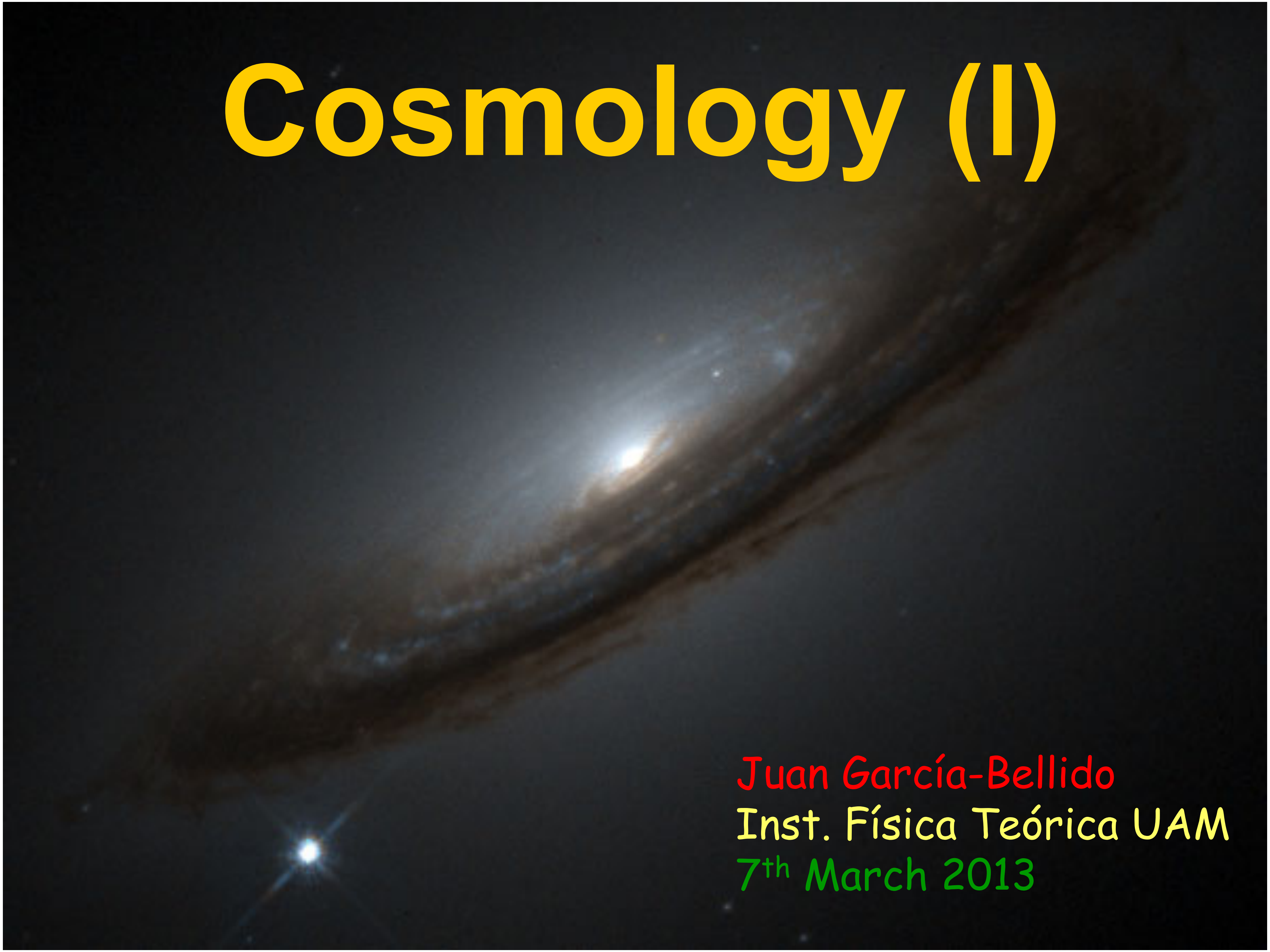
Cosmology (I)



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Inst. Física Teórica UAM
7th March 2013

Overview

I. The accelerating Universe

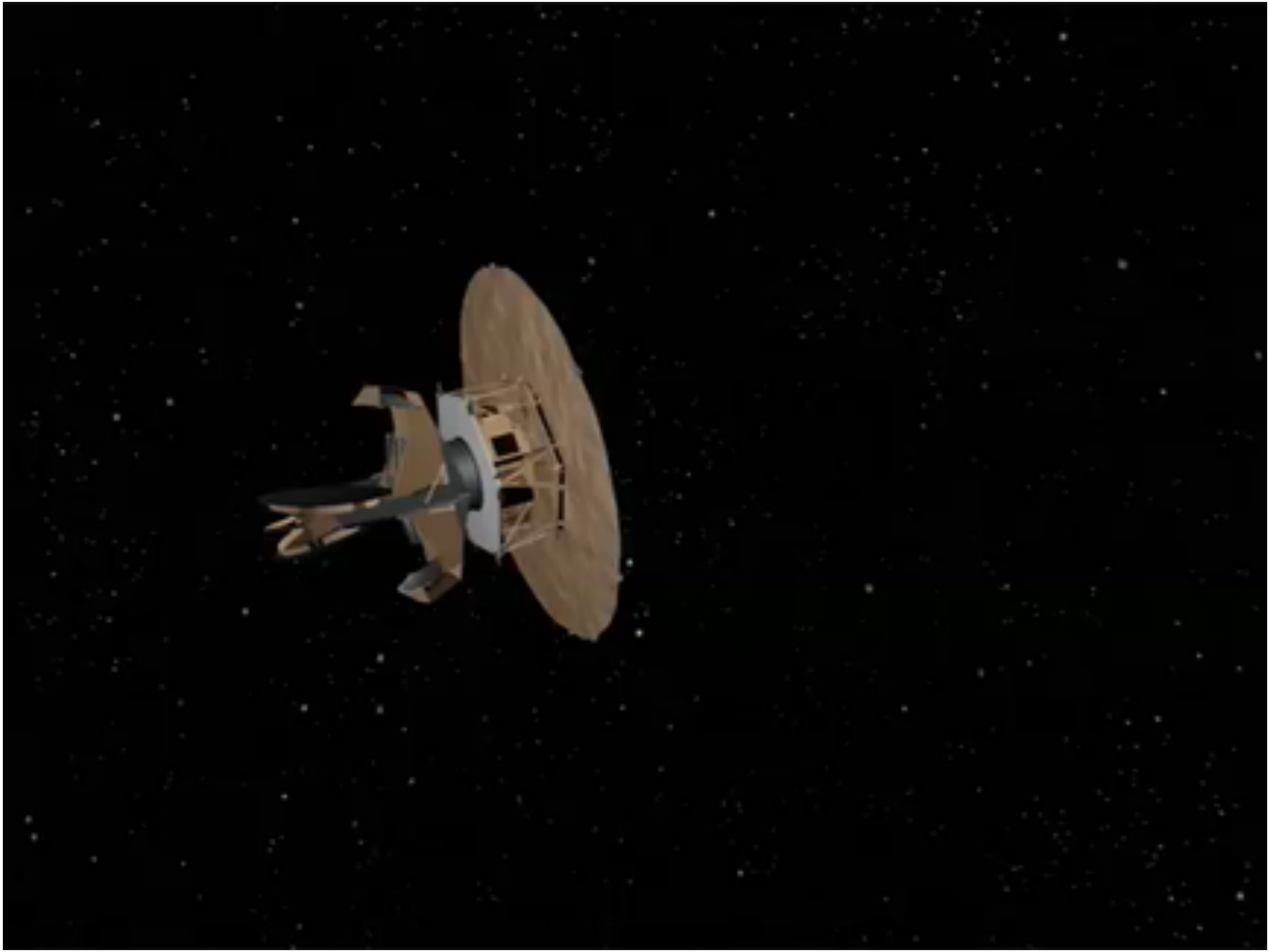
Dark Energy

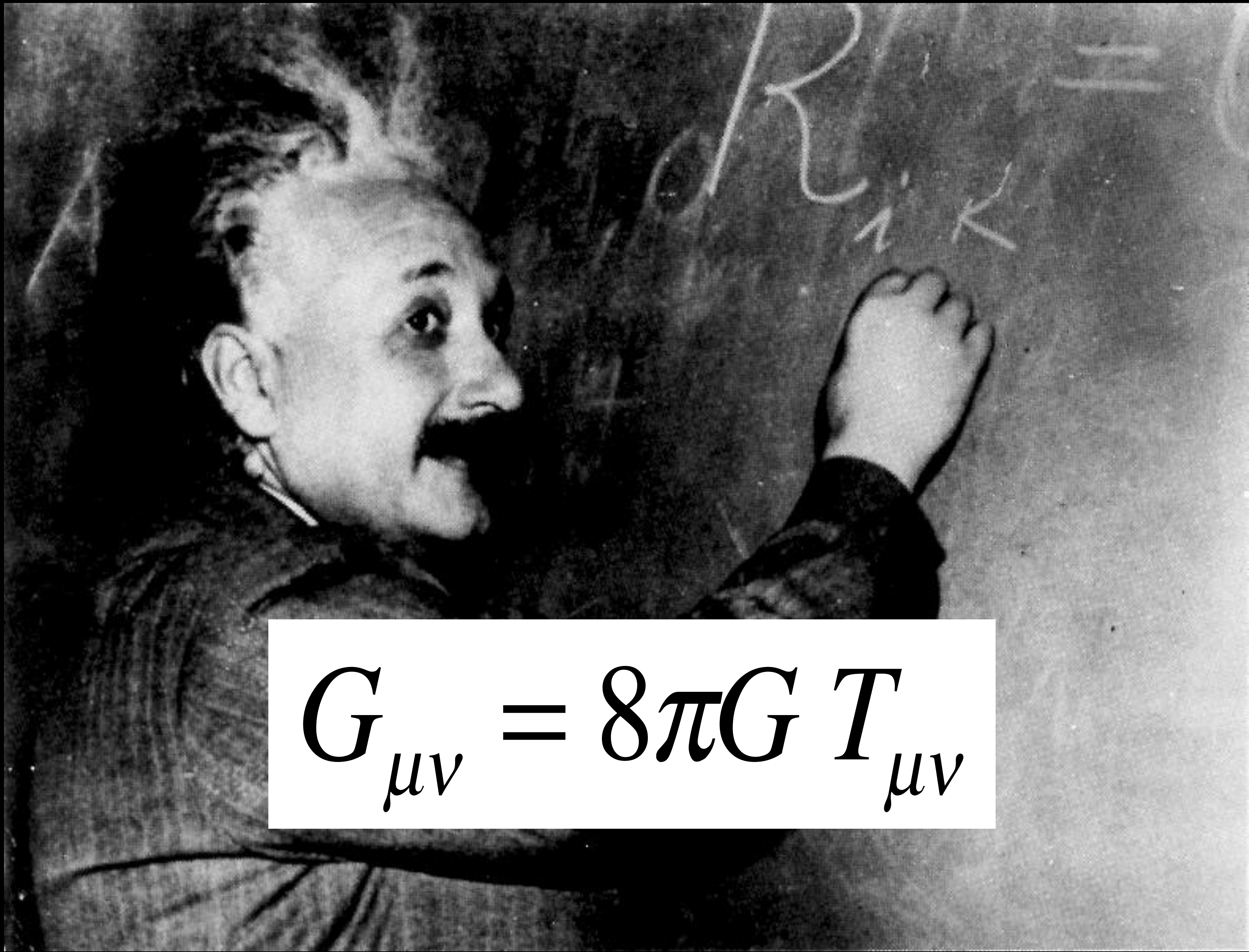
II. Structure Formation

Dark Matter

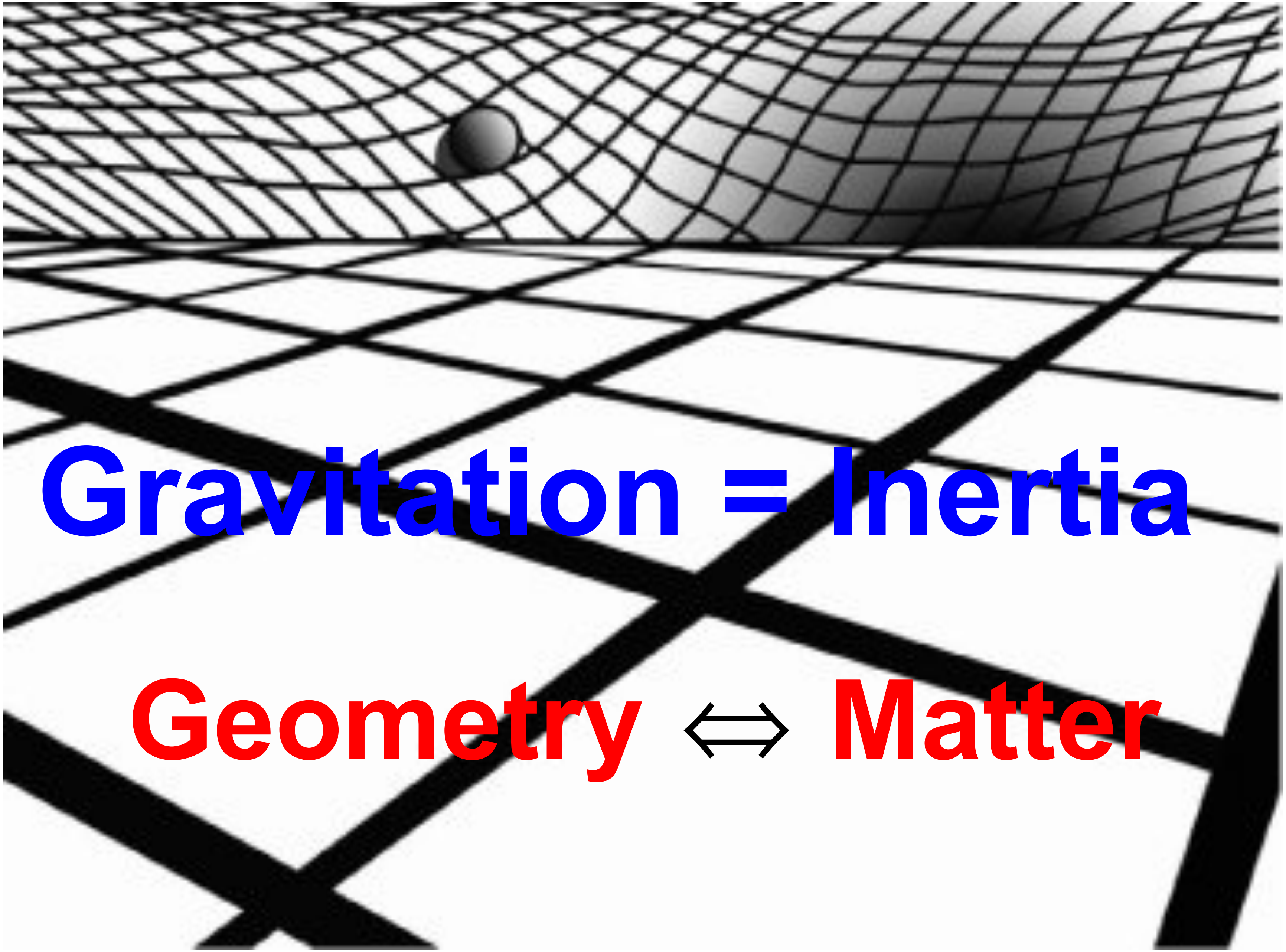
III. CMB Anisotropies

Inflation

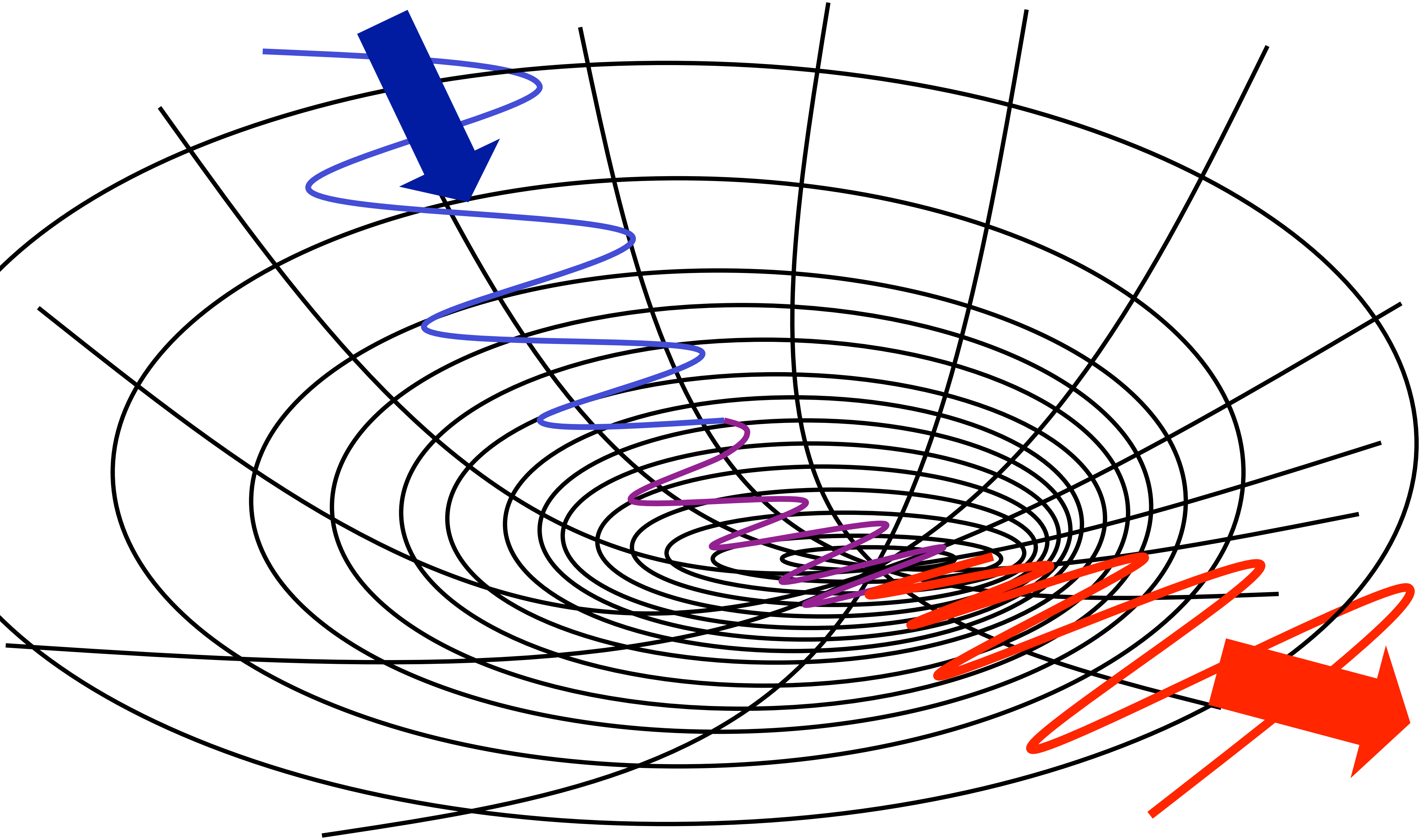




$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

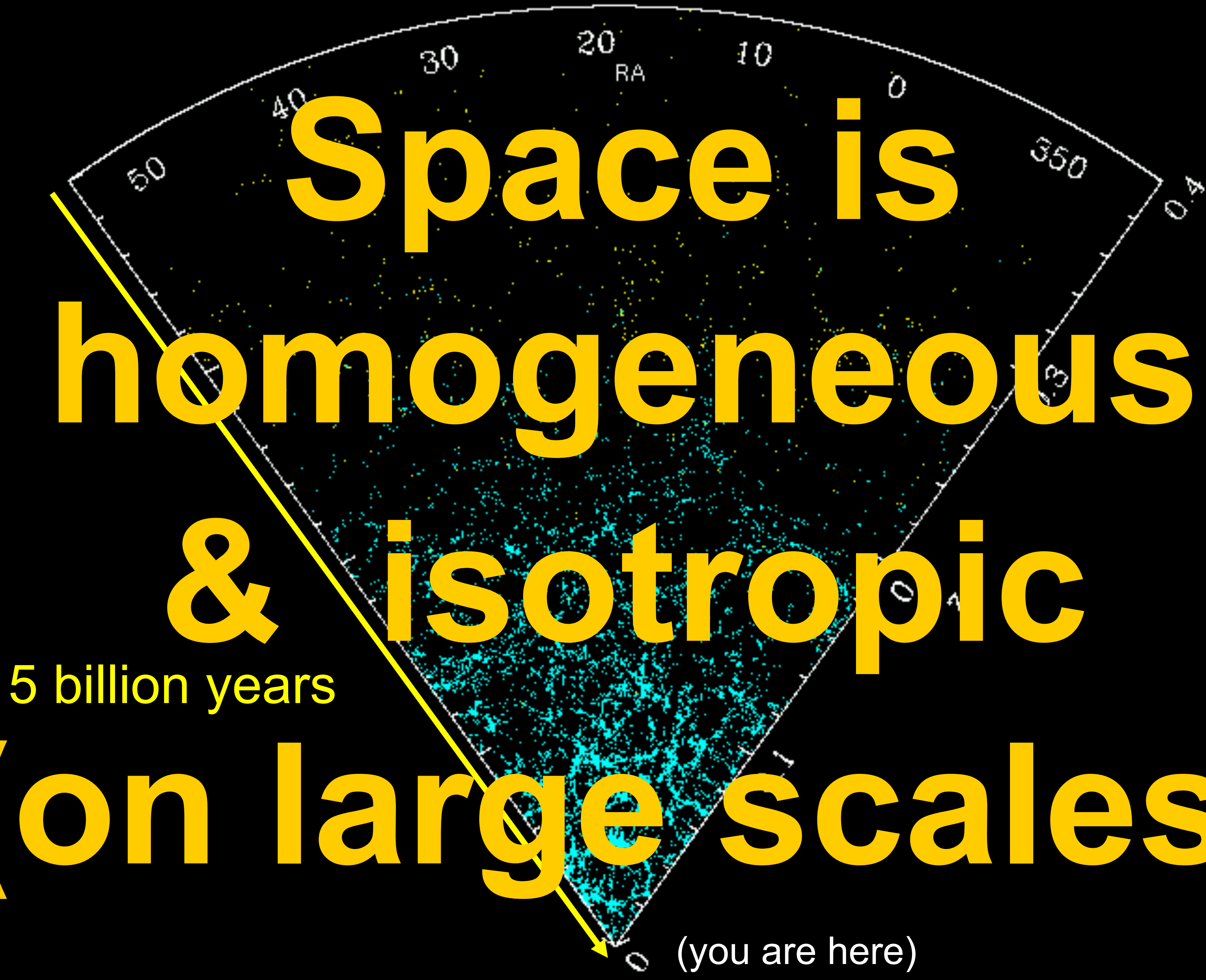

Gravitation = Inertia
Geometry ⇔ Matter

Gravitacional blueshift & redshift



What is the Geometry of Universe?

