The dark side of inflation

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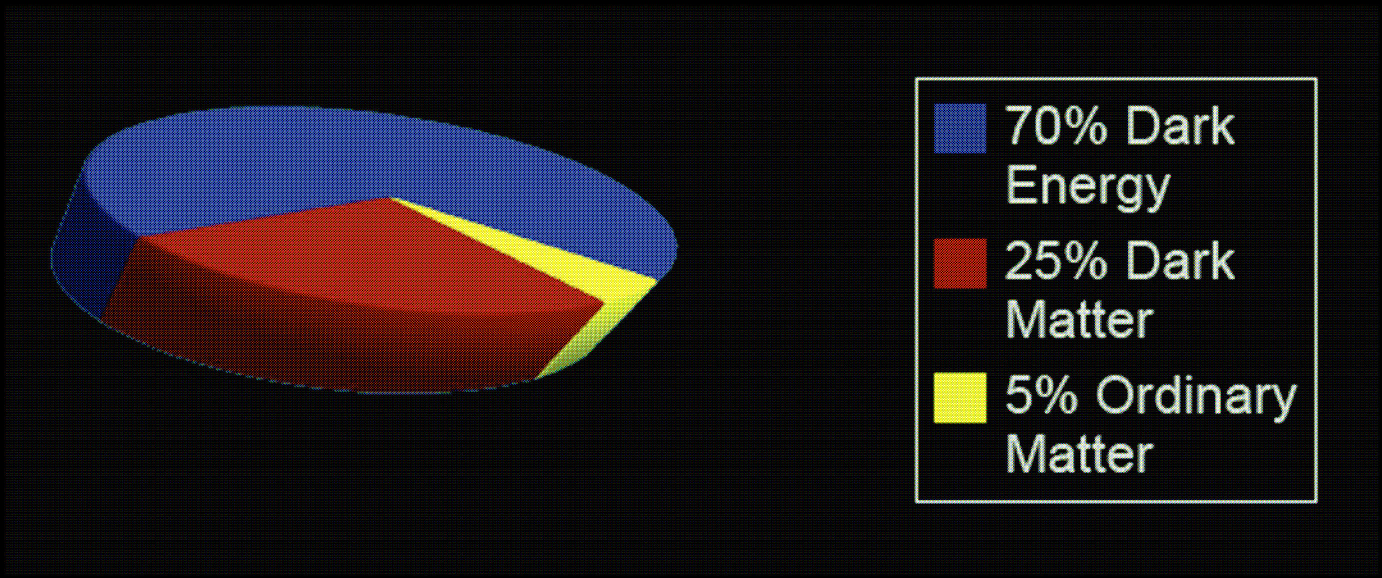
before

after

We seem to have a complete inventory of which the stuff of which our universe is made



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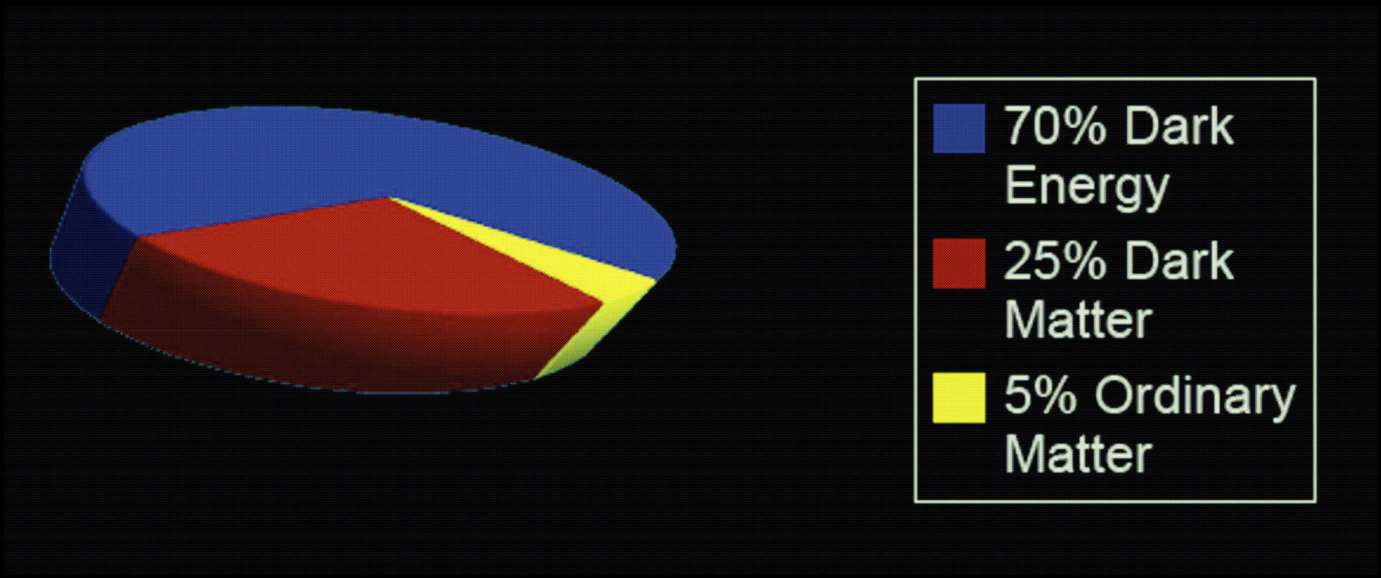
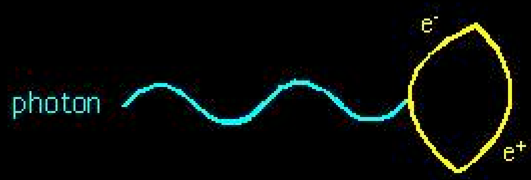
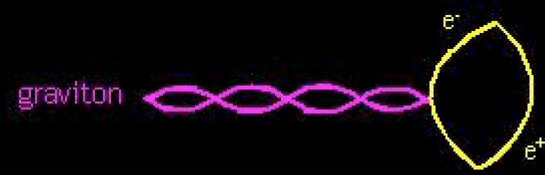


We know much, we understand nothing

Why is the vacumm energy so small ?

We know that virtual particles couple to photons (e.g. Lamb shift); why not to gravity ?





A quick back-of the envelope calculation reveals:

$$\rho = M_{Plank}{}^{4} = 10^{120}\ \rho_{vac}{}^{(obs)}$$

theoretical prediction = 10^{120} times observation

A universe with such a vacuum energy would have been ripped to shreds long ago.

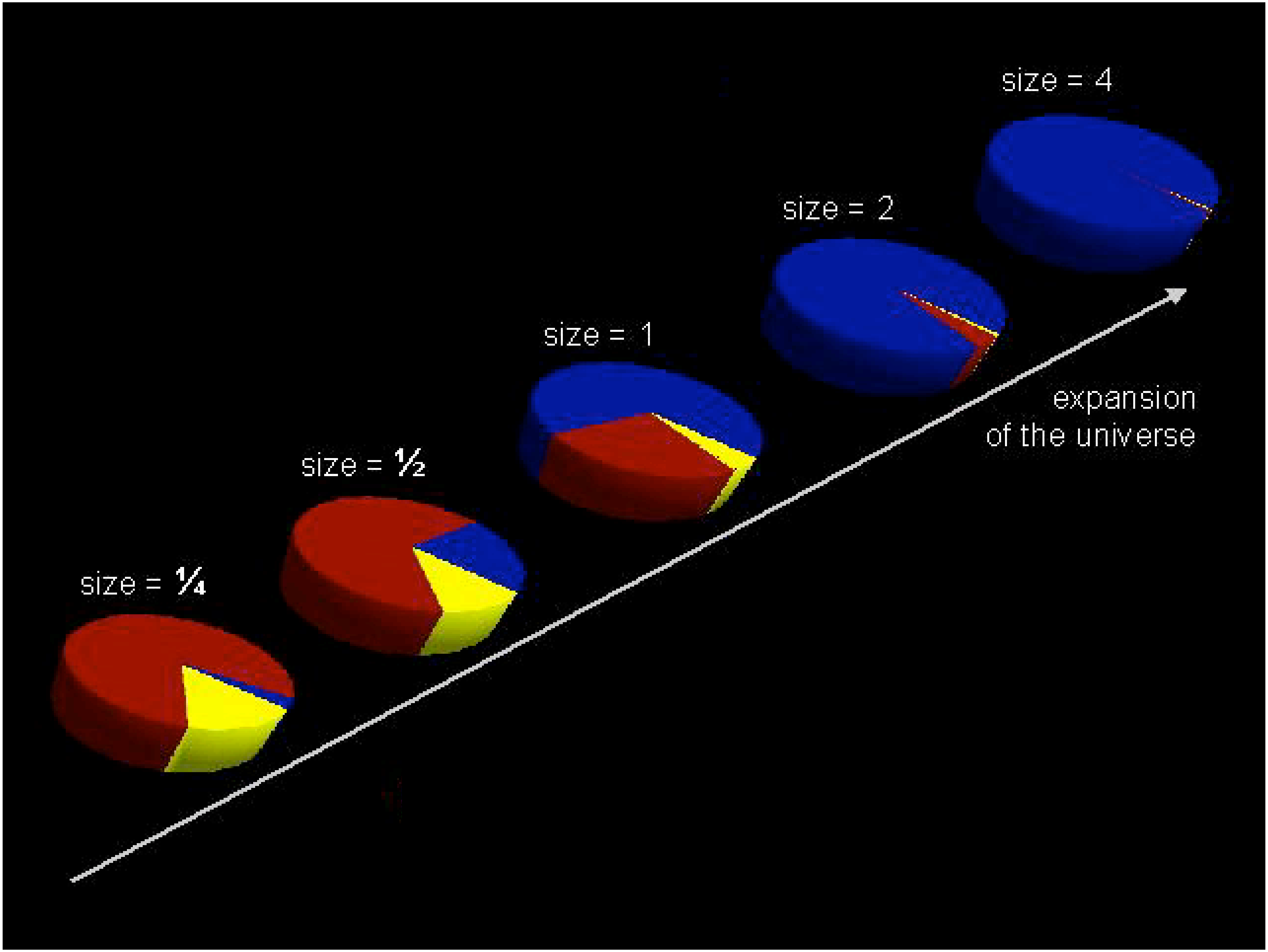
Can supersymmetry help ?

Remember: the huge prediction for dark energy (10^{120}) comes from particles fluctuating in empty space.

