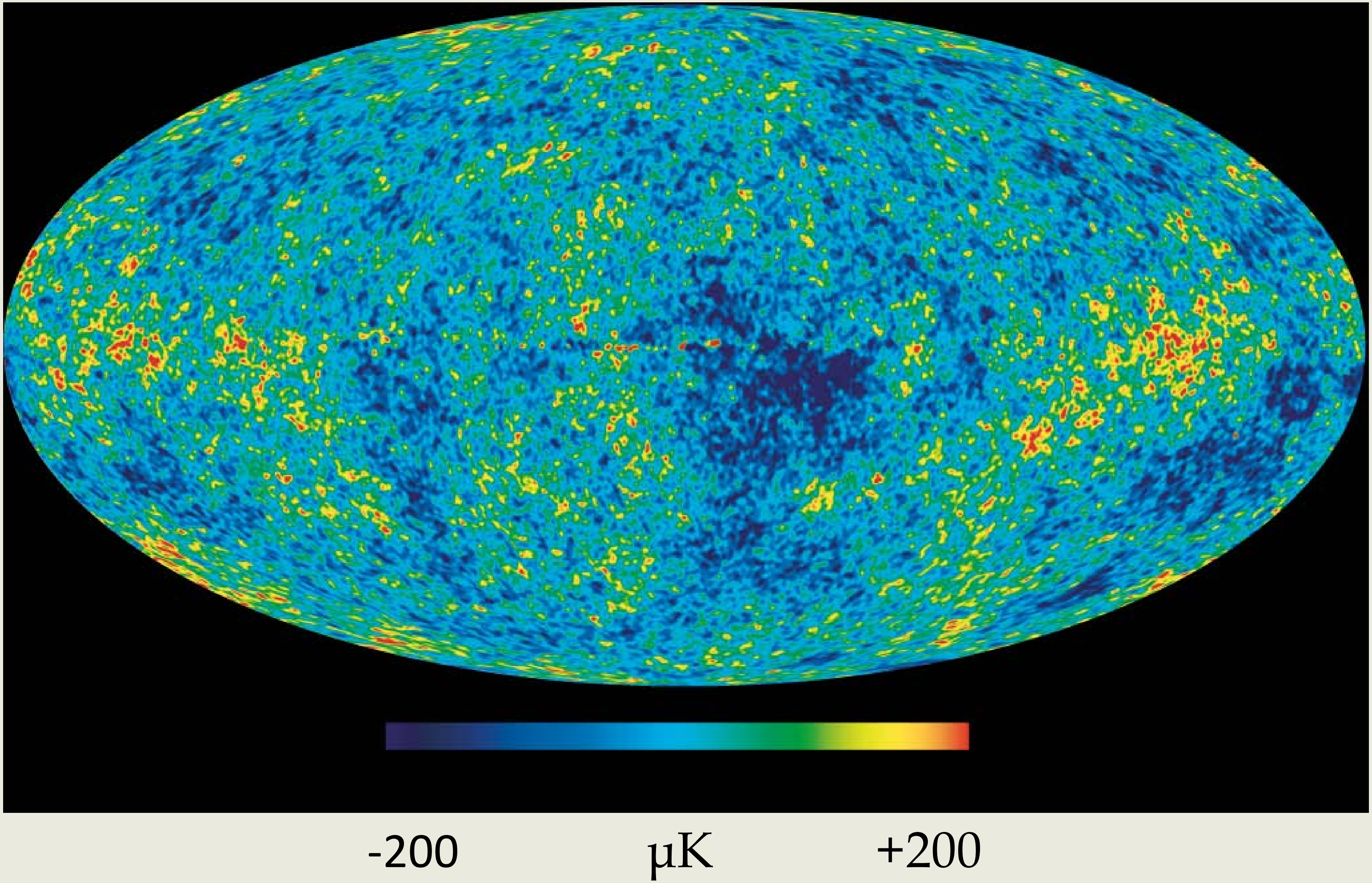
COBE maps

Final map

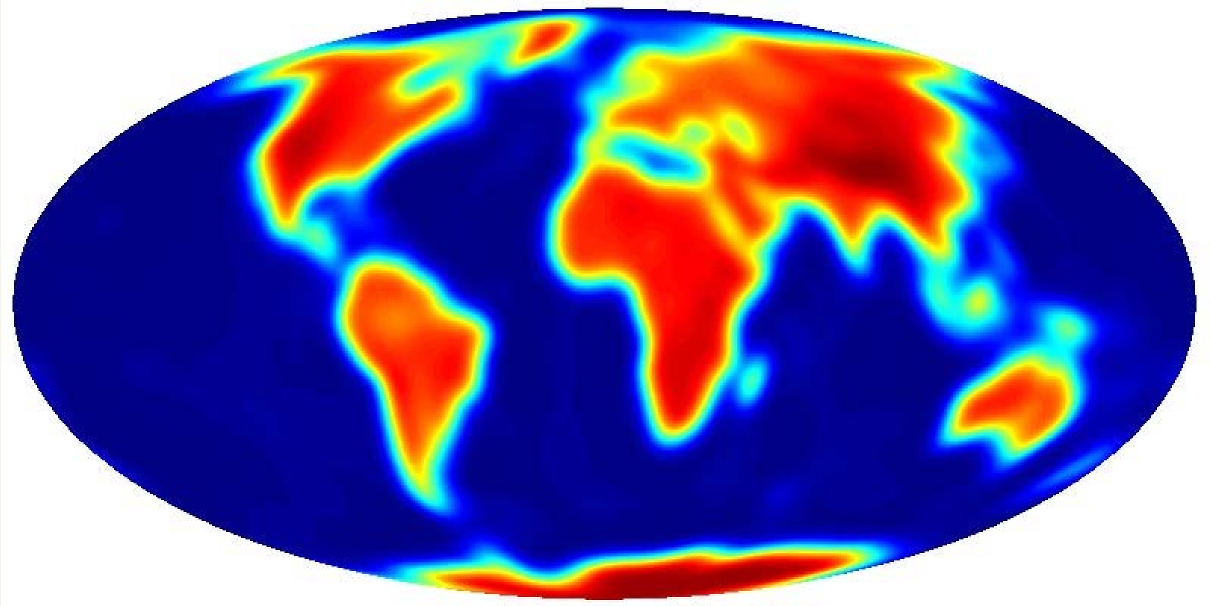


COBE maps

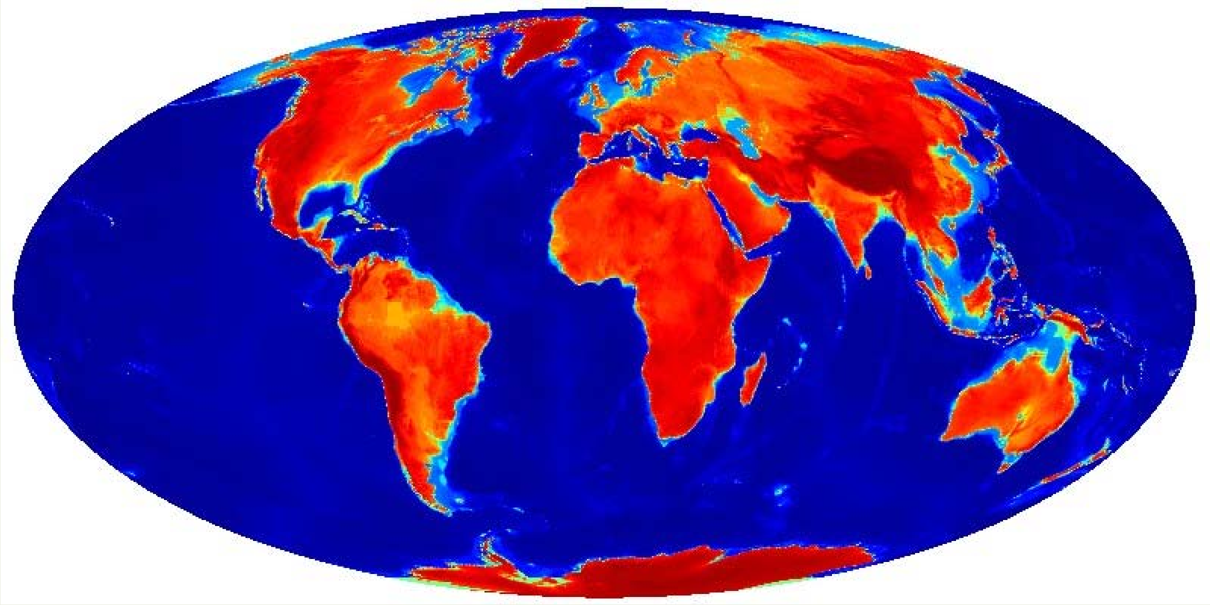
… and for WMAP:



Progress over the years ……



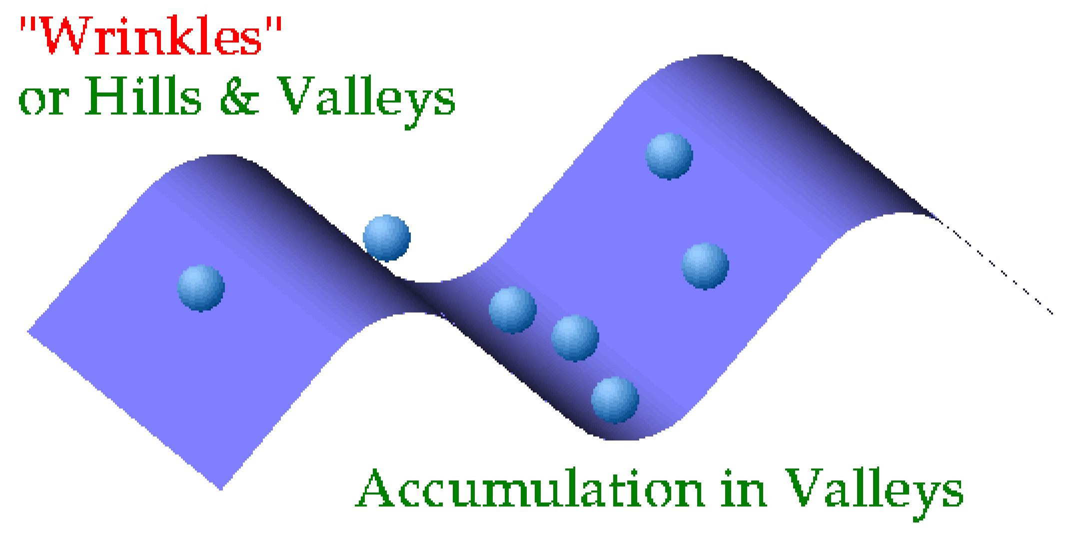
COBE
~1990



WMAP
~2005

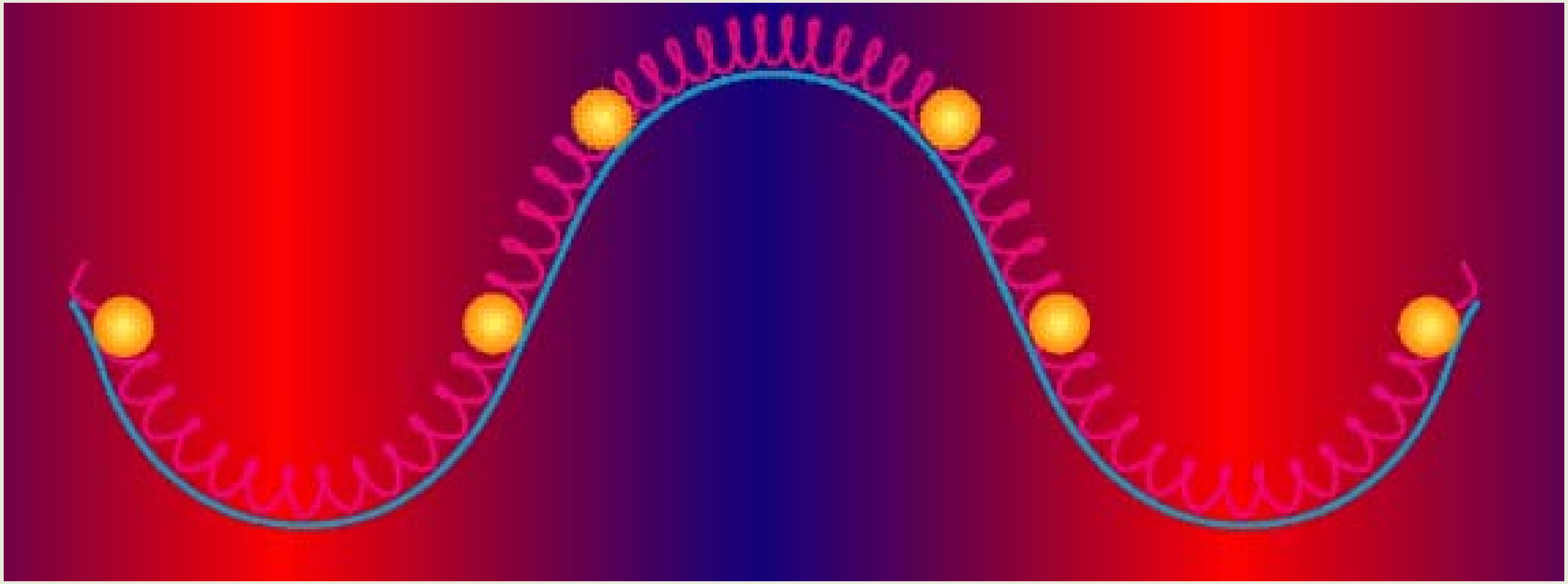
Where do the CMB fluctuations come from ?

- Wrinkles: some regions have a slightly higher gravity, some a slightly lower ("potential wells")
- Matter falls into potential wells



Can we “see” the “sound” of the universe ?

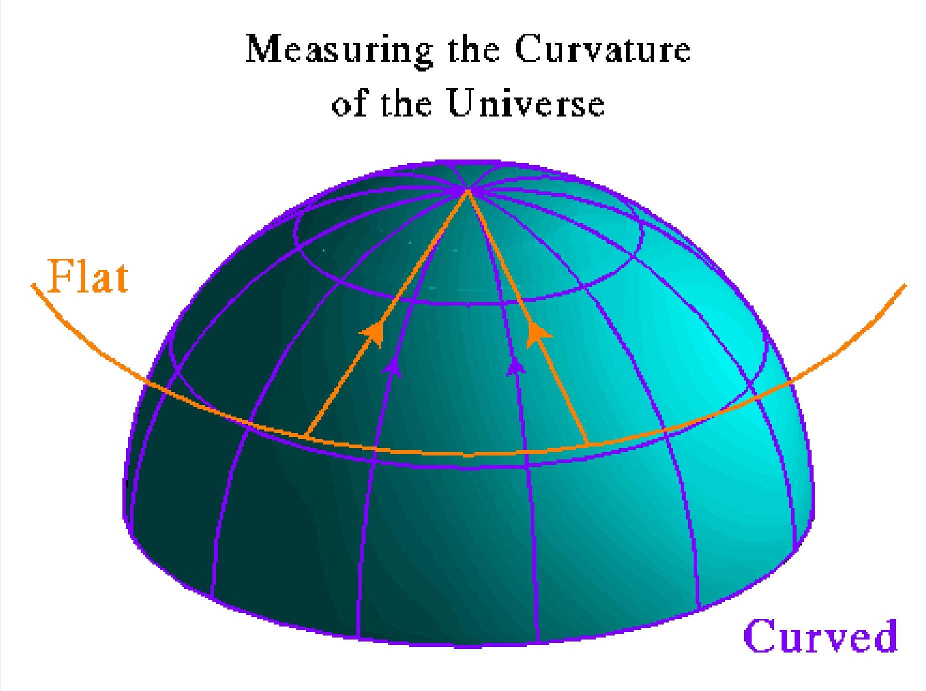
- Compressed gas heats up

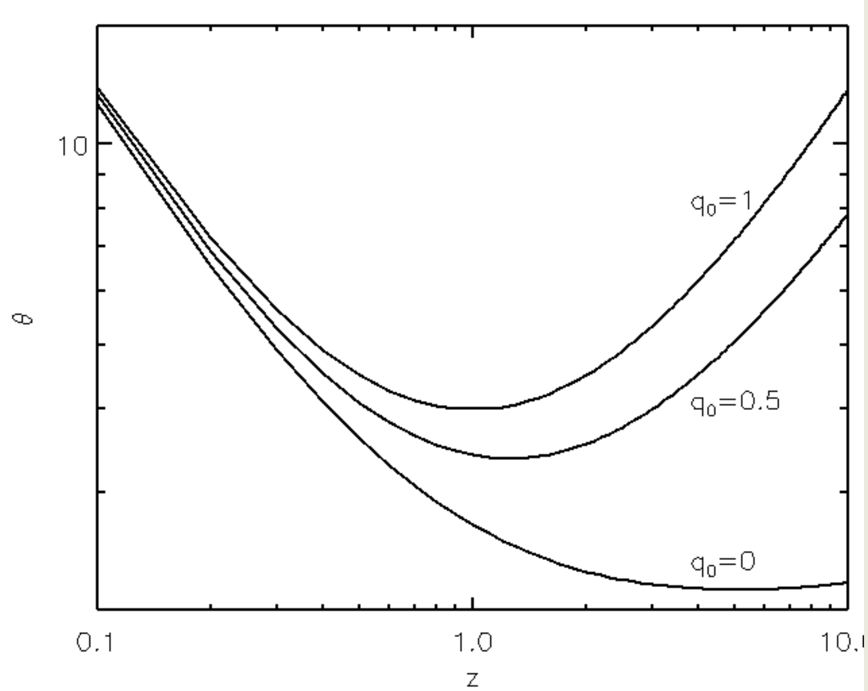


⇒ temperature fluctuations

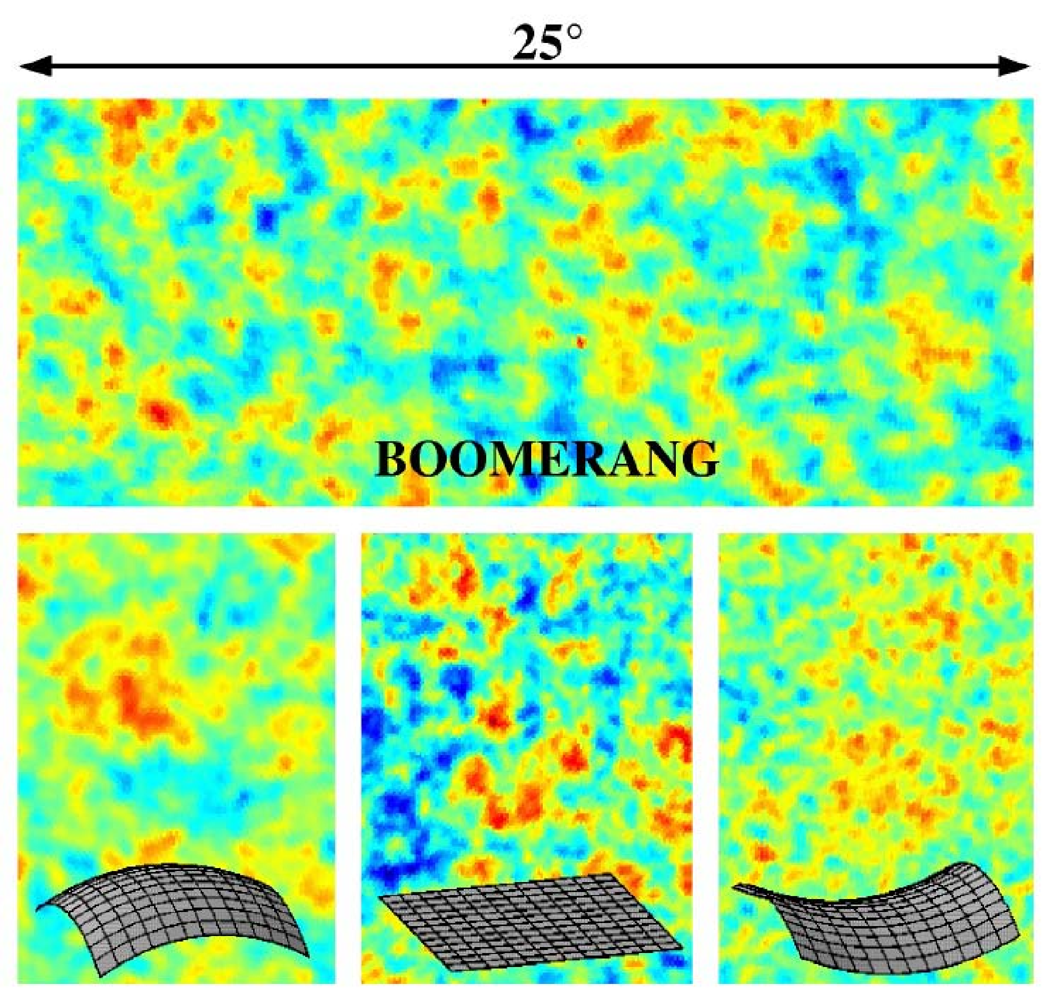
How can we measure the geometry of the universe ?

- We need a yard stick on the CMB
- For different curvatures, a yard stick of given length appears under different angles





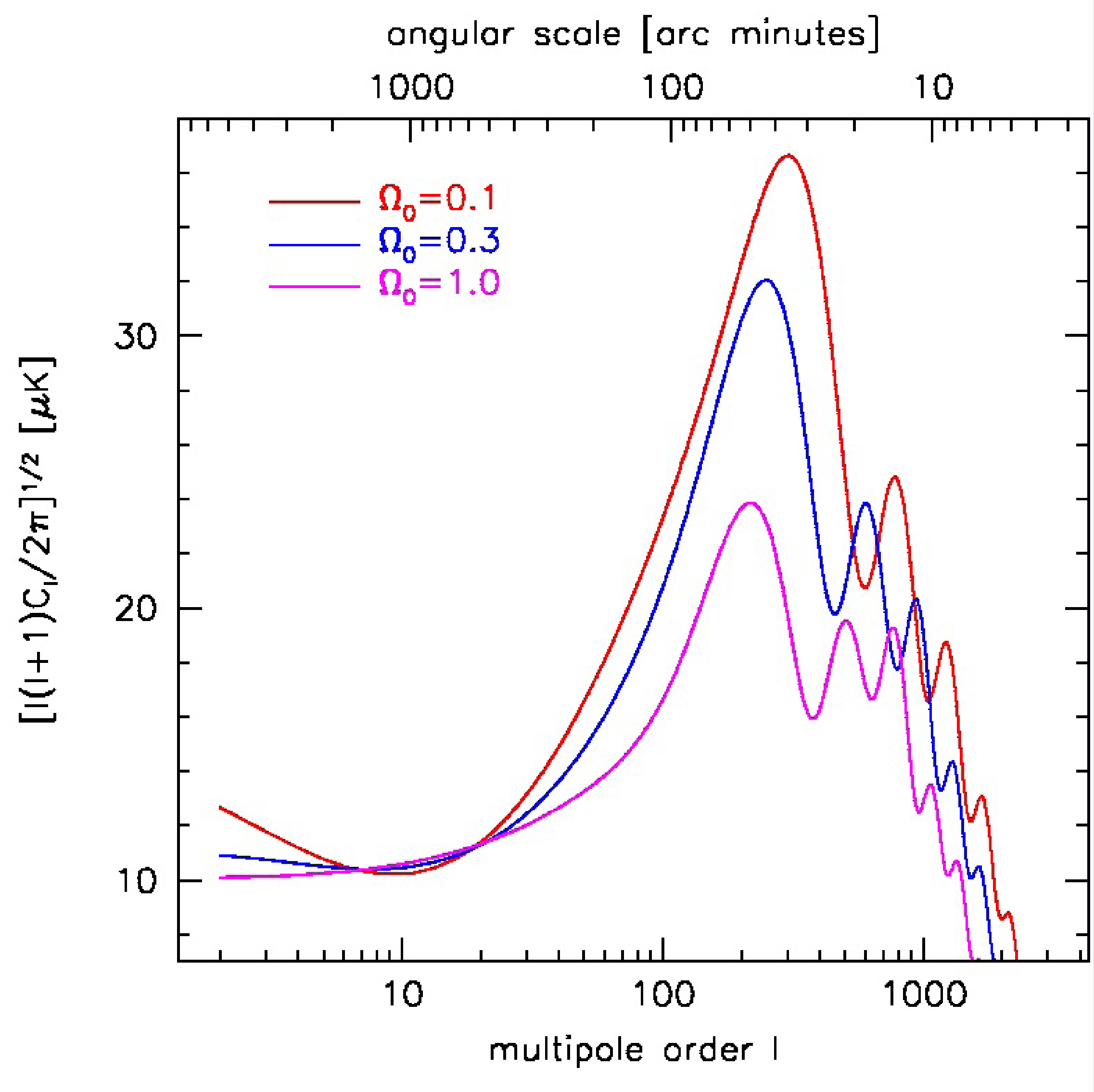
Measuring the Curvature of the Universe Using the CMB



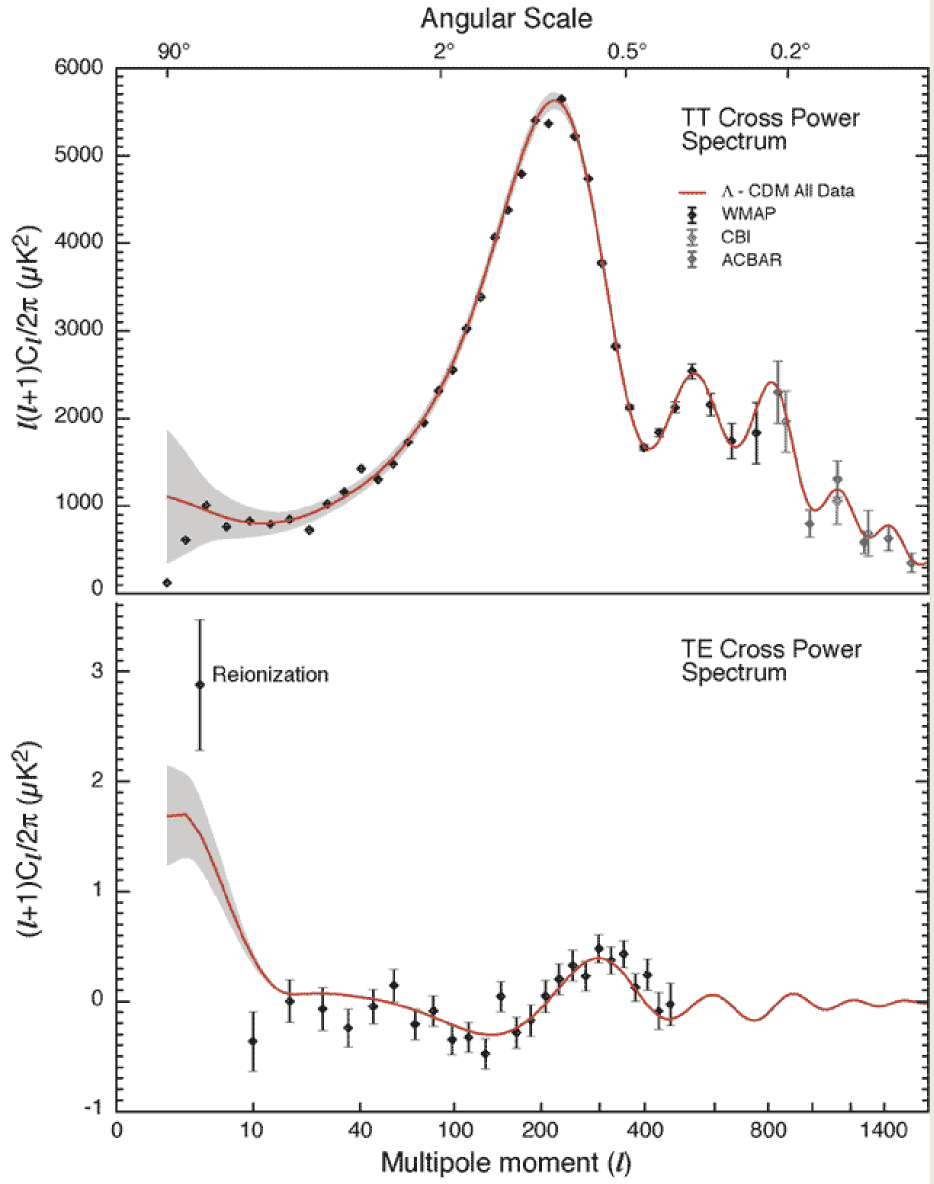
Result from Boomerang:

The Universe is flat to within 10%!

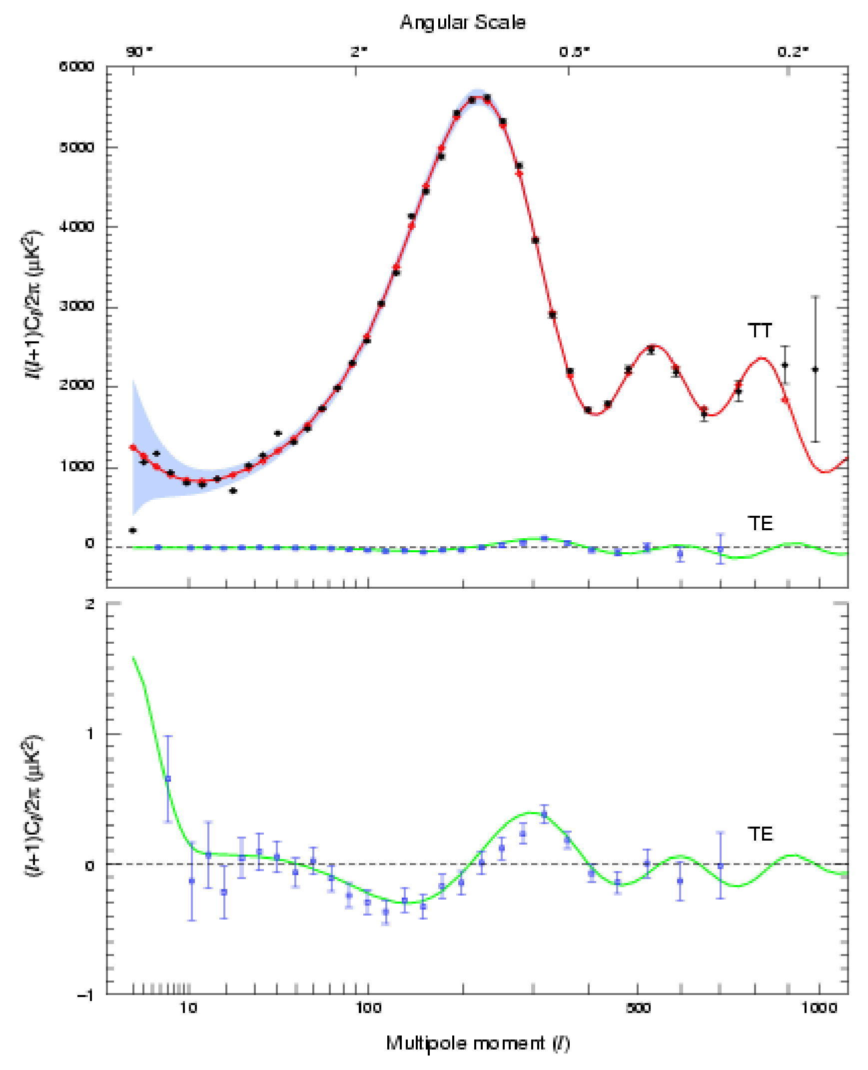
The CMB power spectrum and cosmological parameters



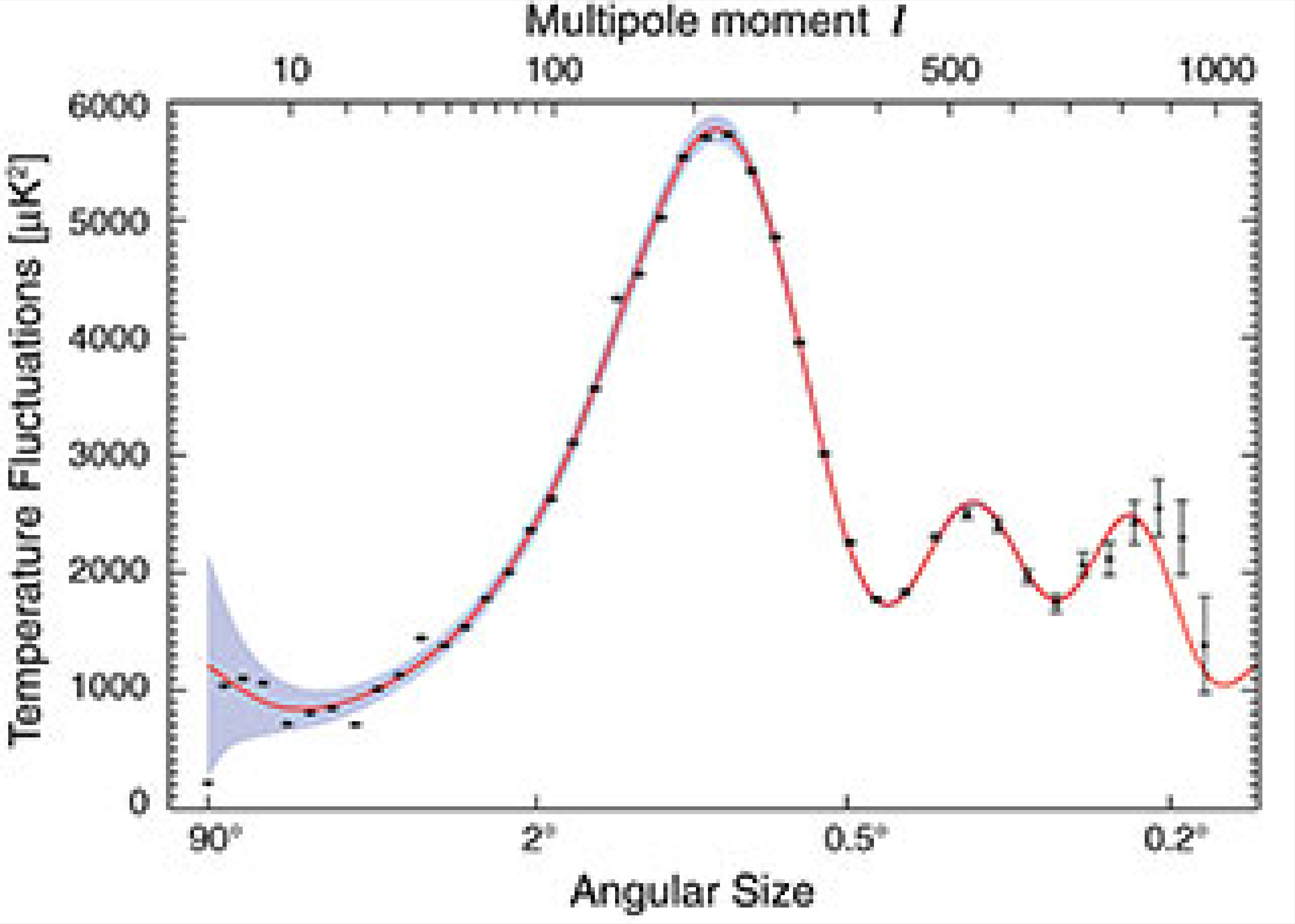
The CMB power spectrum from WMAP (1yr)



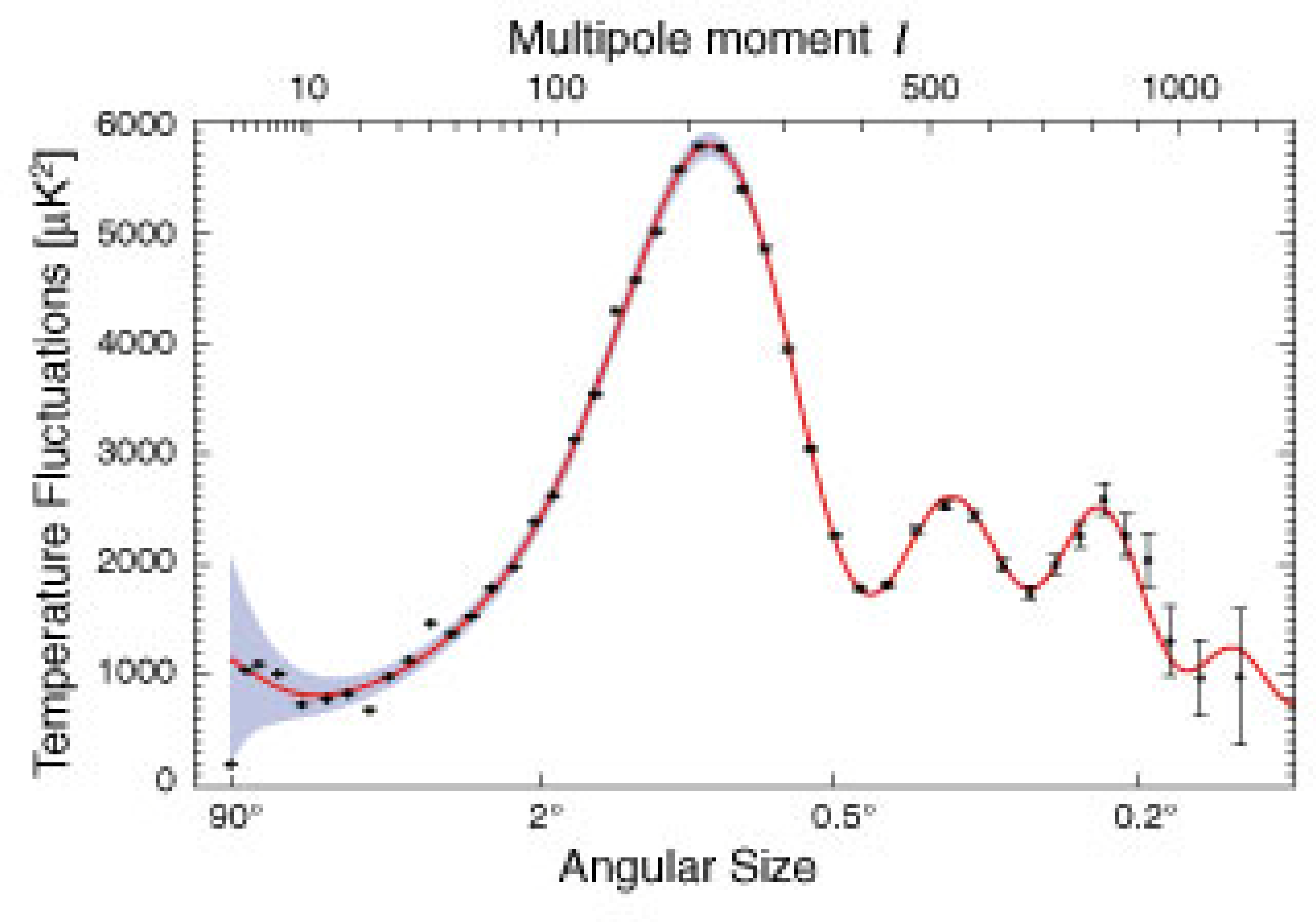
The CMB power spectrum from WMAP (3yr)



