Title: String Pair Production in a Time-Dependent Gravitational Field

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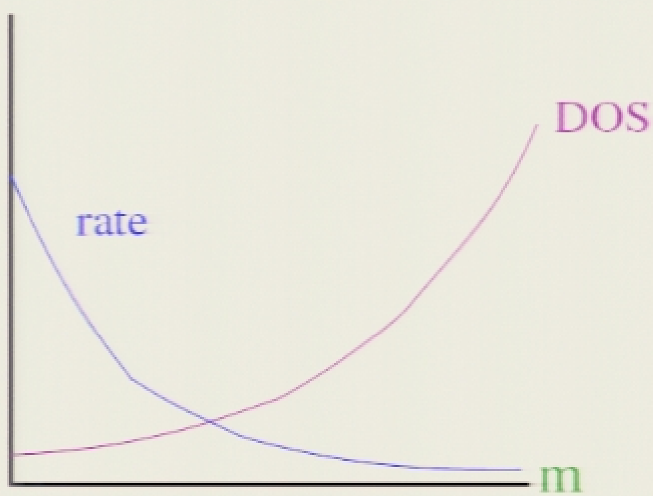
Abstract:

Motivation

- Laboratory for strings in time–dependent backgrounds
- Pair production:
  - Perturbation spectrum in inflation
  - ...or any other model
  - Similar physics in reheating
  - String relics from early universe:



- rate $\sim e^{-A(m/H)}$
- DOS $\sim e^{+B\sqrt{\alpha'}m}$
- (rate $=$ point-particle)

Gubser, Phys. Rev. D **69** *123507 (2004); Friess, Gubser, Mitra, Nucl. Phys. B.* **689** *243 (2004).*

Pair Production in Field Theory

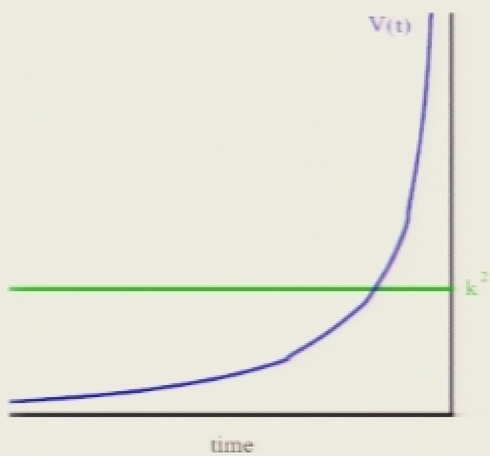
$$S_\phi = -\int g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + m^2\phi^2\,\sqrt{-g}\;d^4x$$

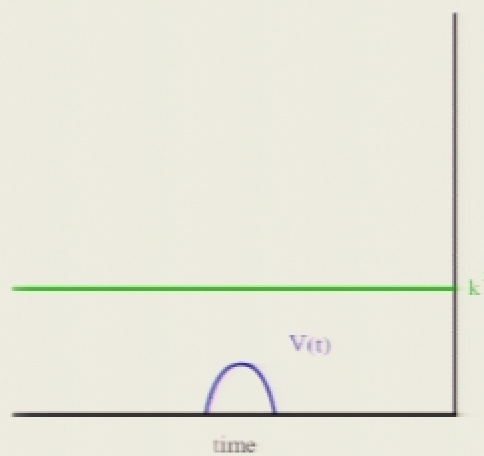
$$g_{\mu\nu} = a(\tau)^2\eta_{\mu\nu}$$

$$\psi(\tau,\vec{x}) = a(\tau)\phi_k(\tau)e^{ik\cdot x}$$

$\psi_k(\tau)$ obeys a Schrödinger equation:

$$-\ddot{\psi}_k + V(\tau)\psi_k = k^2\psi_k, \text{ with } V(\tau) = \ddot{a}/a - m^2a^2.$$





