Starting the Hot Big Bang

Entropy Generation and Simplicity from Complexity in Nonequilibrium Field Theory

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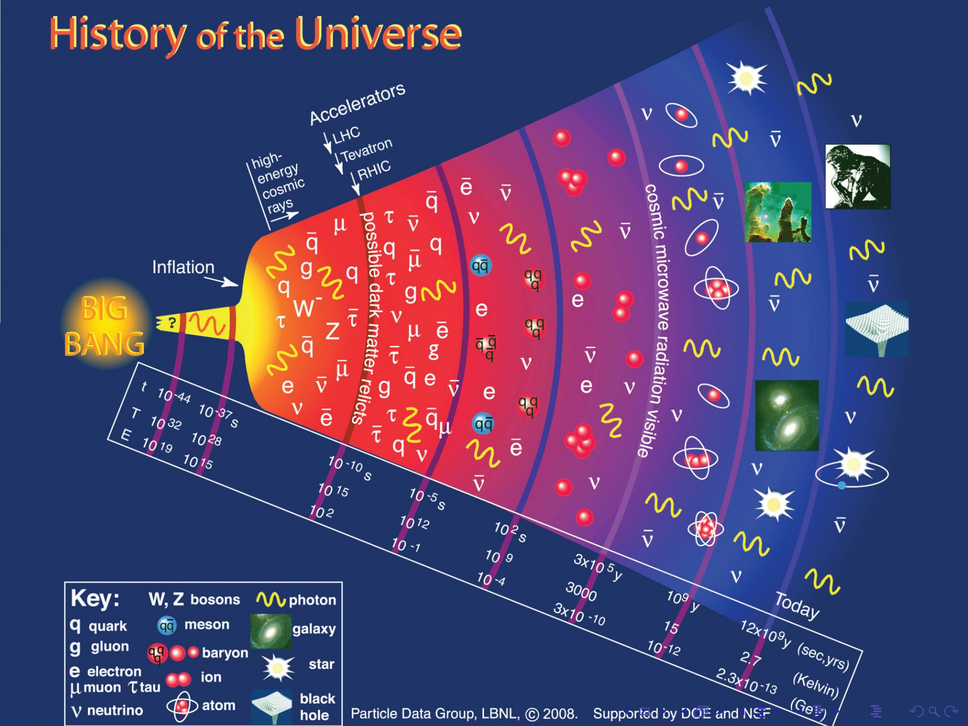
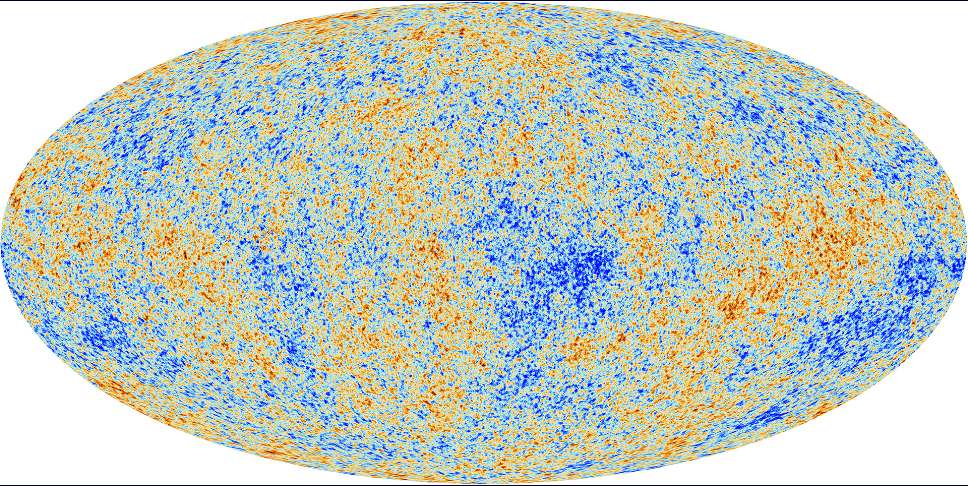
University College London

University of St. Andrews, June 20, 2016

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
t 10 -44 10 -37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 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

Observational Evidence for Inflation



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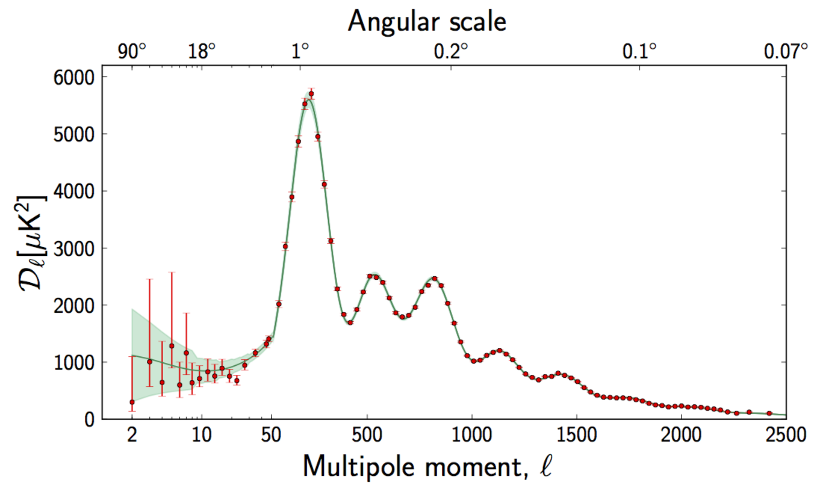
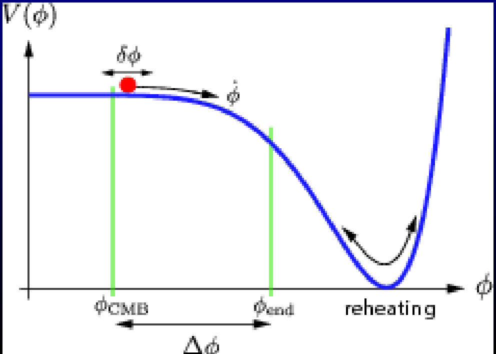