Space is homogeneous & isotropic (on large scales)



General Relativity

⇓

Universe expansion

Hot Big Bang

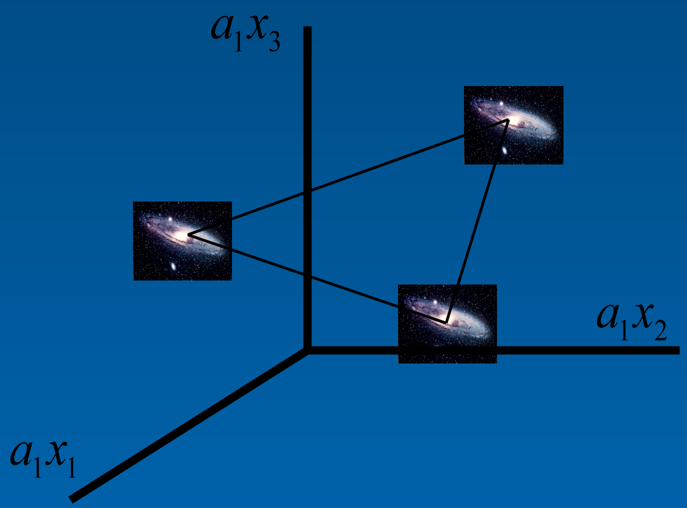
General Relativity

$$G_{\mu\nu} = R_{\mu\nu} + \frac{1}{2} R\, g_{\mu\nu} = 8\pi\, G\, T_{\mu\nu}$$

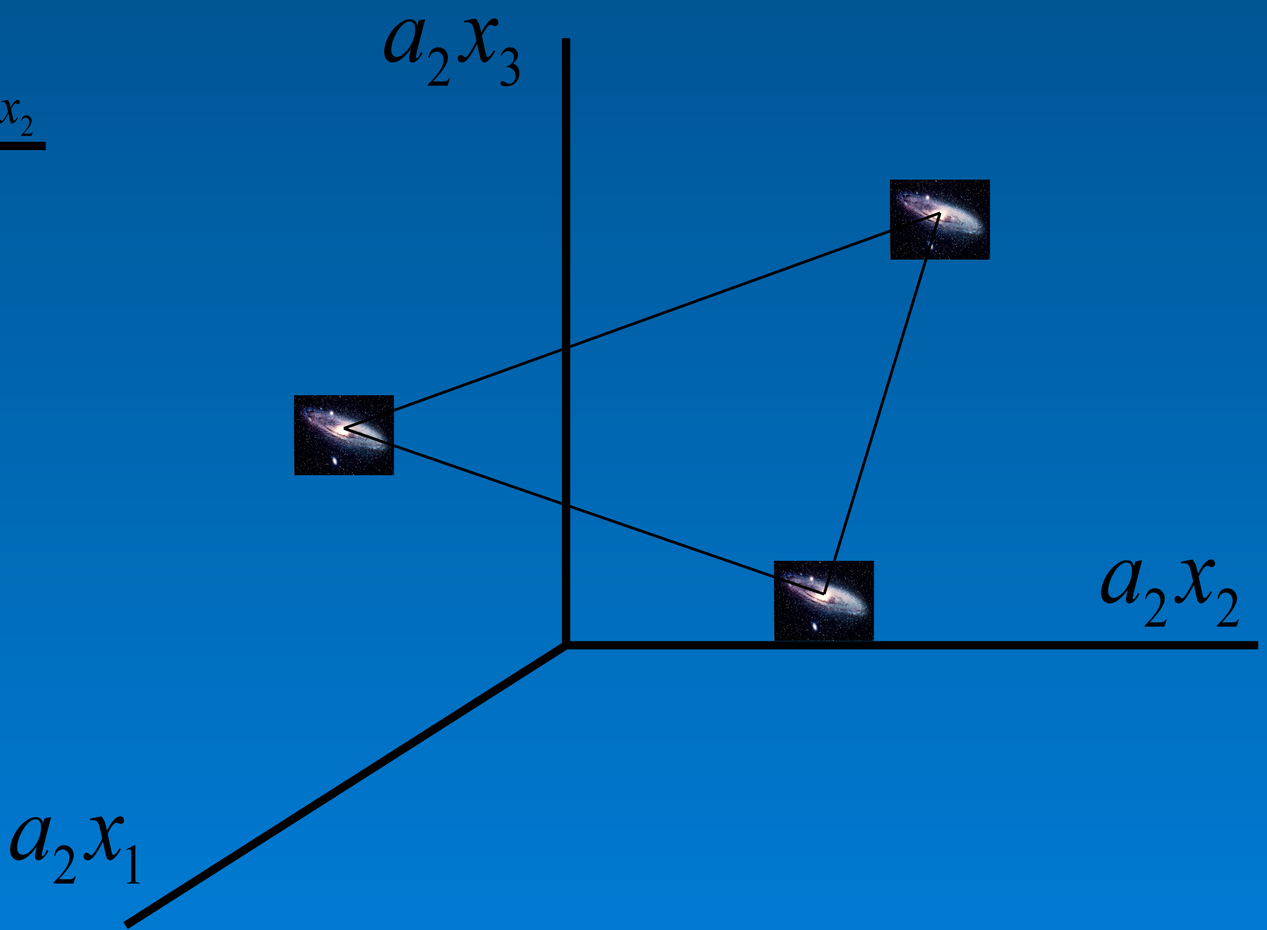
Homogeneity and Isotropy

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2 d\Omega\right] \qquad FRW$$

$$ds^2 = -dt^2 + a^2(t)(dx_1^2 + dx_2^2 + dx_3^2)$$

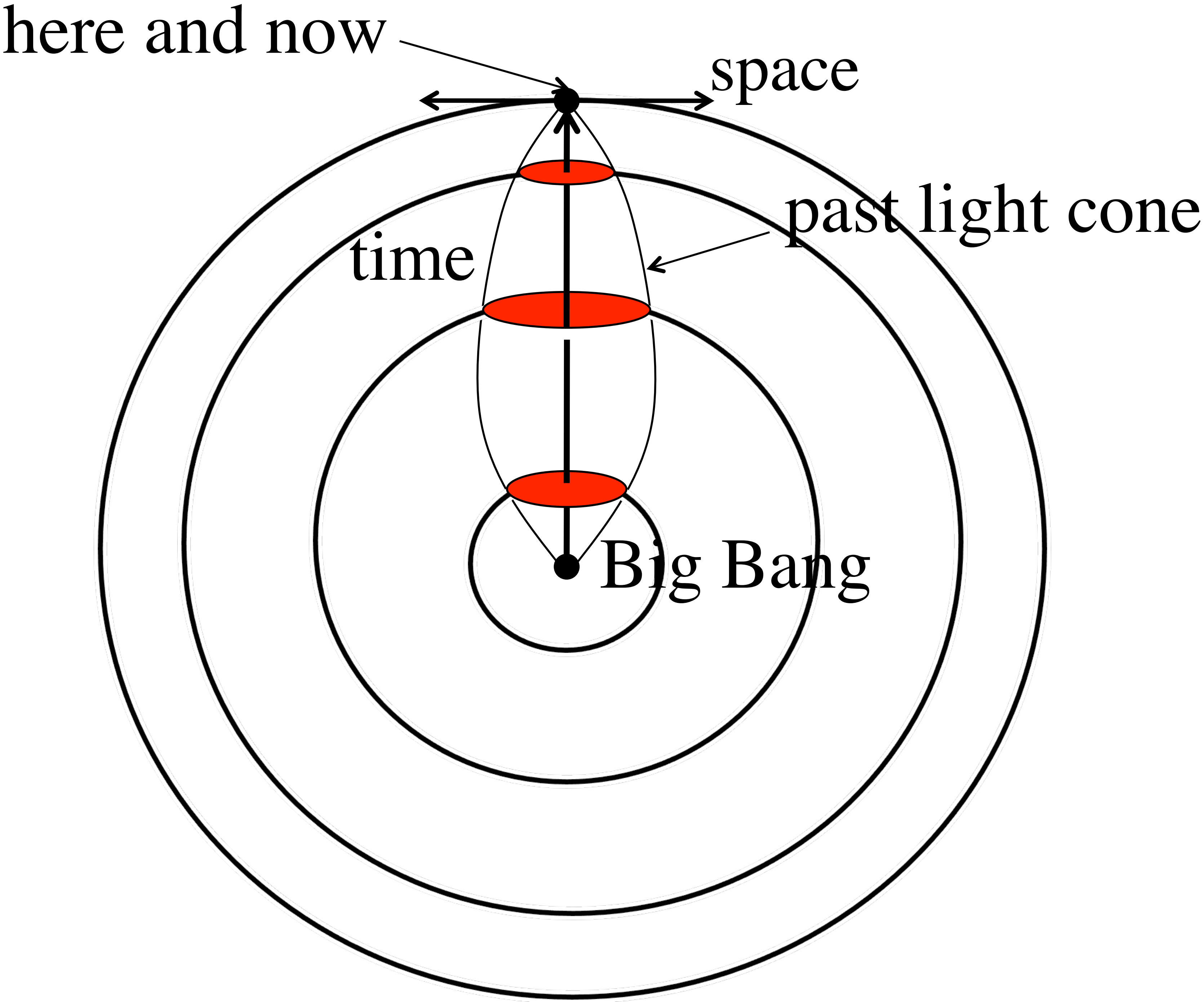


flat space



scale factor

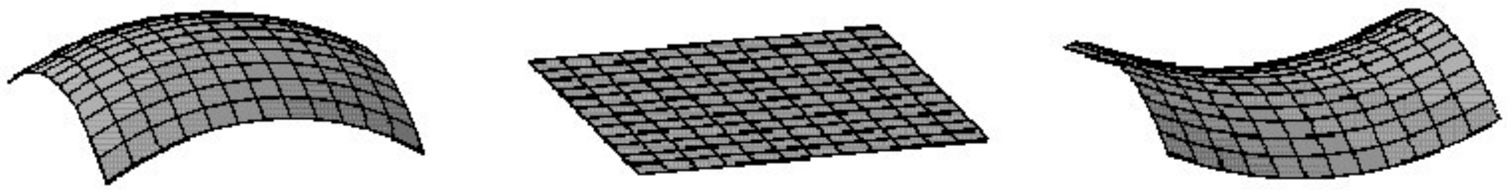
$$a(t_2) > a(t_1)$$


here and now
space
past light cone
time
Big Bang

Spatial Curvature

$$ {}^{(3)}R = \frac{6K}{a^2(t)} $$

Closed	Flat	Open
$K = +1$	$K = 0$	$K = -1$



Matter Content: Perfect Fluid

$$T_{\mu\nu} = p\, g_{\mu\nu} + (\rho + p) U_\mu U_\nu$$

Isotropic in its rest frame:

$$T^\mu{}_\nu = diag(-\rho(t), p(t), p(t), p(t))$$

Energy density conservation:

$$D_\mu T^\mu{}_\nu = 0 \Rightarrow \dot{\rho}(t) + 3\frac{\dot{a}}{a}(\rho(t) + p(t)) = 0$$

Einstein-Friedmann equations

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

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

Equation of state of matter

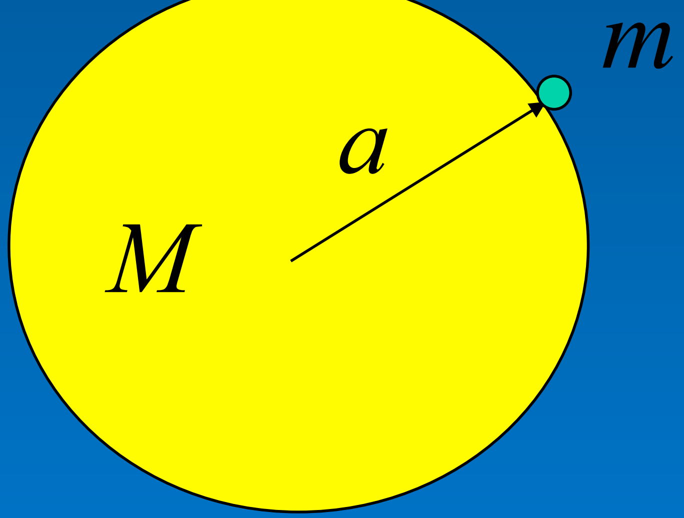
$$p(t) = w\,\rho(t) \qquad \text{barotropic fluid}$$

Friedmann equation

$$\frac{1}{2} m \dot{a}^2 - \frac{GMm}{a} = -\frac{mK}{2}$$

$$T + V = E$$

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



$K = 0$ escape velocity

$K > 0$ recollapse

$K < 0$ expand forever

Universe dynamics (K=0)

Radiation: $p = \rho / 3$

$\rho_R \propto a^{-4}$ $\quad$ $a_R \propto t^{1/2}$

Matter: $p << \rho$

$\rho_M \propto a^{-3}$ $\quad$ $a_M \propto t^{2/3}$

Vacuum: $p = -\rho$

$\rho_V \propto a^{0}$ $\quad$ $a_V \propto e^{Ht}$

Cosmological Parameters

Rate of Expansion (Hubble)

$$H_0 = \frac{\dot{a}}{a}(t_0) = 100\,h \text{ km/s/Mpc}$$

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

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

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

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

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

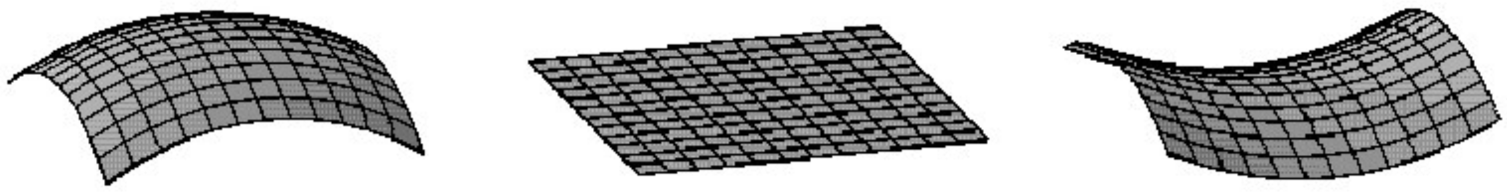
$$\boxed{\Omega_0 = \Omega_R + \Omega_M + \Omega_\Lambda}$$

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

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

Spatial Curvature

$K = +1$	$K = 0$	$K = -1$
Closed	Flat	Open
$\Omega_0 > 1$	$\Omega_0 = 1$	$\Omega_0 < 1$



Cosmic Sum Rule

Friedmann equation

$$H^2 = \frac{8\pi G}{3}(\rho_R + \rho_M) + \frac{\Lambda}{3} - \frac{K}{a^2}$$

Today: $$\boxed{1 = \cancel{\Omega_R} + \Omega_M + \Omega_\Lambda + \Omega_K}$$

No vacuum: $\Omega_\Lambda = 0 \quad \Rightarrow \quad \Omega_K = 1 - \Omega_M$

Flat space: $\Omega_K = 0 \quad \Rightarrow \quad \Omega_\Lambda = 1 - \Omega_M$

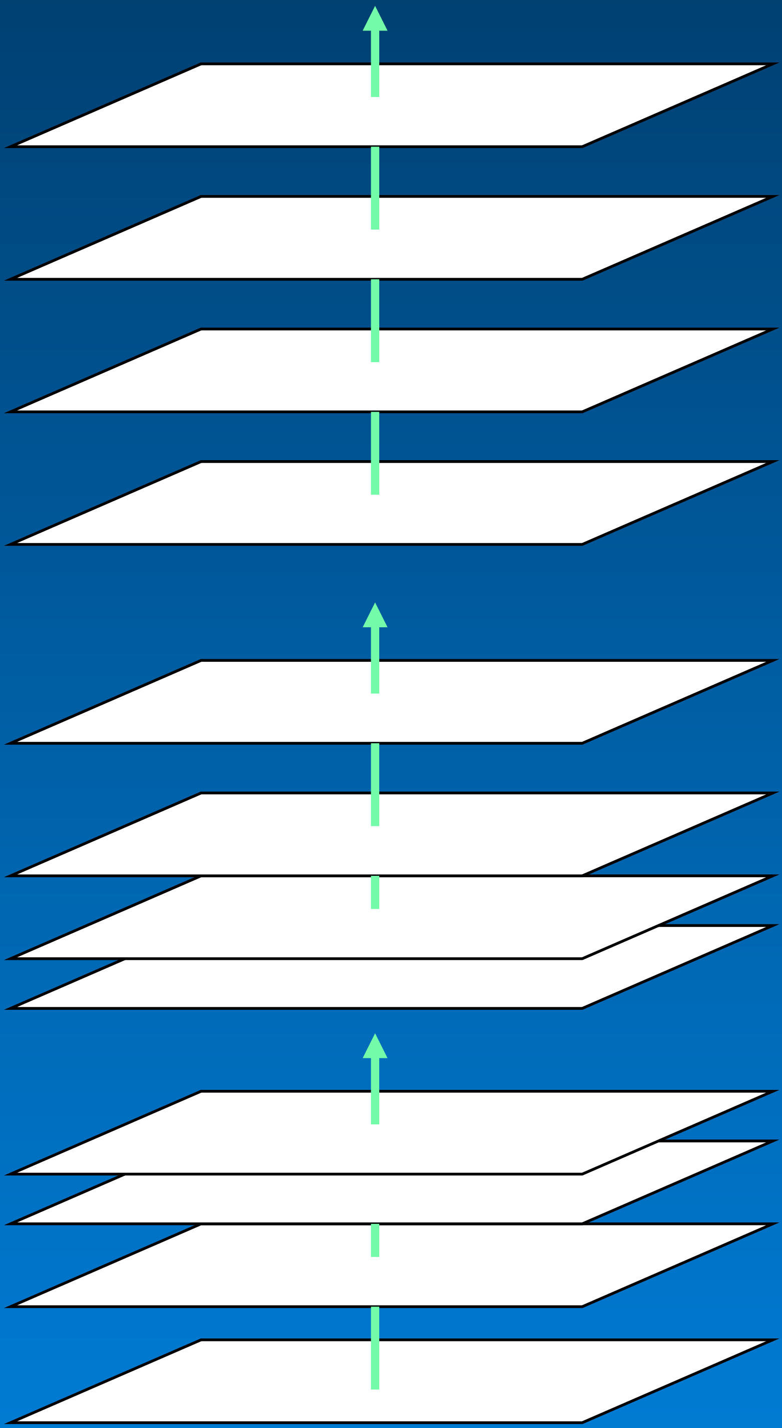
Deceleration parameter

$$q_0 = -\frac{a\ddot{a}}{\dot{a}^2}(t_0) = \frac{4\pi G}{3H_0^2}(\rho + 3p)$$

$$q_0 = \Omega_R + \frac{1}{2}\Omega_M - \Omega_\Lambda + \frac{1}{2}\sum_x (1 + 3w_x)\Omega_x$$

