Comprendre l'infiniment grand:

cosmology and large scales in the Universe

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20th July, 2017

Further references

Popular article from 2010:
http://www.technologyreview.com/view/420529/fine-structure-constant-varies-with-direction-in-space-says-new-data/

Webb paper on PRL: Varying fine-structure constant: http://arxiv.org/abs/1008.3907

Oklo paper: http://arxiv.org/abs/1008.3957

More recent, from observations: http://arxiv.org/abs/1501.00560

http://www.nature.com/scientificamerican/journal/v23/n4s/full/scientificamericantime1114-70.html

Scientific American 23, 70 - 77 (2014)
Published online: 23 October 2014 | doi:10.1038/scientificamericantime1114-70
Inconstant Constants
John D. Barrow & John K. Webb

Uzan, LRR Varying constants, Gravitation and Cosmology : http://relativity.livingreviews.org/Articles/lrr-2011-2/download/lrr-2011-2Color.pdf
Proponent of a varying fine structure constant: Bachall etal 2004
http://www.sns.ias.edu/~jnb/Papers/Preprints/Finestructure/alpha.pdf

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

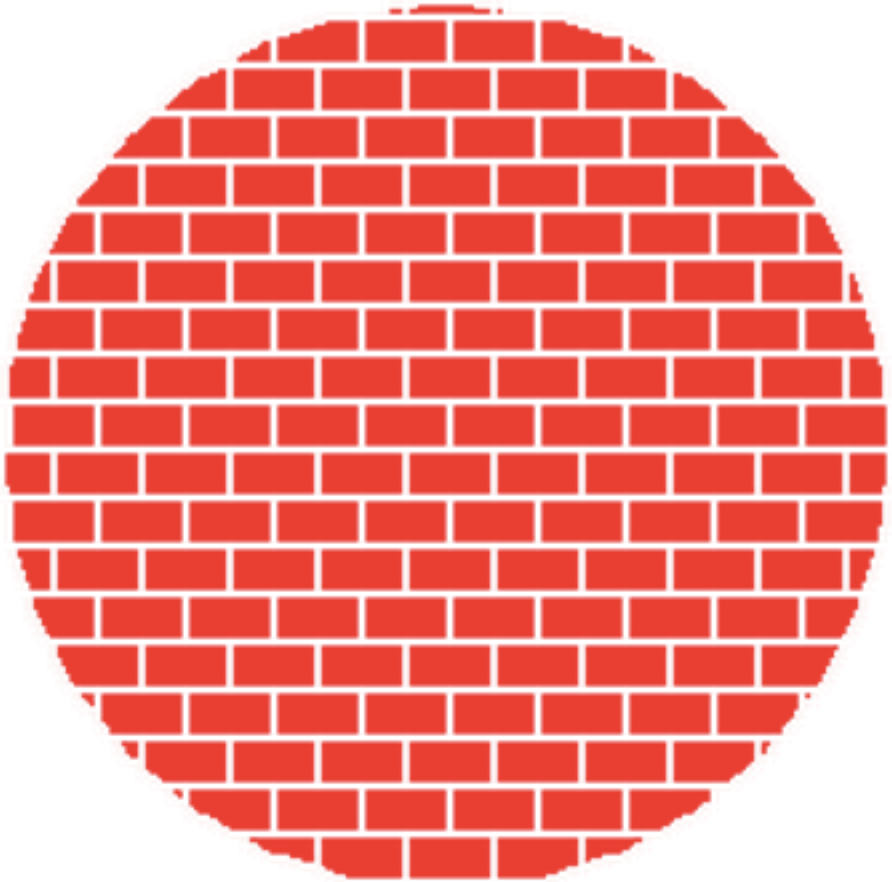
Supernovae and Cosmic acceleration

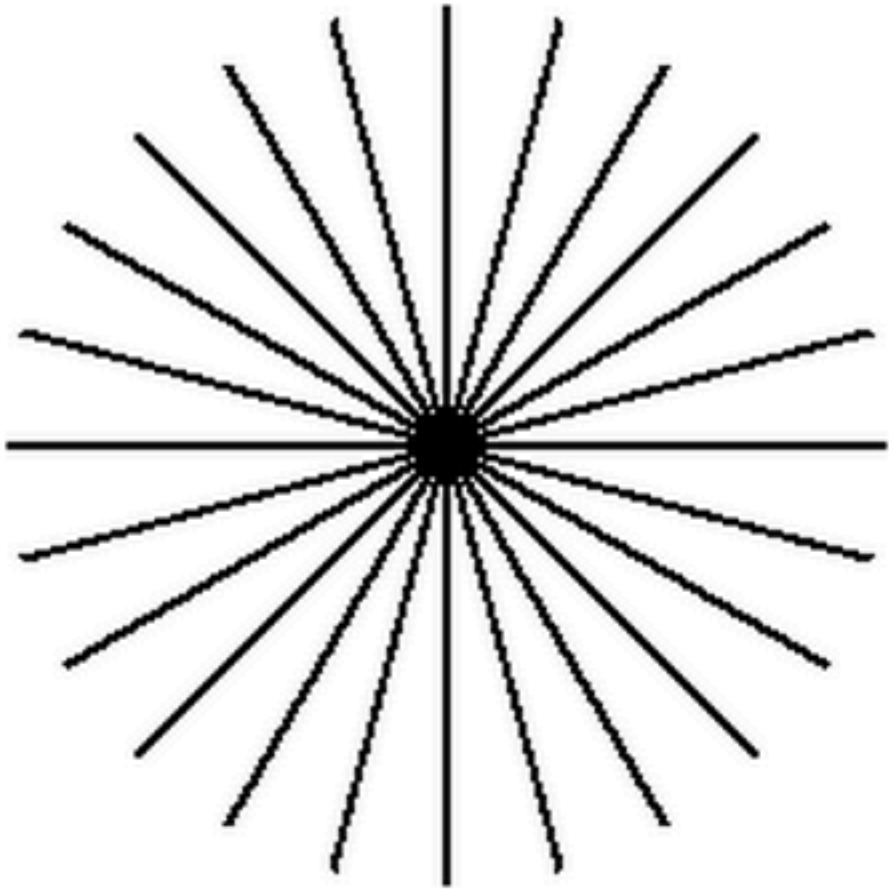
Cosmic Microwave Background

Structure formation

The Dark Universe

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

Cartesian coordinates:

$$ds^2 = -dt^2 + a(t)^2 \left(\frac{1}{1 - Kr^2} (dx^2 + dy^2 + dz^2) \right)$$

We can factorize the expansion completely by defining the **conformal time**:

$$d\tau = \frac{dt}{a(t)} \qquad ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$g_{\mu\nu} \equiv a^2 \cdot \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & (1-Kr^2)^{-1} & 0 & 0 \\ 0 & 0 & (1-Kr^2)^{-1} & 0 \\ 0 & 0 & 0 & (1-Kr^2)^{-1} \end{pmatrix} \equiv a^2 \gamma_{\mu\nu}$$