Perturbative Field Theory Pair Production

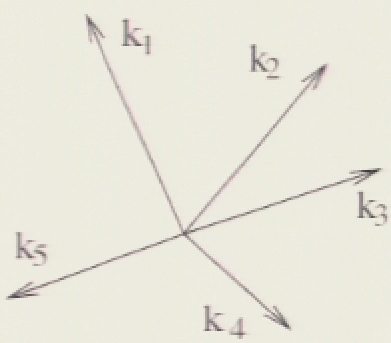
When $a(\tau)$ nearly unity,

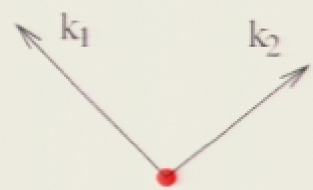
$$n = \frac{1}{D/2-1} \text{ and } g(t) = a(t)^{D/2-1}$$

$$S_\psi = -\int (\partial\psi_k)^2 + m^2\psi_k^2 + \Delta(t)\psi_k^2 \, \frac{d^{D-1}k}{(2\pi)^{D-1}} dt,$$

$$\Delta(t) = (g^{2n} - 1)m^2 - \ddot{g}/g$$

$$\sum k_j = 0 \qquad k_1 + k_2 + k_\Delta = 0$$

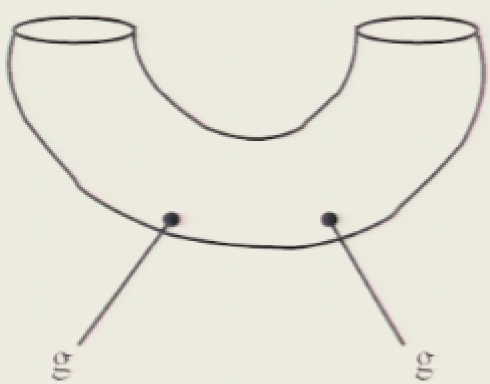




Why should strings be different?

Effective Field Theory:

- $\lambda \gg \sqrt{\alpha'}$ or $E \ll 1/\sqrt{\alpha'}$
- String processes = field theory of point particles



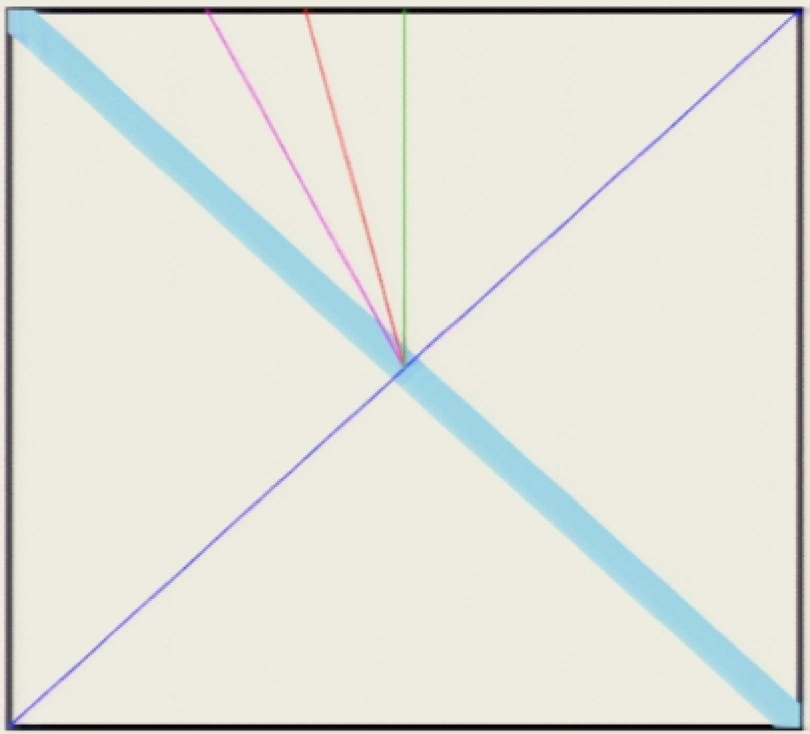
- $k_g \sim m$
- $m \sim 1/\sqrt{\alpha'}$
- $\rightarrow$ *not* EFT

Analogue in Strings

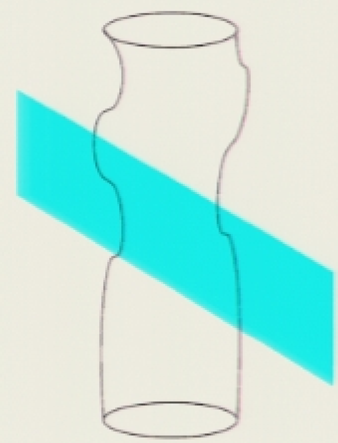
Would like to do calculation with strings...
...but additional conditions must be satisfied for the theory to be consistent.