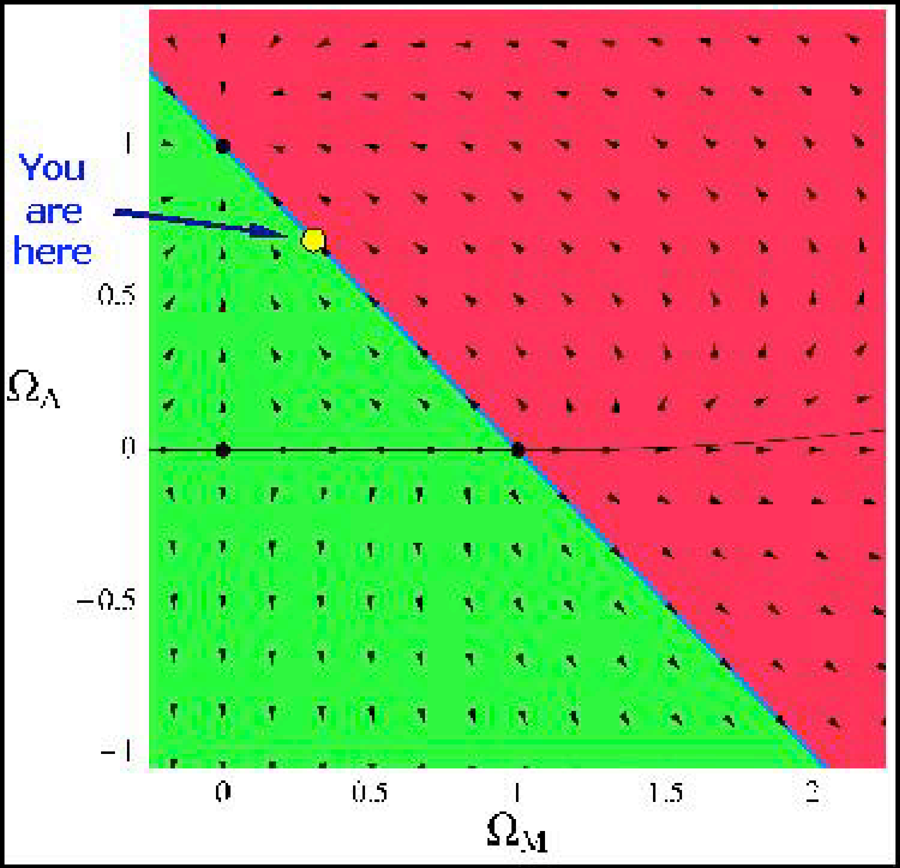
Interestingly: fluctuating bosons always give a positive vacuum energy, while fermions give a negative vacuum energy. Can they cancel ? Not perfectly, because we know supersymmetry is hidden. In fact,

supersymmetry prediction = 10^{60} times observation.

This is a real problem.


size = ¼
size = ½
size = 1
size = 2
size = 4
expansion
of the universe

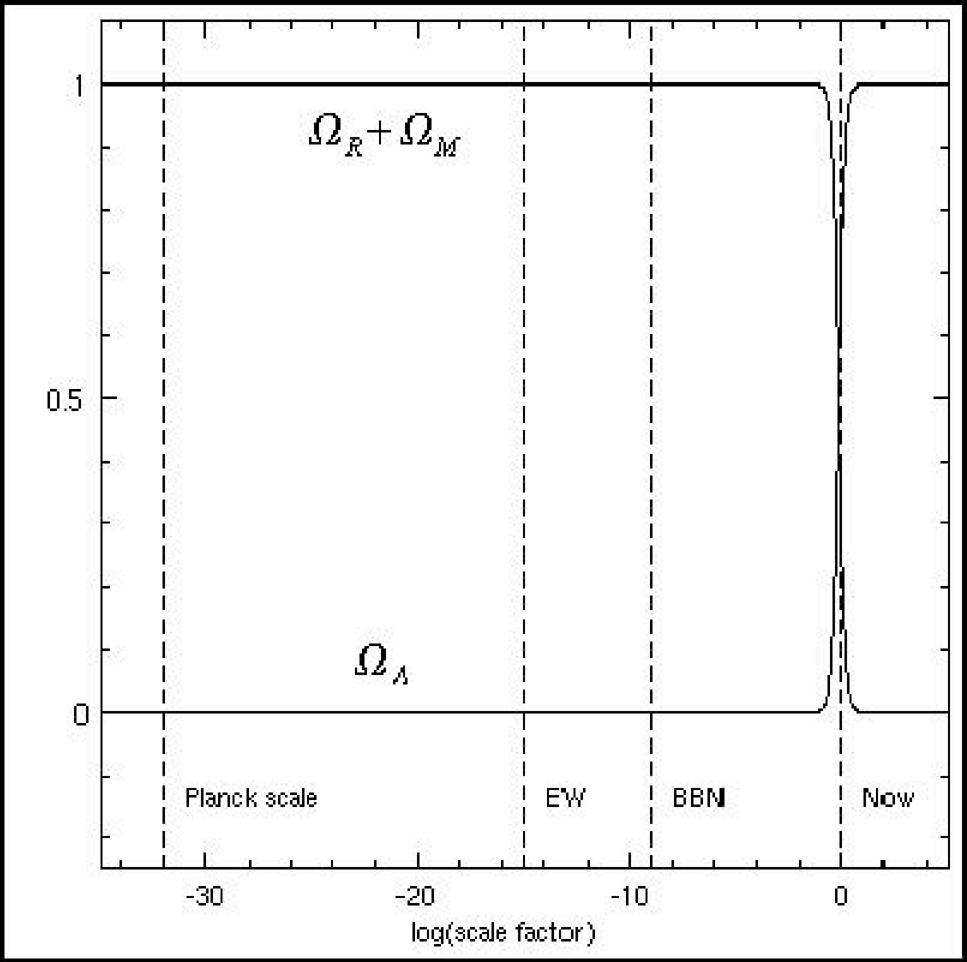
Why are vacuum and matter comparable ?



The best-fit universe with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ is un unstable point caught in the process of evolving from purely matter to purely vacuum

And it's moving quickly:

$$\frac{\Omega_\Lambda}{\Omega_M} \sim a^3$$



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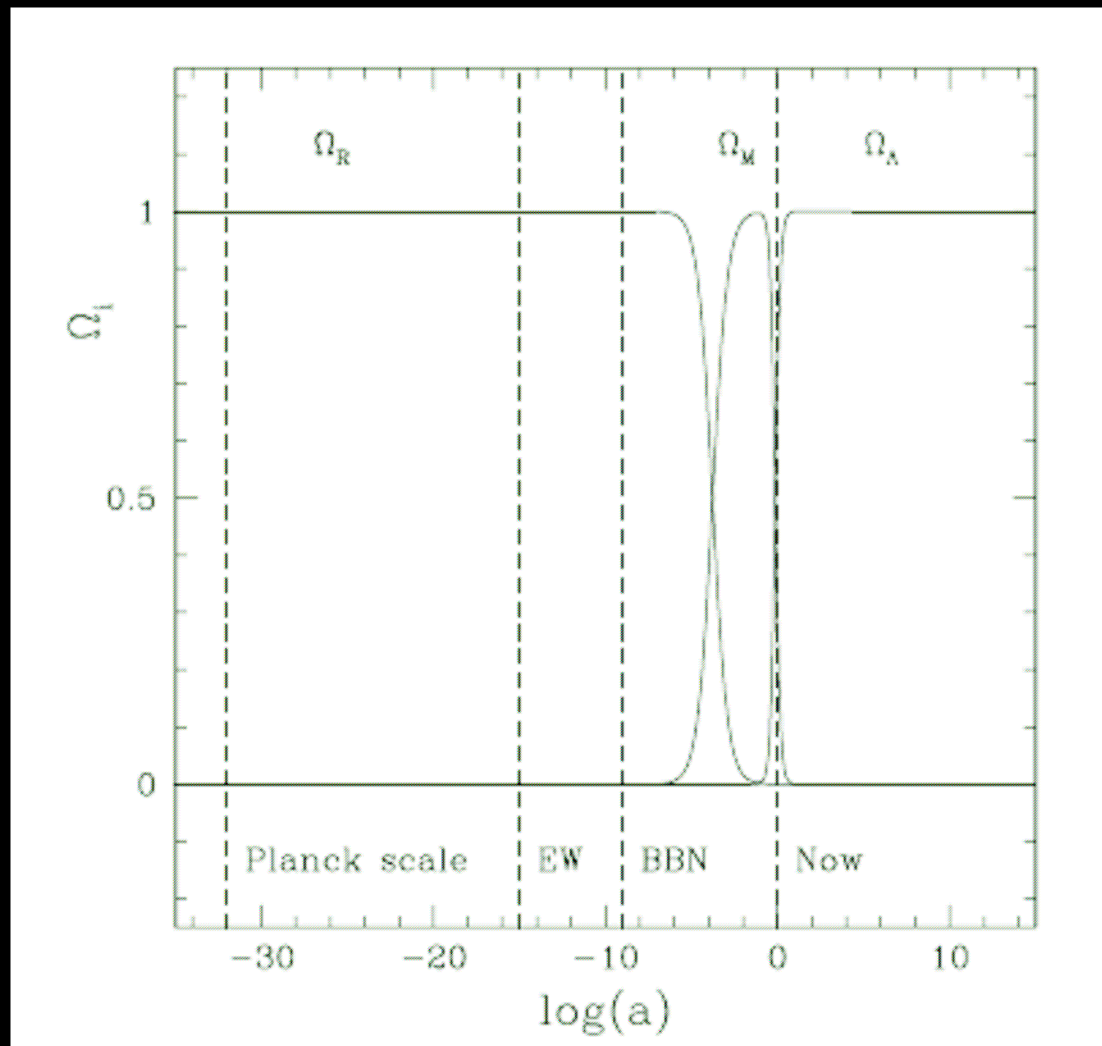
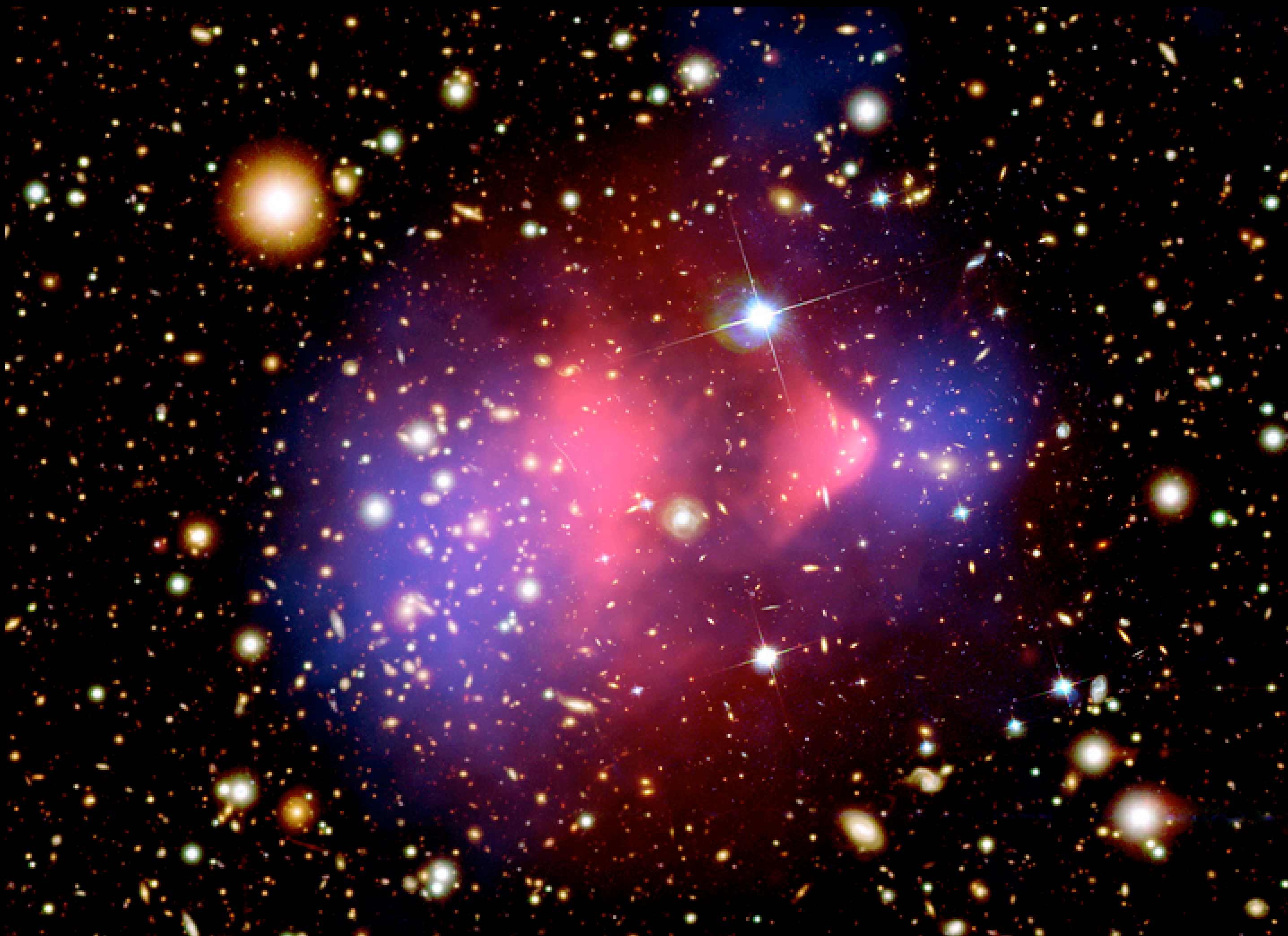


