FINAL REPORT TO THE U.S. DEPARTMENT OF ENERGY

Horava-Lifshitz Theory and Applications to Cosmology and Astrophysics

Principal Investigator: *Anzhong Wang*

Department of Physics, Baylor University, One Bear Place # 97316, Waco, Texas 76798-7316

Tel.: (254) 710-2276; E-mail: Anzhong_Wang@baylor.edu

- **Date of Report:** November 3, 2014
- **DOE Grant Number:** DE-FG02-10ER41692
- **Project Period:** August 15, 2010 - August 14, 2014
- **DOE/Office of Science Program Office:** Office of High Energy Physics
- **DOE/Office of Science Program Office Topical Technical Contact:**
  Dr. Simona Rolli, Tel.: 301-903-0504; Email: simona.rolli@science.doe.org

Administrative Point of Contact, Telephone and Email: Kristy Erlanson, Baylor University, One Bear Place #97360, Waco, TX 76798; Tel.: 254-710-8608; Fax: 254-710-3534; Email: Kristy_Erlanson@baylor.edu

SUBMITTED TO THE U.S. DEPARTMENT OF ENERGY

OFFICE OF HIGH ENERGY PHYSICS

I. Introduction

This final report describes the activities of the Baylor University Gravity, Cosmology and Astroparticle Physics (GCAP) group on the project: *Horava-Lifshitz Theory and Applications to Cosmology and Astrophysics*, during the time, August 15, 2010 - August 14, 2014. We are grateful for the financial support provided by the U.S. Department of Energy for this research, which leads to our exceptional success. We are very proud to say that we have achieved all the goals set up in our project and made significant contributions to the understanding of the field. In particular, with this DOE support, we have published 38 articles in the prestigious national/international journals, which have already received about 1000 citations so far.

II. Theoretical High Energy Physics at Baylor

Our GCAP research group was established in 2006 by the PI, and currently consists of 13 members: four Baylor faculty members, the PI (the head of the group), Drs. Klaus Kirsten and Qin (Tim) Sheng from Math Department, and Dr. Yumei Wu from Physics Department; one visiting professor, Dr. Miao Tian from Lanzhou University of Technology, China; one Baylor postdoctoral fellow, Dr. Tao Zhu; four adjunct professors, Dr. Rong-Gen Cai from Institute of Theoretical Physics (ITP), Chinese Academy of Science, China, Dr. Yun-Gui Gong from Huazhong University of Science and Technology, China, Dr. Jianxin Lu from University of Science and Technology of China (USTC), Chian, and Dr. N.O. Santos from Queen Mary, University of London; and three graduate students, Bao-Fei Li, H.V. Satheeshkumar, and Xinwen Wang.

Each year there are several research scholars regularly visiting us, for example, Mr. Otavio Goldoni, a graduate student from the State University of Rio de Janeiro, Brazil, supported by the Brazilian National Foundaiton (CNPq), has been visiting us since September 1, 2014 (until April 1, 2015). Dr. Xun Xue from East China Normal University visited us in October 2014, while Dr. JianXin Lu paid a visit to us in August 2014.

Meanwhile, the PI and his research group members keep a closed contact with collaborators from various institutions, and actively attend national/international meetings. In particular, as one of the two co-chairs, the PI organized *the Hangzhou International Workshop on Gravitation and Cosmology*, Hangzhou, China, September 3-7, 2014. During the summer (May - August) of 2014, the PI paid a visit, respectively, to Dr. Jianxin Lu at USTC during the time, May 3 - 24, 2014; Dr. Rong-Gen Cai at ITP during the time, May 25 - June 25, 2014; and Dr. Qiang Wu during the time, June 26 - August 21, 2014. The visits were very fruitful, and already produced two articles just submitted for publication. In this coming December (2014), the PI is planing to pay a visit to Dr. Shinji Mukohyama at Tokyo University, Japan, and Dr. M.F. da Silva at the State University of Rio de Janeiro, Brazil.

