Superstring Cosmology: Concepts and Consequences

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2nd Crete Regional Meeting in String Theory, June 2003

The balance sheet

A positive balance? I definitely think so! However..

Inflation is not part of a grander theory of elementary particles and fundamental interactions, e.g.

Two basic problems embedding idea in string theory

1. Lack of an inflaton candidates: steep potentials…
2. Problems with strings in de Sitter background

(if only we needed AdS…)

Is it possible that QST chooses the 2nd solution (an older Universe)?

ST is full of fundamental scalars: the dilaton, the KR (universal) axion, the moduli and the corresponding axions

Instead of telling ST what it should do should why not ask what it would like to do?

I will claim that ST cries in favour of the 2nd solution.. and that it may even work!

Quantum String Theory (QST)

- String theory is a beautiful construction carrying a lot of promise as a unified theory of all particles and interactions. However:
- It is only known as a (perturbative)^2 series in two expansion parameters:
  - ✷ $g_s^2 = e^{\phi}$ ~ loop expansion parameter of QFT, promoted to a scalar field, the dilaton. Perturbatively (closed ST's)

$$g_s^2 \sim \alpha_{GUT} \sim G_N M_s^2 = l_P^2 l_s^{-2}$$

  - ✷ $\lambda^2 = l_s^2 \partial^2$ = new expansion parameter due to the finite size l_s of the string ($\lambda^2 = 0$ => QFT limit of QST)
- Modulo some lucky exceptions (e.g. dualities in highly supersymmetric vacua), our non-perturbative understanding of QST is, so far, very limited

As a result, unfortunately,

- ✶ We are not able to describe what happens at strong coupling (except for using some QFT intuition…)

  ➔ cannot solve the problem of perturbative vacuum degeneracy, of SUSY breaking, of dilaton and moduli stabilization, etc.

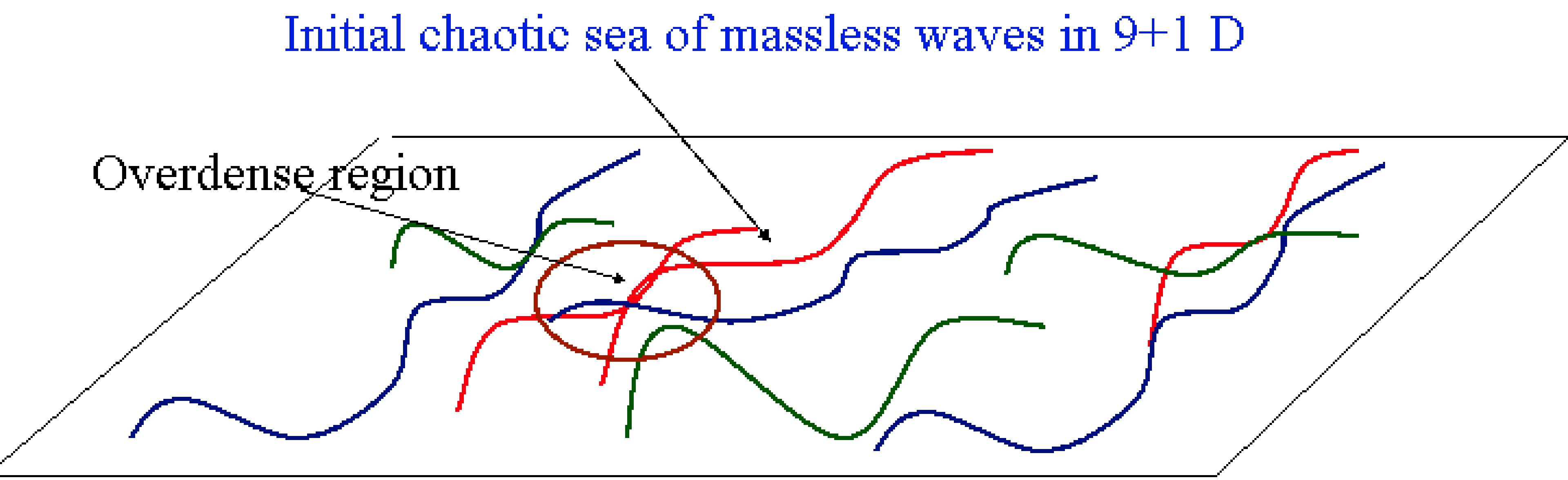
- ✸ We are not able to describe what happens at strong curvatures, $R \sim l_s^{-2}$ (except for educated guesses based on intuition or on analysis of gedanken experiments)

  ➔ do not know what is the fate of CGR's singularities in QST (Big Bang and black-hole singularity, end of evaporation…)

What do we know from PT?

- There are 5 consistent perturbative superstring theories all living in 9+1 space-time dimensions
- They appear to be connected (through a web of dualities) among themselves and to 11-D supergravity => M Theory
- We can find, for each one of them, the massless excitations
- These always include a graviton, a dilaton-axion pair, non-abelian gauge fields, and their supersymmetric partners
- The actual gauge group, the matter content, etc. depend on the specific vacuum around which we are studying the theory (and there are so many of them!)

- Low-energy classical solutions are described in terms of the massless fields
- They consist of a superposition of almost decoupled massless waves of various kinds, amplitude and wavelength, something best described as the (9+1)-D analog of a chaotic sea or sky...
- It looks nothing like the ordered (low-entropy) (3+1)-dimensional, quasi-homogeneous, flat, interacting Universe we live in, however…
- The above solutions are unstable...



- Regions of space satisfying certain criteria evolve towards larger and larger curvatures & coupling, i.e. precisely towards the non-perturbative regimes that we are ignorant about. They are hidden behind « horizons »
- At work here is basically the phenomenon of gravitational instability/collapse leading to black-hole formation in GR
- Amusingly enough, these regions of space, rather than collapsing in size, can inflate (in units of l_s) -together with e^{ϕ}- as one approaches the "singularity" at r=0…
- Inside the horizon r is time-like : approaching r=0 means approaching the BB singularity @t=0... from t<0!
- A symmetry (duality) guarantees the existence of such inflationary solutions without any need to invent an inflaton, a potential, etc.

(*T*)-Duality

- Closed strings do not distinguish a compact dimension of radius R_c from one of radius l_s^2/ R_c

↓Minimal physical value of R_c is not 0 but l_s

- Open strings do feel the difference: as $R_c \Rightarrow l_s^2/ R_c$, Neumann conditions at the ends become Dirichlet conditions, and viceversa. Ends of D-strings get stuck on (hyper)surfaces called "D-branes"
- This observation led the "D-brane revolution" of the mid nineties
- Ekpyrosis uses this development for cosmology

A cosmological variant of duality

- Eqns of string cosmology, unlike the Einstein-Friedmann eqns, are invariant under the replacement:

  $a(t) \Rightarrow a(t)^{-1}$ (together with a change of ϕ)

  They share with them invariance under $t \Rightarrow -t$

➔ In string cosmology we can associate with a cosmology w/ $a(t)$ a "dual" cosmology w/ $a(-t)^{-1}$

- The expansion rates ($H = d\log a/dt$) are related by $H \Rightarrow H$ and $dH/dt \Rightarrow - dH/dt$, thus decreasing-curvature => increasing curvature, inflation

A string-inspired cosmology

- One assumes that the pre-bangian phase is (essentially) the *T*-dual of the post-bangian era. If so it is characterized by:

☆ Accelerated expansion with growing curvature, H.

🕐 Growing ϕ, i.e. growing G_N

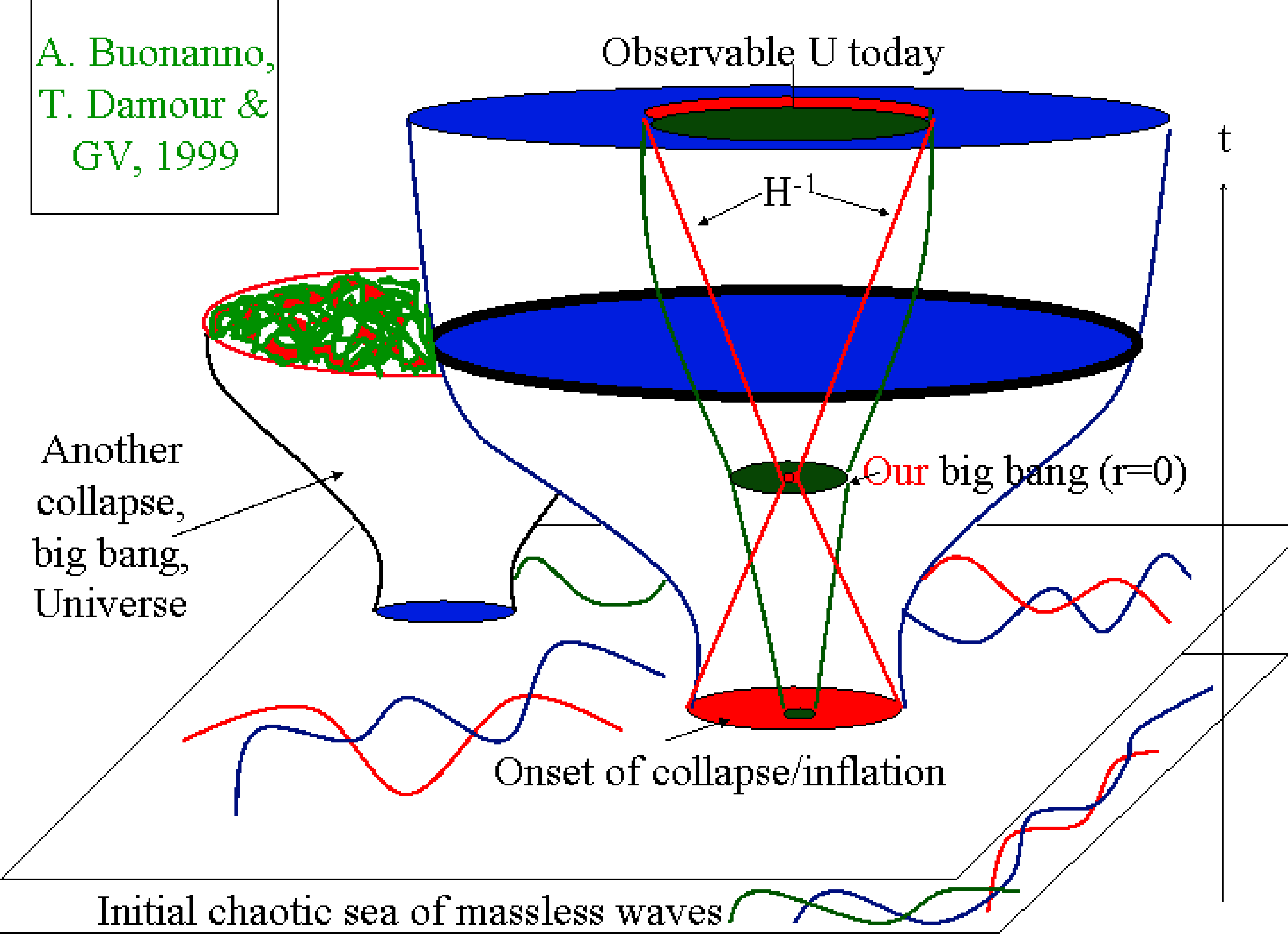
- This implies initial conditions at small curvature and small coupling (APT of BDV, '99) i.e. in the region where we know much about the theory (see previous discussion)
- The hard issue is no longer the initial singularity but "the bounce" i.e. the transition from inflation to FRW