Comoving metric

Expansion rate:

$$H = \frac{a_t}{a} \quad , \quad \mathcal{H} = \frac{\dot{a}}{a} \qquad \mathcal{H} = aH$$

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

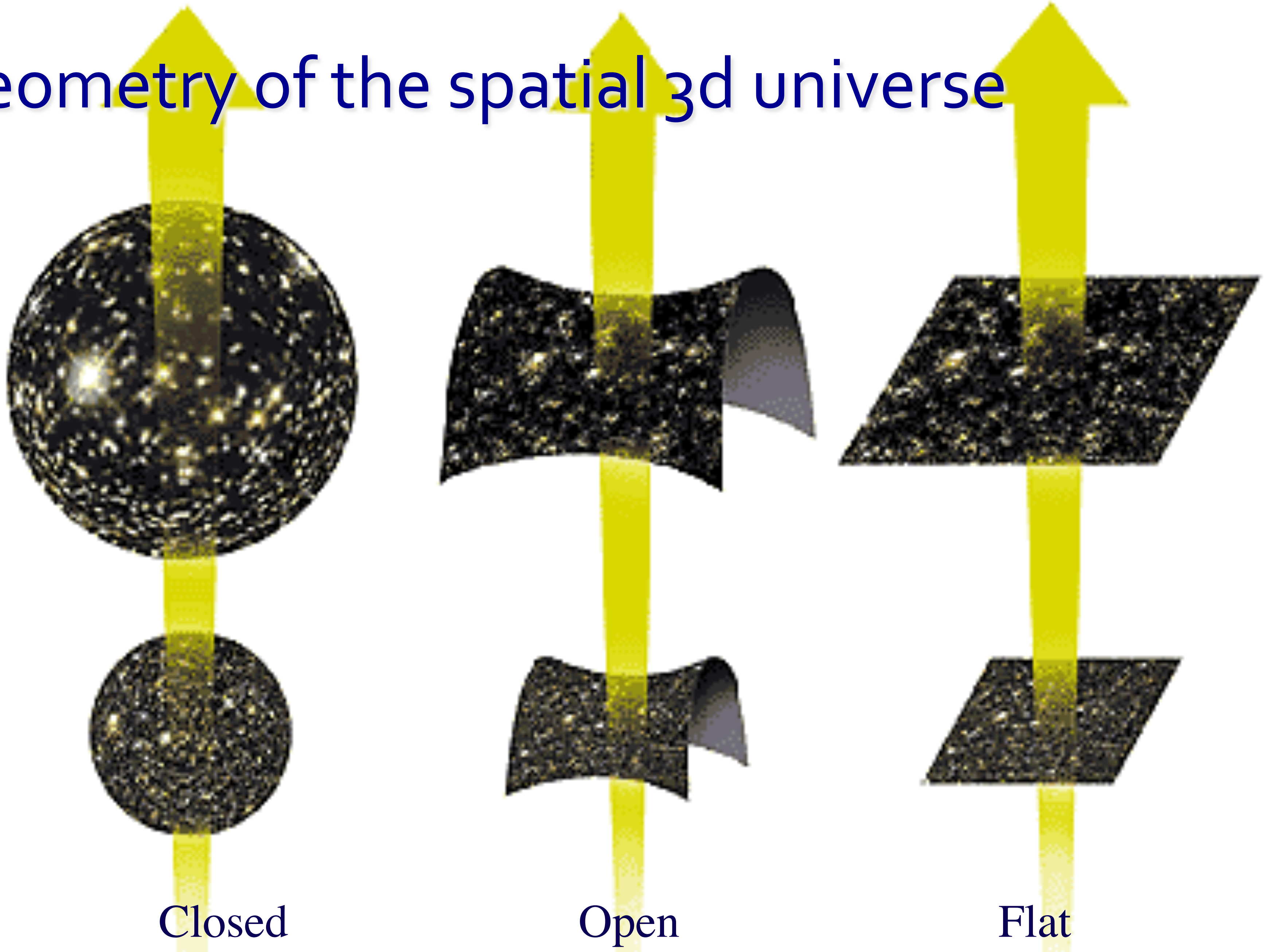
Density ratios and critical density

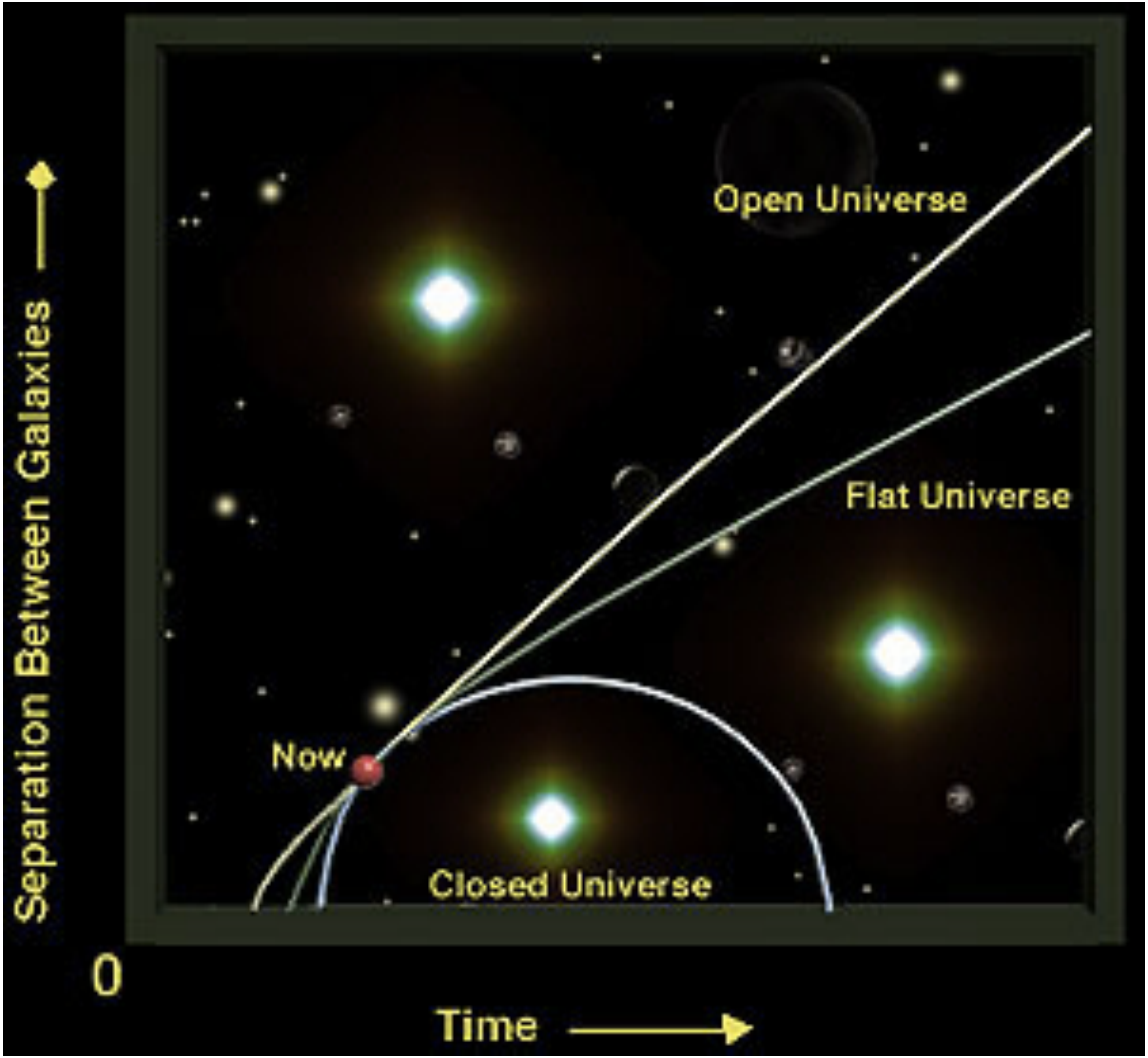
Define the critical density: $\rho_{crit} = 3H_0^2/8\pi G$

$\approx 1.9h^2 x 10^{-29}$ g/cm^3

and the density parameter: $\Omega = \rho/\rho_{crit}$

Geometry of the spatial 3d universe





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

More on Friedmann equation

It can be also written in terms of H_0 as:

$$H^2(z) = H_0^2 \left(\Omega_m (1+z)^3 + \Omega_K (1+z)^2 + \Omega_r (1+z)^4 + \Omega_\Lambda + \cdots \right)$$

$$\Omega_m + \Omega_K + \Omega_r + \Omega_\Lambda + \cdots = 1$$

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

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

$$\boxed{p_i = w_i \rho_i,}$$

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

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

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

$$\boxed{p_i = w_i \rho_i}$$

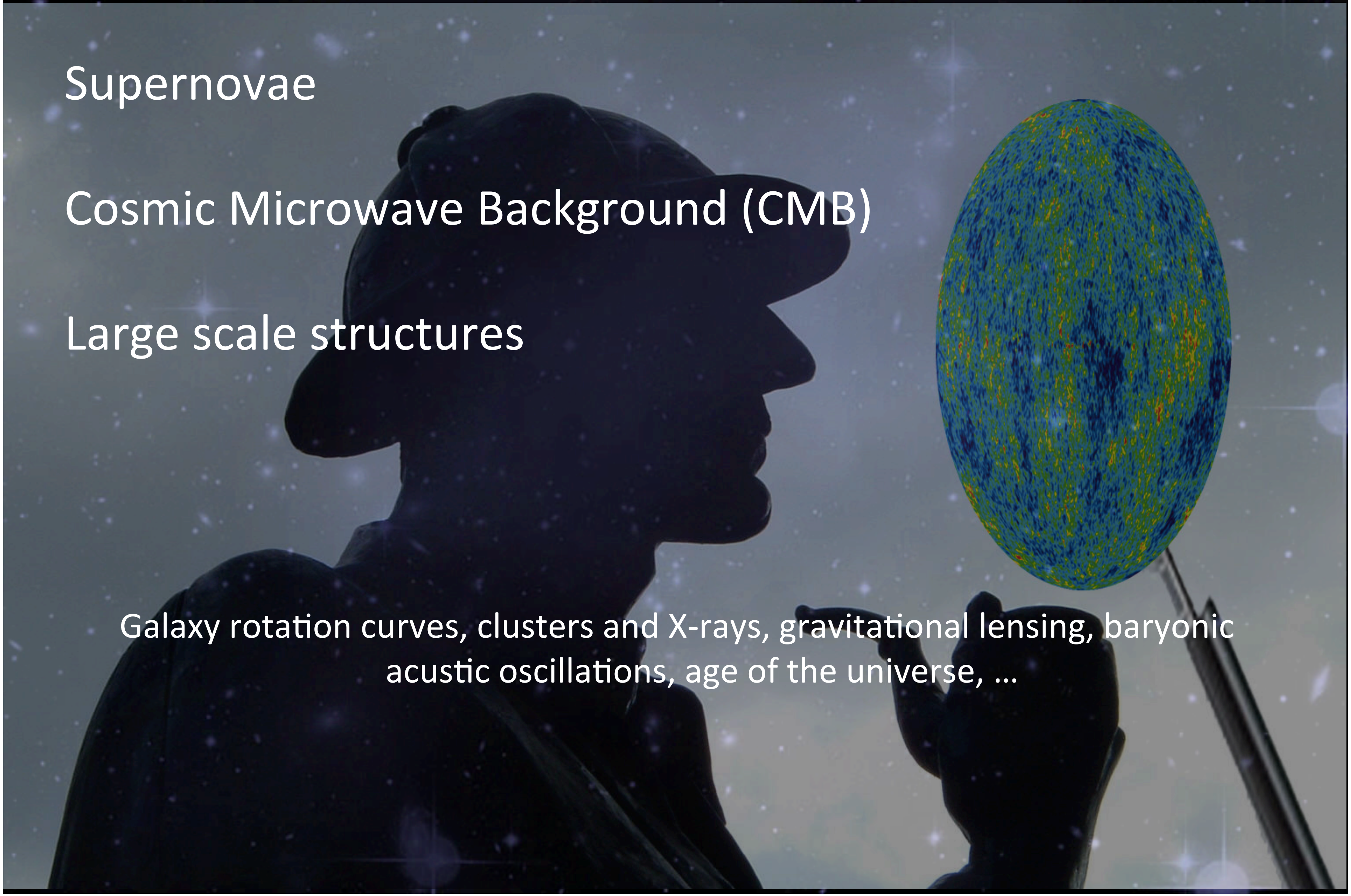
$$\rho_i \propto \exp\left[3\int_0^z [1+w_i(z')]\, d\ln(1+z')\right]$$

