Digital Economy, Entrepreneurship and Collaborative Innovation: An Evidence from China

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Abstract. The influence mechanism of digital economy on collaborative innovation still needs further exploration in terms of theoretical and empirical evidence. Based on the panel data of 30 provincial-level administrative regions in China from 2013-2019, this paper uses the entropy value method to measure the digital economy index and the level of collaborative innovation. Then we conduct a more in-depth discussion on the temporal and spatial evolution characteristics and influence relationship of the digital economy and collaborative innovation from the perspective of entrepreneurship. The results show that, firstly, the digital economy has a significant positive impact on the level of collaborative innovation, and entrepreneurship, specifically entrepreneurial entrepreneurship and entrepreneurial innovation, plays a partly mediating role in this process. Secondly, by using the Spatial Durbin model, we found that the digital economy has a significant siphon effect on the level of collaborative innovation in neighboring provinces. Finally, there is a significant double threshold effect of entrepreneurship on the impact of digital economy on collaborative innovation, and the positive impact of digital economy is characterized by a non-linear incremental marginal effect. The findings of this paper provide a new way of thinking to reveal the inner mechanism of the digital economy's influence on collaborative innovation.

Keywords: Digital economy; Collaborative innovation; Entrepreneurship; Siphon effect; Nonlinear spillover effect.

1. Introduction

Science and technology innovation are important means to promote economic and social development and improve national core competitiveness. However, due to the scarcity of resources and the increasing comprehensiveness, complexity and uncertainty of science and technology development, the model of relying on individual subjects to innovate independently can no longer meet the needs of social and economic development [1]. As the trend and new paradigm of innovation, collaborative innovation can integrate the resources of multiple innovation bodies to form a complementary advantage and finally achieve the synergistic effect of 1+1+1>3, so it has become an inevitable choice for building a strong science and technology country and promoting economic structural transformation in China. However, with the advent of the digital economy, the allocation of innovation resources has begun to break through the geographical and spatial boundaries, causing significant changes to the depth, breadth and even the way of collaborative innovation. Therefore, it is worthwhile to analyze the influence mechanism of the digital economy on collaborative innovation and give full play to its driving effect on collaborative innovation.

Digital economy is an emerging economic form with data as a key production factor, and is the main economic form after the agricultural economy and industrial economy, which has gradually become a pillar of global economic development [2]. The 14th Five-Year Plan issued by the State Council of China defines the digital economy as a new economic form with data resources as the key factor, modern information networks as the main carrier, and the integration and application of information and communication technologies and digital transformation of all factors as the important driving force to promote fairness and efficiency. Therefore, in recent years, a number of scholars have studied the impact mechanisms of the digital economy on SMEs (Small and Medium Enterprises), high-tech enterprises and the innovation capacity of cities. However, the influence

mechanism of digital economy on collaborative innovation still needs to be further explored. Nowadays, with the booming of digital economy and the increasing attention to collaborative innovation, it is of practical significance to further discuss the influence mechanism of digital economy on collaborative innovation, analyze its spatial and temporal evolution characteristics and influence relationships, and propose policy recommendations that can better stimulate the driving effect of digital economy on collaborative innovation.

2. Review of The Liretature

Most of the current research on collaborative innovation has been carried out in the following three aspects: firstly, the measurement of the level and performance of collaborative innovation, the degree of synergy, and the stability of alliances and other indicators. For example, Liu and Chen (2020) used data envelopment analysis (DEA) model to measure the level of collaborative innovation in 30 provinces in China from 1998 to 2016 and empirically study its influencing factors [3]. Xiao et al. (2021) designed a four-helix innovation synergy measure based on mutual information and triple helix algorithm to measure the degree of synergy among innovation agents [4]. Lei et al. (2021) constructed a transferable triple-helix game revenue relationship model, selected the Kernel indicator in game analysis to measure the stability of innovation alliances, and used the Shapley value and Kernel to analyze the stability of innovation alliances [1]. The next is the research on collaborative innovation mechanism. For instance, Wu et al. (2019) construct a tripartite evolutionary game model of collaborative innovation led by each innovation subjects, and use simulation to study the influencing factors for the strategy choices of each innovation subjects [5]. Su et al. (2020) used the perceived utility of prospect theory instead of the traditional expected utility theory to construct a game model of the evolution of each innovation bodies, and simulated the game process of the government's choice of incentive strategy to explore the dynamic evolution of collaborative innovation behavior and mutual influence between enterprises and universities [6]. The third aspect is the study of the influencing factors of collaborative innovation. For example, Wu and Zhao (2020) investigate the influence of institutional proximity, cognitive proximity and economic proximity on the performance of collaborative innovation in Jiangsu, Zhejiang and Shanghai [7]. Huang (2017) used firm-level panel data of Liaoning Province from 2010-2012 to analyze the influencing factors of collaborative innovation, and found that corporate R&D capability has a non-linear effect on collaborative innovation, and the correlation effects of firm size, firm employee training intensity, policy support, and corporate R&D capability and entrepreneurship can positively promote collaborative innovation [8].

Current research on digital economy mainly includes: (1) measurement of digital economy, for example, Liu et al. (2020) constructs an indicator system from three dimensions: Information development, Internet development and digital transaction development to measure the development level of digital economy in 30 Chinese provinces and analyze the driving factors of digital economy [9]. (2) The impact of digital economy on various economic, ecological and social issues, for example, Zhang et al. (2022) based on a panel dataset of 287 cities in China from 2011-2018, found that the increase in the level of digital economy helps to spike the high-quality economic development of the region, and the level of entrepreneurship and innovation is a mediating variable of the digital economy to promote high-quality economic development [10]. Li and Wang (2022) found that there is an inverted U-shaped curve relationship between digital economy development and regional carbon intensity, the economic agglomeration can strengthen the impact of digital economy on spatial carbon emissions, and the spatial emission reduction mechanism of digital economy is mainly originated from economic growth and technological progress [11]. Fan et al. (2022) found that the impact of digital economy on the income gap between urban and rural residents showed a U-shaped trend of decreasing and then increasing [12]. Guo et al. (2022) find that the digital economy not only promotes the upgrading of industrial

structure, but also boosts employment levels based on statistics from 30 Chinese provinces from 2011 to 2019 [13].

