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Inflation in Field and String Theory from the WMAP data

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References :

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3- FJ Cao, HJ de Vega, NG Sanchez, PRD 70, 083528 (2004)

4- H J de Vega, N Sanchez, PRD 50, 7202 (1994).

5- MP Infante, N Sanchez, PRD 61, 083515 (2000).

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7- M Ramon Medrano, N Sanchez, MPLA 18 , 2537 (2003)

8- N G Sanchez, IJMPA 19, 4173 (2004)

Inflation as known today should be considered as an Effective Theory

That is, is Not a fundamental theory but a theory on a condensate (the inflaton field) which follows from a more fundamental theory (the GUT model)

The Inflaton field may NOT correspond to any real particle (even unstable) but is just an effective description while the microscopic derivation should come from the GUT

Inflation is to the microscopic GUT theory,like the effective Ginsburg-Landau theory of superconductivity is to the microscopic BSC theory, or like the O(4) sigma model is to QCD.
Our aim:To provide a clear understanding of Inflationand the Inflaton Potential from Effective Field Theory and the WMAP data.

This clearly places Inflation within the perspective and understanding of effective theories in particle physics, and sets up a clean way to directly confronts the inflationary predictions with the forthcoming CMB data and select a definitive model.

CONCLUSIONS

IMPLICATIONS FOR GRAND UNIFICATION:

GRAND UNIFICATION SCALE:
Three experimental supports:

(1) Unification of couplings in the Standard Model with the Renormalization group For the Standard Model, couplings get unified approximately at $E \sim 10^{16}$ GeV.

(2) Neutrino Oscillations: and Neutrino masses currently explained by the See-Saw mechanism $\Delta m_\nu \sim \frac{M_{FERMI}^2}{M}$

$M_{Fermi} \sim$ ***250 GeV,*** $M \gg M_{Fermi}$ ***and*** Δm_ν ***is the difference of neutrino masses for the different flavors.***

- ***The observed values for*** $\Delta m_\nu \sim$ ***0.009-0.05 eV naturally call for a mass scale*** M ***close to the GUT scale:*** $M \sim 10^{15-16}$ GeV
- ***The inflaton potencial relation*** $V(\phi) = M^4 v\left(\frac{\phi}{M_{Planck}}\right)$

Ressembles the moduli potential from supersymmetry breaking:

$$v_{susy}(\phi) = m_{susy}^4 \, v\left(\frac{\phi}{M_{Planck}}\right)$$

⇨ ***Our approach, combined with*** Δm_ν ***Implies*** $m_{susy} \sim$ $\sim 10^{16}$ ***GeV***

- ***The SUSY breaking scale ms*** ➡ ***is at the GUT scale ms ~ mGUT***

(3) Inflation

- ***We find that the mass scale of the inflaton 10^{13} GeV can be related with M_{GUT} by a see-saw relation***

$$m \simeq \frac{M^2}{M_{Planck}}$$

- ***The Inflaton describes a condensate in a GUT theory (fermion-antifermion) pairs.***

- ***There is no solid basis to identify such a condensate field with a <u>given</u> fundamental field in a SUSY or SUGRA model.***

- ***Moreover, the number of susy models is so large: there is no way to predict the which is THE correct model.***

D. Cirigliano, H.J. de Vega, N.G. Sánchez,
astro-ph/0412634 (Dec. 2004)

CONCLUSIONS

- ***Setting m = 0 in polynomial potentials implies a <u>non-generic</u> choice. WAMP disfavors such a choice and supports a generic quartic polynomial potential***

$\Downarrow$

A purely quartic potential is disfavored $\Rightarrow$ ***<u>Lower Bound for m : m> 10^{13} GeV</u>***

- ***Spectral Indices data*** $\Rightarrow$ ***should help soon to make a clear selection between inflationary models :***

- ***A measured r < 0.16*** $\Rightarrow$ ***<u>excludes Chaotic Inflation</u>***

- ***n_s value above or below unit*** $\Rightarrow$ ***exclude either New or Hybrid inflation respectively***

- ***Our approach, combined with*** $\Delta m_\nu \sim \frac{M^2_{Fermi}}{M}$ $\Rightarrow$ ***Implies $m_s \sim 10^{16}$ GeV***

$\Downarrow$

The SUSY breaking scale m_s $\Rightarrow$ ***is at the GUT scale $m_s \sim m_{GUT}$***

Then the mass scale of the inflaton 10^{13} Gev is related $\Rightarrow$ $m \sim \frac{M^2_{GUT}}{M_{Pl}}$

For both chaotic and new inflation, we find the following properties:

- n_s is bounded as

$$n_s \leq 1 - \frac{2}{N} \simeq 0.96$$

  The value at the bound corresponds to the quadratic monomial.

