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Holographic preheating

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Abstract: We propose a holographic description of cosmic preheating at strong coupling. In this scenario the energy transfer between the inflaton and matter field is mimicked by a model of holographic superconductor. An exponential amplification of the matter field during preheating can be described by the quasi-normal modes of a metastable "black hole" in the bulk spacetime with an expanding boundary. Our results reveal that the matter field can be produced continuously at strong coupling in contrast to the case of weak coupling with a discontinuous matter growth as inflaton oscillates. Furthermore, the amplification of matter field has an enhanced dependence on the vacuum expectation value of the inflaton at strong coupling. By virtue of the proposed mechanism, physics of the very early universe at an extremely high temperature right after inflation may become accessible.

Keywords: cosmic preheating; quasi-normal mode; strong coupling; holographic principle

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Cosmic reheating, which bridges the gap between the end of the primordial inflationary universe and the beginning of the big bang universe, is one significant puzzle in modern cosmology. It is suggested that after inflation, the energy restored in the potential of the inflaton field can be released by producing matter fields in the standard model (SM) of particle physics through their couplings. The reheating was studied using the description of the lowest order perturbation theory in Refs. [1-3] and cosmologists found that this process was typically slow and would lead to an initial state of low temperature for the hot big bang. As was observed in Refs. [4,5], however, an instability of parametric resonance may exist and realize a drastic phase of energy transfer from the inflaton to matter fields, which the inflaton weakly couples to. This phase, dubbed as preheating, was studied extensively in the literature[6-8] (see e.g. Refs. [9-11] for recent reviews; and see Refs. [12] for preheating in bounce cosmology). The instability of parametric amplification may also occur in metric fluctuations, and hence, the study of preheating can play a crucial role to observationally constrain or even rule out inflationary models[13-19].

The perturbative analysis indicates that the parametric resonance, characterized by a period of exponential growth of the matter fields, terminates when the backreaction is non-negligible. Preheating is followed by the continued matter field evolution and its equilibration through the energy redistribution until the universe reaches thermal equilibrium[20,21]. This completes the reheating process and marks the beginning of the hot big bang. Interestingly, an analogous scenario also arises in the context of heavy ion collisions, where the physical system evolves from saturated nucleus to quark gluon plasma in local thermal equilibrium[22]. The above scenario is well established upon the assumption that the inflaton weakly couples to matter fields. Many features characteristic of the weakly coupled theory follows naturally from the assumption, e.g. the SM particles are produced only when the inflaton rolls over the bottom of the potential well. While the nature of the inflaton field and its couplings to matter fields remain mysterious, it is desirable to explore the preheating process in a strongly coupled theory as an alternative. In addressing this issue, we can also gain insights on which features are generic for cosmic preheating and which features are more specific to underlying models.

For pedagogical purposes, we artistically illustrate a holographic description of preheating at strong coupling in Fig. 1. We use a metastable hairy black hole as an initial state. Its evolution towards a stable

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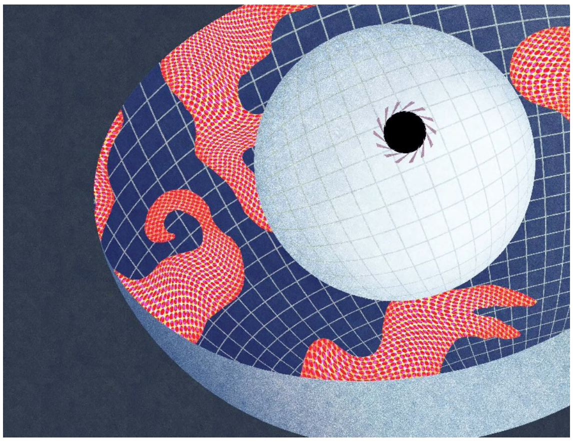

Fig. 1 Artistic illustration of holographic preheating. A 4D FRW universe is holographically described by a 5D AdS-Schwarzschild black hole, which is conformally mapped to an AdS-FRW background. (credit to Mr. Hu Yulin)

black hole can mimic the preheating process. Since preheating occurs in an expanding universe, we apply a holographic model with a Friedmann-Robertson-Walker (FRW) boundary①. The bulk spacetime is then an Anti de Sitter (AdS)-FRW and such a background can be conformally mapped to the familiar AdS-Schwarzschild black hole as analyzed in Ref. [32]. In order to extract the detailed information, one can proceed with the calculation of quasi-normal modes (QNMs) in this background. The QNMs contain an unstable mode, which exactly characterizes the exponential matter creation during preheating at strong coupling.