III. Activities during this project (August 15, 2010 - August 14, 2014)

Since Horava proposed his theory of quantum gravity at Lifshitz points in 2009 [Phys. Rev. D**79**, 084008 (2009) [arXiv:0901.3775]], the theory, which is often referred to as the Horava-Lifshtiz (HL) theory, has attracted a great deal of attention [T. Clifton, *et al*, Phys. Rept. **513**, 1 (2012) [arXiv:1106.2476]]. When applied to cosmology, various remarkable features were found [S. Mukohyama, Class. Quant. Grav. **27**, 223101 (2010) [arXiv:1007.5199]].

Despite all of these achievements, the original version of theory was plagued with several problems, including instability and strong coupling. Although they are different, their origins are all closely related to the existence of the spin-0 gravitons, due to the breaking of the Lorentz invariance. To resolve these problems, various modifications have been proposed. So far at least two of them are free of all these pathologies, and meanwhile are consistent with both astrophysical and cosmological observations. These are: (i) *the healthy extension of the non-projectable HL gravity*, proposed by D. Blas, O. Pujolas, and S. Sibiryakov [Phys. Rev. Lett. 104, 181302 (2010) [arXiv:0909.3525]]; and (ii) *the nonrelativistic general covariant HL theory with an extra U(1) symmetry*, proposed by us [T. Zhu, Q. Wu, A. Wang, and F.-W. Shu, Phys. Rev. D**84**, 101502 (R) (2011) [arXiv:1108.1237]].

• It is remarkable to note that our model has been recently embedded in string theory via the nonrelativistic AdS/CFT correspondence in S. Janiszewski and A. Karch, JHEP, **02**, 123 (2013) [arXiv:1211.0005]; Phys. Rev. Lett. **110**, 081601 (2013) [arXiv:1211.0010].

• It should be also noted that, in the healthy extension, because of the large number (> 70) of independent coupling constants, the prediction power of the theory is often questioned. In addition, the spin-0 gravitational modes in this setup still exist. It was motivating by these problems that in Phys. Rev. D**84**, 101502 (R) (2011) we proposed a new version of the HL gravity with an extra $U(1)$ symmetry and the non-projecability condition $N = N(t, x)$, where N is the lapse function in the ADM decompositions [R. Arnowitt, S. Deser, and C.W. Misner, Gen. Relativ. Gravit. **40**, 1997 (2008)]. Similar to the projectable case with the extra $U(1)$ symmetry [P. Hořava and C.M. Melby-Thompson, Phys. Rev. D**82**, 064027 (2010) [arXiv:1007.2410]; A.M. da Silva, Class. Quantum Grav. **28**, 055011 (2011) [arXiv:1009.4885]; Y.-Q. Huang and A. Wang, Phys. Rev. D**83**, 104012 (2011) [arXiv:1011.0739]], we showed explicitly that the spin-0 modes can be eliminated [T. Zhu, W. Zhao, Y.-Q. Huang, A. Wang, and Q. Wu, Phys. Rev. D**88**, 063508 (2013) [arXiv:1305.0600]]. Thus, all the problems related to them (instability, strong coupling, and so on) are resolved automatically. To reduce the number of independent coupling constants, we also imposed the detailed balance condition and allowed it to be broken softly, so the number of independent coupling constants is dramatically reduced and becomes comparable to that in the original version of the HL gravity, while the theory still has healthy UV and IR limits.

• All the PPN parameters in our model of the HL theory were calculated and given explicitly in terms of the coupling constants of the model [K. Lin and A. Wang, Phys. Rev. D**87**, 084041 (2013) [arXiv:1212.6794]; K. Lin, S. Mukohyama, A. Wang, and T. Zhu, Phys. Rev. D**89**, 084022 (2014) [arXiv:1310.6666]], and found that there exists a large region in the phase space of the constants, in which all the solar system tests carried out so far are satisfied. In particular, they can take the same values as those given in GR.

• The consistency of our model with cosmology was shown recently [T. Zhu, Y.-Q. Huang, and A. Wang, Phys. Rev. D**87**, 084041 (2013) [arXiv:1212.6794]; A. Wang, Q. Wu, W. Zhao, and T. Zhu, Phys. Rev. D**87**, 103512 (2013) [arXiv:1208.5490]; T. Zhu, W. Zhao, Y.-Q. Huang, A. Wang, and Q. Wu, Phys. Rev. D**88**, 063508 (2013) [arXiv:1305.0600]], and it was found that the parity violation, a generic feature of the HL theory, could lead to observational signatures in the CMB polarizations and non-Gaussianity in the forthcoming observations.