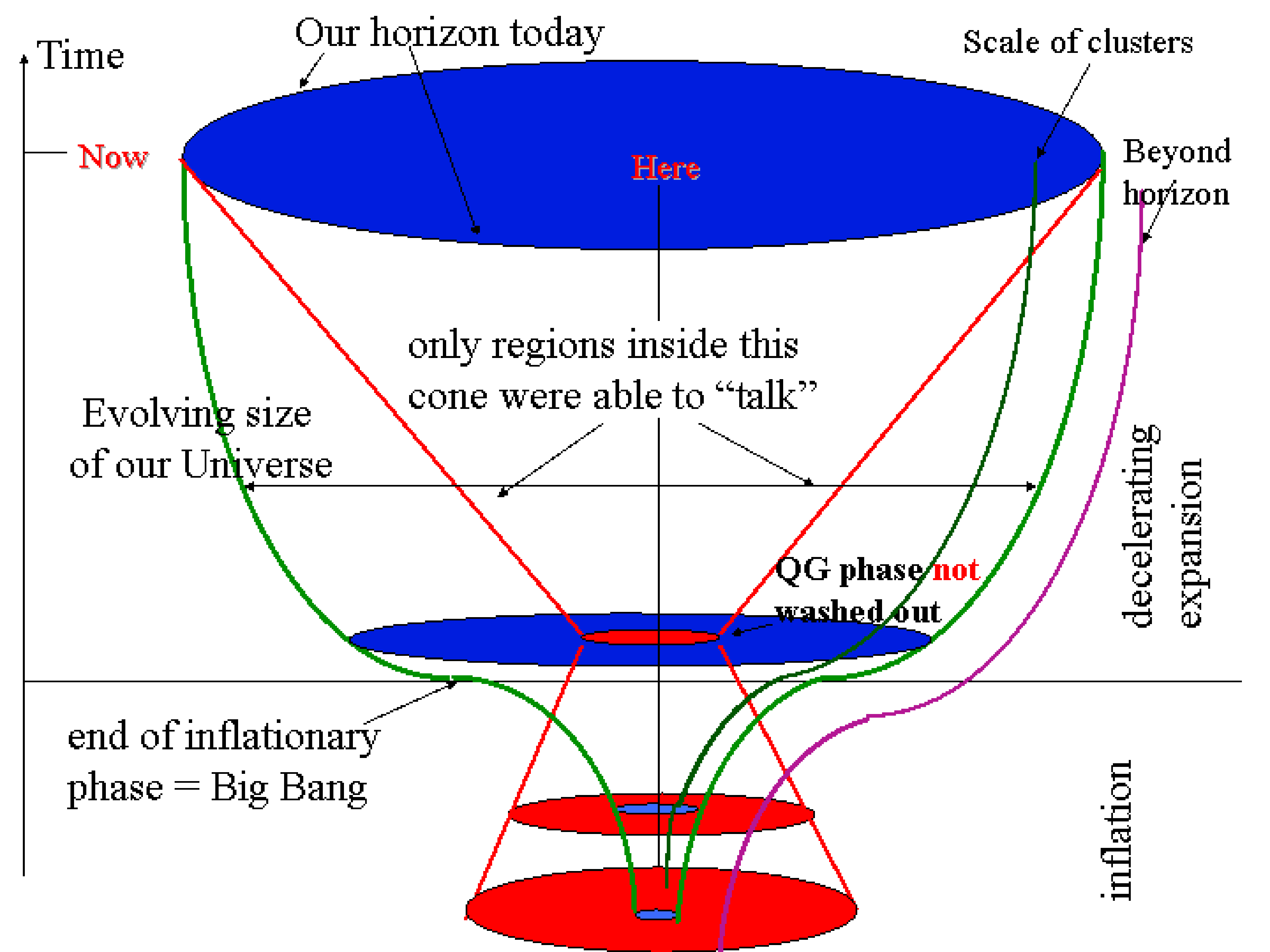
OUTLINE OF PART I

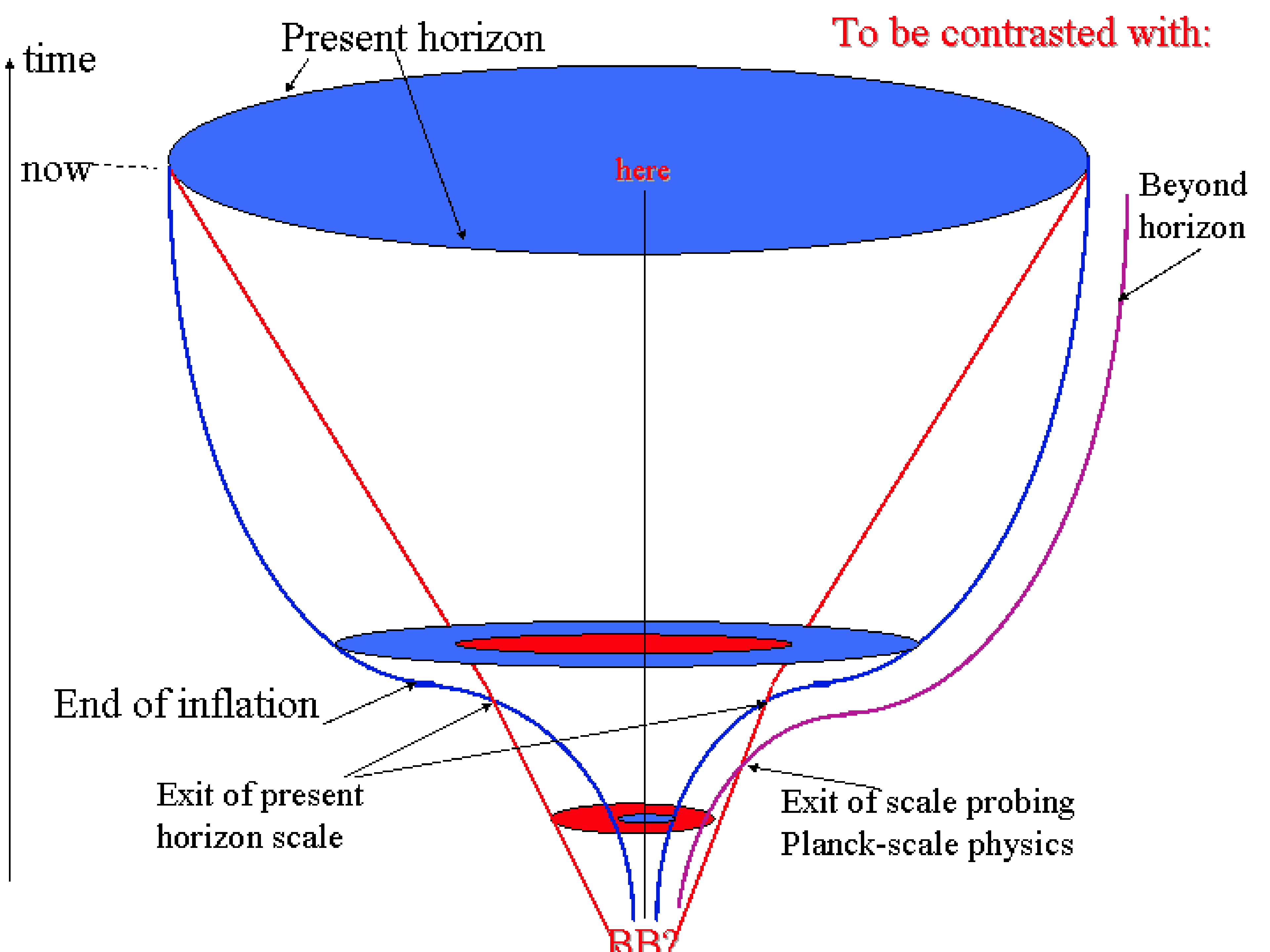
- Cosmo-puzzles
- Two “road-maps”towards a solution
- Standard inflation: input/output balance
- Standard inflation & superstrings: a clash?
- String-inspired cosmologies:
  Pre-big bang, Ekpyrosis, Cyclic, …

The basic assumptions

- For our Universe to be (part of) what came out of one of these collapsing/inflating regions we have to assume that:
  - @ Loop and/or higher-derivative corrections bring about a FRW phase after screening the r=0 BB singularity
  - @ strong coupling non perturbative corrections lift the vacuum degeneracy so that the FRW solution describes the (3+1)-dimensional expanding Universe we live in with frozen couplings and internal dimensions
- Assuming all this, the following pictures will hopefully make sense…..

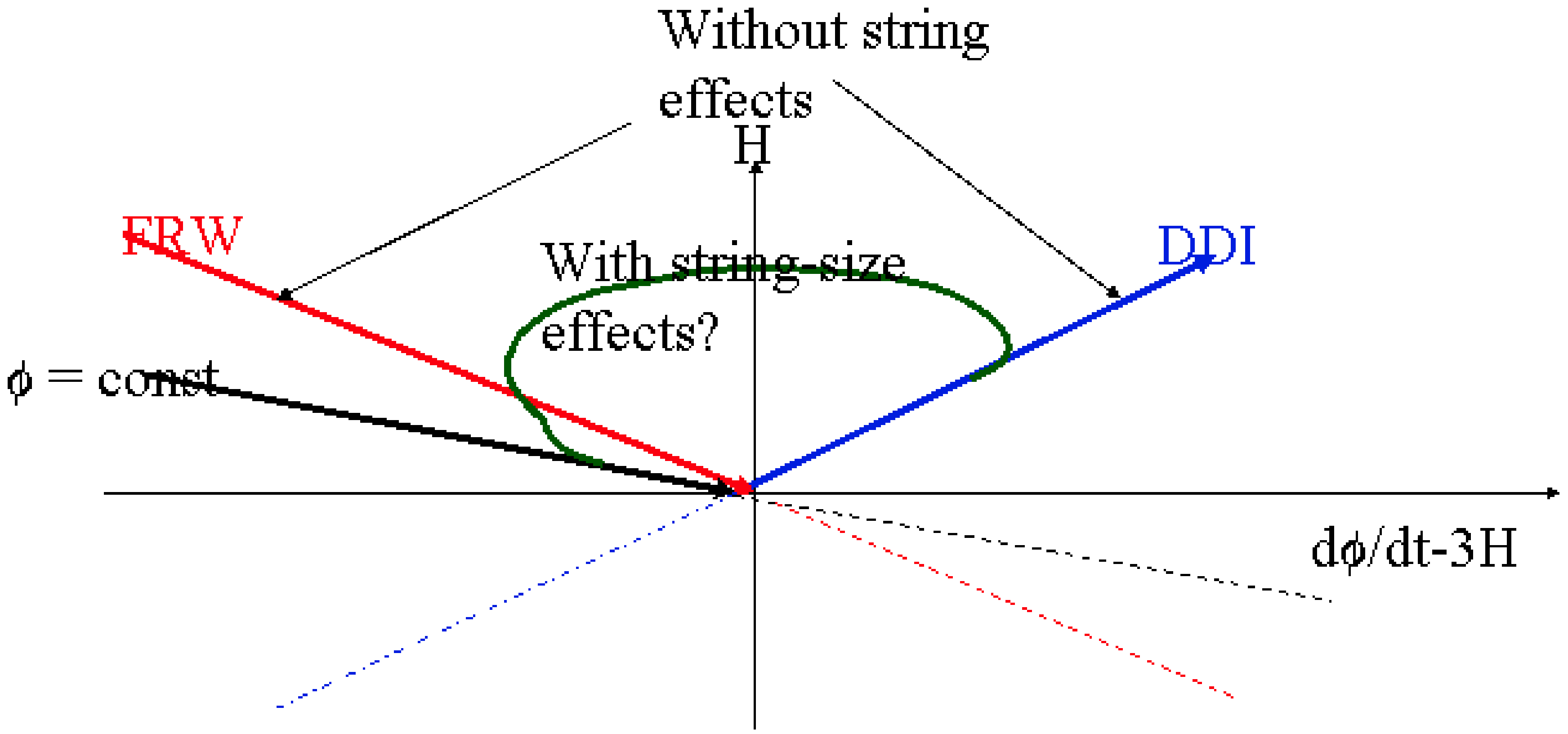

A. Buonanno,
T. Damour &
GV, 1999
Observable U today
H^{-1}
t
Our big bang (r=0)
Another
collapse,
big bang,
Universe
Onset of collapse/inflation
Initial chaotic sea of massless waves