Matter domination: $q_0 > 0$

Vacuum domination: $q_0 < 0$



Uniform expansion

$$q_0 = 0$$

$$\Omega_M = 2\Omega_\Lambda$$

Accelerated expansion

$$q_0 < 0$$

$$\Omega_M < 2\Omega_\Lambda$$

Decelerated expansion

$$q_0 > 0$$

$$\Omega_M > 2\Omega_\Lambda$$

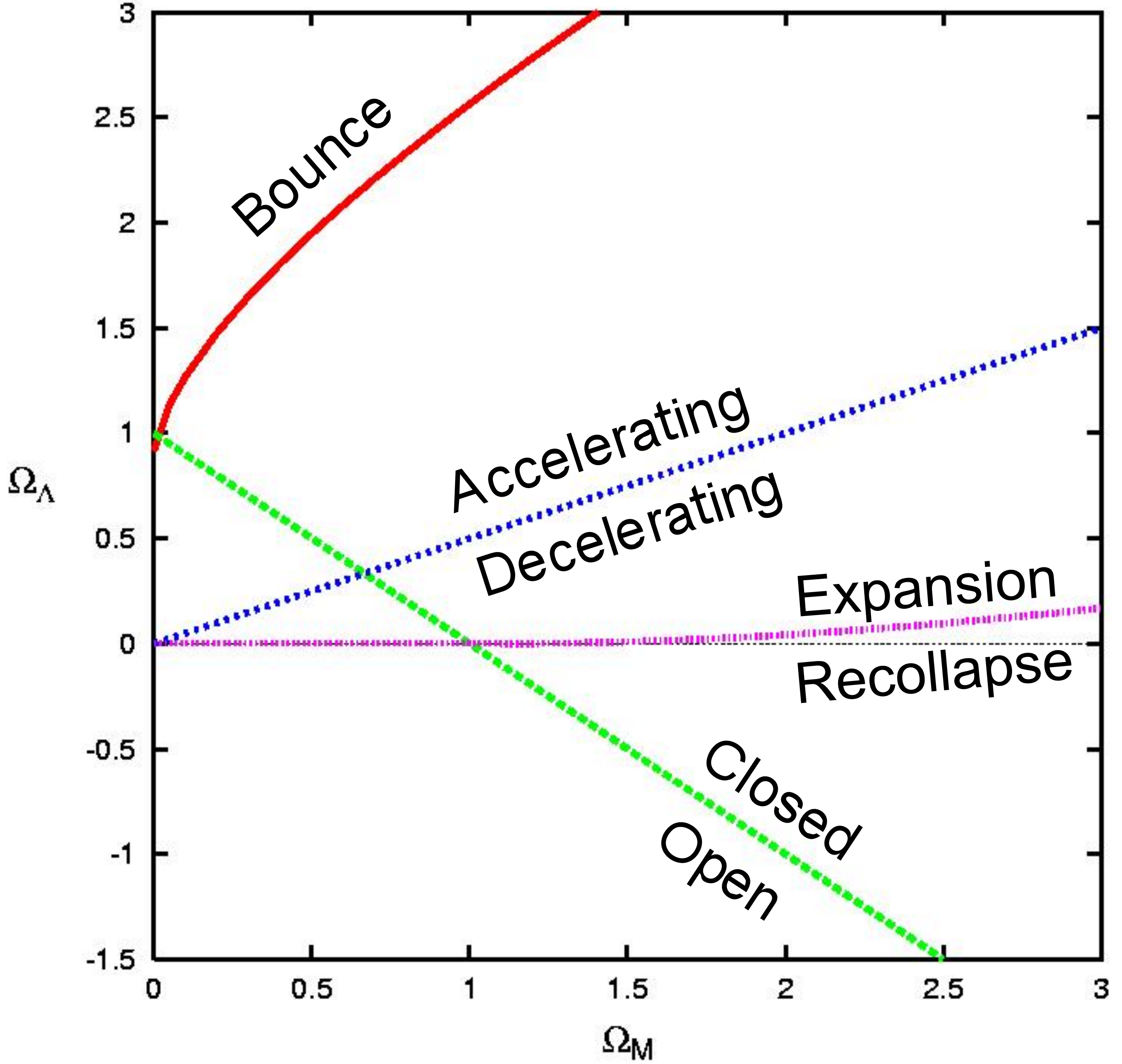
Bounce $$H_0 t_0 = \int_0^1 \frac{da}{\sqrt{1+\Omega_M(\frac{1}{a}-1)+\Omega_\Lambda(a^2-1)}} = \infty$$

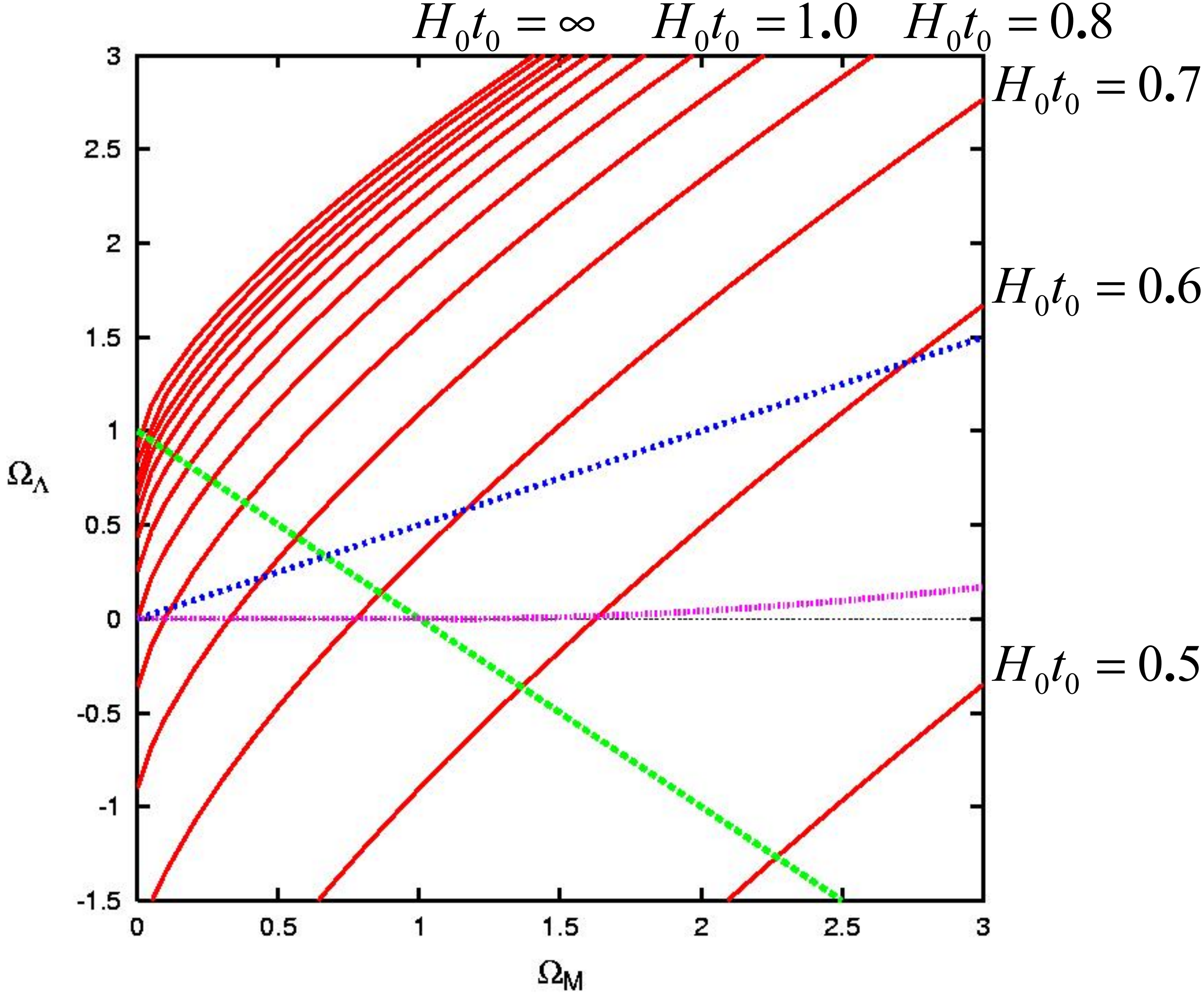
Uniform exp. $$q_0 = 0 \quad \Rightarrow \quad \Omega_\Lambda = \tfrac{1}{2}\Omega_M$$

Critical univ.

$$\Omega_\Lambda = \begin{cases} 0 & \Omega_M \le 1 \\ 4\Omega_M \sin^3[\tfrac{1}{3}\arcsin(\tfrac{\Omega_M - 1}{\Omega_M})] & \Omega_M > 1 \end{cases}$$

Flat space $$\Omega_K = 0 \quad \Rightarrow \quad \Omega_\Lambda = 1 - \Omega_M$$


Bounce
Accelerating
Decelerating
Expansion
Recollapse
Closed
Open
Ω_Λ
Ω_M
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3



$H_0 t_0 = \infty$
$H_0 t_0 = 1.0$
$H_0 t_0 = 0.8$
$H_0 t_0 = 0.7$
$H_0 t_0 = 0.6$
$H_0 t_0 = 0.5$
Ω_Λ
Ω_M
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3

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

The Expanding Universe

Geodesic motion

$$\frac{du^\mu}{ds} + \Gamma^\mu_{\nu\lambda} u^\nu u^\lambda = 0\,; \qquad u^\mu = (\gamma, \gamma\, v^i)$$

$$\Gamma^0_{ij} = \frac{\dot{a}}{a} g_{ij} \quad \Rightarrow \quad |\vec{u}| \propto \frac{1}{a} \quad \Rightarrow \quad |\vec{p}| \propto \frac{1}{a}$$

Photon redshift

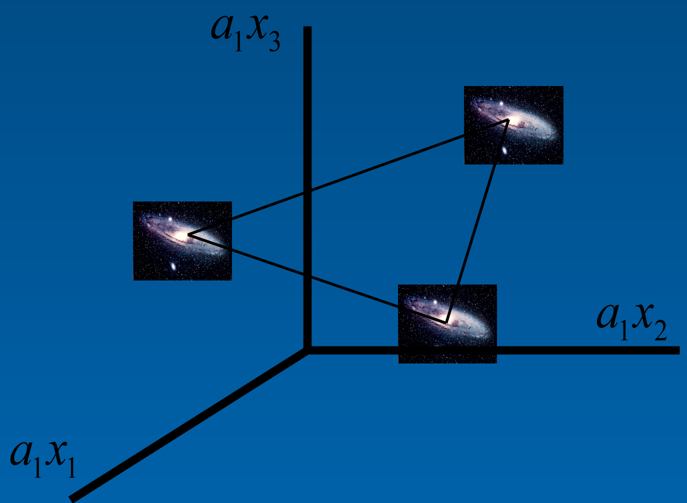
$$p = \frac{h}{\lambda}$$

$$\boxed{\frac{\lambda_1}{\lambda_0} = \frac{a(t_1)}{a(t_0)} \quad \Rightarrow \quad z \equiv \frac{\lambda_0 - \lambda_1}{\lambda_1} = \frac{a_0}{a_1} - 1}$$

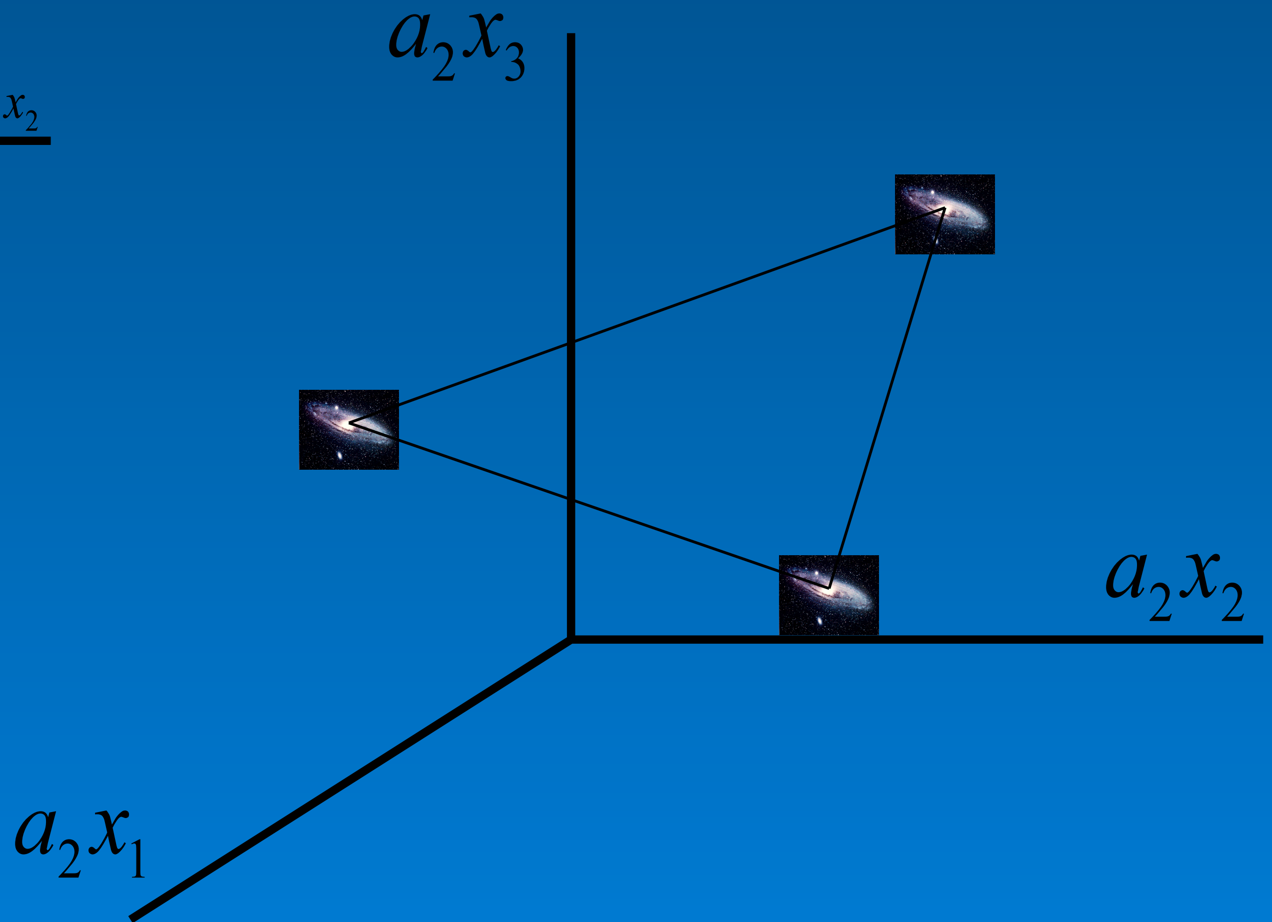
redshift

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

$$ds^2 = -dt^2 + a^2(t)(dx_1^2 + dx_2^2 + dx_3^2)$$



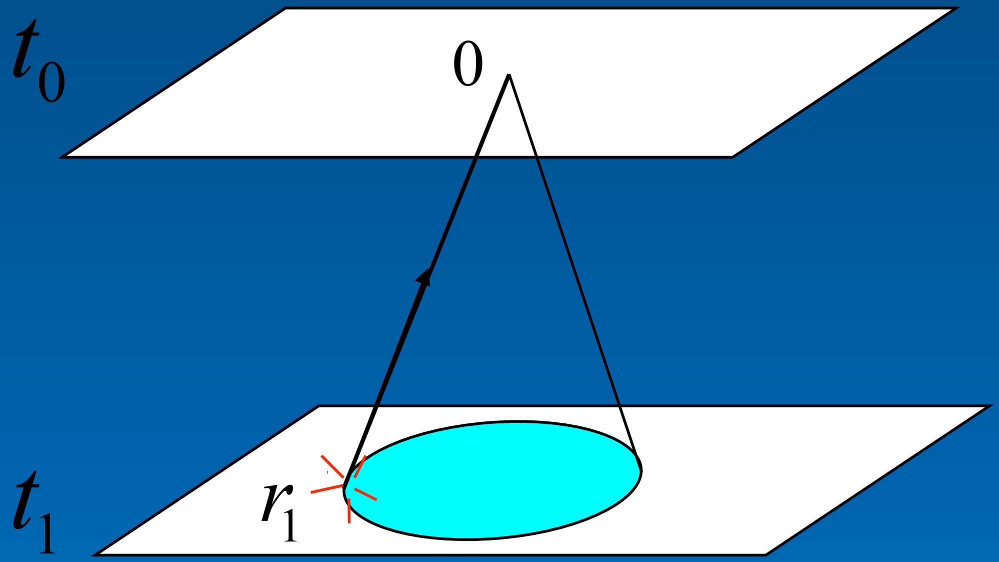
flat space



scale factor

$$\frac{a(t_2)}{a(t_1)} \equiv \frac{1+z_1}{1+z_2}$$

FRW kinematics



Physical distance

$$d = a_0 r_1 \quad (1^{st}\ order)$$

Light cone:

$$0 = -dt^2 + a^2(t)\frac{dr^2}{1-Kr^2}$$

$$\int_{t_1}^{t_0}\frac{dt}{a(t)} = \int_0^{r_1}\frac{dr}{\sqrt{1-Kr^2}} = f(r_1) = \begin{cases} \mathbf{arcsin}\, r_1 & K=1 \\ r_1 & K=0 \\ \mathbf{arcsinh}\, r_1 & K=-1 \end{cases}$$