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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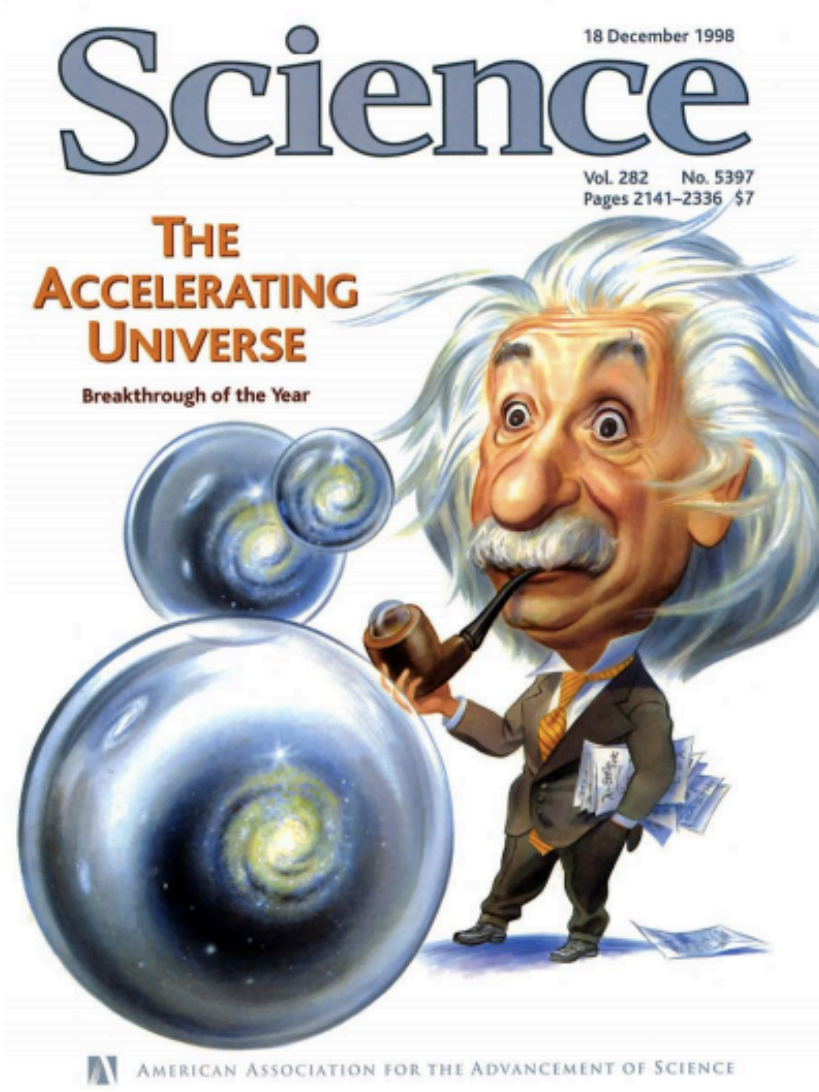
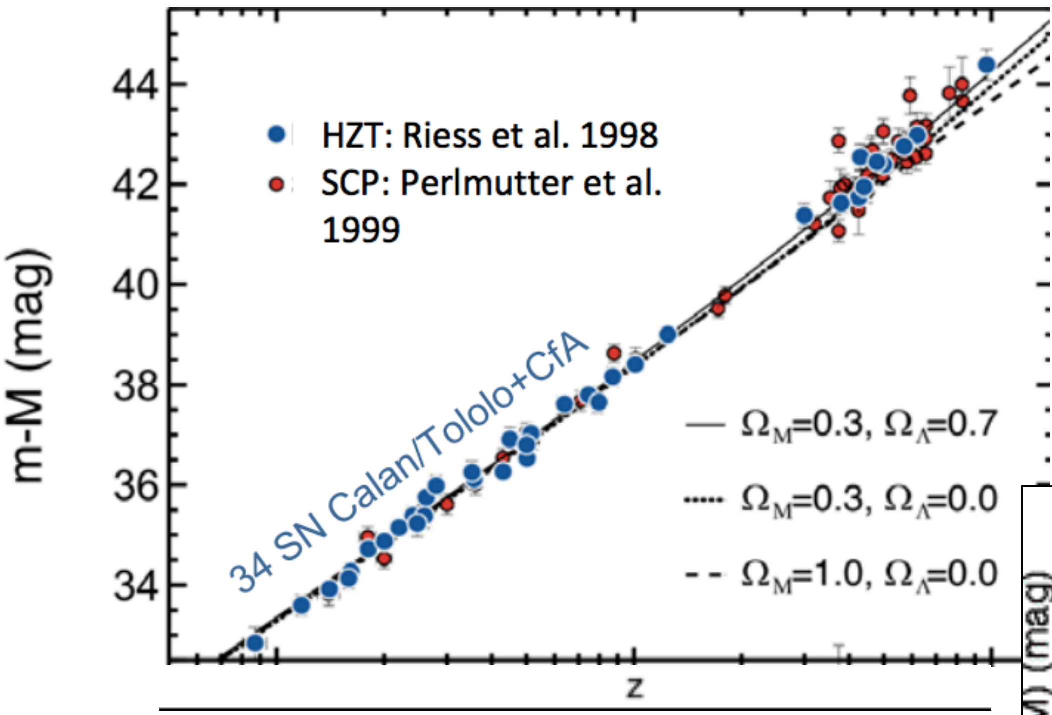
Supernova Cosmology Project and the High-z Team