The CMB power spectrum from WMAP (5yr)



The CMB power spectrum from WMAP (7yr)



WMAP 5 years data

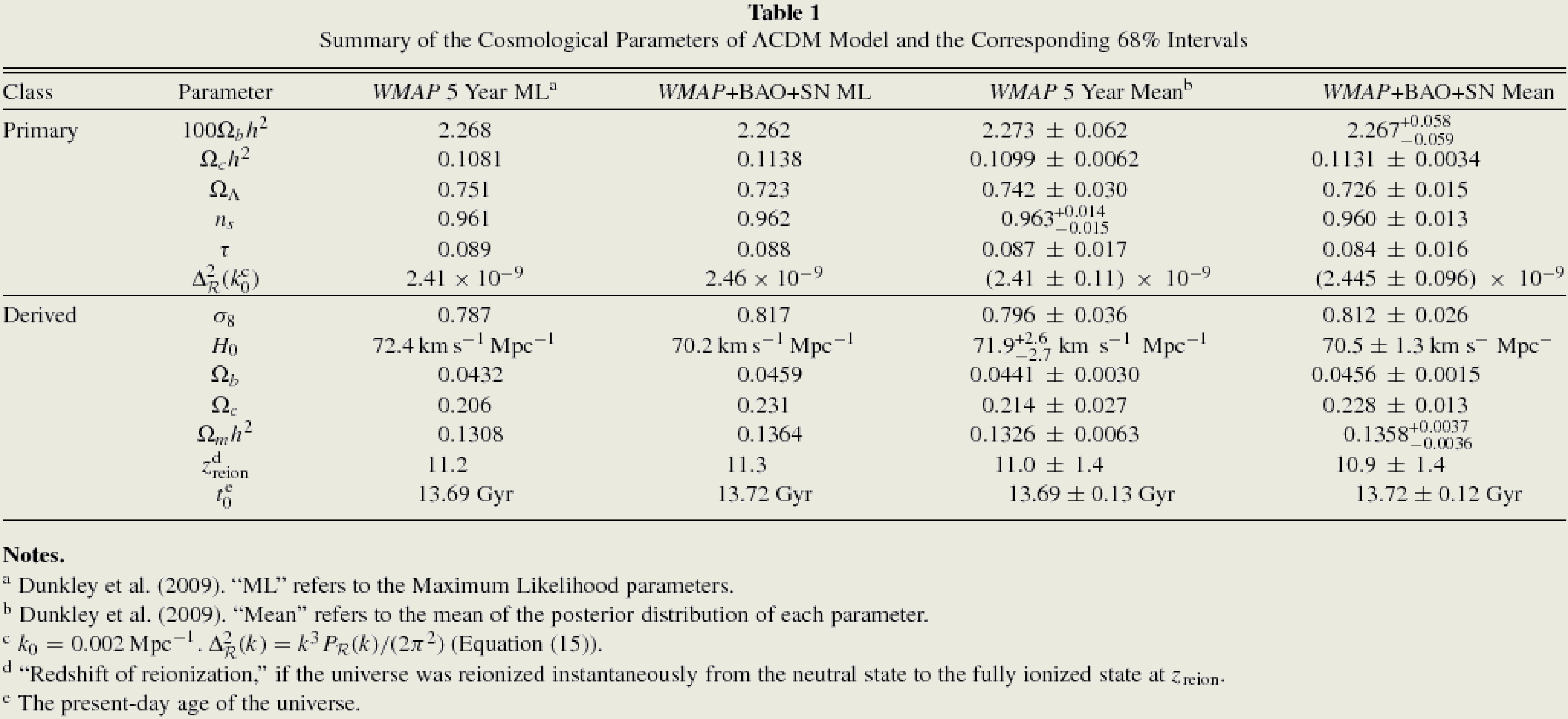


Table 1

Summary of the Cosmological Parameters of ΛCDM Model and the Corresponding 68% Intervals

Class	Parameter	*WMAP* 5 Year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5 Year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.262	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
	$\Omega_c h^2$	0.1081	0.1138	0.1099 ± 0.0062	0.1131 ± 0.0034
	Ω_Λ	0.751	0.723	0.742 ± 0.030	0.726 ± 0.015
	n_s	0.961	0.962	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
	τ	0.089	0.088	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0^{\mathrm{c}})$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$
Derived	σ_8	0.787	0.817	0.796 ± 0.036	0.812 ± 0.026
	H_0	72.4 km s^{-1} Mpc^{-1}	70.2 km s^{-1} Mpc^{-1}	$71.9^{+2.6}_{-2.7}$ km s^{-1} Mpc^{-1}	70.5 ± 1.3 km s^{-} Mpc^{-}
	Ω_b	0.0432	0.0459	0.0441 ± 0.0030	0.0456 ± 0.0015
	Ω_c	0.206	0.231	0.214 ± 0.027	0.228 ± 0.013
	$\Omega_m h^2$	0.1308	0.1364	0.1326 ± 0.0063	$0.1358^{+0.0037}_{-0.0036}$
	$z_{\mathrm{reion}}^{\mathrm{d}}$	11.2	11.3	11.0 ± 1.4	10.9 ± 1.4
	t_0^{e}	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr

Notes.

[a] Dunkley et al. (2009). "ML" refers to the Maximum Likelihood parameters.

[b] Dunkley et al. (2009). "Mean" refers to the mean of the posterior distribution of each parameter.

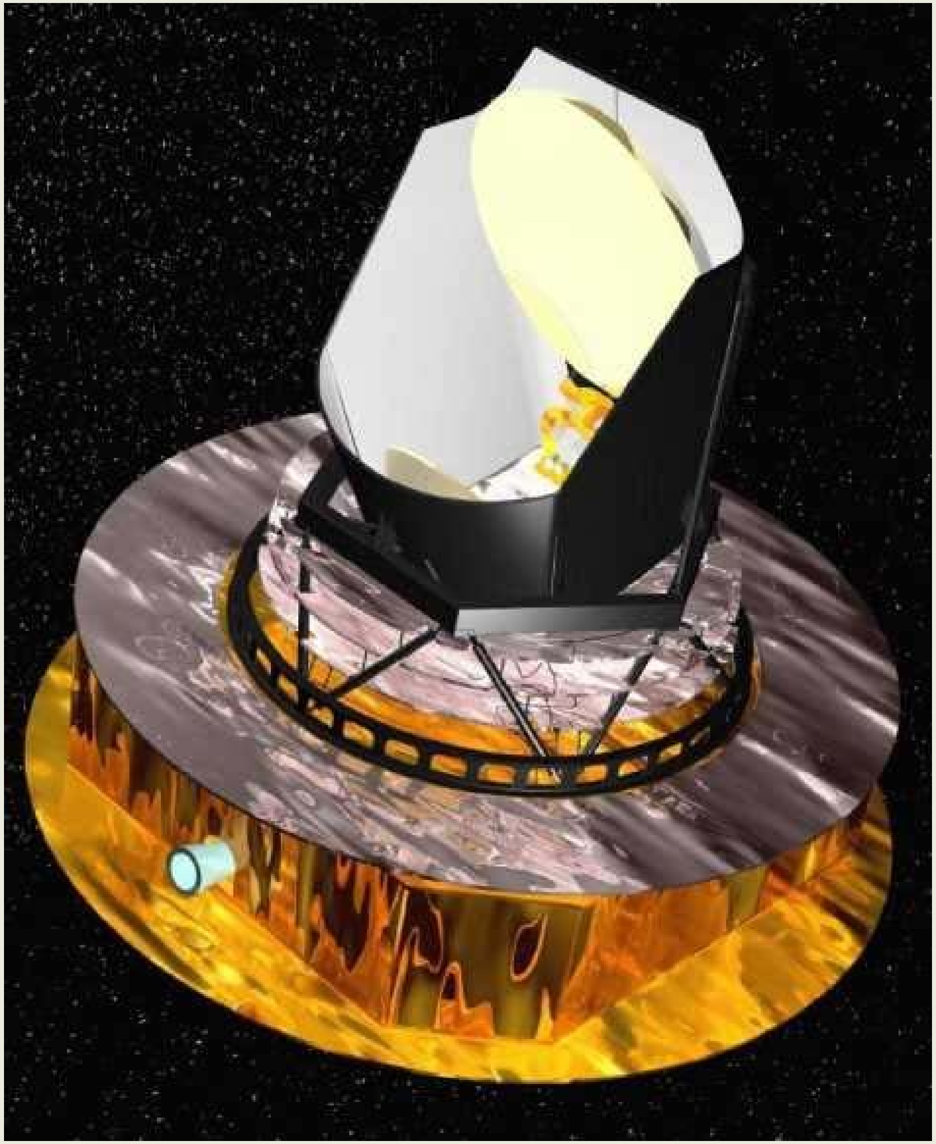
[c] $k_0 = 0.002\,\mathrm{Mpc}^{-1}$. $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ (Equation (15)).

[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at z_{reion}.

[e] The present-day age of the universe.

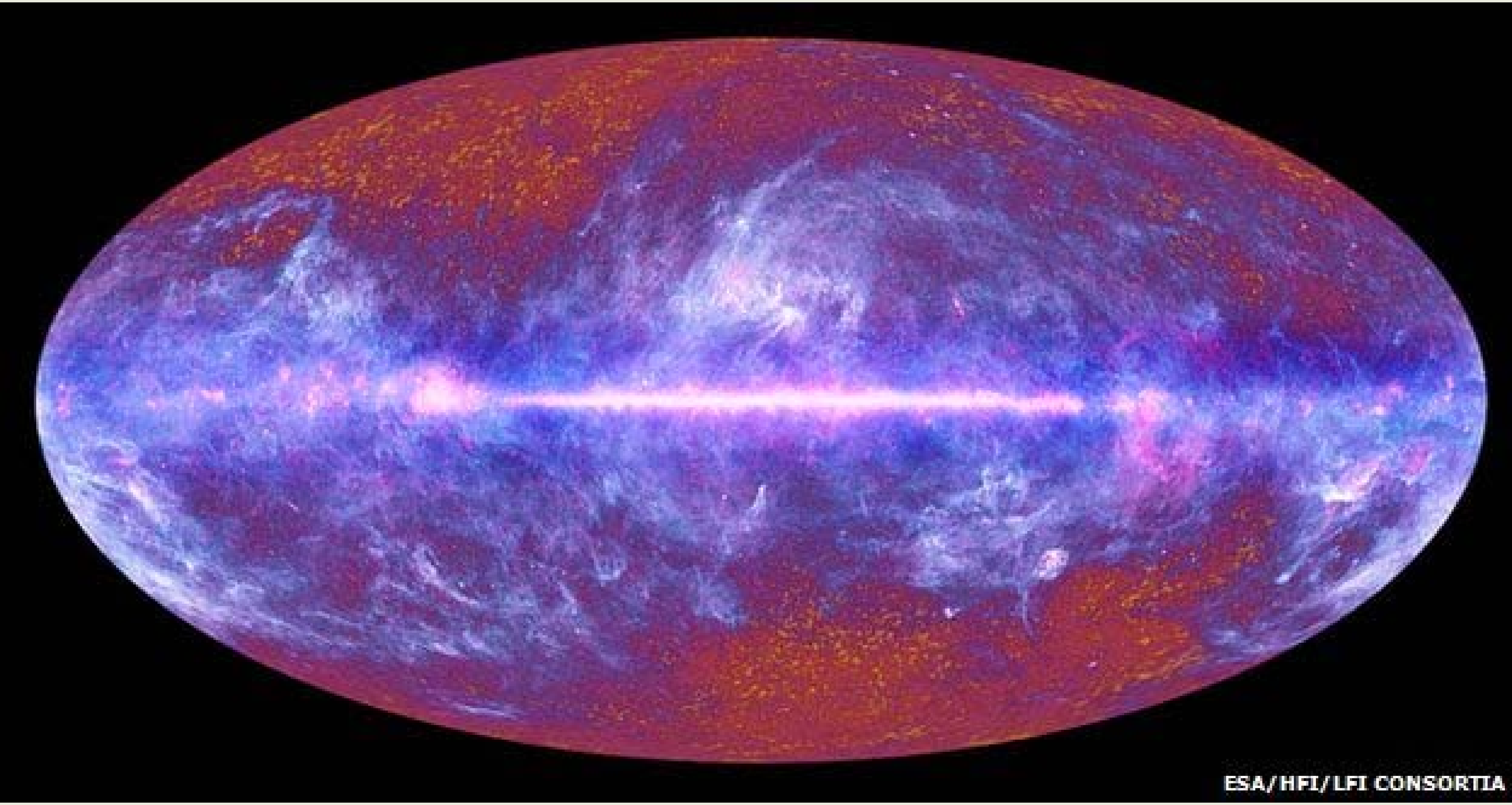
Komatsu et al. ; Astrophys. J. Subl. 180 (2009) 330

Planck Surveyor



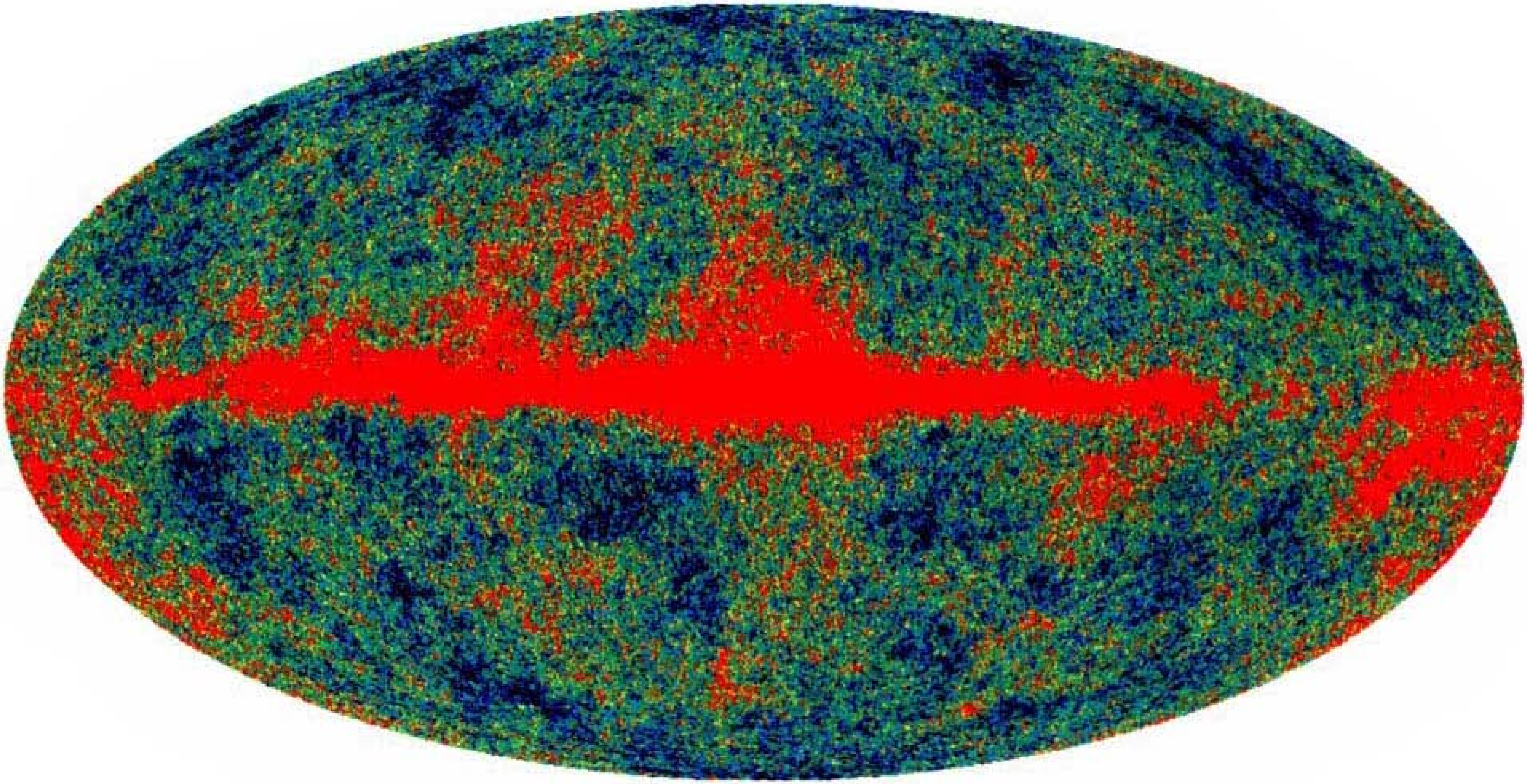
Launch: May14, 2009

Planck Surveyor



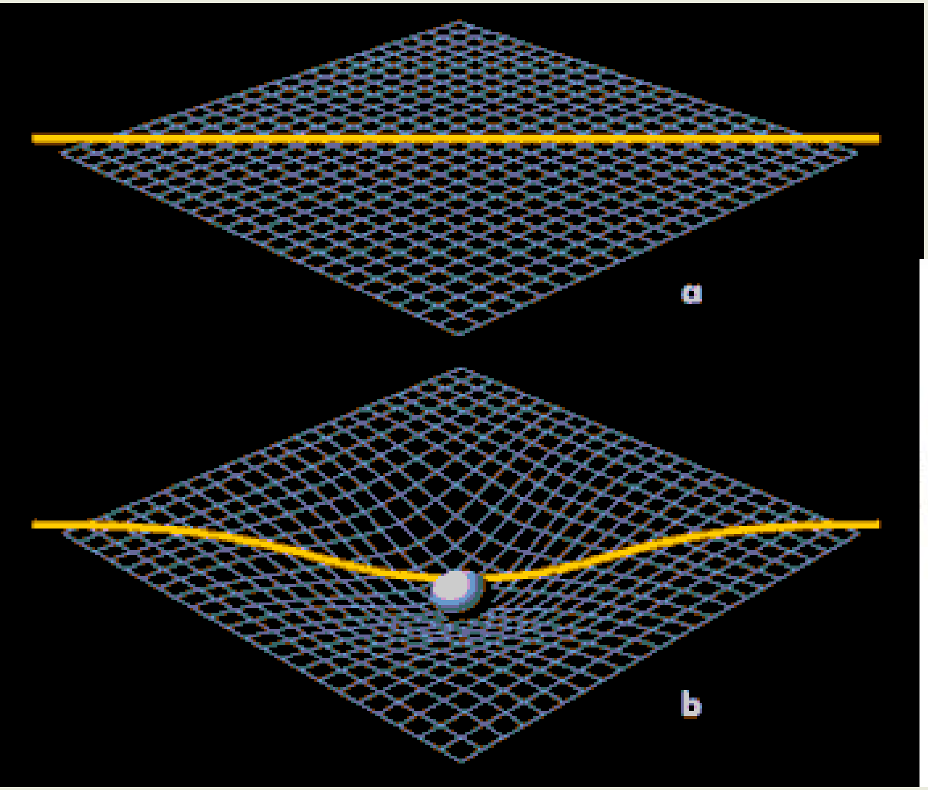
ESA/HFI/LFI CONSORTIA

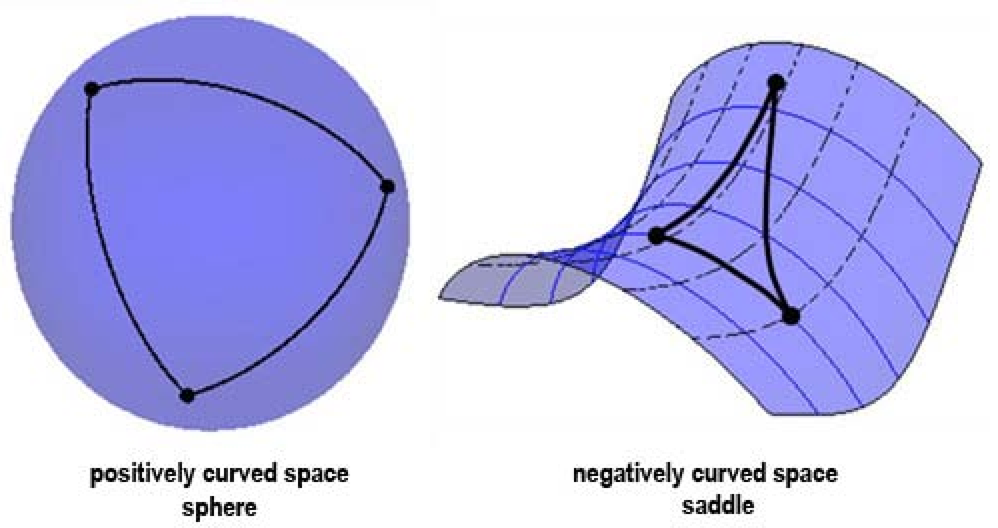
Planck Surveyor



How can we determine the geometry and expansion rate of the Universe?

- By measuring distances and/or angular diameters.





positively curved space
sphere

negatively curved space
saddle

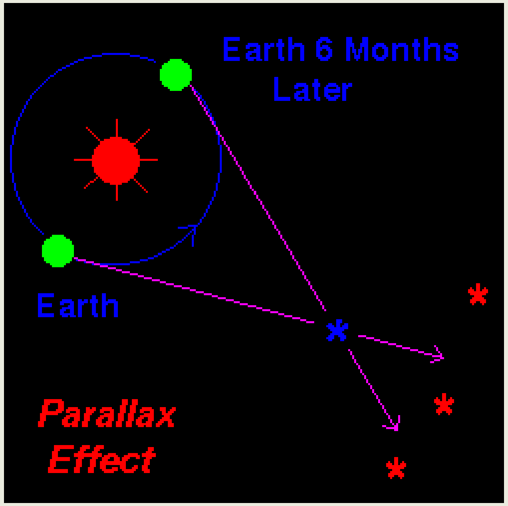
How do we measure distances in “daily life” ?

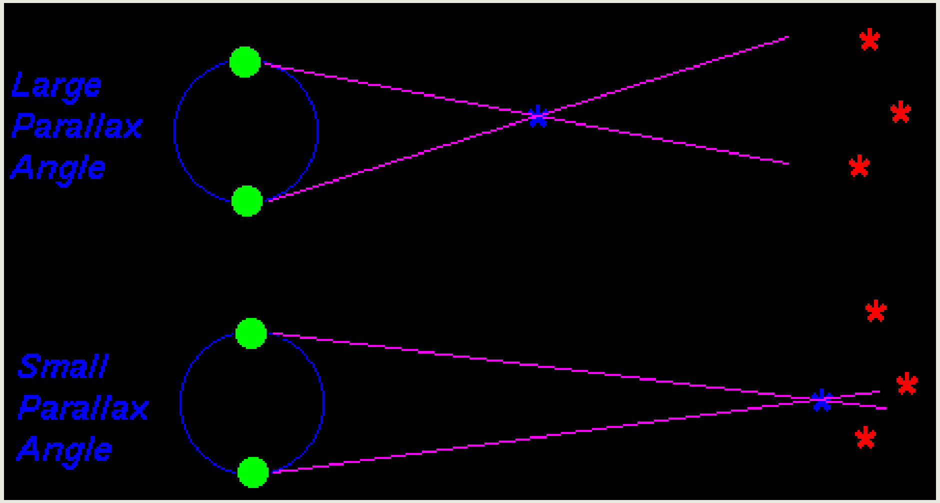
- Parallaxes
- Travel time
- Via size of objects: comparison with standard yard sticks
- Via brightness of objects: comparison with standard candles

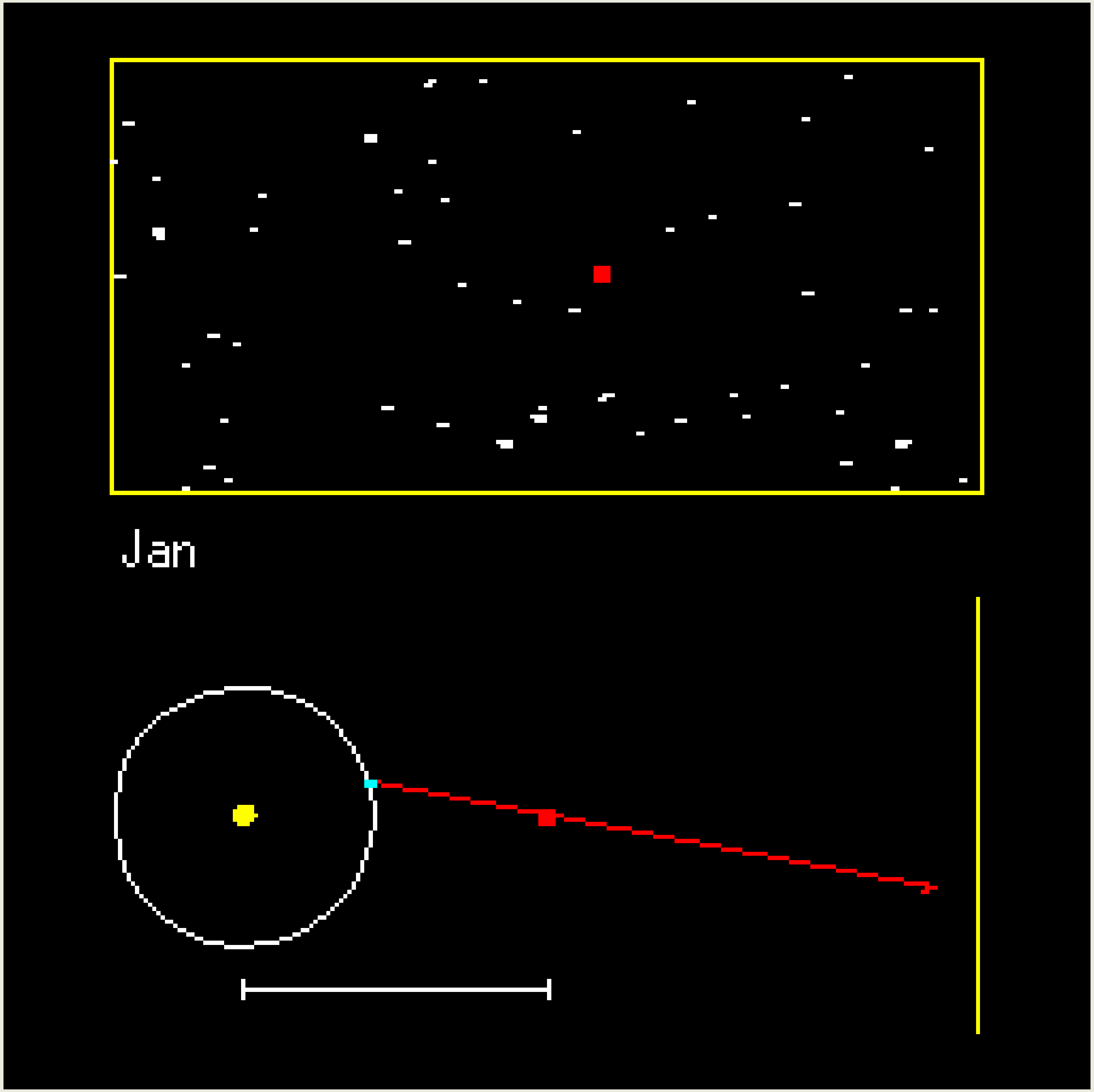
Parallaxes

- Measure the position of an object with respect to its background
- Nearby objects show a larger "motion" than objects far away do
- The parallax angle θ, the distance of the object D and the diameter of the Earth's orbit d are connected by simple geometrical relations. For small angles, it is

  $d = D \times \theta$ [units !!!! θ measured in rad !]






Jan

Travel time

- If you know the speed v you're traveling with and the travel time Δt, the distance D can be obtained by simple multiplication:

$$D = v \, \Delta t$$

- Astronomy: Use light travel times, i.e. v = 300 000 km/sec

Comparison with a standard ruler

- An object nearby spans a larger angle than an object of identical physical size far away
- The physical size l of the object, its distance D and the angle q under which it appears are connected by simple geometrical relations. For small angles, it is

  $l = D \times q$ [units !!!! q measured in rad !]
- If the physical size l of an object is known ($\Rightarrow$ standard ruler), its distance D can be determined by measuring the angle q under which the object appears

Standard Candles

- Cepheid and RR Lyrae variables
  - Pulsating stars which change in brightness with a characteristic period
  - Period is proportional to absolute luminosity
  - Common and bright (esp. Cepheids), thus visible in nearby galaxies
  - Good to ~20 Mpc

Luminosity distances (replaces $1/r^2$ – law):

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[\Omega_\kappa (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+w_i)} \right]^{-\frac{1}{2}} dz' \right\}$$

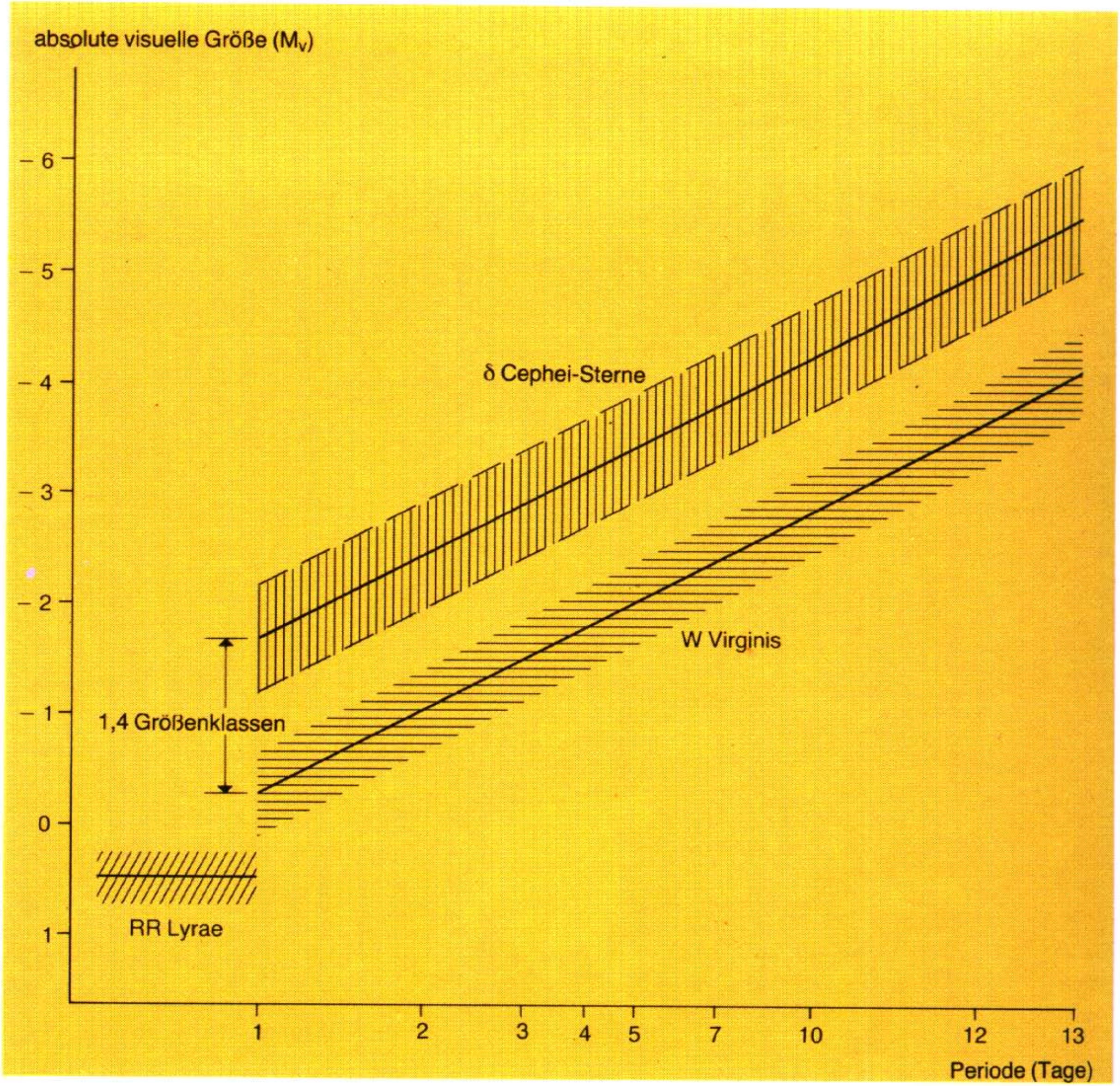
- Where $\Omega_k = 1 - \sum_i \Omega_i$ and $w_i = \dfrac{p_i}{\rho_i c^2}$

w_M = 0 (matter)

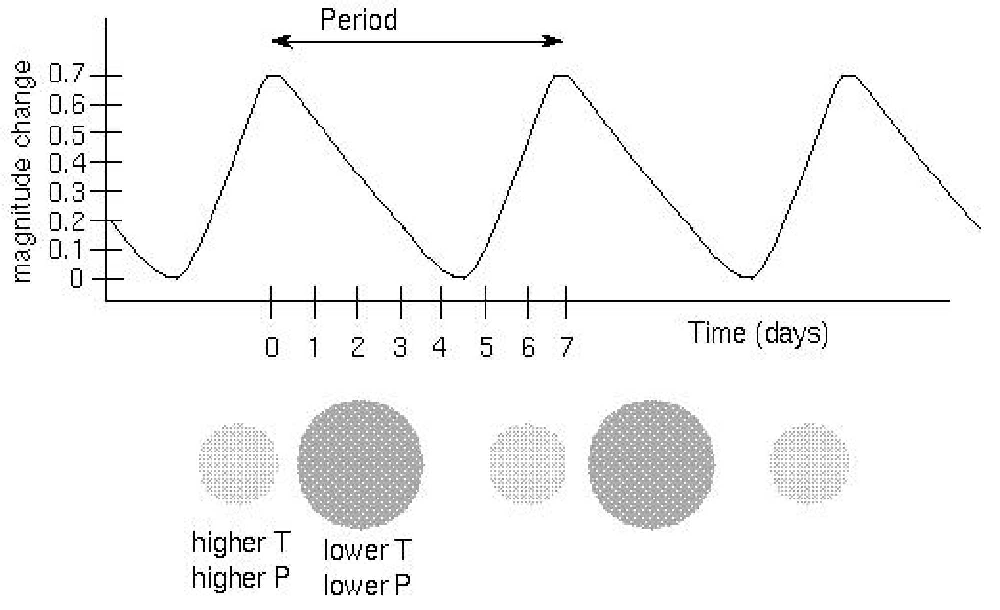
w_R = ⅓ (radiation)

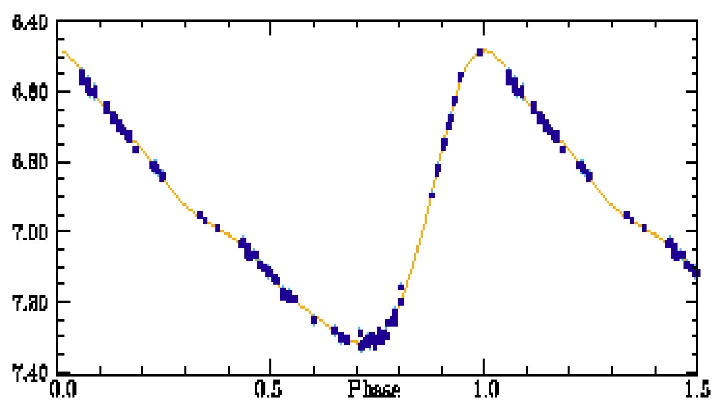
w_Λ = -1 (cosmological constant/vacuum)

Calibrated “standard candles”

