研究計畫中英文摘要：

（一）計畫中文摘要。（五百字以內）

早期宇宙膨脹應該在不同方向各有不同膨脹方式，也就是所謂膨脹解有很大的方向性。然而這一些宇宙最後會演化成各方向膨脹方式相近似，也就是所謂的沒有方向性的現今宇宙，Hawking 等人相信這並不是偶然的結果，而是早期宇宙的方向性在相當自然的初始條件下，會必然地演化成現今無方向性的宇宙。其中有一大類滿足一些合理的初始能量條件的模型，已經由 Wald 的經典論文得到證實，只要滿足這些初始能量條件，任何有方性的膨脹解都是不穩定的，最後一定會朝無方向的 de Sitter 宇宙演進。

同時這幾年來，有一些不滿足 Wald 能量條件的解陸續被發現，然而多數解最後還是一一被證實也是不穩定的解。因而累積的證據似乎指向：所有膨脹的、有方向性的解，似乎都是不穩定的。因此如何放寬初始條件、推廣 Wald 的證明，或者找出必然演化成無方向性宇宙的最終條件，顯然是一個值得挑戰的課題。我們試圖找出最大的不穩定條件，同時也把短程目標鎖定再幾個被宣稱可能是穩定的膨脹解，試圖找出其不穩定的證據與証明。

關鍵詞：早期宇宙 、能量條件、 膨漲宇宙、 de Sitter 宇宙。

(二) 計畫英文摘要。（五百字以內）

The evolution of the Bianchi space and the stability condition of the de Sitter space are closely related. Robert Wald shows that the de Sitter space is a stable final state for any system satisfying certain energy conditions. It is also known that certain anisotropic Bianchi expanding solutions do not approach the de Sitter space during the evolution process. These solutions are known to violate the energy conditions of Wald, and most of these solutions appear, or have been proved, to be unstable. It is important to find out the necessary conditions for the uniqueness and existence of a de Sitter space as a final state for all anisotropic initial states. Hence we propose to derive or clarify a more specific form of the energy conditions for these evolutionary processes. Focus will also be addressed on the importance/relation of various inflationary theories.

Key word: early universe, energy condition, expanding universe, de Sitter space

報告內容：

前言、研究目的、研究方法

The mission of recent astronomical observations is aimed to test and understand how the universe might have evolved from a general initial condition into its present state of large-scale isotropy and homogeneity together with an almost flat spectrum of near-Gaussian fluctuations. The inflationary scenario is known to be a successful model working properly with the cosmological standard model. There should have been a brief moment of accelerated expansion during the epoch of the early universe [1]. For example, a simple physically-motivated inflationary scenario can be induced by the acceleration driven by a scalar field with a constant potential serving as the cosmological constant. It can also be induced by a higher derivative pure gravity models with natural graceful exit. Therefore, it is important to find out whether universal acceleration and asymptotic approach to the de Sitter metric always occurs in these models. For instances, a series of cosmic no-hair theorems of varying strengths and degrees of applicability have been proved in support of certain constraints on the field parameters for its occurrence [2-8]. In addition, the conformal equivalence

between general relativity in the presence of a scalar field and these higher-order theories in vacuum has also been studied in Ref. [9-11].

For example, it was shown that new types of cosmological solution arise when $\Lambda > 0$ which have no counterparts in general relativity in the Bianchi type II and type VI_h spaces [12] if quadratic terms are added to the Lagrangian of general relativity. Theses solutions inflate anisotropically and do not approach the de Sitter spacetime at large times. Hence they provide counter-examples to the expectation that a cosmic no-hair theorem will continue to hold in simple higher-order extensions of general relativity. Other consequences of these higher-order theories have also been studied in [13-17]. We have been able to show that the inflationary solutions found [12] in the Bianchi II space are in fact unstable in the presence of anisotropic perturbations [18].

The no-hair theorem for Einstein gravity states that a positive cosmological constant model will drive the late-time evolution towards the de Sitter spacetime for Bianchi types *I* - *VIII* spaces provided that the matter sources obey the strong-energy condition [6]. It is also known that counter-examples exist if this condition dose not hold exactly [22- 25]. For example, the Bianchi type II and VI solutions in Ref. [12] inflate in the presence of a positive cosmological constant. These new solutions are, however, neither de Sitter, nor asymptotically de Sitter. In addition, it can be shown that similar solutions are also solutions to a Brans-Dicke type scalar tensor theory in the Bianchi type II background space. It is shown, however, that these anisotropically inflating solutions are not stable under field perturbations for the Brans-Dicke model [26-27]. Similar results also apply to the scalar tensor theory in the Bianchi type VI space.

Note that from the point of view of an effective theory of gravity, an action with quadratic curvature terms should be understood as some perturbative corrections to Einstein gravity suitable in some energy scale. Theories quadratic in the curvature give field equations which are higher order than two in time derivatives. These theories generally have run away solutions. The runaway solutions are supposed to be unphysical because they grow with time scales which are beyond the limits of validity of the theory.

Thus, in this context not all solutions have physical significance [28]. For example, the BH expanding solution does not have a limit in general relativity (i.e. it is not defined for $\beta \to 0$). An isotropic example of this is the Starobinsky inflation [29].

Since our de Sitter background appears to be a stable final state of our evolutionary history, it is therefore a very important task to find out the most general energy conditions or constraints for the no-hair theorem. We need to understand whether we end up in a final state by accident or it is the ultimate destiny of any physically motivated models. In particular, the effect of high energy correction terms should be very important in the stability and evolution of the early universe. We therefore propose to study the effects of all possible higher-dimensional, higher derivative models as well as the effective theories derived from the string theory, be it Kaluza-Klein or brane models, to the stability problem of the Bianchi spaces.

文獻探討:

Ref. [1] introduces the inflationary model for the first time. This settles the longstanding debates of the cosmological standard model.

Ref. [4] studies the runaway problem for theories without a limit in general relativity. Higher derivative models present a good example for this problem.

Ref.[6] proposes that for Einstein gravity states that a positive cosmological constant model will drive the late-time evolution towards the de Sitter spacetime for Bianchi types *I* - *VIII* spaces provided that the matter sources obey the strong-energy condition. This energy condition is later known as a no-hair theorem for the cosmological evolution.

Ref. [22- 25] show that counter-examples exist if this condition dose not hold exactly.

Ref. [12] also shows that there exists the Bianchi type II and VI solutions that inflate in the presence of a positive cosmological constant. These new solutions are, however, shown to be neither de Sitter, nor asymptotically de Sitter.