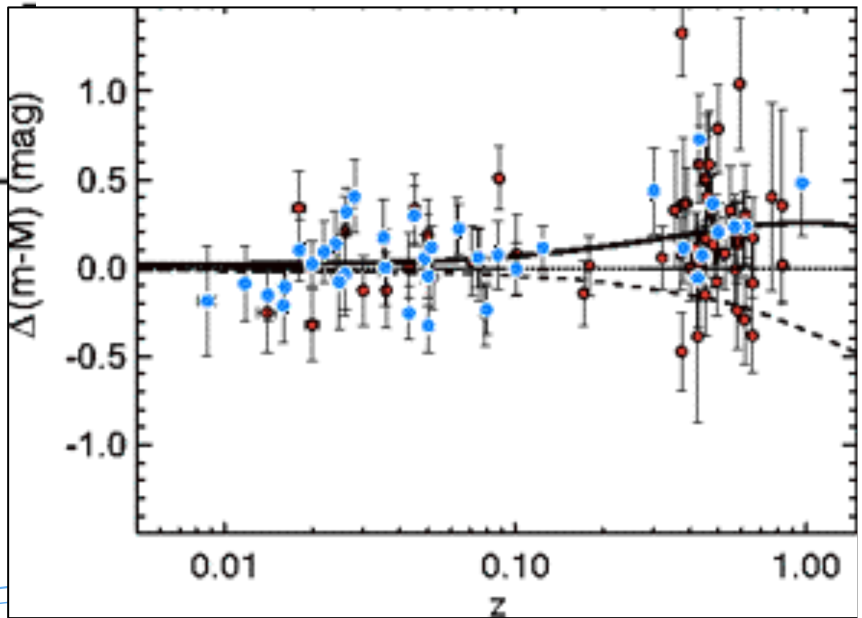
In 1994 the High-z Team was formed:
"To Measure the Cosmic Deceleration
of the
Universe with Type Ia Supernovae"



