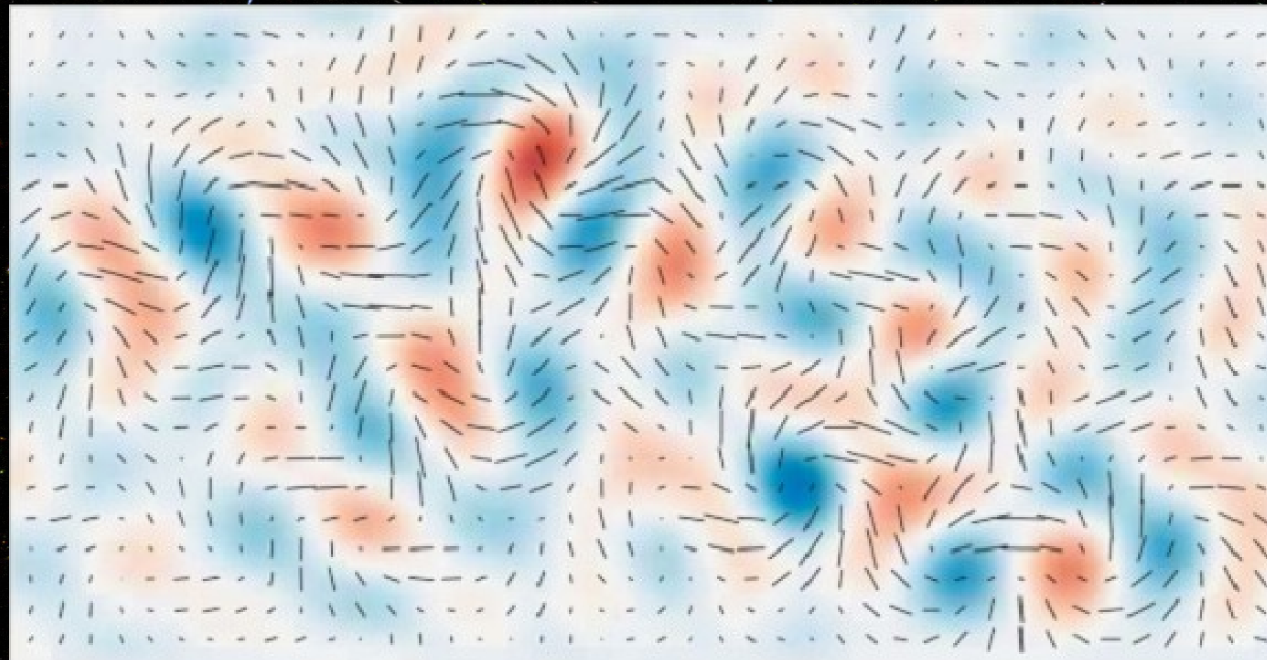


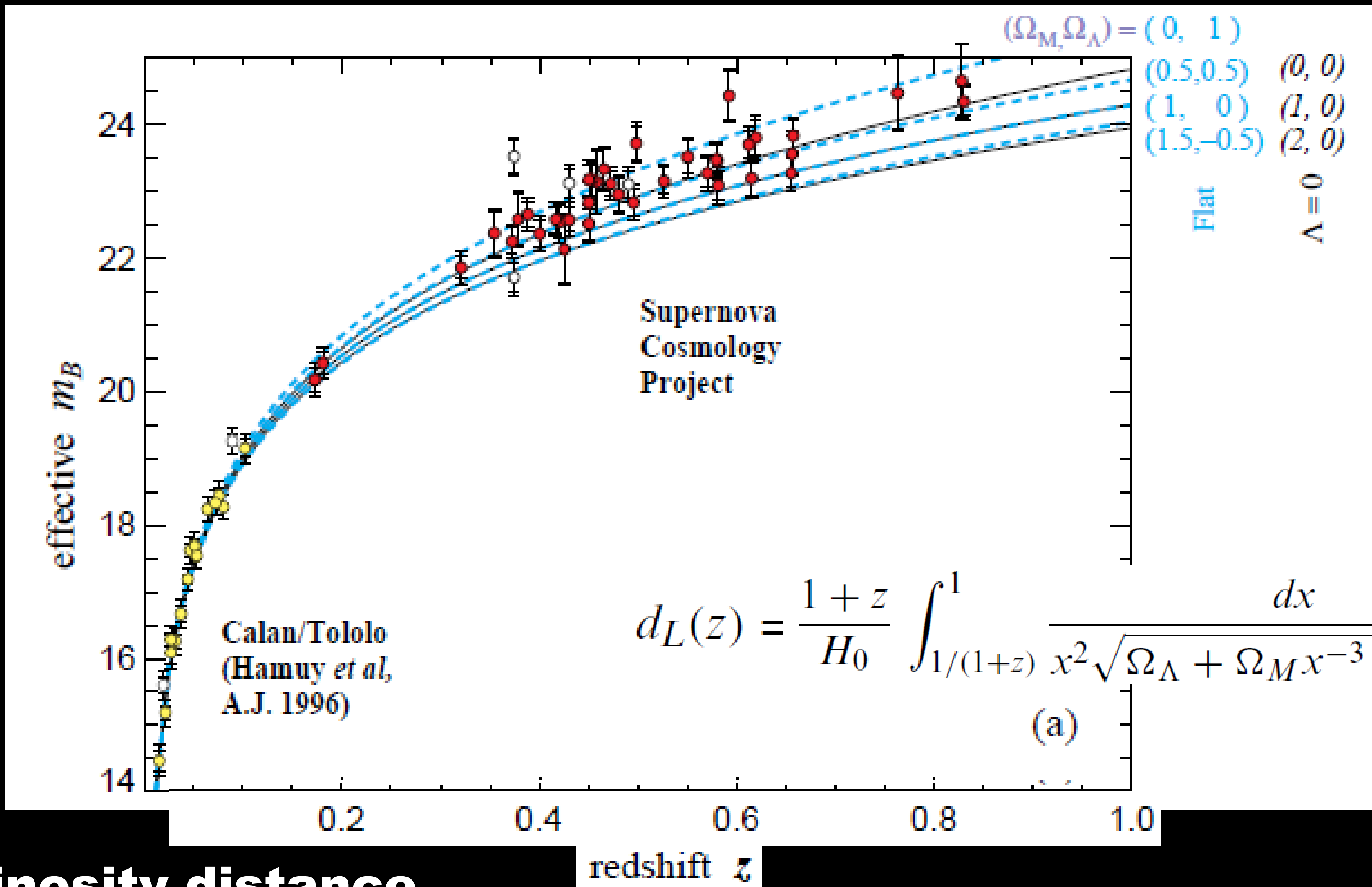
Aplicaciones de GRTensor en Astrofísica y Cosmologia

