Comprendre l'infiniment grand:

cosmology and large scales in the Universe

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CosmoStat

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Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

Where do all elements come from?

In the 1950's and 60's the predominant theory regarding the formation of the chemical elements in the Universe was due to the work of G.Burbidge, M.Burbidge, Fowler, and Hoyle. The BBFH theory postulated that all the elements were produced either in stellar interiors or during supernova explosions.

Problem: BBFH hypothesis could not by itself adequately explain the observed abundances of helium and deuterium in the Universe.

- Predicting an of helium that was too small. It is observed that about 25% of the Universe's total (baryonic) matter consists of helium
- Deuterium cannot be produced in stellar interiors but it is rather destroyed inside of stars.

G.Burbidge, M.Burbidge, Fowler, and Hoyle

Re

Big Bang Nucleosynthesis

BBN describes the origin of light elements (helium, deuterium, lithium)

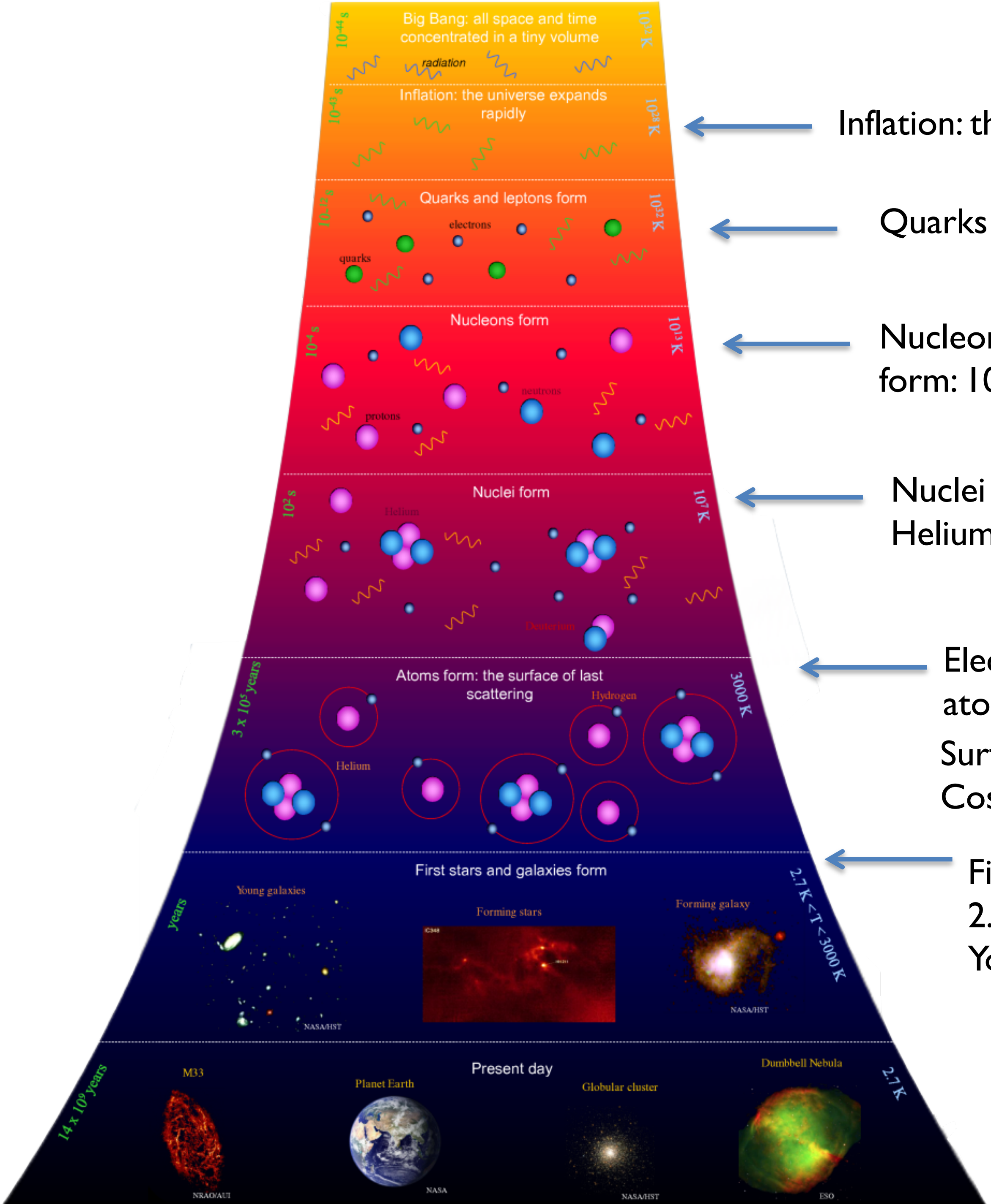
Light elements were produced in the first few minutes of the Big Bang, while elements heavier than helium have their origins in the interiors of stars which formed much later in the history of the Universe

A very hot early universe

When Temperature (T) was very high, there were no neutral atoms or bound nuclei: radiation was so much to ensure that they would be immediately destroyed by a high energy photon.

The Universe cooled down with the expansion: as T dropped below the binding energies of typical nuclei, light elements began to form.

Knowing the conditions of the early universe and the nuclear cross sections, one can calculate the expected primordial abundance of the elements.



Inflation: the Universe expands rapidly

Quarks and leptons form: 10^{15} K

Nucleons (separate protons and neutrons) form: 10^{13} K

Nuclei (protons and neutrons) form 10^{7} K (of Helium and Deuterium)

Electrons join the nuclei and atoms (Hydrogen, Deuterium, Helium) form.

Surface of last scattering. 3000 K, 380,000 yrs

Cosmic Microwave Background

First stars:

$2.7 < T < 3000$ K, 200 $\times 10^{6}$ yrs

Youngest galaxy observed: $t = 400 \times 10^{6}$ yrs

Present day: 2.7 K, 13.6 $\times 10^{9}$ yrs

Relating age, temperature and energy

$$T(t) \approx 10^{10} K \left(\frac{t}{1s} \right)^{-1/2}$$

$$k_B T(t) \approx 1 MeV \left(\frac{t}{1s} \right)^{-1/2}$$

t < 1 s, T > 1 MeV (10^{10}K)

Particles: photons, neutrinos, protons, neutrons, electrons.

Weak interactions can convert protons into neutrons and viceversa

In thermal equilibrium:

$$n \longrightarrow p + e + \nu$$

$$\frac{n_n}{n_p} = e^{-Q/kT}, \quad Q \equiv (m_n - m_p)c^2 = 1.2934\,\mathrm{MeV}.$$

At high T >> Q, there is the same number of neutrons and protons.
As T drops, Q/kT >>1, the interaction rate decreases and there are fewer neutrons (protons don't convert back). The neutron to proton ratio freezes in ($\Gamma/H < 1$) (the rate is smaller than the age of the universe) at kT ≈ 0.7 MeV and t ≈ 3s at a value of:

$$\frac{n_n}{n_p} \approx e^{-1.2934/0.7} \approx 1/6.$$

Baryon to photons

Photons are instead in thermal equilibrium (via Thomson scattering on free electrons) until much later than BBN.

Before decoupling, they follow a blackbody distribution.

