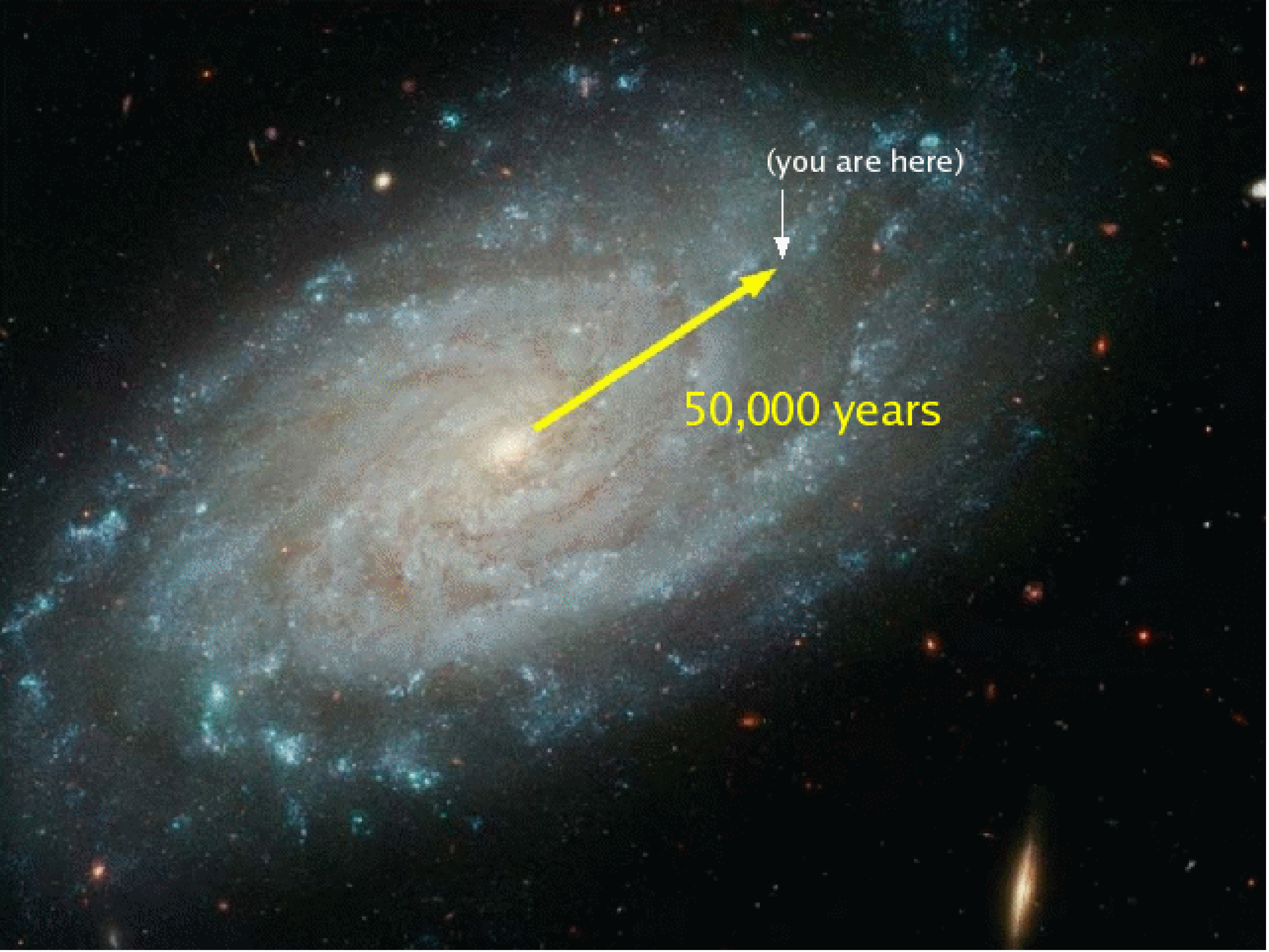
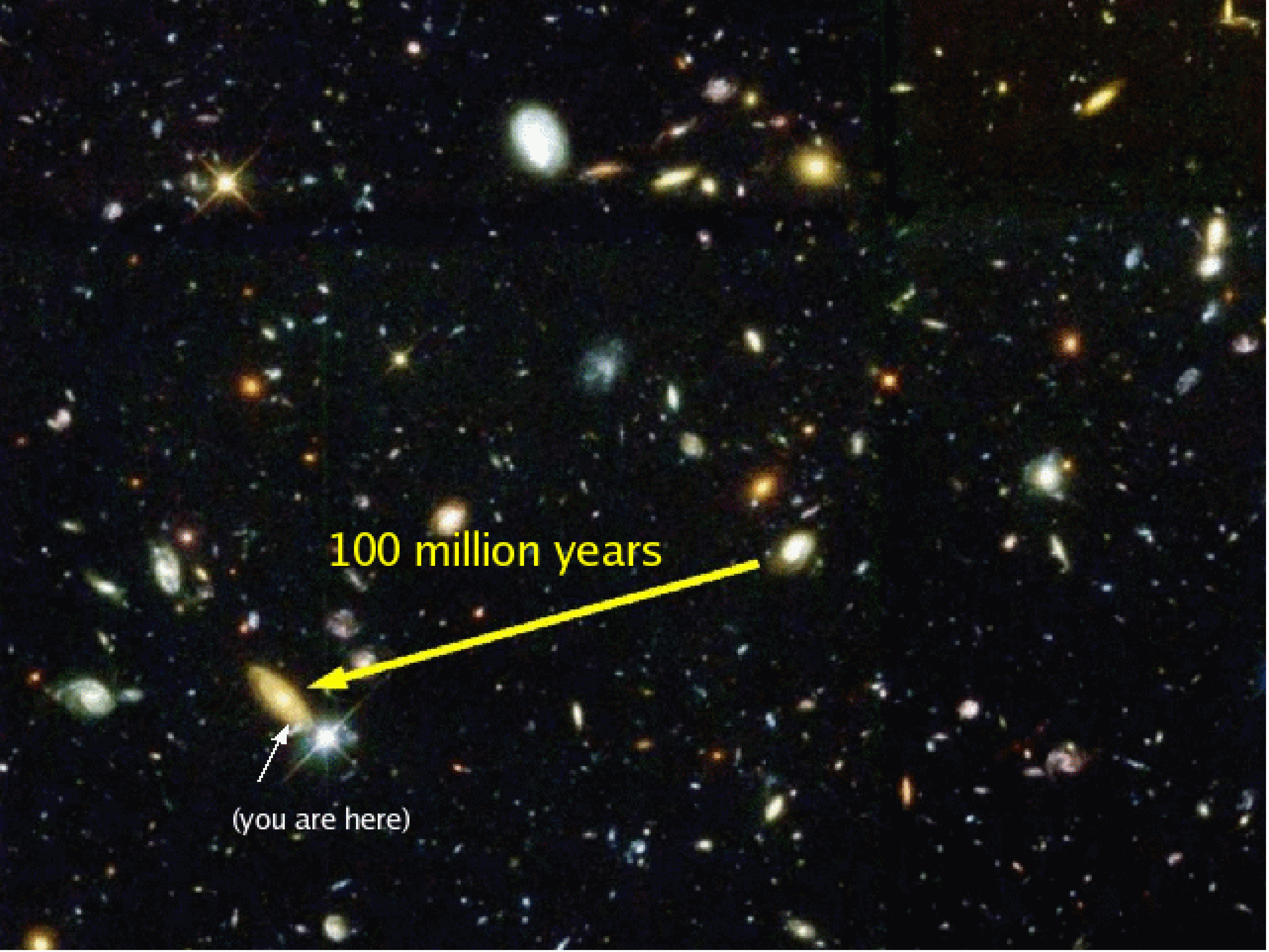
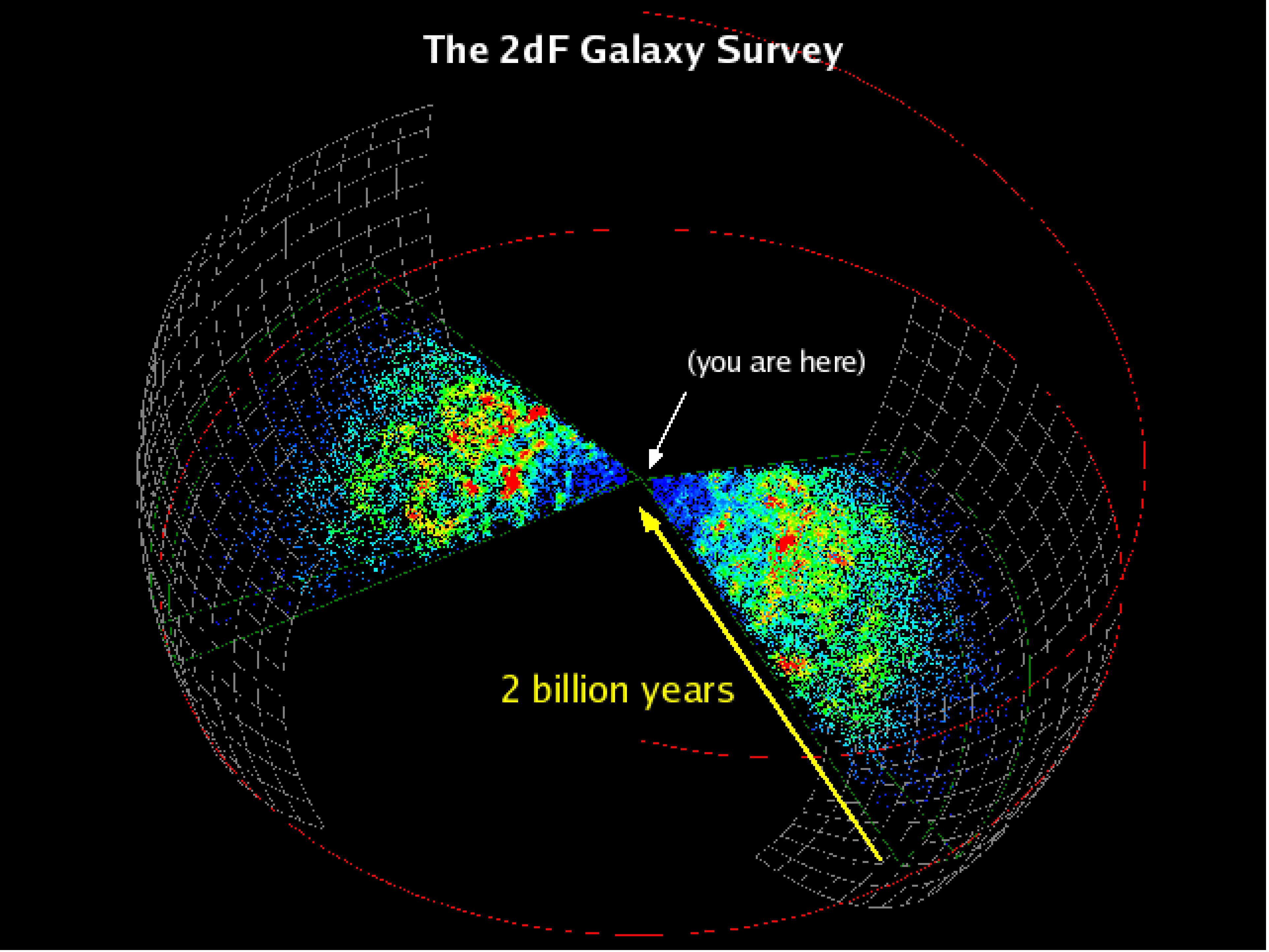
El Universo en Expansion

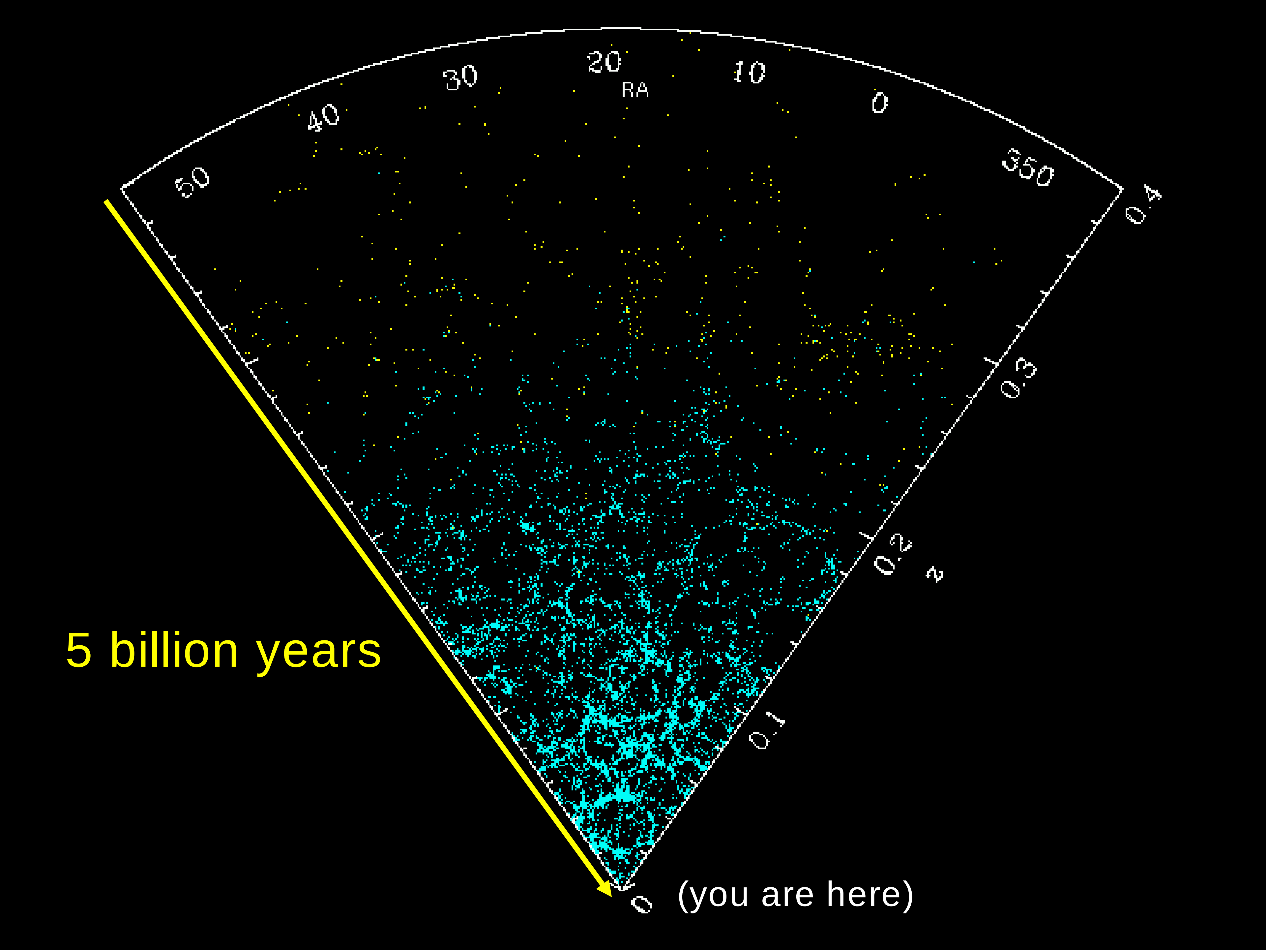
Juan García-Bellido
Inst. Física Teórica UAM
Benasque, 12 Julio 2004


8 minutes


(you are here)
50,000 years

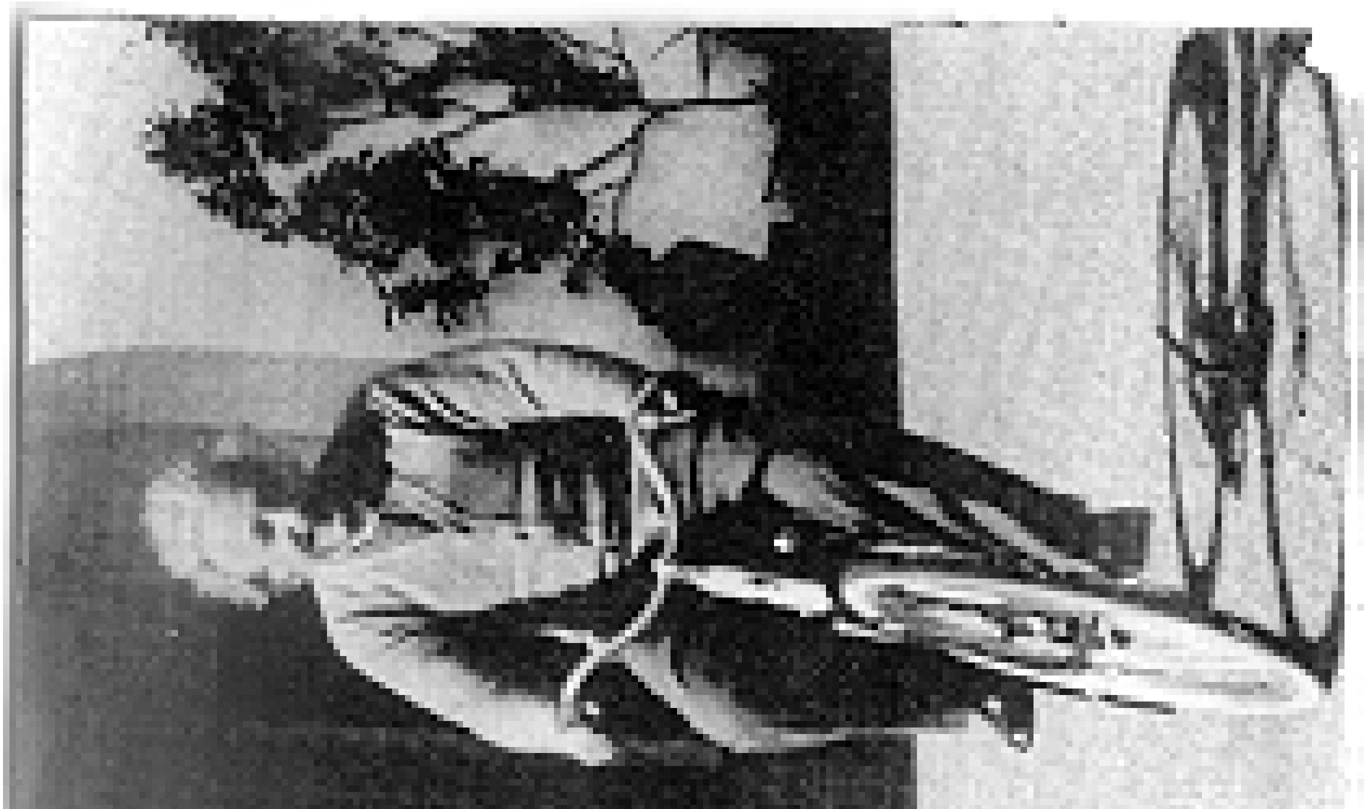

100 million years
(you are here)


The 2dF Galaxy Survey
(you are here)
2 billion years



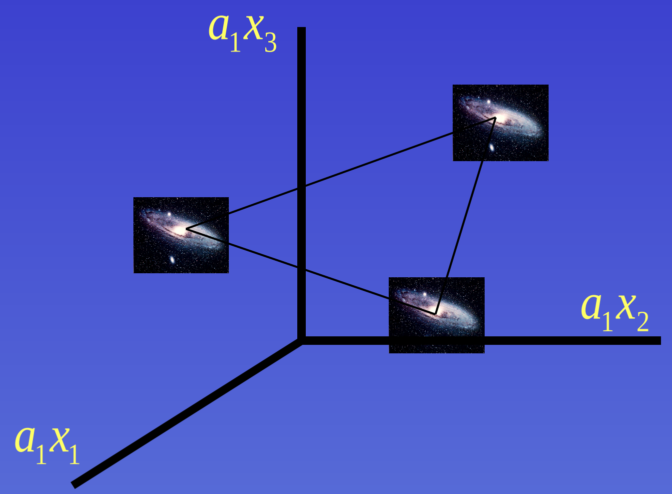
RA
50
40
30
20
10
0
350
0.4
0.3
0.2
z
0.1
0
5 billion years
(you are here)

Space is Homogeneous and Isotropic

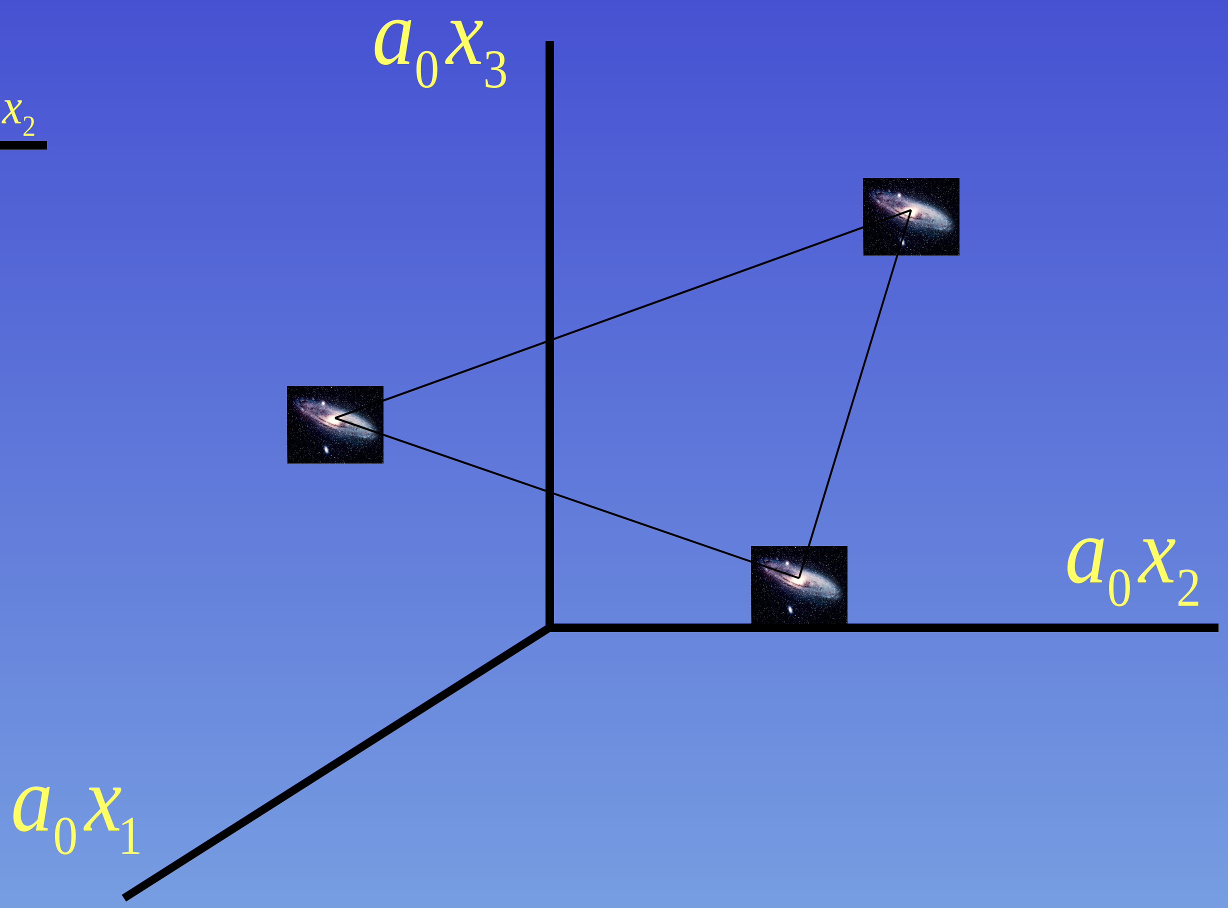


General Relativity

An Expanding Universe

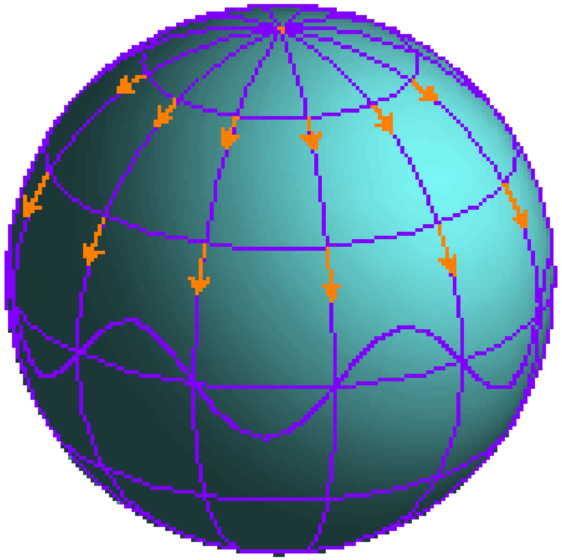


Euclidean space



scale factor

$$a(t_0) > a(t_1)$$



$$\frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_0}{a_1} = 1 + z$$

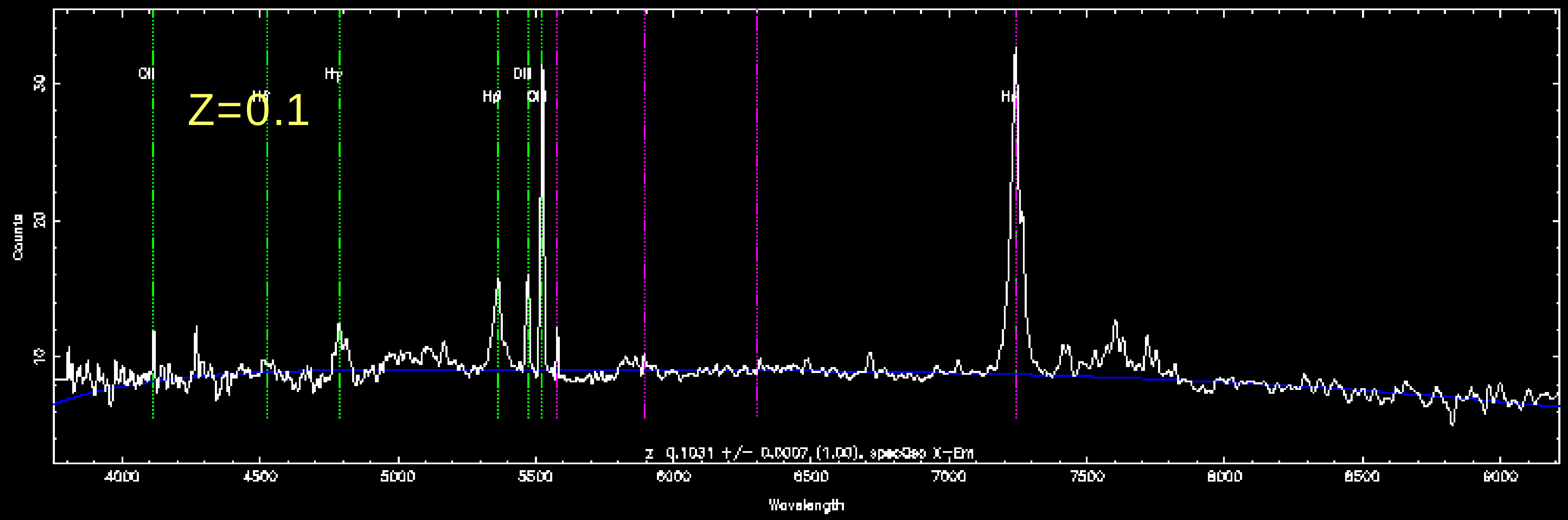
Edwin P. Hubble

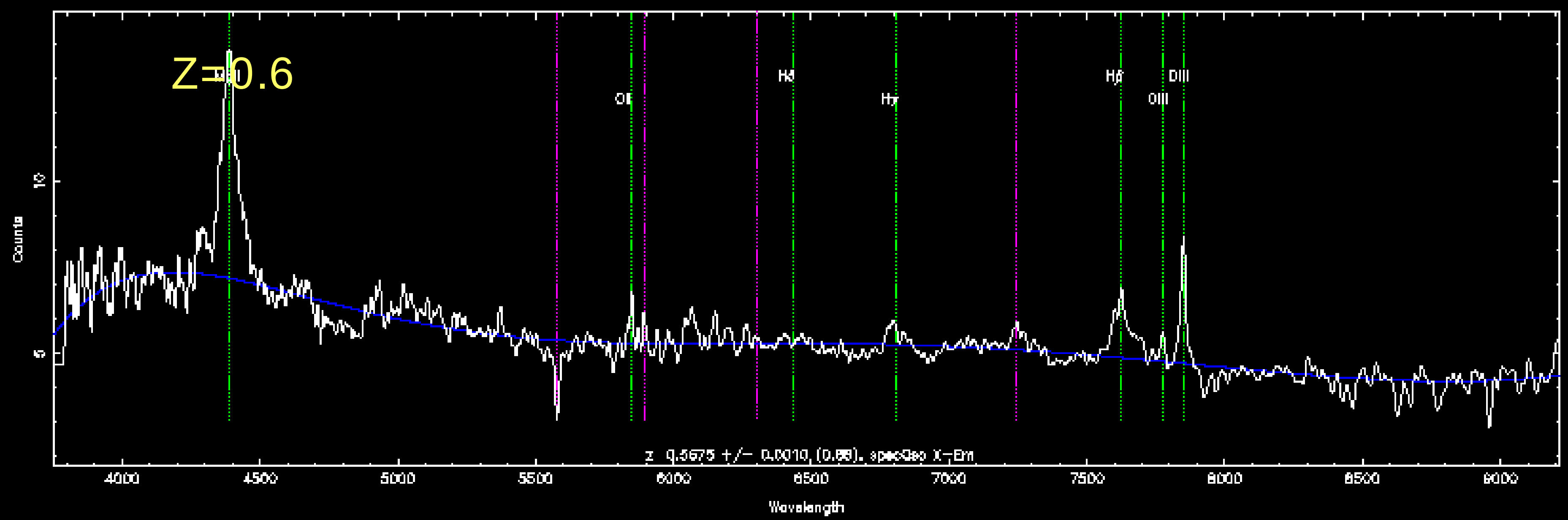
Mount Wilson

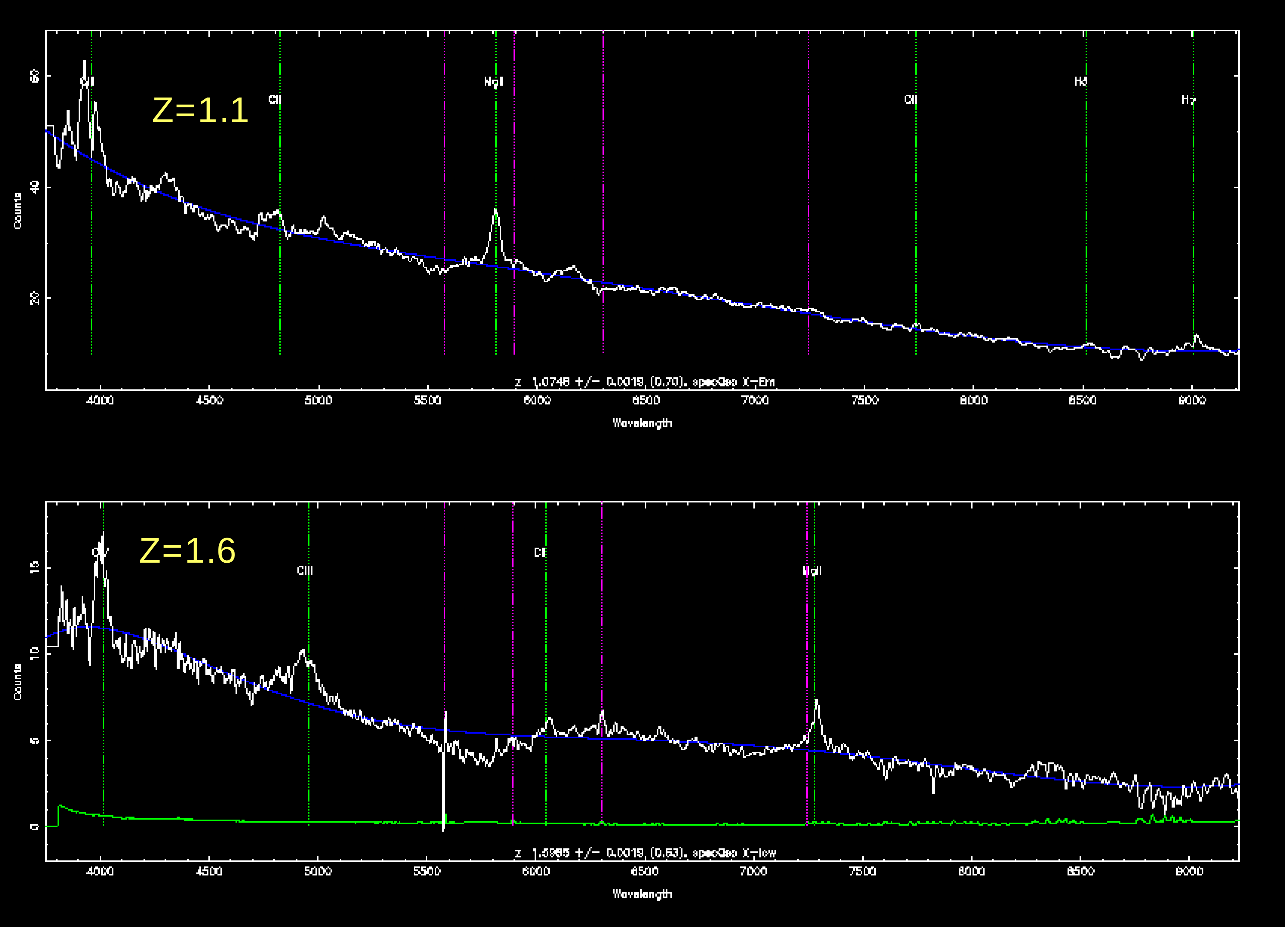
Edwin P. Hubble

Mount Wilson

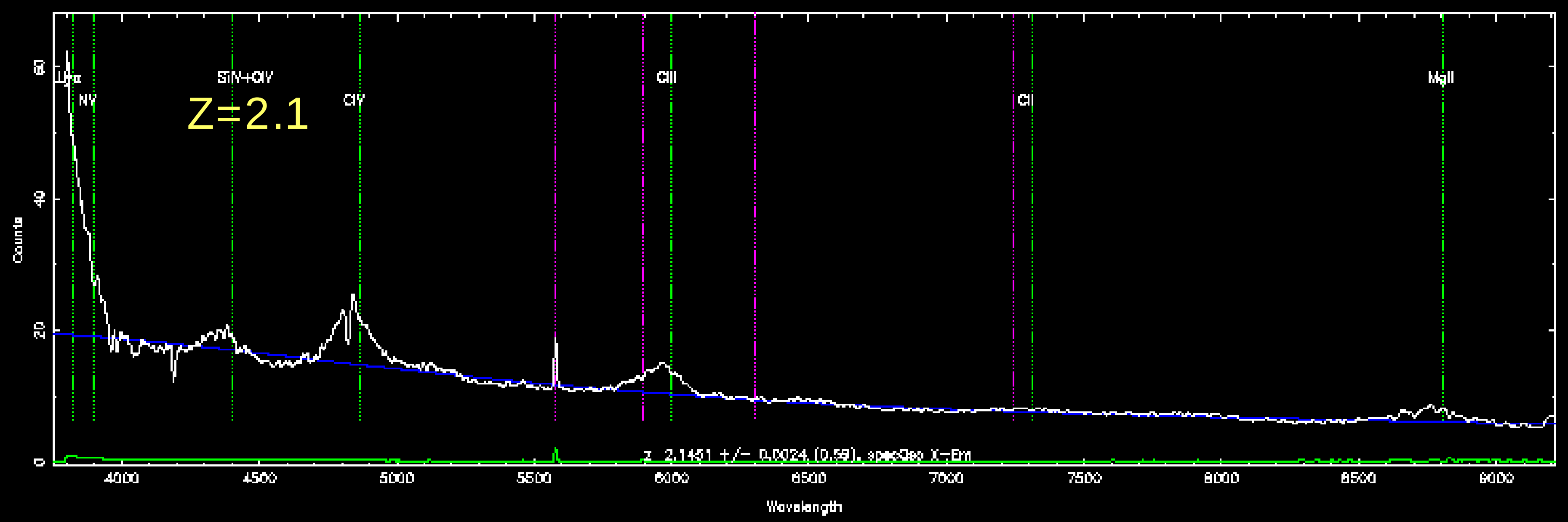
Mount Palomar


Z=0.1
z 0.1031 +/- 0.0007 (1.00), specQso X-Em
Wavelength
Counts

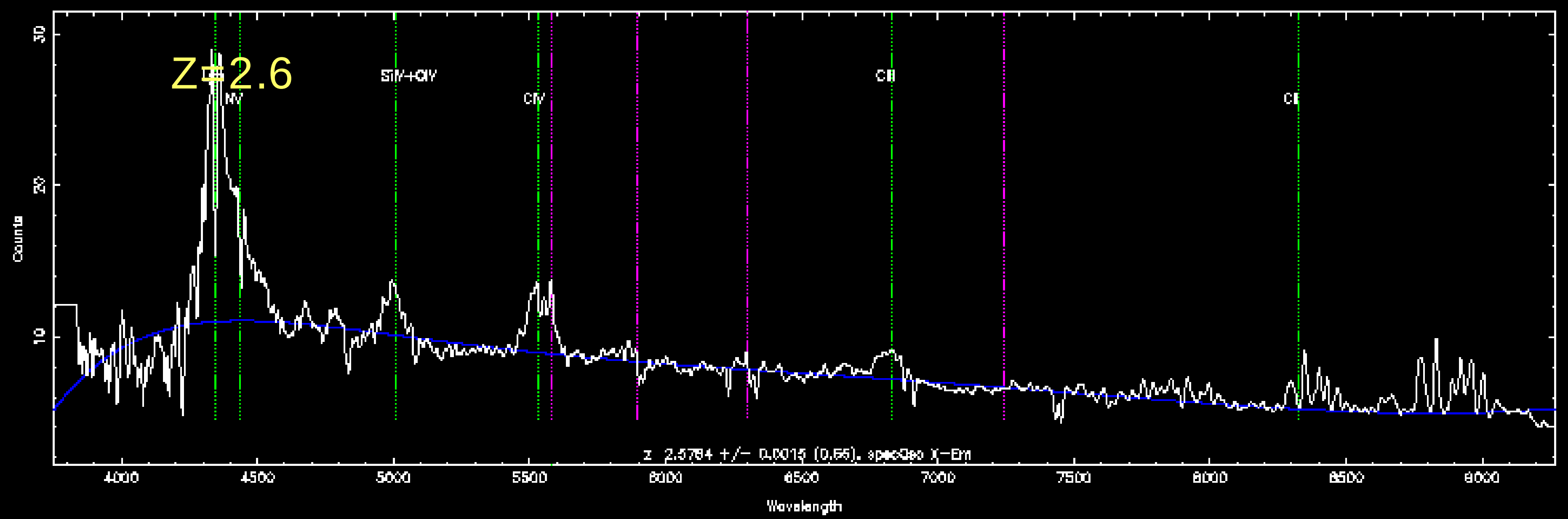

Z=0.6
z 0.5675 +/- 0.0010 (0.88), specQso X-Em
Wavelength
Counts



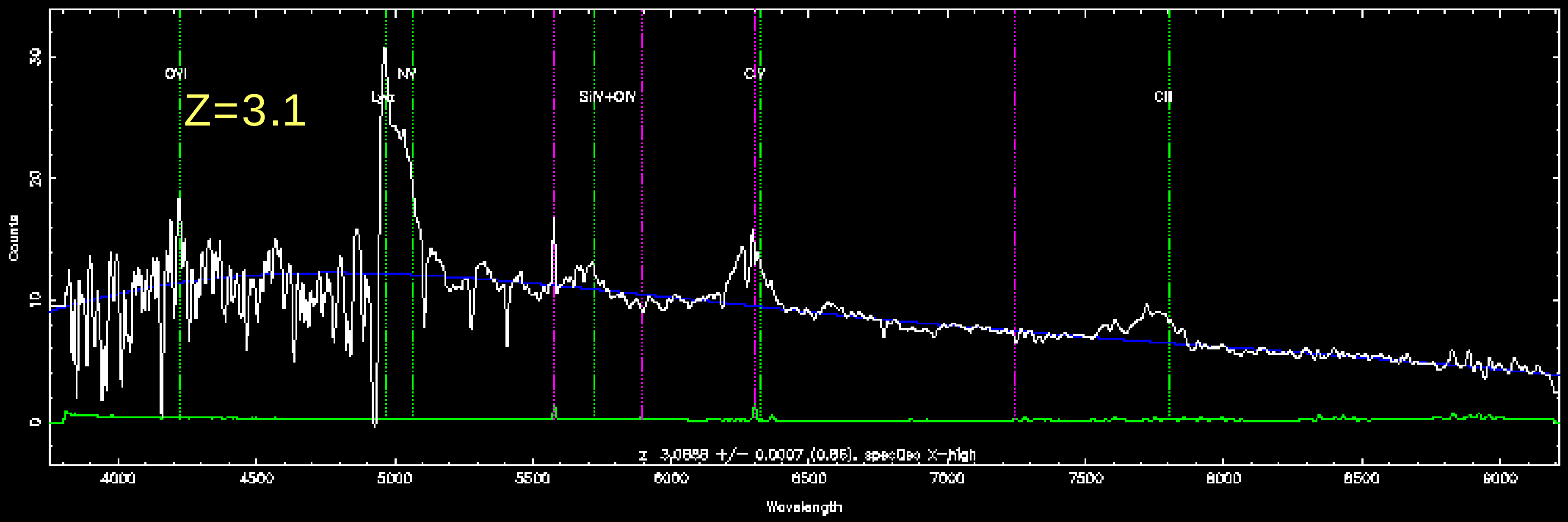
Z=1.1
MgII
Counts
Wavelength
z 1.0748 +/- 0.0019 (0.70), specQso X-Em
Z=1.6
CIII
MgII
Counts
Wavelength
z 1.5985 +/- 0.0019 (0.63), specQso X-low



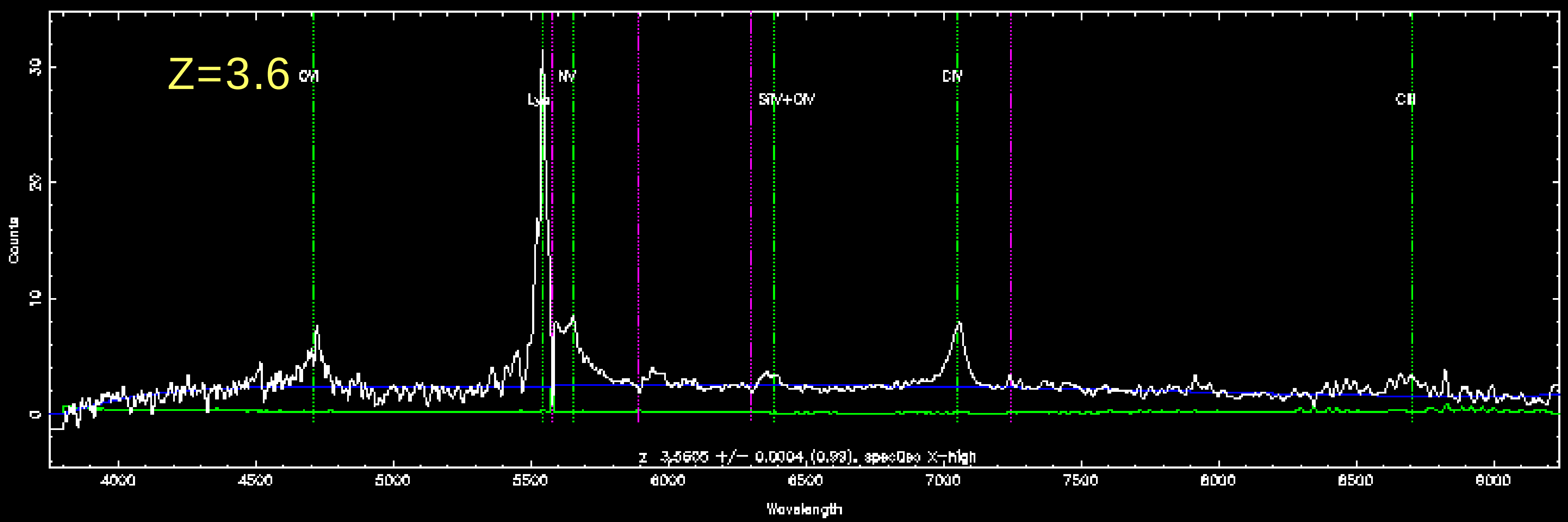
Lyα
NV
SiIV+OIV
CIV
CIII
CII
MgII
Z=2.1
Counts
Wavelength
z 2.1451 +/- 0.0024 (0.59), specQso X-Em



