Dark energy

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Context : the twentieth century legacy

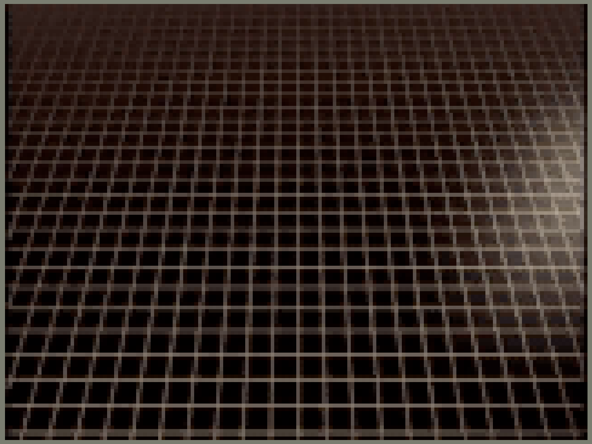
Two very successful theories :

- General relativity

A single equation, Einstein's equation, successfully predicts tiny deviations from classical physics and describes the universe at large as well as its evolution.

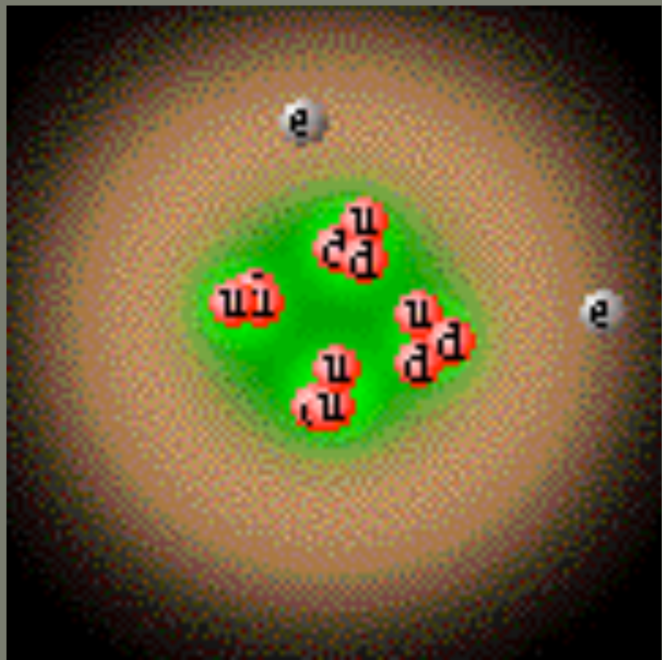
$$R_{\mu\nu} - (R/2)\, g_{\mu\nu} = 8\pi G_N\, T_{\mu\nu}$$

geometry matter



- Quantum theory

Describes nature at the level of the molecule, the atom, the nucleus, the nucleons, the quarks and the electrons .



Difficult to reconcile general relativity with the quantum theory

Three possible manifestations:

- vacuum energy
- equivalence principle : $m_i = m_g$
- extra spatial dimensions (Kaluza-Klein, string theory)

Vacuum energy:

Classically, the energy of the fundamental state (vacuum) is not measurable. Only differences of energy are (e.g. Casimir effect).

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

geometry energy

Hence geometry may provide a way to measure absolute energies i.e. vacuum energy:

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + 8\pi G < T_{\mu\nu} >$$ vacuum energy

similar to the cosmological term introduced by Einstein :

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + \lambda\, g_{\mu\nu}$$

Einstein equations → Friedmann equation

c = 1

$$H^2 = (8 \pi G \rho + \lambda) /3 - k/a^2$$

$$\lambda \equiv \ell_\Lambda^{-2}$$

$$\rho_c = 3 H_0^2 / 8 \pi G$$

$$\rho_\Lambda = \lambda / 8 \pi G$$

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_c = (H_0^{-1} / \ell_\Lambda)^2 / 3 \sim 0.7 \Rightarrow \ell_\Lambda \sim H_0^{-1} \sim 10^{26} \text{ m}$$

A very natural value for an astrophysicist !

Introduce $\hbar$

Planck length $\ell_P = \sqrt{8\pi G_N \hbar / c^3} = 8.1\text{x}10^{-35}\text{m}$

Planck	$\ell_P \sim 10^{-34}$ m	$m_P \sim 10^{27}$ eV
λ	$\ell_\Lambda \sim 10^{26}$ m	$m_\Lambda \sim 10^{-33}$eV

$$mc^2 \equiv \frac{\hbar c}{l} = \frac{200\ \text{MeV.fm}}{\ell}$$

$$\rho_\Lambda = \frac{1}{8\pi G \ell_\Lambda^2} = \frac{\hbar}{\ell_P^2 \ell_\Lambda^2} \equiv \frac{\hbar}{\ell_{DE}^4}$$

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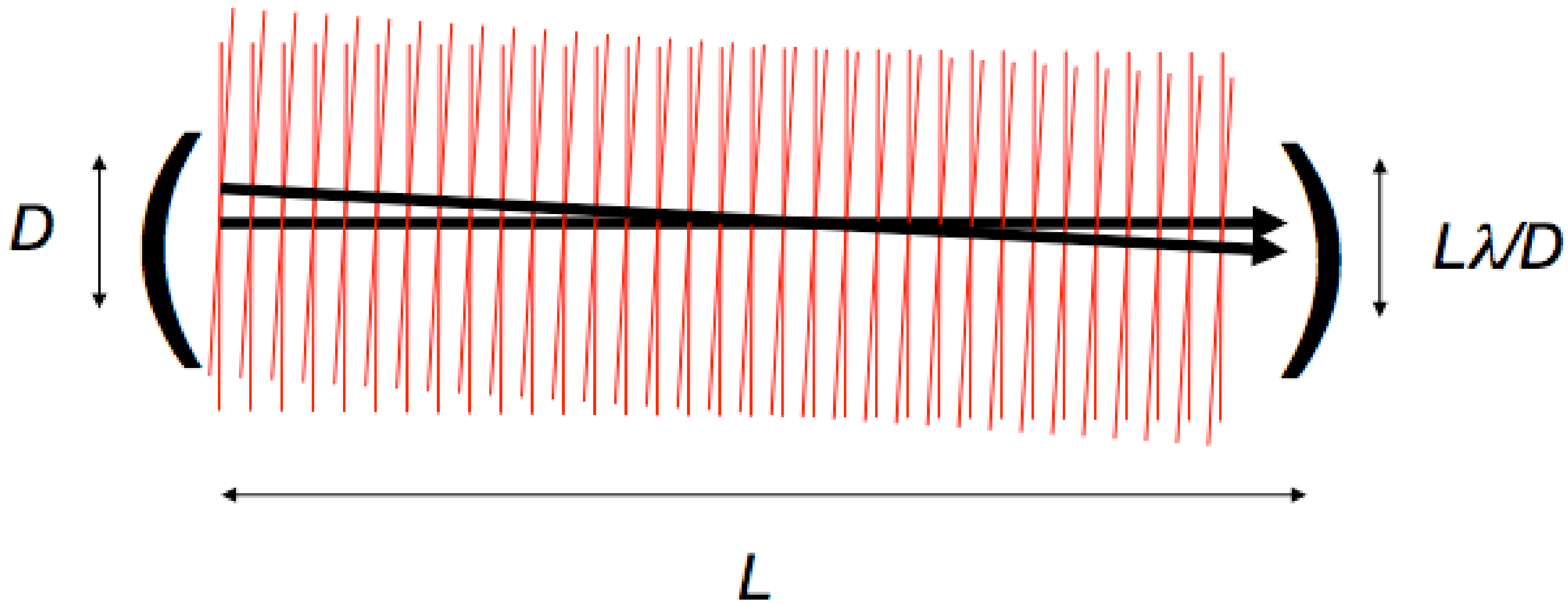
$$\ell_{DE} = \sqrt{\ell_P \ell_\Lambda}$$

