Dark energy: frequently asked questions

Luca Amendola

INAF/Osservatorio Astronomico di Roma

Dark energy:

- Do we really need it ?
- What can it do for us ?
- What we can do for it ?
- Where do we go from here ?

The threefold way to the universe

$$R_{\mu\nu} - Rg_{\mu\nu}/2 \quad = \quad 8\pi\, T_{\mu\nu}$$

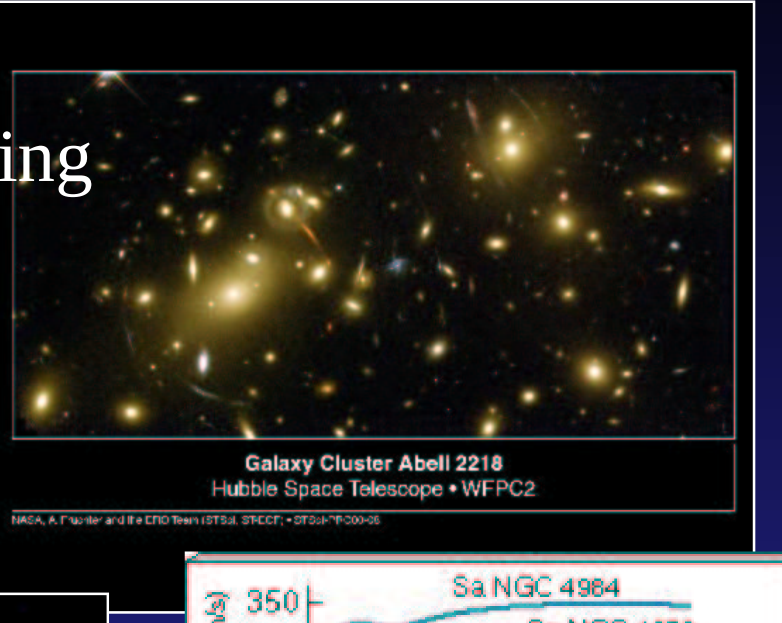
geometry matter

$$T^{\mu}{}_{\nu;\,\mu} \quad = \quad 0$$

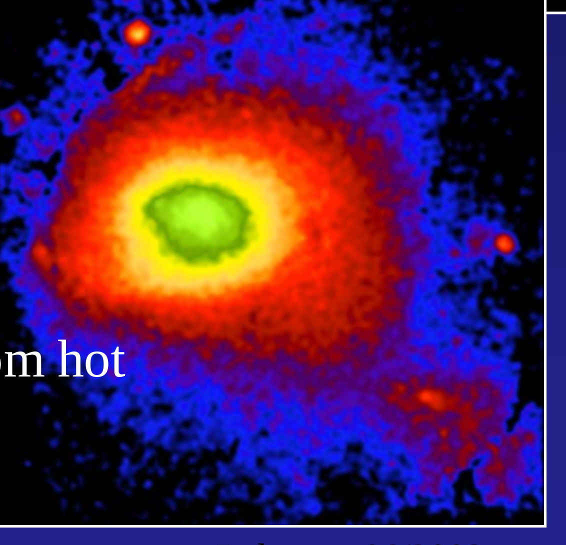
How matter evolves in a given geometry

Where's the matter ?

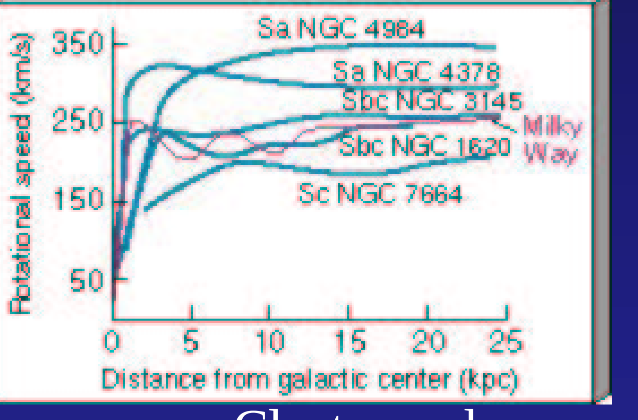
Lensing



- There are several probes of clustered matter:



X-ray emission from hot intracluster gas



Cluster and Galaxy dynamics

Where's the matter?

- Observations give

Ω_{galaxy}=0.2±0.1

$\Omega_{clusters}$=0.3±0.1

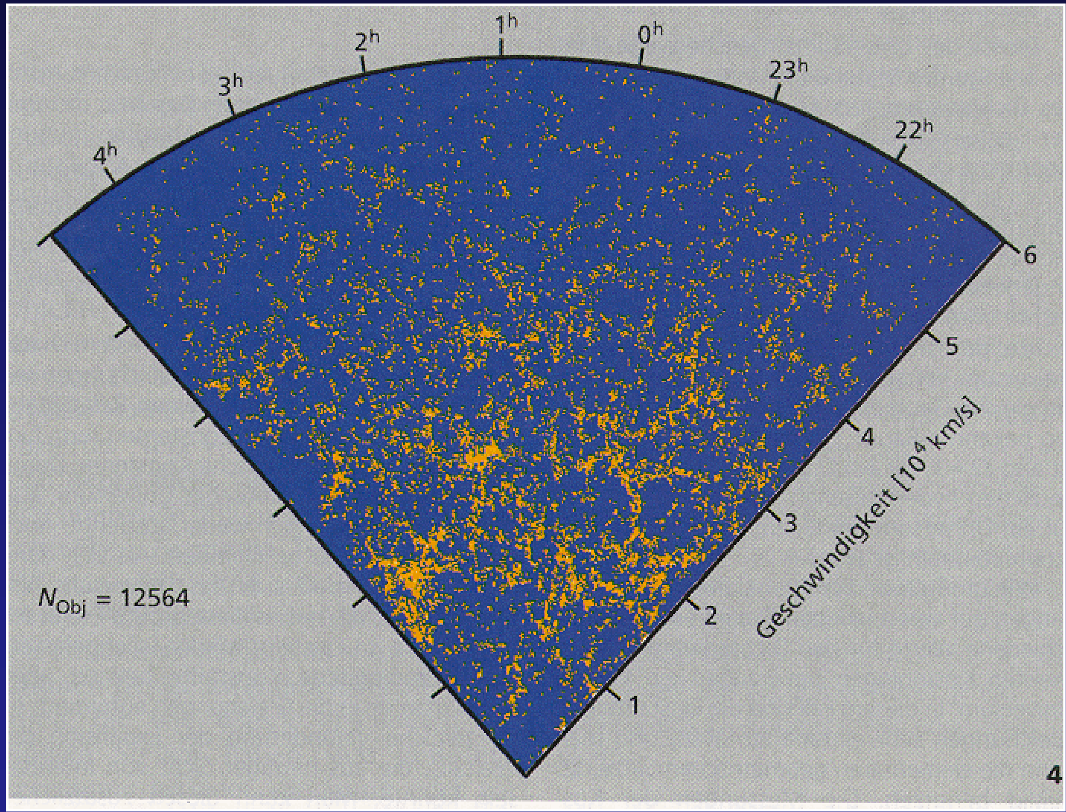
stars	0.005
dust	0.008
Gas	0.008
Dark matter	0.2

Where's the **un**clustered matter?

- No local probes of unclustered components:

  $\Delta\Phi = -4\pi(\delta\rho)$

- To detect unclustered matter we need…



...a cosmological experiment

- Unclustered matter does not affect local dynamics but affects the whole universe !
- The geometry of the universe depends on its total matter content

The unclustered energy...

•If there is a component that is unclustered (homogeneous), then it has to be a cosmological constant:

$$T_\mu{}^\nu = \Lambda \delta_\mu^\nu$$

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

$$\rho = \Lambda$$

$$p = -\Lambda = -\rho$$

$$w = \frac{p}{\rho} = -1$$

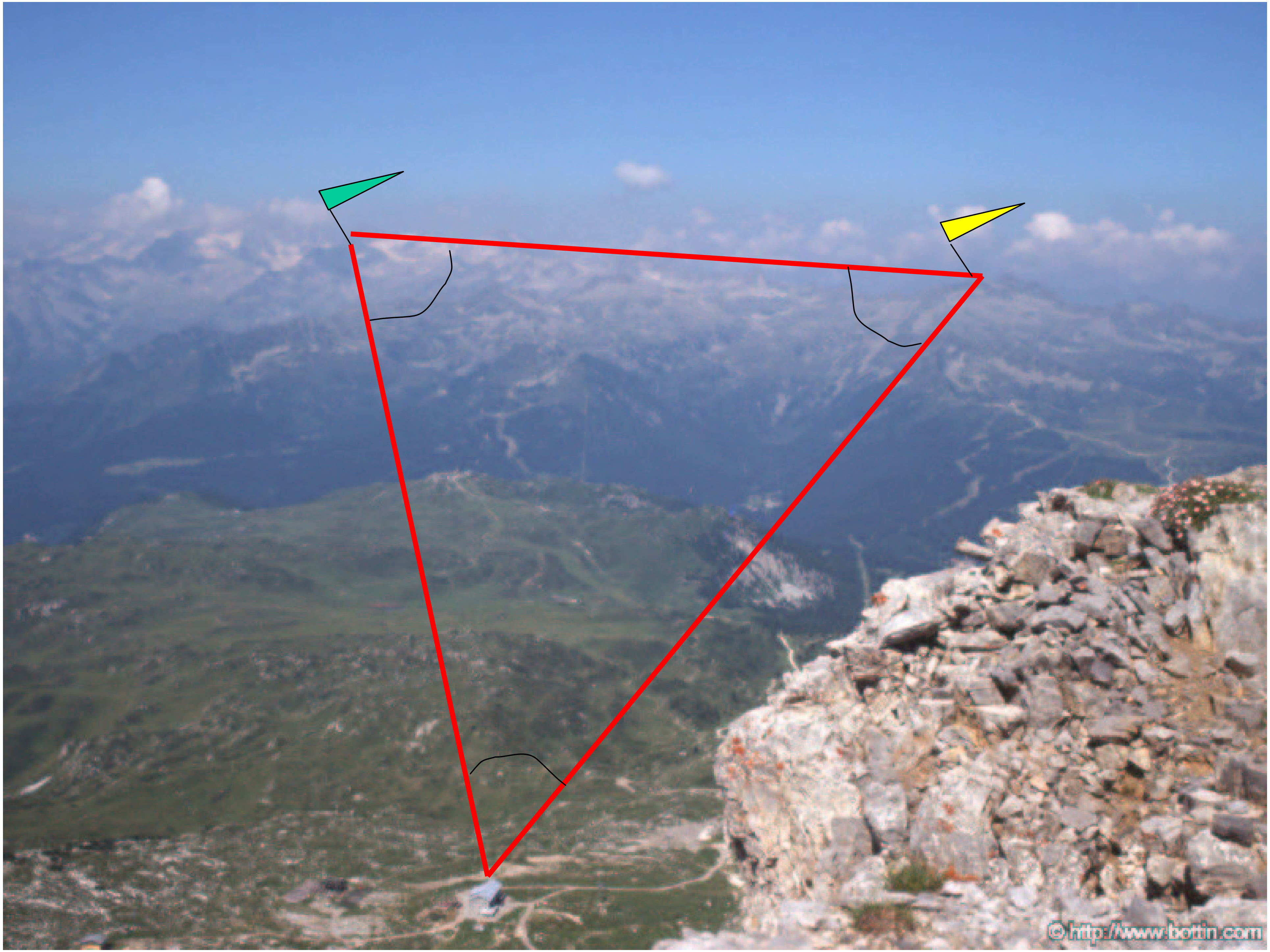
...accelerates the expansion

•The new term has p = - ρ and therefore accelerates:

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

$$a = \exp\left(\frac{\Lambda}{3}\right)^{1/2} t$$

•Homogeneous component = negative pressure = acceleration.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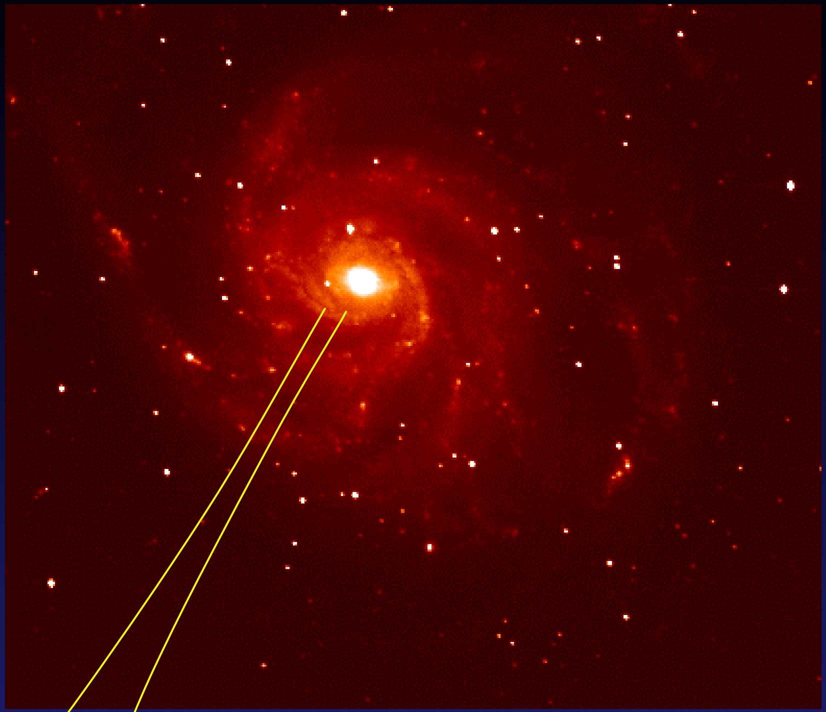
The modern way, I

Instead of angles, we can measure the divergence of light rays. The larger the divergence, the less luminous the source appears.



Astronomers say that the luminosity distance $d_L(z)$ is larger.

The modern way, II

The larger the divergence, the smaller the source appears.

Astronomers say the angular-diameter distance $d_A(z)$ is larger.