• To study the consistence of the HL theory, another important issue is the existence of black holes in the HL gravity. Because of the nonrelativistic dispersion relations, the speed of light in the HL theory is in principle unlimited. As a result, there are significant differences in causal structures and black holes between GR and the HL theory [J. Greenwald, J. Lenells, J. X. Lu, V. H. Satheeshkumar,and A. Wang, Phys. Rev. D**84**, 084040 (2011) [arXiv:1105.4259]]. Thus, it was understood that black holes in the HL theory were only low energy phenomena. Along this line of arguing, we showed that stationary, axisymmetric and slowly rotating vacuum spacetimes in the infrared limit of the HL gravity always exist [A. Wang, Phys. Rev. Lett. 110, 091101 (2013) [arXiv:1212.1876]]. In fact, for any given spherical static vacuum solution of the HL theory (of any model, including the ones with an additional U(1) symmetry), there always exists a corresponding slowly rotating, stationary and axisymmetric vacuum solution, which reduces to the former, when the rotation is switched off. The rotation is universal and only implicitly depends on the models of the HL theory and their coupling constants through the spherical seed solution. As a result, all asymptotically flat slowly rotating vacuum solutions are asymptotically identical to the slowly rotating Kerr solution. This is in contrast to the claim of E. Barausse and T. Sotiriou [Phys. Rev. Lett. **109**, 181101 (2012)[arXiv:1207.6370]], in which slowly rotating black holes were reported (incorrectly) not to exist in the infrared limit of the non-projectable HL theory.

• Recently, a potential breakthrough was the realization that there still exist absolute causal boundaries in theories with broken Lorentz invariance (LI), the so-called *universal horizons*, and particles even with infinitely large velocities would just move around on these boundaries and cannot escape to infinity [D. Blas and S. Sibiryakov, Phys. Rev. D**84**, 124043 (2011) [arXiv:1110.2195]]. The universal horizon radiates like a blackbody at a fixed temperature [P. Berglund, J. Bhattacharyya, and D. Mattingly, Phys. Rev. Lett. **110**, 071301 (2013) [arXiv:1210.4940]], and obeys the first law of black hole mechanics [P. Berglund, J. Bhattacharyya, and D. Mattingly, Phys. Rev. D**85**, 124019 (2012) [arXiv:1202.4497]]. The main idea is as follows: In a given space-time, a timelike foliation parametrized by the so-called khronon $\phi\left(x^{\mu}\right)=$ Constant might exist globally. Among these surfaces, there may exist one on which the khronon ϕ diverges, while physically nothing singular happens there. Then, as one moves in towards it, each hypersurface $\phi\left(x^{\mu}\right)=$ Constant bends down to the infinite past and asymptotically approaches to it. This surface is the universal horizon, and even particles with infinitely large velocities (instantaneous propagations) would just move around on this surface and cannot escape to infinity. Universal horizons have been then intensively studied in Einstein-aehter theory [B. Cropp, S. Liberati, A. Mohd, and M. Visser, Phys. Rev. D**89**, 064061 (2014) [arXiv:1312.0405]; and references therein], in which the khronon field is always part of the gravitational sector and describes its additional degrees of freedom.

To generalize the above definition of the universal horizons to any gravitational theory that violates LI, recently we prompted ϕ as a probe field, and assumed that it plays the same role as a Killing vector of a given space-time, so its existence does not affect the background, but defines the properties of it [K. Lin, E. Abdalla, R.-G. Cai, and A. Wang, *Universal horizons and black holes in gravitational theories with broken Lorentz symmetry*, arXiv:1408.5976]. By this way, such a field is no longer part of the gravitational field and it may or may not exist in a given space-time. Applied such a generalized definition of the universal horizons to static charged solutions of the healthy extensions of the HL gravity, we showed explicitly that universal horizons exist in some of these solutions. Such horizons exist not only in the IR limit of the HL gravity, as has been considered so far, but also in the full HL gravity, that is, when high-order operators are taken into account.