What might be going on ?

Possibilities include:

- We just got lucky.
- The vacuum energy is very different in other parts of the universe.
- A slowly-varying dynamical component is mimicking a vacuum energy.
- Einstein was wrong.

astro-ph/0608407



Could we just be lucky ?

Perhaps, when we can successfully calculate the vacuum energy, it will just happen to coincide with the present matter density.

For example: In supersymmetry, we expect

$$M_{vac} = M_{SUSY}$$

Which is off by 10^{15}. But if instead we found

$$M_{vac} = \left(\frac{M_{SUSY}}{M_{Plank}} \right) M_{SUSY}$$

It would agree with experiment. (All we need is a theory that predicts this relation.)

Could the anthropic principle be responsible ?

What if:

- The vacuum energy ρ_Λ takes on different values, with uniform probability, in different "parts of the universe" (in space, time or banches of the wavefunction).
- Everything else remains the same from place to place: constants of nature, initial conditions, galaxy formation, etc.

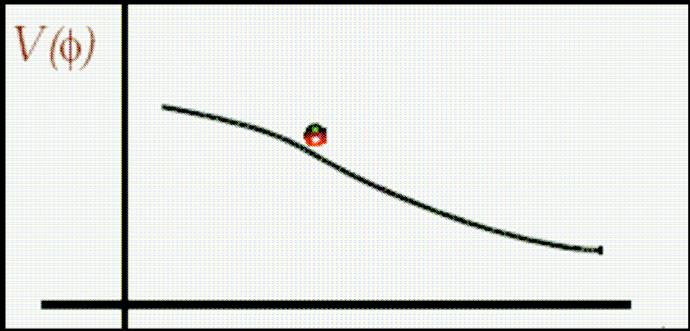
Then, the most likely thing for observers in such an ensemble to find is that $|\rho_\Lambda| < 10\,\rho_M$ (just as we do).

Is the dark energy a slowly-varying dynamical component ?

e.g. A sowly-rolling scalar field:
"quintessence"

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

kinetic energy — gradient energy — potential energy



This is an observationally interesting possibility, and at least holds the possibility of a dynamical explanation of the coincidence scandal.

But in general is wildly finely-tuned: requires a scalar field mass of $m_{\phi} < 10^{-33}$ eV, and very small couplings to matter.

The Lagrangian for a scalar field is given by

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

using Noether´s theorem

$$\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2} \dot{\phi}^2 - V(\phi)$$

In general kinetic and potential energy evolve with time. However.....

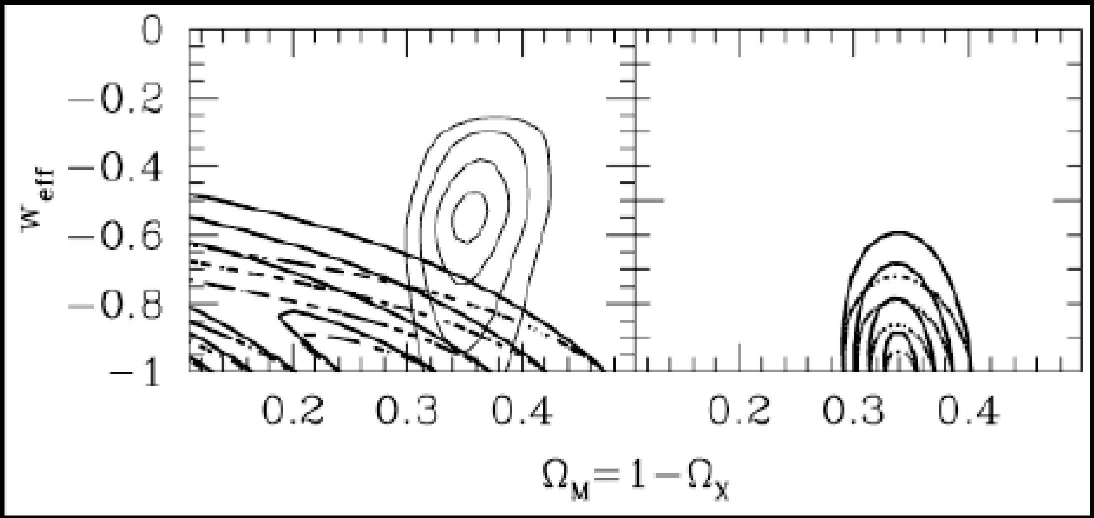
- for a free field $V=0$
- negligible kinetic energy (slow roll case)
- coherent oscillations

Characterize using an effective equation of state relating pressure to energy density:

$$p = w \rho$$

Form matter w = 0; for actual vacuum energy, w = -1.

Limits from supernovae and large-scale structure are already pretty good.



A new (quite bizarre) equation of state

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$$w = -\mathrm{Cos}\left(\mathrm{Log}\,(1+z) \right)$$

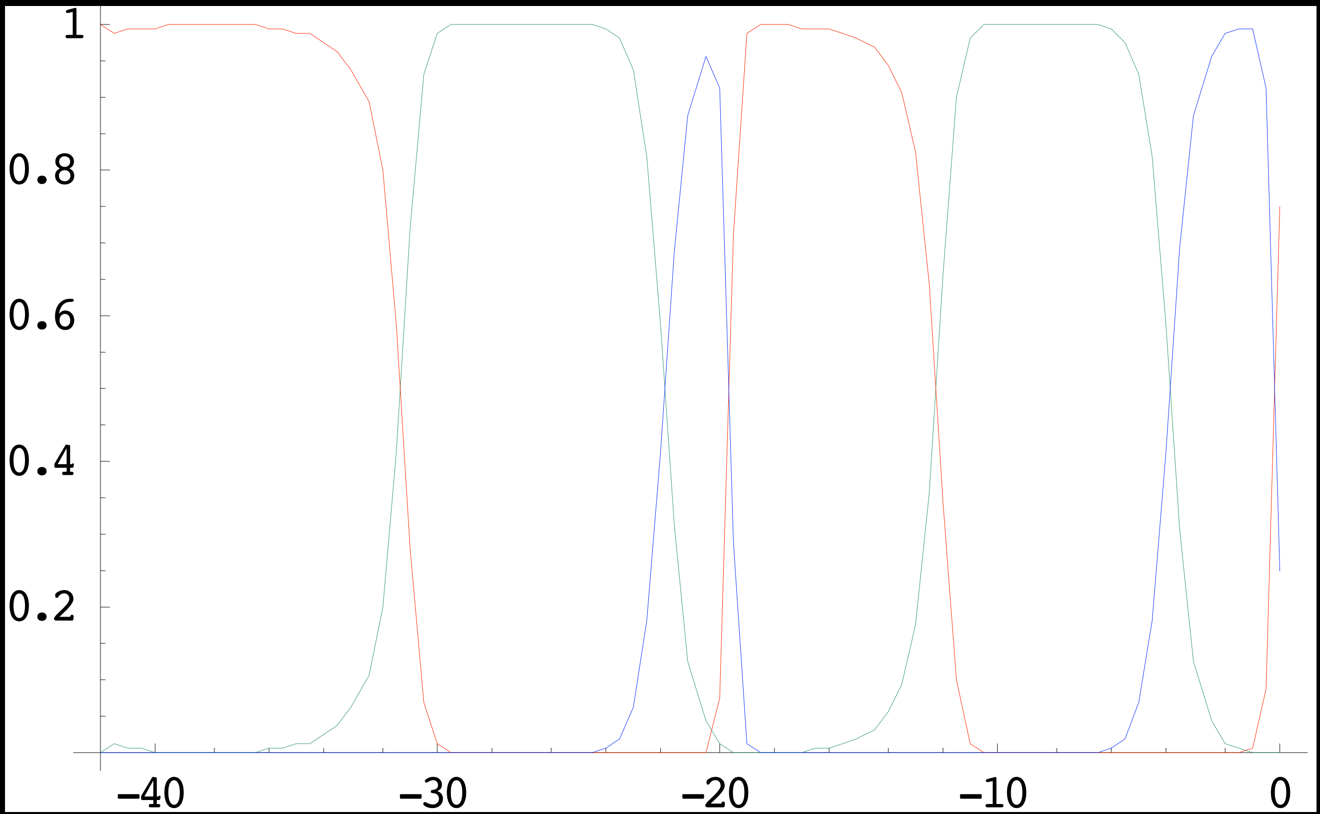
$$= -\mathrm{Cos}\left(\mathrm{Log}\,(a) \right)$$

