STARS 2013

Havana, Cuba, maio de 2013

Bouncing models and inflation

Nelson Pinto Neto

CBPF

ICRA

I-THE STANDARD COSMOLOGICAL MODEL (FRIEDMANN-1922)

1) Successes:

expansion of the Universe,

cosmic microwave background radiation (CMBR) (isotropy and anisotropy),

nucleosynthesis,

large scale structures

The problem: the initial singularity

- All Friedmann models contain one.

- A point where no physics is possible.

- General Relativity indicates its own limits:
what really happens when we approach the singularity?

- New physics!

Puzzles: <u>INITIAL CONDITIONS</u>

a) Why the Universe was so much homogeneous and isotropic in the past?

$n\ \infty^3$ initial constants equal to zero!

b) Existence of particle horizons makes things worst:

at recombination time there were approximately 100 regions without causal contact with the same temperature!

c) Where the structures come from?

d) Why the spatial hypersurface is so flat, or why the total density of matter in the Universe today is so close to the critical density today?

Flatness is unstable if the Universe is decelerating.

$$ds^2 = dt^2 - a^2(t)\left(\frac{1}{1-Kr^2}dr^2 + r^2 d\theta^2 + r^2 sen^2\theta d\phi^2\right)$$

$$\Omega_T = \frac{\epsilon_T}{\epsilon_c}$$

dl(t) = a(t) dx

$$|\Omega_T{}^{\cdot} - 1| = -2\frac{\ddot{a}}{\dot{a}^3}$$

$(\Omega_T - 1)_N < 10^{-18}$

BIG IMPROVEMENT ON THE STANDARD MODEL:

INFLATION

(1981: Starobinski, Mukhanov, Guth, Linde)

Period in the past when the Universe was accelerated

- Driven by a scalar field.

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

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

- It solves the horizon, structure formation and flatness problems (see however the transplanckian problem).

$$\Omega_T = \frac{\epsilon_T}{\epsilon_c}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right)$$

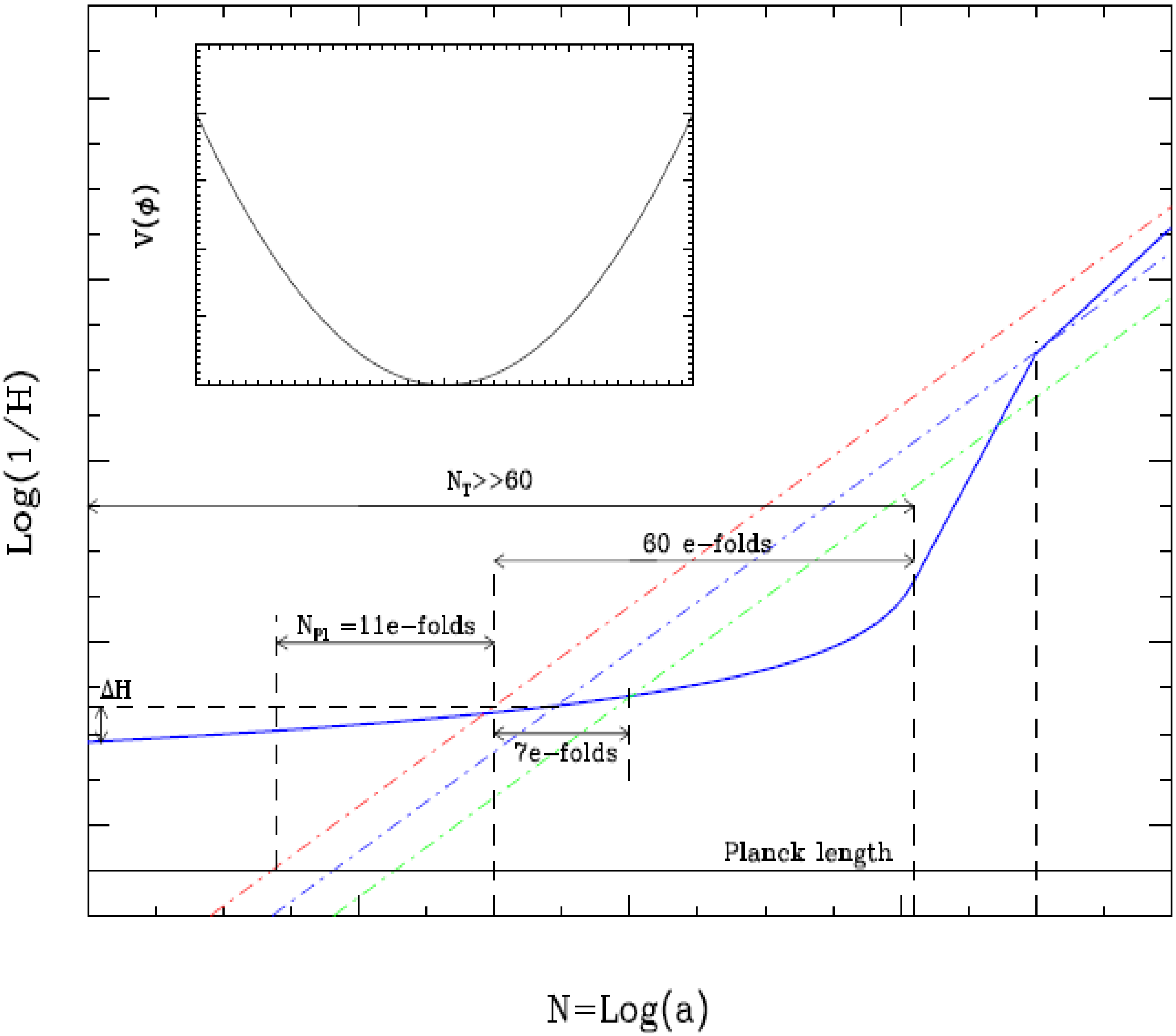
$$|\Omega_T \dot{} - 1| = -2\frac{\ddot{a}}{\dot{a}^3}$$