Time
Our horizon today
Scale of clusters
Now
Here
Beyond horizon
only regions inside this cone were able to "talk"
Evolving size of our Universe
decelerating expansion
QG phase not washed out
end of inflationary phase = Big Bang
inflation



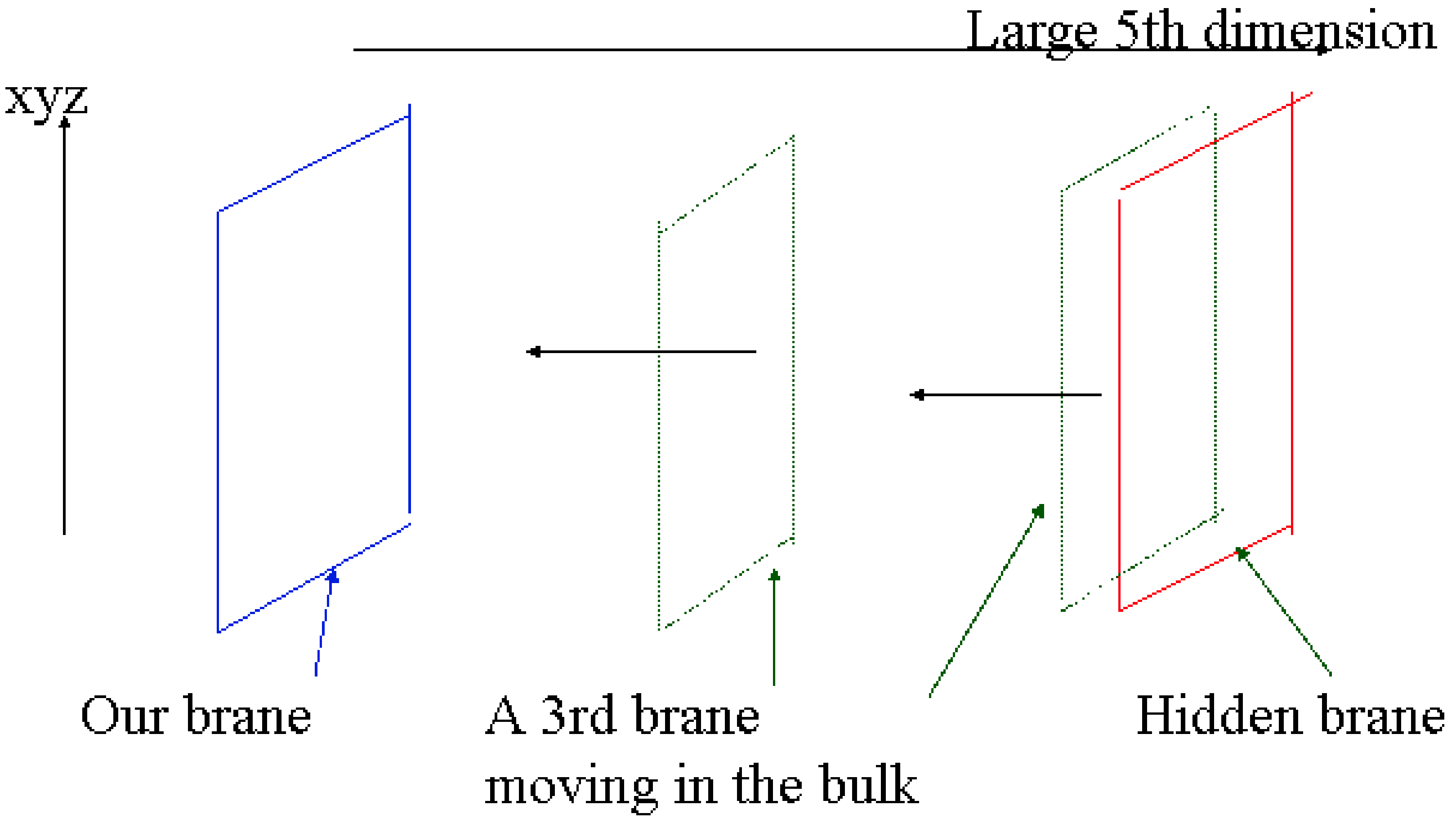
To be contrasted with:
time
Present horizon
now
here
Beyond
horizon
End of inflation
Exit of present
horizon scale
Exit of scale probing
Planck-scale physics
BB?

PBB doc (GV '91, Gasperini & GV '93)



The ekpyrotic Universe

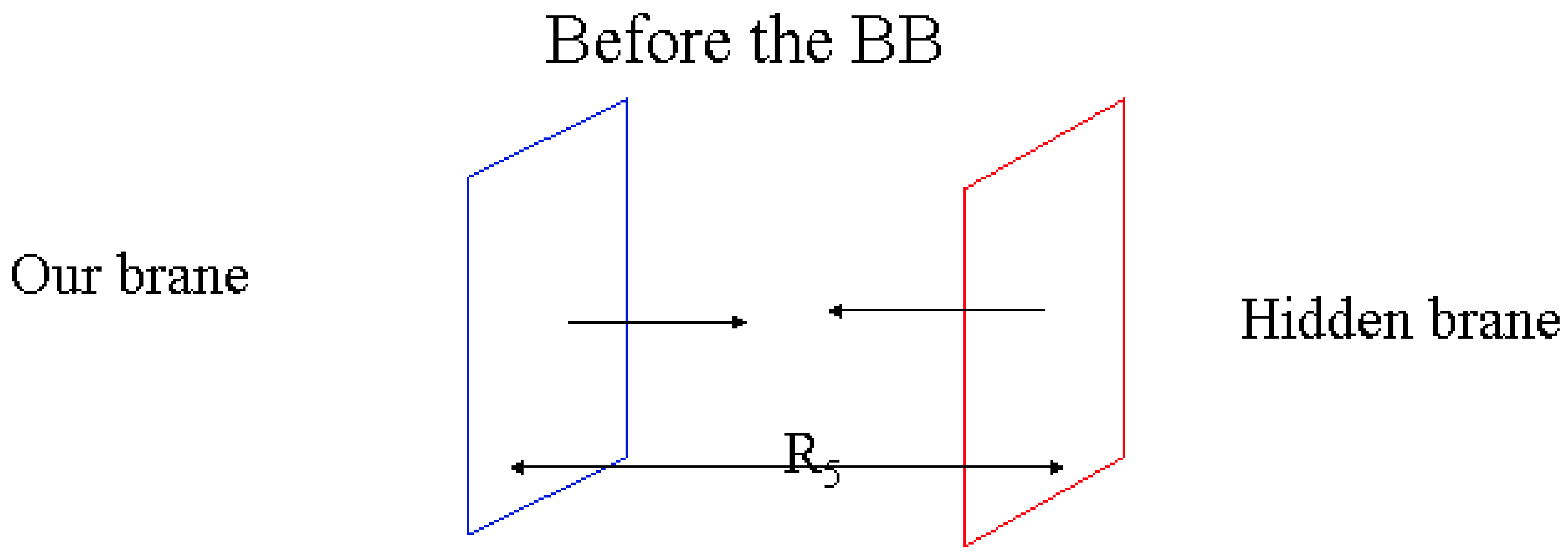
(Khouri, Ovrut, Steinhardt&Turok '01)



BB as result of impact of 3rd brane on ours

PBB renversé (KOST + Seiberg)

(uses Horawa-Witten)

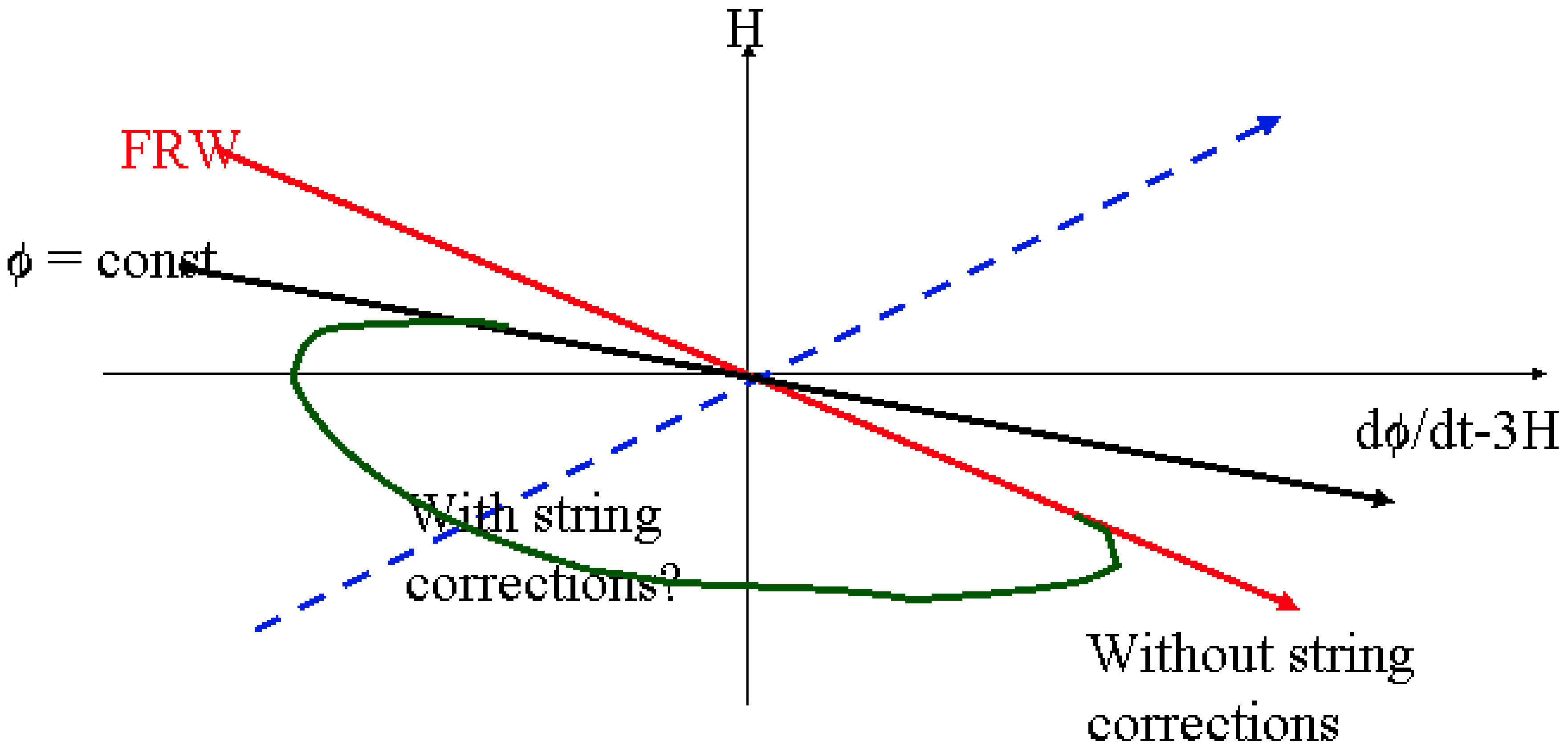


The BB is just due to the collapse of the 5th dimension to zero size. Given the relation between R_5 and the dilaton, this means a BB at zero coupling, i.e. the opposite of what is assumed in PBB doc.