Santiago Esteban Perez Bergliaffa

Departamento de Física Teórica

Instituto de Física

Inhomogeneous models



$$d_L(z) = \frac{1+z}{H_0} \int_{1/(1+z)}^{1} \frac{dx}{x^2\sqrt{\Omega_\Lambda + \Omega_M x^{-3} + \Omega_R x^{-4}}} \cdot$$

$\Omega_K = 0$

Luminosity distance

Best fit : $\Omega_m \sim 0.26$, $\Omega_\Lambda \sim 0.74$ (with $\Omega_K = 0$)

S. Perlmutter et al (1999).

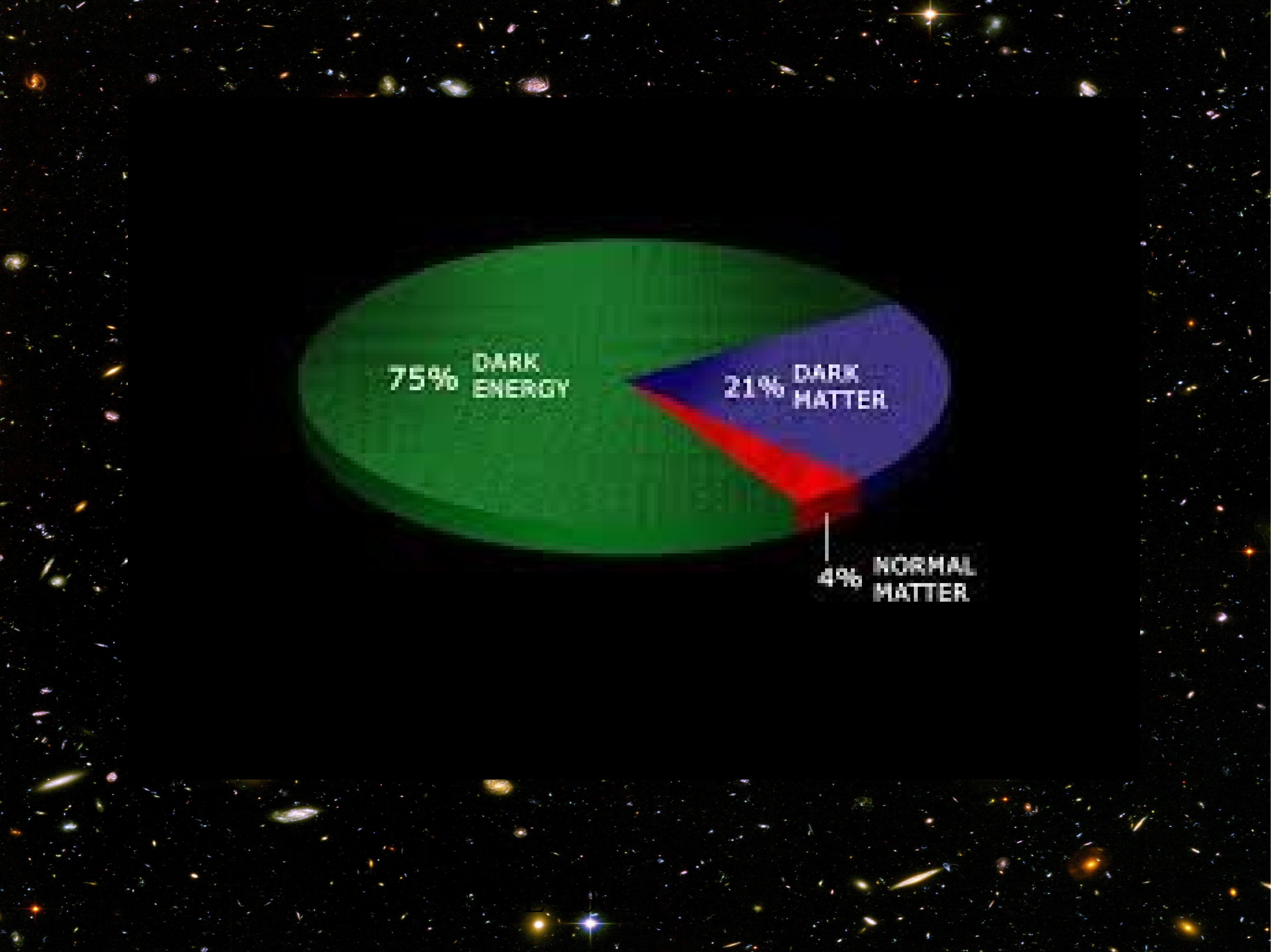
What kind of matter yields accelerated expansion in the SCM?