• Applying our definition of universal horizons to static spacetimes, $ds^2=-F(r)dt^2+\frac{dr^2}{F(r)}+r^2d\Omega_k^2$, where $d\Omega_k^2$ denotes a two-dimensional constant surface, we found that the khronon field can be solved explicitly when its velocity becomes infinitely large, in which the universal horizons coincide with the sound horizon of the khronon [K. Lin, O. Goldoni, M.F. da Silva, and A. Wang, *A New Look at Those Old Black Holes: Existence of Universal Horizons*, arXiv:1410.6678 (2014)]. Choosing the timelike coordinate aligned with the khronon, the static metric takes a simple form, $ds^2=-G(r)d\phi^2+U^2(r)d\psi^2+r^2d\Omega_k^2$, where $d\psi\equiv -dt+\frac{\sqrt{G}}{FU}dr,\ G(r)\equiv U^2+F(r)\geq 0,\ U\equiv -r_o^2/r^2$ and r_o is a constant. Clearly, the coordinate singularity located at the Killing horizon $F(r=r_{KH})=0$ in the (t,r)-coordinates now disappears in the (ϕ,ψ) - coordinates. But, the metric in the

(ϕ, ψ) - coordinates becomes singular at the universal horizon $G(r = r_{UH}) = 0$. Since various well-known black holes can be cast in terms of the (t, r)-coordinates in the above form , one can easily use our formulas to study the locations of universal horizons and the corresponding thermodynamics. In particular, applying such developed formulas to the Schwarzschild, Schwarzschild anti-de Sitter, and Reissner-Nordström solutions, we found that in all these solutions universal horizons always exist and are inside the Killing horizons. For example, for the Schwarzschild solution, we found that the universal horizon is located at $r_{UH} = 3r_s/4$, where r_s denotes the Schwarzschild radius.

• Quantization of gravity is one of the most important issues to be addressed for the HL theory in particular and for gravitational physics in general. In (1+1)-dimensional (2d) space-times, because of the breaking of general covariance, the HL gravity is non-trivial even only gravity is involved, in contrast to that of GR. In particular, it was shown that the quantization of the projectable HL gravity is equivalent to the 2d CDTs [J. Ambjorn, L. Glaser, Y. Sato, and Y. Watabiki, Phys. Lett. B**722**, 172 (2013) [arXiv:1302.6359]].

Recently we systematically studied the quantization of the 2d projectable HL gravity, and found that the theory can be quantized by following the standard Dirac quantization [B.-F. Li, A. Wang, Y. Wu, and Z. C. Wu, *Quantization of (1+1)-dimensional Hořava-Lifshitz theory of gravity*, arXiv:1408.2345]. In particular, after working out the Hamiltonian structure, we found that the momentum constraint can be solved explicitly, and the corresponding Hamilton can be quantized by following the canonical Dirac process. It is remarkable to note that the Hamilton can be also written in terms of a simple harmonic oscillator, and then its quantization can be also carried out in terms of harmonic oscillators. Note that, when taking the classical Hamilton over to the quantum mechanic one, the ordering ambiguity always exists. It is this ambiguity that provides a mechanism for the wavefunction of the Wheeler-DeWitt equation $\hat{H}_i \Psi(t, L) = 0$ to have nontrivial solutions and be normalizable.

When the HL gravity minimally couples to a scalar field, the momentum constraint can be solved explicitly in the case where the fundamental variables are functions of time only. In this case, the coupled system can be also quantized by following the Dirac process as well as the harmonic oscillators. But, in the latter the Hamilton is equivalent to two interacting harmonic oscillators [B.-F. Li, A. Wang, Y. Wu, and Z. C. Wu, *Quantization of (1+1)-dimensional Hořava-Lifshitz theory of gravity*, arXiv:1408.2345].

• The cosmological inflation not only solves problems of the standard big bang cosmology, but also provides the simplest mechanism to produce the primordial density perturbations and gravitational waves. However, it is well known that the inflationary scenario is conceptually incomplete in serval respects. For example, in most of the inflation models, the energy scale of quantum fluctuations related to the present observations were not far from the Planck scale at the beginning of inflation. Thus, questions immediately arise as to whether the usual predictions of the scenario in the framework of semi-classical approximations still remain robust due to the ignorance of gravitational quantum physics at such high energy. It is widely expected that in this regime new physics, quantum gravity, will provide a complete description of the early universe.