As a result, in this scenario the PBB phase is a contracting phase & the BB is a scale-factor bounce..In both cases it is a curvature bounce

From Big Crunch to Big Bang

(KOSST)



Testing pre-bangian models

- Characteristic predictions stem from several peculiarities of string/M cosmology:
- Primordial evolution towards higher and higher curvature and coupling
- Presence of dilaton and axion fields both as backgrounds and as perturbations
- Extra dimensions of space needed for consistency

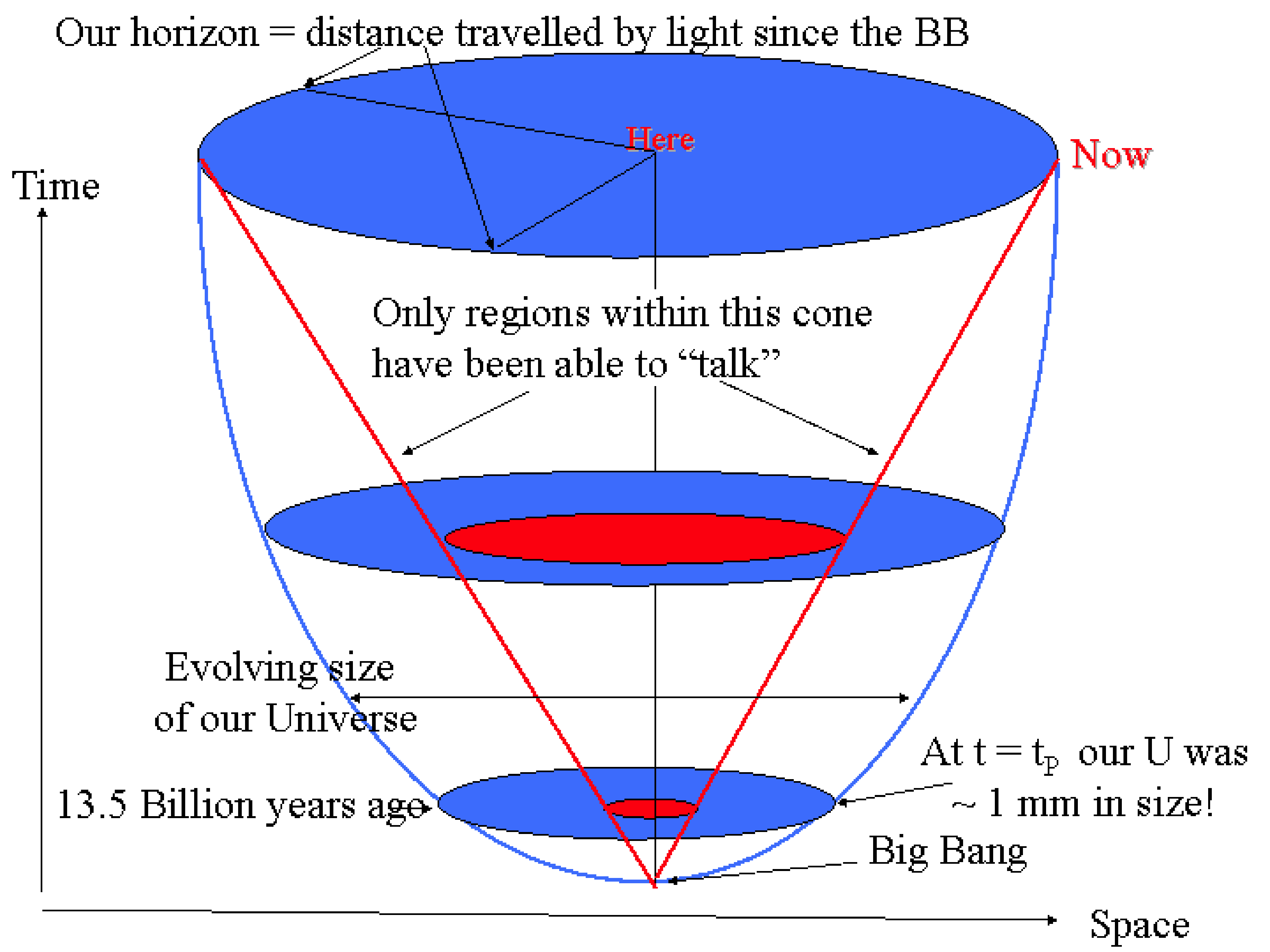
==> 2nd part

OUTLINE OF PART II

- The transplanckian problem revisited
- Perturbations in a non-singular bouncing Universe
- Is the KR axion a good curvaton candidate?
- PBB cosmology: input/output balance
- EKP cosmology: input/output balance
- Conclusions

Cosmo-puzzles: a common origin

- In the standard Big Bang model far-away points on the sky have always been too-far apart to "talk" to each other
- Not enough time has elapsed, since the BB, to establish thermal equilibrium throughout our visible Universe
- The Universe has always been too big to be able to thermalize in the "little" time it had since the BB



Our horizon = distance travelled by light since the BB
Here
Now
Time
Only regions within this cone
have been able to “talk”
Evolving size
of our Universe
At t = t_P our U was
~ 1 mm in size!
13.5 Billion years ago
Big Bang
Space

Two road maps: a smaller or an older Universe?

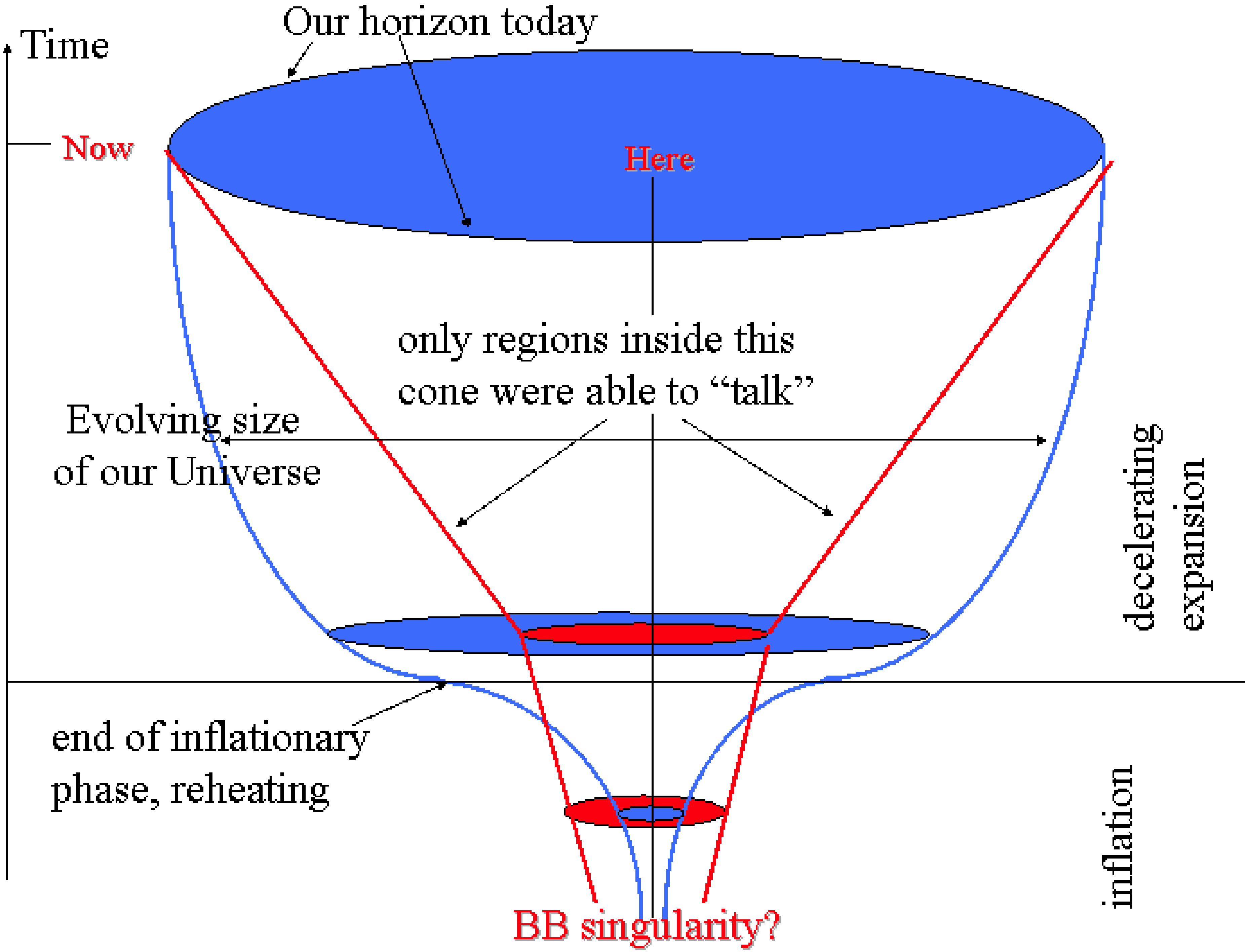
- Stick to the assumption that there was an initial singularity & a beginning of time, and introduce an early phase of accelerated expansion

  => Standard Inflation a la Guth, Linde, ...

- Assume that string theory eliminates (or makes harmless) the BB singularity and postulate a long phase of pre-bangian evolution towards (a non singular version of) the BB

  => Pre-Bang Cosmologies

NB: We discard of course the third solution: extreme fine-tuning of initial conditions



Time
Our horizon today
Now
Here
only regions inside this
cone were able to "talk"
Evolving size
of our Universe
decelerating
expansion
end of inflationary
phase, reheating
inflation
BB singularity?