$$\ln(R_H) = \frac{1}{q}\ln(a)$$

Universe was accelerated in the past, q > 1.

We can justify the spectrum of perturbations by physical arguments: initial vacuum state for the perturbations yielding the observed spectrum (Planck).

THIS WAS THE MAIN ACHIEVEMENT OF INFLATION!



V(φ)
Log(1/H)
N_T>>60
60 e−folds
N_Pl =11e−folds
ΔH
7e−folds
Planck length
N=Log(a)

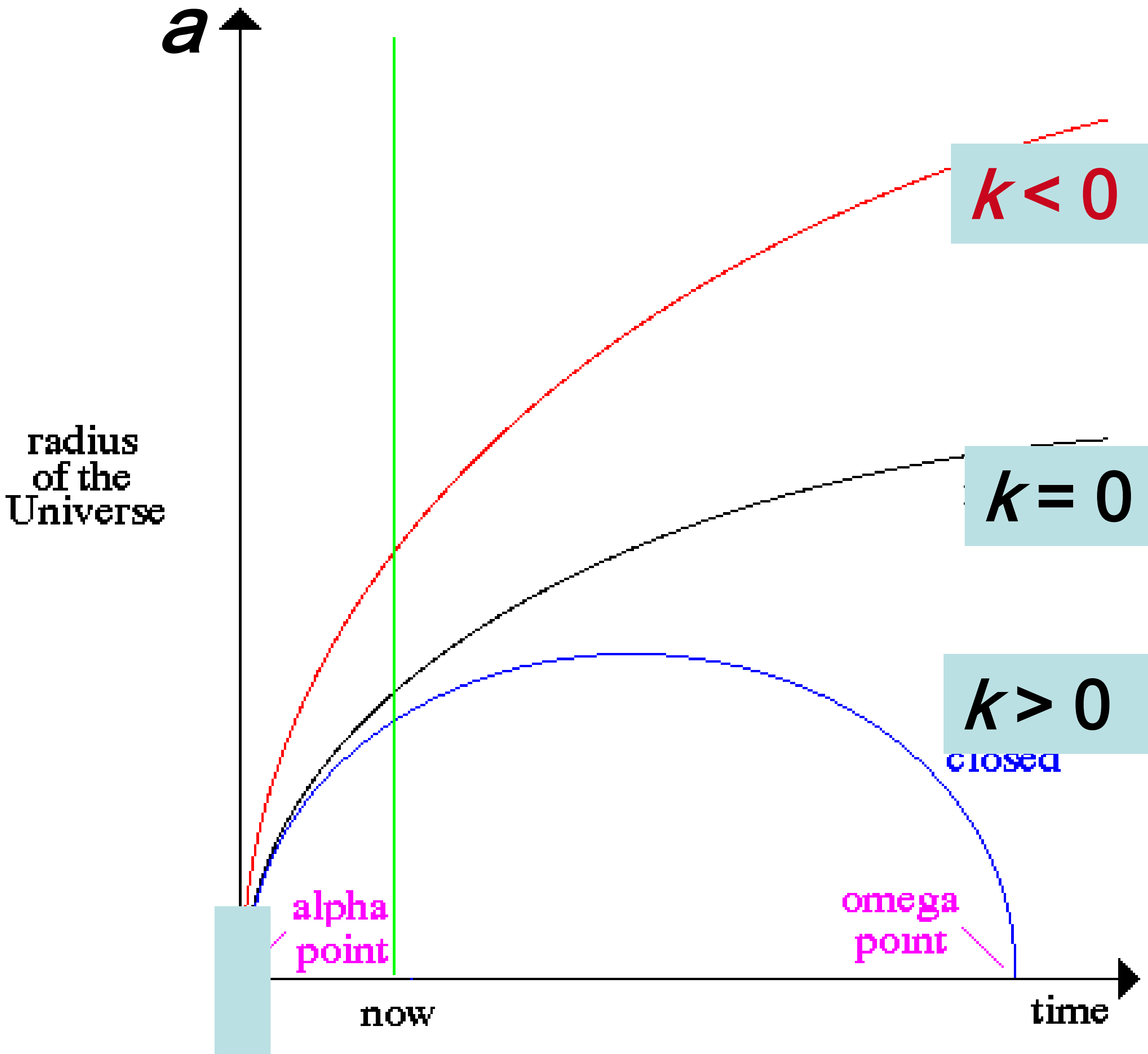
HOWEVER:

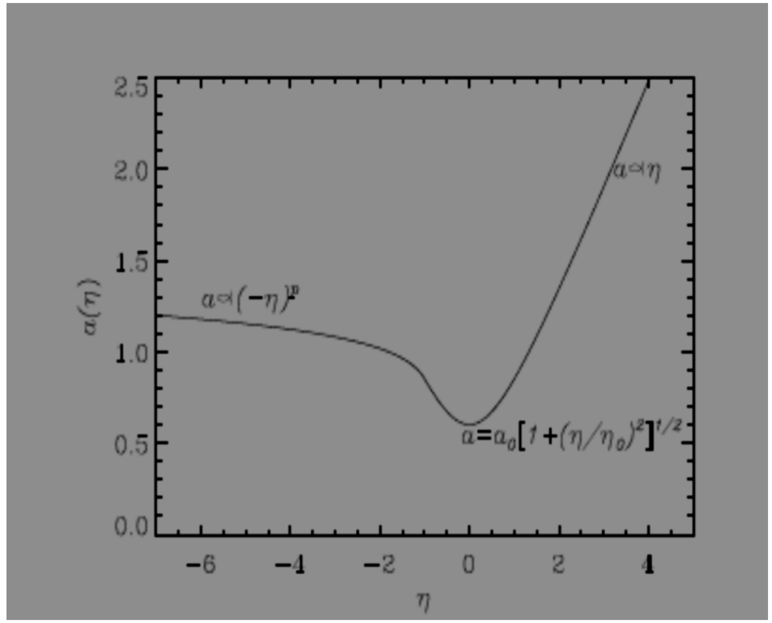
- IT DOES NOT SOLVE THE HOMOGENEITY PROBLEM.

