The Shock-in-Time : Generating the Entropy of the Early Universe

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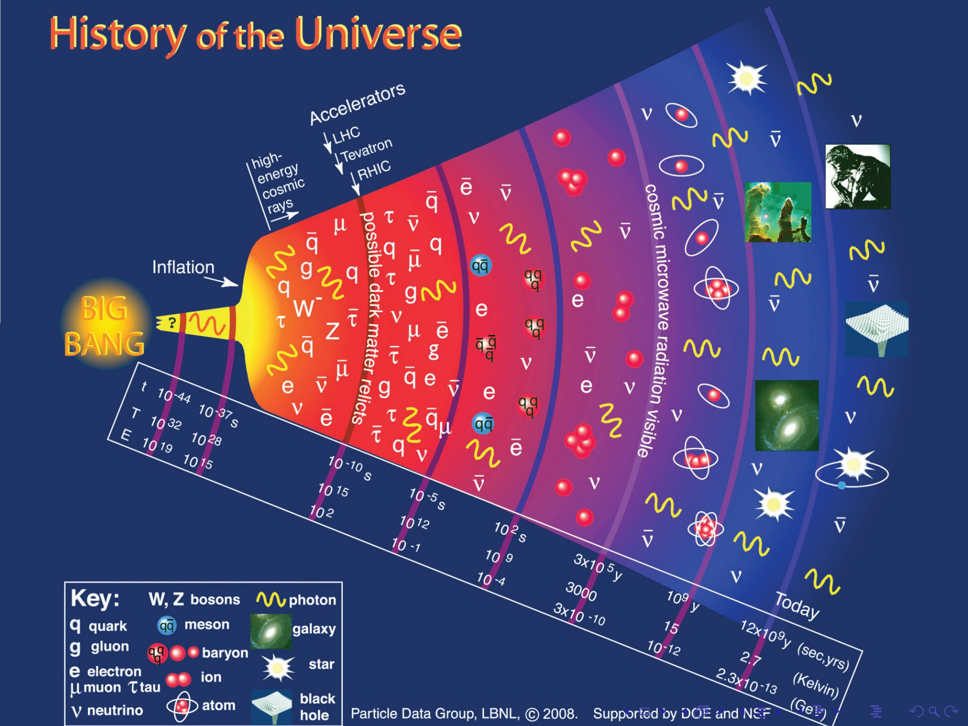
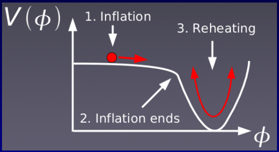
The Information Universe, Groningen, Oct. 8, 2015

in collaboration with Dick Bond, Andrei Frolov and Zhiqi Huang (in preparation)

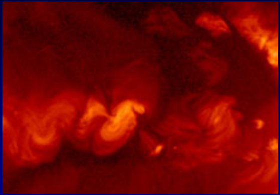

History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Starting the Big Bang

Inflation



Hot Big Bang



- Cold $(T \sim 0)$, $\frac{S}{V} \approx 0$
- Few active d.o.f.

- Hot $(T > MeV)$, $\frac{S}{V} \propto g_{eff}(T) T^3$
- Many active d.o.f.

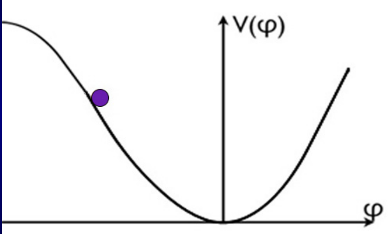
Huge entropy production (information processing)

But how does it happen?

Lightning Review of Inflation and Preheating

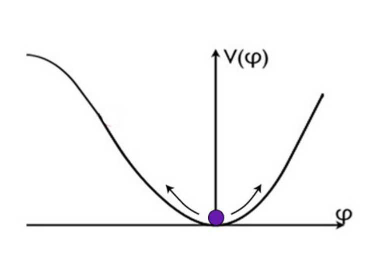
$$\mathcal{L} = -\frac{G_{IJ}(\vec{\phi})}{2}\partial_\mu \phi^I \partial^\mu \phi^J - V(\vec{\phi})$$