Ref. [31] shows that solutions found in Ref. [12] are also solutions to a Brans-Dicke type scalar tensor theory in the Bianchi type II background space. It is shown, however, that these anisotropically inflating solutions are not stable under field perturbations for the Brans-Dicke model [26-27]. Similar results also apply to the scalar tensor theory in the Bianchi type VI space [30].

References:

[1] A. Guth, Phys. Rev. D 23, 347 (1981); A.D. Linde, Phys. Lett. B129, 177 (1983).

[2] J.D. Barrow, Perturbations of a De Sitter Universe, In *The Very Early Universe*, eds. G. Gibbons, S.W. Hawking and S.T.C Siklos, (Cambridge UP, Cambridge, p.267, 1983).

[3] W. Boucher and G.W. Gibbons, In *The Very Early Universe*, ed. G. Gibbons, S.W. Hawking and S.T.C Siklos, (Cambridge UP, Cambridge, p. 273, 1983).

[4] A.A. Starobinskii, Sov. Phys. JETP Lett. 37, 66 (1983).

[5] L.G. Jensen and J. Stein-Schabes, Phys. Rev. D 35, 1146 (1987).

[6] R. Wald, Phys. Rev. D 28, 2118 (1983).

[7] J.D. Barrow, Phys. Lett. B, 187, 12 (1987).

[8] J.D. Barrow, Phys. Lett. B, 235, 40 (1990); J.D. Barrow and P. Saich, Phys. Lett B 249, 406 (1990); J.D. Barrow and A.R. Liddle, Phys. Rev. D 47, R5219 (1993); A.D. Rendall, Class. Quant. Grav. 22,1655 (2005).

[9] J.D. Barrow, Nucl. Phys. B 296, 697 (1988).

[10] J.D. Barrow and S. Cotsakis, Phys. Lett. B. 214, 515 (1988).

[11] K.I. Maeda, Phys. Rev. D 39, 3159 (1989).

[12] J.D. Barrow and Sigbjorn Hervik, PHYSICAL REVIEW D 73, 023007 (2006).

[13] A. Berkin, Phys. Rev. D 44, 1020 (1991).

[14] E. Bruning, D. Coule, C. Xu, Gen. Rel. Grav. 26, 1197 (1994).

[15] H.-J. Schmidt, gr-qc/0407095.

[16] A.D. Linde, Phys. Lett. B 175, 395 (1986); A. Vilenkin, Phys. Rev. D 27, 2848 (1983).

[17] J.D. Barrow and F.J. Tipler, *The Anthropic Cosmological Principle*, (Oxford UP, Oxford, 1986).

[18] W.F. Kao and I.C. Lin, *Stability conditions for a Bianchi type II anisotropically inflating universes*, (2009) JCAP, to appear.

[19] J. Patera, R.T. Sharp, P. Winternitz and H. Zassenhaus, J. Math. Phys. 17, 986 (1976).

[20] J. Lauret, Math. Ann. 319, 715 (2001), Quart. J. Math. 52, 463 (2001), Math. Z. 241, 83 (2002), Dff. Geom. Appl. 18, 177 (2003).

[21] S. Hervik, talk held at the CMS Summer 2004 meeting, Halifax, NS, Canada.

[22] J.D. Barrow, Phys. Lett. B 180, 335 (1986).

[23] J.D. Barrow, Nucl. Phys. B 310, 743 (1988).
[24] J.D. Barrow, Phys. Lett. B 183, 285 (1987).
[25] N. Kaloper, Phys. Rev. D 44, 2380 (1991).
[26] W.F. Kao, "Anisotropically Infating Universes in a scalar tensor theory', CTU preprint (2008).
[27] W.F. Kao, Anisotropic perturbation of de Sitter space, The European Physical Journal C53 (2008) 87;
[28] E.E. Flanagan and R.M. Wald, Phys. Rev. D 54, 6233 (1996).
[29] A.A. StarobinskyA, Phys. Lett. B91, 99, (1980).
[30] W.F. Kao, *Stability conditions for a Bianchi type VI anisotropically inflating universes*, CTU preprint.
[31] W.F. Kao and I.C. Lin, Anisotropically Inflating Universes in a scalar tensor theory;, (2008) CTU preprint .
[32] Inflation with blowing-up solution of cosmological constant problem, Jihn E. Kim hep-th/0210117 ;
[33] The Cosmological Constant and Dark Energy, P. J. E. Peebles, Bharat Ratra, astro-ph/0207347, RMP (2003) in press.
[34] Origin of Small Cosmological Constant in Brane-World, Kazuo Ghoroku, Masanobu Yahiro, Phys.Rev. D66 (2002) 124020;
[35] Generalized Assisted Inflation, E. J. Copeland, Anupam Mazumdar, N. J. Nunes, Phys. Rev. D60 (1999) 083506,
[36] Assisted Chaotic Inflation in Higher Dimensional Theories, Panagiota Kanti, Keith A. Olive, Phys. Lett. B464 (1999) 192-198,
[37] Quintessential inflation, P. J. E. Peebles, A. Vilenkin, Phys. Rev. D 59, 063505 (1999) ,
Oscillating Inflation with a non-minimally coupled scalar field, Jae-weon Lee, Seoktae
[38] Koh, Chanyong Park, Sang Jin Sin, Chul H. Lee, Phys. Rev. D61 (2000) 027301,
[39] Inflation from extra dimensions, James M. Cline, Phys. Rev. D 61, 023513 (2000),
[40] Extra Dimensions and Inflation, Anupam Mazumdar, Phys. Lett. B469 (1999) 55-60,

References listed above are some recent work on the inflationary theory and the cosmological constant model involving various kinds of symmetry breaking potentials and/or higher dimensional theories and/or higher derivative models. In order to study these models in a consistent and complete manner, we have been able to derive a model-independent representation of the Friedmann equation in the presence of many different Bianchi metric spaces[30]. This equation has a compact form ready for thorough analysis on a variety of inflationary models. We also found that there are many mistakes in some important results of others. Even some of the final results they found were not affected by the mistakes we just mentioned, we will take a thorough check throughout all these calculations to make sure no serious mistakes may take place.

In addition, we will also generalize the system to see the inter-relations of the scale symmetry and the physical origin of these newly proposed symmetry breaking potentials and the evolution of the dark energy.