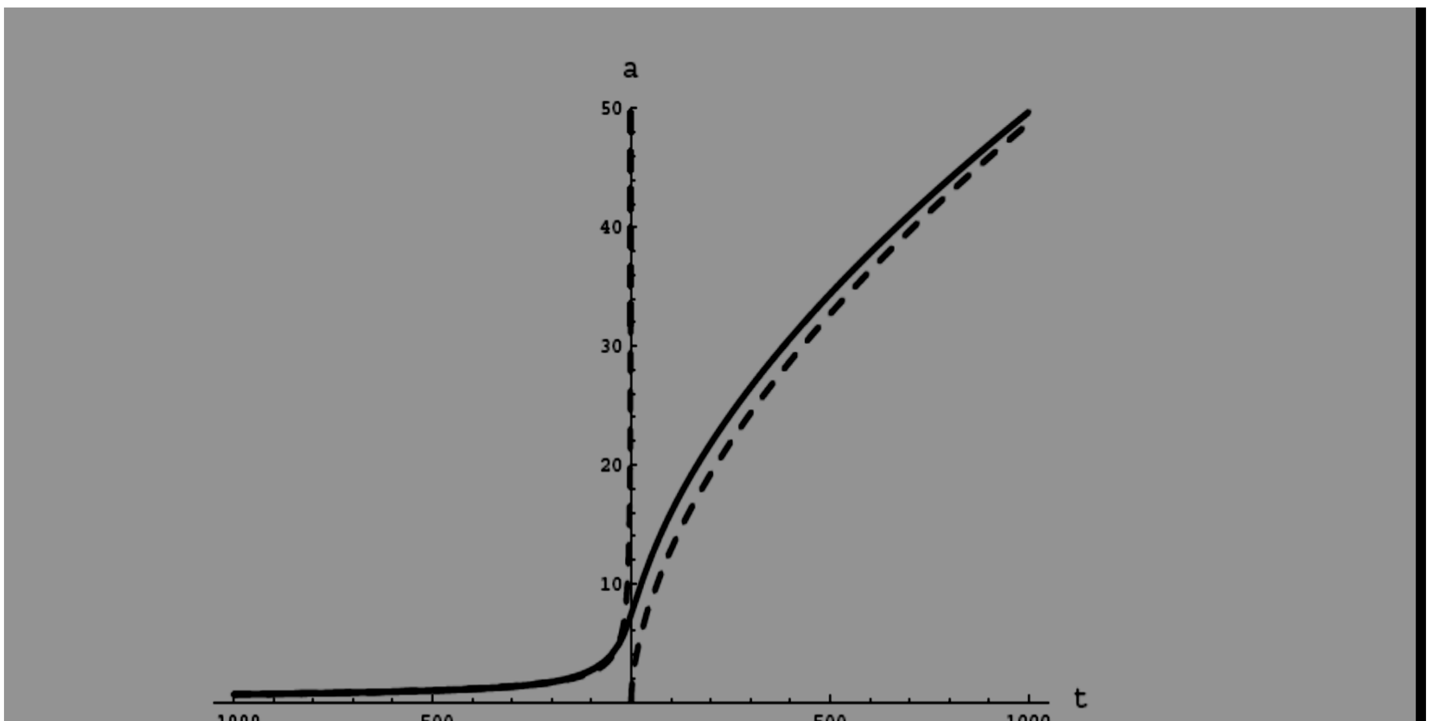
- IT DOES NOT ADDRESS THE SINGULARITY PROBLEM.

LET US CONCENTRATE ON THE SINGULARITY PROBLEM

THE SINGULARITY: THREE POSSIBILITIES



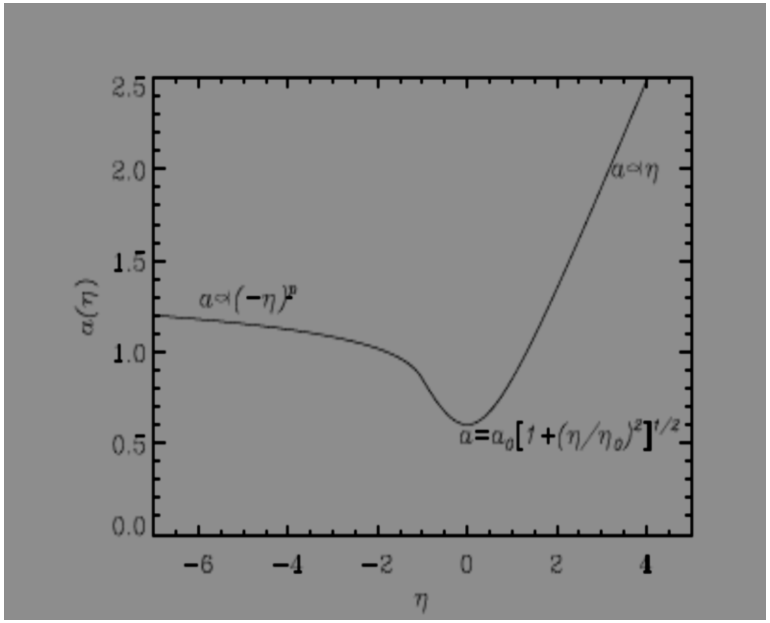

2.5
2.0
1.5
1.0
0.5
0.0
−6
−4
−2
0
2
4
η
a(η)
a∝(−η)^p
a∝η
a=a_0[1+(η/η_0)^2]^{1/2}


a
50
40
30
20
10
-1000
-500
500
1000
t

THE BOUNCE

Radiation solution in GR:
conformal time ($dt = a\, d\eta$): $a = \eta$

Corrections:
$$a(\eta) = a_0 [(\eta/\eta_0)^2 + 1]^{1/2}$$



Situations where bounces may occur:

- **Nonminimal coupling:** Novello, Salim, Melnikov
- **Scalar fields with a potential:** Brandenberger, Finelli, Martin, Peter, Falciano
- **K-essence:** Abramo, Peter.
- **Negative energy fluids:** Bozza, Veneziano, Peter, NPN.
- **Non-linear vector fields:** Bergliaffa, Novello, Salim, Nogueira.
- **Weyl geometries:** Novello, Oliveira, Salim.
- **Interacting ordinary fluids:** Fraga, NPN.
- **String motivated theories:** Steinhardt, Turok.
- **Quantum cosmology:** Alvarenga, Ashtekar, Bojowald, Colistete, Fabris, Lemos,
-Peter, Pinho, NPN.