During Inflation



- Subhorizon Homogeneity
- (Small) Superhorizon Inhomogeneity

End of Inflation



$$\left[\delta\phi, \delta\dot{\phi}\right] \neq 0$$

$$\Longrightarrow \langle|\delta\tilde{\phi}_k|^2\rangle, \langle|\delta\tilde{\dot{\phi}}_k|^2\rangle > 0$$

- Variety of instabilities

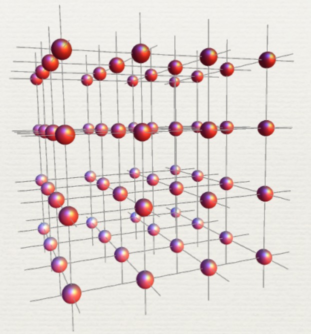
Numerical Approach is Essential [JB, in preparation]

Hybrid MPI/OpenMP Lattice Code

- Solve field equation (e.g.)

$$\ddot{\phi}_i + 3\frac{\dot{a}}{a}\dot{\phi}_i - \frac{\nabla^2\phi_i}{a^2} + V'(\vec{\phi}) = 0$$

- 10th order Gauss-Legendre integration (general) or 8th order Yoshida (nonlinear sigma models)
- Finite-difference (fully parallel) or Pseudospectral (OpenMP)
- Optional absorbing boundaries
- Quantum fluctuations → realization of random field



- Energy conservation $\mathcal{O}(10^{-9} - 10^{-14})$

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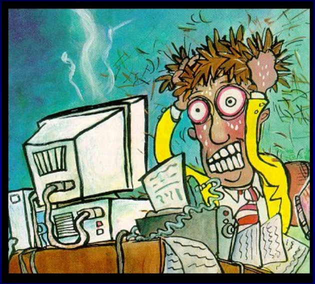

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Developing Complexity of $\ln(\rho/\bar{\rho})$

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Entropy and Information

Shannon Entropy

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Entropy and Information

Shannon (or von Neumann) Entropy

$$S_{shannon} \equiv -\int \mathcal{D}\varphi f[\varphi] \ln f[\varphi] \qquad S_{vN} = -\mathrm{Tr}\hat{\rho}(\hat{\varphi}) \ln \hat{\rho}(\hat{\varphi})$$

Entropy and Information

Entropy : Expectation Value of Information

$$S = -\langle \ln f \rangle_f = -\langle \ln \hat{\rho} \rangle$$

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Relative Entropy (KL-Divergence) - Continuum Variables

$$S_{KL} \equiv \int \mathcal{D}\varphi f[\varphi] \ln \left(\frac{f[\varphi]}{Q[\varphi]} \right) = \left\langle \ln \left(\frac{f}{Q} \right) \right\rangle_f$$

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- What is Q? (phase space partitioning)
- What is $f[\varphi]$?
- What fields φ should we use?

Coarse Graining Prescription : Maximum Entropy

Maximise S Subject to Measured $\mathcal{C}_{\varphi\vartheta}(x,y) = \langle \varphi(x)\vartheta(y)\rangle$

$$S_{ME} = \frac{1}{2}\ln\det(\mathcal{C}) + \frac{N_{\rm dof}}{2} + \frac{N_{\rm dof}}{2}\ln 2\pi$$

NonCanonical Variables $(\mathcal{Q} \to \mathcal{J})$

$$S_{ME}^{\rm nc} = \frac{1}{2}\ln\left(\frac{\det\mathcal{C}}{\mathcal{J}^2}\right) + \dots$$

$$\det\mathcal{C} \sim V_{\rm fluc}^2 \qquad \mathcal{J}^2 = \left|\frac{\partial\varphi}{\partial\varphi_{\rm can}}\right|^2 \sim V_{\rm quantum}^2$$

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$$S_{ME} = \frac{1}{2}\sum_i \ln \Delta^2(k_i) + \frac{N_{\rm dof}}{2} + \frac{N_{\rm dof}}{2}\ln 2\pi$$

NonCanonical Case

$$S^{\rm nc}_{ME} = \frac{1}{2}\sum_i \ln\left(\frac{\Delta^2(k_i)}{\tilde{\mathcal{J}}^2_k}\right) + \ldots$$

$$\det\mathcal{C} \sim V^2_{\rm fluc} \qquad \mathcal{J}^2 = \left|\frac{\partial\varphi}{\partial\varphi_{\rm can}}\right|^2 \sim V^2_{\rm quantum}$$

$$\Delta^2 = \det(\tilde{\mathcal{C}}_{ij}(k)) \qquad \tilde{\mathcal{C}}_{ij}(k) = \left\langle \varphi_i(k)\varphi^*_j(k)\right\rangle$$