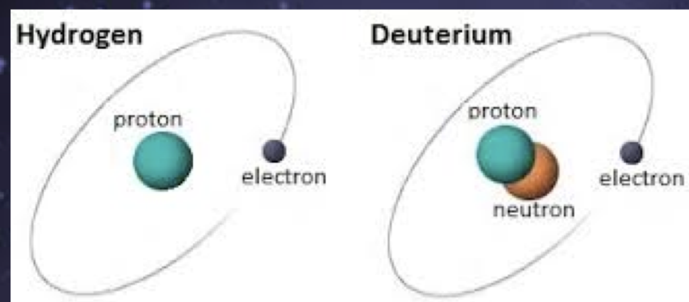
$$\eta \equiv n_b/n_\gamma = 5.4 \times 10^{-10} \left(\frac{\Omega_b h^2}{0.02}\right)$$

The photon density is 413 cm^{-3}
There is one baryon (proton or neutron) for every billion CMB photons.

t ≈ 2 min, T ≈ 0.1 MeV (10^9K)

Deuterium (1 neutron + 1 proton) is the first to form

$$(n + p \rightarrow \mathrm{D} + \gamma).$$

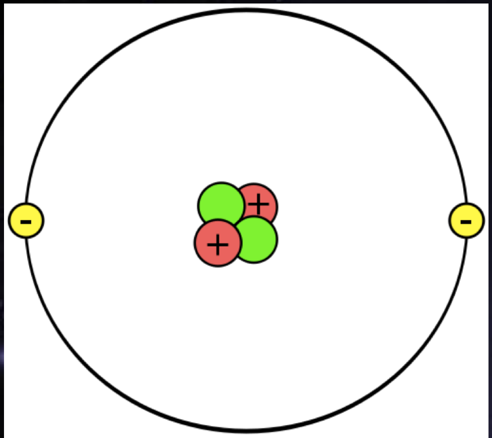


Deuterium has a binding energy of B_D = 2.22 MeV but its synthesis starts later.
At 0.1 MeV the process is very fast and deuterium is quickly formed.

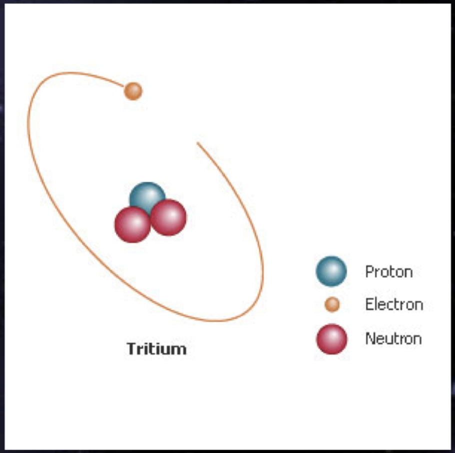
The baryon to photon ratio is very small: the photons in the tail of the blackbody distribution can still dissociate deuterium even when kT is below B_D.

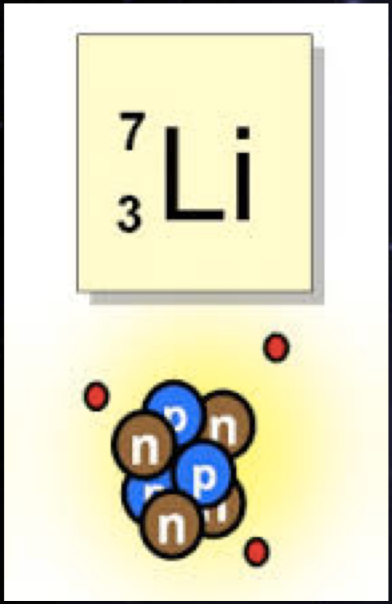
n/p ≈ 1/7 when deuterium forms

t ≈ 2 min, T ≈ 0.1 MeV (10^9K)



Most of the deuterium then collides with other protons and neutrons to produce helium and a small amount of tritium (one proton and two neutrons). Lithium 7 could also arise from one tritium and two deuterium nuclei.





Big Bang Nucleosynthesis

The Big Bang Nucleosynthesis theory predicts that roughly 24±1% of the baryonic mass of the Universe consists of He^4, with the rest made of mainly Hydrogen.
Small amounts: 0.01% of deuterium and even smaller quantities of lithium.

The prediction depends on the density of baryons (i.e. neutrons and protons) at the time of nucleosynthesis.

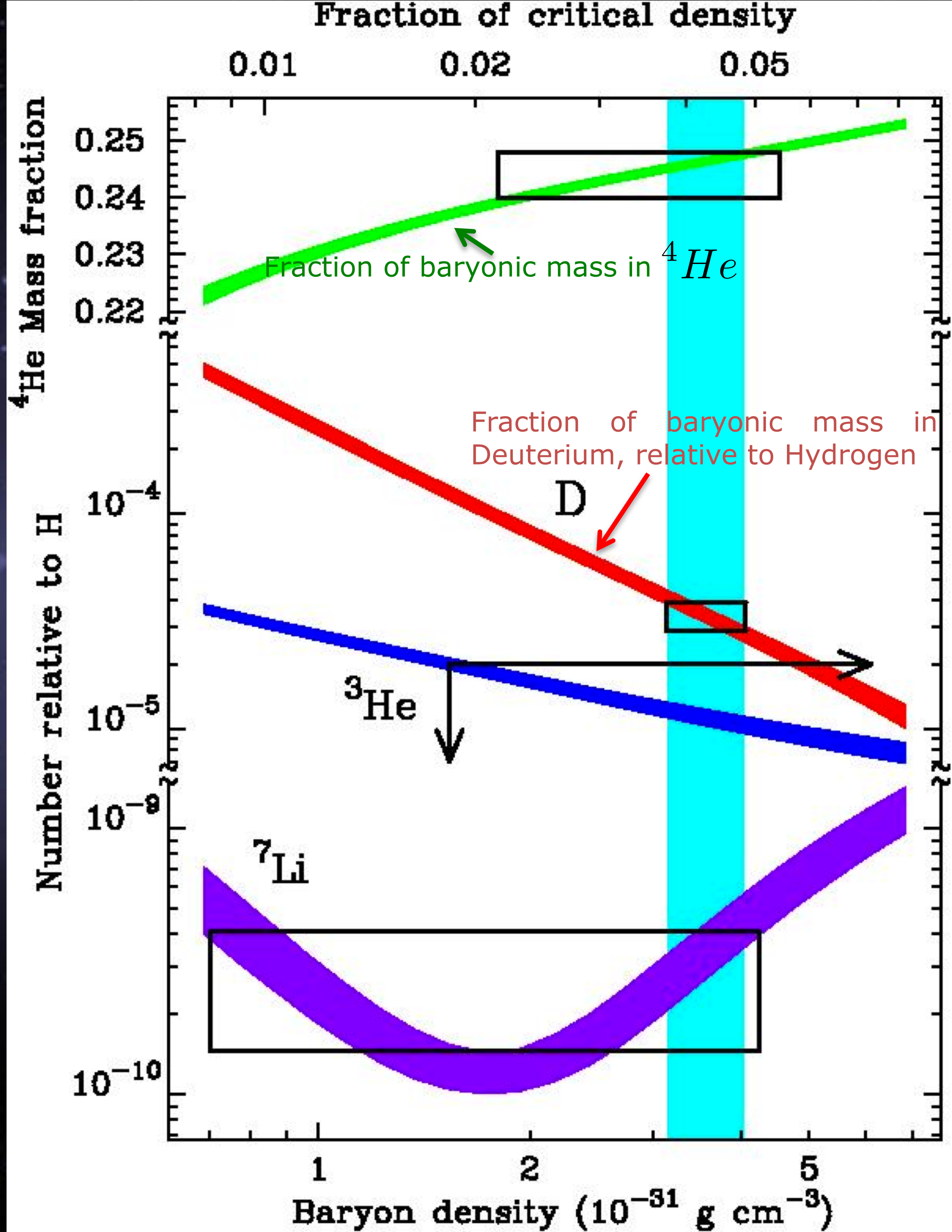
Ref: M.White

BBN

Lines are the predicted abundance of light elements vs baryons density

Vertical cyan band indicates range fixed mainly by measurements of primordial deuterium (QSO absorption lines): the same value of baryon density (few per cent of the critical one) matches all observations.