- n_s decreases with κ for fixed $h \equiv \gamma \sqrt{\frac{8}{\kappa}} < 0$ and grows with $|h|$ for fixed κ.

For chaotic inflation r grows with κ for fixed $h < 0$ and decreases with $|h|$ for fixed κ. Also, in chaotic inflation r decreases with n_s.

For new inflation r does the opposite: **it decreases** with κ for fixed $h < 0$ while it grows with $|h|$ for fixed κ. Also, in new inflation r grows with n_s.

All this is valid for the general trinomial potential eq.(1.1) and can be seen in figs. 7, 18, 20 and 21. In addition, r **decreases** for increasing $|h|$ at a fixed n_s in new inflation (with $h < 0$). As a consequence, the trinomial potential eq. (1.1) can yield **very small** r with $n_s < 1$ **and near unit** for new inflation.

Hybrid inflation always gives $n_s > 1$, allowing $n_s - 1$ and r to be as small as desired. Interestly enough, we obtain a formula for the mass ratio x with a similar structure to eq.(1.2) for hybrid inflation:

$$x = 10^6 \, \frac{m}{M_{Pl}} = 127 \sqrt{r \left(n_s - 1 + \frac{3}{8} \, r \right)} \; .$$

This is plotted in fig. 22-23 showing that $\frac{m}{M_{Pl}}$ **decreases** when r **and** $n_s - 1$ both approach zero. We relate the cosmological constant in the hybrid inflation Lagrangian with the ratio r as

$$\frac{\Lambda_0}{M_{Pl}^4} = 0.329 \times 10^{-7} \, r \; .$$

where the $\pm 6\%$ correspond to the error bars in the amplitude of adiabatic perturbations[8]. From figs. 9, 12 and 15 we can understand how the mass ratio $\frac{m}{M_{Pl}}$ varies with n_s and r. We find a **limiting** value $x_0 \equiv 10^5 \frac{m_0}{M_{Pl}} \simeq 1$ for the inflaton mass such that $m_0 \simeq 10^{-5} M_{Pl}$ is a **minimal** inflaton mass for chaotic inflation, and a **maximal** mass for new inflation in order to keep n_s and r within the WMAP data.

New inflation arises for broken symmetric potentials (the minus sign in front of the φ^2 term) while chaotic inflation appears both for unbroken and broken symmetric potentials. For broken symmetry, we find that analytic continuation connects the observables for chaotic and new inflation: the observables are **two-valued** functions of $y \equiv \kappa N$. (N being the number of efolds from the first horizon crossing to the end of inflation). One branch corresponds to new inflation and the other branch to chaotic inflation. As shown in figs. 4-7, 9, 12 and 15, n_s, r and $|\delta^{(S)}_{k\,ad}|^2$ for chaotic inflation are connected by analytic continuation with the same quantities for new inflation. The branch point where the two scenarios connect corresponds to the monomial $+\varphi^2$ potential ($\kappa = \gamma = 0$).

The potential which **best fits** the present data for $n_s < 1$ and which **best prepares** the way to the expected data (a small $r \lesssim 0.1$) is given by the trinomial potential eq.(1.1) with a negative φ^2 term, that is **new** inflation.
In new inflation we have the upper bound

$$r \leq \frac{8}{N} \simeq 0.16 \quad .$$

NEW INFLATION

This upper bound is attained by the quadratic monomial. On the contrary, in chaotic inflation for both signs of the φ^2 term, r is bounded as

$$0.16 \simeq \frac{8}{N} < r < \frac{16}{N} \simeq 0.32 \quad ,$$

CHAOTIC INFLATION

This bound holds for all values of the cubic coupling γ. The lower and upper bounds for r are saturated by the quadratic and quartic monomials, respectively.

In summary, for small $r \lesssim 0.1$ and n_s near unit **new** inflation from the trinomial potential eq.(1.1) and **hybrid** inflation emerge as the **best candidates**. Whether n_s turns to be **above** or below unit will choose hybrid or new inflation, respectively.

(8)

arXiv: astro- ph/ 0409406 **16 Sep 2004**

PHYS REV D71 023509 (2005)

Particle Decay during Inflation: Self-decay of the Inflaton Quantum Fluctuations

D. Boyanovsky, H. J. de Vega and N. G. Sanchez

We find that quantum fluctuations can *self-decay* as a consequence of the inflationary expansion through processes which are forbidden in Minkowski space-time.

We compute the *self-decay* of the inflaton quantum fluctuations during slow roll inflation. *And its observational consequences*

For wavelengths deep inside the Hubble radius the decay is enhanced by the emission of ultrasoft collinear quanta, i.e. bremsstrahlung radiation of superhorizon quanta , the leading decay channel for physical wavelengths $H \ll k_{ph}(\eta) \ll H / (\eta_V - \varepsilon_V)$.