There are only a few literatures studying the impact of digital economy on collaborative innovation. They elaborate the Influence Mechanism from the following 2 aspects: (1) From the perspective of integration. The digital economy can reconstruct the resource allocation and spatial layout of integration (including micro-market integration, medium-level industry integration, and macro-regional integration), break down the geographical and physical barriers of innovation subjects, which can ultimately promote collaborative innovation [14]. (2) From the perspective of communication between innovation subjects. Yuan (2022) found that digitalization can promote the collaborative innovation by enhancing knowledge exchange and cooperation among innovation subjects [15]. However, there is little existing literature exploring the influence mechanism of digital economy on collaborative innovation from the perspective of entrepreneurship.

Therefore, the possible marginal contributions of this paper are: firstly, exploring the influence mechanism of the digital economy on collaborative innovation from the perspective of entrepreneurship, demonstrating that entrepreneurship plays a partly mediating role in this influence mechanism, and a double threshold of increasing marginal effects exists. Secondly, the digital economy has a significant siphon effect on the level of collaborative innovation in neighboring provinces, and the influence also has regional heterogeneity. Our research not only re-examined the influence mechanism of digital economy on collaborative innovation from the perspective of entrepreneurship, but also further deepens the influence mechanism from both time and space aspects, which enriches the existing research.

3. Theoretical Framework

First of all, in the industrial economy, due to the existence of information silos and digital divide, the synergy between innovation factors will be affected by geographical barriers, resulting in the failure of innovation output [14]. However, the digital economy with data as the core resource allows information to penetrate organizational boundaries more efficiently, diminishes or even eliminates the digital divide, promotes the interconnection of information silos, drives technology, capital and talent to the more efficient areas of utilization, and corrects resource mismatch. Therefore, the digital economy cannot only effectively help innovation agents optimize factor allocation and enhance their own innovation capabilities, but also improve the efficiency of information production and dissemination by eliminating information silos and digital divide, and effectively empower the synergy between innovation factors. Secondly, the digital economy has changed the traditional business model, through the transformation of production, marketing, logistics and other aspects of information technology to promote the development of the overall industrial innovation, in the process of continuous integration of the digital economy and the traditional economy, a variety of innovation needs are constantly created, attracting more innovative subjects to research and development innovation, and thus improve the level of innovation [16]. However, due to the scarcity of resources and the comprehensive, complex and uncertain market demand, the trend of refining the division of labor in the industrial chain, innovation through collaboration has become the most popular choice of innovation subjects. Finally, the digital economy, while generating innovation demand, also shows the development trend of platform and sharing, and the latter has given rise to platform and sharing tools such as crowdsourcing, which can effectively reduce the information asymmetry among innovation subjects, help innovation subjects integrate resources more efficiently, and provide them with more convenient, fast and low-cost services, thus enhancing the motivation of innovation subjects to participate in collaborative innovation. This will improve the motivation of each innovation body to participate in collaborative innovation and ultimately improve the level of collaborative innovation.

H1: The digital economy can enhance the level of collaborative innovation.

The exploration of entrepreneurship can be traced back to the mid-18th century. According to Hebert and Link's categorization, the three most classic theoretical schools are: the Austrian school, with Mises and Kozner and others as the core, which emphasizes the entrepreneur's ability to identify profit opportunities from the market. The German school, represented by Schumpeter, Baumol and others, which focuses more on the entrepreneur's innovative spirit. The Chicago School, with Knight and Schultz at its core, particularly values the entrepreneur's ability to cope with risk and address market imbalances. Although there is still no standard definition of the theoretical connotation of entrepreneurship, academics have reached a consensus on the basic characteristics of entrepreneurship, for instance, entrepreneurship generally has a sense of innovation, the ability to take risks and identify opportunities, good management talent, and a strong sense of mission and commitment, etc. Huang (2017) pointed out that there is a non-linear influence of enterprise R&D capability on the efficiency of Collaborative Innovation, and the correlation effect of enterprise R&D capability and entrepreneurship has a facilitating effect on Collaborative Innovation [8]. In this paper, we refer to Sun & Liu (2019) and Guo et al. (2016) to divide entrepreneurship into entrepreneurial innovation and entrepreneurial entrepreneurship [17,18].

Innovative production activities led by entrepreneurial innovation spirit can transform basic knowledge into commercialized knowledge and new ideas discovered and explored into commercialized ideas [19]. Wang et al. (2021) point out that entrepreneurial innovation is not only manifested in the enthusiasm and initiative of enterprises to acquire external knowledge, but also in their ability to continuously meet market demand by investing large amounts of human and financial resources in new product development, implying that they are increasingly capable of transforming, applying and commercializing external knowledge [20]. At the micro level, the digital economy can nurture entrepreneurial innovation by stimulating innovative thinking and improving innovation methods [14]. Digital technology has given rise to new business scenarios, new products, more optimal resource allocation methods and organizational management models, while new products and new marketing models have brought about new user groups and new markets. Combined with Schumpeter's innovation theory, the digital economy brings product innovation, technological innovation, market innovation, resource allocation innovation and organizational innovation for the whole society, especially for the entrepreneurs who are the main body of innovation. What’s more, the strong permeability of the digital economy strengthens the knowledge spillover effect, enabling entrepreneurs to access the frontier of technology more rapidly and widely, strengthen communication with the outside world, and stimulate their innovative thinking. At the macro level, the digital economy can also enhance the innovation spirit of entrepreneurs by optimizing the innovation ecosystem. In particular, innovation resources can be integrated more efficiently through the digital economy, and various innovation agents can enhance the efficiency of synergy through the digital economy. Secondly, the digital management platform for patents created by digital technology can shorten the patent approval process, reduce transaction costs, and lower information asymmetry, thus significantly increasing the commercial value of patents. In summary, digital economy can stimulate entrepreneurial innovation from both micro and macro dimensions. The entrepreneurial spirit of innovation is the core of Schumpeter's idea of creative destruction, but due to the lack of resources and the detailed division of labor, the process of innovation is inseparable from the acquisition of external knowledge, and the innovative spirit of entrepreneurship reflects the enthusiasm and initiative of enterprises to acquire external knowledge. Secondly, while the innovation spirit of entrepreneurs is stimulated, market competition will gradually become fierce, forcing enterprises to invest more human, material and financial resources in research and development of new products and technologies to meet the ever-changing market demand, which eventually stimulates the motivation of entrepreneurs to seek synergy, so as to obtain the maximum benefit with the shortest time and the least cost. The result is the shortest time and the least cost to obtain the maximum benefit. Finally, since the allocation of innovation resources and inter-organizational knowledge sharing in the digital era are no longer constrained by geographical and spatial boundaries, the entrepreneurial spirit of innovation can be better released

and inter-organizational collaborative innovation can be accomplished by relying on digital technology.