Standard Inflation

what we put in:

- Classical General Relativity (GR): ***
- An inflaton (a scalar field) ϕ: ** (?)
- A sufficiently flat potential $V(\phi)$: *
- Suitable initial conditions (at least in a patch): ??
  - Large-enough displacement of ϕ from minimum of V
  - Small quantum corrections (displacement not too large)
  - Sufficiently small spatial gradients

what we get out:

- Homogeneity, isotropy (within our patch)
- Flatness: generically, $|\Omega_{tot} - 1| << 1$ (in our patch)
- Quasi scale-invariant ($n_s \sim 1$) spectrum of gaussian, adiabatic, density/curvature (scalar) perturbations S
- Quasi scale-invariant ($n_T \sim 0$) spectrum of tensor perturbations T
- Absolute normalization of S not predicted; ratio T/S related to slow-roll parameter $T/S \sim n_T \sim (n_s - 1) << 1$ (to be checked via polarization of CMB)
- Non-gaussianity computed in simplest models: too small to be measured by MAP/PLANCK (another test?)

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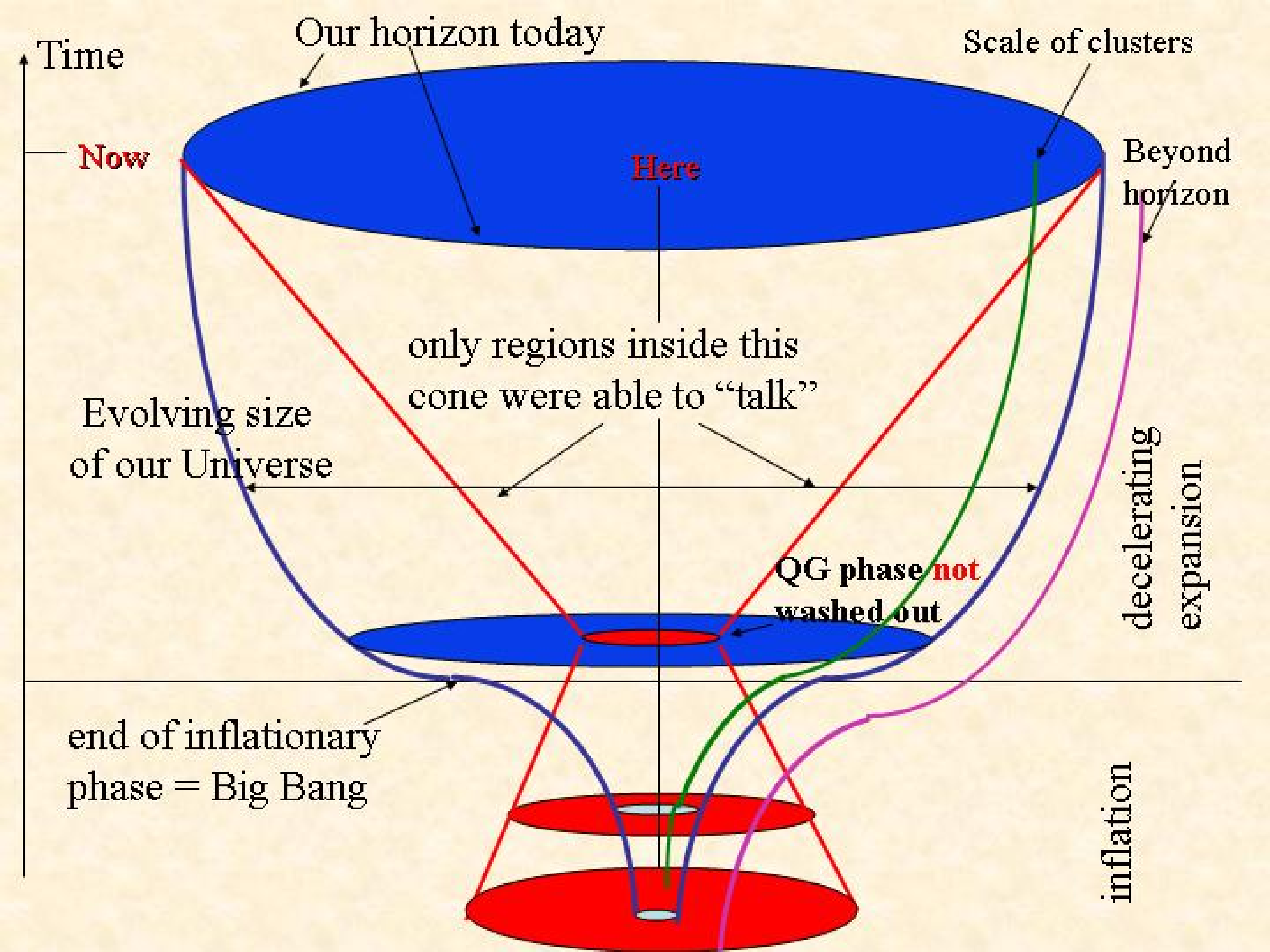
Left as exercises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Perturbations in a bouncing-curvature Universe

(M. Gasperini-M. Giovannini-GV hep-th/0306113+to appear)

Much debated issue: how do we compute correctly the spectrum of adiabatic curvature perturbations in a bouncing-curvature cosmology of the PBB or ekpyrotic (EKP) type?

PBB claims: both tensor and adiabatic scalar perturbations have tilted blue spectra => irrelevant for CMB or LSS

One can have ~ flat isocurvature perturbations but these give wrong structure of acoustic peaks (see part 3)

EKP claims: a blue spectrum of tensor perturbations (GW's) + an almost scale-invariant spectrum of adiabatic scalar perturbations

=> quite some controversy (Lyth, Brandenberger & Finelli, Peter et al., Durrer & Vernizzi, Cartier, Durrer & Copeland... ...Steinhardt, Turok et al. last week..together w/ ours)

A non-singular bouncing-curvature Universe

Solution of a covariant, non-local action:

$$S = -\frac{1}{2\lambda_s^{d-1}} \int d^{d+1}x \sqrt{|g|}\, e^{-\varphi} \left[R + (\nabla\varphi)^2 + V(\overline{\varphi}) \right]$$

$$e^{-\overline{\varphi}(x)} = \int \frac{d^{d+1}y}{\lambda_s^d} \sqrt{|g_y|}\, e^{-\varphi_y} \sqrt{\partial_\mu \varphi(y) \partial^\mu \varphi(y)}\, \delta(\varphi_x - \varphi_y)$$ ==> $\exp(-\phi)\, V_d$ in homogeneous case

NB: $\exp(-\phi)\, V_d \sim g_1^{-2}$ i.e. the reduced coupling in 0+1 dimensions

Example (representative of a large class of non-singular cosmologies)

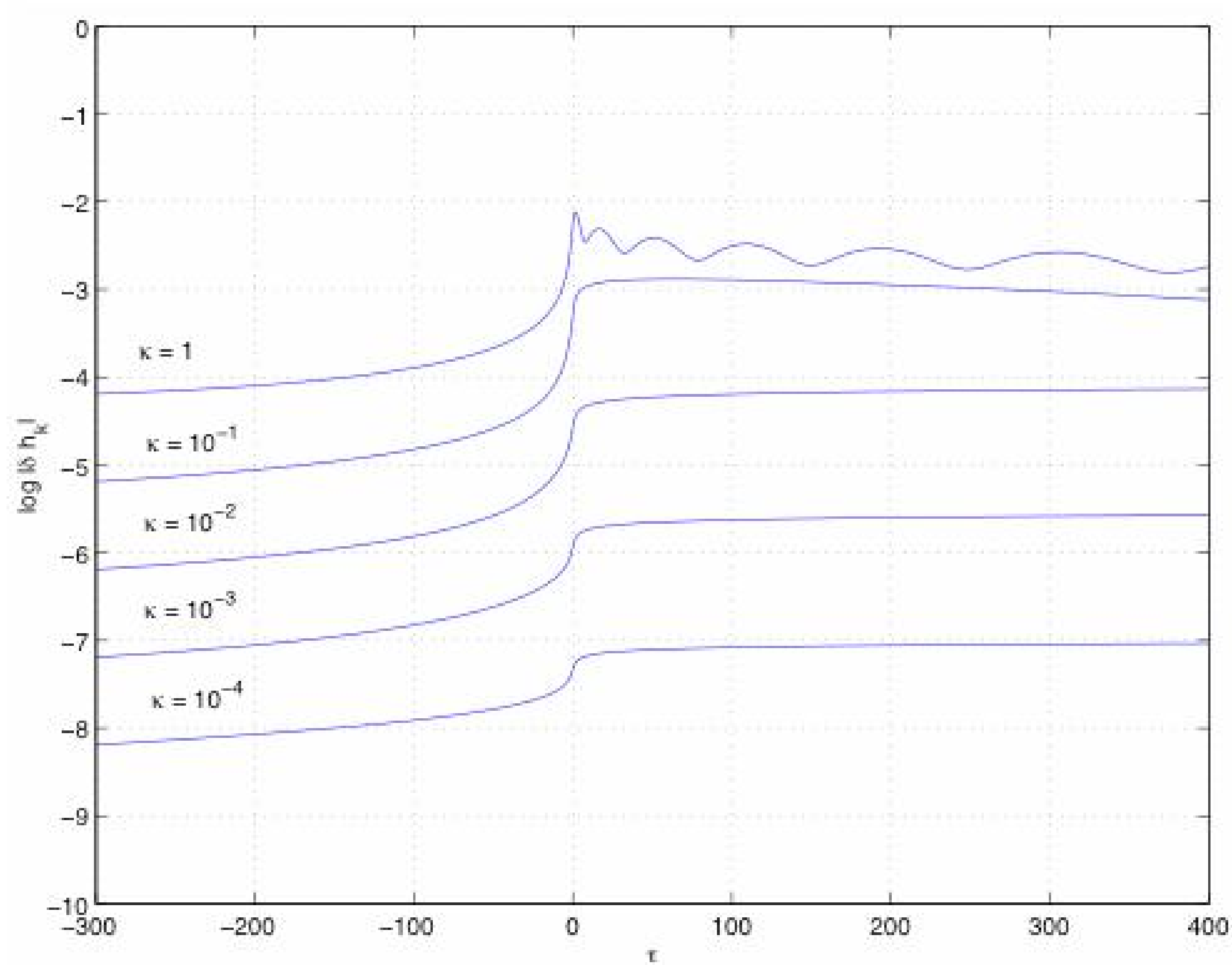
$$V(\overline{\varphi}) = -V_0 e^{4\overline{\varphi}}$$

$$a(\tau) = [\tau + \sqrt{\tau^2 + 1}]^{1/\sqrt{3}}, \qquad \overline{\varphi} = -\frac{1}{2} \ln(1 + \tau^2) + \varphi_0,$$