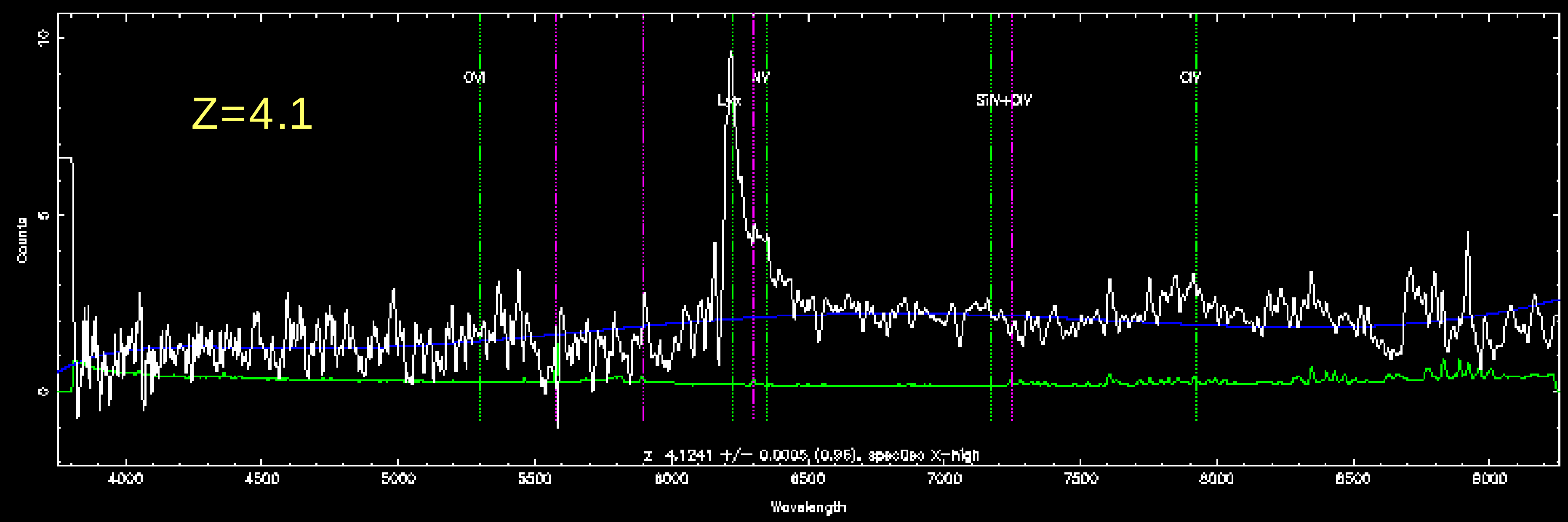
Z=2.6
NV
SiIV+OIV
CIV
CIII
CII
Counts
Wavelength
z 2.5784 +/- 0.0015 (0.65), specQso X-Em



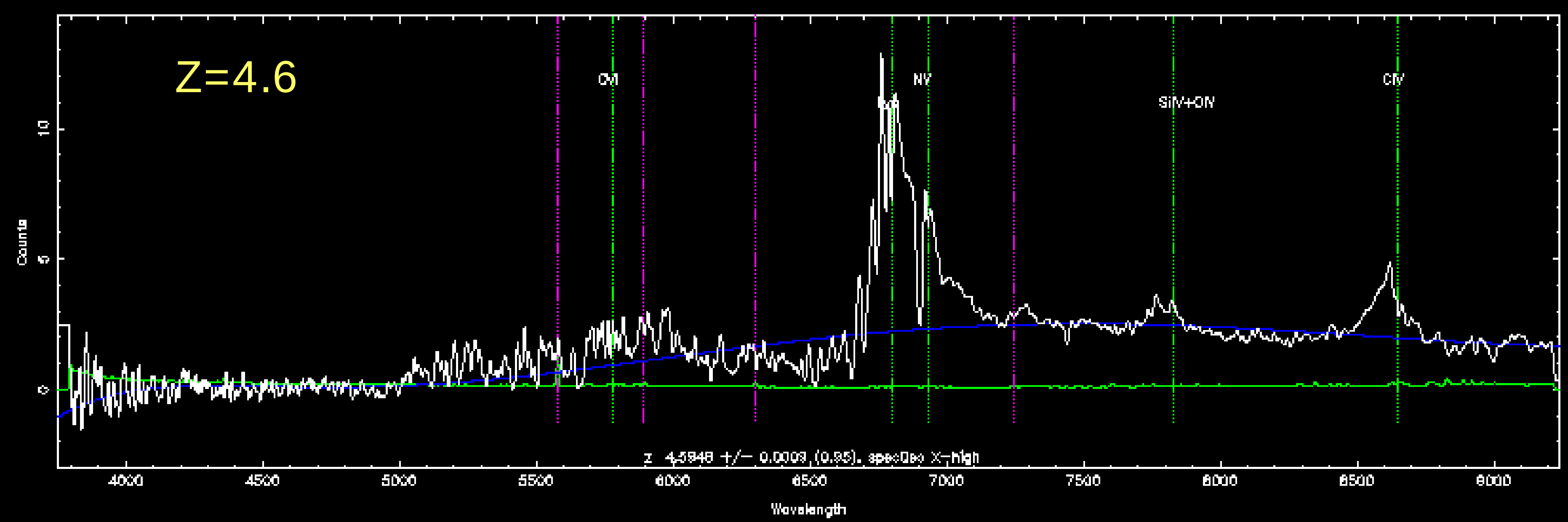
Z=3.1
OVI
Lyα
NV
SiIV+OIV
CIV
CIII
Counts
Wavelength



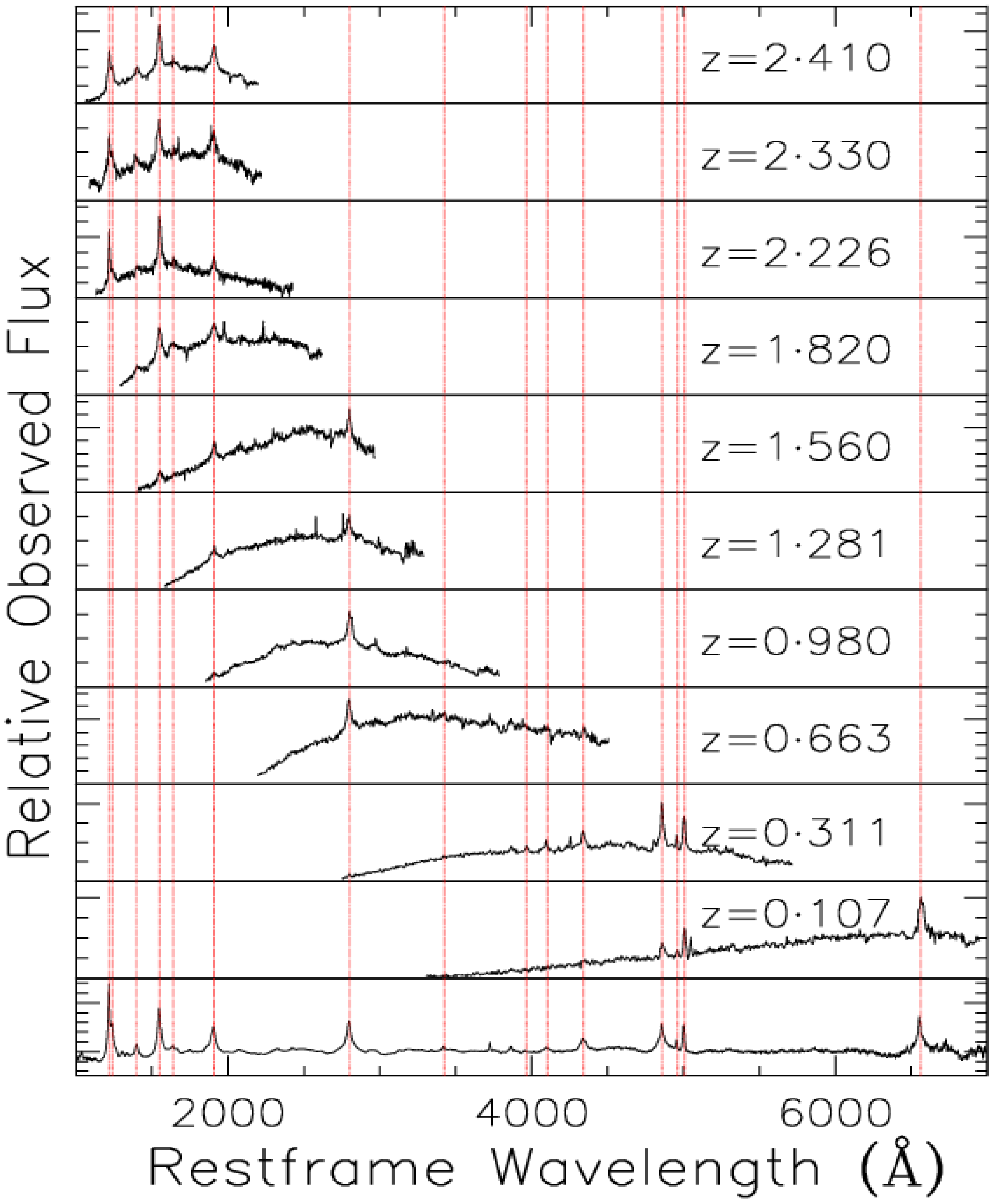
Z=3.6
OVI
Lyα
NV
SiIV+OIV
CIV
CIII
Counts
Wavelength



Z=4.1
OVI
Lyα
NV
SiIV+OIV
CIV
z 4.1241 +/- 0.0005 (0.95), spec0ex X-high
Counts
Wavelength



Z=4.6
OVI
NV
SiIV+OIV
CIV
z 4.5948 +/- 0.0009 (0.95), spec0ex X-high
Counts
Wavelength

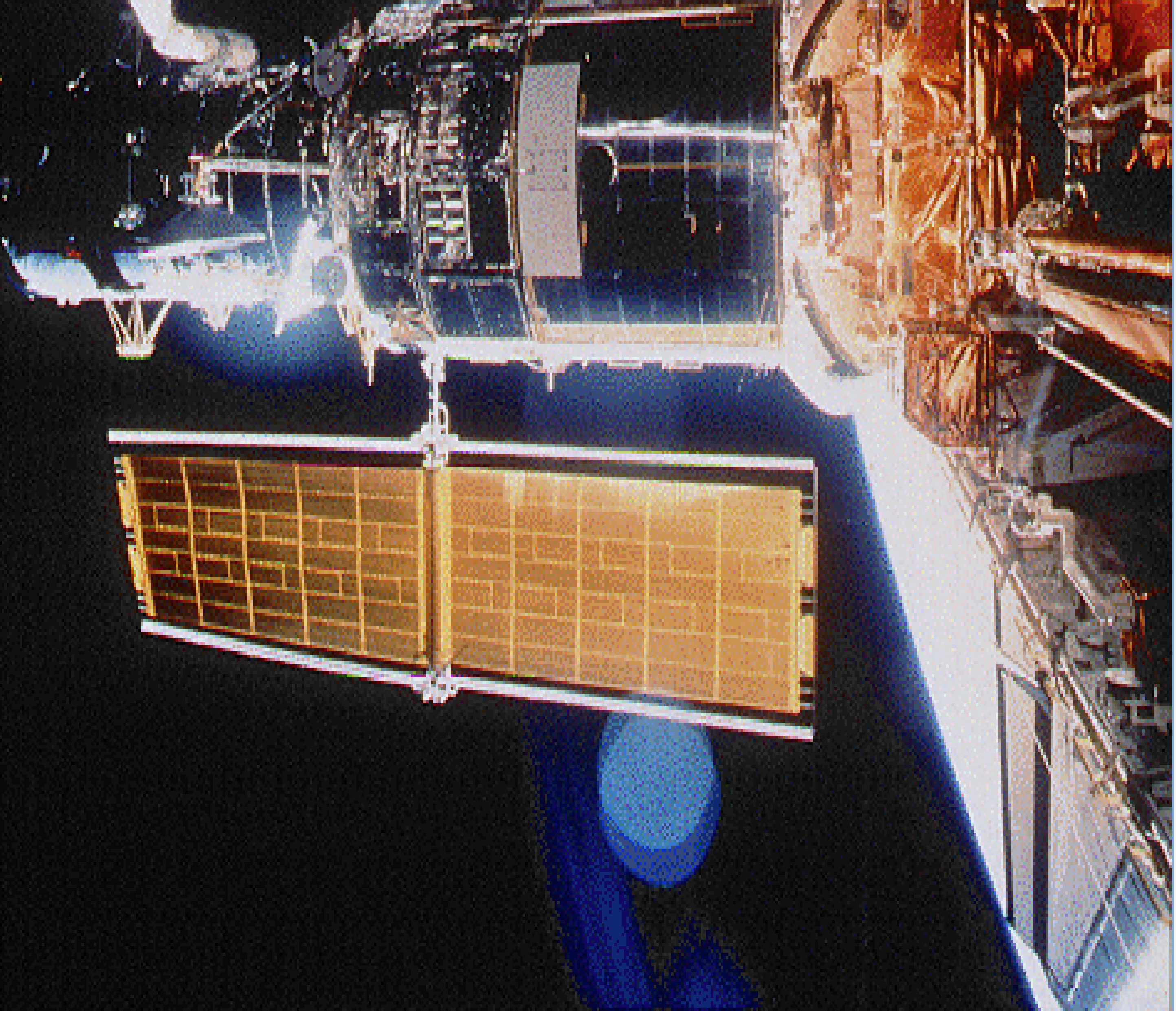


Redshifts to galaxies

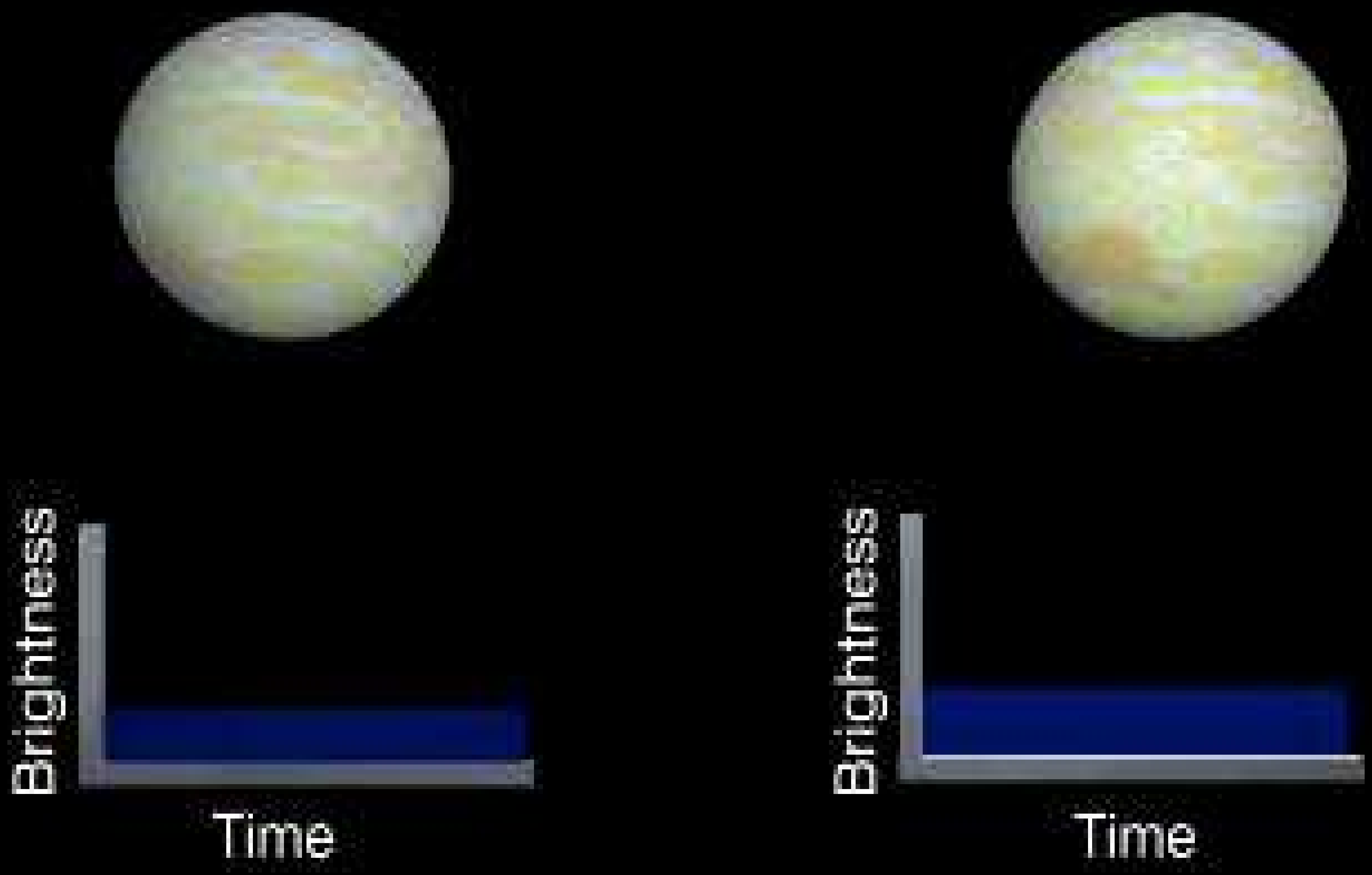
Hubble law

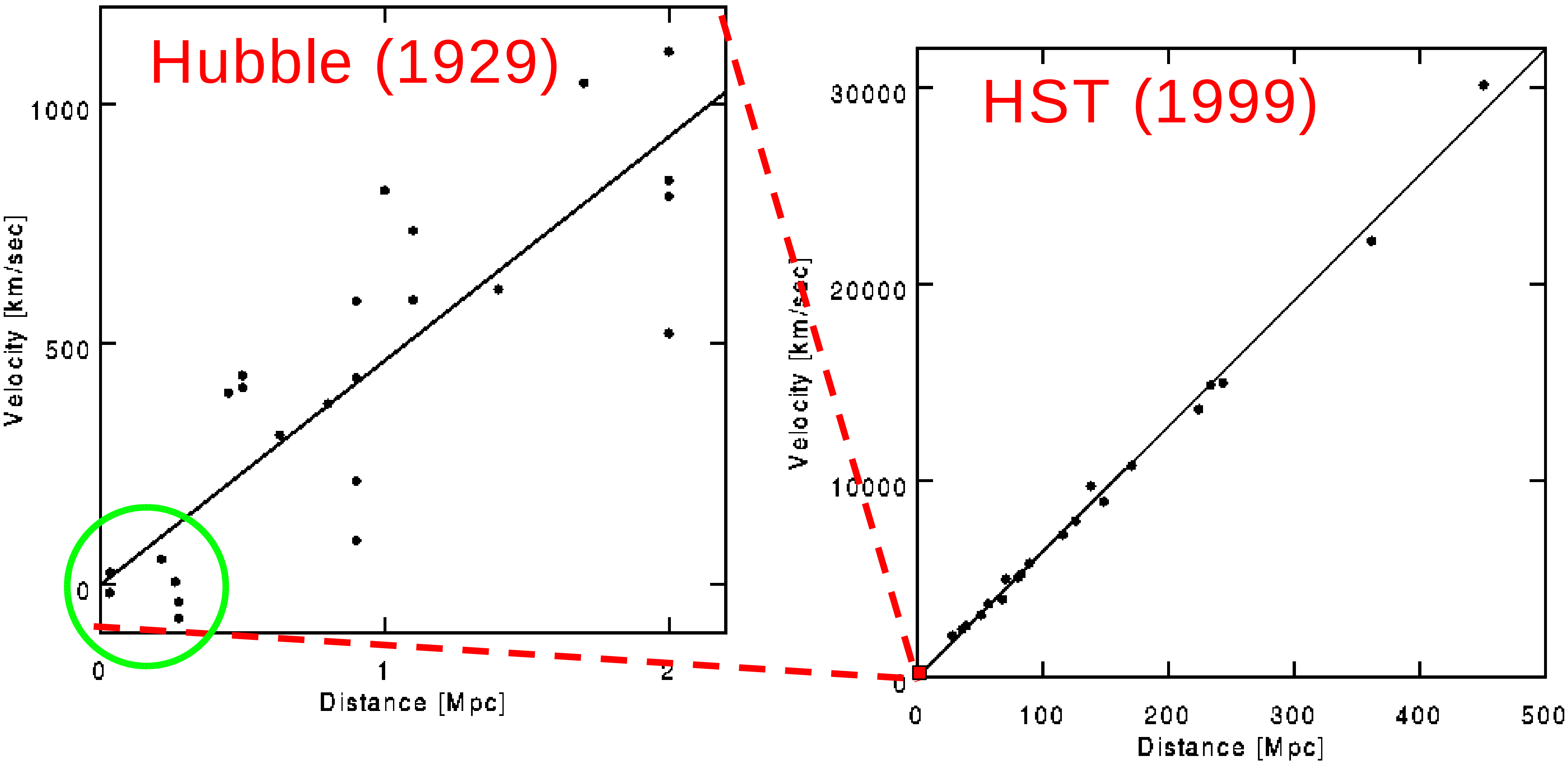
$$H_0 d = zc \approx v$$

for $z \ll 1$



HST Key Project





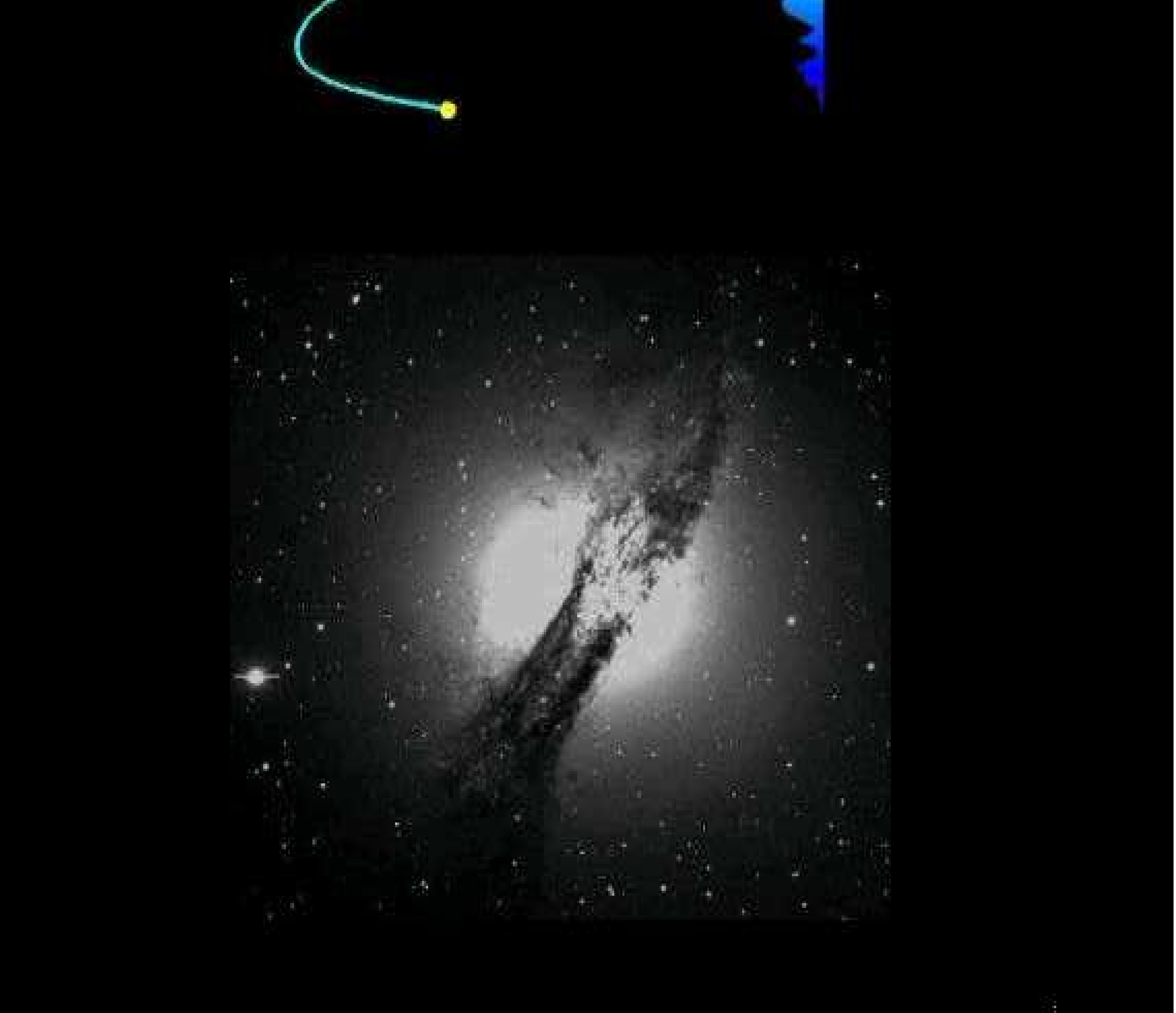
$$H_0 = 500\,\text{km/s/Mpc}$$

Dominated by systematic errors!

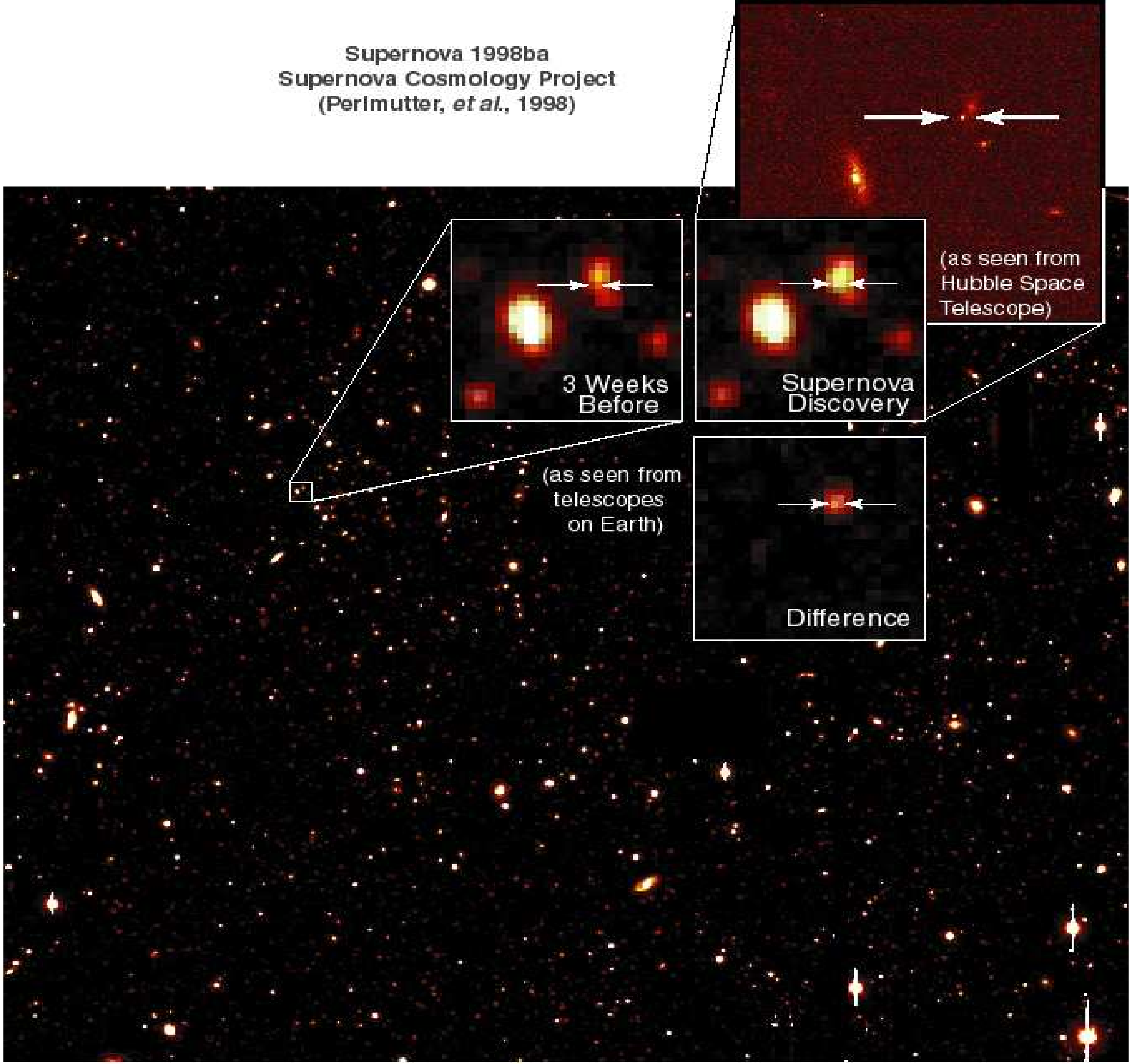
$$H_0 = 70 \pm 7\,\text{km/s/Mpc}$$

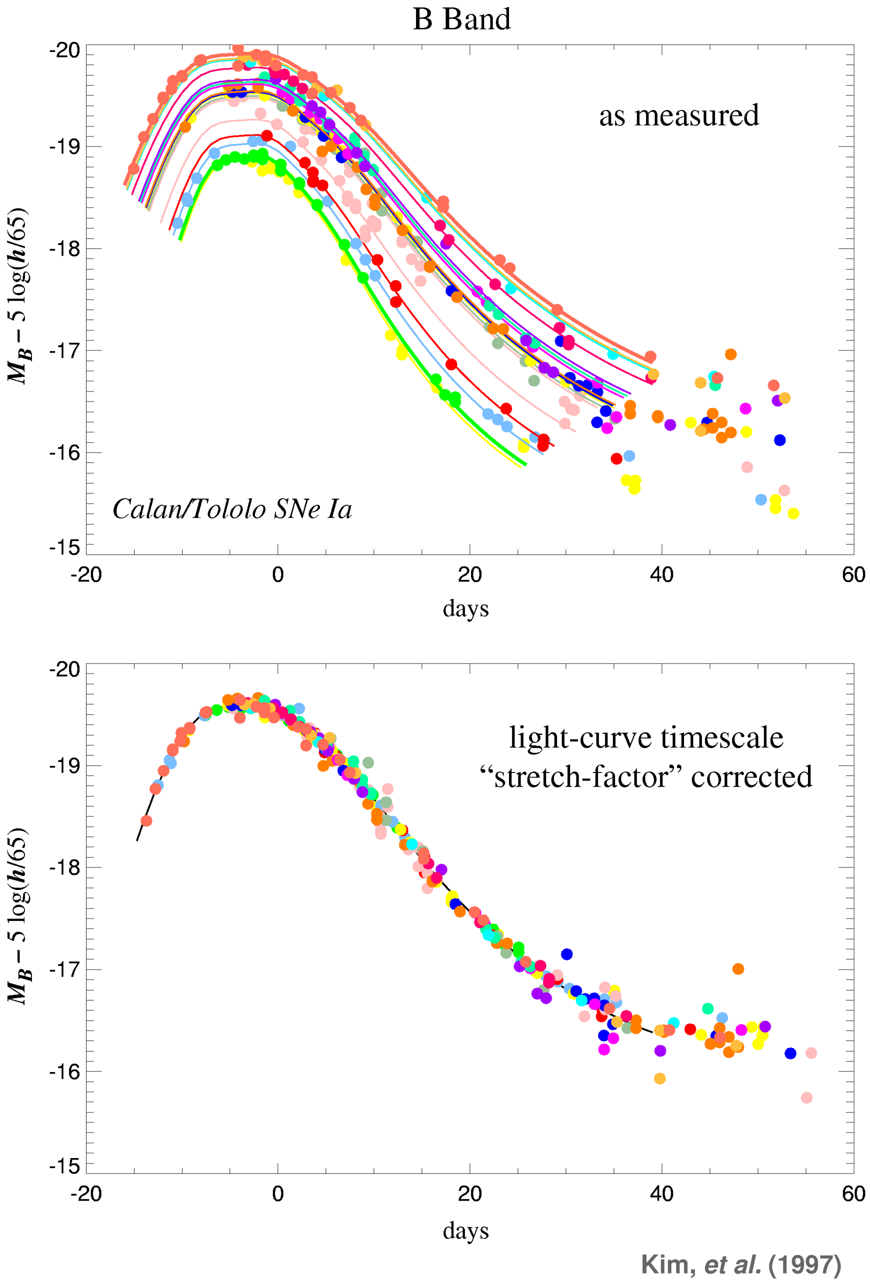
$$z \leq 0.1$$

The Accelerating Universe



Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

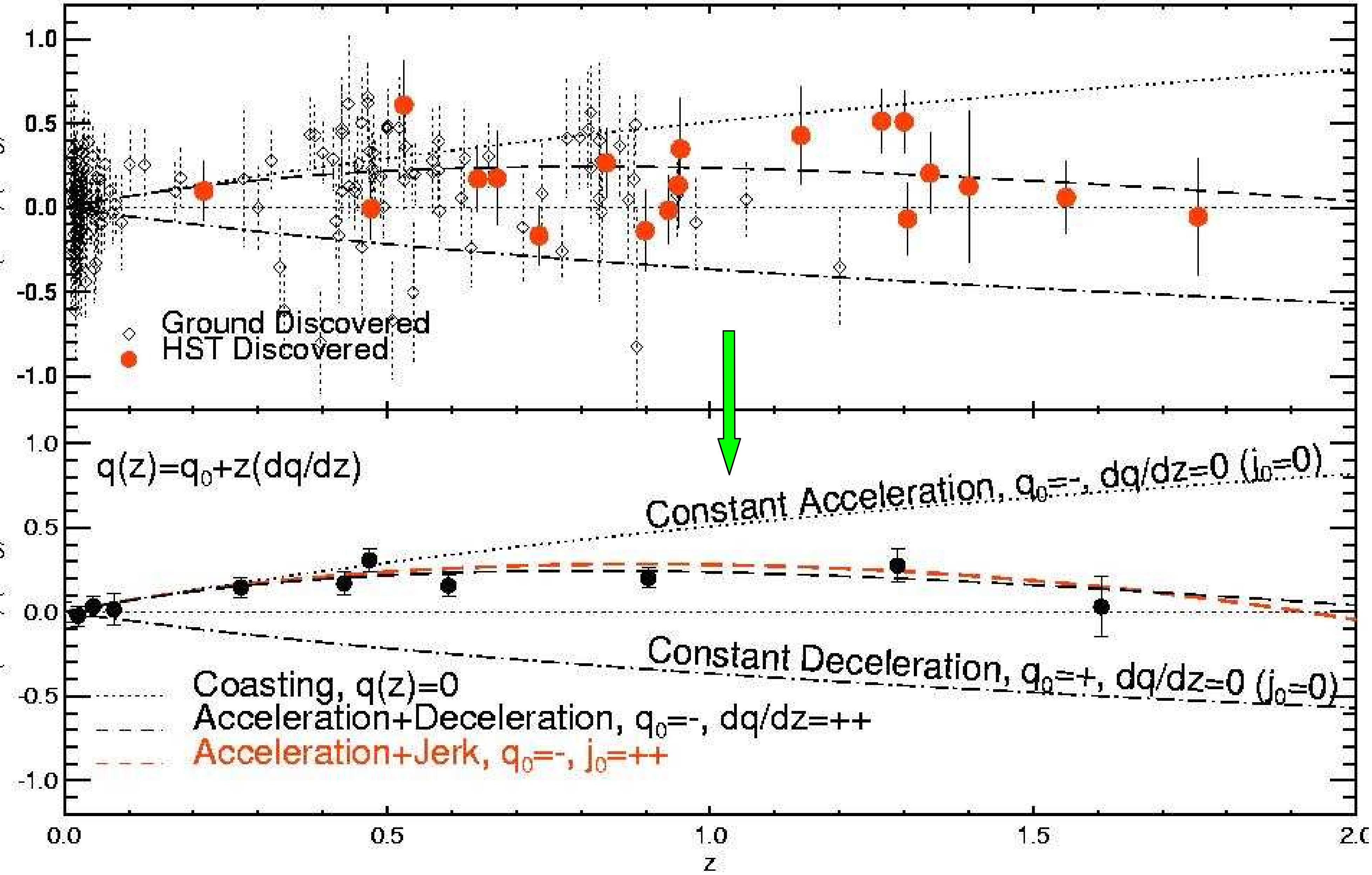


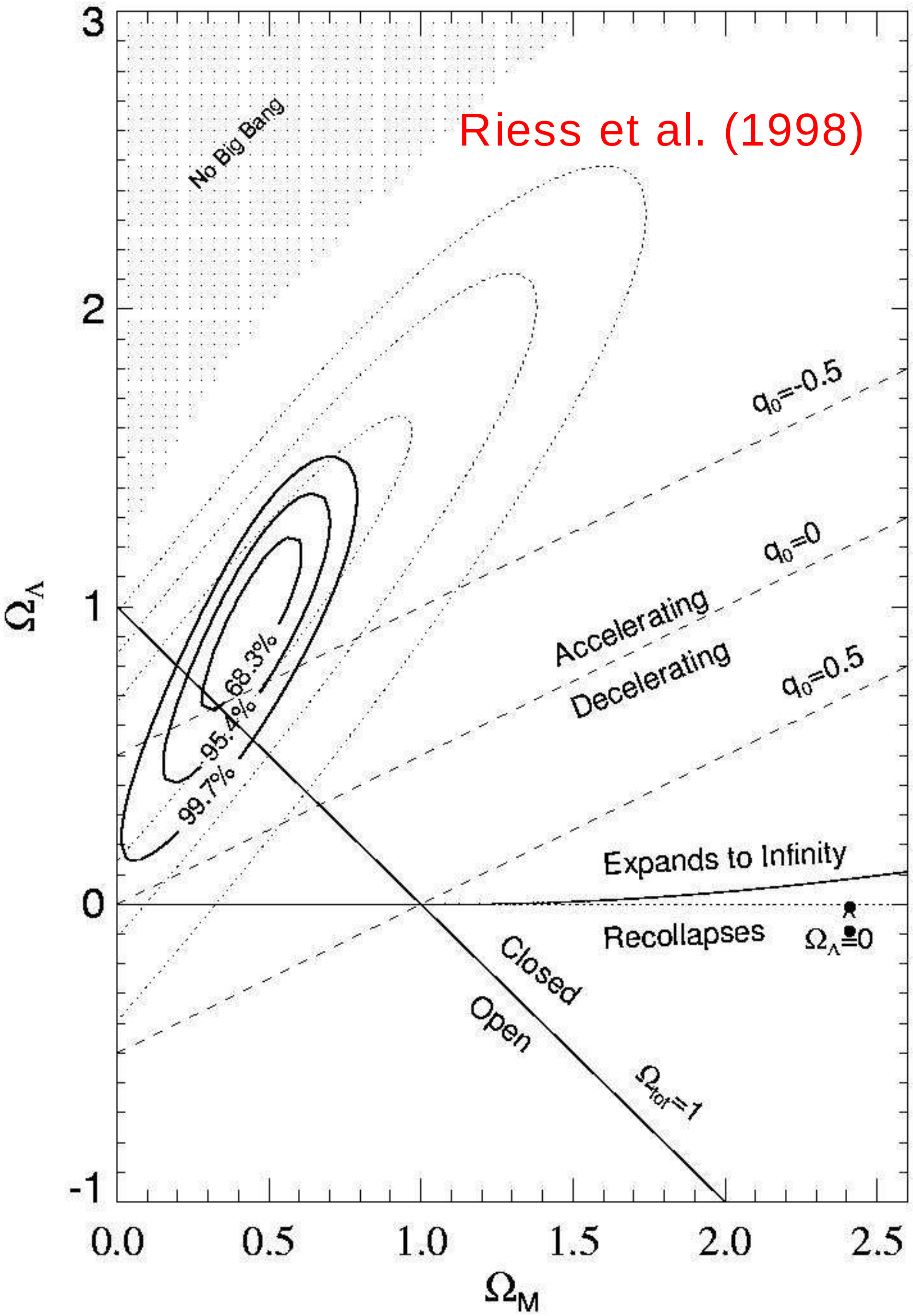


Supernovae Ia Lightcurves & Stretch-factor

SNIa as Standard Candles

Riess et al. (2004)



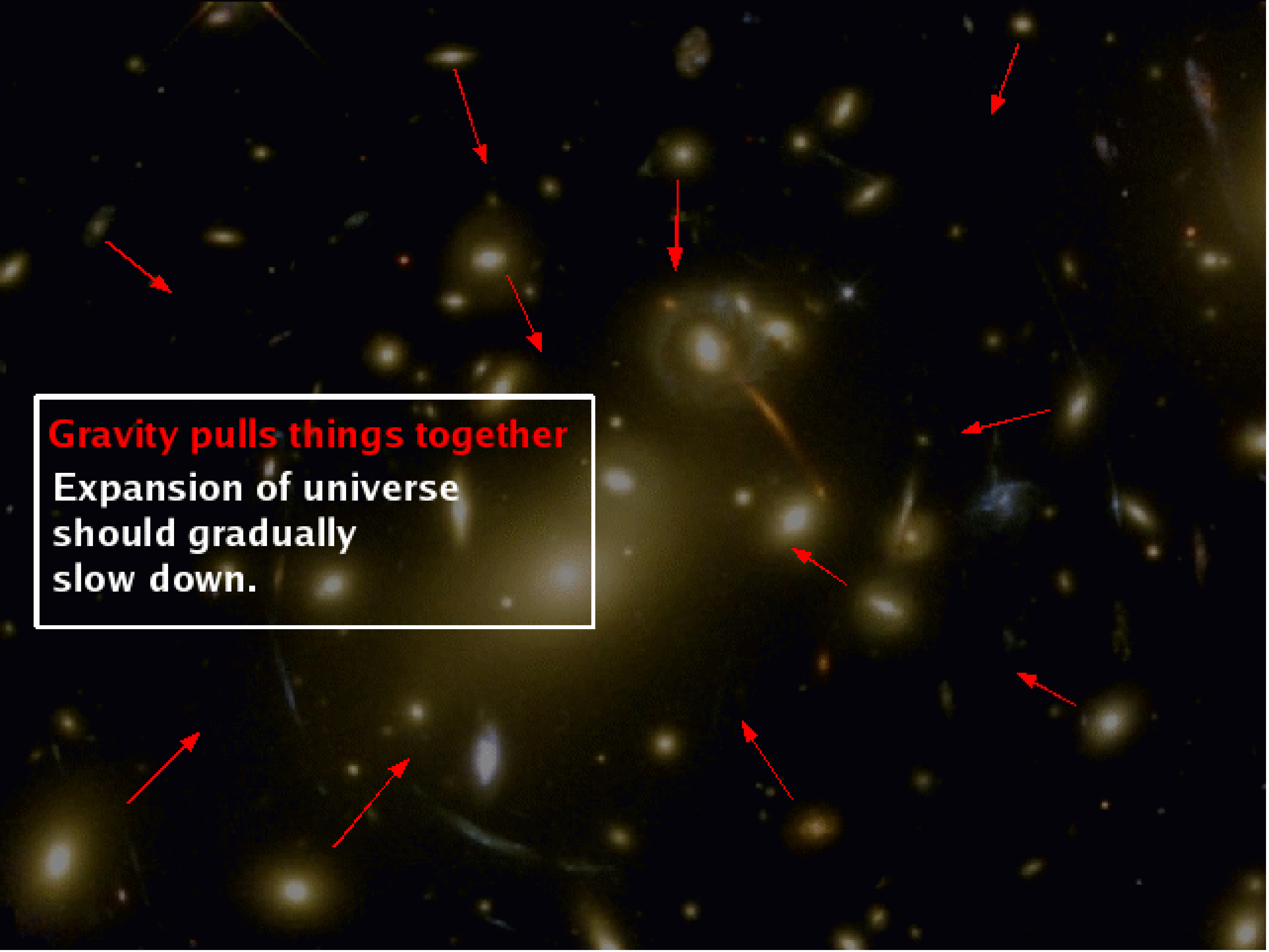


Riess et al. (2004) 129+16 SNIa

Flat Universe

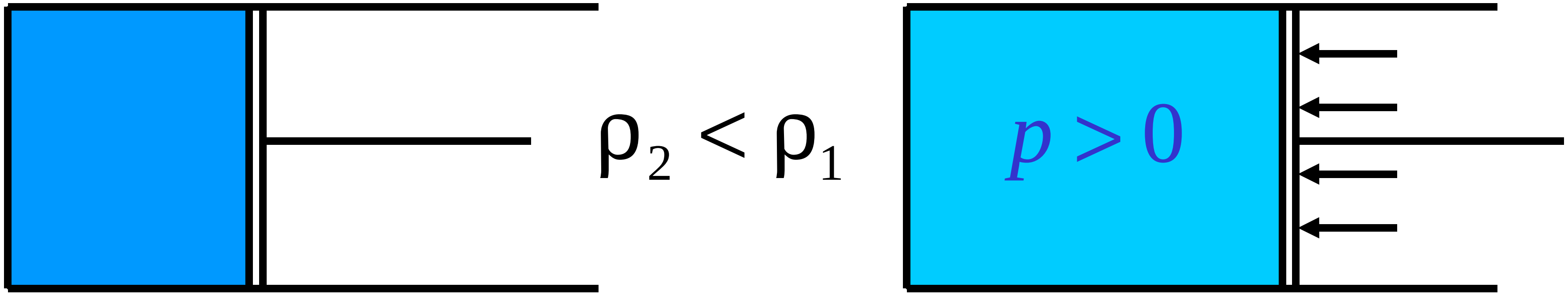
$$\Omega_M = 0.29 \pm 0.05$$

$$\Omega_\Lambda = 0.71 \pm 0.05$$

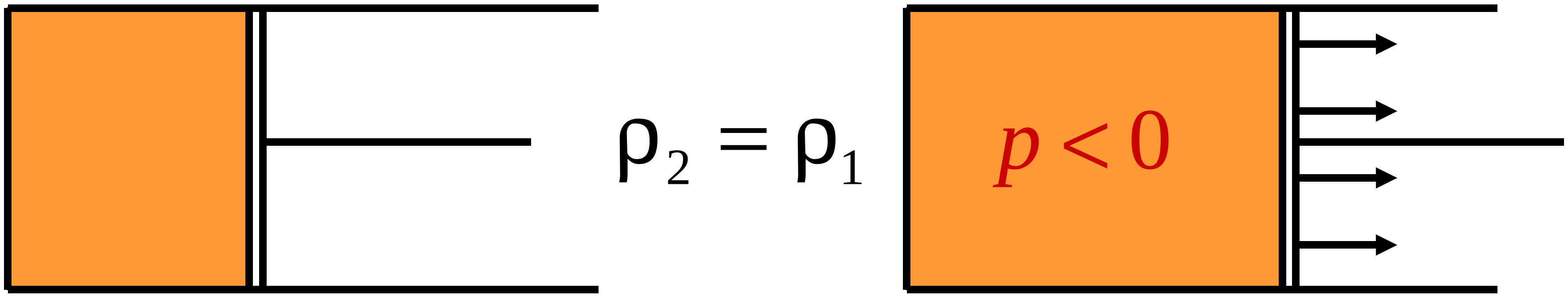

Gravity pulls things together
Expansion of universe
should gradually
slow down.


