課題番号 jh250066

宇宙初期における位相欠陥の一般相対論的シミュレーション

General relativistic simulation of topolotial defects in the early universe

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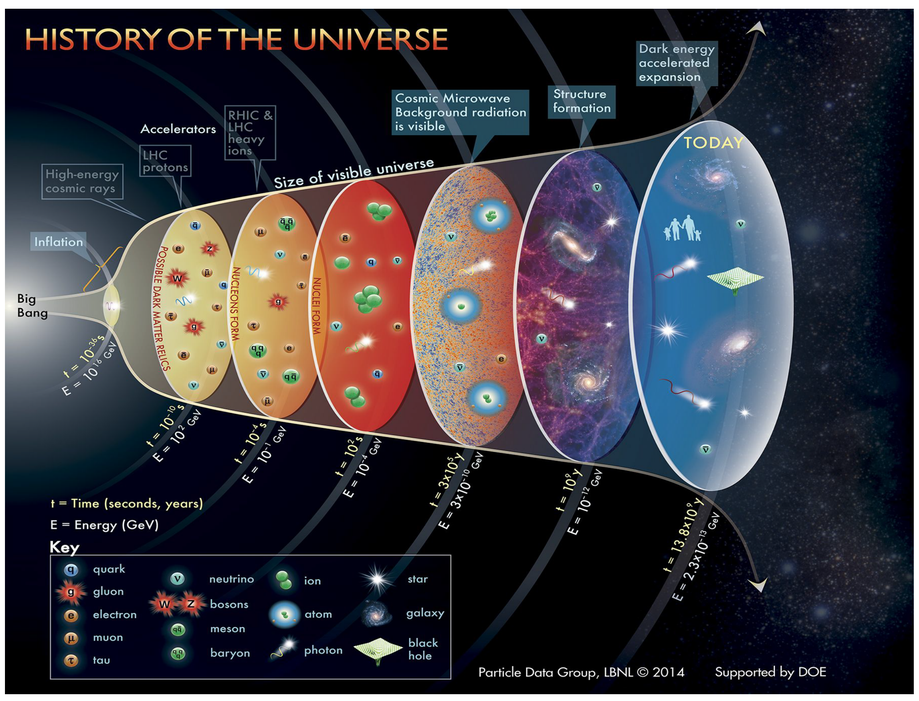
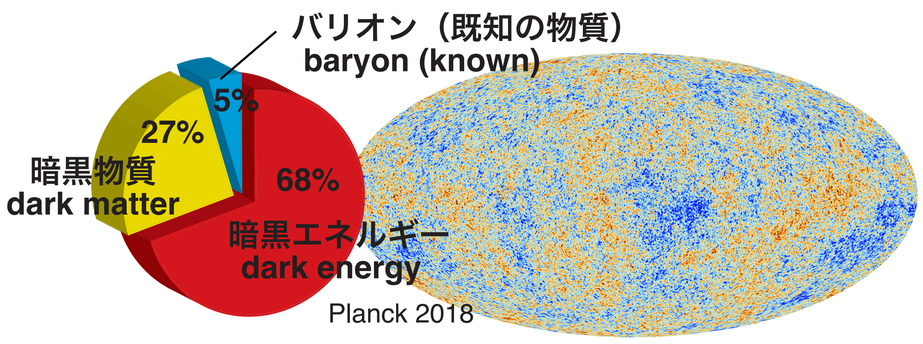
Q. 宇宙はどのようにして始まったのか？
How did the Universe begin?



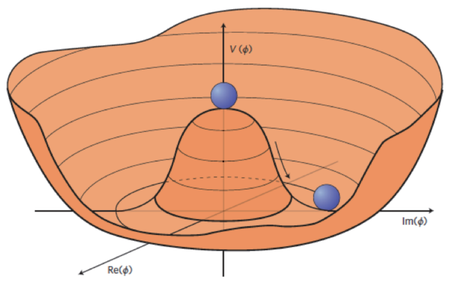
Q. 宇宙は何でできているか？
What is the Universe made of?