Boxes are the observations: baryon density (width) consistent with the measured light-element abundance (height). Boxes overlap with cyan: consistency between observation and all predictions. On ^3He there is only an upper limit.



Big Bang Nucleosynthesis

Heavier nuclei than ^7Li are produced in stars, via reactions that require higher temperature and density. Ex.:

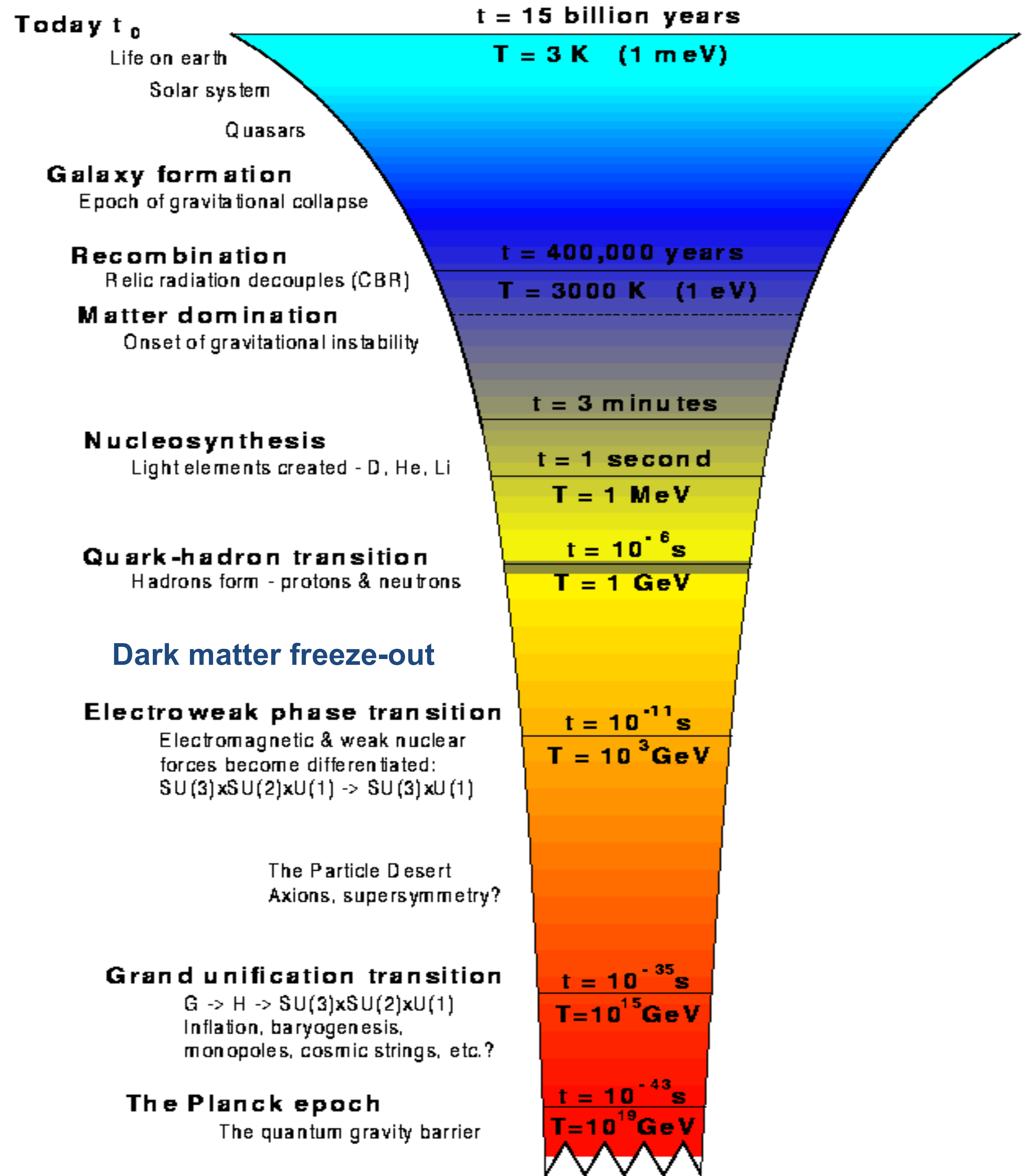
$$^4He + ^4He + ^4He \rightarrow ^{12}C^*$$

Big Bang Nucleosynthesis and CMB

The Cosmic Microwave Background (CMB) has also been used to get a completely independent measurement of the baryon density:

$$\Omega_b h^2 = 0.022 \pm 0.001$$

In very good agreement with other determinations.



Looking for signatures of the early universe, relics of the physics at early times, observables that required hot temperature and densities to be produced

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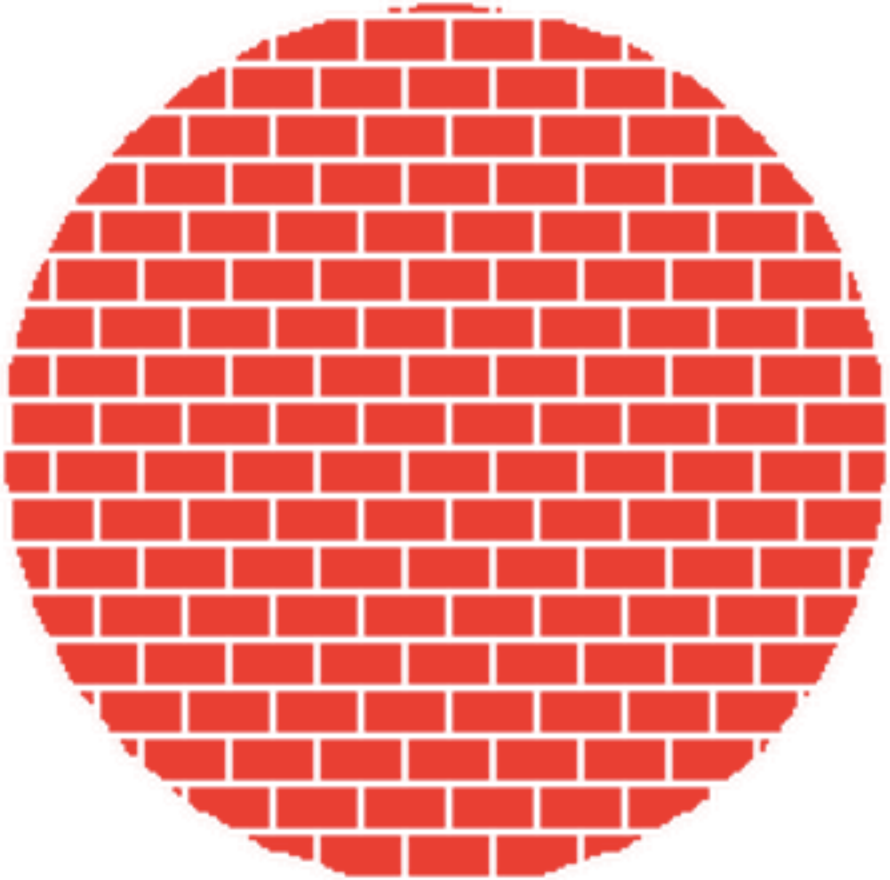
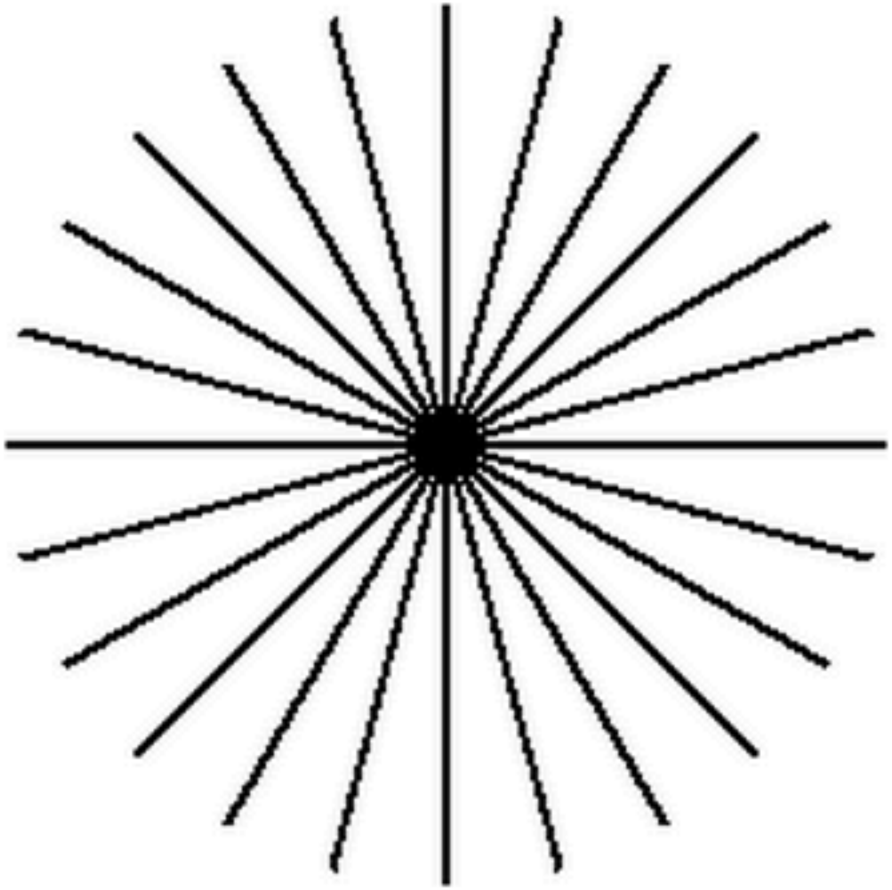
Start from a homogeneous and isotropic Universe