The decay of short wavelength fluctuations hastens as the physical wave vector approaches the horizon. Superhorizon fluctuations decay with a power law η^{Γ} $\eta^{\varepsilon V - \eta V + \Gamma}$

in conformal time where in terms of the amplitude of curvature perturbations Δ^2_R ***, the scalar spectral index*** n_s ***, the tensor to scalar ratio*** r ***and slow roll parameters :***

$$\Gamma \sim 32\, \xi_v^2\, \Delta^2_R / (n_s - 1 + r/4)^2 \; [\, 1 + O(\varepsilon_V, \eta_V)\,]$$

The behavior of the growing mode η **features an anomalous scaling dimension** Γ

From the recent WMAP data we find:

$$3.6 \times 10^{-9} < \Gamma < 3 \times 10^{-8}$$

$H \sim 10^{14}$ **GeV**

$$10^{6}\ \mathrm{GeV} < H\Gamma < 10^{7}\ \mathrm{GeV}$$

IMPLICATIONS FOR STRING THEORY

To generates Inflation Needs first to generate a mass scale like the inflaton mass m.

Such scale is NOT present in the string action neither in the effective fields (dilaton, graviton,antisymmetric tensor).

Without the presence of the mass scale m and M_{GUT}, there is NO hope in string theory to describe a correct inflationary cosmology describing the CMB fluctuations.

Such scale should be generated dynamically perhaps from the string vacuum, but this is still an open problem far from being solved.

Since No microscopic derivation of inflation from a GUT model is available so far, it would seem too ambitious at this stage to look for a microscopic derivation of Inflation from string theory.

The derivation of Inflation reproducing observed CMB fluctuations is at present too hard.

An effective description of Inflation in String theory (string matter plus background) could be at reach
H J de Vega and N Sanchez, PRD 50, 7202 (1994)
M.P Infante and N Sanchez, PRD 61, 0831515 (2000)

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3. GRAVITATIONAL WAVE
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   - Generation of gravit. waves
   - POWER SPECTRUM
   - ROLE OF THE Dilaton

4. CONCLUSIONS

Table I

STRING PROPERTIES FOR ARBITRARY $R(X^0)$

H.J. de Vega & N. Sánchez, PRD 50, 7202 (1994)

	Energy	Pressure	Equation of State: $p = (\gamma - 1)\rho$
$D = 1 + 1$: two families of solutions			
(i) $\eta \pm X = f_\pm(\sigma \pm \tau)$ (ii) $\eta \pm X =$ constant	$E = u\,R$ $E = d/R$	$P = -E$ $P = +E$	$\gamma = 0$ $\gamma = 2$
$D = 2 + 1$: Ring Solutions, three asymptotic behaviours (u, d, s)	$E = \frac{1}{\alpha'}\,\dot{X}^0(\tau)$	$P = \frac{R(\tau)^2}{2\alpha'\lvert\dot{X}^0(\tau)\rvert}\,[\dot{f}^2 - f'^2]$	
(i) unstable for $R \to \infty$ (ii) dual to (i) for $R \to 0$ (iii) stable for $R \to \infty$	$E_u \overset{R\to\infty}{=} u\,R \to \infty$ $E_d \overset{R\to 0}{=} d/R \to \infty$ $E_s =$ constant	$P_u = -E/2 \to -\infty$ $P_d = +E/2 \to \infty$ $P_s = 0$	$\gamma_u = 1/2$ $\gamma_d = 3/2$ RADIATI $\gamma_s = 1$ cold matter
D-Dimensional spacetimes: general asymptotic behaviour			
(i) unstable for $R \to \infty$ (ii) dual to (i) for $R \to 0$ (iii) stable for $R \to \infty$	$E_u \overset{R\to\infty}{=} u\,R \to \infty$ $E_d \overset{R\to 0}{=} d/R \to \infty$ $E_s =$ constant	$P_u = -\frac{E}{D-1} \to -\infty$ $P_d = +\frac{E}{D-1} \to \infty$ $P_s = 0$	$\gamma_u = (D-2)/(D-1)$ $\gamma_d = D/(D-1)$ $\gamma_s = 1$ cold matter

Table II

STRING ENERGY DENSITY AND PRESSURE FOR ARBITRARY $R(X^0)$

	Energy density: $\rho \equiv E/R^{D-1}$	Pressure
Qualitatively correct formulas for all R and D	$\rho = \left(u\,R + \frac{d}{R} + s\right)\frac{1}{R^{D-1}}$	$p = \frac{1}{D-1}\left(\frac{d}{R} - u\,R\right)\frac{1}{R^{D-1}}$