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \quad > 0$$

$\rho + 3p < 0 \quad \rightarrow \quad p < 0 \quad (\rho > 0)$

This matter must not cluster in galaxies. It must be smoothly distributed, hence it is important only at cosmological scales:

"Dark Energy"


75% DARK ENERGY
21% DARK MATTER
4% NORMAL MATTER

$G_{\mu\nu} = T_{\mu\nu}$

Candidates: Li et al (2011).

* Cosmological constant Λ ($p = - \rho = -\Lambda \rightarrow \rho + 3p < 0$)

* (Nonlinear) scalar field + potential

* Fluids with unusual equation of state (ex.: Chaplygin gas)

* Spinors, vectors...

For a number of reasons, none of these is satisfactory.

Options?

Option 1:

$$G_{\mu\nu} = T_{\mu\nu}$$

Gravity is not described by Einstein´s equations at the cosmological level

1a) Alternative theories of gravity

Example: *f(R)* theories

$$S_{\mathrm{EH}} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\,R, \quad \longrightarrow \quad S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\,f(R).$$

Antonio De Felice, Shinji Tsujikawa (2010), SEPB (2011) .

Option 1:

$$G_{\mu\nu} = T_{\mu\nu}$$

Gravity is not described by Einstein´s equations at the cosmological level

1b) Back-reaction: does the small-scale structure influence the dynamics of the universe on larger scales?

Inhomogeneous model $\longrightarrow$ (Approximately) FLRW model

~1 Mpc ~300 Mpc

"Averaging"

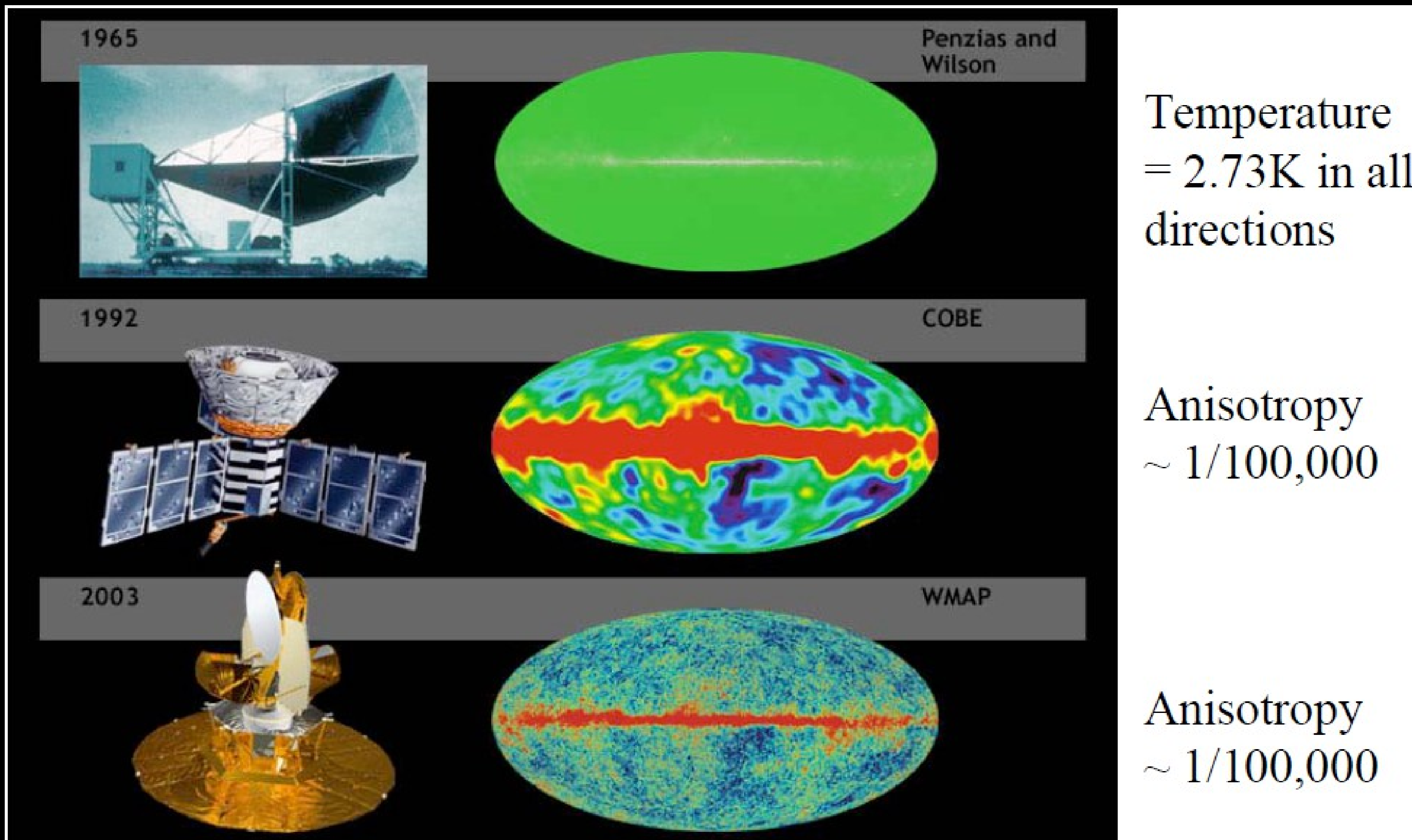
Under some conditions, it is possible to get "source terms" on the rhs of EE that produce accelerated expansion.