Picture from Ned Wright's Cosmology Tutorial

Friedmann Roberson Walker (FRW) metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$ds^2 = -dt^2 + a(t)^2 \left(\frac{1}{1 - Kr^2} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right)$$

a(t) scale factor

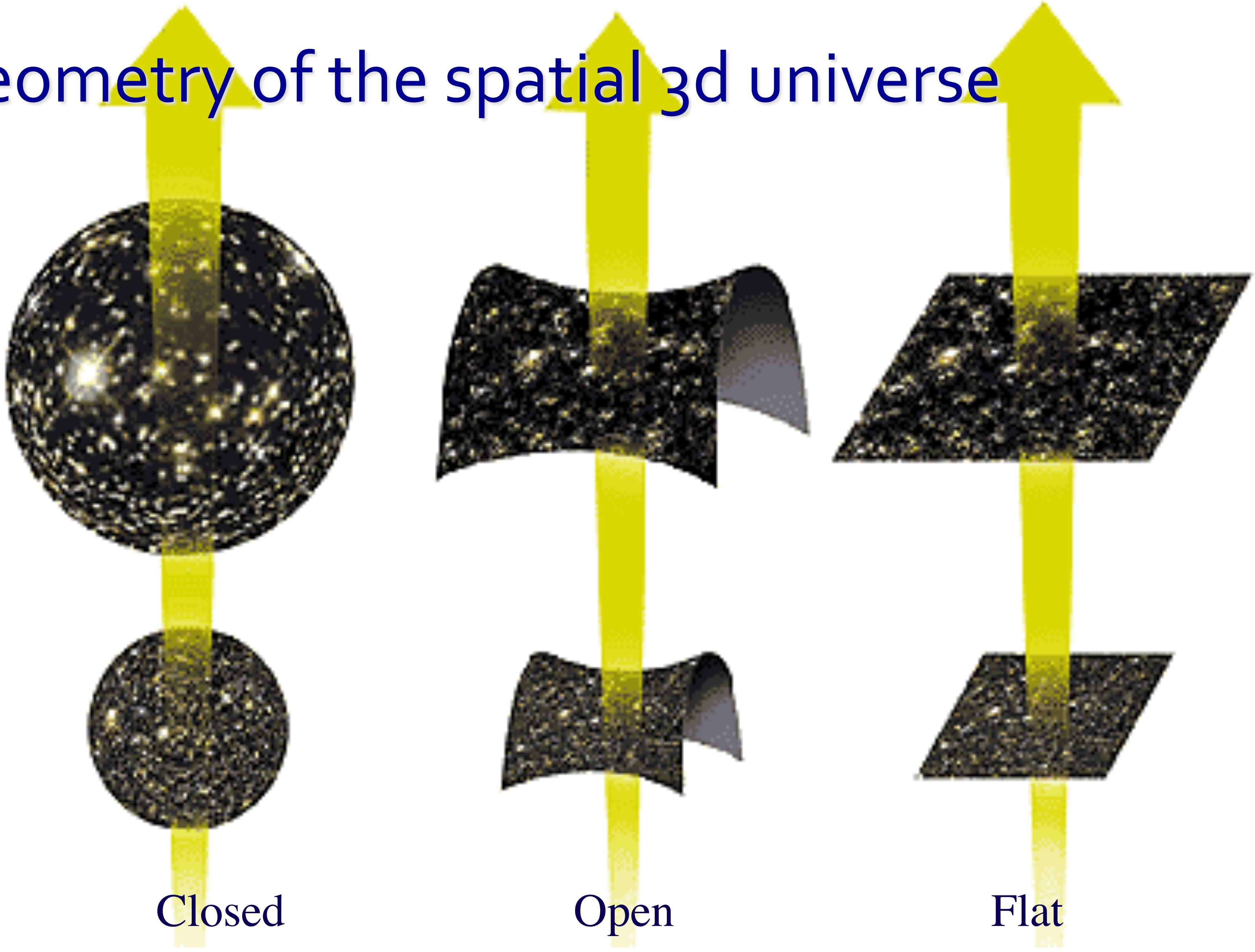
K curvature: K > 0 (closed, at r = 1/sqrt(K), infinite distance)
K < 0 (open, no singularity)
K = 0 Flat

One can always change the overall normalization of a and r.

r, θ, ϕ are the spherical coordinates

Comoving coordinates (at rest with respect to the expansion):
r, θ, ϕ are constant

Geometry of the spatial 3d universe



Stress energy tensor

Energy momentum tensor for a perfect relativistic fluid, homogeneous and isotropic

$$T_\mu^\nu \equiv \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

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

Trace $\quad T = T_\mu^\mu = -\rho + 3p$

Einstein equations

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

Left hand side: Einstein tensor, function of the metric and its derivatives, i.e. it depends on the geometry of the space time

Right hand side: stress energy tensor, function of the content of the Universe, i.e. matter, radiation, baryons, ecc.