H2: The digital economy affects collaborative innovation by enhancing entrepreneurial innovation.

Entrepreneurship means any act of creating a new business. Identifying market opportunities and realizing them with appropriate strategies is the core of entrepreneurial entrepreneurship [21]. In the early stages of entrepreneurship, the digital economy can increase the entrepreneurial opportunities, and in the process of entrepreneurship, the digital economy can help entrepreneurs reduce uncertainty and reduce or even avoid entrepreneurial risks [14]. Specifically, the digital economy constantly gives rise to new business scenarios and new technologies, generating new demands and markets and providing more opportunities for entrepreneurial activities. In addition, entrepreneurs can use business intelligence technologies such as data warehousing and data mining to identify market gaps and capture potential entrepreneurial opportunities in a timely manner. In the process of entrepreneurship, the above business intelligence technologies can also help entrepreneurs adjust their business decisions and control business risks in a timely manner. Secondly, the strong connectivity and sharing of the digital economy can significantly reduce information asymmetry and provide more reliable information sources, minimizing entrepreneurial risks [14]. Finally, e-government and digital finance can greatly enhance the convenience of entrepreneurial activities, with the former simplifying the administrative approval process and saving time costs, and the latter alleviating the problem of difficult financing and reducing financing costs, ultimately motivating entrepreneurs to start their own businesses. However, with the increase in the number of new enterprises, market competition will also be fierce and specialized, leading to a stronger incentive for entrepreneurs to participate in synergy, to complete new product development and capture the market in a strong combination. Thirdly, the formation of new enterprises is an important way to industrialize scientific and technological achievements. The newer enterprises there are, the higher the entrepreneurial spirit of entrepreneurs, and the more it helps to promote knowledge sharing among collaborative innovation organizations [20]. Therefore, entrepreneurial entrepreneurship can directly enhance the level of collaborative innovation.

H3: The digital economy affects collaborative innovation by enhancing entrepreneurial entrepreneurship.

The siphon effect first appeared in fluid physics and refers to the phenomenon of liquid rising and then flowing to a lower level caused by the gravitational and potential energy differences between liquid molecules [22]. In the field of humanities and social sciences, some scholars have used it to explain the external economic phenomena such as single loss of labor, capital transfer, and policy bias caused by central cities to peripheral cities [23]. In a collaborative innovation system, the potential difference in the knowledge stock of each innovation agent leads to the mutual flow of knowledge between the superior and inferior parties, which is the siphon effect of knowledge spillover [24]. Usually, the disadvantaged party will actively seek the advantageous party for cooperation and sharing, so as to obtain more knowledge in a short period of time and get the maximum benefit with less cost [25]. The open, border-less and digital resource flow characteristics of the digital economy can effectively promote knowledge flow, exchange and sharing, and eventually form a network with each sharing subject as a node. The higher the level of digital economy development, the higher the efficiency of knowledge flow, exchange and sharing, which naturally generates more innovation subjects with more quantity and knowledge stock, while the efficiency of knowledge accumulation of each innovation subject in the regions with lower level of digital economy is relatively low, so the knowledge stock of innovation subjects is also relatively low, where the knowledge disadvantaged side is more. Under this circumstance, the regions with higher level of digital economy development will continue to attract the knowledge disadvantaged parties in their regions to carry out collaborative innovation, which eventually causes the improvement of digital economy index in neighboring regions to negatively affect the level of collaborative innovation in the region, that is the siphon effect.

H4: The digital economy has a siphoning effect on the level of collaborative innovation in neighboring provinces, which is manifested as a negative spatial spillover effect.

Firstly, the widespread use of the digital economy not only enables each innovation agent to effectively improve its own operational efficiency, but also provides higher quality, convenient and high-end network technologies and product services [26]. The former improves the innovation efficiency of a single innovation agent, while the latter effectively reduces the marginal cost of linkage among innovation agents, making the benefits obtained by the participants increase exponentially. Secondly, in the era of digital economy, the boundary nature of economic activities among various sectors is gradually weakened, and the cost of obtaining information from the network drops significantly. Therefore, increasing innovation agents will be attracted to join the innovation network built by the digital economy, causing the value of the network to increase exponentially. Moreover, this effect will become more and more obvious as the level of digital economy increases.

Finally, with the stimulation of entrepreneurship, increasing companies and products are entering the market, resulting in fiercer competition. However, due to the constraints of resource endowment, expertise, industrial chain division of labor and other objective conditions on the one hand, and the attraction of collaborative innovation network built by various digital tools on the other hand, entrepreneurs are more willing to join the network and complete innovation in a collaborative way. Based on the network effect and Metcalfe's law, the impact of digital economy on collaborative innovation is also non-linear with increasing marginal effect.

H5: There is a non-linear spillover effect of the digital economy on the level of collaborative innovation, which is characterized by an increasing non-linear marginal effect.

4. Reserach Design

4.1 Econometric model

4.1.1 Baseline regression

$$\mathrm{CoInnovation}_{i,t} = \lambda + c\mathrm{Digit}_{i,t} + \alpha_c Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (1)$$

In the above equation, the $\mathrm{CoInnovation}_{i,t}$ and $\mathrm{Digit}_{i,t}$ denote the level of collaborative innovation and the digital economy index respectively, and $Z_{i,t}$denotes all control variables, and μ_i denotes individual fixed effects, and λ denotes the intercept term.

4.1.2 Intermediary effect model

$$\mathrm{CoInnovation}_{i,t} = \lambda_1 + c\mathrm{Digit}_{i,t} + \beta_c Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (2)$$
$$\mathrm{EntInnovation}_{i,t} = \lambda_2 + a\mathrm{Digit}_{i,t} + \gamma_c Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (3)$$
$$\mathrm{CoInnovation}_{i,t} = \lambda_3 + c'\mathrm{Digit}_{i,t} + a'\mathrm{EntInnovation}_{i,t} + \beta_c' Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (4)$$
$$\mathrm{EntBusiness}_{i,t} = \lambda_4 + b\mathrm{Digit}_{i,t} + \eta_c Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (5)$$
$$\mathrm{CoInnovation}_{i,t} = \lambda_5 + c''a\mathrm{Digit}_{i,t} + b'\mathrm{EntBusiness}_{i,t} + \beta_c'' Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (6)$$

In the above equation, EntInnovation and EntBusiness correspond to two mediating variables, namely entrepreneurial innovation and entrepreneurial entrepreneurship, respectively.