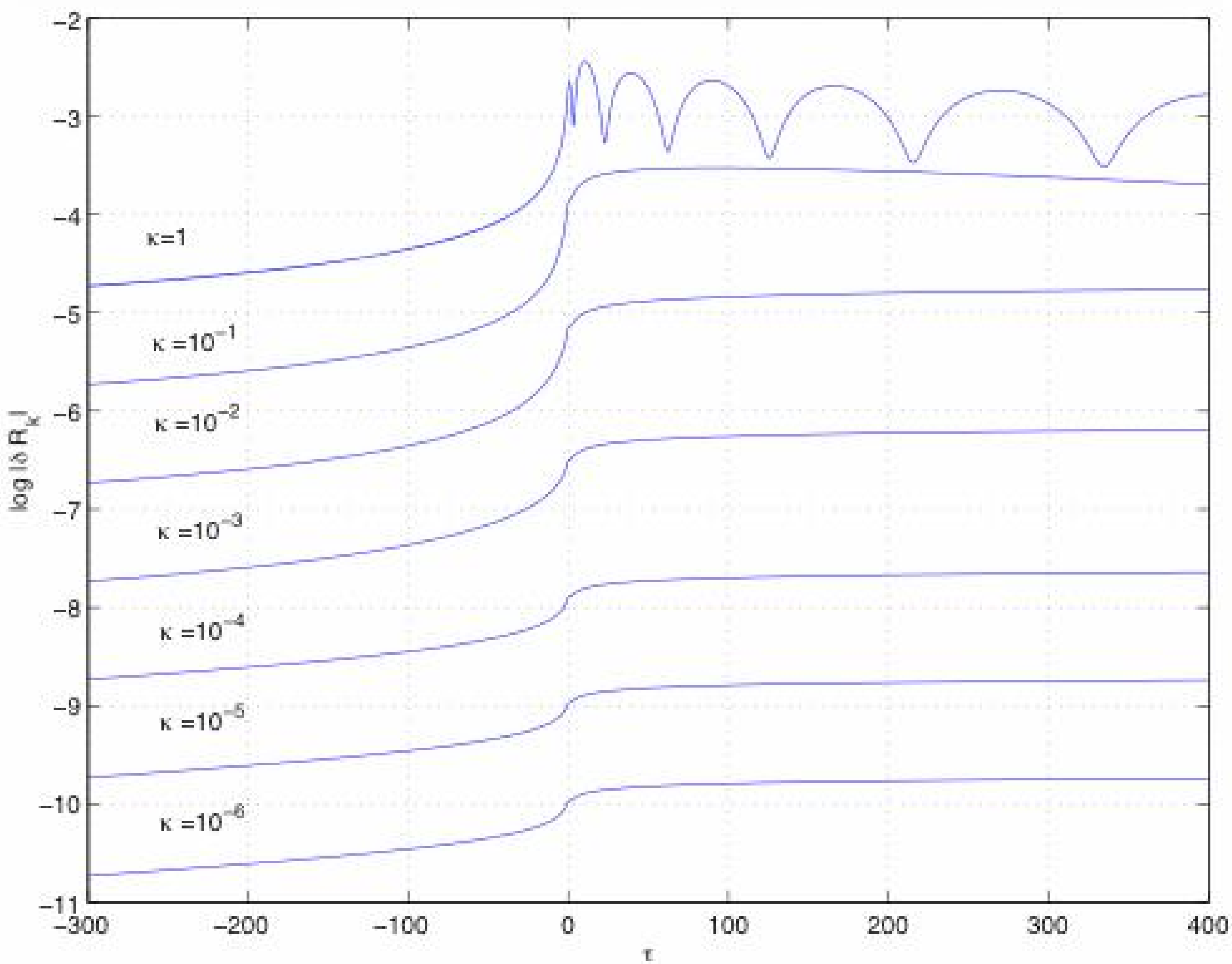
$$\tau = t/t_0$$

Characterized by coupling and curvature-scale at t=0 (the bounce)

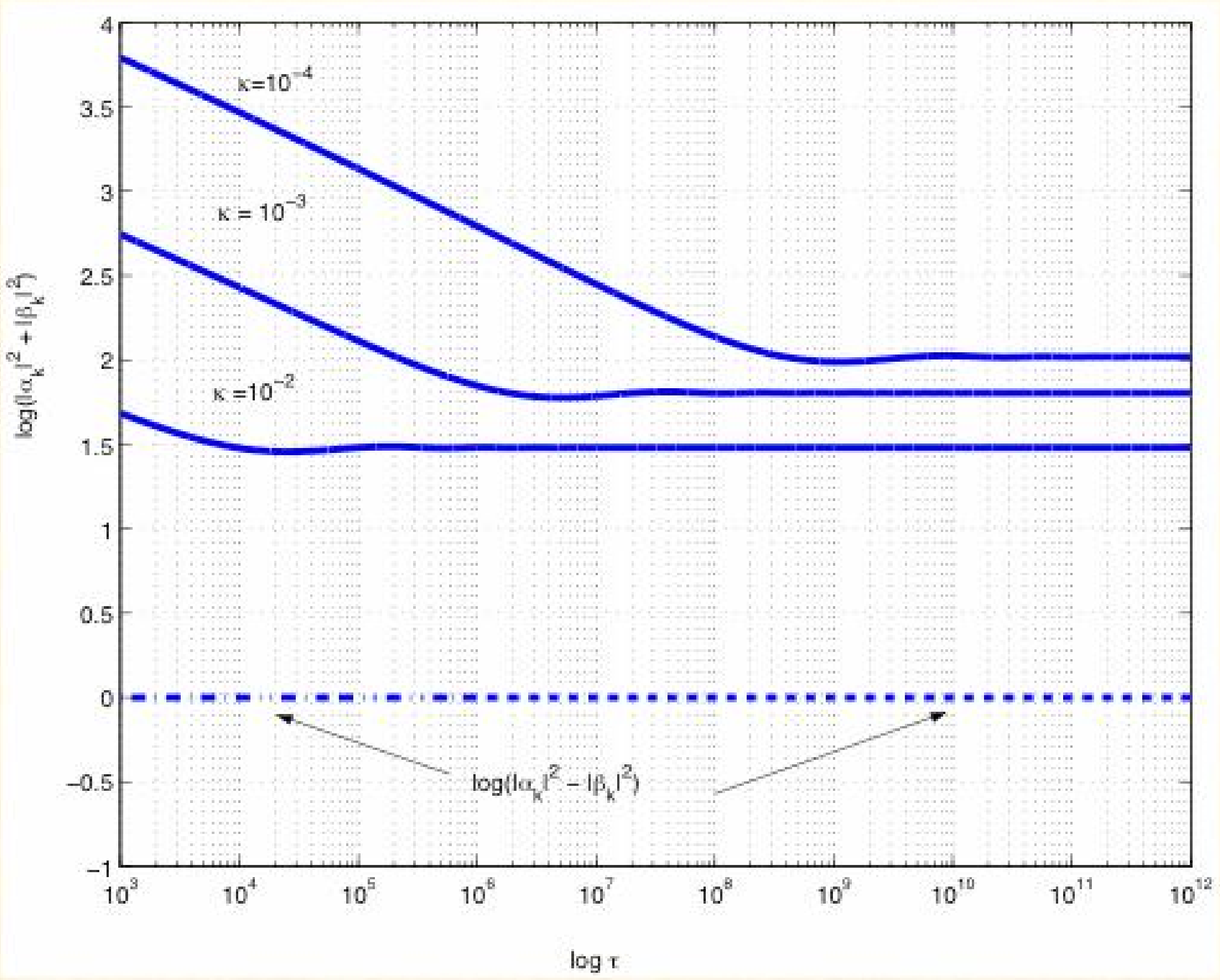
Perturbations can be followed from beginning to end



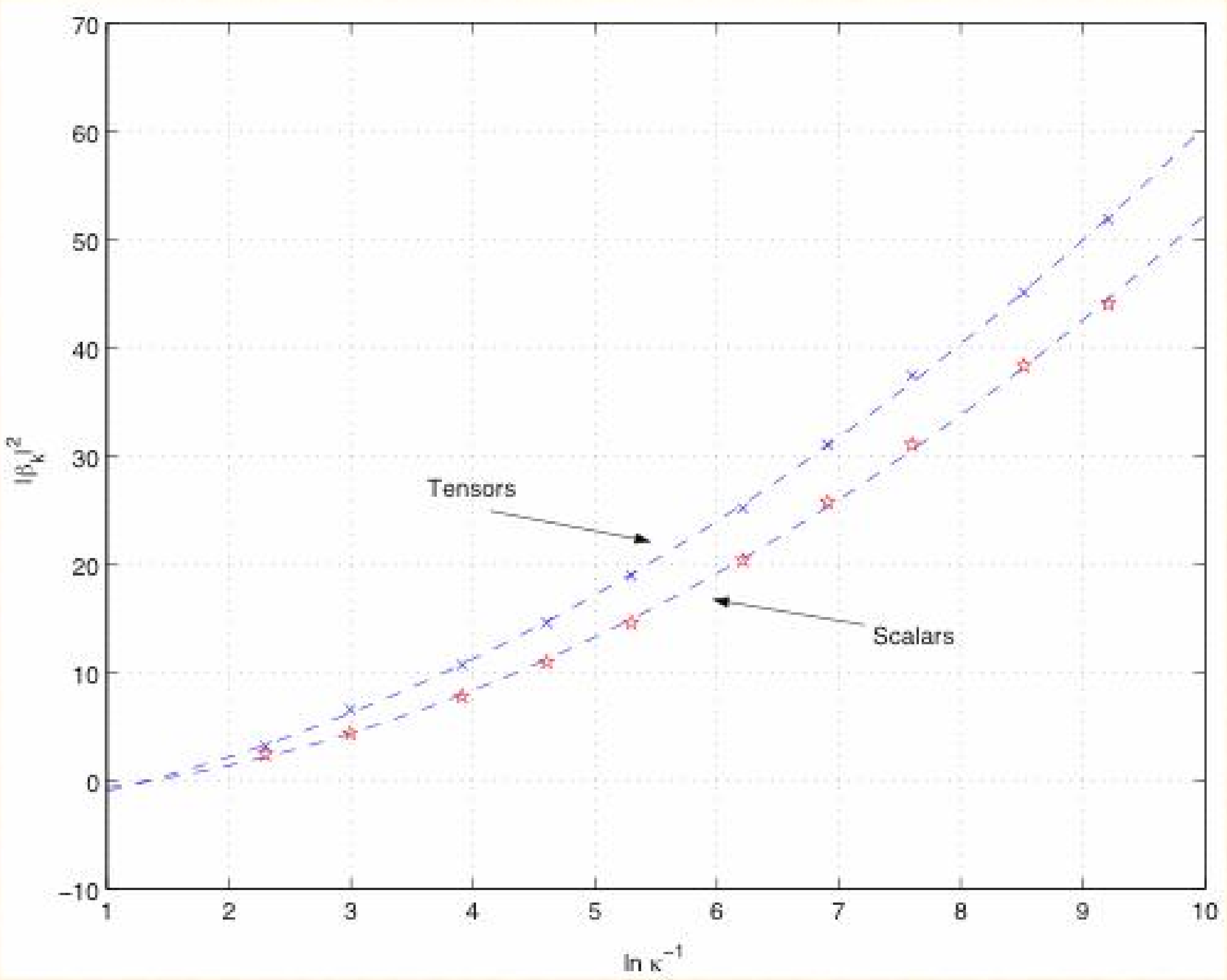
Tensor perturbations going across bounce for different k