結果與討論計畫，成果自評

我們積極研討所有大尺度相關重力理論的相關課題，已經發表 8 篇相關論文，成果算是豐碩。發表期刊論文如下：[部分附錄於後]

- Kazuharu Bamba, C. Q. Geng, S. H. Ho, W. F. Kao, Large-scale magnetic fields from inflation due to a CPT-even Chern-Simons-like term with Kalb-Ramond and scalar fields, Eur. Phys. J. C (2012) 72:1978, DOI 10.1140/epjc/s10052-012-1978-1
- Tuan Q. Do, W. F . Kao, Anisotropic power-law inflation for the Dirac-Born-Infeld theory, Phys. Rev. D84 (2011) 123009; DOI: 10.1103/PhysRevD.84.123009
- ChiaMing Chang, W.F. Kao and Ing-Chen Lin, The stability analysis of the Lorentz Chern-Simons expanding solutions, Phys. Rev. D 84 (2011) 063014, DOI: 10.1103/PhysRevD.84.063014 [View PDF (230 kB)]
- Tuan Q. Do, W. F . Kao, and Ing-Chen Lin, Anisotropic power-law inflation for a two scalar fields model, Phys. Rev. D83, (2011), 123002,
- W.F. Kao and Ing-Chen Lin, The stability of the anisotropically inflating Bianchi type VI expanding solutions, Phys. Rev. D 83 (2011), 063004,
- W.F. Kao, Scalar tensor theory and the anisotropic perturbations of the inflationary universe; The European Physical Journal C,10.1140/epjc/s10052-009-1176-y, http://www.springerlink.com/content/e8x17g55r101166w/
- W.F. Kao and Ing-Chen Lin, Anisotropically Inflating Universes in a scalar tensor theory, Phys. Rev. D79 (2009) 043001;
- W.F. Kao and Ing-Chen Lin, Stability conditions for the Bianchi type II anisotropically inflating Universes, Journal of Cosmology and Astroparticle Physics,JCAP01(2009)022,

這幾篇論文的內容，摘錄如下:

1.
題目為 Scalar-tensor theory and the anisotropic perturbations of the inflationary universe
作者為 W.F. Kao
發表於 The European Physical Journal C65 (2010) 555;
內容為
Inflationary higher derivative scalar-tensor theory is analyzed in this paper in a de Sitter background space. A useful model-independent formula of the Friedmann equation is derived and used to study the stability problem associated with the anisotropic perturbations of the inflationary solution. The stability conditions of the de Sitter solution are derived for a general class of models. For a simple demonstration, an induced gravity model is considered in this paper for the effects of the higher derivative interactions including a cubic term.

2.
題目為 Anisotropically Inflating Universes in a scalar tensor theory,
作者為 W.F. Kao and Ing-Chen Lin,
發表於 Phys. Rev. D79 (2009) 043001

內容為

We show that a Brans-Dicke model admits some anisotropically inflating solutions which are identical to the solutions found in a higher derivative pure gravity theory. These inflating solutions were shown to break the cosmic no-hair theorem such that they do not approach the de Sitter universe at large times. The stability conditions of these solutions in this scalar-tensor theory are shown explicitly in this paper. It is shown that there exist unstable modes of the anisotropic perturbations. Therefore the inflating solutions are unstable in the scalar-tensor theory.

3.

題目為 Stability conditions for the Bianchi type II anisotropically inflating universes

作者為 **W.F. Kao and Ing-Chen Lin,**

發表於 JCAP01(2009)022

內容為

Stability conditions for a class of anisotropically inflating solutions in the Bianchi type II background space are shown explicitly in this paper. These inflating solutions were known to break the cosmic no-hair theorem such that they do not approach the de Sitter universe at large times. It can be shown that unstable modes of the anisotropic perturbations always exist for this class of expanding solutions. As a result, we show that these set of anisotropically expanding solutions are unstable against anisotropic perturbations in the Bianchi type II space.

4.

Stability of the anisotropically inflating Bianchi type VI expanding solutions.

作者為：W.F. Kao,Ing-Chen Lin

發表於 **Phys.Rev.D83:063004,2011**

作者為：A special class of the Bianchi typeVI expanding solutions was speculated to break the cosmic no-hair theorem that will not approach the late-time de Sitter solution. We will show that an unstable mode always exists when the perturbation of the field equations is applied to the system. In addition to a model-independent perturbation formula, a simplification is also achieved by the introduction of a δR=0solution good for quadratic models in all Bianchi spaces. The result shows that this special class of anisotropically expanding solutions is unstable.

5.

Anisotropic power-law inflation for a two scalar fields model

作者為：Tuan Q. Do, W. F. Kao, and Ing-Chen Lin

發表於 Phys. Rev. D83, (2011), 123002

內容為：A special class of Bianchi type I expanding solutions in a string motivated theory with a single scalar field has been speculated to break the cosmic no-hair theorem that will not approach the late time isotropic expanding solution. We will show by a new perturbation approach that an unstable mode for the inflationary solutions exists when an additional phantom field is introduced. The result indicates that the existence of an unstable mode is closely related to the extra fields that could be present during the very early Universe.

6.

The stability analysis of the Lorentz Chern-Simons expanding solutions

作者為：ChiaMing Chang, W. F. Kao, and Ing-Chen Lin

發表於　Phys. Rev. D 84, 063014 (2011) [11 pages]

內容為：

A class of Bianchi type II expanding solutions in a Lorentz Chern-Simons theory has been known to break the cosmic no-hair theorem. These solutions do not approach the late-time de Sitter Universe. We will show that there are two independent solutions classified by the parameter p for each given cosmological constant Λ. One of them is in the small-p phase; the other solution is in the large-p phase. It can be shown that an unstable mode always exists for the solution in its small-p phase that comes with smaller energy T_{00} and $T_{00}+T/2$. The result indicates that the large-p phase is unlikely to be stable from an observation of a modified version of Wald's theorem.

7.

Anisotropic power-law inflation for the Dirac-Born-Infeld theory,

作者為：Tuan Q. Do, W. F . Kao,

發表於　Phys. Rev. D84 (2011) 123009

內容為：

We find a new set of the Bianchi type I power-law expanding solutions in a string-motivated Dirac-Born-Infeld theory. Stability analysis shows that these power-law inflationary solutions remain stable with or without the contribution of the Dirac-Born-Infeld effect. We also find a new set of Bianchi type I expanding power-law solutions in a two scalar Dirac-Born-Infeld model with an additional phantom field. It is shown that the inclusion of the phantom field turns the Bianchi type I power-law solutions unstable during the inflationary phase.

8.

Large-scale magnetic fields from inflation due to a CPT-even Chern-Simons-like term with Kalb-Ramond and scalar fields,

作者為：Kazuharu Bamba, C. Q. Geng, S. H. Ho, W. F. Kao,

發表於 : Eur. Phys. J. C (2012) 72:1978

內容為：

We investigate the generation of large-scale magnetic fields due to the breaking of the conformal invariance in the electromagnetic field through the CPT-even dimension-six Chern–Simons-like effective interaction with a fermion current by taking account of the dynamical Kalb–Ramond and scalar fields in inflationary cosmology. It is explicitly demonstrated that magnetic fields on 1 Mpc scale with the field strength of $\sim 10^{-9}$ G at the present time can be induced.