4.1.3 Spatial Durbin model (SDM)

$$\mathrm{CoInnovation}_{i,t} = \lambda + \rho W\mathrm{CoInnovation}_{i,t} + \phi_1 W\mathrm{Digit}_{i,t} + \alpha_1 \mathrm{Digit}_{i,t} + \phi_c W\mathrm{Controls}_{it} + \alpha_c Z_{i,t} + \mu_i + \varepsilon_{i,t} \quad (7)$$

where ρ represents the spatial auto-regressive coefficients, W is the spatial weight matrix, and to verify the robustness of the regression results, this paper uses the neighboring matrix, geographic distance matrix and economic distance matrix in 3 methods for regression.ϕ_1 and ϕ_c denote the elasticity coefficients of the spatial interaction terms of the core explanatory and control variables.

2) Panel Threshold Model

For the test of indirect transmission mechanism, in addition to using the mediating effect model, we should also consider the Metcalfe's law and network effect of the Internet, that is the value of the

Internet is squarely proportional to the number of users [26]. In this paper, a panel threshold regression model is developed to test whether the digital economy index, entrepreneurial innovation, and entrepreneurial entrepreneurship have indirect effects on the nonlinear dynamic spillover of the digital economy to promote the level of collaborative innovation.

$$\mathrm{CoInnovation}_{i,t} = \lambda + \varphi_1 \mathrm{Digit}_{i,t} \cdot \mathrm{I}(\mathrm{Adj}_{i,t} \le \theta) + \varphi_2 \mathrm{Digit}_{i,t} \cdot \mathrm{I}(\mathrm{Adj}_{i,t} > \gamma) + \alpha_c Z_{i,t} + \varepsilon_{i,t} \quad (8)$$

Where λ is the intercept term, the $\mathrm{Adj}_{i,t}$ represents the threshold variables of digital economy index, entrepreneurial innovation spirit kernel entrepreneurial entrepreneurship, θ is the threshold value to be estimated, and $\mathrm{I}(*)$ is the indicator function, which takes the value of 1 when the conditions in the parentheses are satisfied, and 0 otherwise. Equation (8) considers a single threshold case, and can be expanded to multiple threshold cases according to the actual situation of the problem.

4.2 Data sources and variable measures

This paper uses panel data from 2013-2019 for 30 provincial-level administrative regions across China to study the impact of digital economy on collaborative innovation, excluding Hong Kong, Macao, Taiwan and Tibet in view of the availability of raw data. The raw data are obtained from China Statistical Yearbook, China Science and Technology Statistical Yearbook, China City Statistical Yearbook, China High Technology Statistical Yearbook, China Electronic Industry Statistical Yearbook, Yangtze River Economic Belt Statistical Yearbook, China Regional Economic Statistical Yearbook, China Social Statistical Yearbook, CSMAR database, and provincial and municipal statistical yearbooks and official websites of statistical bureaus. The variables are measured as follows.

4.2.1 Explained variables

The explanatory variable is the level of collaborative innovation (CoInnovation) in each region. Since CoInnovation emphasizes the collaboration and interaction among innovation subjects and also responds to the overall innovation level of the region, this paper refers to the approach of Gong Qinlin et al. (2022) and uses the entropy value method to measure the level of collaborative innovation in two dimensions: the level of basic innovation and the level of collaborative innovation, the innovation environment, innovation input, innovation results, collaborative innovation of subjects and regional innovation [27]. The five dimensions of collaborative innovation, the index system of collaborative innovation level measurement is established as table 4-1.

4.2.2 Core explanatory variables

The core explanatory variable is the digital economy index (Digit) of each region. In recent years, the index system of measuring digital economy is emerging, but there is not yet a set of authoritative index system, so this paper, based on the index system of Liu et al. (2020), follows the principles of scientific, validity and feasibility, and constructs the index system of measuring digital economy as table 4-2 [9].

4.2.3 Intermediate variables

The intermediate variables are entrepreneurship (EntBusiness) and entrepreneurial innovation (EntInnovation). Referring to the ideas of Kong Lingchi (2020) and Yuan Huiwen et al. (2022) Considering data availability, use the ratio of the number of private individuals and private enterprises to the number of resident populations is used to measure entrepreneurship, the ratio of the number of invention patents, utility model patents and design patents granted to the number of resident populations is selected to measure entrepreneurial innovation [28, 29]. The ratio of the sum of the number of invention patents, utility model patents and design patents granted to the number of resident populations is selected to measure entrepreneurial innovation.

4.2.4 Control variables

Other control variables that may affect the level of collaborative innovation were selected, including: openness to the outside world (open), measured by the total import and export of foreign-invested enterprises; education level (edu), measured by the number of students in general higher education institutions; economic development level (gdp), measured by the GDP per capita of each region; government support (gov), measured by the amount of local financial expenditures on science and technology; and Industrial structure (chanye), measured by the proportion of added value of secondary industry to GDP.

Table 4-1 Digital Economy Index Measurement Indicator System

	Tier 1 Indicators	Secondary indicators	Positive / Negative
The index system of digital economy	Informatization Development	Long-haul fiber optic cable density (km/km2)	+
		Local exchange capacity (million units)	+
		Cell phone exchange capacity (million units)	+
		Total telecom business (billion yuan)	+
		Software business revenue (million yuan)	+
	Internet Development	Number of Internet access ports (million)	+
		Number of domain names (million)	+
		Number of pages (million)	+
		Number of IPV4 addresses (million)	+
	E-commerce	E-commerce sales (billion yuan)	+
		E-commerce procurement volume (billion yuan)	+
		Percentage of corporate websites (number of corporate websites/number of companies)	+
		Number of computers as a percentage (number of computers owned by enterprises/number of enterprises)	+
		There are e-commerce trading activities of enterprises accounted for (%)	+
	Digital Finance	Peking University Digital Inclusive Finance Index	+

In order to eliminate the effect of magnitude and to alleviate the problem of heteroskedasticity, the variables: openness to the outside world (open), education level (edu), government support (gov) and economic development level (gdp) are treated logarithmically in this paper. Finally, in order to eliminate the influence of individual extreme values on the regression results, all variables are treated by shrinking the tails.