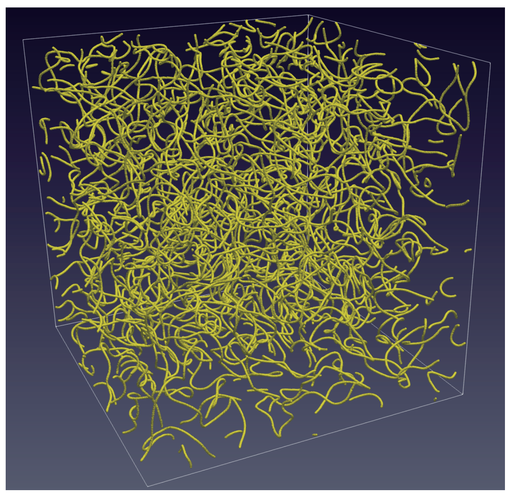


Q. どのようにして初期宇宙を探るか？
How can we probe the early Universe?

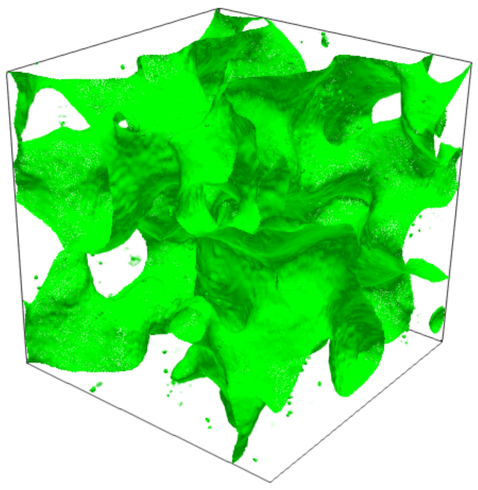
自発的対称性の破れ

Spontaneous symmetry breaking



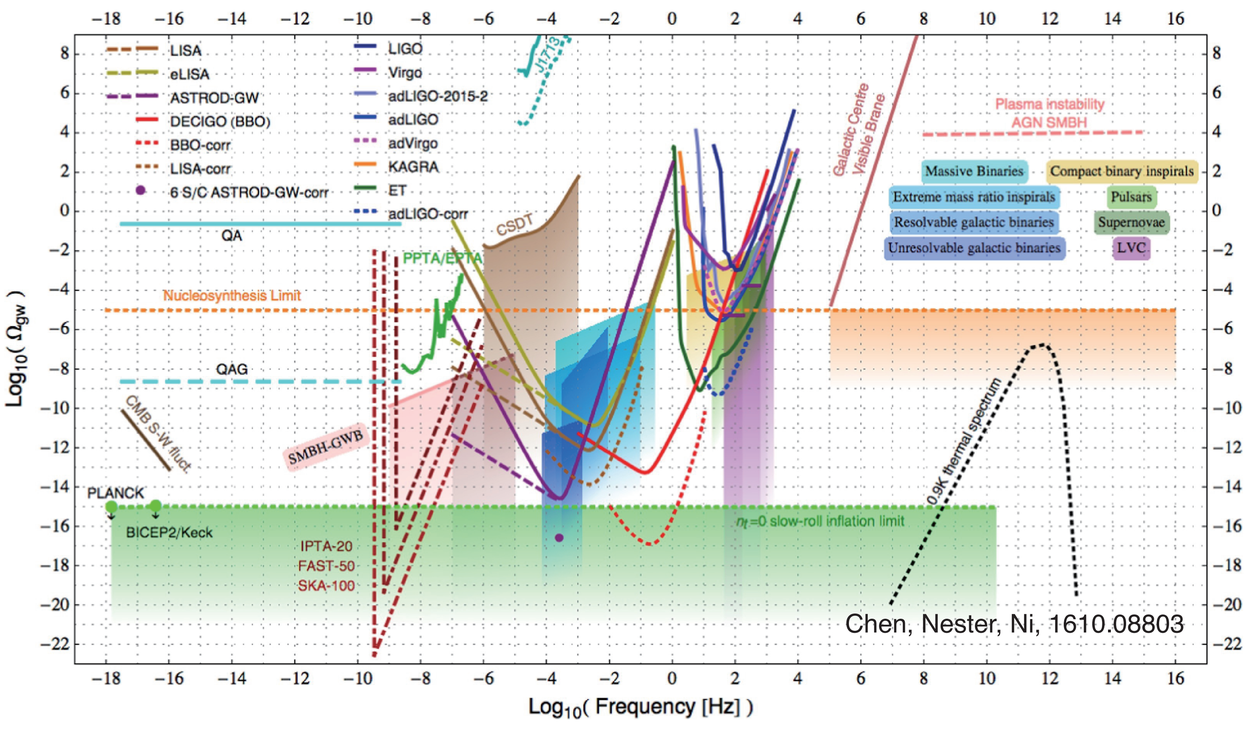


宇宙ひも / Cosmic string



ドメインウォール / domain wall