UV cut-off

IR cut-off

Cosmological constant problem : where the two ends meet

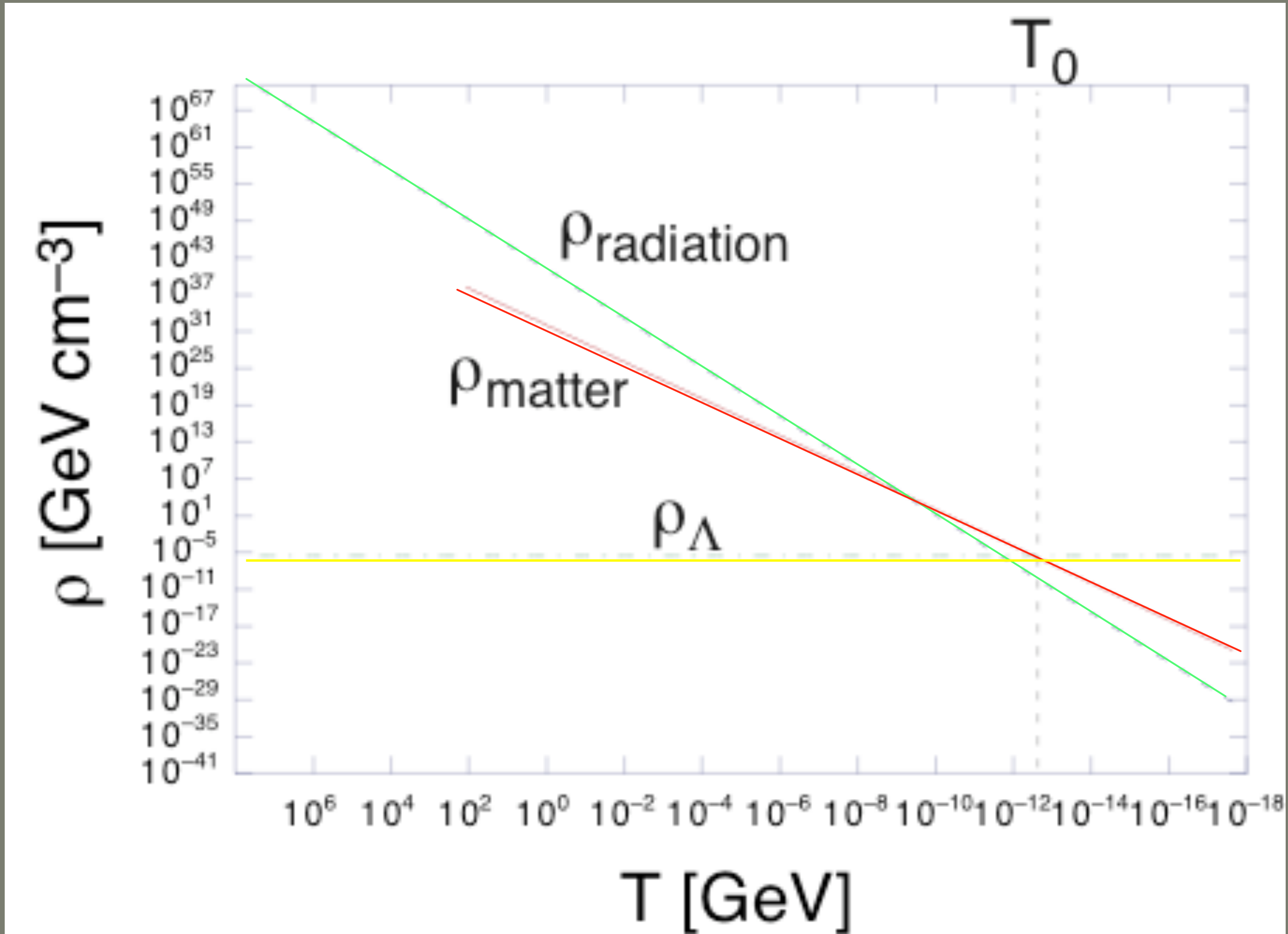
Ray limit of wave optics: Rayleigh uncertainty