Table 4-2 Collaborative Innovation Level Measurement Index System

	Tier 1 Indicators	Secondary indicators	Secondary indicators	Positive / Negative
collaborative Innovation level measurement index system	Basic Innovation Level	Innovation Environment	Number of R&D institutions (pcs)	+
			GDP per capita (yuan)	+
			Public library holdings per capita (volumes)	+
		Innovation input	Share of R&D personnel in resident population (%)	+
			R&D investment intensity (%)	+
			R&D personnel full time equivalent (people per years)	+
			Internal expenditure on R&D funding by region (RMB million)	+
		Innovation results	The number of domestic patent applications received (pieces)	+
			The number of domestic patent applications authorized (pieces)	+
			Number of scientific and technical papers in China included in major foreign search tools (number of articles)	+
			New product sales revenue of industrial enterprises above the scale (million yuan)	+
			Technology Market Turnover (RMB)	+
	Collaborative Innovation Level	Main Body Collaborative Innovation	The share of corporate funding in R&D funding in universities	+
			Share of corporate funding in R&D funding for research and development institutions	+
			Number of patent ownership transfers and licenses of research and development institutions (pieces)	+
			Income from transfer of patent ownership and licensing of research and development institutions (RMB million)	+
		Regional Collaborative Innovation	External expenditure on R&D expenses (million yuan)	+
			Number of contracts in the technology market output geography (pieces)	+
			Technology market output geographical contract amount (RMB million)	+
			Technology market flow to the geographical contract number (pieces)	+
			Technology market technology flow to the number of geographic contracts amount (million yuan)	+

5. Analysis Of Empirical Results

5.1 The Kernel Density Function of Digital Economy Index and Collaborative Innovation

In this paper, after using the entropy value method to measure the digital economy index and the level of collaborative innovation, the kernel density functions of the two are plotted as Figure 5-1 and Figure 5-2. In Figure 5-1, from 2013 to 2019, the kernel function of collaborative innovation level has a weak right-shift characteristic, with the peak decreasing and the width increasing, the

right tail of the curve lengthening, and the side peaks gradually disappearing. It indicates that the collaborative innovation level of 30 provinces and cities in China has improved over time, but the improvement is not large, the degree of difference between provinces becomes larger, and the phenomenon of bifurcation has been improved significantly. In Figure 5-2, from 2013-2019, the kernel density function keeps shifting to the right, the peak of the wave shows a decreasing trend, and the width of the wave shows an increasing trend, indicating that the level of digital economy is improving year by year, and the difference between provinces is gradually increasing. Meanwhile, the kernel density function in 2013 has relatively more obvious two peaks, and the side peaks weaken in the subsequent years, indicating that the phenomenon of polarization of digital economy index in each province has been improved to some extent.

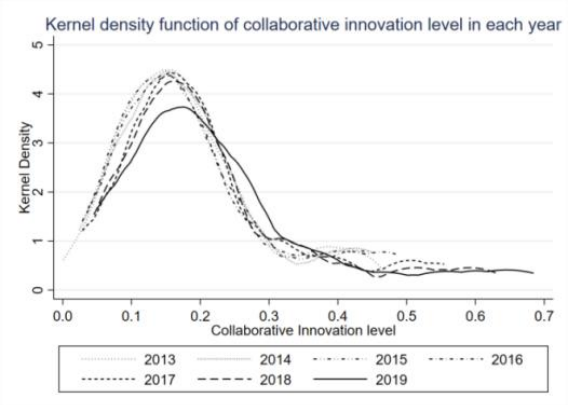

Figure 5-1 Kernel Density Function of Collaborative Innovation

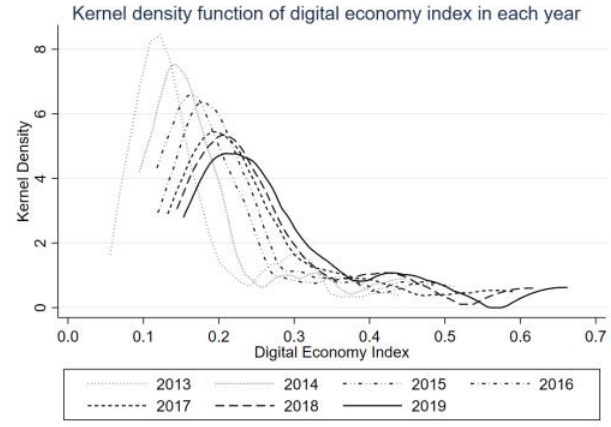

Figure 5-2 Kernel density function of digital economy index

5.2 Baseline regression results

5.2.1Main effects test

In order to test hypothesis H1, the regression results of equation (1) are presented in Table 5-1, where the first column shows the regression results of the digital economy index on the level of collaborative innovation without any control variables. The coefficients of the digital economy index are always positive and statistically significant at the 1% level of significance, and the sign and significance do not change with the addition of the control variables.

Table 5-1 Baseline regression results

	(1)	(2)	(3)	(4)	(5)	(6)
	CoInnovation	CoInnovation	CoInnovation	CoInnovation	CoInnovation	CoInnovation
Digit	0.536***	0.537***	0.665***	0.631***	0.593***	0.610***
	(16.365)	(16.309)	(16.478)	(10.369)	(9.627)	(9.874)
open		-0.001	0.001	0.000	-0.002	-0.001
		(-0.239)	(0.123)	(0.002)	(-0.418)	(-0.176)
edu			-0.112***	-0.123***	-0.123***	-0.133***
			(-4.961)	(-4.582)	(-4.664)	(-4.986)
gdp				0.017	-0.006	0.013
				(0.757)	(-0.249)	(0.516)
gov					0.023***	0.022**
					(2.648)	(2.589)
chanye						0.142*
						(1.908)
_cons	0.049***	0.065	0.490***	0.366*	0.554***	0.315
	(6.460)	(0.977)	(4.618)	(1.878)	(2.710)	(1.324)
N	210	210	210	210	210	210

Note: *, **, *** indicate significant at 10%, 5%, 1% significance level respectively, and the values in parentheses are test statistics, the same below

5.2.2Robustness tests

Firstly, replacing the measures of the explanatory variables, this paper introduces sparse principal component analysis (SPCA) to measure the level of collaborative innovation in order to examine the robustness of the measure of the level of collaborative innovation. Unlike the principal component analysis method, sparse principal component analysis (SPCA) constrains the number of non-zero loading factors in each principal component, which means that the loading factors are sparse, and finally achieves only a small number of core original explanatory variables to define each principal component, easing the interpretation of each principal component [30]. In this paper, when using SPCA to re-measure the level of collaborative innovation, the number of non-zero loading factors is set to 8, which means that the sparsity is 40%, and the interpretable variance is greater than 80%. The final regression results are presented in column (1) of Table 5-2. The regression results indicate that the coefficients of the digital economy indices are all positive and significant at the 1% level, which is consistent with the previous findings.