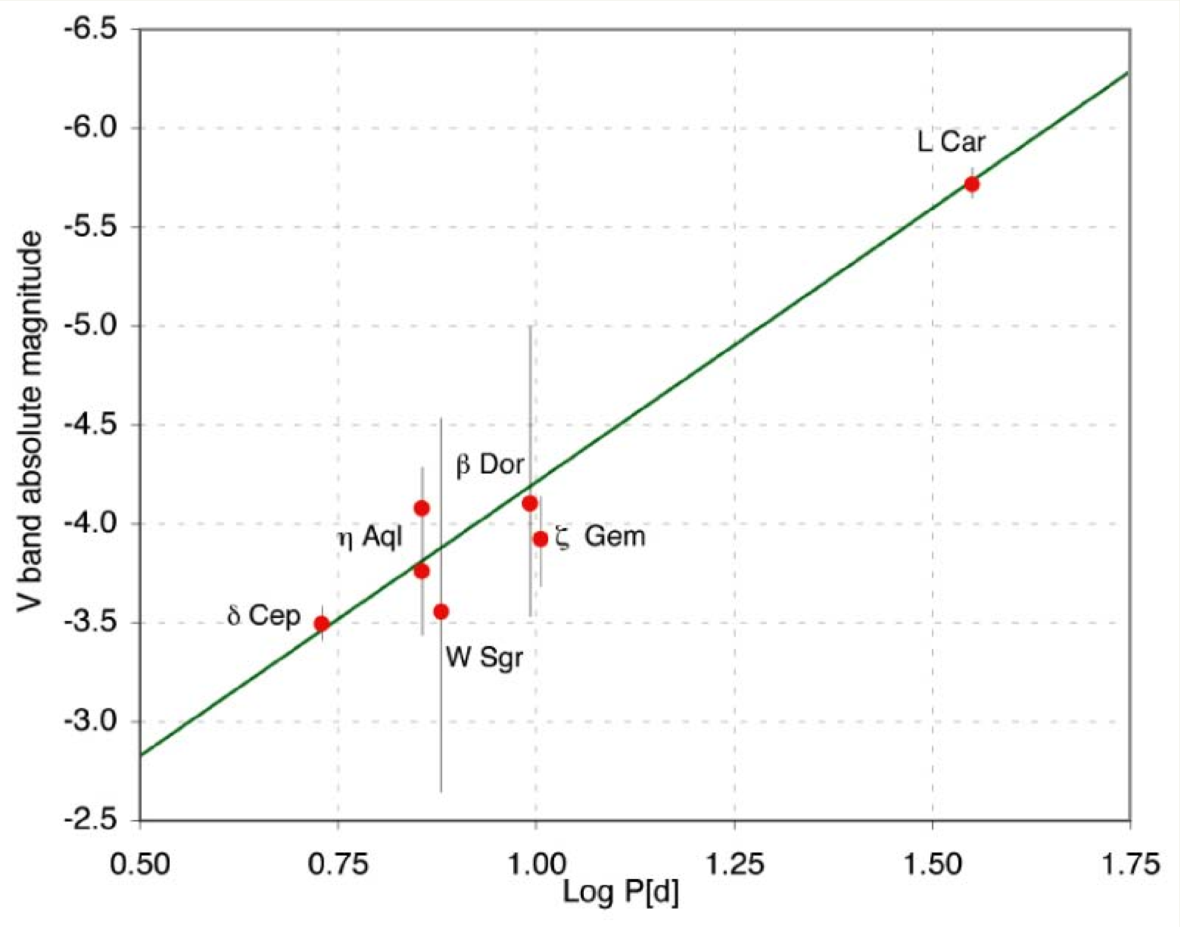


Calibrated "standard candles" (e.g., δ-Cephei stars)



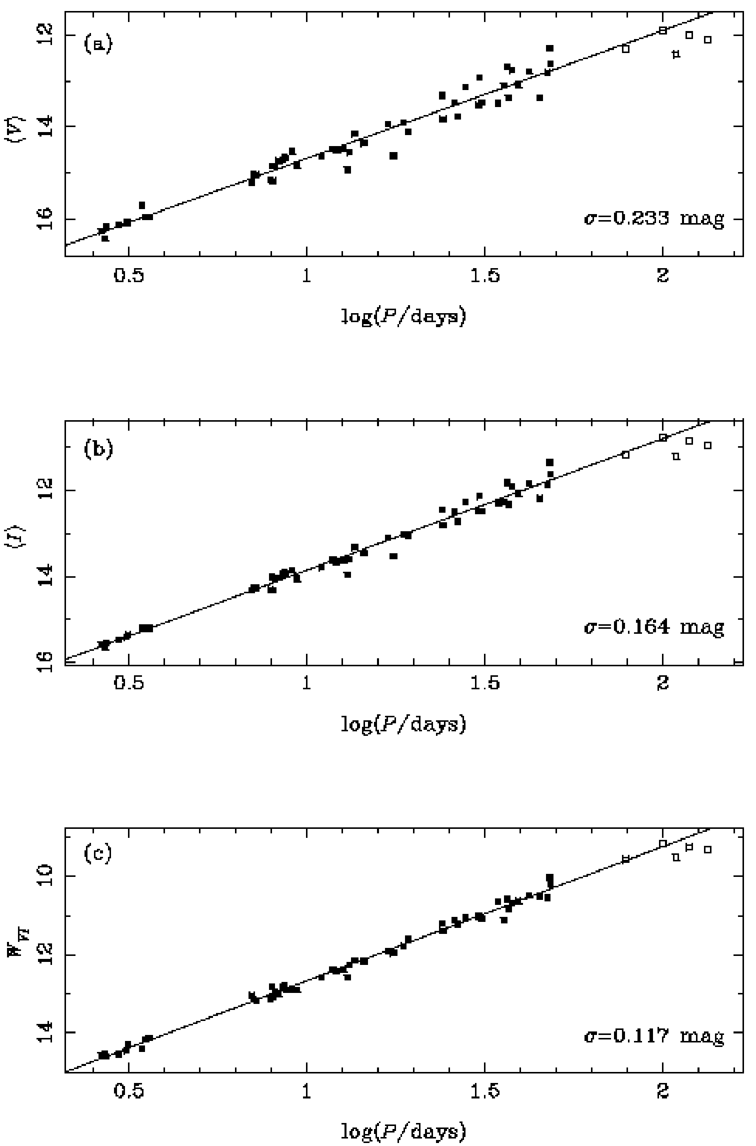


Distances with δ Cephei stars



Direct measurement of the change in angular diameter plus spectroscopic radial velocity (Kervella et al. 2004)

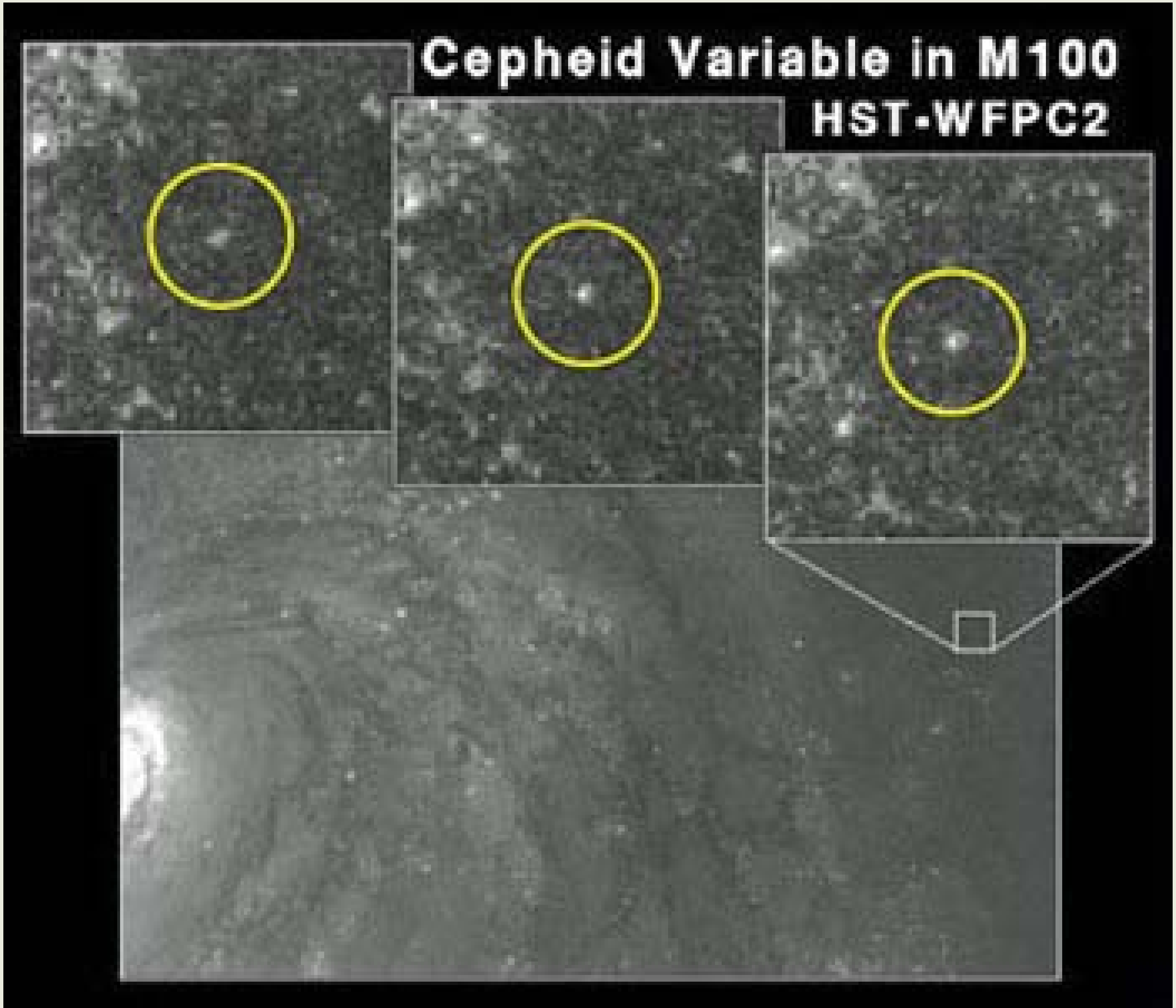
Distances with δ Cephei stars



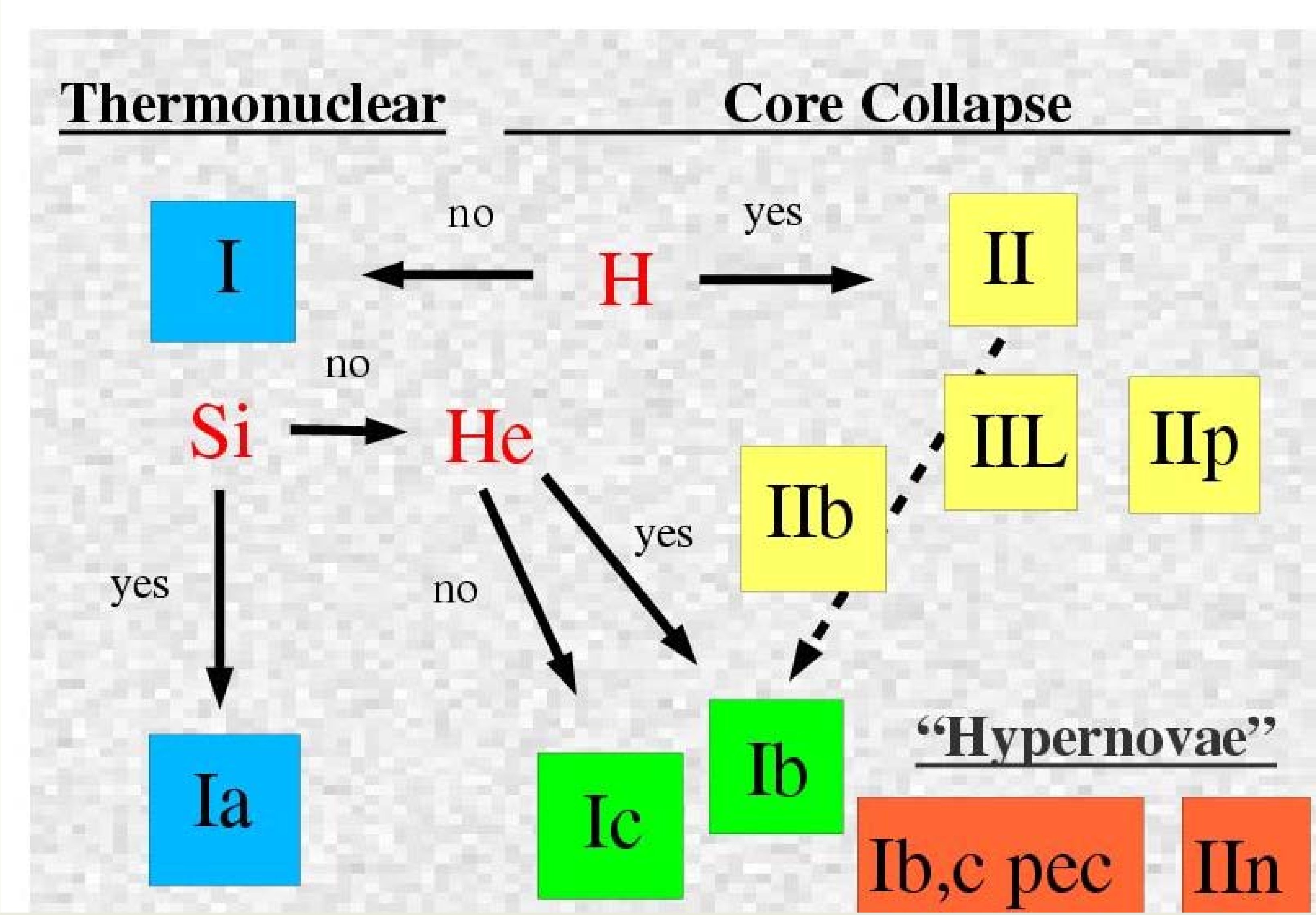
LMC Cepheids:
D = (51 ± 3) kpc

Calibrated “standard candles” (e.g., δ-Cepheі stars)

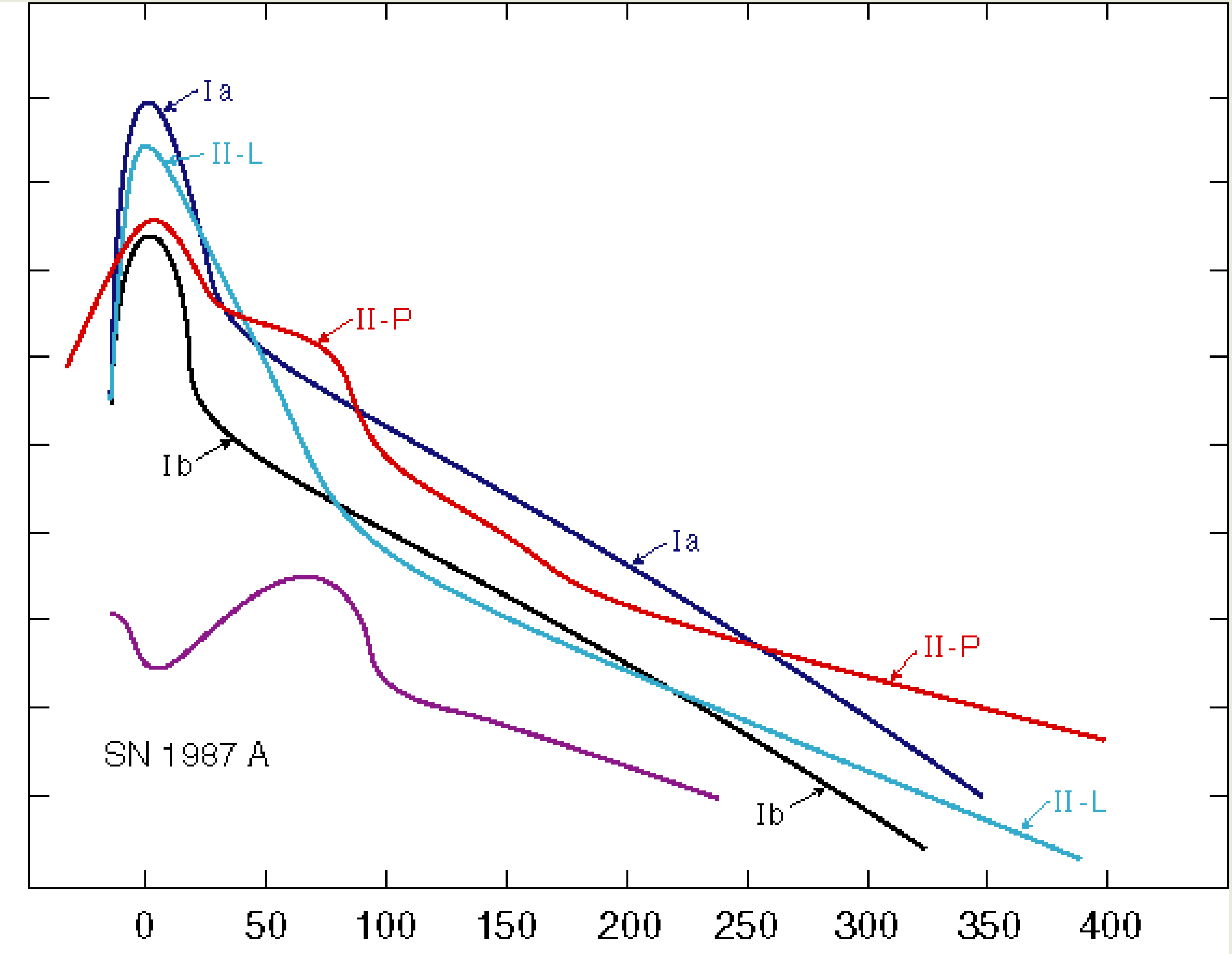
D = (17±2) Mpc



Supernova classification



Supernova light curves



Distances with Type Ia Supernovae

- Use the Hubble diagram (m-M *vs.* log z)
  - $m-M=5\log(z)+25+5\log(c)-5\log(H_0)$
- Note that the slope is given here.
- Hubble constant can be derived when the absolute luminosity M is known
  - $\log H_0=\log(z)+5+\log(c)-0.2(m-M)$

Give relative distances only!

Hubble constant from SNe Ia

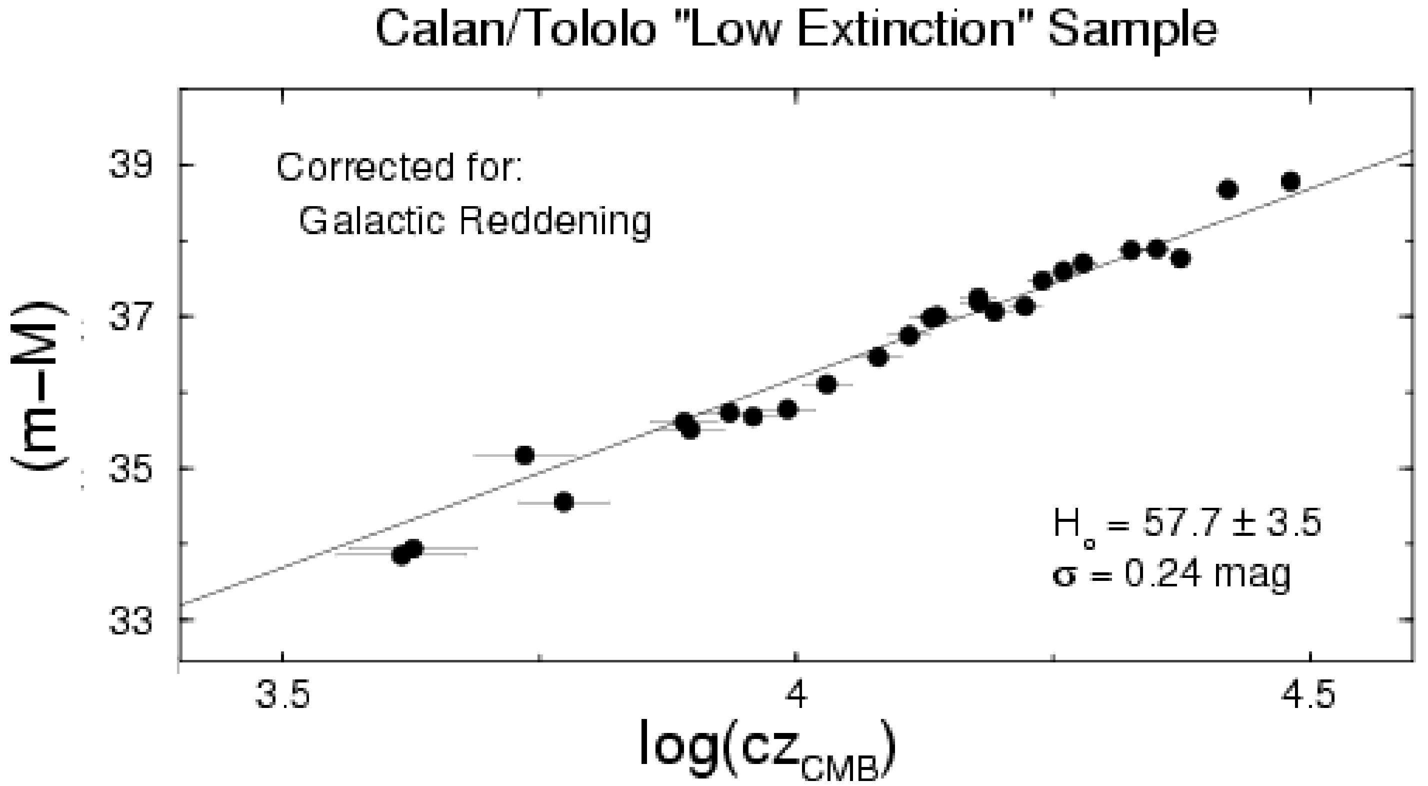
- Calibrate the absolute luminosity
  - through Cepheids
    - ‘classical distance ladder’
      - depends on the accuracy of the previous rungs on the ladder
      - LMC distance, P-L(-C) relation, metallicities
    - HST program (Sandage, Tammann)
    - HST Key Programme (Freedman, Kennicutt, Mould, Madore)
  - through models
    - extremely difficult (but possible!)

Absolute Magnitudes of SNe Ia

SN	Galaxy	m-M	M_B	M_V	M_I	Δm_{15}
1937C	IC 4182	28.36 (12)	-19.56 (15)	-19.54 (17)	-	0.87 (10)
1960F	NGC 4496	31.03 (10)	-19.56 (18)	-19.62 (22)	-	1.06 (12)
1972E	NGC 5253	28.00 (07)	-19.64 (16)	-19.61 (17)	-19.27 (20)	0.87 (10)
1974G	NGC 4414	31.46 (17)	-19.67 (34)	-19.69 (27)	-	1.11 (06)
1981B	NGC 4536	31.10 (12)	-19.50 (18)	-19.50 (16)	-	1.10 (07)
1989B	NGC 3627	30.22 (12)	-19.47 (18)	-19.42 (16)	-19.21 (14)	1.31 (07)
1990N	NGC 4639	32.03 (22)	-19.39 (26)	-19.41 (24)	-19.14 (23)	1.05 (05)
1998bu	NGC 3368	30.37 (16)	-19.76 (31)	-19.69 (26)	-19.43 (21)	1.08 (05)
1998aq	NGC 3982	31.72 (14)	-19.56 (21)	-19.48 (20)	-	1.12 (03)
Straight mean			-19.57 (04)	-19.55 (04)	-19.26 (0 6)	
Weighted mean			-19.56 (07)	-19.53 (06)	-19.25 (0 9)	

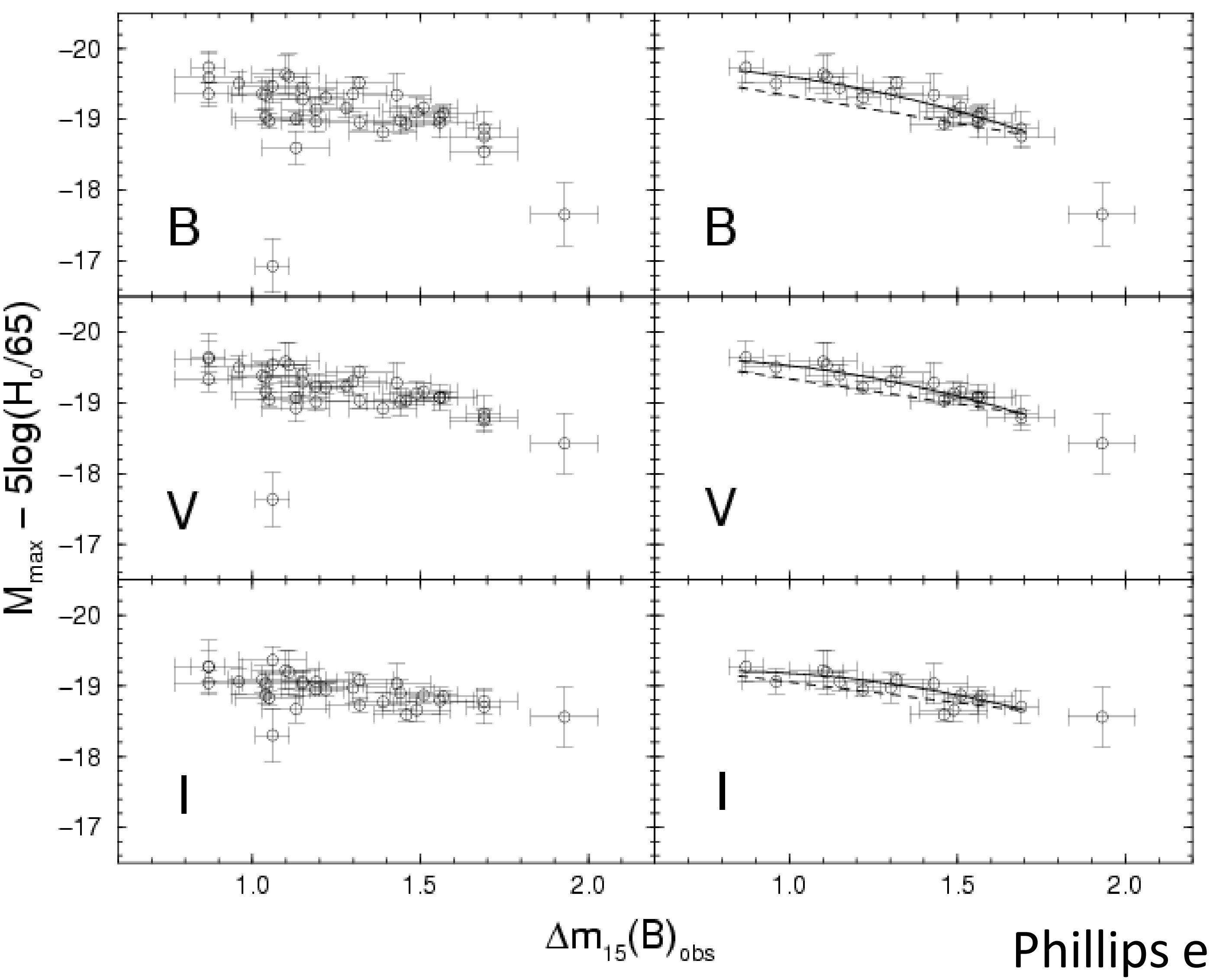
(Saha et al. 1999)

Nearby SNe Ia



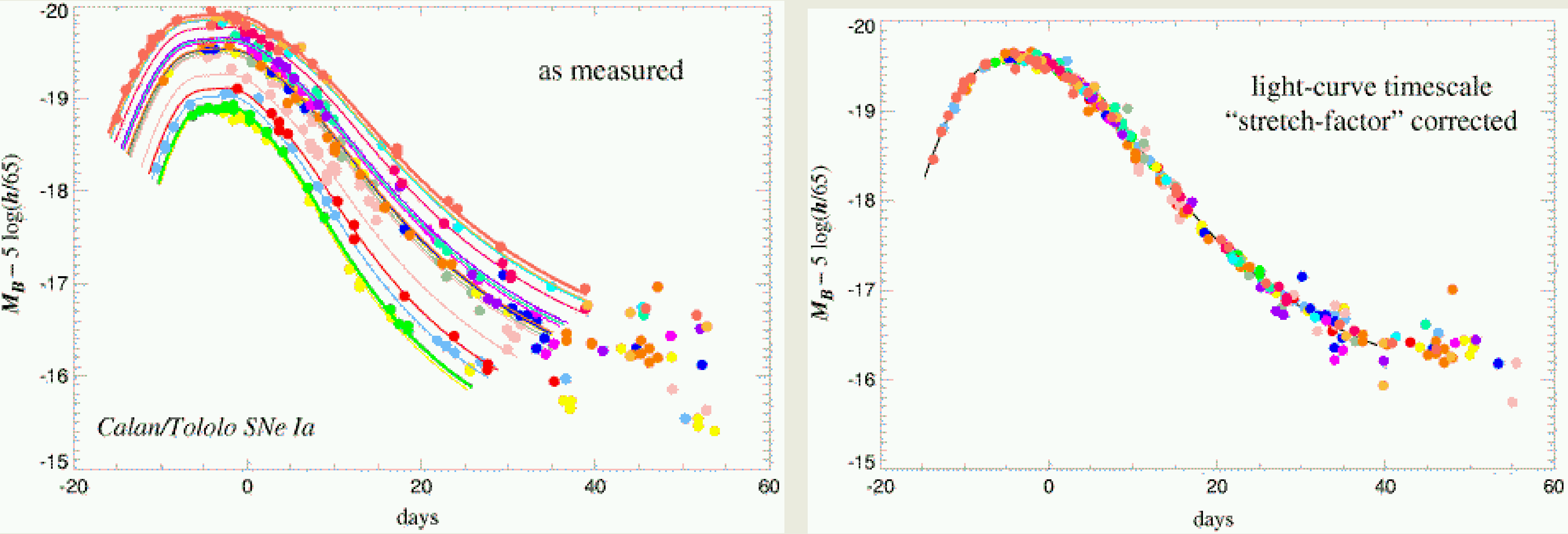
Phillips et al. (1999)

Correlations between peak luminosity and LC shape



Phillips et al. 1999

Light curve shape – luminosity

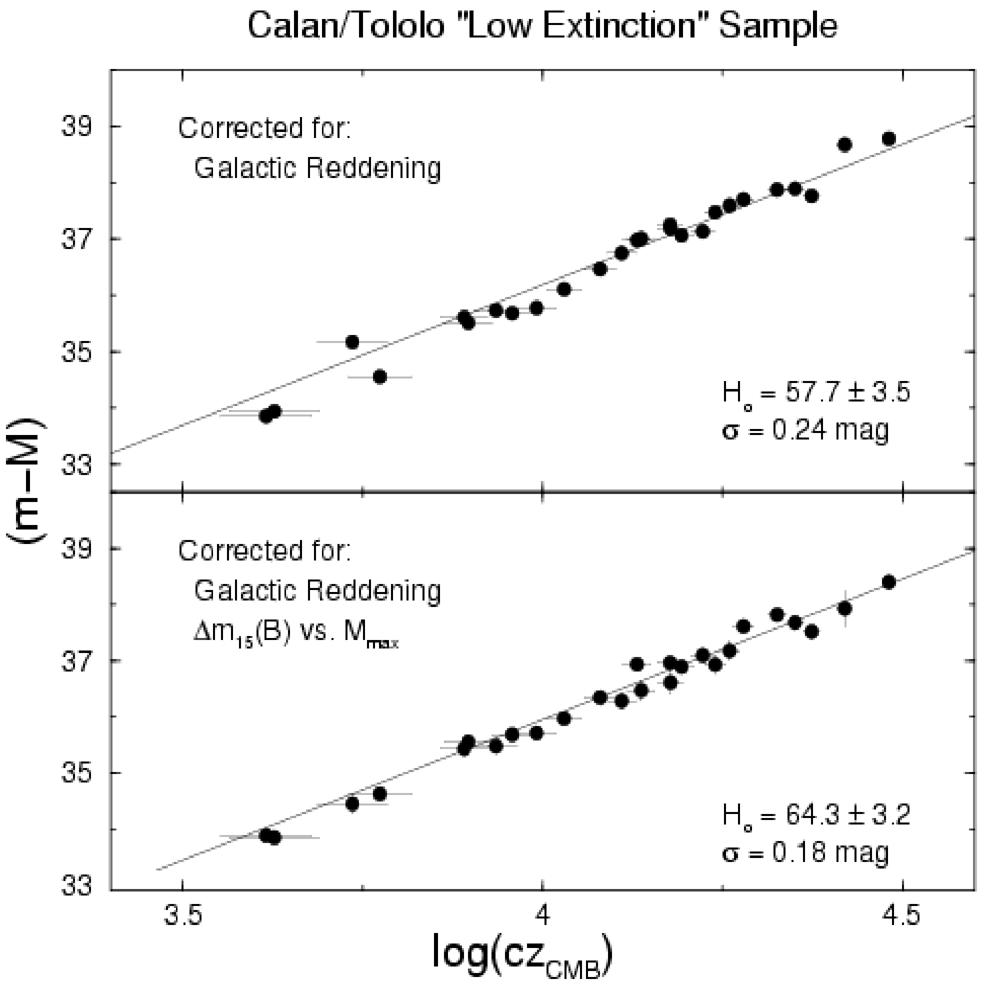


(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

After calibration: *SNe Ia look like good "standard candles"!*

Normalisation of the peak luminosity

Phillips et al. 1999



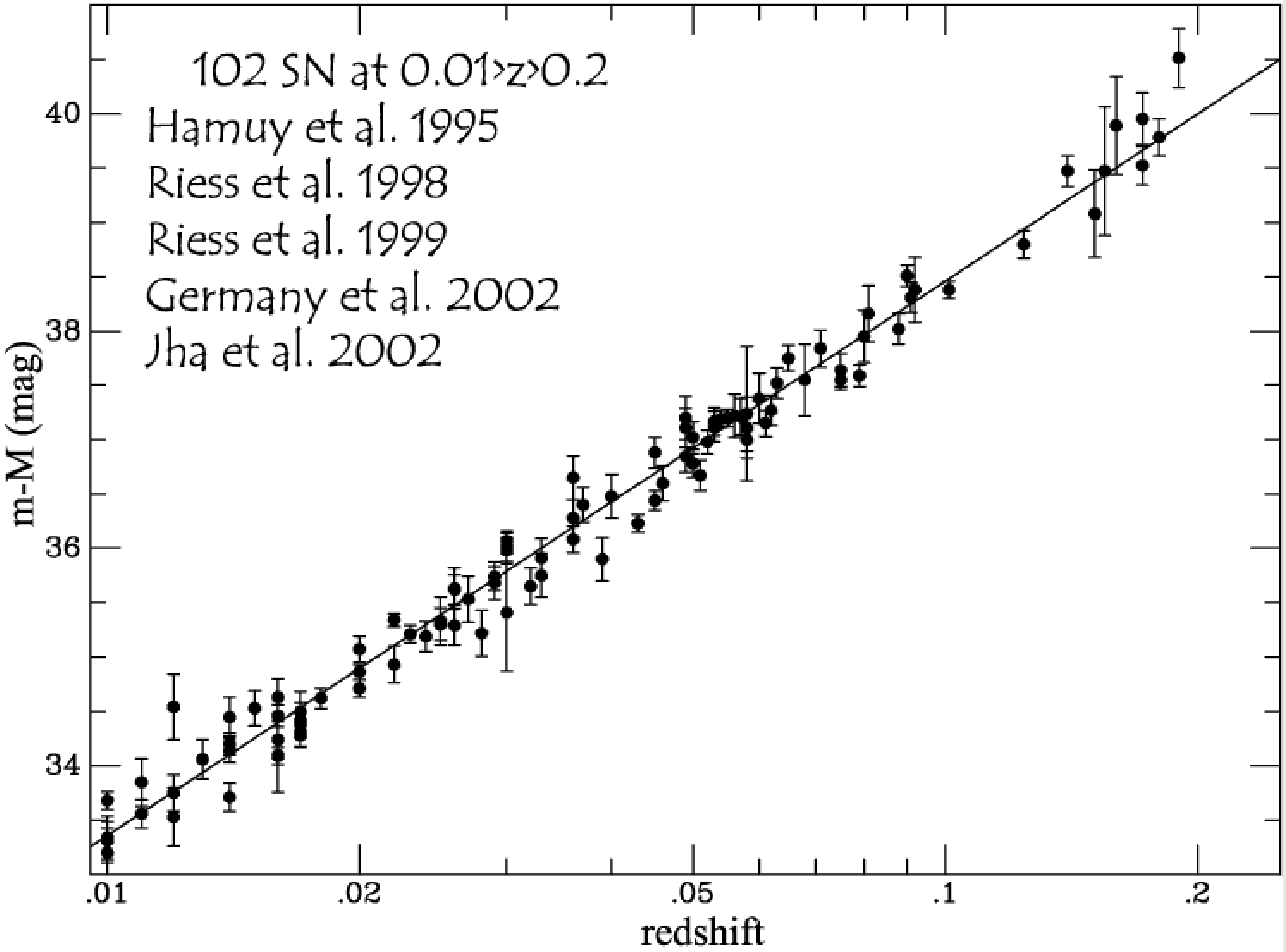
Calan/Tololo "Low Extinction" Sample

Using the luminosity-decline rate relation one can normalise the peak luminosity of SNe Ia

→

Reduces the scatter!

The nearby SN Ia sample



Evidence for good distances

Hubble constant from SNe Ia

- Extremely good (relative) distance indicators
  - distance accuracy better than 10%
- Uncertainty in H_0 mostly from the LMC and the Cepheid P-L relation
- Today's best value (Cepheids + SNe Ia):

$$\boxed{H_0 = (72 \pm 6)\ \mathrm{km/s/Mpc}}$$

Note: This enters as an uncertainty in many other places!

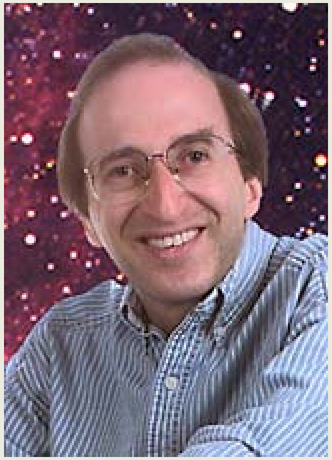
Measuring the deceleration parameter q_0

- How do we do that?
  - Measure the rate of expansion at different times, i.e. measure and compare the expansion based on nearby galaxies and based on high redshift galaxies or other objects, e.g., Type Ia supernovae.

- Gravity is slowing down the expansion $\Rightarrow$ expansion rate should be higher at high redshift.

Nobel Prize for Physics 2011....