Table IV

EFFECTIVE STRING EQUATIONS SOLUTIONS IN COSMOLOGY

Effective String equations	$R(X^0) \to 0$ behaviour	$R(X^0) \to \infty$ behaviour
$X^0 \to 0$	$\sim (X^0)^{+1/\sqrt{D-1}}$	$\sim (X^0)^{-1/\sqrt{D-1}}$
$X^0 \to \infty$	$\sim (X^0)^{-1/\sqrt{D-1}}$	$\sim (X^0)^{+1/\sqrt{D-1}}$

- Asymptotic solution (including the dilaton) -

ⓑ

M.I. Infante &
N. Sánchez

PRD61, 083515
(2000)

From eq.(4.13) and with eqs.(4.8) and (4.14), we obtain:

$$\Omega = \frac{2(d-1)}{3d} \frac{\mathcal{T}_0^{-2}}{H_0^{2}} \tag{4.15}$$

As like as $H_0 \sim \mathcal{T}_0^{-1}$, we have finally

$$\Omega = \frac{2(d-1)}{3d} \tag{4.16}$$

In our three-dimensional expanding Universe, it gives $\Omega = \frac{4}{9}$.

In the last, we have taken $\mathcal{T}_0 \leq H_0^{-1}$ following the usual computation. In General Relativity framework, it holds:

$$\mathcal{T}_0 = \frac{2}{3} H_0^{-1} \tag{4.17}$$

if the deceleration parameter $q_0 = -\ddot{a}(t_0)\frac{a(t_0)}{\dot{a}(t_0)^2} > \frac{1}{2}$. For our model, the deceleration parameter is found:

$$q_0 = \frac{1-M}{M}$$

that for standard matter dominated behaviour gives exactly $q_0 = \frac{1}{2}$. For this and as well as observations give $q_0 \sim 1$, we compute the value of Ω in this framework. From eq.(4.15) and eq.(4.17) we obtain:

$$\Omega = \frac{2}{3}\frac{d-1}{d}\left(\frac{2}{3}\right)^{-2}$$

which in the three dimensional case gives exactly:

$$\Omega = 1$$

SELF CONSISTENT

STRING
COSMOLOGY

PREDICTION

!! $\Omega = 1$
$(d=3)$

PRIMORDIAL GRAVITATIONAL WAVE SPECTRUM

$$
\begin{aligned}
\mid \beta \mid^2 = \frac{\pi}{8}\, X \Bigg[\left(1 + \frac{\left(\frac{q}{r}\right)^2}{X^2} \right) & \mathcal{H}_\nu{}^{(1)}(X)\mathcal{H}_\nu{}^{(2)}(X) + \\
& + \mathcal{H}_{\nu-1}{}^{(1)}(X)\mathcal{H}_{\nu-1}{}^{(2)}(X) \\
& - 2\frac{\frac{q}{r}}{X}\mathcal{H}_\nu{}^{(1)}(X)\mathcal{H}_{\nu-1}{}^{(2)}(X) - i\frac{4}{\pi}\frac{\frac{q}{r}}{X^2} - \frac{4}{\pi X} \Bigg]
\end{aligned} \tag{5.82}
$$

5.3.1 The Power Spectrum in the Full Dilaton Case

Using eq.(4.29) and (5.82), we have for the power spectrum the next expression

$$
\begin{aligned}
P(\omega)d\omega = \frac{\hbar}{8\pi c^3}\omega^2 \frac{\left(\frac{q}{r}\right)^2}{S} d\omega \Bigg[\left(1 + \frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2} \right) & \mathcal{H}_\nu{}^{(1)}(\omega S)\mathcal{H}_\nu{}^{(2)}(\omega S) + \\
+ \frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2} \mathcal{H}_{\nu-1}{}^{(1)}(\omega S)\mathcal{H}_{\nu-1}{}^{(2)}(\omega S) \; + & \\
- \; 2\frac{\omega S}{\frac{q}{r}}\mathcal{H}_\nu{}^{(1)}(\omega S)\mathcal{H}_{\nu-1}{}^{(2)}(\omega S) - i\frac{4}{\pi \frac{q}{r}} - \frac{4}{\pi}\frac{\omega S}{\left(\frac{q}{r}\right)^2} \Bigg] &
\end{aligned} \tag{5.83}
$$

$\omega_{max} \sim 3{,}85$ MHz

The fraction of critical energy density takes the expression:

$$
\begin{aligned}
\Omega_{GW} = \frac{\hbar\, G}{3{H_0}^2 c^5} \frac{\left(\frac{q}{r}\right)^2}{S}\, \omega^3 \Bigg[\left(1 + \frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2} \right) & \mathcal{H}_\nu{}^{(1)}(\omega S)\mathcal{H}_\nu{}^{(2)}(\omega S) + \\
+ \frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2} \mathcal{H}_{\nu-1}{}^{(1)}(\omega S)\mathcal{H}_{\nu-1}{}^{(2)}(\omega S) \; + &
\end{aligned}
$$

(17

Infante & Sanchez
PRD 61, 083515 (2000)

