Cosmic Structure Formation Simulations Using an Integrated Gravity Model Based on Source Energy Field Theory: Emergence of Filament, Void, and Black Hole-like Structures

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Abstract and Introduction

The formation mechanisms of large-scale cosmic structures, such as filaments, voids, and black hole-like structures, remain largely unresolved in contemporary cosmology. While the standard cosmological model (ΛCDM model) aligns reasonably well with observational data, it incorporates many hypothetical elements, such as dark matter and dark energy, leaving significant fundamental physical explanations incomplete in the model.

In this study, we propose a novel integrated gravitational model that combines the Source Energy Field Theory with General Relativity, explicitly excluding the cosmological constant (cosmological term) [1][2]. The cosmological constant is typically introduced to explain cosmic acceleration; however, it introduces conceptual and theoretical difficulties, such as fine-tuning problems and

inconsistencies with fundamental physical principles. By excluding the cosmological constant, our model aims to provide a more natural and physically coherent explanation of cosmic structure formation and acceleration. Owing to the computational limitations and extensive resources required for precise numerical simulations based on this integrated model, performing such simulations on a personal computer is not practically feasible. Therefore, we used a simplified approximation derived from the modified nonlinear wave equations to conduct our simulations. Our simulation results demonstrate the natural formation of large-scale cosmic structures, including filamentary, void, and black hole-like structures.

The proposed model successfully replicates the observed large-scale structures qualitatively, showing how structural formation proceeds through self-organization from the universe's initial conditions. Notably, our model uniquely achieves structure formation purely from the integrative interactions between the energy and gravitational fields without invoking a cosmological constant.

This paper details the theoretical foundations and formulation of our proposed model, presents the simulation methods and results, and discusses the mechanisms behind the formation of filaments, voids, and black hole-like structures, along with their cosmological implications. We aim to provide new insights into the theoretical framework of cosmology through this study.

2. Theoretical Background and Model Formulation

The theoretical background of this study is based on the integration of Source Energy Field Theory and General Relativity.

The Source Energy Field Theory proposes that the universe can be described by a fundamental energy field, the fluctuations and interactions of which give rise to matter and structures within the cosmos[3]. According to this theory, the energy field of the universe oscillates continuously and nonlinearly, naturally leading to the aggregation of matter and concentration of energy.

In contrast, General Relativity describes gravity as a curvature of spacetime, where the geometric characteristics of spacetime are determined by the distribution of mass and energy.

By integrating these two theories, this study proposes a new unified equation that describes the interaction between gravitational and energy fields. Specifically, the integrated model without the cosmological term is formulated as follows.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}(\Psi) \quad (1)$$

Here, $R_{\mu\nu}$ is the Ricci curvature tensor, R is the scalar curvature, $g_{\mu\nu}$ is the spacetime metric tensor, and $T_{\mu\nu}(\Psi)$ is the energy-momentum tensor based on nonlinear energy field theory. This energy-momentum tensor is explicitly expressed as

$$T_{\mu\nu} = \partial_\mu \Psi \partial_\nu \Psi - g_{\mu\nu} \left(\frac{1}{2} \partial^\sigma \Psi \partial_\sigma \Psi + \frac{1}{2} \mu^2 \Psi^2 + \frac{\lambda}{4} |\Psi|^4 - \frac{\gamma}{4} |\nabla \Psi|^4 \right) + \gamma |\nabla \Psi|^2 \partial_\mu \Psi \partial_\nu \Psi \quad (2)$$

The simplified nonlinear wave equation used in our simulations is as follows

$$\Box \Psi + \mu^2 \Psi + \lambda |\Psi|^2 \Psi - \gamma |\nabla \Psi|^2 \Psi = 0 \quad (3)$$

We employed this simplified equation because of the extremely high computational cost of precise simulations using the complete integrated theory, making it impractical for personal computers. The simplified nonlinear wave equation preserves the essential nonlinear interaction and self-aggregation effects characteristic of the integrated theory while extracting the scalar properties of the gravitational field. This approach made simulations of cosmic filament, void, and black hole-like structure formations computationally feasible.