FEATURES OF THE MODEL

1) No singularity.
2) No horizon problem.
3) Flatness problem: if the contraction phase is much longer then the expansion phase, then the Universe is almost flat because it has not expanded enough!
4) Homogeneity problem may be less severe.

1) Perturbations of quantum mechanical origin.
2) Enhancement of perturbations at the bounce.
3) One fundamental parameter: the curvature radius L_0 at the bounce, which must have the reasonable value $10^3\, l_{pl}$.
4) Transplanckian problem can be solved.

$$\Omega_T \equiv \epsilon_T / \epsilon_c \approx 1$$

$$|\Omega_T - 1|^{\cdot} = -2\frac{\ddot{a}}{\dot{a}^3}$$

Connection with observations

Are there observational consequences of a primordial contracting phase in our Universe?

Cosmological perturbations → structures → anisotropies of CMBR

What happens with the perturbations in the case of a bounce with a preceding contracting phase?

Realistic geometrical description of the primordial Universe:

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu},$$

$$ds^2 = g^{(0)}_{\mu\nu} dx^\mu dx^\nu = N^2(t)dt^2 - a^2(t)\delta_{ij}dx^i dx^j,$$

Scalar perturbations:

$$\mathrm{d}s^2 = a^2(\eta)\left[(1+2\Phi)\mathrm{d}\eta^2 - (1-2\Phi)\gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j\right],$$

Φ(x) is the inhomogeneous perturbation, related to the Newtonian potential in the nonrelativistic limit. dt = a dη

Hamiltonian describing the dynamics of the perturbations

$$\hat{H}_{2U} = \frac{1}{2}\int d^3x \left[\frac{\hat{\pi}^2}{\sqrt{\gamma}} + \sqrt{\gamma}\,\hat{v}^{,i}\hat{v}_{,i} - \frac{a''}{a}\sqrt{\gamma}\,\hat{v}^2\right] \qquad \Phi^{,i}{}_{,i} \propto \left(\frac{\mathcal{H}^2 - \mathcal{H}'}{\mathcal{H}}\right)\left(\frac{v}{a}\right)',$$

Generates evolution along η.

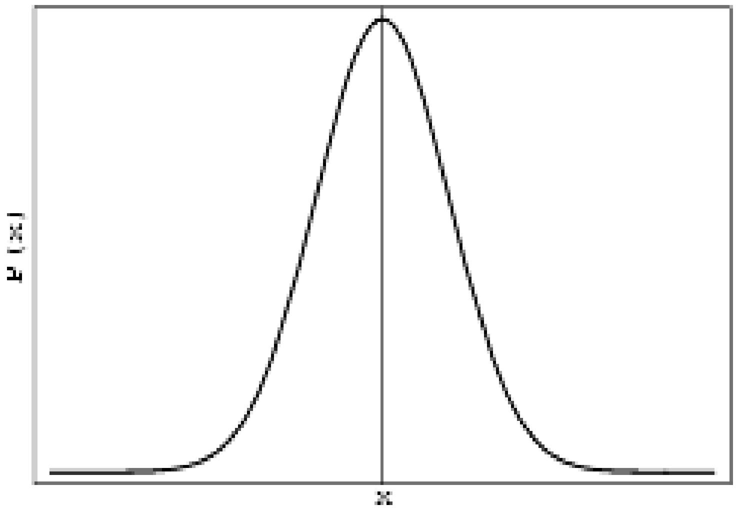
Schroedinger equation:

$$i\frac{\partial \Psi_{(2)}[v,\eta]}{\partial \eta} = \int \mathrm{d}^3x \left(-\frac{1}{2}\frac{\delta^2}{\delta v^2} + \frac{\lambda}{2}v_{,i}v^{,i} - \frac{a''}{2a}v^2\right)\Psi_{(2)}[v,\eta].$$

$$v''_k + \left(\lambda k^2 - \frac{a''}{a}\right) v_k = 0.$$

Curvature scale: $l_c \approx R^{-1/2} \approx a^3/a''$; Physical wavelength: $l_{phys} = a/k$

Before the bounce, in the contracting phase



After the bounce, In the expanding phase.