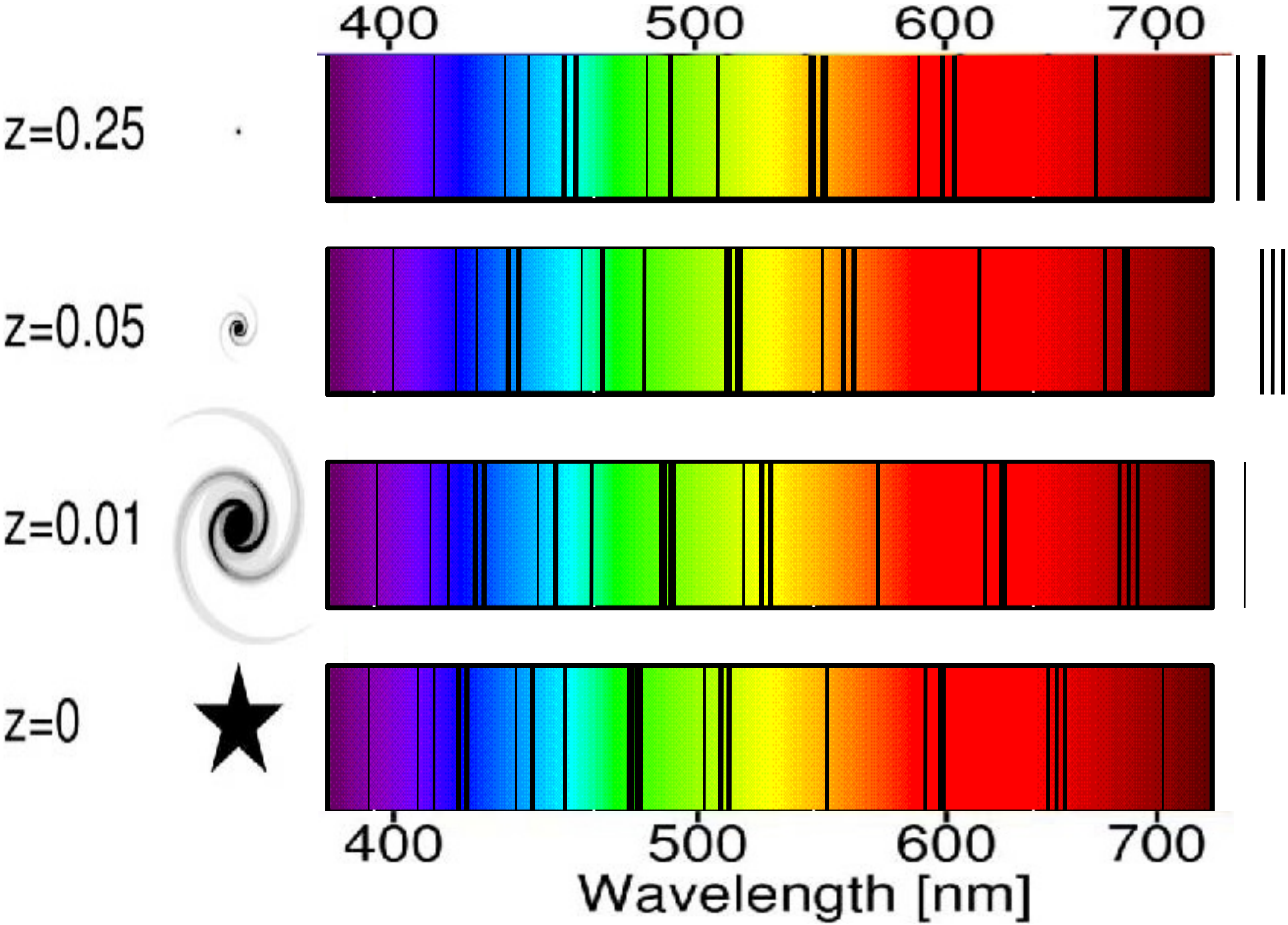
Taylor expansion

$$\frac{1}{1+z} = \frac{a(t)}{a_0} = 1 + H_0(t - t_0) + \mathrm{O}(t - t_0)^2$$

To first approximation

$$r_1 \approx f(r_1) = \int_{t_1}^{t_0} \frac{dt}{a(t)} = \frac{1}{a_0}(t_1 - t_0) + \ldots = \frac{z}{a_0 H_0} + \ldots$$

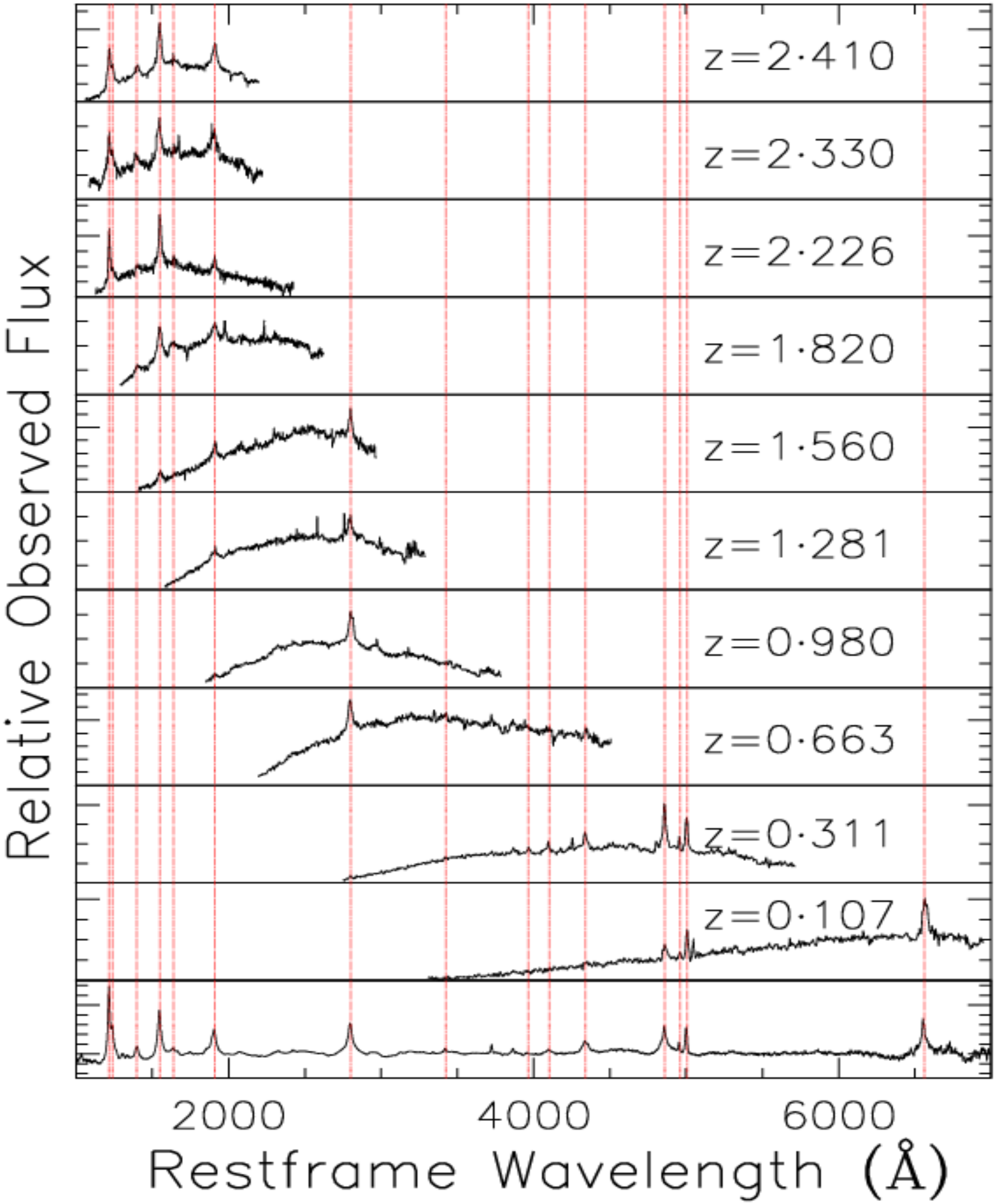
Hubble law $\boxed{H_0 d = H_0 a_0 r_1 = z \approx vc}$


400
500
600
700
z=0.25
z=0.05
z=0.01
z=0
400
500
600
700
Wavelength [nm]

Edwin P. Hubble

Mount Wilson

Mount Palomar

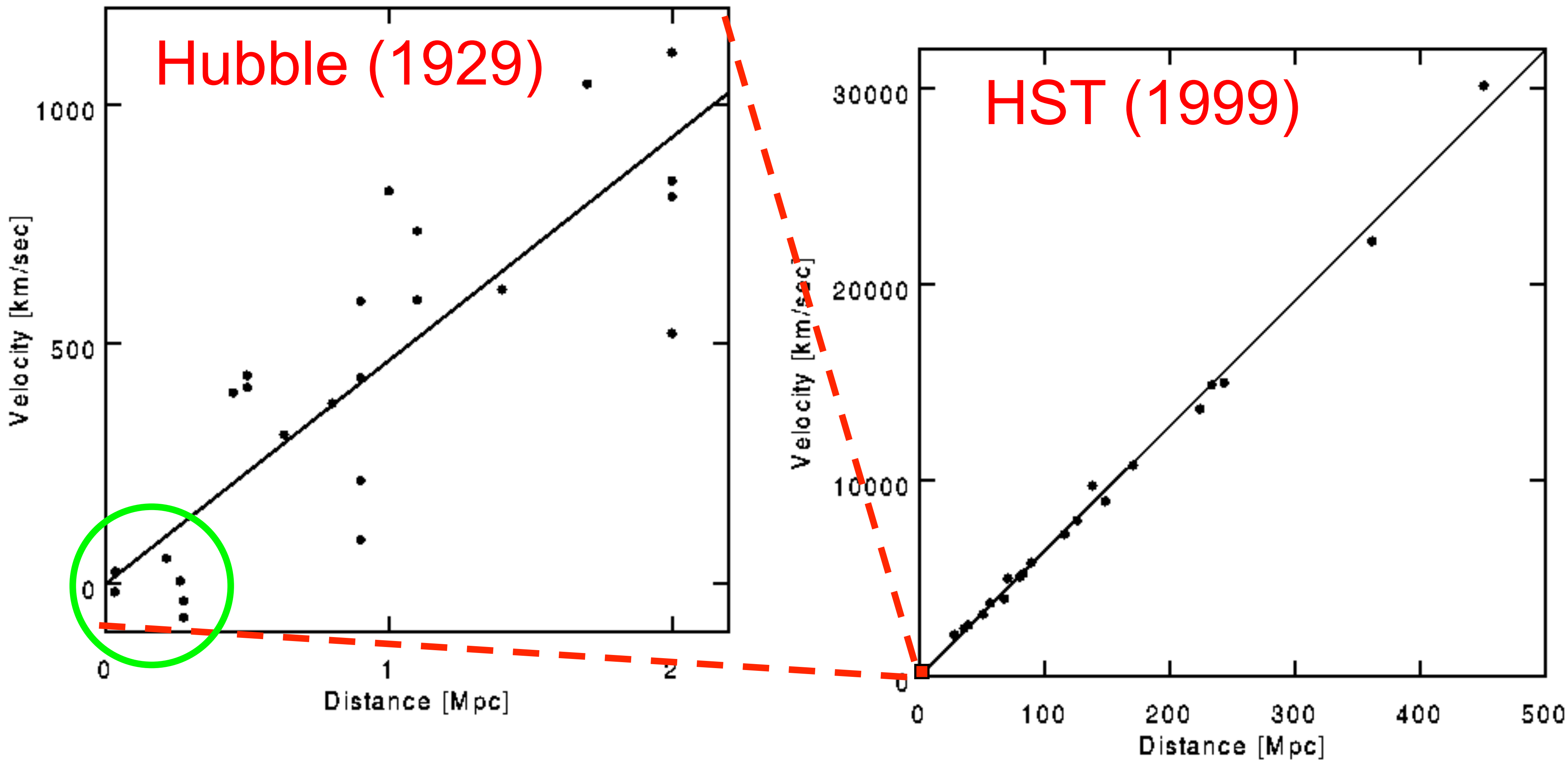


Redshifts to galaxies

Hubble law

$$H_0 d = z \approx vc$$

Hubble Space Telescope



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

Dominated by systematic errors!

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

$$z \leq 0.1$$

The

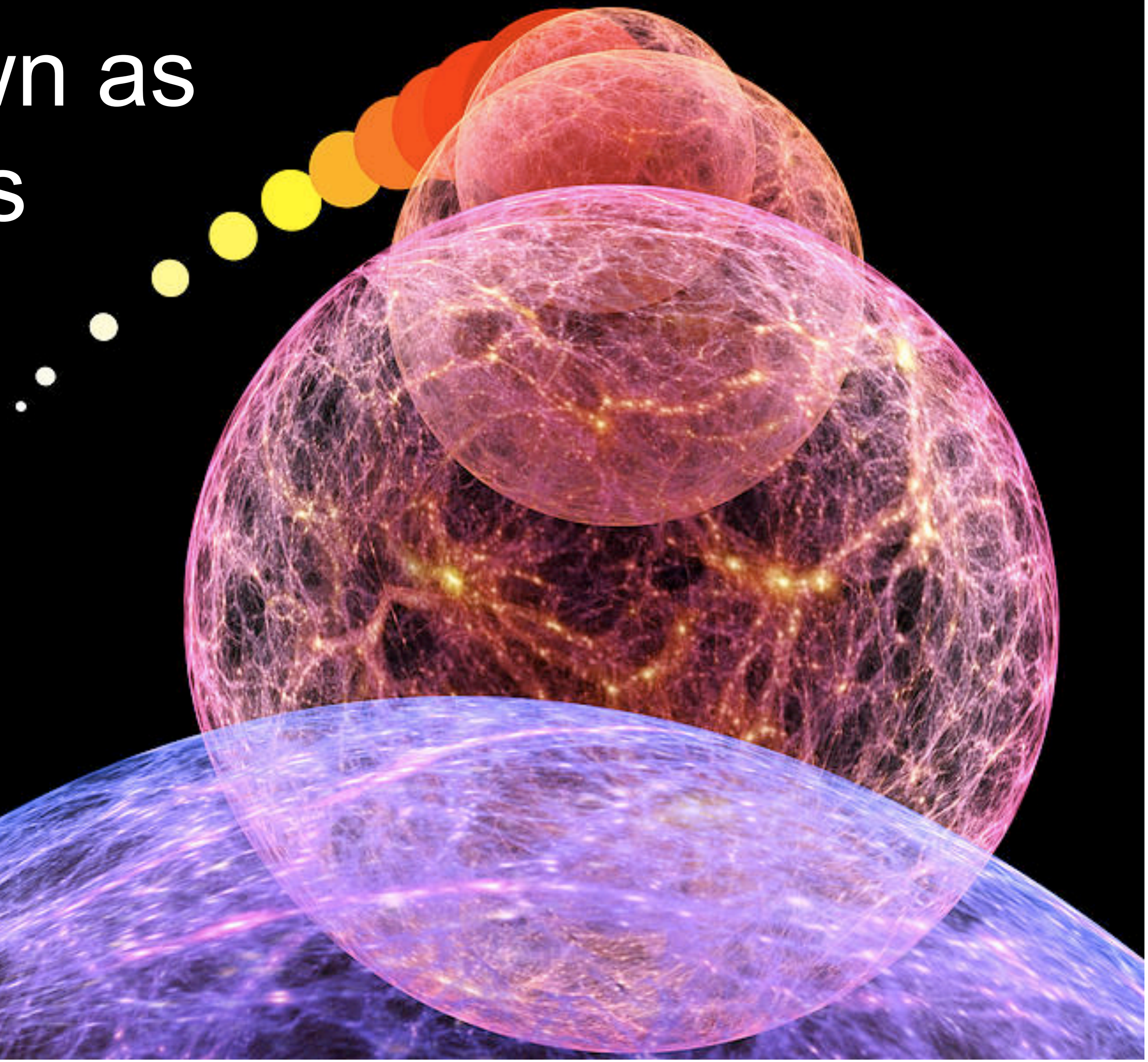
Aging

Universe

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

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

The Universe cools down as it expands



Fluids in thermal and chemical equilibrium

$$n = \frac{g}{2\pi^2} \int_m^\infty dE \, \frac{E(E^2 - m^2)^{1/2}}{e^{(E-\mu)/T} \pm 1} ,$$

$$\rho = \frac{g}{2\pi^2} \int_m^\infty dE \, \frac{E^2(E^2 - m^2)^{1/2}}{e^{(E-\mu)/T} \pm 1} ,$$

$$p = \frac{g}{6\pi^2} \int_m^\infty dE \, \frac{(E^2 - m^2)^{3/2}}{e^{(E-\mu)/T} \pm 1} .$$

Relativistic particles

Gas of relativistic $(m \ll T)$, non degenerate $(\mu \ll T)$ particles

$$n = \frac{g}{2\pi^2}\int_0^\infty \frac{E^2\, dE}{e^{E/T} \pm 1} = \begin{cases} \dfrac{\zeta(3)}{\pi^2}\, g\, T^3 & \text{Bosons} \\ \dfrac{3}{4}\,\dfrac{\zeta(3)}{\pi^2}\, g\, T^3 & \text{Fermions} \end{cases},$$

$$\zeta(3) = 1.20206\ldots$$

$$\rho = \frac{g}{2\pi^2}\int_0^\infty \frac{E^3\, dE}{e^{E/T} \pm 1} = \begin{cases} \dfrac{\pi^2}{30}\, g\, T^4 & \text{Bosons} \\ \dfrac{7}{8}\,\dfrac{\pi^2}{30}\, g\, T^4 & \text{Fermions} \end{cases},$$

$$p = \frac{1}{3}\rho\,,$$

$$\langle E \rangle \equiv \frac{\rho}{n} = \begin{cases} \dfrac{\pi^4}{30\zeta(3)}\, T \simeq 2.701\, T & \text{Bosons} \\ \dfrac{7\pi^4}{180\zeta(3)}\, T \simeq 3.151\, T & \text{Fermions} \end{cases}$$

Non-relativistic particles

Gas of non-relativistic $(m \gg T)$ particles, with chemical pot. μ

$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-(m-\mu)/T} \,,$$

$$\rho = m\, n \,, \qquad \langle E \rangle \equiv \frac{\rho}{n} = m + \frac{3}{2} T$$

$$p = n\, T \ll \rho \,.$$

Its contribution to the total energy of the universe is always subdominant (Boltzman suppressed) w.r.t. relativistic species.

Energy density and entropy of the Universe

$$\rho_{\rm R} = \frac{\pi^2}{30}\, g_*\, T^4 \,, \qquad p_{\rm R} = \frac{1}{3}\,\rho_{\rm R}\,,$$

$$g_*(T) = \sum_{\rm bosons} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{\rm fermions} g_i \left(\frac{T_i}{T}\right)^4 \,,$$

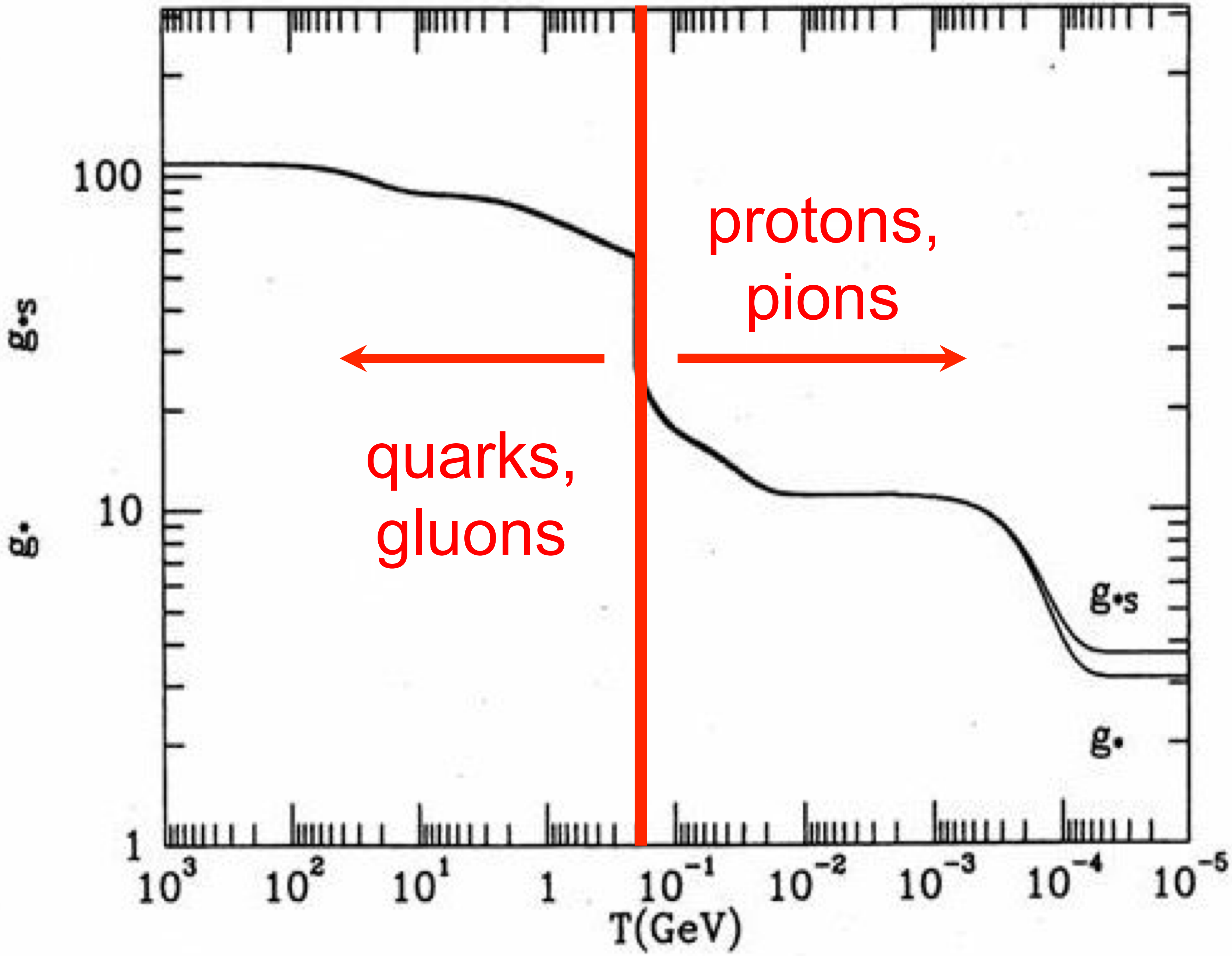
Relation between time and temperature

$$H = 1.66\, g_*^{1/2}\, \frac{T^2}{M_P} = \frac{1}{2t} \quad \Longrightarrow \quad \boxed{t = 0.301\, g_*^{-1/2}\, \frac{M_P}{T^2} = 2.42\, g_*^{-1/2} \left(\frac{\rm MeV}{T}\right)^2 \,{\rm s}}$$