Something is pushing the galaxies apart
DARK ENERGY

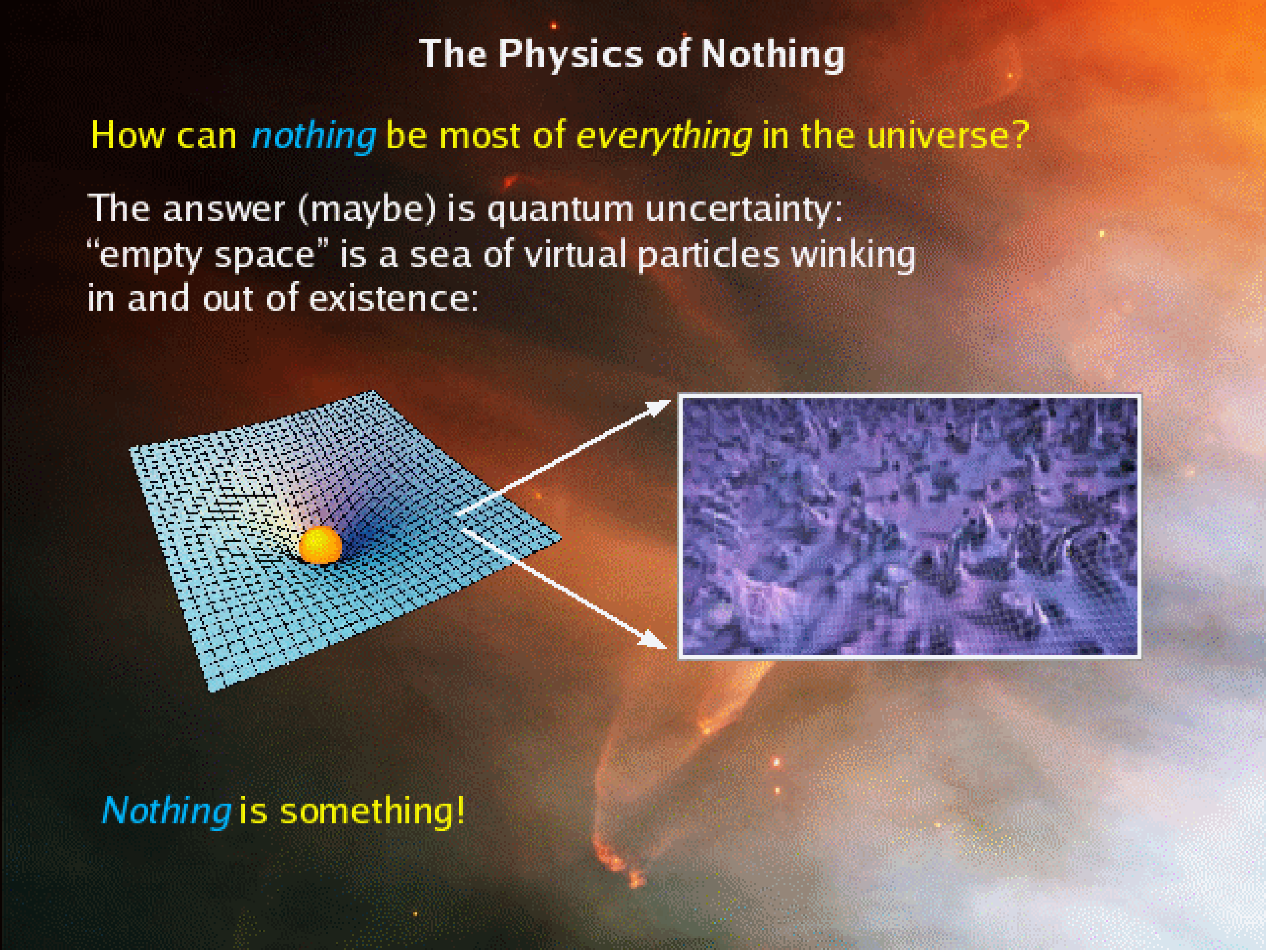
Normal Matter



$$d(\rho V) + p\,dV = T\,dS = 0$$

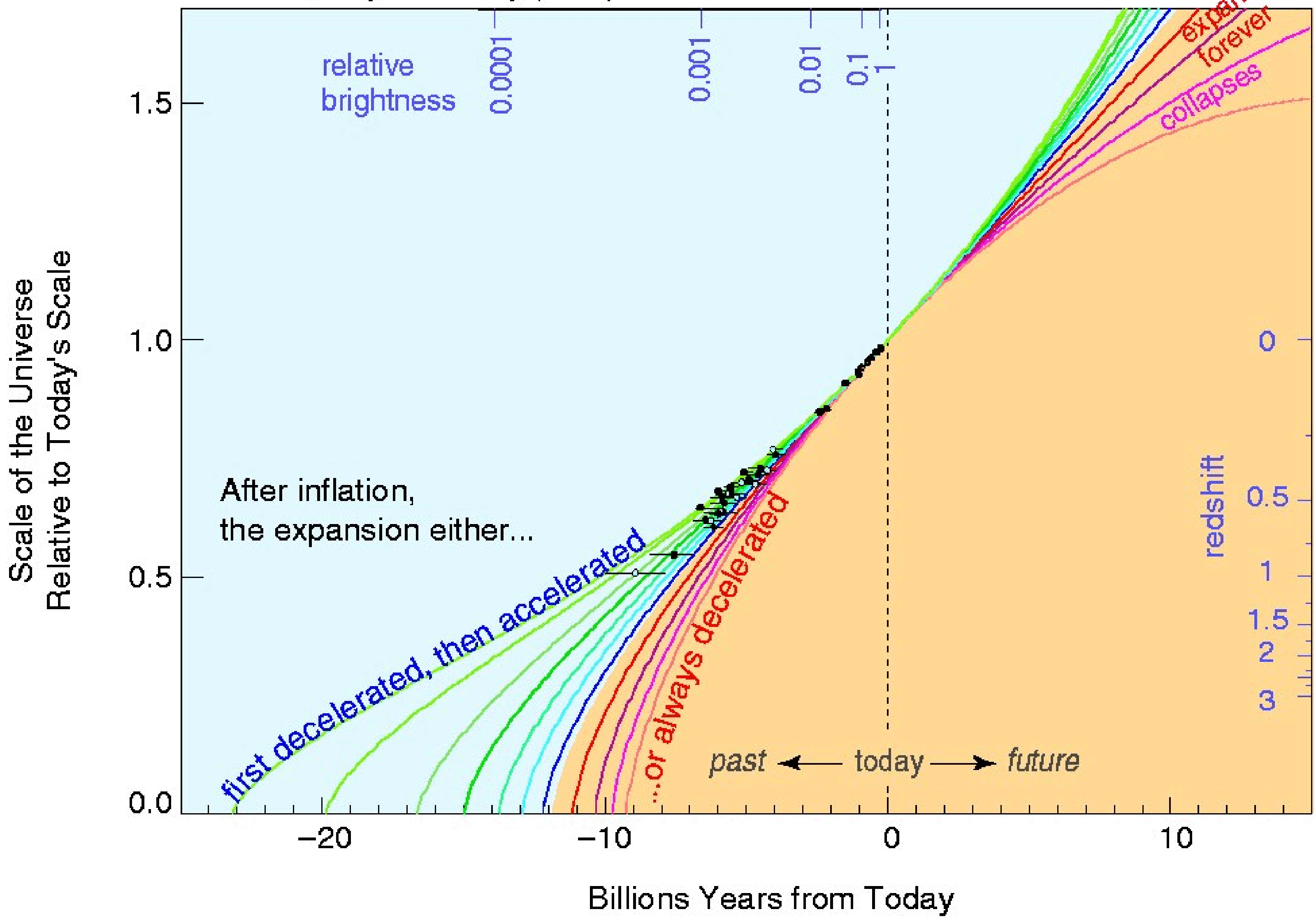


Vacuum Energy


The Physics of Nothing
How can *nothing* be most of *everything* in the universe?
The answer (maybe) is quantum uncertainty:
"empty space" is a sea of virtual particles winking
in and out of existence:
Nothing is something!

Expansion History of the Universe

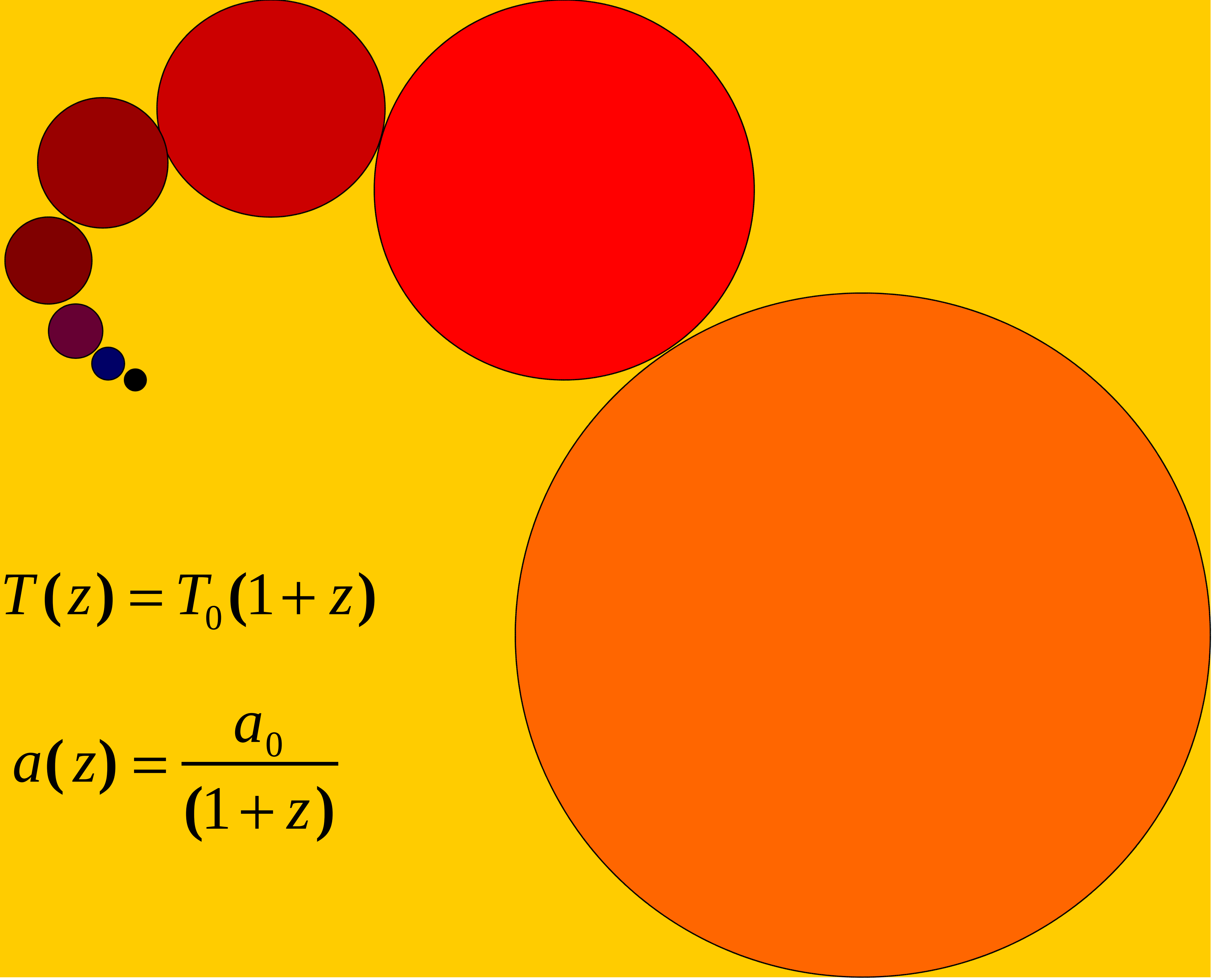
Perlmutter, Physics Today (2003)



The Aging Universe

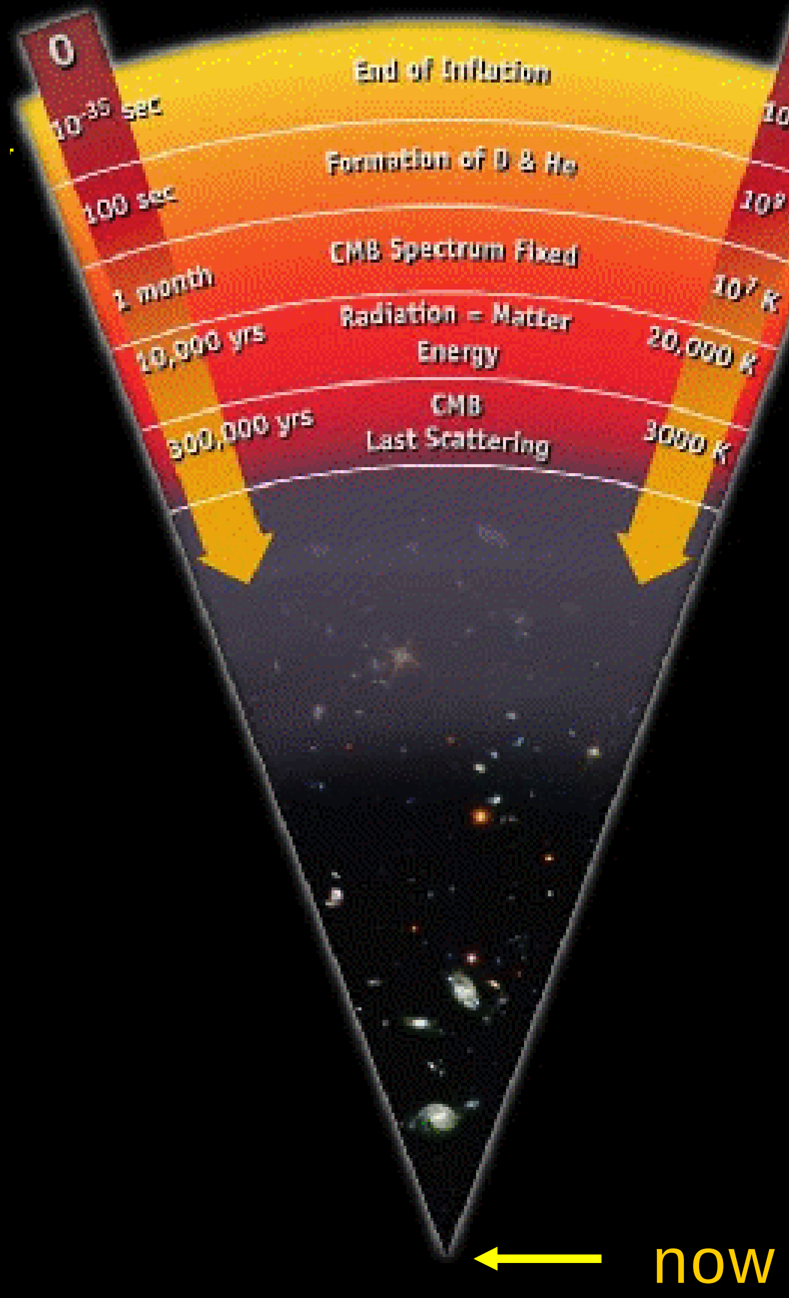
If the universe is expanding, necessarily it must have been denser and hotter in the past

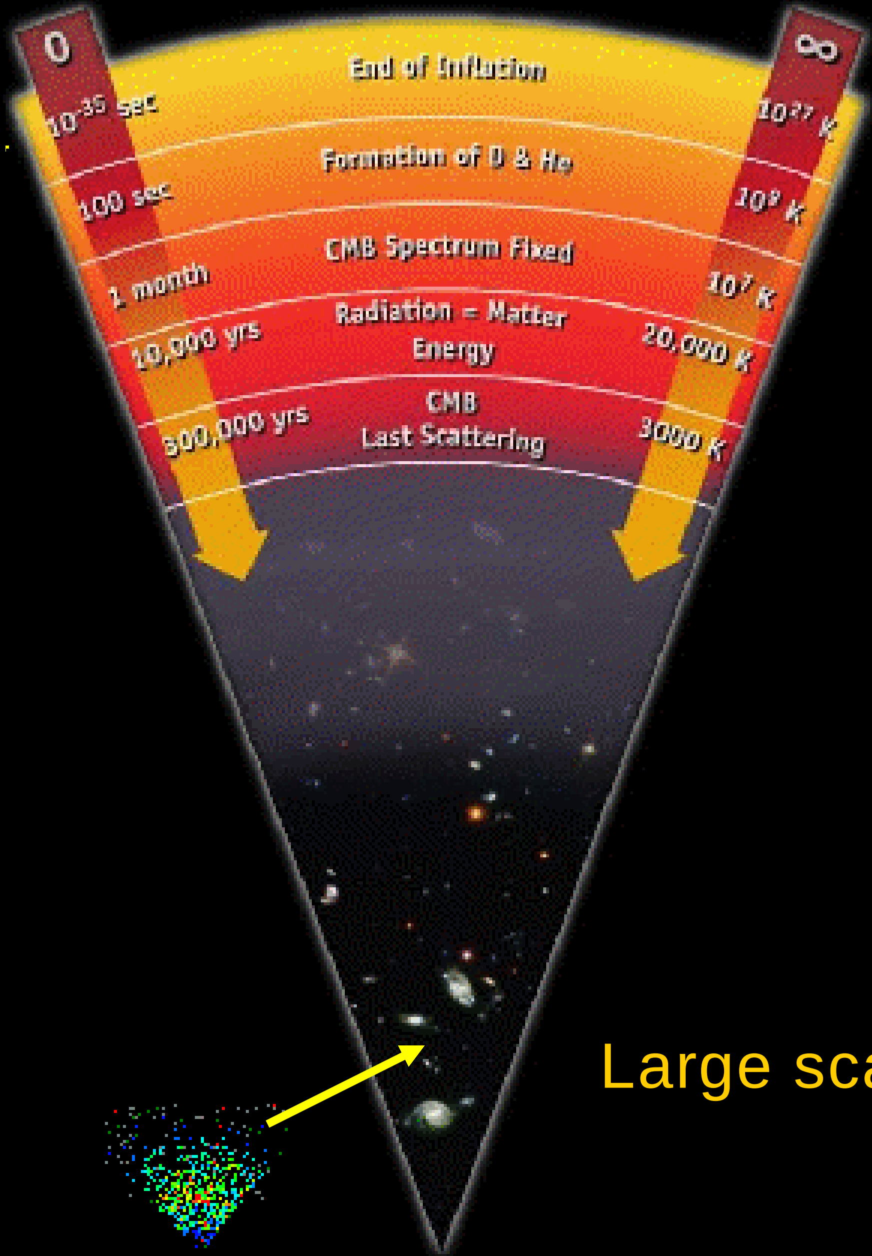
Tracing the past history of the universe, we reach the realm of high energy physics and particle accelerators



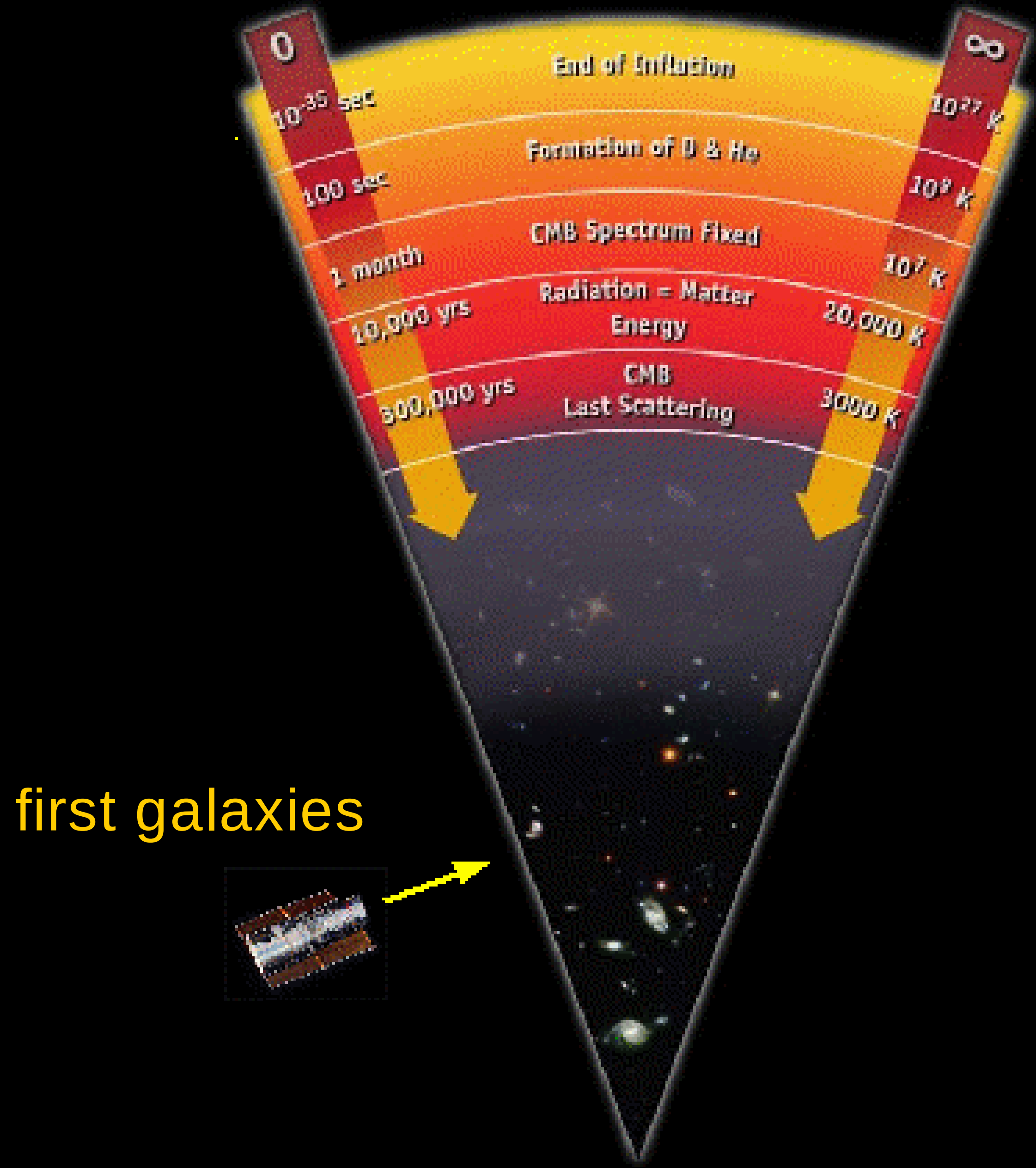
$$T(z) = T_0(1+z)$$

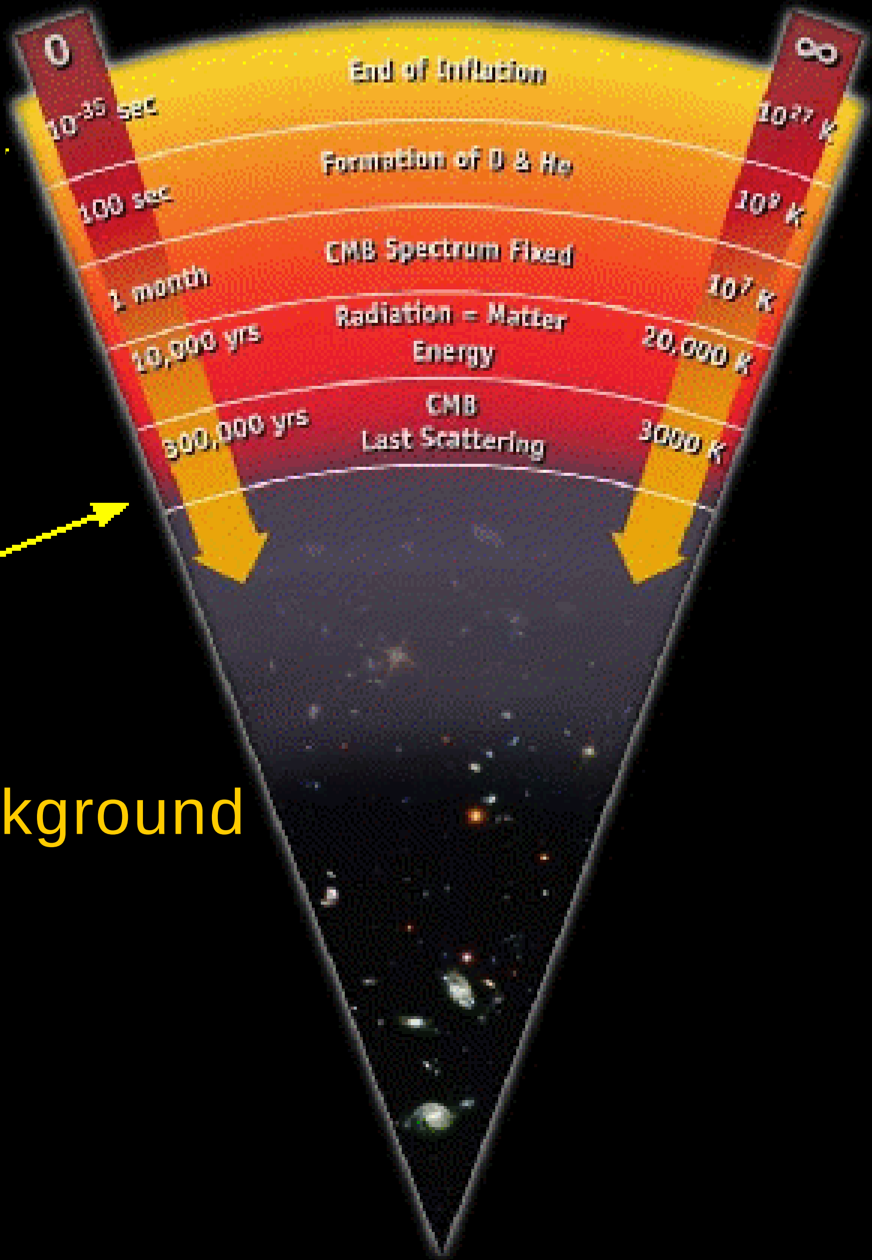
$$a(z) = \frac{a_0}{(1+z)}$$


0
∞
End of Inflation
10^{-35} sec
10^{27} K
Formation of D & He
100 sec
10^{9} K
CMB Spectrum Fixed
1 month
10^{7} K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
300,000 yrs
3000 K
now



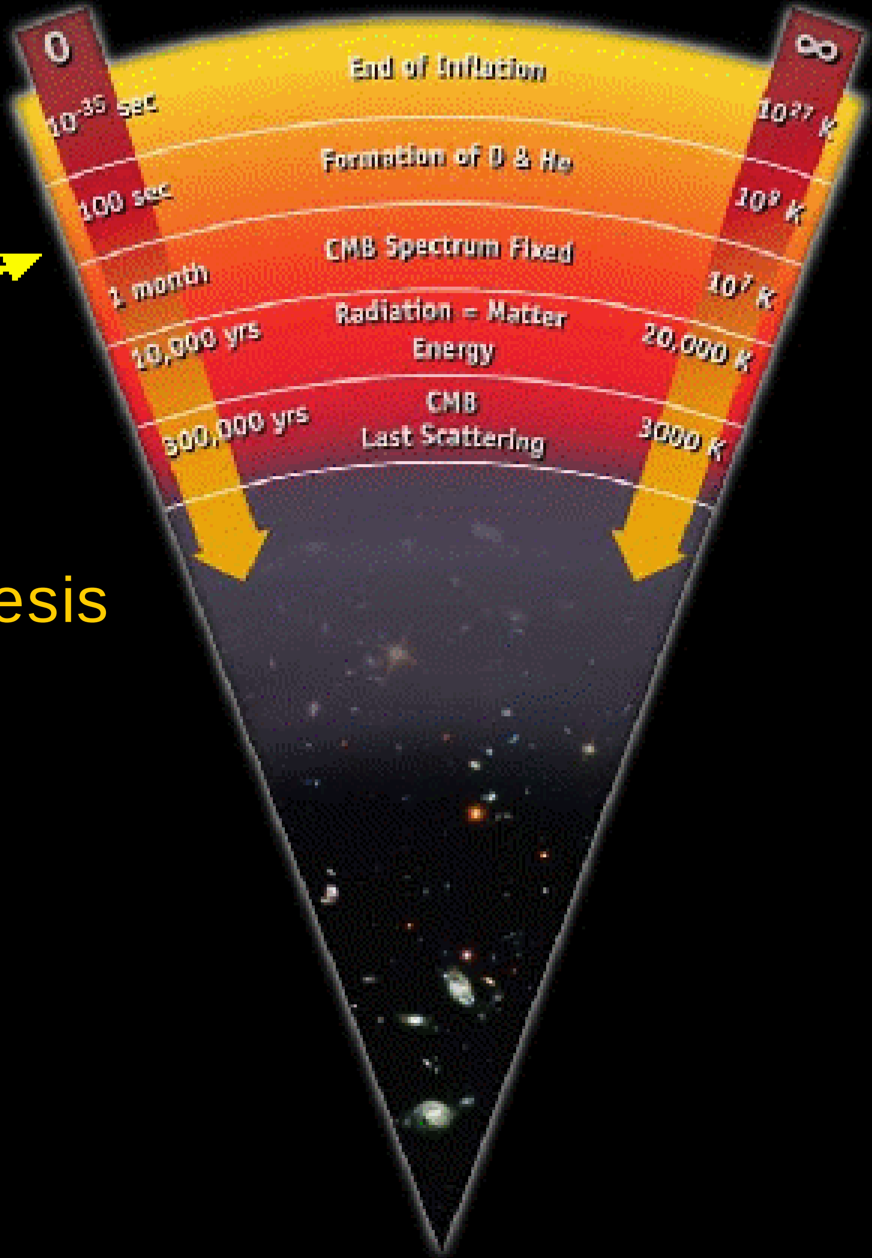
Large scale structure

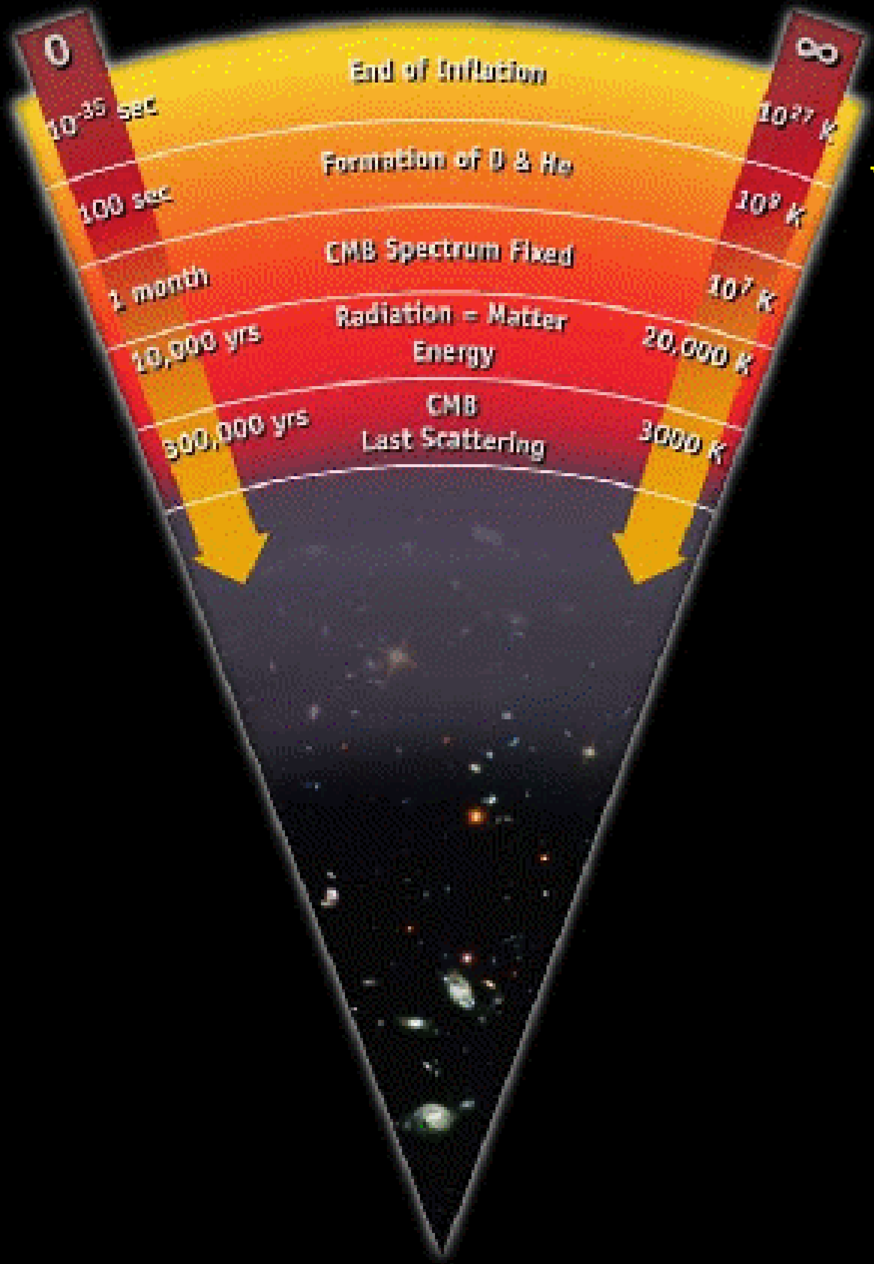

0
∞
End of Inflation
10^{-35} sec
10^{27} K
Formation of D & He
100 sec
10^{9} K
CMB Spectrum Fixed
1 month
10^{7} K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
300,000 yrs
3000 K
first galaxies



microwave background

primordial
nucleosynthesis

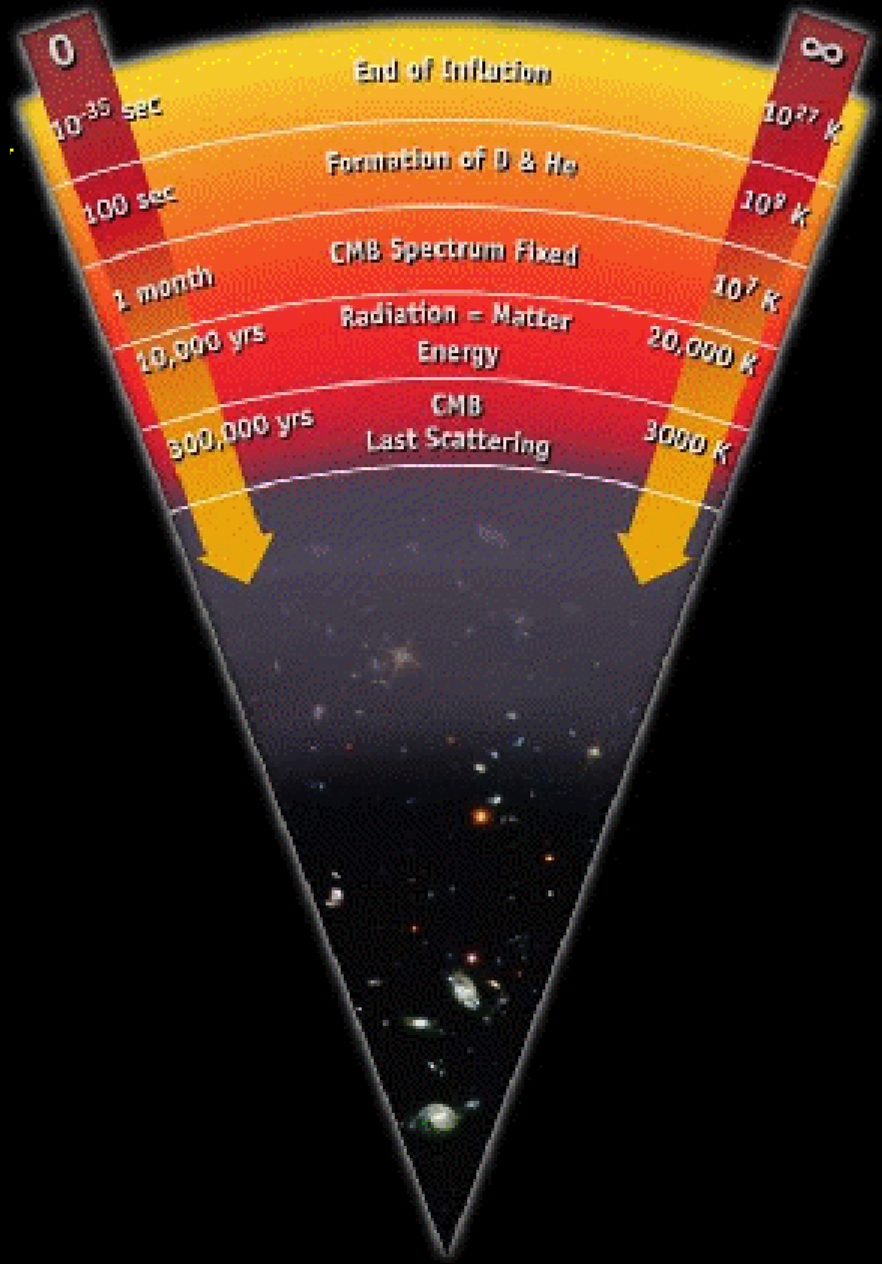


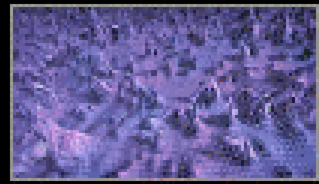


baryogenesis

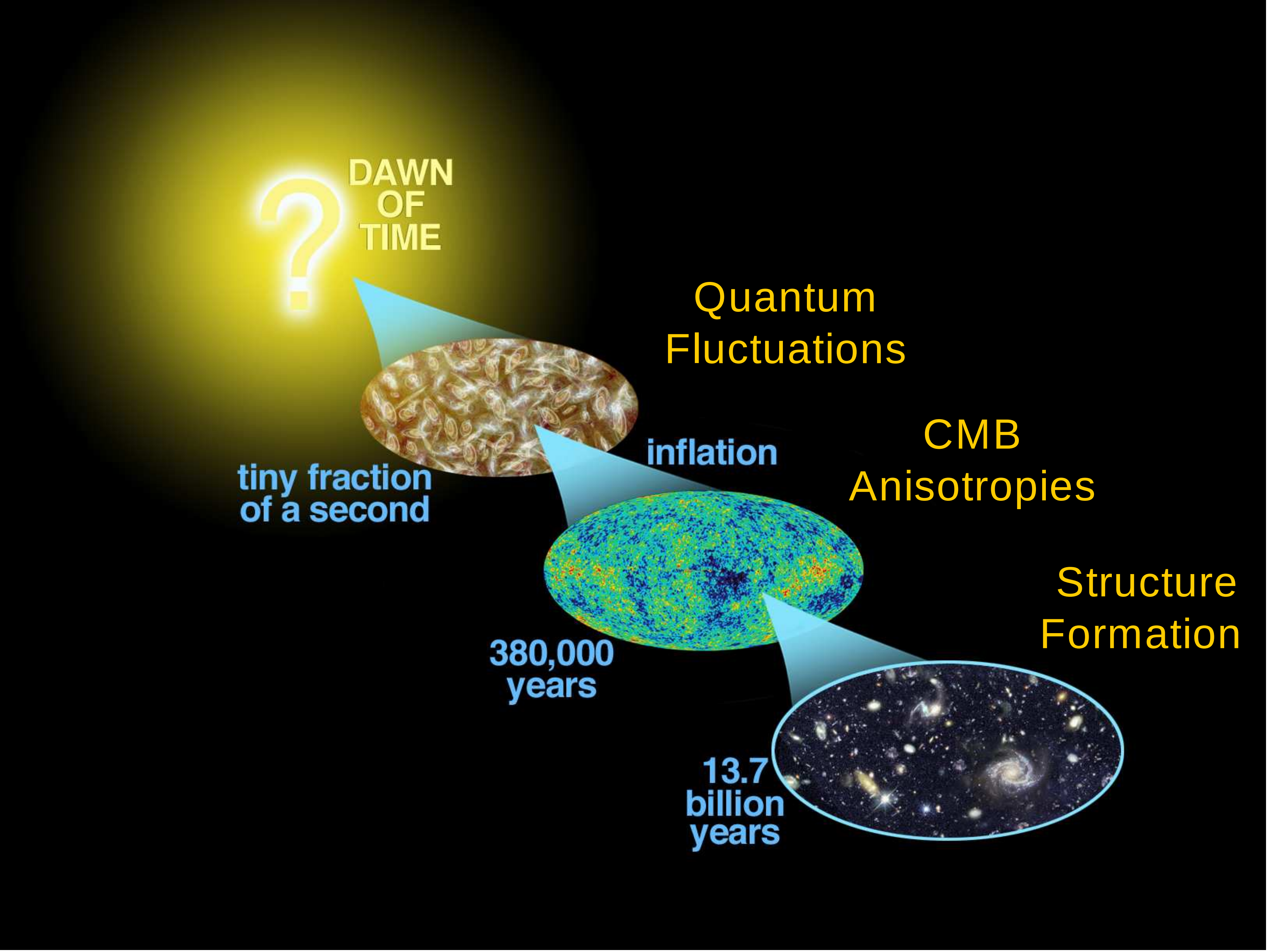

Fermilab's
Primordial
SOUP


CAUTION:
Contents are extremely dense and are under enormous pressure.
INGREDIENTS
Quarks....58%
Force Carriers....29%
Electron-like Particles....9%
Neutrinos....5%
Higgs Bosons....1%
INSPECTED BY U.S. Department of Energy


0
∞
End of Inflation
10^{-35} sec
10^{27} K
Formation of D & He
100 sec
10^{9} K
CMB Spectrum Fixed
1 month
10^{7} K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
300,000 yrs
3000 K



inflation


DAWN
OF
TIME
Quantum
Fluctuations
inflation
tiny fraction
of a second
CMB
Anisotropies
380,000
years
Structure
Formation
13.7
billion
years

Inflationary Paradigm

- Why is the Universe spatially flat?