A Theorist's Description of the Universe

Perturbed FRW Metric + Scalar Fields

$$ds^2 = -e^{2\nu(x,t)}dt^2 + a^2(t)e^{2\zeta(x,t)}\left(\delta_{ij} + h_{ij}\right)dx^i dx^j$$

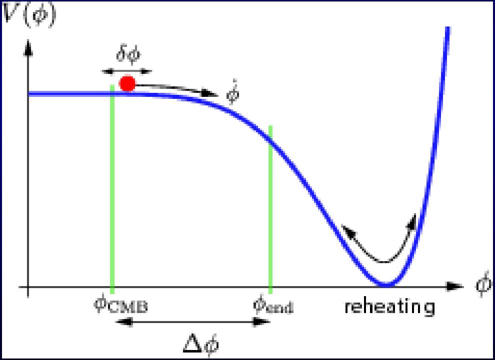
$$\mathcal{L} = \sqrt{|g|}\left(-\frac{G_{IJ}(\phi)}{2}\partial_\mu\phi^I\partial^\mu\phi^J - V(\phi) + \frac{M_P^2}{2}R\right)$$



Leading Order: Homogeneous Evolution

$$ds^2 = -dt^2 + a^2(t)dx^2$$

$$\ddot{\phi}_i + 3H\dot{\phi} + \frac{\partial V}{\partial \phi_i} = 0 \qquad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$



$\ddot{a} > 0 \implies$ inflation

What About Inhomogeneity? Long-Short Split

$$\phi_i = \phi_i^{\text{long}} + \delta\phi_i$$

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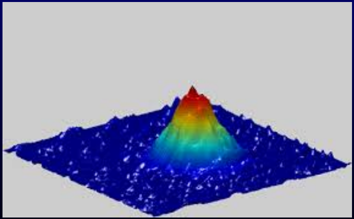
$$\phi_i = \phi_i^{\rm long} + \delta\phi_i$$

$$\phi_i^{\rm long} = \int d^d x' W(x - x')\phi_i(x')$$

$\phi_i^{\rm long}$: $k \lesssim H$ modes

$\phi_i^{\rm long}$ coherent "classical" condensate



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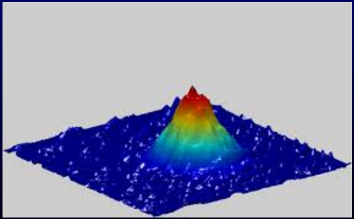
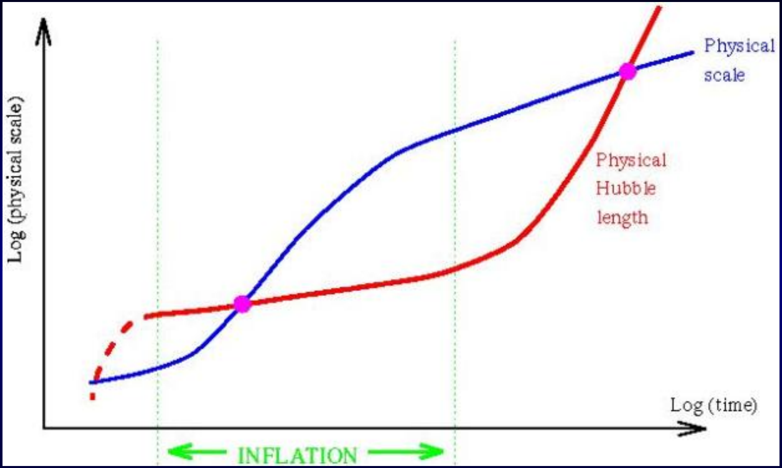
$\phi_i^{\mathrm{long}} : k \lesssim H$ modes
$\delta\phi : k \gtrsim H$ modes

ϕ_i^{long} coherent "classical" condensate
$\delta\phi$ incoherent "quantum" noise