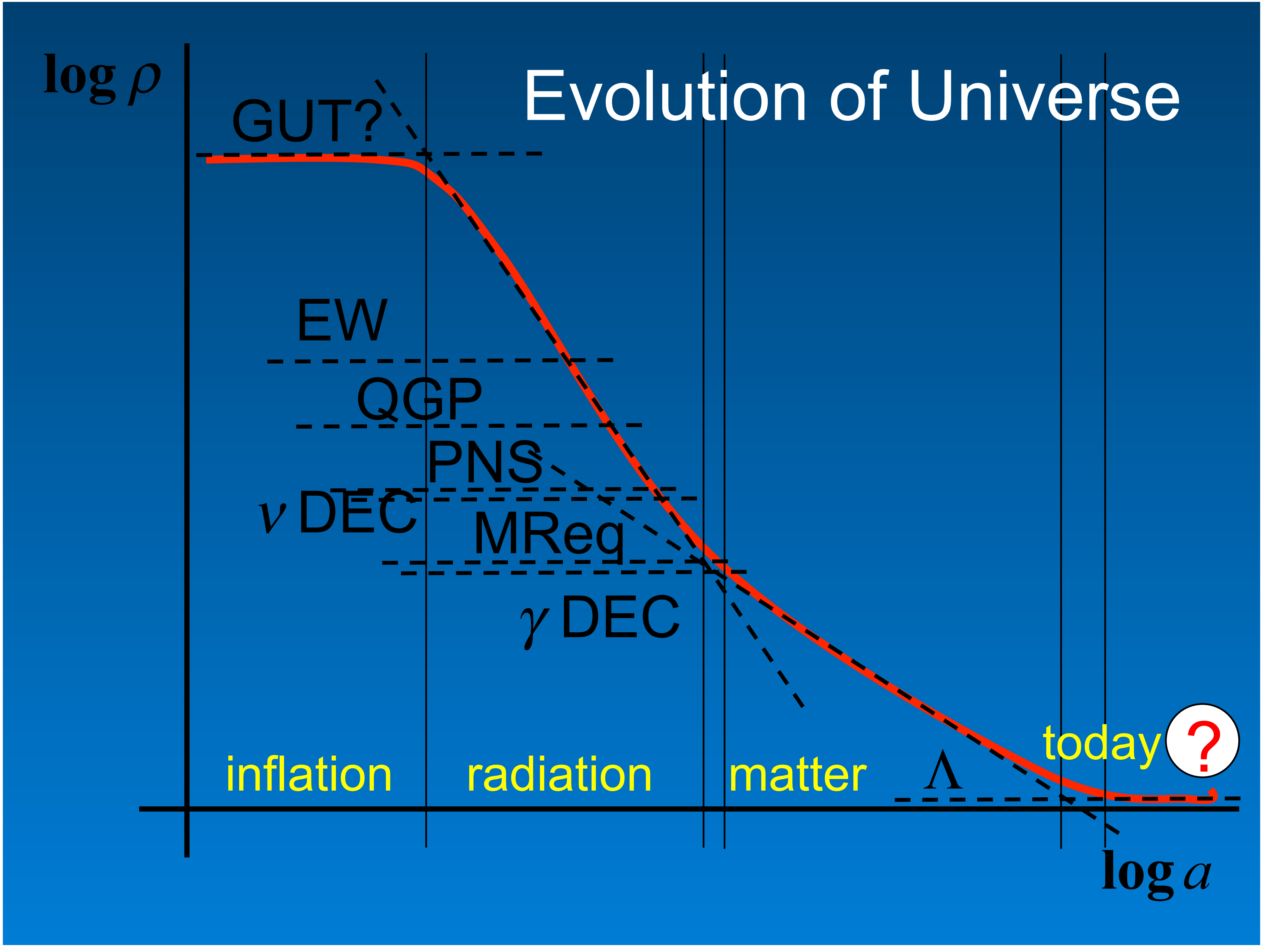
Entropy is conserved, while the Universe expands adiabatically

$$S = \frac{2\pi^2}{45}\, g_{*S}\, (aT)^3 = {\rm const.}\,,$$

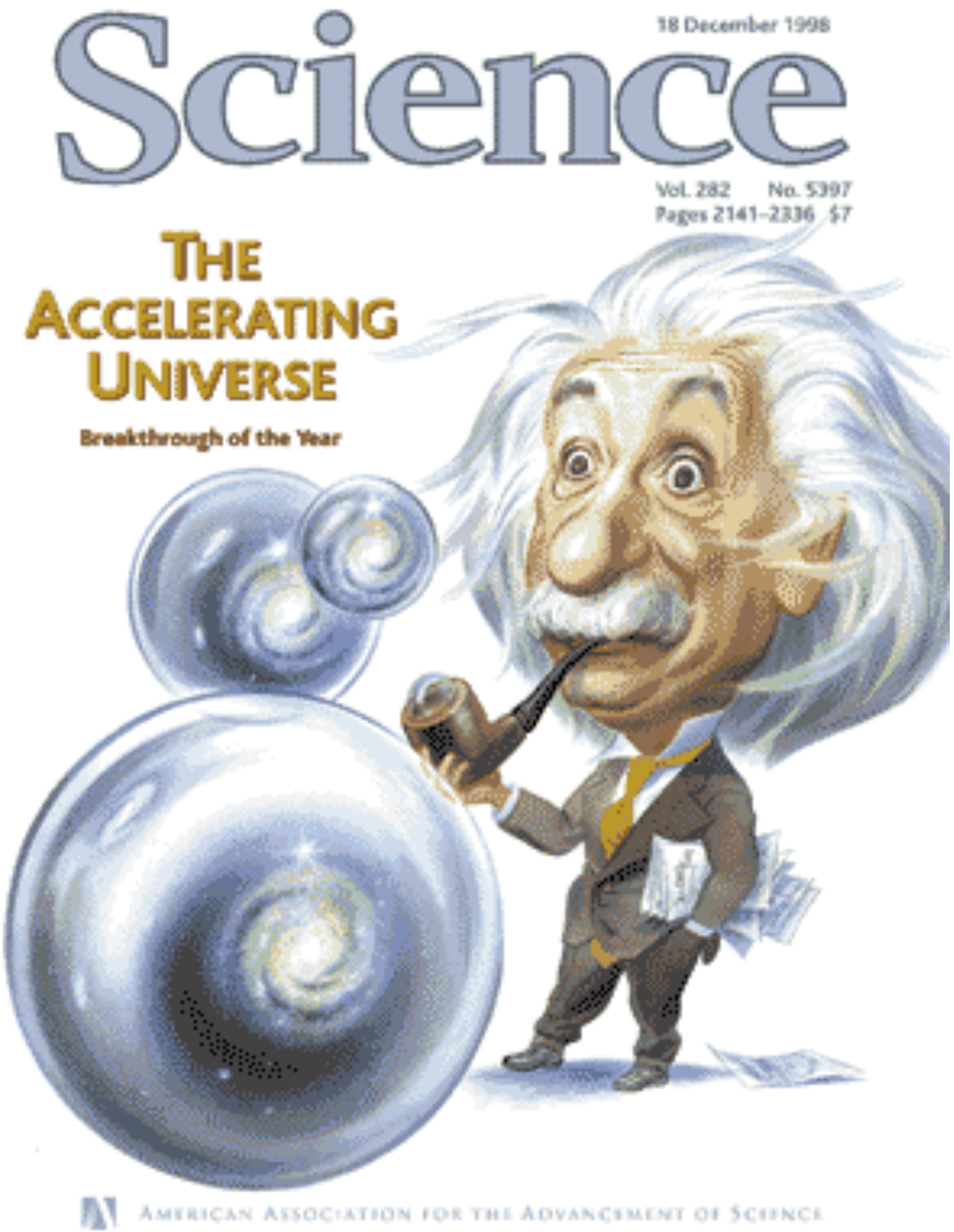
$$g_{*S}(T) = \sum_{\rm bosons} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{\rm fermions} g_i \left(\frac{T_i}{T}\right)^3$$



protons,
pions
quarks,
gluons
100
10
1
g_{*s}
g_*
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
T(GeV)


log ρ
Evolution of Universe
GUT?
EW
QGP
PNS
ν DEC
MReq
γ DEC
inflation
radiation
matter
Λ
today
?
log a

The Accelerating Universe


Science
18 December 1998
Vol. 282 No. 5397
Pages 2141–2336 $7
The Accelerating Universe
Breakthrough of the Year
American Association for the Advancement of Science

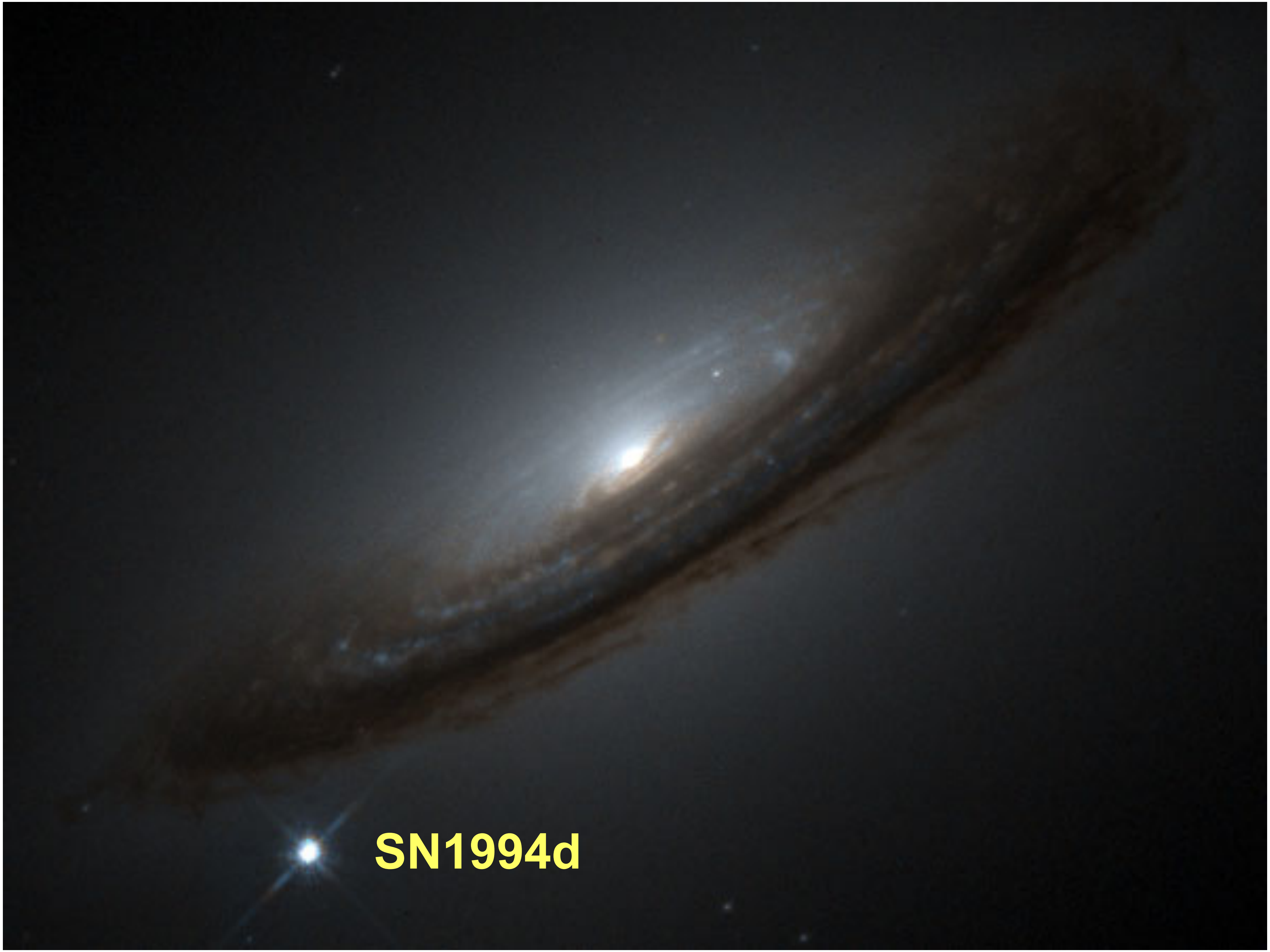
The Nobel Prize in Physics 2011

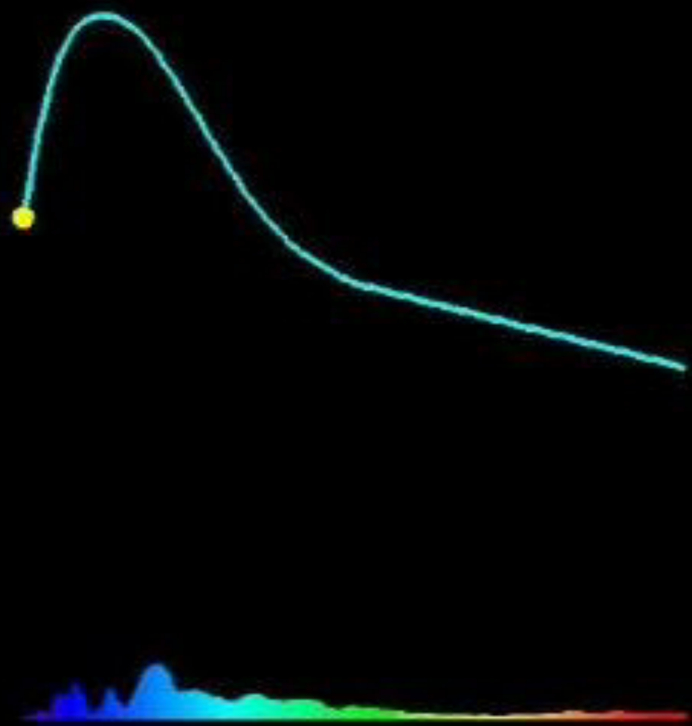
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