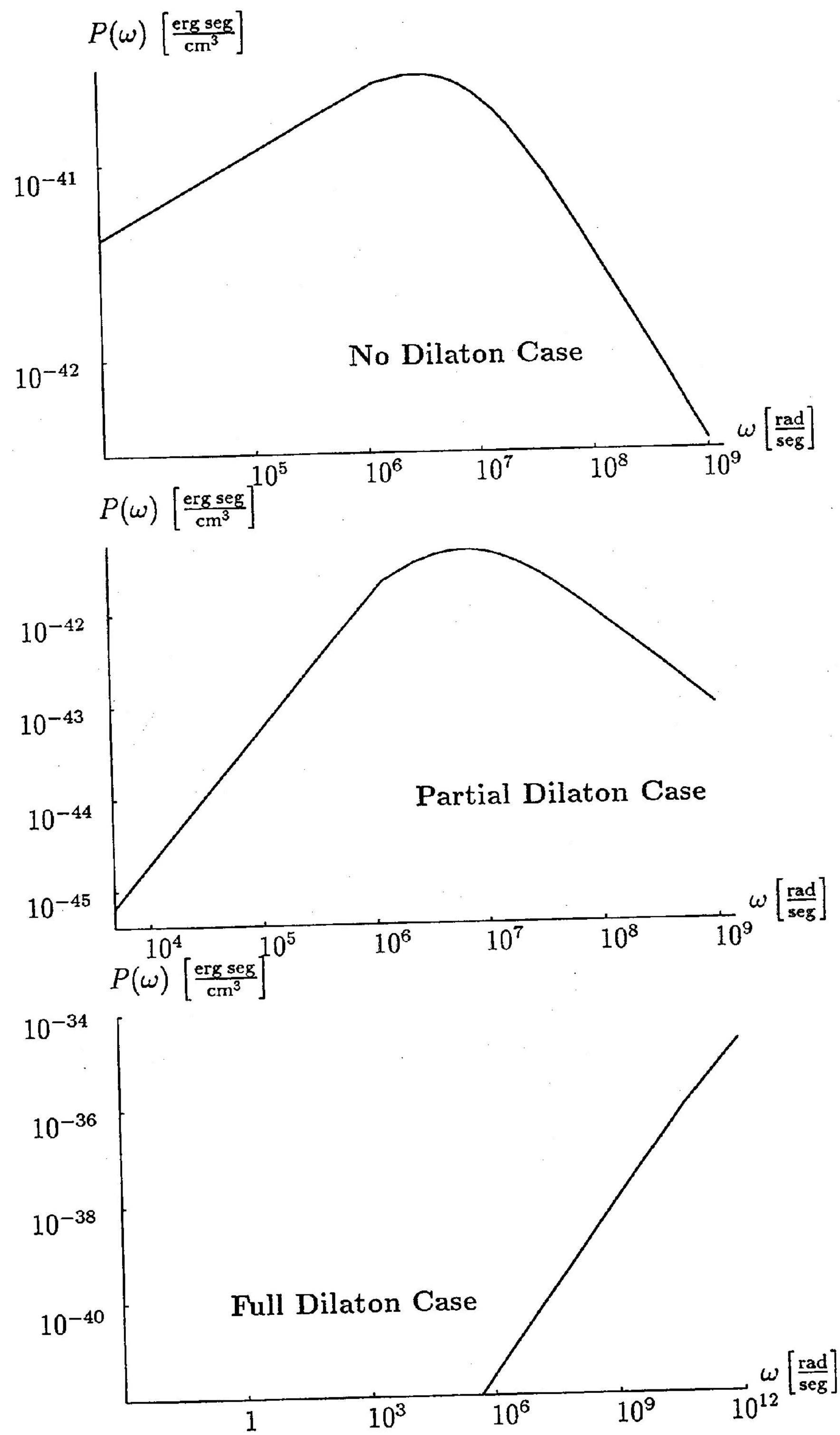


Figure 1: Power spectrum for No Dilaton, partial Dilaton and Full Dilaton Case

The fraction of critical energy density takes the expression:

$$\Omega_{GW} = \frac{\hbar\, G}{3{H_0}^2 c^5}\,\frac{\left(\frac{q}{r}\right)^2}{S}\,\omega^3 \left[\left(1+\frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2}\right)\mathcal{H}_\nu{}^{(1)}(\omega S)\mathcal{H}_\nu{}^{(2)}(\omega S) + \right.$$

$$+\frac{(\omega\, S)^2}{\left(\frac{q}{r}\right)^2}\mathcal{H}_{\nu-1}{}^{(1)}(\omega S)\mathcal{H}_{\nu-1}{}^{(2)}(\omega S) +$$

$$\left. - 2\frac{\omega S}{\frac{q}{r}}\mathcal{H}_\nu{}^{(1)}(\omega S)\mathcal{H}_{\nu-1}{}^{(2)}(\omega S) - i\frac{4}{\pi\frac{q}{r}} - \frac{4}{\pi}\frac{\omega S}{\left(\frac{q}{r}\right)^2}\right] \tag{5.84}$$

