

# Non-Equilibrium Cosmologies and Astroparticle Phenomenology

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# OUTLINE

- **WHY NON-EQUILIBRIUM COSMOLOGIES?** Theoretical models and ideas on the Early Universe: from Brane worlds to space-time foam pictures
- **WHAT CONSEQUENCES ?** Models of Early Universe implying quantum decoherence (gravity environment), microscopic time irreversibility (fundamental CPT Violation), Dissipation, Off-shellness of Einstein's eqs.
- **WHAT KIND OF PHENOMENOLOGY ?**
  - Astrophysics: ( → V. Mitsou talk)
    - (i) Supernovae Data
    - (ii) Cosmic Microwave Background Anisotropies (CMB) (WMAP etc.)
    - (iii) Baryonic Acoustic Oscillations .....
  - Particle & Atomic Physics Tests of CPT Violation:
    - Neutral mesons, antimatter factories, atomic physics, Low energy atomic physics experiments, Ultra cold neutrons, Neutrino Physics, Terrestrial & Extraterrestrial tests of Lorentz Invariance (modified dispersion relations of matter probes: GRB, AGN photons, Crab Nebula synchrotron-radiation...)

# CPT THEOREM

**C**(harge) -**P**(arity=reflection) -**T**(ime reversal) **INVARIANCE** is a property of any quantum field theory in Flat space times which respects:

(i) **Locality**, (ii) **Unitarity** and (iii) **Lorentz Symmetry**.

$$\Theta \mathcal{L}(x) \Theta^\dagger = \mathcal{L}(-x) ,$$

$$\Theta = CPT , \quad \mathcal{L} = \mathcal{L}^\dagger \text{ (Lagrangian)}$$

Theorem due to: Jost, Pauli (and John Bell).

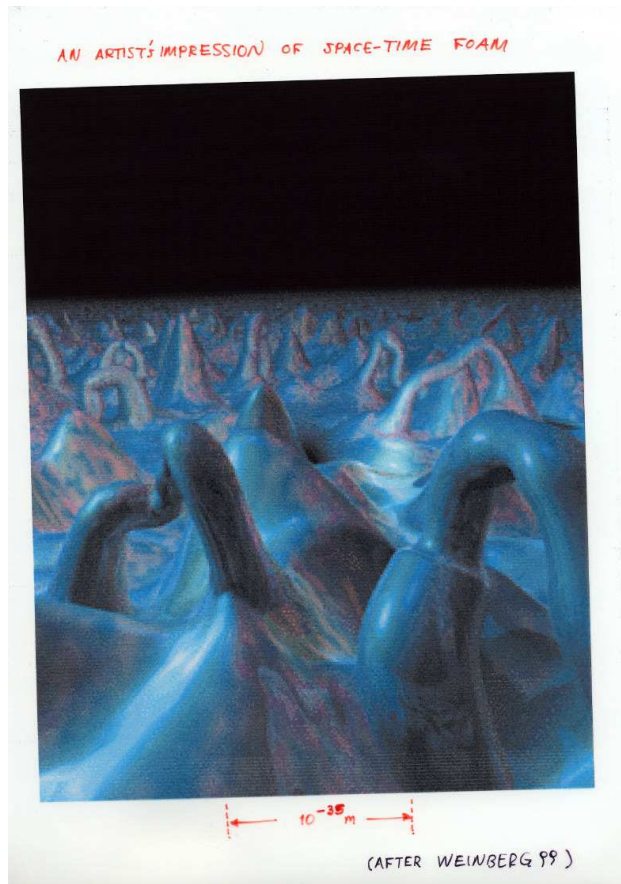
Jost proof uses covariance trnsf. properties of Wightman's functions (i.e. quantum-field-theoretic (off-shell) correlators of fields  $\langle 0 | \phi(x_1) \dots \phi(x_n) | 0 \rangle$ ) under Lorentz group. (O. Greenberg, hep-ph/0309309)

Theories with **HIGHLY CURVED SPACE TIMES** , with space time boundaries of black-hole or cosmic horizon type, may **violate (ii) & (iii)** and hence **CPT**.