A new (quite bizarre) equation of state

$$w = -\cos\left(b \log(1+z) \right)$$

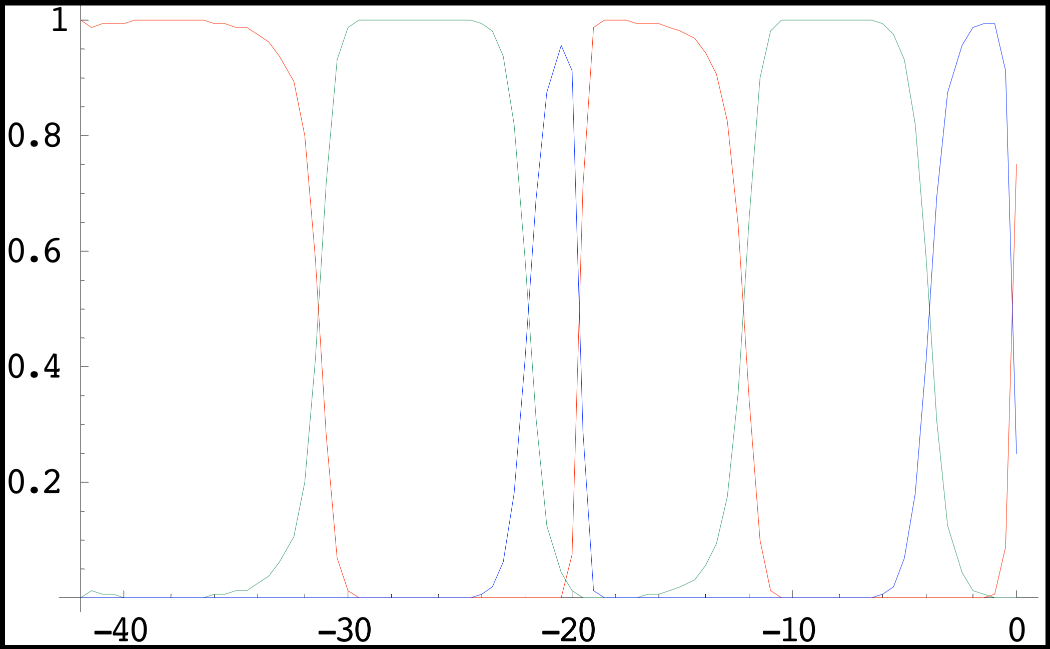
$$= -\cos\left(b \log(a) \right)$$

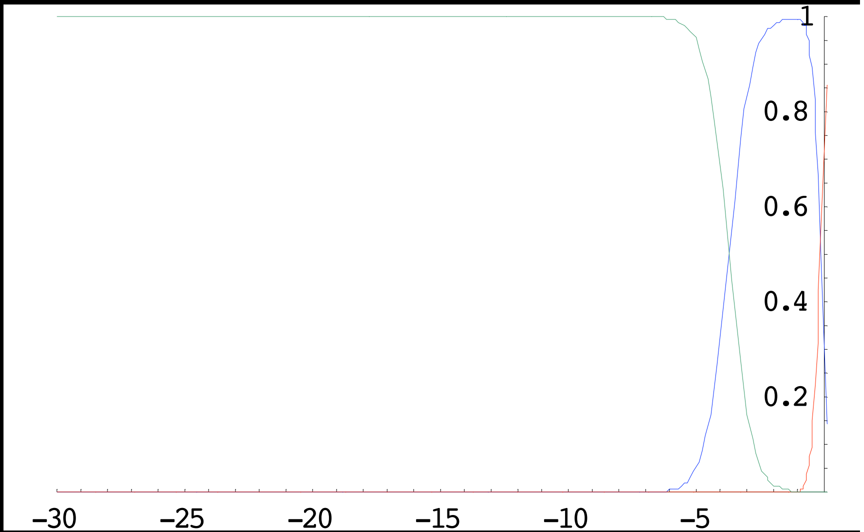
The thermal history of the Universe



$$\Omega_i = \frac{\rho_i}{\rho_R + \rho_{DE} + \rho_M}$$

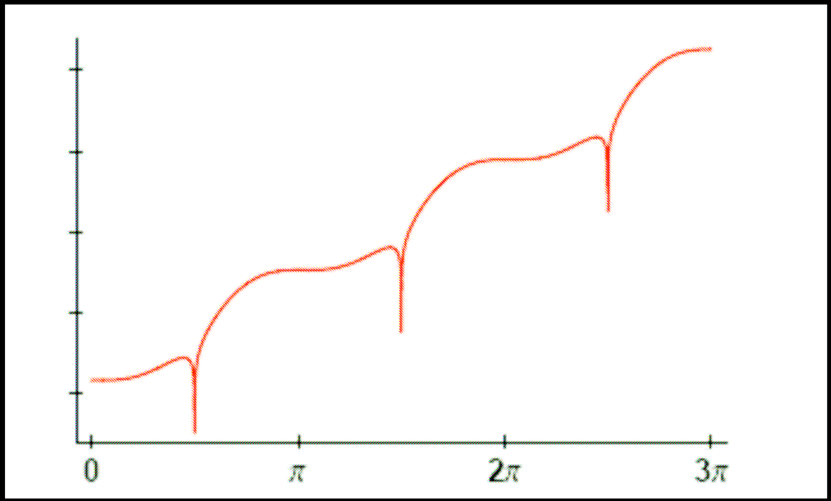
The thermal history of the Universe



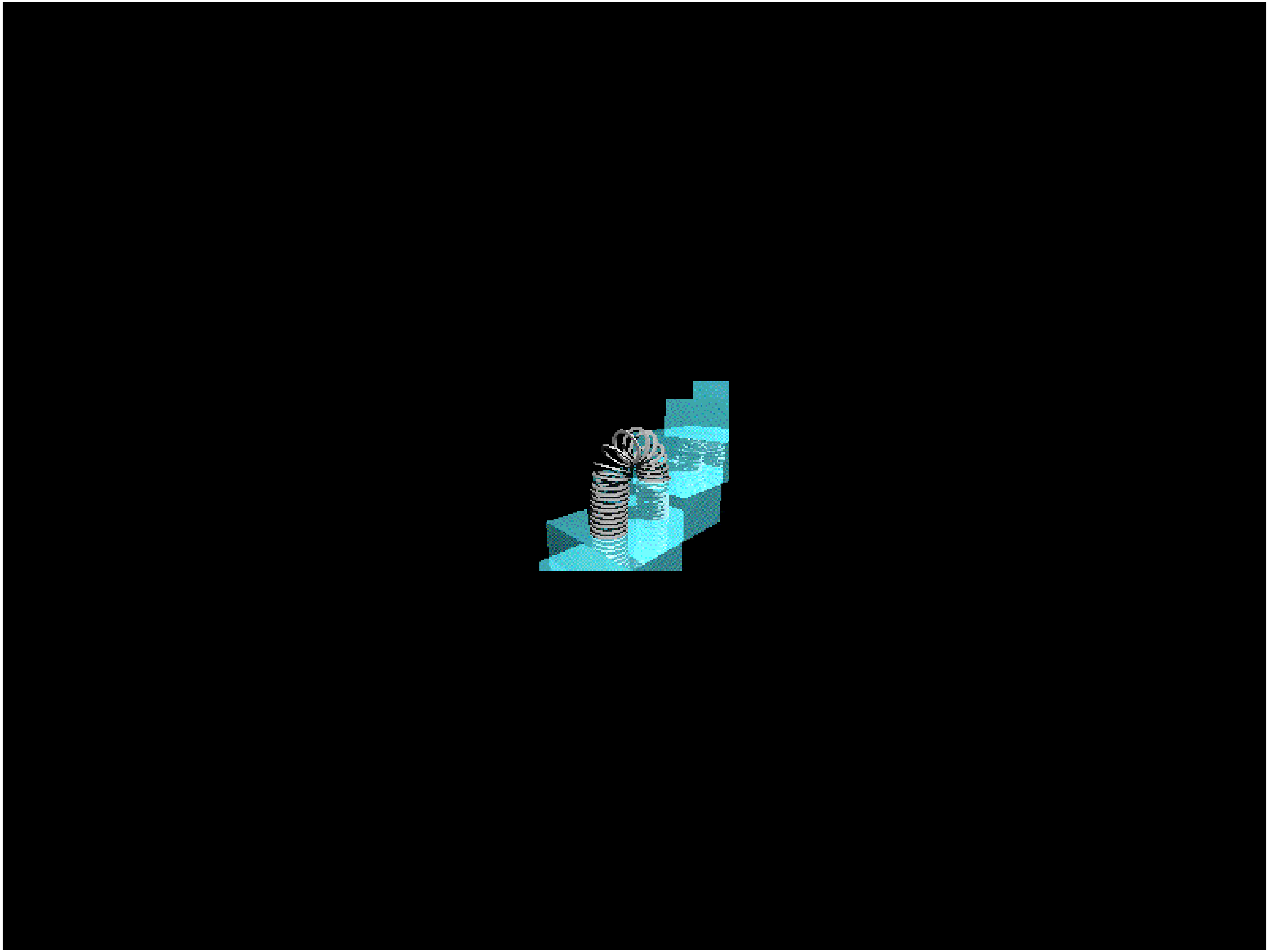


$$\Omega_i = \frac{\rho_i}{\rho_R + \rho_{DE} + \rho_M}$$

How to get this pattern ?



$$V(\theta) = \rho_0 \cos^2\theta \exp\left[\frac{3}{b}(2\theta - \sin 2\theta)\right]$$