The distance in a curved universe

- **Local Hubble law:**

$$r(z) = c\frac{z}{H_0}$$

- **Global Hubble law:**

$$ds^2 = c^2dt^2 - a(t)^2 dr'^2/(1-kr'^2) = 0$$

$$r(z) \equiv S_k[r'(z)] = c\int\frac{dt}{a(t)} = c\int\frac{dz}{H(z)}$$

$$a = (1+z)^{-1}$$

The physics of the distance

- Friedmann equation with two components:

$$H^2 = \frac{8\pi}{3}(\rho_M + \rho_\Lambda) - \frac{k}{a^2}$$

$$H(z) = H_0 E(z)$$

$$E^2(z) = \Omega_M (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2$$

$$r(z) = \frac{c}{H_0} \int_0^z \frac{dz}{E(z)}$$

- *The distance is an integral over the cosmic geometry.*

The universe at a distance

Which observables depend on distance?

- **Angular sizes !**
- **Light flux !**
- **Number density !**
- **Ages !**
- **Correlations !**

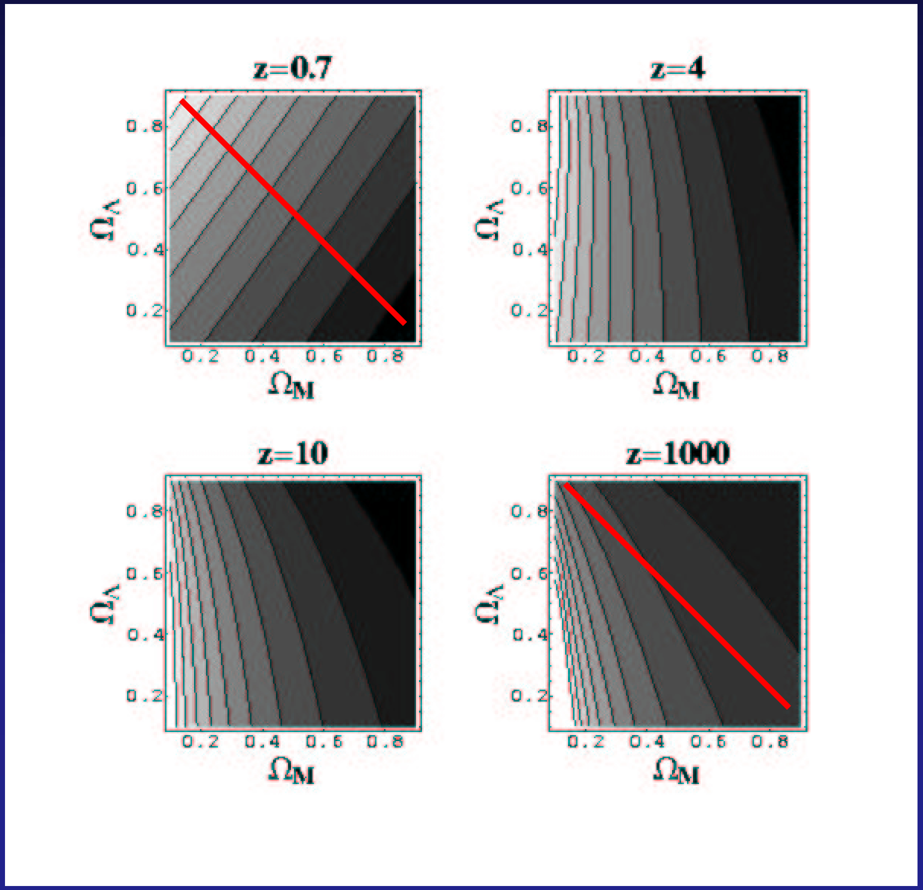
The many aspects of the Hubble law

$$r(z) = \frac{c}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2\right]^{1/2}}$$

z infinity	age of the universe
z = 1000 **sensitive to $\Omega_\Lambda + \Omega_M$**	acoustic peaks on the CMB
z < 10 **sensitive to $\Omega_\Lambda - \Omega_M$**	standard candles (SNIa) standard rods (QSO clustering) standard clocks (galaxy ages) lensing statistics

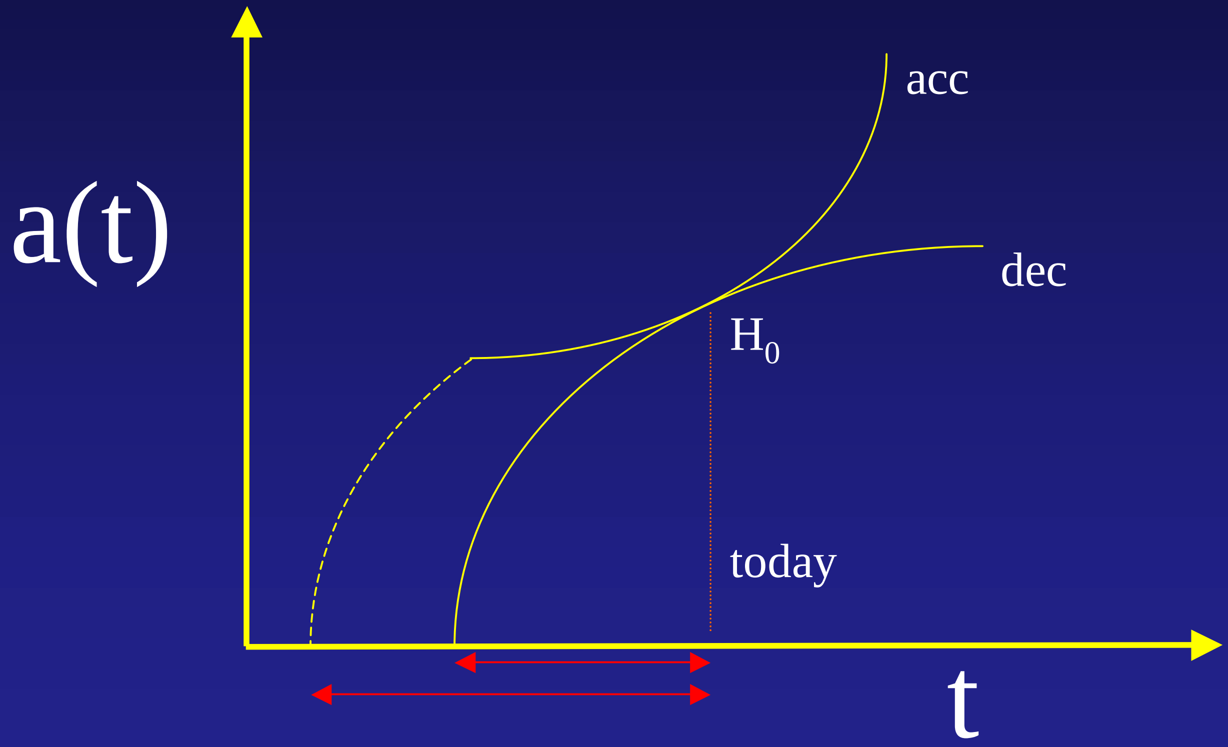
Breaking the degeneration

$$r(z) = \frac{c}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2\right]^{1/2}}$$



z infinity: Age of the universe

$$t(z) = \frac{c}{H_0} \int_0^z \frac{dz}{(1+z)\left[\Omega_M (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2\right]^{1/2}}$$



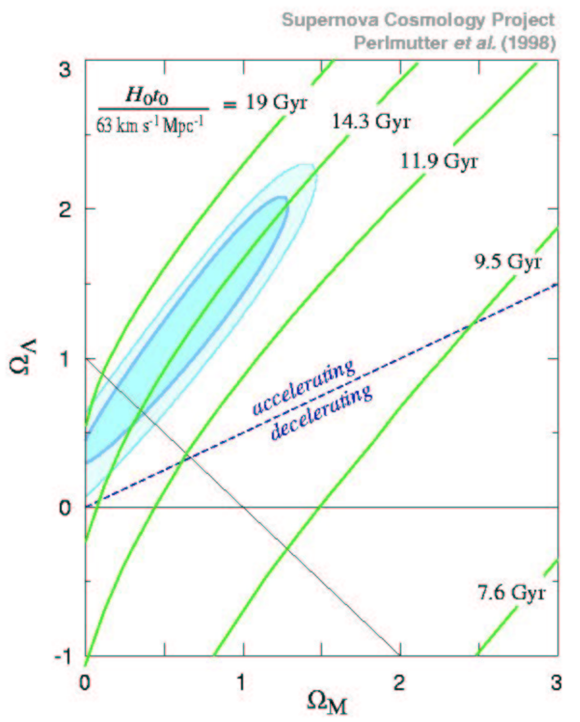
Accelerated universes are older

z infinity: Age of the universe

$$t_0 - t_1 = H_0^{-1} \int_0^{z_1} \frac{dz'}{(1+z')E(z')}$$

$$H_0^{-1} = 9.76 h^{-1} Gyr$$

For Ω_Λ increasing
t(z) increases:
the age of the universe increases



Best fit age of universe: $t_o = 14.5 \pm 1\ (0.63/h)$ Gyr

Best fit in flat universe: $t_o = 14.9 \pm 1\ (0.63/h)$ Gyr

z < 10: Standard candles

$$f = \frac{L}{4\pi d_L^2}$$

$$d_L(z) = r(z)(1+z) = (1+z)cH_0^{-1}\int_0^z \frac{dz'}{E(z')}$$

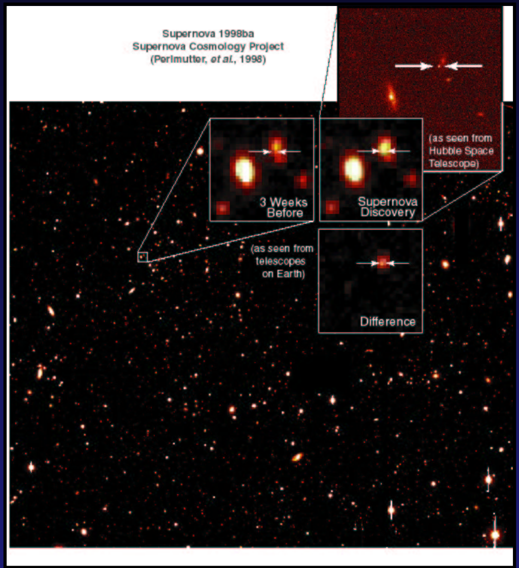
$$cH_0^{-1} = 3000h^{-1}Mpc$$

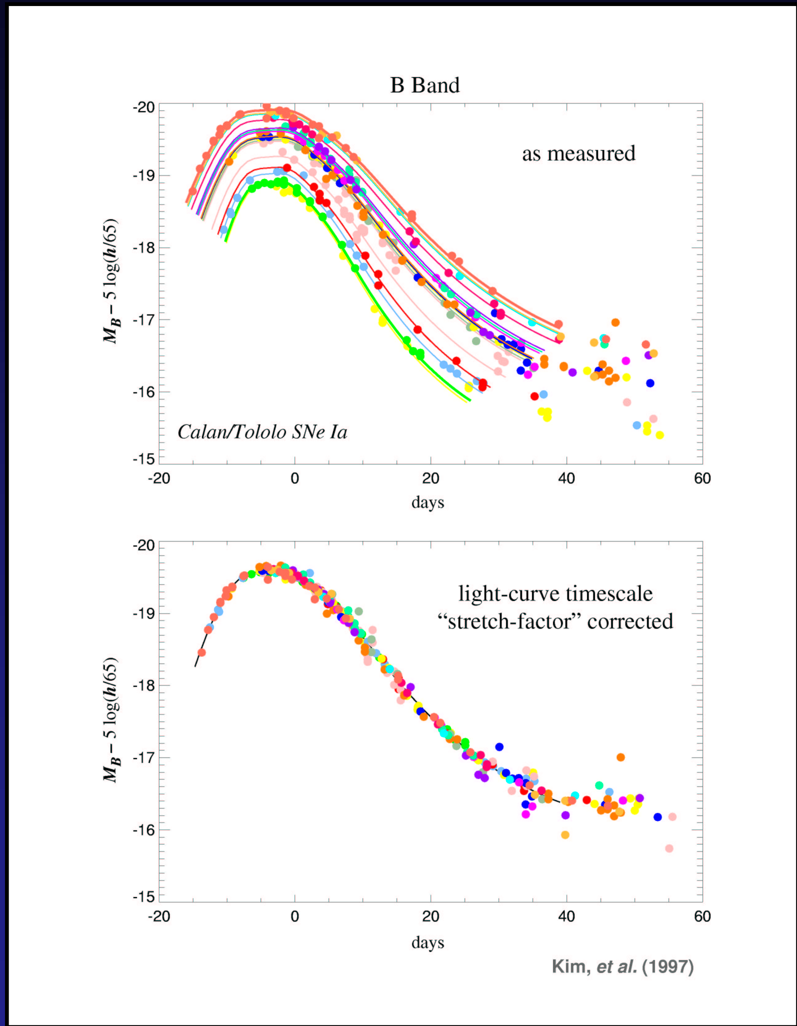
For Ω_Λ increasing

r(z) increases :

light diverges more than in a euclidean matter-dominated universe: sources are expected to be fainter.