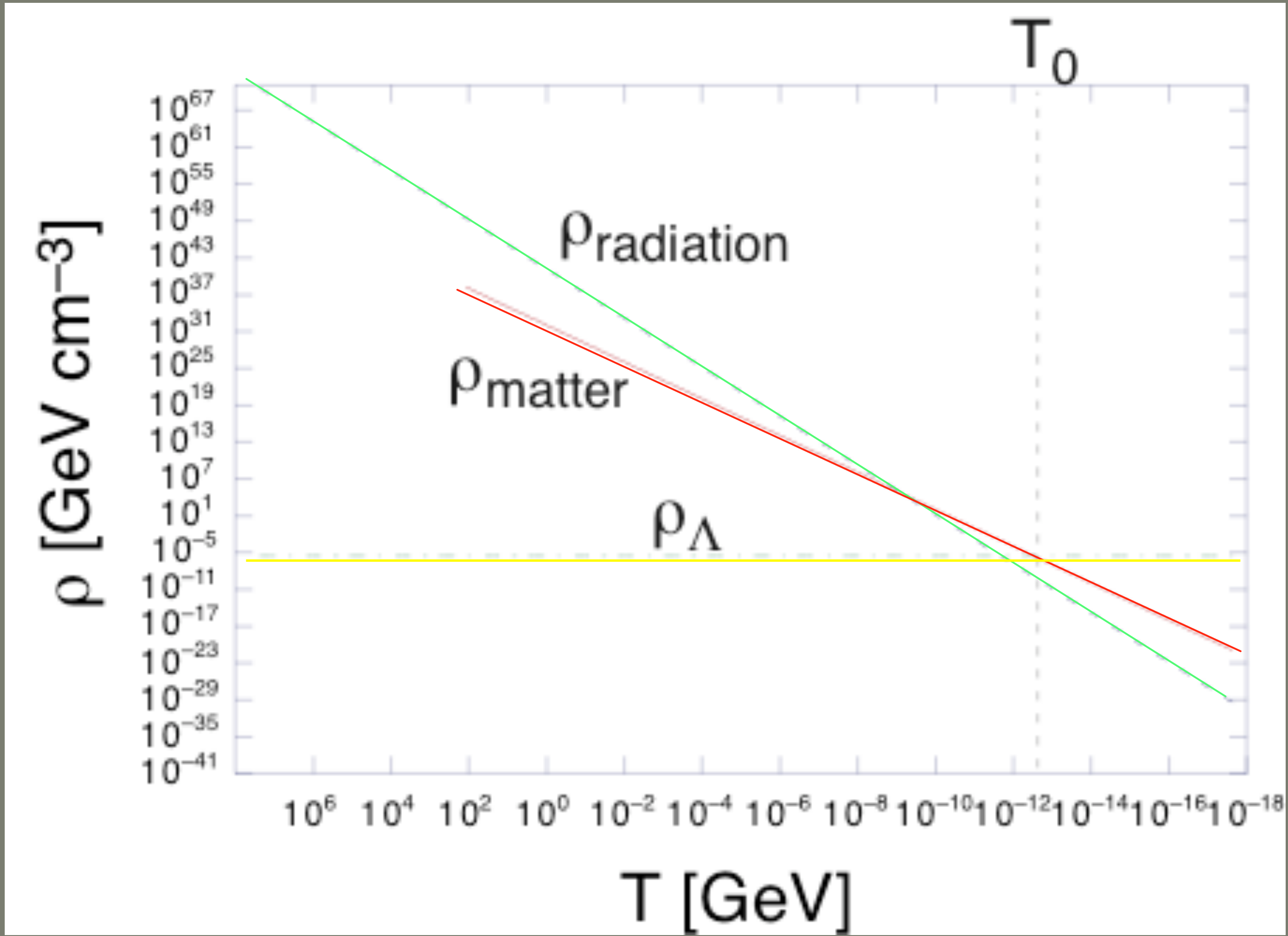
- Aperture D, wavelength λ : angular resolution λ/D
- Size of diffraction spot at distance L: $L\lambda/D$
- Endpoints of a ray can be anywhere in aperture, spot
- path is determined imprecisely by waves
- Minimum uncertainty at given L when aperture size =spot size, or

$$D = \sqrt{\lambda L}$$

Central question : why now?
why is our Universe so large, so old?



Cosmic coincidence problem:
Why does the vacuum energy starts to dominate at a time t_Λ ($z_\Lambda \sim 1$) which almost coincides with the epoch t_G of galaxy formation ($z_G \sim 3$)?



Are there more general ways than a cosmological constant to account for the acceleration of the expansion?

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

geometry matter-energy

modify gravity

add new form of energy

Friedmann equation : $H^2 = 8\, \pi G\, \rho\, /3 - k/a^2$

Dark energy

Assume the existence of a new component assmilated to a perfect fluid with pressure p and energy density ρ :

equation of state $p = w\,\rho$

Friedmann equation at late epochs :

$$H^2 = H_0^2\,[\,\Omega_m\,(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}$$

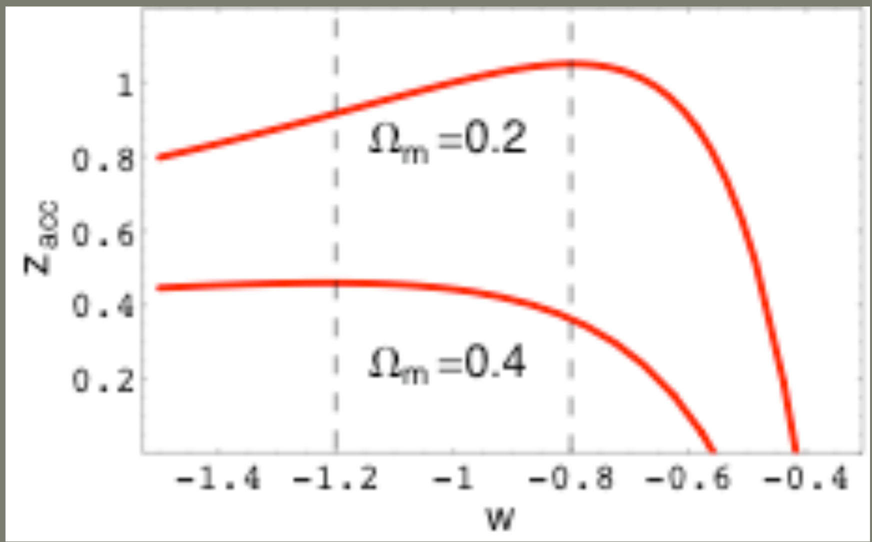
$$\Omega_{DE} \sim 1 - \Omega_m$$

In the case of z dependent w, w in previous formula is some averaged value

Acceleration of the expansion : $3\ \ddot{a} / a = -4\pi G (\rho+3p) /3$

Then redshift at beginning of acceleration :