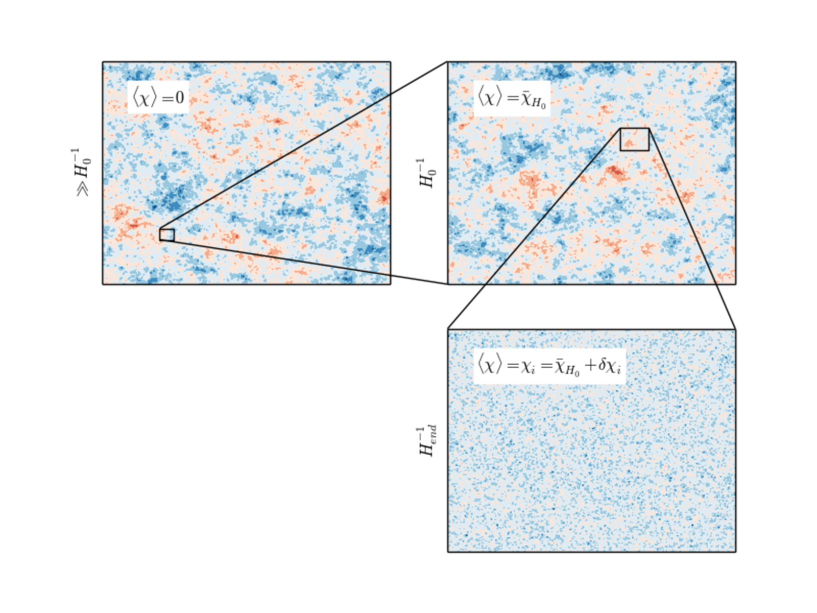


Evolution of Length Scales



Modes exiting horizon act as a noise term on the long-wavelength condensate

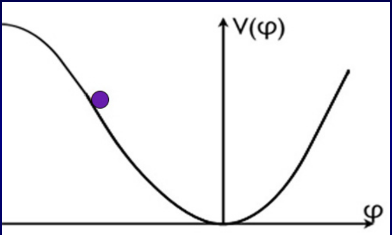
Multiresolution View of the Universe



The Takeaway Message From Inflation

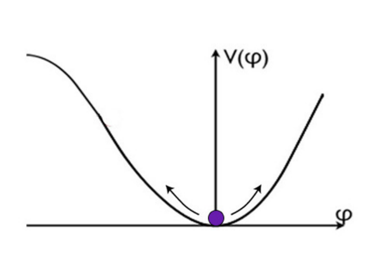
Post-Inflation Universe is Nearly Homogeneous

During Inflation



- Subhorizon Homogeneity
- (Small) Superhorizon Inhomogeneity

End of Inflation



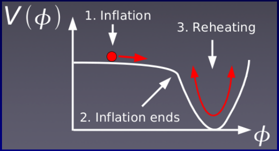
$$\left[\delta\phi, \delta\dot{\phi}\right] \neq 0$$

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

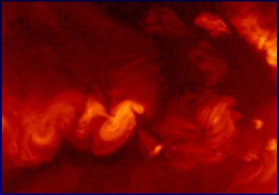
- Variety of instabilities

Starting the Hot 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?

The Cosmic Recipe?

Why Is This Regime Interesting

Theoretical Consistency

- Inflationary cosmology is incomplete without this transition
- Understand nonequilibrium quantum field theory

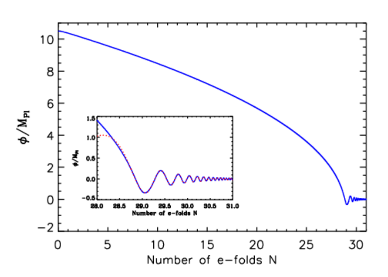
More practical concerns

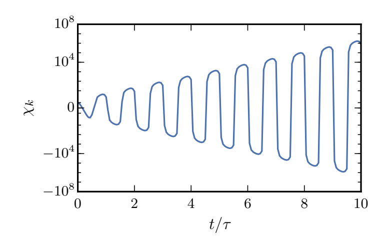
- $N \equiv \ln(a_0/a_{end})$ needed to match observations to inflationary models
- Production of
  - nonGaussian density perturbations [Bond,Frolov,Huang,Kofman],[Rajantie,Chambers]
  - tensors [Easter,Giblin,Lim],[Figueroa,Garcia-Bellido],[Dufaux,Felder,Kofman,Huang]
- Linear structure growth depends on background expansion
- Nonequilibrium - baryogenesis?, nonthermal DM production?

Linear Instability Analysis: Preheating

$$\phi(x,t) = \bar{\phi}(t) + \delta\hat{\phi}(x,t)$$

$$\delta\ddot{\tilde{\phi}}_k + 3H(t)\delta\dot{\tilde{\phi}}_k + m_{\text{eff}}^2(\bar{\phi}(t))_{ij}\delta\phi_j = 0$$



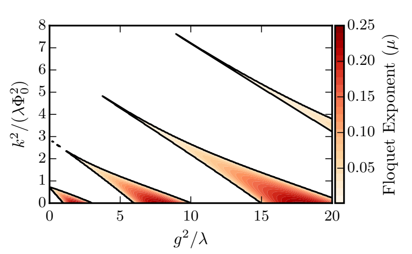


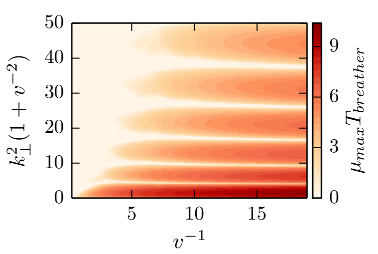
$m_{\text{eff}}^2(t)$ oscillatory

Linear Instability Analysis: Preheating

Floquet Theory for $m^2_{\rm eff}$ approximately periodic

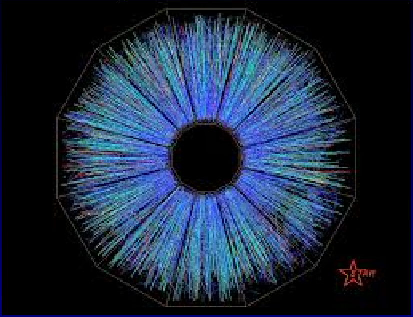
$$\dot{\vec{y}} = \mathbb{M}(t)\vec{y} \qquad \mathbb{M}(t+T) = \mathbb{M}(t)$$