總計研究進行前後期間，共發表 8 篇和計畫相關的論文:2009 兩篇，2010 一篇，2011 四篇，2012

一篇，其中包含 JCAP 一篇，PRD 五篇，EPJC 兩篇。除了已經發表的論文外外，還有一篇在投稿中，三篇正在修稿準備投稿中。相關論文，大致在證實 Hawking 的推測猜想，宇宙演化的終點，似乎會傾向演化成目前的軍像宇宙。

部分的研究主題，集中在處理以前學界存疑的結論，部分為新發展的理論和近年的發展。過去很多研究，都發現一些無法證明是否為不穩定的非均向解，發現者都相信他們找到的解，應該是穩定的不均向解，我們在過去的一年中，逐件檢視，發現這些存疑多年的解，其實都是不穩定的，這些結論似乎更強化 Hawking 猜解的正確性。

這幾年也因為弦論的進展，讓一些新的模型引起大家的注意。這是一些不一樣，新型態的解。通常是利用指數純量函數，和電磁場的交互作用，抑制非均向解的不穩定。早期宇宙電磁場的演化，也因為相關研究，引起大家的注意。我們也在這方面多所著墨，利用我們自行發展的新技術，試圖對相關宇宙演化穩定性的發展，有更深入的了解。
這些結果，

除了這些已經發表的論文之外，另外有兩篇相關論文正在投稿中，有關模型和能量條件的推演也有相當的進展。

總結:

1977年起，Hawking 等人 [Gibbons and Hawking, 1977] 、[Hawking and Moss, 1982] 提出一個 no-hair conjecture，推論只要有一個宇宙常數項，宇宙演化最終會趨近於 de Sitter space。1983年， Wald [Wald, 1983] 提出一個廣泛的證明，證明只要系統滿足強能量條件(SEC)和主要能量條件(DEC)，則這個有宇宙常數項的宇宙，最終會演化程 de Sitter space。但是，陸續有人提出不滿足兩種能量條件的不均向宇宙演化解，宣稱這些解違背Hawking的推論。

我們發展出一套簡化微擾的模式，陸續證明這些解都是不穩定的。因為有了這些進展，我們可以持續研究是否可以提出類似 Wald 所提出的廣泛證明，並試圖降低宇宙演化所需的條件限制。我們也將利用這果，繼續對不均勻微擾所可以得到的訊息，做廣泛而深入的分析，也將對黑洞解的穩定性進行廣泛與一般的分析與研究，試圖探討黑洞解和宇宙演化解之間的相互關連，與期穩定性之間的對應關係。希望藉由這個分析，探討最低能量狀態下，這些解析解的穩定性與期對稱性間的可能關連。

過去幾年我的研究計畫，早期宇宙的方向性演化與穩定性，主要在研究宇宙大尺度的結構與演化的過程，與暗物質暗能量等的相關物理機制。尤其是著重在早期宇宙演化的相關物理。這些論文都是針對Bianchi space的穩定性與相關高維度、高微分修正項的影響與貢獻所做的研究。我們成功地將該系統的微分方程式，化簡成易於推導的模式，讓後續原本無法進行的研究工作變成可行、也變得容易驗證。推導出的簡化方程式適用所有模型，這是這領域近年來重要的突破。

Bianchi空間的複雜度加上相關高維度、高微分修正項的模型在研究困難度上是該領域研究的首

要挑戰，因此這幾年我們潛心相關化簡工作，完成之後已經幫助我們的研究進入結果期。最近我們將這個方法用來證明，宇宙演化發展的重要議題。這些研究成果發表於前述論文之中。

論文[參考後列參考論文 2]、[4-9]，就是利用簡化的方法，分別是證明這些不均向解，其實都是不穩定的。尤其是在 Lorenz-Chern-Simons (Kaloper, 1991) 理論的解，我們進一步分析發現，Kaloper找到的解其實是一組我們稱為small-p and large-p 的對偶解 [2]。我們成功地證明，small-p 解釋不穩定的，也利用較廣泛的推論，說明另一組解也是不穩定的。總而言之，證據似乎支持Hawking的推論。而且我們已經開始試圖推廣Wald的證明，用比較廣泛的方法證明這個推論。

比較有趣的是，2009 年，KWS 找到一組加入電磁場的數值解[Kanno-Watanabe-Soda , 2009] 。2010他們 [Kanno-Soda-Watanabe, 2010] 更找到一組解析解，宣稱這組非均向解不會遵守Hawking的推論。這類解裡，電磁場可以取代宇宙常數項的角色，造成宇宙不均向的演化。我們也證明只要加入同樣來自弦理論的魅場 (phantom field) 介入[GPZZ, 2005] ，這組解就會不穩定。

同樣地，我們將系統推廣到 Dirac-Born-Infeld [DBI] 理論，也找到一組非均向的解析解，這不但是一組新的解，也似乎是穩定的解。同樣的，我們證明只要加入魅場，又可以找到一組新的解，也可以證明整個系統會不穩定，也就是這個系統，即使在沒有宇宙常數項的影響下，宇宙似乎還是傾向於演化成均向的宇宙。(結果已被接受[1]，即將發表於2011 12 月或者2012 1月的Physical Review D。) 也就是，宇宙演化成我們今天均向的宇宙，看起來不是偶然的。

有了上述成果，我們可以更進一步研究是否可以提出類似 Wald 所提出的廣泛證明，並試圖降低宇宙演化所需的條件限制。我們也正在對不均勻微擾所可以得到的訊息，做廣泛而深入的分析。另外下一階段的工作，也將對黑洞解的穩定性進行廣泛與一般的分析與研究 [MMS, 2011]，試圖探討黑洞解和宇宙演化解之間的相互關連，與期穩定性之間的對應關係。希望藉由這個分析，探討最低能量狀態下，這些解析解的穩定性與期對稱性間的可能關連。[Coleman, 1977]

總而言之，過去這三年的研究計畫，我們得到相當程度穩定的成果和進展，在這個基礎下，我們可以很樂觀的面對後續研究的進行，繼續探討宇宙演化的必然性或機率性，期待對宇宙演化的歷史有更完整，更全面的理解。