**E.g.: SPACE-TIME FOAMY SITUATIONS IN QUANTUM GRAVITY.**

**E.g.: SPACE-TIMES WITH COSMOLOGICAL CONSTANT (de Sitter)**

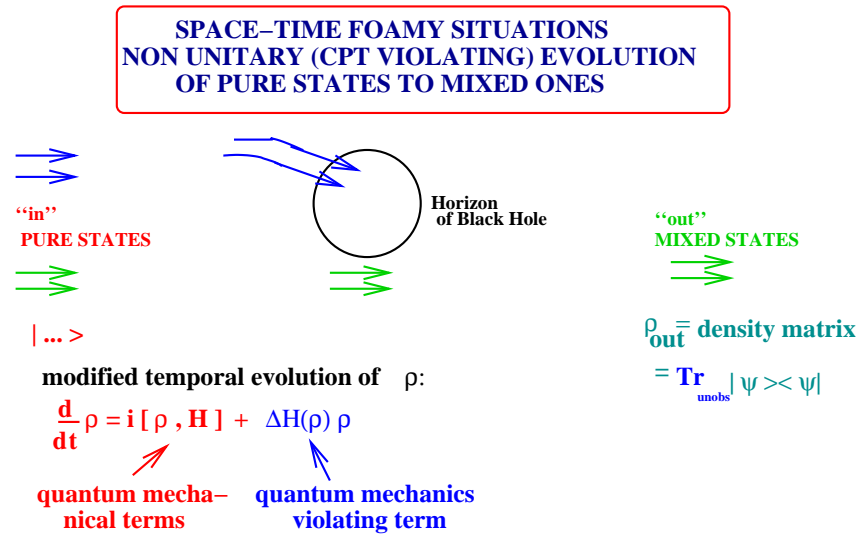
# SPACE-TIME FOAM



Space-time **MAY BE DISCRETE** at scales  $10^{-35}$  m (**Planck**) → **LORENTZ VIOLATION (LV)?** (and hence **CPTV**); also there may be **ENVIRONMENT** of **GRAVITATIONAL d.o.f.** **INACCESSIBLE** to low-energy experiments (**non-propagating d.o.f.**, **no scattering, topology-changing**) → **CPT VIOLATION** (and may be **LV**)

**EARLY UNIVERSE:** might be characterised by intense foamy environments

# FOAM AND UNITARITY VIOLATION



SPACE-TIME FOAM: Quantum Gravity SINGULAR Fluctuations (microscopic (Planck size) black holes etc) **MAY** imply: pure states  $\rightarrow$  mixed

$\$ \neq S S^\dagger$ ,  $S = e^{iHt}$  = scattering matrix,  $\$ = \text{non invertible}$ , unitarity lost in effective theory.

**BUT...HOLOGRAPHY** can change the picture (Strings in anti-de-Sitter space times (Maldacena, Witten), Hawking 2003- superposition of space-time topologies (Quantum Gravity) (but in Euclidean space time) may solve info-problem?: observer not quite sure (in QG) if the BH is there) **BUT NO PROOF AS YET**

... **OPEN ISSUE**

## SPACE-TIME FOAM and Intrinsic CPT Violation

A THEOREM BY R. WALD (1979): **If  $S \neq S^\dagger$ , then CPT is violated, at least in its strong form.**

PROOF:

Suppose CPT is conserved, then there exists unitary, invertible operator  $\Theta$  :

$$\Theta \bar{\rho}_{in} = \rho_{out}$$

$$\rho_{out} = S \rho_{in} \rightarrow \Theta \bar{\rho}_{in} = S \Theta^{-1} \bar{\rho}_{out} \rightarrow \bar{\rho}_{in} = \Theta^{-1} S \Theta^{-1} \bar{\rho}_{out}$$

But  $\bar{\rho}_{out} = S \bar{\rho}_{in}$ , hence :  $\bar{\rho}_{in} = \Theta^{-1} S \Theta^{-1} S \bar{\rho}_{in}$

BUT THIS IMPLIES THAT  $S$  HAS AN INVERSE-  $\Theta^{-1} S \Theta^{-1}$ , **IMPOSSIBLE** (information loss), hence **CPT MUST BE VIOLATED** (at least in its strong form).

NB: IT ALSO IMPLIES:  $\Theta = S \Theta^{-1} S$  (fundamental relation for a full CPT invariance).