Einstein equations

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

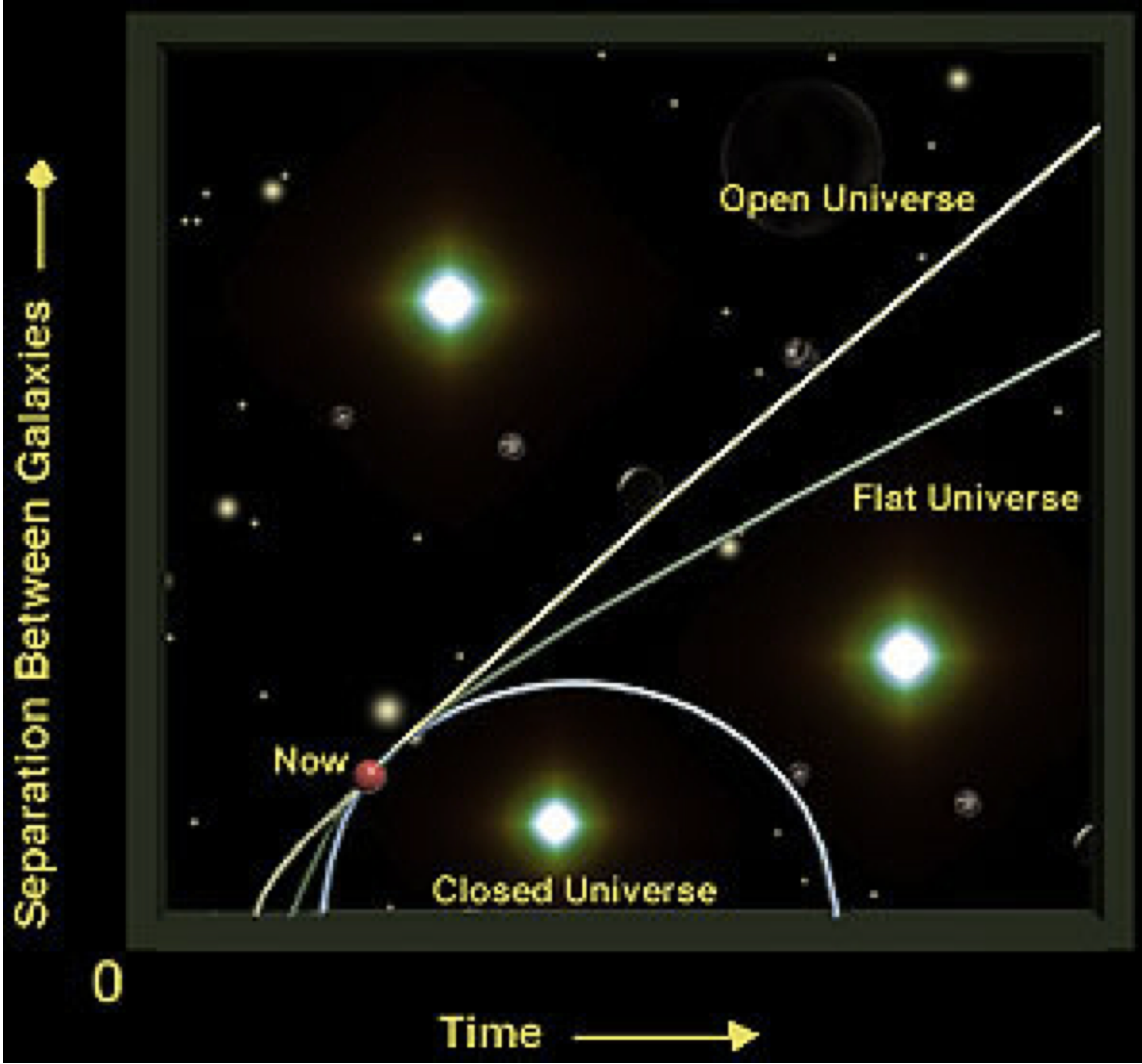
Friedmann equations for a multi-component Universe:

$$H^2(t) \equiv \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i(t) - \frac{k}{a^2(t)}$$

$k = 0, +1, -1$ for zero, positive, and negative curvature,

Expansion ⟷ Matter content and geometry

Acceleration equation: $$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}\sum_i(\rho_i + 3p_i)$$



Open Universe
Flat Universe
Now
Closed Universe
Separation Between Galaxies
0
Time

Conservation equations

$$T_{\mu\nu}^{;\nu} = 0$$

The (covariant) derivative of the stress energy tensor (which depends on energy density and pressure of each fluid) is zero, i.e. energy is conserved.

Valid for the total stress energy tensor (summed up over all components).

If each species has an evolution which is not coupled to the one of other species, then also each separate stress energy tensor is conserved.

Conservation equations

$$\frac{d\rho_i}{dt} + 3(\rho_i + p_i)H = 0$$

$$p_i = w_i\rho_i,$$

$$\rho_i \propto \exp\left[3\int_0^z [1 + w_i(z')] d\ln(1+z')\right]$$

Exercise 1: derive the evolution of matter in MDE and radiation in RDE in a flat universe as a function of the scale factor and of redshift. Assume matter is cold (zero pressure) and radiation has $w = 1/3$

Exercise 2: using the Friedmann equations, show whether the universe is decelerating or accelerating in MDE and RDE.

Exercise 3: using the Friedmann equations, calculate the evolution of the Hubble parameter H as a function of a and t.

Conservation equations

$$\frac{d\rho_i}{dt} + 3(\rho_i + p_i)H = 0$$

$$p_i = w_i \rho_i$$

$$\rho_i \propto \exp\left[3\int_0^z [1 + w_i(z')] d\ln(1+z')\right]$$

Matter	w = 0	$\rho_m \sim a^{-3}$
Radiation	w = 1/3	$\rho_r \sim a^{-4}$

$\ddot{a} < 0$

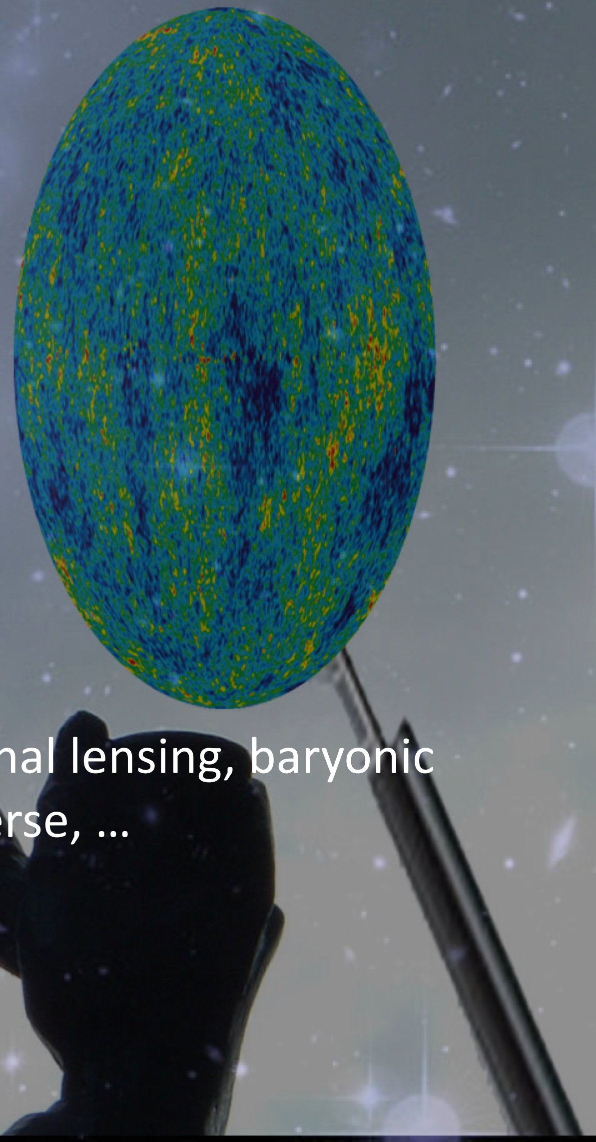
deceleration

Clues of the Universe

Supernovae

Cosmic Microwave Background (CMB)

Large scale structures



Galaxy rotation curves, clusters and X-rays, gravitational lensing, baryonic acustic oscillations, age of the universe, …