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



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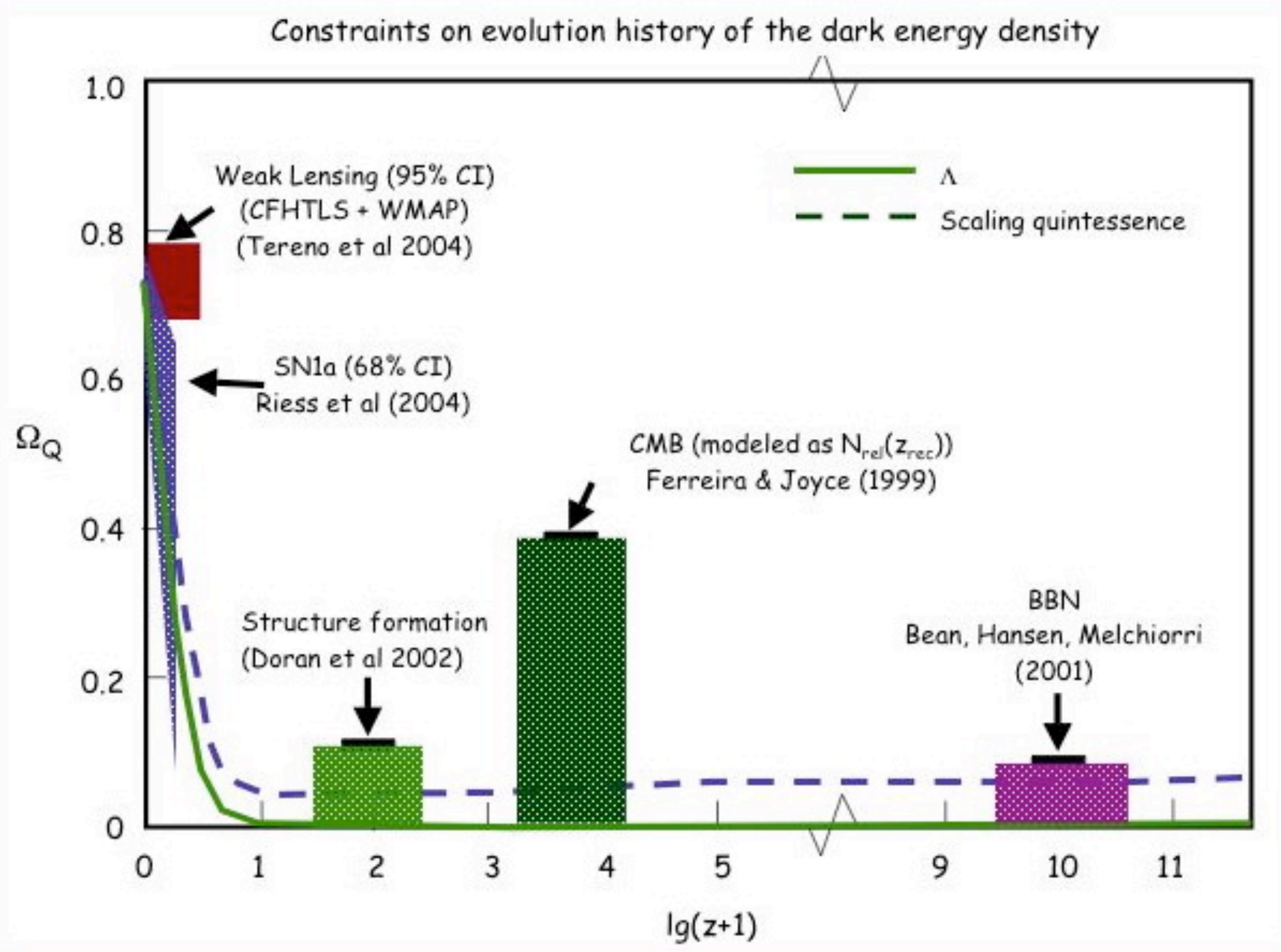
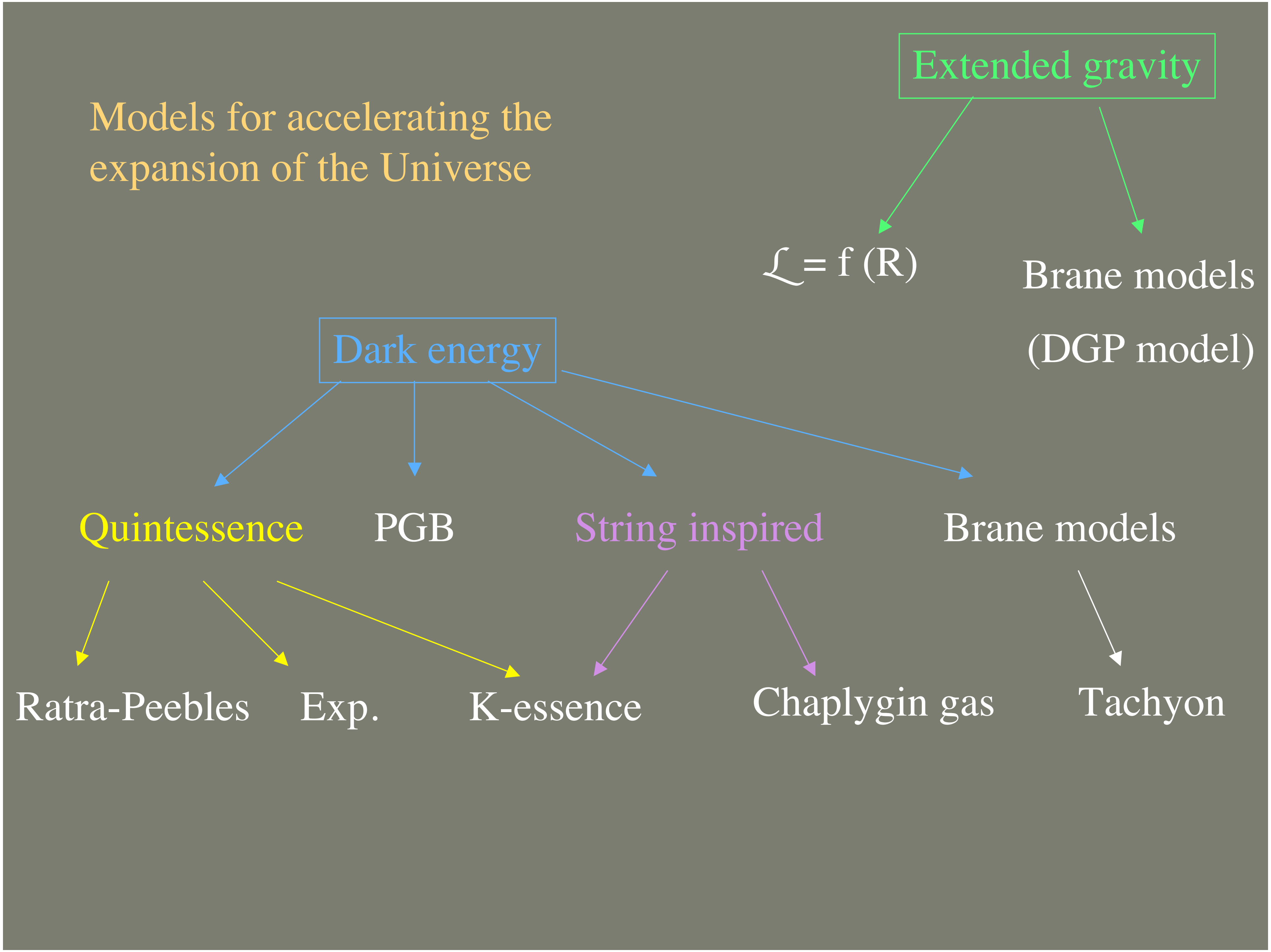
$\Omega_{DE}(z)$



Constraints on evolution history of the dark energy density
1.0
0.8
0.6
0.4
0.2
0
Ω_Q
Weak Lensing (95% CI)
(CFHTLS + WMAP)
(Tereno et al 2004)
SN1a (68% CI)
Riess et al (2004)
CMB (modeled as $N_{rel}(z_{rec})$)
Ferreira & Joyce (1999)
Structure formation
(Doran et al 2002)
BBN
Bean, Hansen, Melchiorri
(2001)
Λ
Scaling quintessence
0
1
2
3
4
5
9
10
11
lg(z+1)

More dynamics: why scalar fields?


Extended gravity
Models for accelerating the
expansion of the Universe
$\mathcal{L} = f(R)$
Brane models
(DGP model)
Dark energy
Quintessence
PGB
String inspired
Brane models
Ratra-Peebles
Exp.
K-essence
Chaplygin gas
Tachyon

Why scalar fields to model dark energy?