**NB: My preferred way of CPTV by Quantum Gravity**

**Introduces fundamental arrow of time/microscopic time irreversibility**

## CPT SYMMETRY WITHOUT CPT SYMMETRY?

**But...nature may be tricky:** WEAK FORM OF CPT INVARIANCE might exist, such that the fundamental “arrow of time” does not show up in any experimental measurements (scattering experiments) → Probabilities for transition  $\psi = \text{initial pure state} \rightarrow \phi = \text{final pure state}$  ( i.e. “in” and “out” Decoherence-free (expt.) subspaces )

$$P(\psi \rightarrow \phi) = P(\theta^{-1}\phi \rightarrow \theta\psi)$$

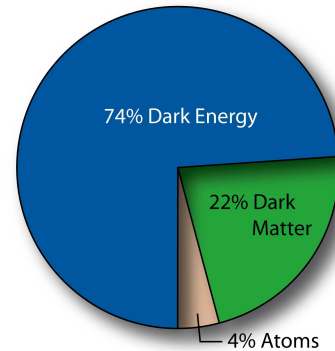
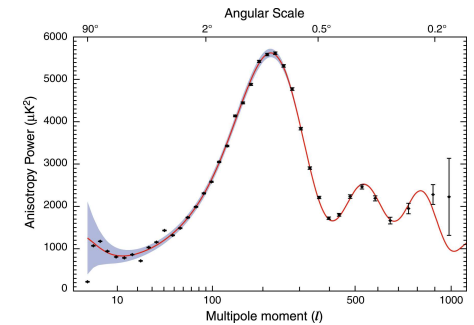
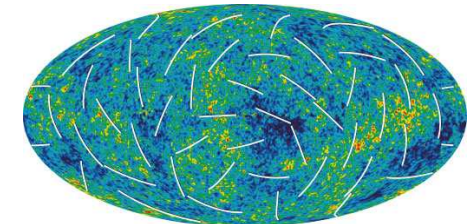
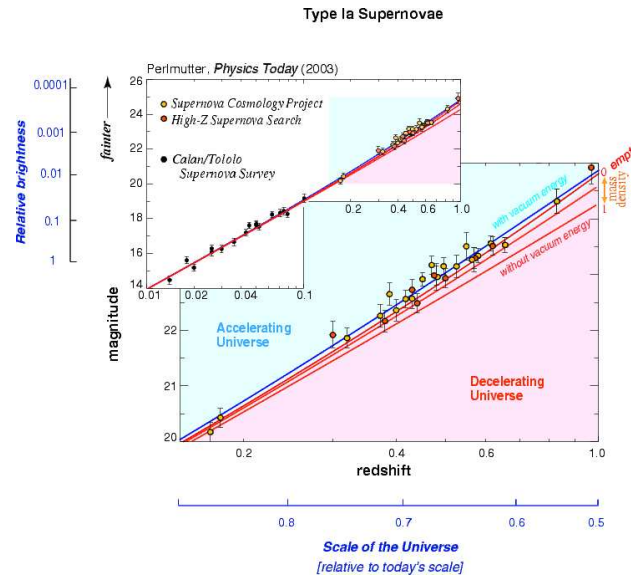
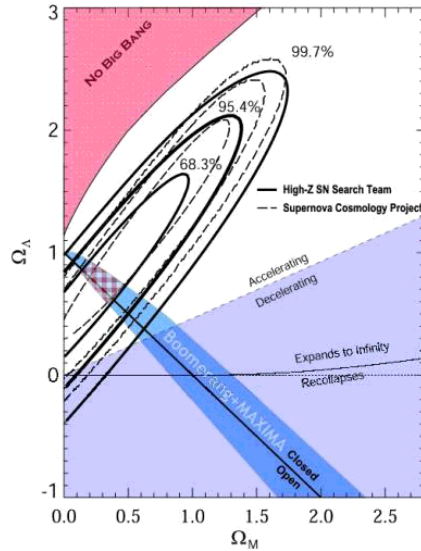
$\theta: \mathcal{H}_{\text{in}} \rightarrow \mathcal{H}_{\text{out}}, \Theta\rho = \theta\rho\theta^\dagger, \theta^\dagger = -\theta^{-1}$  (anti – unitary),  $\$^\dagger = \Theta^{-1}\$\Theta^{-1}$ .