這個計劃除了研究成果外，最主要的工作，就是傳承。計畫參與的博士後研究人員是吳尚育，是替代役博士後，和交大高能研究團隊互動密切。另外前後有張家銘、林益弘、林英程、杜國俊等博士班學生參與研究工作，以及胡理策、黃宣翰、張一鳴、張育誠、陳俊憲、李傳睿、江建廷、袁珮閎、王仁宏等碩士班研究生參與研究工作，學生得到適度的補助，完成碩士論文，或者持續相關的研究工作。其中杜國俊是外籍生，目前所有補助來自交大國際處的補助。

張家銘和杜國俊分別在計畫期中出國參加研討會兩次，但是張家銘去韓國開會，有得到對方全額補助。另外兩個人出國開會都有得到日本的補助，計畫僅需補助

來回機票。博士後出國開會，也是一樣，得到主辦單位全額補助，沒有用到計畫的補助經費。總之，參與研究的人員，都有得到計畫的補助，也在計畫進行中得到相關的訓練和成長，是計畫主要的成果之一。

References:

[1.] Tuan Q. Do and W.F. Kao*, Anisotropic power-law inflation for the Dirac-Born-Infeld theory, Phys. Rev. D84, (2011) 123009; DOI: 10.1103/PhysRevD.84.123009: IF=4.964;

[2.] ChiaMing Chang, W.F. Kao* and Ing-Chen Lin, The stability analysis of the Lorentz Chern-Simons expanding solutions, Phys. Rev. D 84 (2011) 063014, DOI: 10.1103/PhysRevD.84.063014 [View PDF (230 kB)], IF=4.964

[3.] Tuan Q. Do, W. F . Kao*, and Ing-Chen Lin, Anisotropic power-law inflation for a two scalar fields model, Phys. Rev. D83, (2011), 123002, IF=4.964

[4.] W.F. Kao* and Ing-Chen Lin, The stability of the anisotropically inflating Bianchi type VI expanding solutions, Phys. Rev. D 83 (2011), 063004, IF=4.964

[5.] W.F. Kao*, Scalartensor theory and the anisotropic perturbations of the inflationary universe; The European Physical Journal C,10.1140/epjc/s10052-009-1176-y, IF=3.248

[6.] W.F. Kao* and Ing-Chen Lin, Anisotropically Inflating Universes in a scalar tensor theory, Phys. Rev. D79 (2009) 043001; IF=4.964

[7.] W.F. Kao* and Ing-Chen Lin, Stability conditions for the Bianchi type II anisotropically inflating Universes, Journal of Cosmology and AstroparticlePhysics,JCAP01(2009)022, IF=6.497

[8.] W.F. Kao*, Anisotropic perturbation of de Sitter space, The European Physical Journal C53 (2008) 87; DOI:10.1140/epjc/s10052-007-0430-4; IF=3.248

[9.] W.F. Kao*, Kaluza-Klein Higher Derivative Induced Gravity, Class. Quantum Grav., 24 (2007) 4295; IF=3.098

[Gibbons and Hawking, 1977] G.W. Gibbons and S.W. Hawking, Phys. Rev. D15, 2738 (1977). [Hawking and Moss, 1982] S.W. Hawking and I.G. Moss, Phys. Lett. 110B, 35 (1982).

[Wald, 1983] R. Wald, Phys. Rev. D 28, 2118 (1983).

[Kaloper, 1991] N. Kaloper, Phys. Rev. D 44, 2380 (1991).

[Kanno-Watanabe-Soda , 2009]S. Kanno, M. Watanabe and J. Soda, Phys. Rev. Letts. 102, 191302 (2009).

[Kanno-Soda-Watanabe, 2010] S. Kanno, J. Soda and M. Watanabe, arxiv: 1010.5307v2 (2010), JCAP12, 024 (2010).

[GPZZ, 2005] Z. -K. Guo, Y. -S. Piao, X. Zhang, Y. -Z. Zhang, Phys. Lett. B 608 (2005) 177, astro-ph/0410654.

[DBI] E. Silverstein and D. Tong, Phys. Rev. D 70 (2004) 103505 [arXiv:hep-th/0310221]; M. Al-ishahiha,

E. Silverstein, and D. Tong, Phys. Rev. D 70 (2004) 123505 [arXiv:hep-th/0404084]; X. Chen, Phys. Rev. D 71 (2005) 063506 [arXiv:hep-th/0408084]; X. Chen, JHEP 0508 (2005) 045 [arXiv:hep-th/0501184]; S. E. Shandera and S. H. Tye, JCAP 0605 (2006) 007 [arXiv:hep-th/0601099].

[MMS,2011] E. Barausse and T. P. Sotiriou, Phys. Rev. Lett. 101, 099001 (2008); Y. S. Myung, T. Moon, and E. J. Son, Stability of f(R) black holes, PHYSICAL REVIEW D 83, 124009 (2011)

[Coleman, 1977] S. Coleman, Phys. Rev. D 15, 2929–2936 (1977), Phys. Rev. D 16, 1762–1768 (1977)

I would like to quote a few lines in our paper describing the result in our paper:

An inflationary universe is a nice resolution to many important phenomenona coded with cosmic microwave, background radiation that is consistent with the observations by theWilkinson Microwave Anisotropy Probe. Research interests have been pretty active in trying to understand the physical origin of the highly isotropic universe. One of the most important predictions associated with the inflation is the cosmic no-hair conjecture. This conjecture claims that all classical hair should disappear once the vacuum energy dominates. Note that the field equations of the gravitational system with a cosmological constant can always be cast as

$$G_{ab} - T_{ab} + \Lambda g_{ab} = 0$$

with the Einstein tensor G_{ab} representing the geometric impact of the gravitational effect driven by the energy momentum tensor T_{ab} and the cosmological constant Λ.

Gibbons and Hawking and Hawking and Moss claimed that all models with a positive cosmological constant will approach a late time de Sitter space, which was later named as the cosmic no-hair theorem for Einstein gravity. Robert Wald [5] provided a partial proof of this conjecture. It was shown in Ref. [5] that the universe will eventually evolve towards the late time de Sitter space time, at least locally, for all non-type-IX Bianchi spaces under certain physical conditions:
(a) there is a positive cosmological constant coupled tothe system,
(b) the matter sources obey both the dominant energy condition and the strong-energy condition (SEC).

Note that the dominant energy condition (strong-energy condition) is defined by the inequality $T_{ab}t^a t^b \geq 0$ ($(T_{ab} - \frac{1}{2} g_{ab} T) t^a t^b \geq 0$) for all timelike vectors t^a with T_{ab} and T denoting the energy momentum tensor and its trace for all the fields coupled to the gravitational system. It was also shown in Ref. [5] that the type IX Bianchi space behaves similarly provided that the cosmological constant is sufficiently large.