Scalar fields easily provide a diffuse background

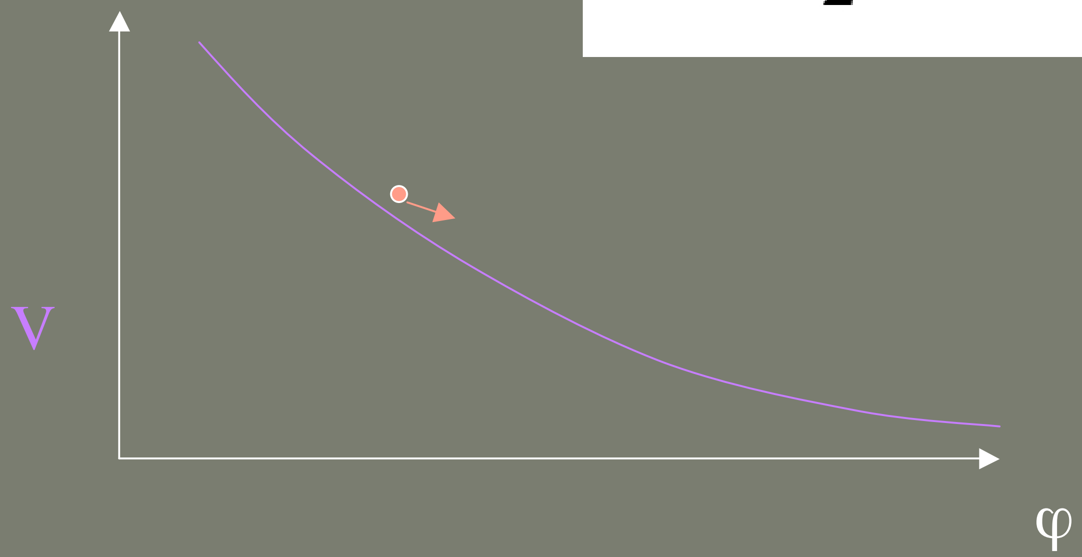
Speed of sound $c_s^2 = (\delta p / \delta\rho)_{adiabatic}$

In most models, $c_s^2 \sim 1$, i.e. the pressure of the scalar field resists gravitational clustering :

scalar field dark energy does not cluster

First example (quintessence)

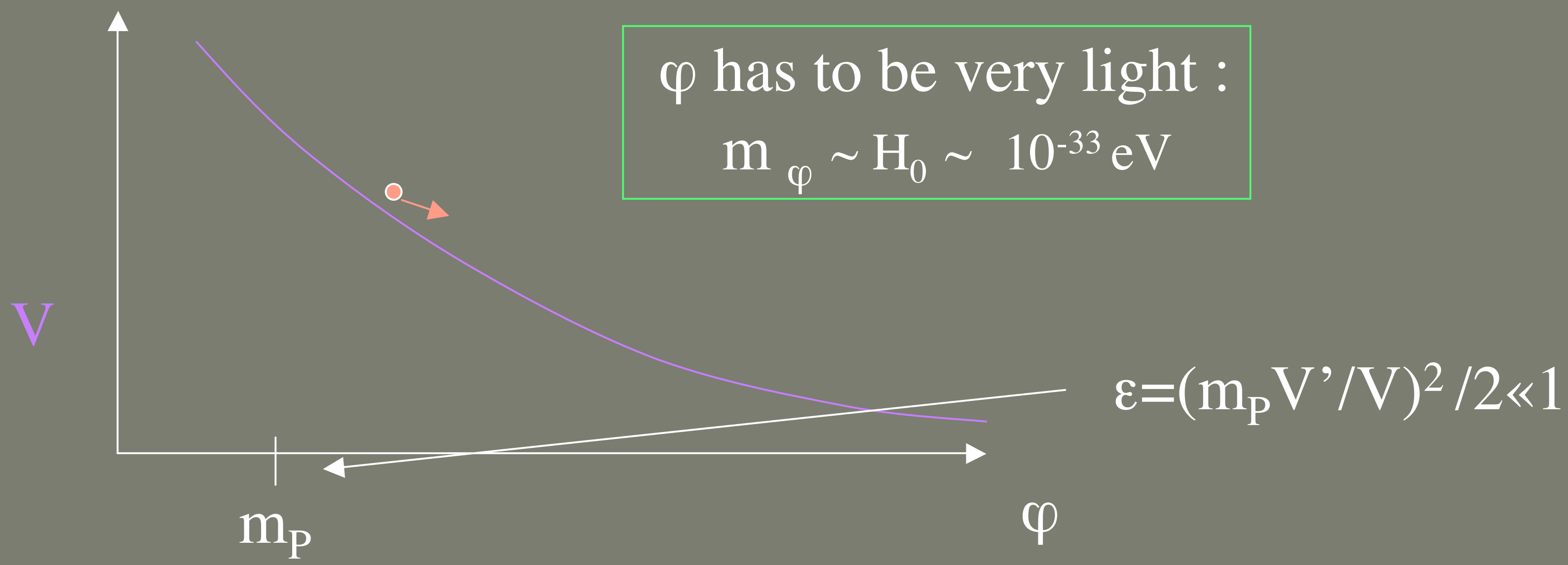
$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi)$$



$$w = p_\varphi/\rho_\varphi = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)} > -1$$

The problems of scalar field models of dark energy

Example of quintessence :



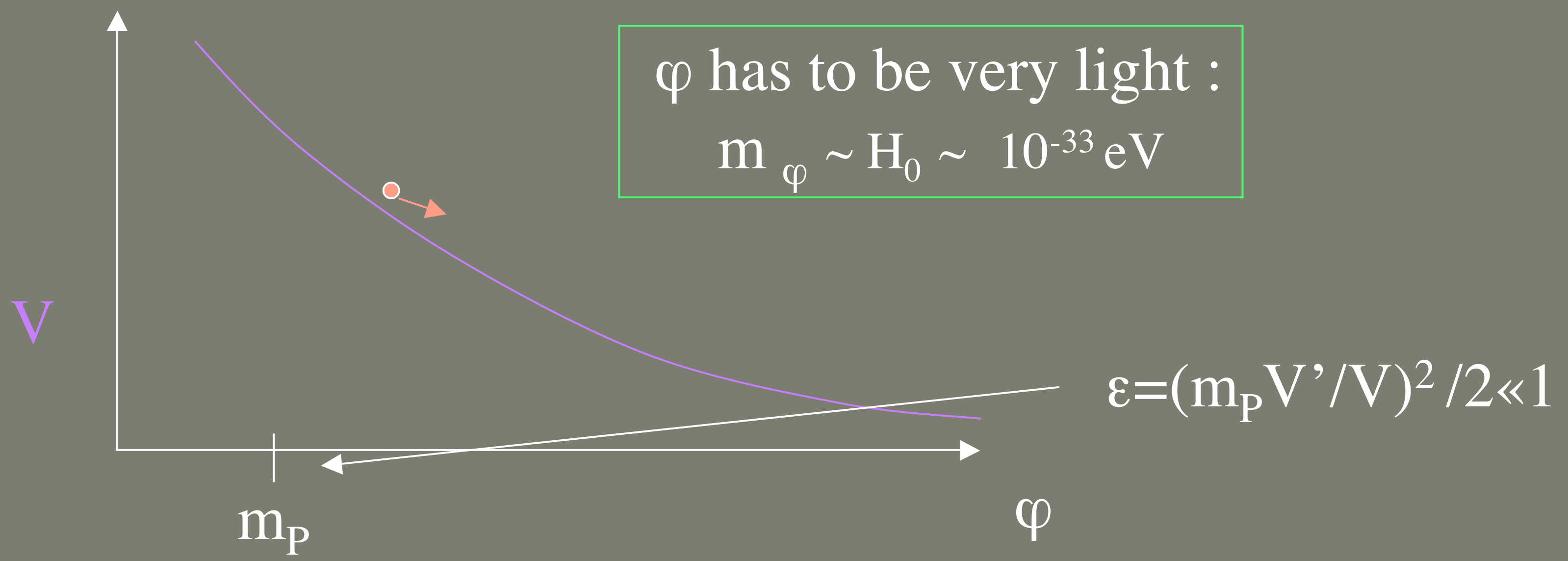
φ has to be very light :