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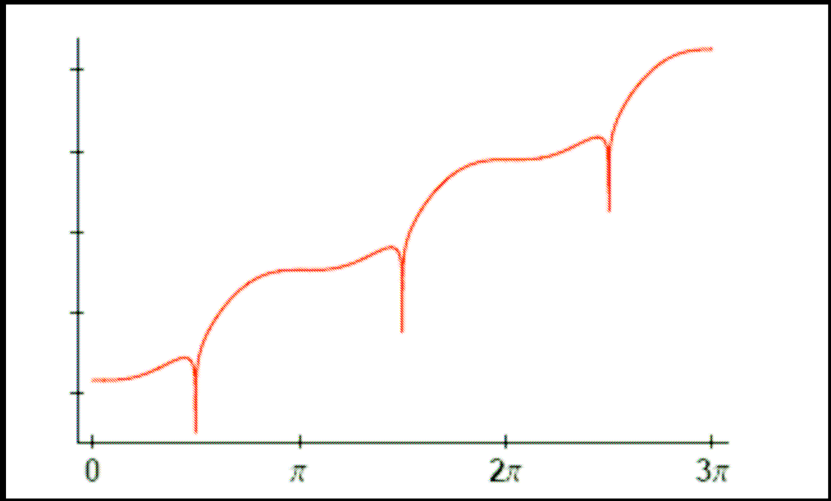
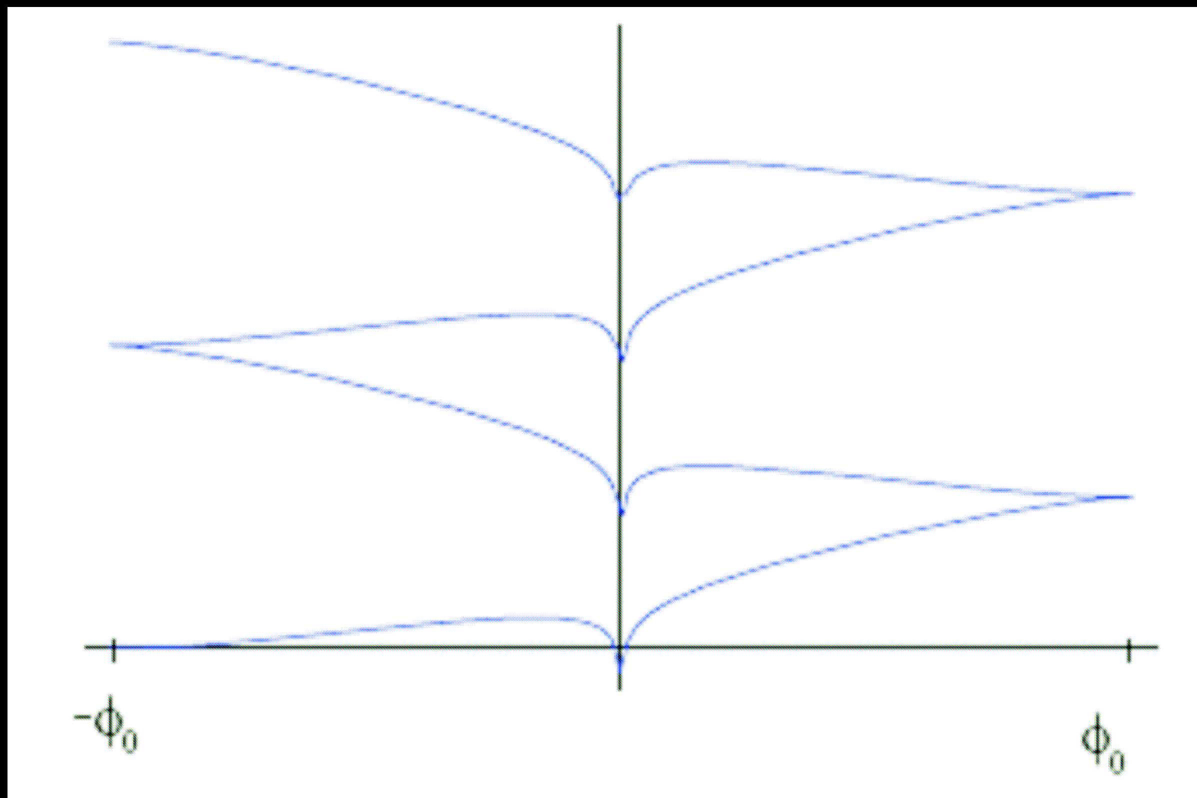


$$V(\theta) = \rho_0 \cos^2\theta \exp\left[\frac{3}{b}(2\theta - \sin 2\theta)\right]$$

$$\int d^4x\sqrt{-g}\left[\frac{1}{2}f(\theta)g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\theta)\right]$$

$$\begin{aligned} f(\theta) &= \frac{3M_{\rm P}^2}{\pi b^2}\sin^2\theta\ ; \\ V(\theta) &= \rho_0\cos^2\theta\exp\left[\frac{3}{b}\left(2\theta - \sin 2\theta\right)\right] \end{aligned}$$


-Φ0
Φ0

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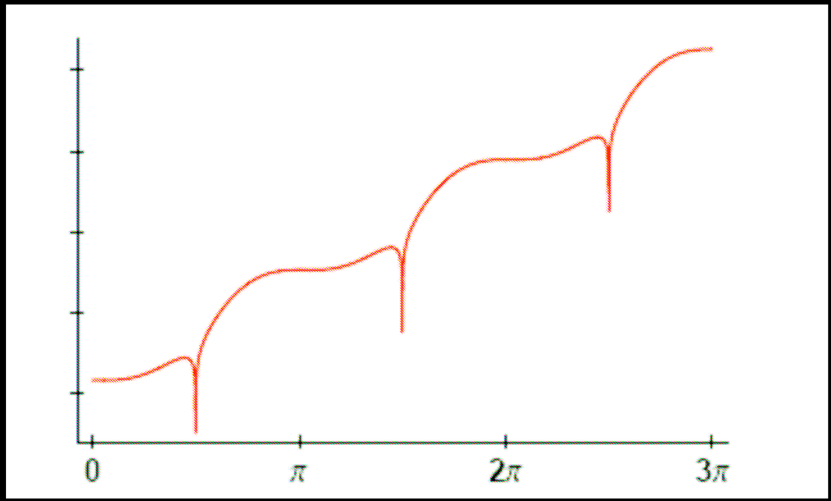
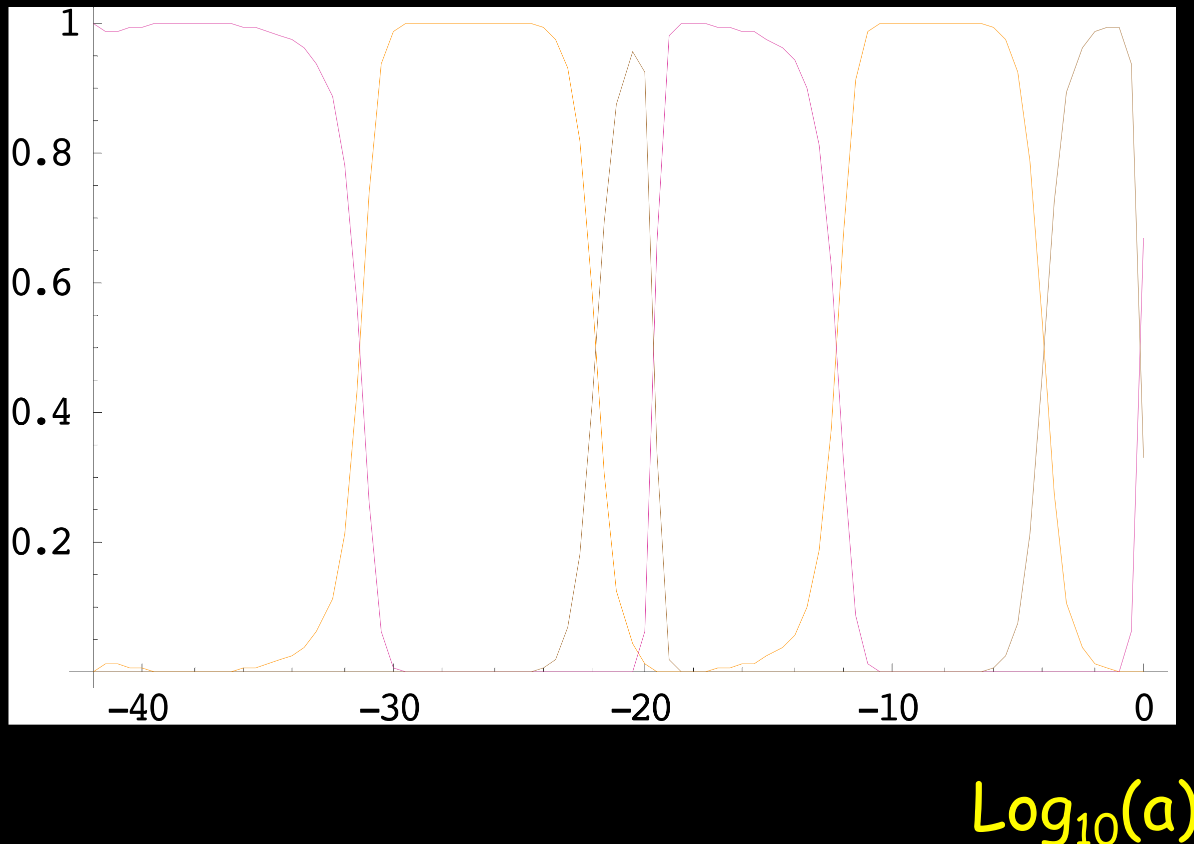


$$V(\theta) = \rho_0 \cos^2\theta \exp\left[\frac{3}{b}(2\theta - \sin 2\theta)\right]$$