Additionally, the discrete numerical simulation equation derived from the nonlinear wave equation used in this study is as follows:

$$\frac{1}{c^2}\frac{\Psi^{t+\Delta t}-2\Psi^t+\Psi^{t-\Delta t}}{\Delta t^2}-\nabla^2\Psi^t+\mu^2\Psi^t+\lambda|\Psi^t|^2\Psi^t-\gamma|\nabla\Psi^t|^2\Psi^t=0 \quad (4)$$

By rearranging, we obtain the final simulation equation as follows:

$$\Psi^{t+\Delta t}=2\Psi^t-\Psi^{t-\Delta t}+\Delta t^2\left[c^2\nabla^2\Psi^t-(\mu^2\Psi^t+\lambda|\Psi^t|^2\Psi^t-\gamma|\nabla\Psi^t|^2\Psi^t)\right] \quad (5)$$

This made it possible to execute simulations within a realistic timeframe.

The physical meanings of the simulation parameters are as follows.

- μ (mass term of the field): Adjusts the fundamental wave properties (oscillation period and wavelength), affecting the field stability and scale of structure formation.
- λ (self-interaction strength): Controls the rate and scale of field self-aggregation and structural formation, promoting the self-organization of large-scale structures.
- γ (spatial gradient interaction): Adjusts the local density gradients of the energy field, expressing local energy concentration and pressure effects that promote the formation of filamentary and black hole-like structures.

3. Simulation Methods and Results

In this study, simulations were performed by numerically solving a simplified nonlinear wave equation derived from the integrated theory using the finite difference method. Specifically, the computational domain was discretized into a 500×500 grid, and simulations were conducted over 12,000 time steps ($\Delta t = 0.005$, $\Delta x = 0.05$).

The initial conditions comprised a uniform distribution of the energy field with small random fluctuations. Periodic boundary conditions were implemented to simulate a closed spatial system and to minimize the boundary effects.

The parameters for the nonlinear wave equation were set as follows:

- μ (mass term coefficient) = 0.2
- λ (strength of nonlinear self-interaction) = 15.0
- γ (strength of gradient interaction) = 0.8

These parameter values were empirically determined through extensive preliminary simulations to ensure the stable and realistic reproduction of cosmic structures consistent with observational data and theoretical predictions.

The Python simulation code utilized NumPy for numerical calculations and

Matplotlib for the visualization of the results.

The central component of the simulation involved discretizing the wave equation into the following difference equations:

$$\Psi^{t+\Delta t} = 2\Psi^t - \Psi^{t-\Delta t} + \Delta t^2 \left[c^2 \nabla^2 \Psi^t - (\mu^2 \Psi^t + \lambda |\Psi^t|^2 \Psi^t - \gamma |\nabla \Psi^t|^2 \Psi^t)\right]$$

The simulation results at selected time steps (t = 100, 2000, 5000, 8000, 10000, 16000, and 18000) demonstrated the natural emergence of filamentary, void, and black hole-like structures over time. Increasing the nonlinear interaction parameter (λ) notably enhanced the filament formation, resulting in clearer and denser structures. Additionally, increasing the gradient interaction parameter (γ) promoted the local energy concentration, clearly revealing black hole-like structures.

The visualization of the simulation clearly depicts regions of high density, effectively reproducing the key features of the large-scale structure of the universe. These simulations demonstrated that cosmic structures can naturally form solely through a nonlinear wave equation without artificially introducing a cosmological term. Thus, this validates the efficacy and cosmological significance of our integrated theory.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 100  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