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



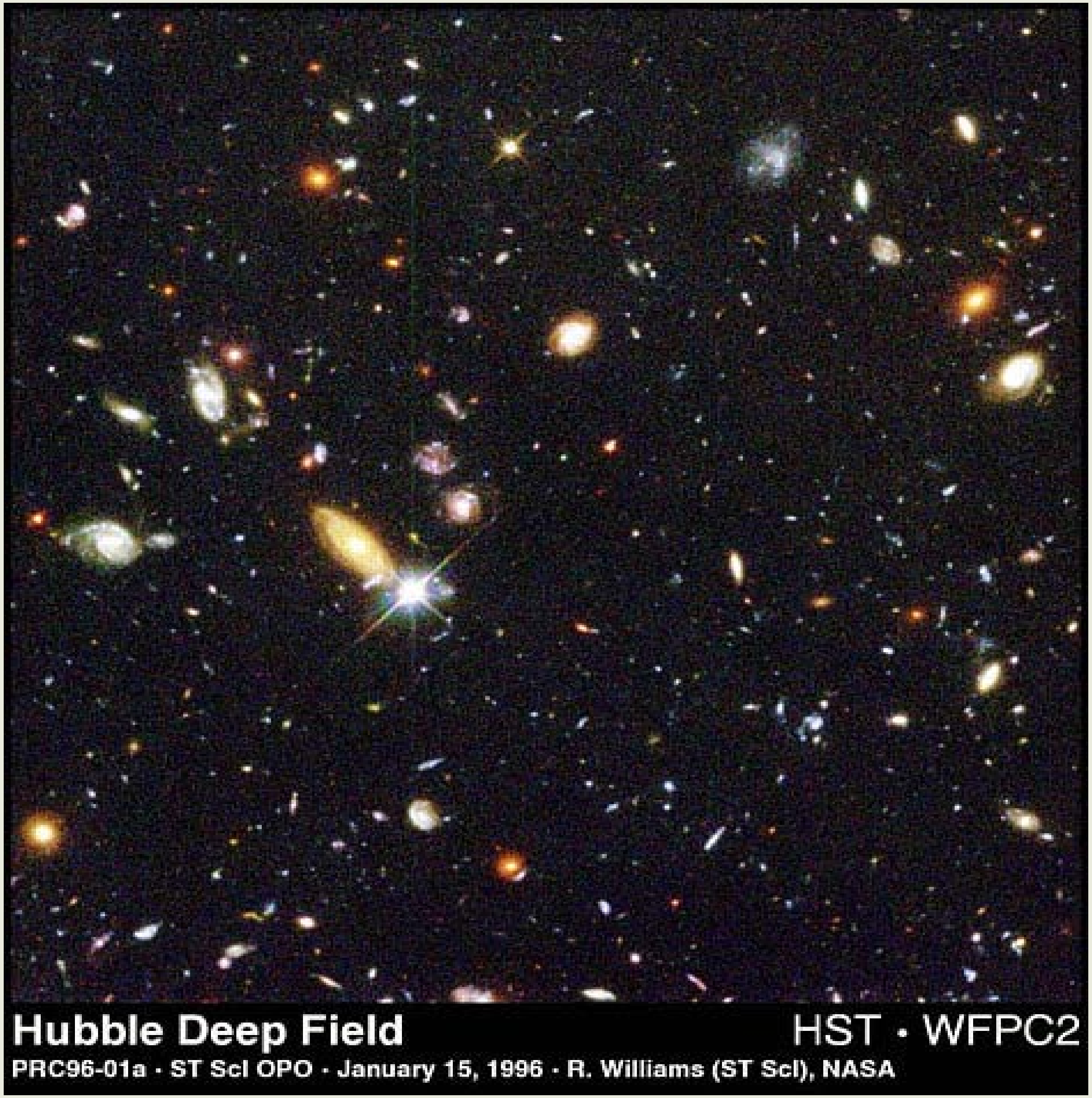
Saul Perlmutter

Brian Schmidt

Adam Riess

“... for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Distant supernovae

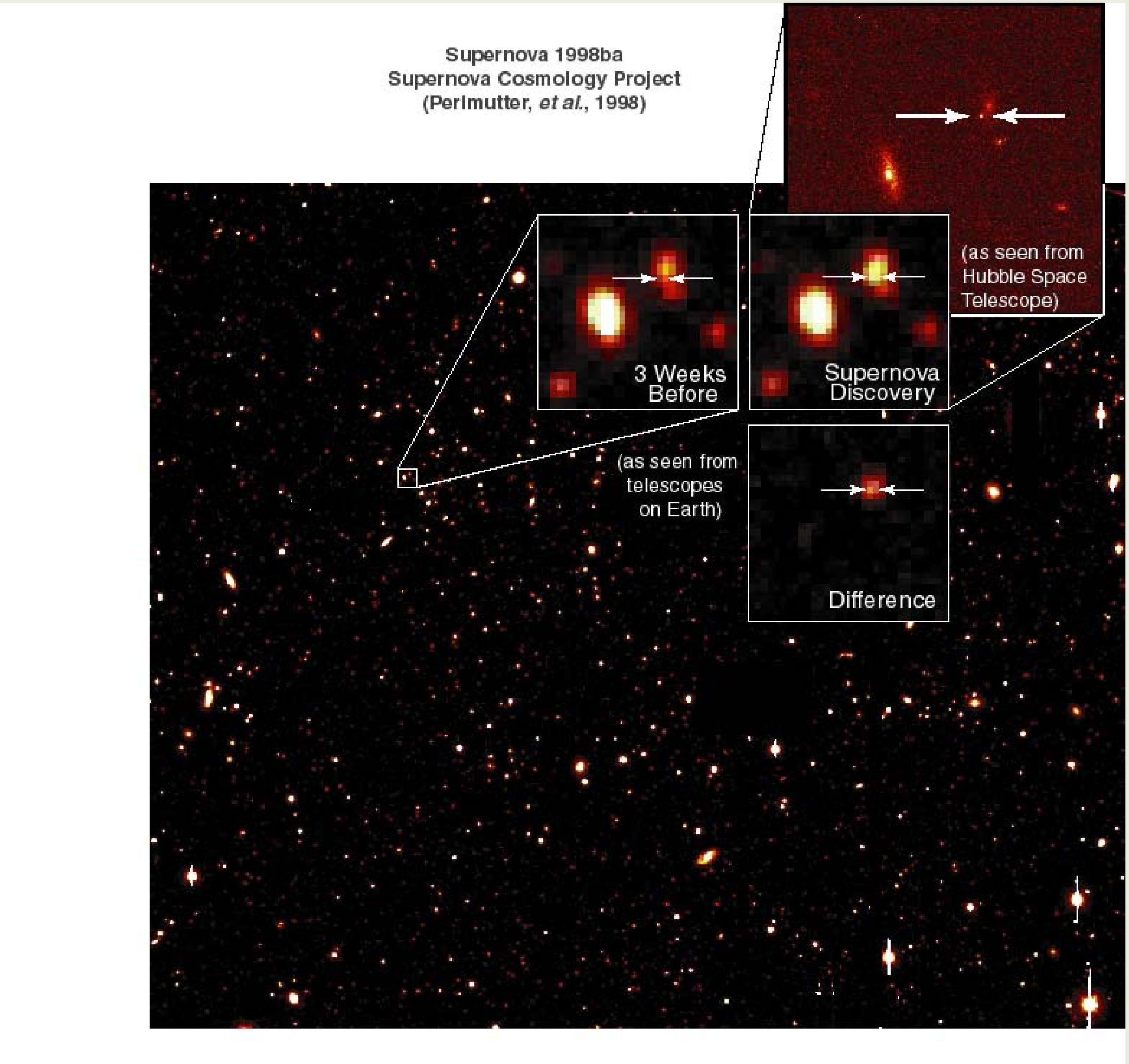


Supernovae are very rare, ~ 1 SN per 100 years and galaxy.

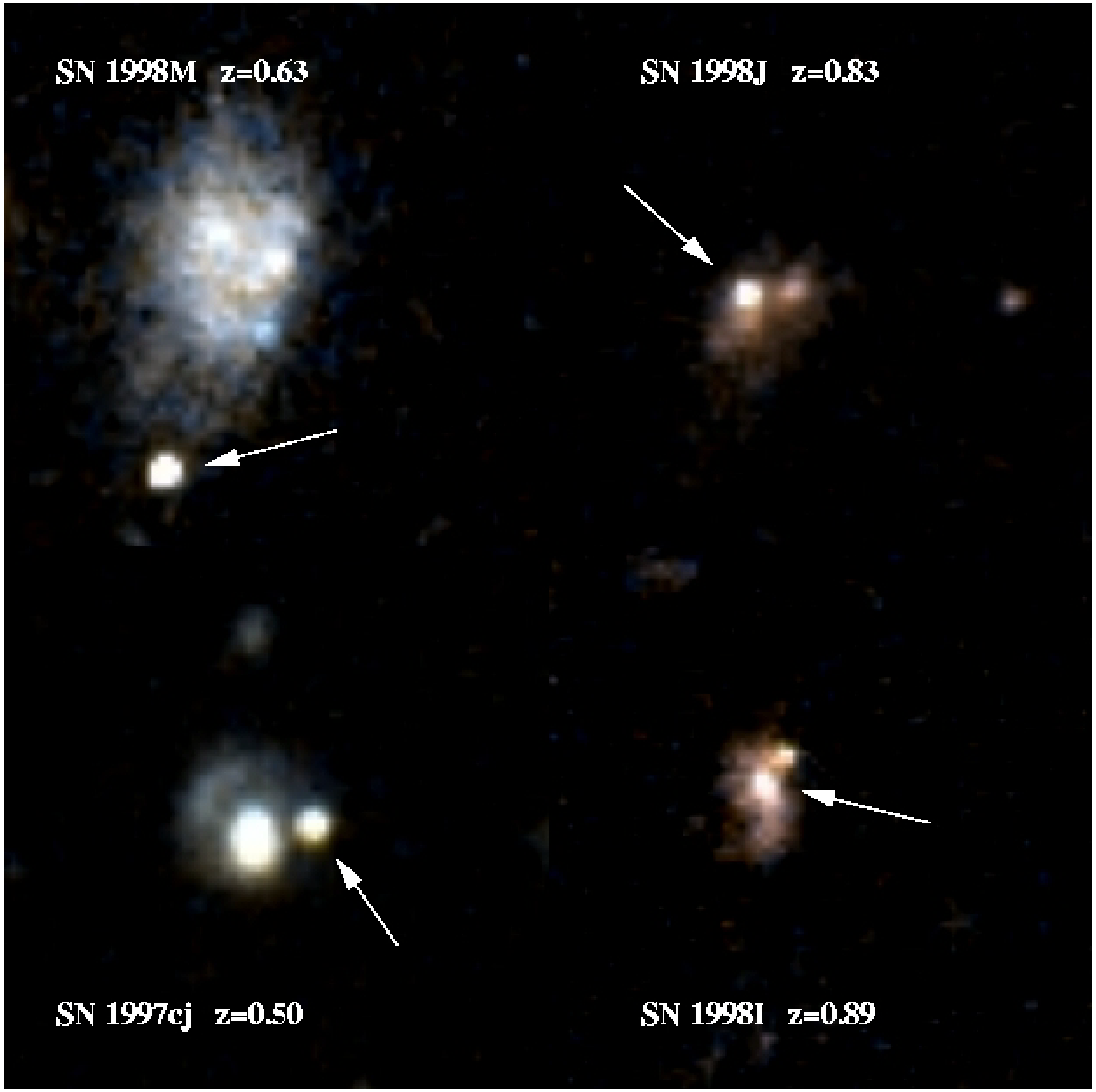
→

One has to observe very many galaxies!

Search strategy:



1. Repeated scanning of a certain field.
2. Electronic readout of the data.
3. Follow-up observations, e.g., HST, VLT, …



Supernovae are routinely detected at redshifts Z > 0.1:

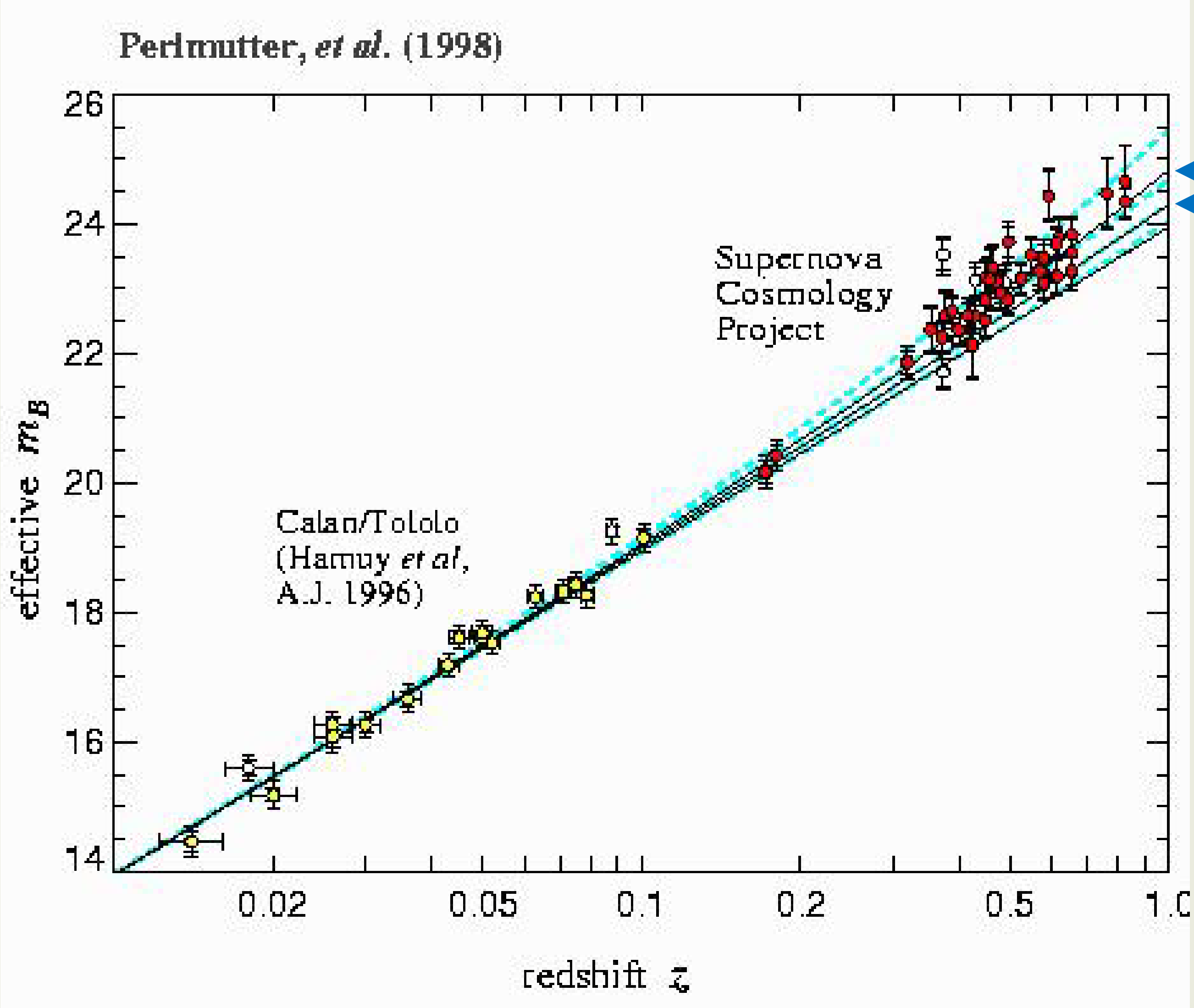
What is the intrinsic scatter in luminosities?

Are they different from the local sample?

Do we understand the differences?

So let's measure q_0!

fainter



$q_0 = 0$

$q_0 = 0.5$

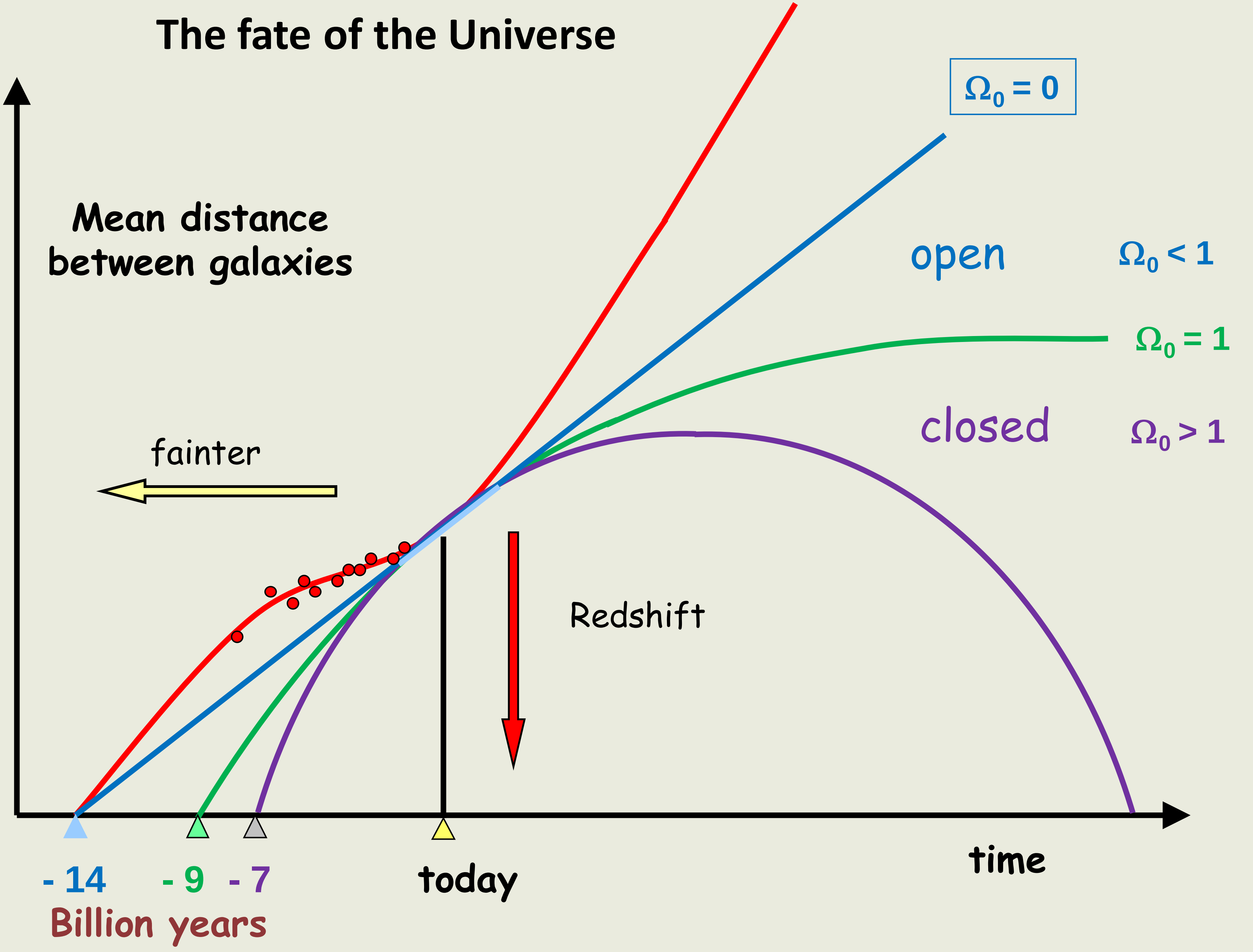
Data indicates:

$q_0 < 0$

⇒ Expansion is accelerating

more distant

The fate of the Universe



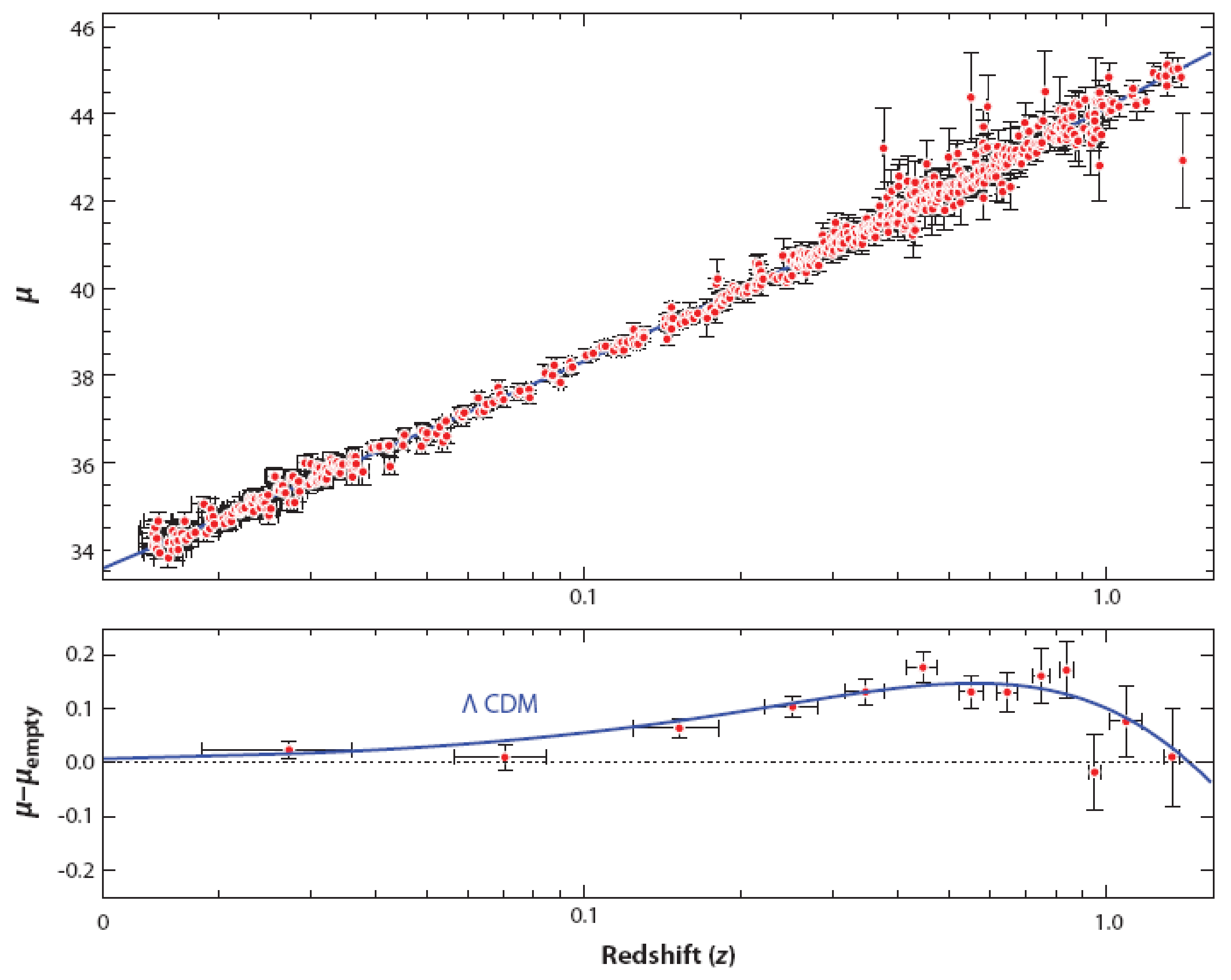
Friedmann's equation for Λ>0

$$v^2 = \frac{8\pi G}{3}\rho a^2 - kc^2 + \frac{\Lambda a^2}{3}$$

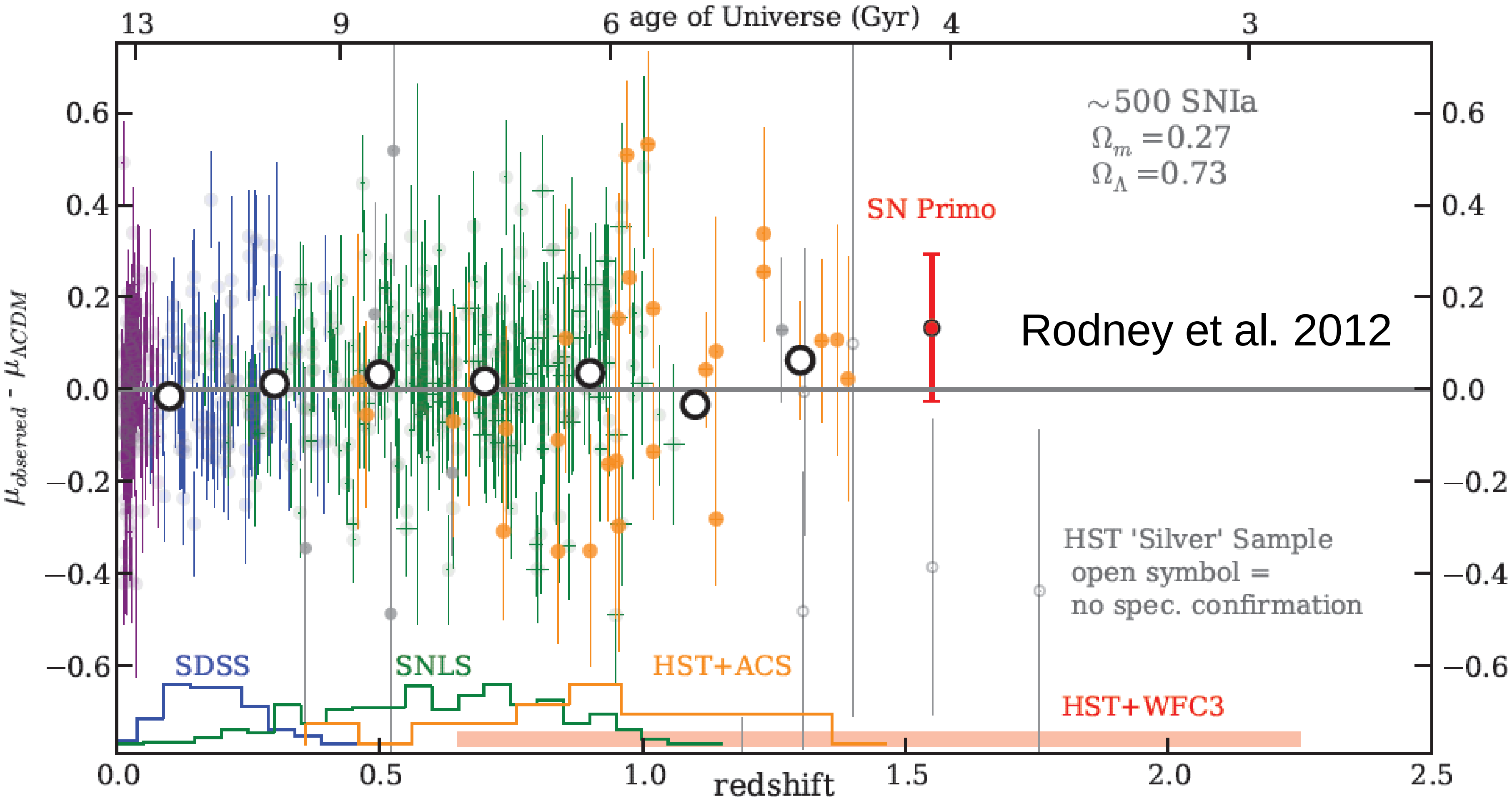
- *k* is the curvature constant
  - *k=0*: flat space
  - *k>0*: spherical geometry
  - *k<0*: hyperbolic geometry
- but for sufficiently large Λ a spherically curved universe may expand forever

Most recent supernova data (January 2011) (557 SNe)

$\mu = m - M$



The most recent Hubble diagram



Rodney et al. 2012

General luminosity distance

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}}\, S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+w_i)}\right]^{-\frac{1}{2}} dz'\right\}$$

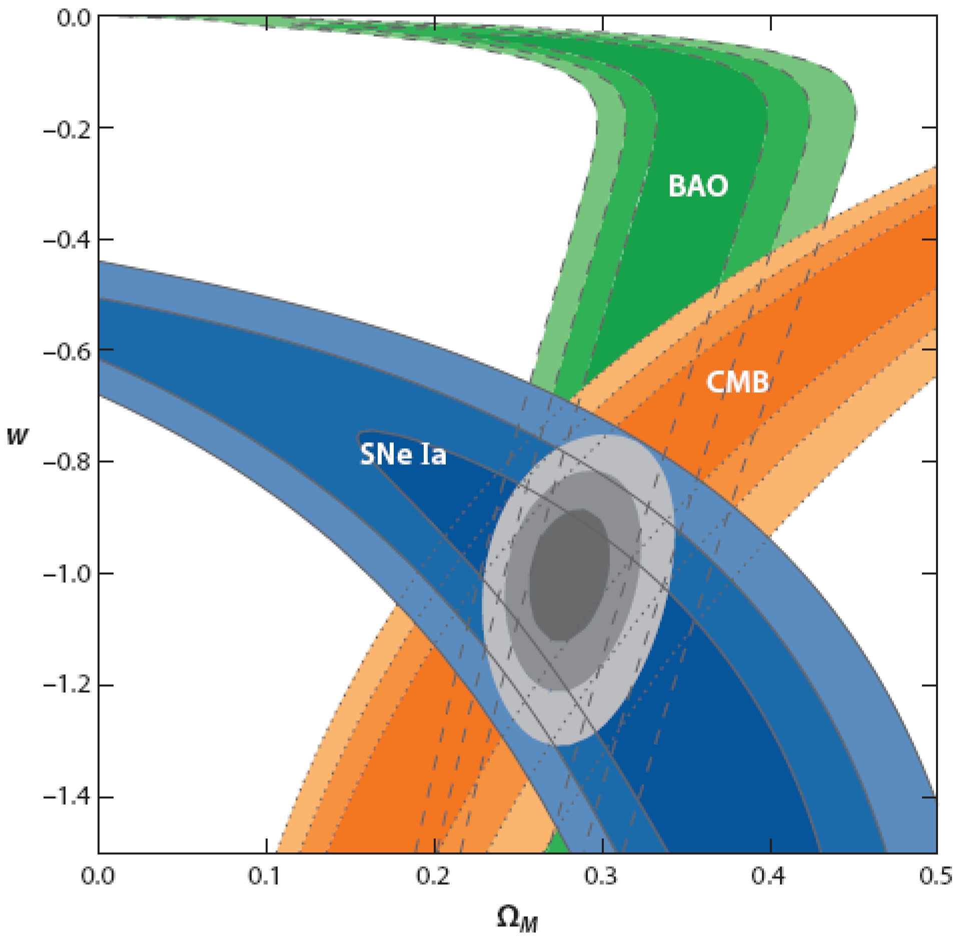
- with $\Omega_k = 1 - \sum_i \Omega_i$ and $w_i = \frac{p_i}{\rho_i c^2}$

w_M= 0 (matter)

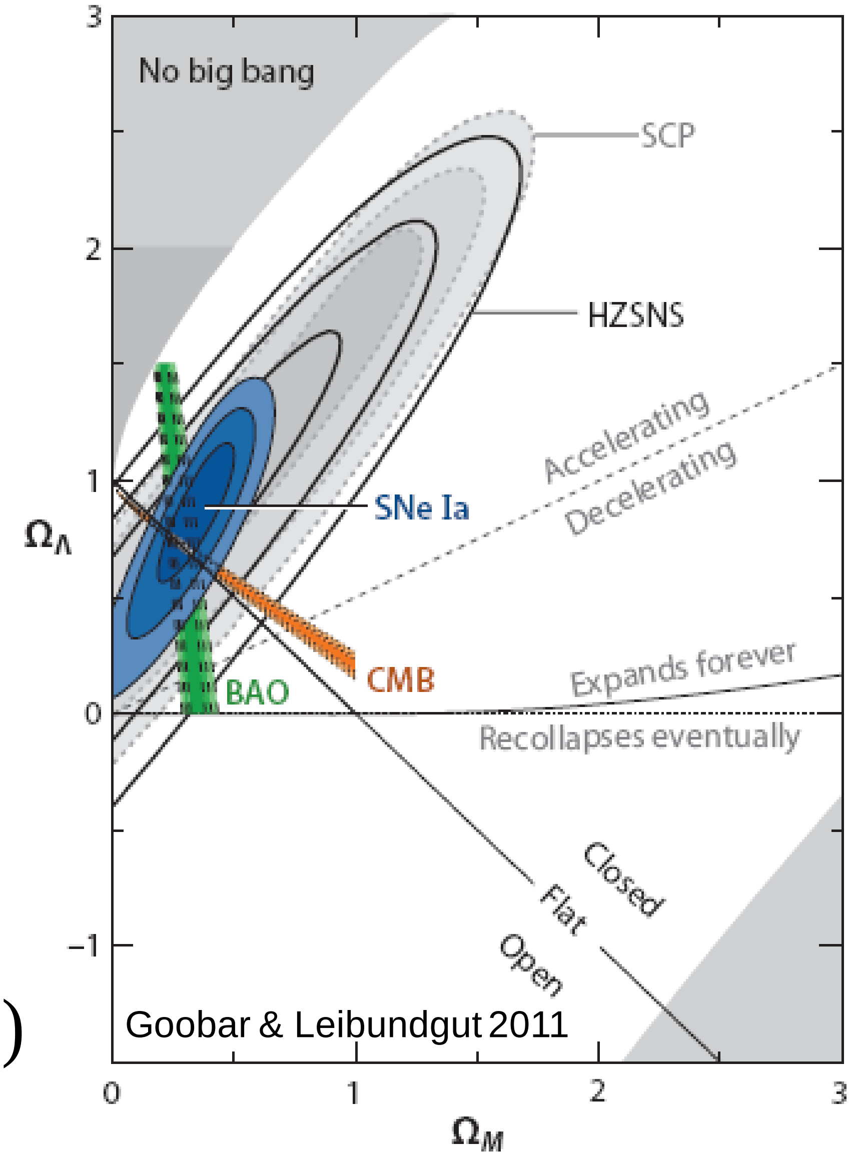
w_R= ⅓ (radiation)

w_Λ= -1 (cosmological constant)