We begin with a holographic superconductor model with the action[33-36] in form of

$$S = \int \mathrm{d}^5 x \sqrt{-g}\left[-\frac{1}{4}F_{MN}F^{MN} - \frac{1}{2}(\partial\Psi)^2 - \frac{1}{2}m^2\Psi^2 - \Psi^n(\partial_M p - A_M)(\partial^M p - A^M)\right] \tag{1}$$

where $F_{MN}=\partial_M A_N-\partial_N A_M$ is the field strength of the bulk $U(1)$ gauge field. We use a complex scalar Ψ as dual to the inflaton and the gauge field A_M as dual to (fermionic) matter field by assuming that the inflaton decays to fermionic fields only. The fermionic fields could affect the cosmic expansion through backreaction. In order to focus on the holographic description of the strongly coupled preheating, we do not consider backreaction in the present study. The model is realized in an AdS-FRW background, which can be applied to describe our universe. In the probe limit, this background can be found from a coordinate transformation on an AdS-Schwarzschild black hole[32]. This offers a simplification, i. e.: as a first step we can study the dynamics of Φ and A_M in an AdS-Schwarzschild black hole. With a conformal transformation, the results can be translated to the dynamics of inflaton and matter field in an expanding universe.

We consider a $(d+1)$-D AdS-Schwarzschild black hole background as follows,

$$\mathrm{d}s^2 = -f(r)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{f(r)} + \frac{r^2}{L^2}\mathrm{d}x_i^2 \tag{2}$$

where $f(r)=\frac{r^2}{L^2}-\frac{M^{d-2}}{r^{d-2}}$ and $i=1,2,\cdots,d-1$. The horizon is given by $r_H \equiv M^{(d-2)/d}$. In the probe limit, the temperature is fixed by the horizon radius as: $T=\frac{r_H d}{4\pi L^2}$. From now on we set the AdS radius $L\equiv 1$ for simplicity. To find the metastable background, we turn on both Ψ and $A_t\equiv\Phi$. The dynamics of Ψ and Φ can be obtained by solving the bulk equation of motion (EoM).

Near the AdS boundary $r\to\infty$, we get

$$\begin{cases} \Psi = \Psi_+ r^{-\Delta_+} + \Psi_- r^{-\Delta_-} + \cdots, \\ \Phi = \mu - \dfrac{\rho}{r^{d-2}} + \cdots \end{cases} \tag{3}$$

with $\Delta_\pm=\frac{d\pm\sqrt{d^2+4m^2}}{2}$.

For the application of cosmic preheating, we set $d=4$ and $m^2=-3$ such that $\Delta_+=3$ and $\Delta_-=1$. Both Ψ_+ and Ψ_- are normalizable modes. We take the quantization by adopting the Dirichlet boundary condition with Ψ_+ as the vacuum expectation value (*vev*) and Ψ_- the source. Thus the conformal dimension of the inflaton is Δ_+. Moreover, the boundary value of Φ gives the chemical potential μ for the fermionic matter. In analogy to holographic superconductors, there is a phase transition at a critical chemical potential μ_c, i. e., above μ_c the phase is characterized by an inflaton condensate, while, below μ_c the phase is normal matter with a vanishing *vev* of the inflaton. In analogy to holographic superconductors, there is a phase transition at a critical temperature T_c, i. e., below T_c the phase is a hairy black hole, characterized by an inflaton condensate, while, above T_c the phase is a hairless black hole, which is matter dominated with a vanishing *vev* of the inflaton. The order of the phase transition depends on the choice of n, namely, it is second order for $n=2$ and first order for $n\geqslant 3$[33]. We choose the case of $n=3$, in which a metastable hairy black hole is present. The bulk EoM yields two possible solutions. The first is analytic: $\Phi=\mu(1-r_H^2/r^2)$ and $\Psi=$