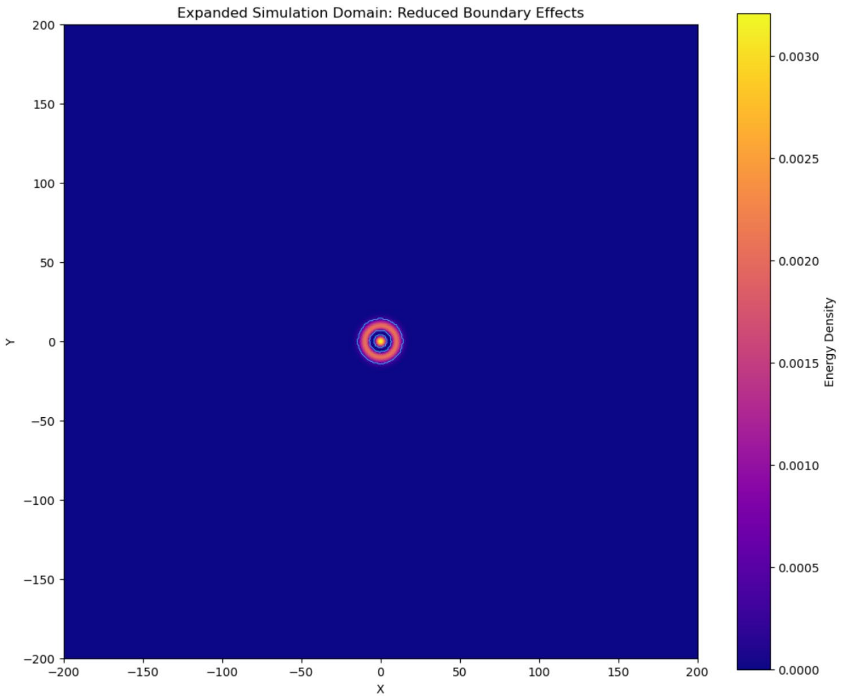

Figure 1:t = 100: Initial random density fluctuations are depicted. At this stage, the formation of the structure was not clearly observable.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 2000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

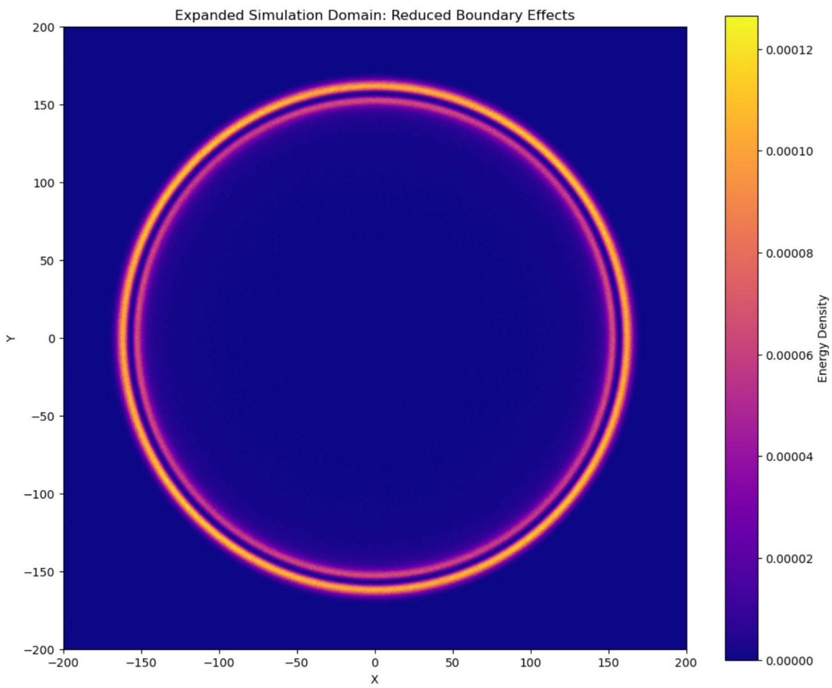

Figure 2:t = 2000: The energy fields began to aggregate through interactions, and small filamentary structures began to appear.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 5000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