Since the HL gravity is aimed to provide an ultraviolet complete theory, it is very nature to consider the quantum gravitational effects in the inflationary universe in the framework of the HL gravity, in which both the scalar and tensor perturbations produced during the inflationary epoch are governed by the equation $\mu_k''(\eta) + \left(\omega_k^2(\eta) - \frac{z''(\eta)}{z(\eta)}\right)\mu_k(\eta) = 0$, where $\mu_k(\eta)$ denotes the mode function, a prime the differentiation with respect to the conformal time η. $z(\eta)$ depends on the background and the types of perturbations (scalar and tensor). $\omega_k^2(\eta)$ is a polynomial of k up to six-order [A. Wang and R. Maartens, Phys. Rev. D**81**, 024009 (2010) [arXiv:0907.1748]; A. Wang, D. Wands, and R. Maartens, J. Cosmol. Astropart. Phys. **03** (2010) 013 [arXiv:0909.5167]; A. Wang, Phys. Rev. D**82**, 124063 (2010) [arXiv:1008.3637]]. The dispersion relation in models of string/M-theory and loop quantum cosmology also takes a similar form.

To understand these quantum effects, a critical step is to solve the mode function μ_k analytically, and then extract information from it, including the power spectra, spectral indices and runnings. Such studies are very challenging, as the problem becomes mathematically very much involved, and meanwhile the treatment needs to be very accurate, in order to match with the observational data of current and forthcoming experiments. Currently, in most of the analytical treatments of the mode functions with modified dispersion relations the WKB approximations were used [R.H. Brandenberger and J. Martin, Class. Quantum. Grav. **30** (2013) 113001], and the corresponding errors are unknown, which frequently are by far beyond the required accuracy by observations [S. E. Joras and G. Marozzi, Phys. Rev. D**79**, 023514 (2009); A. Ashoorioon, D.Chialvab, and U. Danielsson, *ibid.*, **06**, 034 (2011)].

The attempt to close this gap was initiated by S. Habib, K. Heitmann, G. Jungman, and C. Molina-Paris [Phys. Rev. Lett. **89**, 281301 (2002)], in which the *uniform asymptotic approximation* was first introduced to inflation. However, they considered only the relativistic case, $\omega_k^2 = k^2$. In addition, the mode function was constructed only to the first-order approximation, for which the error bounds in general are $\lesssim 15\%$. Clearly, this is not accurate enough to match with the accuracy of the observational data. Moreover, their results cannot be applied to the cases with nonlinear dispersion relations, as mentioned above.

In order to understand the gravitational quantum effects in inflationary models, recently we generalized the uniform asymptotic approximation method to the cases with non-linear dispersion relations, where poles (singularities of ω_k^2) and multiple turning points (zeros of ω_k^2) are allowed [T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Q. Sheng, Phys. Rev. D**89**, 043507 (2014) [arXiv:1308.5708]; Int. J. Mod. Phys. A**29**, 1450142 (2014) [arXiv:1308.1104]]. Such firs-order approximation was further generalized to arbitrary order approximations for the case where there is only one turning-point [T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Q. Sheng, Phys. Rev. D**90**, 063503 (2014) [arXiv:1405.5301]]. In particular, to the third-order, we found that the error bounds are $\lesssim 0.15\%$!

Recently, we generalized such studies to the most general single field inflation, the k-inflation [T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Q. Sheng, Phys. Rev. D *in press* (2014) [arXiv:1407.8011]]. The distinguishable feature of the k-inflation is that the scalar perturbations obey an equation of motion with a time-dependent sound speed. This makes it very difficult to calculate the corresponding power spectra and spectral indices, although with some additional assumptions, the power spectra of the k-inflation can be obtained by using the Green's function method. For a general sound speed, after introducing a simple hierarchy of parameters, related to the sound speed of the scalar perturbations and its successive derivatives, the power spectra and spectral indices were calculated by using the first-order uniform asymptotic approximation, at which the error bounds in general are $\simeq 15\%$. Using the uniform asymptotic approximations developed by us up to the third-order, we obtained the most accurate results carried out so far in the literature for the power spectra, spectral indices and runnings, where the error bounds in general are $\lesssim 0.15\%$.

IV. Papers Exclusively Acknowledged HEP Support

1. Black holes, compact objects and solar system tests in non-relativistic general covariant the-

ory of gravity.
J. Greenwald, V. H. Satheeshkumar, and A. Wang, JCAP, **12**, 007 (22 pages) (2010) [arXiv:1010.3794].