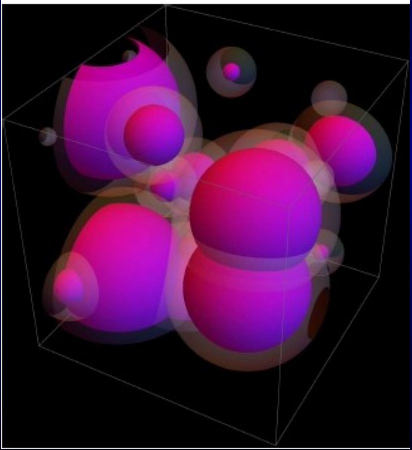




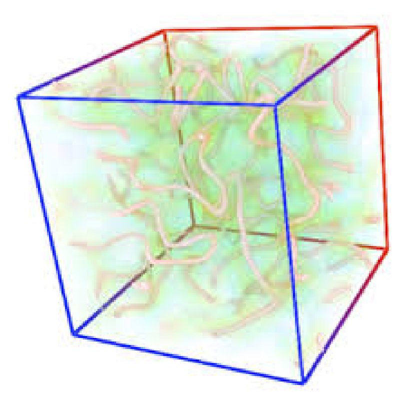
$$\vec{y}(t) = e^{\mu t}\mathbb{P}(t)\vec{y}_0$$

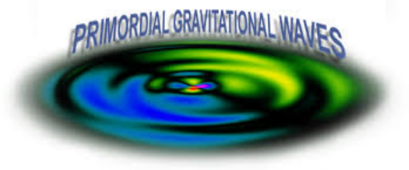
The Many Realms of Nonequilibrium Field Theory

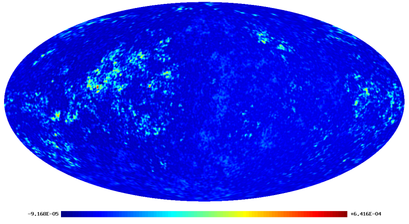




Preheating: A Zoo of Interesting Phenomena







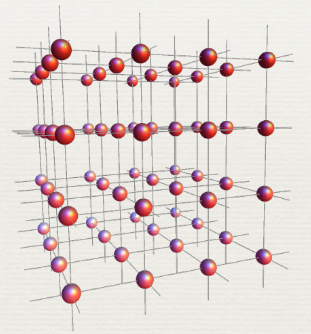
Numerical Approach is Essential [JB, in preparation]

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 $\rightarrow$ realization of random field



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

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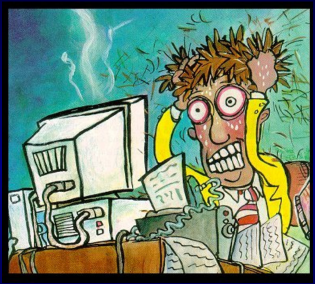

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Developing Complexity of $\ln(\rho/\bar{\rho})$

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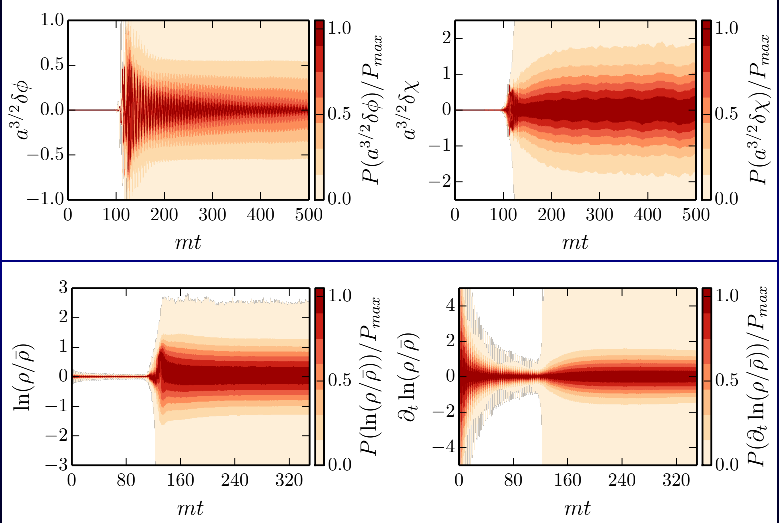
Evolution of Power Spectra of Fluctuations

Evolution of One-Point PDFs



How Do We Characterize This Transition?

Dick Bond **Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity**

recombination

the nonlinear COSMIC WEB

dS_G/dt

I N F L A T I o67 N

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave
- tightly-coupled photon-baryon fluid: oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$
- viscously damped
- polarization $\pi\gamma$
- gravitational redshift

Φ SW $d\Phi/dt$

Type to enter text

dS/dt>0

DarkM

Decoupling LSS

Type to enter text

7

BAO

17 kpc (19 Mpc)

Lsound/ 2 Lsound

secondary anisotropies

- nonlinear evolution
- weak lensing
- thermal SZ +kinetic SZ
- $d\Phi/dt$
- dusty/radio galaxies, dGs