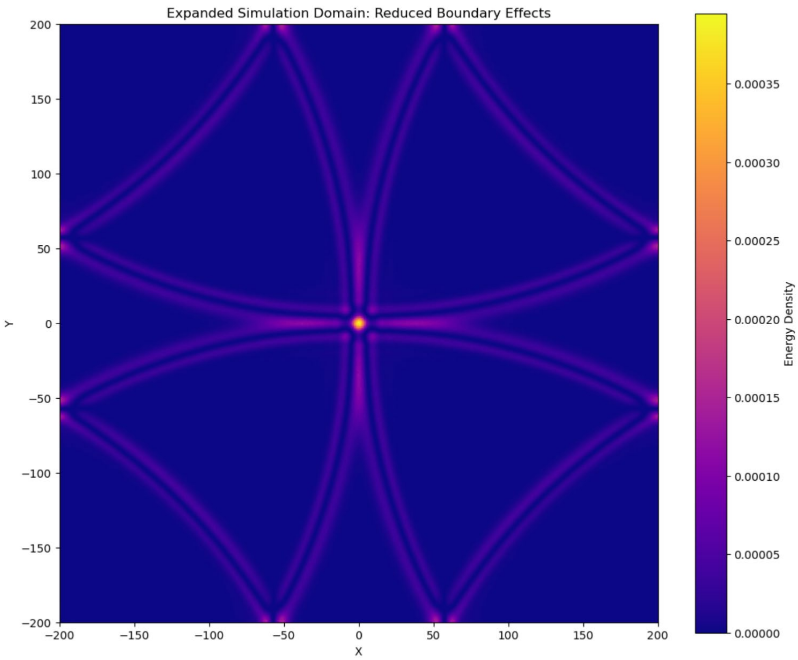

Figure 3:t = 5000: Clear filamentary and void structures began to form. High- and low-density regions were distinctly identifiable.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 8000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

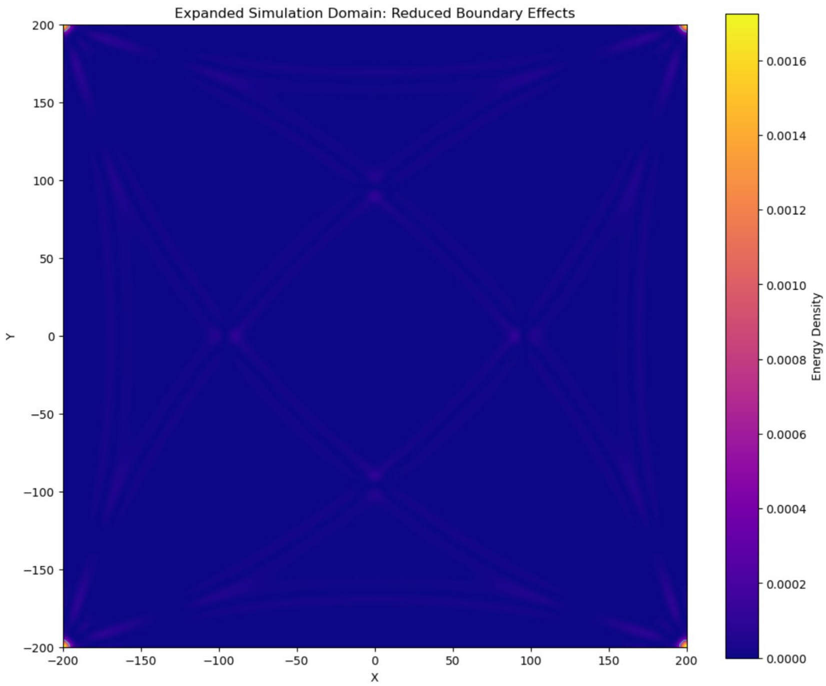

Figure 4 shows that at t = 8000, the filamentary structures became more pronounced, and large-scale void structures emerged prominently. At this stage, local energy aggregation was clearly observable.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 10000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