Supernovae Ia as standardized candles

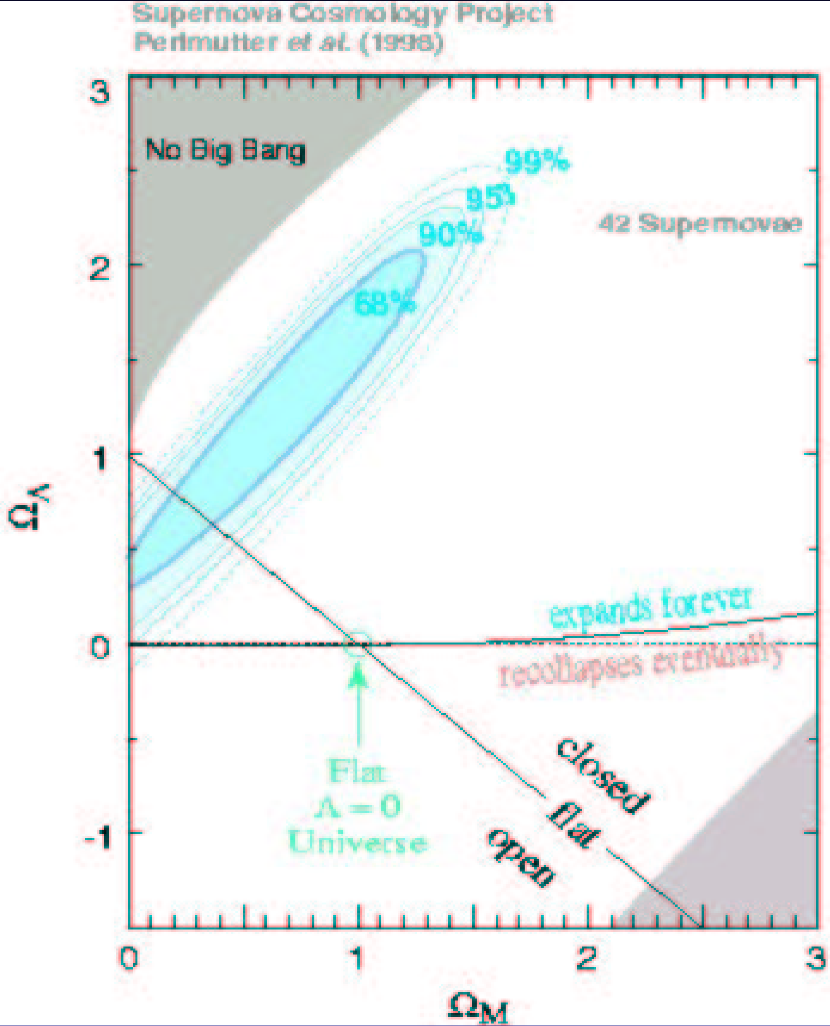


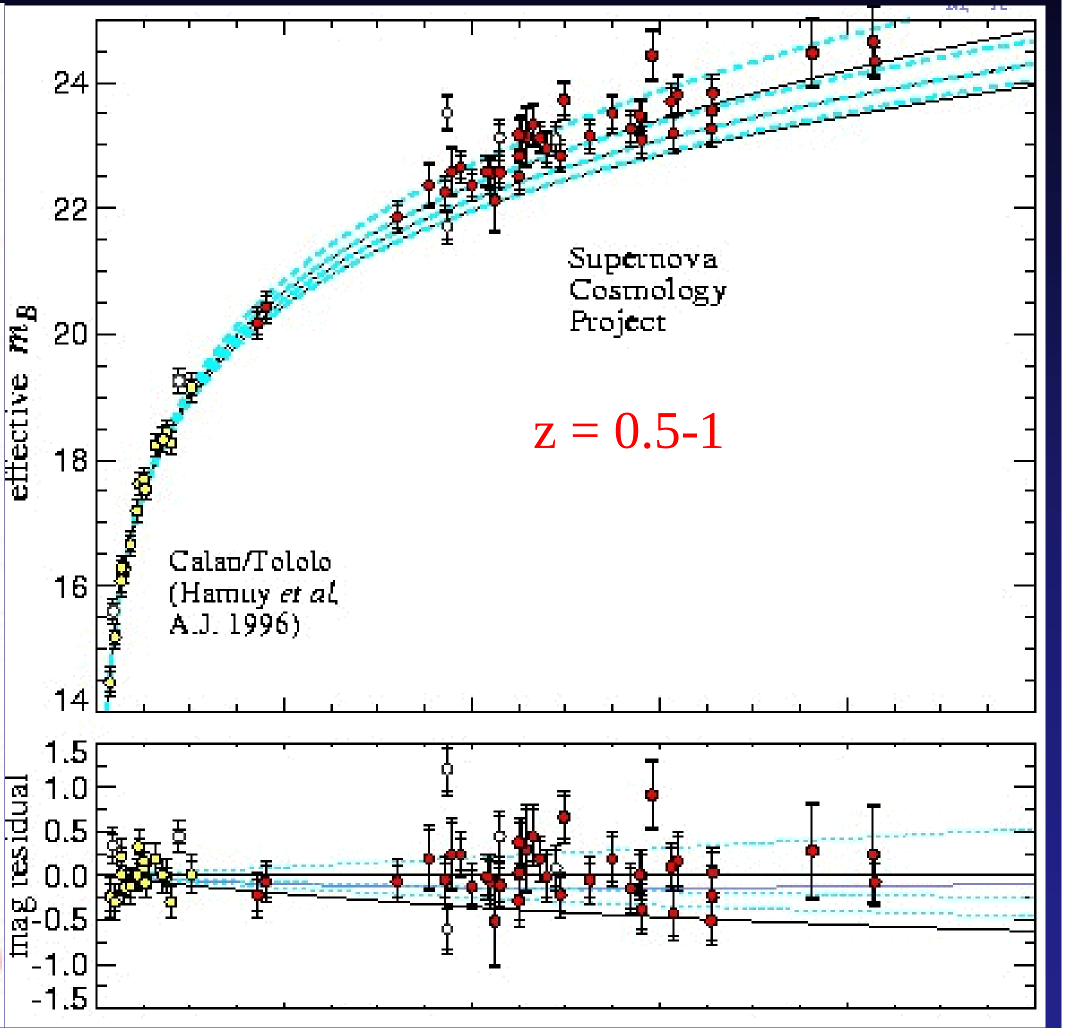


SNIa light curves

Perlmutter et al.; Riess et al. 1998

Supernovae Ia: results





z = 0.5-1

Facts are like cows: if you look at them into the eyes for sufficiently long they generally run away.

Alternative explanations

- Gray dust
- Inhomogeneities (= two different values for H_0)
- Variable Chandrasekhar mass (= variable G, c, m,…)
- Evolutionary effects

Better to double check !

Standard rods in the universe

$$d_A(z) = \frac{\text{"rod" length}}{\text{angular size}} = (1+z)^{-1} cH_0^{-1} \int_0^z \frac{dz'}{E(z')}$$

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

- **(An)isotropy of Correlation function** (Alcock-Paczynsky effect; see e.g. Szalay & collaborators on SDSS)

- **Sound horizon at decoupling**.

The sound horizon at decoupling

- The decoupling occurred 500,000 yrs after the big bang
- Acoustic perturbations in the photon-baryon plasma travelled at the sound speed

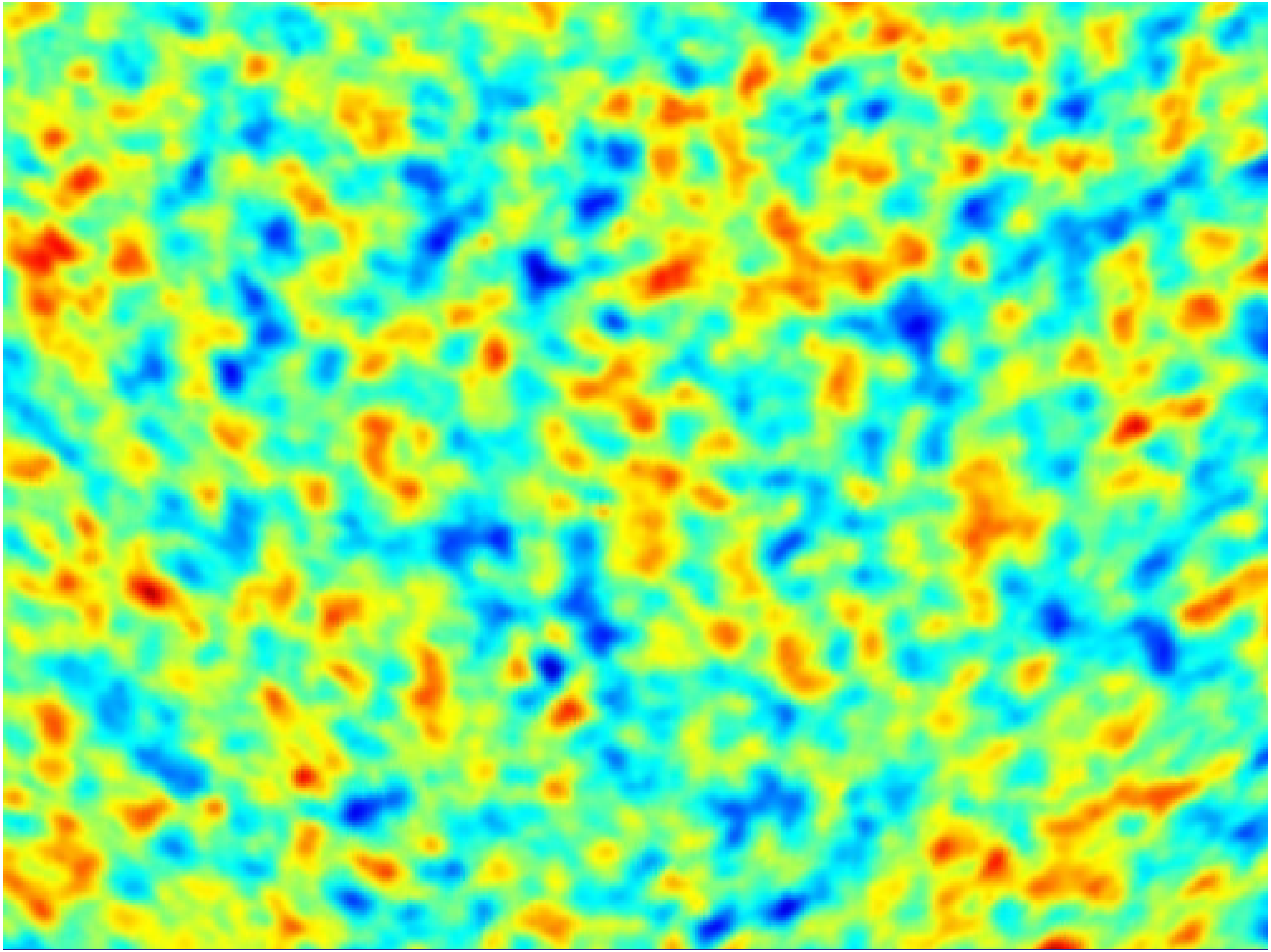
$$c_s = c/\sqrt{3}$$

Therefore they propagated for

$$\mathbf{280{,}000}\,\boldsymbol{lyr} \approx \mathbf{0.09}\,\boldsymbol{Mpc}$$

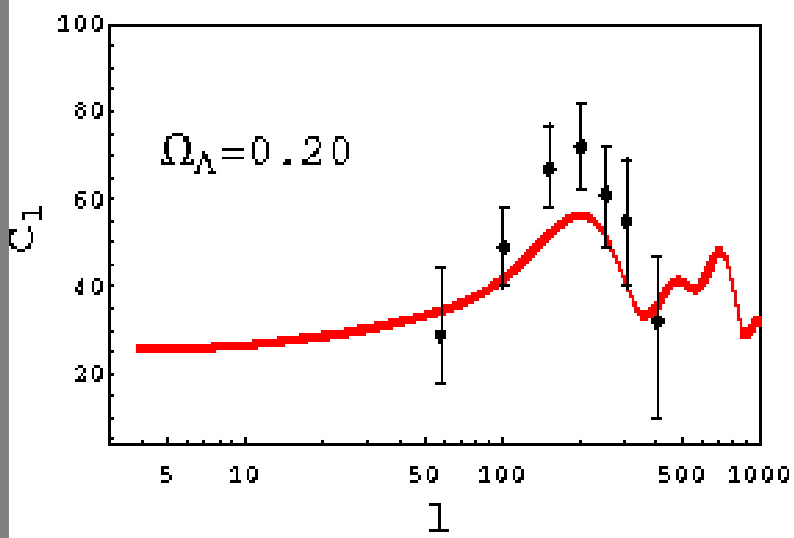
independently of cosmology.

This is a perfect standard rod !

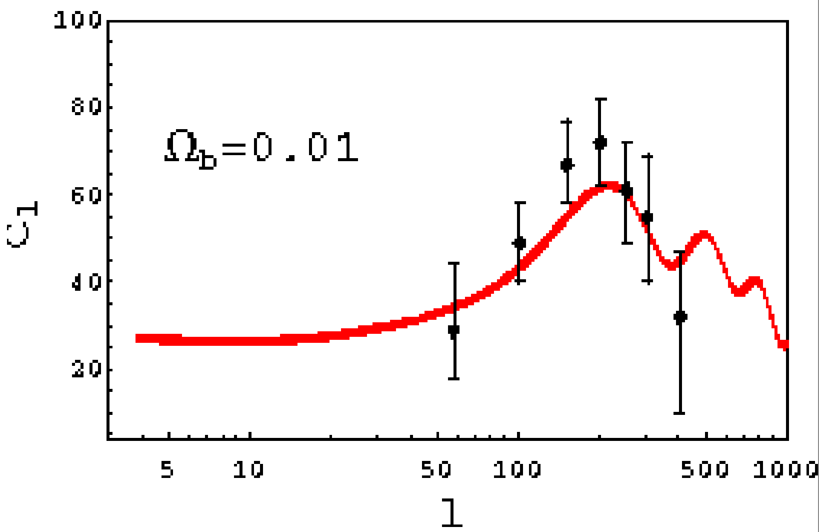


Acoustic peaks

Peak position



Peak height



Data: Boomerang 1999

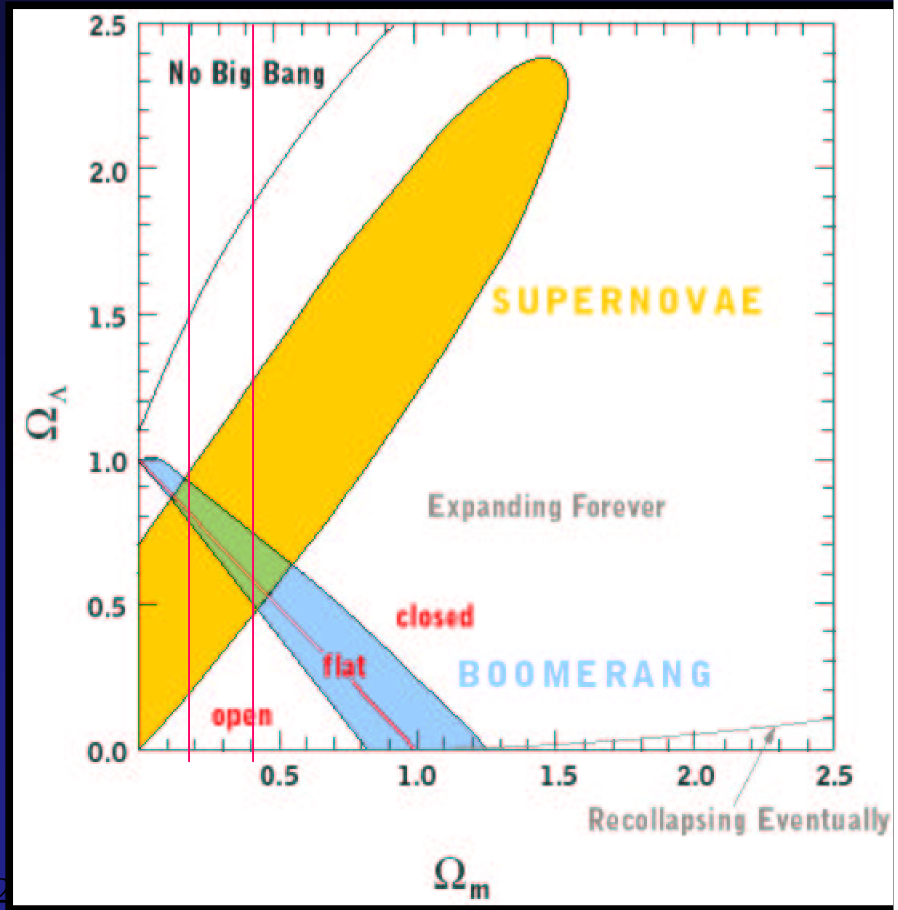
To be precise: a full likelihood analysis