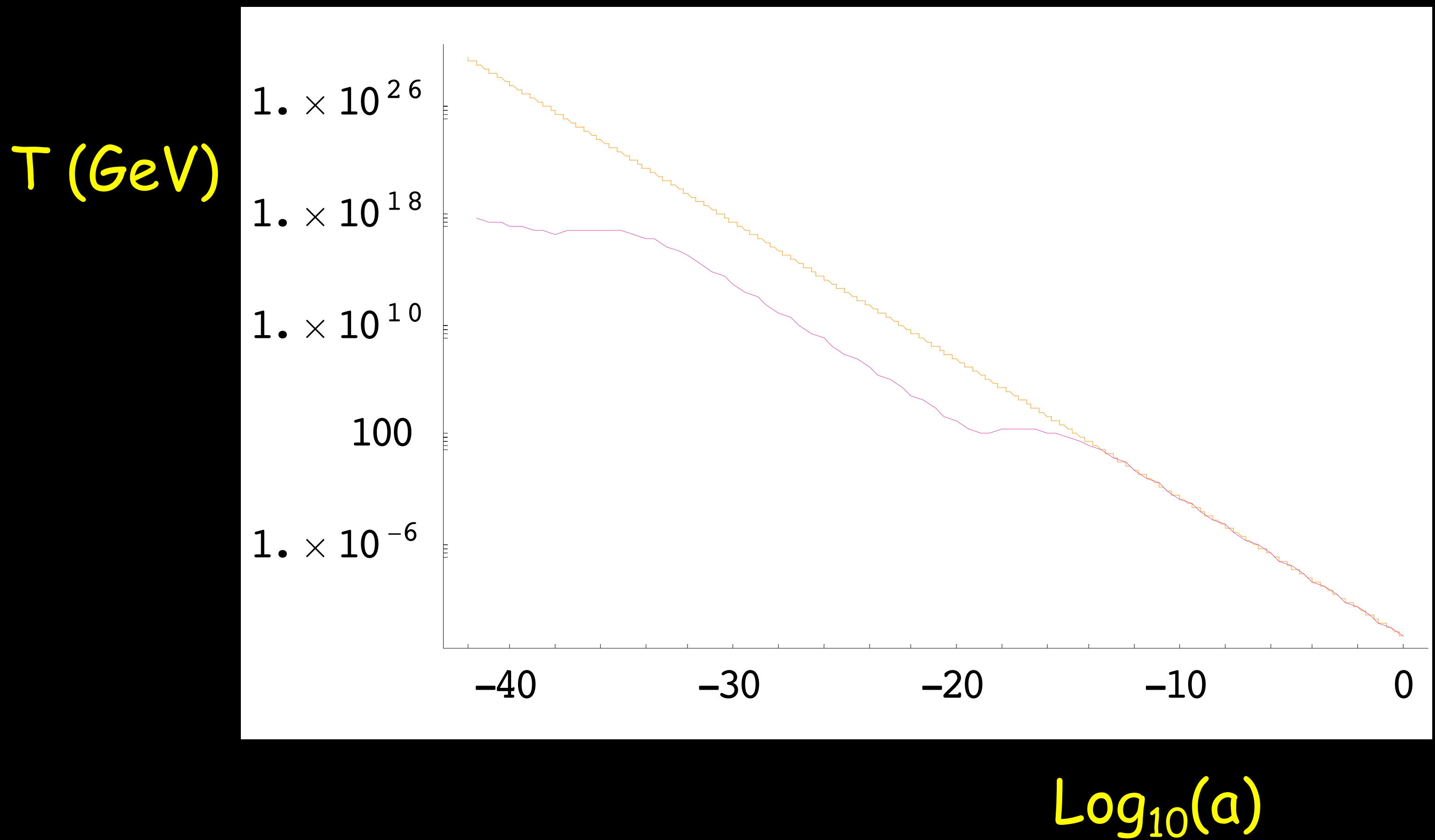
plus a weak perturbative coupling to light fermions (friction)



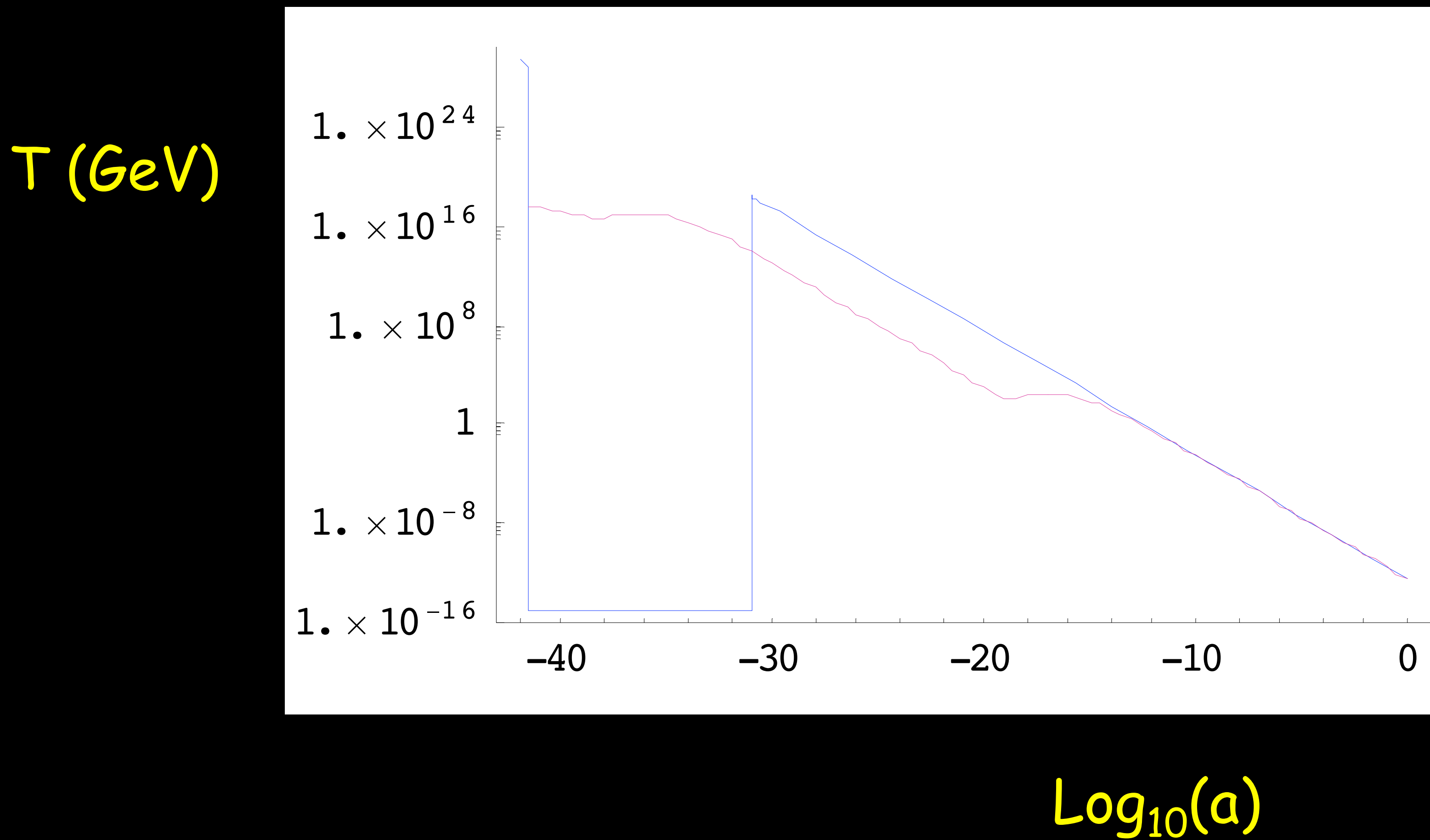
$$\dot{\rho}_\theta = -3H(1+w)\rho_\theta - k_0 H(1+w)\rho_\theta$$

$$\dot{\rho}_r = -4H\rho_r + (1-f_m)k_0 H(1+w)\rho_\theta$$

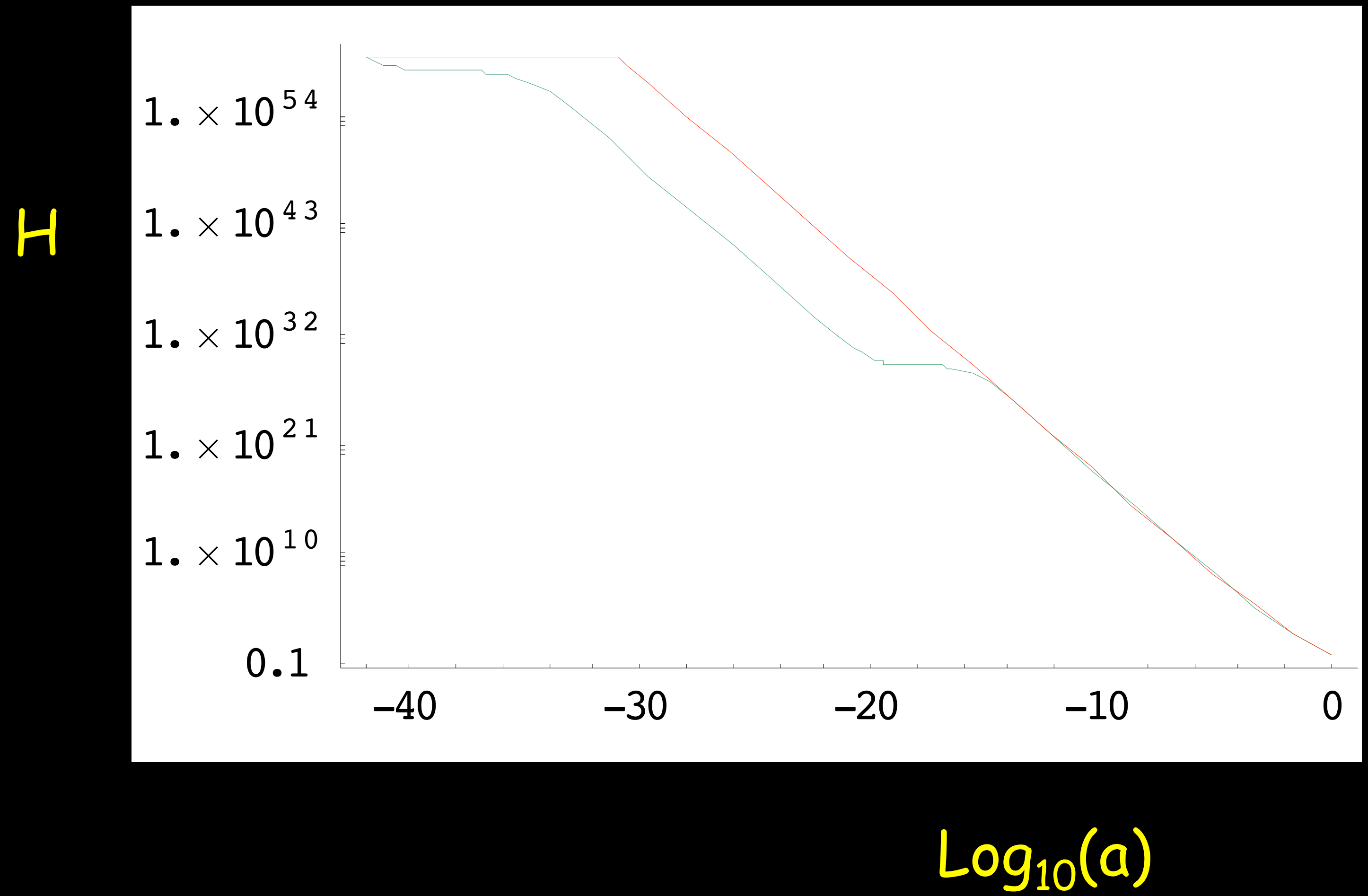
$$\dot{\rho}_m = -3H\rho_m + f_m k_0 H(1+w)\rho_\theta$$