Gravitational wave observation as a probe of the early Universe



Chen, Nester, Ni, 1610.08803

Numerical relativity

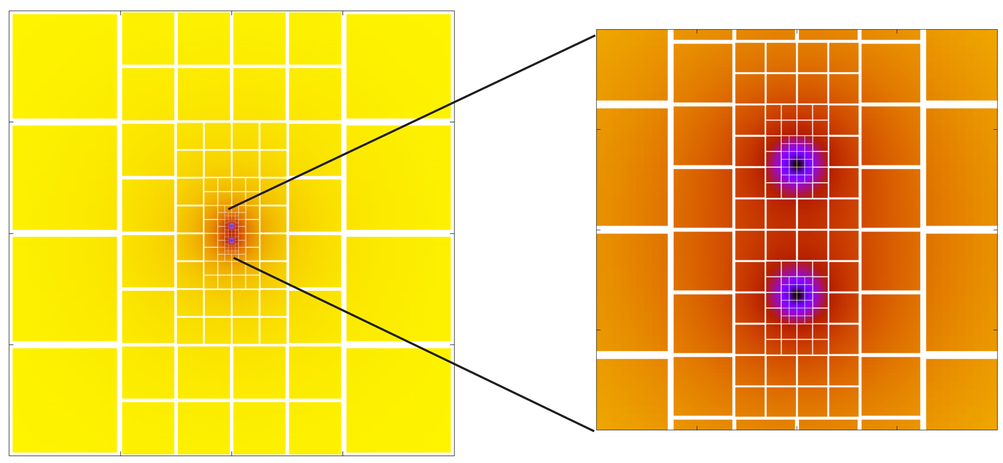
"Matter tells spacetime how to curve,
and spacetime tells matter how to move."
John A. Wheeler