- Generating a grid of CMB spectra for each value of the parameters h, Ω_b, Ω_m, Ω_Λ n, one can evaluate a general multi-dimensional likelihood function

  $\log L = \Sigma(C_t - C_o)^2/\sigma^2$

- $\Omega_m = 0.3$

  $\Omega_\Lambda = 0.7$

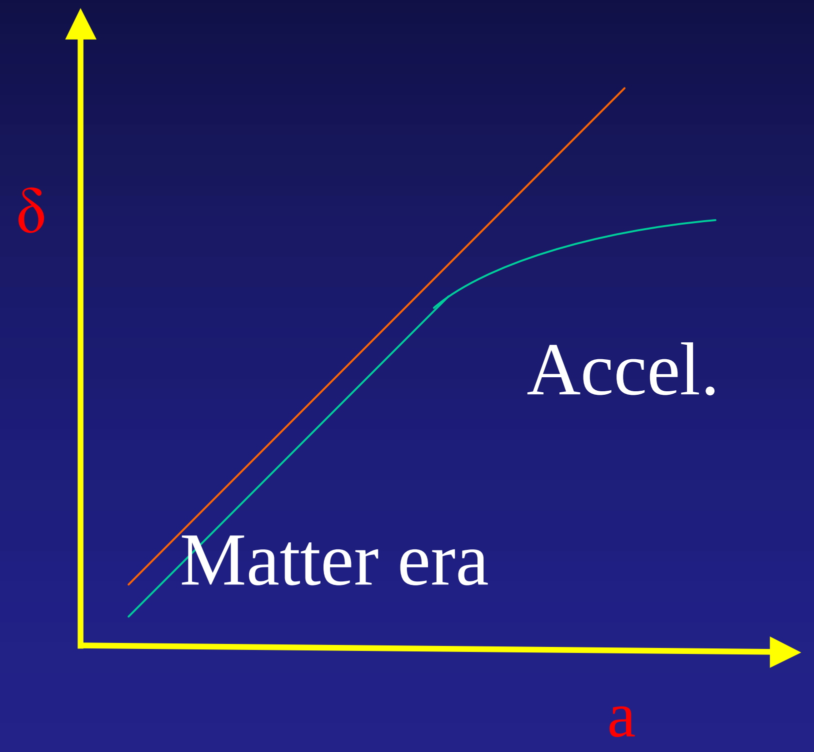


The third way: perturbations in a changing geometry

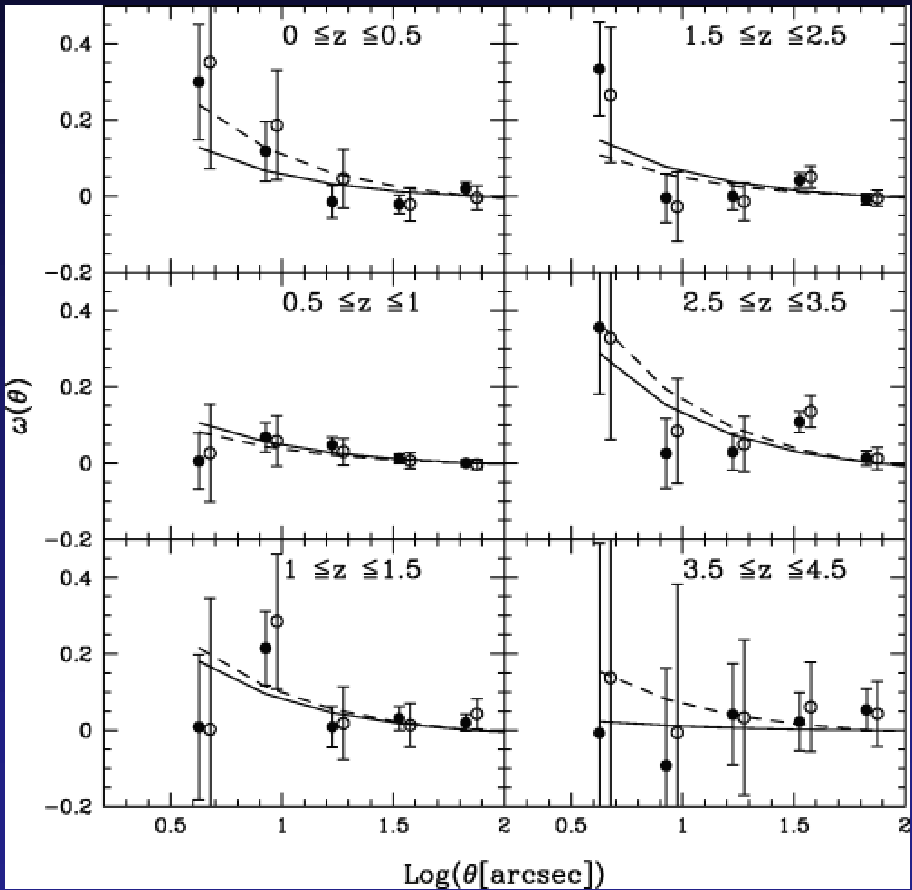
In the Newtonian approximation, the perturbations grow as

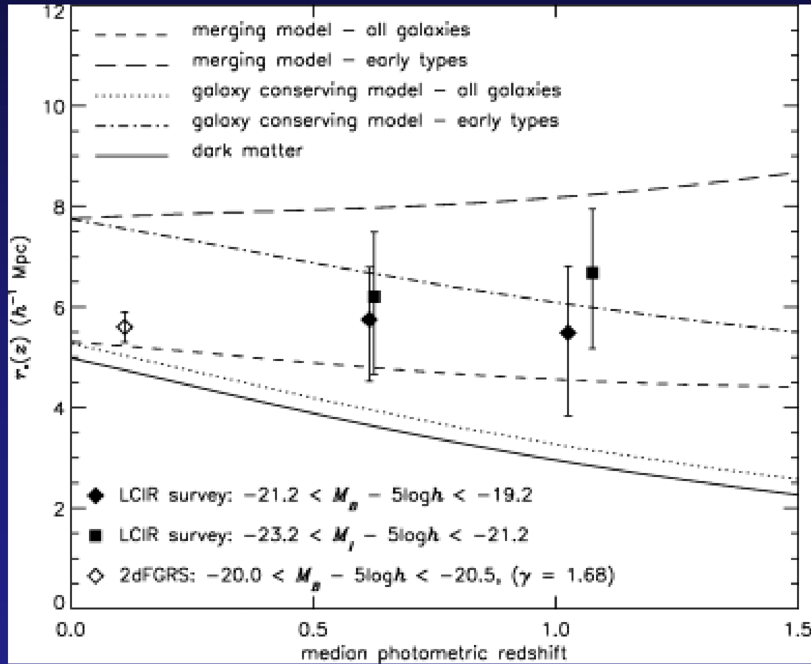
$$\delta = a$$

as long as matter dominates. When the cosmological constant dominates, the perturbation stops growing.

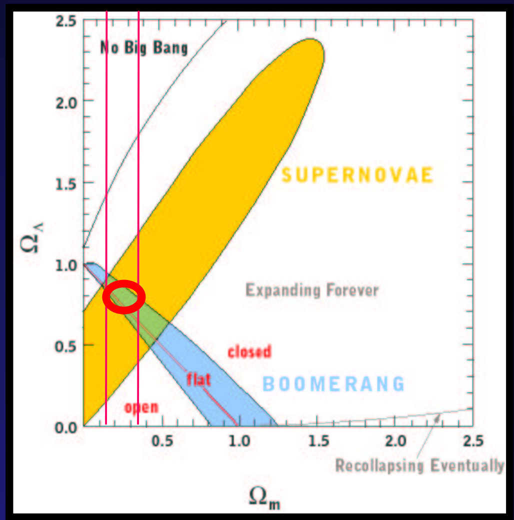


Evolution (?) of clustering





Observations are converging…



…to an unexpected universe

Two questions (at least!)

What is Ω_Λ ?
(the fine-tuning problem)

Why is Ω_Λ almost equal to Ω_M ?
(the coincidence problem)

What is Ω_Λ?

QFT expectation of the vacuum energy:

$$E_0 = \frac{1}{2}\hbar L^3 \int \frac{d^3k}{(2\pi)^3}\omega_k$$

$$\rho_{vacuum} = \hbar \frac{k^4_{\max}}{16\pi^2} = 10^{92}\ g/cm^3$$

$$\Omega_{vacuum} = 10^{120}\ !!$$

Why is Ω_Λ almost equal to Ω_M?

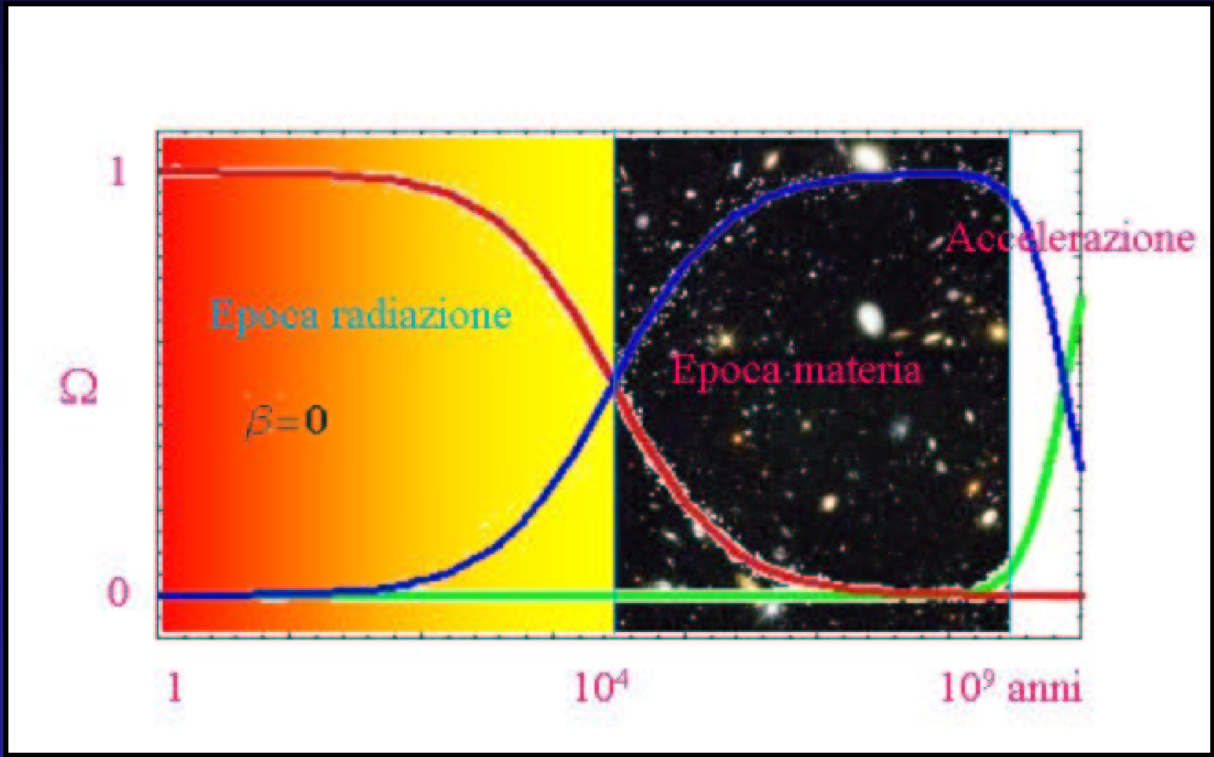
Matter dilutes as universe expands as

$\rho_M = a^{-3}$

But the vacuum energy does not dilute:

$\rho_\Lambda = a^0$

Therefore, sooner or later the cosmological constant dominates the cosmic fluid

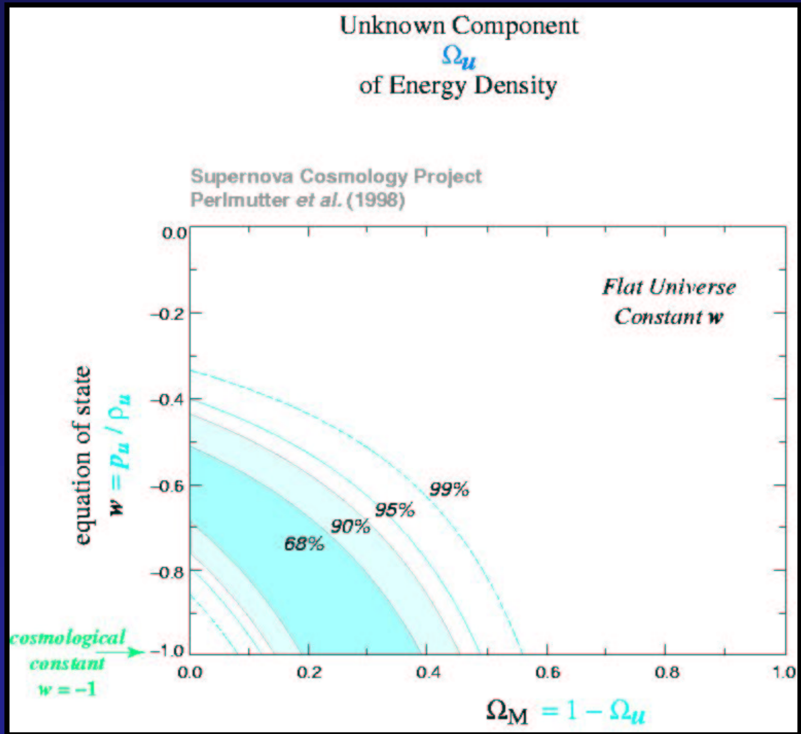


Enters Dark energy

$$w = p/\rho$$

$$H(z) = H_0 E(z)$$

$$E^2(z) = \Omega_M (1+z)^3 + \Omega_\phi (1+z)^{3(w_\phi+1)}$$



Dark energy as a scalar field

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\text{eq. of state} \quad w_\phi = \frac{p_\phi}{\rho_\phi}$$

- A perfect fluid with w<0 is unstable
- Scalars are predicted by fundamental theories
- do not cluster on subhorizon scales

$$p = \rho - 2V(\phi)$$

$$\text{sound speed} \quad c_s^2 = \frac{\partial p_\phi}{\partial \rho_\phi} = 1$$

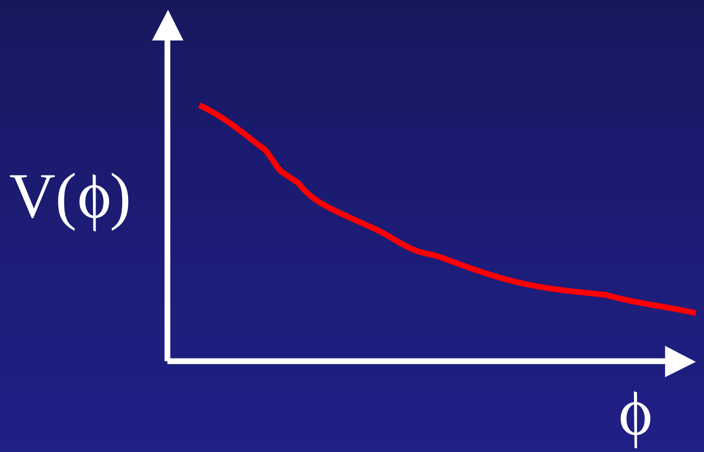
Then, we can characterize the new component by

•The self-interaction potential

•The coupling to the other fields

The potential

- Any potential sufficiently flat can give acceleration sooner or later



$$V(\phi) = \phi^{-n}, e^{\lambda\phi}, \ldots$$

- But why just now ?

Evolution of background

Dark Energy Potential $V = Ae^{-\mu\phi}, A\phi^{-\alpha}$

$$x^2 = \Omega_{\phi,K} = kinetic\ \ energy$$

$$y^2 = potential\ \ energy$$

$$z^2 = radiation\ \ energy$$

$$x' = \frac{1}{2}(3 - 3x^2 + 3y^2)x - \mu y^2$$

$$y' = \mu xy + \frac{1}{2}(3 + 3x^2 - 3y^2)y$$

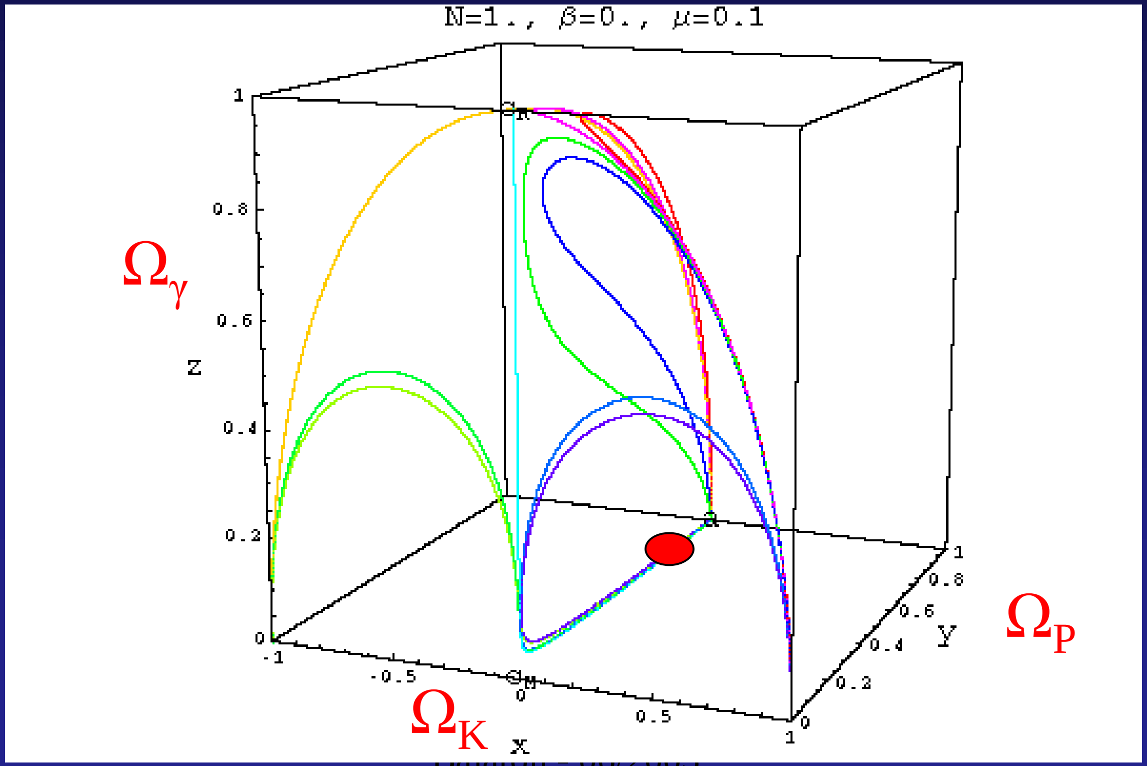
$$z' = -\frac{1}{2}(1 - 3x^2 + 3y^2 - z^2)z$$

Flat space:

$$\Omega_m = 1 - (x^2 + y^2 + z^2)$$

Tracking vs. attractors

In a phase space, tracking is a curve, attractor is a point

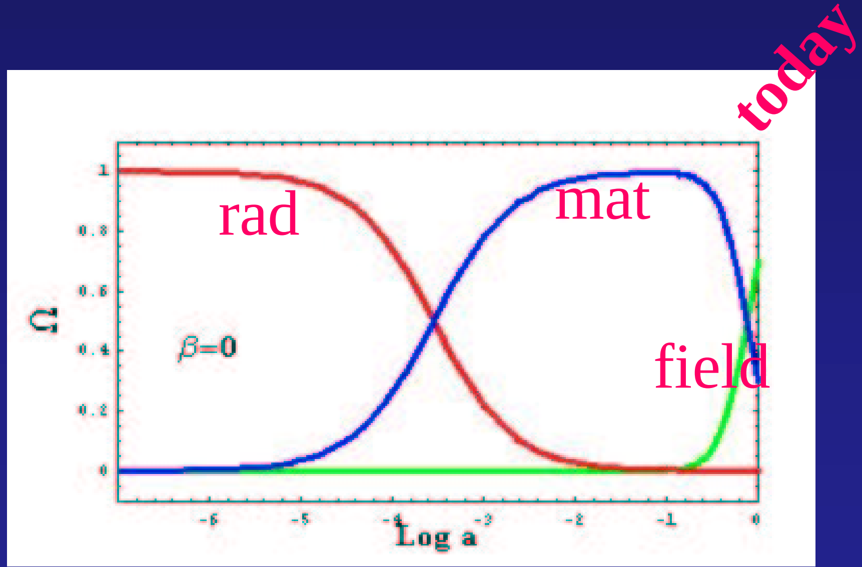


Tracking and attractors are very different:

- In the tracking case, most trajectories converge on the tracking solution, but the values of the variables on the tracking still depend on the initial conditions
- In the attractor case, all the solutions converge to the same state. This state is therefore independent of the initial conditions.

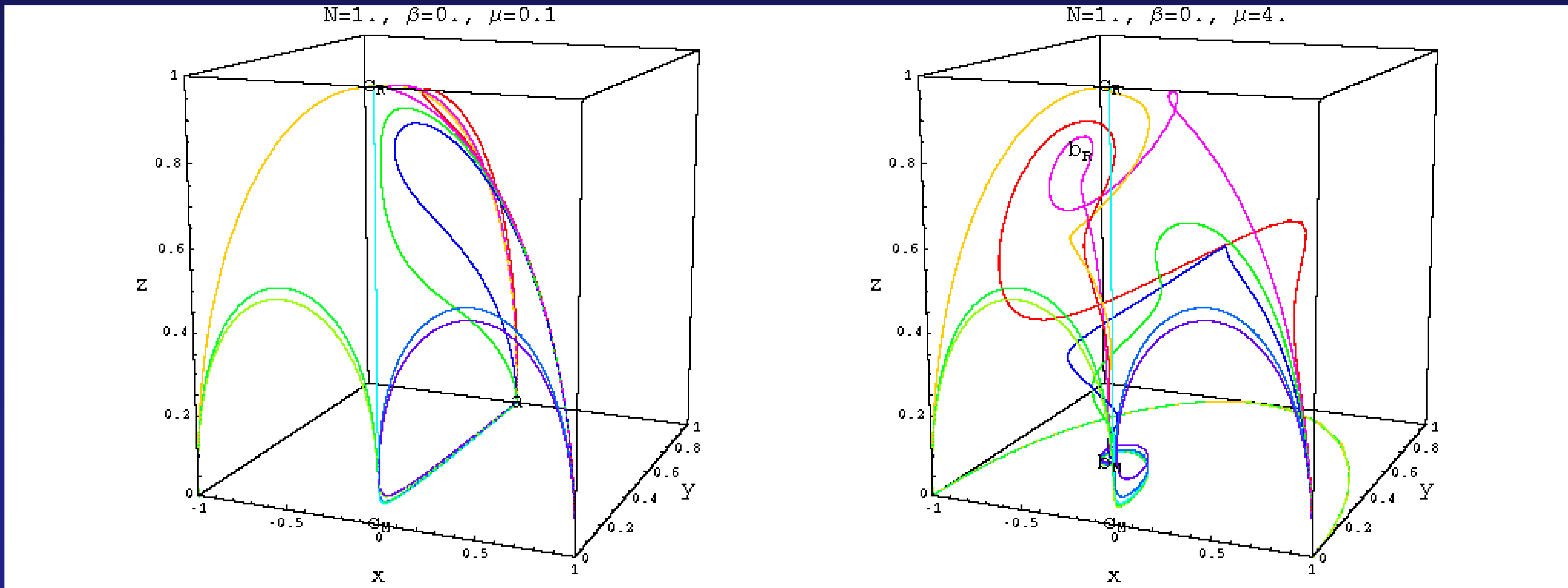
The trouble with tracking :

- Not all initial conditions fall on the tracking solution
- The tracking guarantees that when $\Omega_\varphi = \Omega_m$ the expansion is accelerated
- But the coincidence problem remains: the DE was negligible in the past and will dominate in the future



The trouble with attractors :

- The final state is independent of initial conditions
- However, for this state to resemble our universe, it has to accelerate and to retain a finite content of matter
- But matter scales as a^{-3} : this behavior cannot accelerate
- No realistic attractor exists



$$\Omega_m = 1 - (x^2 + y^2 + z^2)$$

The coupling

- So far, people focused mostly on the potential (or w_ϕ) rather than on the coupling…

$$T^{\mu}_{(m)\nu;\mu} = C\, T_{(m)}\, \phi_{;\nu}$$

$$T^{\mu}_{(\phi)\nu;\mu} = -C\, T_{(m)}\, \phi_{;\nu}$$

Dark energy as a fundamental force

$$T^{\mu}_{(m)\nu;\mu} = CT\phi_{;\nu}$$

$$T^{\mu}_{(\phi)\nu;\mu} = -CT\phi_{;\nu}$$

now the conservation laws in a homogeneous Universe are modified:

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = C\dot{\phi}\rho_m$$

$$\dot{\rho}_m + 3H\rho_m = -C\rho_m$$

$$\rho_m = \rho_0 a^{-3} e^{C\phi}$$

$\beta^2 \sim C^2/G$ = scalar-to-tensor ratio

Why ?