Many known examples have been shown to support the cosmic no-hair theorems under a number of different constraints on the field parameters [5–14]. Counterexamples are, however, known to exist.

These are examples that the energy conditions do not hold exactly. Many of these solutions can be shown to be unstable. Therefore, these results all appear to support the Hawking's no-hair conjecture. Consequently, it is very important to examine all existing counterexamples to test the validity of the no-hair conjecture.

Some of the studies focus on the effect of the higher derivative corrections. Recently, a new set of anisotropic inflationary solutions seems to act as one more counterexample to the no-hair conjecture. It shows that, with a vector field coupled with the inflaton, there could be a small anisotropic expansion in the Bianchi type I (BI) space. This set of newly found anisotropic inflation is also shown to be an attractor solution.
Analytic power-law solutions can also be found in a model with an exponential scalar potential motivated by supergravity theory. In this approach, the anisotropic hair seems to persist without the presence of a cosmological constant. The one-scalar-field model studied in Kanno-Soda-Watanabe's paper will be referred to as the Kanno-Soda-Watanabe (KSW) model in this paper. In the hope that the no-hair conjecture will prevail one way or the other, a phantom field is introduced. The two-scalar-fields model also admits a new set of power-law solutions. As a result, we can show that the phantom field contribution does lead the new set of solutions to collapse.

Note that the Dirac-Born-Infeld (DBI) model motivated by string theory has attracted much attention lately. It is known that DBI inflation is driven by the motion of a D3-brane in a warped throat region of a closed and bounded internal space. In addition to a non-canonical kinetic term, the effective action incorporates a potential
arising from the quantum interaction between D-branes. In particular, one of the main reasons for the popularity of this model is due to its large non-Gaussianity. Indeed, it was
shown that the DBI model has a strict lower bound on the non-Gaussianity of the cosmic microwave background radiation power spectrum. More discussions on this subject can be found in Refs.

Therefore, we would like to study the effect of the DBI scalar field on the KSW model. A new set of power-law solutions will be shown to exist shortly in this paper. To investigate the stability of the obtained anisotropic powerlaw inflation, we will extend the method proposed in our previous paper for the stability analysis of the DBI field in the isotropic universe. Stability analysis shows, however, that this new set of solutions is still stable under the power-law perturbations. In fact, we can extract the large-f effect of the perturbation equations. The result shows that this set of inflationary solutions remains stable even if the f term is pretty large.

Therefore, we will turn our attention to the two-scalar fields DBI model with an additional phantom field coupled to the system. We will study the effect of this new model on the stability of the BI space. Indeed, we will show that a new set of power-law anisotropic expanding solutions does exist in the BI space. A detailed stability analysis will also be performed. The result shows that the phantom field does lead to the collapse of this new set of solutions as expected. This is the summary and outline of the paper we presented to discuss the effect of the DBI model on the evolution of our early universe.

附件一

行政院國家科學委員會補助專題研究計畫 □期中進度報告 ■期末報告

早期宇宙的方向性演化與穩定性

計畫類別：個別型計畫

計畫編號：NSC 98-2112-M-009-002-MY3

執行期間： 2009 年 8 月 1 日至 2013 年 1 月 31 日

計畫主持人：高文芳

計畫參與人員：

博士後: 吳尚育、

博士班：張家銘、林益弘、林英程、杜國俊。

碩士班：胡理策、黃宣翰、張一鳴、張育誠、陳俊憲、李傳睿、江建廷、袁珮閎、王仁宏

本計畫除繳交成果報告外，另含下列出國報告，共 _3_ 份：

出席國際學術會議心得報告

處理方式：除列管計畫及下列情形者外，得立即公開查詢

中 華 民 國 102 年 4 月 30 日

附件二

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估
   - □ ■ 達成目標
   - □ 未達成目標（請說明，以 100 字為限）
     - □ 實驗失敗
     - □ 因故實驗中斷
     - □ 其他原因

   說明：

2. 研究成果在學術期刊發表或申請專利等情形：

   論文：■已發表 □未發表之文稿 □撰寫中 □無

   專利：□已獲得 □申請中 □無

   技轉：□已技轉 □洽談中 □無

   其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

   研究進行前後期間，共發表 8 篇和計畫相關的論文:2009 兩篇，2010 一篇，2011 四篇，2012 一篇，其中包含 JCAP 一篇，PRD 五篇，EPJC 兩篇。除了已經發表的論文外外，還有一篇在投稿中，三篇正在修稿準備投稿中。相關論文，大致在證實 Hawking 的推測猜想，宇宙演化的終點，似乎會傾向演化成目前的軍像宇宙。

附件三

附件四

國科會補助專題研究計畫移地研究心得報告一

日期：2012 年 3 月 5 日

計畫編號	NSC 98-2112-M-009-002-MY3		
計畫名稱	早期宇宙的方向性演化與穩定性		
出國人員姓名	Tuan Quoc Do	服務機構及職稱	交通大學物理研究所/博士生
出國時間	2012 年 2 月 29 日至 2012 年 3 月 5 日	出國地點	Yukawa Institute for Theoretical Physics, Kyoto University, Japan

一、 移地研究過程

This trip consists of two days of traveling and four workshop days. The workshop "*2012 Asia Pacific School/Workshop on Cosmology and Gravitation*" was held in Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Japan from March 1 to 4, 2012. The website of this workshop is *http://www2.yukawa.kyoto-u.ac.jp/ws/2011/aps2012/index.html*. Its topics includes gravitational waves, numerical relativity, black hole physics, cosmic microwave background radiation, inflationary universe, dark matter and dark energy, string cosmology, and quantum gravity. This workshop consists of 4 invited lecturers: Larry Ford, Gregory Gabadadze, Akihiro Ishibashi, and Jun'ichi Yokoyama and many talks contributed by many speakers among 108 participants mostly coming from East Asia countries.

二、 研究成果

Our research goal is cosmology, especially inflationary models. Therefore, this workshop could provide us some new interesting directions for future works. There are three lectures in this workshop that inspire me too much, one given by Prof. J. Yokoyama with a title "*Inflationary cosmology*", one given by Prof. G. Gabadadze with a title "*Massive general relativity* ", and the last one given by Prof. A. Ishibashi with a title "*Black holes in higher dimensions*". Let me briefly give some views on these wonderful lectures. According to Prof. Yokoyama's lecture, cosmic inflation has been considered one of main paradigms of modern cosmology because of its powerful in solving some important problems, e.g. magnetic-monopole, horizon, and flatness problems. He also lists many interesting inflationary models, some of them were ruled out, and some of them still make sense. In addition, Prof. Yokoyama introduces cosmological perturbation theories and some comparisons between predictions of inflationary models and observational data.