Supernovae



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

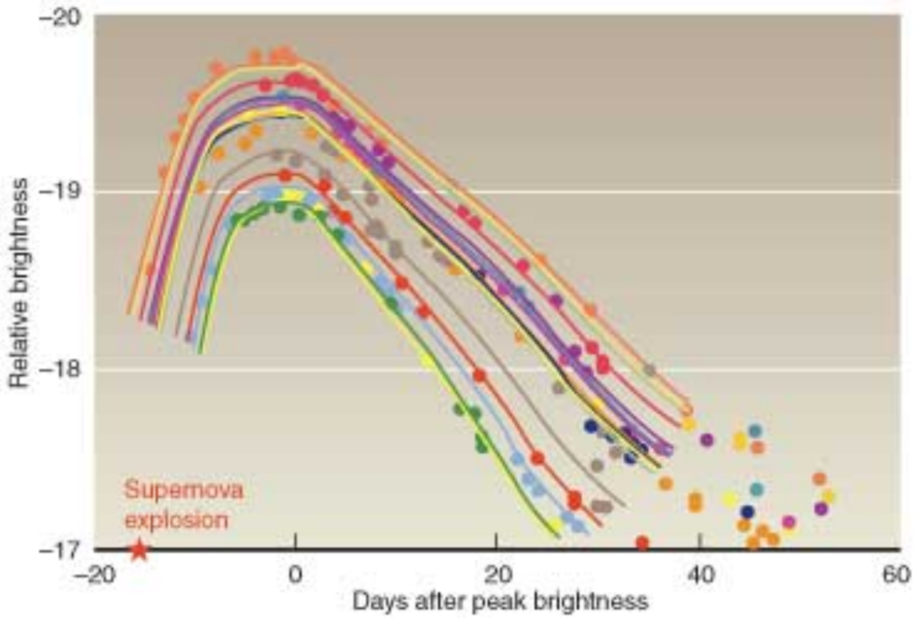


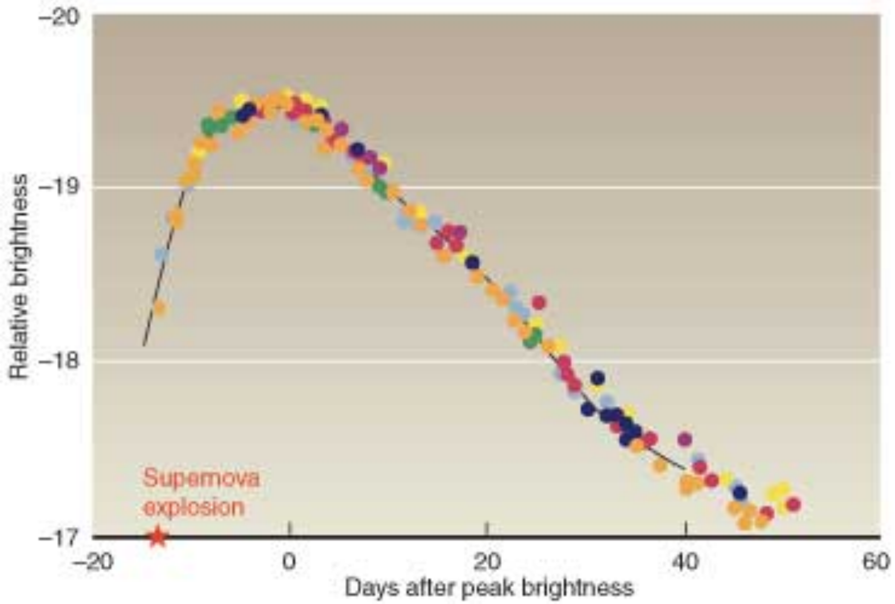
Supernovae

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

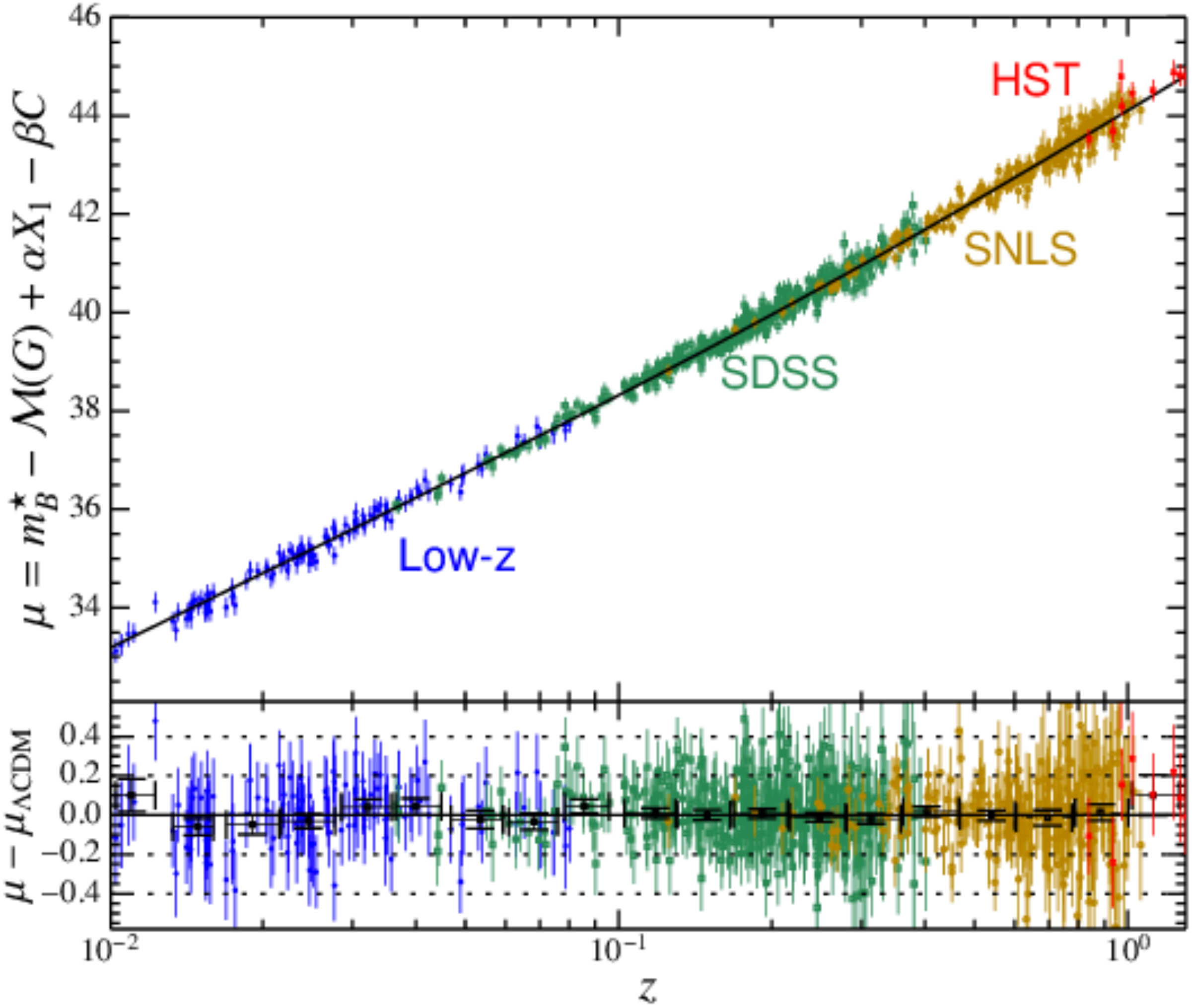
$$f = \frac{L d\Omega}{4\pi} = \frac{L}{4\pi a_0^2 r^2 (1+z)^2} \equiv \frac{L}{4\pi d_L^2}$$