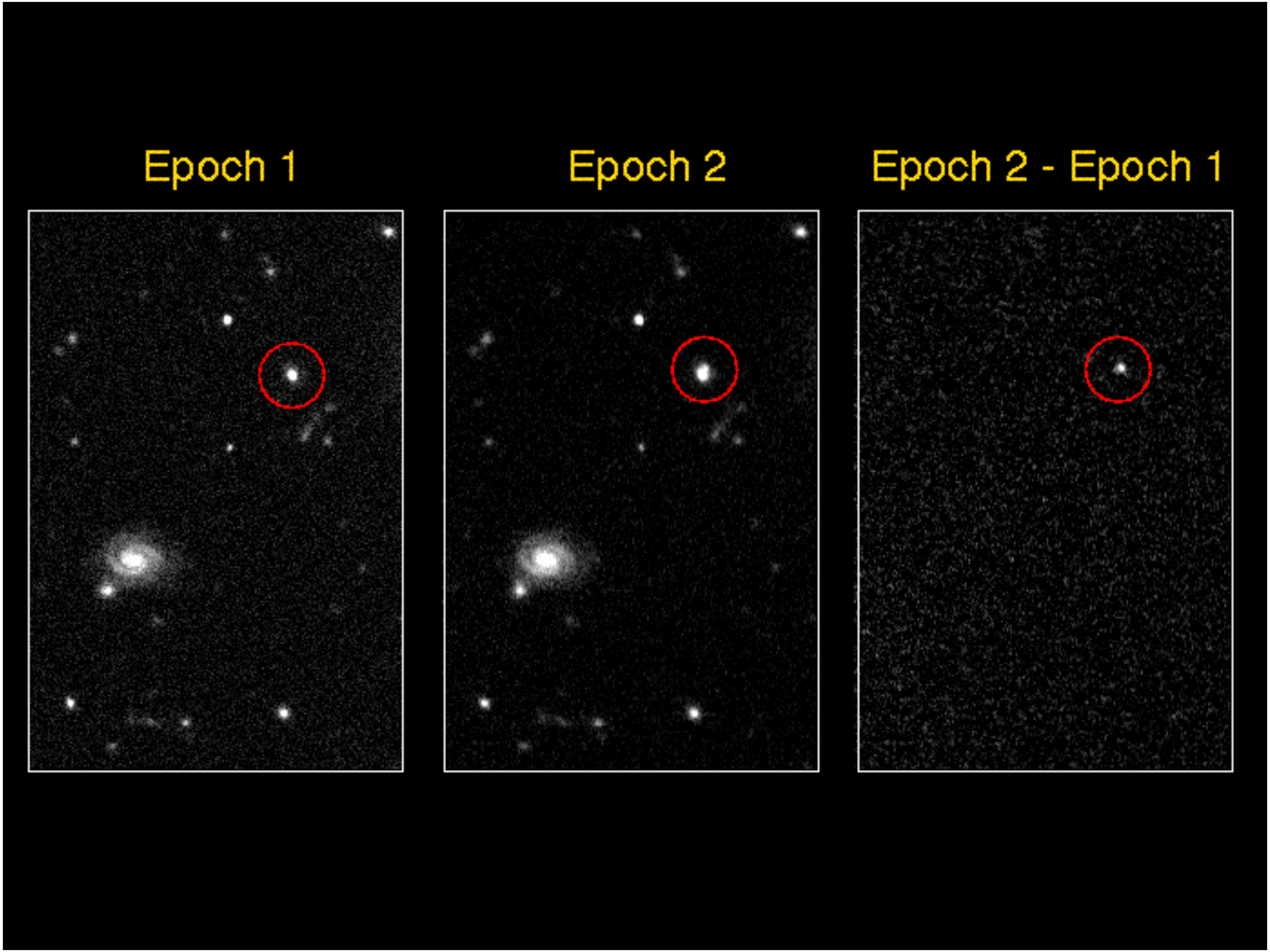

Saul Perlmutter

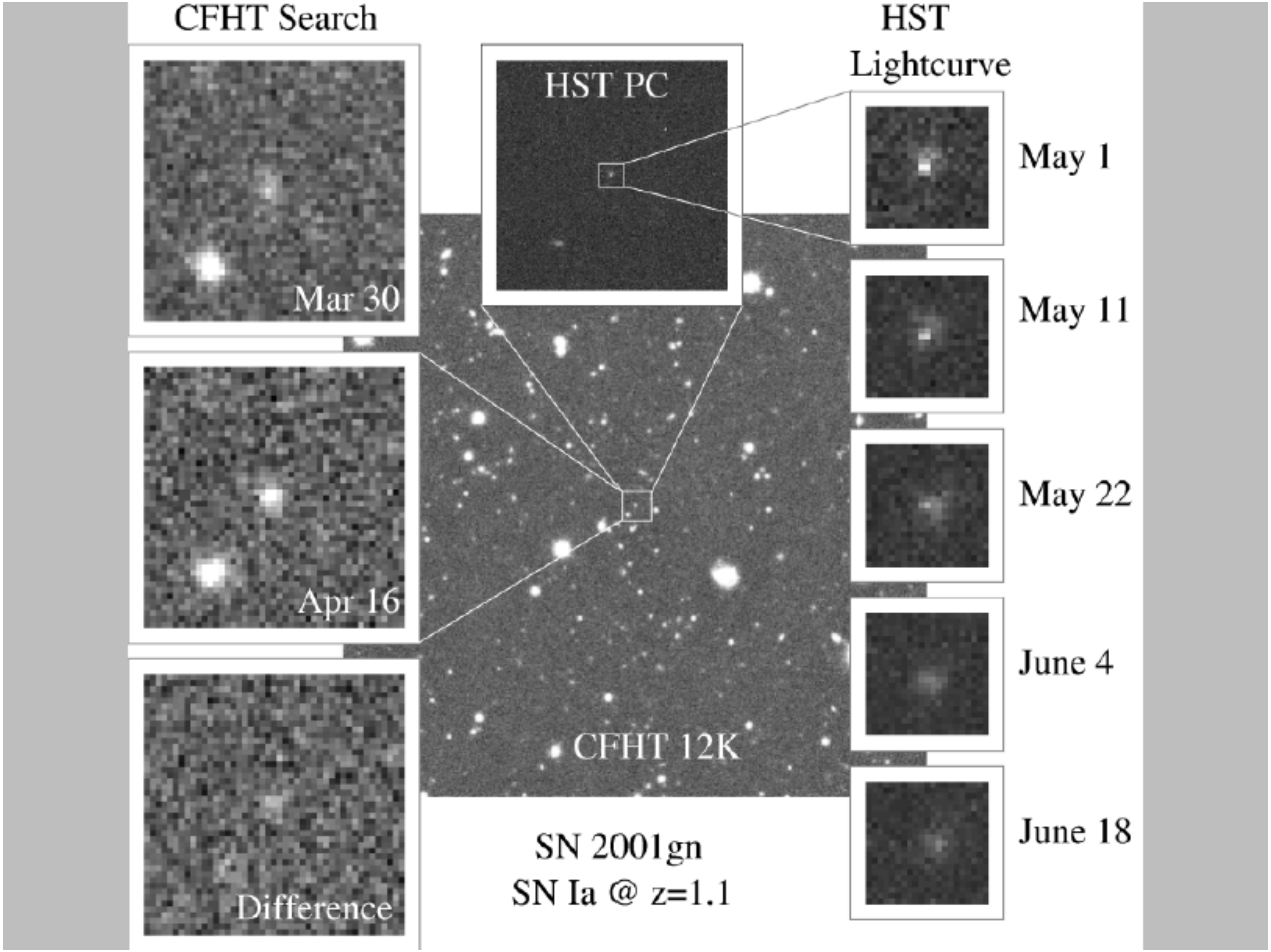

Brian P. Schmidt

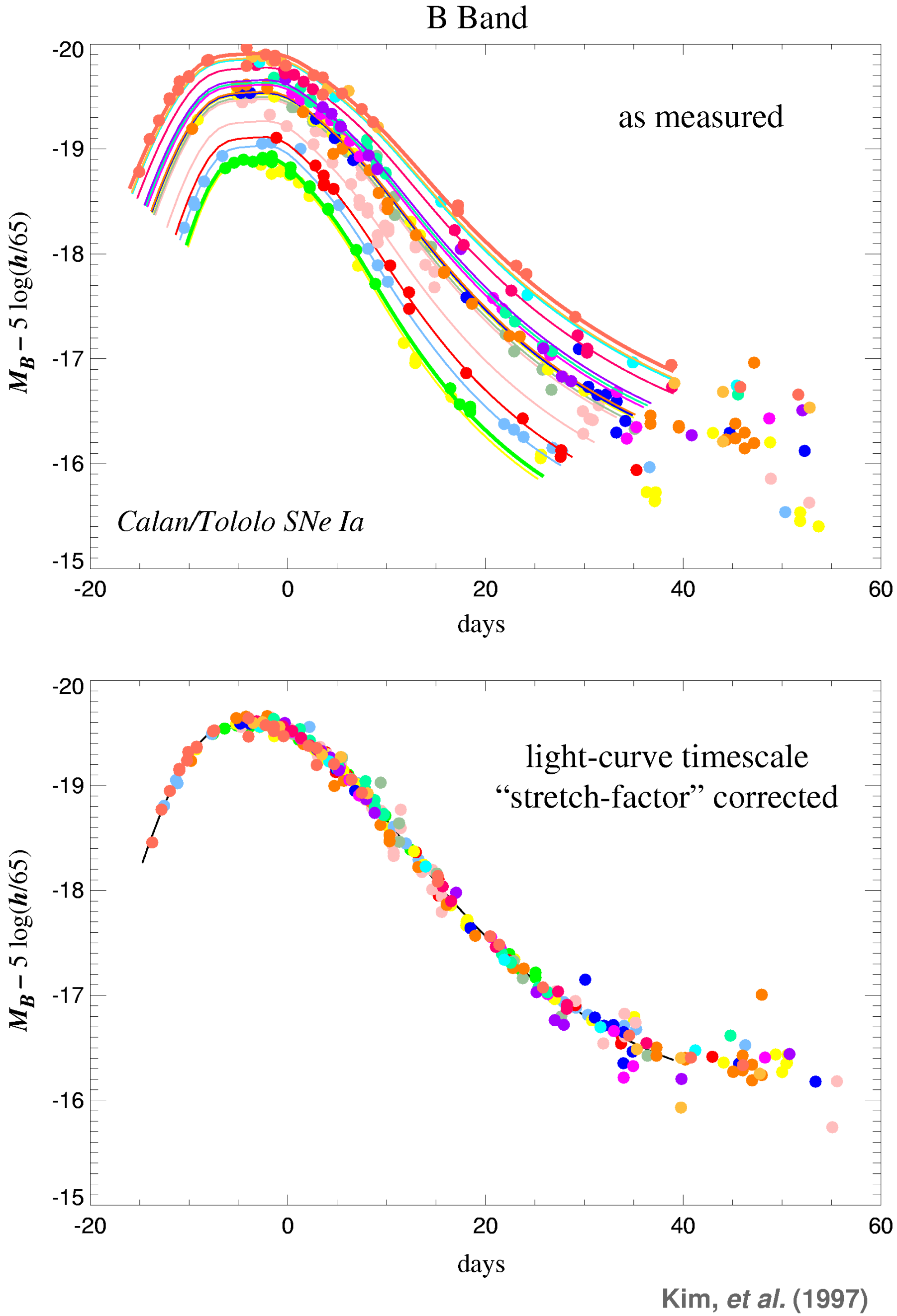

Adam G. Riess


SN1994d




Epoch 1
Epoch 2
Epoch 2 - Epoch 1


CFHT Search
Mar 30
Apr 16
Difference
HST PC
CFHT 12K
HST
Lightcurve
May 1
May 11
May 22
June 4
June 18
SN 2001gn
SN Ia @ z=1.1



Supernovae Ia Lightcurves & Stretch-factor

SNIa as Standard Candles

Luminosity distance

L Absolute Luminosity of source (dE/dt)

F Measured Flux at detector (dE/dt dA)

$$F = \frac{L}{4\pi\,(1+z)^2 a_0^2 r^2(z)} \equiv \frac{L}{4\pi\, d_L^2(z)}$$

$$H_0 d_L(z) = (1+z)\left|\Omega_K\right|^{-1/2} \mathbf{sinn}\left[\int_0^z \frac{\left|\Omega_K\right|^{1/2} dz'}{H(z')}\right]$$

Effective magnitude

$$m(z) \equiv M + 5\,\mathbf{log}_{10}\left(\frac{d_L(z)}{\text{Mpc}}\right) + 25$$

$$= \overline{M} + 5\,\mathbf{log}_{10}[H_0 d_L(z)]$$

Taylor expansion to third order

$$\frac{a(t)}{a_0} = 1 + H_0(t-t_0) - \frac{q_0}{2!}H_0^2(t-t_0)^2 + \frac{j_0}{3!}H_0^3(t-t_0)^3 + \ldots$$

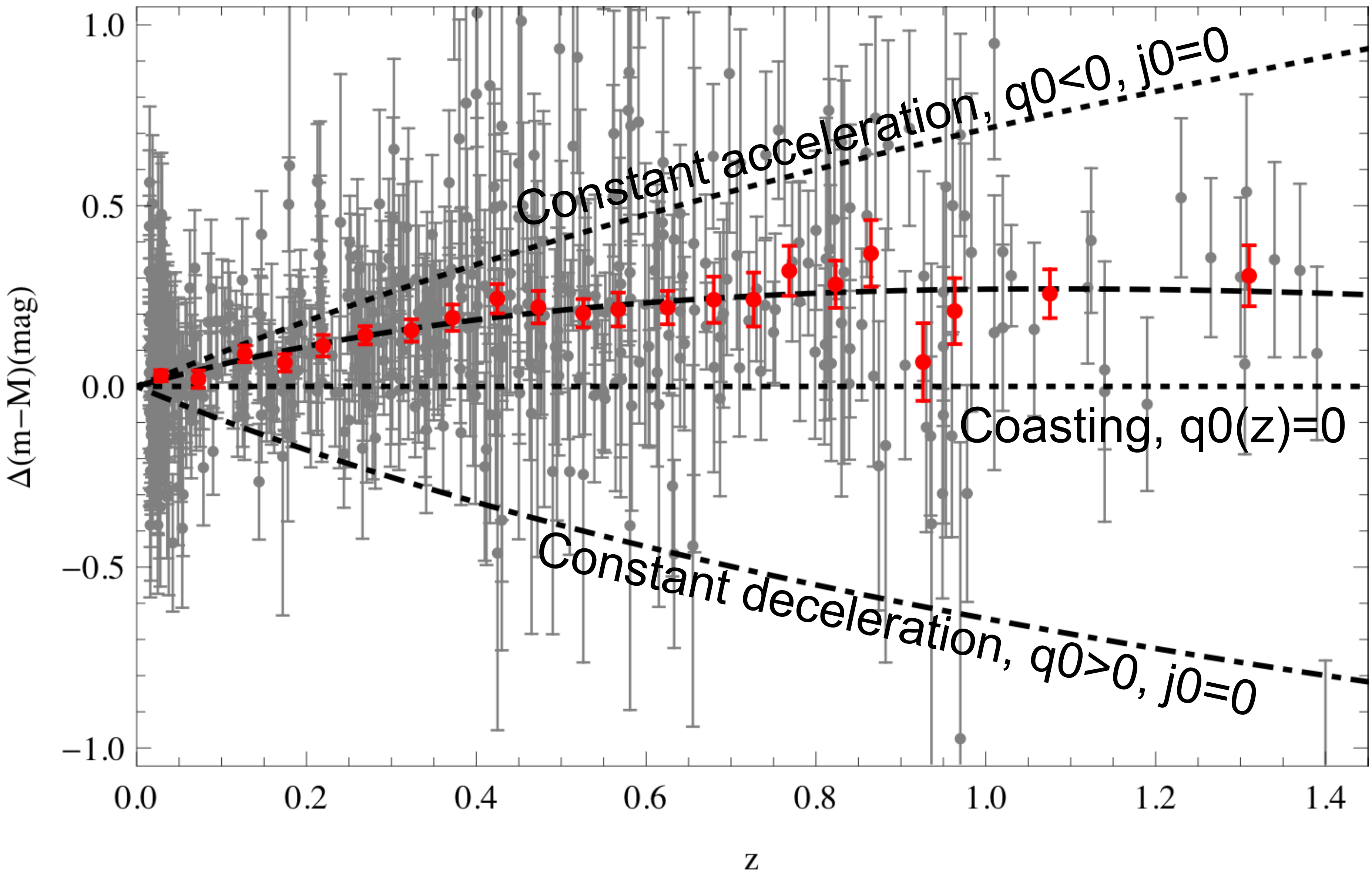
$$H(t) = \frac{\dot{a}}{a} \qquad q(t) = -\frac{\ddot{a}}{aH^2} \qquad j(t) = \frac{\dddot{a}}{aH^3}$$

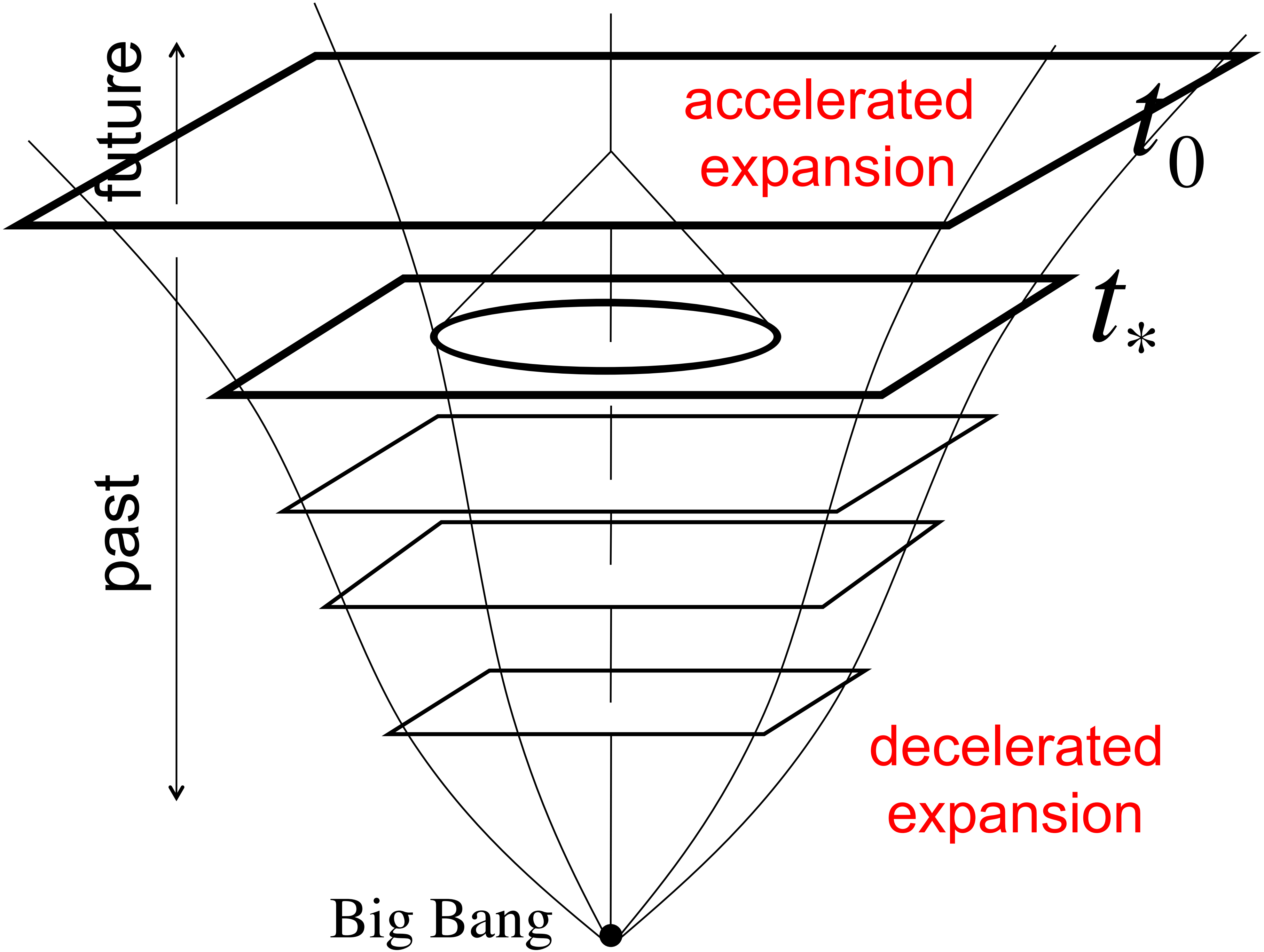
To very good approximation, to $O(z^3)$

$$d_L(z) = \frac{cz}{H_0}\left\{1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}(1-q_0-3q_0^2+j_0)z^2 + \ldots\right\}$$

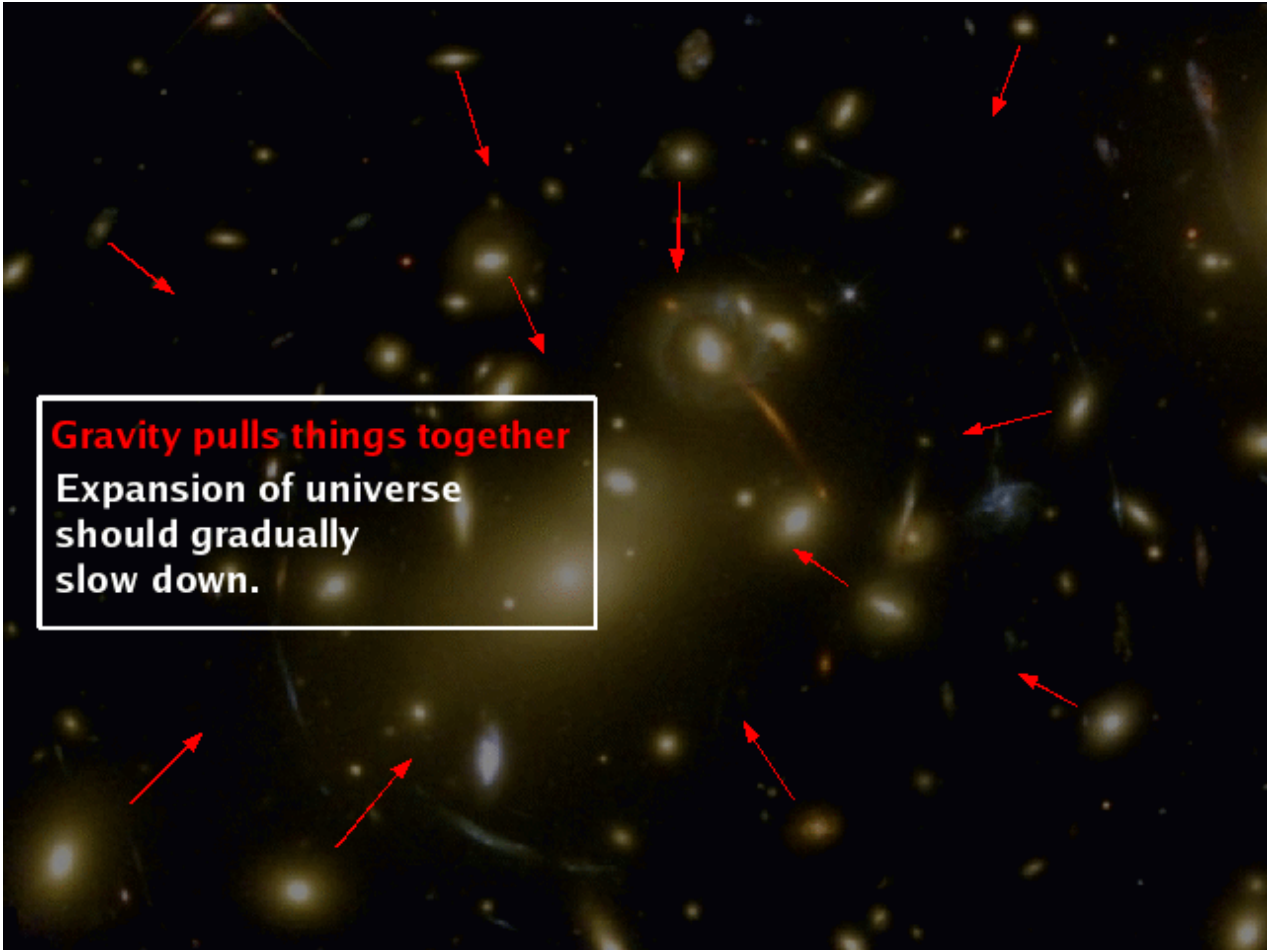
Union-2 SNe

Amanullah et al. (2010)





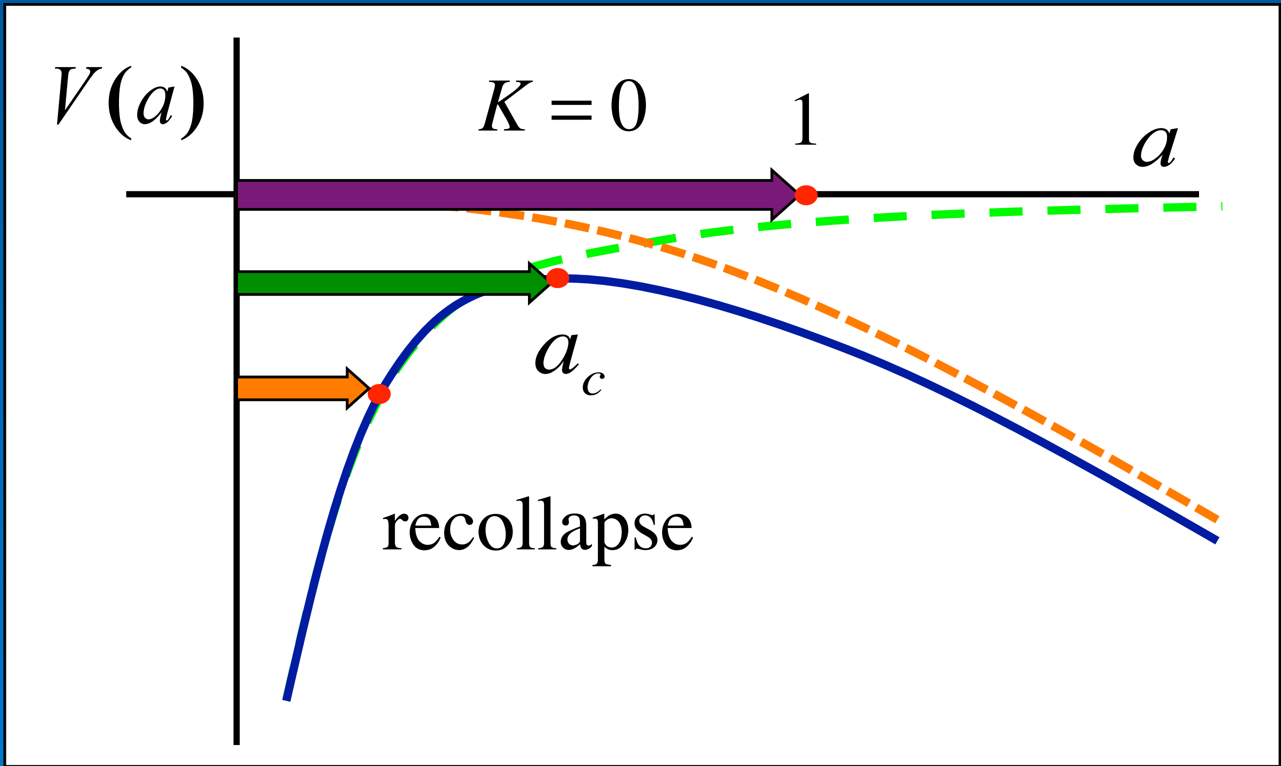
future
past
accelerated
expansion
t_0
t_*
decelerated
expansion
Big Bang


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


Something is pushing the galaxies apart
DARK ENERGY

Einstein-de Sitter model ($\Lambda>0$)

$$\frac{1}{2}\dot{a}^2 - \frac{GM}{a} - \frac{\Lambda}{6}a^2 = -\frac{K}{2} \qquad T + V = E$$



$$a_c = \left(\frac{3GM}{\Lambda}\right)^{1/3}$$

coasting point (unstable)

What is the acceleration of the universe today?