Cosmological parameters from different probes

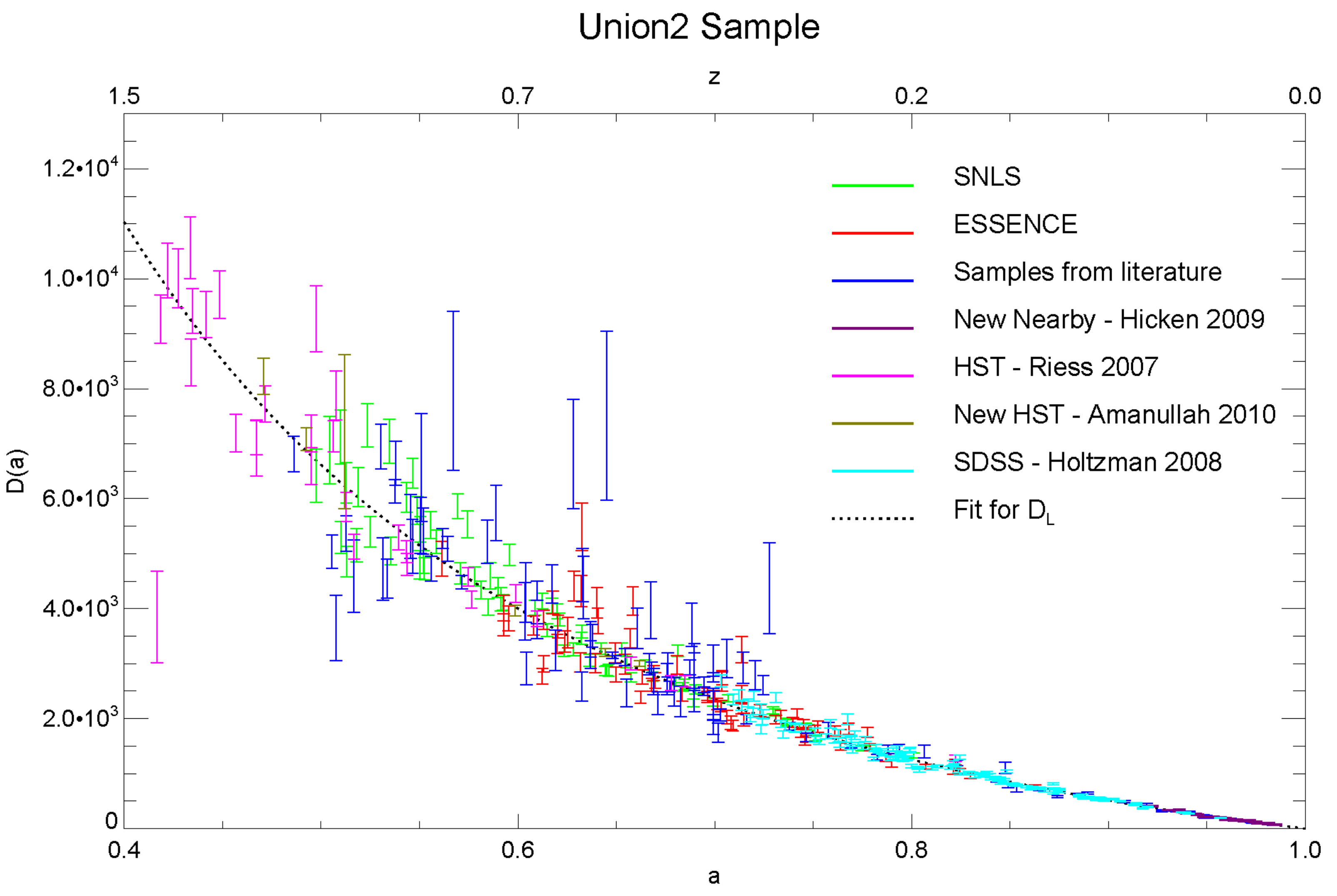


$$w = -1.001 \pm 0.071(\text{stat}) \pm 0.081(\text{sys})$$



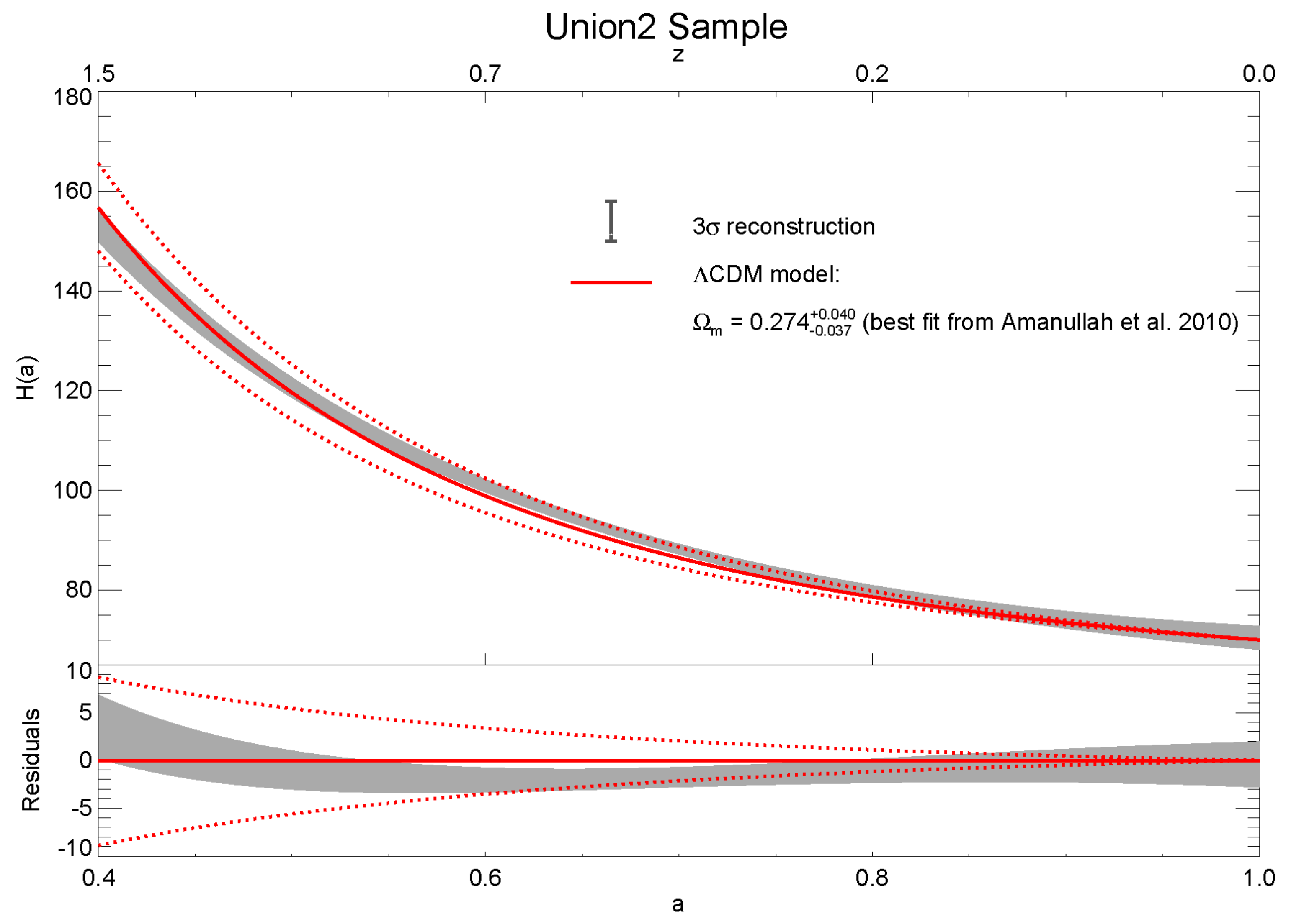
Goobar & Leibundgut 2011

H(z) reconstruction from D_L



Benitez-Herrera et al. 2011

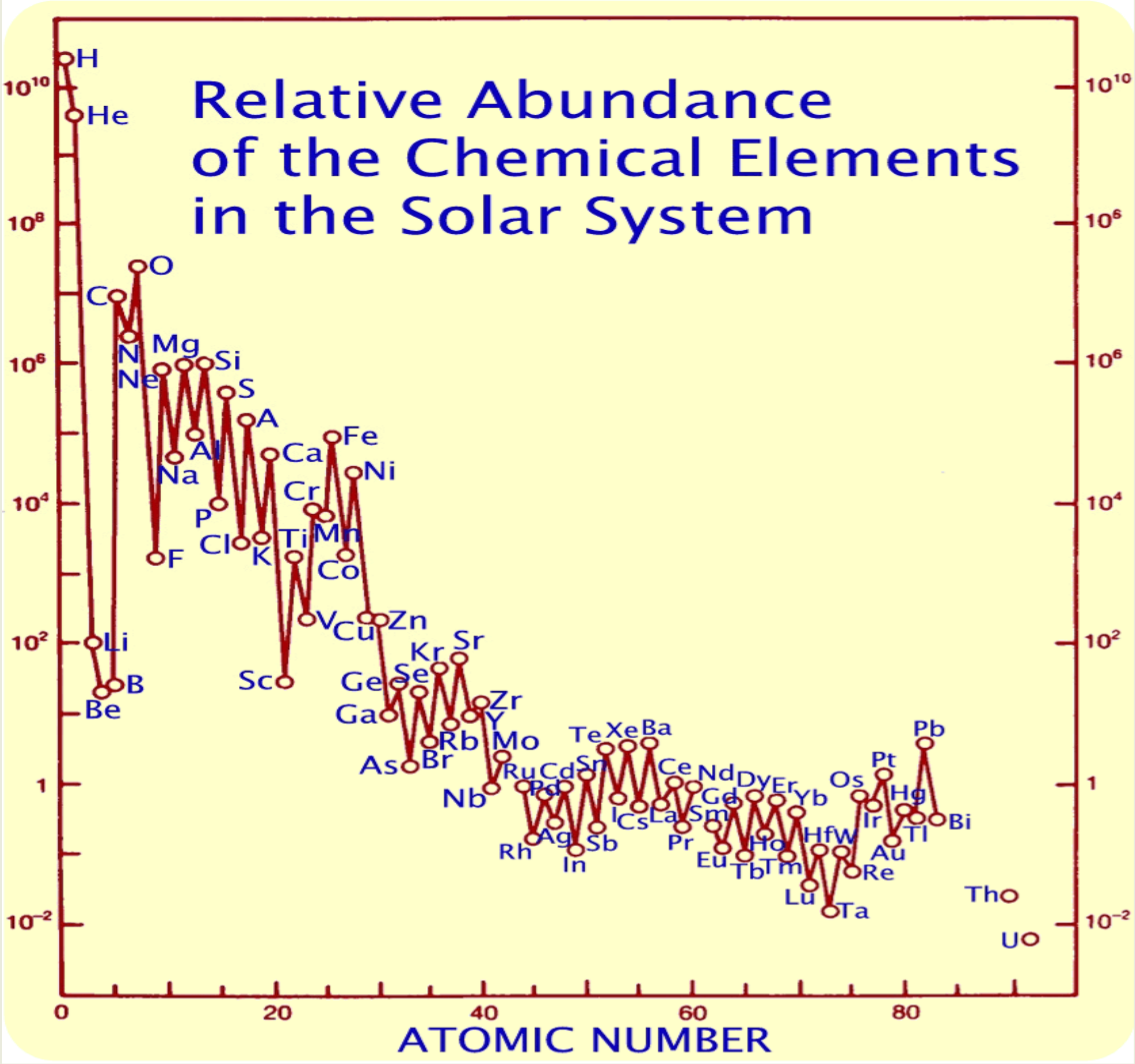
H(z) reconstruction from D_L



Georgy Gamov (1904-1968)

- If the universe is expanding, then there has been a big bang
- Therefore, the early universe must have been very dense and hot
- Optimum environment to breed the elements by nuclear fusion (Alpher, Bethe & Gamow, 1948)
  - success: predicted that helium abundance is 25%
  - failure: could not reproduce elements more massive than lithium and beryllium (⇒ formed in stars)

Abundances of elements

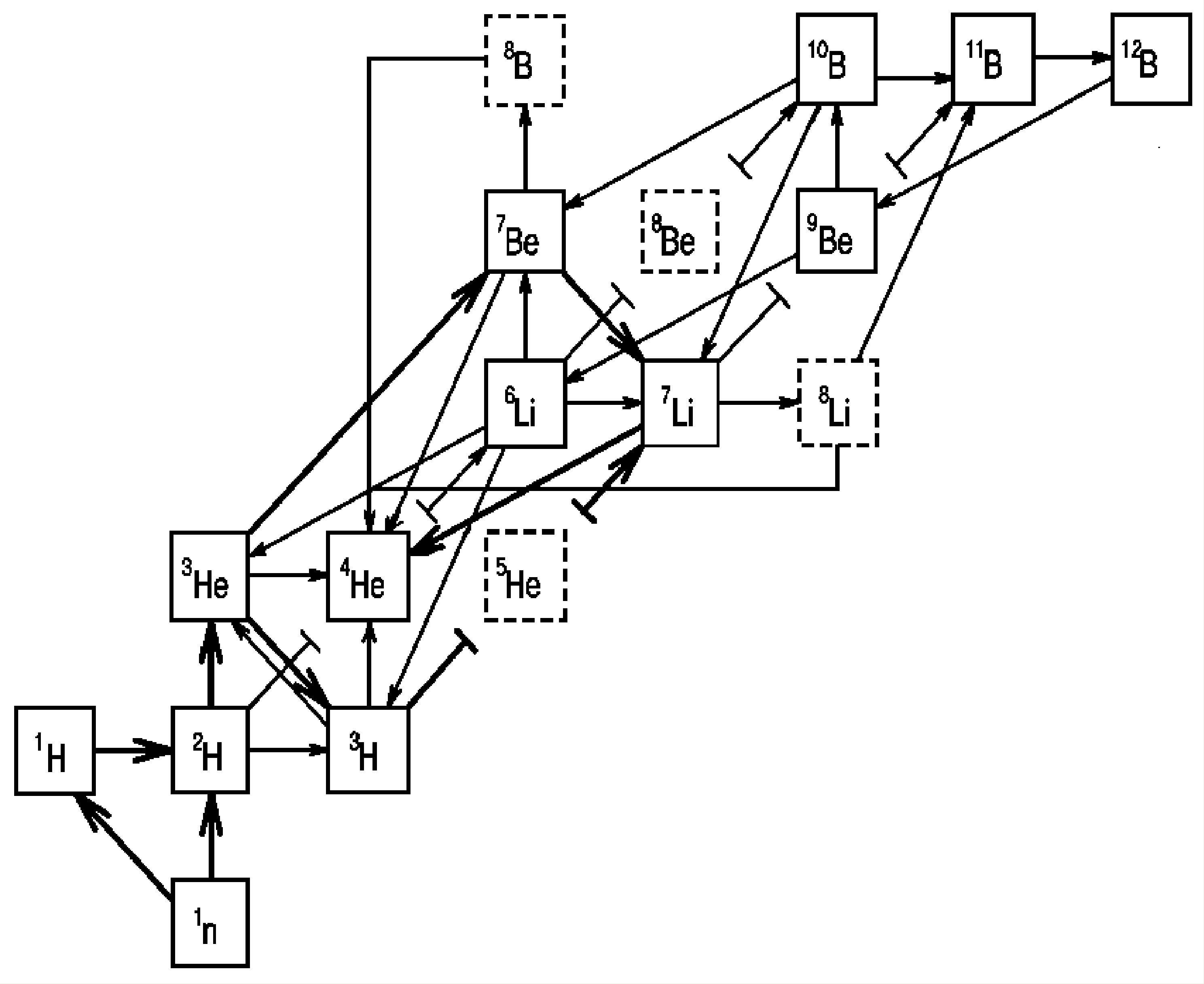


- Hydrogen and helium most abundant
- gap around Li, Be, B

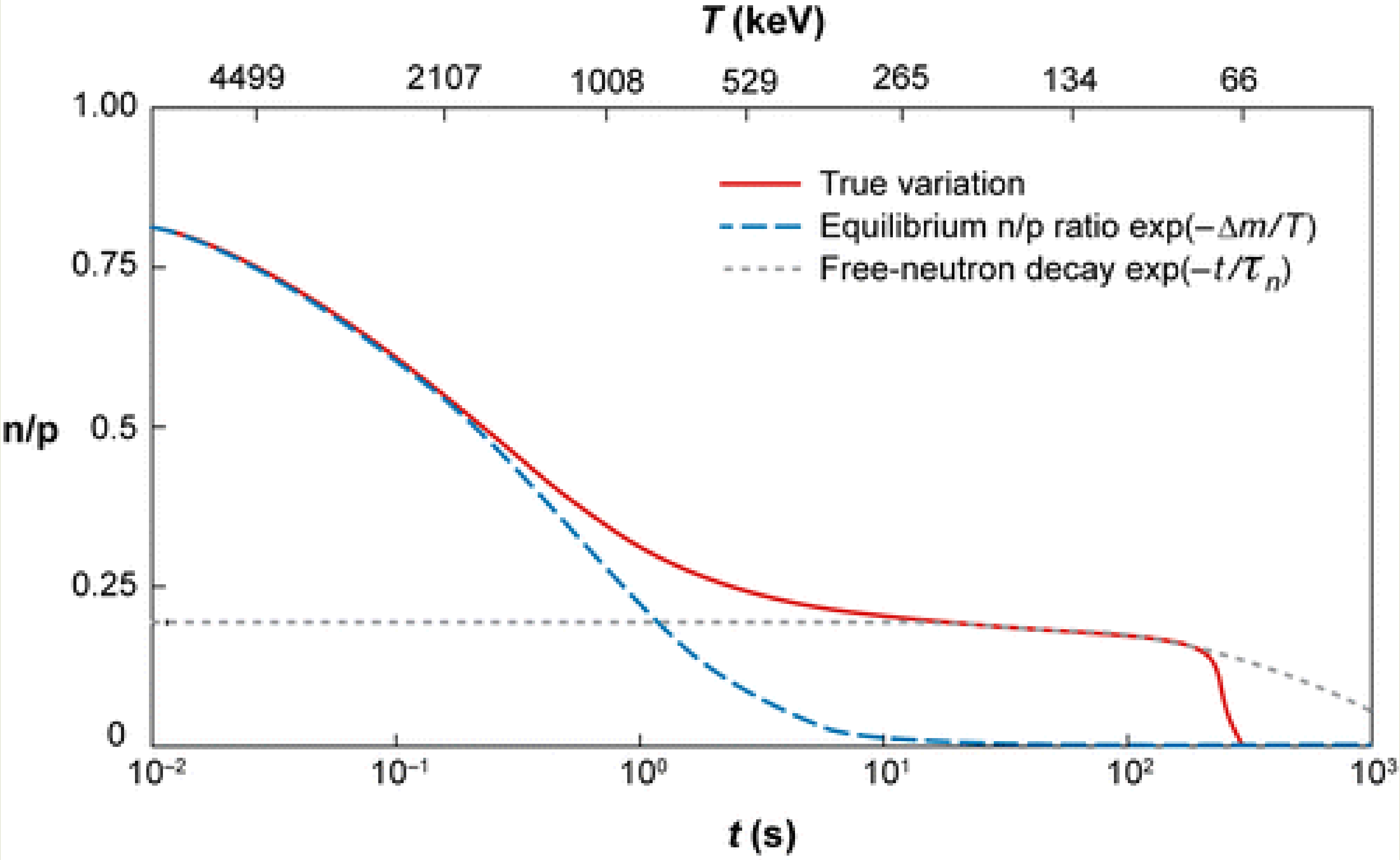
Transforming hydrogen into helium

- Hot big bang: neutrons and protons
- Use a multi step procedure:
  - $p + n \rightarrow {}^{2}H$
  - $p + {}^{2}H \rightarrow {}^{3}He$
  - $n + {}^{2}H \rightarrow {}^{3}H$
  - ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$
- some side reactions:
  - ${}^{4}He + {}^{3}H \rightarrow {}^{7}Li$
  - ${}^{4}He + {}^{3}He \rightarrow {}^{7}Be$

Relevant nuclear reactions



Ratio of free neutrons to protons

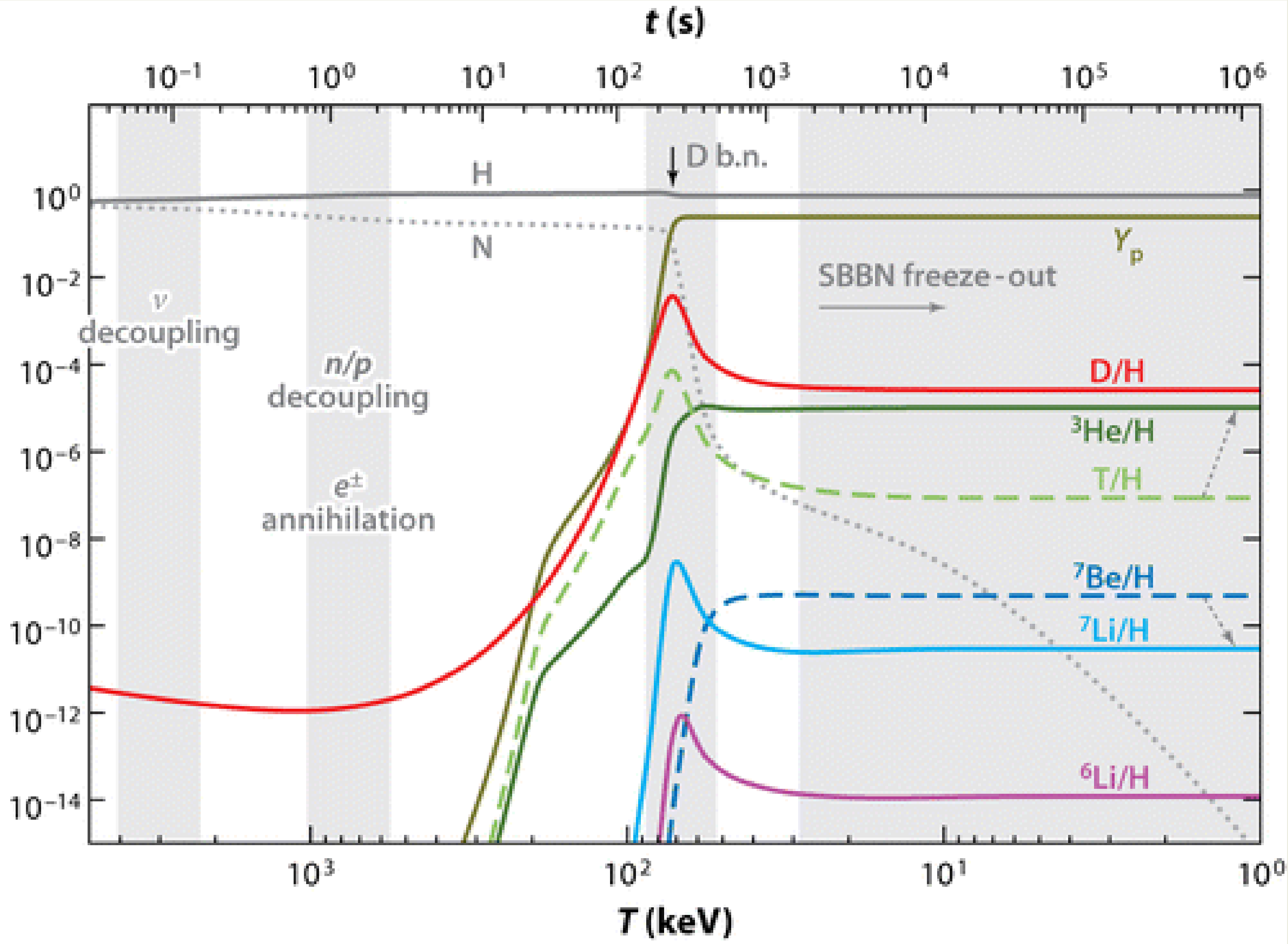


Steigman G. 2007.
Annu. Rev. Nucl. Part. Sci. 57:463–91

Mass gap/stability gap at A=5 and 8

- There is no stable atomic nucleus with 5 or with 8 nucleons
- Reaction chain stops at ^{7}Li
- So how to form the more massive elements?
- There exist a meta-stable nucleus (^{8}B*). If this nucleus is hit by another ^{4}He during its lifetime, ^{12}C and other elements can be formed

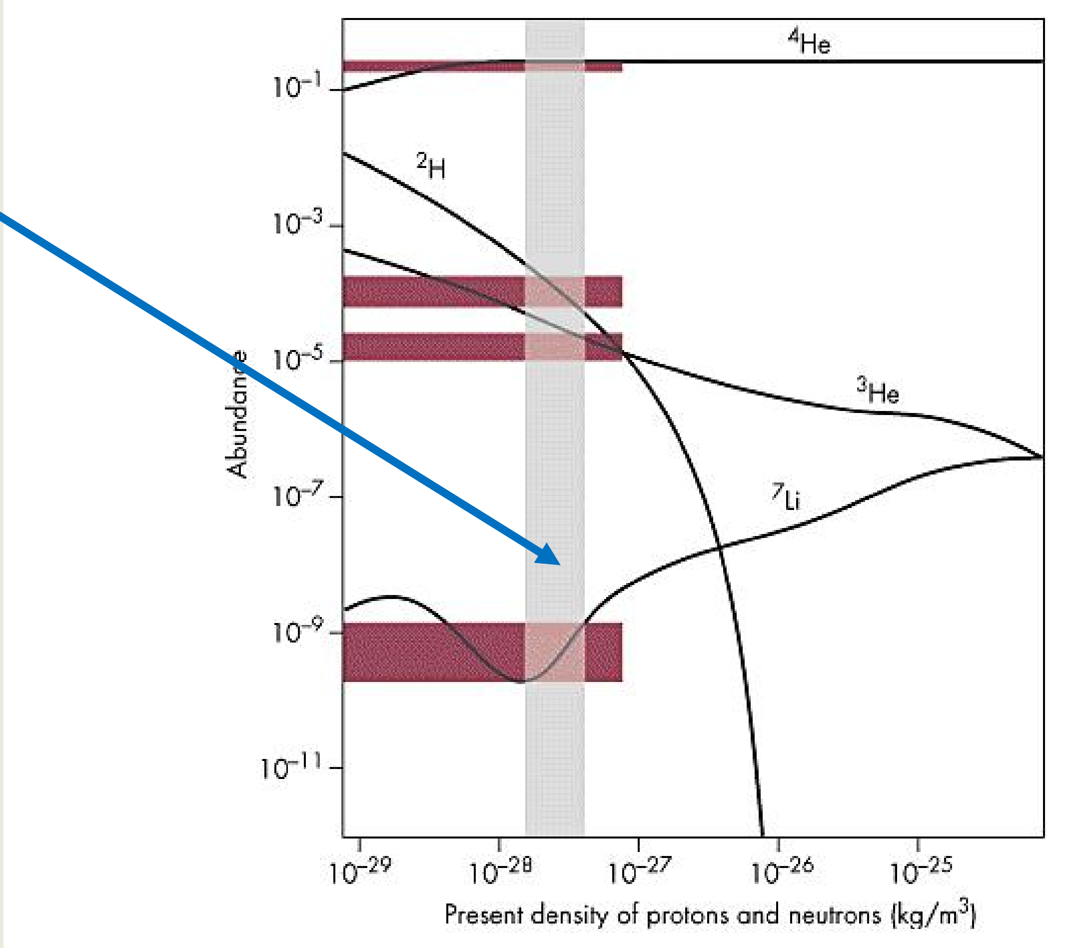
Primordial nucleosynthesis



Pospelov M, Pradler J. 2010.
Annu. Rev. Nucl. Part. Sci. 60:539–68

Primordial nucleosynthesis

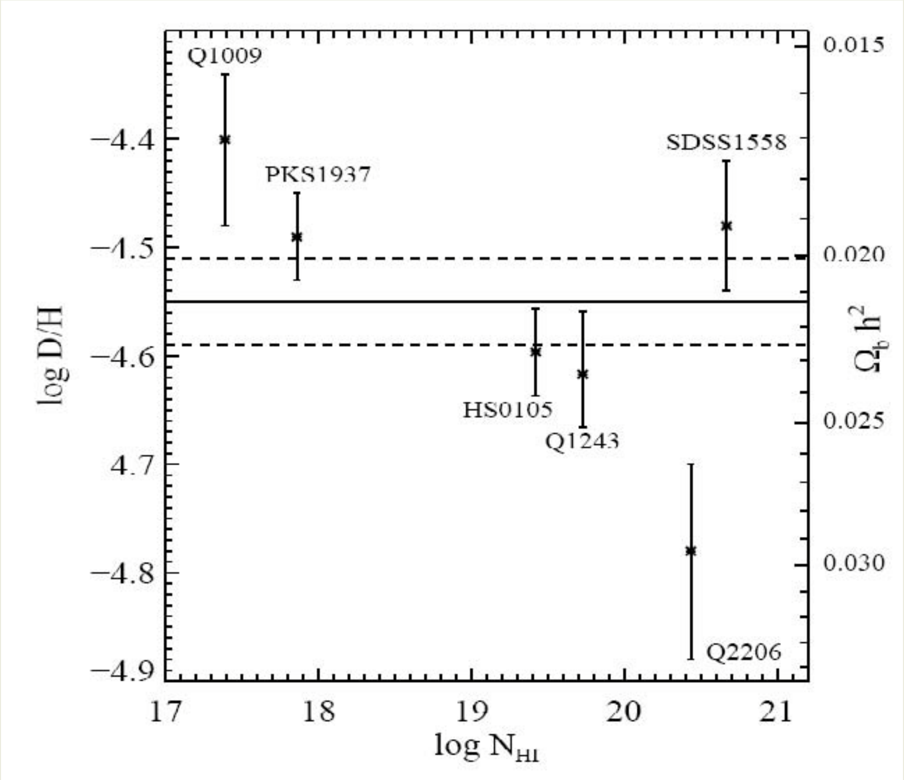
Consistent with abundance of H, He and Li



Result:

- abundances of H, He and Li are consistent
- but: Ω_b(CMB) ~0.04 (too high!)

Primordial nucleosynthesis

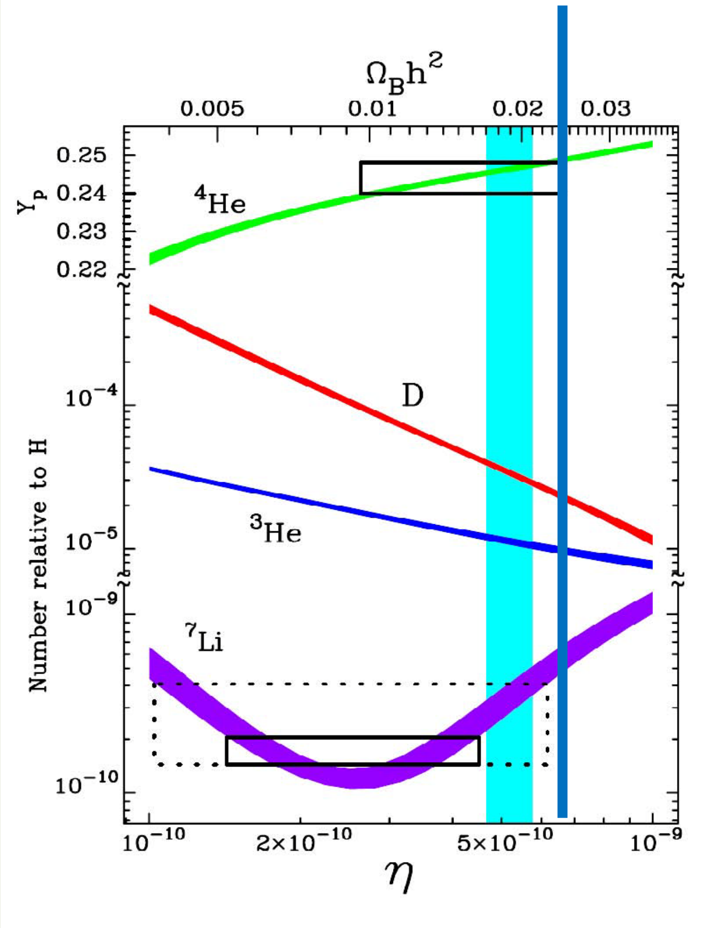


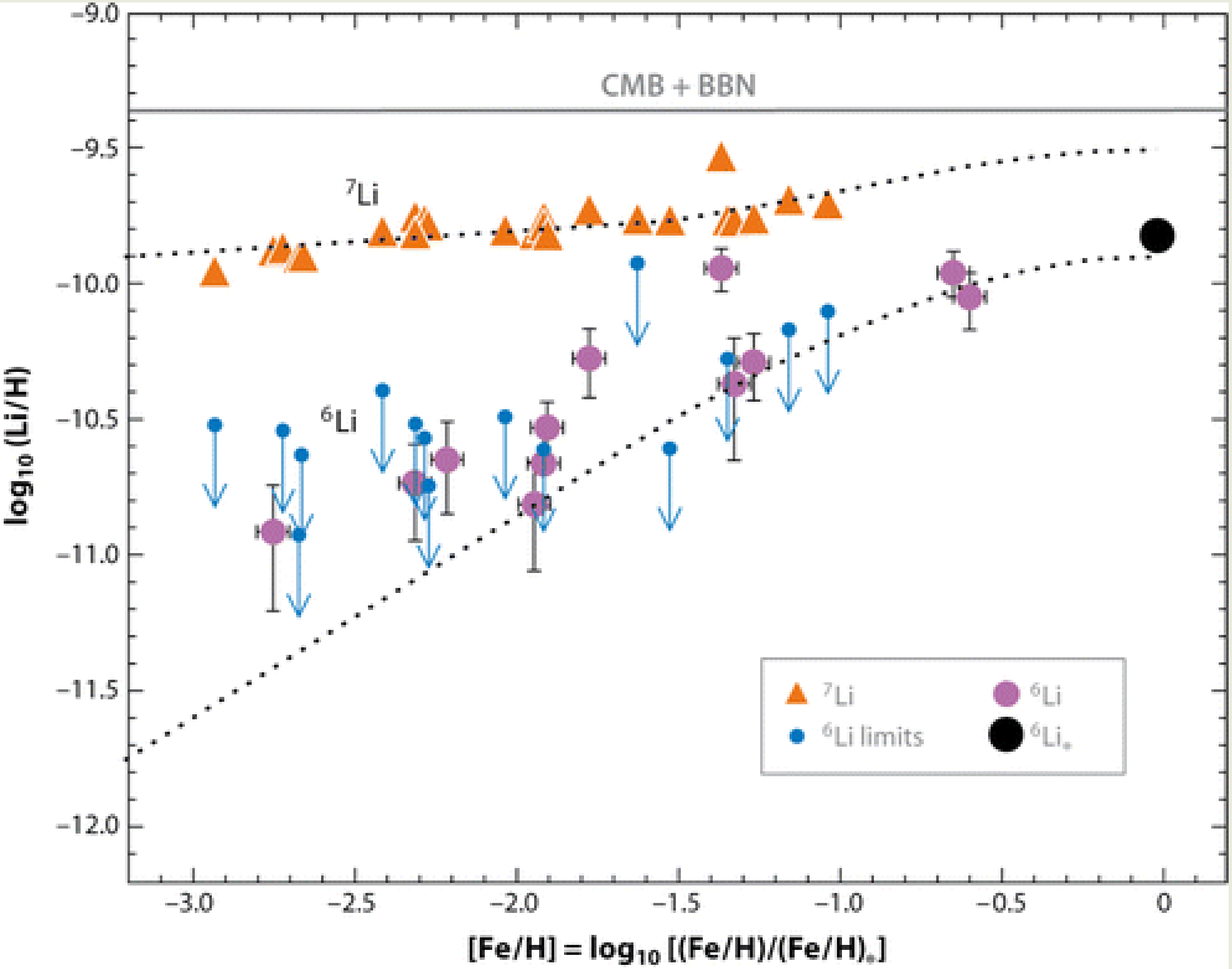
CMB: $\Omega_b h^2 = 0.0225 \pm 0.0006$

Perfect agreement!

But:

The Li problem!

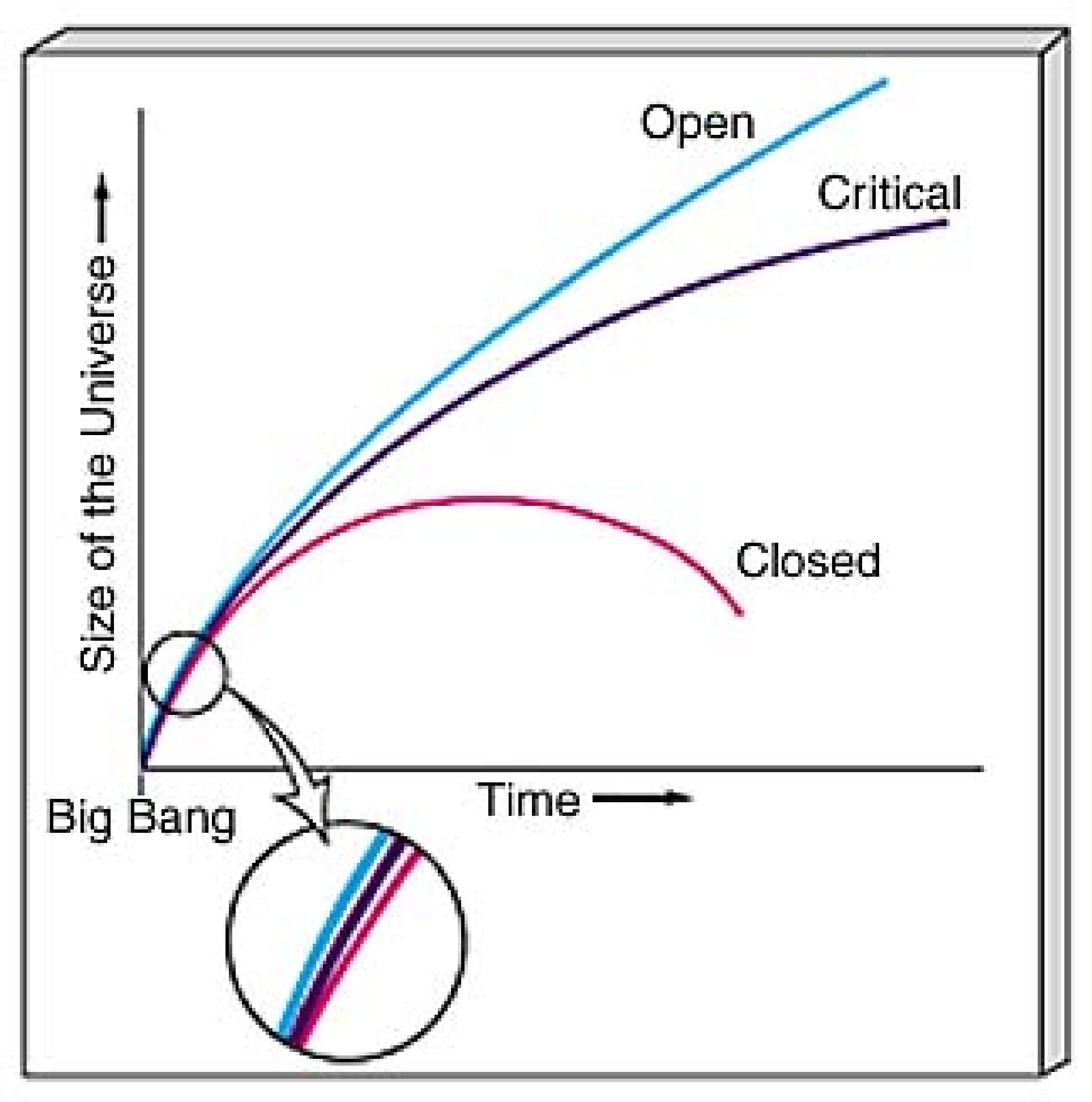




Fields BD. 2011.
Annu Rev. Nucl. Part. Sci. 61:47–68

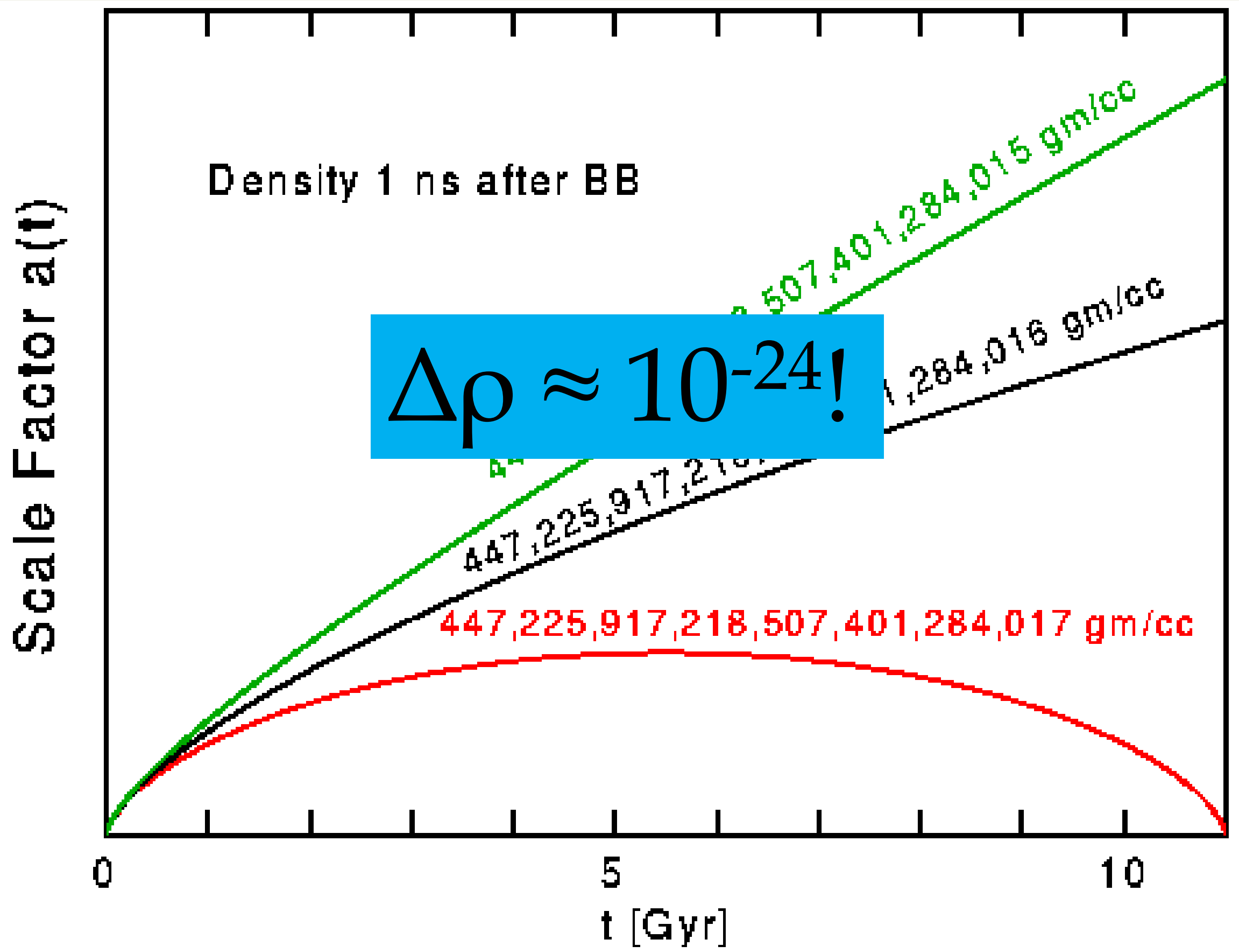
Problems of the ‘standard model’

1. ‘Flatness’: Why is Ω close to 1?