- Why is the Universe homogeneous on large scales?

- What is the origin of all matter and radiation?

- What is the origin of the fluctuations that gave rise to galaxies and other large structures?

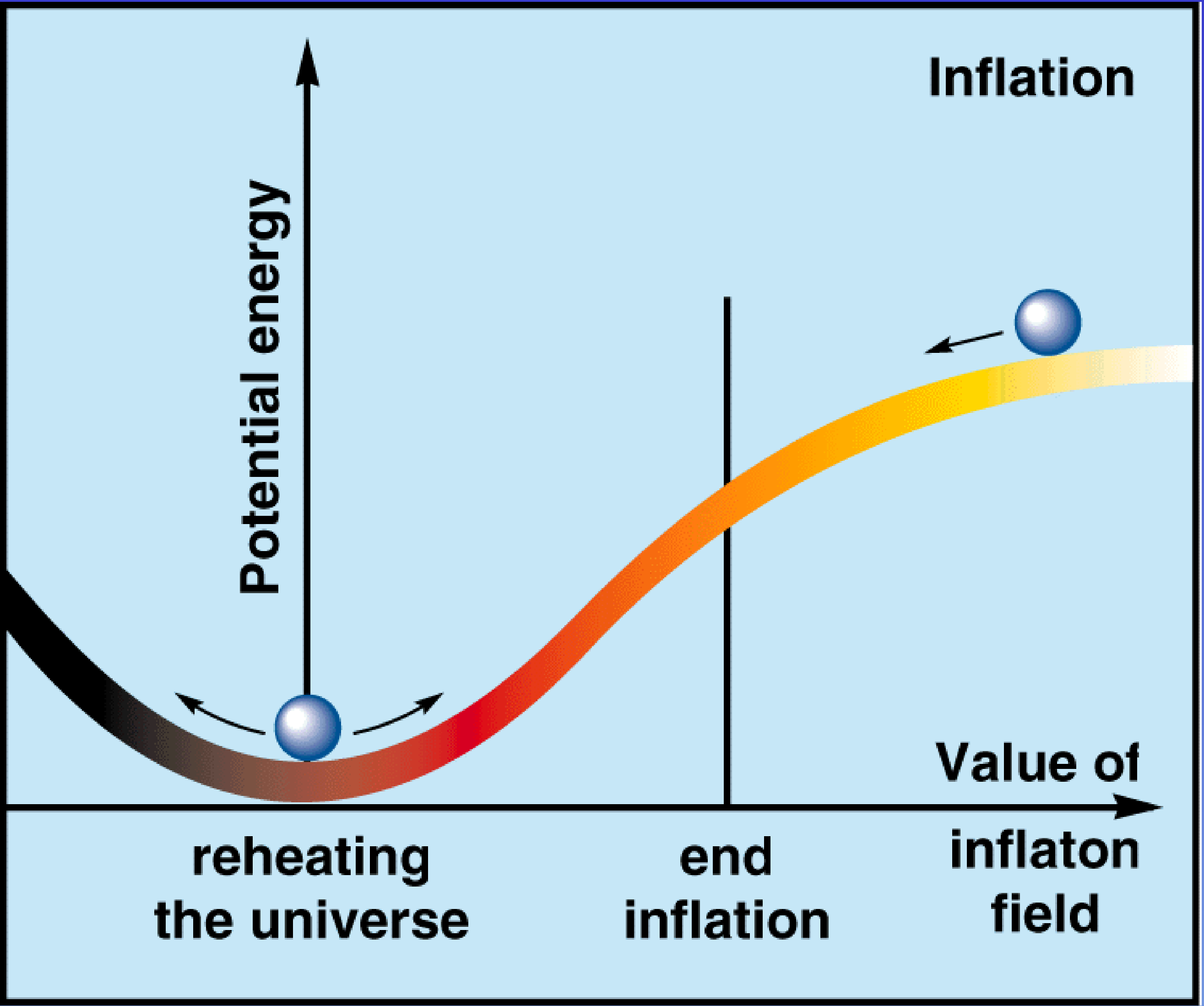
Inflation

The universe itself could be a product of quantum uncertainty.

Inflation: a small bubble of quantum vacuum (*i.e.*, *nothing*) expands exponentially and becomes the entire universe.

Alan Guth

Andrei Linde

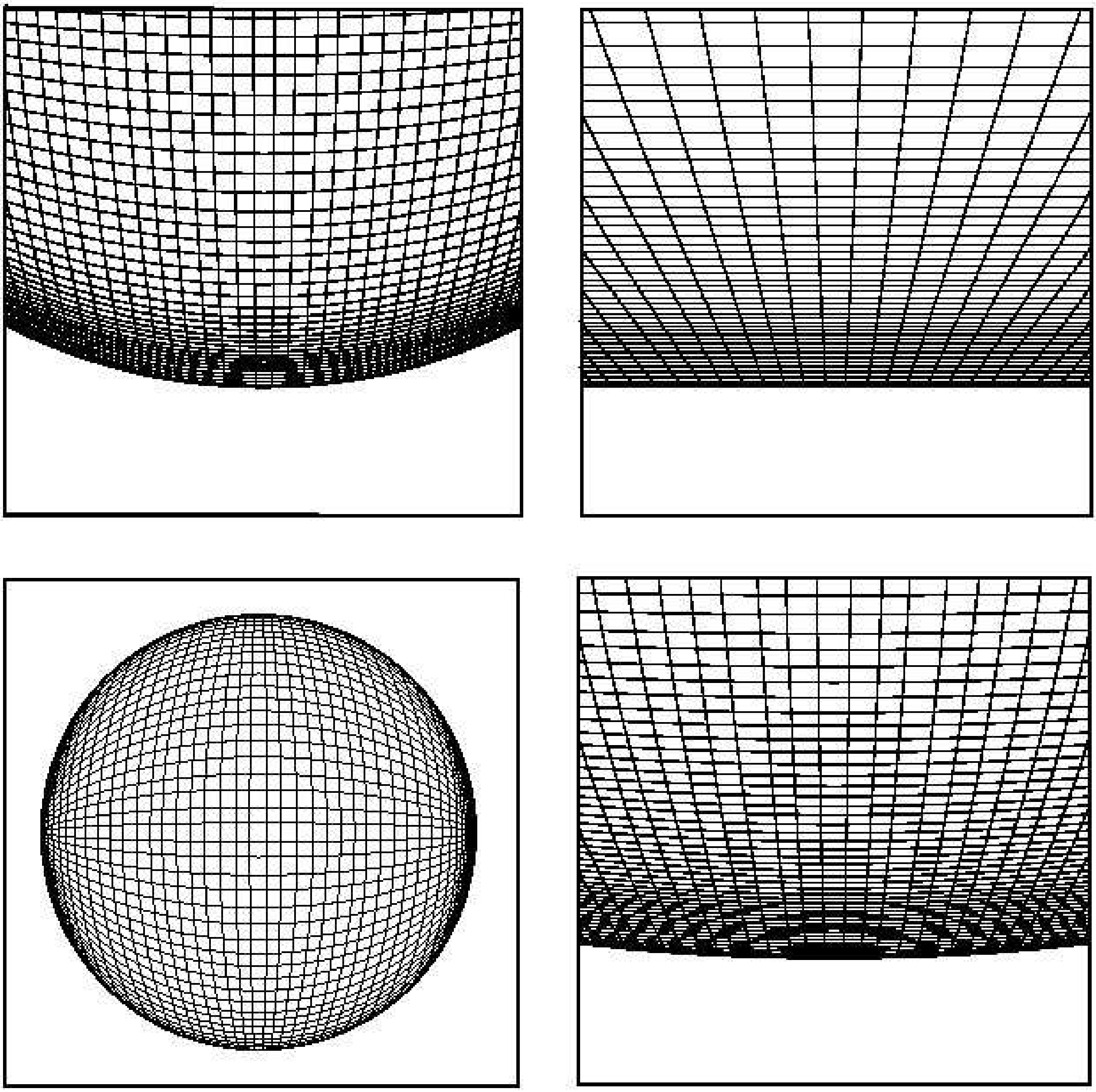


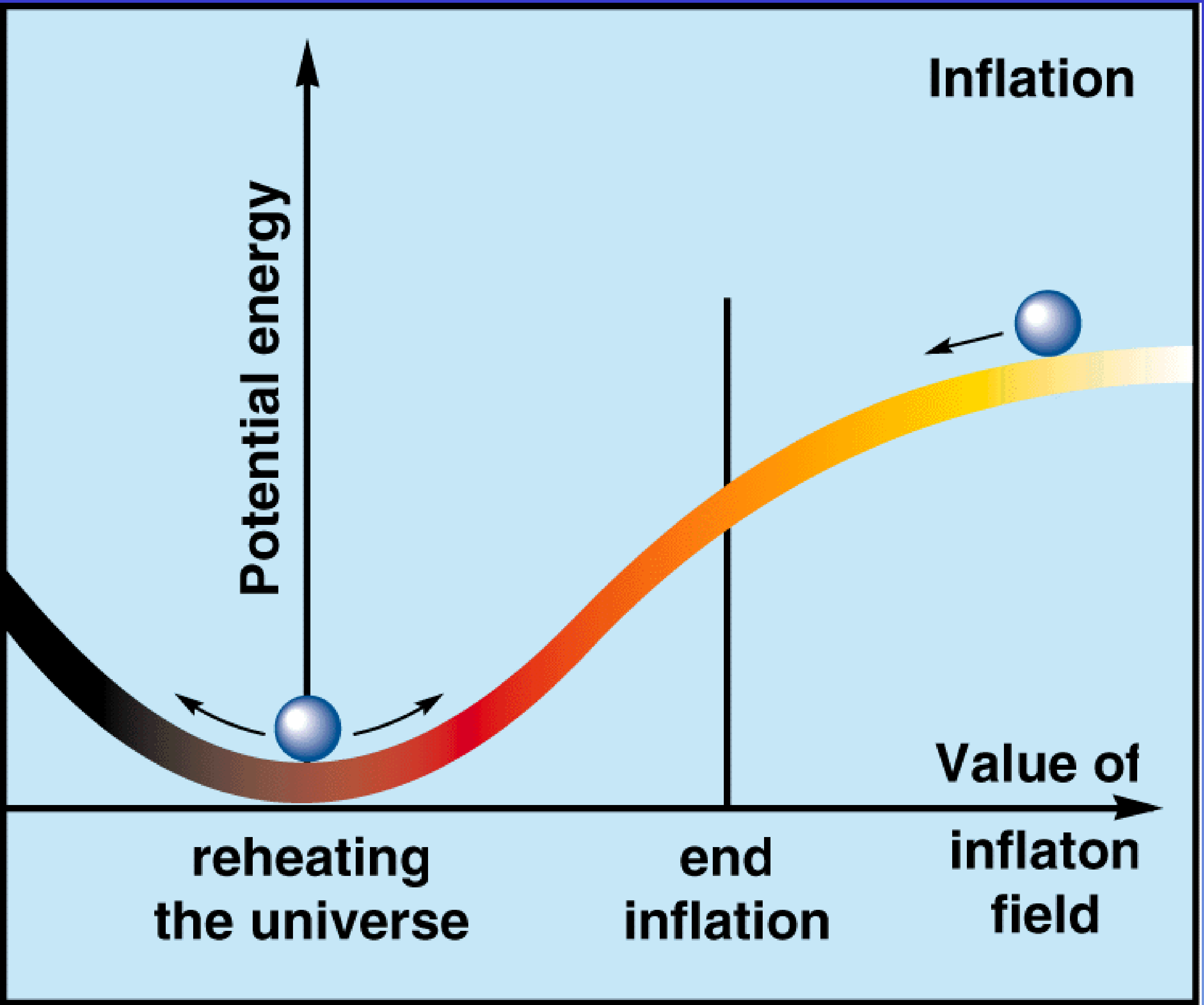
Constant Density

GR

Exponential growth

Flatness



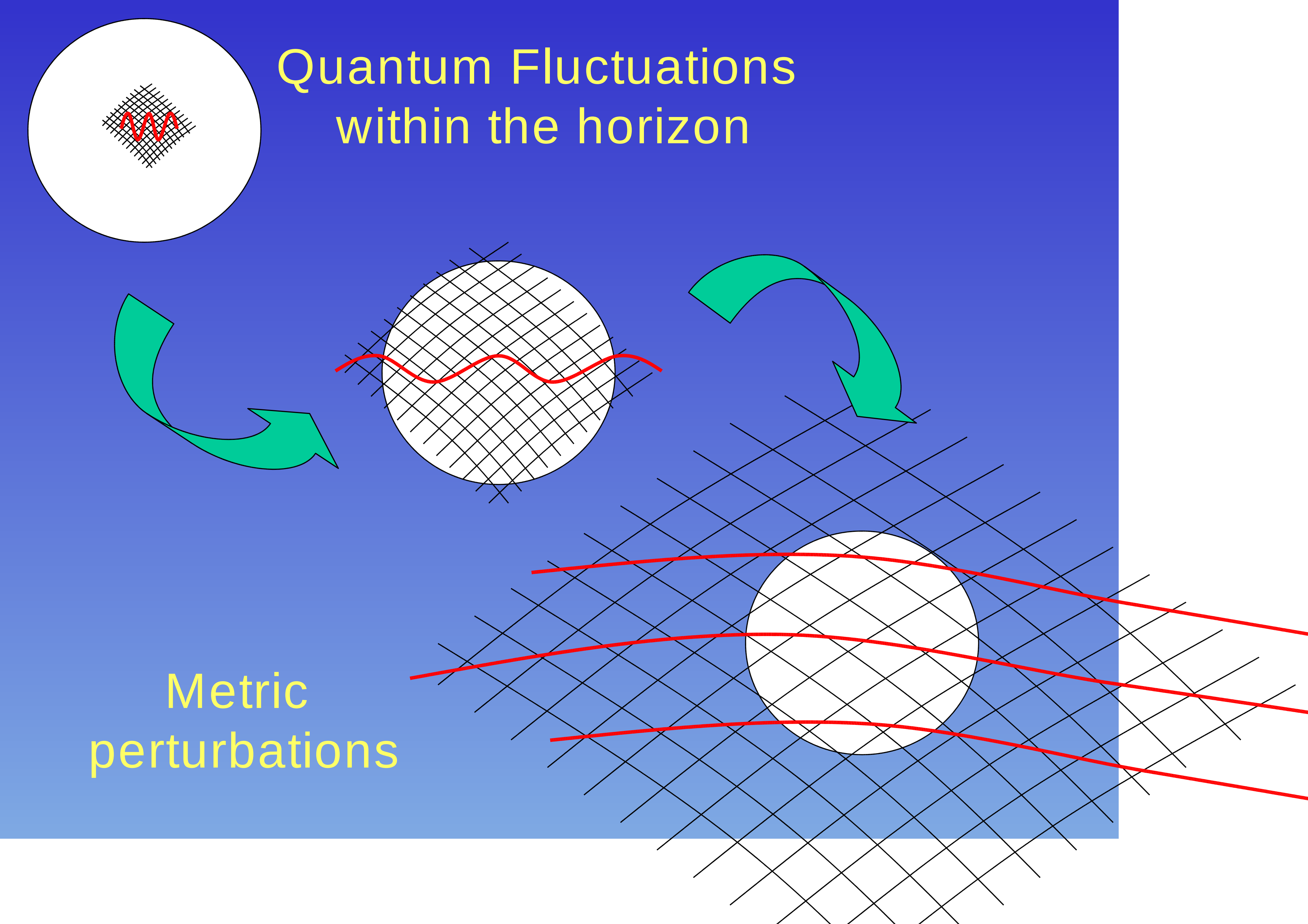


Constant
Density

GR

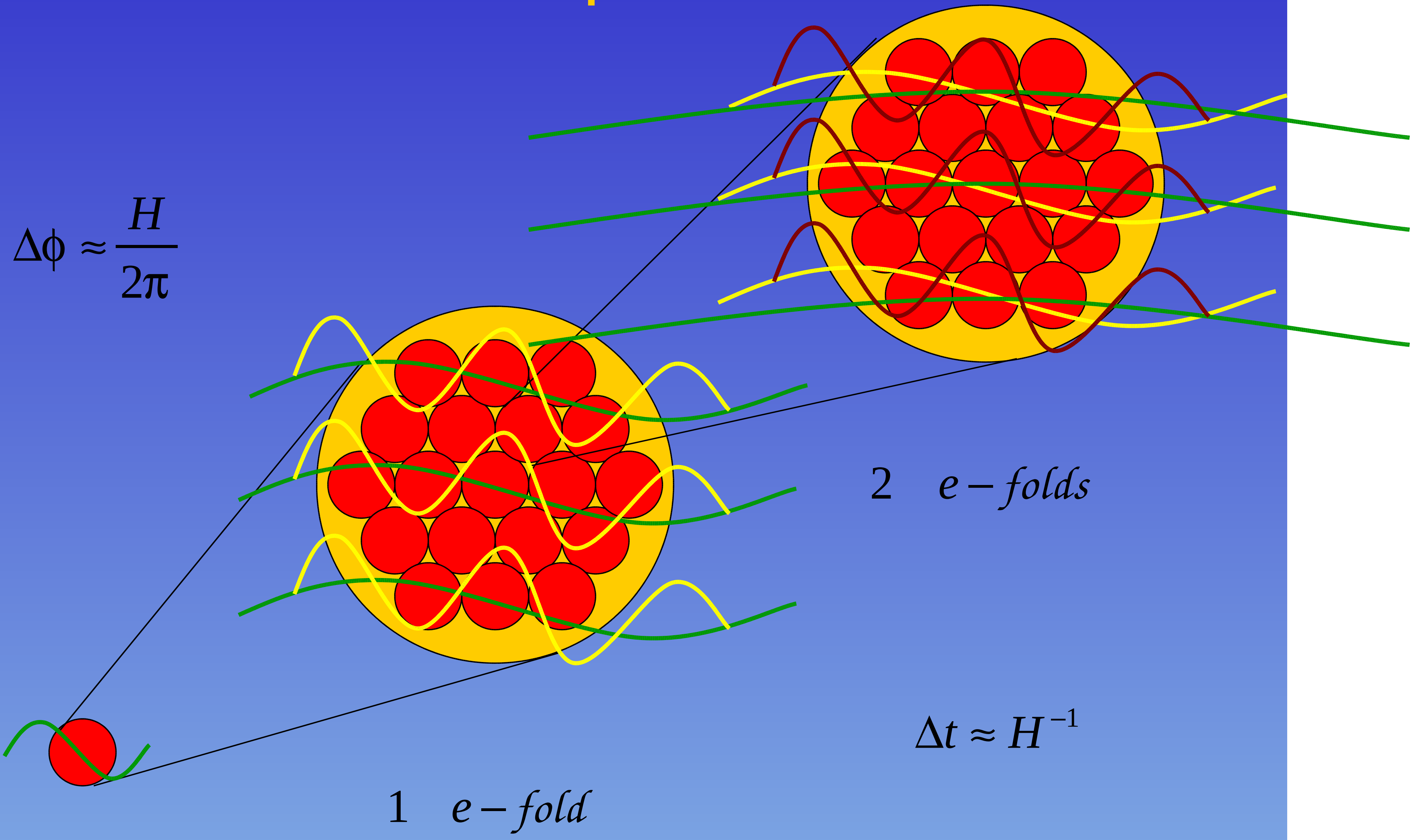
Exponential
growth

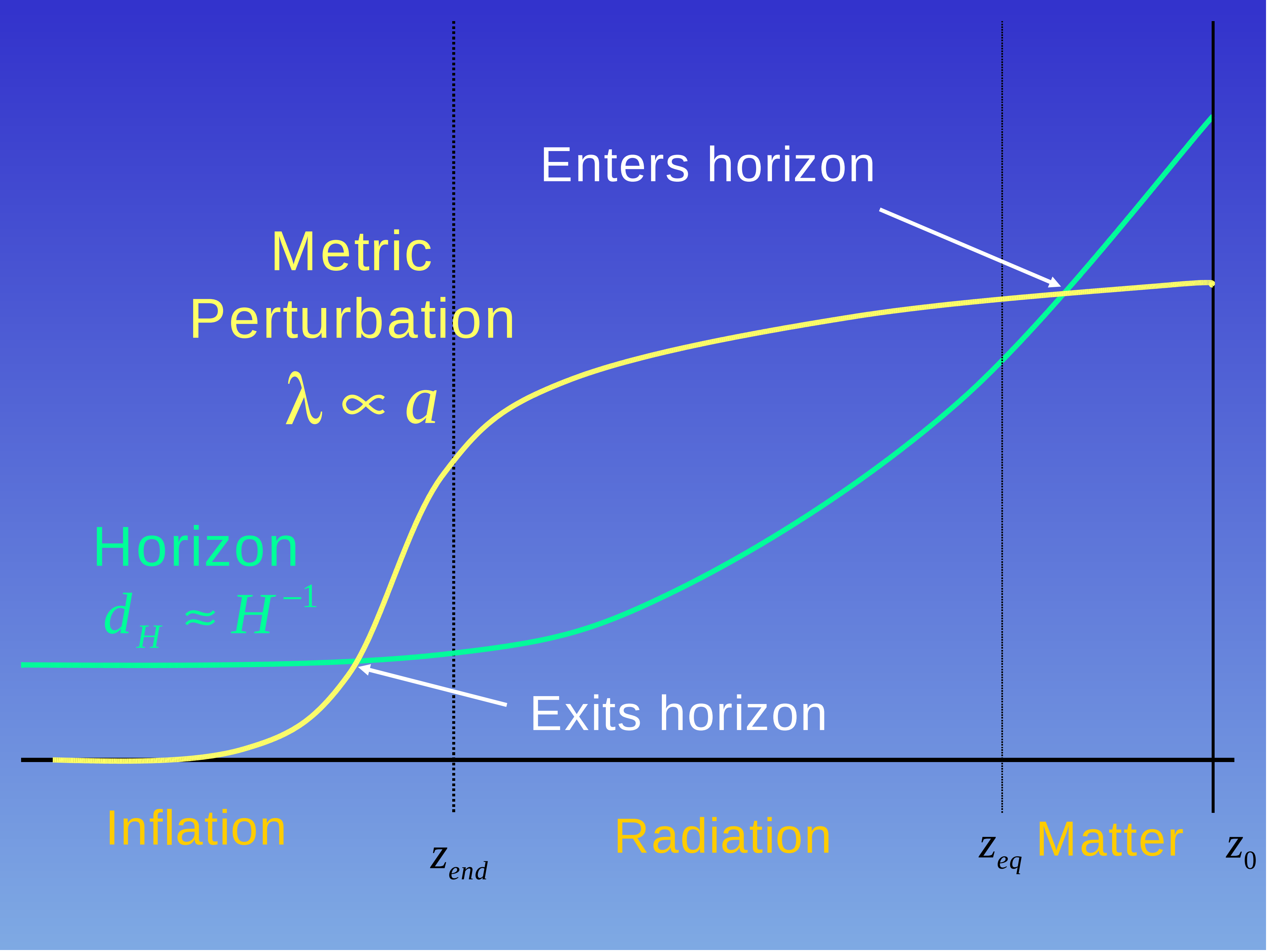
Flatness
+
Homogeneity
+
Reheating


Quantum Fluctuations
within the horizon
Metric
perturbations

Scale Invariant Spectrum

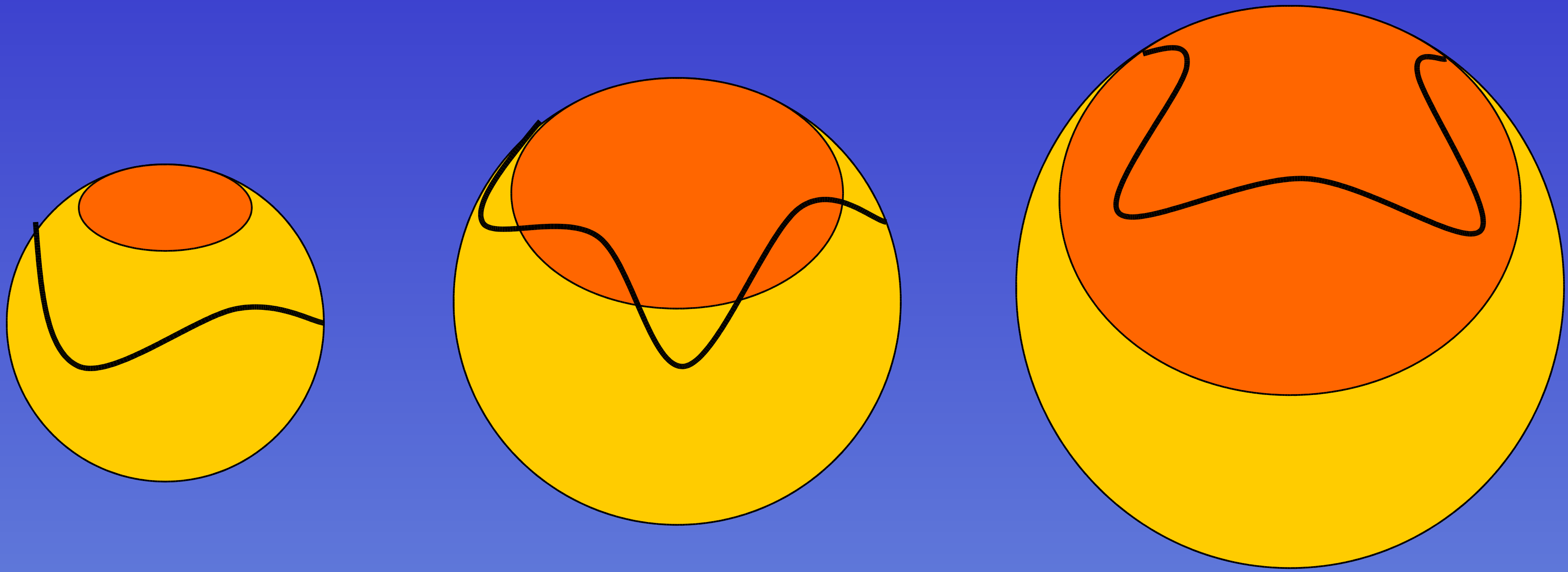
$$\Delta\phi \approx \frac{H}{2\pi}$$





Enters horizon
Metric
Perturbation
$\lambda \propto a$
Horizon
$d_H \approx H^{-1}$
Exits horizon
Inflation
z_{end}
Radiation
z_{eq}
Matter
z_0

After Inflation



$\lambda > d_H$

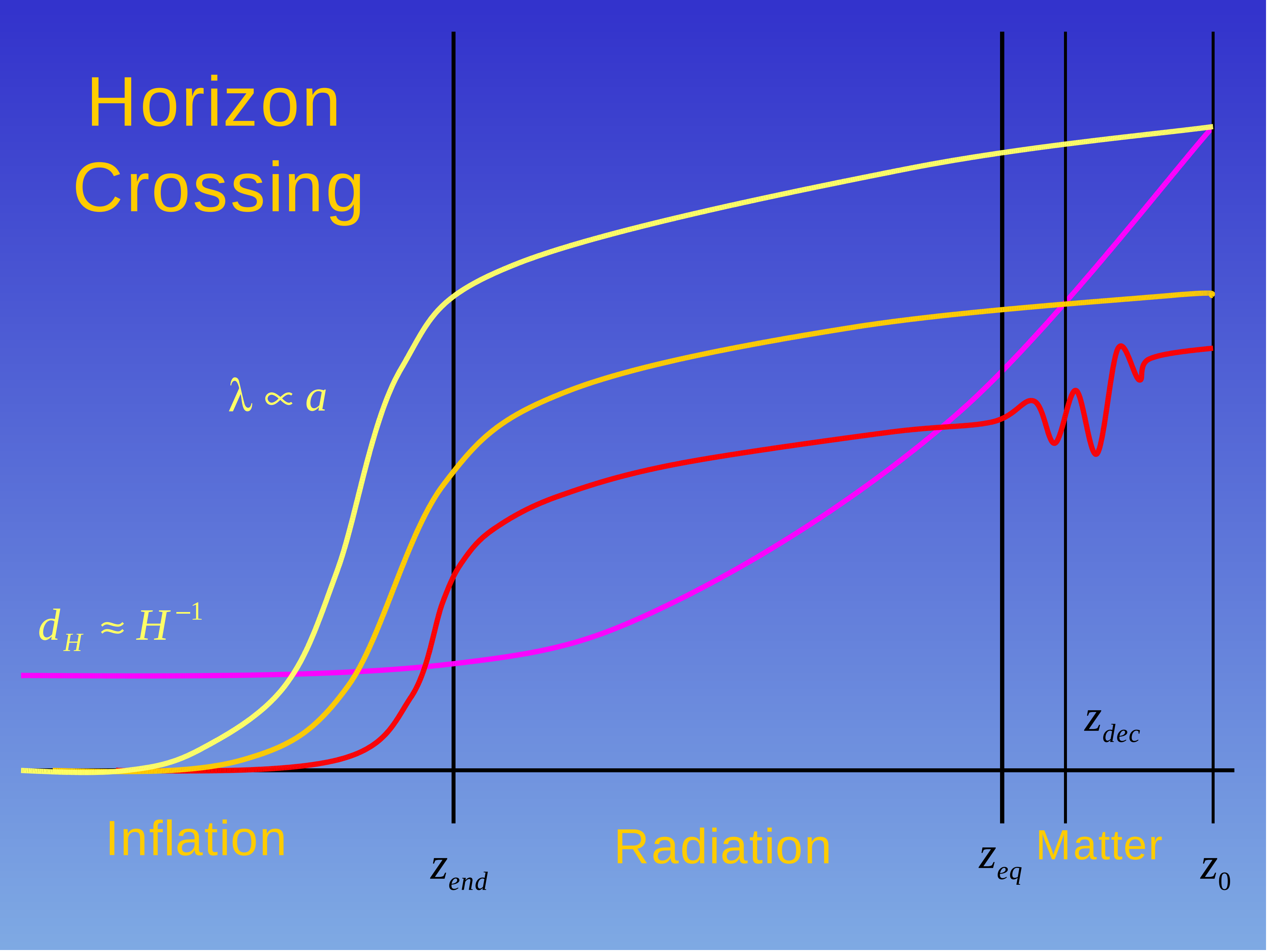
Outside Horizon

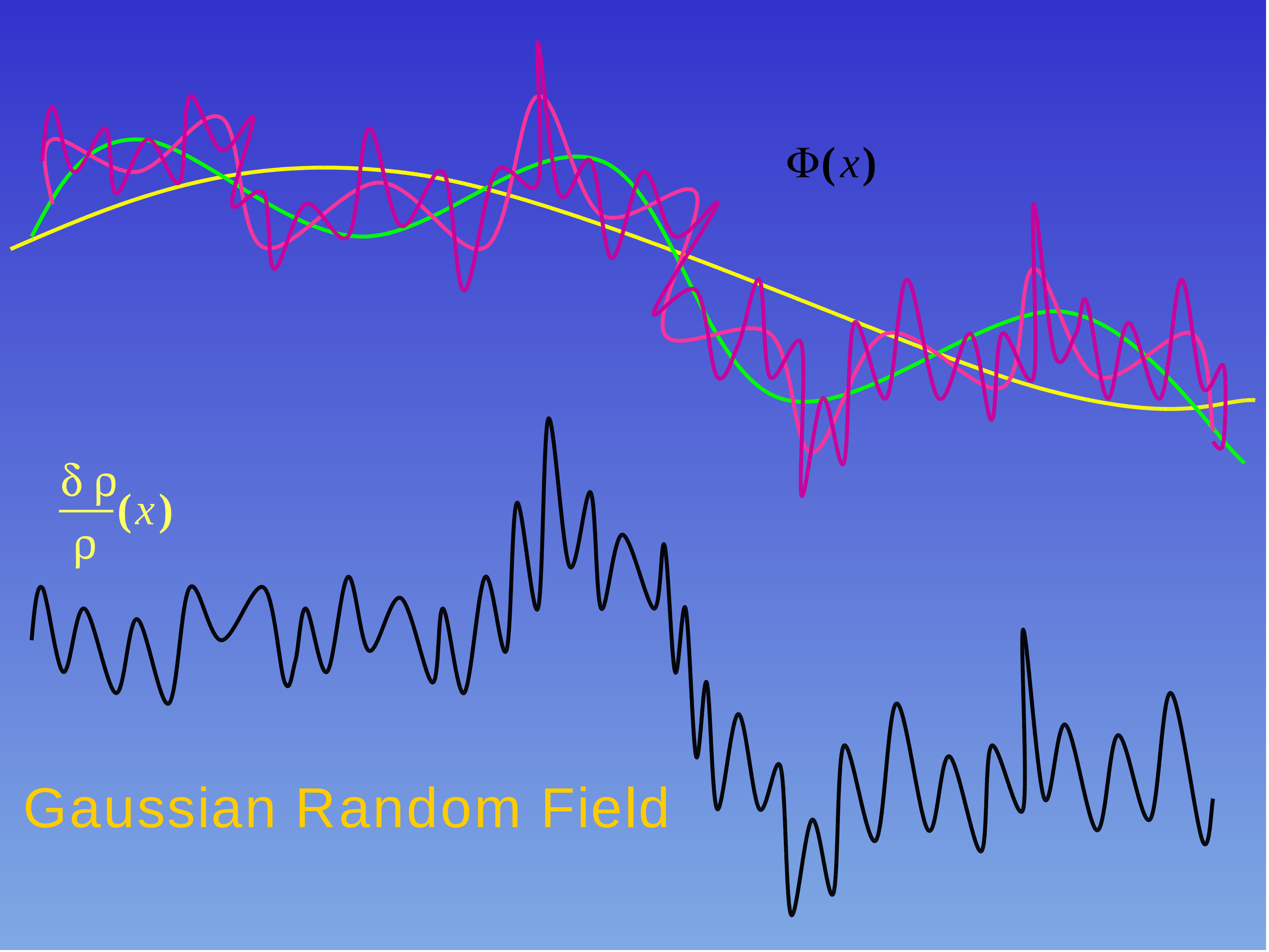
$\lambda \approx d_H$

Enters the Horizon

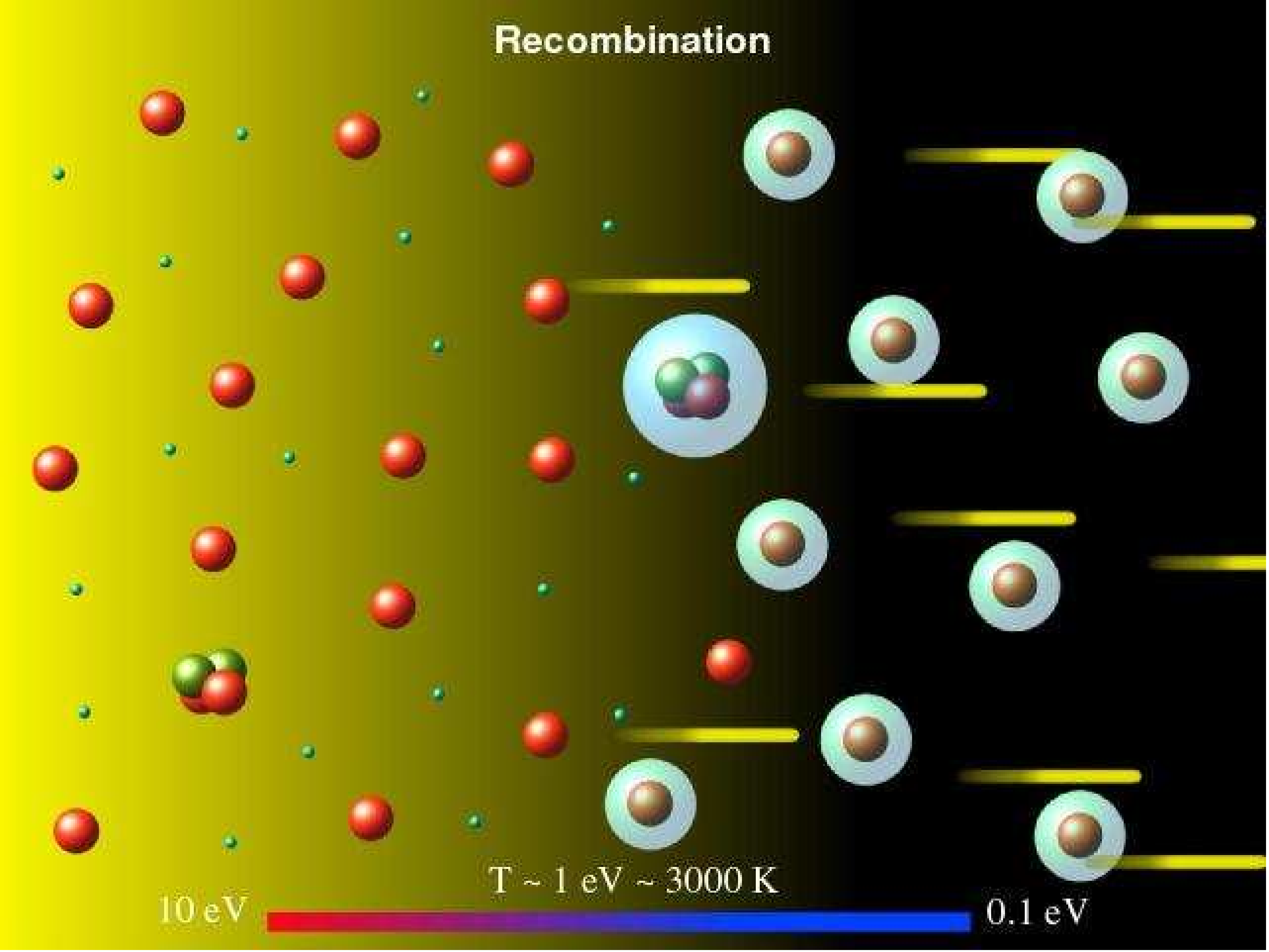
$\lambda < d_H$

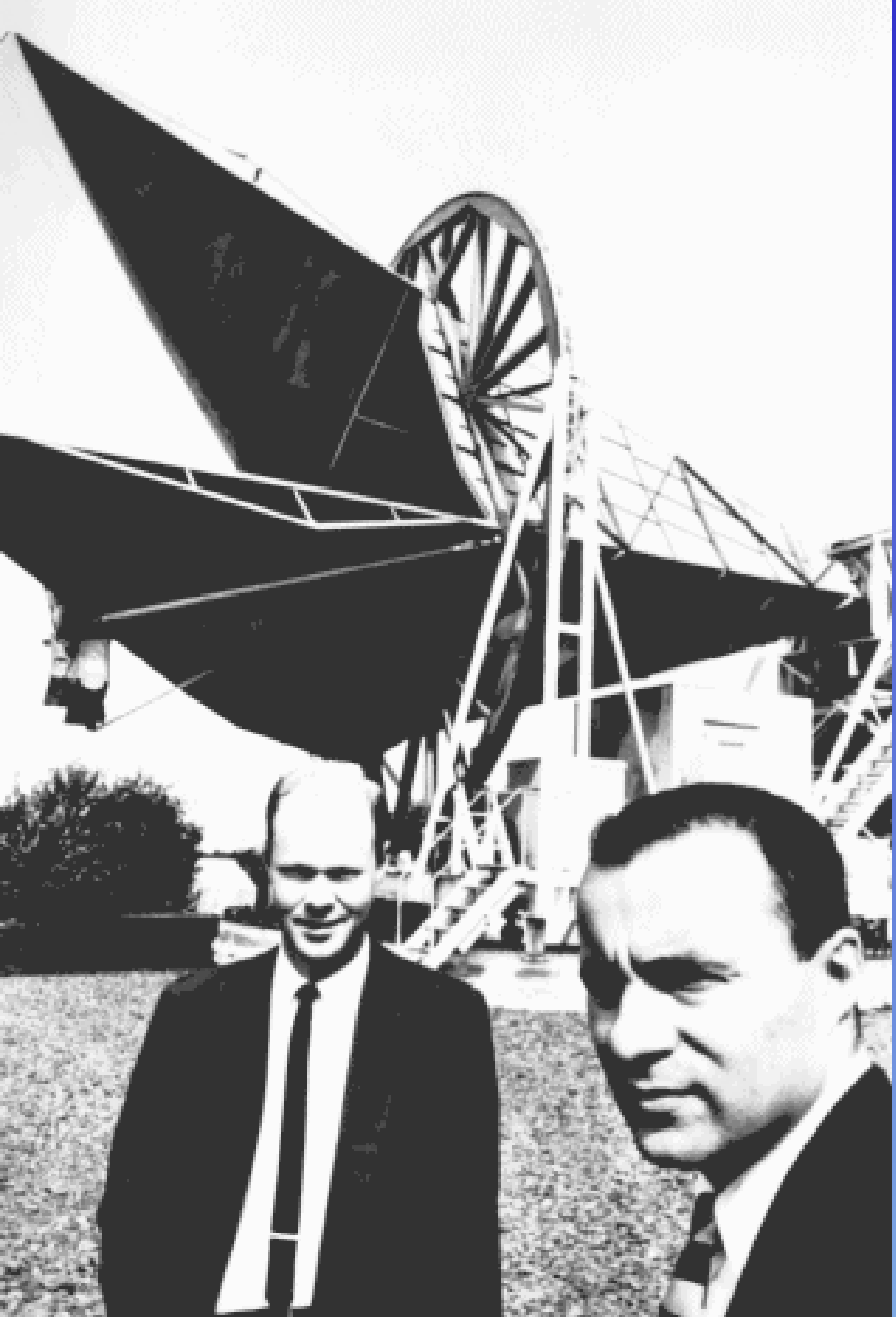
Inside Horizon


Horizon
Crossing
$\lambda \propto a$
$d_H \approx H^{-1}$
z_{dec}
Inflation
z_{end}
Radiation
z_{eq}
Matter
z_0