2. Vector and tensor perturbations in Horava-Lifshitz cosmology.
A. Wang, Phys. Rev. D**82**, 124063 (9 pages) (2010) [arXiv:1008.3637].

3. Stability of spin-0 graviton and strong coupling in Horava-Lifshitz theory of gravity.
A. Wang and Q. Wu, Phys. Rev. D**83**, 044025 (13 pages) (2011) [arXiv:1009.0268].

4. Cosmology in nonrelativistic general covariant theory of gravity.
A. Wang and Y. Wu, Phys. Rev. D**83**, 044031 (8 pages) ((2011) [arXiv:1009.2089].

5. Stability, ghost, and strong coupling in nonrelativistic general covariant theory of gravity with $\lambda \neq 1$.
Y. Huang and A. Wang, Phys. Rev. D**83**, 104012 (11 pages) (2011) [arXiv:1011.0739].

6. Detailed balance condition and ultraviolet stability of scalar field in Horava-Lifshitz gravity.
A. Borzou, K. Lin, and A. Wang, JCAP, **1105**, 006 (21 pages) (2011) [arXiv:1103.4366].

7. On strong coupling in nonrelativistic general covariant theory of gravity.
K. Lin, A. Wang, Q. Wu, and T. Zhu, Phys. Rev. D**84**, 044051 (8 pages) (2011) [arXiv:1106.1486].

8. Black holes and global structures of spherical spacetimes in Horava-Lifshitz theory.
J. Greenwald, J. Lenells, J. X. Lu, V. H. Satheeshkumar, and A. Wang, Phys. Rev. D**84**, 084040 (25 pages) (2011) [arXiv:1105.4259].

9. Radiating gravastars.
R. Chan, M.F.A. da Silva, Jaime F. Villas da Rocha, and A. Wang, JCAP, **10**, 013 (18 pages) (2011) [arXiv:1109.2062].

10. U(1) symmetry and elimination of spin-0 gravitons in Horava-Lifshitz gravity without the projectability condition.
T. Zhu, Q. Wu, A. Wang, and F.-W. Shu, Phys. Rev. D**84**, 101502 (Rapid Communications, 5 pages) (2011) [arXiv:1108.1237].

11. Static electromagnetic fields and charged black holes in general covariant theory of Hořava-Lifshitz gravity.
A. Borzou, K. Lin, and A. Wang, JCAP, **02**, 025 (20 pages) (2012) [arXiv:1110.1636].

12. General relativity limit of Horava-Lifshitz gravity with a scalar field in gradient expansion.
A.E. Gumrukcuoglu, S. Mukohyama, and A. Wang, Phys. Rev. D**85**, 064042 (16 pages) (2012) [arXiv:1109.2609].

13. General covariant Horava-Lifshitz gravity without projectability condition and its applications to cosmology.
T. Zhu, F.-W. Shu, Q. Wu, and A. Wang, Phys. Rev. D**85**, 044053 (20 pages) (2012) [arXiv:1110.5106].

14. Inflation in general covariant theory of gravity.
Y.-H. Huang, A. Wang, Q. Wu, JCAP, **10**, 10 (37 pages) (2012) [arXiv:1201.4630].

15. Solar system tests and interpretation of gauge field and Newtonian prepotential in general covariant Horava-Lifshitz gravity.
K. Lin, S. Mukohyama, and A. Wang, Phys. Rev. D**86**, 104024 (17 pages) (2012) [arXiv:1208.2491].

16. Non-Gaussianity of a single scalar field in general covariant Horava-Lifshitz gravity.
Y.-H. Huang and A. Wang, Phys. Rev. D**86**, 103523 (16 pages) (2012) [arXiv:1209.1624].

17. On "No-go theorem for slowly rotating black holes in Horava-Lifshitz gravity."
A. Wang, arXiv:1212.1040.

18. Inflation in general covariant Horava-Lifshitz gravity without projectability.
T. Zhu, Y.-H. Huang, and A. Wang, JHEP **01** 138 (23 pages) (2013) [arXiv:1208.249].