Secondly, the core explanatory variables are replaced to examine the robustness of the digital economy index measure, and the digital economy index is re-measured using principal component analysis and brought into equation (1) for estimation, and the regression results are shown in column (2) of Table 5-2, and the test results are consistent with the findings described in the previous section.

Thirdly, considering that municipalities directly under the central government have certain special characteristics in terms of political status, jurisdictional area, population and policy making, this paper reduces the scope of the sample. More specifically, exclude four municipalities: Beijing, Tianjin, Shanghai and Chongqing to estimate equation (1) again, the regression results are shown in column (3) of Table 5-2. The coefficients of the digital economy are still significant at the 1% level and the coefficients are positive, consistent with the previous findings.

Finally, considering the possible endogeneity problem of the model, this paper selects the one-period lagged digital economy index as the instrumental variable and builds a two-stage least squares model (2SLS) for estimation, and the findings obtained are consistent with the benchmark regression.

Table 5-2 Robustness tests

	(1)	(2)	(3)	(4)
	Substitution of explanatory variables	Substitution of core explanatory variables	Reduced sample	Instrumental Variables Method
	CoInnovation	CoInnovation	CoInnovation	CoInnovation
Digit	6.165***	0.115***	0.632***	0.777***
	(4.017)	(15.673)	(8.254)	(8.121)
open	0.079	0.000	-0.001	-0.003
	(0.691)	(0.083)	(-0.221)	(-0.526)
edu	1.741***	-0.077***	-0.124***	-0.127***
	(2.622)	(-3.524)	(-4.346)	(-4.167)
gdp	0.093	0.055***	-0.001	0.001
	(0.145)	(2.923)	(-0.053)	(0.024)
gov	0.345	0.012*	0.024***	0.012
	(1.642)	(1.677)	(2.784)	(1.251)
chanye	-0.220	0.133**	0.121	0.071
	(-0.119)	(2.232)	(1.565)	(0.819)
_cons	-11.455*	-0.207	0.429*	0.482*
	(-1.935)	(-1.199)	(1.760)	(1.713)
N	210	210	182	180

5.3 Intermediation effect test

The results of the mediating effects test are shown in Table 5-3, where column (1) shows the results of the baseline regression, columns (2)-(3) show the estimated results with entrepreneurial entrepreneurship as the mediating variable, and columns (4)-(5) show the estimated results with entrepreneurial innovation as the mediating variable. For entrepreneurial entrepreneurship, the coefficient c in the previous mediating effect model in equation (2), the coefficient a in equation (3) and the coefficient in equation (4) a' are significantly non-zero, where c is significant at the 1% level of significance, a and a' both are significant at the 5% level, indicating that the mediating effect of entrepreneurial entrepreneurship holds. Meanwhile, when entrepreneurial entrepreneurship is added to the benchmark regression model, the regression coefficient of digital economy index decreases from 0.610 to 0.590, indicating that entrepreneurial entrepreneurship plays a partial mediating effect between the digital economy index and the level of collaborative innovation, so hypothesis H2 holds. For entrepreneurial innovation, the coefficients c in the previous mediating effect model in equation (2), b in equation (5) and coefficient in equation (6) b' All of them are significantly non-zero, and all three are significant at the 1% level. After adding entrepreneurial innovation spirit to the benchmark regression model, the regression coefficient of digital economy index decreases from 0.610 to 0.389, indicating that entrepreneurial innovation spirit plays a partial mediating effect between digital economy index and collaborative innovation level, so hypothesis H3 is valid.

Specifically, with other factors held constant, each unit increase in the digital economy index leads to 0.554 and 65.473 units increase in entrepreneurial entrepreneurship and entrepreneurial innovation respectively, which leads to an indirect increase in the level of collaborative innovation by 0.0199 and 0.1964 units, thus indicating that entrepreneurial innovation has a stronger driving effect on the level of collaborative innovation.

Table 5-3 Mediation effect test

	(1)	(2)	(3)	(4)	(5)
	CoInnovation	EntBusiness	CoInnovation	EntInnovation	CoInnovation
Digit	0.610***	0.554**	0.590***	65.473***	0.389***
	(9.874)	(2.081)	(9.523)	(8.453)	(5.833)
open	-0.001	-0.002	-0.001	-0.918	0.002
	(-0.176)	(-0.114)	(-0.160)	(-1.592)	(0.544)
edu	-0.133***	-0.103	-0.130***	-15.345***	-0.081***
	(-4.986)	(-0.893)	(-4.881)	(-4.578)	(-3.168)
gdp	0.013	0.067	0.011	7.469**	-0.012
	(0.516)	(0.600)	(0.427)	(2.310)	(-0.501)
chanye	0.142*	0.369	0.129*	9.329	0.110
	(1.908)	(1.150)	(1.740)	(1.000)	(1.629)
gov	0.022**	0.044	0.020**	0.767	0.019**
	(2.589)	(1.209)	(2.415)	(0.723)	(2.509)
EntInnovation			0.036**		
			(2.042)		
EntBusiness					0.003***
					(6.148)
_cons	0.315	-0.491	0.333	-13.504	0.361*
	(1.324)	(-0.478)	(1.409)	(-0.452)	(1.667)
N	210	210	210	210	210

5.4 The siphon effect test

This paper establishes a Spatial Durbin model (SDM) to test the siphon effect of the digital economy on the level of collaborative innovation. Before conducting the spatial econometric analysis, we need to test whether there is a spatial effect of the research object, that is to test the spatial autocorrelation between the digital economy index and the level of collaborative innovation, and we use Moran's I to test the spatial effect of each year under the geographic distance matrix, the results can be seen in Table 5-4. Where, I>0 indicates positive spatial autocorrelation, I<0 indicates negative spatial autocorrelation, and I close to 0 indicates no spatial autocorrelation [31]. From Table 5-4, it can be seen that the Moran indexes of digital economy index and collaborative innovation level in 2013-2019 under the economic distance weight matrix are both significant at the 1% level, indicating that there is significant spatial autocorrelation between digital economy index and collaborative innovation level in 30 provinces of China in 2013-2019.