$\Phi(x)$
$\frac{\delta\rho}{\rho}(x)$
Gaussian Random Field

Cosmic Microwave Background

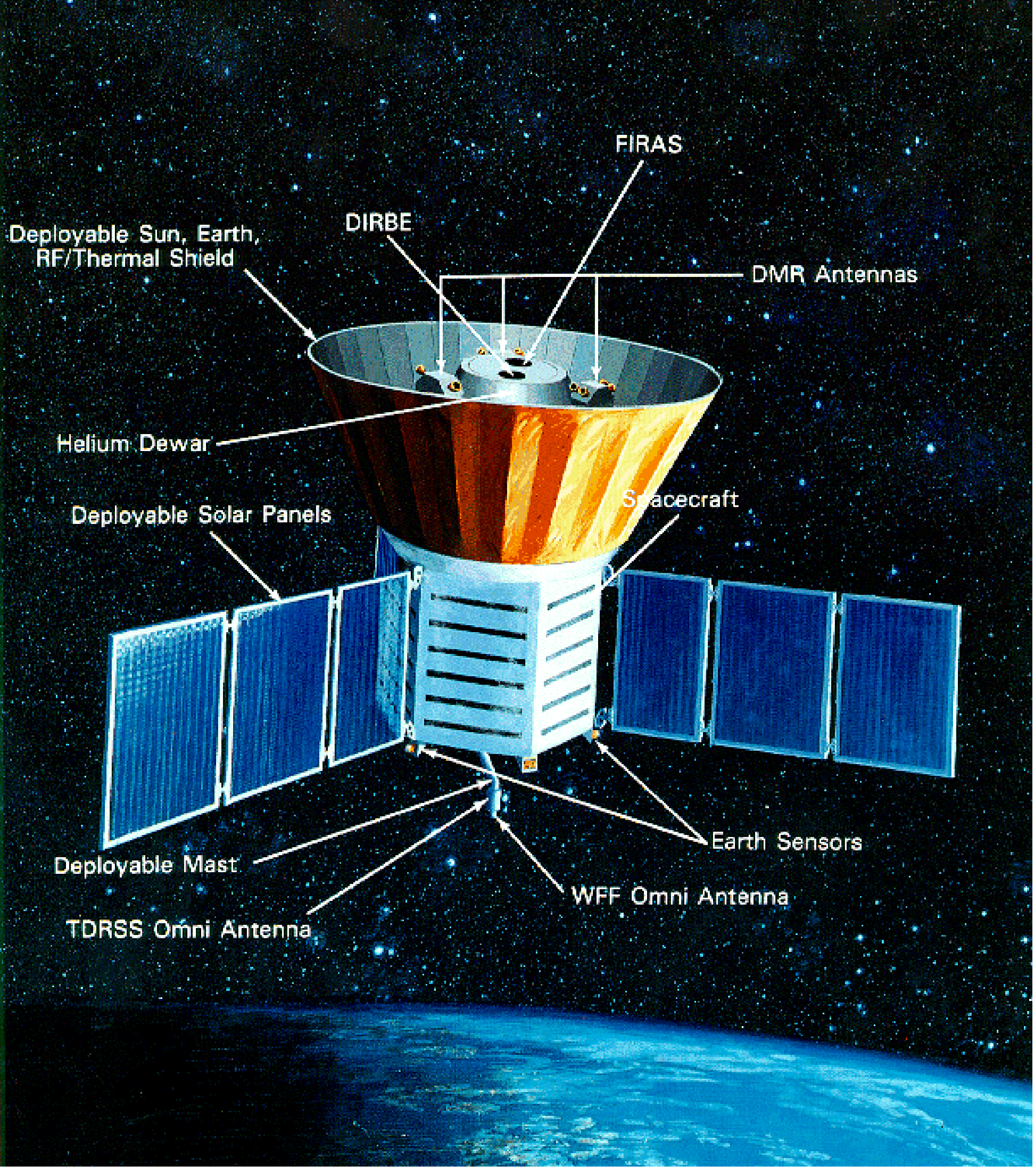

Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV

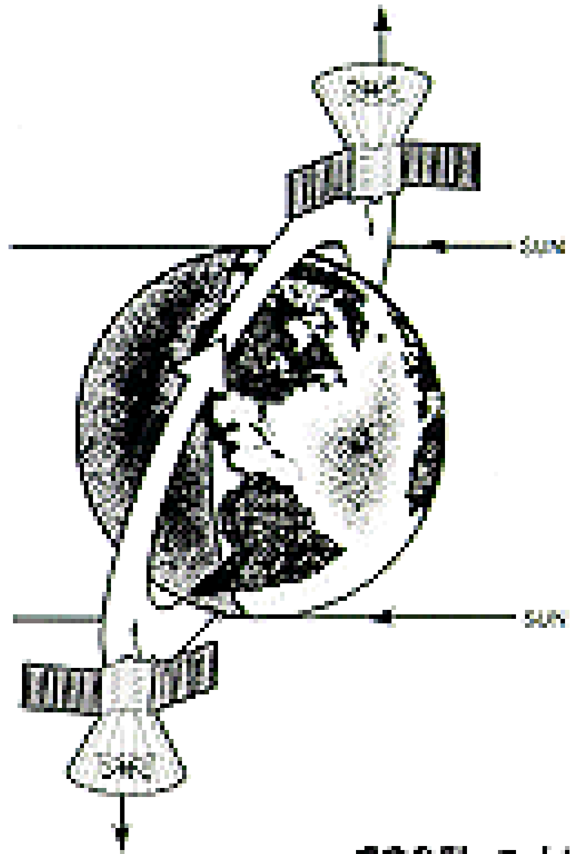


Discovery of CMB

Arno Penzias
Robert Wilson
(1965)

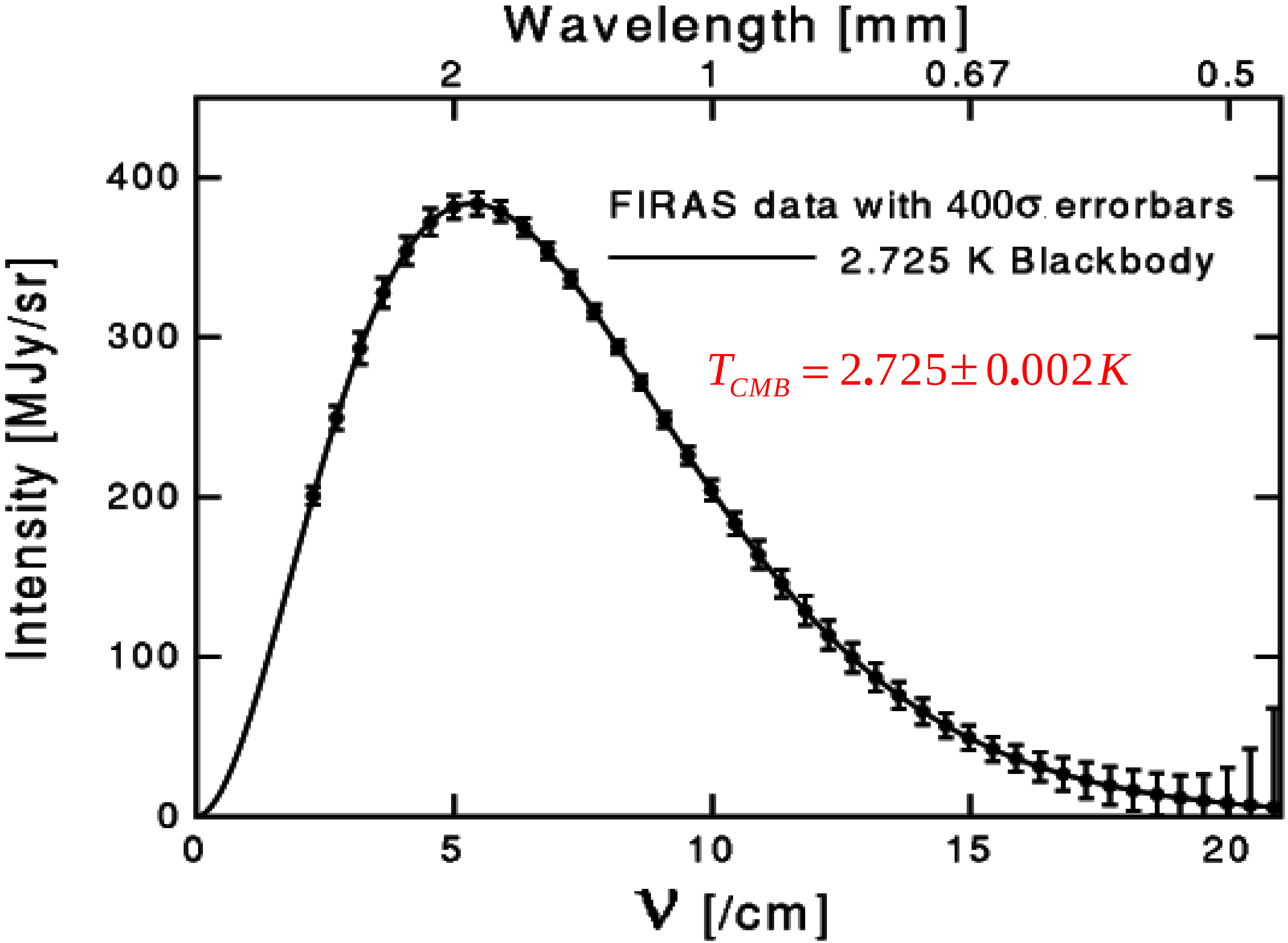
Blackbody Spectrum
T=3K
very isotropic





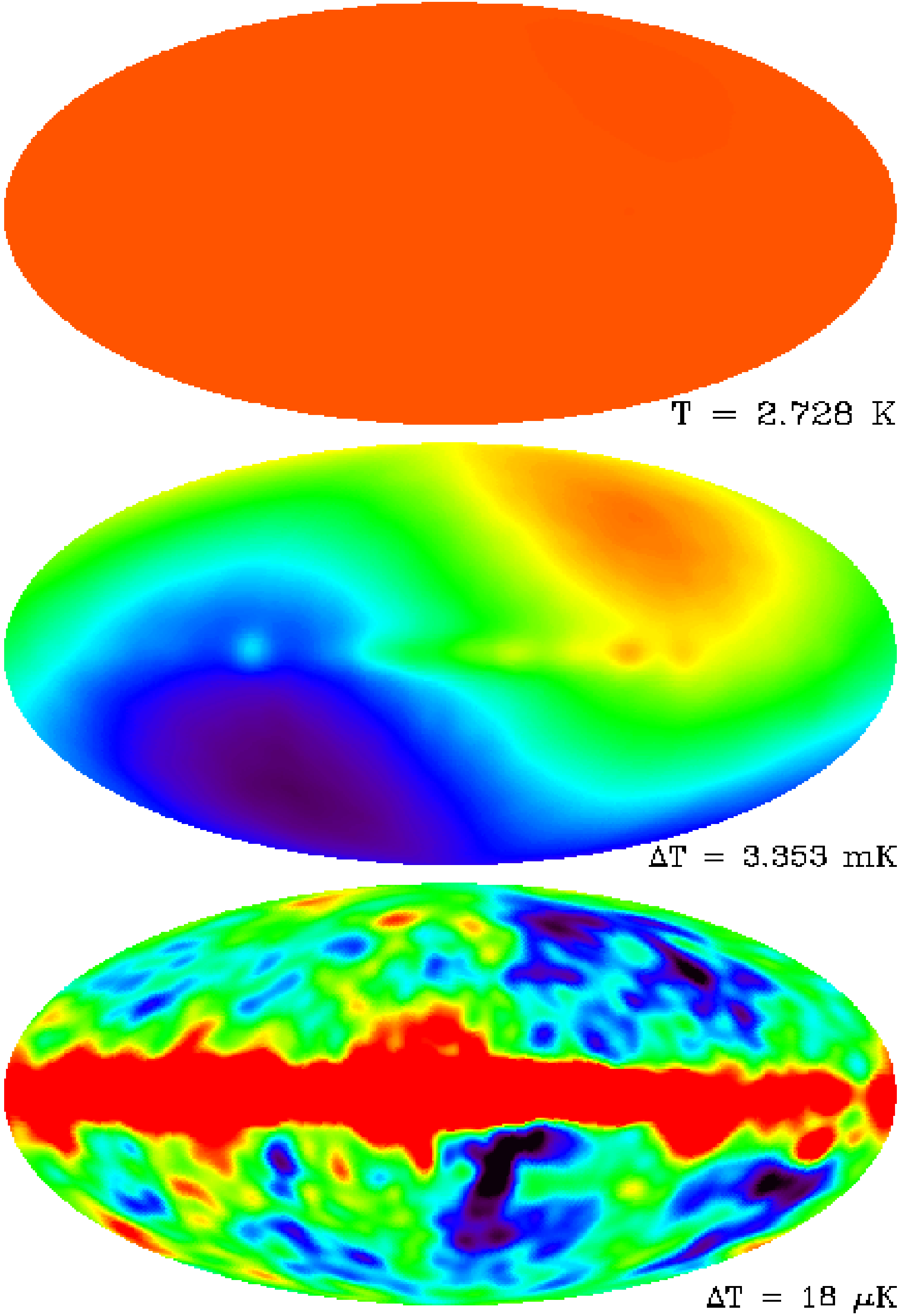
COBE's Orbit

COBE
(1989-1996)



Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
$T_{CMB} = 2.725 \pm 0.002 K$
0
5
10
15
20
ν [/cm]

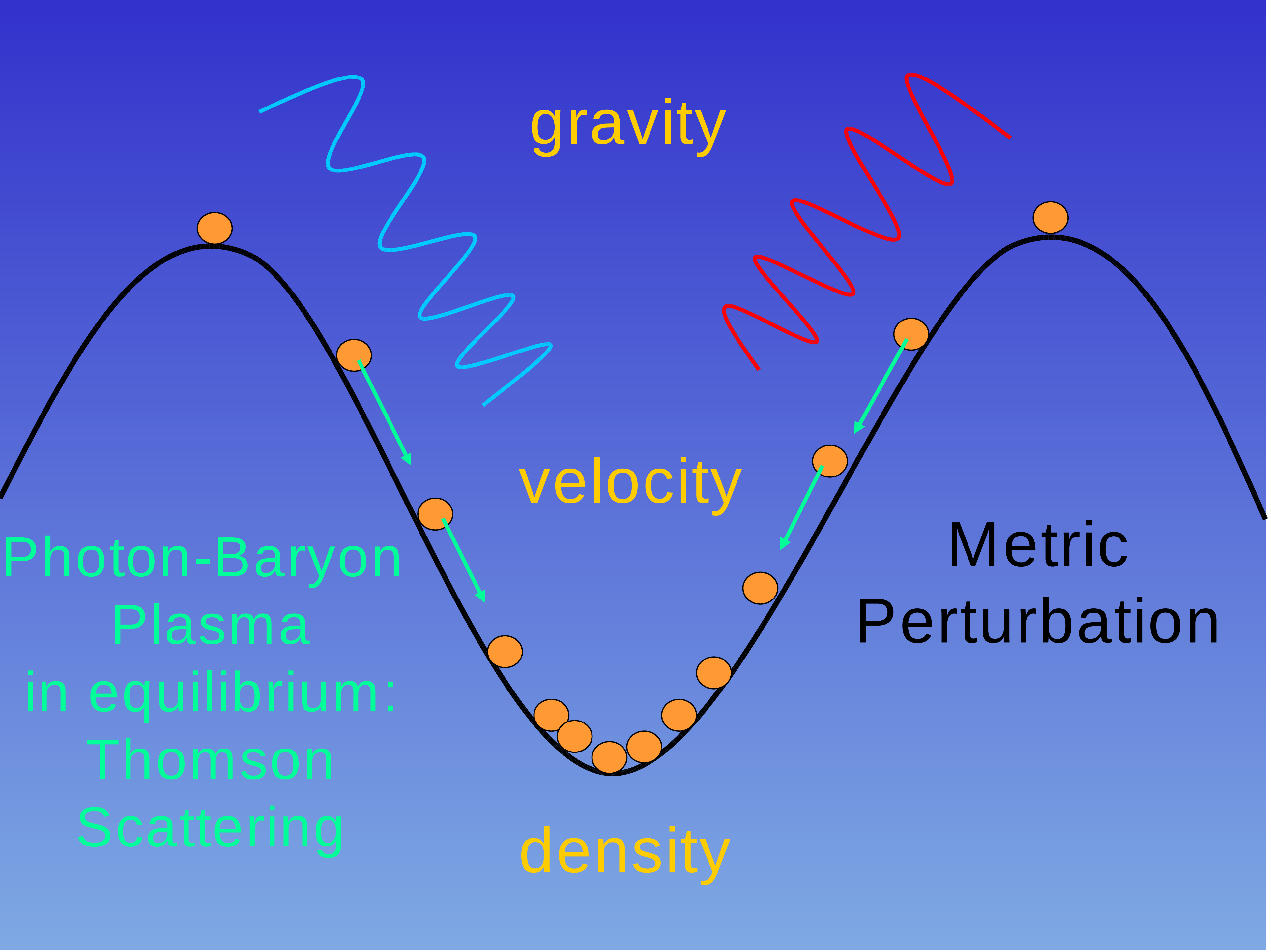
Temperature Anisotropies



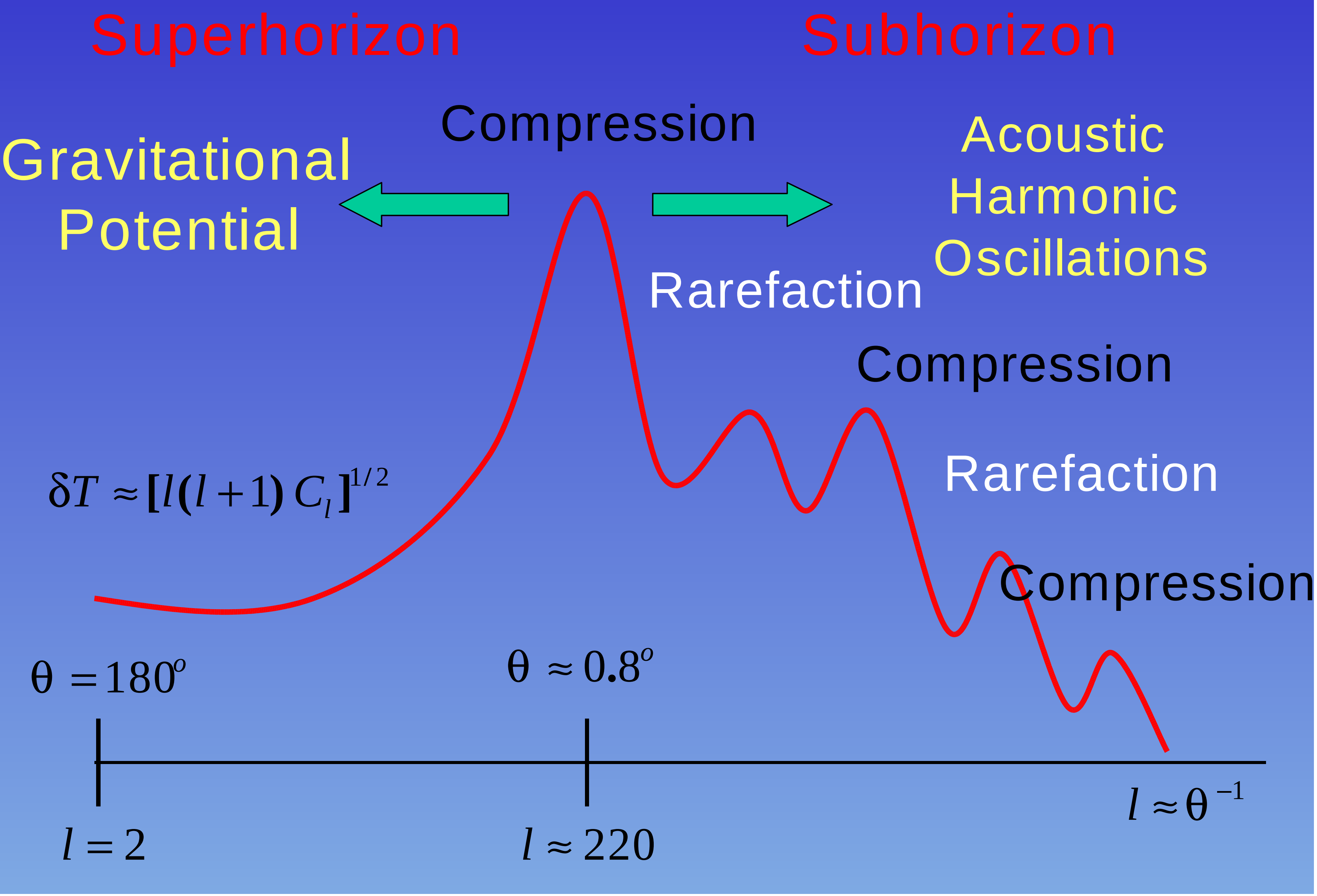
COBE 4-year Measurements (1992-1996)

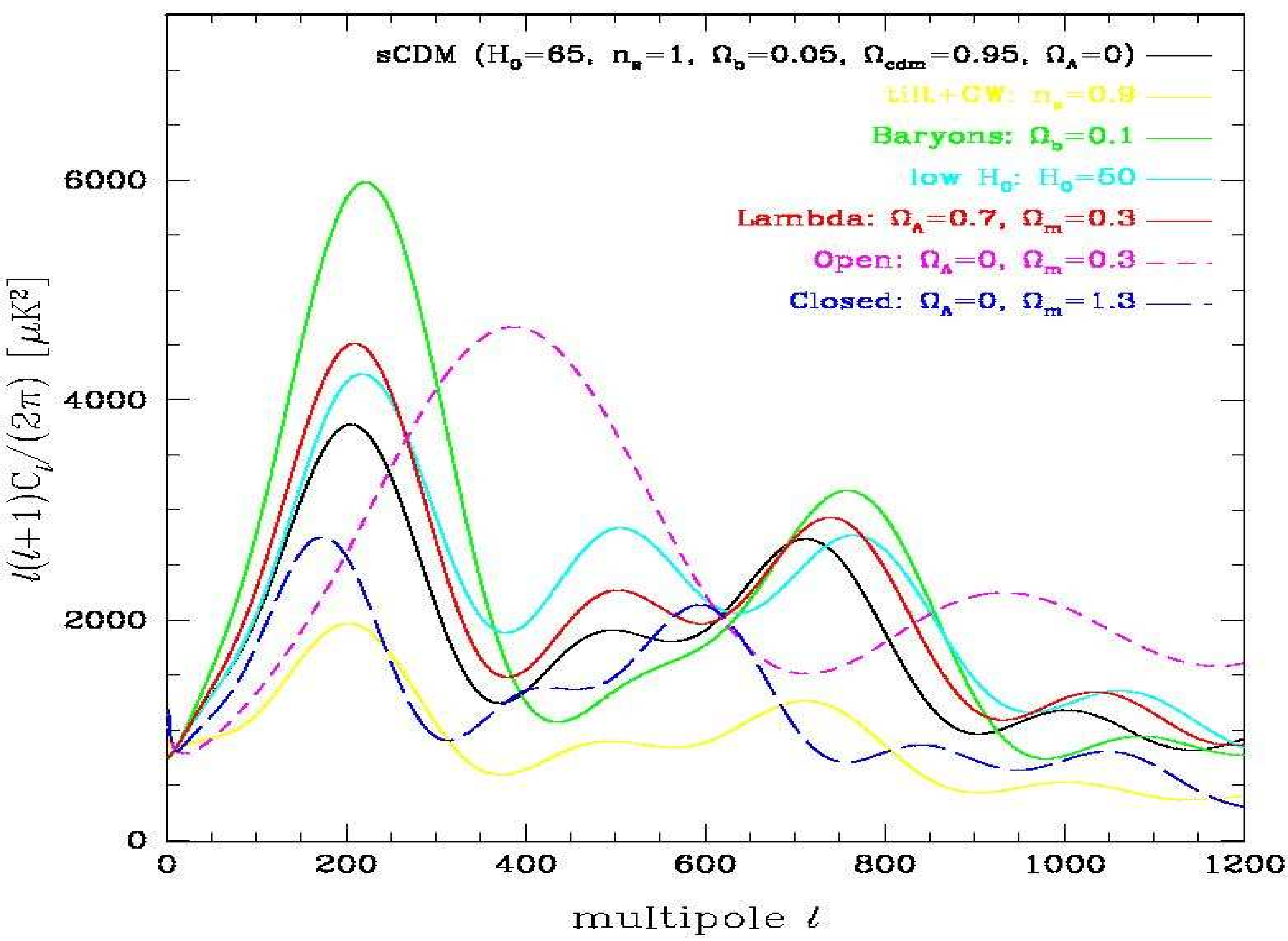
First Measurements Temperature Anisotropies (1992)

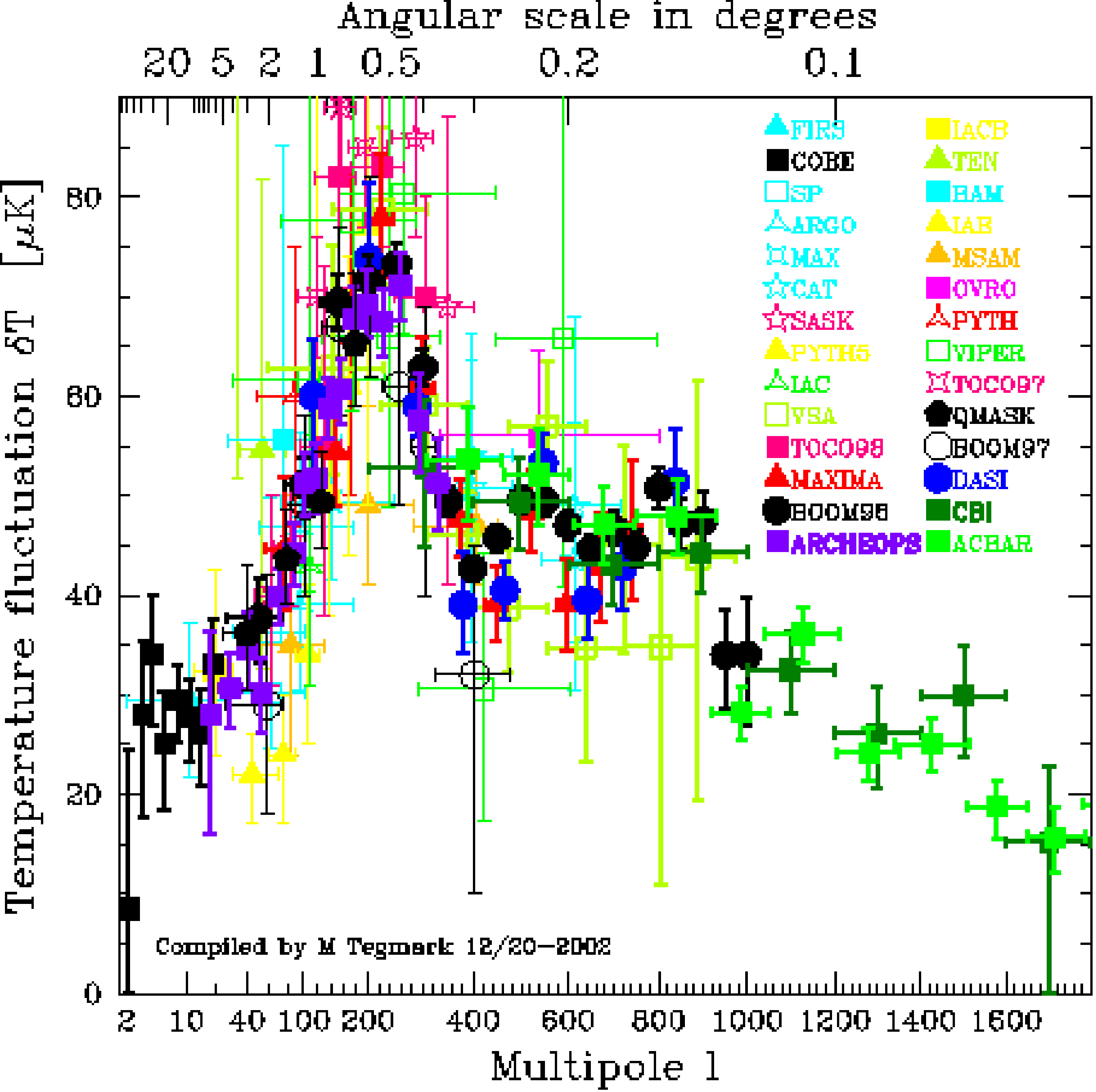
$$\frac{\Delta T}{T_0} \approx 10^{-5}$$


gravity
velocity
Metric
Perturbation
Photon-Baryon
Plasma
in equilibrium:
Thomson
Scattering
density

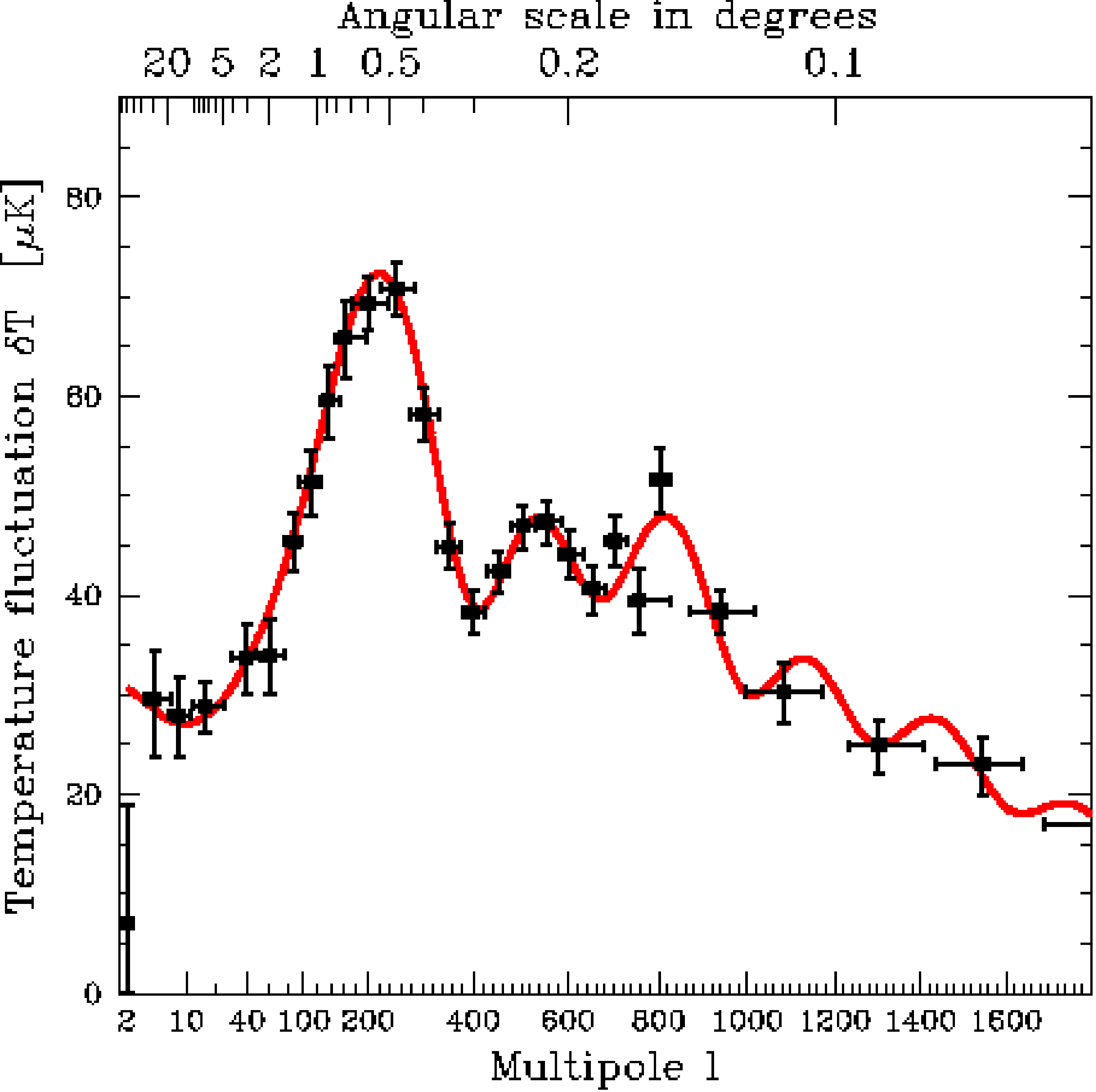
Angular Power Spectrum




sCDM (H_0=65, n_s=1, Ω_b=0.05, Ω_{cdm}=0.95, Ω_Λ=0)
tilt+GW: n_s=0.9
Baryons: Ω_b=0.1
low H_0: H_0=50
Lambda: Ω_Λ=0.7, Ω_m=0.3
Open: Ω_Λ=0, Ω_m=0.3
Closed: Ω_Λ=0, Ω_m=1.3
6000
4000
2000
0
$l(l+1)C_l/(2\pi)$ [μK^2]
0
200
400
600
800
1000
1200
multipole l

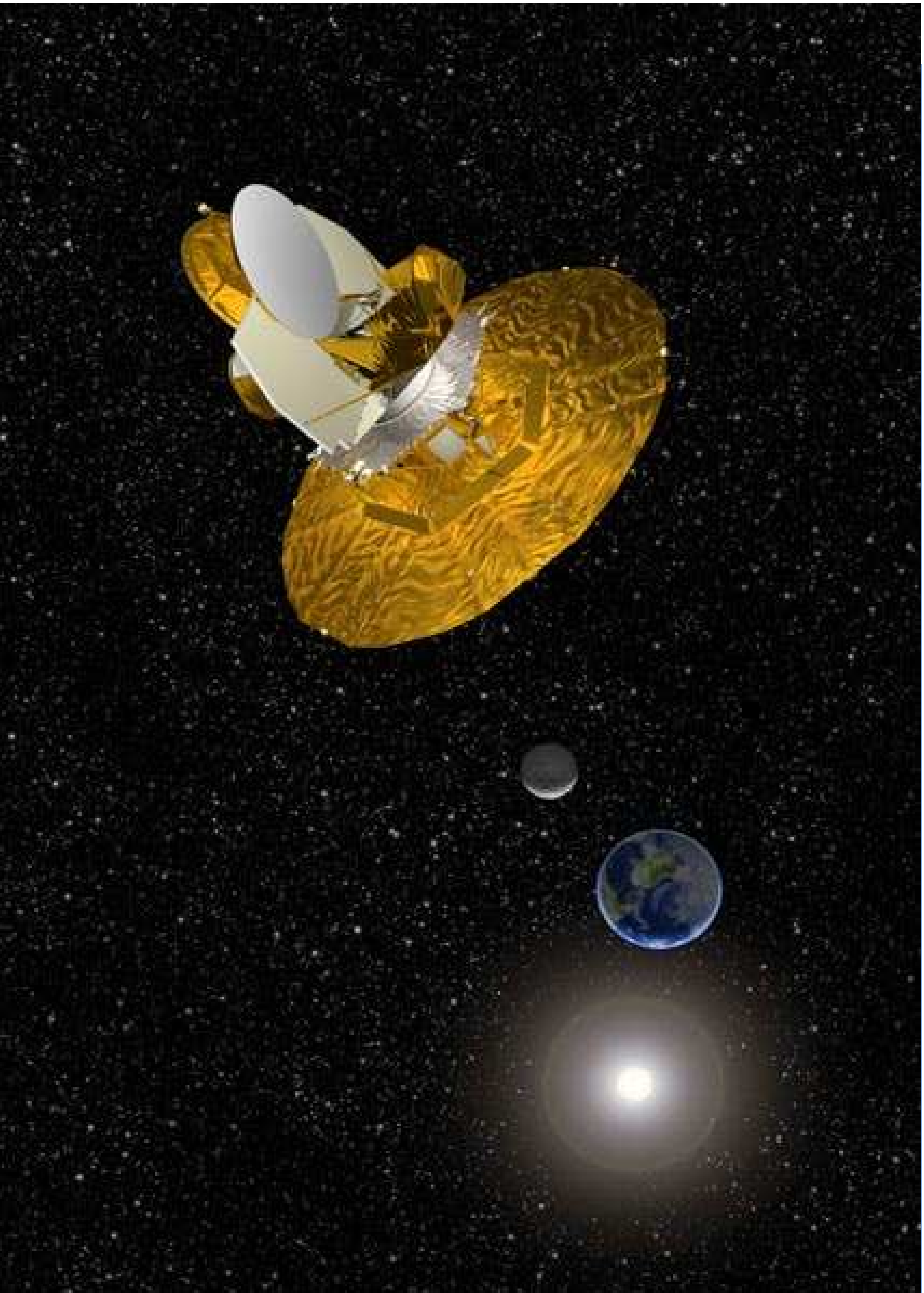


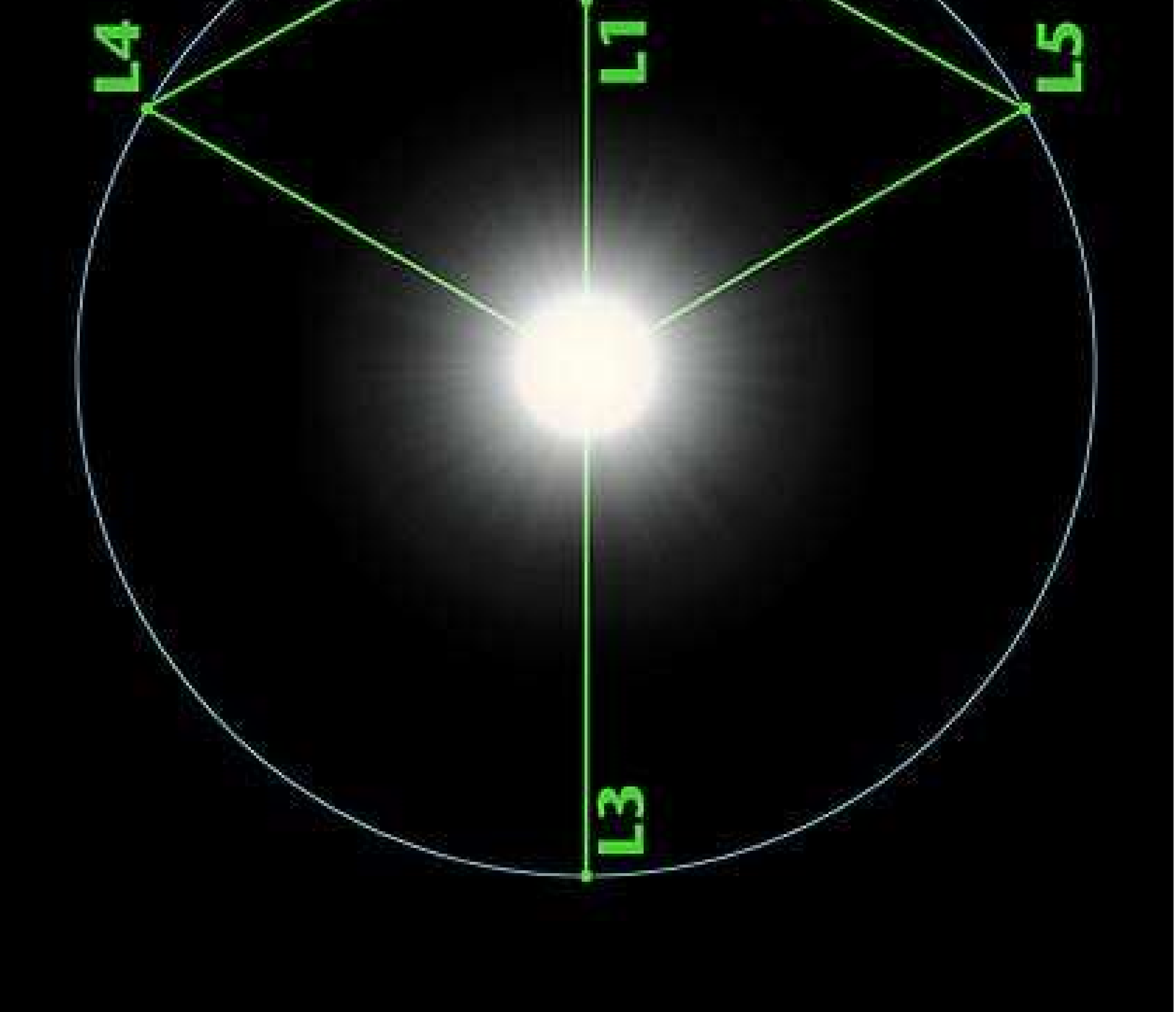
All
CMB
Exp.
(2002)

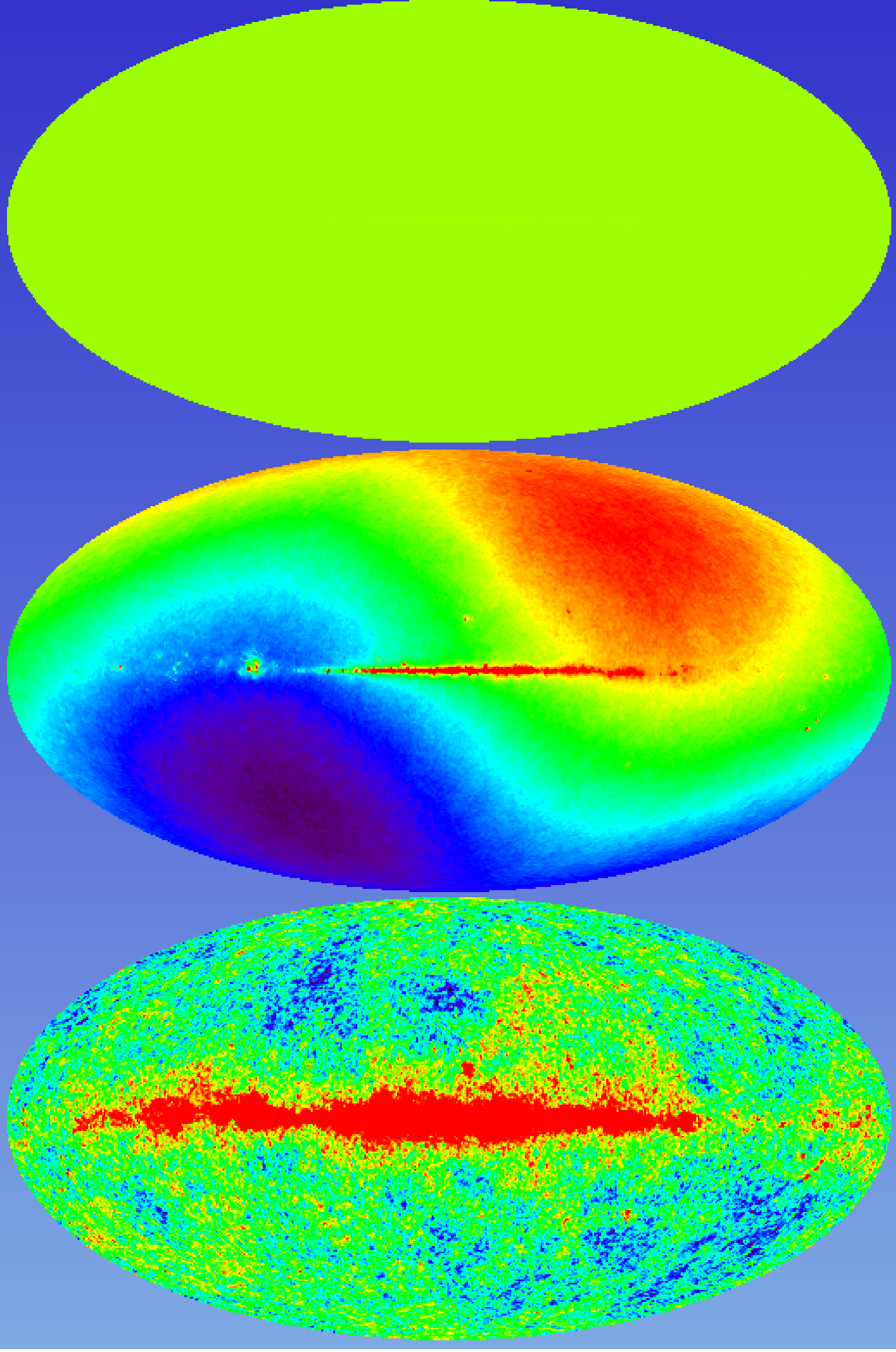


Best fit
to all
CMB data
(2002)