3

2⇓1

CMB LENS

SNIa LENS H0 BAO (z) cls ISW

DarkE

Type to enter text

0

z=0

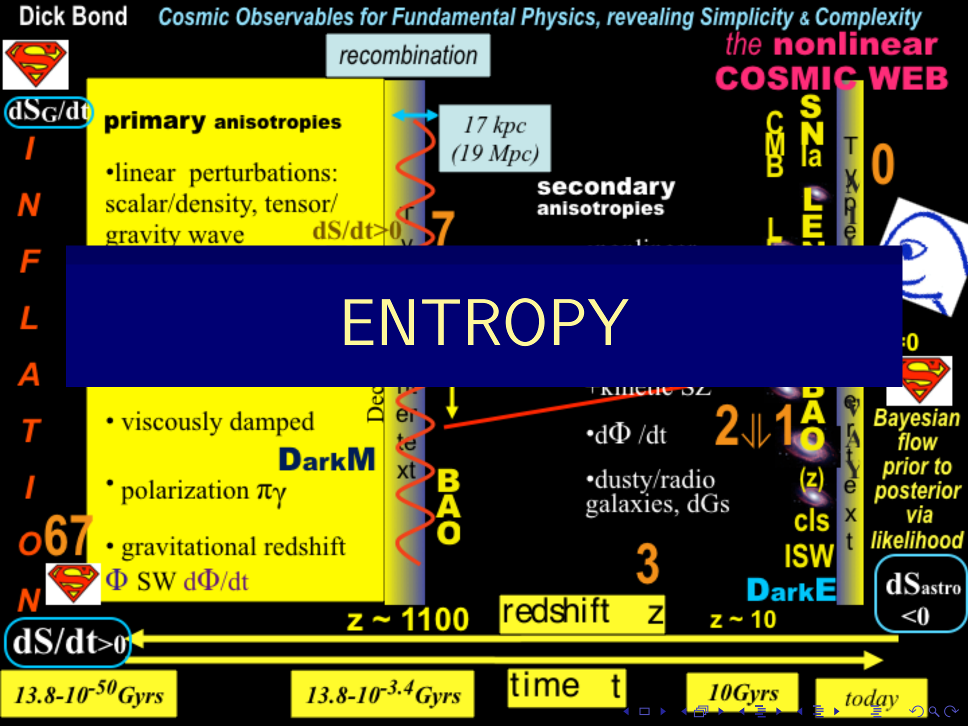
Bayesian flow prior to posterior via likelihood

dS_astro <0

z ~ 1100 redshift z z ~ 10

time t

13.8-10^-50 Gyrs 13.8-10^-3.4 Gyrs 10Gyrs today


Dick Bond
Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity
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dS/dt>0
17 kpc
(19 Mpc)
secondary anisotropies
7
ENTROPY
INFLATION
o67
• viscously damped
DarkM
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
BAO
•dΦ /dt
•dusty/radio galaxies, dGs
2⇓1
3
CMB
SN Ia
LEN
BAO(z)
cls
ISW
DarkE
0
Bayesian flow prior to posterior via likelihood
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
13.8-10^-50 Gyrs
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time t
10Gyrs
today

Entropy and Information

Shannon Entropy

$$S_{shannon} \equiv -\int \mathcal{D}\varphi f[\varphi] \ln f[\varphi]$$

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

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2. What fields φ should we use?

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Approximating $f[\varphi]$: Maximum Entropy Coarse Graining

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

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

Same as entropy of a Gaussian Random Field with same covariance

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

$\frac{dS}{dt} = 0$ for linear fluctuation evolution of canonical fields

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Homogeneous Field

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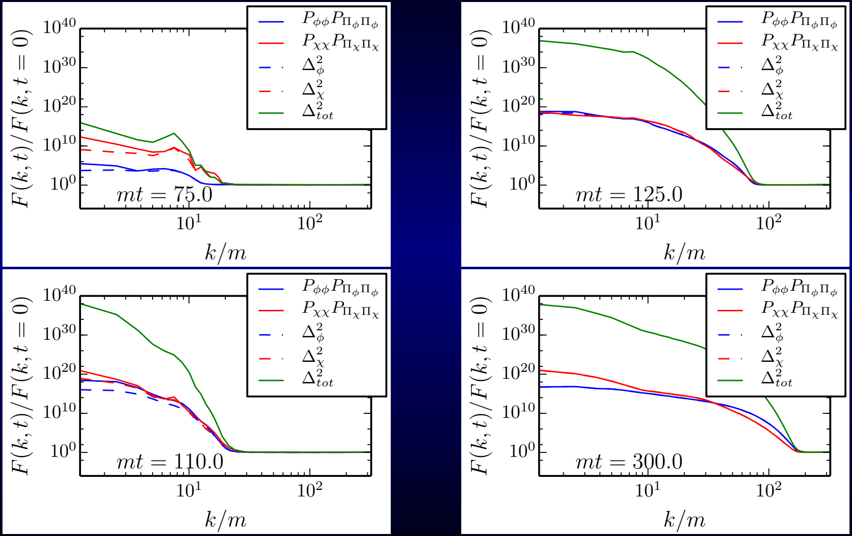
Evolution of Determinants: Fundamental Fields