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

Calculate from flux and intrinsic luminosity

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

Hubble Diagram

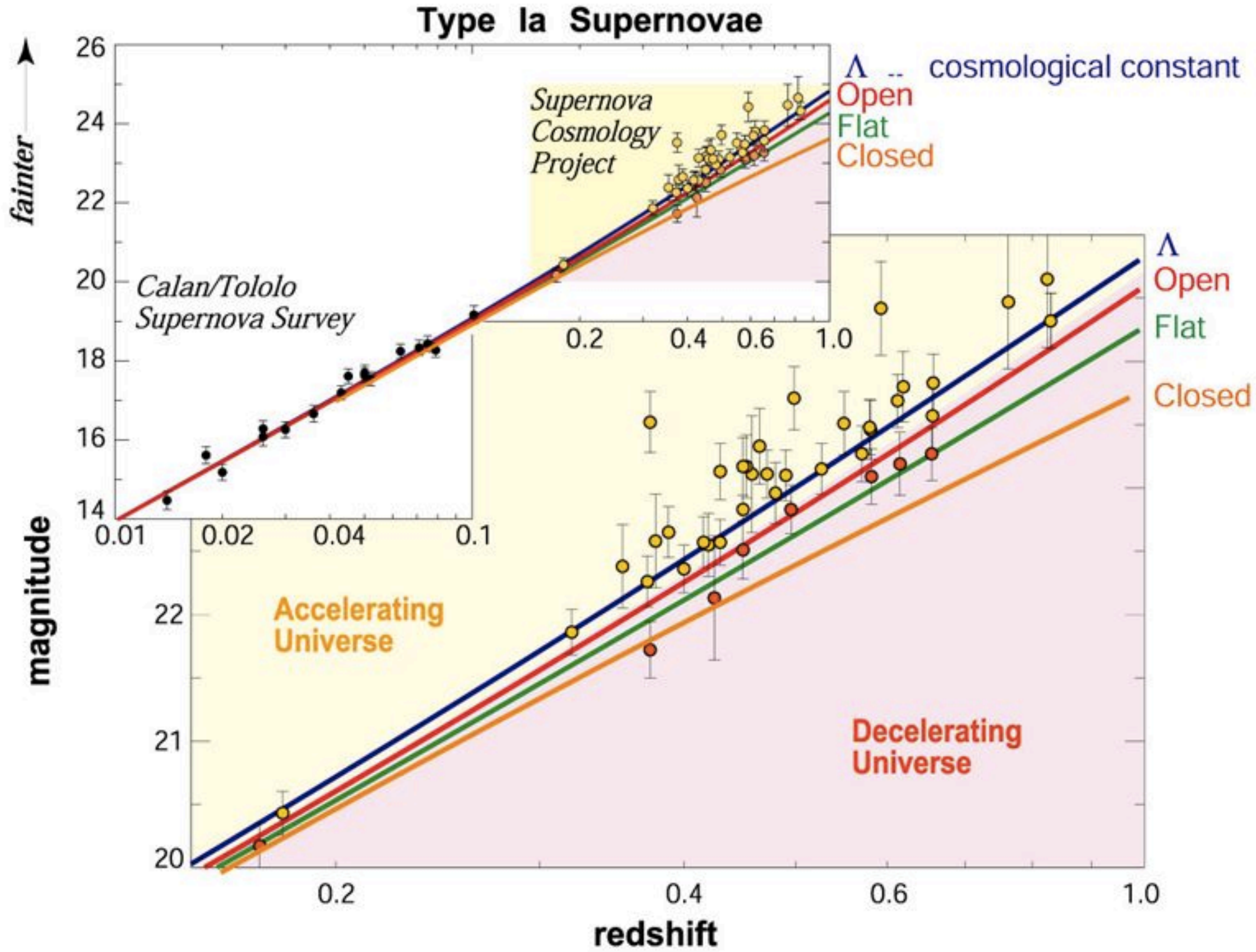


Hubble (Leavitt) diagramme, JLA analysis

Betoule et al. 2014

Older results, compared to different geometries

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



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 and H, required accelerated expansion

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

$$\boxed{p_i = w_i \rho_i}$$

Matter	w = 0	$\rho_m \sim a^{-3}$
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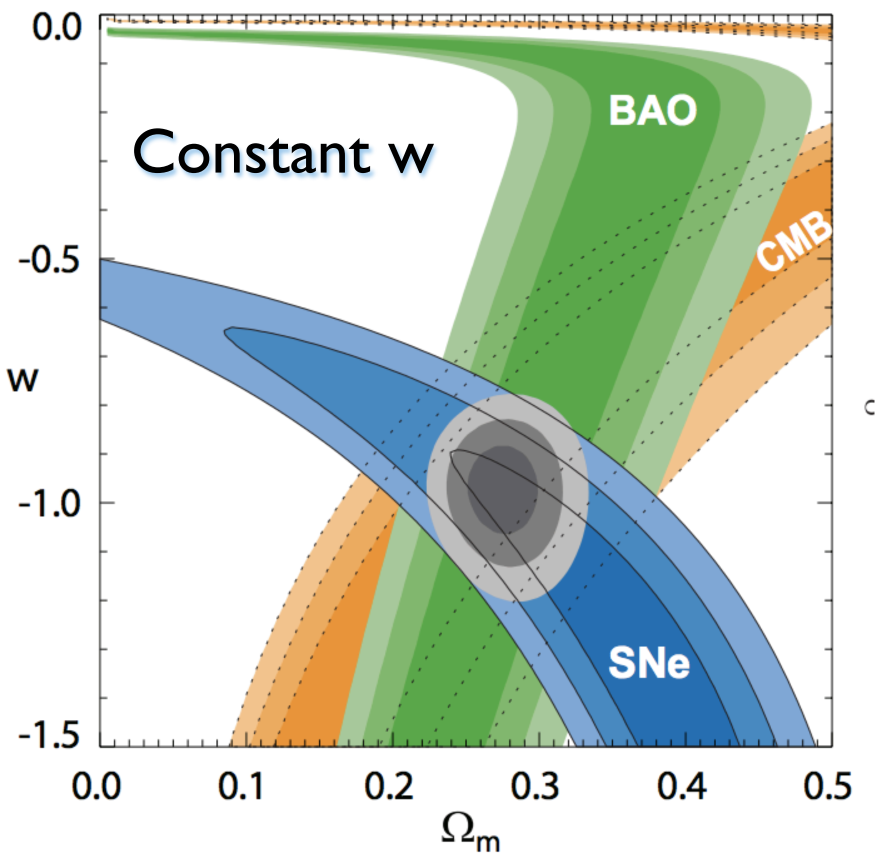
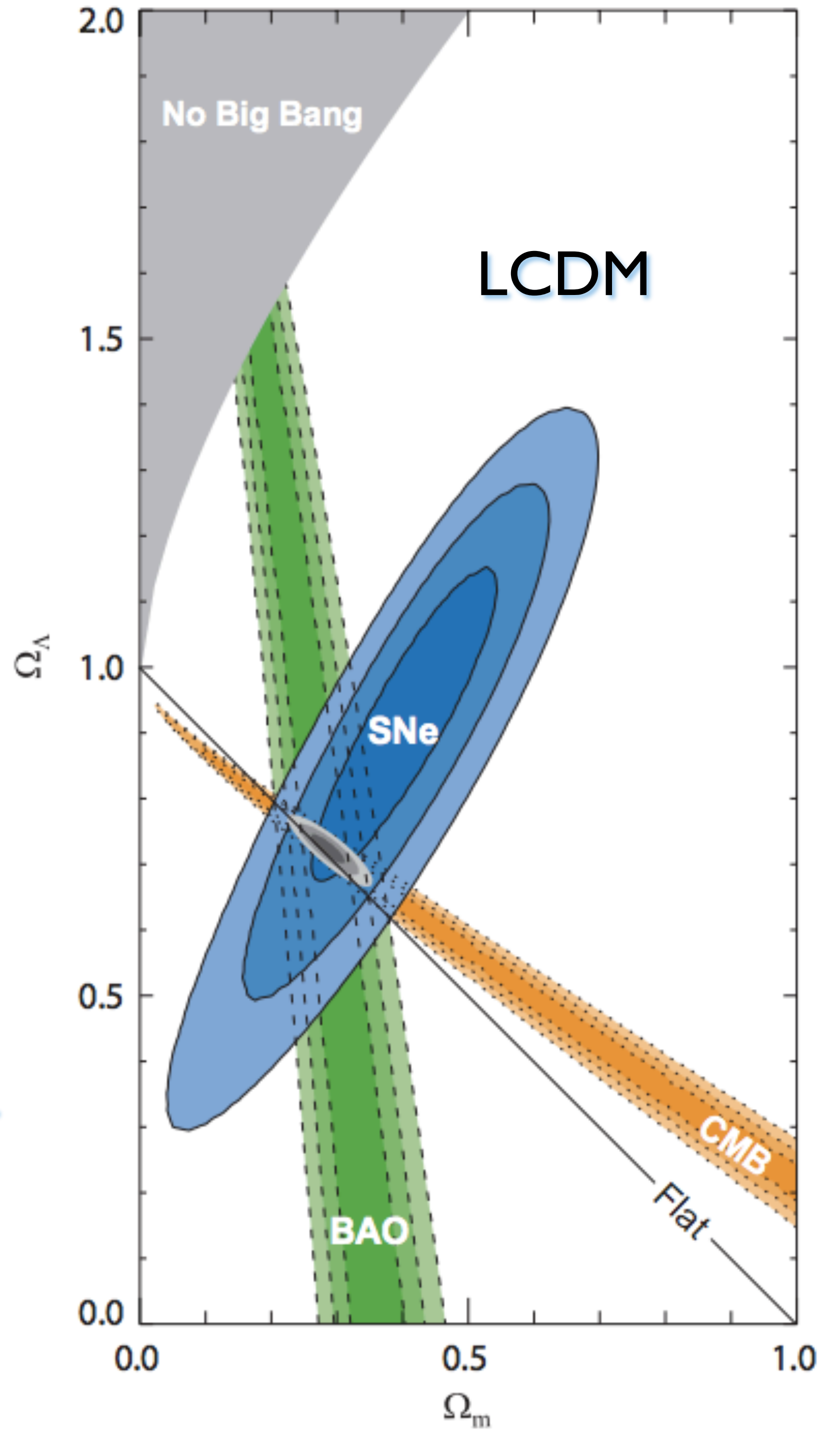
$$\ddot{a} < 0$$