We compute for the three-dimensional case the values of the coefficients in front of the square brackets in eqs.(5.83) and (5.84). These values differ from our previous computations on (5.39) and (5.46) in a factor $\left(\frac{\frac{q}{r}}{\nu-\frac{1}{2}}\right)^2$. Thus, in the full dilaton case, we have:

Peak:

$P(\omega)d\omega$: $$\frac{\hbar}{8\pi c^3}\,\frac{\left(\frac{q}{r}\right)^2}{S} \sim 4.008\;10^{-55}\;\frac{\text{erg seg}^3}{\text{cm}^3} \tag{5.85}$$

Ω_{GW} : $$\frac{\hbar\, G}{3{H_0}^2 c^5}\,\frac{\left(\frac{q}{r}\right)^2}{S} \sim 6.220\;10^{-47}\;\text{seg}^{-3} \tag{5.86}$$

$\boxed{\omega_{max} \sim 3.85\ \text{MHz}}$

ENERGY DENSITY $/\rho_c \equiv \Omega_{GW}$

Macroscopic black holes → gravitational collapse of stellar bodies

Microscopic black holes

→ Could arise from high density concentrations (of the order of the Planck energy scale) in the early universe, as well as from the collisions of particles at such energy scales.

→ Are necessarily quantum and their properties governed by quantum or semi-classical gravity, evaporation through Hawking radiation is a typical effect of these black holes.

→ Share in some respects analogies with elementary particles, and on the other hand, show many important differences.

→ A theory of quantum gravity, or "theory of everything" such as string theory, should account for an unified and consistent description of both black holes and elementary particles, and the physics of the early universe as well.

N. Sanchez, IJMPA 19, 4173 (2004)

Unified quantum decay of QFT elementary particles, black hole and strings

Quantum decay rate of unstable particles $\longrightarrow$ $\Gamma = \dfrac{g^2\, m}{numerical\ factor}$

String decay rate $\longrightarrow$ $\Gamma_s = \dfrac{G}{n^{\underline{o}}} T_s^3 \sim \dfrac{G}{l_s^3}$ or $\Gamma_s = \dfrac{g^2}{n^{\underline{o}}} m_s \left[\text{with } g \equiv \sqrt{\dfrac{G}{\alpha'}}\right]$

Loss mass rate :

Semi-classical black Hole decay ('grey body at Hawking Temperature') $\longrightarrow$ $\left(\dfrac{dM_{cl}}{dt}\right) = -\sigma L_{cl}^2 T_{sem}^4 \sim T_{sem}^2$

Semi-classical black Hole decay rate $\longrightarrow$ $\Gamma_{sem} = \left|\dfrac{d}{dt} \ln M_{cl}\right| \sim \dfrac{G}{n^{\underline{o}}} T_{sem}^3 \sim \dfrac{G}{L_{cl}^3}$

Evaporation ➡ Black hole enters its string regime $T_{sem} \to T_s,\ L_{cl} \to L_s$

with decay rate $\longrightarrow \Gamma_{sem} \to G T_s^3 \sim \dfrac{G}{l_s^3} \to \Gamma_s$

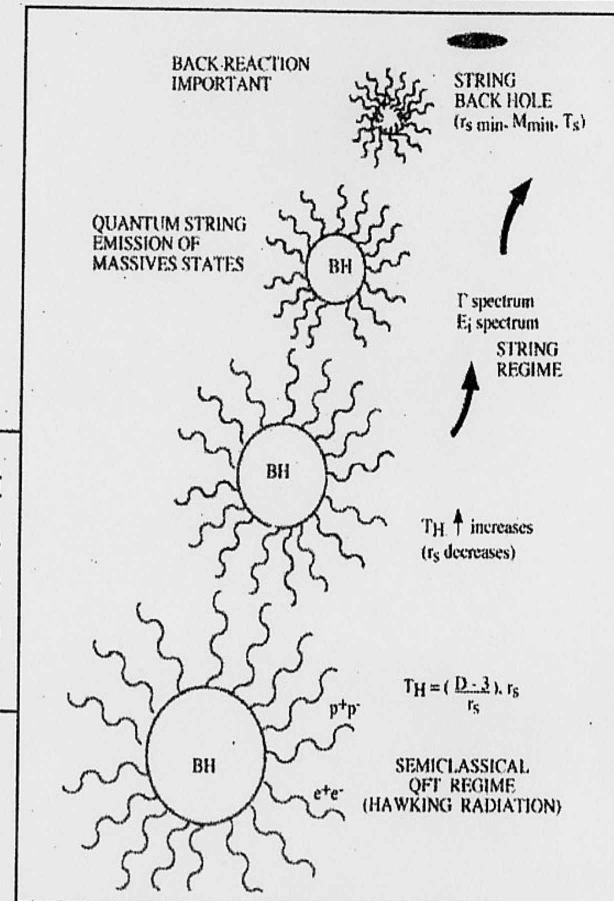
The semiclassical black hole decay rate Γ_{sem} tends to the string decay rate Γ_s