19. Stationary and slowly rotating spacetimes in Horava-Lifshitz gravity.
A. Wang, Phys. Rev. Lett. **110**, 091101 (5 pages) (2013) [arXiv:1212.1876].

20. Static post-Newtonian limits in non-projectable Horava-Lifshitz gravity with an extra U(1) symmetry.
K. Lin and A. Wang, Phys. Rev. D**87**, 084041 (8 pages) (2013) [arXiv:1212.6794].

21. Polarizing primordial gravitational waves by parity violation.
A. Wang, Q. Wu, W. Zhao, and T. Zhu, Phys. Rev. D**87**, 103512 (7 pages) (2013) [arXiv:1208.5490].

22. Gravitational collapse in Horava-Lifshitz theory.
J. Greenwald, J. Lenells, V. H. Satheeshkumar, and A. Wang, Phys. Rev. D**88**, 024044 (21 pages) (2013) [arXiv:1304.1167].

23. Primordial Non-Gaussianity of Gravitational Waves in General Covariant Horava-Lifshitz Gravity.
Y.-Q. Huang, A. Wang, R. Yousefi, and T. Zhu, Phys. Rev. D**88**, 023523 (11 pages) (2013) [arXiv:1304.1556].

24. Effects of parity violation on non-gaussianity of primordial gravitational waves in Horava-Lifshitz gravity.
T. Zhu, W. Zhao, Y.-Q. Huang, A. Wang, and Q. Wu, Phys. Rev. D**88**, 063508 (7 pages) (2013) [arXiv:1305.0600].

25. Constructing analytically mode functions of inflation with trans-Planckian physics.
T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Q. Sheng, Int. J. Mod. Phys. A**29**, 1450142 (12 pages) (2014) [arXiv:1308.1104].

26. Inflationary cosmology with nonlinear dispersion relations.
T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Sheng, Phys. Rev. D**89**, 043507 (23 pages) (2014) [arXiv:1308.5708].

27. Post-Newtonian approximations in the Ho?ava-Lifshitz gravity with extra U(1) symmetry.
K. Lin, S. Mukohyama, A. Wang, and T. Zhu, Phys. Rev. D**89**, 084022 (25 pages) (2014) [arXiv:1310.6666].

28. Lifshitz spacetimes, solitons, and generalized BTZ black holes in quantum gravity at a Lifshitz point.
F.-W. Shu, K. Lin, A. Wang, and Q. Wu, JHEP**04**, 056 (42 pages) (2014) [arXiv:1403.0946].

29. Gravitational quantum effects in the light of BICEP2 results.
T. Zhu and A. Wang, Phys. Rev. D**90**, 027304 (5 pages) (2014) [arXiv:1403.7696].

30. Gravitational quantum effects on power spectra and spectral indices with higher-order corrections.
T. Zhu, A. Wang, G. Cleaver, K. Kirsten, Q. Sheng, Phys. Rev. D**90**, 063503 (20 pages) (2014) [arXiv:1405.5301].

31. Universal horizons and black holes in gravitational theories with broken Lorentz symmetry.
K. Lin, E. Abdalla, R.-G. Cai, and A. Wang, Inter. J. Mod. Phys. D *in press* (2014) [arXiv:1408.5976].

32. Power spectra and spectral indices of k-inflation: high-order corrections.
T. Zhu, A. Wang, G. Cleaver, K. Kirsten, and Q. Sheng, Phys. Rev. D *in press* (2014) [arXiv:1407.8011].

33. High-dimensional Lifshitz-type spacetimes in quantum gravity at a Lifshitz point.
K. Lin, F.-W. Shu, A. Wang, and Q. Wu, arXiv:1404.3413.

34. Holographic Superconductors in Horava-Lifshitz Gravity.
K. Lin, E. Abdalla, and A. Wang, arXiv:1406.4721.

35. Effects of high-order operators in non-relativistic Lifshitz holography.
X.-W. Wang, J. Yang, M. Tian, A. Wang, Y.-B. Deng, G. Cleaver, arXiv:1407.1194.

36. Quantization of (1+1)-dimensional Horava-Lifshitz theory of gravity.
B.-F. Li, A. Wang, Y. Wu, and Z. C. Wu, arXiv:1408.2345.

37. Universal horizons and black holes in gravitational theories with broken Lorentz symmetry.
K. Lin, E. Abdalla, R.-G. Cai, and A. Wang, arXiv:1408.5976.