- The simplest extension of Einstein's gravity: Brans-Dicke gravity
- Extra dimensions, superstrings, dilaton…
- Varying dark matter mass, $m_{DM}=m_0(\varphi)$

An extra gravity

Newtonian limit: the scalar interaction generates an attractive extra-gravity

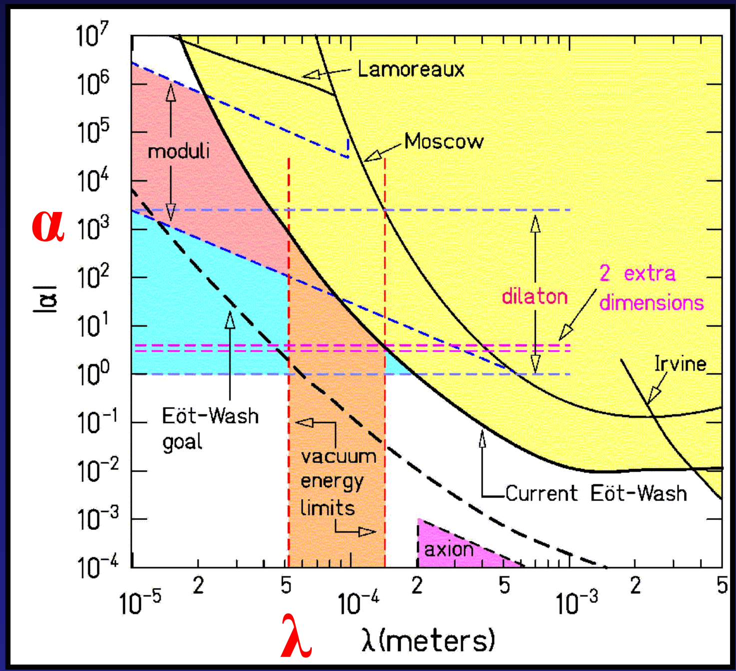
$$\delta''+\left(1+\frac{H'}{H}-2\beta x\right)\delta'+4\pi G\left(1+\frac{4}{3}\beta^2\right)\rho\delta=0$$

$$G^*=G\left(1+\frac{4}{3}\beta^2\right)$$

Local tests of gravity: λ<1 a.u.

- Only on baryons and on sublunar scales
- Scalar component:

$$G(r) = G(1 + \alpha_{bar} e^{-r/\lambda})$$



$$\alpha_{bar} < 0.001$$

Adelberger et al. 2002

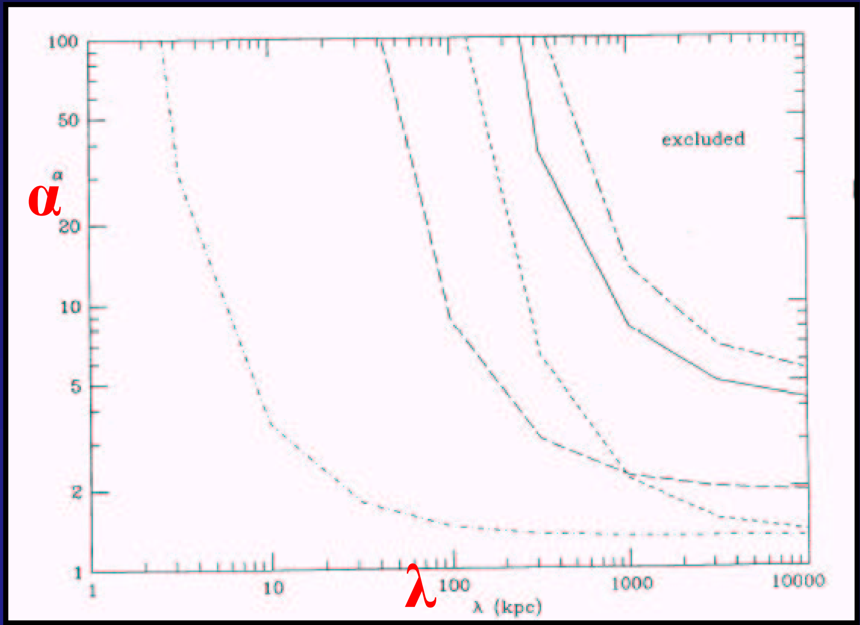
Astrophysical tests of gravity: $\lambda<1$ Mpc

- Distribution of dark matter and baryons in galaxies and clusters

(rotation curves, virial theorem, X-ray clusters,…)

$$G(r) = G(1+\alpha_{dm} e^{-r/\lambda})$$

$$\alpha_{dm} < 1.5$$



Gradwohl & Frieman 1992

Cosmological tests of gravity: $\lambda > 1/H_0$

- gravitational growth of structures: CMB, large scale structure

$$G_X(r) = G(1+\alpha_X e^{-r/\lambda}) \rightarrow G(1+\alpha_X)$$

$$G^* = G(1 + \frac{4}{3}\beta_X{}^2)$$

Since $\alpha_b=\beta_b{}^2<0.001$, baryons must be very weakly coupled

Since $\alpha_c=\beta_c{}^2<1.5$, dark matter can be strongly coupled

A species-dependent interaction

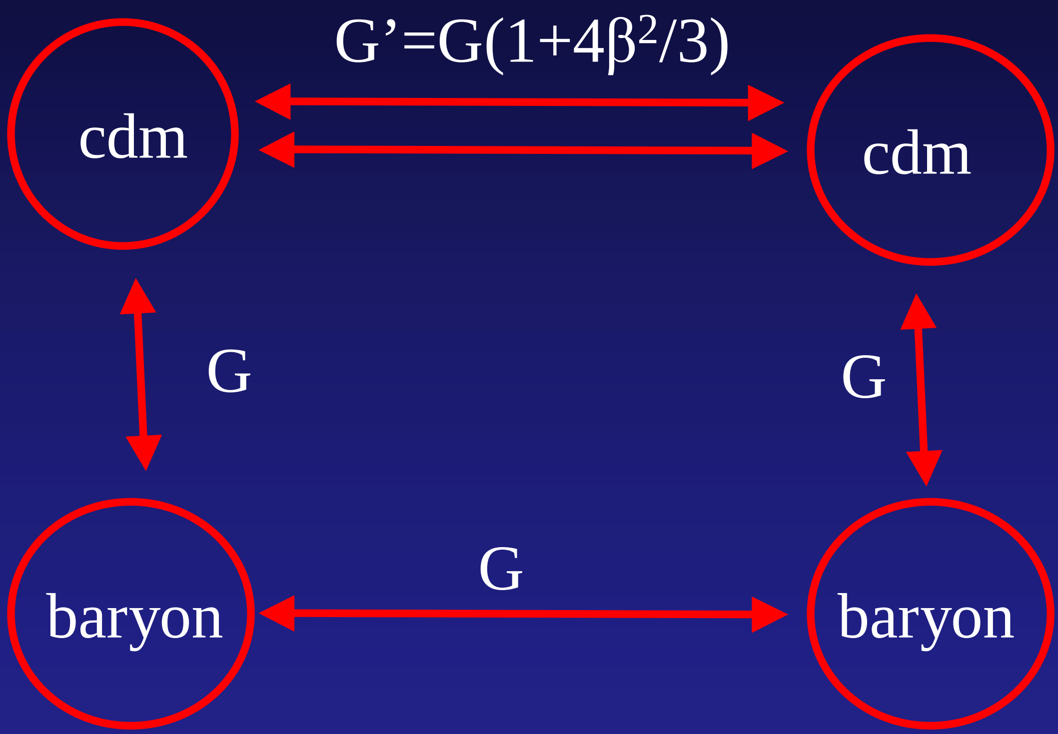
$$T^{\mu}{}_{(cdm)\,\nu;\mu} = C T_{(cdm)} \phi_{;\nu}$$

$$T^{\mu}{}_{(\phi)\,\nu;\mu} = -C T_{(cdm)} \phi_{;\nu}$$

$$T^{\mu}{}_{(bar)\,\nu;\mu} = 0$$

$$T^{\mu}{}_{(rad)\,\nu;\mu} = 0$$

Dark energy and the equivalence principle



Two qualitatively different cases:

weak coupling $\beta << 1$

strong coupling $\beta > 1$

Weak coupling: density trends

No coupling

MDE: $\Omega_\phi = 0$

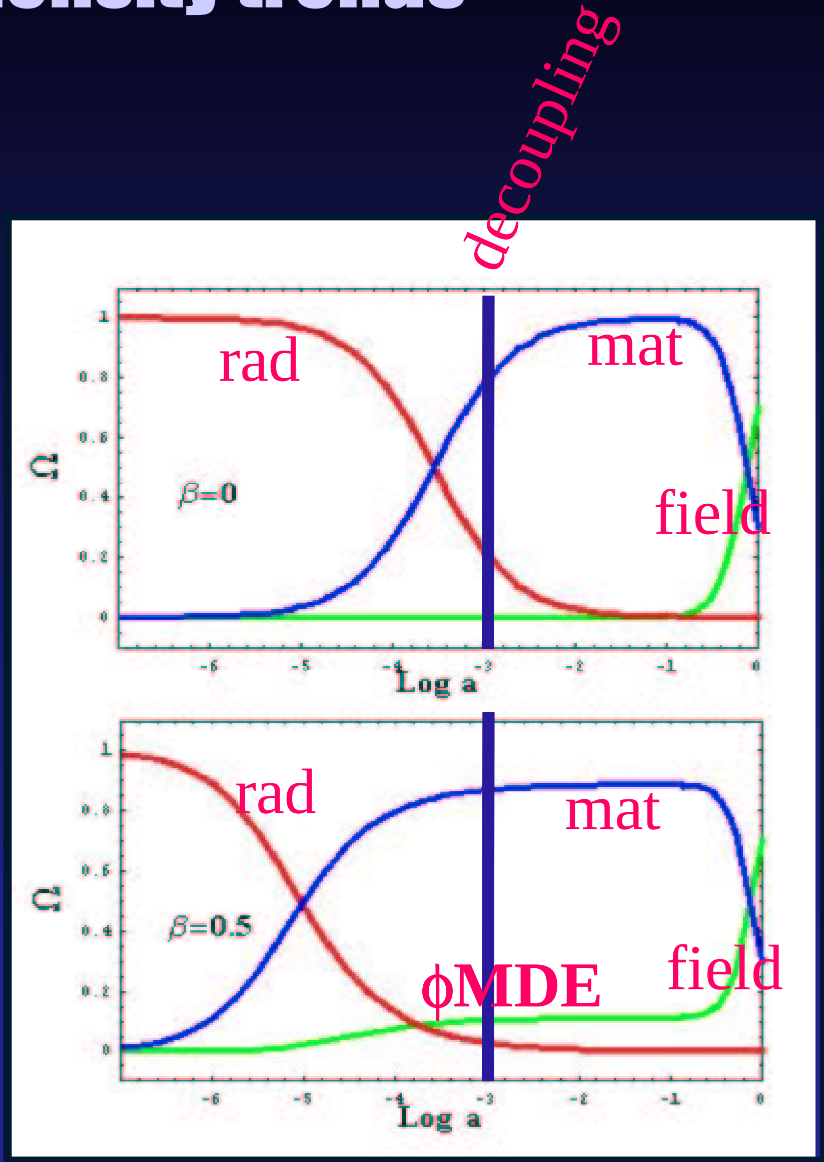
$p = 2/3$

coupling

ϕMDE: $\Omega_\phi = 4\beta^2/9$

$p = 6/(4\beta^2+9)$

kinetic phase, indep. of potential!



Weak coupling: density trends

$V(\phi) = \phi^{-\alpha}$

The equation of state

$w = p/\rho$

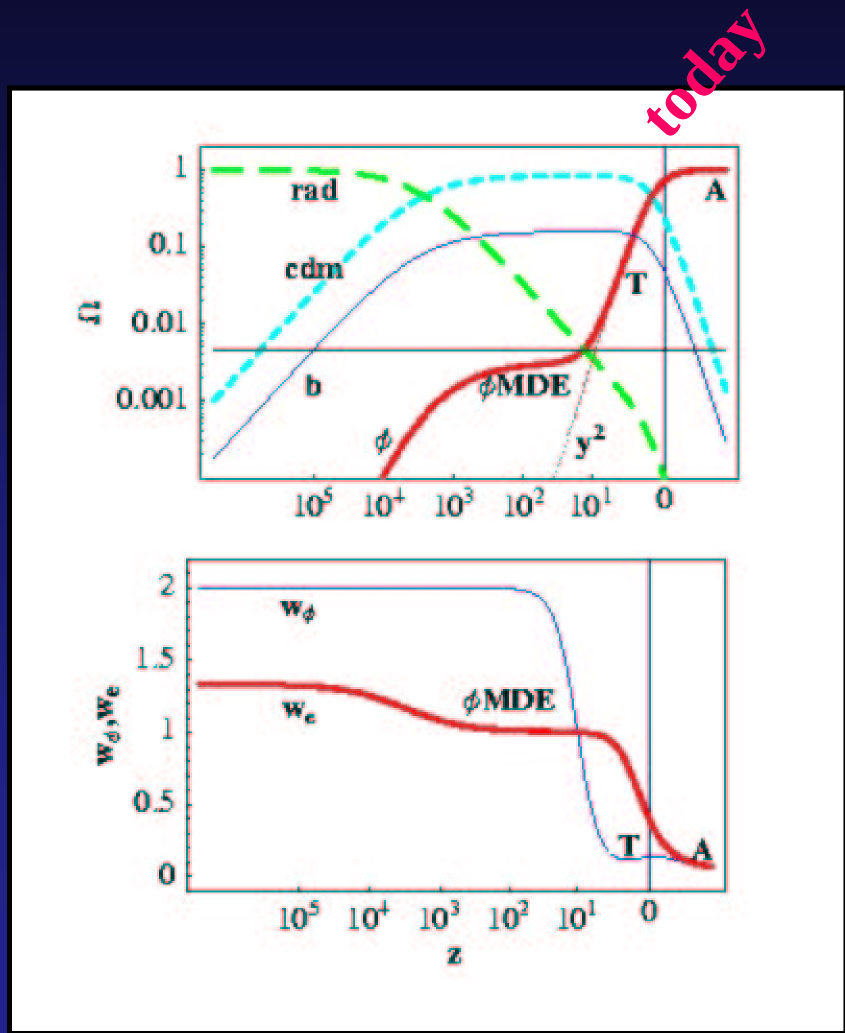
depends on **the coupling** during ϕMDE

and on **the potential** during tracking:

$w_e = 4\beta^2/9$: past value

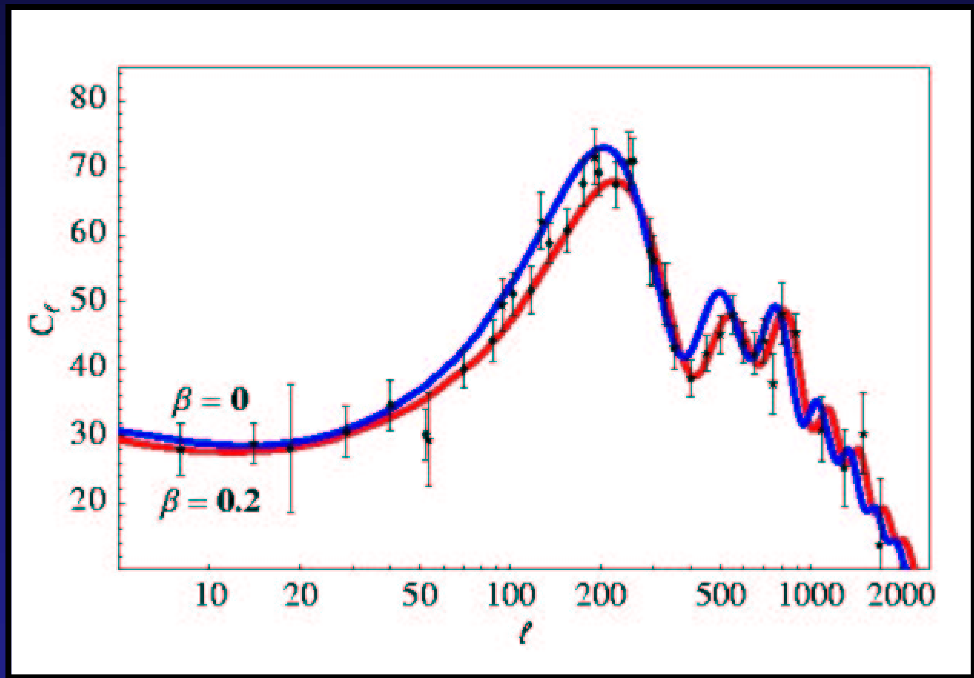
$w_\phi = -2/(\alpha+2)$: present value

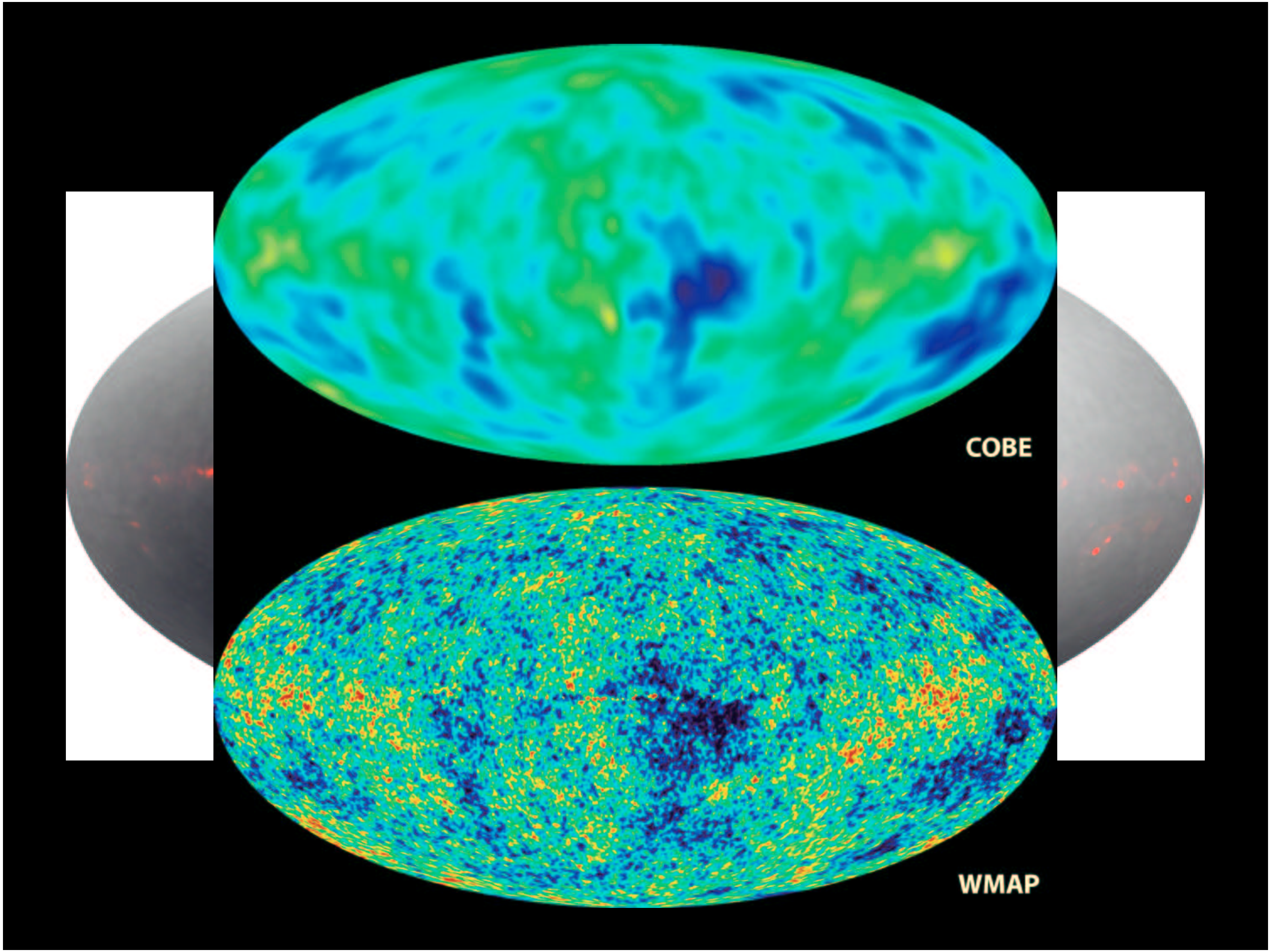
CMB constraints on both !



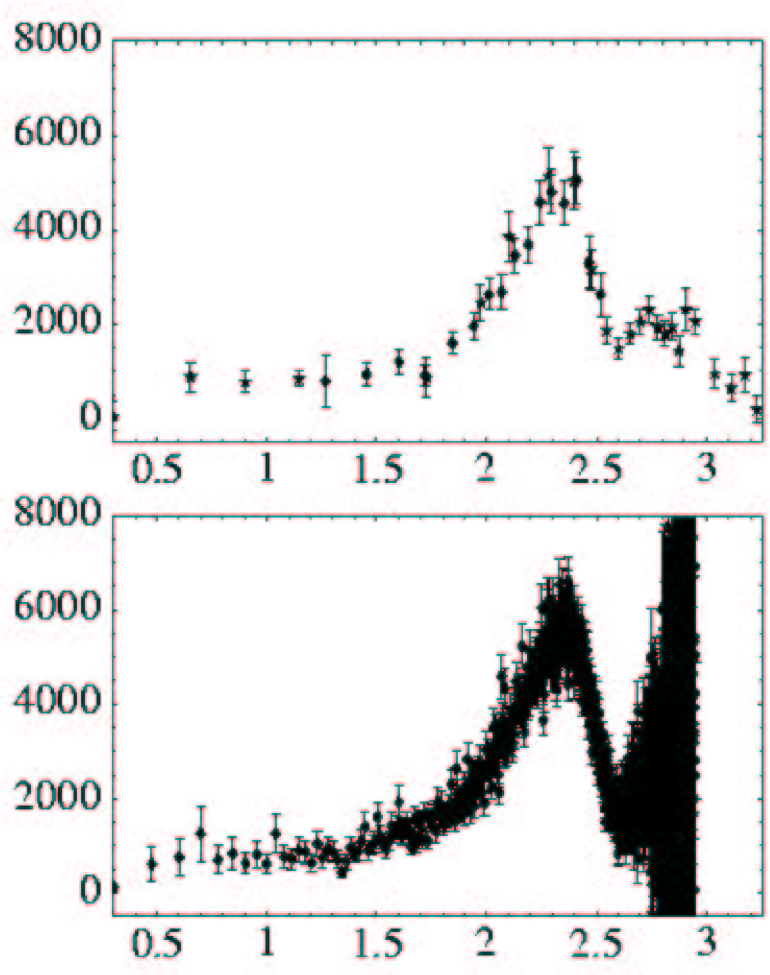
Weak coupling: CMB effects

The expansion during
ϕMDE
is slower: the peaks move to
the right
Since this epoch lasts from
decoupling to recently,
this effect is quite strong




COBE
WMAP

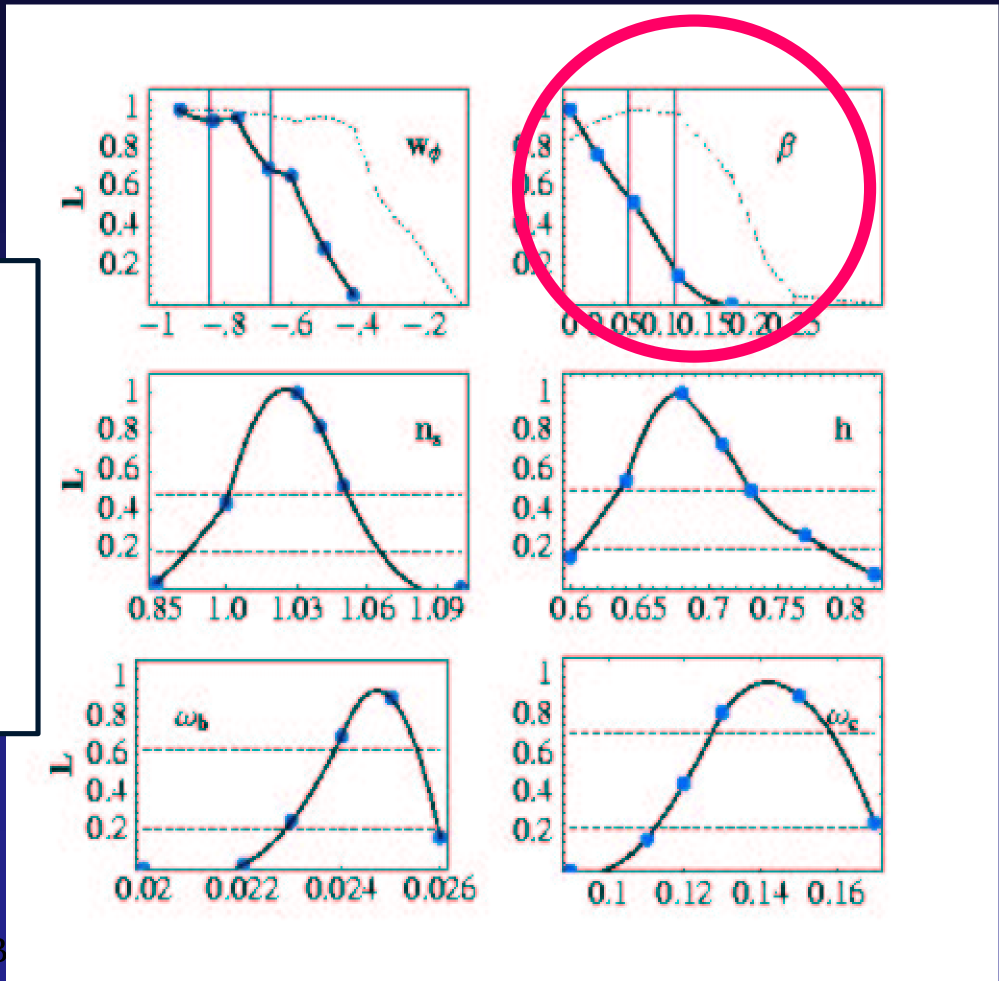
CMB
before
and
after
WMAP



WMAP and the coupling β

$0 < \beta < 0.12$ (95%cl)