Here,  $\Theta$  is well defined on pure states, but  $\$$  has no inverse, hence  $\$^\dagger \neq \$^{-1}$  (full CPT invariance:  $\$ = S S^\dagger, \$^\dagger = \$^{-1}$ ).

Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate: the states resulting from black hole evaporation are precisely the CPT reverse of the initial states which collapse to form a black hole.*

# Evidence for Dark Energy

Recent Astrophysical Evidence for Dark Energy (acceleration of the Universe (SnIA), CMB anisotropies (WMAP...))





# COSMOLOGICAL CPTV?

(NM: hep-ph/0309221, Sarben Sarkar, NM: PRD 72, 065016 (2005))

WMAP improved results on CMB:  $\Omega_{\text{total}} = 1.02 \pm 0.02$ , high precision measurement of secondary (two more) acoustic peaks (c.f. new determination of  $\Omega_b$ ).

Agreement with S<sub>nl</sub>a Data. Best Fit :  $\Omega_{\Lambda} = 0.74$ ,  $\Omega_{\text{Matter}} = 0.26$

Best fit models of Universe consistent with **cosmological constant**  $\Lambda > 0$  (de Sitter)  
(**BUT see Dissipative, Non-equilibrium Cosmologies**, → **LAHANAS, MITSOU talks !** )

$\Lambda$ -universe eternally accelerating, will enter an inflationary phase again:  $a(t) \sim e^{\sqrt{\Lambda/3}t}$ ,  
 $t \rightarrow \infty$ , → **cosmological Horizon**.

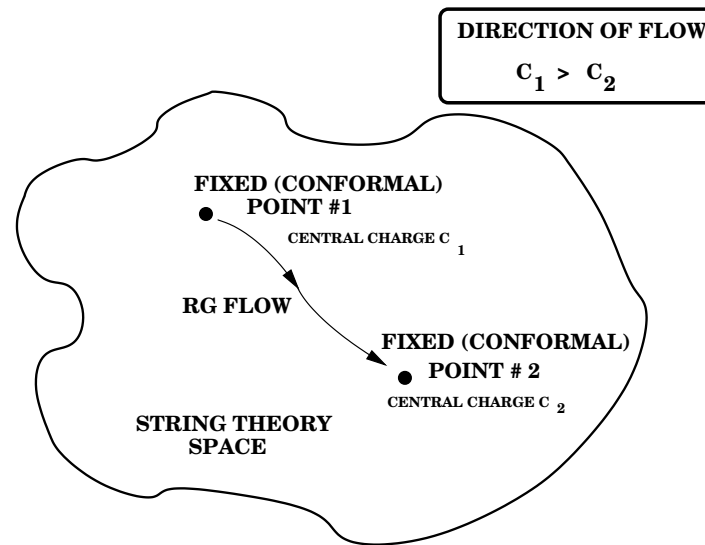
Horizon implies incompatibility with S-matrix & decoherence: no proper definition of asymptotic state vectors, **environment of d.o.f. crossing the horizon** (c.f. **dual picture of black hole, now observer is inside the horizon**).

**Theorem by Wald on S-matrix and CPTV: CPT is violated due to  $\Lambda > 0$  induced decoherence:** (e.g. from Liouville strings → **below** )

$$\partial_t \rho = i[\rho, H] + \frac{\Lambda}{M_P^3} [g_{\mu\nu}, [g^{\mu\nu}, \rho]]$$

**Tiny cosmological CPTV(damping) effects, but detected via Universe acceleration!**

# Liouville-String (Dissipative, Non-Equilibrium) Cosmology: Formalism



Space of background space-time fields, over which strings propagate:

$\{g^i\} = \{\text{graviton} = G_{\mu\nu}, \text{matter}, \dots\}$ , and Dilaton  $\phi(X^0, \rho)$   $\rho =$  Liouville mode, Relaxation Flow (RG) between string vacua (equilibrium points).

$\rho$  is ESSENTIAL in restoring conformal invariance, perturbed by a NON-EQUILIBRIUM PROCESS, e.g. Catastrophic Cosmic Events (Brane World Collision), or space-time foam, ...