Information Processing → Generation of Higher Order Correlators

Information spreads into the reservoir of higher n-point functions

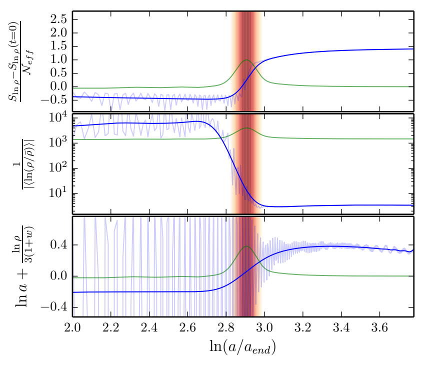
$$\frac{dS}{dt} \propto \sum_k \frac{d\ln\Delta(k)}{dt}$$

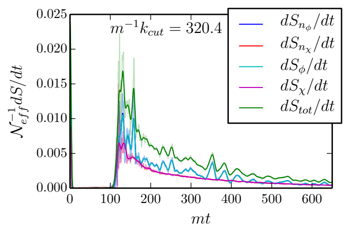
$$\frac{d\ln\Delta(k)}{dt} = a_{23}\langle 3 - pt\rangle + a_{24}\langle 4 - pt\rangle + \ldots$$

Note : $dS/dt = 0$ for linear evolution equations.