- **Résultats pour l'évaporation finale des trous noirs**

(i) Le trou noirs vers sa fin se désintègre comme une corde quantique, en radiation pure (non thermique)

(ii) Unification conceptuelle des particules élémentaires et trous noirs en incluant les états primordiaux de l'univers

Évolution de l'évaporation d'un trou noir depuis le début (radiation de Hawking, spectre de corps noir) jusqu'a l'étape finale (transition de phase dans une corde quantique avec spectre non thermique sans perte d'information



Références: Medrano & Sanchez PRD(2000), Larsen & Sanchez Nuc.Phys B(2001), Medrano & Sanchez IJMPA(2003), Sanchez, hep-th/0312018, IJMPA 19, (2004) October

Semiclassical Regime

Asymptotic expression (for high M)

$$e^{S_{sem}/k_B} = \rho_{sem}(M) = f(M)\left(\frac{S_{sem}^{(0)}}{k_B}\right)^{-a} e^{S_{sem}^{(0)}/k_B}$$

$$S_{sem}^{(0)}(M) = \frac{1}{2p}\frac{Mc^2}{T_{sem}}, \qquad T_{sem} = \frac{1}{2\pi k_B} M_{sem}\, c^2$$

$$\left(M_{sem} = \frac{m_{Pl}^2}{M} \right)$$

$p = 4$, $M = \dfrac{2}{(D-3)}\dfrac{c^2}{G} R_{BH}$, $f = 1$ B-H

$p = 1$, $M = \dfrac{c^3}{G\,H}$, $f = \sqrt{\dfrac{M_{sem}}{M_{sem} - M}}$ dS

$p = 1$, $M = \dfrac{c^3}{G\,H}$, $f = 1$ AdS

de Sitter & Antide Sitter. Black Holes

String Regime

Asymptotic expression (for high M)

$$e^{S_s/k_B} = \rho_s(M) = f(M)\left(\frac{S_s^{(0)}}{k_B}\right)^{-a} e^{S_s^{(0)}/k_B}$$

$$S_S^{(0)}(M) = \frac{1}{2p}\frac{Mc^2}{T_S}, \quad T_S = \frac{1}{2\pi k_B} M_S c^2$$

$$p = 4, \quad M_S = \frac{1}{8b}\sqrt{\frac{\hbar}{\alpha' c}}, \quad f = 1: \quad BH$$

$$p = 1, \quad M_S = \frac{1}{8b}\frac{c}{\alpha' H}, \quad f = \sqrt{\frac{M_S}{M_S - M}}: \quad dS$$

$$p = 1, \quad M_S = \frac{1}{8b}\frac{c}{\alpha' H}, \quad f = 1: \quad AdS\,.$$

de Sitter & Anti de Sitter, Black Holes

Classical Physics c

L_{cl}, c, M

$K_{cl} = \frac{c^2}{L_{cl}}$

$T = \frac{1}{2\pi k_B} M c^2$

Quantum Physics $c, \hbar$

$L_q = \frac{\hbar}{Mc}$

$K_q = \frac{c^2}{L_q}$

$T = \frac{1}{2\pi k_B} M c^2$

Gravity c, G

$L_{cl} = \frac{G}{c^2} M$

$K_{cl} = \frac{c^4}{GM}$

$T = \frac{1}{2\pi k_B} M c^2$

Semiclassical Gravity

$T_{sem} = \frac{\hbar}{2\pi k_B} K_{cl} = \frac{1}{2\pi k_B} \frac{m_{Pl}^2 c^2}{M}$

$T_{sem} = \frac{1}{2\pi k_B} M_{sem} c^2$

$L_q = \frac{l_{Pl}^2}{L_{cl}}$

$M_{sem} = \frac{m_{Pl}^2}{M}$

$T_{sem} = \frac{t_{Pl}^2}{T}$

$$L_{cl} L_g = l_{Pe}^2 \,, \quad M M_{sem} = m_{Pe}^2 \,, \quad T T_{sem} = t_{Pe}^2$$

$$\left(l_{Pe}^2 = \hbar G / c^3 \,, \quad m_{Pe}^2 = \hbar c / G \,, \quad t_{Pe} = \frac{1}{2\pi k_B} m_{Pe} c^2 \right)$$