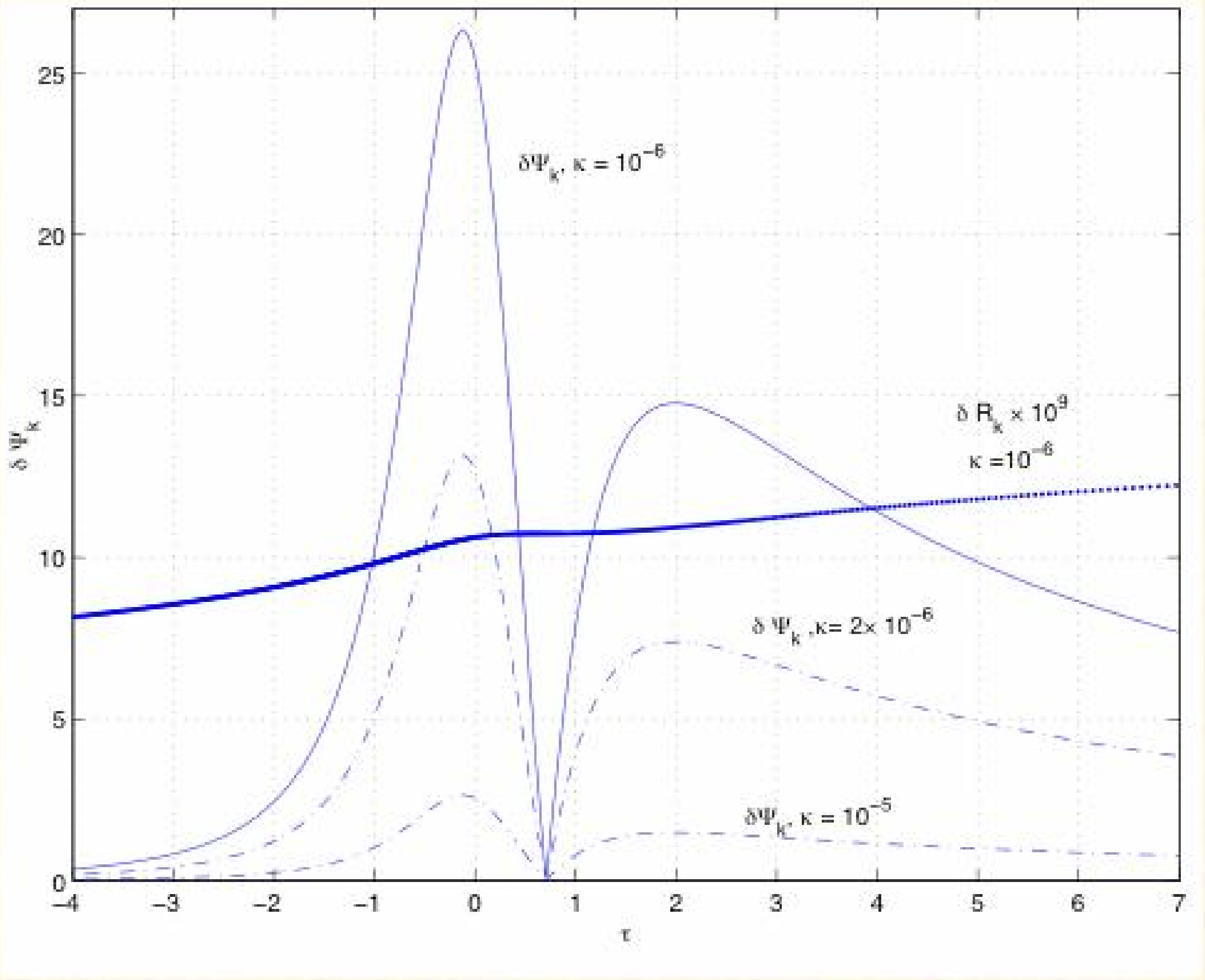
Curvature perturbation on comoving slices R going across bounce



Tensor mixing coefficients (asymptotically related to Bogolubov)



Fitting numerical results for T &S to analytic expectations ~ $\ln^2 k$



Comparing behaviour of R and of Bardeen potential Ψ across the bounce

Is this bad news for PBB and EKP cosmology?

Perturbations in PBB cosmology

- Gravitational waves: $n_T = 3$ (insensitive to extra dim.s)

=> Good for detection, irrelevant for CMB, LSS

- Adiabatic dilaton/curvature perturbations: $n_S = 4$ (from previous discussion)

=> Hard to detect, irrelevant for CMB, LSS

- Photons: not as blue, but still blue, sensitive to evolution of internal dimensions and to details of $U(1)_{em}$ embedding: the whole effect is due to the time-dependence of f ...

=> Seeds of Cosmic Magnetic fields?

The transplanckian "problem" revisited

(V. Bozza-M. Giovannini-GV hep-th/0302184)

- Minimal duration of inflation to solve homogeneity/flatness problems: > 65 e-folds needed, >> expected ?
- Most (if not all) cosmologically interesting scales were sub-Planckian at the beginning of the inflationary epoch

Two sides of same coin:

☆ Are the predictions of inflation robust? E.g. QM gives:

$h_{TT} \sim l_P \, \omega_{in} > 1$ => is linear perturbation theory justified?

◷ Are CMB predictions sensitive to unknown physics?

Is CMB a window on transplankian physics?

- KR-axions: blue, red or flat (the good news...)

$$|\delta\sigma_k|^2 = (H^*/M_P)^2 \, (\omega/\omega^*)^{n_\sigma - 1}; \quad (4-2\sqrt{3}) \sim 0.53 < n_\sigma < 2$$

($H^* \sim M_s$, $\omega^* \sim M_s\, a^*/a_0 \sim 10^{11}$ Hz, σM_P = can. axion field)

Flat spectrum ($n_\sigma = 1$) for symmetric 9-d evolution (mod. T-duality). Again t-dependence of ϕ plays a crucial role...

- KR axion gives isocurvature (entropy) perturbations (the bad news...)
- Its fluctuations appear quadratically in S_{eff}

=> no mixing to first order w/ metric pert.s (unlike dilaton)

- Isocurvature perturbations give "wrong" structure of acoustic peaks (DGMVV) (Cf. Boomerang, Maxima, DASI, WMAP,...

However:

Is the KR axion a good "curvaton"?

(Bozza, Gasperini,Giovannini,&GV, PLB 543 & hep-ph/ 0206131-0212112)

- If V_σ generated (by PQ-symmetry breaking), and if $\langle\sigma\rangle$ is not initially at its minimum, axion pert.s induce calculable curvature pert.s. This "curvaton" idea (M,LWC,ES, LW, MT,BP, ...BGGV) needs
  - phase of axion "dominance", $\Omega_\sigma = O(1)$
  - axion decay before NS ($m_\sigma > 10$ TeV)
- Conversion efficiency can be computed. Bardeen potential Φ_k at decay if $\Omega_\sigma=1$

$$|\Phi_k|^2 = f^2(\sigma_i)\,|\delta\sigma_k|^2 = f^2(\sigma_i)\,(H^*/M_P)^2\,(\omega/\omega^*)^{n_\sigma-1}$$

$$f(\sigma_i) \sim (0.13\,\sigma_i + 0.18/\sigma_i) > 0.3$$

- COBE normalization: $C_2 = (1.09 +/- 0.23)10^{-10}$ to be compared with

$C_2 = \alpha_n^2\, f^2(\sigma_i)\, (H_1/M_P)^2\, (\omega_0/\omega^*)^{n_\sigma - 1}$; $\alpha_n^2 \sim (1/54\pi)$; $f^2(\sigma_i) \sim 0.1$ (n_σ, $\sigma_i \sim 1$)

=> acoustic-peaks come out fine provided primordial axion spectrum is nearly flat ($n_\sigma \sim 1$) and appropriately normalized.

=> PBB parameter space consistent with CMB observations: see figure (a possible break δ in the tilt n_σ has been inserted above the AP scale)

A particularly simple case: $n_\sigma = 1$, $\delta = 0$, $(H^*/M_P) \sim 0.5\ 10^{-3}$

In general slightly blue spectra ($n_s > 1$) and/or low (H^*/M_P) preferred

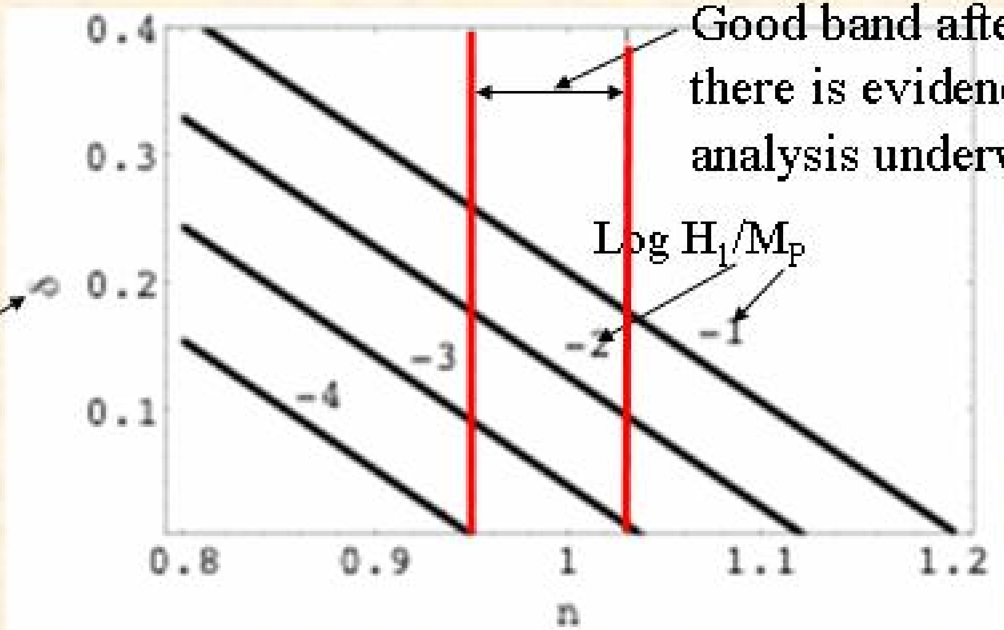
Q: Is standard inflation really doing better than this with its fine-tuning of inflaton potentials and an arbitrary normalization?