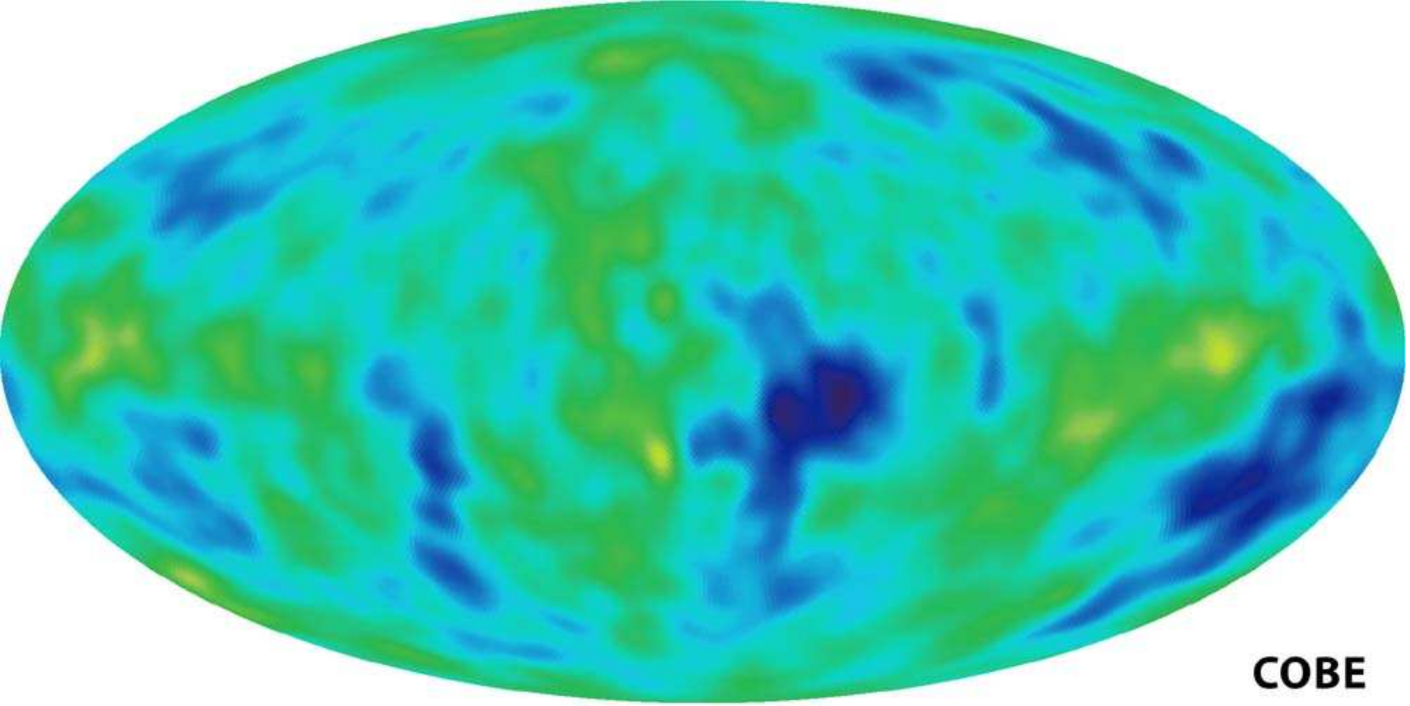
Wilkinson Microwave Anisotropy Probe



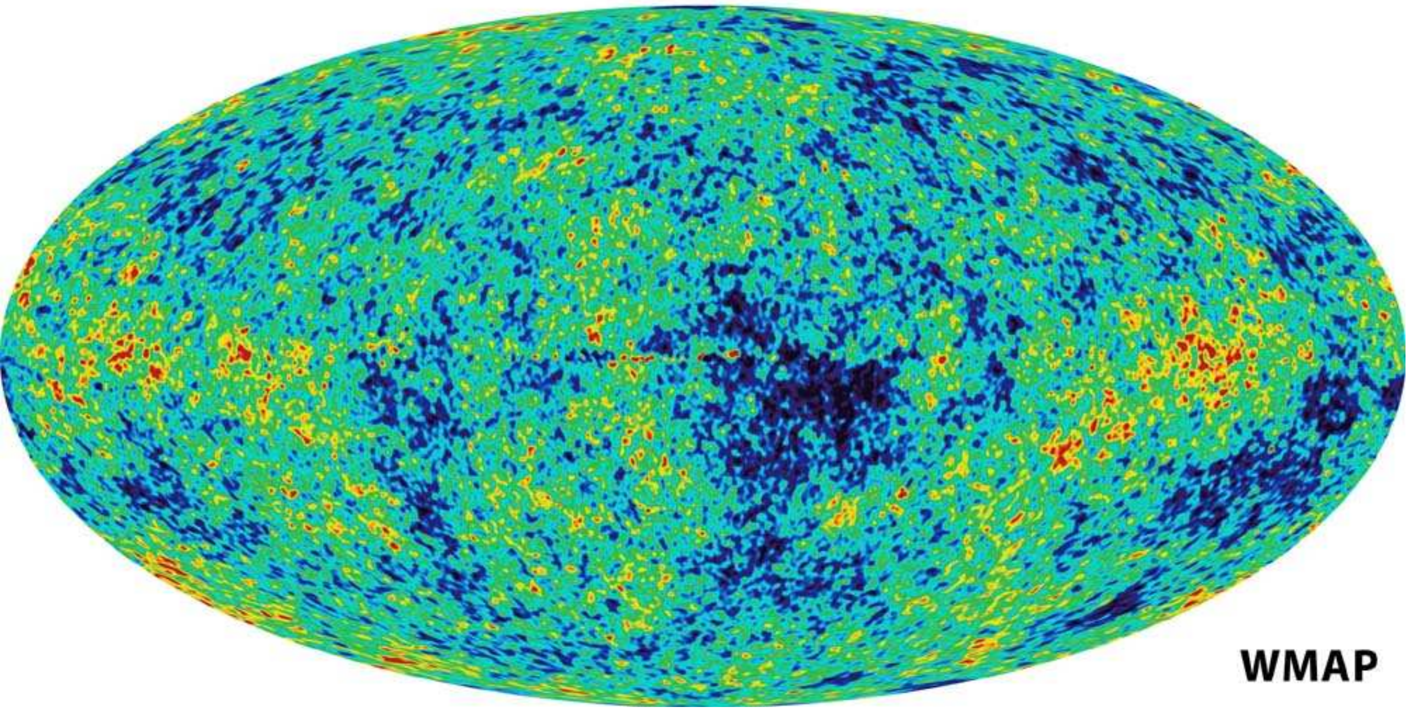

L2
L1
L4
L5
L3



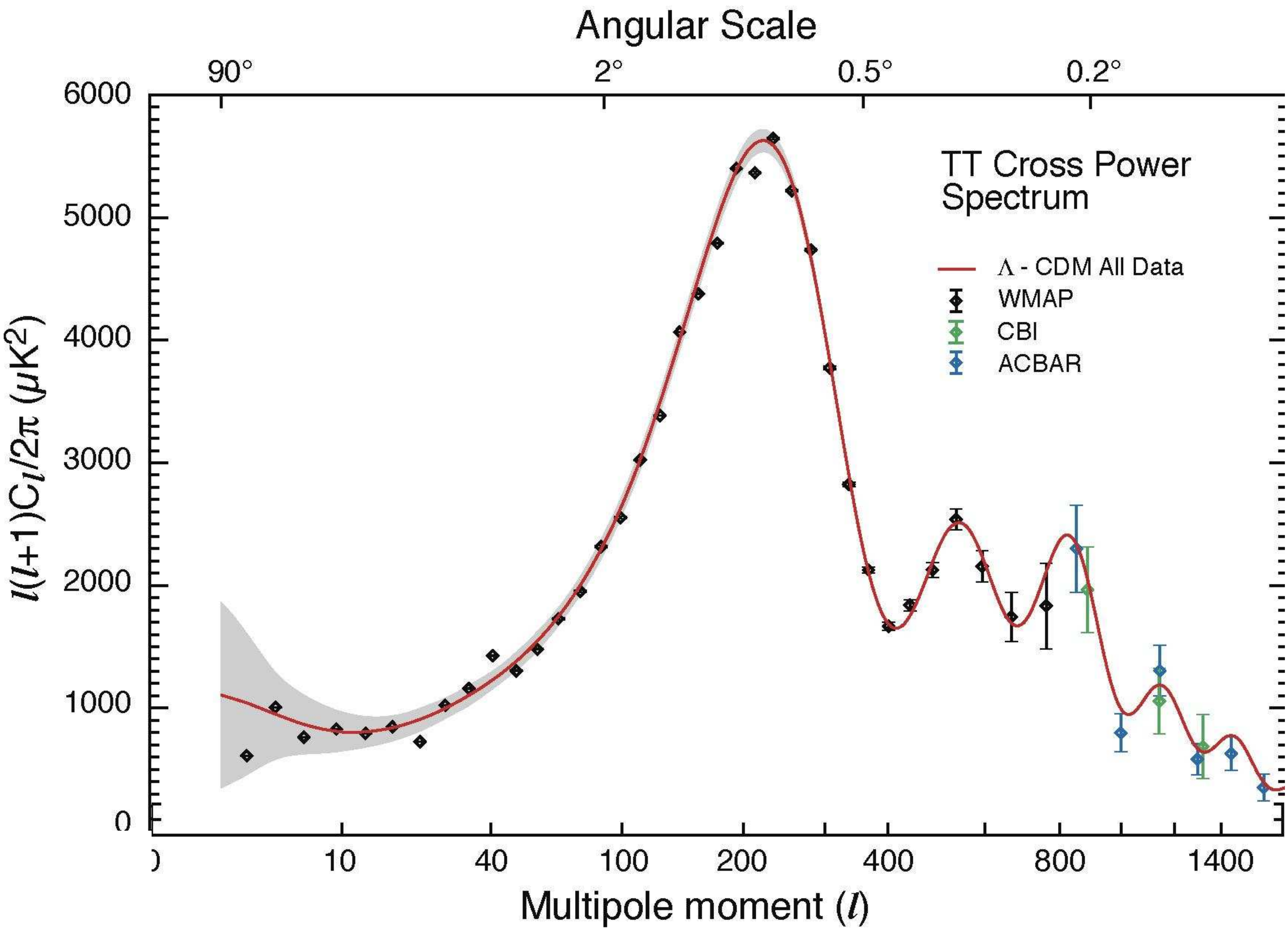
Wilkinson
Microwave
Anisotropy
Probe
(2003)



COBE
(1992)
7°

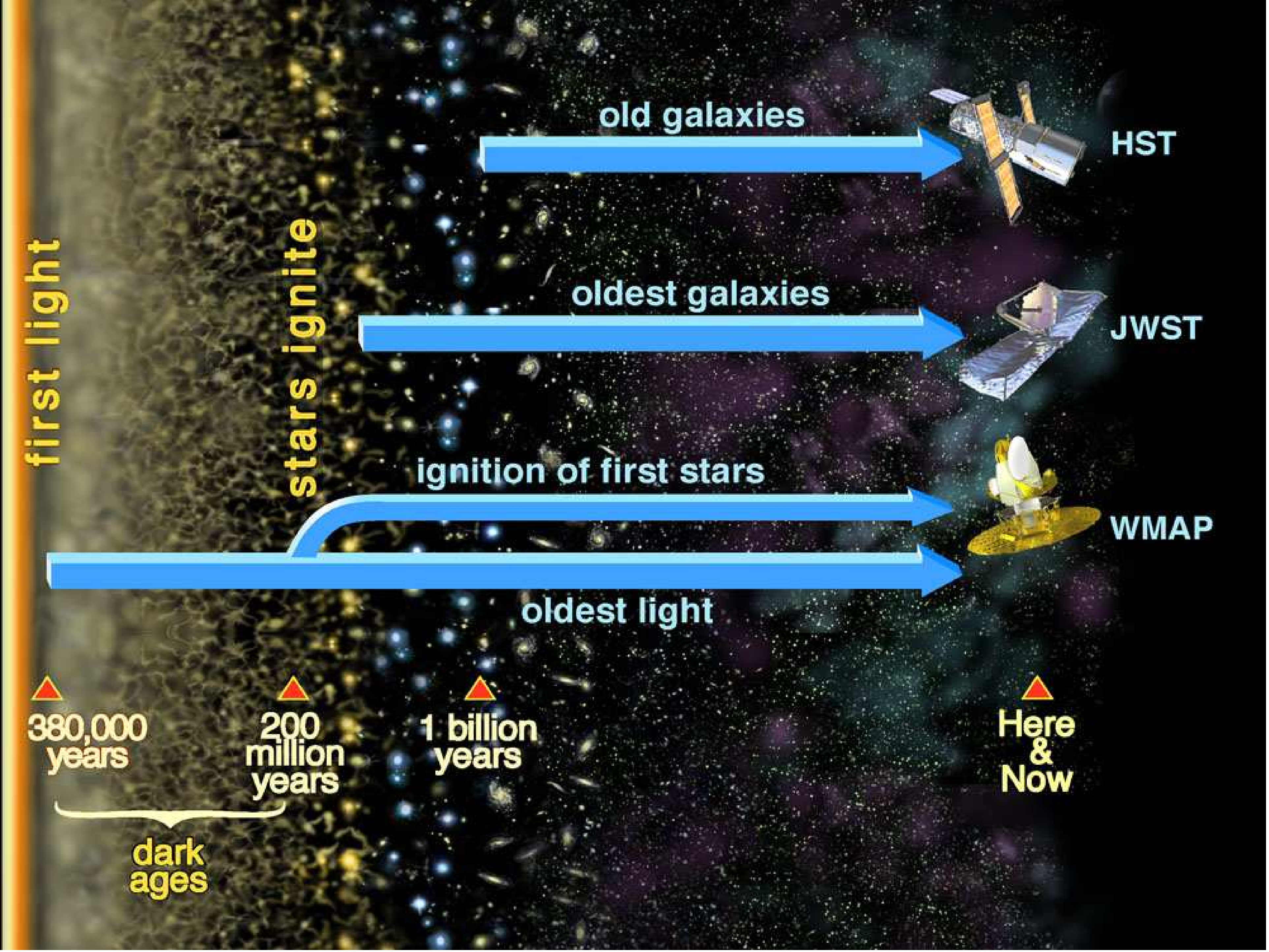


WMAP
(2003)
10’


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
10
40
100
200
400
800
1400
Multipole moment (l)

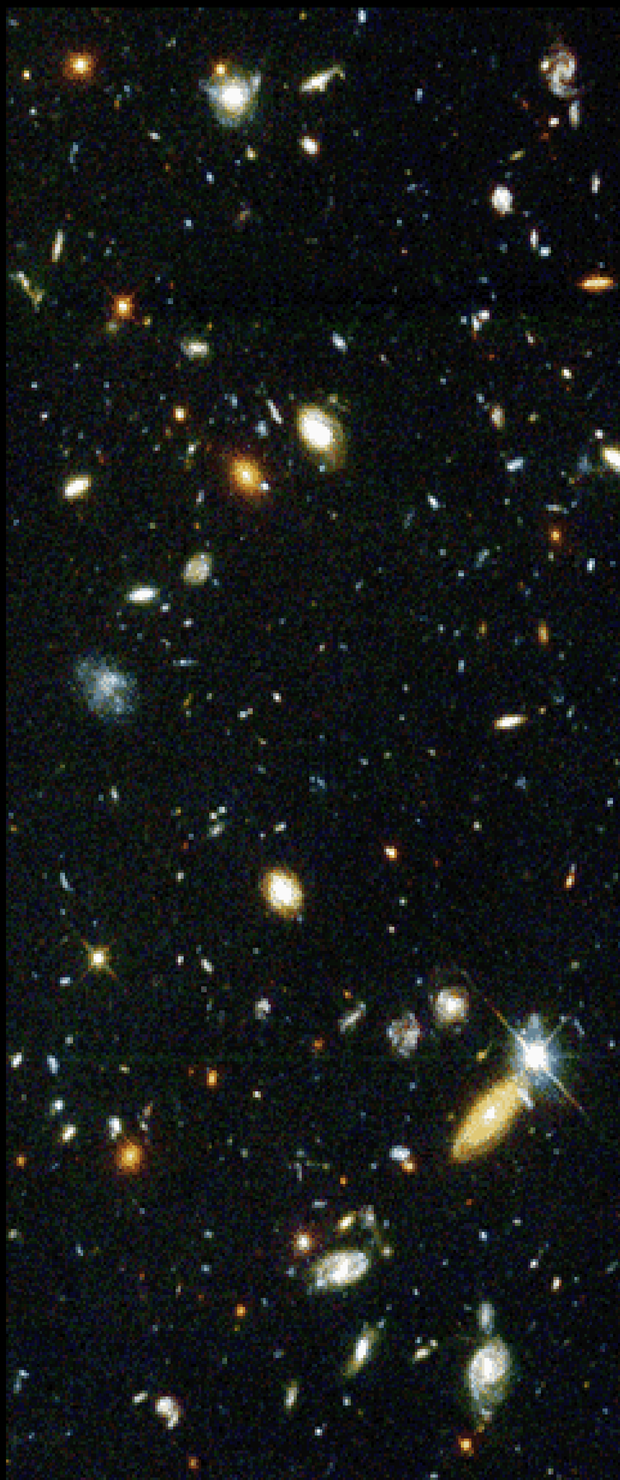
Cosmological Parameters: WMAP et al.

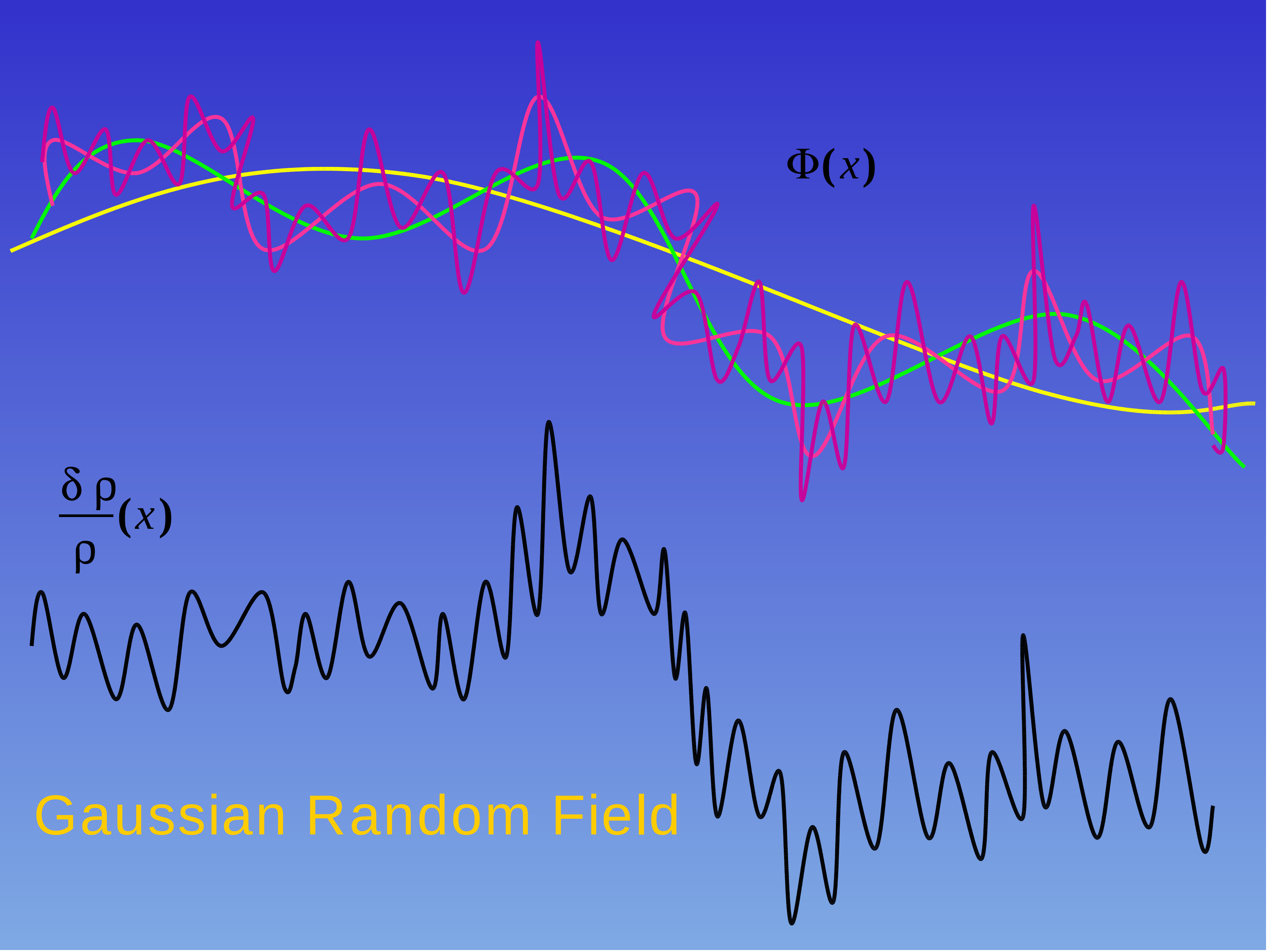
Rate of expansion	$H_0 = 71 \pm 3$ km/s/Mpc
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr
Spatial Curvature	$\Omega_K < 0.02 \quad (95\%\ c.l.)$
Cosmological Constant	$\Omega_\Lambda = 0.73 \pm 0.04$
Dark Matter	$\Omega_M = 0.23 \pm 0.04$
Baryon Density	$\Omega_B = 0.044 \pm 0.004$
Neutrino Density	$\Omega_\nu < 0.0076 \quad (95\%\ c.l.)$
Spectral Amplitude	$A_s = 0.833 \pm 0.085$
Spectral tilt	$n_s = 0.93 \pm 0.03$
Tensor-scalar ratio	$r < 0.71\ (95\%\ c.l.)$



first light
stars ignite
old galaxies
HST
oldest galaxies
JWST
ignition of first stars
WMAP
oldest light
380,000 years
200 million years
dark ages
1 billion years
Here & Now

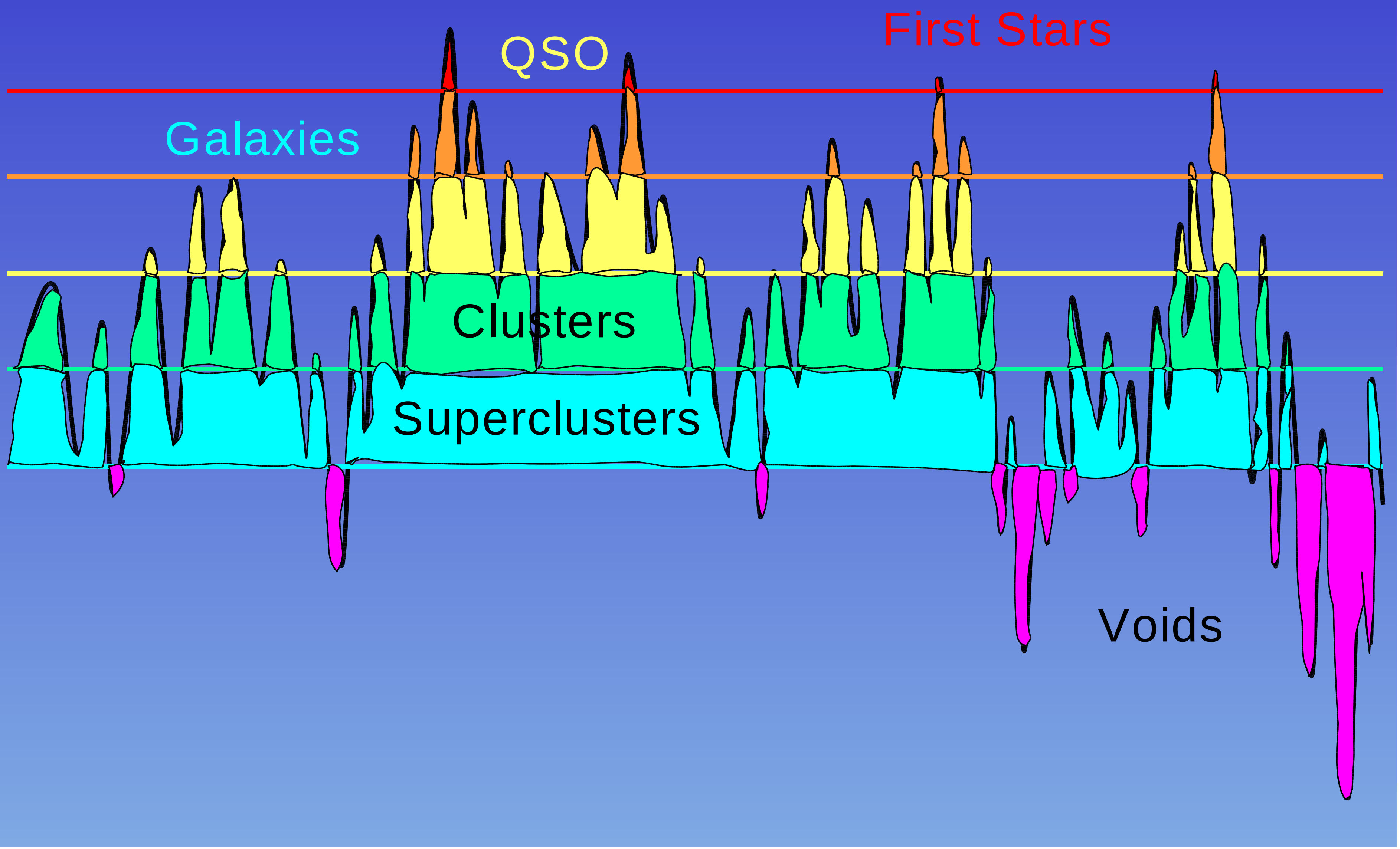
Structure Formation

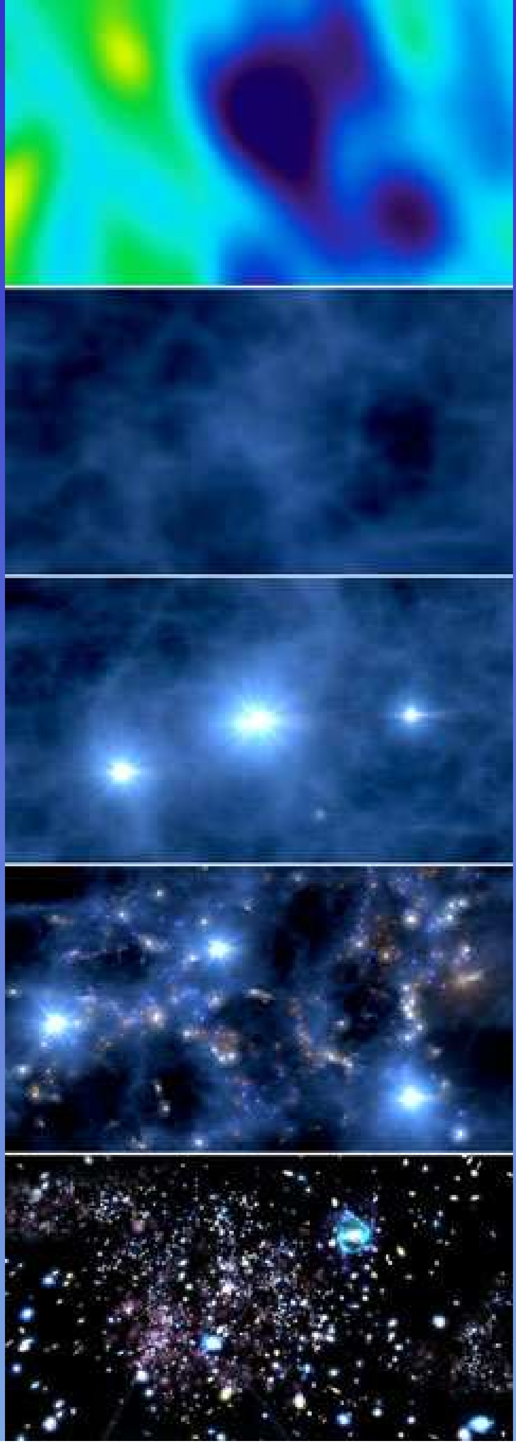




$\Phi(x)$
$\frac{\delta\rho}{\rho}(x)$
Gaussian Random Field

Density Contrast Thresholds





$z \approx 1100$ CMB Anisotropies

$z \approx 100$ Dark ages

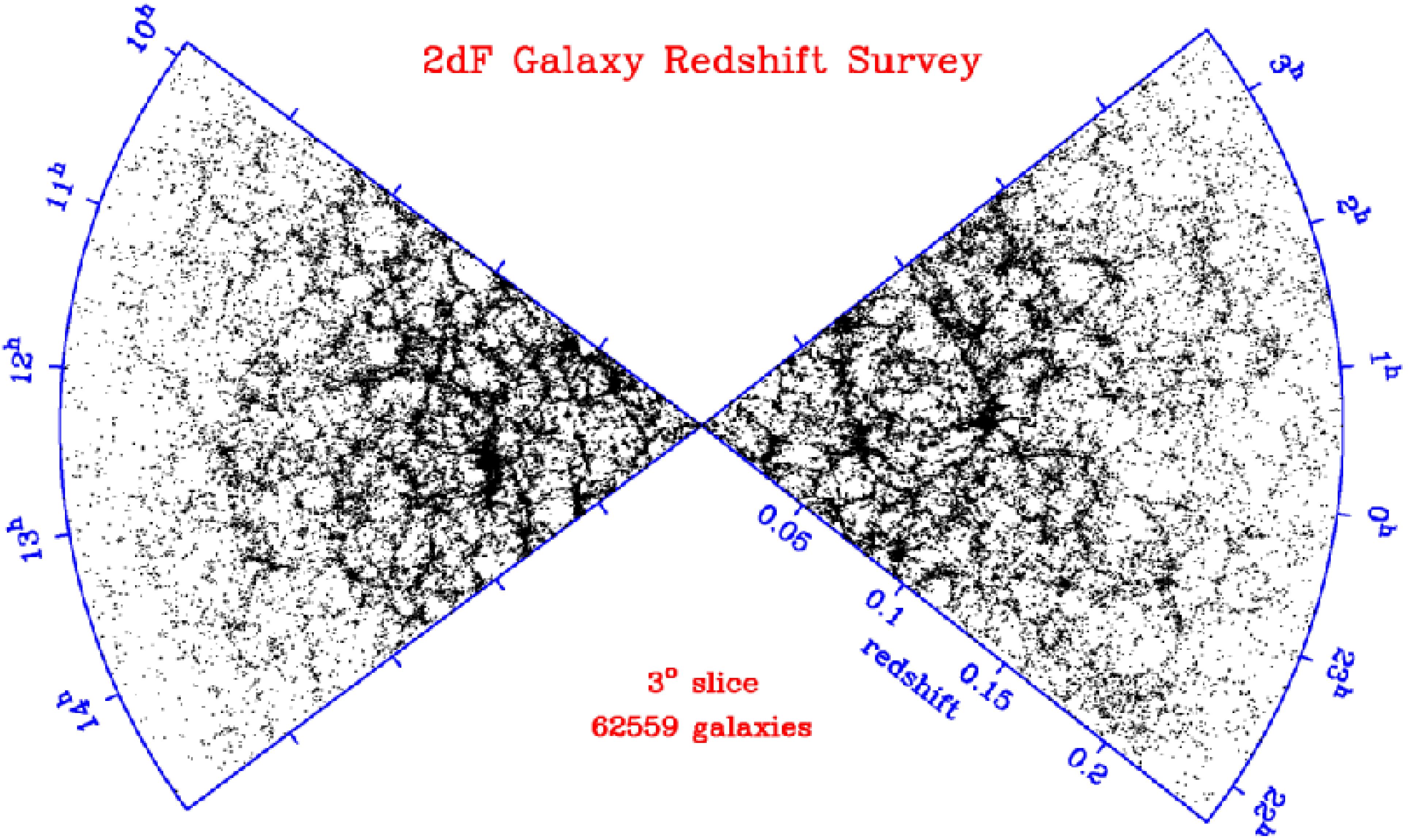
$z \approx 20$ First stars

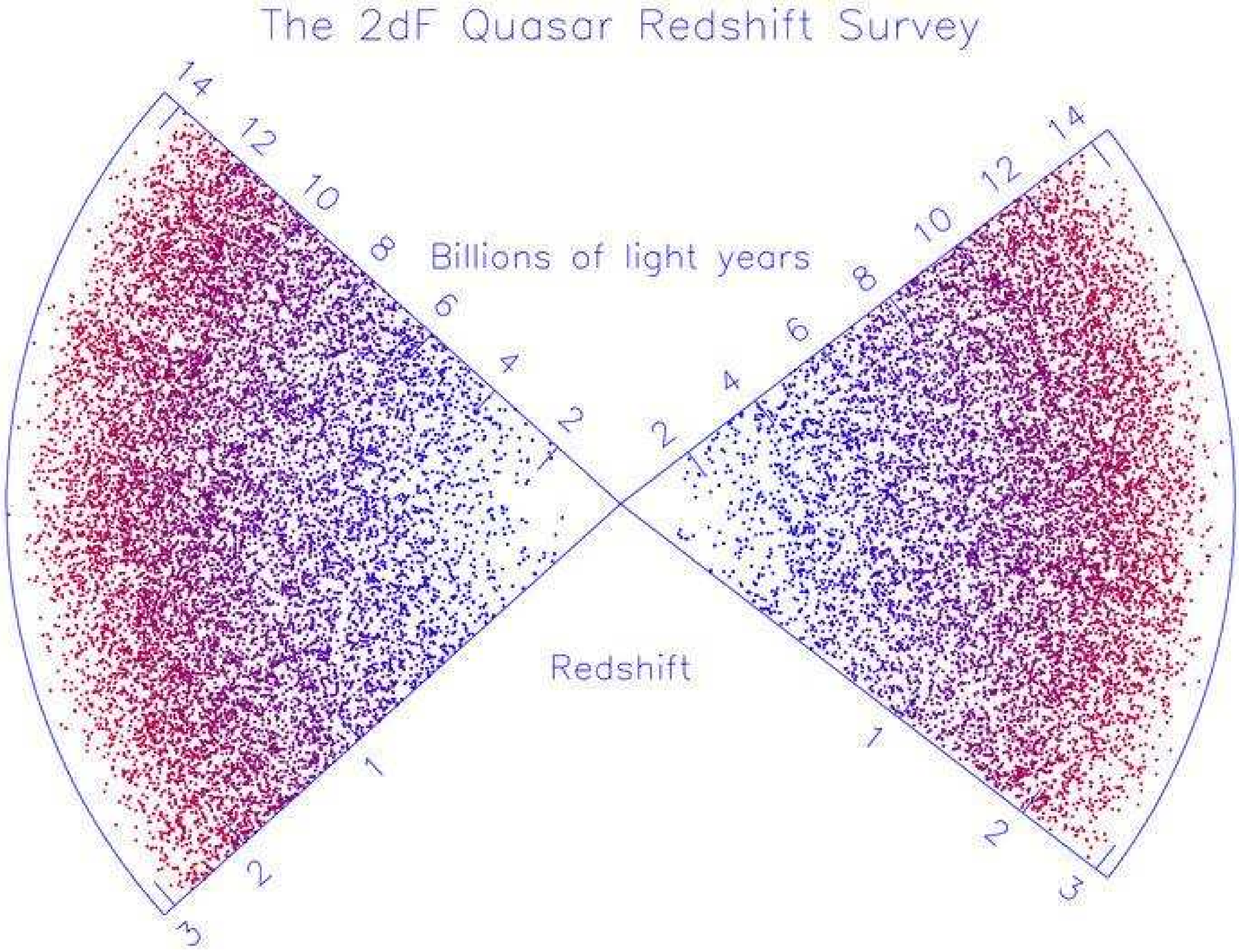
$z \approx 10$ Galaxies & Quasars

$z \approx 1$ Clusters & Superclusters

Large Scale Structure

Cone diagram: 3-degree slice





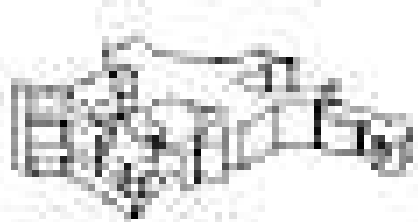
The 2dF Quasar Redshift Survey
Billions of light years
Redshift
2
4
6
8
10
12
14
1
2
3

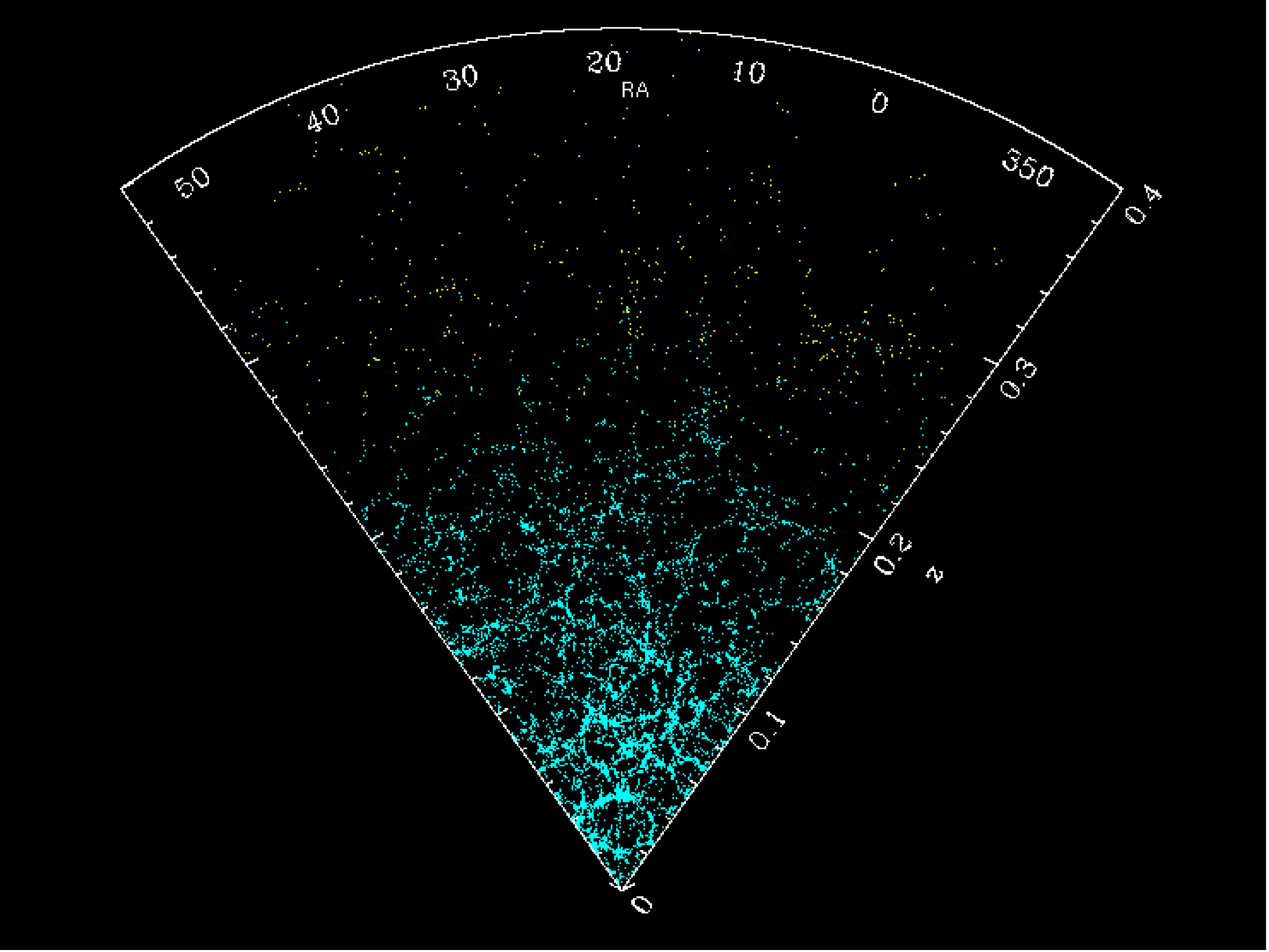
Numerical Simulations

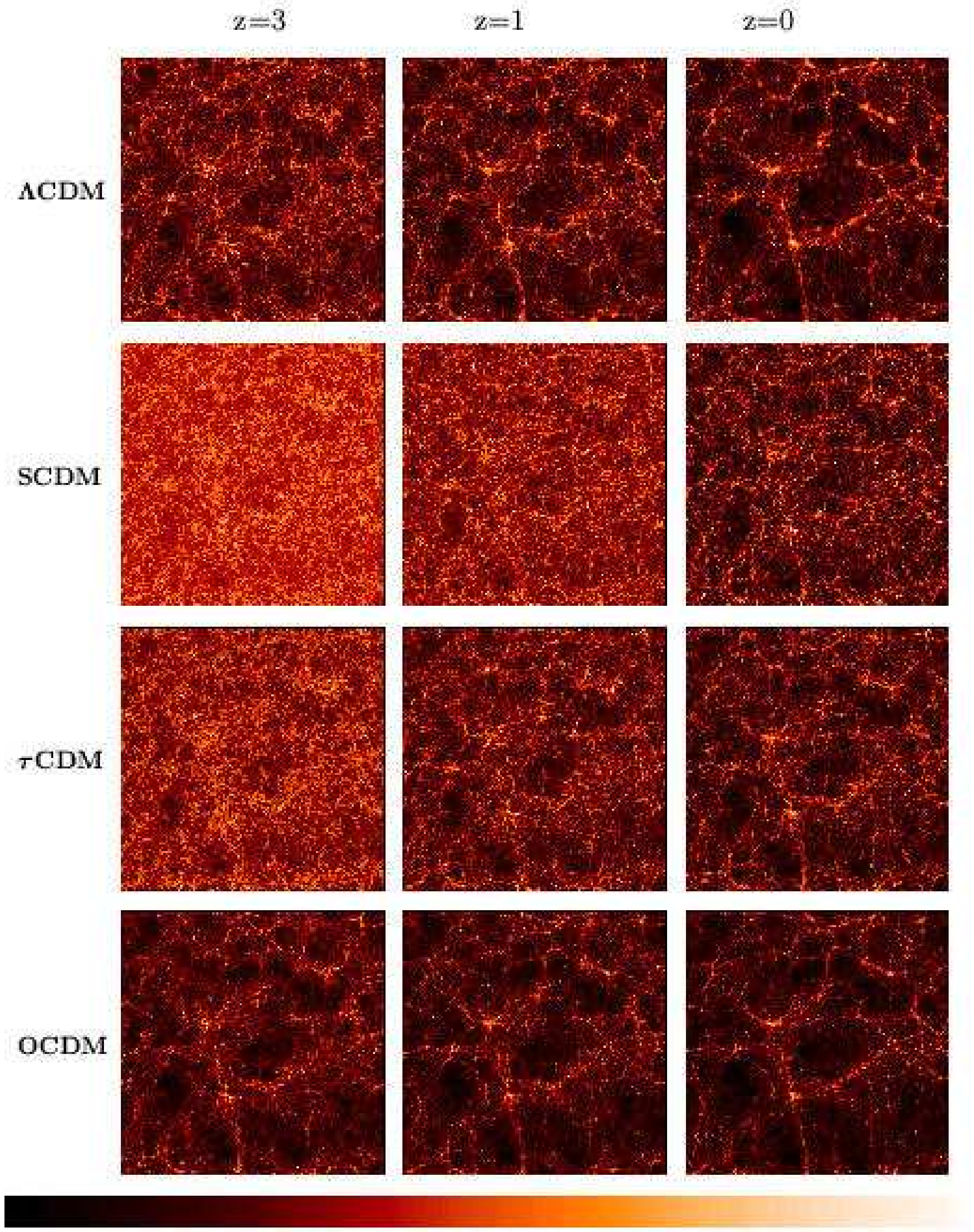
(beyond pert. Theory)