The Shock-in-Time

$\ln\rho$ Phonon DOF

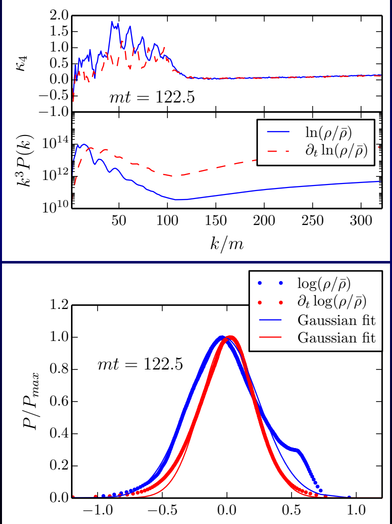




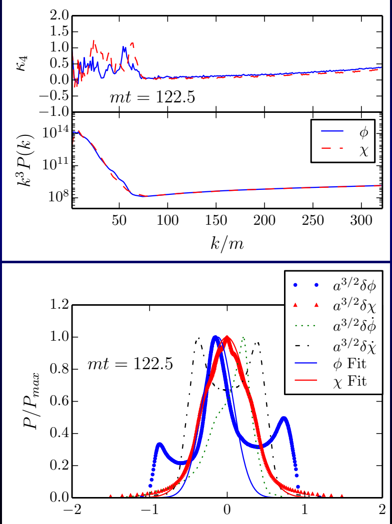
Field DOF

Phonons as Collective Variables : During Shock

$\ln\rho$ Phonons

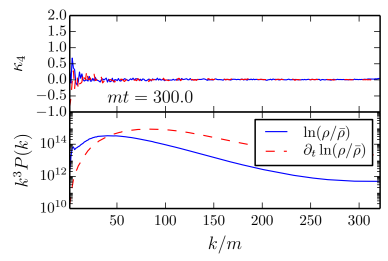


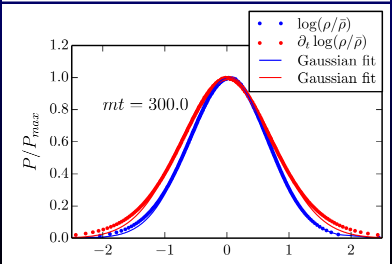
Fundamental Fields



Phonons as Collective Variables : Post Shock

$\ln \rho$ Phonons





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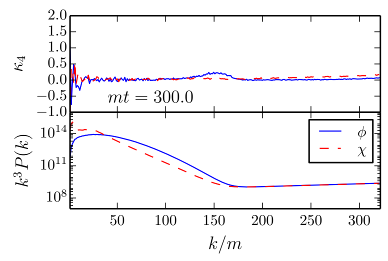
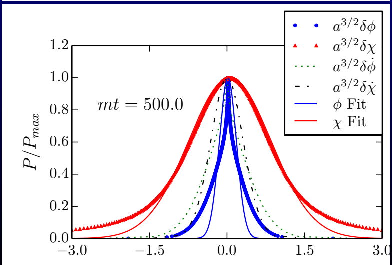
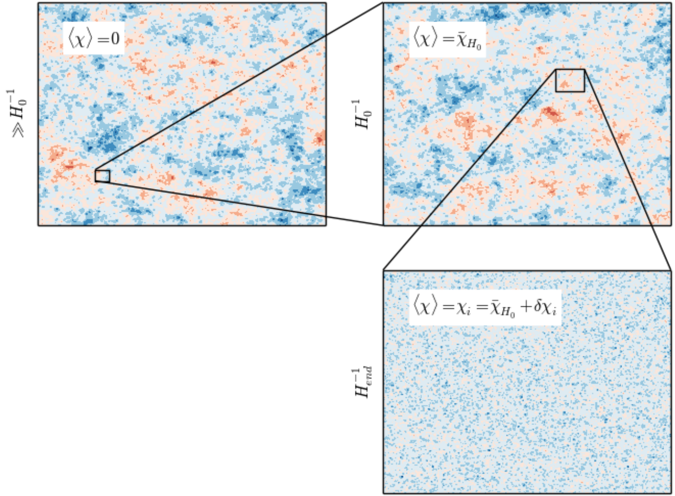