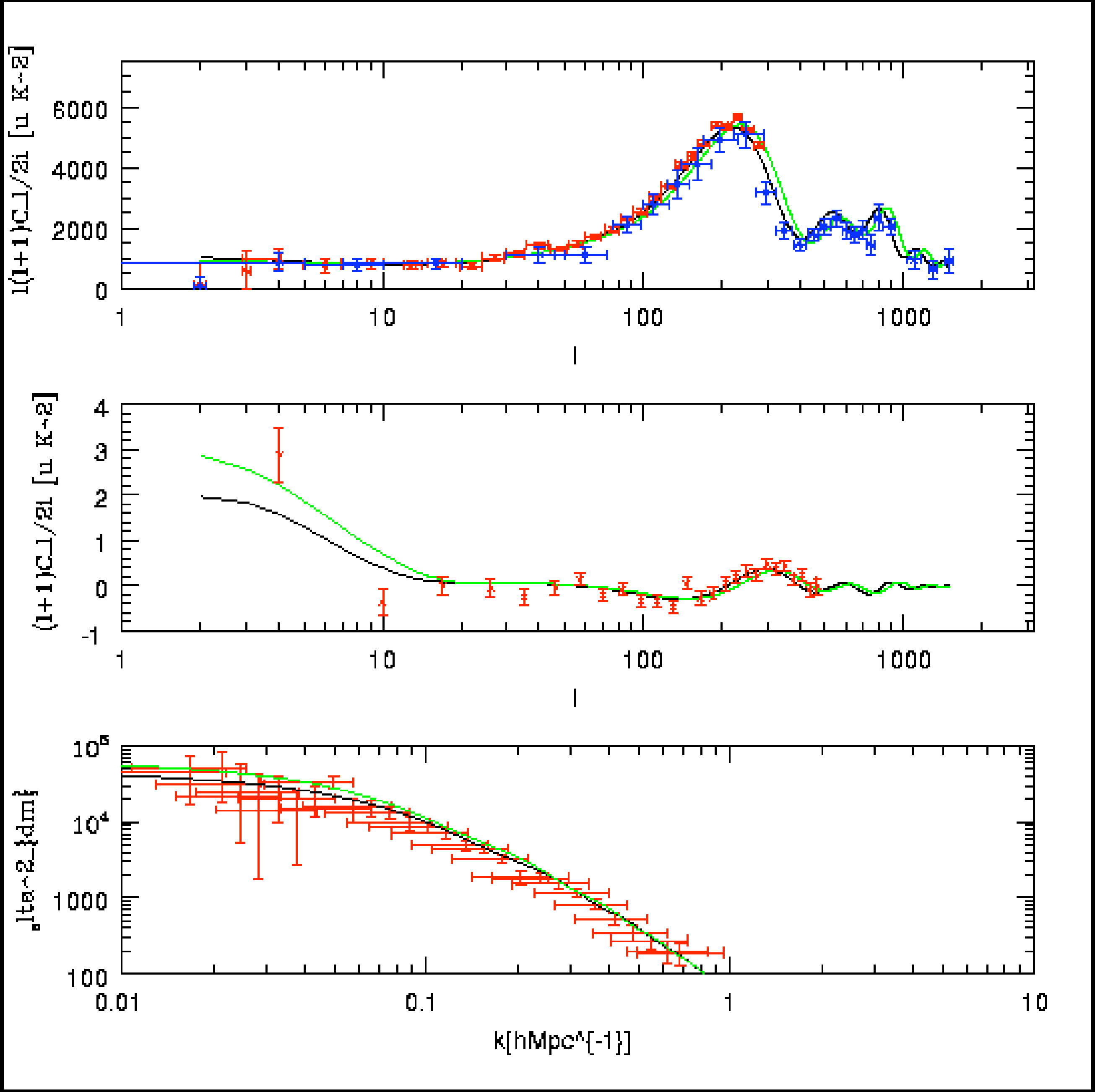


T (GeV)
1. × 10 26
1. × 10 18
1. × 10 10
100
1. × 10 -6
-40
-30
-20
-10
0
Log10(a)



T (GeV)
1. × 10^24
1. × 10^16
1. × 10^8
1
1. × 10^-8
1. × 10^-16
-40
-30
-20
-10
0
Log10(a)


H
1. × 10^54
1. × 10^43
1. × 10^32
1. × 10^21
1. × 10^10
0.1
−40
−30
−20
−10
0
Log10(a)



l(l+1)C_l/2l [u K^2]
6000
4000
2000
0
1
10
100
1000
l
(l+1)C_l/2l [u K^2]
4
3
2
1
0
-1
1
10
100
1000
l
10⁵
10⁴
1000
100
0.01
0.1
1
10
k[hMpc^{-1}]

A noncanonical framework for FRW cosmology

All you need is a(t)....

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$$1 + w(\theta) = \frac{2b}{3}\frac{H'}{H}$$

A noncanonical framework for FRW cosmology

All you need is a(t)....

$$1 + w(\theta) = \frac{2b}{3}\frac{H'}{H}$$

$$\theta(a) = -b\ln a \,,$$

$$F(\theta) = \frac{3k^2}{2b^2}(1 + w(\theta)) \,,$$

$$V(\theta) = \frac{3k^2}{4}(1 - w(\theta))H^2$$

Go slinky !!!

$$w(a) = -\cos 2\theta(a)$$

$$F(\theta) = \frac{12k^2}{b^2} \sin^2\theta \; ;$$

$$V(\theta) = \rho_0 \cos^2\theta \exp\left[\frac{3}{b}(2\theta - \sin 2\theta)\right]$$

Go slinky !!!