- $\rightarrow$ Cannot insert arbitrary $a(\tau)$.
- Can use exact solutions: *pp*–waves.

Single Wave

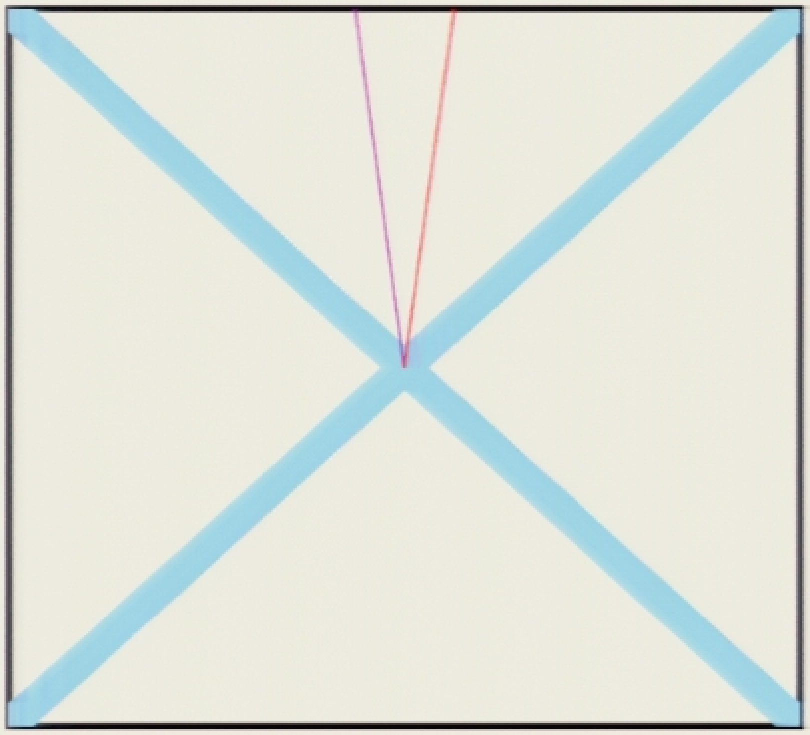


- No pair creation.
- Mode excitation

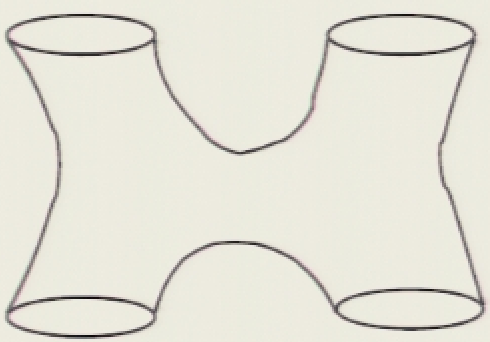


Horowitz, Steif, Phys. Rev. D **42***, 1950 (1990); de Vega, Medrano, Sanchez, Nucl. Phys. B* **351***, 277 (1991).*

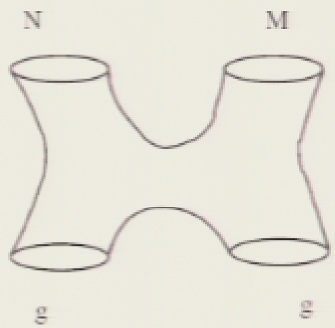
Two Waves



- Now pair production.