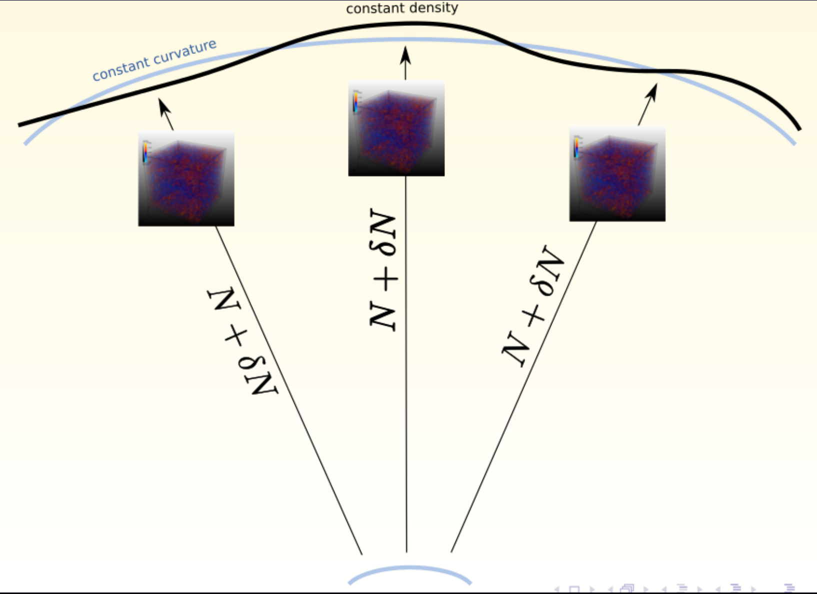


Density Perturbations from the Shock-in-Time

Ultra Large Scale Modulating Isocurvature Field



$\zeta = \zeta_{\text{inf}} + F_{NL}(\chi)$ $\zeta = (\delta \ln a)\,|_{\rho}$



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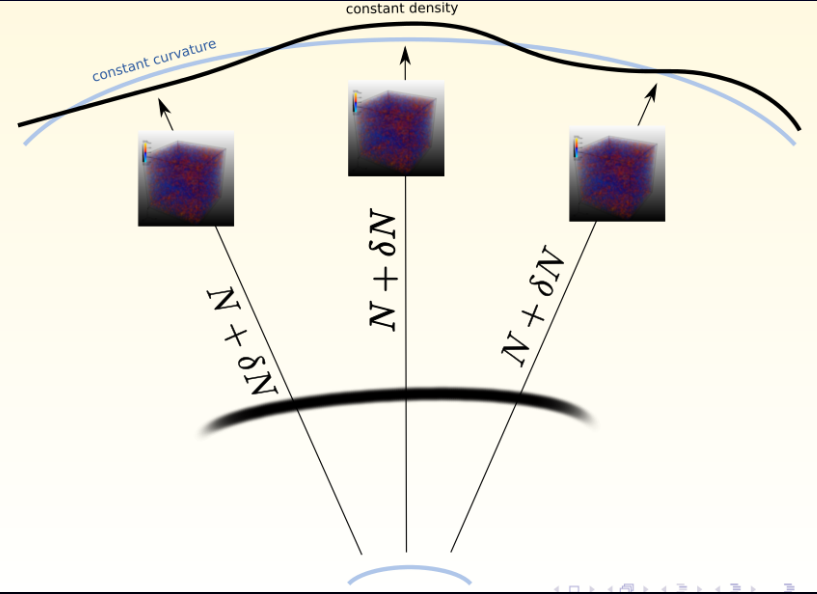
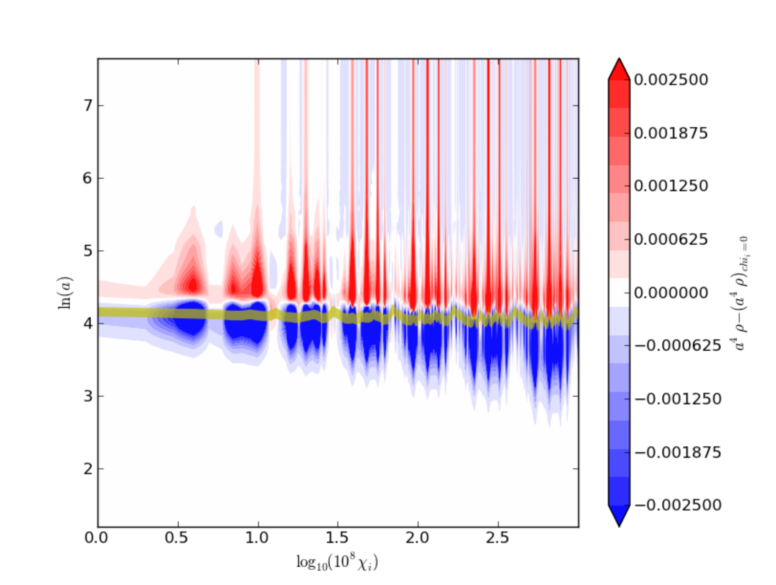
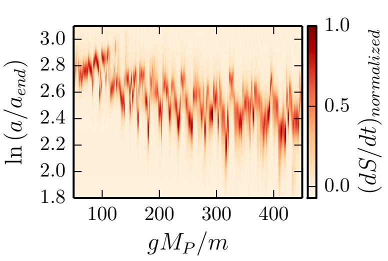
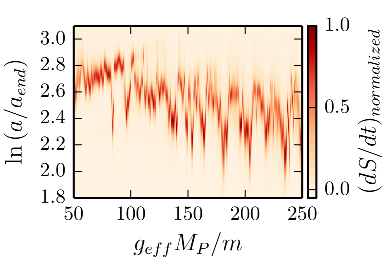


In-Shock Modulation [Bond, **JB**, Frolov, Huang]

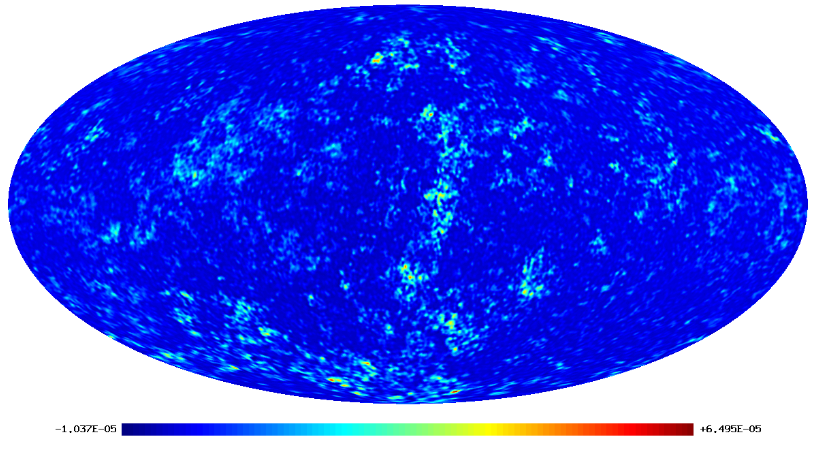


Shock Surface Modulation [Bond, **JB**]