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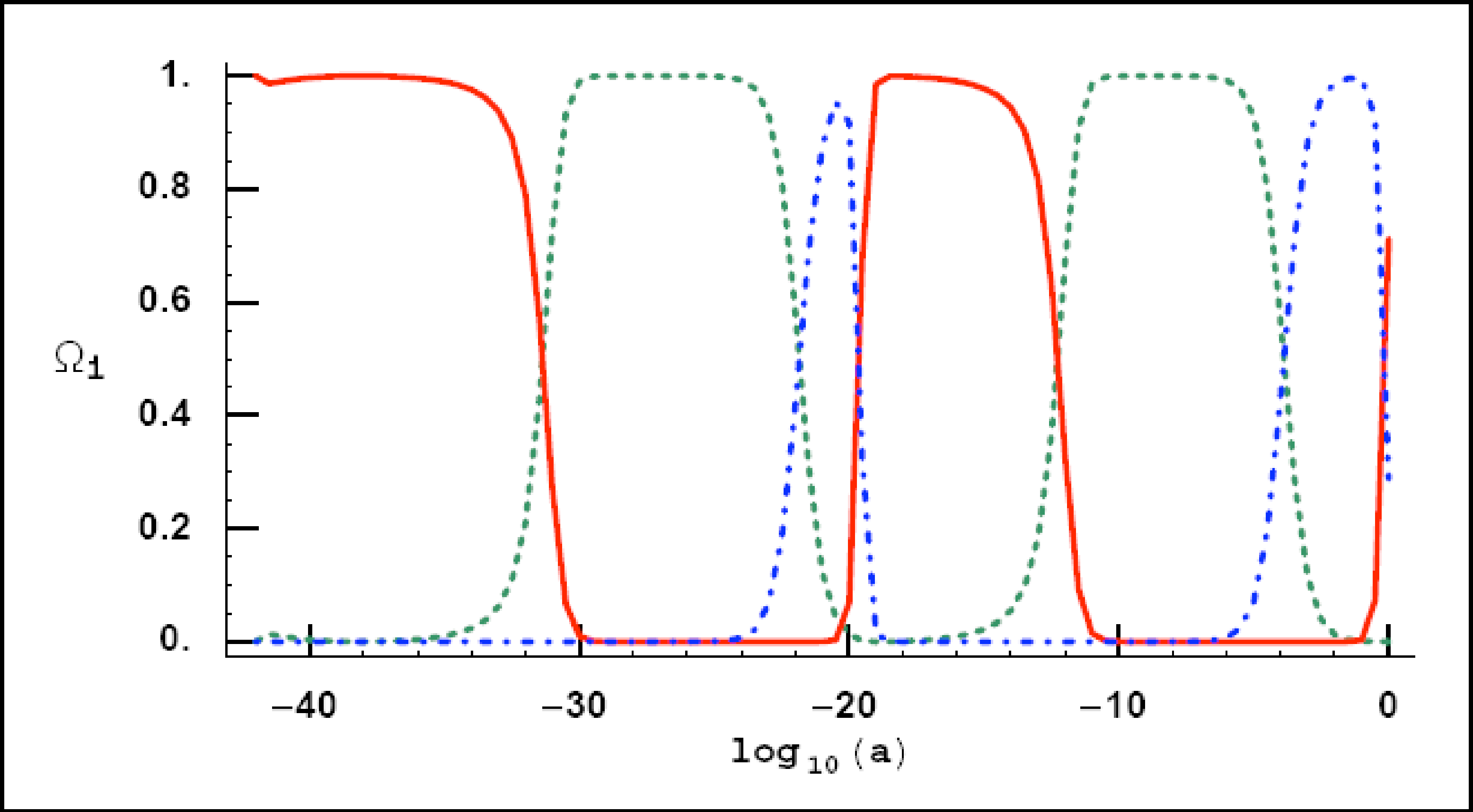
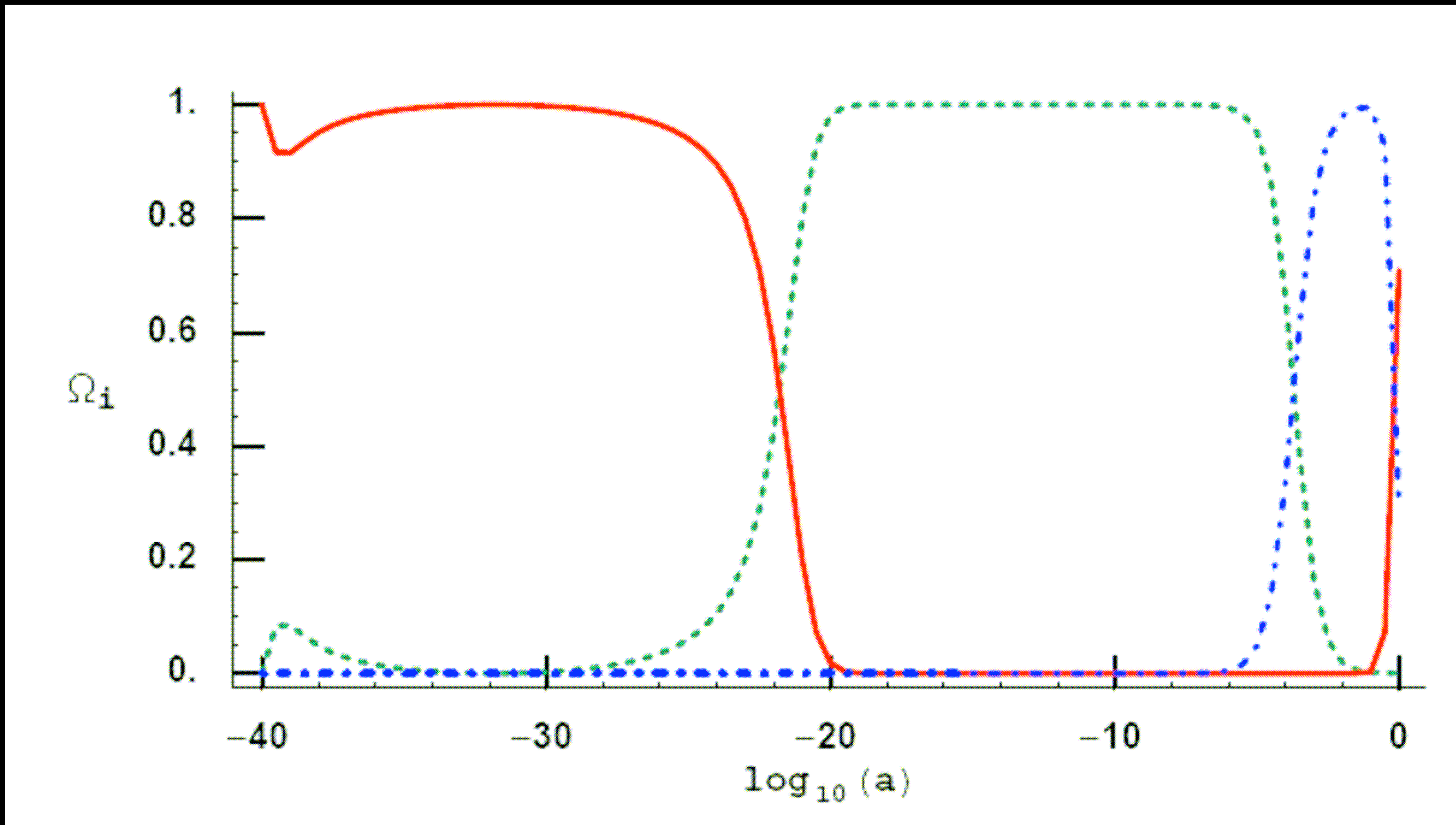
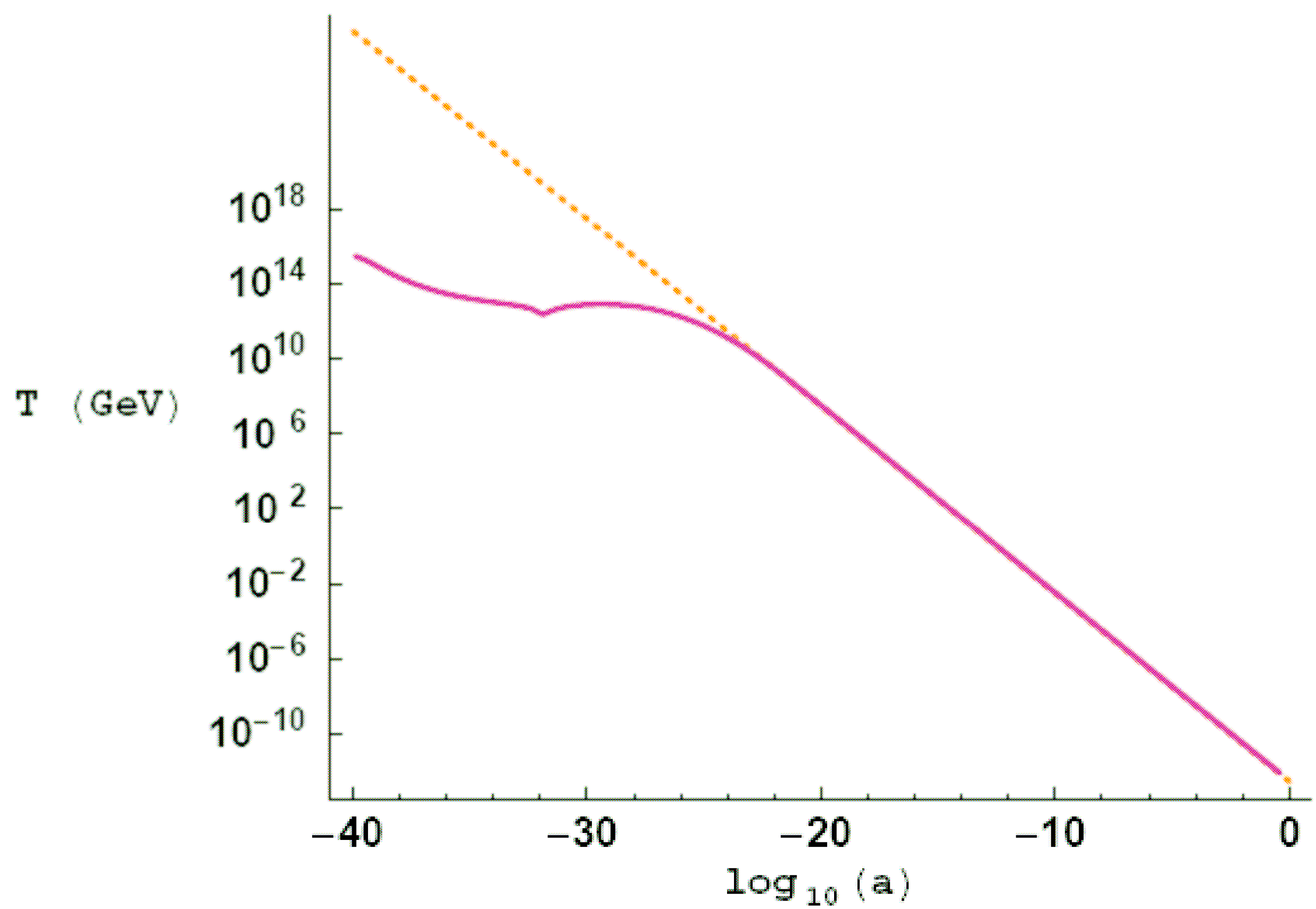
\end{aligned}$$



$b \cong 1/7$, $k_o \cong .06$



$b \cong 1/12$, $k_o \cong .02$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10^18
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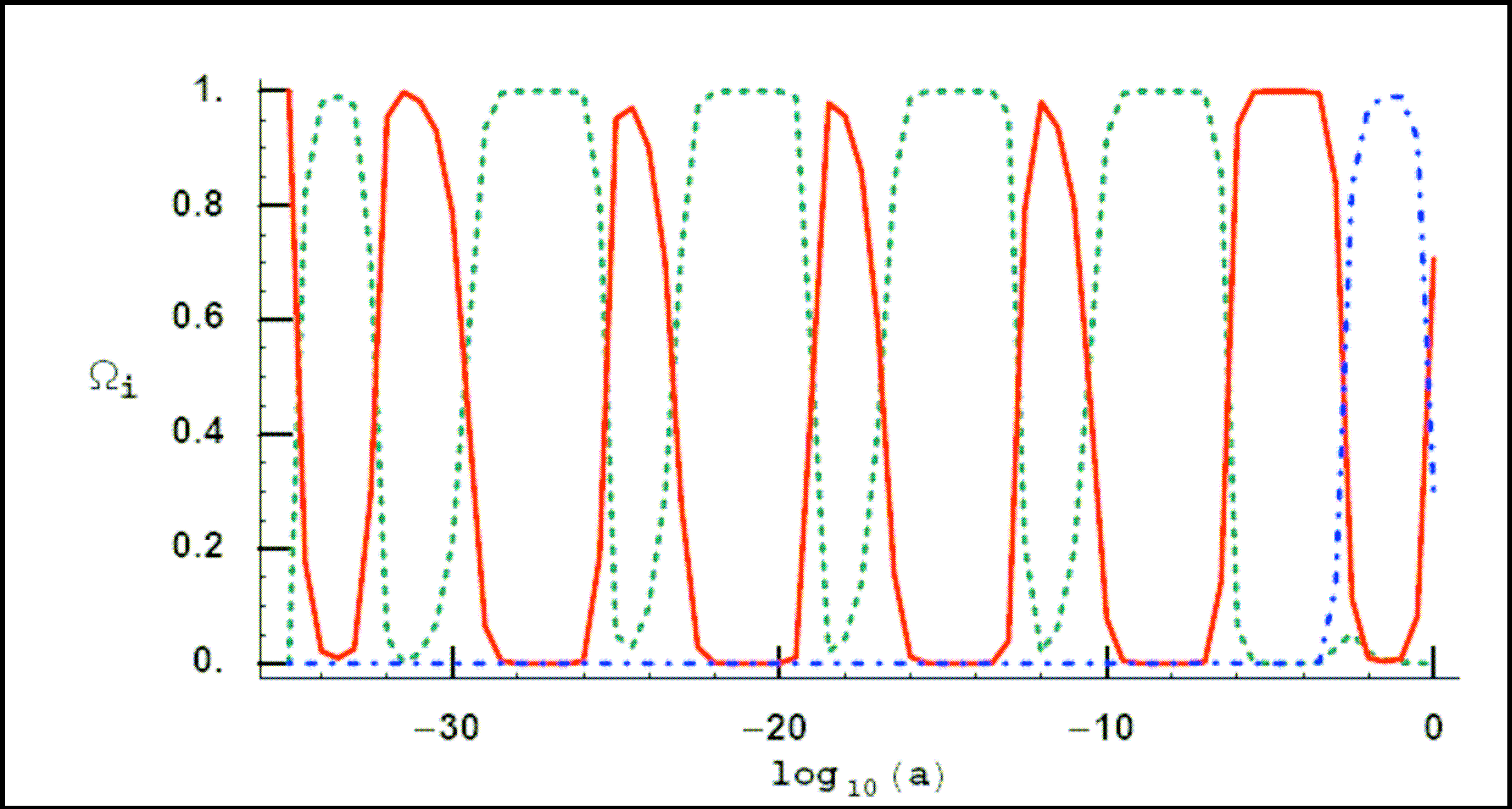

$b \cong 1/2$, $k_o \cong .3$

Conclusions

Dark energy and inflation can be explained both by the evolution of a single scalar field.

It needs only three parameters to agree with all available data

The thermal history of the Universe is far from being known...

We are absolutely clueless about dark energy, and should be correspondingly humble.