Prof. Gabadadze brings to audience of the workshop information of nonlinear massive gravity. Recently, people have been successfully constructed a ghost-free nonlinear version of massive gravity theory proposed long time ago by Fierz and Pauli. Prof. Gabadadze shows basic details of nonlinear massive gravity and some interesting cosmological solutions for this theory. Many physicists have studied this new theory because it is expected to help us to solve some remaining important problems in cosmology, e.g. dark matter and dark energy problems.

Prof. A. Ishibashi provides to participants of the workshop a general picture of black holes in higher dimensions (D>4). It is known that black hole(s) is one of important subjects of gravitational physics. Inspired by string theories, higher dimensional black holes have been expected to exist in very high energy scales. Therefore, studying higher dimensional black holes might lead us to some exotic predictions that could be observed in the future.

三、 建議

We are living in the golden age of cosmology with many interesting ideas proposed to solve many unclear problems related to high precise observations, e.g. the nature of dark matter and dark energy, the origin of anisotropy of cosmic microwave background radiation. One of new research directions inspires me too much is the nonlinear massive gravity. I hope that I could do something with this theory in the near future.

四、 其他

I would like to thank the NSC for financial support.

國科會補助專題研究計畫移地研究心得報告二

日期：2012 年 11 月 10 日

計畫編號	NSC 98-2112-M-009-002-MY3		
計畫名稱	早期宇宙的方向性演化與穩定性		
出國人員 姓名	Tuan Quoc Do	服務機構 及職稱	交通大學物理研究所/博士生
出國時間	2012 年 11 月 5 日至 2012 年 11 月 10 日	出國地點	KEK, Japan

五、 移地研究過程

This trip consists of two days of traveling and four workshop days. The workshop "*AIU2012-Axion Cosmophysics*" was held in KEK Tsukuba campus, Japan from November 6th to 9th, 2012. The website of this workshop is *http://www-conf.kek.jp/AIU12/*. Its topics includes axiverse, string axions, hidden sector, higher-dimensional theories, axion astrophysics, moduli cosmology, axion experiments, variation of fundamental constants, cosmic background radiations (IR, optical, X, gamma), cosmic jsets, cosmic ray acceleration and propagation, CMB, gravitational lensing, 21cm cosmology, and gravitational wave astronomy. The workshop consists of 23 invited lecturers and 74 participants from many countries.

六、 研究成果

From talks given in this workshop, I have known that QCD axion is the Nambu-Goldstone boson associate with Peccei-Quinn (PQ) mechanism which solves the QCD strong CP problem. Motivated by the success of investigating the QCD axion, an **axino** with its mass and interactions (axion associate with SUSY Peccei-Quinn symmetry), an axionic string, axion domain walls, the cosmology with axino, an axion in the inflationary universe, a string axion (**axiverse**) have been proposed and studied extensively. Recently, the QCD axion has been expected to be one of alternative solutions to the dark matter problem. Therefore, there are some axion experiments around the world, e.g. ADMX in United States, CARRACK in Kyoto, Japan, built in order to detect the dark matter axion. Besides them, some experiments designed to observe the solar axion have been made in Japan (Sumico), CERN-Europe (CAST).

七、 建議

The axion subject is really interesting to study. The QCD axion might help us to solve dark matter problem. Since our research goal is cosmic inflation, we hope that we could find some inflationary solutions for axion models in future.

八、 其他 I would like to thank the NSC for financial support.

國科會補助專題研究計畫移地研究心得報告三

日期：2012 年 11 月 10 日

計畫編號	NSC 98-2112-M-009-002-MY3		
計畫名稱	早期宇宙的方向性演化與穩定性		
出國人員 姓名	Chang, Chia-Ming and Tuan Do	服務機構 及職稱	交通大學物理研究所/博士生
出國時間	2012 年 11 月 5 日至 2012 年 11 月 10 日	出國地點	KEK, Japan

九、 移地研究過程

This project included two-day traveling and a four-day workshop. The Aim of the four-day workshop focused on the Axiverse (a composite word of the Axion and the Universe). The topics included Axiverse, string Axions, hidden sector, higher-dimensional theories, Axion astrophysics, Axion astrophysics, moduli cosmology, Axion experiments, variation of fundamental constants, cosmic background radiations (IR, optical, X, gamma), cosmic jets, cosmic ray acceleration and propagation, CMB, gravitational lensing, 21cm cosmology, and gravitational wave astronomy.

十、 研究成果

Our group has done the research on Chern-Simons theory in several Bianchi spaces. And Chern-Simons interaction is one of the possible theories that could produce Axion. Therefore, this workshop provided us a wonderful opportunity to learn more on Axions.

Axion is a particle produced by the Nambu-Goldstone boson associate with Peccei-Quinn (PQ) mechanism. The importance of the Axion is it provides a possibility mechanism to solve the QCD strong CP problem. Moreover, with the property of weakly interaction with other particles, Axion is also one of the possible candidates of dark matter. On the other hand, in String theory sector, Axions provide us the possibility to probe physics on the highest energy scales by low energy cosmophysical phenomena. Thus Axions provide physicists an opportunity to test the validity of String theory. In the later sections, we will briefly mention some interesting topics we heard in this workshop.

Theoretically, Axion could have interaction with magnetic field and emit X-ray photo. And sun is considered as a powerful source of Axions. Therefore, Axion helioscope is an experiment that uses superconducting magnets and PIN photodiode X-ray detectors to indirectly probe the existence of Axion. Several experiments are currently in progress, such as Tokyo Axion helioscope (Sumico) and CERN Axion solar Telescope (CAST). On the other hand, another possible way to detect Axion is Laser Axion search.

The idea of Laser Axion search is simply an inverse process of Axion helioscope experiment. By using the Laser as a source of photo, the Axions could be produced when the photos interact with magnetic field. We then use another magnetic field to converse the produced Axions to photos. A famous experiment of Laser Axion search is PVLAS at Italy.

Moreover, ADMX (Axion Dark Matter Xperiment) is also an interesting experiment to search Axion. ADMX is a similar experiment as Axion helioscope. The different point is the target of ADMX is cosmic Axion. Especially, ADMX focuses on the dark matter since Axion could be one of the candidate of dark matter.

Dr. Pani from the Instituto Superior Técnico – Lisbon (Portugal) also gave an interesting talk on black hole bombs. The idea of black hole bomb is the nature of the black hole provides a mirror of its own. The Gravitational Wave (Gravitons) could escape from the black hole but the Axion could not. The black hole produces Axion and its nature performs a mirror of itself. It is obviously that the mechanism will amplify the number of Axions in the black hole and therefore form a bomb.