Problems: the average depends on the choice of the 3+1 splitting, gauge problem (only scalars are invariants).

T. Buchert (2011)

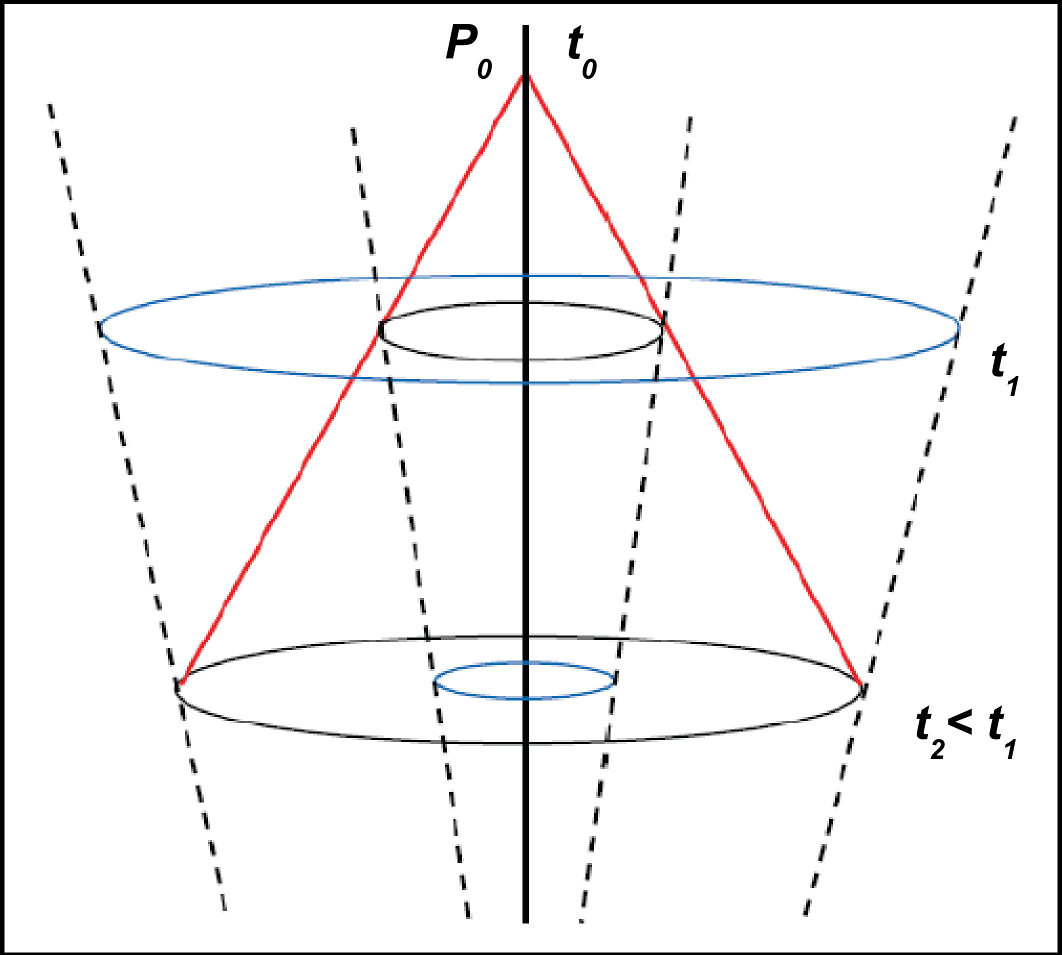
Option 2:

There is strong observational support for the hypothesis of isotropy:



(plus galaxy distr., gamma-ray distr., ...)

But we cannot have direct evidence of the homogeneity, because it is defined on the hypersurfaces t = constant, and the portion of space we can observe at t_0 from P_0 is limited by the lightcone at t_0:



This opens the door for inhomogeneous models

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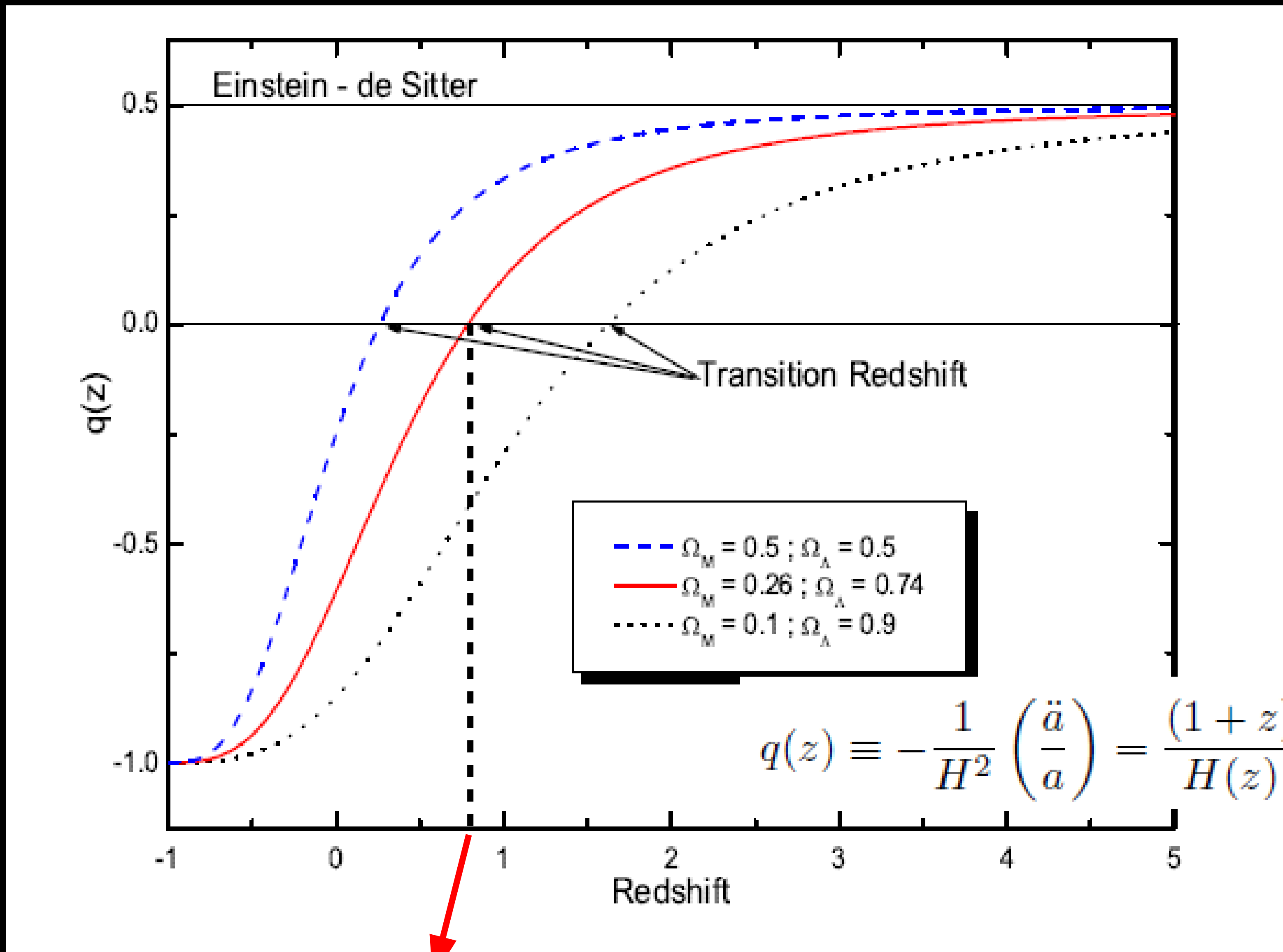

$$q(z) \equiv -\frac{1}{H^2}\left(\frac{\ddot{a}}{a}\right) = \frac{(1+z)}{H(z)}\frac{dH(z)}{dz} - 1$$

z ~ 0.7, which corresponds to structure formation

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Inhomogeneous models

Example: Lemâitre-Tolman-Bondi (LTB) geometry

(<u>spherical symmetry</u> + <u>dust</u> as a source)

$$\mathrm{d}s^2 = \mathrm{d}t^2 - \frac{{R_{,r}}^2}{1+2E(r)}\mathrm{d}r^2 - R^2(t,r)(\mathrm{d}\vartheta^2 + \sin^2\vartheta\,\mathrm{d}\varphi^2),$$

$$G_{\mu\nu} = T_{\mu\nu} \longrightarrow {R_{,t}}^2 = 2E + \frac{2M}{R} + \frac{\Lambda}{3}R^2,$$

$$\kappa\rho = \frac{2M_{,r}}{R^2 R_{,r}},$$

$$\int_0^R \frac{\mathrm{d}\widetilde{R}}{\sqrt{2E + 2M/\widetilde{R} + \frac{1}{3}\Lambda\widetilde{R}^2}} = t - t_B(r),$$

One of the three arbitrary functions *E(r)*, *M(r)*, and $t_B(r)$ can be chosen at will because of the gauge freedom *r ' = f(r)*.

$$R(t,r) = \frac{M}{(-2E)}(1-\cos\eta),$$
$$\eta - \sin\eta = \frac{(-2E)^{3/2}}{M}(t - t_B(r)),$$

$E < 0$ (elliptic evolution)

$$R(t,r) = \left[\frac{9}{2}M(t - t_B(r))^2\right]^{1/3}$$

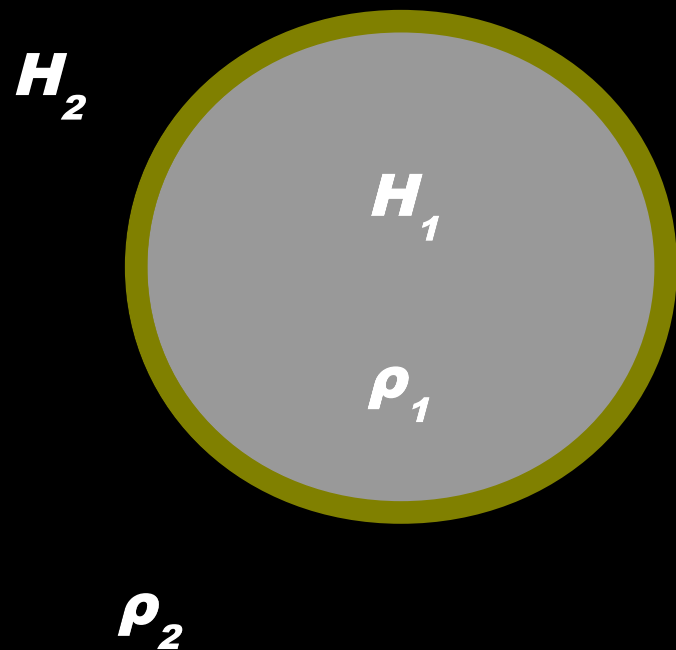
$E = 0$ (parabolic evolution)

$$R(t,r) = \frac{M}{2E}(\cosh\eta - 1),$$
$$\sinh\eta - \eta = \frac{(2E)^{3/2}}{M}(t - t_B(r)).$$

$E > 0$ (hyperbolic evolution)

Reduces to FLRW for $t_B = \text{const}, \qquad |E|^{3/2}/M = \text{const},$ $M = M_0 r^3$

Is it possible to choose the functions in the LTB model in order to fit the SNIa data without dark energy?