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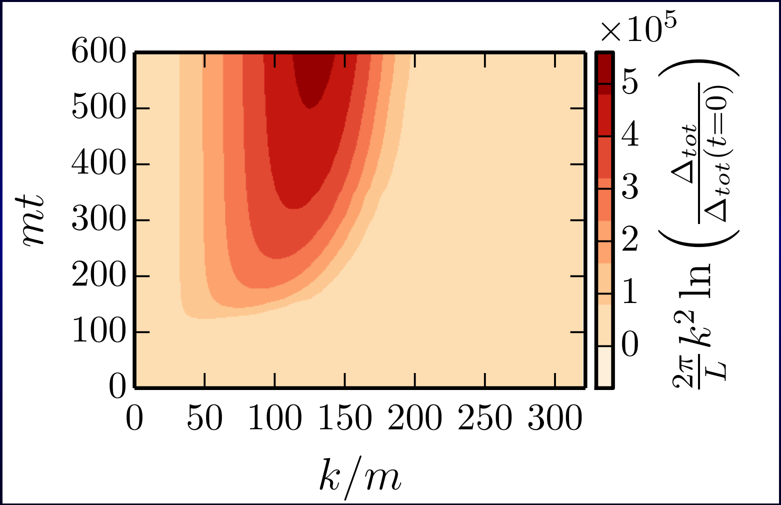
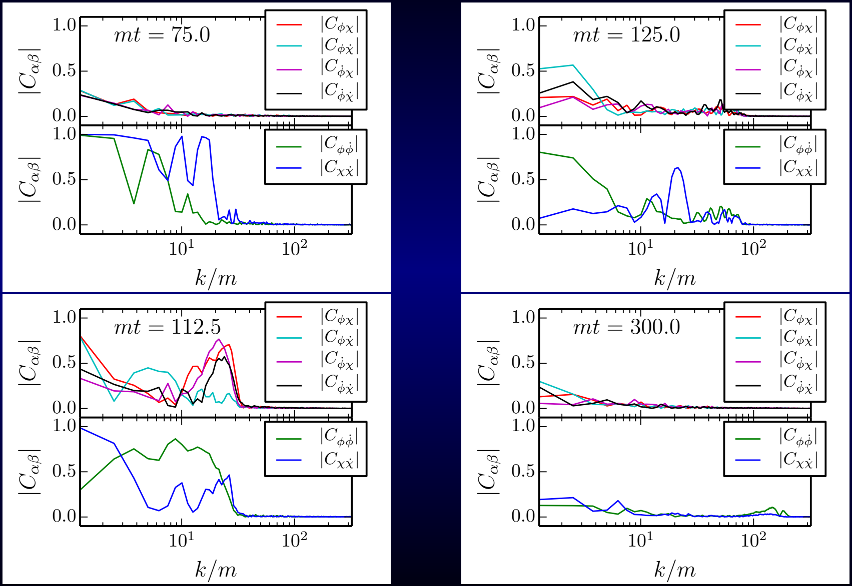
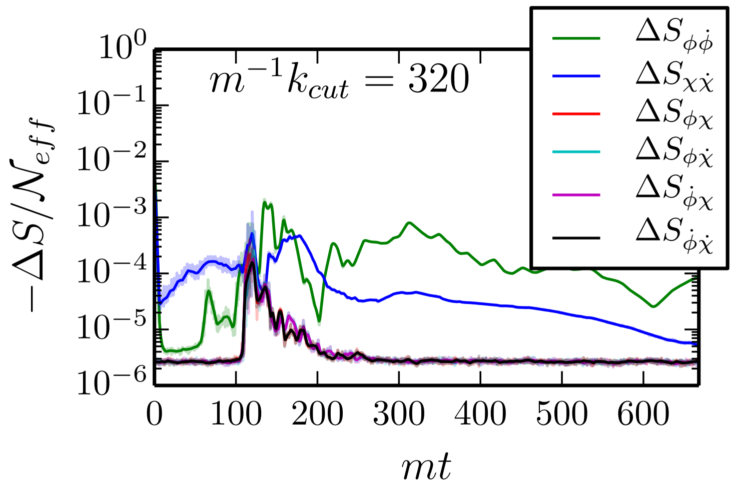


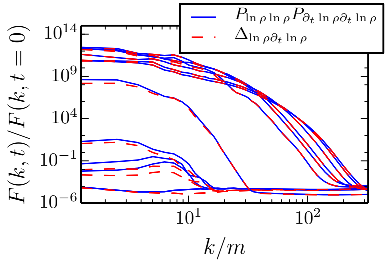
Information Stored In Cross-Correlations

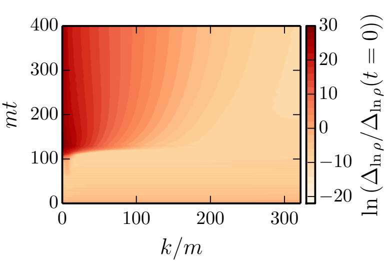


Information Content of Cross-Correlations



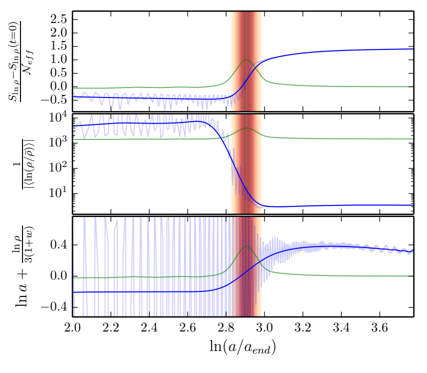
Evolution of Determinants: Phonons

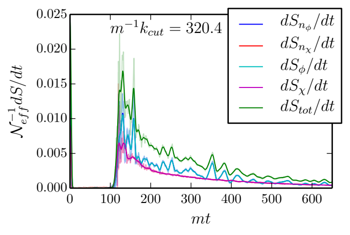




The Shock-in-Time

$\ln \rho$ Phonon DOF





Field DOF

The Shock-in-Time

The Analogy

Spatial Shock

- $v_{bulk}^2 > c_s^2 \rightarrow v_{bulk}^2 < c_s^2$
- Characteristic spatial scale
- Mediated by viscosity or collisionless dynamics
- Randomizing : shock front ΔS
- Post-shock evolution towards thermalization
- Jump in conserved quantities
- Timelike surface

Shock-in-Time

- $ln(\frac{\rho}{\bar{\rho}})^{-1} \gg 1 \rightarrow \ln(\frac{\rho}{\bar{\rho}})^{-1} \sim 1$
- Characteristic time scale
- Mediated by gradients and nonlinearities
- Randomizing : cascade/part. production ΔS
- Slow post-shock evolution
- Jump in $a^{3(1+w)}\rho$
- Can be spacelike surface