Problems of the ‘standard model’

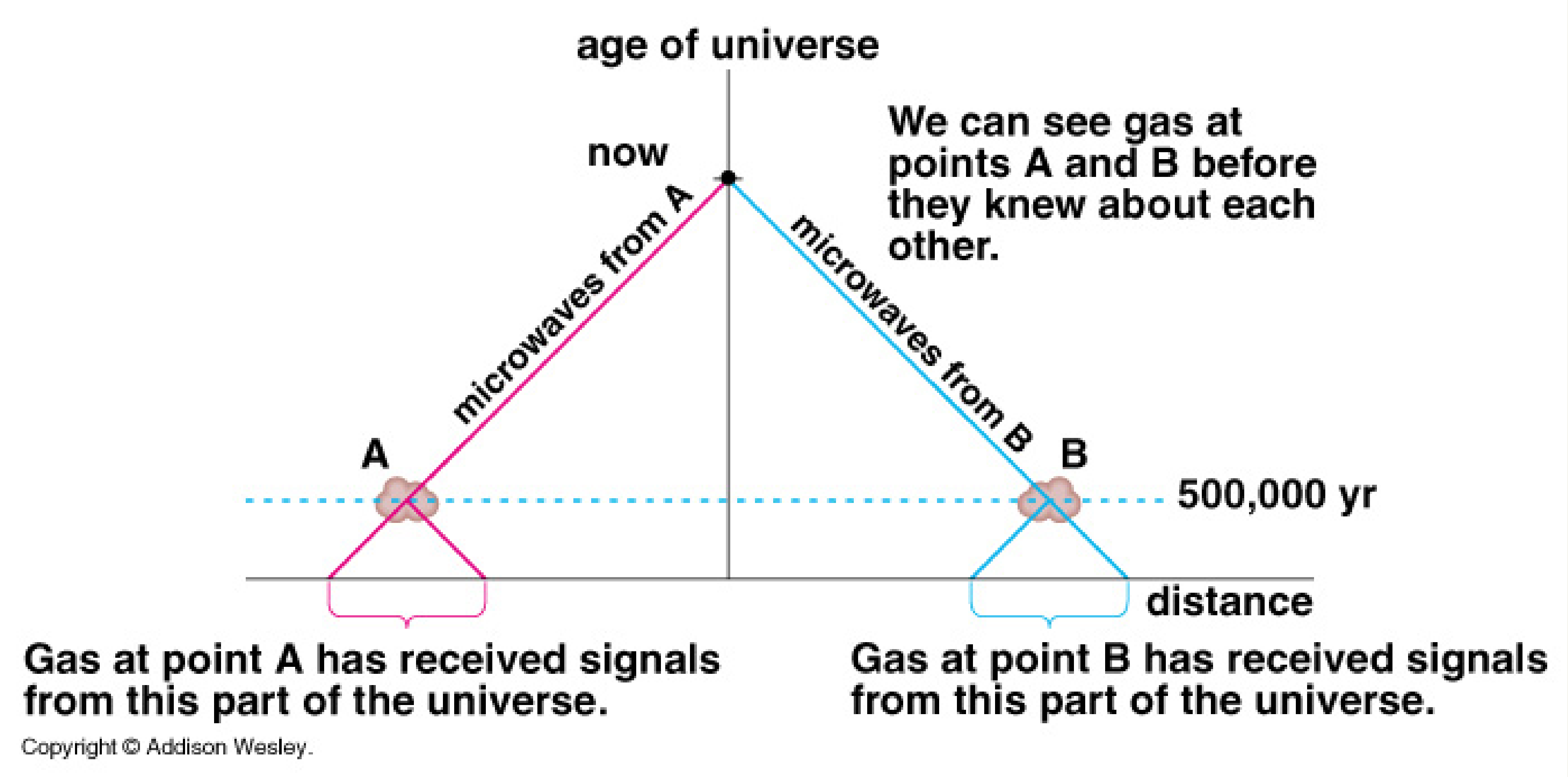
1. ‘Flatness’: Why is Ω close to 1?



$\Delta\rho \approx 10^{-24}$!

Problems of the 'standard model'

2. *'Horizon': Why is the Universe so homogenous?*



Problems of the 'standard model'

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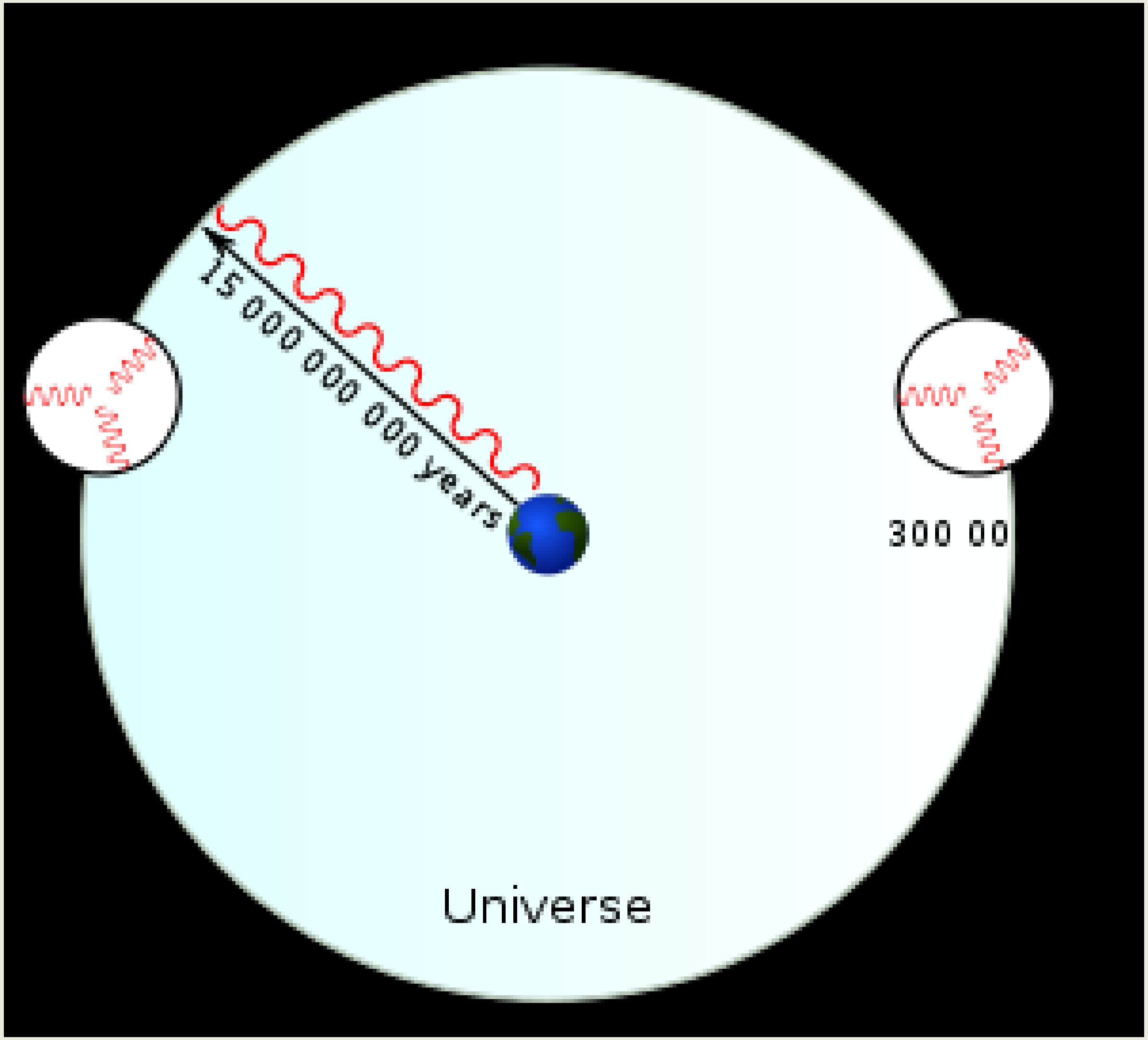
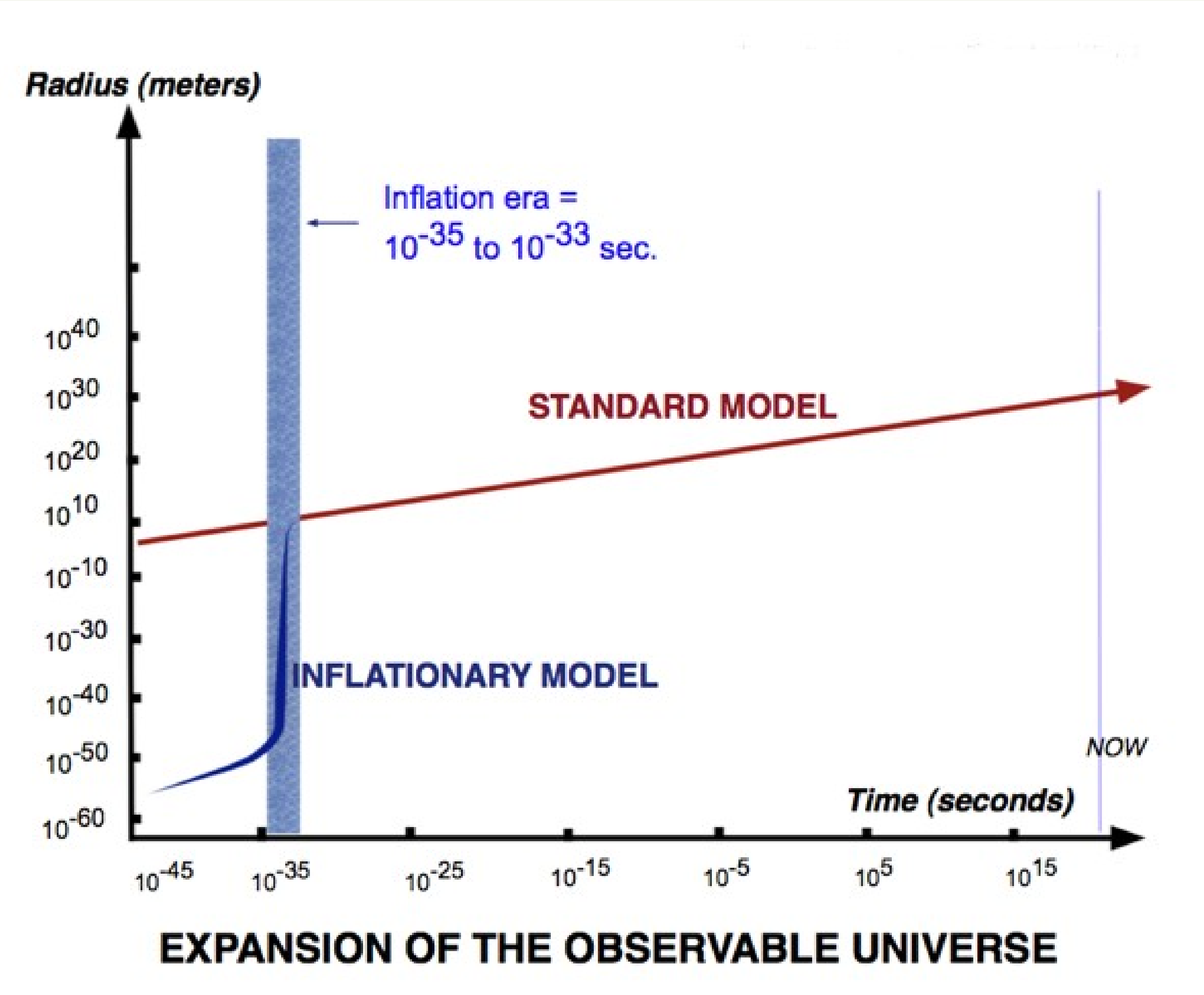
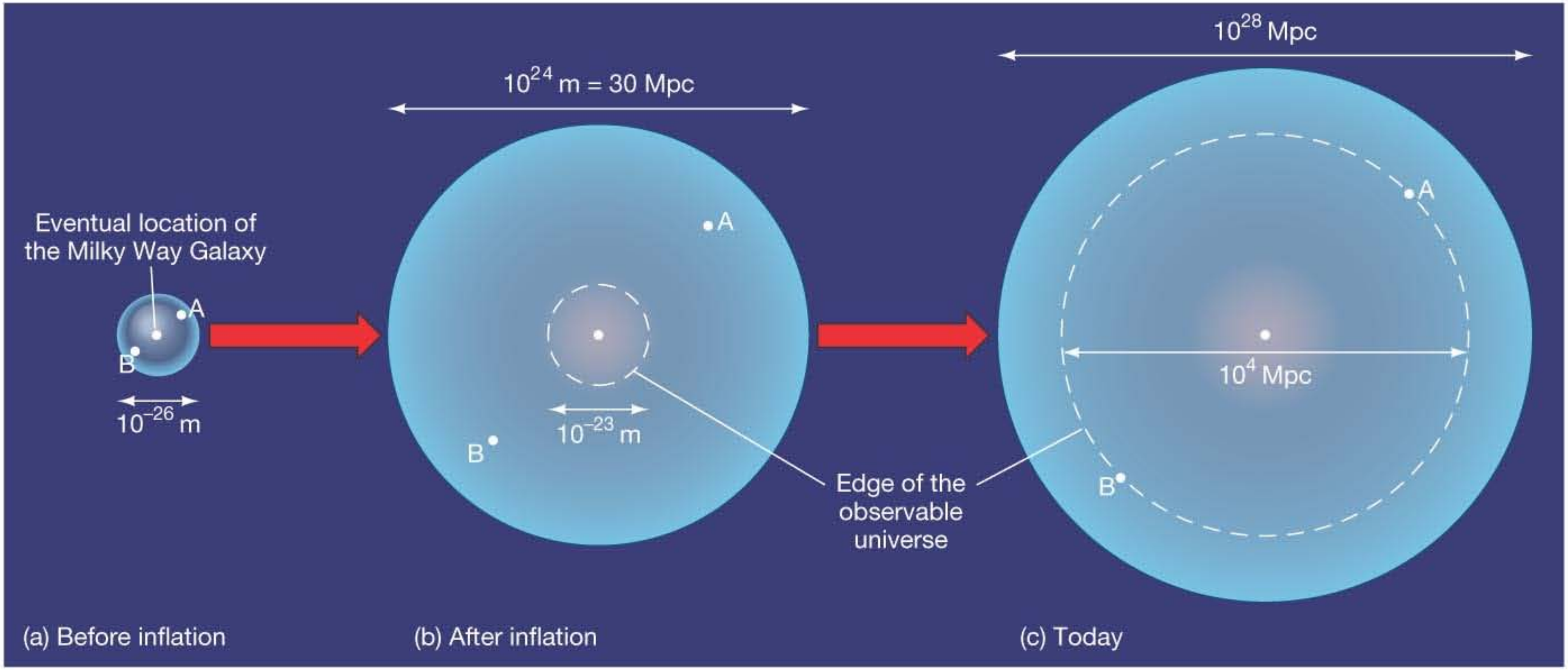


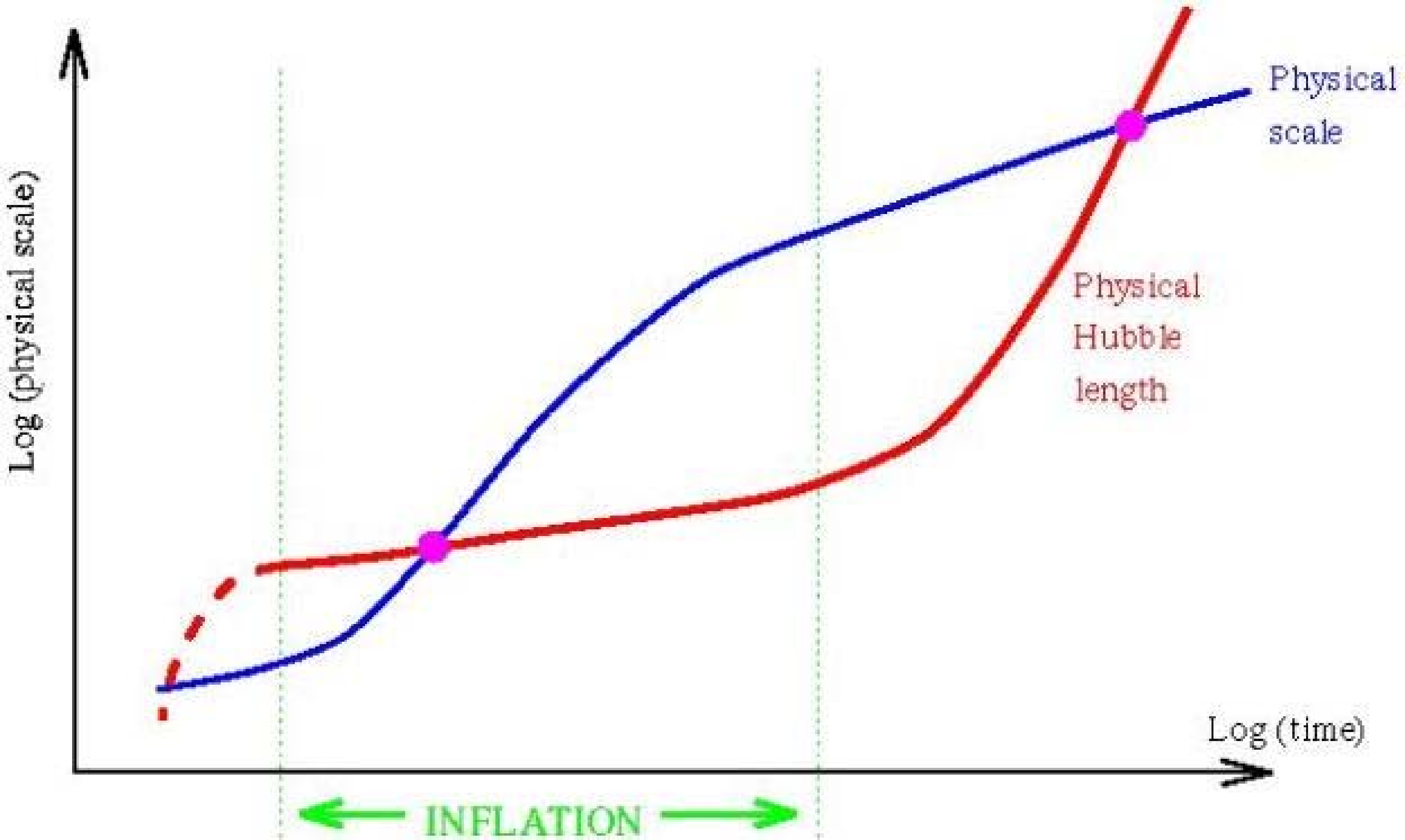
Solution: *Inflation?*



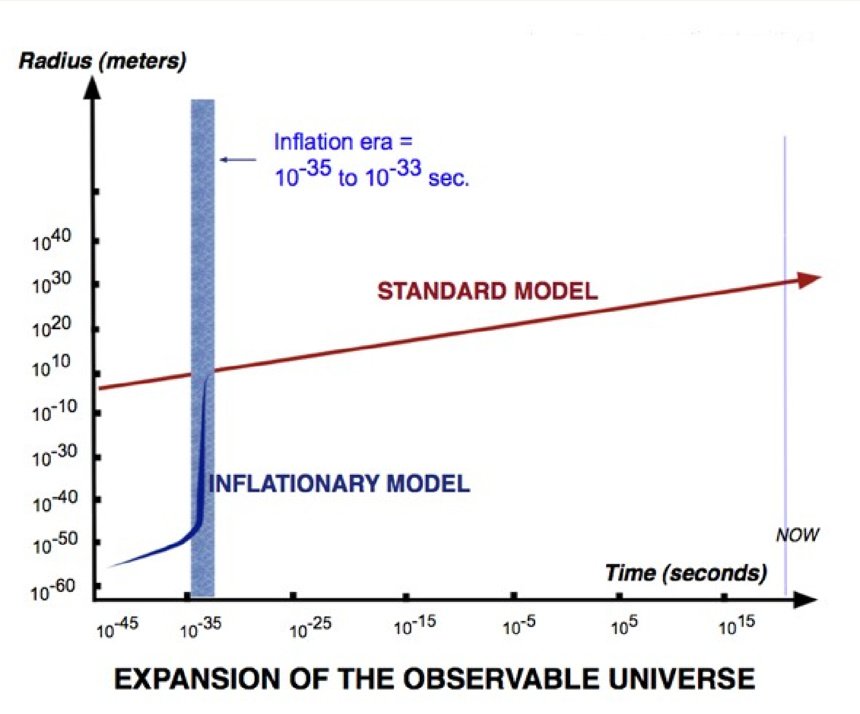
Inflation and the horizon problem

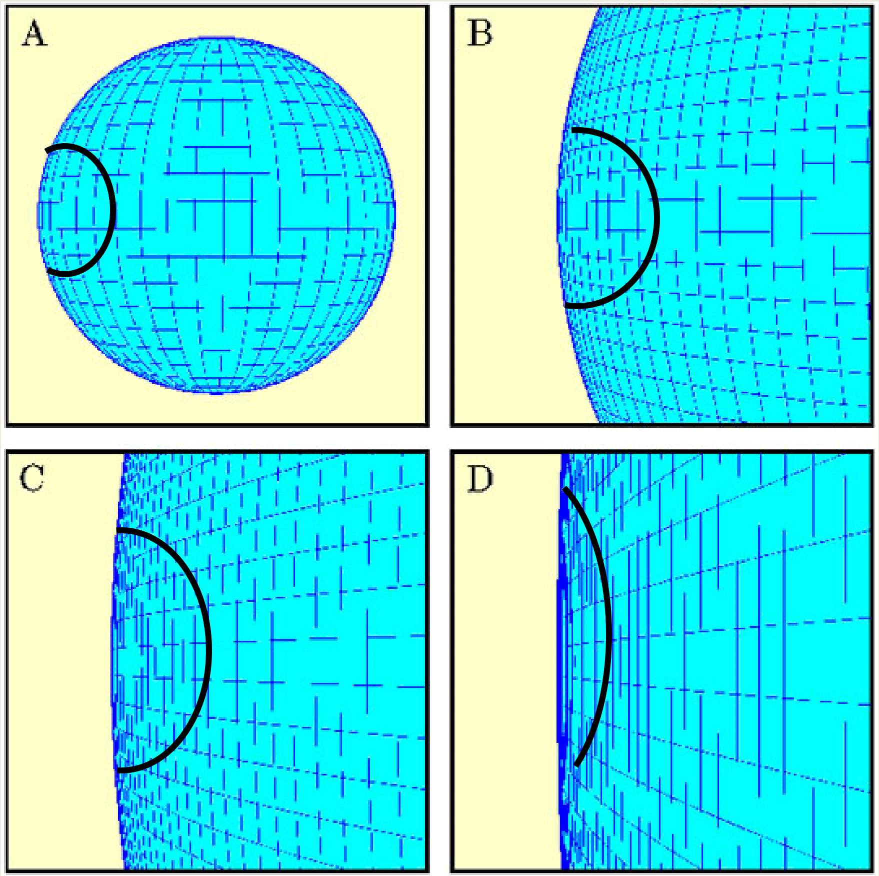


Inflation and the horizon problem



Inflation and the flatness problem

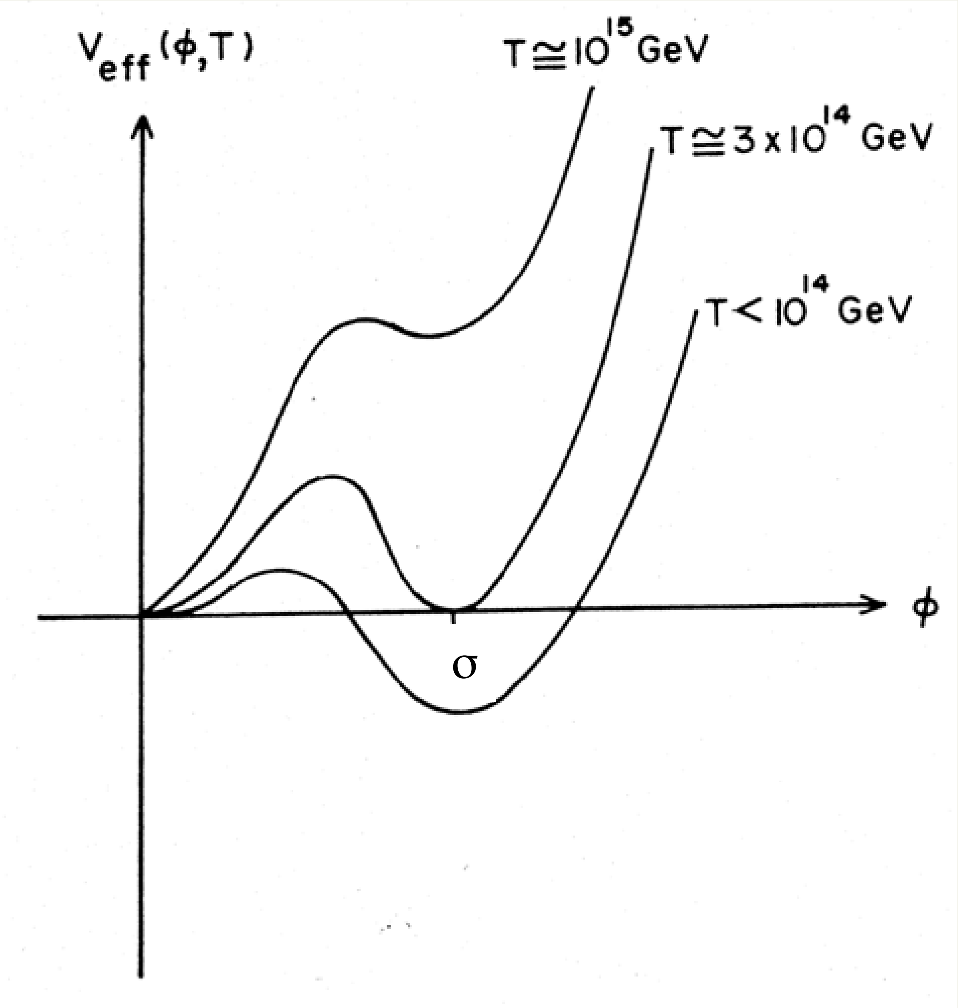




Models for Inflation

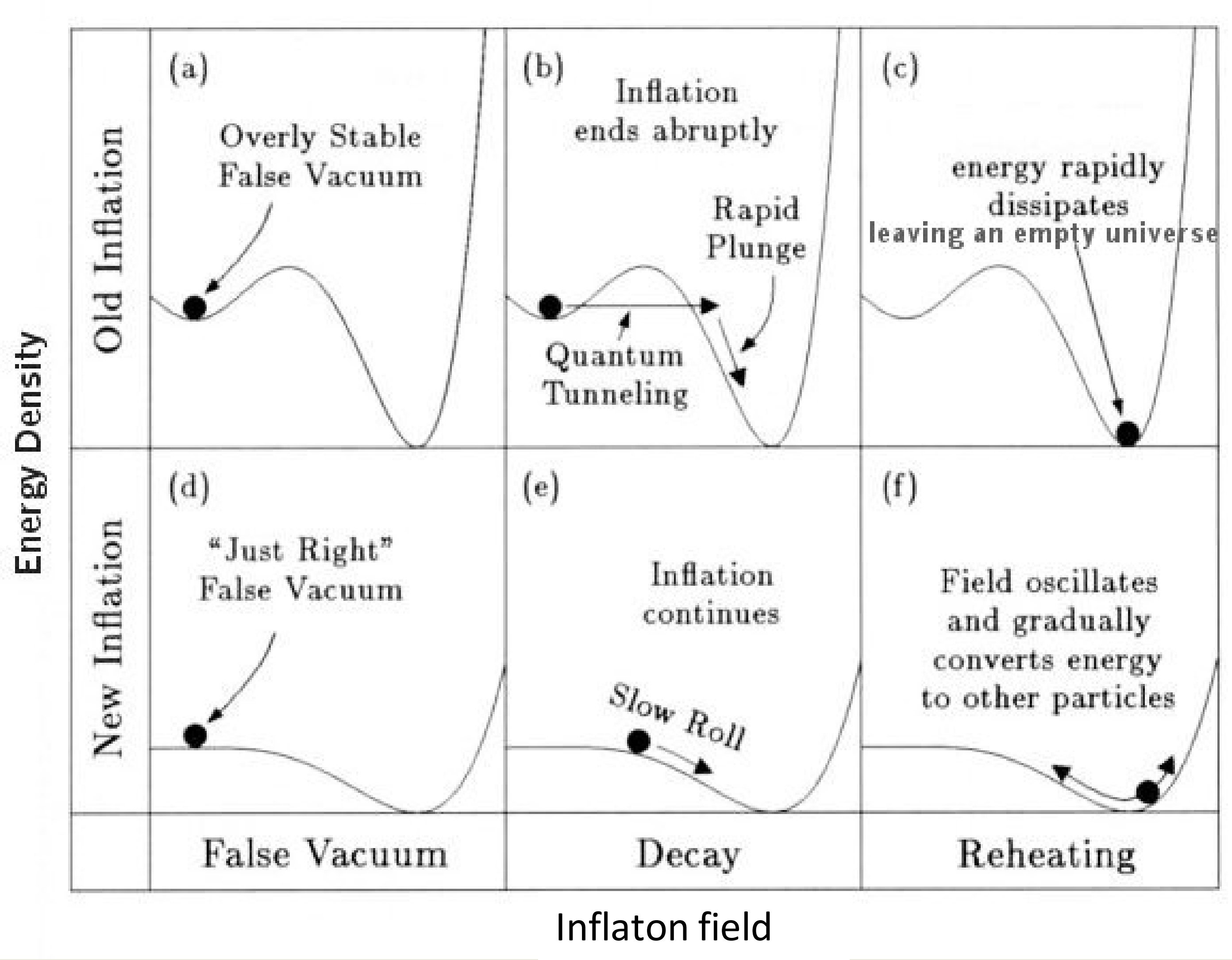
Basic idea (Guth, Sato, Linde, …, 1981, 1982):

$V_{eff} = V(\Phi) + T^4 f(\Phi/T)$; *$\Phi$: scalar field; $f \rightarrow 0$ if $\Phi \rightarrow 0$*



Models for Inflation

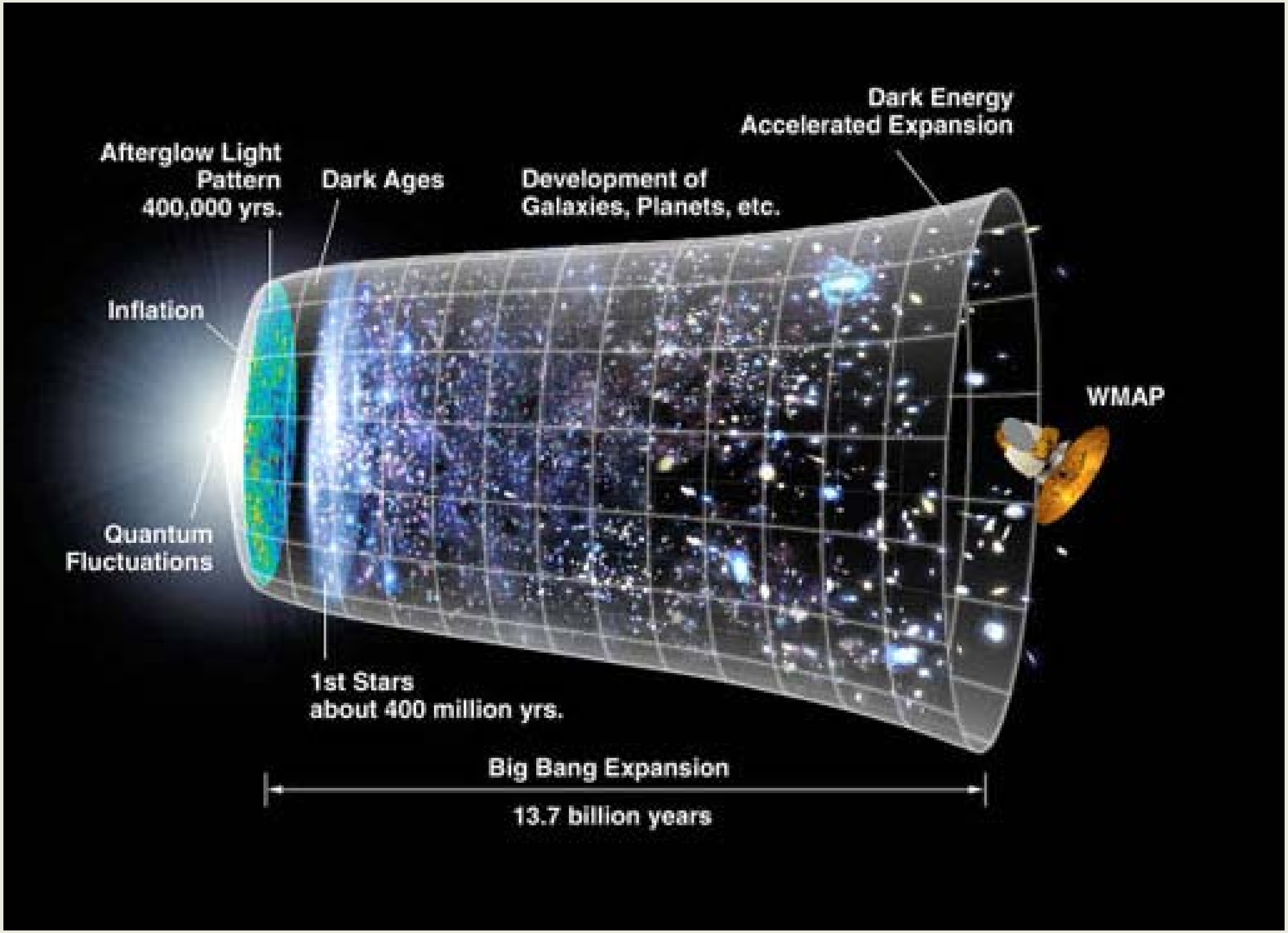
‘Old’ vs ‘new’ inflation (Albrecht & Steinhardt 1982):



General acceptance of the big bang model

- Until mid 60ies: big bang model very controversial, many alternative models
- After mid 60ies: little doubt on validity of the big bang model
- Four pillars on which the big bang theory is resting:
  - Hubble's law ✓
  - Cosmic microwave background radiation ✓
  - The origin of the elements ✓
  - Structure formation in the universe ←

Structure formation in the Big-Bang model



A galaxy census: spiral galaxies

- Most common type among the luminous galaxies (~75%)
- Two major classes, S and SB
  - regular spirals (S)
  - barred spirals (SB)
- Further classified from a to d according to the bulge-to-disk ratio
  - a: very large, prominent bulge
  - d: essentially no bulge at all
- The Milky Way is a Sbc or a SBbc galaxy

A galaxy census: spiral galaxies

- Spiral galaxies are disk like and in centrifugal equilibrium
- The are “cold”, i.e. the velocity dispersion (random motion of individual stars) σ is much smaller than the rotation velocity v_{rot} (Milky Way: σ=20 km/s; v_{rot}=220 km/s)
- They mainly consist of stars, but ~10% of the mass is gas and dust
- They actively form stars (Milky Way: ~ 1 star per year)