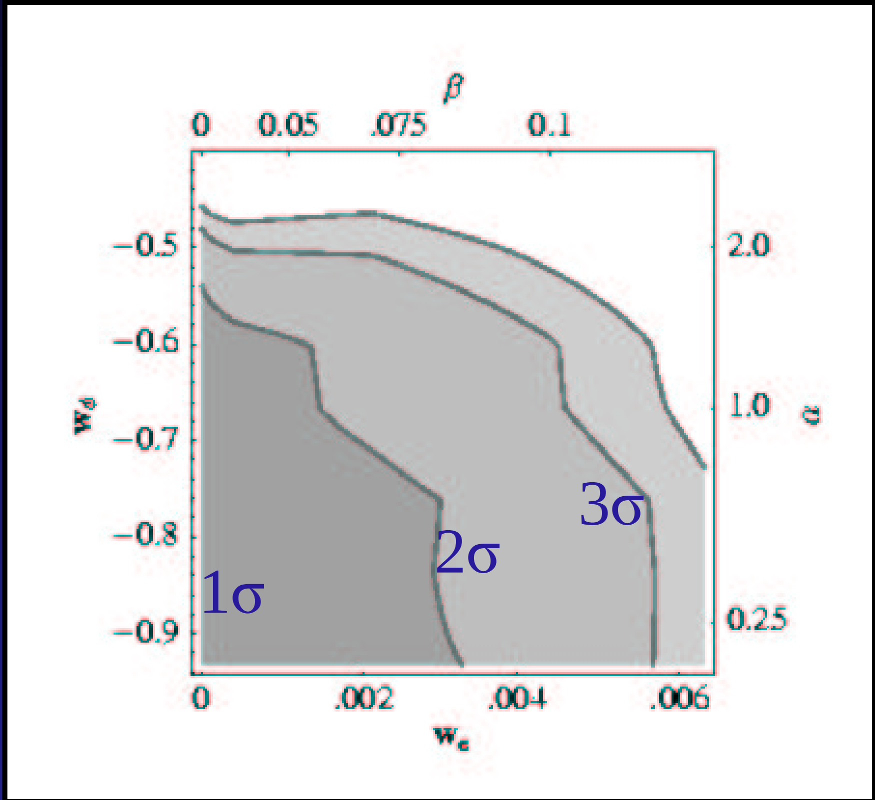
Planck: $\beta < 0.05$



Scalar force 100 times weaker than gravity

Constraints on two equations of state

$w_\phi = -2/(2+\alpha)$



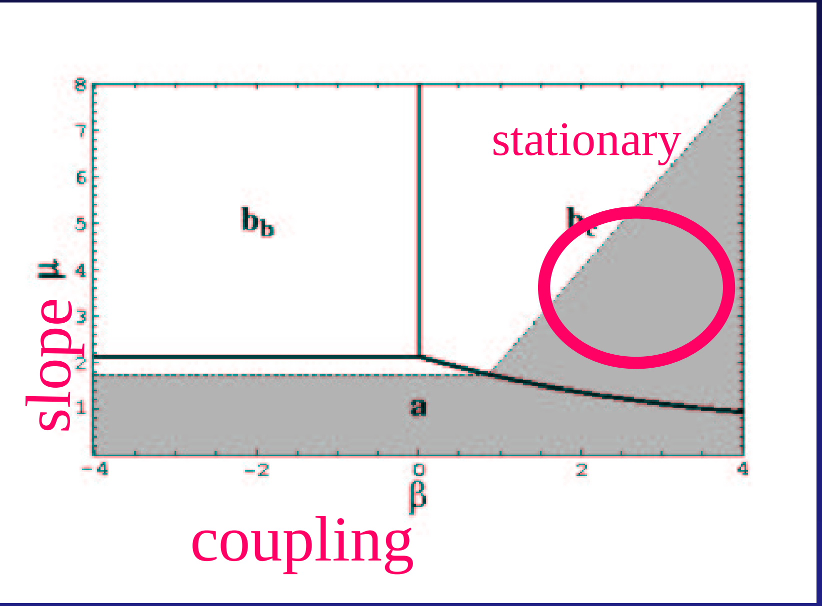
$w_e = 4\beta^2/9$

Strong coupling in an exponential potential

$$x' = \frac{1}{2}(3 - 3x^2 + 3y^2)x - \mu y^2 + \beta(1 - x^2 - y^2)$$

$$y' = \mu xy + \frac{1}{2}(3 + 3x^2 - 3y^2)y$$

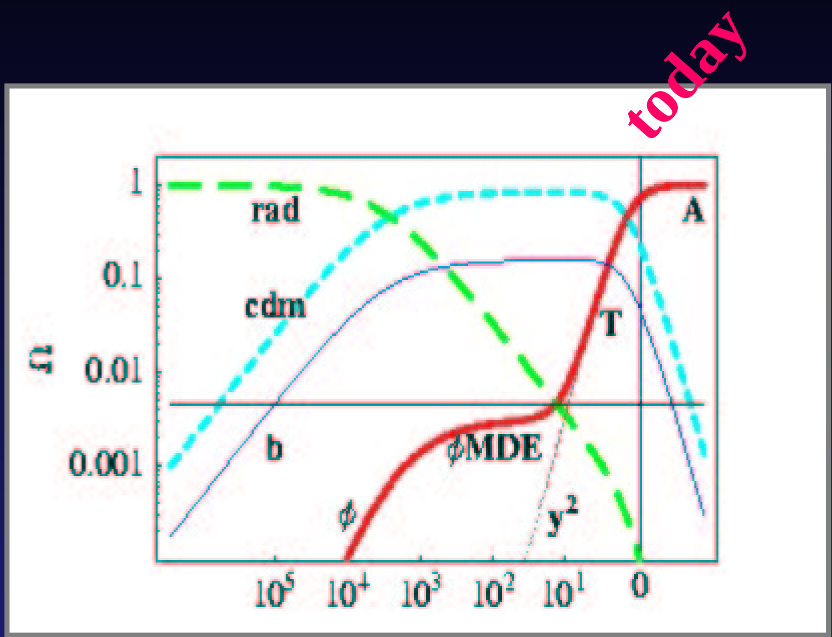
$$z' = -\frac{1}{2}(1 - 3x^2 + 3y^2 - z^2)z$$



Strong coupling solves the coincidence problem …

Weak:

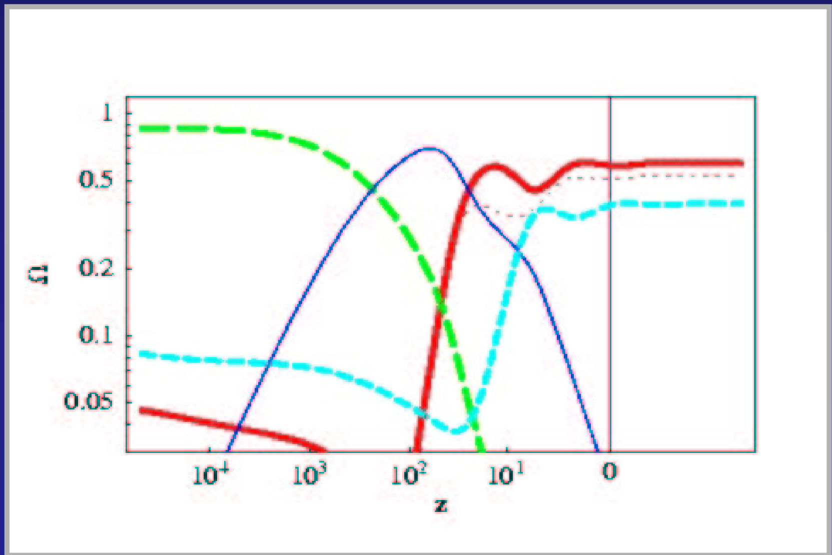
$\beta < 1$



$$\Omega_M \rightarrow 0$$

Strong:

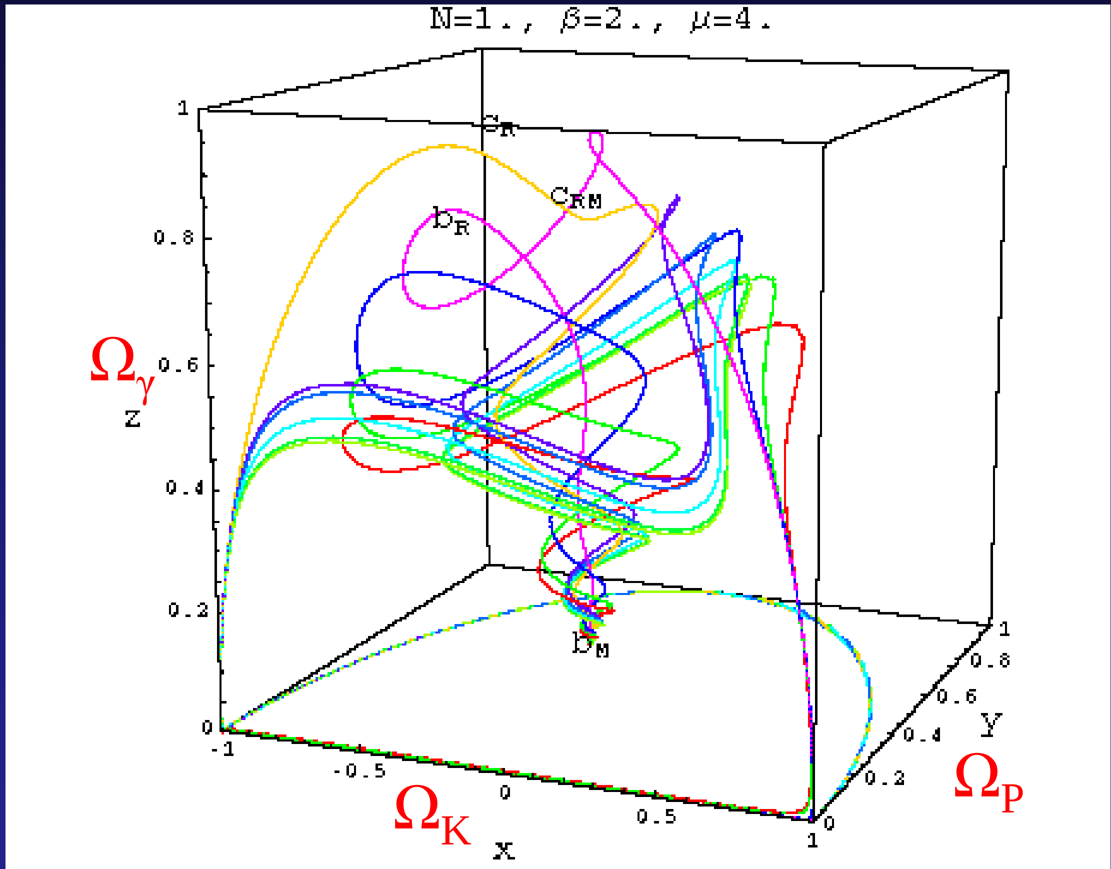
$\beta > 1$



$$\Omega_M = \frac{\beta^2 + 4\beta\mu + 18}{4(\beta + \mu)^2}$$

$$a = t^{\frac{2}{3}(1+\frac{\beta}{\mu})}$$

Phase space for strong coupling



A. Pasqui, 2002

Stationary regime

- The coupling allows to reach a stationary regime (Ω_m,w=const.) in which dark matter and dark energy evolve at the same rate, while baryons decay away
- Setting all constants of order unity in Planck units we obtain Ω_Λ similar to Ω_M independently of the initial conditions
- Stationary: dark matter is created out of dark energy

A stationary accelerated universe...

$$\Omega_M = \mathrm{const}(\beta, \mu)$$

$$\rho_M \approx \rho_\phi = a^{-3} \times a^{3\beta/(\mu+\beta)}$$

$$w = -\frac{\beta}{\mu + \beta}$$

...in which perturbations grow

$$\frac{\delta\rho}{\rho} = \mathrm{a}^{\mathrm{m}(\beta,\mu)}$$

...in a biased way

$$\delta_b = \mathrm{b}\delta_c$$

$$b = b(\beta, \mu)$$

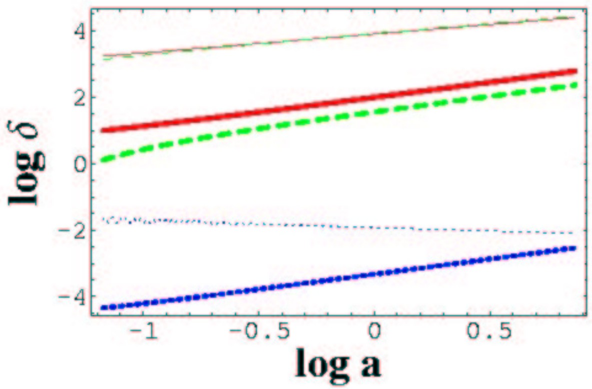


Figure 1: Numerical evolution of the density contrast for a 100 Mpc/h perturbation of dark matter (continuous lines), baryons (dashed lines) and scalar field (dotted lines).

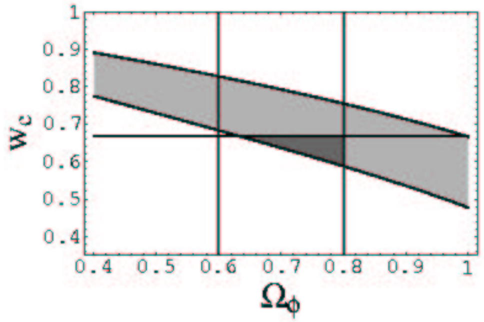


Figure 2: Constraints on the stationary model: below the horizontal line the expansion is accelerated; in the light grey region the bias is between 0.5 and 1; between the vertical lines Ω_ϕ is within the observed range. The dark grey region is the surviving parameter space.

Early acceleration

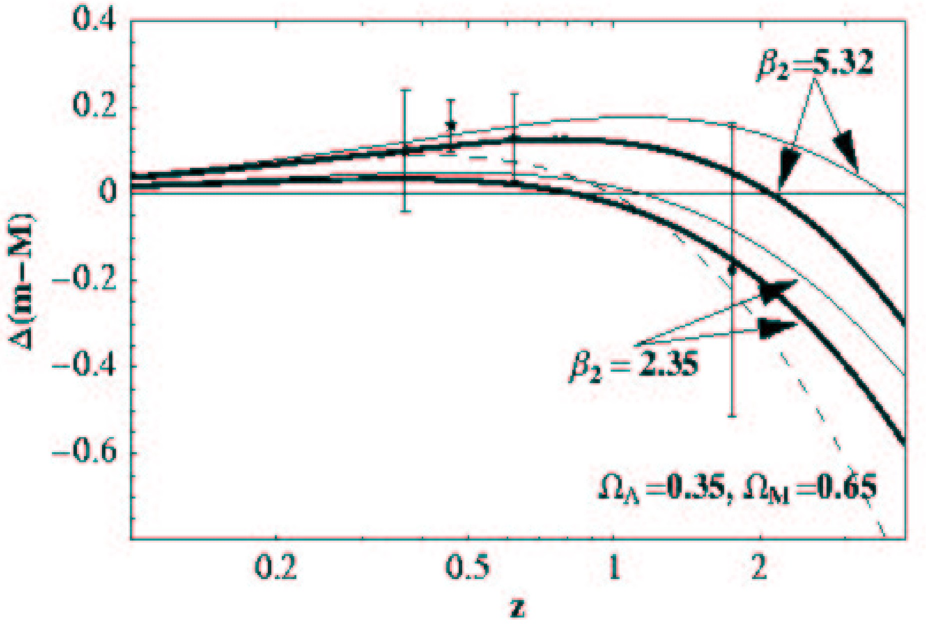
In any uncoupled DE model,
the acceleration is a recent phenomenon

$$z_{acc} = [-(1+3w)(1-\Omega_m)/\Omega_m]^{-1/3w} - 1 \leq 1$$

But in a stationary model
the acceleration can start at z = 5:

$$z_{acc} = [-(1+3w)(1-\Omega_b)/\Omega_m]^{-1/3w} - 1 > 1$$

And what about Supernova SN1997ff ?



Dark energy:

- Q: Do we really need it ?
- A: yes, unless…
- Q: What can it do for us ?
- A: it can perhaps explain fine tuning and coincidence. It provides a new degree of freedom that could prove necessary to explain observations.
- Q: What we can do for it ?
- A: find a compelling theoretical explanations within e.g. superstrings, brane worlds,…
- Q: Where do we go from here ?
- A: Find new observables (e.g. bias, early acceleration, growth of DE structures); produce new observations.

References

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Phase spaces