Point of matching: $\lambda k^2 = a''/a \Longrightarrow l_{phys} = \lambda^{1/2}\, l_c$

THE POWER SPECTRUM

$$k^3\mathcal{P}_s \equiv \frac{2k^3}{\pi^2}\,|\Phi|^2 \qquad n_{\rm s} = 1 + \frac{d\ln(\mathcal{P})}{d\ln(k)}.$$

$$n_{\rm s} = 1 + \frac{12\lambda}{1+3\lambda}$$

- Non relativistic fluid (dark matter?): scale invariant.

It is not necessary to have ordinary matter dominating all along; just at the moment when perturbation scale becomes comparable with the curvature scale.

Another fluid or field may dominate at the bounce: radiation.

Calculation of $\delta T/T$ with radiation at the bounce and a non relativistic fluid at curvature scale crossing:

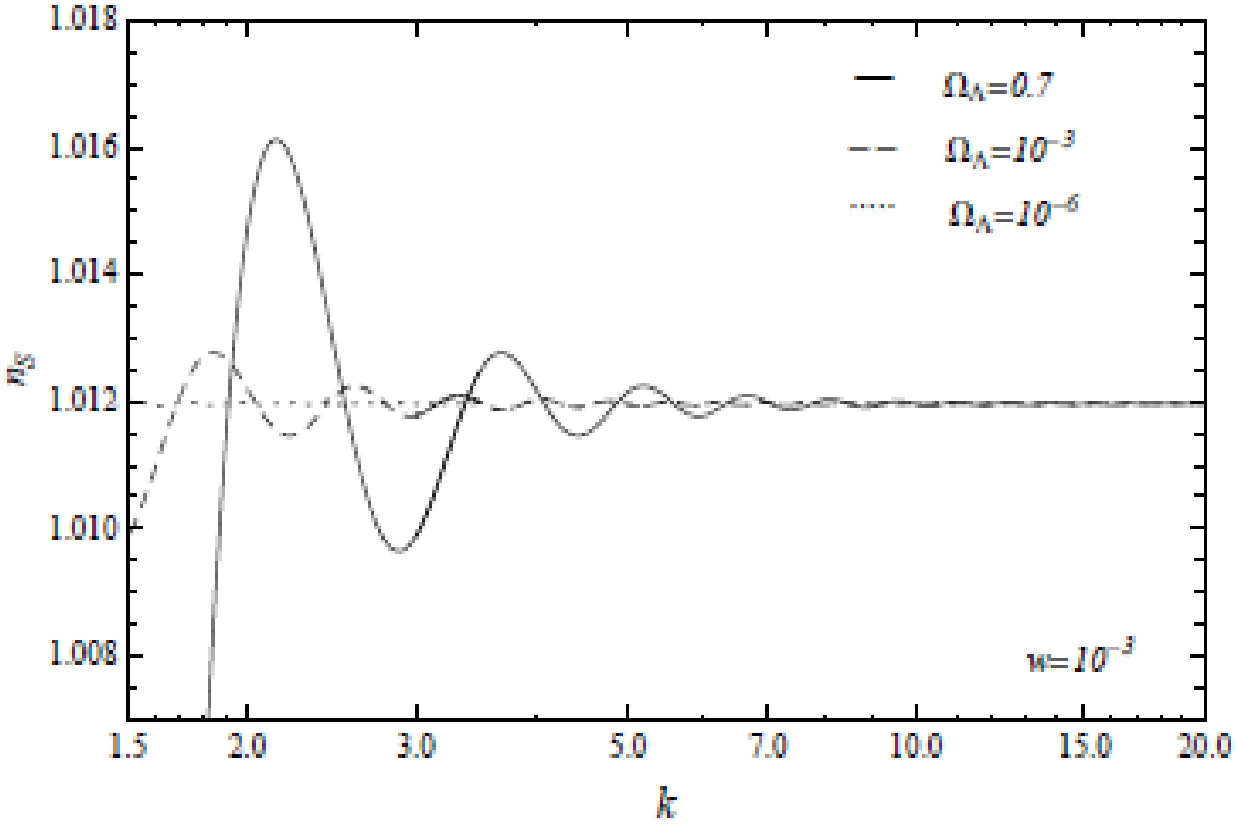
Three free parameters: η_0 **(cuvature scale at the bounce).**
a_0 **(scale factor at the bounce).**
λ_{nr} **(state equation parameter).**