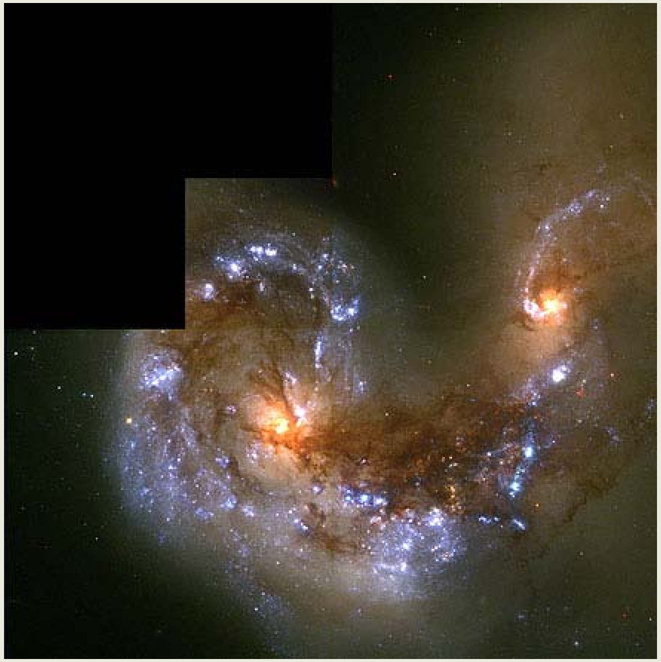
A galaxy census: elliptical galaxies

- ~20% of the luminous galaxies are ellipticals
- Classified according to the flattening E0-E7: $n=10\times(1-b/a)$
  - E0: circular
  - E7: minor axis only 30% of major axis
- They are ‘hot’, i.e. the velocity dispersion σ is much larger than the rotation velocity v_{rot}
- Flattened by an anisotropic velocity dispersion
- Little gas, no recent star formation
- Predominantly in clusters of galaxies

A galaxy census: other galaxies

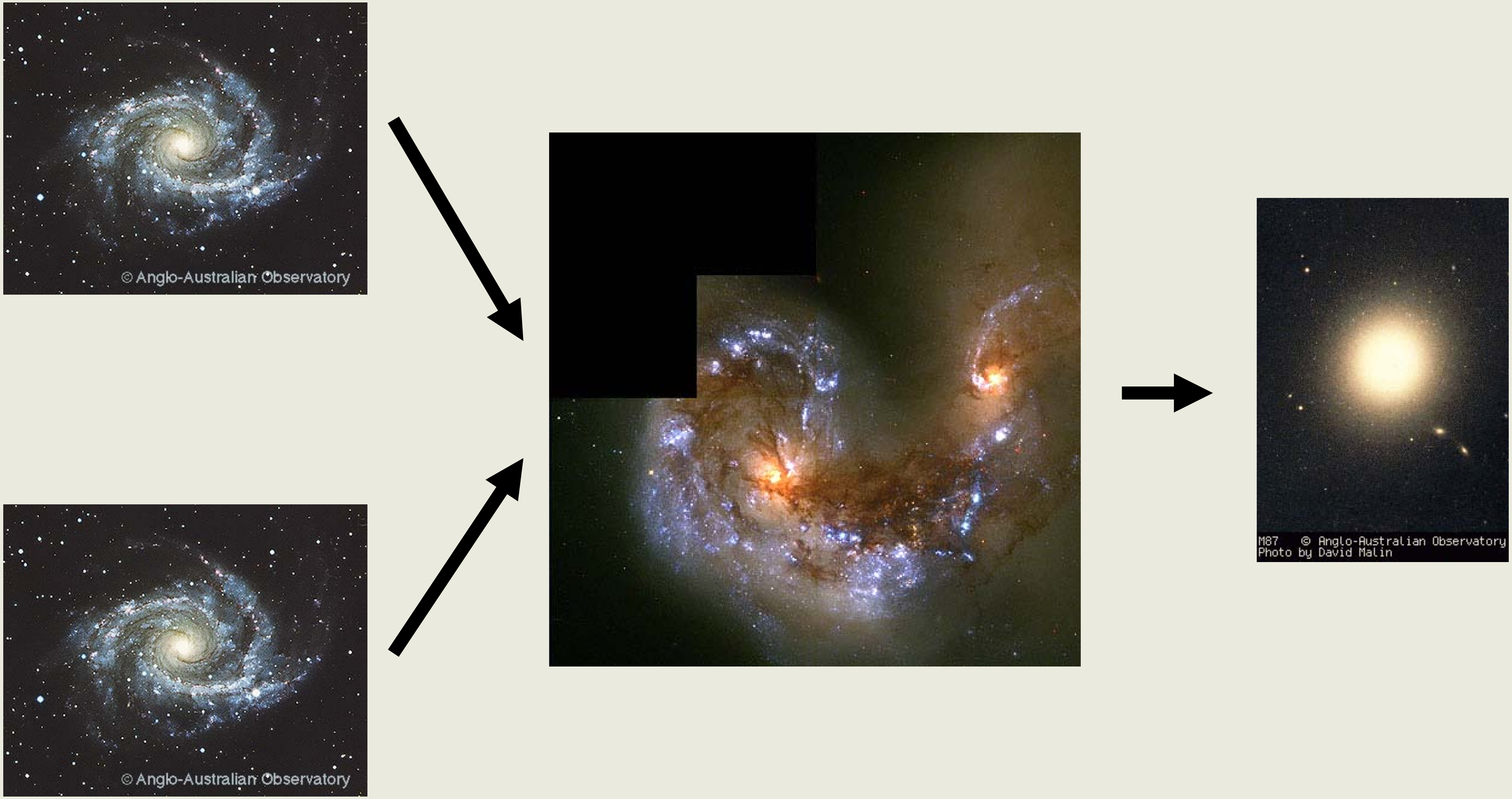
- Irregular galaxies (~ 5% of the luminous galaxies)
- Dwarf galaxies
  - dwarf irregulars
  - dwarf spheroidals
  - dwarf ellipticals
  - blue compact dwarfs
  - …

Toomre & Toomre (mid 70s)



- 11 out of the 4000 galaxies in the New General Catalog (NGC) show indications of recent interactions (e.g. tails)
- Those tidal features last a few 10^8 years
- Over the age of the universe, several hundred of those interactions must have taken place
- There are several hundred elliptical galaxies in the NGC

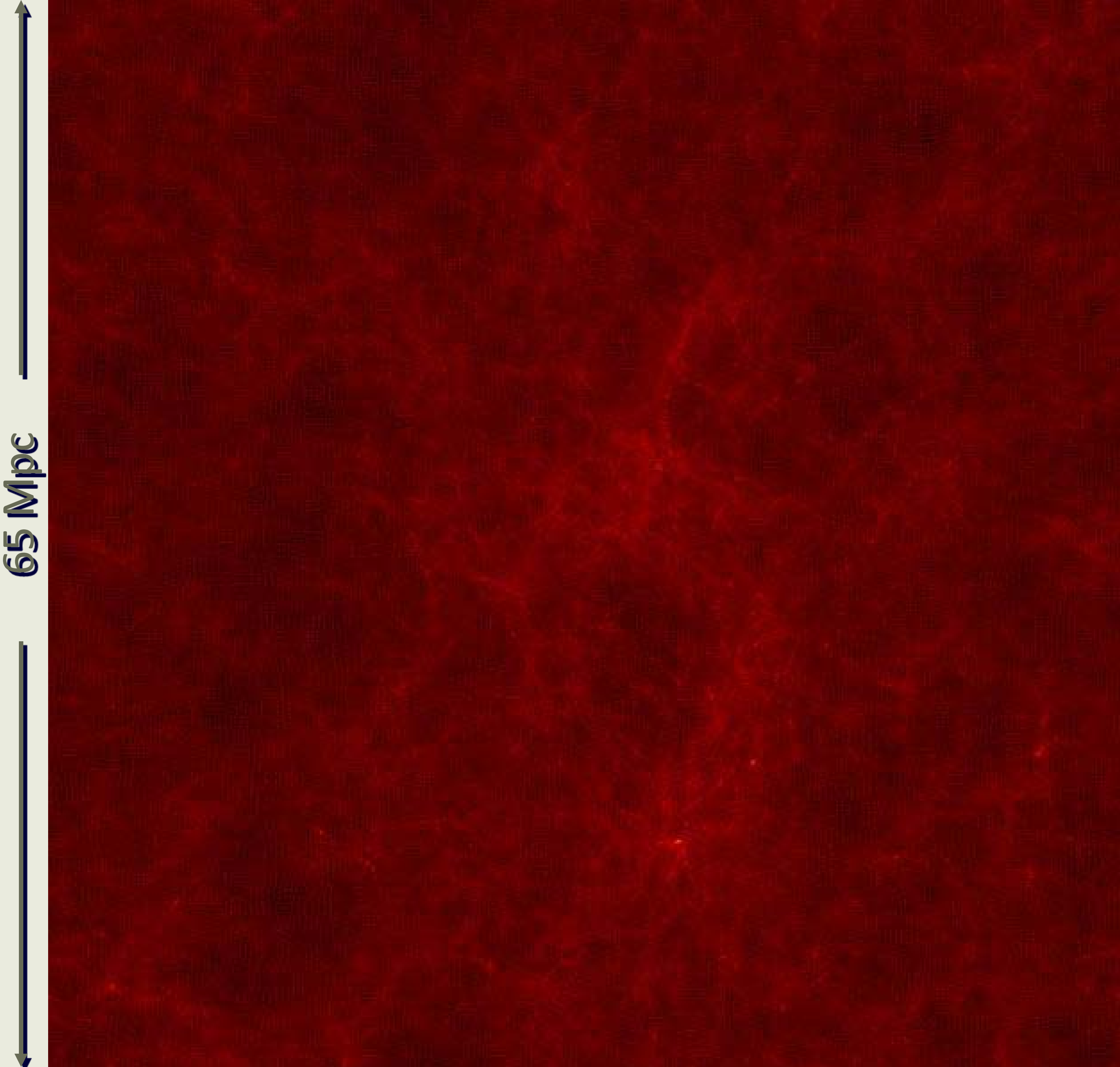
Do ellipticals form by merging spirals ?



How does structure form ?

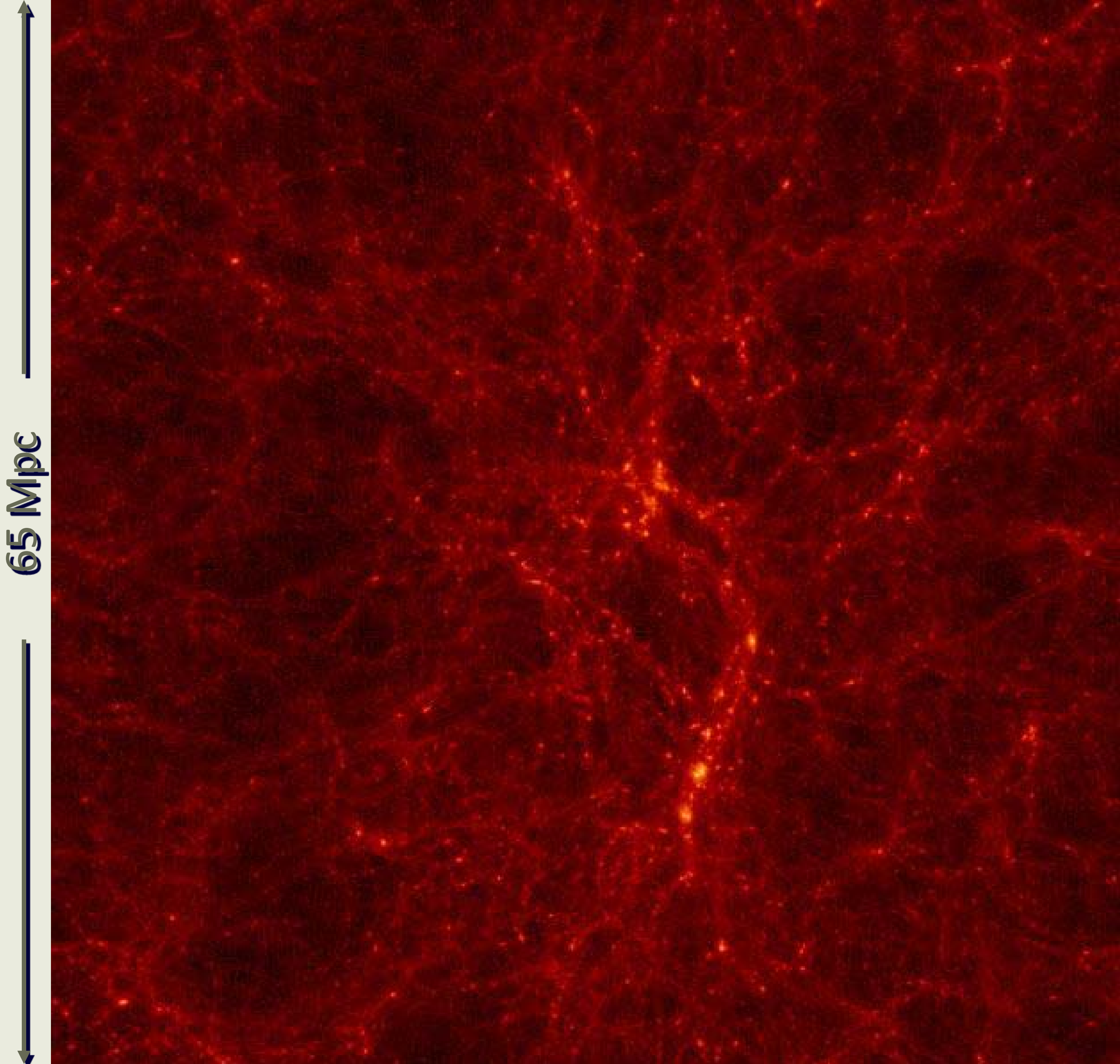
- Wrinkles in the CMB: regions of higher and lower temperature
- Those regions correspond to density fluctuations, regions of slightly higher/lower density than average
- Gravitational instability
  - higher density ⇒ more mass in a given volume
  - more mass ⇒ stronger gravitational attraction
  - stronger gravitational attraction ⇒ mass is pulled in ⇒ even higher density

z=9.00



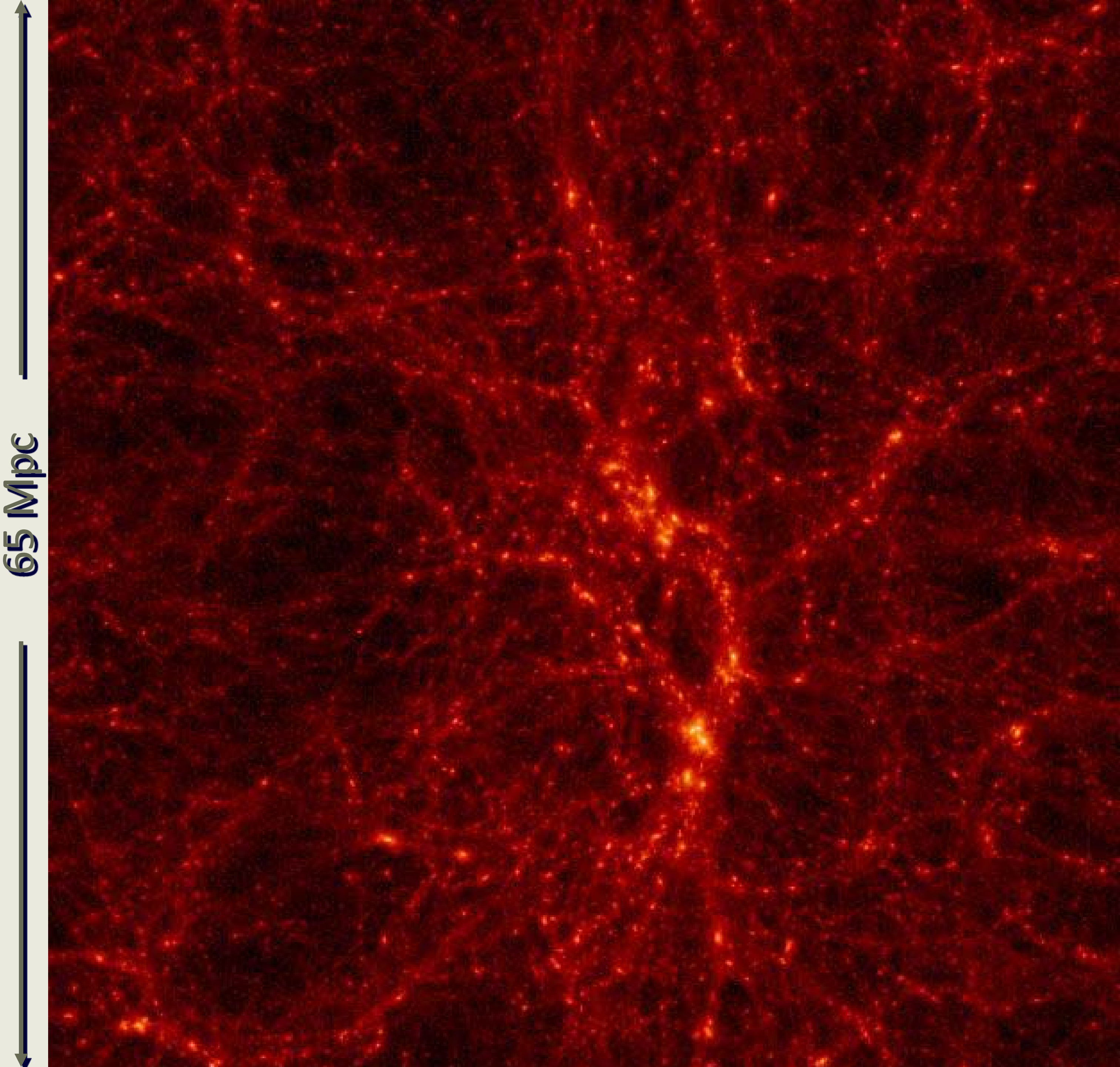
50 million
particle
N-body
simulation

z=4.00



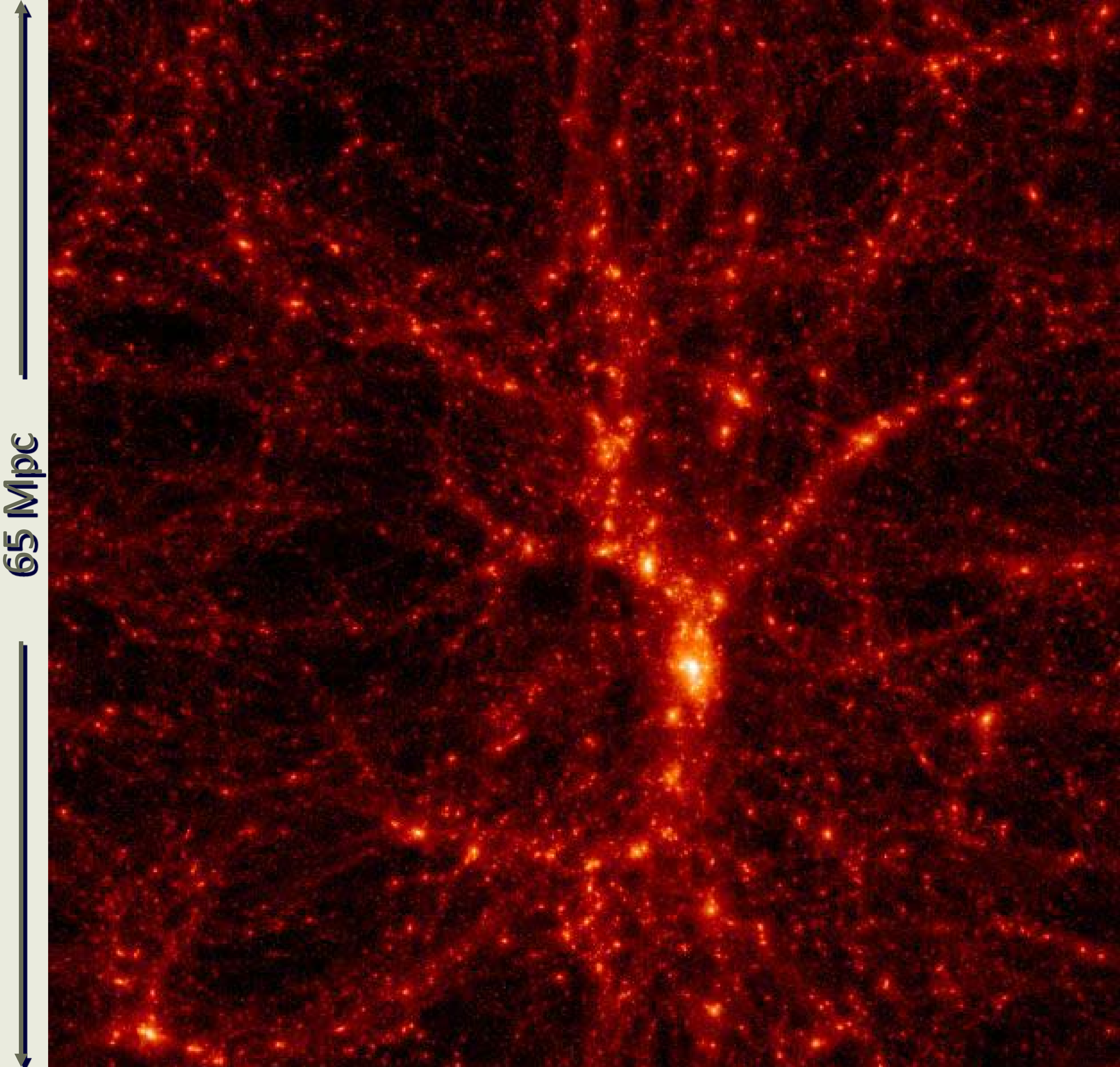
50 million
particle
N-body
simulation

z=2.33



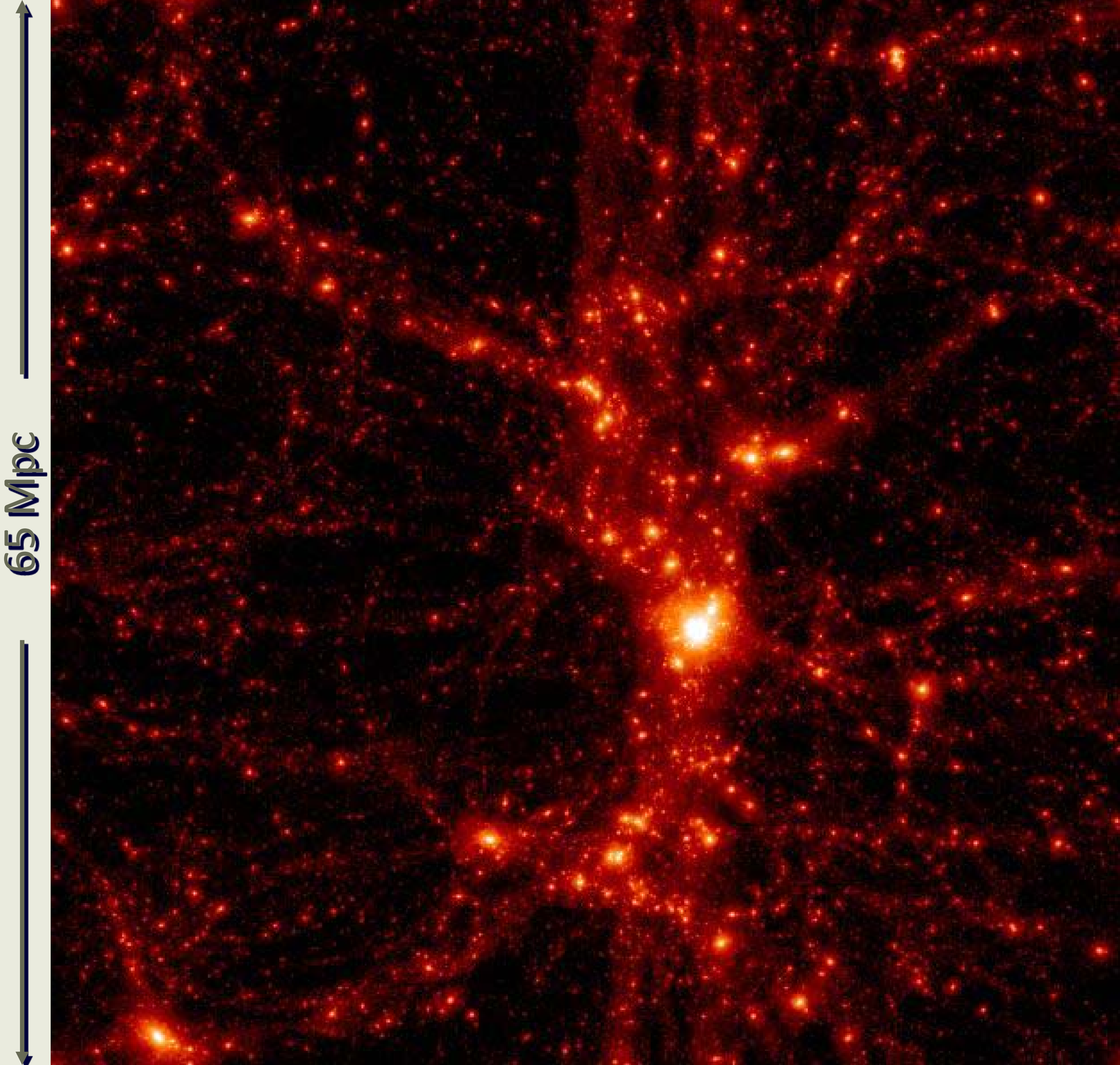
50 million particle N-body simulation

z=1.00



50 million
particle
N-body
simulation

z=0.00

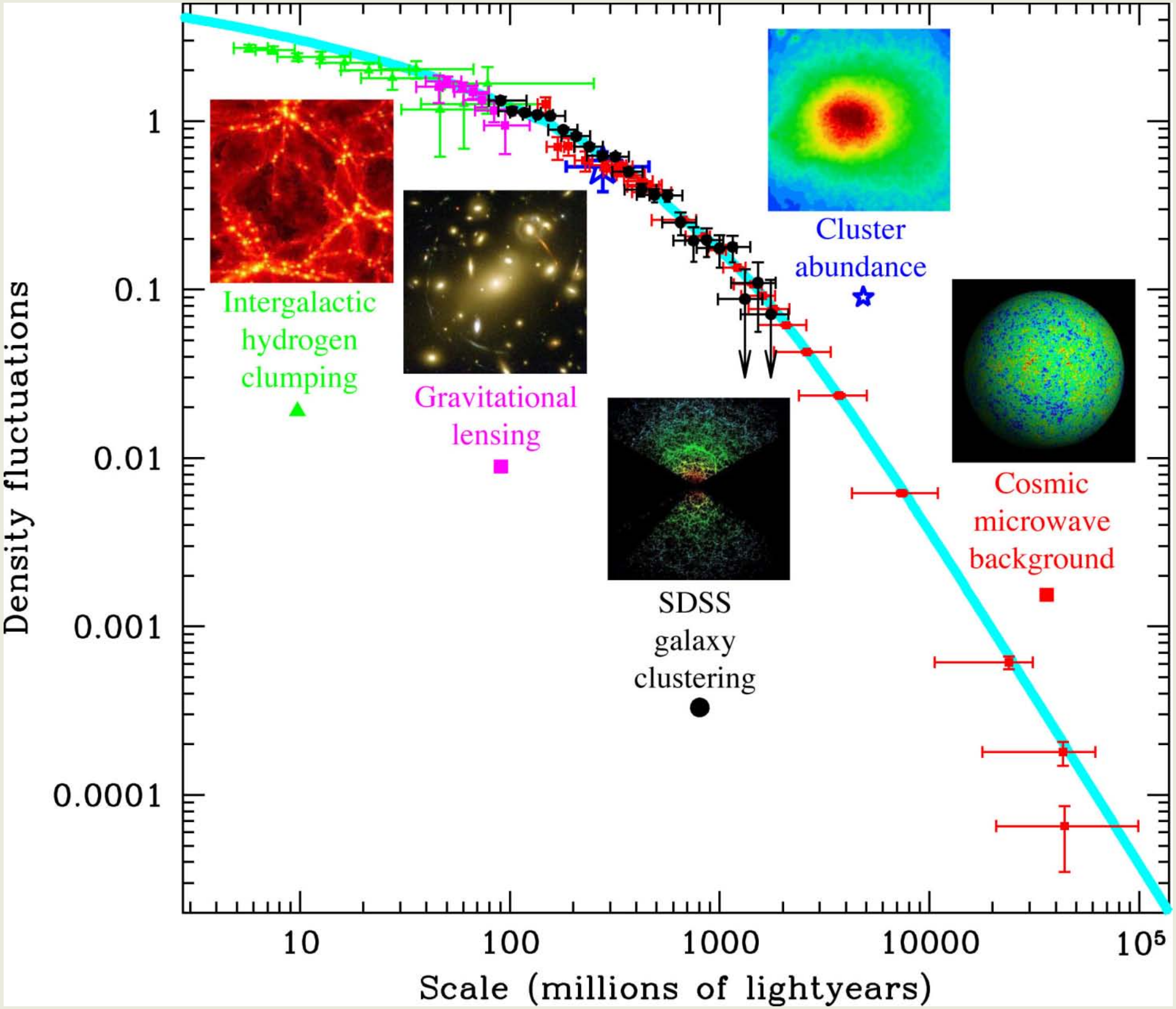


50 million particle N-body simulation

Recent simulations (MPA group)

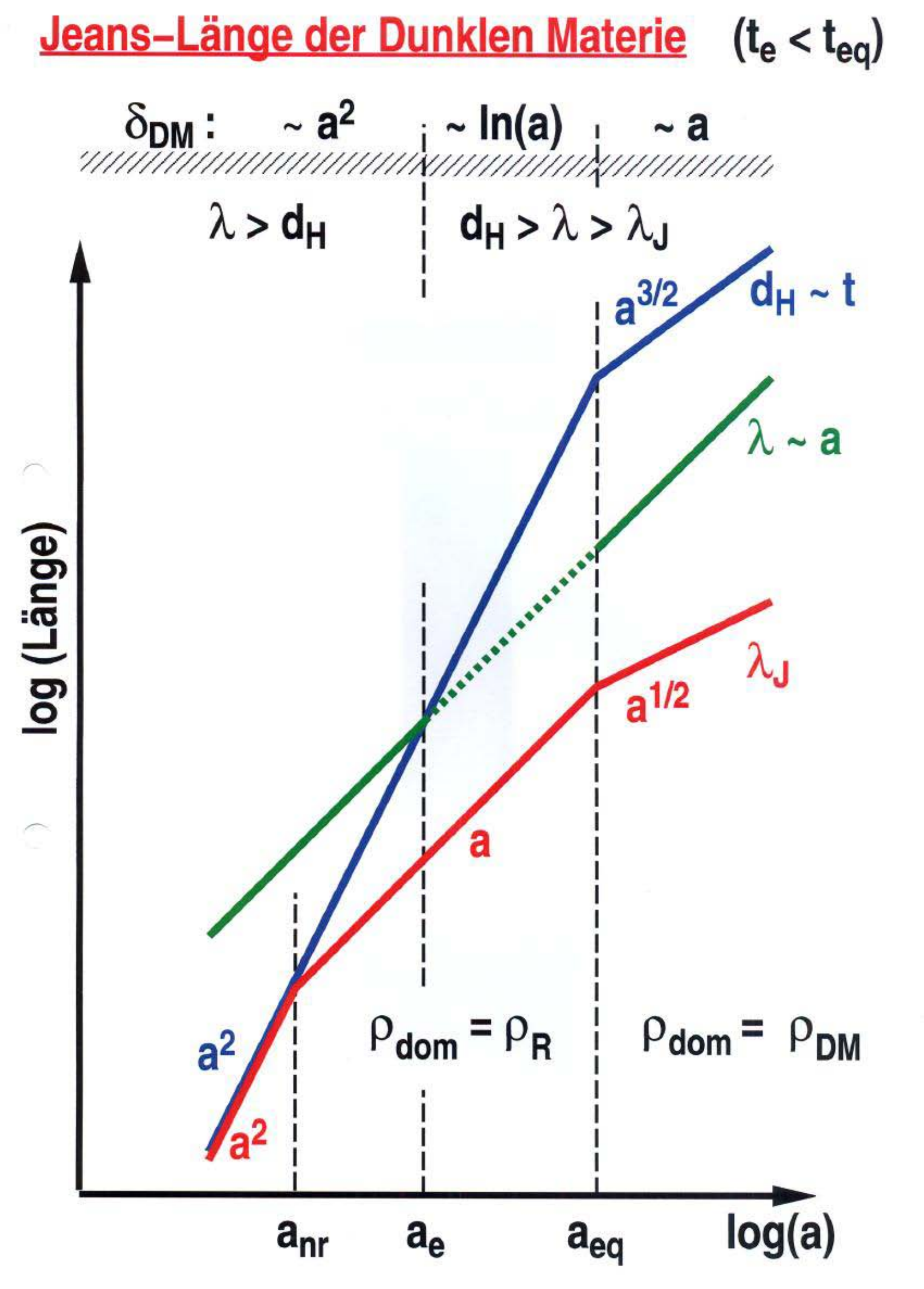
(Court. V. Springel)