The 4–pt process



- Gravitons: h^L, h^R and k_L, k_R
- Strings: in excited states N_+, N_- polarizations ϵ_+, ϵ_-

$$S = \epsilon^{+}_{\mu_1,\bar{\mu}_1\cdots\mu_N\bar{\mu}_{N+}}\epsilon^{-}_{\nu_1,\bar{\nu}_1\cdots\nu_N\bar{\nu}_{N-}} h^L_{\sigma\bar{\sigma}} h^R_{\sigma\bar{\sigma}} \frac{16\pi i}{\alpha'}\left(\frac{\alpha'}{2}\right)^{N_+ + N_-} \times$$

$$\prod_{j=1}^{N_+} k_R^{\mu_j} k_R^{\bar{\mu}_j} \prod_{k=1}^{N_-} k_R^{\nu_k} k_R^{\bar{\nu}_k} \eta^{\sigma\tau}\eta^{\bar{\sigma}\bar{\tau}} \left[\frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}\right]^2 \frac{\sin(\pi a)\sin(\pi b)}{\sin\left[\pi(a+b)\right]} \quad (1)$$

$$a = N_+ - \frac{\alpha'}{4}t \qquad b = N_- - \frac{\alpha'}{4}u$$

Identical vs. Non–Identical I

$$S \sim \frac{\sin(\pi a)\sin(\pi b)}{\sin[\pi(a+b)]}$$

$$a = N_+ - \frac{\alpha'}{4}t \qquad b = N_- - \frac{\alpha'}{4}u$$

Near threshold (long λ):

- $N_+ = N_-$:
  1. $a = b = 2N - 1 + \mathcal{O}(k_T^2)$
  2. $S \sim k_T^2$: vanishes as $k_T \to 0$.
  3. point particles: S independent of k_T
- Occurs for any $a, b \in \mathbf{Z}$:
  $(N_+, N_-) = (2, 5), (2, 10), (2, 17), (3, 9), \ldots$
- $N_+ \neq N_-$:
  Recover expected spectrum, independent of k_T for $\lambda \gg \sqrt{\alpha'}$

Identical vs. Non–Identical II

Why does this happen?

$$\frac{\sin(\pi a)\sin(\pi b)}{\sin\left[\pi(a+b)\right]}\frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}\frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}$$

- Open string (Veneziano)
- Closed string (Virasoro–Shapiro)
- Cancel double poles

Softening of pair production I

- Field theory: amplitude $\sim e^{-A(m/H)}$
  - ...origin in falloff of graviton Fourier modes:
  - $h_{L,R} \sim e^{-\tilde{A}(m/H)}$
- Strings:
  - Same Fourier mode falloff,
  - But additional suppression:

$$\left[\frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}\right]^2 \sim \frac{2\pi}{N} 2^{-8N} \sim e^{-C\alpha' m^2}$$

$\rightarrow$ production of massive string states falls off faster with m.

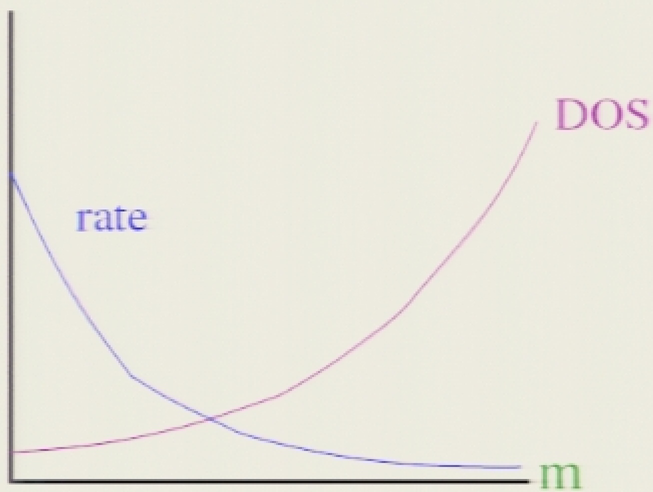
Softening of pair production II

Again an expected feature of strings.

The "hard scattering" limit:

$$s \to \infty, \qquad t/s \text{ fixed.}$$

$$\text{amplitude} \sim e^{-sf(\theta)}$$

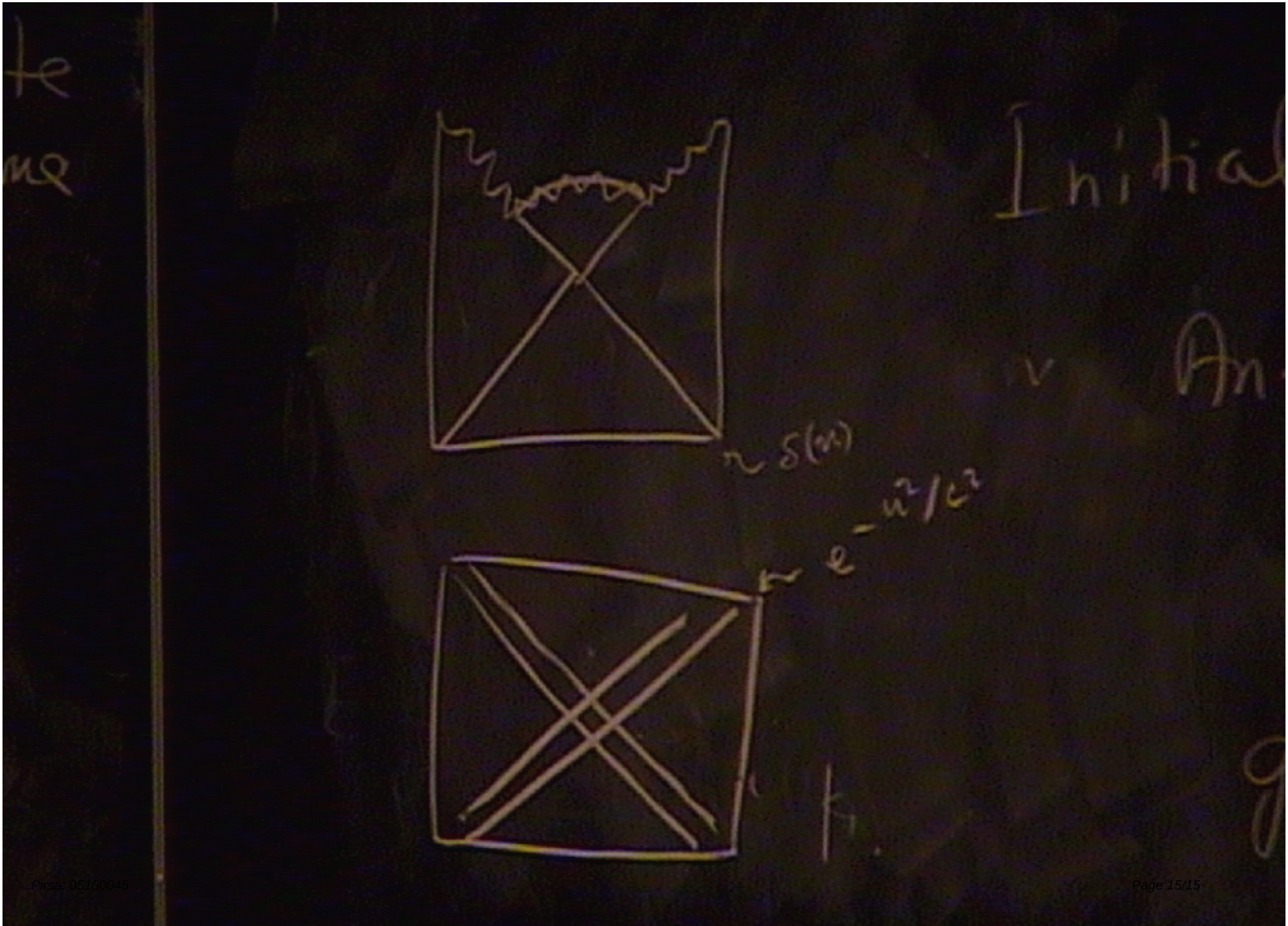


- rate $\sim e^{-A(m/H)}$
- DOS $\sim e^{+B\sqrt{\alpha'}m}$
- string suppression $\sim e^{-C\alpha' m^2}$
- ...far fewer relics

Gross and Mende, Nucl. Phys B **303**, *407 (1988): Phys. Lett. B* **197**, *129 (1987): Gross, Phys. Rev. Lett.* **60** *1229 (1988)*

Conclusions

- In our background:
  - Spectrum of string pairs differs from field theory expectations.
  - Overall rate of string pair production differs too.
  - $\rightarrow$ production of massive *strings* very different from massive *particles*.
- Outlook:
  - Extrapolating to cosmological spacetime, reduced production of stringy relics.
  - Clues of new string effects in time–dependent spacetimes.


Initial