$m_\varphi \sim H_0 \sim 10^{-33}\,\mathrm{eV}$

φ pseudo-Golstone boson?

The problems of scalar field models of dark energy

Example of quintessence :



φ has to be very light :

$m_\varphi \sim H_0 \sim 10^{-33}$ eV

φ exchange would provide a long range force :
φ has to be extremely weakly coupled to ordinary matter
(more weakly than gravity!)

Second class

Point particle :

$$L = -m\sqrt{1-\dot{q}^2}$$

$$E = \frac{m}{\sqrt{1-\dot{q}^2}}$$

$$k = \frac{m\dot{q}}{\sqrt{1-\dot{q}^2}}$$

Replace $\dot{q}^2$ by $\partial_a\phi\partial^a\phi$ and m by $K(\phi)$

$$\mathcal{L} = p = -K(\phi)\sqrt{1-\partial_a\phi\partial^a\phi}$$

$$E = \frac{K(\phi)}{\sqrt{1-\partial_a\phi\partial^a\phi}}$$

Explicit realization: K-essence

Armendariz-Picon, Mukhanov, Steinhardt
Chiba, Okabe, Yamaguchi

$$S = \int d^4x \sqrt{-g}\,[R/2 + K(\phi)\, p(X)], \qquad X \equiv D^\mu\phi\, D_\mu\phi/2$$

Pressure $\quad p_k = K(\phi)\, p(X)$

Energy density $\quad \rho_k = K(\phi)\, \rho(X), \quad \rho(X) \equiv 2X\, p'(X) - p(X)$

Hence $\quad w_k = p(X) / \rho(X) = p(X) / [2X\, p'(X) - p(X)]$

$\quad c_s^2 = p'(X) / \rho'(X)$

$$\text{Equation of motion}: \ddot{\phi} + 3Hc_s^2\, \dot{\phi} + \frac{K'(\phi)\, \rho(X)}{K(\phi)\, \rho'(X)} = 0$$

Two classes of attractors :

- $\rho_\phi / \rho_B = cst$ and $w_\phi = w_B$
- $\rho_\phi / (\rho_B + \rho_\phi) \rightarrow 0$ or 1 and $w_\phi \neq w_B$

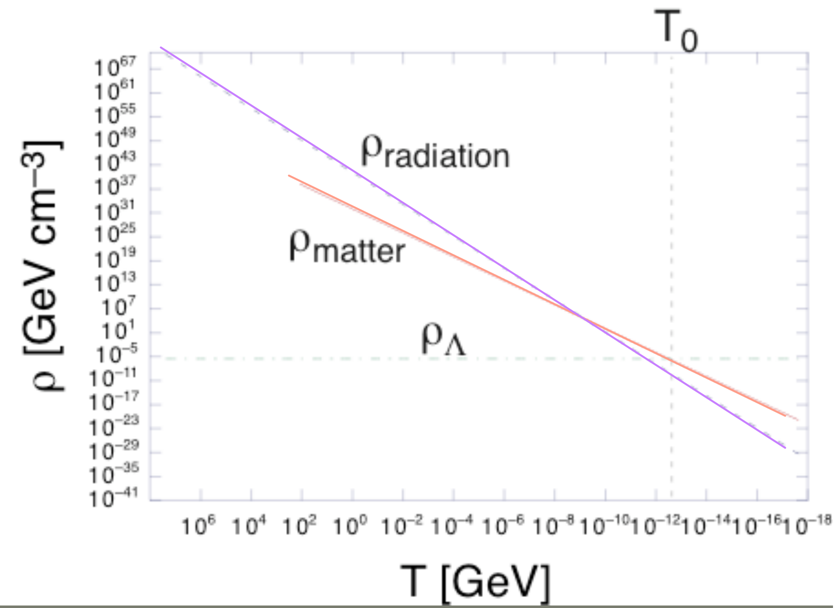
Some k-essence models may help to understand the coincidence pb

- radiation domination:

  $\rho_\phi / \rho_{rad} = cst$
- matter domination:

  $p_\phi < 0$

  $\rho_\phi / \rho_{matter} \nearrow$ until ρ_ϕ dominates



Can the dark energy scalar field be coupled to some form of matter?

- sterile neutrinos
- environmental coupling
- dark matter

Mass varying neutrinos

Imagine a sterile neutrino with mass depending on scalar field ϕ: $m_\nu(\phi)$

Effective coupling $\beta = d\log m_\nu/d\phi$

Uniform neutrino background : $\rho_\nu(\phi) = n_\nu\, m_\nu(\phi)$,

$p_\nu(\phi)$ negligible if non-relativistic

Effective potential : $V_{eff}(\phi) = V(\phi) + n_\nu\, m_\nu(\phi)$

Dark energy is the coupled fluid neutrino-scalar: $\rho_{DE} = \rho_\phi + \rho_\nu(\phi)$

$m_\phi^2 = d^2V_{eff}/d\phi^2 = V'' + \rho_\nu(\phi)[\beta' + \beta^2]$

can be chosen much larger than H^2

The scalar field tracks its minimum given by

$$n_\nu \, m_\nu' + V' = 0$$

Conservation of energy :

$$\dot{\rho}_{DE} + 3H \, \rho_{DE}(1+w) = 0$$

gives $1+w = -\,\partial \log \rho_{DE} / 3\partial \log a \sim -\,\partial \log V_{eff} / 3\partial \log a$

$$1 + w = - \; m_\nu V'(\phi) / [m_\nu' \, V_{eff}(\phi)]$$

Not too constraining to have $w \sim -1$.