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① Note that, our starting point differs from other holographic descriptions of cosmology where the universe itself is a bulk spacetime with a field theory boundary, such as, involving a time-varying gravitational coupling[23-26], in a nontrivial unstable state[27,28], or, including field fluctuations[29,30]. The reheating through holographic thermalization was studied in Ref. [31].

0, where Ψ is trivial and corresponds to a normal, uncondensed phase; the second is solved numerically, which gives a vanishing source for the inflaton $\Psi_- = 0$ but a non-vanishing *vev* $\Psi_+ \neq 0$.

To obtain the phase diagram, we calculate the free energy associated with two solutions. The free energy per unit volume for a general solution is given by

$$W = -\mu\rho - r_H^4 \Psi_+ \Psi_- - \frac{3}{2}\int_{r_H}^{\infty} \frac{\Psi^3 \Phi^2 r \mathrm{d}r}{1 - r_H^4/r^4}\,^{[33]}.$$

For the first uncondensed solution, the free energy density takes $W_0 = -\mu^2 r_H^2$. Thus, the difference of free energy density between the condensed and uncondensed phases is

$$\Delta W = W - W_0 = \mu^2 r_H^2 - \mu\rho - \frac{3}{2}\int_{r_H}^{\infty} \frac{\Psi^3 \Phi^2 r \mathrm{d}r}{1 - r_H^4/r^4} \quad (4)$$

where we have set the source of the bulk scalar $\Psi_- = 0$. We numerically plot ΔW as a function of μ in Fig. 2. The uncondensed phase corresponds to $\Delta W = 0$. There exist two branches of the condensed phase as shown in Fig. 2, of which the upper always has $\Delta W > 0$ and thus is unphysical. The lower branch is stable ($\Delta W < 0$) above a critical μ_c, and has a metastable ($\Delta W > 0$) region when $\mu < \mu_c$, indicating a first order phase transition.

We choose a metastable phase as the initial state. As the inflaton dominated phase is thermodynamically unstable, the cosmic system will evolve towards the uncondensed phase, which is dominated by the matter field. The detailed evolution of this process can be described by the QNMs of the background. To this end, we consider the following perturbations: $A_t \to \Phi i + a_t$, $A_x \to a_x$, $\Psi \to \Psi + \sigma$ and $p \to \eta/\Psi$, with a_t, a_x dual to the density and current of the produced matter and σ dual to the inflaton condensate drained. The details will be presented in an accompanied study[37]. Here we quote the results, which are generic from the perspective of black hole QNMs and are crucial for cosmological implications. The QNMs yield a dispersion relation $\omega = \omega(k)$ for a plane wave $e^{-i\omega t + ikx}$ fluctuation, among which there is one mode containing positive imaginary part. This corresponds to an exponential growing mode associated with the instability of the metastable black hole; the real part of the QNM vanishes in the homogeneous limit $k = 0$, indicating a purely growing mode. A numerically small real part does show up for inhomogeneous fluctuations $k \neq 0$. Also, the dependence of QNMs on the inflaton's *vev* reveals that a large *vev* tends to trigger a fast conversion to matter field with the imaginary part being approximately linear in the *vev*[37].