Other topics such as 21cm cosmology, theory of varying alpha, Axion as a Bose-Einstein condensate, finite-time future singularities in modified gravity, and some theoretical backgrounds of Axion are also interesting and important. String theory is currently the only theory that could unify all the physical forces. We believe that the Axion will be the most promising research in the future, since Axion could be used to test the validity of String theory.

十一、 建議

Since Axion could be an important research in the future. We suggest that we could hold some workshops or schools to provide the opportunity for all scientists to learn more on the Axion.

十二、 其他

We would like to thank the NSC for financial support.

國科會補助專題研究計畫移地研究心得報告

日期：___年___月___日

計畫編號	NSC　　—　　—　　—　　—　　—		
計畫名稱			
出國人員 姓名		服務機構 及職稱	
出國時間	年　月　日至 年　月　日	出國地點	

一、移地研究過程

二、研究成果

三、建議

四、其他

附件五

國科會補助專題研究計畫出席國際學術會議心得報告

日期：

年___月___日

計畫編號	NSC　　—　　—　　—　　—　　—		
計畫名稱			
出國人員姓名		服務機構及職稱	
會議時間	年　月　日 至 年　月　日	會議地點	
會議名稱	(中文) (英文)		
發表題目	(中文) (英文)		

一、參加會議經過

二、與會心得

三、發表論文全文或摘要

四、建議

五、攜回資料名稱及內容

六、其他

附件六

國科會補助專題研究計畫國際合作研究計畫國外研究報告

日期：

年___月___日

計畫編號	NSC　　—　　—　　—　　—　　—		
計畫名稱			
出國人員姓名		服務機構及職稱	
出國時間	年　月　日 至 年　月　日	出國地點	
合作國家		外國合作計畫主持人英文姓名	(First Name) (Last Name)
外國合作機構			

註：1.若出國人員不只一位，應分列姓名。2.外國合作機構及主持人應寫全名。

一、國際合作研究過程（若不只一位研究人員出國，應敘明分工情況及個人角色）

二、研究成果

三、心得與建議

四、本項與國外合作研究之性質，屬：(可複選)

□分工收集研究資料
□交換分析實驗或調查結果
□共同執行理論建立模式並驗証
□共同執行歸納與比較分析
□元件或產品分工研發
□其他 (請填寫) _____

五、其他：(本項國合計畫若有下列各項情況，但不以為限，請分項敘述說明)

(一)除了我方派員前往研究，是否有國外研究人員來台參與研究?若是，請補充來台人員姓名、期間及其活動重點。
(二)是否包括年輕研究人員(一般指博士生或博士後研究人員)之培育？
(三)雙方合作成果，是否有與國外共同產生之期刊或會議論文已/擬進行發表？論文名稱(若已有)為何？
(四)雙方是否已/將有申請共同專利或展開技術移轉之研發成果?若已進行，則擬申請專利之國家或期間為何？
(五)未來雙方是否有持續合作之規劃？

國科會專題研究計畫成果報告撰寫格式

101 年 8 月 22 日本會第 367 次學術會報修正通過

一、說明

國科會基於學術公開之立場，鼓勵一般專題研究計畫主持人發表其研究成果，但主持人對於研究成果之內容應負完全責任。計畫內容及研究成果如涉及專利或其他智慧財產權、違異現行醫藥衛生規範、影響公序良俗或政治社會安定等顧慮者，應事先通知國科會不宜將所繳交之成果報告蒐錄於學門成果報告彙編或公開查詢，以免造成無謂之困擾。另外，各學門在製作成果報告彙編時，將直接使用主持人提供的成果報告，因此主持人在繳交報告之前，應對內容詳細校對，以確定其正確性。

成果報告繳交之期限及種類（期中進度報告及期末報告），應依本會補助專題研究計畫作業要點及專題研究計畫經費核定清單之規定辦理。至報告內容之篇幅，期中進度報告以 4 至 10 頁為原則，並應忠實呈現截至繳交時之研究成果，期末報告不得少於 10 頁。

二、報告格式：依序為封面、目錄、中英文摘要及關鍵詞、報告內容、參考文獻、計畫成果自評、可供推廣之研發成果資料表、附錄。

(一)報告封面：請至本會網站（http：//www.nsc.gov.tw）線上製作（格式如附件一）。

(二)中、英文摘要及關鍵詞 (keywords)。

(三)報告內容：包括前言、研究目的、文獻探討、研究方法、結果與討論（含結論與建議）等。

(四)計畫成果自評部分：請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值(簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性)、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估，並請至本會網站線上製作（格式如附件二）。

(五)頁碼編寫：請對摘要及目錄部分用羅馬字 I 、II、 III……標在每頁下方中央；報告內容至附錄部分請以阿拉伯數字 1.2.3……順序標在每頁下方中央。

(六)附表及附圖可列在文中或參考文獻之後，各表、圖請說明內容。

(七)可供推廣之研發成果資料表：

1.研究計畫所產生之研發成果，應至國科會科技研發成果資訊系統（STRIKE 系統，https://nscnt66.nsc.gov.tw/strike/）填列研發成果資料表（如附件三），循執行機構行政程序，由研發成果推廣單位（如技

轉中心）線上繳交送出。

2.每項研發成果填寫一份。

(八)若該計畫已有論文發表者(須於論文致謝部分註明補助計畫編號)，得作為成果報告內容或附錄，並請註明發表刊物名稱、卷期及出版日期。若有與執行本計畫相關之著作、專利、技術報告、或學生畢業論文等，請在參考文獻內註明之。

(九)該計畫若列屬「國際合作研究計畫」，應將雙方互訪及合作研究情況、共同研究成果及是否持續雙方合作等，於報告中重點式敘明。

三、計畫中獲補助國外差旅費，出國進行移地研究、出席國際學術會議或因執行國際合作研究計畫至國外機構執行合作研究者，每次均須依規定分別撰寫出國心得報告（其中，出席國際學術會議者須另附發表之論文全文或摘要，但受邀專題演講或擔任會議主持人者不在此限)，並至本會網站線上繳交電子檔，出國心得報告格式如附件四、五、六。

四、報告編排注意事項

(一)版面設定：A4 紙，即長 29.7 公分，寬 21 公分。

(二)格式：中文打字規格為每行繕打（行間不另留間距)，英文打字規格為 Single Space。

(三)字體：以中英文撰寫均可。英文使用 Times New Roman Font，中文使用標楷體，字體大小以 12 號為主。