$$\left(l_s^2 = \frac{\hbar \alpha'}{c} \,, \quad m_s^2 = \hbar / c\alpha' \,, \quad t_s = \frac{1}{2\pi k_B} m_s c^2 \right)$$

$$\left(l_s = L_g = \frac{\hbar}{m_s c} \,, \quad l_s = \alpha' m_s \right)$$

$$[\alpha'] \longleftrightarrow \left[\frac{G}{c^2} \right] \,, \quad \text{tension} = \frac{\text{mass}}{\text{length}} = \frac{c^2}{G}$$

$$L_{cl} L_s = l_s^2 \,, \quad M_s M_{sem} = m_s^2 \,, \quad T_s T_{sem} = t_s^2$$

$$O_{cl,\, sem} = o_{Pe}^2 \, O_g^{-1} \,, \quad O_{cl,\, sem} = o_s^2 \, O_s^{-1}$$

Set of quantities

Classical / semi-classical gravity regime $O_{cl,sem} = \left(L_{cl}, M_{cl}, K_{cl}, T_{sem}\right)$

- Length
- Mass
- Gravity Acceleration
- Hawking Temperature

Quantum gravity regime $O_q = \left(L_q, M_q, K_q, T_q\right)$

Duality

$$O_{cl,sem} = o_{Pl}^{2}\, O_q^{-1} \Longleftrightarrow O_{cl,sem} = o_s^{2}\, O_s^{-1}$$

String theory

$$O_s = \left(L_s, M_s, K_s, T_s\right)$$

$$o_{Pl}^{2}\,(\hbar, G, c) \Longleftrightarrow o_s^{2}\,(\hbar, \alpha', c)$$

DE SITTER STATES

$$L_{cl} = \frac{c}{H}, \quad K_{cl} = cH, \quad M = \frac{c^3}{GH}$$

$$T_{sem} = \frac{\hbar c}{2\pi k_B} L_{cl}^{-1} = \frac{\hbar}{2\pi k_B c} K_{cl} = \frac{\hbar}{2\pi k_B} H$$

$$T_{sem} = \frac{1}{2\pi k_B} M_{sem} c^2, \quad M_{sem} = \frac{m_{Pl}^2}{M} = \frac{\hbar}{c^2} H$$

$$L_q \equiv L_s = \frac{\alpha' \hbar}{c^2} H, \quad K_s = \frac{c^4}{\hbar \alpha' H}, \quad M_s = \frac{c}{\alpha' H}$$

$$T_s = \frac{\hbar c}{2\pi k_B} \frac{1}{L_s} = \frac{\hbar}{2\pi k_B c} K_s = \frac{c^3}{2\pi k_B} \frac{1}{\alpha' H}$$

$$T_s = \frac{1}{2\pi k_B} M_s c^2, \quad M_s = \frac{c}{\alpha' H}$$

$\forall D$: $\quad R = D(D-1)\frac{H}{c^2}, \quad H = c\sqrt{\frac{2\Lambda}{(D-1)(D-2)}}$

$$L_s = l_s^2 L_{cl}^{-1}, \quad M_s = m_s^2 M_{sem}^{-1}, \quad T_s = t_s^2 T_{sem}$$

DISCRETE SPECTRUM

(Quantum (or string) regime of Gravity)

$$M_n = m_{Pl}\, 2bp\sqrt{n} \quad , n = 1, 2, \ldots$$

$$\begin{cases} p = 4 : \text{BH} \\ p = 1 : \text{dS \& AdS} \end{cases} \qquad \left(b = 2\sqrt{\frac{D-2}{6}} \right)$$

$$H_n = m_{Pl}^2\, 2bp \frac{1}{2\sqrt{n}} \, , \quad \Lambda_n = \frac{3}{4 l_{Pl}^2} \frac{(D-1)(D-2)}{n}$$

BLACK HOLES, DE SITTER & ANTI DE SITTER STATES

Concluding Remarks (1)

- The Hawking temperature, elementary particle and string temperatures are shown to be the same concept in different energy regimes and turn out to be the precise classical-quantum duals of each other.

- This result holds for the black hole decay rate, heavy particle and string decay rates; black hole evaporation ends as quantum string decay into pure (non mixed) non thermal radiation.

- Microscopic density of states and entropies in the two (semi-classical and quantum) gravity regimes are related, an unifying formula for black holes, de Sitter and anti-de Sitter states is provided in the two regimes.

Concluding Remarks *(2)*

- A phase transition towards the de Sitter string temperature (which is shown to be the precise quantum dual of the semi-classical (Hawking-Gibbons) de Sitter temperature) is found.

- Cosmological evolution goes from a quantum string phase to a semi-classical phase (inflation) and then to the classical (standard Friedman-Robertson-Walker) phase.

- The wave-particle-string duality precisely manifests in this evolution, and can be viewed as a mapping between asymptotic states and so as a scattering -matrix description.