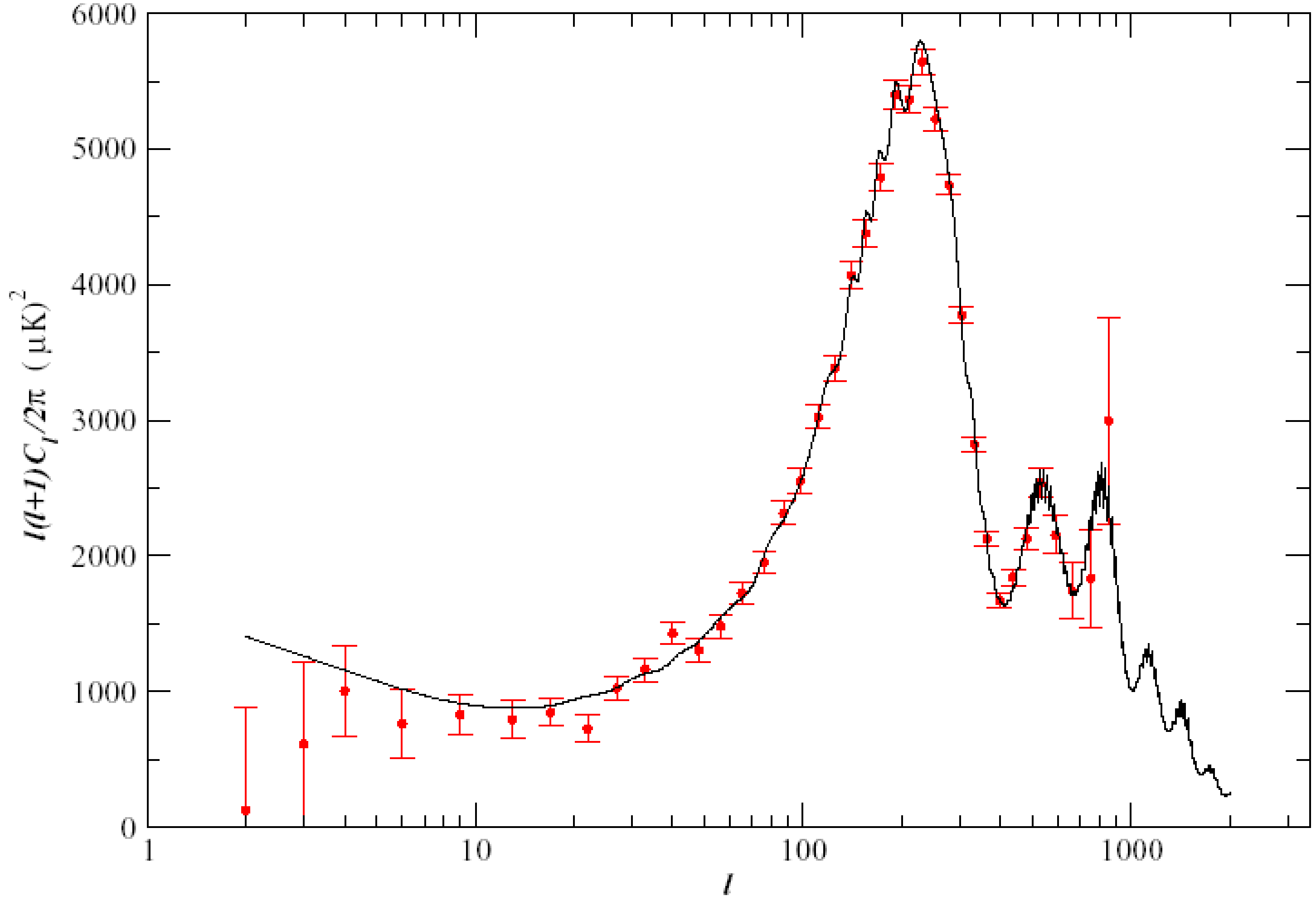
$\eta_0 \sim 10^3 (\lambda_{nr})^{-1/4} l_{pl}$
Large range of values for a_0: avoid transplanckian problems.

We are founding the best fit parameters.