Table 5-4 Spatial autocorrelation test

Year	Digital Economy Index		Collaborative Innovation Level	
	Moran's I	Z-value	Moran's I	Z-value
2013	0.267***	3.368	0.248***	3.175
2014	0.240***	3.075	0.242***	3.104
2015	0.244***	3.106	0.222***	0.002
2016	0.235***	3.008	0.228***	2.963
2017	0.237***	3.064	0.215***	2.826
2018	0.205***	2.686	0.210***	2.763
2019	0.187***	2.483	0.221***	2.899

Secondly, Table 5-5 reports the results of the Spatial Durbin model regression of the digital economy index on the level of collaborative innovation under three different spatial weight matrices (adjacency matrix, geographic distance matrix, and economic distance matrix), based on the Hausman test results, using individual fixed effects in this paper. The results in Table 5-5 show that

in the SDM models with three different spatial weight matrices, the spatial auto-regressive coefficients of the collaborative innovation level are all significantly positive, while the coefficients of the spatial interaction terms of the digital economy are all significantly negative, indicating that there is not only an exogenous digital economy interaction effect but also an endogenous interaction effect of the collaborative innovation level in each province in space. However, the regression coefficient values of the spatial interaction terms do not directly account for the marginal effects of the digital economy on the level of collaborative innovation, and require the use of partial differential interpretation of variable changes, that is the use of direct and indirect effects to explain the effects of the explanatory variables in a region on the explanatory variables in that region and in other regions [31]. Where direct effects indicate the impact of changes in the explanatory variables in the region on the explanatory variables in the region, and indirect effects indicate the impact of changes in the explanatory variables in neighboring regions on the explanatory variables in the region, which is spatial spillover effects [31].

Table 5-5 Siphon effect test

Spatial weight matrix type	Adjacency matrix	Geographical distance matrix	Economic Distance Matrix
Variables	(1)	(2)	(3)
Spatial auto-regressive coefficient (rho)	0.258***	0.553***	0.450***
	(3.844)	(4.522)	(4.951)
Digit	0.737***	0.767***	0.716***
	(12.179)	(12.577)	(11.930)
W× Digit	-0.406***	-0.594***	-0.464***
	(-4.338)	(-5.828)	(-5.054)
Control variables	YES	YES	YES
Direct effect	0.725***	0.762***	0.706***
	(11.943)	(12.212)	(11.568)
Indirect effects (spillover effects)	-0.280***	-0.370*	-0.246*
	(-2.943)	(-1.763)	(-1.783)
Total effect	0.445***	0.392*	0.459***
	(4.157)	(1.813)	(3.103)

From Table 5-5, the spatial spillover effects of digital economy on the level of collaborative innovation under different spatial weight matrices are all significantly present, and the regression coefficients are all negative, indicating that the improvement of digital economy index in neighboring regions will have a negative impact on the level of collaborative innovation in the region, so hypothesis H4 holds.

5.5 Test for nonlinear spillover effects

The baseline regression results indicate that the digital economy effectively promotes the level of collaborative innovation. To further investigate the nonlinear effects of the digital economy on the level of collaborative innovation, a panel threshold regression model is established for empirical testing. Since the digital economy index varies significantly among provinces and the level of entrepreneurship also varies, the digital economy index, entrepreneurial entrepreneurship and entrepreneurial innovation spirit are chosen as threshold variables. The results show that the digital economy index, entrepreneurship and entrepreneurial innovation do not pass the triple threshold test at 10% significance level, but all three pass the double threshold test after repeated sampling 1000 times by bootstrap. Based on this, a panel threshold regression model with a set number of thresholds is established, and the regression results in Table 5-7 below are obtained. It is easy to see that in model (1) with the digital economy index as the threshold variable, the spillover effect of the

digital economy on collaborative innovation shows a positive and increasing non-linear marginal effect as the digital economy index increases. Meanwhile, in models (2) and (3) with entrepreneurial entrepreneurship and entrepreneurial innovation as threshold variables, although the digital economy shows a very short non-linear characteristic of decreasing marginal effect in model (2), the overall marginal effect of the digital economy on the level of collaborative innovation. So, the non-linear characteristic of increasing marginal effect of digital economy on the level of collaborative innovation still exists. It indicates that the dynamic impact of digital economy on the level of collaborative innovation is not only influenced by its own level, but also moderated by entrepreneurial entrepreneurship and entrepreneurial innovation, so hypothesis H5 is confirmed.

Table 5-6 Tests for nonlinear spillover effects

Variables	Number of thresholds	F-value	P-value	10% Threshold	5% critical value	1% critical value
Digital Economy Index	Single Threshold	95.80	0.0000	21.5665	26.4865	36.2709
	Double Threshold	22.90	0.0470	15.6837	21.2485	165.3436
	Three-fold threshold	18.77	0.3290	35.8115	46.8055	120.6024
Entrepreneurship	Single Threshold	55.00	0.0010	16.9356	21.4291	29.9247
	Double Threshold	40.64	0.0020	14.9895	18.5532	26.3518
	Three-fold threshold	28.78	0.3960	79.4717	95.5223	136.2189
Entrepreneurial Innovation	Single Threshold	106.89	0.0000	20.8453	24.1313	33.2674
	Double Threshold	54.68	0.0000	18.4494	22.9255	30.6696
	Three-fold threshold	21.70	0.2280	44.4741	64.5690	95.3089

Table 5-7 Regression results of the threshold of digital economy affecting collaborative innovation