# Off-Equilibrium Dynamics

Stringy  $\sigma$ -model **GENERALIZED CONFORMAL INVARIANCE:**

$$\ddot{g}^i + Q\dot{g}^i = -\beta^i,$$

$\dot{g}^i = \frac{dg^i}{d\rho_0}$ ,  $\rho_0$  **world-sheet zero mode of the Liouville field**. NB: “Liouville friction term”  
 $\propto Q$ =central charge deficit.

$\beta^i$ = $\sigma$ -model Renormalization Group (RG)  $\beta$ -functions,

e.g. for gravitons, to  $\mathcal{O}(\alpha')$  ( $\alpha'$ =Regge slope):  $\beta_{\mu\nu}^G = R_{\mu\nu}$  (Ricci tensor)

**CONFORMAL INVARIANCE CONDITIONS**  $\beta^i = 0 \iff$  **EQUATIONS OF MOTION FROM ON-SHELL TARGET-SPACE ACTION**

$$-\beta^i = -\delta S / \delta g^i = 0$$

**GENERALIZED (LIOUVILLE) CONFORMAL INVARIANCE CONDITIONS**  $\iff$   
**EQUATIONS OF MOTION FROM OFF-SHELL TARGET-SPACE ACTION**

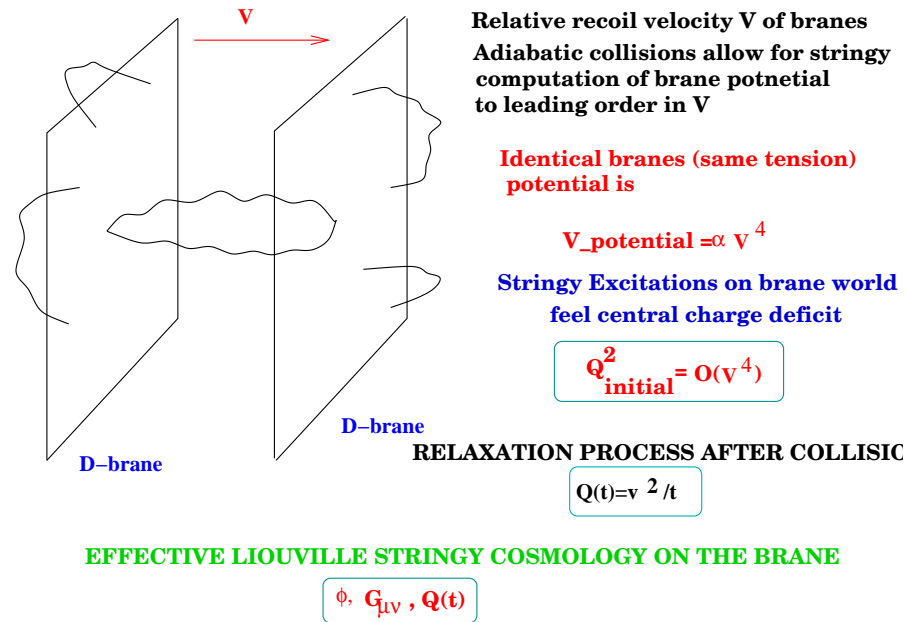
$$\beta^i = \delta S / \delta g^i = \ddot{g}^i + Q\dot{g}^i \neq 0$$

Energetics (some **supercritical** models)  $\implies$

**Time-like Liouville**  $\rho \iff$  **(Cosmic)Time**  $X^0(t)$  (Ellis, NM, Nanopoulos, Lahanas talk)

# A Specific Model

## Colliding Brane Worlds with Recoil (Ellis, NM, Nanopoulos, Westmuckett )



Logarithmic (super)Conformal Field Theory Techniques to compute scaling with cosmic time, PLUS identification of Liouville mode (IRREVERSIBLE local RG scale on world-sheet) with time (Gravanis, Szabo, N.M.)