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \quad \text{Friedmann}$$

$$\ddot{a}_0 = \left(-\frac{\Omega_M}{2} + \Omega_\Lambda\right) a_0 H_0^2$$

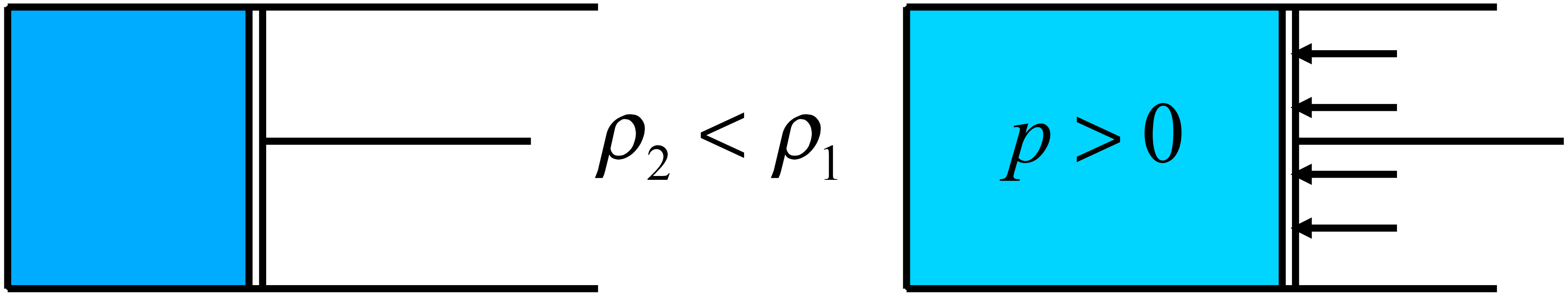
$$= 0.5863\, a_0 t_0^{-2}$$

$$= 9.2 \times 10^{-10} \text{ ms}^{-2}$$

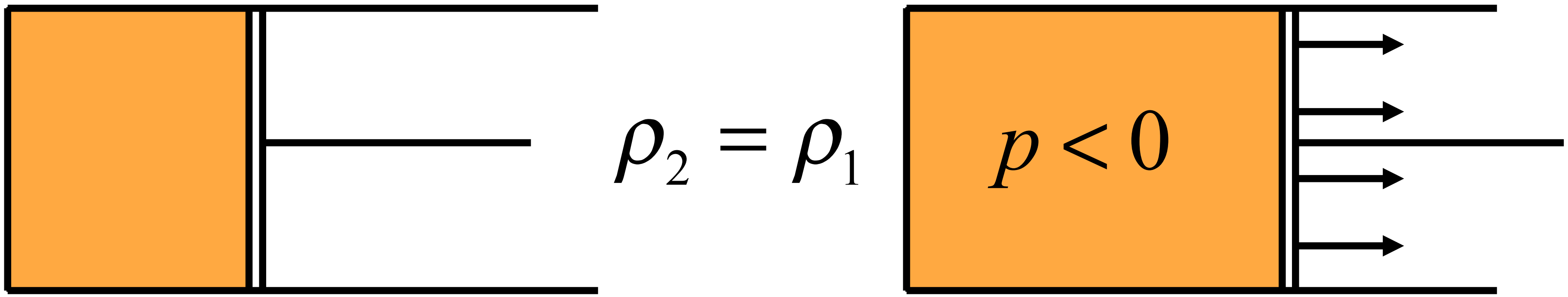
"THE UNIVERSE IS EXPANDING FASTER THAN EVER, AND I DON'T EVEN FEEL A BREEZE."

How do we interpret this DE?

Normal Matter



$$d(\rho V) + pdV = TdS = 0$$

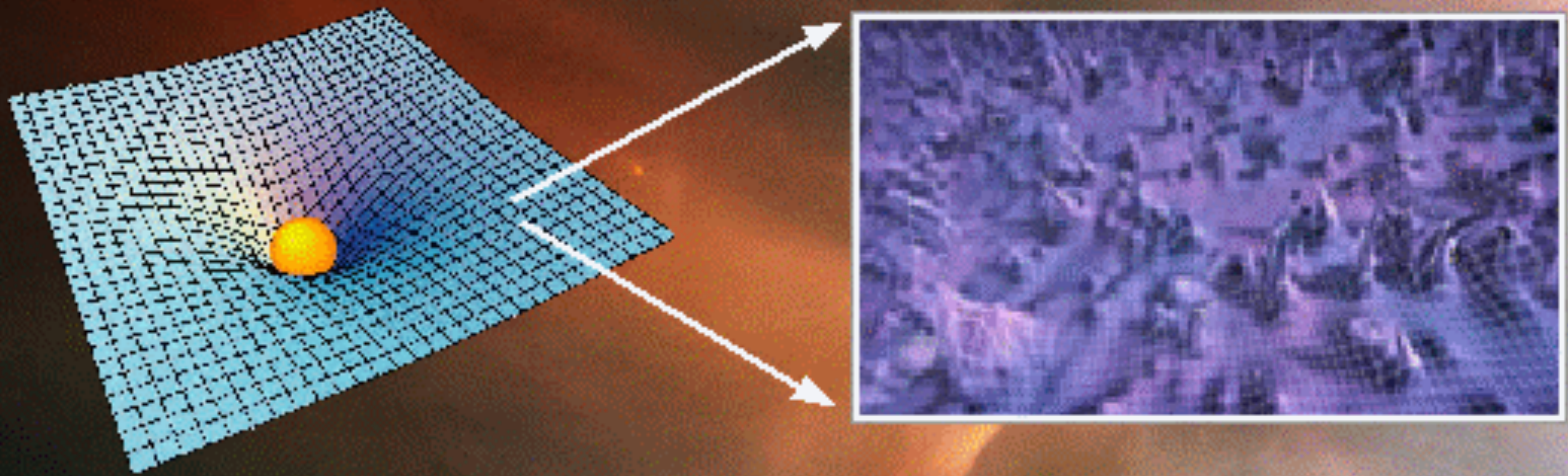


Vacuum Energy

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:

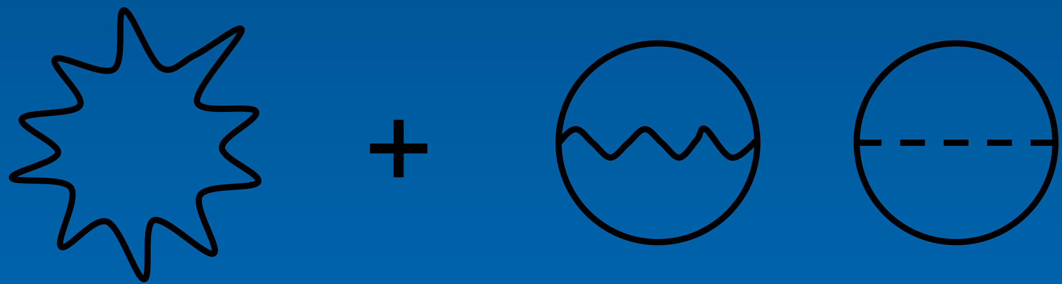


Nothing is something!

Cosm. Const. = Vacuum Energy

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$T_{\mu\nu} = p_\upsilon\, g_{\mu\nu} = -\rho_\upsilon\, g_{\mu\nu} \quad \Rightarrow \quad \Lambda = 8\pi G\, \rho_\upsilon$$

$\rho_\upsilon =$  $+ \ \dots$

$$\rho_\upsilon = \sum_i \int_0^{\Lambda_{UV}} \frac{d^3k}{(2\pi)^3} \frac{\hbar\omega_i(k)}{2} = \frac{\hbar\Lambda_{UV}^4}{16\pi^2} \sum N_i + \mathrm{O}(m^2\Lambda^2)$$

$$\Lambda_{UV} \approx M_{Pl} \quad \Rightarrow \quad \rho_\upsilon^{th} \approx 10^{120} \rho_\upsilon^{obs} = 10^{120} \left(10^{-3} eV\right)^4$$

$$\Lambda_{UV} \approx M_{Higgs} \quad \Rightarrow \quad \rho_\upsilon^{th} \approx 10^{65} \rho_\upsilon^{obs}$$

Nature of Dark Energy?

$$\Lambda = 8\pi G\,\rho_\upsilon = \text{const.} \quad \Rightarrow \quad w_\upsilon = \frac{p_\upsilon}{\rho_\upsilon} = -1$$

$$\rho_x \neq \text{const.} \quad \Rightarrow \quad w_x \neq -1$$

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_x e^{\int_0^z (1+w_x(u))\frac{3du}{1+u}} + \Omega_K(1+z)^2\right]$$

$$q(z) = -1 + \frac{d\ln H(z)}{d\ln(1+z)}$$

$$= \frac{1}{2}\Omega_0 + \frac{3}{2}w_x(z)\Omega_x(z)$$

Coasting Point

Assuming $w_x = w = \text{const.} < 0$

$$q(z) = \frac{1}{2}\left[\frac{\Omega_M + (1+3w)\Omega_x(1+z)^{3w}}{\Omega_M + \Omega_x(1+z)^{3w} + \Omega_K(1+z)^{-1}}\right] = 0$$

$$\Rightarrow \quad z_c = \left(\frac{(3|w|-1)\Omega_x}{\Omega_M}\right)^{\frac{1}{3|w|}} - 1$$

$z > z_c$ universe decelerating

$z < z_c$ universe accelerating

e.g. $w = -1 \quad \Rightarrow \quad z_c = \left(\frac{2\Omega_\Lambda}{\Omega_M}\right)^{\frac{1}{3}} - 1 \approx 0.7$

Model Building

SCDM $H(z) = H_0(1+z)^{3/2}$ ruled out!

ΛCDM $H(z) = H_0[\Omega_M(1+z)^3 + 1 - \Omega_M]^{1/2}$

$$\Rightarrow \quad \Omega_M = 0.27 \pm 0.03$$

ΛwCDM $H(z) = H_0[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}$

$$\Rightarrow \quad \Omega_M = 1 - \Omega_\Lambda = 0.3\ , \quad w = -1.02 \pm 0.10$$

ΛCDM - w(z)

$$H(z) = H_0[\Omega_M(1+z)^3 + \Omega_\Lambda \exp[\,3\int_0^z (1+w(u))\tfrac{du}{1+z}]]^{1/2}$$

New Observational Probes

Modern Cosmological Probes

- We have a whole array of tools at our disposal for studying the Universe with increasing detail.

- It allows us to disentangle the astrophysics from the cosmology and both from fundamental physics.

- We are now learning how to deal with systematic errors inherent to observations.

Four main observational probes:

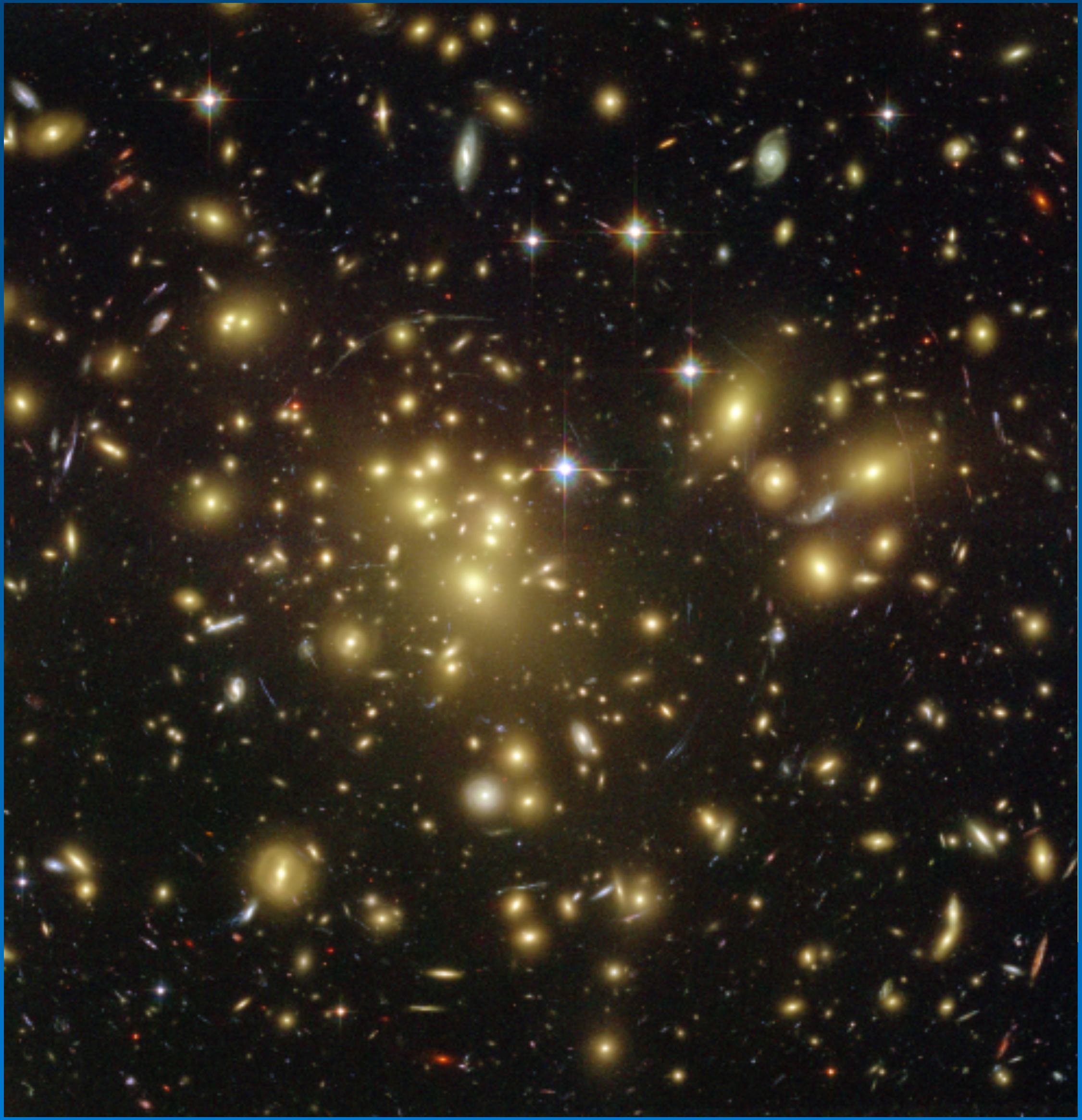
- Gravitational lensing
- Supernovae
- Clusters of galaxies
- Baryon Acoustic Oscillations

Gravitational lensing

Purely geometric phenomenon,
only depends on the distribution of matter between the source and us.

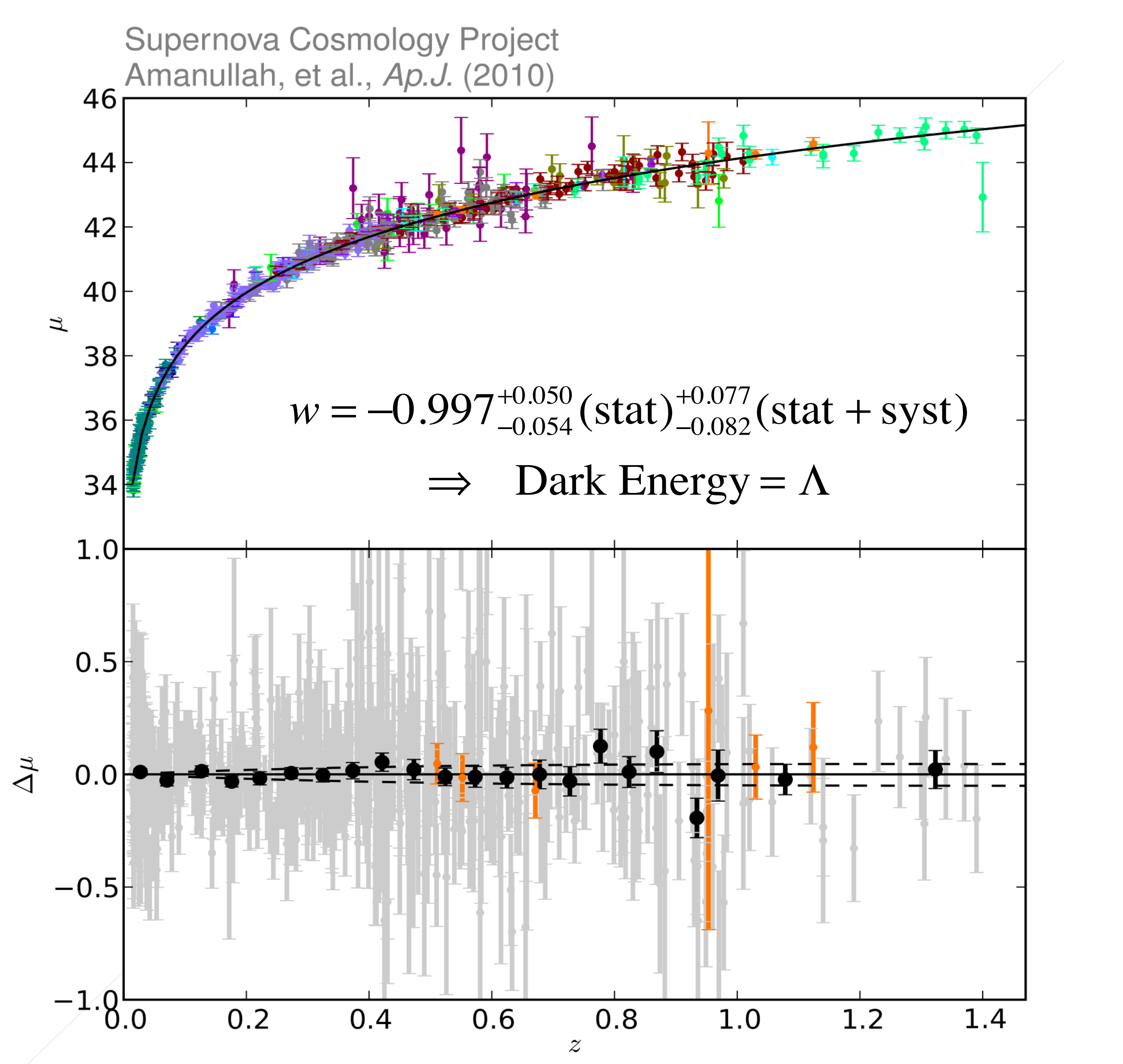
Allows us to model the mass distributions and measure their content.

It is a clean and reliable probe.