But neutrinos have a tendancy to cluster!

Chameleon dark energy

Brax, van de Bruck, Davis, Khoury, Weltman
astro-ph/0309300,0309411,0408415

$$V_{eff}(\phi) = V(\phi) + f(\phi)\, \rho_m$$

Then, possible to have a heavy enough scalar field ($m_\phi > 10^{-3}$ eV) in matter where constraints on the fifth force or equivalence principle apply, whereas it can be ultralight outside matter.

Coupled dark energy

Anderson, Carroll; Casas, Garcia-Bellido, Carroll; Farrar, Peebles; Amendola; Comelli, Pietroni, Riotto; …

It could be that dark matter is coupled to the dark energy scalar field e.g. φ-dependent mass for the dark matter particle χ:

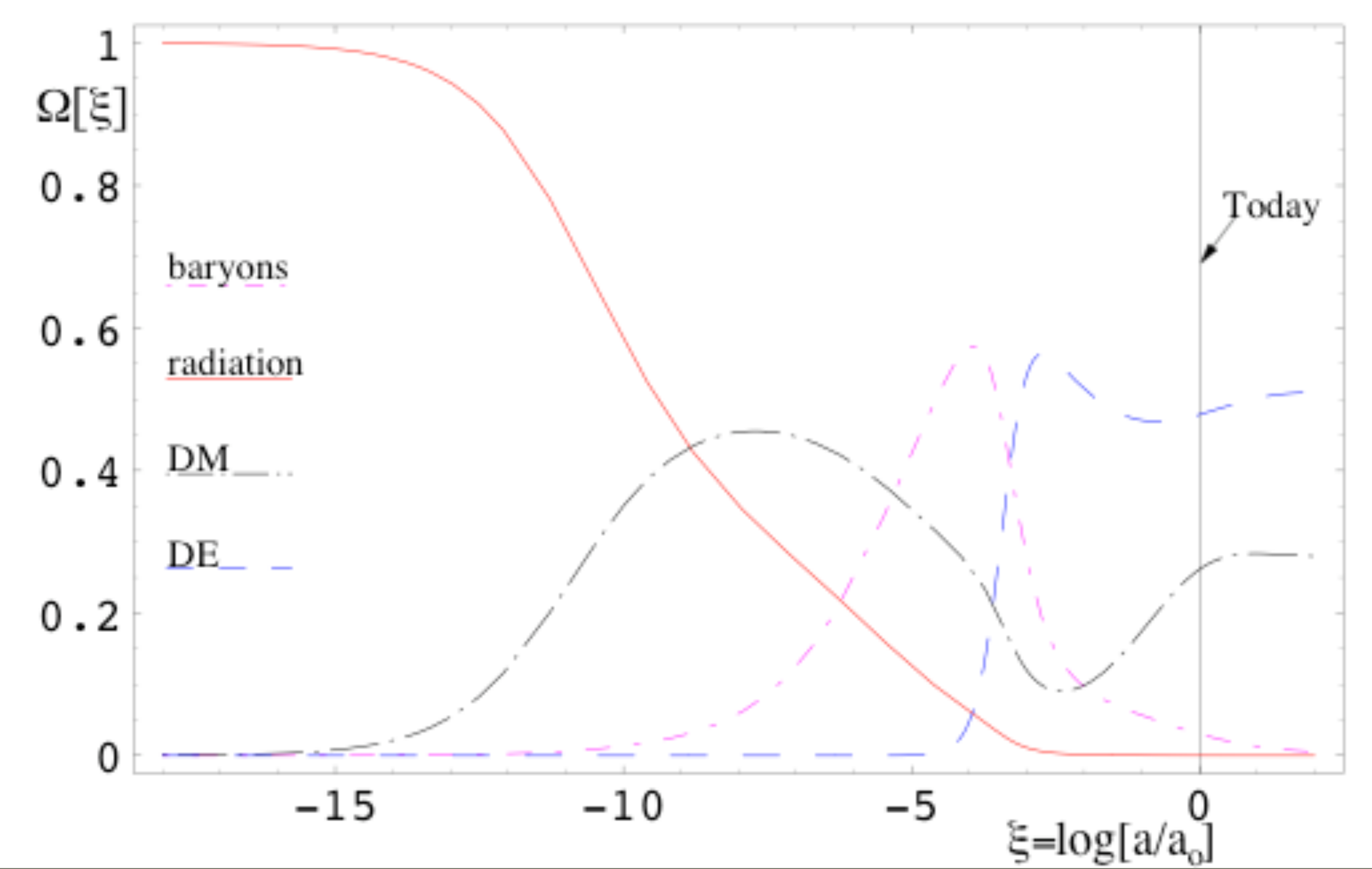
$$M_\chi(\varphi) = M_0 \exp(-\lambda\varphi)$$

If the scalar potential is $V(\varphi) = V_0 \exp(\beta\varphi)$, there is an attractor corresponding to

$$\Omega_\varphi \sim \Omega_\chi = [3+\lambda(\lambda+\beta)]/(\lambda=\beta)^2$$

$$2a\,\ddot{a}/\dot{a}^2 = -(1+3W) \qquad \text{with } W = -\lambda/(\lambda+\beta)$$