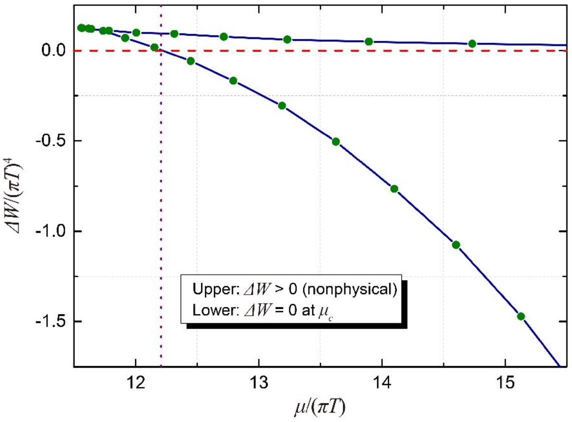

Fig. 2 The dimensionless free energy density difference ΔW as a function of dimensionless chemical potential μ (normalized by πT). Model parameters are chosen as: $d = 4$, $m^2 = -3$ and $n = 3$ in detailed numerics. The background temperature is fixed at $T = 0.2$, which is related to the energy scale of the system.

Now we conformally map the above results to the AdS-FRW background to study cosmological implications. It can be derived from the AdS-Schwarzschild black hole via coordinate transformations[32]. To be explicit, the 5D AdS-FRW in terms of the Fefferman-Graham coordinates takes,

$$\mathrm{d}s^2 = \frac{1}{\xi^2}[\mathrm{d}\xi^2 - \mathcal{N}(\tau,\xi)^2 \mathrm{d}\tau^2 + \mathcal{A}(\tau,\xi)^2 \mathrm{d}\vec{x}^2] \quad (5)$$

where $\mathrm{d}\vec{x}^2 \equiv (\mathrm{d}x_1^2 + \mathrm{d}x_2^2 + \mathrm{d}x_3^2)$. The boundary of AdS-FRW is located at $\xi \to 0$ with $\mathcal{N} \to 1$ and $\mathcal{A} \to a(\tau)$, which corresponds to a 4D FRW universe. $a(\tau)$ is the scale factor, governing the cosmic expansion. The explicit forms of $\mathcal{N}$ and $\mathcal{A}$ can be expressed as[32]

$$\mathcal{A}^2 = a^2 - \frac{\dot{a}^2}{2}\xi^2 + \frac{(\dot{a}^4 + 4r_H^4)}{16a^2}\xi^4,\ \mathcal{N} = \frac{\dot{\mathcal{A}}}{\dot{a}},$$

with the dot being derivative with respect to τ. These two backgrounds are related via the following coordinate transformations,

$$r = \mathcal{A}/\xi,\ \dot{t} = -(\mathcal{A}r')/(f\dot{a}),\ t' = -\dot{a}/(\xi f) \quad (6)$$

with the prime being the derivative with respect to ξ. The form of $t(\tau, \xi)$ can be obtained by integrating (6). The coordinate transformations can be reduced to the conformal transformation on the boundary, which relates the energy stress tensor in FRW to that in Minkowski[32].

We start with the AdS-Schwarzschild background, with only $A_t = \Phi$ and Ψ non-vanishing. To apply holography, we consider the AdS-FRW background in the axial gauge with $A_\xi = 0$. Then we perform the coordinate transformations and a gauge tranformation with $A_\xi = (A_t + \partial_t \Lambda)t' + \partial_r \Lambda r'$. The gauge condition $A_\xi = 0$ fixes $\Lambda(\tau,\xi)$ as $\Lambda' = -A_t t'$. With a non-vanishing Λ, p gains a non-vanishing *vev* $p(\tau,\xi) = \Lambda$ in the AdS-FRW. We further consider the QNMs parametrized by η, σ, a_t and a_x as analyzed in Ref. [37]. Again, we impose the axial gauge condition $A_\xi + a_\xi = 0$. It requires an additional gauge transformation with the parameter $\delta\Lambda$ satisfying

$a_\xi = (a_t + \partial_t\delta\Lambda)t' + \partial_r\delta\Lambda r' = 0$, which fixes: $\delta\Lambda' = -a_t t'$.