CR

z=20.0

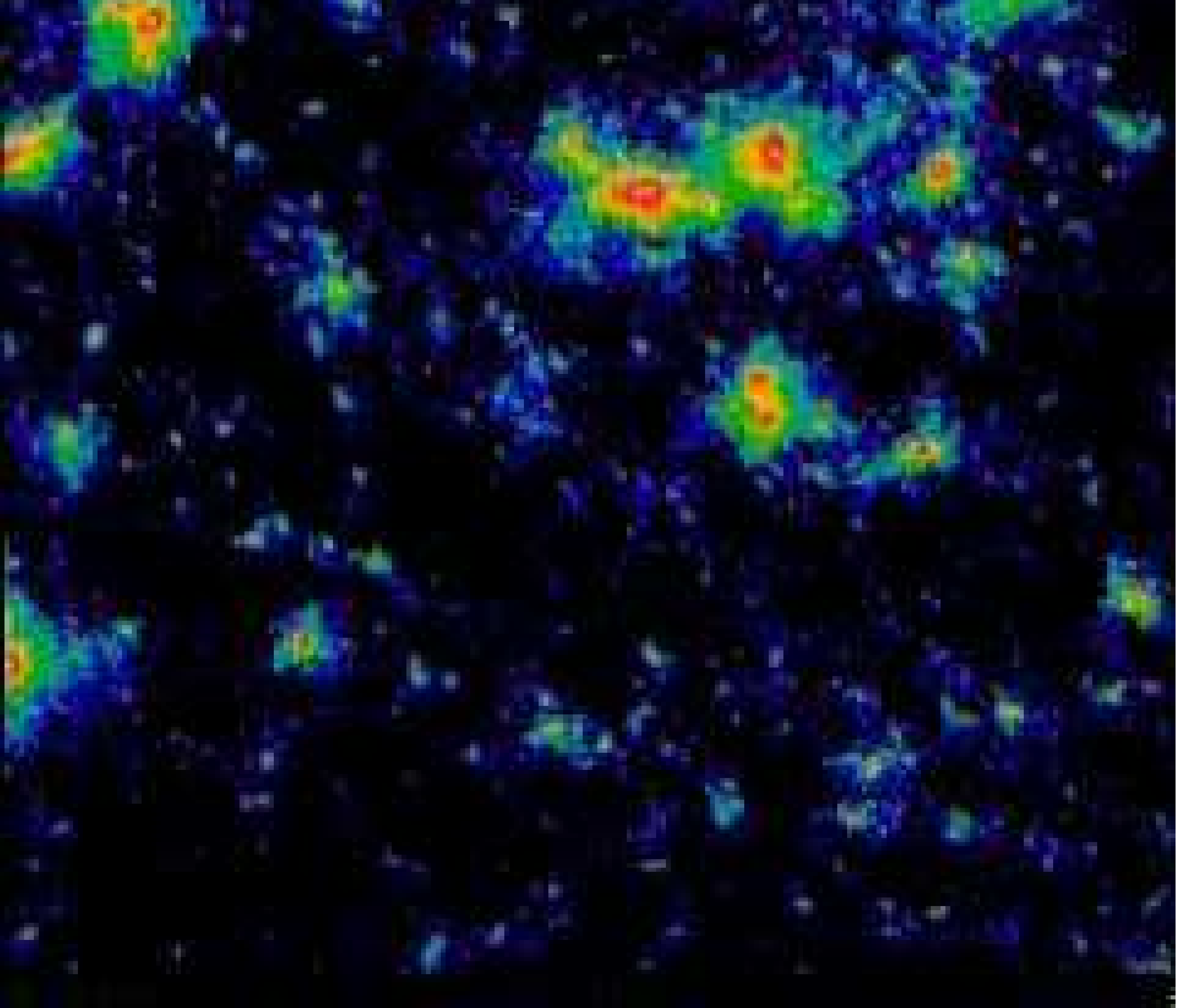


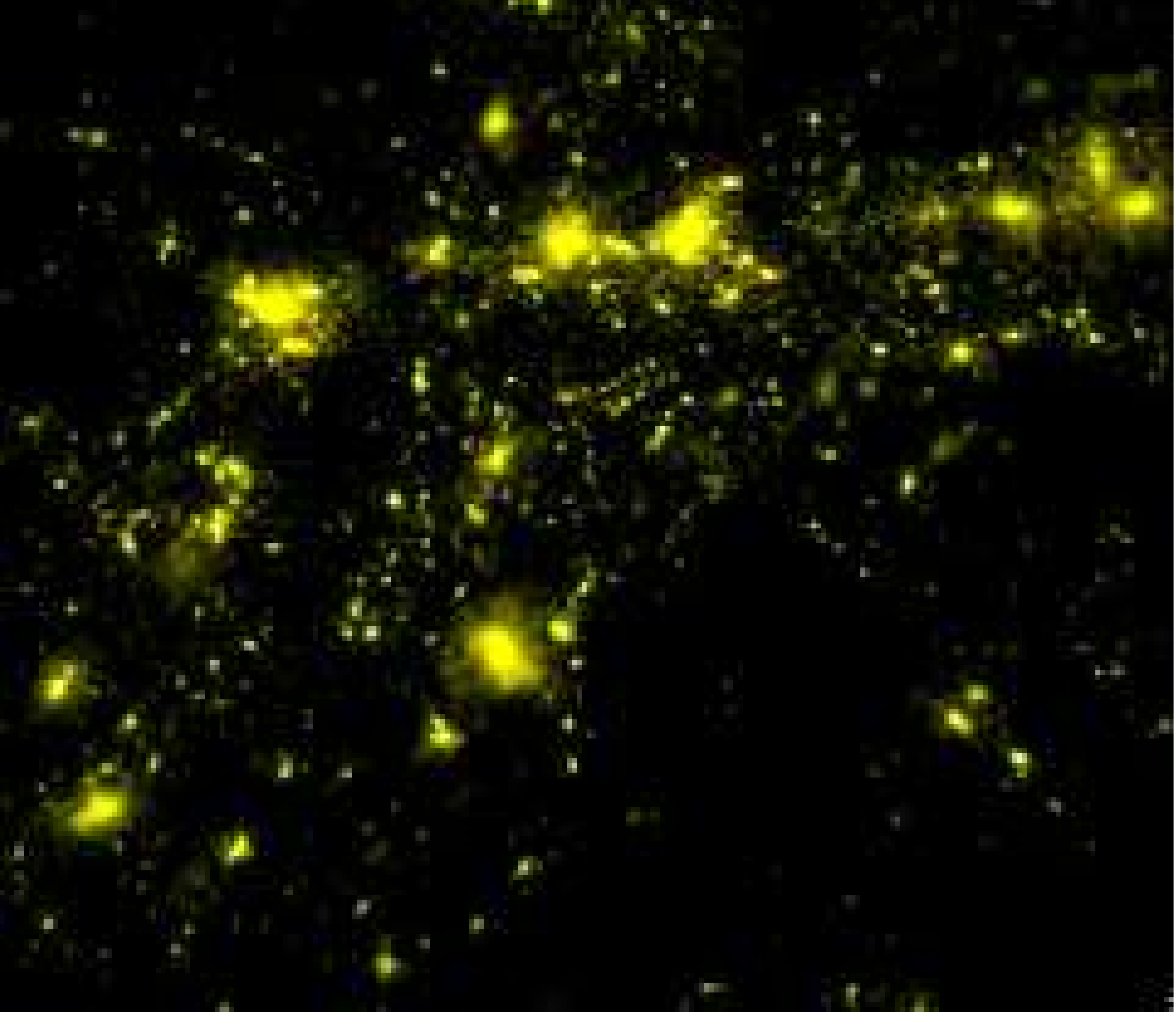

50
40
30
20
RA
10
0
350
0.4
0.3
0.2
z
0.1
0



The VIRGO Collaboration 1996

Large Scale Structure Simulations (1996)





Dark Matter

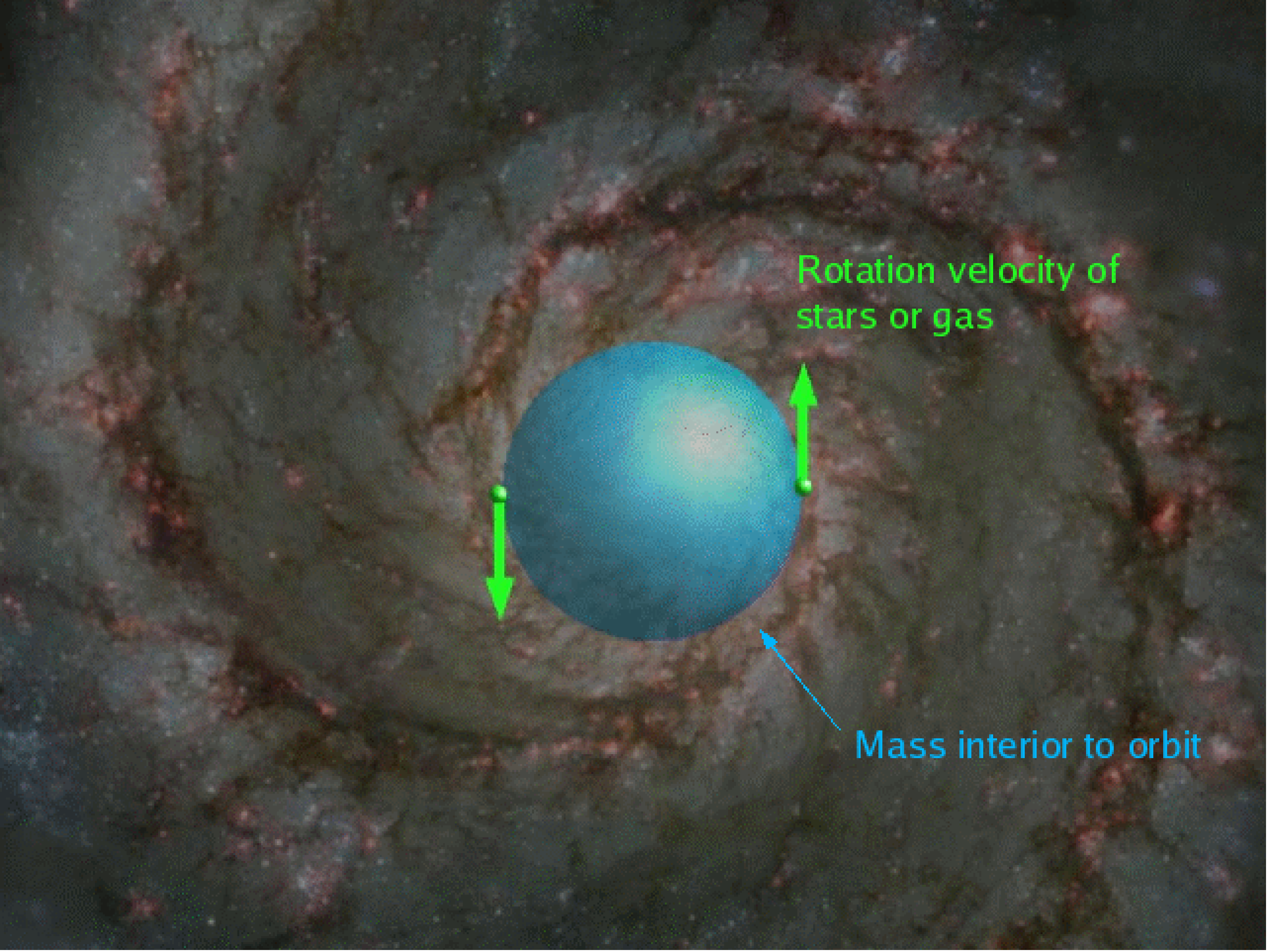
What is the dark matter?

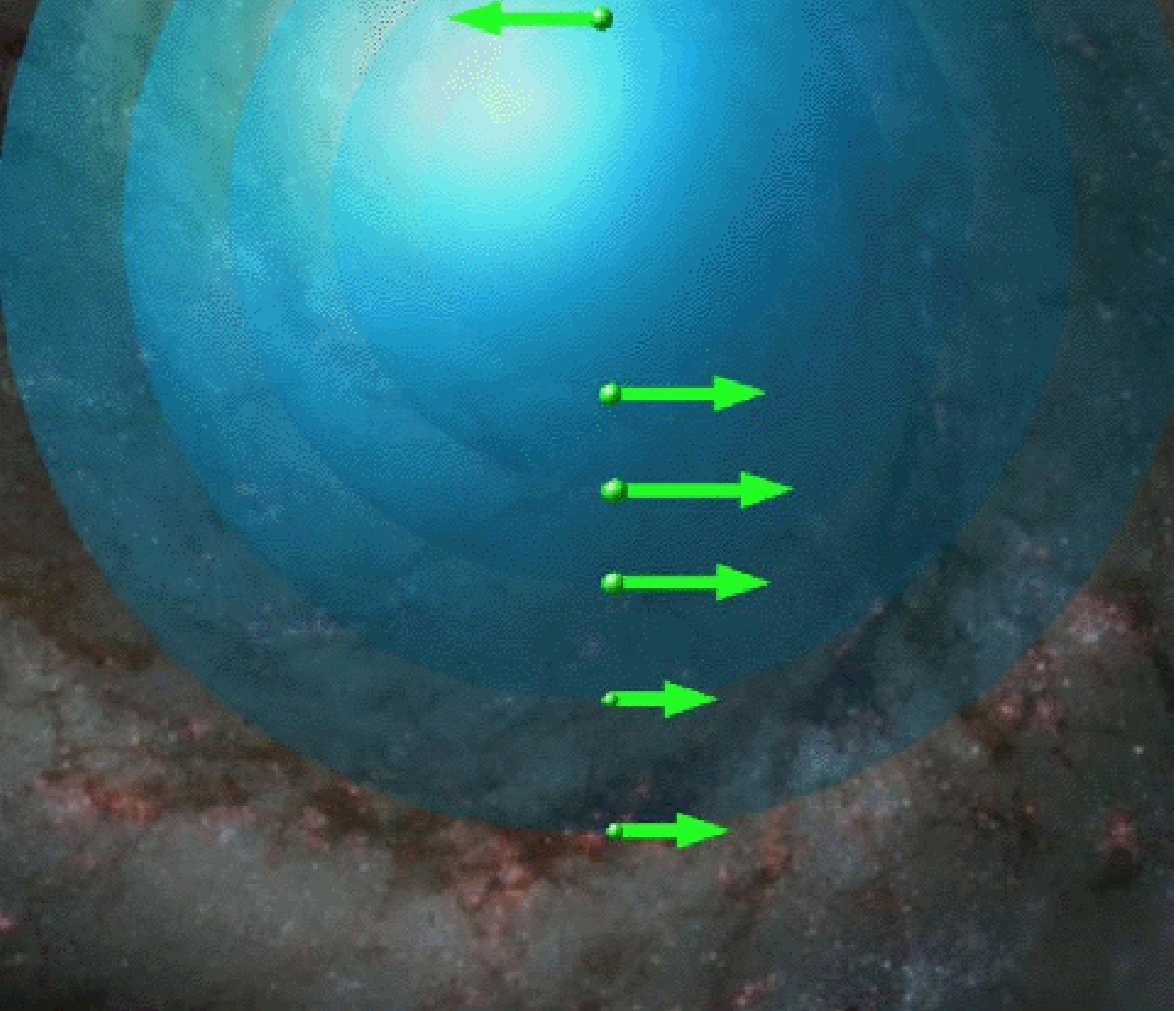
- Planets?
- Failed stars, aka "brown dwarfs"?
- Black holes?
- Relic particles from the Big Bang?
  - neutrinos
  - axions
  - neutralinos

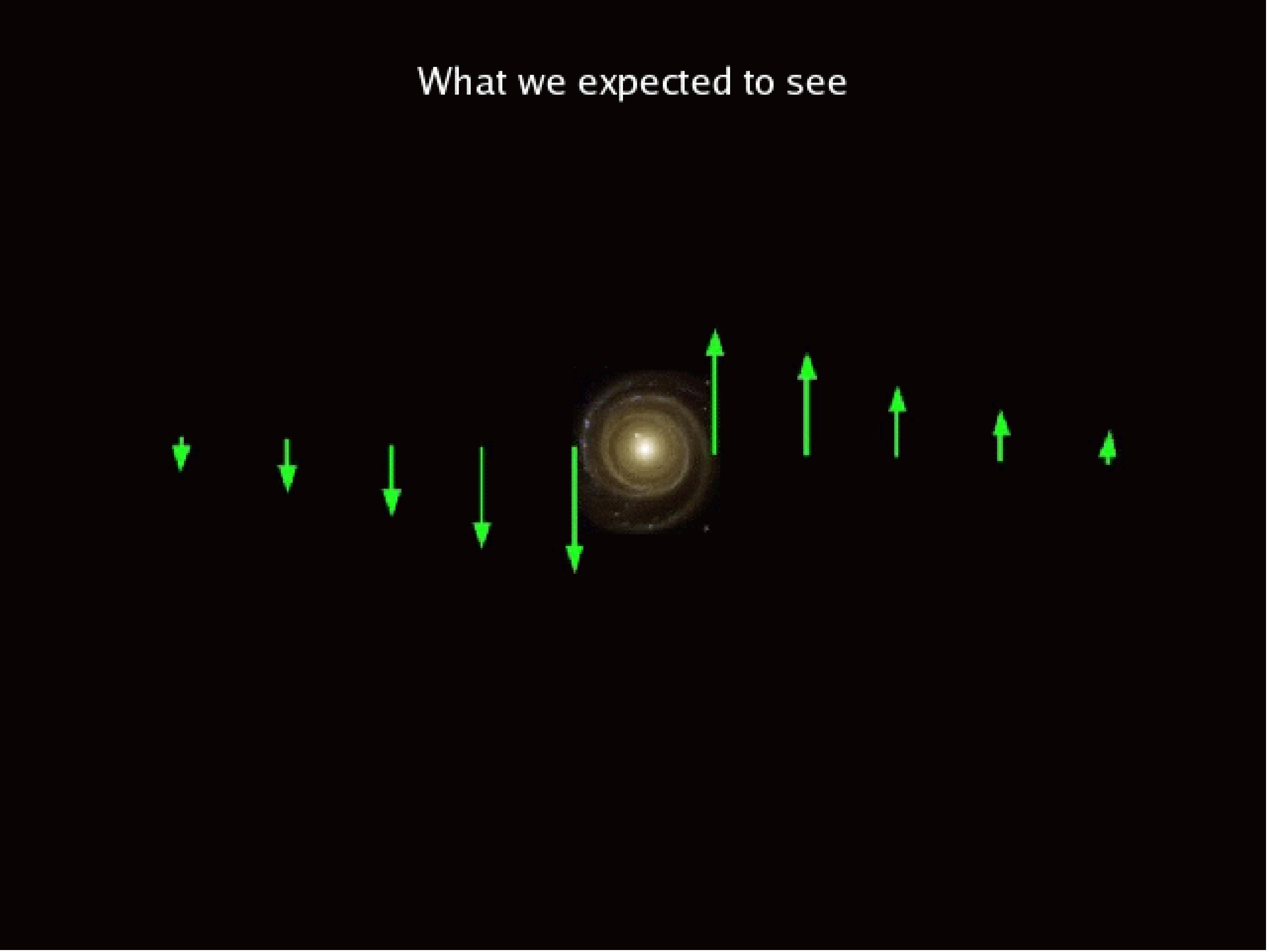
**Lots of good ideas,
but nobody knows for sure...**

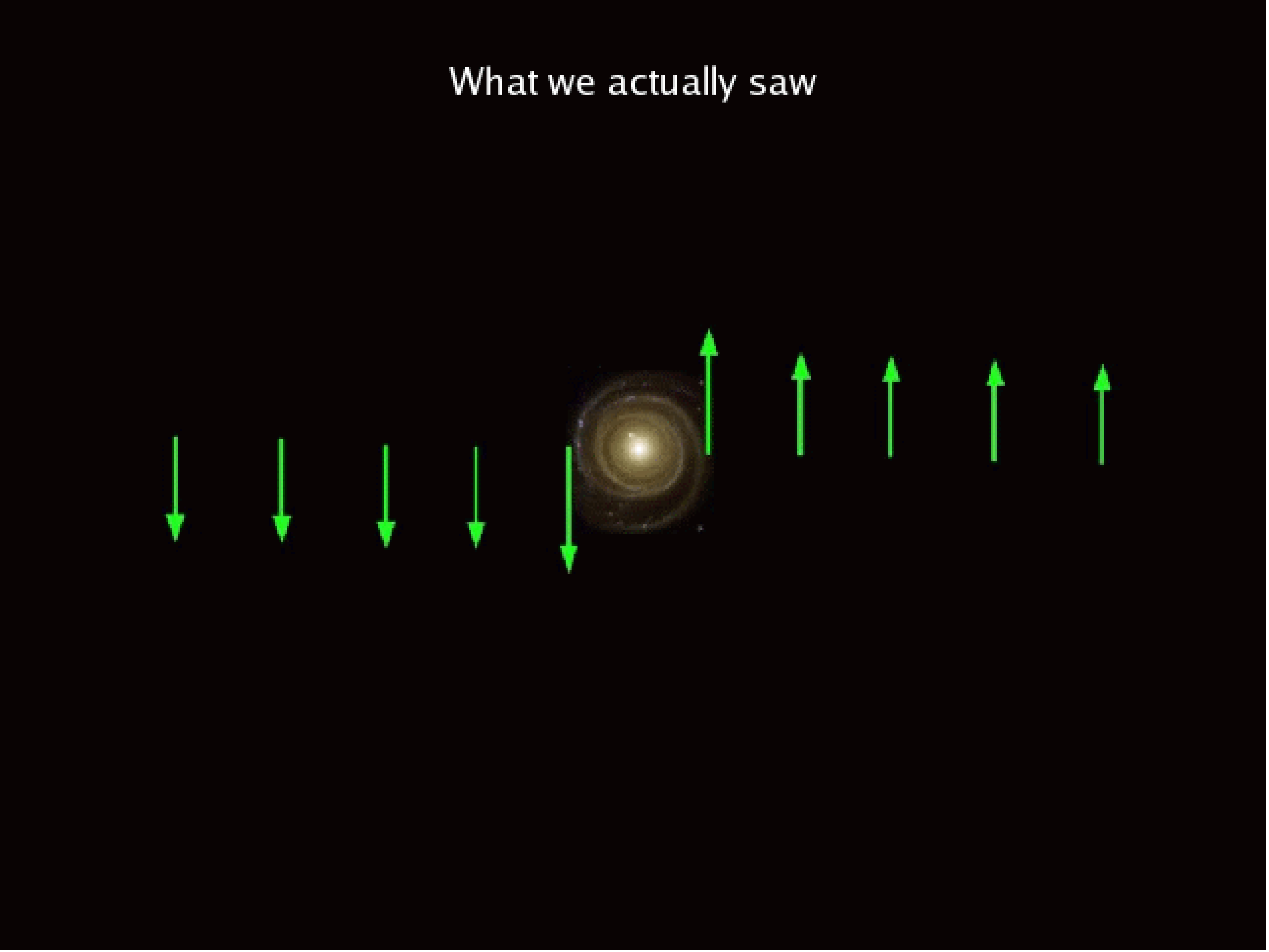

Dark Matter


Rotation velocity of
stars or gas

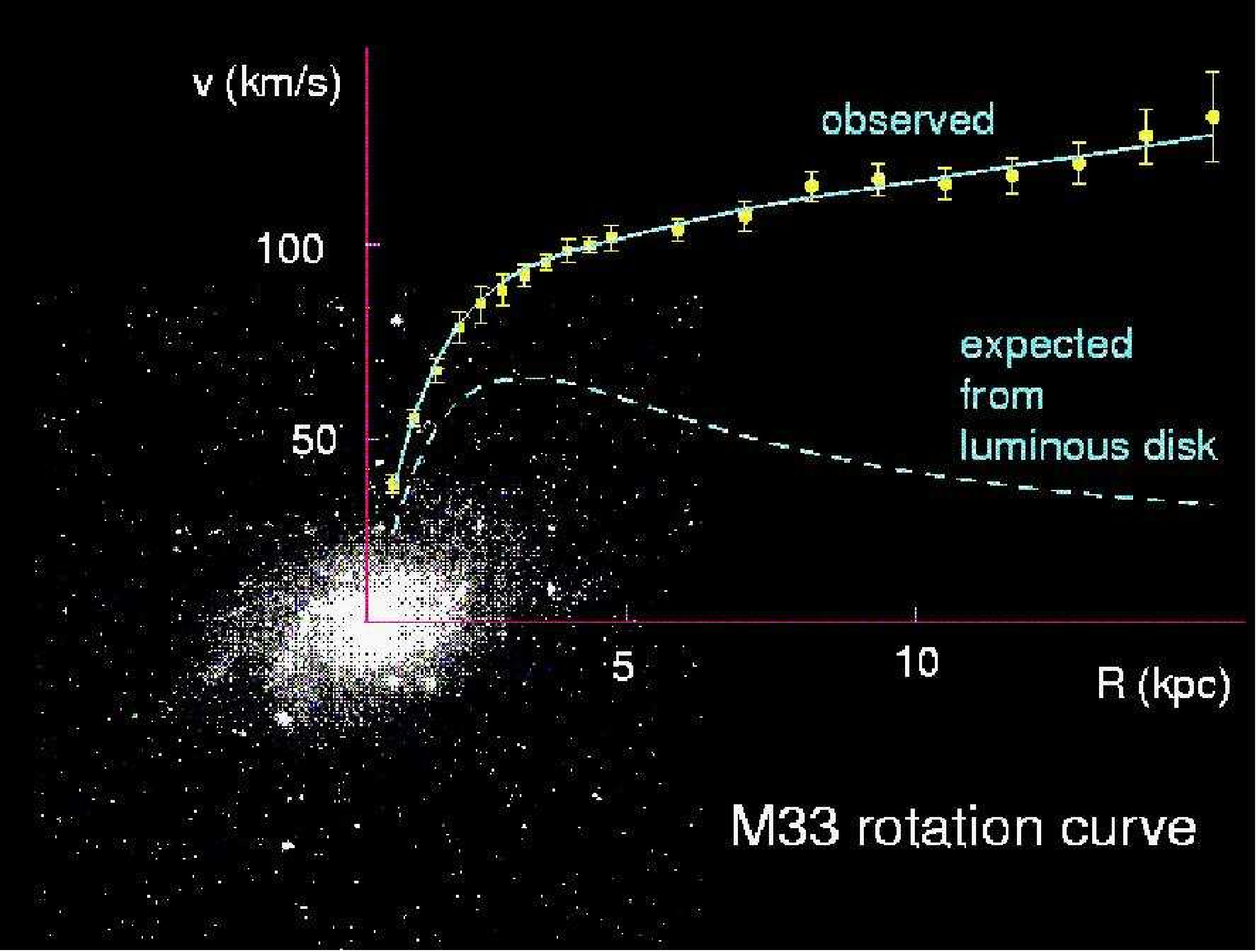

Rotation velocity of
stars or gas
Mass interior to orbit

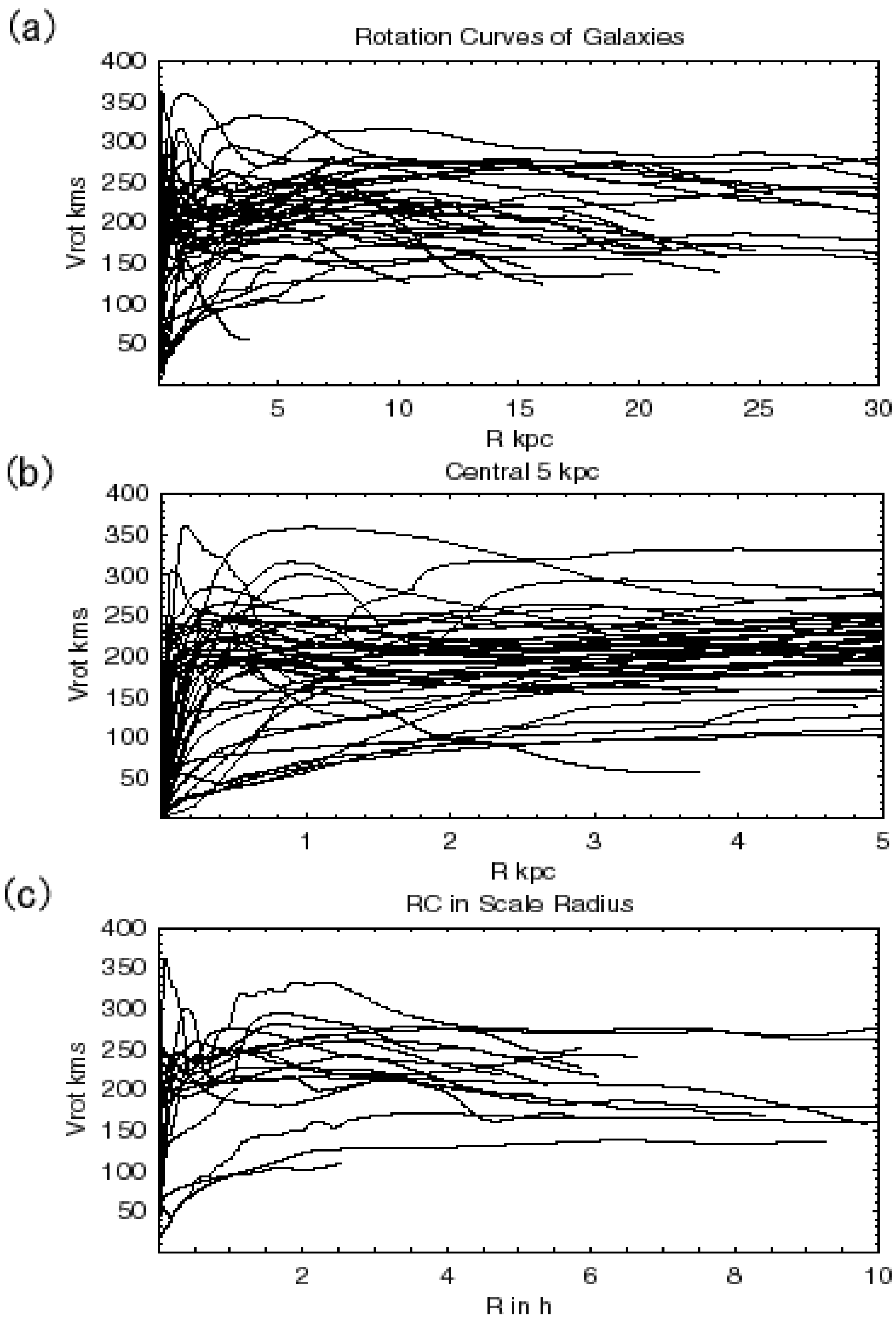



What we expected to see


What we actually saw

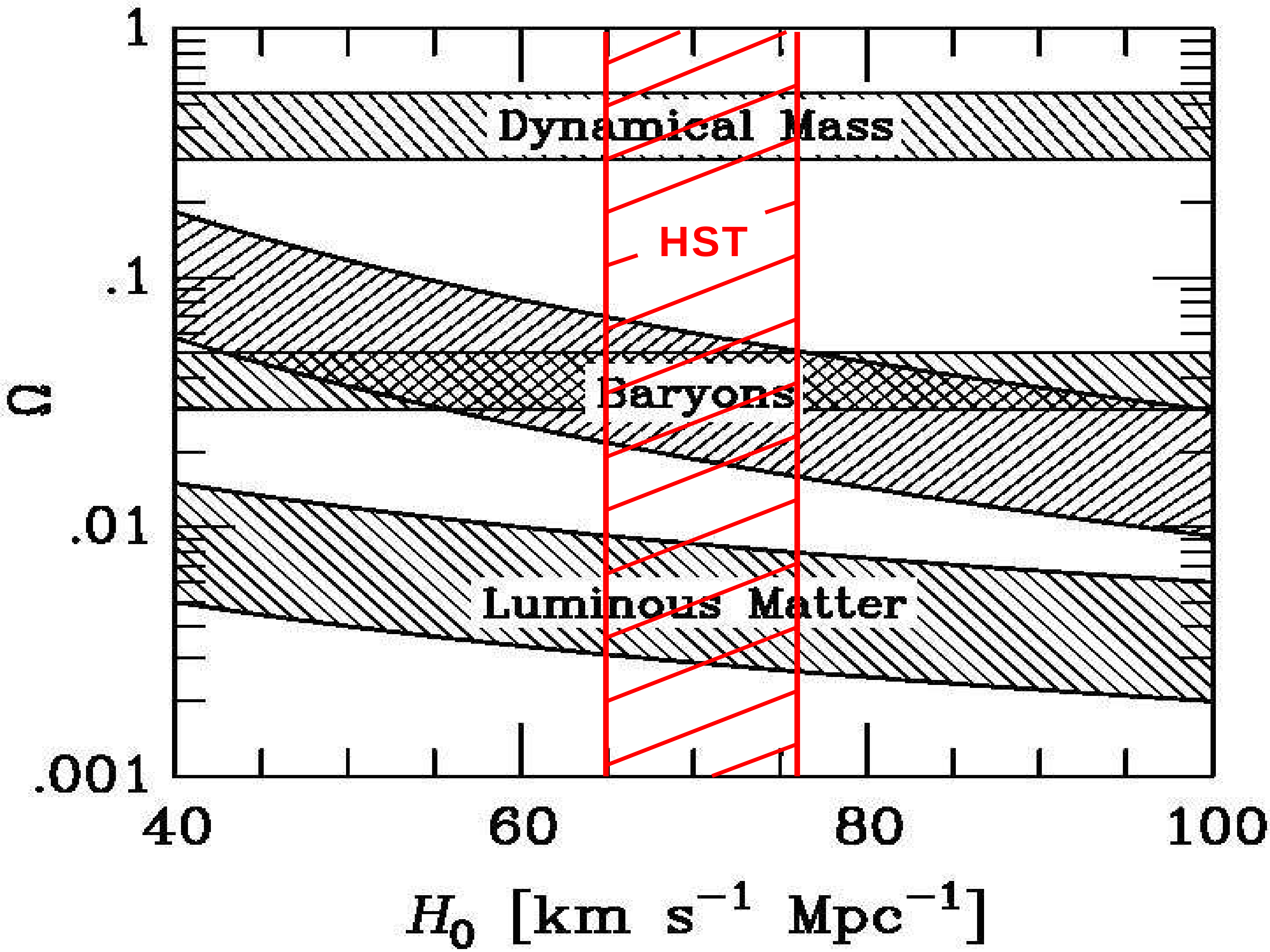

Galaxies have dark halos


v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

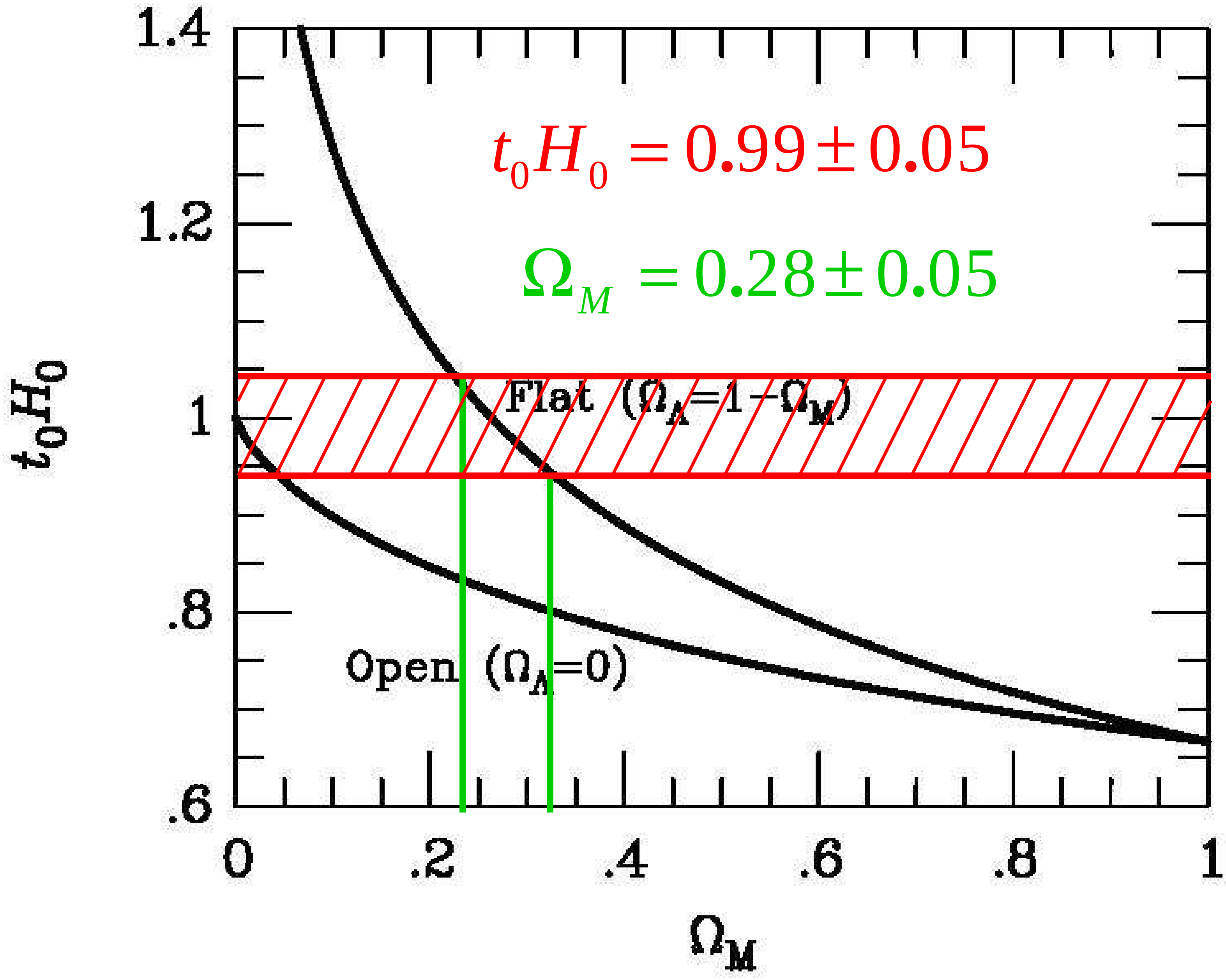


Rotation curves of galaxies

$$\Omega_{dark} \approx 10\,\Omega_{stars}$$

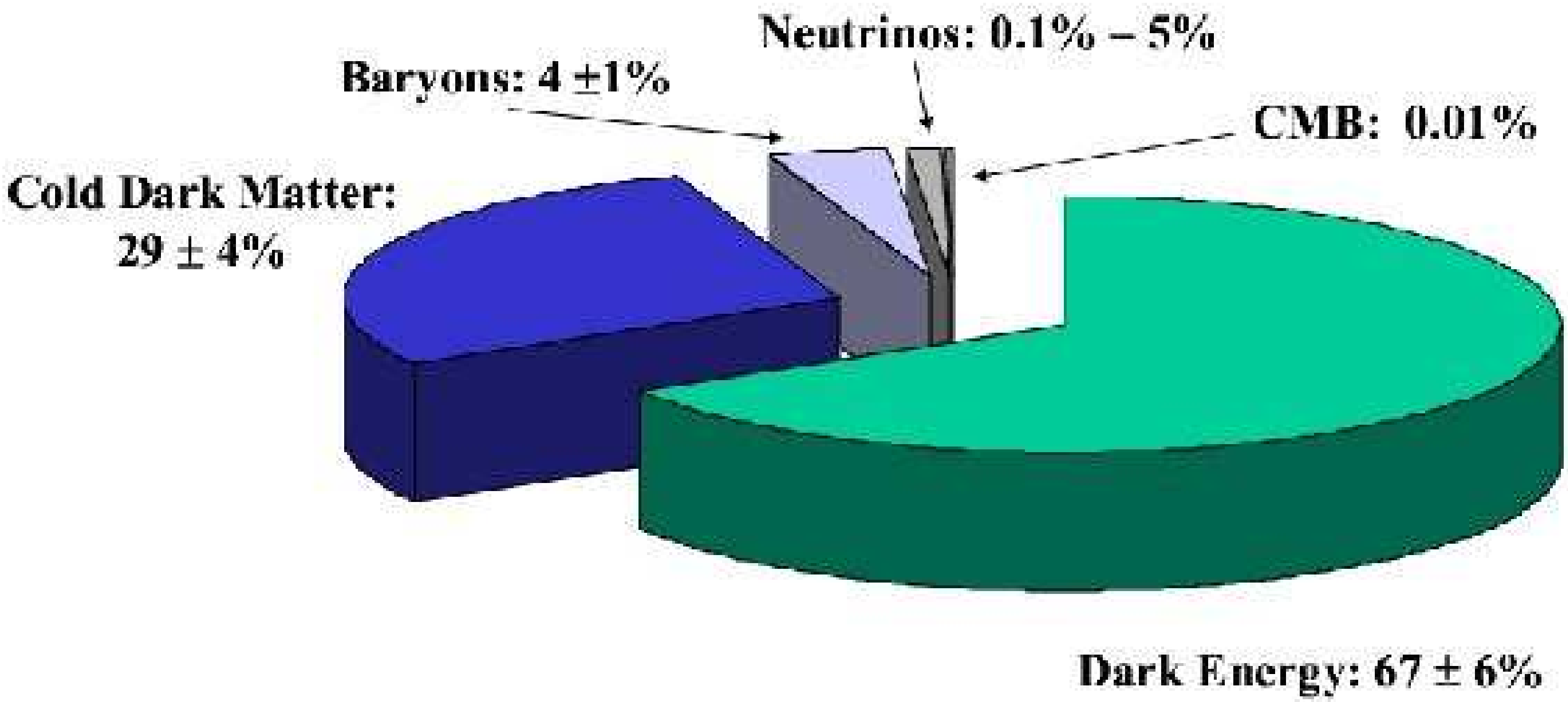


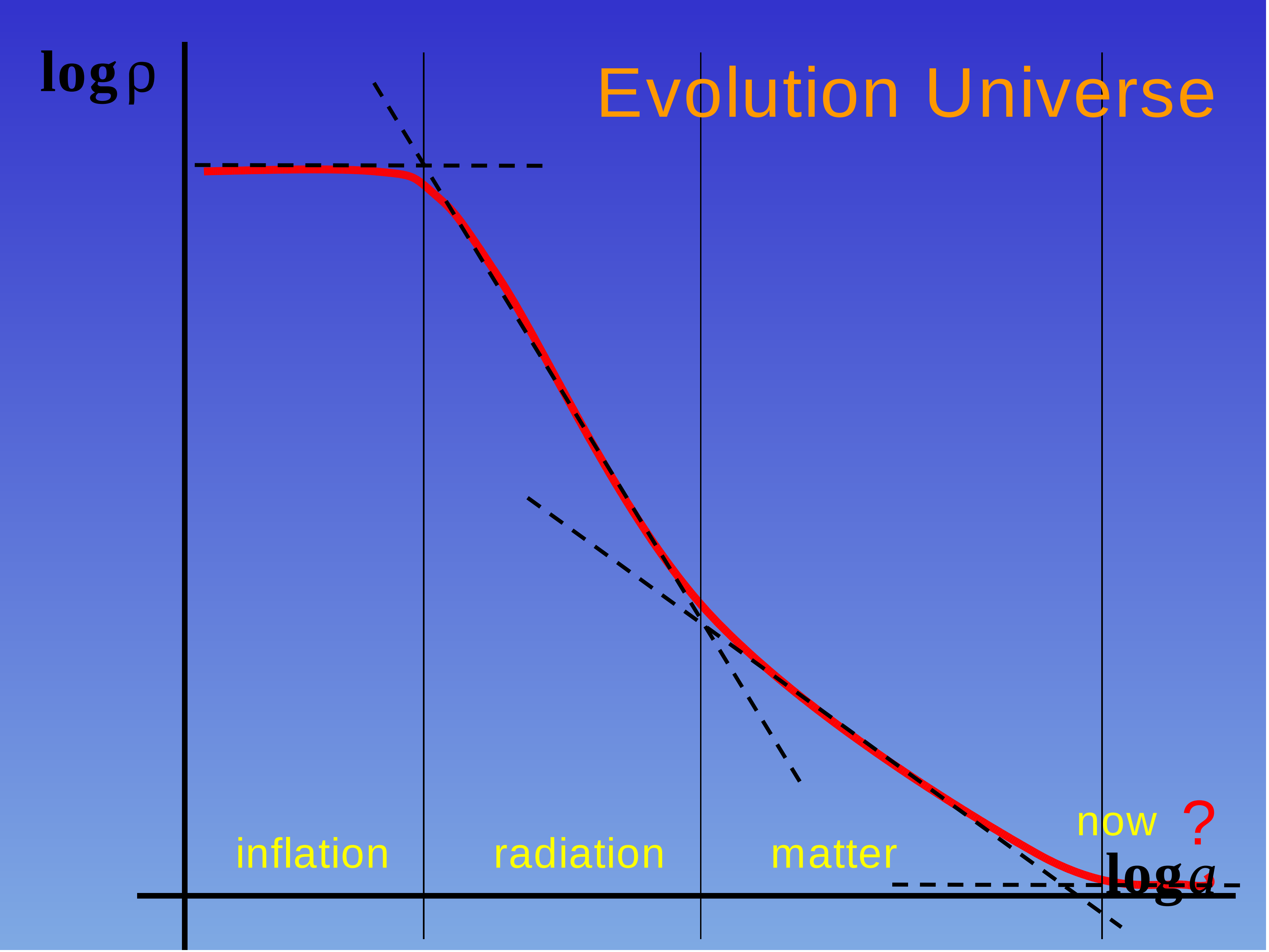
1
.1
.01
.001
Ω
Dynamical Mass
HST
Baryons
Luminous Matter
40
60
80
100
H_0 [km s^{-1} Mpc^{-1}]