$$\rho_\chi \sim \rho_\varphi \sim a^{-3(1+W)}$$



hep-ph/0302080

$$\rho_\chi = M_\chi(\varphi)\, n_\chi \sim a^{-3(1+W)}$$

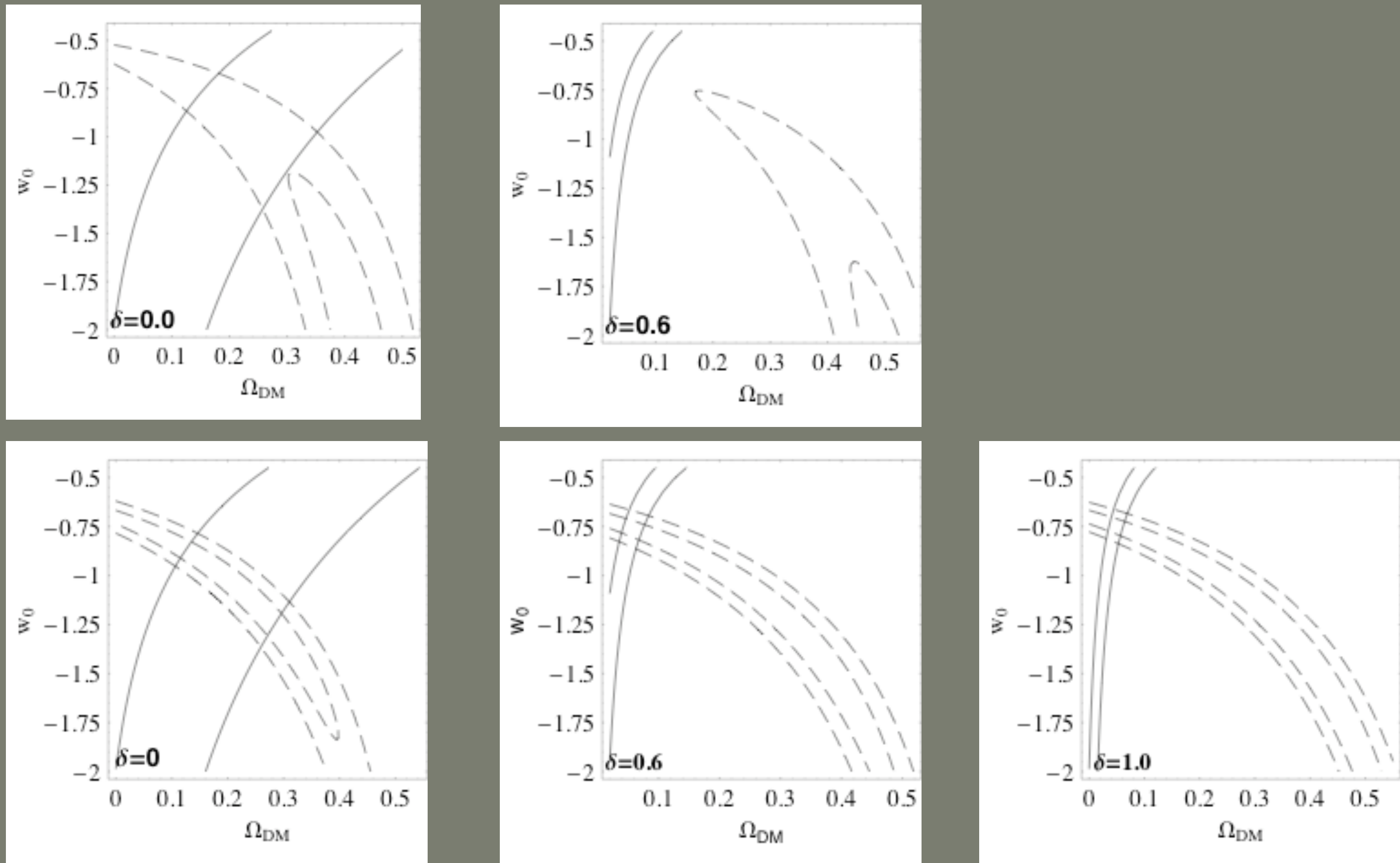
$\sim a^{-3}$

Note: in this case, z_{acc} may be significantly larger than 1.

Large dark matter/dark energy couplings do not seem to be favored by CMB data:

Sn1a gold set →

SNLS →



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$\delta \equiv d\ln M_\chi(\varphi)/d\ln a$

Back to the cosmological constant

Adjustment mechanisms

A no-go theorem by S. Weinberg : not possible to have a vanishing λ as a consequence of the equation of motion of some fields.

Gravity as an emergent, long wavelength phenomenon

Padmanabhan

Action invariant under the shift :

$$T_{\mu\nu} \rightarrow T_{\mu\nu} + \lambda\, g_{\mu\nu}$$

Allows to gauge away the cosmological constant

Anthropic approach

Vilenkin, Weinberg, Linde, string theorists

Consider regions (universes) with different values of t_G and t_Λ :

- when ρ_Λ starts to dominate (at t_Λ), the Universe enters a de Sitter phase of exponential expansion
- galaxy formation (at t_G) must precede this phase (otherwise no observer available)

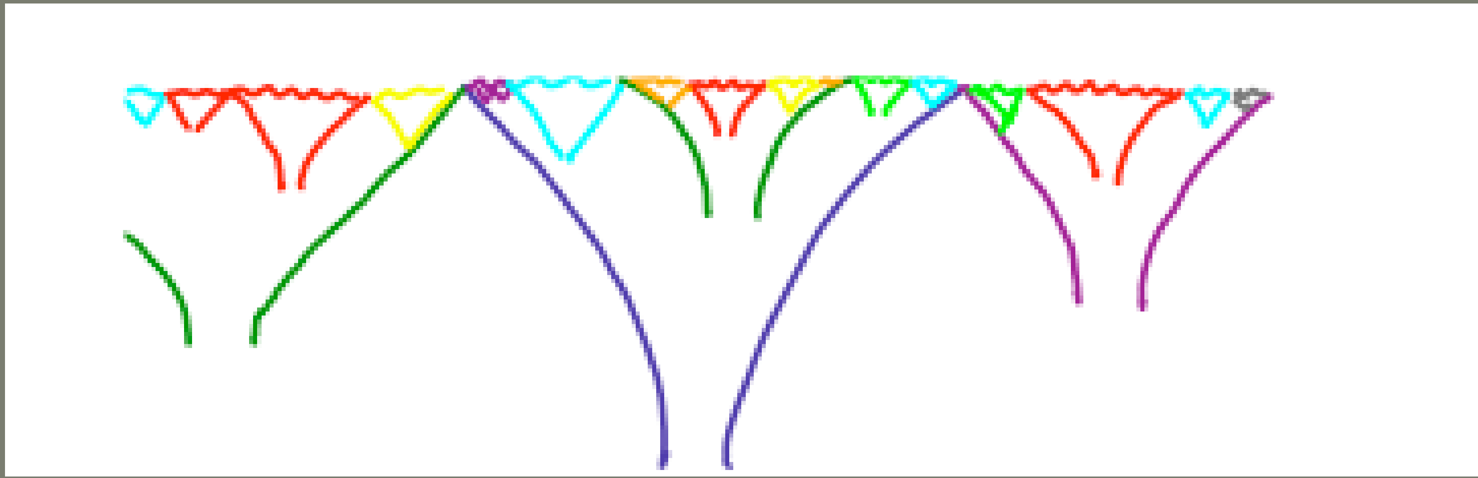
Hence $t_G \leq t_\Lambda$

- Regions with $t_\Lambda \gg t_G$ have not undergone yet any de Sitter phase of reacceleration and are thus phase space suppressed compared with regions with $t_\Lambda \sim t_G$:

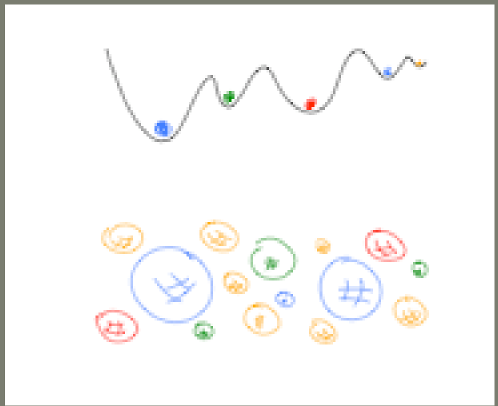
Hence $t_\Lambda \gtrsim t_G$

$\rho_\Lambda \sim \rho_M$

A multitude of universes?



Eternal inflation



String theory

Towards a a cosmological statistical mechanics ?

THE END