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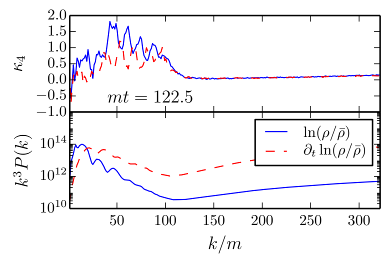
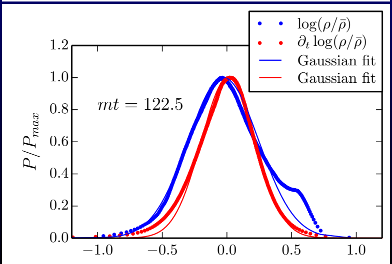
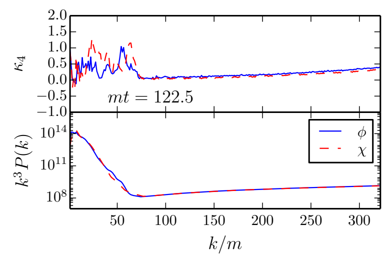
What is φ - Phonons as Collective Variables : In Shock

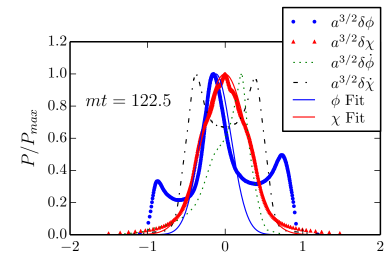
$\ln \rho$ Phonons





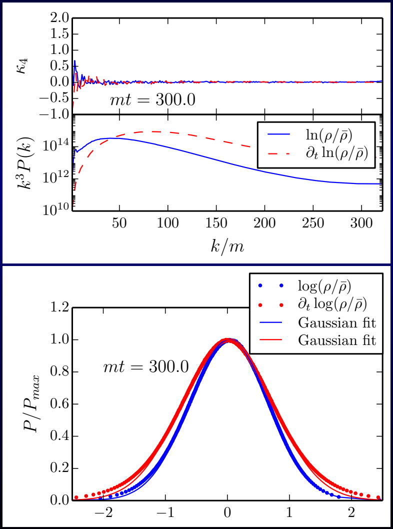
Fundamental Fields





What is φ - Phonons as Collective Variables : Post Shock

$\ln \rho$ Phonons



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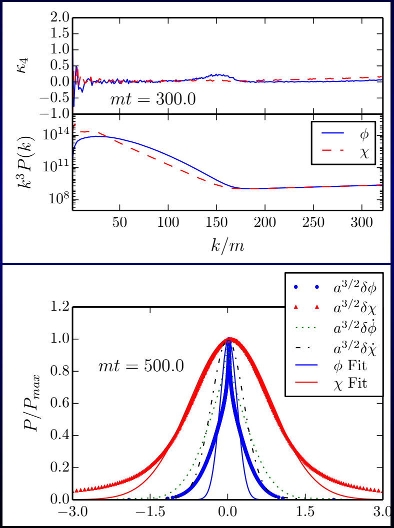
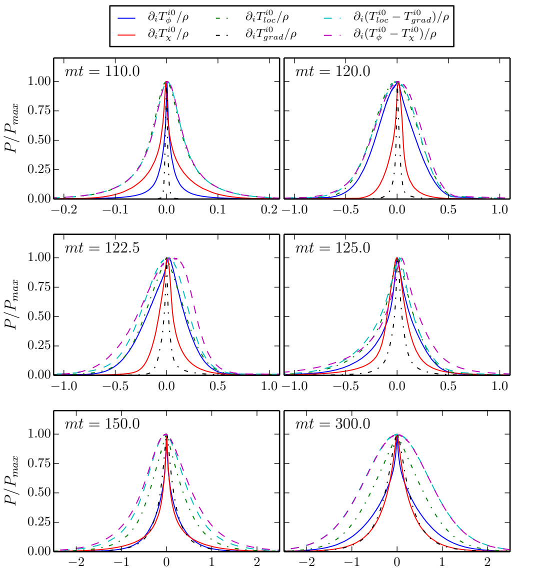
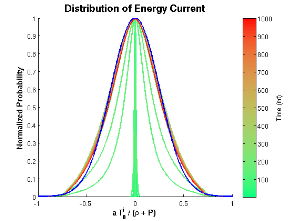
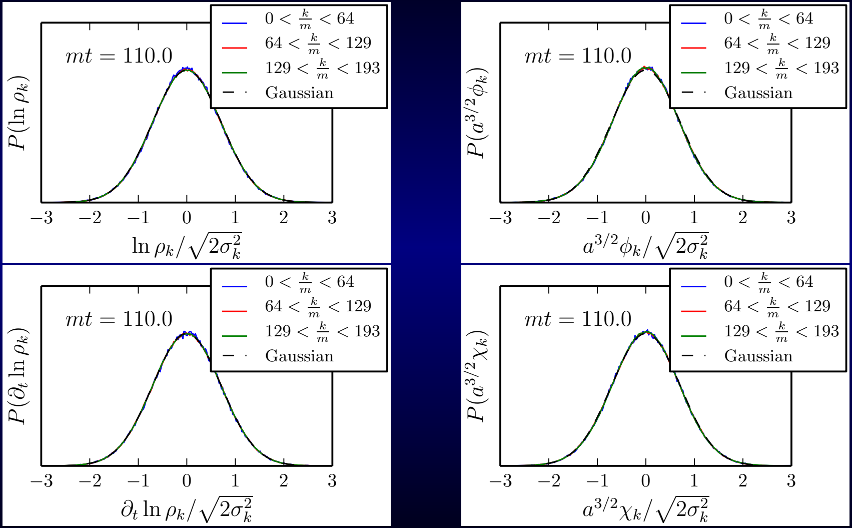