- **n_s very close to one.**
- **power of gravitational waves is very small.**
- **superimposed oscillations and running due to a cosmological constant**
- **non gaussianities**

Efeito da constante cosmológica:





6000
5000
4000
3000
2000
1000
0
1
10
100
1000
l(l+1)C_l/2π (μK)^2
l

Gravitational waves in bouncing models

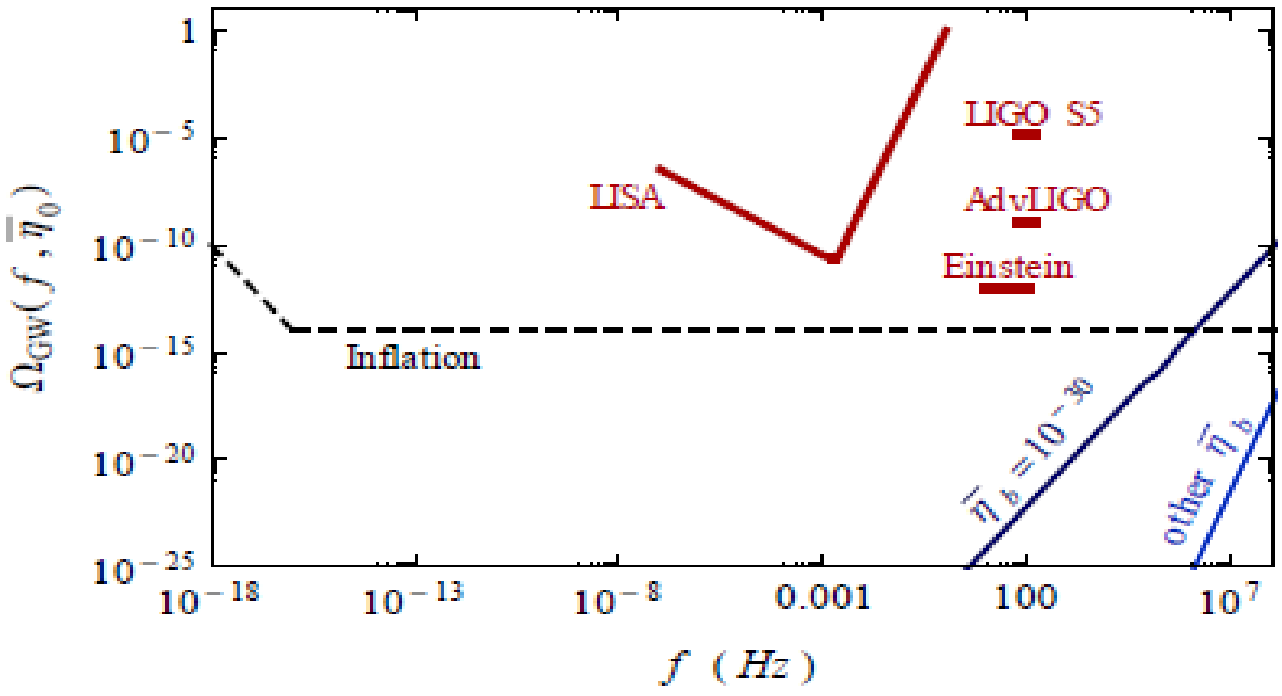


FIG. 3. Comparison of our results (blue curves at the bottom right) with experimental sensitivities (red curves) and a prediction the upper limits on the spectrum of primordial gravitational waves generated in inflationary models (black dashed curve). The red curves show the sensitivities achieved by LIGO's 5th run and the ones predicted for Advanced LIGO, the Einstein Telescope and LISA [19]. See [20] and references therein.

IV - CONCLUSION

-- There are no observational reasons for a beginning of the Universe, so why not exploring the consequences of bouncing models?

-- Basic General Relativity and Quantum Mechanics yield a sensible bouncing model which can explain the origin of cosmological perturbations like inflation as they also have a period with $d^2a/dt^2 > 0$.

-- Complete different perspective concerning initial conditions.

-- Bouncing models may complete or even be competitive with usual inflation.

REFERENCES

P. Peter, E. Pinho and NPN, JCAP 07, 014 (2005).

P. Peter, E. Pinho and NPN, Phys. Rev. D 73, 0104017 (2006).

P. Peter, E. Pinho and NPN, Phys.Rev. D 75, 023516 (2007).

E. Pinho and NPN, Phys. Rev. D 76, 023506 (2007).

F. T. Falciano and NPN, Phys. Rev. D 79, 023507 (2009).

R. Maier, S. Pereira, N. Pinto-Neto, and B. B. Siffert, Phys. Rev. D85, 023508 (2012).

S. D. P.Vitenti and N. Pinto-Neto, Phys. Rev. D85, 023524 (2012).