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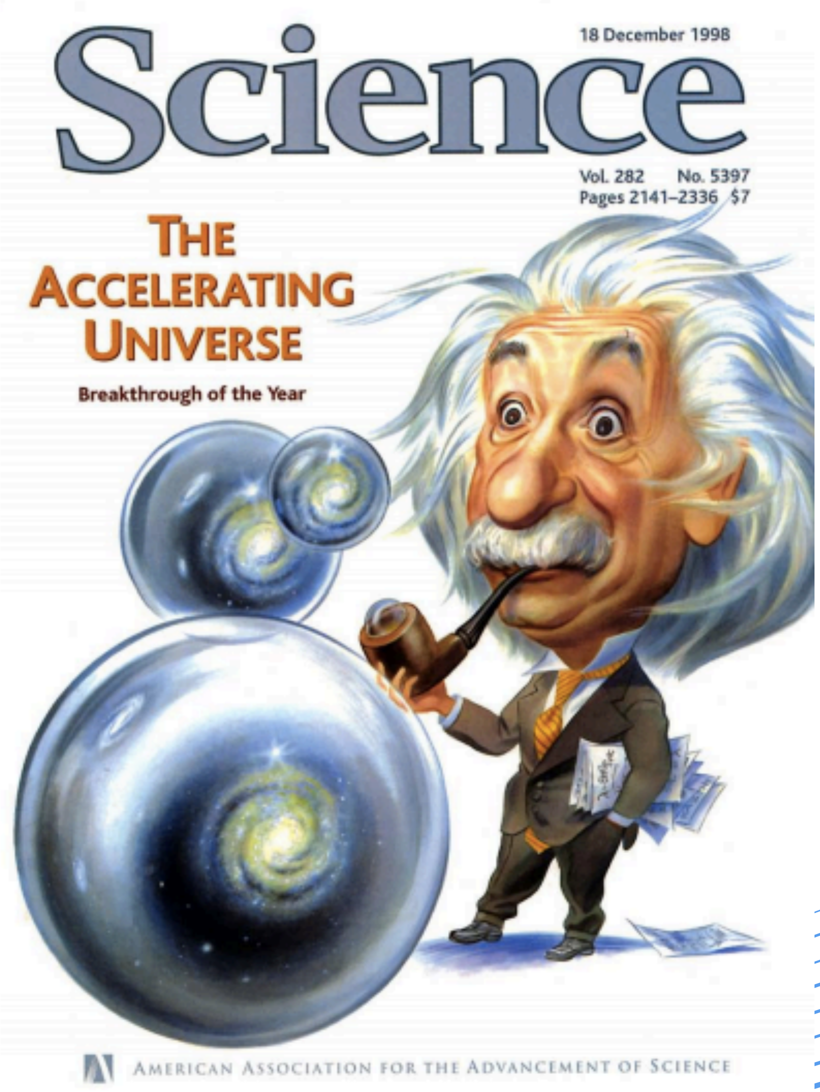
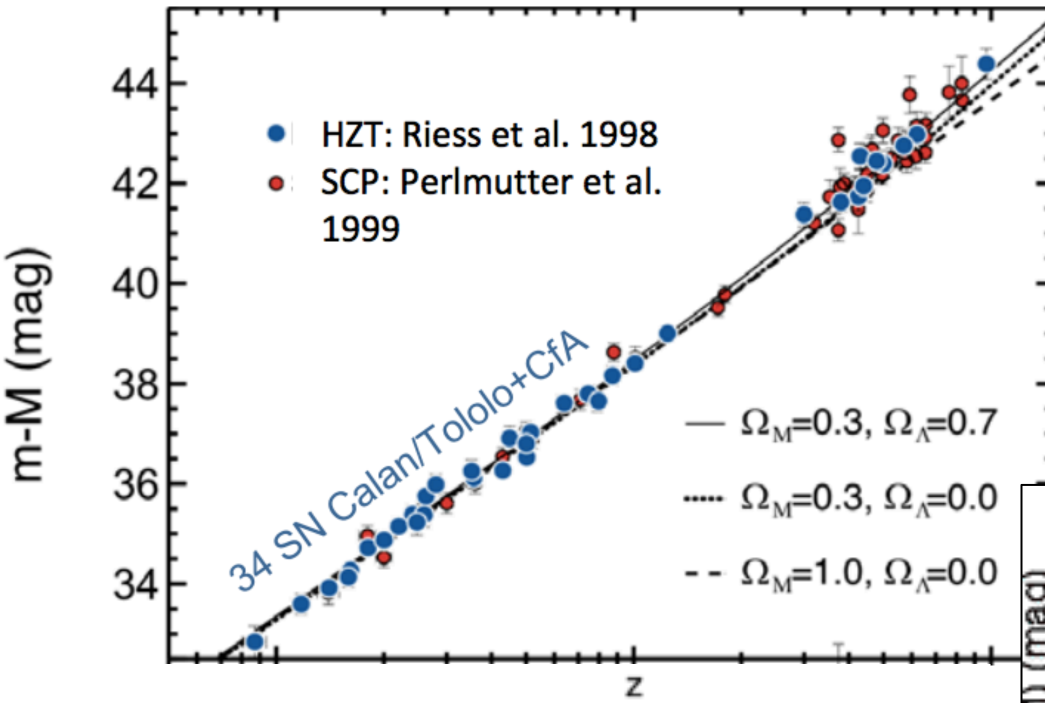
Supernova Cosmology Project and the High-z Team

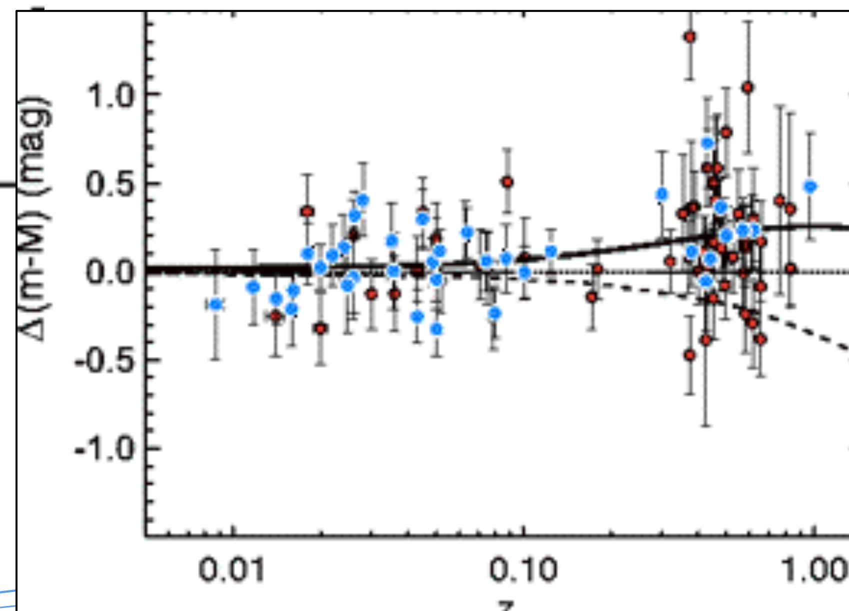
In 1994 the High-z Team was formed: “To Measure the Cosmic Deceleration
 of the
Universe with Type Ia Supernovae”