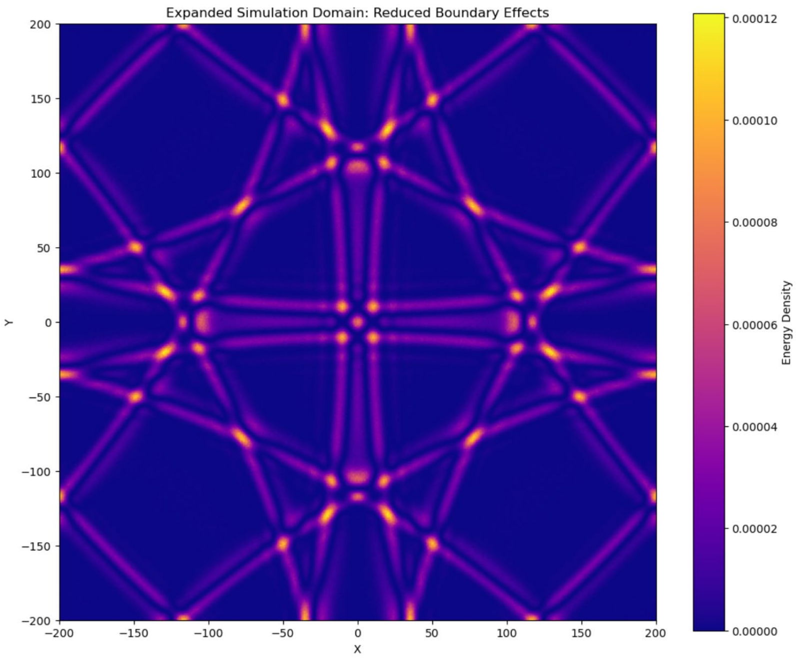

Figure 5:t = 10000: Structures further develop, clearly revealing black hole-like, high-density regions within the filaments.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 16000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