Afterwards, we are ready to derive the QNMs in the AdS-FRW by applying the previous coordinate and gauge transformations. We focus on the a_t component that is related to the matter field creation. Parametrizing the form of a_t as

$$a_t = \mathrm{e}^{-\mathrm{i}\omega t + \mathrm{i}kx} F_t(r), \text{ with } F_t(r) = \frac{\#}{r^2} + \cdots,$$

where # is a numerical prefactor that encodes the dependence on the inflaton ' s *vev*. Using asymptotic forms of coordinate transformations,

$$a_t \simeq \mathrm{e}^{\left[-\mathrm{i}\omega\int\frac{\mathrm{d}\tau}{a(\tau)} + \mathrm{i}kx\right]}\left(\frac{\#\xi^2}{a^2} + O(\xi^3)\right) \tag{7}$$

and hence, $a_t t' \sim O(\xi^3)$, $\delta\Lambda \sim O(\xi^4)$. The QNM a_τ in the AdS-FRW background takes

$$a_\tau = (a_t + \partial_t\delta\Lambda)\dot{t} + \partial_r\delta\Lambda\dot{r} = a_t\dot{t} + \dot{\delta\Lambda}.$$

From the gauge condition, $\delta\Lambda \sim O(\xi^4)$, we find that it is negligible in contributing to matter field. Eventually, one gets

$$a_\tau = \mathrm{e}^{\left[-\mathrm{i}\omega\int\frac{\mathrm{d}\tau}{a(\tau)} + \mathrm{i}kx\right]}\left(\frac{\#\xi^2}{a^3} + \cdots\right) \tag{8}$$

in the AdS-FRW. Using the dictionary derived in Ref. [37], one obtains the growth of matter density as

$$j^\tau = \mathrm{e}^{\left[-\mathrm{i}\int\frac{\omega\,\mathrm{d}\tau}{a(\tau)} + \mathrm{i}kx\right]}\frac{\#}{a^3}. \tag{9}$$

The structure of Eq. (9) is very instructive. It consists of an exponent and an overall factor. The scale factor $a(\tau)$ enters both in the exponent and the overall factor. In the exponent, it appears through the "rescaled time" $\int\mathrm{d}\tau/a(\tau)$. As we have discussed before, QNMs with the positive imaginary part correspond to the existence of an instability, which grows according to the rescaled time. An expanding universe would typically suppress the instability and thus slow down the amplification of matter field. On the other hand, the overall factor $1/a^3$ depicts the damping effect due to the cosmic expansion. Additionally, the prefactor # encodes the dependence on the inflaton ' s *vev*, as is inherited from the Minkowski result.

Eventually, we compare the results of holographic preheating at strong coupling with those obtained at weak coupling. Here we quote the results from a comprehensive review[10] (adapted in our notations)

$$n(\tau) \sim \frac{(m\Phi_0)^{3/2}\mathrm{e}^{2m\mu\tau}}{a^3\sqrt{1 + \frac{m\mu\tau}{2\pi}}} \tag{10}$$

where μ and Φ_0 are the mass and *vev* of inflaton. In the weak coupling case, the inflaton field oscillates in the potential and produces matter particles every time it passes the bottom, which corresponds to the moment when the adiabaticity condition breaks down. We note several interesting properties between (8) and (9) as follows:

(ⅰ) Unlike in the weak coupling case with particles being produced discontinuously, the strong coupling scenario is featured by continuous particle production. Oscillation is only seen in the amplification of inhomogeneous matter density in the strong coupling case.

(ⅱ) Both two share the same overall factor $1/a^3$, which is due to the damping effect from the cosmic expansion. It is tempting to conjecture that the factor is generic for any homogeneous density. We stress that the damping effect at strong coupling is nonadiabatic as a also appears in the rescaled time.

(ⅲ) The qualitative dependence of the growth rate on the inflaton's *vev* is the same: a large *vev* leads to a rapid growth. But the details are different. The strong coupling result (9) gives a stronger dependence on the inflaton ' s *vev*, i. e. the exponent of matter growth/inflaton depletion grows with the inflaton ' s *vev*; while, in the weak coupling case (10), the inflaton ' s *vev* appears merely in a power law form.

In this letter we proposed a brand new description of cosmic preheating at strong coupling by virtue of a holographic dictionary. Our results are different from those obtained in the weak coupling case. The most distinguished difference is that in the strongly coupled case, the matter field can be amplified continuously in contrast to the weakly coupled case where the matter field is only produced when the parametric resonance is triggered. The scenario of holographic preheating is expected to be generic from the viewpoint of the QNMs in a metastable black hole background.