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

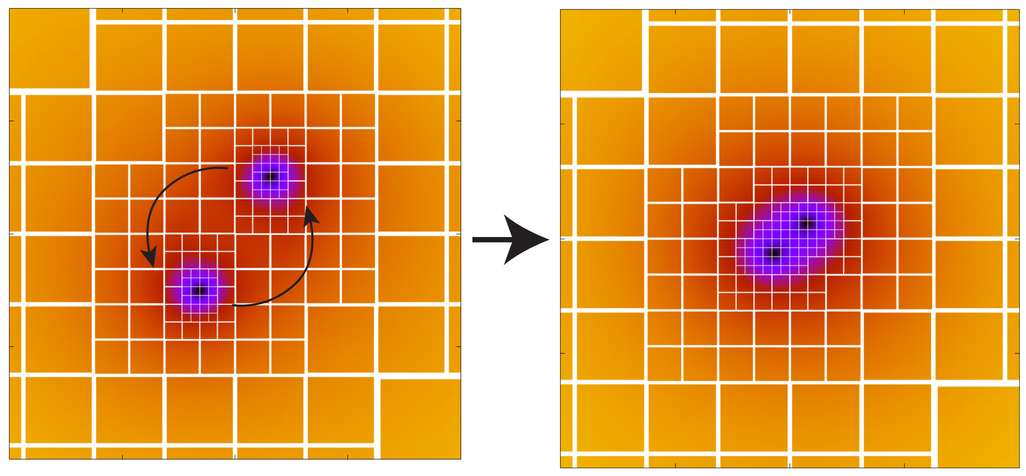
CCZ4 formulation

$$
\begin{aligned}
\partial_t \chi &= \frac{2}{3}\alpha\chi K - \frac{2}{3}\chi\partial_k\beta^k + \beta^k\partial_k\chi, \\
\partial_t \tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} + 2\tilde{\gamma}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\beta^k + \beta^k\partial_k\tilde{\gamma}_{ij}, \\
\partial_t \tilde{A}_{ij} &= \chi\left[-D_iD_j\alpha + \alpha(R_{ij} + D_iZ_j + D_jZ_i - 8\pi S_{ij})\right]^{\mathrm{TF}} \\
&\quad + \alpha\left[\tilde{A}_{ij}(K - 2\Theta) - 2\tilde{A}_{il}\tilde{A}^l_j\right] + 2\tilde{A}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\beta^k + \beta^k\partial_k\tilde{A}_{ij}, \\
\partial_t K &= -D_iD^i\alpha + \alpha(R + 2D_iZ^i + K^2 - 2\Theta K) + \beta^i\partial_i K - 3\alpha\kappa_1(1+\kappa_2)\Theta + 4\pi\alpha(S - 3\rho), \\
\partial_t \Theta &= \frac{\alpha}{2}\left(R + 2D_iZ^i - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}K^2 - 2\Theta K\right) - Z^i\partial_i\alpha + \beta^k\partial_k\Theta - \alpha\kappa_1(2+\kappa_2)\Theta - 8\pi\alpha\rho \\
\partial_t \hat{\Gamma}^i &= -2\tilde{A}^{ij}\partial_j\alpha + 2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - \frac{3}{2\chi}\tilde{A}^{ij}\partial_j\chi - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right) \\
&\quad + 2\tilde{\gamma}^{ij}\left(\alpha\partial_j\Theta - \Theta\partial_j\alpha - \frac{2}{3}\alpha K Z_j\right) \\
&\quad + \beta^k\partial_k\hat{\Gamma}^i + \tilde{\gamma}^{jk}\partial_j\partial_k\beta^i + \frac{1}{3}\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \frac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k - \tilde{\Gamma}^k\partial_k\beta^i \\
&\quad + 2\kappa_3\left(\frac{2}{3}\tilde{\gamma}^{ij}Z_j\partial_k\beta^k - \tilde{\gamma}^{jk}Z_j\partial_k\beta^i\right) - 2\alpha\kappa_1\tilde{\gamma}^{ij}Z_j - 16\pi\alpha\tilde{\gamma}^{ij}S_j,
\end{aligned}
$$

Adaptive mesh refinement (AMR)

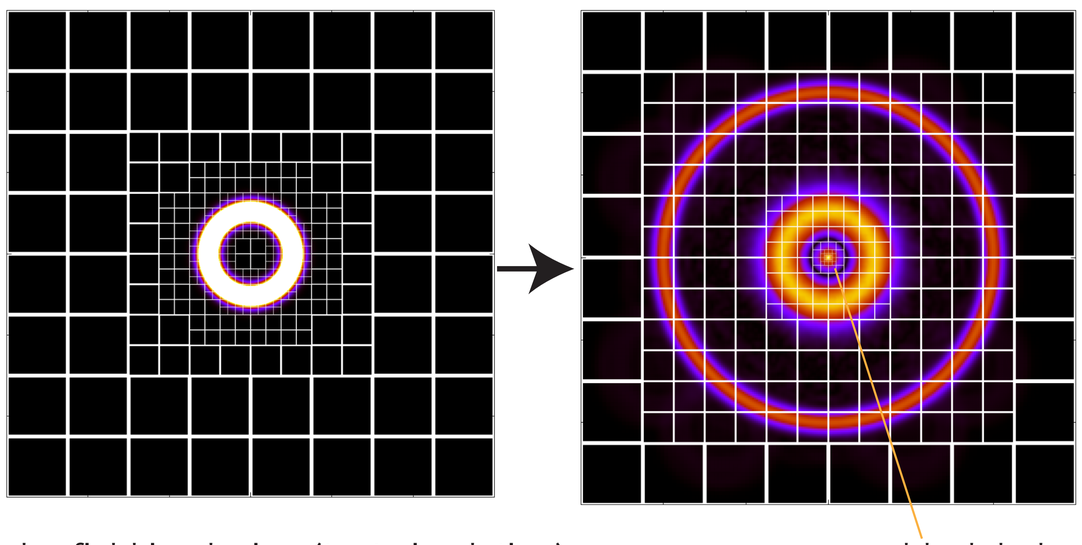


Binary black hole merger (test)



Purpose of this project

Cosmic string loop →
Domain wall collapse →
Black hole



scalar field implosion (test simulation)

black hole