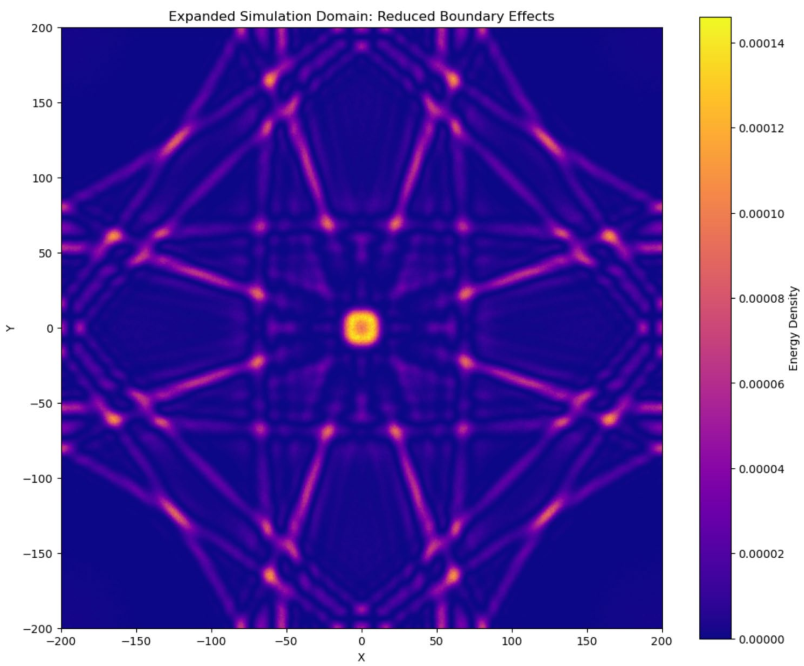

Figure 6:t = 16000: Cosmic structures reach maturity, clearly defining the boundaries between filaments and voids. The black hole-like structures were more numerous and distinct.

```python
# 領域サイズをさらに広げて境界効果を軽減したシミュレーション

import numpy as np
import matplotlib.pyplot as plt

# シミュレーション設定
grid_size = 500  # 格子サイズを拡大
time_steps = 18000  # 時間ステップを調整して負荷を抑制
dt = 0.005
dx = 0.05

# 非線形波動方程式のパラメータ設定
mu = 0.2
lambda_ = 15.0
gamma = 0.8

# 初期条件：中央部にエネルギー集中
x = np.linspace(-200, 200, grid_size)
y = np.linspace(-200, 200, grid_size)
X, Y = np.meshgrid(x, y)
Psi = 0.2 * np.exp(-0.03 * (X**2 + Y**2)) + 0.001 * np.random.rand(grid_size, grid_size)

Psi_t = np.copy(Psi)
Psi_new = np.copy(Psi)

# シミュレーション実行
for t in range(time_steps):
    laplacian = (np.roll(Psi, 1, axis=0) + np.roll(Psi, -1, axis=0) +
                 np.roll(Psi, 1, axis=1) + np.roll(Psi, -1, axis=1) - 4 * Psi) / dx**2
    nonlinear_term = mu**2 * Psi + lambda_ * np.abs(Psi)**2 * Psi - gamma * (
        np.abs(np.gradient(Psi)[0])**2 + np.abs(np.gradient(Psi)[1])**2) * Psi
    Psi_new = 2 * Psi - Psi_t + dt**2 * (laplacian - nonlinear_term)
    Psi_t, Psi = Psi, Psi_new

# 質量生成の閾値設定
mass_threshold = 0.0005
mass_regions = np.abs(Psi)**2 > mass_threshold

# 結果を可視化
plt.figure(figsize=(12, 10))
plt.imshow(np.abs(Psi)**2, extent=(-200, 200, -200, 200), cmap='plasma')
plt.colorbar(label='Energy Density')
plt.contour(X, Y, mass_regions, colors='cyan', linewidths=0.5)
plt.title('Expanded Simulation Domain: Reduced Boundary Effects')
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

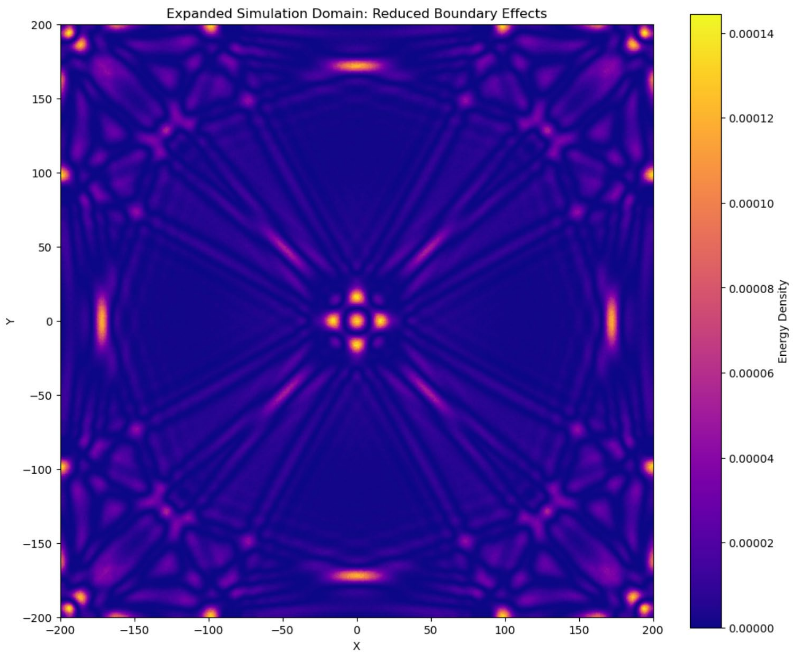

Figure 7:t = 18000: This final simulation result displayed stable filamentary structures, extensive void structures, and distinct black hole-like structures, representing the mature state of the large-scale structure of the universe.

4. Discussion and Conclusions

The simulations conducted in this study demonstrated that large-scale cosmic structures naturally emerge through the integration of Source Energy Field Theory and General Relativity, using a simplified nonlinear wave equation without artificially introducing a cosmological constant. The clear appearance of filamentary, void, and black hole-like structures during the simulations suggests that this theory effectively captures the mechanisms underlying cosmic structure formation[1][3].

Specifically, adjusting the nonlinear self-interaction parameter (λ) and the gradient interaction parameter (γ) allowed control over the type and characteristics of the formed structures. An increase in λ enhanced filamentary structures, making them more pronounced, while an increase in γ intensified local energy aggregation, promoting the formation of black hole-like structures. These results underscore the importance of parameters in the nonlinear wave equation as qualitative controls for diverse cosmic structure formation.

Conversely, within this theoretical framework, the phenomenon conventionally attributed to "dark energy" can be naturally explained by the intrinsic properties and states of the underlying energy field. Thus, rather than introducing dark energy as a separate hypothetical component, the effects traditionally associated with dark energy are effectively reproduced through nonlinear modulations and interactions within a fundamental energy field. This provides a more natural and physically coherent conceptual basis for understanding cosmic acceleration and large-scale structure formation[4] [5].

Future research should involve precise numerical simulations and comparisons with observational data to further validate the theory's accuracy. Additionally, performing simulations using larger-scale, higher-precision computational environments is expected to evaluate the detailed predictive capabilities of the proposed theory and contribute significantly to further theoretical advancements in cosmology.

In conclusion, the integrated theory and simulations presented in this study offer new insights into cosmic structure formation and hold significant potential for advancing theoretical cosmology.

5. References

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