Both FLRW regions are decelerating. The properties of the shell are chosen in such a way that

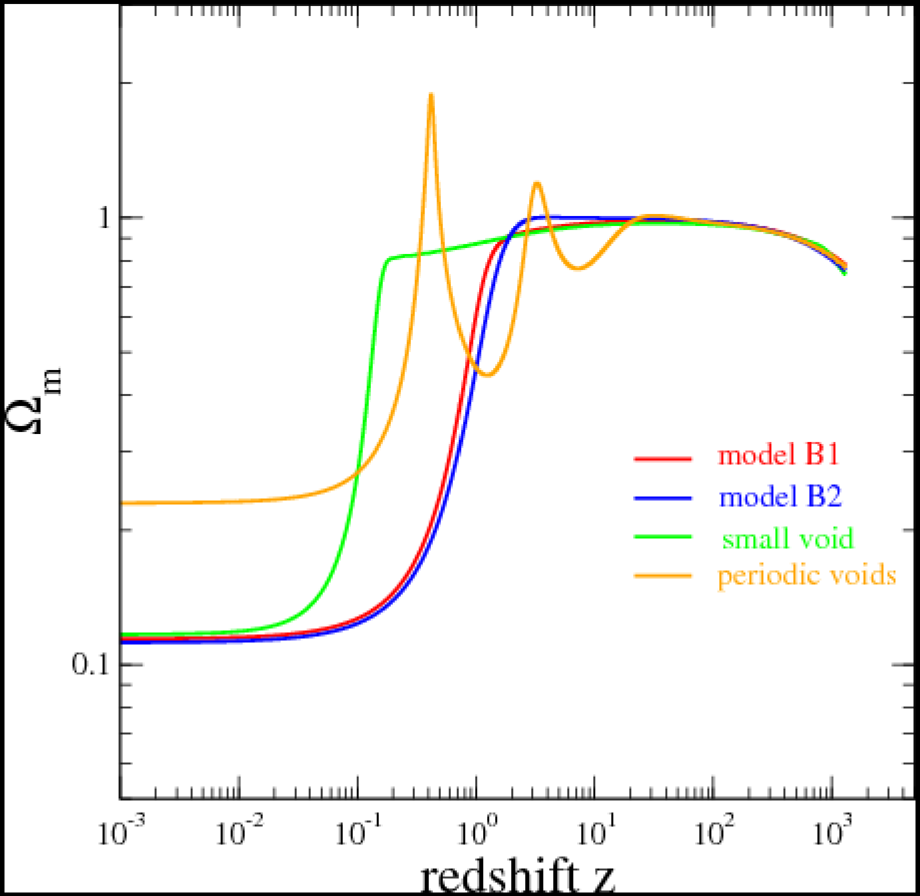
$$\rho_1 < \rho_2 \wedge H_1 > H_2$$

The "void" expands faster that the outer region

↓

Relative acceleration

Tomita (2000)


Ω_m
1
0.1
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
redshift z
model B1
model B2
small void
periodic voids

Redshift drift

Es la variación temporal del redshift cosmológico causada por la expansión del universo.

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THE CHANGE OF REDSHIFT AND APPARENT LUMINOSITY OF GALAXIES DUE TO THE DECELERATION OF SELECTED EXPANDING UNIVERSES

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
(With an Appendix by G. C. McVITTIE, University of Illinois Observatory, Urbana)