**COLLISION  $\iff$  NON-EQUILIBRIUM, IRREVERSIBLE**

# Dissipative Liouville Cosmologies

Robertson-Walker Space times. **Effective 4-d action with matter  $I_m$  and radiation in Einstein frame**

$$S^{(4)} = \frac{1}{2\alpha'} \int d^4x \sqrt{-G} [e^{-\Psi(\phi)} R(G) + Z(\phi)(\nabla\phi)^2 + 2\alpha' V(\phi) \dots] - \frac{1}{16\pi} \int d^4x \sqrt{G} \frac{1}{\alpha(\phi)} F_{\mu\nu}^2 - I_m(\phi, G, \text{matter})$$

including string loops,  $e^{\Psi(\phi)} = c_0 e^{-2\phi} + c_1 + c_2 e^{2\phi} + \dots$ ,  $Z(\phi) = 4 + \dots$ , ...

$$V(\phi) = 2Q^2 e^{2\phi} + \tilde{V}, \quad \tilde{V} = \alpha_3 e^{3\phi} + \beta_4 e^{4\phi} * \dots$$

**Off-Shell Liouville Equations:**  $(\rho_\phi = (\dot{\phi})^2 + V(\phi)/2$ ,  $p_\phi = (\dot{\phi})^2 - V(\phi)/2$ )

$$3H^2 = \rho_m + \rho_\phi + \frac{e^{2\phi}}{2} \mathcal{J}_\phi,$$

$$2 \frac{dH}{dt_E} = -\rho_m - \rho_\phi - p_m - p_\phi + a^{-2} (t_E) \mathcal{J}_{ii}, \quad i = 1, 2, 3,$$

$$\frac{d^2\phi}{dt_E^2} + 3H \frac{d\phi}{dt_E} + \frac{1}{4} \frac{\partial V}{\partial \phi} + \frac{1}{2} (\rho_m - 3p_m) = -\frac{3}{2} \frac{\mathcal{J}_{ii}}{a^2} - \frac{e^{2\phi} \mathcal{J}_\phi}{2},$$

$$\mathcal{J}_\phi = e^{-2\phi} (\ddot{\phi} - \dot{\phi}^2 + Q e^\phi \dot{\phi}), \quad \mathcal{J}_{ii} = 2a^2 (\ddot{\phi} + 3H\dot{\phi} + \dot{\phi}^2 + (1-q)H^2 + Q e^\phi (\dot{\phi} + H)).$$

**Matter (non) Conservation equations:**

$$\dot{\rho}_m + 3H(\rho_m + p_m) + \dot{Q}(\partial V(\phi))/2\partial Q - \dot{\phi}(\rho_m - 3p_m) = 6(H + \dot{\phi})a^{-2} \mathcal{J}_{ii}$$

## Predictions on Cosmological Parameters

A detailed analysis leads to the following scaling with the redshift  $z$  **AT LATE EPOCHS** ( $z < 2$ ):

Central charge deficit (off-equilibrium, non-criticality )

$$Q^2(z) \simeq Q_*^2 + \rho_{\text{dust}}^0(1+z), \quad Q_*^2 > 0$$

Matter (including exotic scaling dark matter)

$$\rho_{\text{matter}} \sim \rho_{\text{dust}}^0(1+z)^3 + \rho_{\text{exotic}}^0(1+z)^4 + \dots, \quad a = a_0/(1+z)$$

**Dilaton Dark Energy**

$$\rho_\phi \sim H^2 + \frac{Q_*^2}{a^2} + \frac{\rho_{\text{dust}}^0 + \alpha/2}{a^3} + \frac{\beta}{2a^4} + \dots = \mathcal{O}(a^{-2}) + \mathcal{O}(a^{-3}) + \frac{\beta}{2} a^{-4} + \dots$$