The proposed scenario may initiate fruitful studies from many perspectives. Note that, we modelled a specific initial state with a metastable black hole in the probe limit, which can be generalized. Also, we assumed that the inflaton only decays to fermionic matter, which can be extended to the bosonic case. The analysis of cosmic preheating should include the backreaction, which under holographic description corresponds to the evolution from a metastable hairy black hole to a stable hairless black hole. The end of this evolution is dual to the matter field dominated phase of the universe. While the process of equilibration is hard to be realized in the weak coupling case[20,21], it becomes natural from the holographic point of view of the black hole dynamics. These issues are left for forthcoming study.

We also interestingly note that, the *holographic preheating* that describes preheating at strong coupling may be applied to inflationary models from fundamental theories, such as, string theory. With the proposed scenario, we could better understand the universe with strong coupling and further discriminate various models of the very early universe by combining with cosmological observations.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Abbott L F, Farhi E, Wise M B. Particle production in the new inflationary cosmology. Phys. Lett. B, 1982, 117: 29-33.

[2] Dolgov A D, Linde A D. Baryon asymmetry in inflationary universe. Phys. Lett. B, 1982, 116: 329-334.

[3] Albrecht A, Steinhardt P J, Turner M S, et al. Reheating an inflationary universe. Phys. Rev. Lett., 1982, 48: 1437-1440.

[4] Dolgov A D, Kirilova D P. On particle creation by a time dependent scalar field. Sov. J. Nucl. Phys., 1990, 51: 172-177.

[5] Traschen J H, Brandenberger R H. Particle production during out-of-equilibrium phase transitions. Phys. Rev. D, 1990, 42: 2491-2504.

[6] Kofman L, Linde A D, Starobinsky A A. Reheating after Inflation. Phys Rev Lett, 1994, 73: 3195-3198.

[7] Shtanov Y, Traschen J H, Brandenberger R H. Universe reheating after inflation. Phys. Rev. D, 1995, 51: 5438-5455.

[8] Kofman L, Linde A D, Starobinsky A A. Towards the theory of reheating after inflation. Phys. Rev. D, 1997, 56: 3258-3295.

[9] Bassett B A, Tsujikawa S, Wands D. Inflation dynamics and reheating. Rev. Mod. Phys., 2006, 78: 537-589.

[10] Allahverdi R, Brandenberger R, Cyr-Racine F Y, et al. Reheating in inflationary cosmology: Theory and applications. Ann. Rev. Nucl. Part. Sci., 2010, 60: 27-51.

[11] Amin M A, Hertzberg M P, Kaiser D I, et al. Nonperturbative dynamics of reheating after inflation: A review. Int. J. Mod. Phys. D, 2014, 24: 1530003.

[12] Cai Y F, Brandenberger R, Zhang X. Preheating a bouncing universe. Phys. Lett. B, 2011, 703: 25-33.

[13] Finelli F, Brandenberger R H. Parametric amplification of metric fluctuations during reheating in two field models. Phys. Rev. D, 2000, 62: 083502.

[14] Bassett B A, Viniegra F. Massless metric preheating. Phys. Rev. D, 2000, 62: 043507.

[15] Brandenberger R H, Frey A R, Lorenz L C. Entropy fluctuations in brane inflation models. Int. J. Mod. Phys. A, 2009, 24: 4327-4354.

[16] Brandenberger R H, Dasgupta K, Davis C. Study of structure formation and reheating in the D3/D7 brane inflation model. Phys. Rev. D, 2008, 78: 083502.

[17] Bazrafshan Moghaddam H, Brandenberger R H, Cai Y F, et al. Parametric resonance of entropy perturbations in massless preheating. Int. J. Mod. Phys. D, 2015, 24: 1550082.

[18] McDonough E, Bazrafshan Moghaddam H, Brandenberger R H. Preheating and entropy perturbations in axion monodromy inflation. JCAP, 2016, 2016: 012.