Received February 2, 1962; revised April 13, 1962

El redshift drift en los modelos FLRW

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)\right]$$

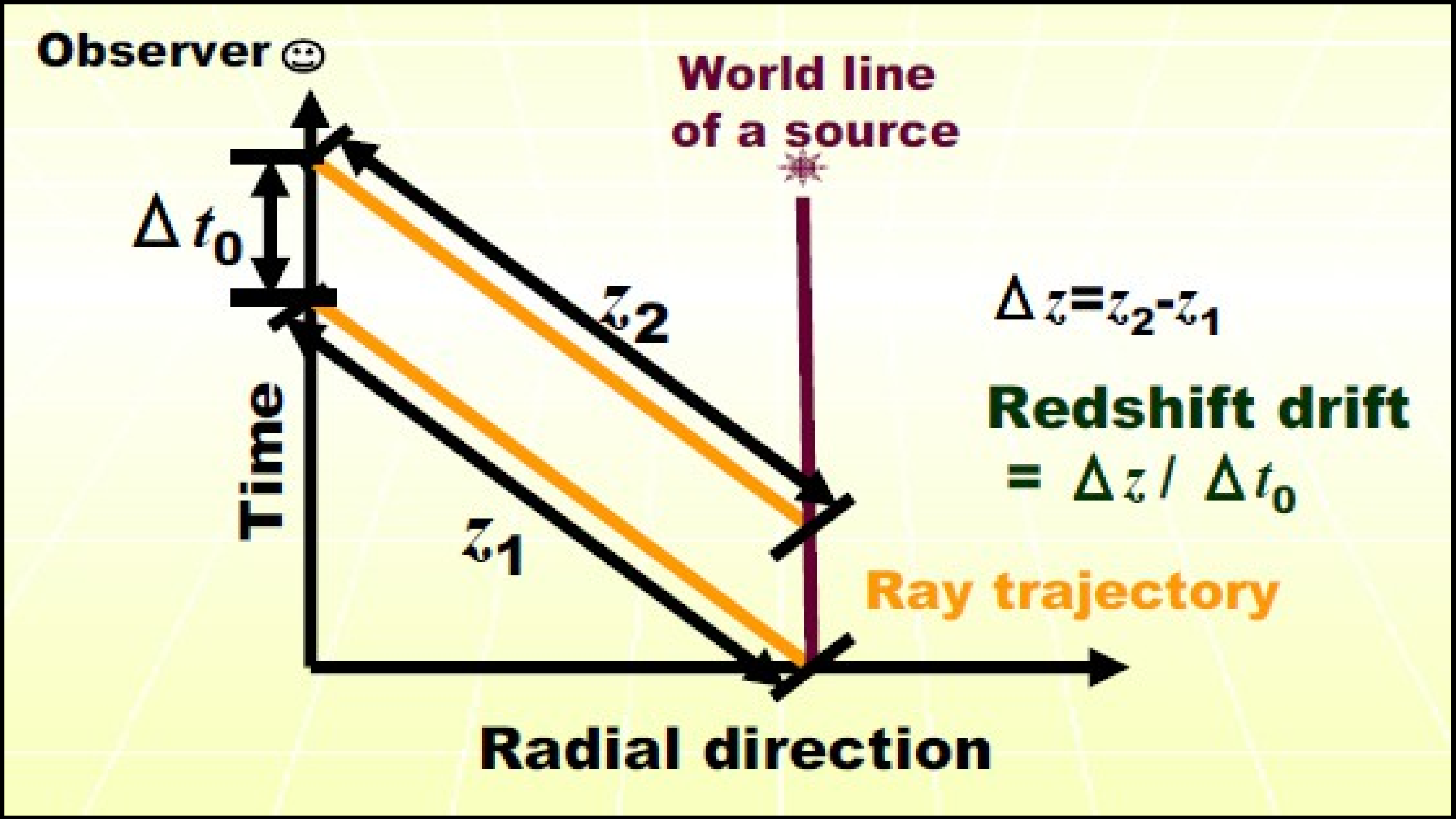
The radiation emitted by the source at two different times t_s and $t_\mathrm{s} + \Delta t_\mathrm{s}$ will be observed at later times t_o and $t_\mathrm{o} + \Delta t_\mathrm{o}$, related by

$$\int_{t_\mathrm{s}}^{t_\mathrm{o}} \frac{dt}{a(t)} = \int_{t_\mathrm{s}+\Delta t_\mathrm{s}}^{t_\mathrm{o}+\Delta t_\mathrm{o}} \frac{dt}{a(t)}$$

$$(\Delta t/t) \ll 1 \quad \rightarrow \quad \Delta t_\mathrm{s} = [a(t_\mathrm{s})/a(t_\mathrm{o})]\Delta t_\mathrm{o}$$

$$z(t_s) = \frac{a(t_{obs})}{a(t_s)} - 1.$$

$$\Delta z = z(t_s + \Delta t_s) - z(t_s)$$



$$1 + z \equiv \frac{\nu_E}{\nu_R}$$

$$\Delta z \equiv \frac{a(t_o + \Delta t_o)}{a(t_s + \Delta t_s)} - \frac{a(t_o)}{a(t_s)} \approx \left[\frac{\dot{a}(t_o) - \dot{a}(t_s)}{a(t_s)}\right] \Delta t_o$$

$$H(t) \equiv +\frac{1}{a(t)} \frac{\mathrm{d}a}{\mathrm{d}t};$$

$$z(t_s) = \frac{a(t_{obs})}{a(t_s)} - 1.$$

$$\frac{\Delta z}{\Delta t_{obs}} = (1+z)H_{obs} - H(z).$$

Hasta aquí no se ha hecho mención de la dinámica.

RG: ecuación de Friedmann

$$H^2(z) = H_0^2\left[\Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\mathrm{r},0}(1+z)^4 + \Omega_{\Lambda,0} + \Omega_{k,0}(1+z)^2\right].$$

$$\Omega_k(t) = -\frac{c^2 k}{H^2(t)R^2(t)}$$

$$\Omega_i(t) \equiv \frac{8\pi G}{3H^2(t)}\rho_i(t)$$

$$(\Delta z/\Delta t) = H_0\left[(1+z) - \left(\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_{\Lambda,0}\right)^{1/2}\right]$$

(resultado válido para todo *z*)

Loeb (1998)

In the case of LTB models,
and an observer at the center:

$$\frac{\mathrm{d}t}{\mathrm{d}r} = -\frac{R_{,r}(t,r)}{\sqrt{1+2E(r)}}.$$

In terms of the redshift:

$$\frac{\mathrm{d}r}{\mathrm{d}z} = \frac{\sqrt{1+2E(r)}}{(1+z)R_{,tr}[t_n(r),r]}.$$

$$\frac{\mathrm{d}t}{\mathrm{d}z} = -\frac{R_{,r}[t_n(r),r]}{(1+z)R_{,tr}[t_n(r),r]}.$$