$\alpha$  = string loop correction parameter

**Combination appearing in Hubble  $H(z)$**

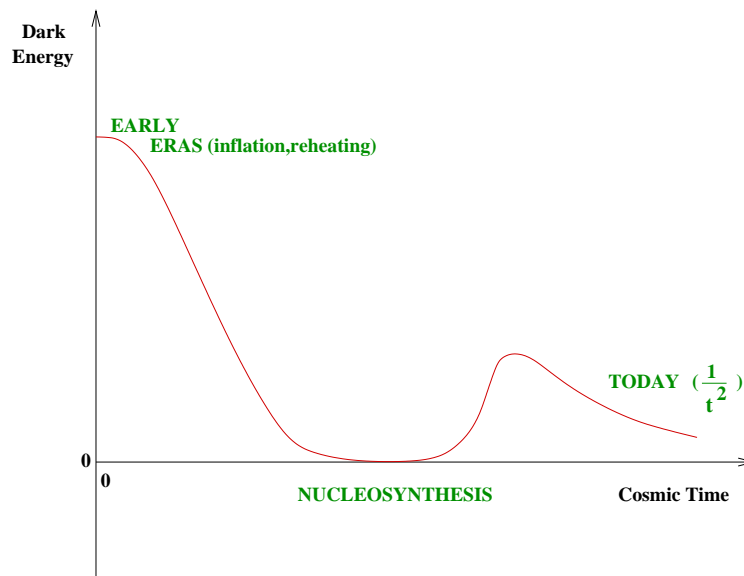
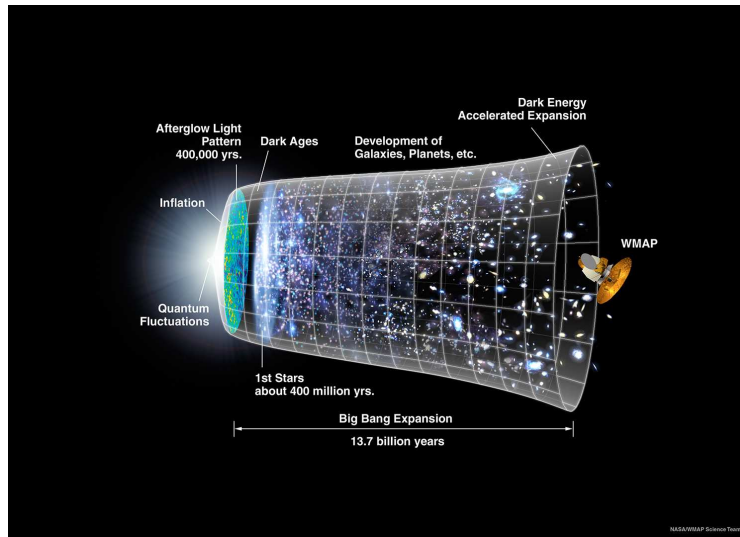
$$\rho_\phi + \rho_M \simeq |\mathcal{O}(a^{-2})| + \frac{(4\rho_{\text{dust}}^0 + \alpha)}{2} a^{-3} - \left( \frac{|e^{2\phi} \mathcal{J}_\phi|}{2} + \dots \right) a^{-4},$$

**Hubble parameter**

$$H(z) = H^0 \left( \Omega_3^0(1+z)^3 + \Omega_\delta^0(1+z)^\delta + \Omega_2^0(1+z)^2 \right)^{1/2}, \quad \delta \simeq 4$$

**Fits with data can constrain Liouville Q-Cosmology Dilaton Potential !**

# EVOLUTION OF A LIOUVILLE UNIVERSE



In Liouville string (Non-Equilibrium, off-shell) Dark Energy Models, Dilaton Dark Energy may be negligible at NUCLEOSYNTHESIS epoch.

Conformal Field Theory (Logarithmic CFT, in brane recoil models)  $\rightarrow$  asymptotic scaling with cosmic time  $\sim 1/t^2$  (E.Gravanis, N.M., Lahanas talk).

NB: Cosmic Time  $\iff$  world-sheet Renormalization Group (RG) local Scale (Liouville mode), Irreversible (Zamolodchikov C-theorem) !

## CONCLUSIONS & OUTLOOK

Discussed models of non equilibrium Cosmologies, in (non-critical, Liouville) string theory framework.

Off-shell Einstein Equations, expressing coupling of system with off-equilibrium dilaton sources, and gravitational environments. **Microscopic Time Irreversibility.**

Common scaling between matter and dilaton dark energy, due to off-shell terms. **In particular, Dust-like contributions appear in Dilaton dark energy, but their sign is ambiguous and depends on details of underlying string theory (loop corrections etc.)**

c.f. Negative Dust due to Kaluza-Klein graviton modes in brane models **(Minamitsuji, Sasaki, Langlois).**

**No Cosmological Constant, but relaxing to zero Dark Energy in Liouville Cosmology ... Can define asymptotic states, no cosmic horizons,  $\implies$  (perturbative) strings OK.**

**Can have excellent Fit with Astro Data  $\implies$  V. Mitsou talk.**