$F_{NL}(\chi)$ on the CMB Sky



[Couresty of Andrei Frolov]

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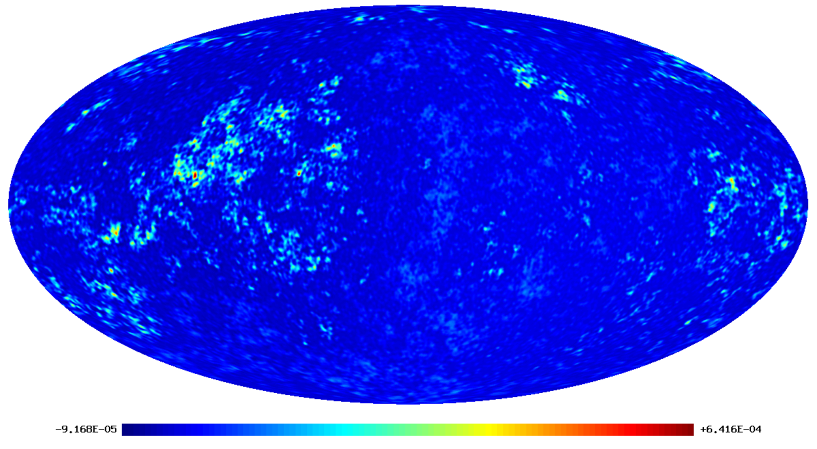

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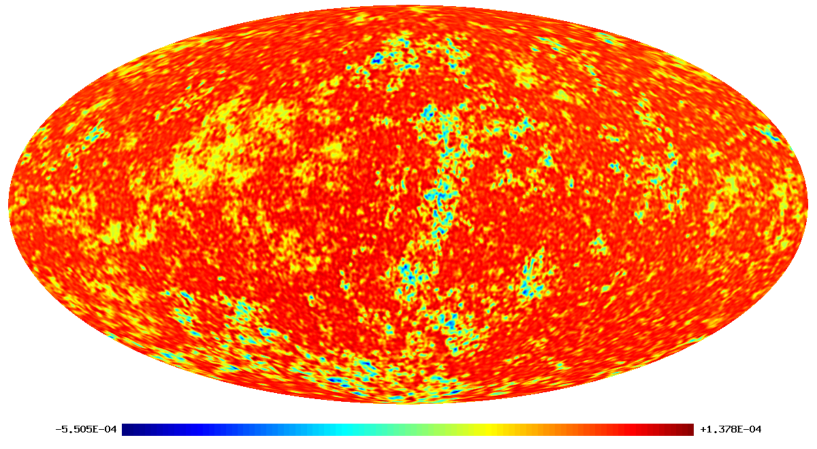

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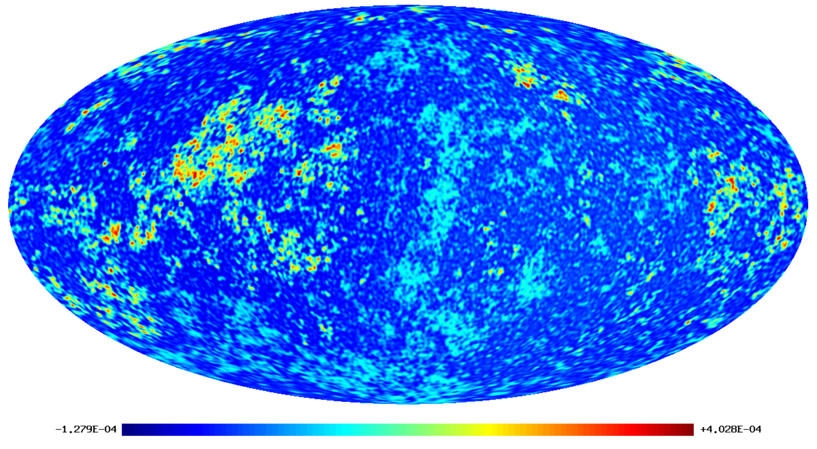

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