Supernovae

Stars th   een at
great di   ed as
standar



Clusters of galaxies

The largest virialized structures in the Universe.

Their X-ray emission allow us to estimate their mass.

Help determine the Halo Mass Function

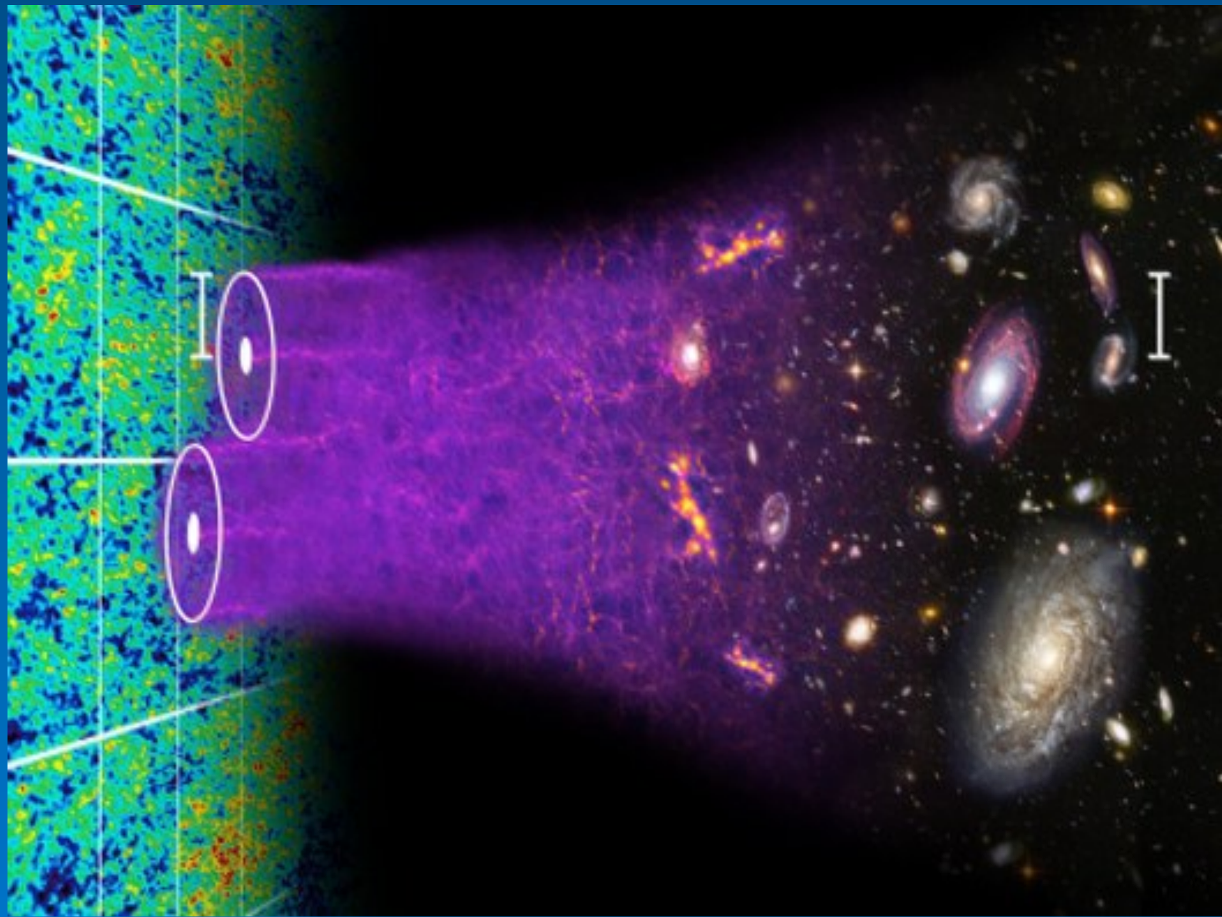
Their number density in the Universe is very sensitive to cosmological parameters.

Baryon Acoustic Oscillations

The plasma before photon decoupling has fluctuations that propagate like sound waves.

At decoupling there is a characteristic scale, the sonic horizon, that can be used as a standard ruler.

Its evolution with redshift since then is an excellent cosmic probe.



DARK ENERGY SURVEY

Blanco
4m telescope
Cerro Tololo,
Chile

Dark Energy Survey

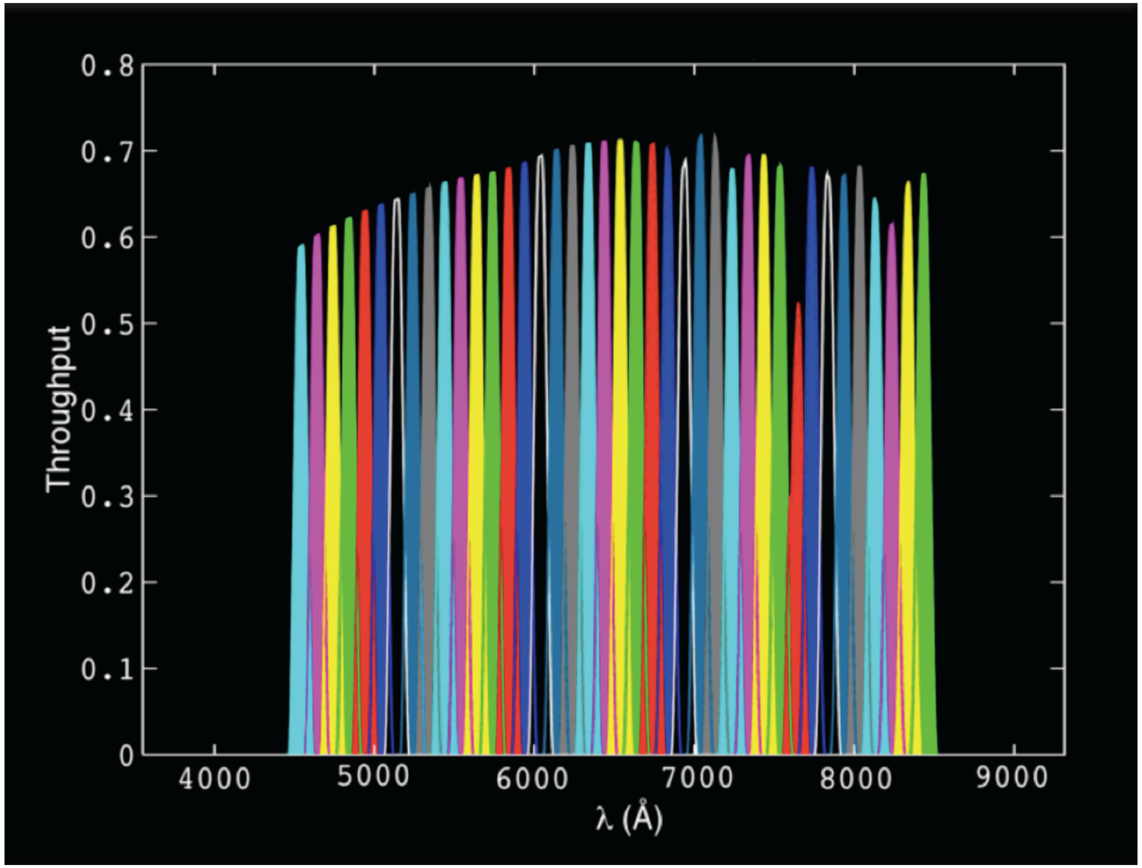
500 million galaxies
5000 deg sq.
$\Delta z_{photo} = 0.05\ (1+z)$
20 bins z range [0.2,1.5]

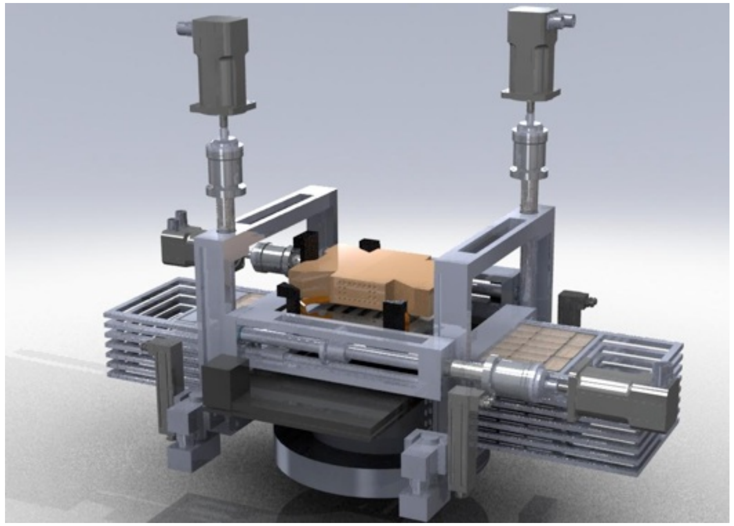
Cost: 100M$

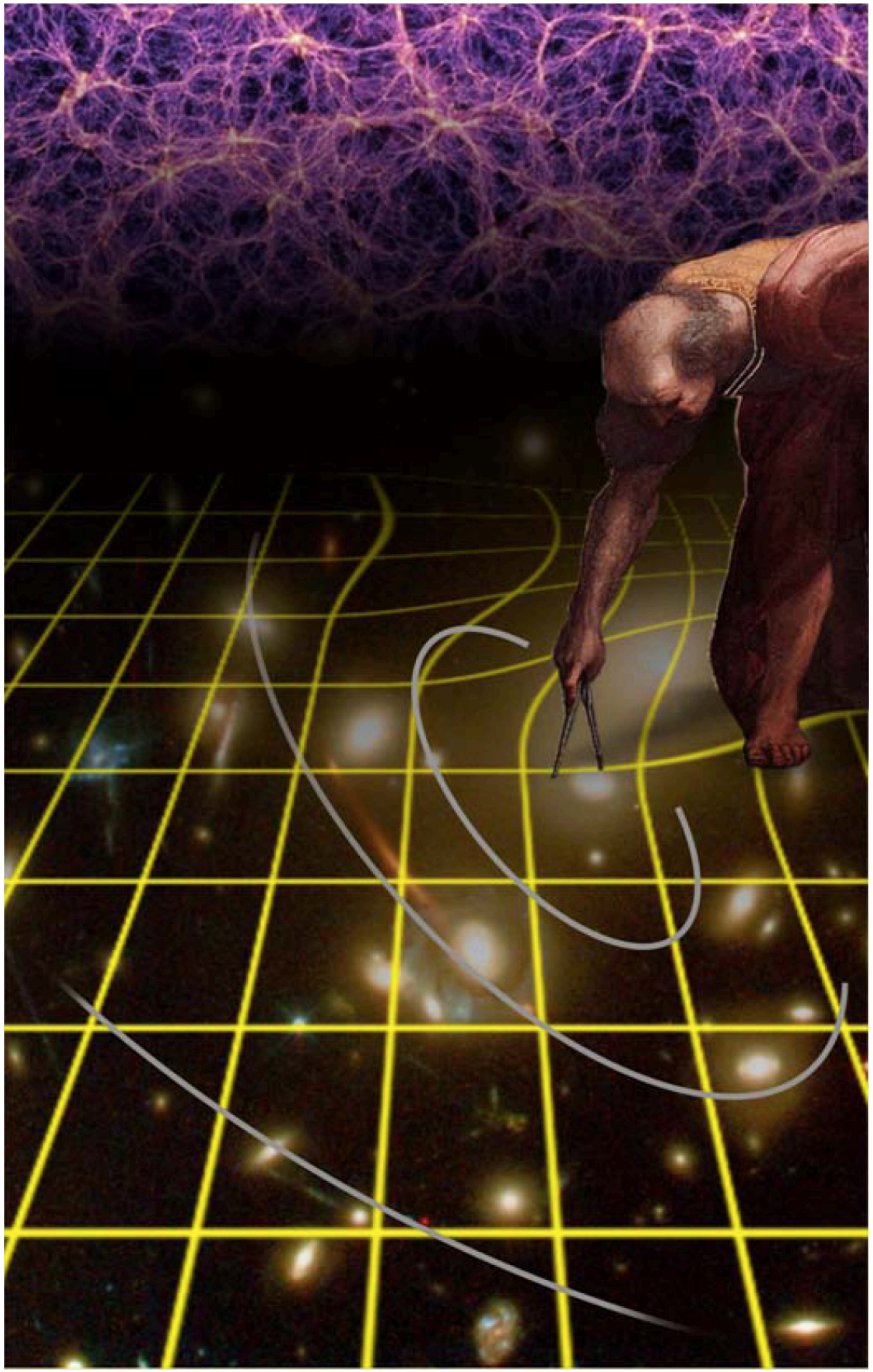
PAU photometric survey

100 million galaxies
200 – 1000 deg sq.
$\Delta z_{photo} = 0.0035\ (1+z)$
100 bins z range [0.2,1.5]
“Tomography”

Cost: 10M$







esa

EUCLID

Spectroscopic survey

100 million galaxies
15,000 sq. deg
$\Delta z_{spec} = 0.001\ (1+z)$
8 bins z range [0.5,2.1]

Cost: 1B$

Imaging survey

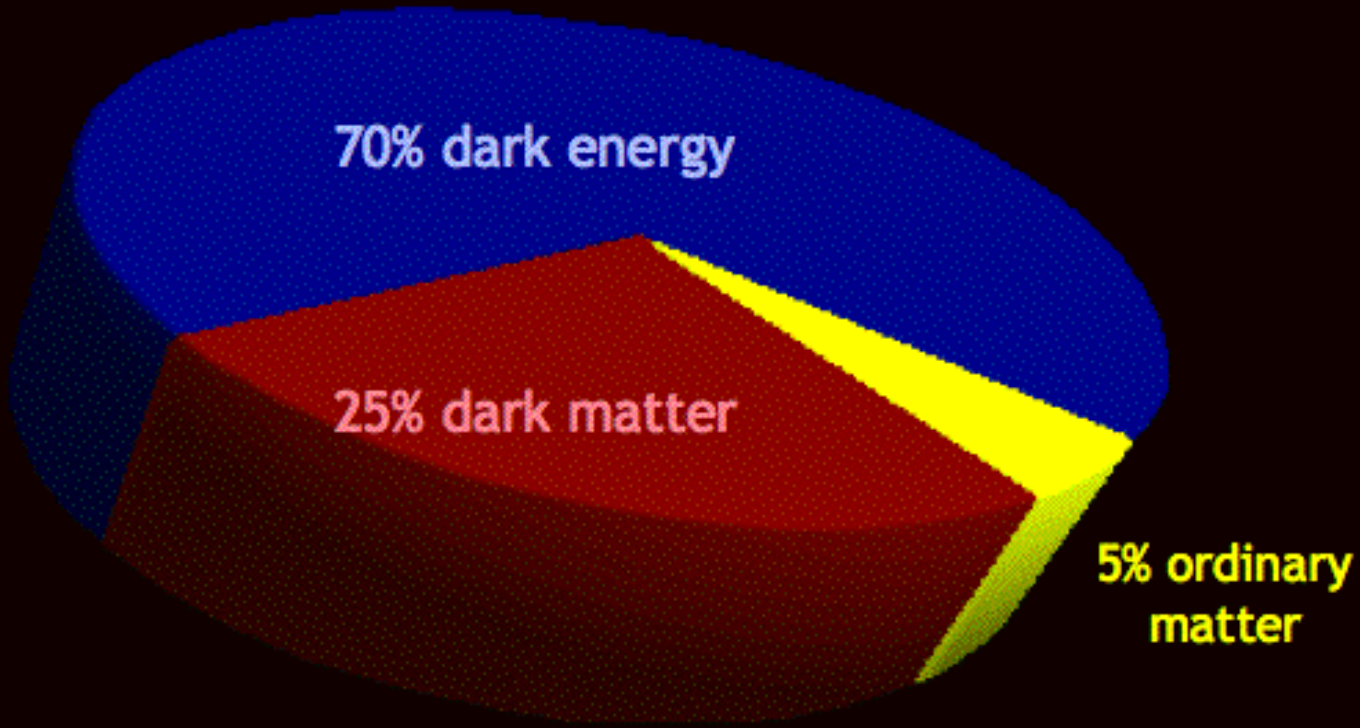
1000 million galaxies
15,000 deg sq.
$\Delta z_{photo} = 0.05\ (1+z)$
5 bins z range [0.5,3.0]

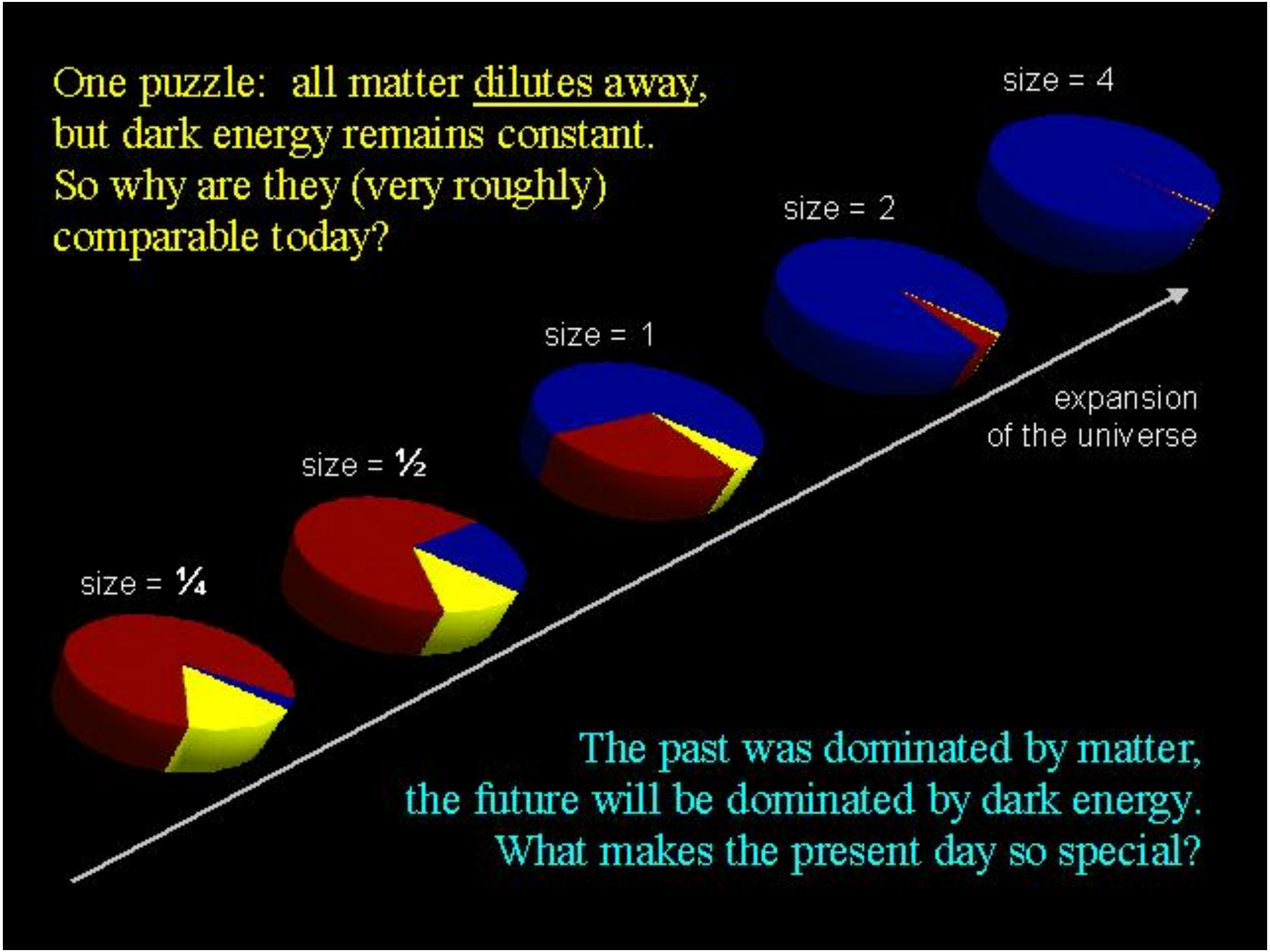
Towards

the

FUTURE

We have a complete inventory of the universe.




One puzzle: all matter dilutes away,
but dark energy remains constant.
So why are they (very roughly)
comparable today?
size = 4
size = 2
size = 1
size = ½
size = ¼
expansion
of the universe
The past was dominated by matter,
the future will be dominated by dark energy.
What makes the present day so special?

The fate of the universe:

Three scenarios