Supernovae



Distant SNe are 0.25 mag dimmer than they would be in a decelerating Universe

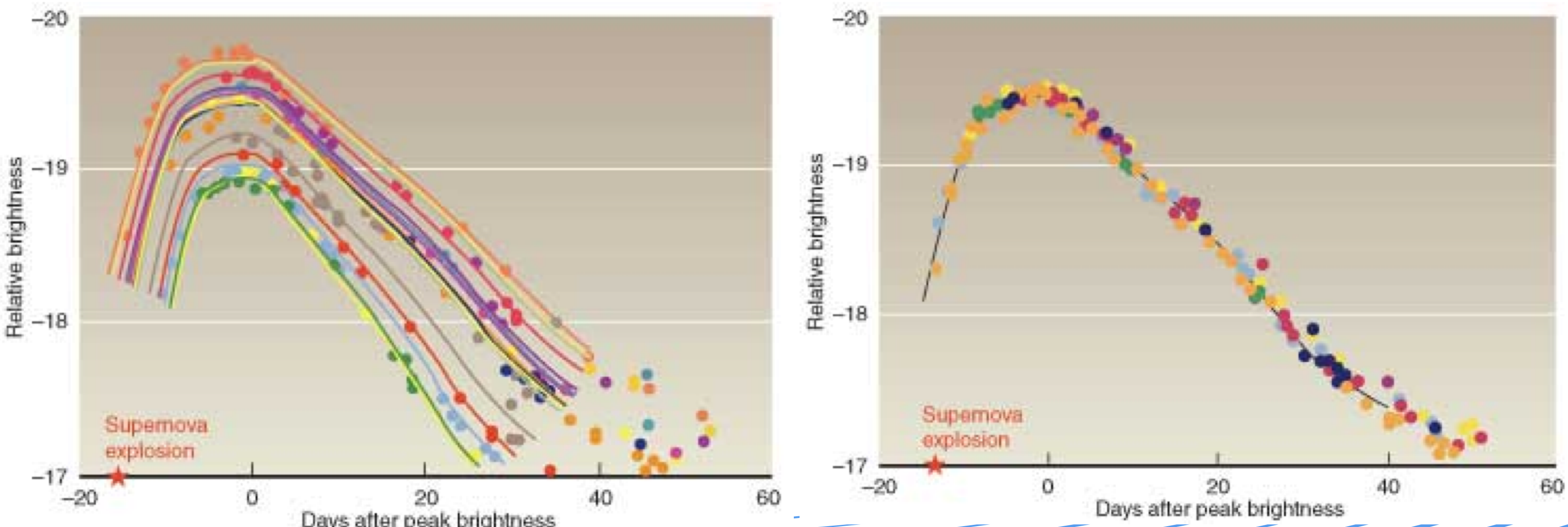


Supernovae

SNIa not standard candles, 1 sigma spread of 0.3 mag in B-band luminosity
Works in 1990's establishes an empirical correlation between SN Ia peak brightness and the rate at which the luminosity declines with time after the peak: Intrinsically brighter SNe decline more slowly
-> standardizable candles with a dispersion of 15% in peak brightness.

Shape and color corrections plus a third parameter describing variation of SNe luminosity with host galaxy mass

Different light-curve fitters



Luminosity distance

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

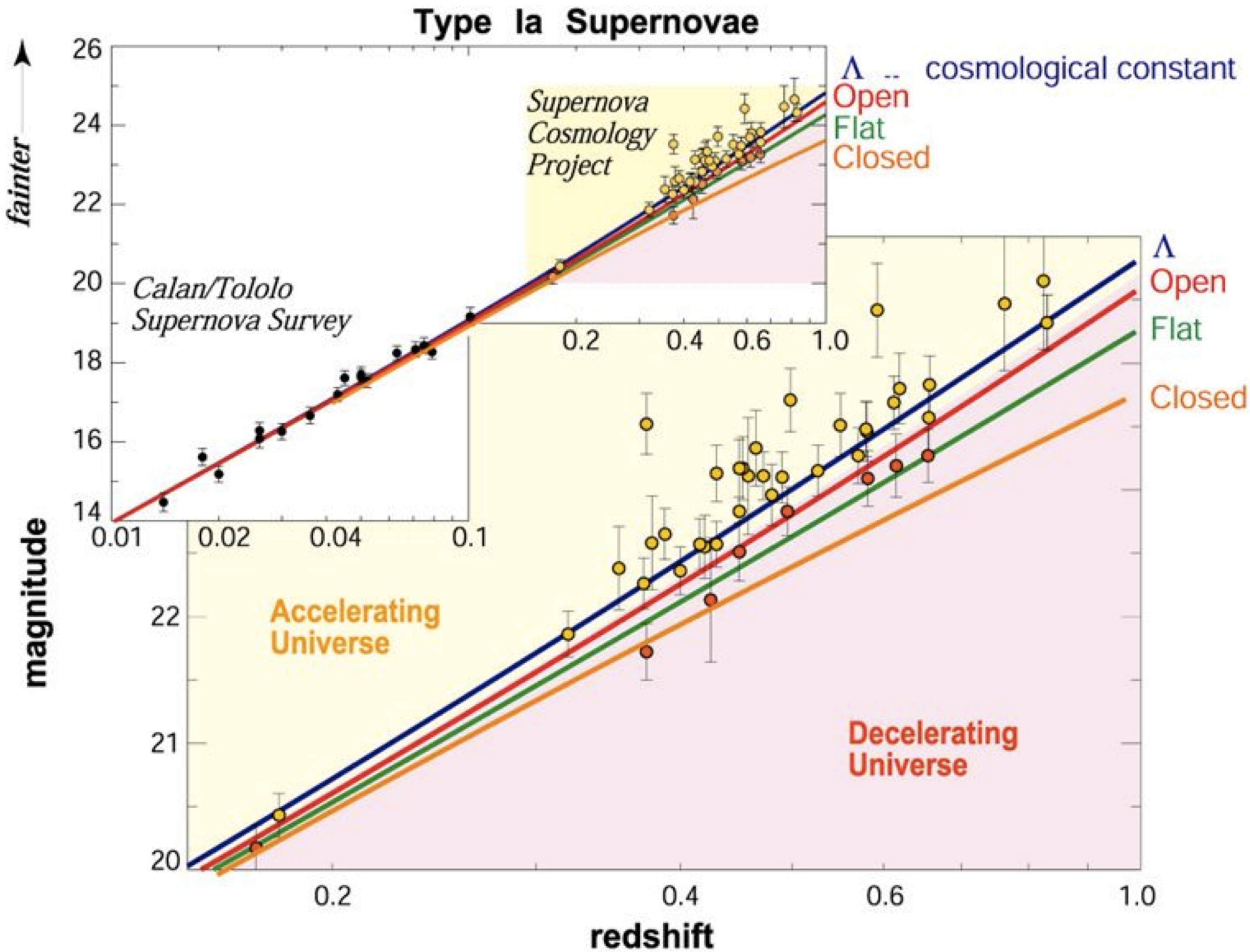
$$d_L = r(1+z) = c(1+z)|\Omega_k|^{-1/2} S_k\left(\int |\Omega_k|^{1/2} \frac{da}{H_0 a^2 (H(a)/H_0)}\right)$$