$t_0 H_0 = 0.99 \pm 0.05$
$\Omega_M = 0.28 \pm 0.05$
Flat (Ω_Λ=1−Ω_M)
Open (Ω_Λ=0)
$t_0 H_0$
Ω_M
1.4
1.2
1
.8
.6
0
.2
.4
.6
.8
1

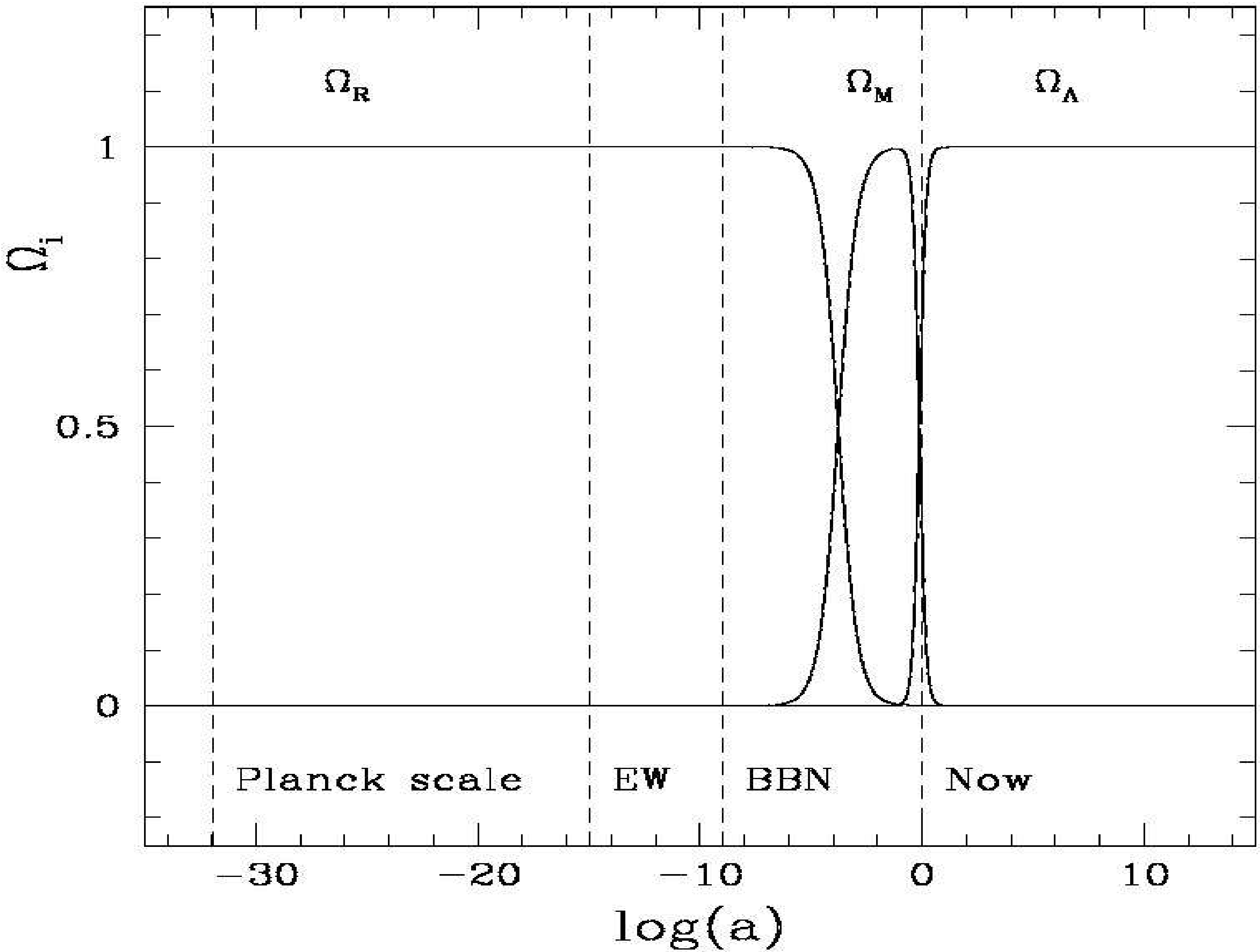
Matter and Energy in the Universe: A Strange Recipe



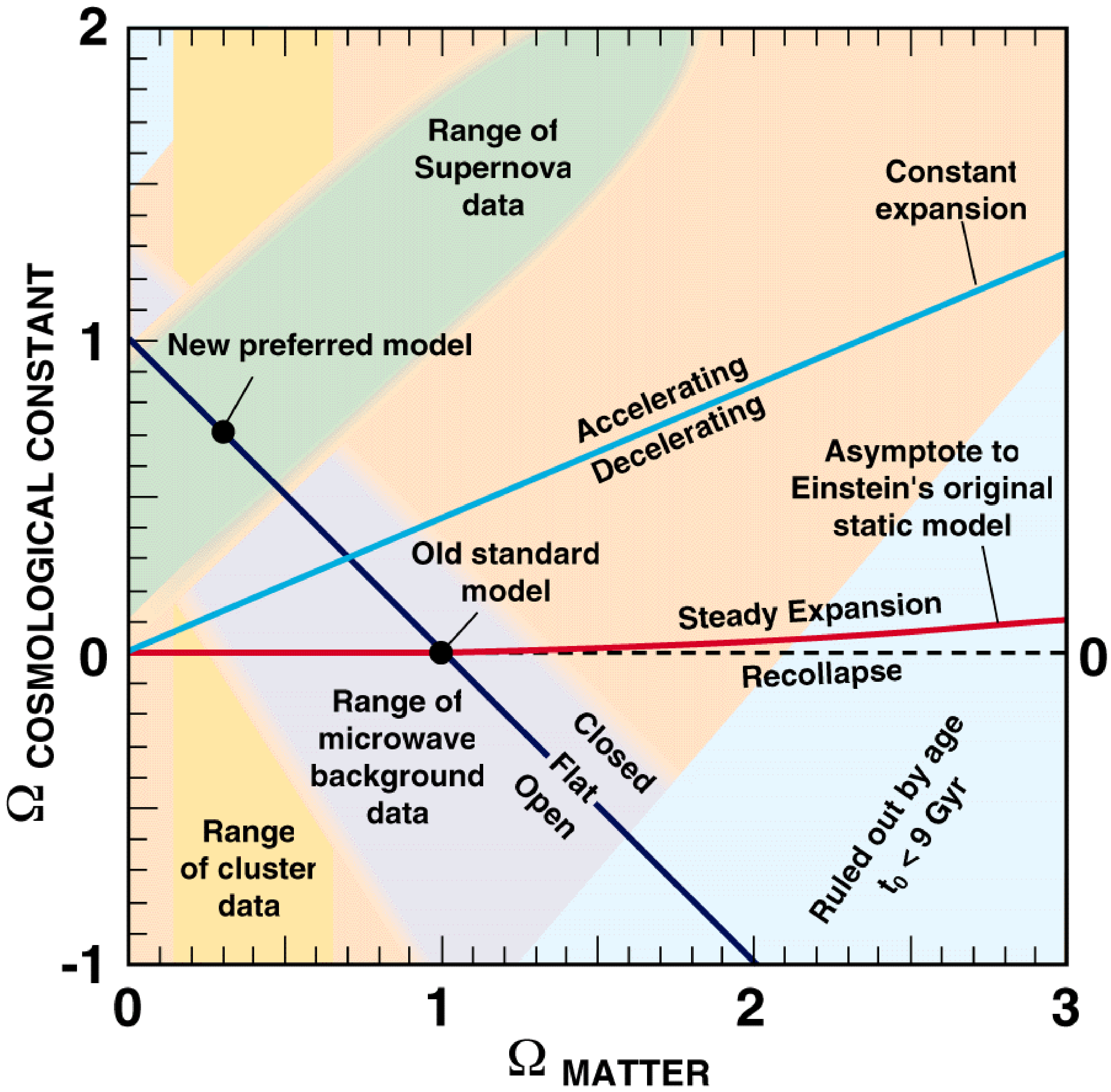


log ρ
Evolution Universe
inflation
radiation
matter
now
?
log a

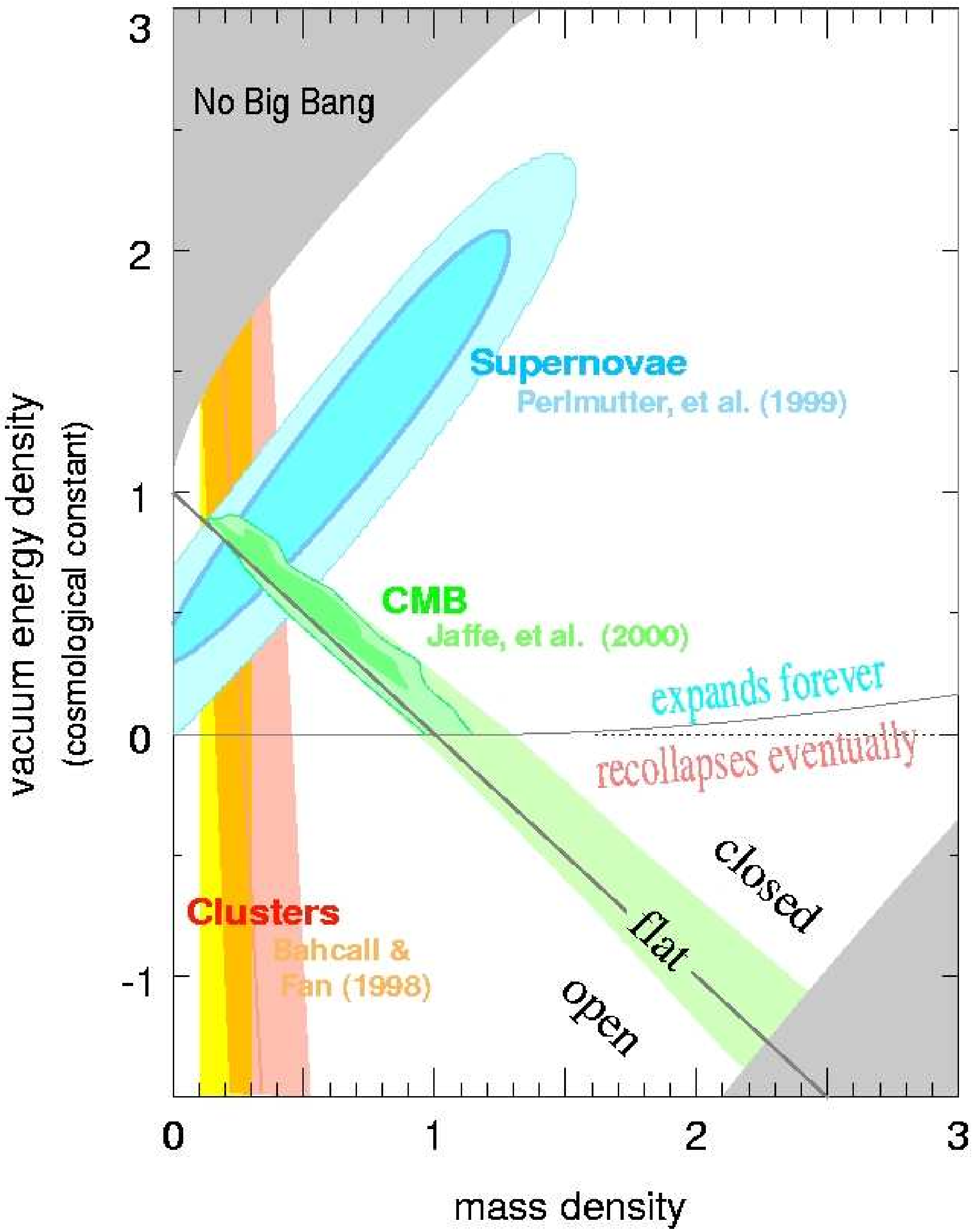
Cosmic coincidence?



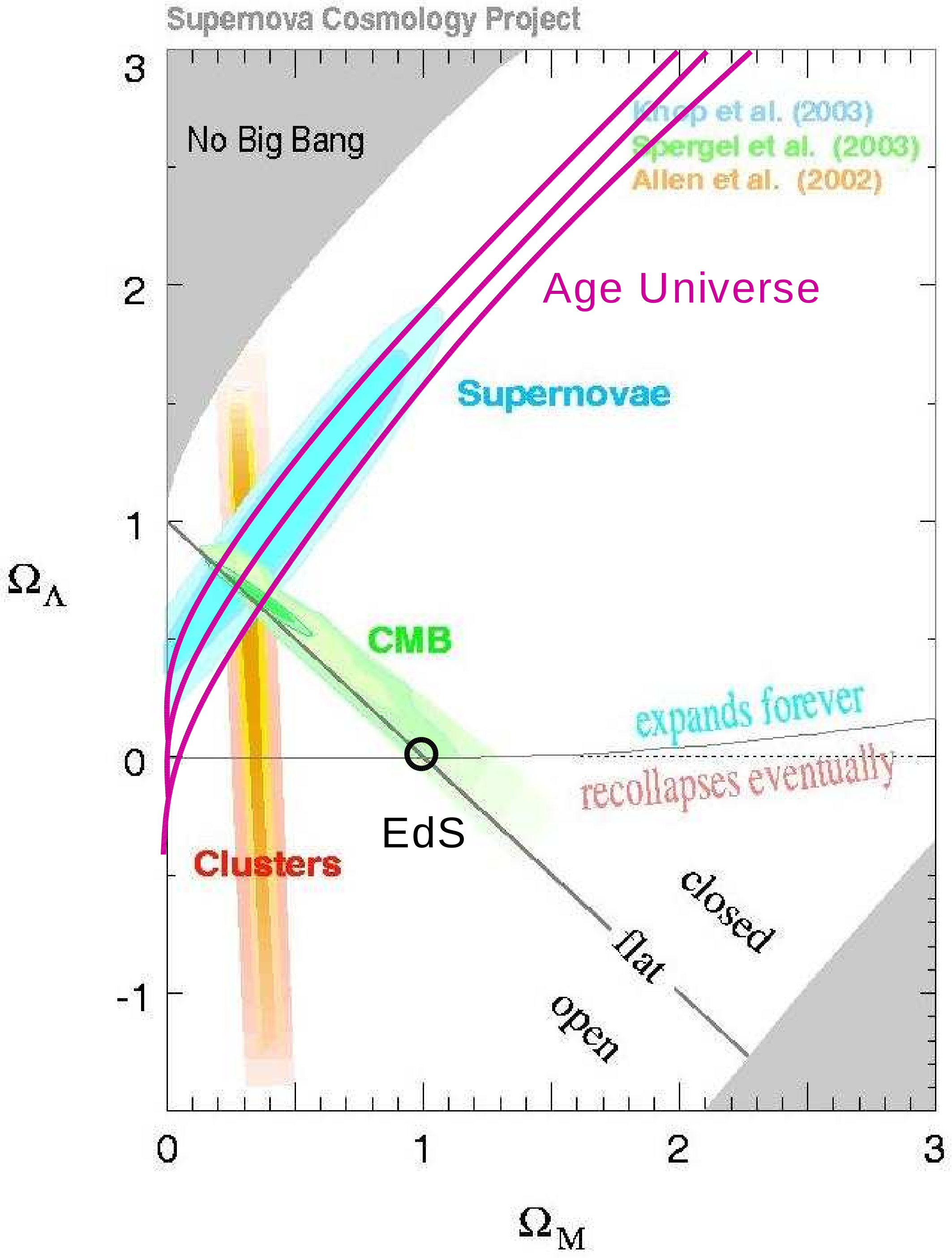
From Concordance to Standard Model



Cosmic Data (1999)



THE
CONCORDANCE
MODEL
(2001)



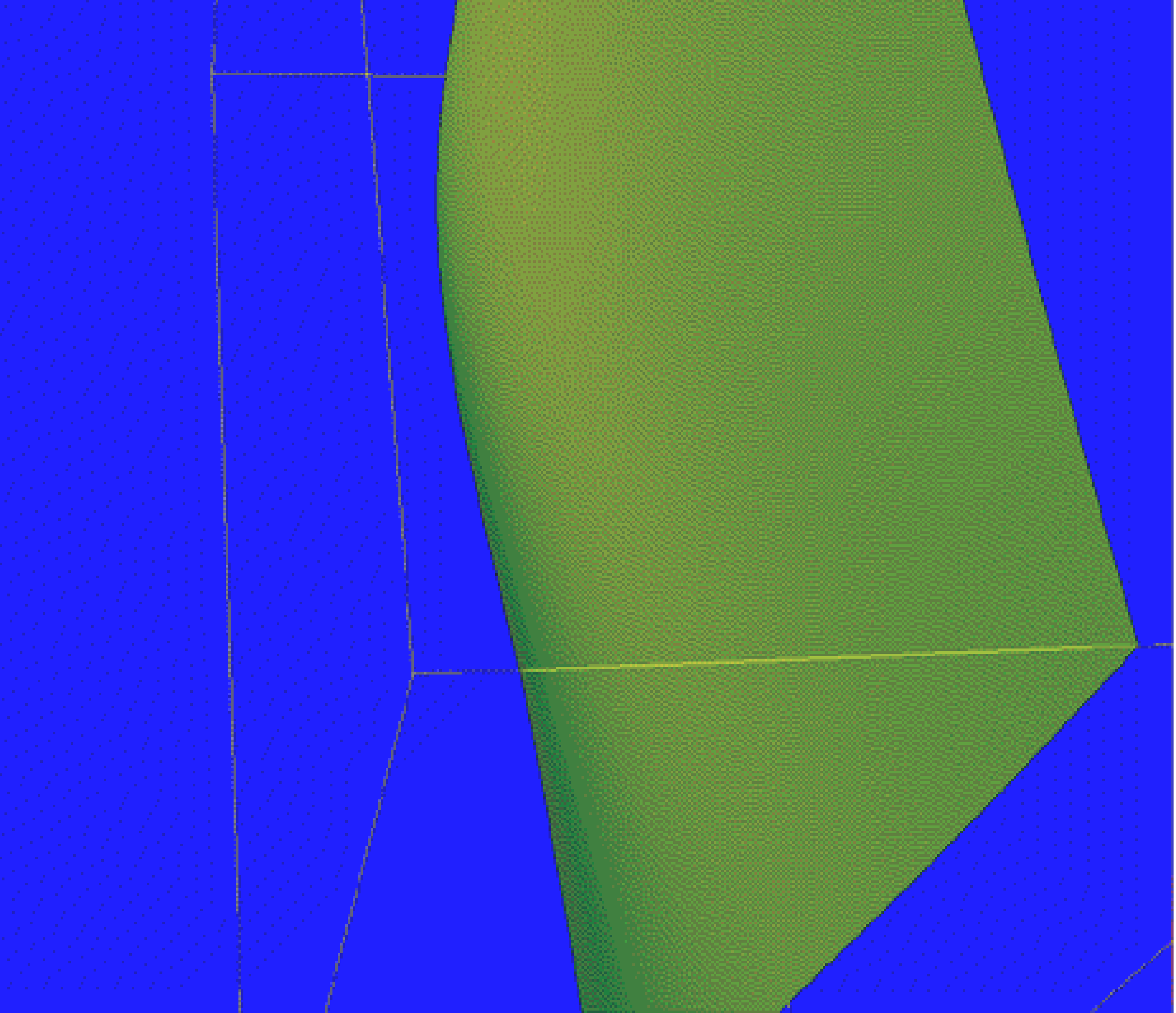
STANDARD COSMOLOGICAL MODEL (2003)

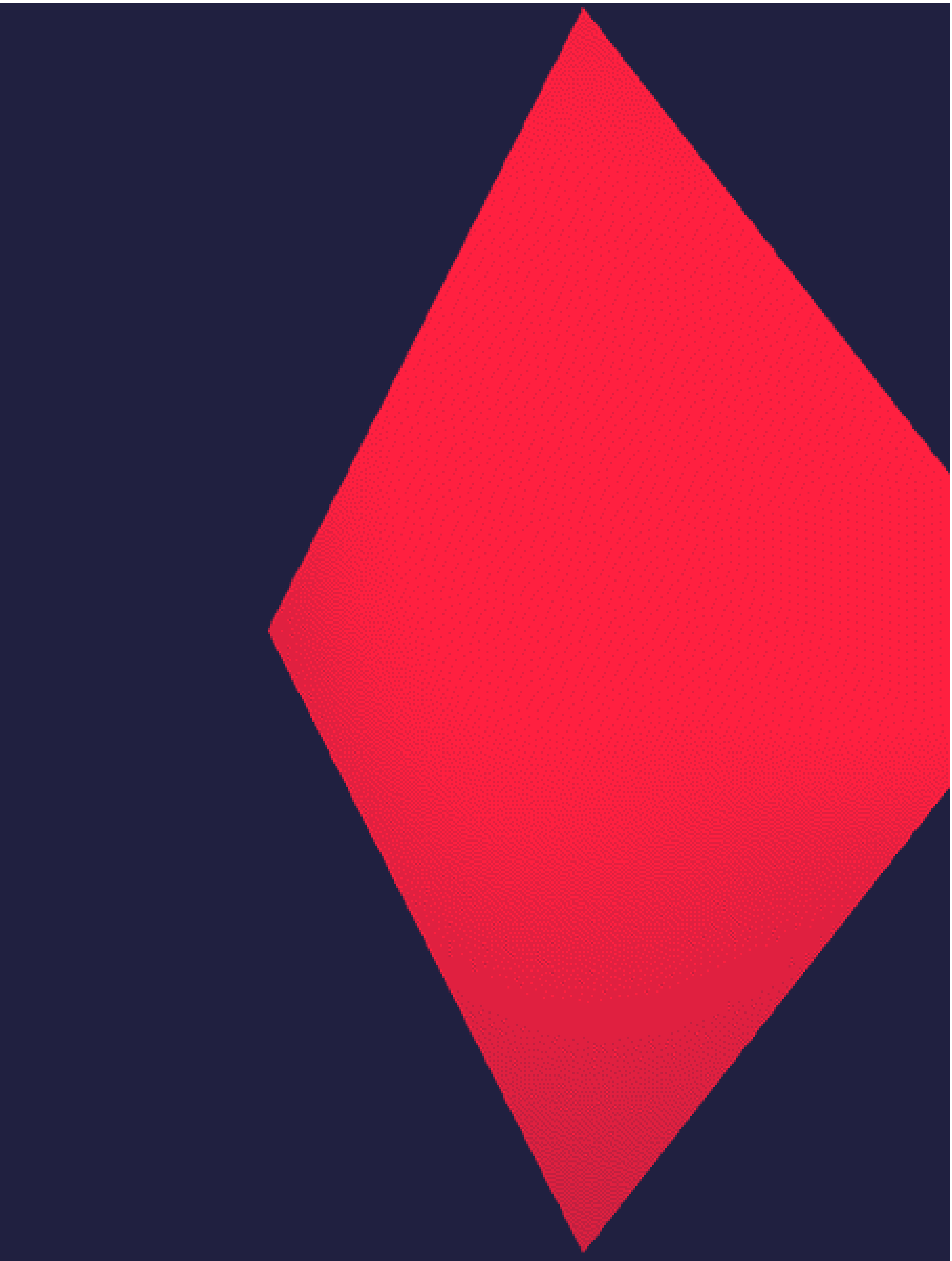
$$\Omega_M = 0.27 \pm 0.04$$
$$\Omega_\Lambda = 0.73 \pm 0.04$$
$$\Omega_0 = 1.02 \pm 0.02$$
$$\Omega_B = 0.044 \pm 0.004$$
$$H_0 = 71 \pm 3 \text{ km/s/Mpc}$$
$$t_0 = 13.6 \pm 0.2 \text{ Gyr}$$

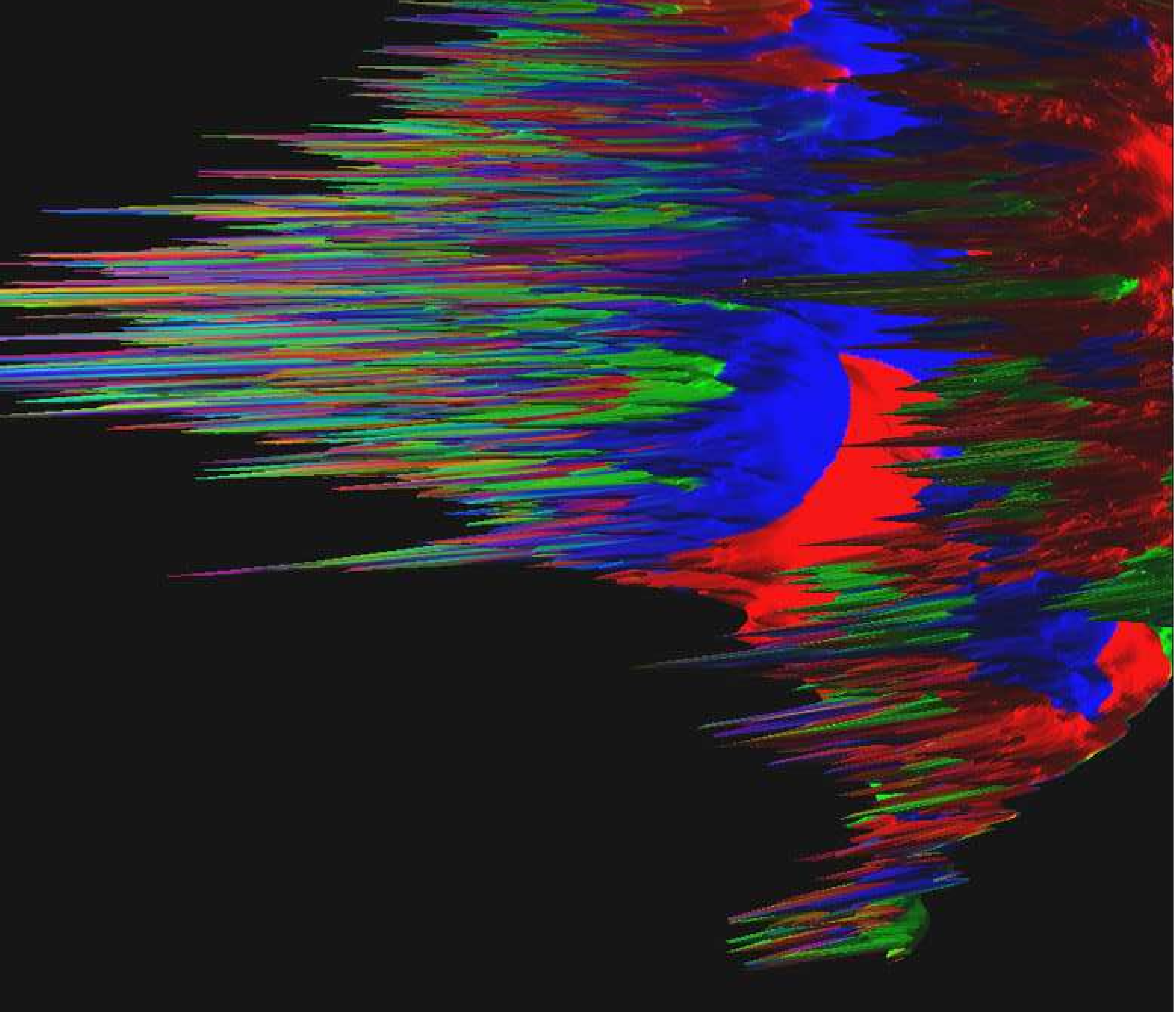
Precision Cosmology!
Errors < few%

THE FUTURE MODEL (2010)

The Global structure of the universe







Conclusions

- Cosmology is becoming “Cosmonomy”, the science of measuring the Cosmos
- The stuff we are made of amounts to just a few percent of all the matter/energy
- Dark matter is here to stay. It could open the door to a new type of particle species (e.g. susy)
- Some kind of dark energy or “smooth tension” is responsible for the acceleration of the Universe. We have no idea of what it is
- We may measure our Local Universe but we ignore its Global Structure

- The inflationary paradigm provides a general framework in which one can describe all cosmological observations

- The microwave background anisotropies contain a huge amount of information on the cosmological parameters, with very small systematic errors

- The Standard Cosmological Model, with errors of 1%, has two unsolved fundamental problems: the nature of dark matter and the dark energy

Addendum

Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2} \qquad ij+00$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \qquad 00$$

Equation of state of matter

$$p(t) = w\rho(t)$$

Spatial curvature

Closed

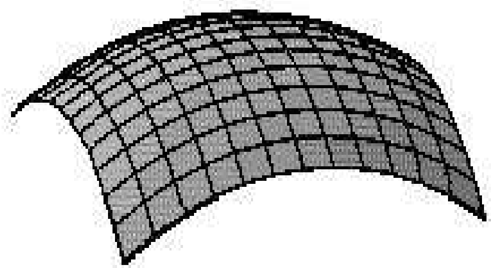
$K = +1$

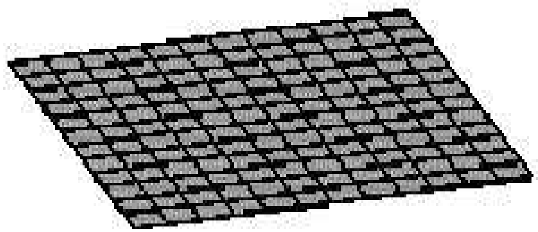
Flat

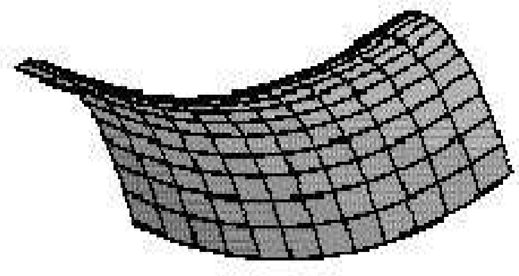
$K = 0$

Open

$K = -1$





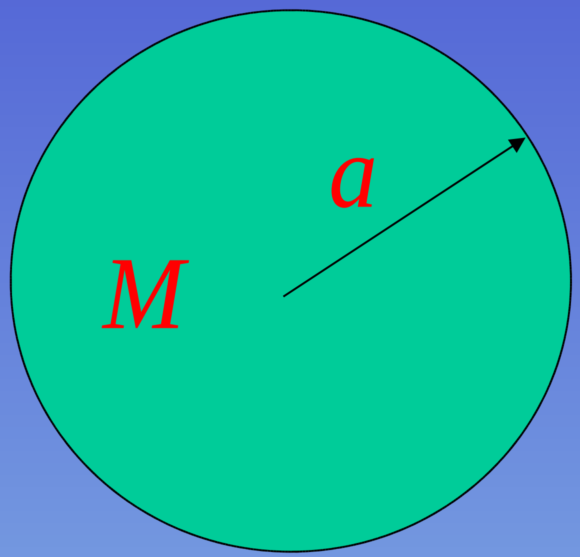


Friedmann equation $(\Lambda = 0)$

$$\frac{1}{2}\dot{a}^2 - \frac{GM}{a} = -\frac{K}{2}$$

$$E = T + V$$

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



$K = 0$ escape velocity

$K > 0$ recollapse

$K < 0$ expand forever

Friedmann equation $(\Lambda \neq 0)$

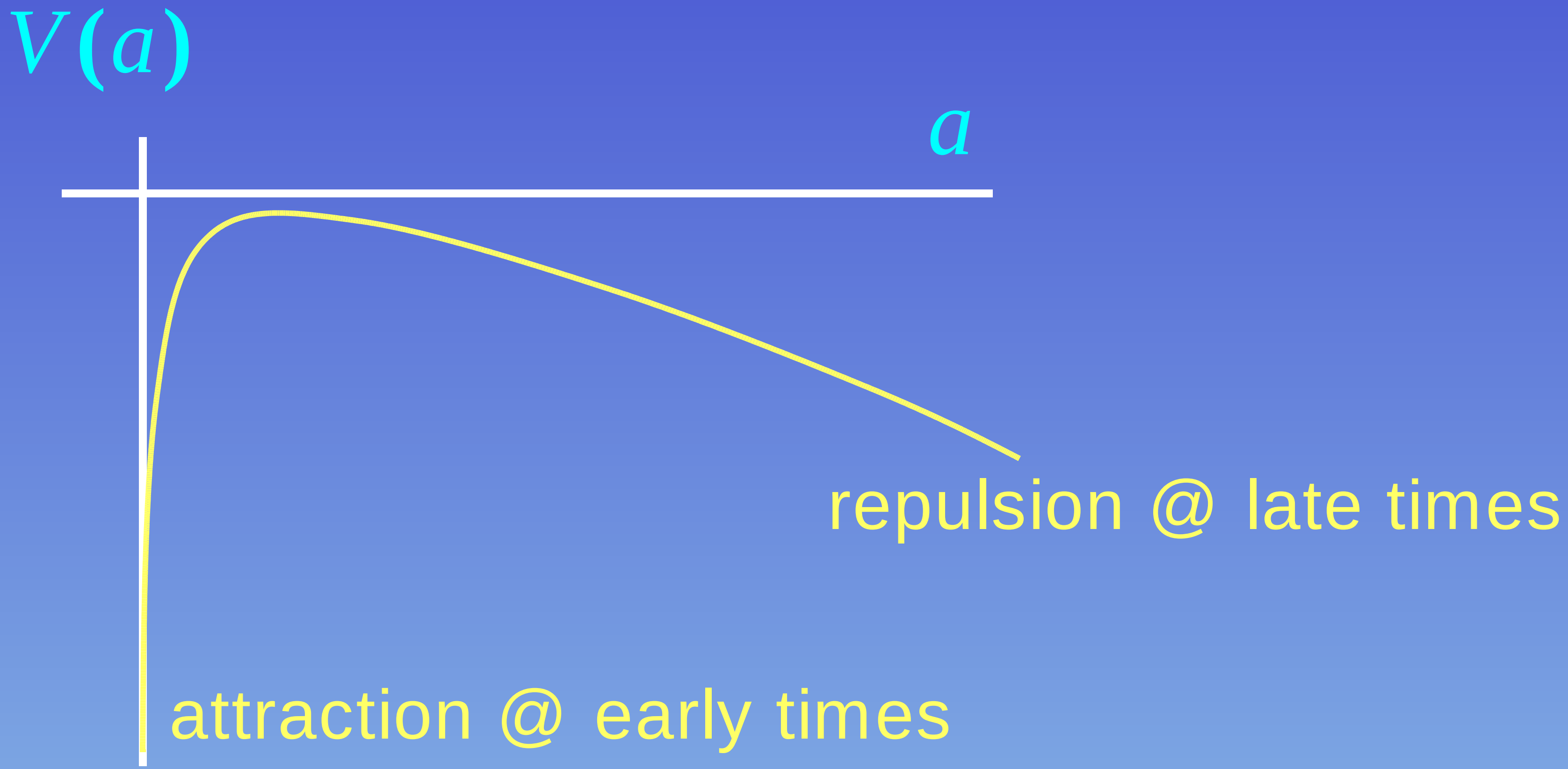
$$\ddot{a} = -\frac{GM}{a^2} + \frac{\Lambda}{3} a \qquad F = m\ddot{x}$$

Matter attraction   Cosmic repulsion

Who wins? and when?

Friedmann equation $(\Lambda \neq 0)$

$$E = T + V$$



Cosmological Parameters

Rate of Expansion (Hubble)

[illegible]

$$H_0^{-1} = 9.773\,h^{-1}\ \text{Gyr}$$ time

$$cH_0^{-1} = 3000\,h^{-1}\ \text{Mpc}$$ distance

$$1\,\text{pc} = 3.262\,\text{ly} = 3.086\times 10^{16}\,\text{m}$$

Critical density (K=0)

$$\rho_c(t_0) = \frac{3H_0^2}{8\pi G}$$

$$= 1.88\ h^2\ 10^{-29}\ \text{g/cm}^3$$

$$= 2.77\ h^{-1}\ 10^{11}\ \text{M}_\Theta / (h^{-1}\text{Mpc})^3$$

$$= 11.26\ h^2\ \text{protons/m}^3$$

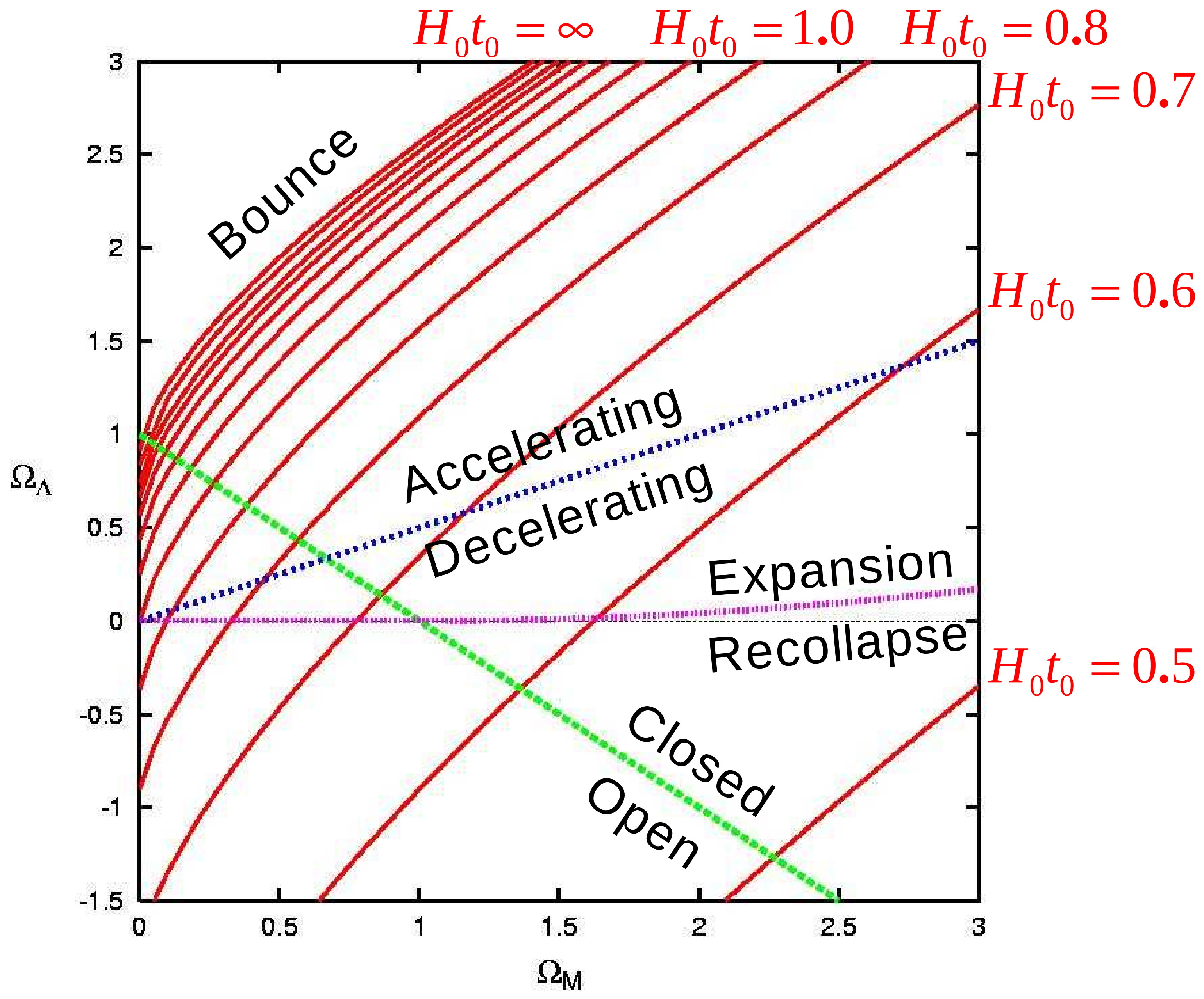
Density parameter

$$\Omega_0 = \frac{8\pi G}{3H^2}\rho(t_0) = \frac{\rho}{\rho_c}(t_0)$$

$$\Omega_0 = \Omega_R + \Omega_M + \Omega_\Lambda$$ Friedmann Eq.

$$\Omega_R = \frac{\rho_R}{\rho_c}(t_0) \qquad \Omega_M = \frac{\rho_M}{\rho_c}(t_0)$$

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2} \qquad \Omega_K = \frac{-K}{a_0^2 H_0^2}$$



$H_0 t_0 = \infty$
$H_0 t_0 = 1.0$
$H_0 t_0 = 0.8$
$H_0 t_0 = 0.7$
$H_0 t_0 = 0.6$
$H_0 t_0 = 0.5$
Bounce
Accelerating
Decelerating
Expansion
Recollapse
Closed
Open
Ω_Λ
Ω_M

Cosmological Parameters

H_0	Rate of expansion
t_0	Age of the Universe
q_0	Acceleration Parameter
Ω_K	Spatial Curvature
Ω_M	Dark Matter
Ω_Λ	Cosmological Constant
Ω_B	Baryon Density
Ω_ν	Neutrino Density