[19] Jiang J, Liang Q, Cai Y F, et al. Numerical study of inflationary preheating with arbitrary power-law potential and a realization of curvaton mechanism. Astrophys. J., 2019, 876(2): 136.

[20] Micha R, Tkachev I I. Relativistic turbulence: A long way from preheating to equilibrium. Phys. Rev. Lett., 2003, 90: 121301.

[21] Micha R, Tkachev I I. Turbulent thermalization. Phys. Rev. D, 2004, 70: 043538.

[22] Berges J. What the inflaton might tell us about RHIC/LHC. Nucl. Phys. A, 2009, 820: 65C-73C.

[23] Chu C S, Ho P M. Time-dependent AdS/CFT duality and null singularity. JHEP, 2006, 2006: 013.

[24] Das S R, Michelson J, Narayan K, et al. Time-dependent cosmologies and their duals. Phys. Rev. D, 2006, 74: 026002.

[25] Das S R, Michelson J, Narayan K, et al. Cosmologies with null singularities and their gauge theory duals. Phys. Rev. D, 2007, 75: 026002.

[26] Awad A, Das S R, Ghosh A, et al. Slowly varying dilaton cosmologies and their field theory duals. Phys. Rev. D, 2009, 80: 126011.

[27] Hertog T, Horowitz G T. Holographic description of AdS cosmologies. JHEP, 2005, 2005: 005.

[28] Craps B, Hertog T, Turok N. Quantum resolution of cosmological singularities using AdS/CFT correspondence. Phys. Rev. D, 2012, 86: 043513.

[29] Brandenberger R H, Ferreira E G M, Morrison I A, et al. Fluctuations in a cosmology with a spacelike singularity and their gauge theory dual description. Phys. Rev. D, 2016, 94: 083508.

[30] Ferreira E G M, Brandenberger R. Holographic curvature perturbations in a cosmology with a space-like singularity. JCAP, 2016, 7: 030.

[31] Kawai S, Nakayama Y. Reheating of the Universe as holographic thermalization. Phys. Lett. B, 2016, 759: 546-549.

[32] Apostolopoulos P S, Siopsis G, Tetradis N. Cosmology from an anti-de Sitter-Schwarzschild black hole via holography. Phys. Rev. Lett., 2009, 102: 151301.

[33] Franco S, García-García A, Rodríguez-Gómez D. A general class of holographic superconductors. JHEP, 2010, 2010: 092.

[34] Gubser S S. Breaking an Abelian gauge symmetry near a black hole horizon. Phys. Rev. D, 2008, 78: 065034.

[35] Hartnoll S A, Herzog C P, Horowitz G T. Holographic superconductors. JHEP, 2008, 12: 015.

[36] Hartnoll S A, Herzog C P, Horowitz G T. Building a holographic superconductor. Phys. Rev. Lett., 2008, 101: 031601.

[37] Cai Y F, Lin S, Liu J, etal. Holographic preheating: Quasi-normal modes and holographic renormalization. https://arxiv.org/abs/1612.04394.

全息预加热宇宙学模型

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摘要：提出了一个存在强耦合的宇宙预加热过程的全息理论描述. 在这一描述下，极早期宇宙中的暴胀子与物质场之间的能量交换可以通过一个全息超导模型来模拟实现. 其中，预加热过程的物质场会经历近乎于指数放大，而这正好可以用边界扩展的整体时空中的亚稳态“黑洞”的准正态模式来刻画. 我们的结果揭示了，物质场可以在强耦合环境中连续产生，这与弱耦合情况是截然不同的. 此外，在强耦合下的物质场放大对暴胀子真空期望值的依赖性增强. 基于我们所提出的理论机制，暴胀结束后尚处于极高温度下的极早期宇宙很可能是可以被探知的.