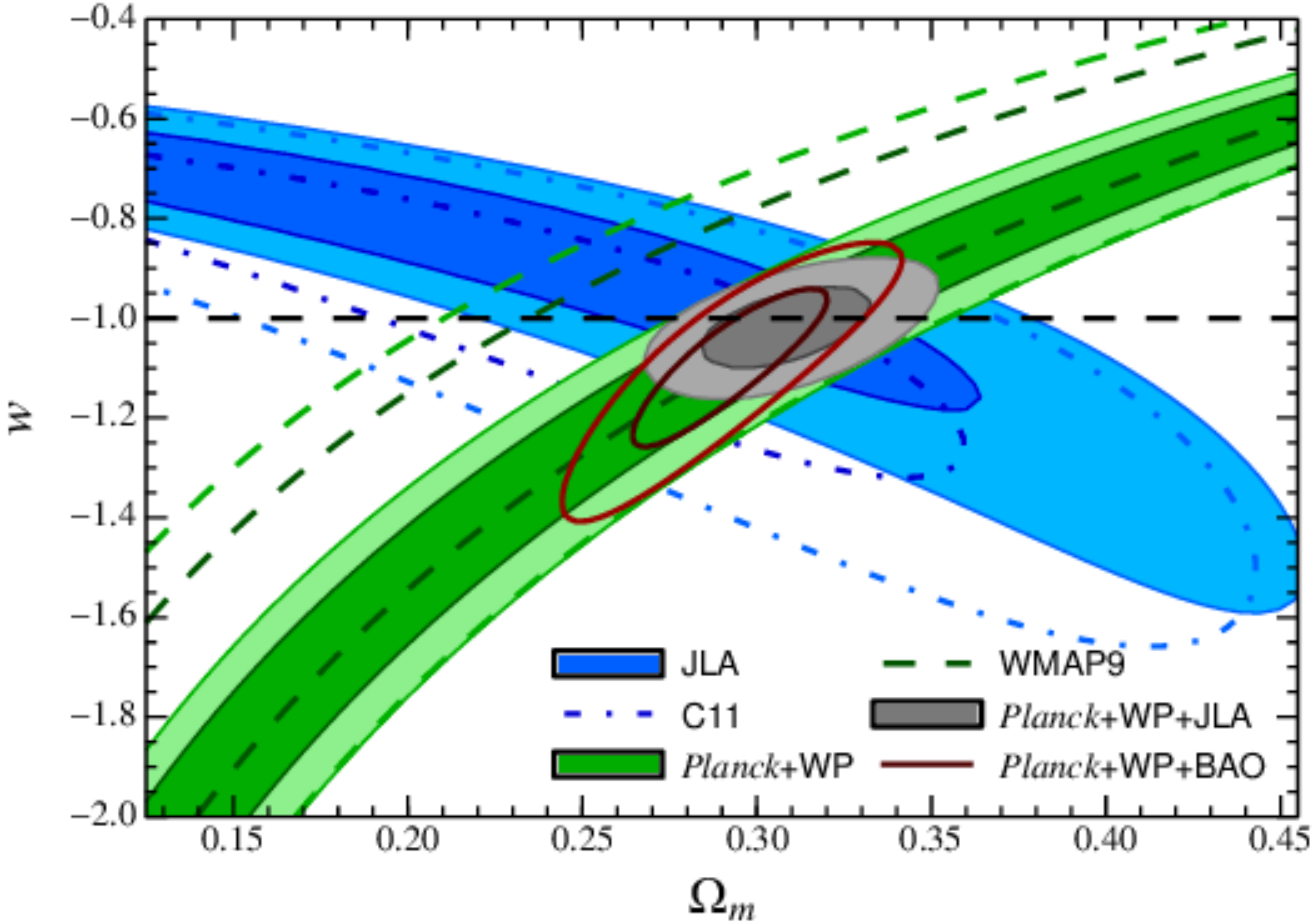
deceleration

Most of the universe is not made of ordinary matter!



Followed by SNLS, ESSENCE, HST, …





Flat w-CDM fit parameters, JLA analysis

Betoule et al. 2014