Calculate from flux and intrinsic luminosity

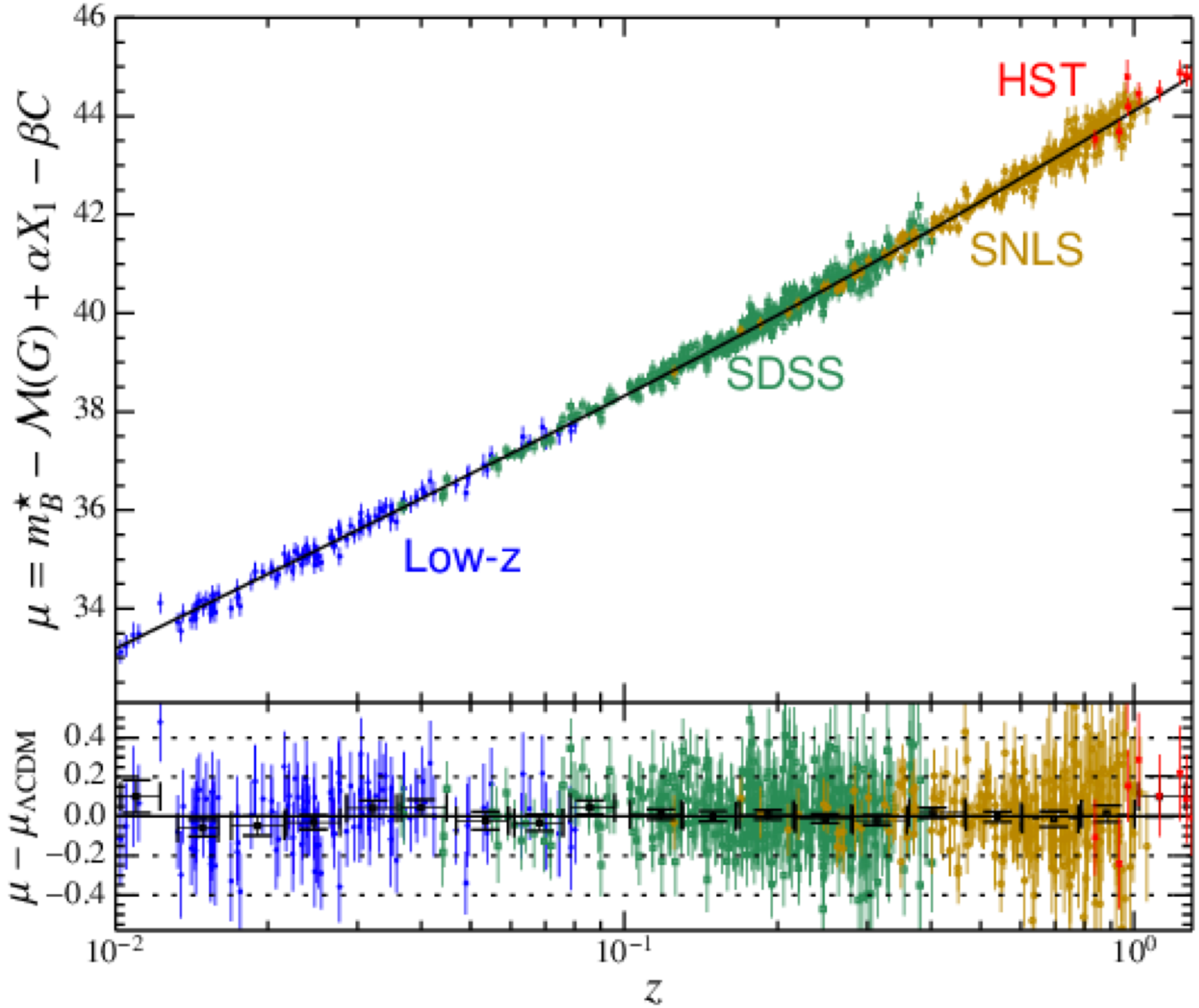
Given a model, it can be written in terms of the various Ω_α

Older results, compared to different geometries

- **Two groups, the Supernova Cosmology Project and the Hi-Z Team, find evidence for an accelerating Universe.**



Hubble Diagram



Hubble (Leavitt) diagramme, JLA analysis

Betoule et al. 2014

Surprise?

- 1998: Supernovae
- 1988: already a theoretical framework for dark energy.
  - Inflation predicts a flat Universe $\Omega_0 = 1$
  - Observations on DM were pointing towards $\Omega_m \simeq 0.25$
  - Ages of globular clusters were too old wrt the age of a decelerating universe

- Need of 0.75 missing energy dominating at recent epochs to allow structure formation.

Expansion and acceleration

It started accelerating about 5 billion years ago

Most of the universe is not made of ordinary matter!

Expansion

Expansion → $$\ddot{a}/a = -\frac{1}{6}(\rho + 3p)$$ ← Density and pressure

$$p_i = w_i \rho_i$$

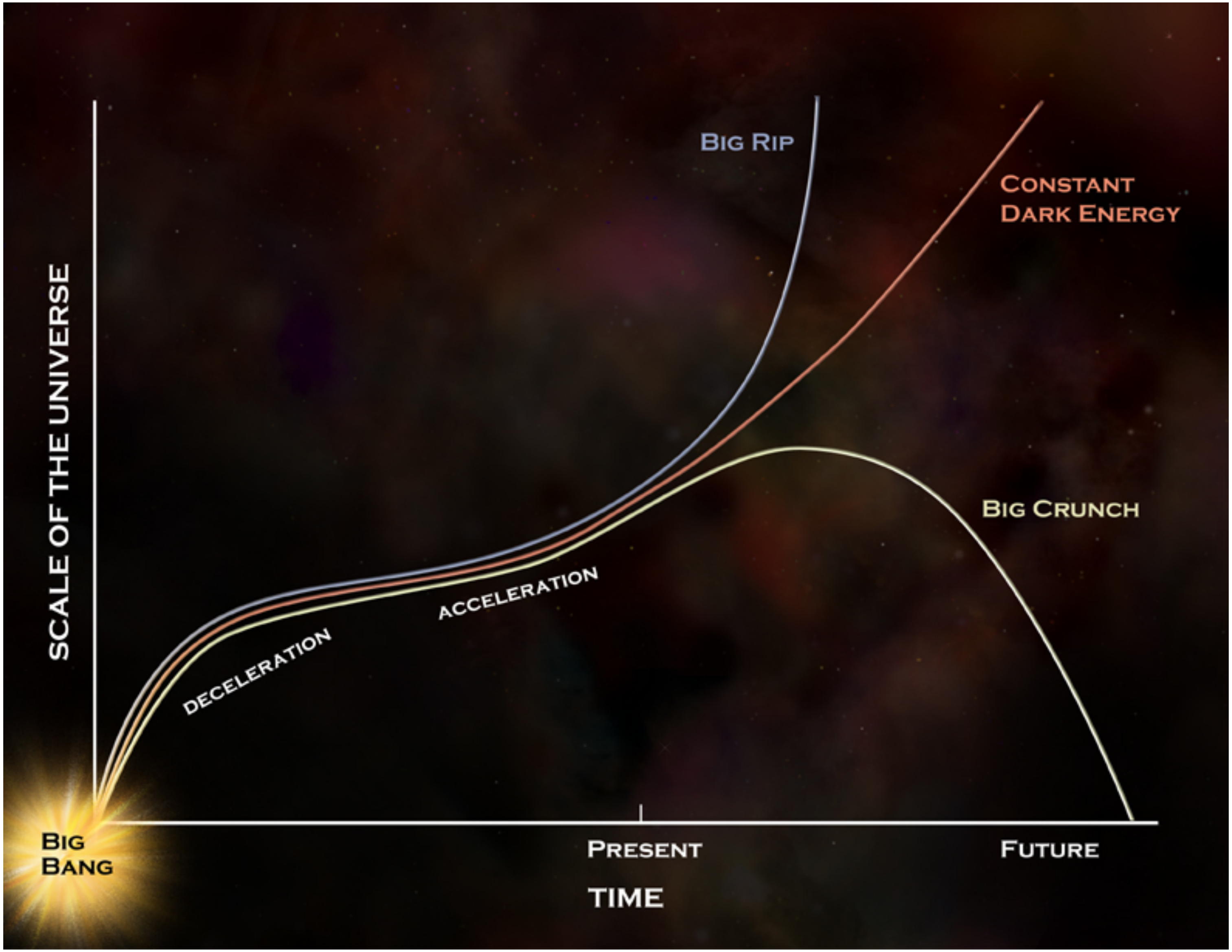
Matter	w = 0	$\rho_m \sim a^{-3}$
Radiation	w = 1/3	$\rho_r \sim a^{-4}$

$$\ddot{a} < 0$$

deceleration

Most of the universe is not made of ordinary matter!

A tail of three futures



(Credit: NASA/CXC/M.Weiss)