Variables		Adjustment variables		
		(1) Digital Economy Index	(2) Entrepreneurial innovation spirit	(3) Entrepreneurship
Threshold value	q1	0.3232	0.4053	29.5567
	q2	0.5421	0.4058	41.7321
$Digit \cdot I\ (Th \leq q_1)$		0.1514**	0.4453***	0.2528***
		(2.21)	(7.40)	(4.67)
$Digit \cdot I\ (q_1 < Th \leq q_2)$		0.2342***	0.6600***	0.3886***
		(3.85)	(11.12)	(7.47)
$Digit \cdot I\ (Th \geq q_1)$		0.4206***	0.5030***	0.5082***
		(8.04)	(9.30)	(11.03)
Control variables		YES	YES	YES

5.6 Regional heterogeneity test

Due to the differences in comprehensive resource endowment, economic development stage, and degree of openness to the outside world, there are more obvious heterogeneous characteristics in the regional distribution of both digital economy index and collaborative innovation level. Therefore,

there may also be regional heterogeneity in the drive of the digital economy on the level of collaborative innovation, so a more in-depth discussion is necessary. In this paper, we refer to the official document related to regional geography, and also consider that the number of provinces in Northwest and Qinghai-Tibet region is too small, so we combine the two, and categorize 30 provinces in China into Northern region, Southern region, Northwest and Qinghai-Tibet region. The northern region contains: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Heilongjiang, Jilin, Liaoning, Shandong, Henan and Shaanxi, the Northwest and Qinghai-Tibet region contains: Gansu, Qinghai, Ningxia and Xinjiang, and the remaining region is the southern region.

The regional heterogeneity regression results in Table 5-8 show that the contribution of digital economy to the level of collaborative innovation is significant in the Northern and Southern regions, but not in the Northwest and Qinghai-Tibet regions, and the contribution of digital economy to the level of collaborative innovation is stronger in the Southern region compared to the Northern region. The possible reason for this result is that the digital economy in the southern region has been developed earlier and at a higher level than that in the Northern region, so it can release the digital economy dividend more fully, while the digital economy in the Northwest and Qinghai-Tibet region has been developed at a lower level and the digital infrastructure is not perfect, so the digital economy cannot effectively empower collaborative innovation.

Table 5-8 Regional heterogeneity test

	Northern Region	Southern Region	Northwest and Qinghai-Tibet region
	CoInnovation	CoInnovation	CoInnovation
Digit	0.504***	0.864***	-0.007
	(8.125)	(6.728)	(-0.067)
open	-0.005	-0.004	0.002
	(-0.547)	(-0.441)	(0.978)
edu	-0.153***	-0.115**	-0.011
	(-3.302)	(-2.441)	(-0.434)
gdp	0.063**	-0.078	0.052**
	(2.036)	(-1.621)	(2.467)
gov	0.018	0.032**	0.000
	(1.516)	(2.061)	(0.051)
chanye	0.191**	0.128	-0.063
	(2.364)	(0.609)	(-1.315)
_cons	-0.010	1.193**	-0.448**
	(-0.027)	(2.570)	(-2.464)
N	77	105	28

6. Conclusions And Policy Suggestions

Based on the provincial panel data in China from 2013-2019, this paper empirically tested the impact of digital economy on collaborative innovation and its intrinsic mechanism in multiple dimensions using panel fixed-effects model, mediated-effects model, Spatial Durbin model and panel threshold regression model on top of measuring digital economy index and collaborative innovation development level by entropy method, and the findings are as follows: firstly, the digital economy significantly promotes the level of collaborative innovation, and this conclusion still holds after robustness testing by various methods. In terms of regional heterogeneity, the Southern region enjoys a greater digital economy dividend than the Northern region due to its higher level of digital economy development, which leads to a stronger role of the digital economy in promoting the level of collaborative innovation in the southern region. In the Northwest and Qinghai-Tibet region, the development level of digital economy is too low, so the digital economy cannot effectively empower the level of collaborative innovation. Secondly, stimulating entrepreneurship, specifically entrepreneurship and entrepreneurial innovation, is the theoretical mechanism for the digital

economy to empower collaborative innovation, and there is a double threshold effect of entrepreneurial innovation and entrepreneurship, which has a non-linear characteristic of increasing marginal effect. Thirdly, the development of digital economy will have a siphon effect on the level of collaborative innovation in the surrounding areas, indicating that the inter-regional differences in digital economy index will intensify the inter-regional imbalance in the level of collaborative innovation. Finally, the spillover effect of the digital economy on the level of collaborative innovation shows a non-linear characteristic of increasing marginal effect, which is consistent with the characteristics of its network effect and proves that the Metcalfe's law exists significantly in the improvement of the level of collaborative innovation.

This paper not only provides new ideas and deeper research on the theoretical mechanism of digital economy influencing collaborative innovation, but also contains the following policy inspirations: first and foremost, based on the fact that digital economy can effectively drive the level of collaborative innovation, and the driving mechanism is non-linear with increasing marginal effect, we should vigorously implement the development strategy of digital economy, and continuously improve the construction of digital infrastructure such as 5G network base stations, big data centers, industrial internet and block chain. Use digital technology to build collaborative innovation platforms among various subjects of industry, academia and research, reduce the information asymmetry among innovation subjects, realize resource integration, and cultivate new business models of digital economy. Use digital technology to empower key links such as enterprise financing, administrative approval, talent recruitment in order to promote digital industrialization, digitization of industry, and create a favorable innovation environment for the society. Secondly, since the digital economy has a siphon effect and strong regional heterogeneity on the level of collaborative innovation in neighboring regions, it is more important to strengthen the construction of digital economy in regions lagging behind, especially in central and western regions, so as to ensure the balanced development of digital economy in each region. Specifically, on the one hand, we should focus on the construction of digital infrastructure around the central cities to drive the development of digital economy in the surrounding areas, and on the other hand, we should follow the national strategic of channels computing resources from the east to the west, strengthen the construction of digital infrastructure in the central and western regions in China, cultivate new digital economy according to local conditions, and focus on the introduction and training of digital economy professionals training. Thirdly, based on the theoretical contribution of this paper, entrepreneurship can be regarded as an important grip of the digital economy to promote the level of collaborative innovation, and each region should rely on the digital economy to empower the transformation of scientific and technological achievements, reduce taxes and fees, attract investment and other key aspects, and give full play to the role of the digital economy in stimulating entrepreneurship, so as to promote the level of collaborative innovation in each region. Finally, the digital economy may pose new challenges to the protection of intellectual property rights, so it is necessary to draw the attention of the government and put it into practice by strengthening the supervision and updating the supervision technology, so as to facilitate the long-term development of collaborative innovation between industry, academia and research.

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