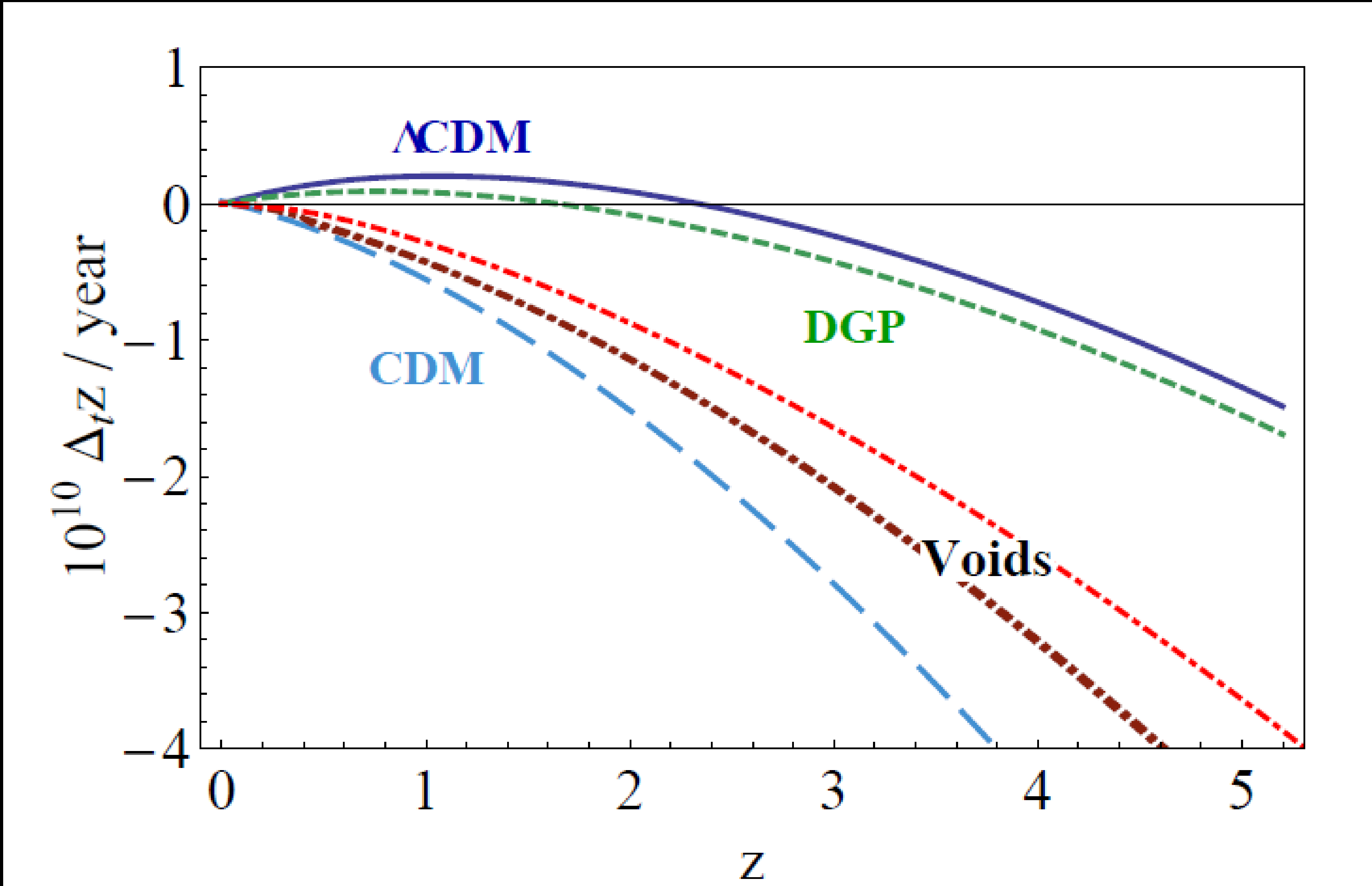
From these,

$$\frac{\delta z}{\delta t_0} = -\frac{1}{2}\Omega_{\mathrm{m}0}z + \mathcal{O}(z^2).$$

Negative for an observer in the center (Yoo et al (2011)), and also for an observer outside the center (F. Teppa Pannia and SEPB (2012)).

Theorem.—In LTB void models, the redshift drift of an off-center source observed at the symmetry center is negative.

Yoo et al (2011)



The RD may be measured by the CODEX at the E-ELT

Quartin and Amendola (2009)

E-ELT, CODEX

http://www.eso.org/public/teles-instr/e-elt.html

◎European Extremely Large Telescope (E-ELT)

△Aperture : 39.3m

△Location : Cerro Armazones, Chile

△Operations start : 2023

"The E-ELT will gather 100 000 000 times more light than the human eye, 8 000 000 times more than Galileo's telescope, and 26 times more than a single VLT Unit Telescope. In fact, the E-ELT will gather more light than all of the existing 8–10-metre class telescopes on the planet, combined."

◎COsmic Dyanamics and EXo-earth experiment

△Stable, high spectral resolution instrument

"very stable, high spectral resolution instrument proposed for the E-ELT. CODEX is currently undergoing the Phase A feasibility study "

Talk by Chulmoon Yoo (2011)

Outlook

* The RD can discriminate between homogeneous and inhomogeneous models.

* The RD does not rely on the calibration of standard candles (such as SNIa) or on standard rulers (such as the acoustic scale for the CMB).

* Although it is a very small effect, it may be measured in the next decade.

Thank you.

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