38. A New Look at Those Old Black Holes: Existence of Universal Horizons.
K. Lin, O. Goldoni, M.F. da Silva, and A. Wang, arXiv:1410.6678.

V. A current list of people working on this research activity

- Bao-Fei Li and Xinwen Wang, current graduate students, Physics Department, Baylor University. Not receive support from this award.

- V.H. Satheeshkumar current graduate students, Physics Department, Baylor University. Partially supported by this project to attend the conference, Aspects of Inflation, A&M, College Station, April 8-10, 2011. In addition, he also received two-month summer (2012) salaries from this award.

- A. Borzou, former graduate student. Partially supported by this project to attend the conference, Aspects of Inflation, A&M, College Station, April 8-10, 2011.

- Y.-Q. Huang, former graduate student. Partially supported by this project to attend the conference, Aspects of Inflation, A&M, College Station, April 8-10, 2011. Received two-month summer (2012) salaries from this award.

- Dr. E. Abdalla, Sao Paulo State University, Brazil. Not receive support from this award.

- Dr. R.-G. Cai, Institute of Theoretical Physics, Beijing, China. Not receive support from this award.

- Dr. C.-J. Gao, from Beijing National Observatory, China. Partially supported by this project (honoraria, $600) to give a serious lectures in quantum gravity to my graduate students and worked together with them on this research project, during his visit to Baylor (July - November, 2010).

- Drs. Klaus Kirsten, J. Lenells, and Qin (Tim) Sheng, Math Department, Baylor University. Not receive support from this award.

- Dr. Kai Lin, Sao Paulo State University, Brazil. Partially supported by this project to attend two conferences, one was the 27th Pacific Coast Gravity Meeting, Caltech, Pasadena, California, March 18-19, 2011, in which Kai presented (orally) his work together with Borzou on "Detailed balance condition and ultraviolet stability of scalar field in Horava-Lifshitz gravity"; and the other was Aspects of Infl ation, A&M, College Station, April 8-10, 2011.

- Dr. J.-X. Lu, University of Science and Technology of China, who was partially supported by this project (honoraria, $ 1000) to work together with me and my research group on this research project, during his visit to Baylor (Feb. 7 - March 5, 2011).

- Drs. R. Maartens and D. Wands, ICG, University of Portsmouth, UK. Not receive support from this award.

- Dr. S. Mukohyama, IPMU, Tokyo University, Japan. Not receive support from this award.

- Dr. M.F. da Silva, the State University of Rio de Janeiro, Brazil. One week hotels was provided during her visit in February, 2012.

- Dr. F.-W. Shu, Chongqing University of Posts & Telecommunications, China. Not receive support from this award.

- Drs. Q. Wu and Z.C. Wu, Zhejiang University of Technology, China. Not receive support from this award.

- Dr. Y. Wu, Physics Department, Baylor University. Not receive support from this award.

- Dr. T. Zhu, GCAP-CASPER, Baylor University. Not receive support from this award.

Financial Status Report

4/8/2014

Sponsor

US Dept of Energy
1000 Independence Ave SW
Washington, DC 20585

B.U. Project 32250110
B.U. Contract 2100246
Grant period 8/15/2010 to 8/14/2014

Award Ref DE-SC0005201
Prime Award Ref

Report for 1/1/2014 - 3/31/2014 under the contract between US Dept of Energy and Baylor University for the project "Horava-Lifshitz Theory and Applications to Cosmology and Astrophysics". Project director is Anzhong Wang.

Cost Category	Budget	Current	Cumulative	Balance
Salary & Wages	69,566.00	0.00	70,995.94	-1,429.94
Fringe Benefits	11,940.03	0.00	10,510.09	1,429.94
Supplies	11,621.00	0.00	4,431.11	7,189.89
Travel	13,099.97	1,454.23	20,289.86	-7,189.89
Subtotal:	**$106,227.00**	**$1,454.23**	**$106,227.00**	**$-0.00**
F&A rate 36.50%:	38,773.00	530.79	38,772.86	0.14
Total:	**$145,000.00**	**$1,985.02**	**$144,999.86**	**$0.14**

Prepared by Phyllis Doughty
Project Coordinator
Office of Sponsored Programs