PBB parameter-space in the axion=curvaton scenario

Good band after WMAP (actually there is evidence for n'≠ 0, better analysis underway)

$\sigma_i = 1$

Break in spectrum

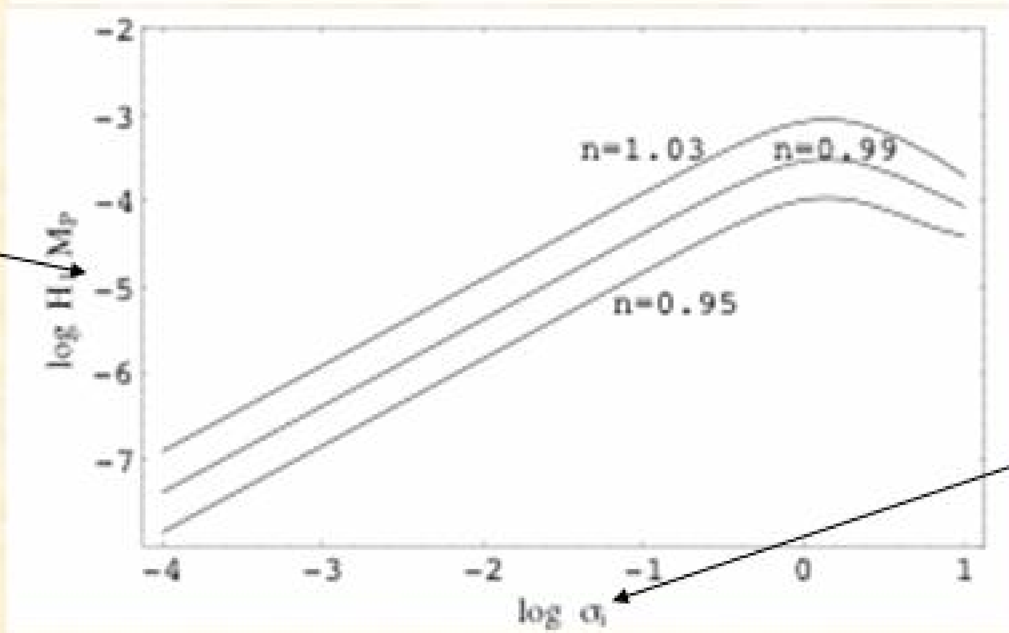


Is $H_1 \sim M_s$?

How large is M_s / M_P?

Log H_1/M_P

$\delta = 0$



Initial displacement of axion from mimimum of potential

Main conclusions on part II

- Inflation's predictions on LSS look quite robust wrt trans-planckian physics: good or bad?

- Within a non-singular bouncing cosmology model perturbations support the old PBB claim of blue S and T spectra rather than the EKP claim of flat S and blue T perturbations

- Best way to rescue the phenomenological viability of bouncing cosmologies consists of adding a non vanishing $\delta p_{na} = \delta p - p'/\rho' \, \delta\rho$ ==> curvaton mechanism
- String theory has a good curvaton candidate: the KR axion. Parameter space is constrained by existing data (particularly after WMAP)
- Detailed predictions are different from those of standard slow-roll inflation (small T, possible non-gaussianity and/or isocurvature component)...and can/will be tested

CONCLUSIONS

Cosmology looks like the most promising way to put String Theory to experimental verification. Why?

Only the Universe as a whole is a powerful enough accelerator to allow us to test the laws of physics at length scales at which the difference between points and strings becomes crucial

(a welcome use of the singularity theorems?)

The cosmological redshift kindly blows up those tiny distances to a more human scale (e.g. the CMB)

Observational cosmology presents us today with a number of puzzles...and so does gravity, both classically and at the quantum level

These puzzles are among the deepest questions physics has ever encountered since the beginning of last century

String theory is, at present, the only available consistent framework in which such questions can and should be asked, since

“PHYSICS THRIVES IN CRISES”

(S. Weinberg, 1988, on the Cosmological Constant)

Finally, if the building of the standard model of particle physics can teach us something, a good blending of bottom-up and top-down is the best guarantee for progress in fundamental physics

For that to be possible, theory and experiments must fulfill comparable standards of precision and reliability

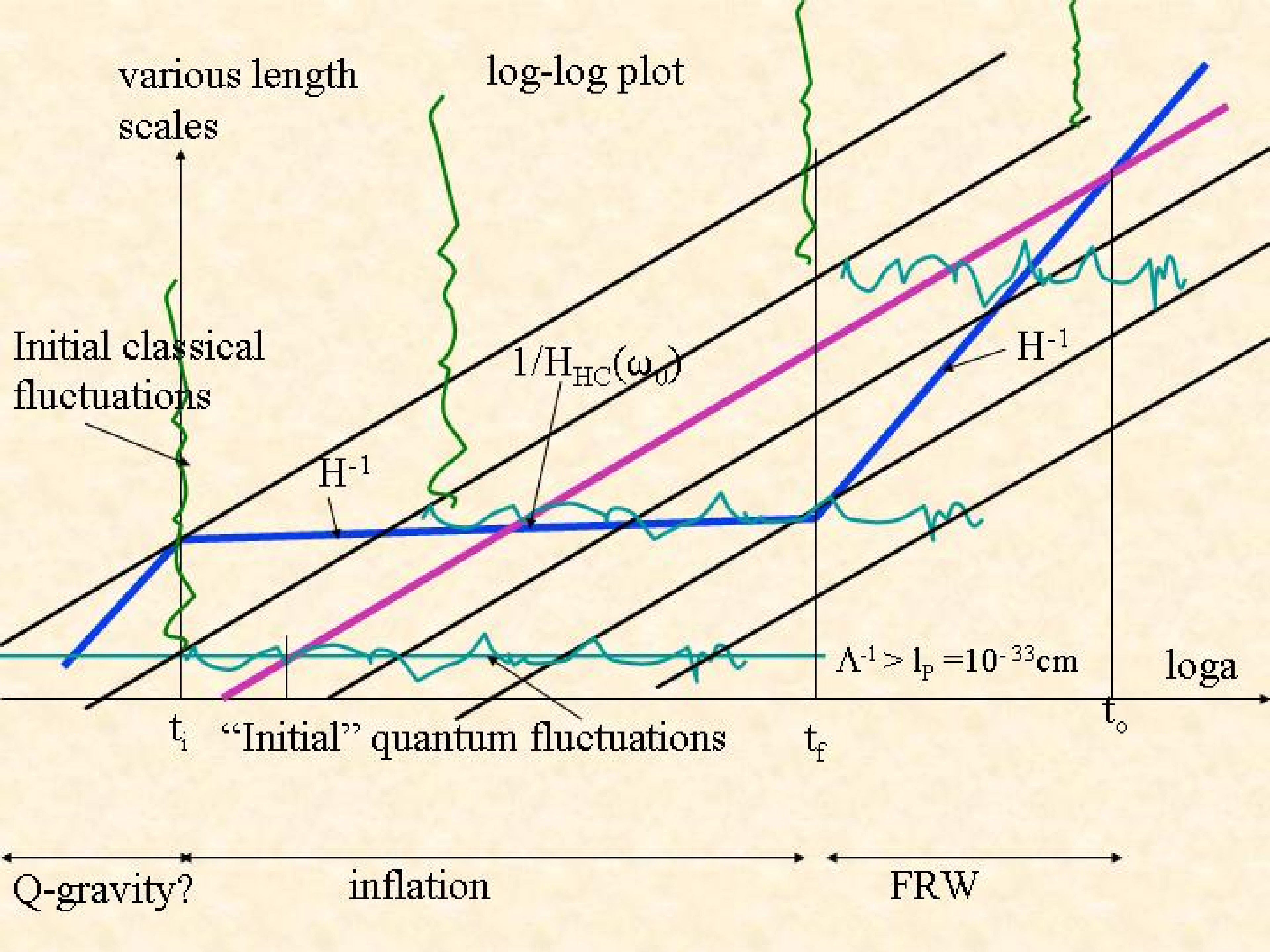
Such standards appear to be met today in the field of observational cosmology (see, e.g. WMAP data) and, hopefully, will be met by string/M theory in the not-too-distant future…

LET'S GO FOR IT!

Classical vs. Quantum fluctuations

Standard inflation's lore:

- Initial classical inhomogeneities are washed out.
- Replaced by a calculable spectrum of amplified quantum fluctuations => observed LSS of the Universe.
- Why are the latter not washed out as well? After all classical & quantum fluctuations evolve according to the same evolution equations.
- The (well known?) answer is that initial classical fluctuations are there just…initially, while quantum fluctuations are created all the time at different scales (with a magnitude controlled by the Uncertainty Principle)



various length scales
log-log plot
Initial classical fluctuations
H^{-1}
$1/H_{HC}(\omega_0)$
H^{-1}
$\Lambda^{-1} > l_P = 10^{-33}$cm
loga
t_i
"Initial" quantum fluctuations
t_f
t_o
Q-gravity?
inflation
FRW

Cosmological perturbations from a NPH

Admit ignorance about physics beyond an energy scale Λ (e.g. Λ = M_P or M_s)

A model-independent way to proceed is:

1. Introduce a "New-Physics-Hypersurface" or NPH, defined, for each scale $\lambda = a\, k^{-1}$, by $\lambda = \Lambda^{-1}$
2. Give "initial conditions" on the NPH
3. Discuss sensitivity of today's observables upon such a choice of initial conditions

- Early work by Starobinsky (contains most of main ideas)
- Claim by U. Danielsson (PRD 66, 2002): by choosing some initial conditions on the NPH one gets corrections to standard (de-Sitter inflation) predictions of $O(H/\Lambda)^{*)}$ times rapidly oscillating factors ~ $\sin(\Lambda/H)$ => possibly observable?

- UD simply minimized the Hamiltonian for each mode on the NPH, something looking very reasonable, even conservative, but…

****

*) In standard Infl. $H/M_P < 10^{-5}$ but in PBB or EKP cosm. It may grow up to $O(M_s/M_P \sim 1/10)$ before the bounce, relevant issue for exit problem?

…but…which Hamiltonian?

- In a time-dep. QM problem the Hamiltonian H is not conserved, worse it is ambiguous, e.g. changes under canonical transformations…
- Is QM ambiguous? Certainly not! All physical predictions are independent of choice of H
- States & operators for diff. H's are related by unitary transformations => same $\langle O_i \rangle$ for each observable O_i
- **The subtle point**: in spite of above, minimizing different H's at a given "initial" time defines physically different "initial" states and thus leads to different results

Example: tensor perturbations

$$S = \frac{1}{2}\int d^4x\, a^2\, \eta^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi\,, \quad \Psi = \frac{h}{\sqrt{2}\,\ell_P}.$$

$$H^{(1)}(\eta) = \int d^3x \frac{1}{2}[\frac{\Pi^2}{a^2} + a^2(\partial_i\Psi)^2]$$

$$H^{(2)}(\eta) = \int d^3x \frac{1}{2}[\pi^2 + 2\mathcal{H}\psi\pi + (\partial_i\psi)^2]$$

$$H^{(3)}(\eta) = \int d^3x \frac{1}{2}[\tilde{\pi}^2 + (\partial_i\psi)^2 - \frac{a''}{a}\psi^2]$$

$$\Pi = a^2\Psi', \quad \psi = a\Psi, \quad \pi = \frac{\Pi}{a}, \quad \tilde{\pi} = \psi'$$

UD used $H^{(2)}$ to evolve but defined state on the NPH by minimizing $H^{(1)}$.

BGV repeated the calculation using $H^{(1)}$ throughout, reproduced (generalized) UD's result (to power-law inflation)

BGV also repeated the calculation minimizing $H^{(2)}$ or $H^{(3)}$ on the NPH and obtained completely different size for the corrections, $O((H/\Lambda)^2)$ and $O((H/\Lambda)^3)$, respectively

No solid prediction but it looks that minimizing $H^{(3)}$ is the most sensible thing to do….

minimizing $H^{(1)}$ problematic even today (Starobinsky+Tkachev)

NB: In general $H = H_{exNPH}$ depends on scale

Most adiabatic Hamiltonians give smallest (& unobservable?) effects

Perturbations in string-inspired cosmologies