关键词：宇宙预加热；准正态模式；强耦合；全息原理

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中国腐泥煤中微量元素的研究进展

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摘要：煤是我国的主要能源，煤炭大量使用会造成一系列环境问题，特别是煤中伴生的有害微量元素迁移、析出，进而影响人类生存生活环境. 关于煤中微量元素的研究已经形成了相对完整的体系，然而，由于腐泥煤的次要经济地位，其微量元素地球化学研究远不如腐植煤. 腐泥煤分布广泛、厚度大，具有一定的工业价值，腐泥煤中微量元素含量特征已有部分报道，而对腐泥煤中微量元素的赋存状态、富集机理、地质成因等地球化学机理方面有待系统研究. 在综合分析国内外腐泥煤研究基础上，详细阐述了腐泥煤中微量元素地球化学研究的热点问题、重点内容和发展方向. 腐泥煤的地球化学研究是对煤地质学和煤地球化学理论的补充和完善，具有重要科学意义，对我国特殊煤种成煤理论体系和资源开发利用亦具重要现实意义.

关键词：腐泥煤；微量元素；地球化学
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1　引言

煤是中国的主要能源，煤炭大量使用会造成一定的环境问题. 煤中有害微量元素是环境的主要污染物之一：首先，在风、雨水淋滤等作用下，煤中部分微量元素随气体、飘尘或粉尘进入大气，部分直接渗入到土壤或含水层中；其次，煤燃烧过程中释放出的气体及粉尘、飘尘会携带有害物质或元素进入大气，引起大气污染[1]. 长期生活于此类环境会产生一些相关疾病，危害人体健康. 此外，煤中有害微量元素渗入地下水或土壤可通过污染饮用水和农作物间接危及人体健康[2].

近半世纪来，随着煤中微量元素地球化学方面研究广泛且深入，出现了一系列重要研究成果，煤地球化学研究体系也日趋完善. 自 20 世纪 30 年代开始，国内外学者在煤中先后发现 80 多种微量元素；40 年代转向对微量元素的赋存状态及其成因方面进行研究，且逐步进入到应用阶段，形成较完整的研究体系[1]. 按成煤物质来源，可将煤划分为腐植煤、腐植腐泥煤和腐泥煤[4]. 然而，从煤的类型来看，煤种划分多，而对某些特殊煤种煤中微量元素地球化学研究相对很少，从而导致煤地球化学研究体系部分缺失；由于腐泥煤相对腐植煤数量较少，分布较小，相关研究也相对欠缺.

从环境学方面来看，微量元素作为煤的伴生物质，其赋存和富集不仅具煤地质学理论意义，而且更重要的是具有资源化、洁净利用和环境保护等多方面现实意义. 腐泥煤作为特殊煤种，其微量元素的地球化学研究是对煤地质学和煤地球化学理论体系的补充和完善.

2　腐泥煤的定义

煤的成因分类将煤划分为腐植煤、腐植腐泥煤和腐泥煤三类；腐泥煤占特殊地位，代表泥炭沼泽某一时期具有不同于形成腐植煤的古地理面貌及生物输入[3].

腐泥煤是由低等植物和浮游生物残骸，在湖泊、潟湖、海湾等环境中，经腐泥化和煤化作用形成的煤[4]. 一般而言，腐泥煤光泽较暗淡，结构均一，块状构造，常具贝壳状断口，韧性较大. 腐泥煤多呈透镜状或薄层状产出于腐植煤煤层中，偶尔形成单独可采煤层. 腐植煤是高等植物在泥炭沼泽中经泥炭化和煤化作用形成的煤；根据煤化程度，可分为泥炭、褐煤、烟煤和无烟煤四类. 腐植腐泥煤，是由低等植物和高等植物经成煤作用形成的，介于在腐植煤和腐泥煤之间以腐泥为主.

常见腐泥煤有藻煤和胶泥煤. 藻煤是腐泥煤的典型代表，是保存有藻类、菌类等低等植物结构的腐泥煤，光泽暗淡呈褐色，致密状或略显层理. 胶泥煤是成

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GUI Lin, LIU Guijian, LIU Yuan. Progress in the research of trace elements in sapropelic coal of China. J. Univ. Sci. Tech. China, 2020, 50(12): 1453-1459.