Density fluctuations and relevant scales

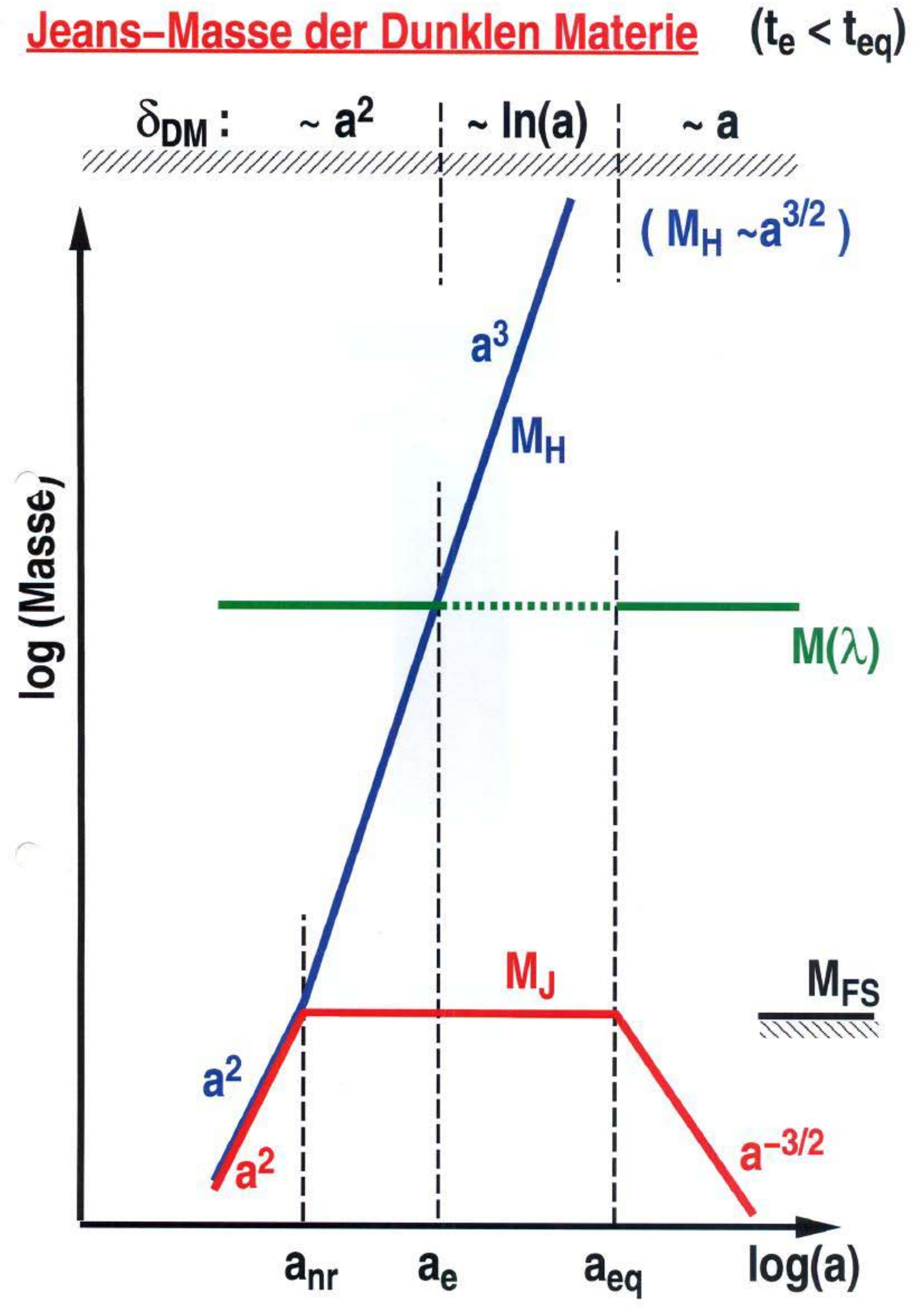


SDSS collaboration

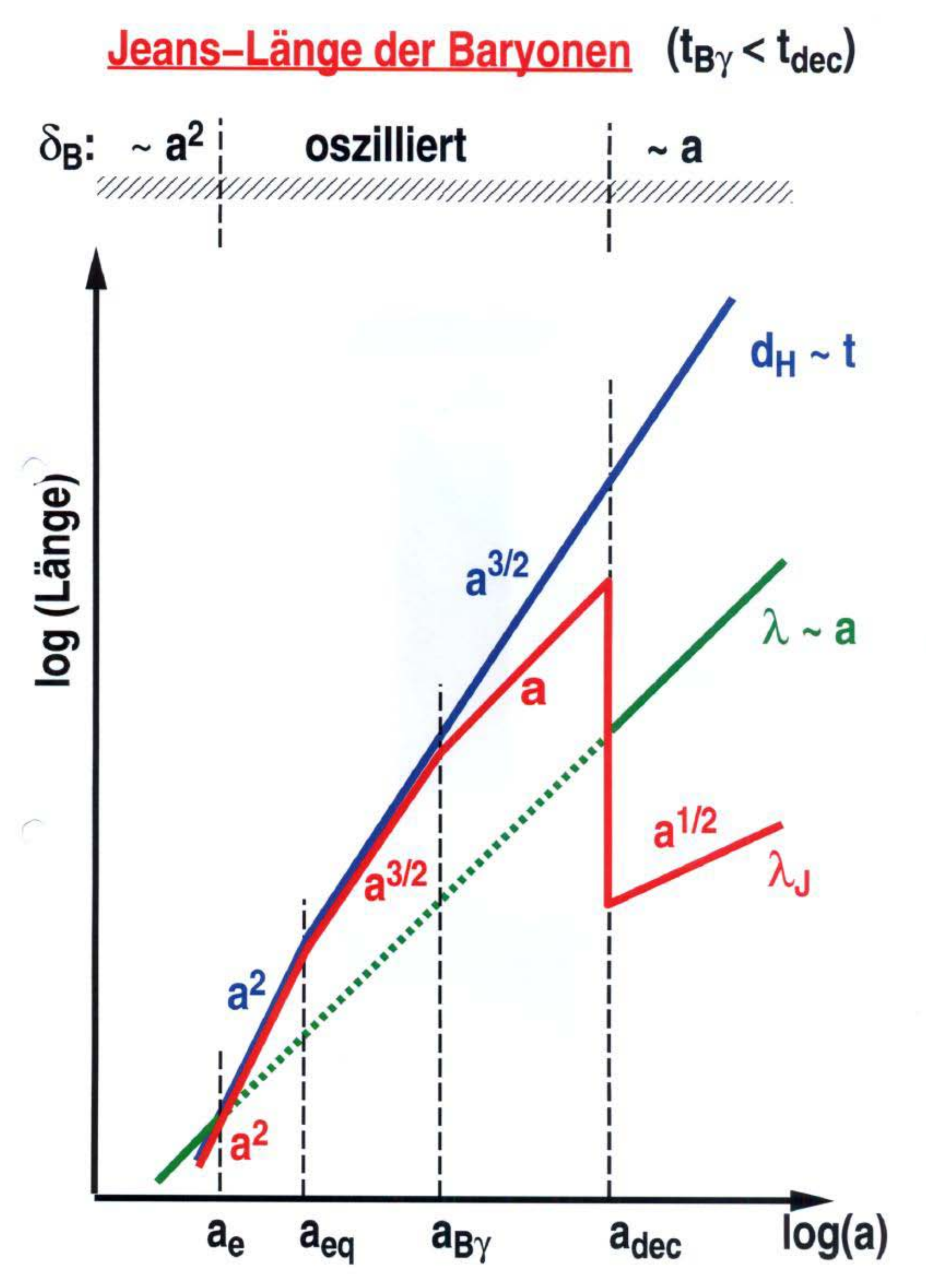
Jeans length and mass: dark matter



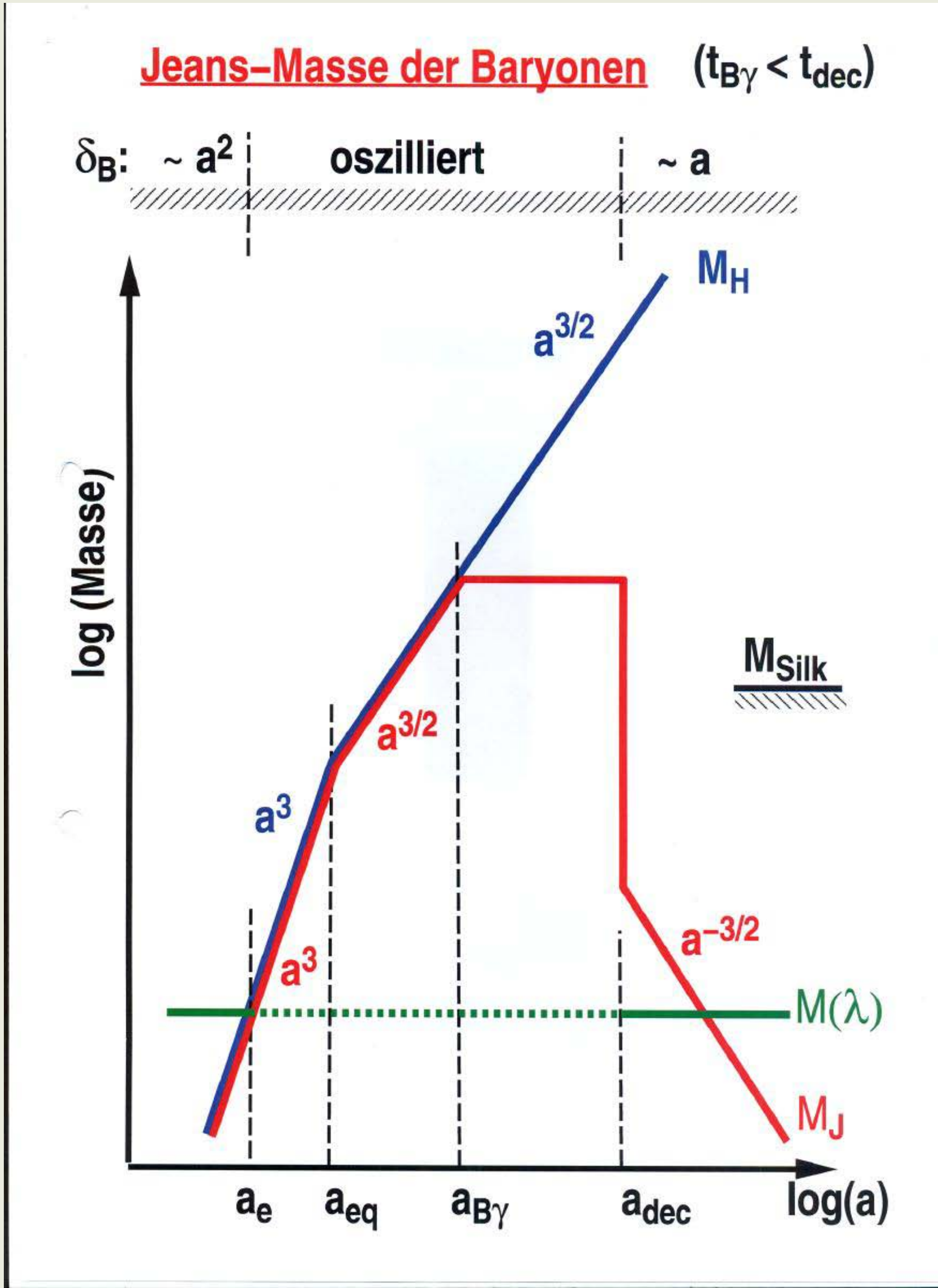
Jeans length and mass: dark matter



Jeans length and mass: baryonic matter



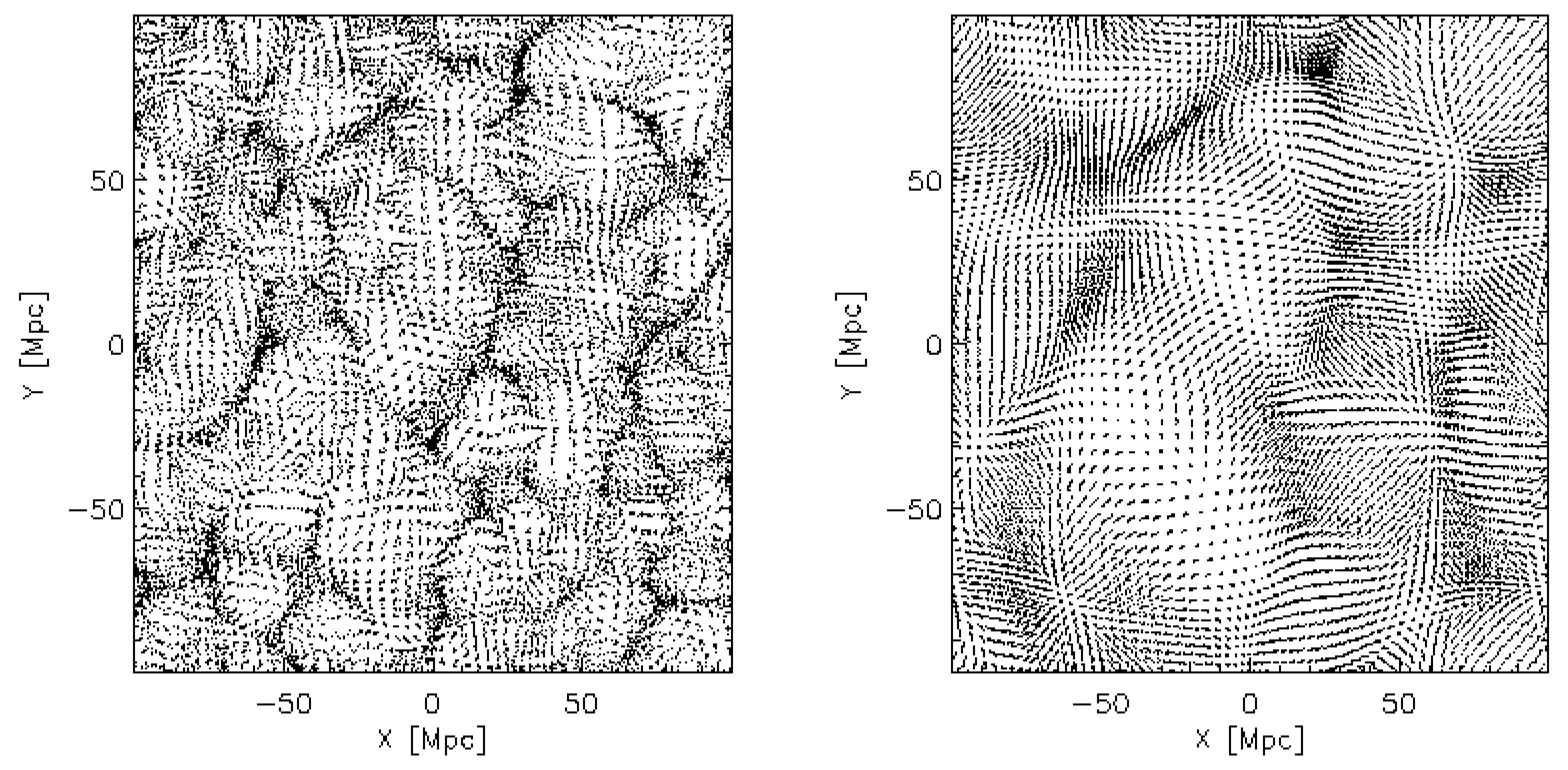
Jeans length and mass: baryonic matter



Can astronomy help to discriminate between neutrinos and neutralinos ?

- Neutrinos: Hot Dark Matter (HDM)
  - mass in the tens of eV ⇒ very low mass
  - very low mass ⇒ high velocities ⇒ “hot”
  - can travel several tens of Mpc over the age of the universe
- Neutralinos: Cold Dark Matter (CDM)
  - mass in the hundredst of GeV ⇒ very high mass
  - very high mass ⇒ low velocities ⇒ “cold”
  - cannot travel significant distances over the age of the universe

Can astronomy help to discriminate between hot and cold dark matter ?



CDM **HDM**

Structure formation: HDM vs CDM

- Hot dark matter:
  - initial small scale structure (anything smaller than a galaxy cluster) washed out due to the high velocities of neutrinos
  - clusters and supercluster form first
  - galaxies form due to fragmentation of collapsing clusters and superclusters

➡ top-down structure formation

Structure formation: HDM vs CDM

- Cold dark matter:
  - plenty of small scale structure
  - small galaxies form first, clusters last
  - larger structures form due to merging of smaller structures

➡ bottom-up or hierarchical structure formation

Structure formation: HDM vs CDM

- CDM fits observations much better than HDM
  - high-z galaxies are smaller
  - irregular shape of galaxy clusters indicate that they formed recently
  - there are only a very few clusters at high redshift, but many galaxies
  - two-point correlation function is much better reproduced

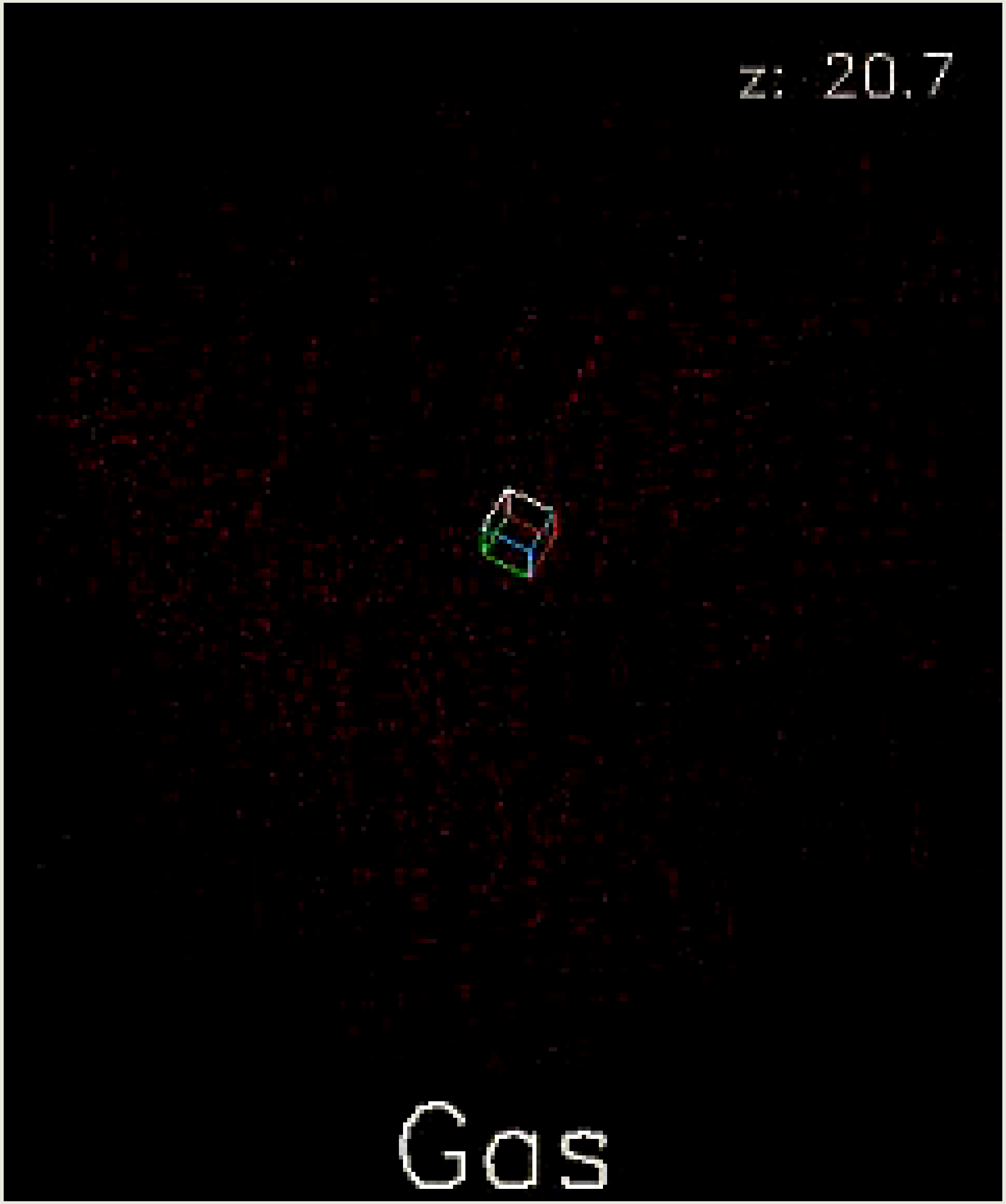
Recent simulations (MPA group)

(Court. V. Springel)

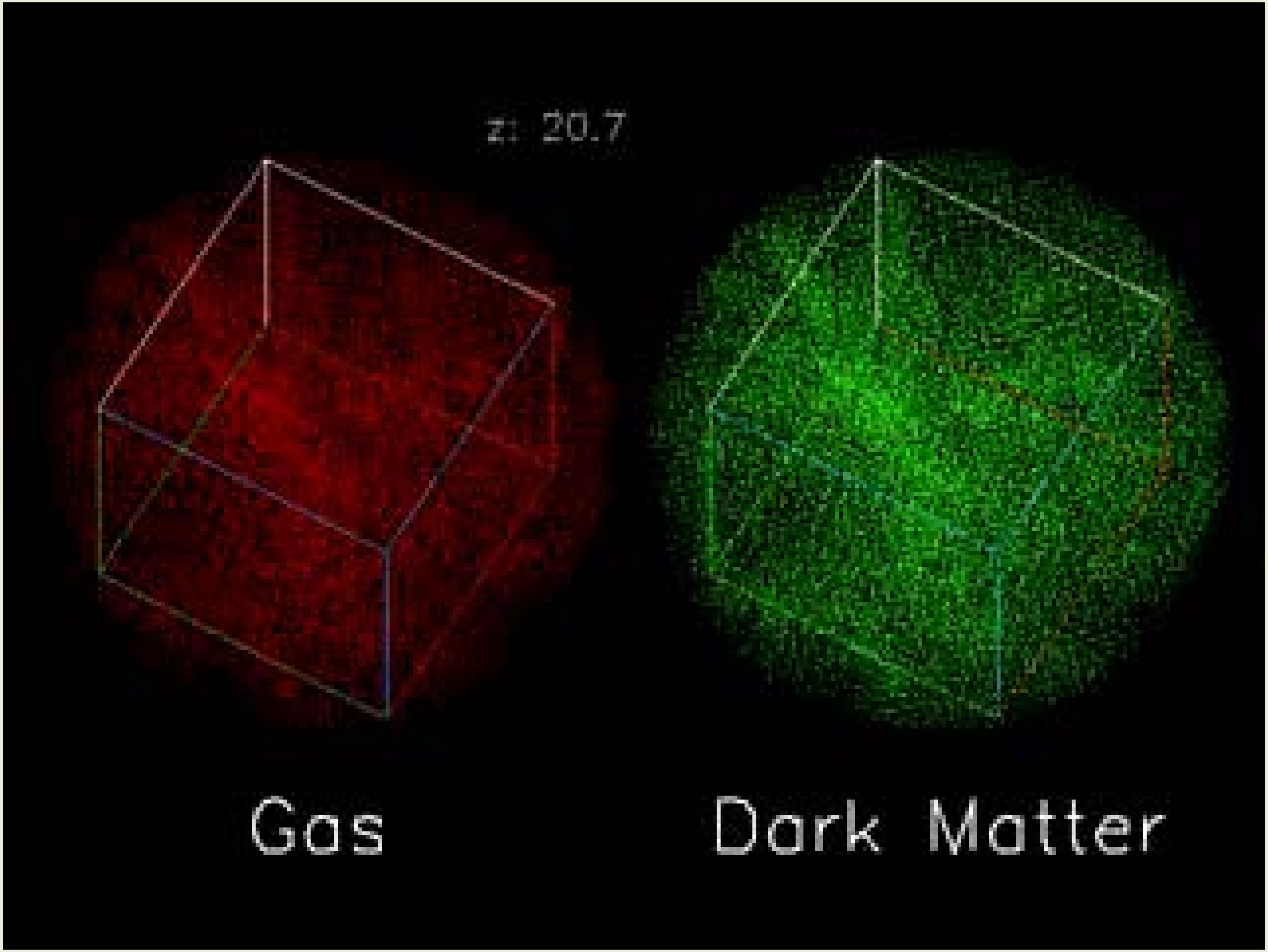
A voyage through a CDM universe

A galaxy formation recipe

- Ingredients: gas, radiation, gravity
- Pick a model for the Universe
- Add some seeds (perturbations) to trigger growth of structure
- Combine it with some recipe of your star formation cookbook



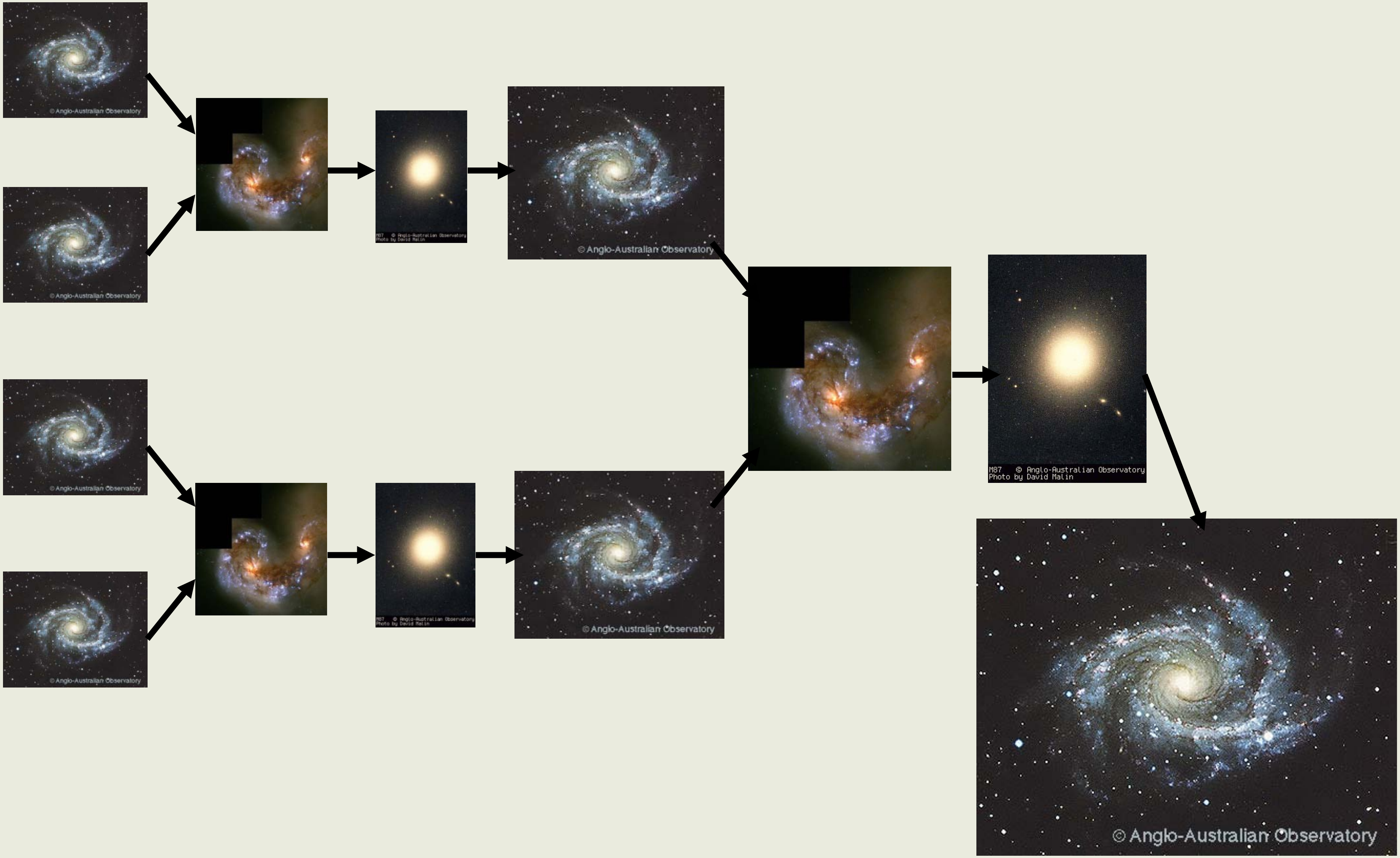
(Courtesy: M. Steinmetz)

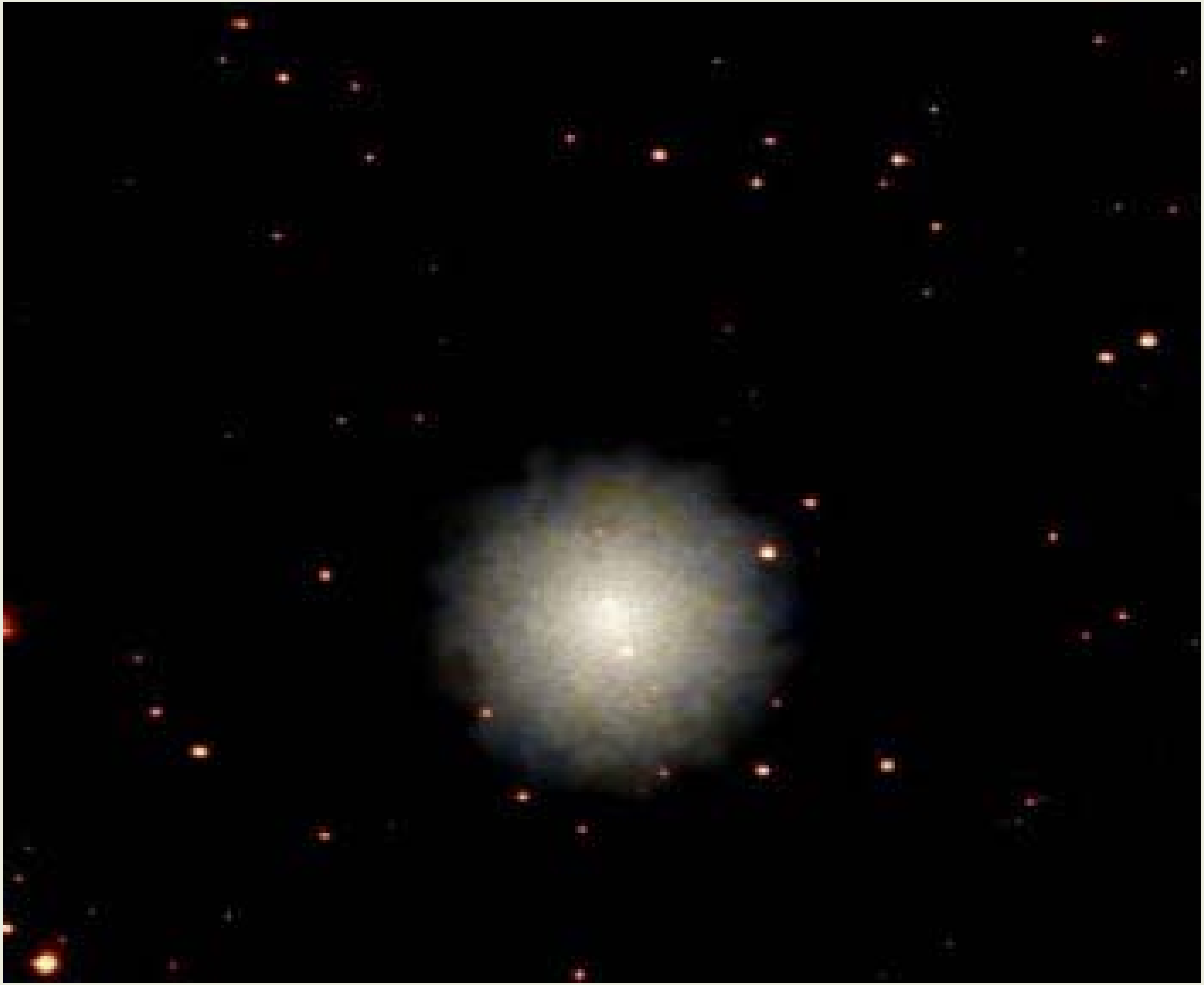


(Courtesy: M. Steinmetz)

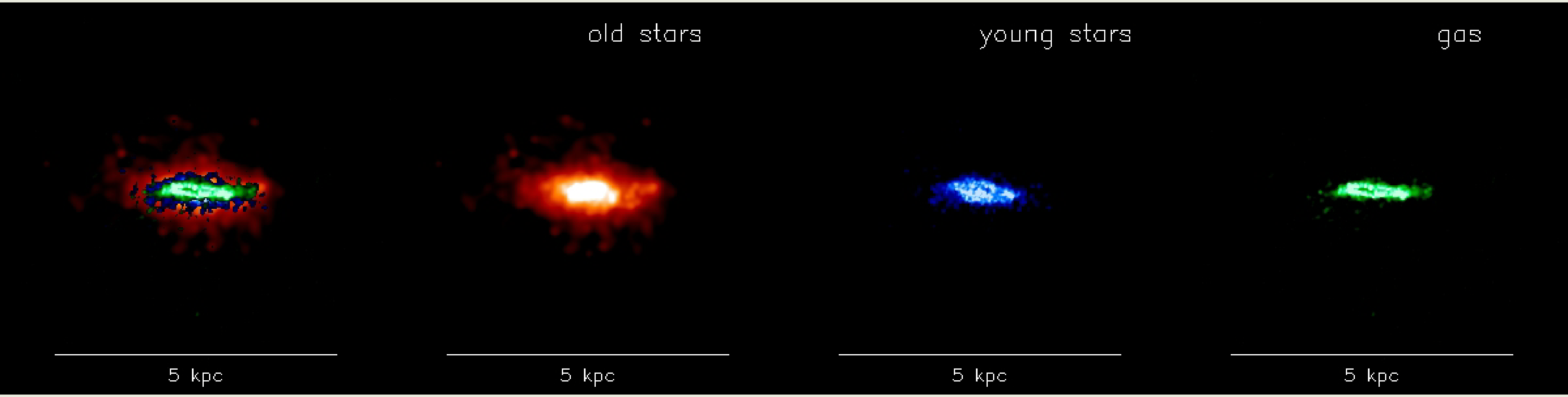
(Court. V. Springel)

Hierarchical galaxy formation



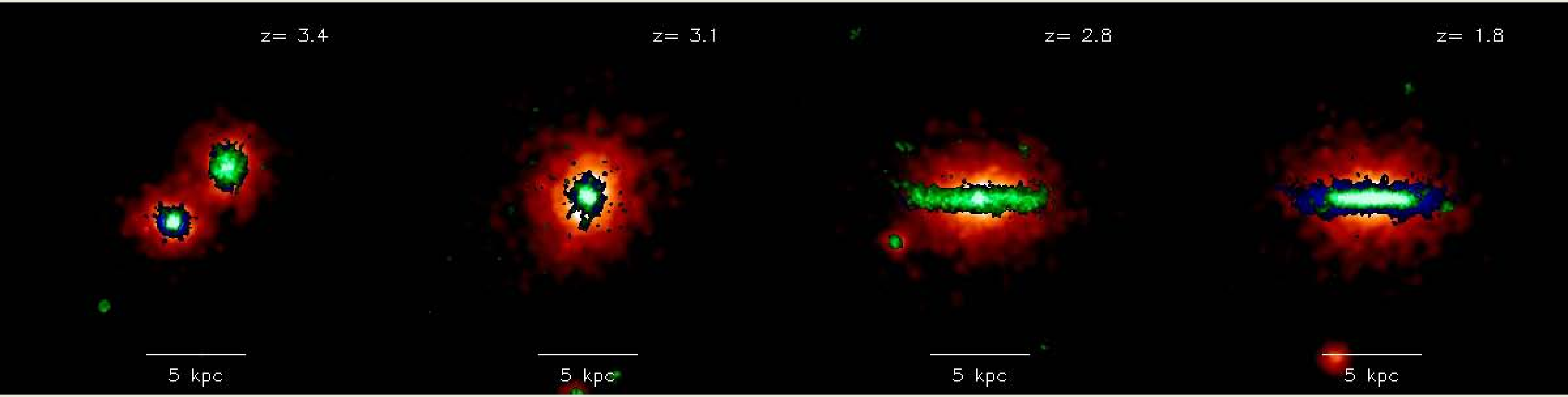


Phase I: Formation of First Galactic Disks (1Gyr)



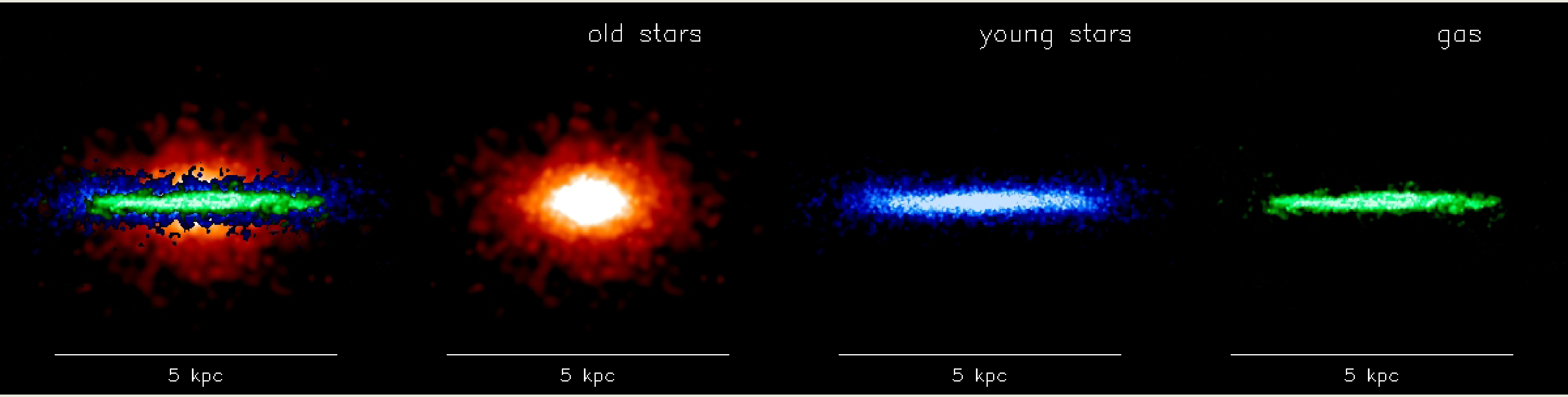
- first relaxed small disks

Phase II: Bulge Formation and Disk Reassembly (2 Gyr)



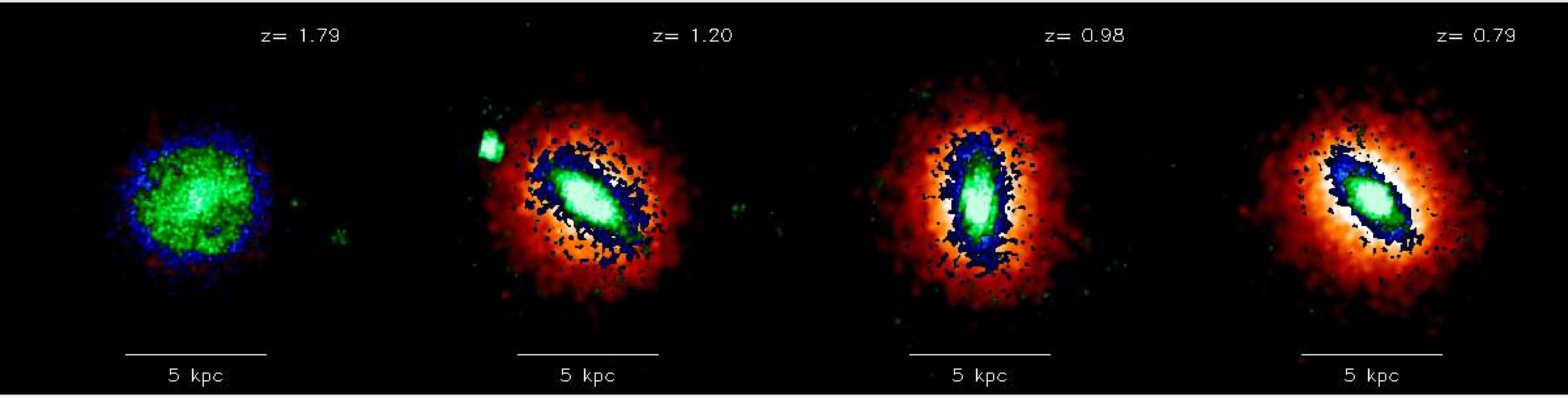
- Disks are destroyed by merging, formation of an elliptical
- Later on: disk reassemble

Phase III: Well Developed Disk+Bulge Structure (3 Gyr)



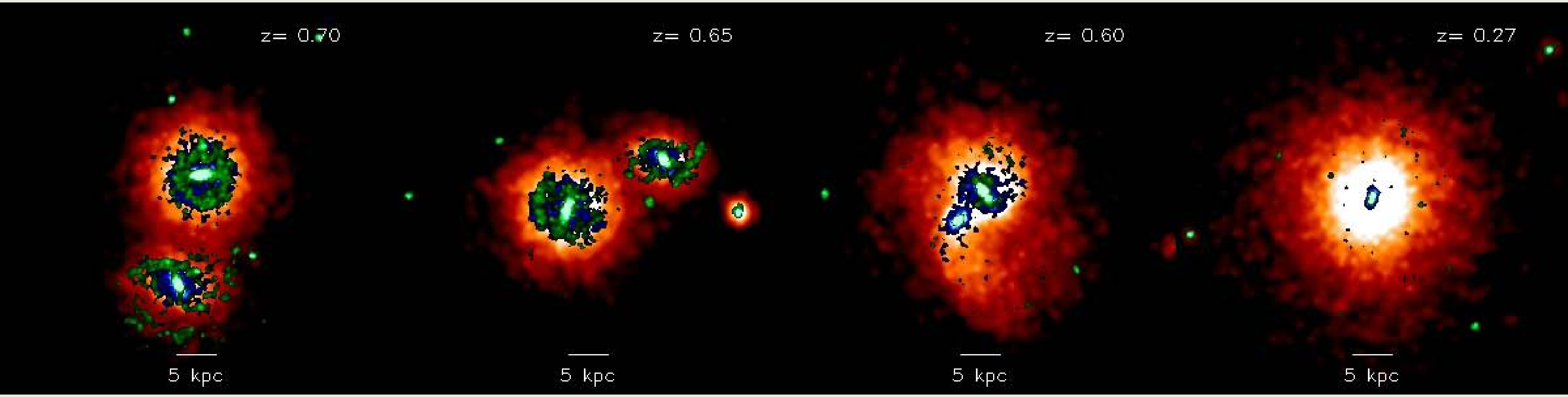
- slowly growing disk
- young stars and gas in thin disk, bulge of old stars

Phase IV: Tidally Triggered Bar Formation (5 Gyr)



- several minor mergers
- rapidly rotating bar

Phase V: Formation of a Giant Elliptical (7 Gyr)



- nuclear star burst consumes nearly all remaining gas