Fluid-Like Description

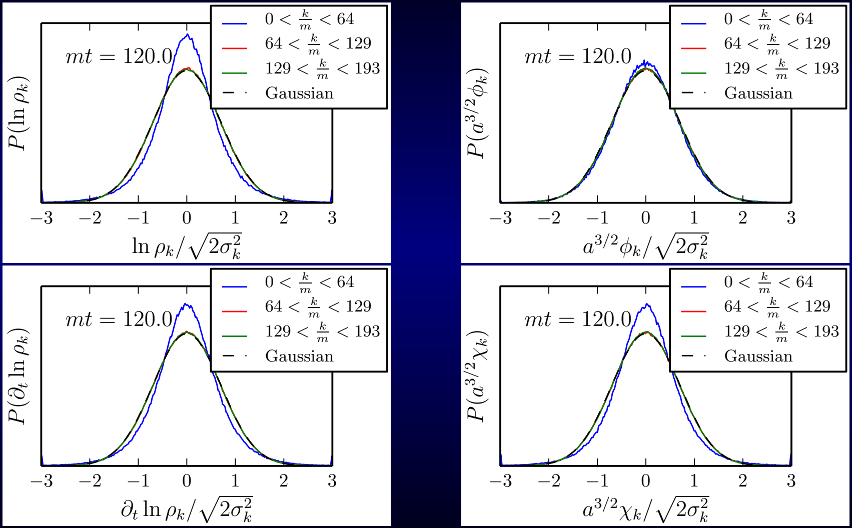




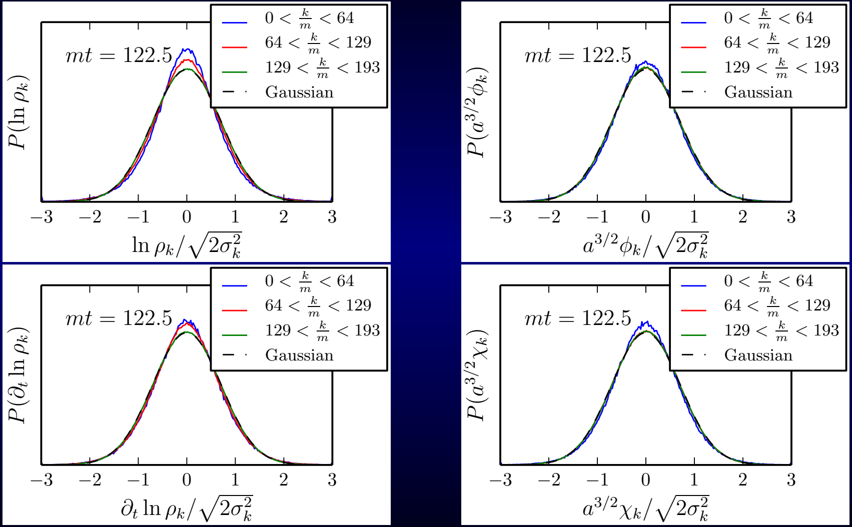
Fourier Mode Distributions: Pre-Shock



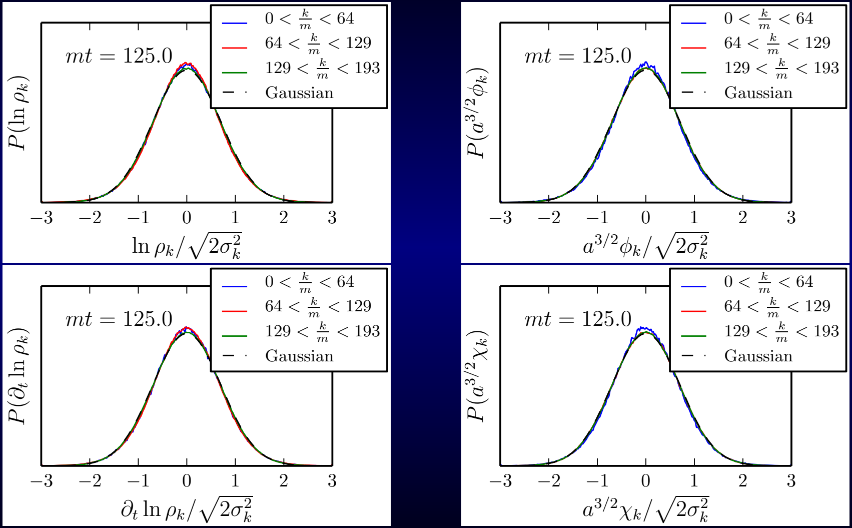
Fourier Mode Distributions: In-Shock



Fourier Mode Distributions: In-Shock



Fourier Mode Distributions: Post-Shock



Entropy and Information

Entropy : Expectation Value of Information

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

Relative Entropy (KL-Divergence) - Continuum Variables

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

1. What is $f[\varphi]$? (MaxEnt Coarse Graining)
2. What fields φ should we use?
3. What is Q?

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3. What is Q? (phase space partitioning)

Approximating $f[\varphi]$: Maximum Entropy Coarse Graining

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

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

Same as entropy of a Gaussian Random Field with same covariance

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

$\frac{dS}{dt} = 0$ for linear fluctuation evolution of canonical fields

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

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

Same as entropy of a Gaussian Random Field with same covariance

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

$\frac{dS}{dt} = 0$ for linear fluctuation evolution of canonical fields

NonCanonical Variables and Phase Space Discretisation

Q represents partitioning of phase space

Choice of Phase Space Discretisation and Quantum Theory

$$C^{\text{quantum}}_{\vartheta,\varphi}(x,y) = \left\langle \hat{\vartheta}(x)\hat{\varphi}(y) \right\rangle = \frac{1}{2}\left\langle \left\{ \hat{\vartheta}, \hat{\varphi} \right\} \right\rangle + \frac{1}{2}\left\langle \left[\hat{\vartheta}, \hat{\varphi} \right] \right\rangle = C^{\text{S}} + C^{\text{A}}$$

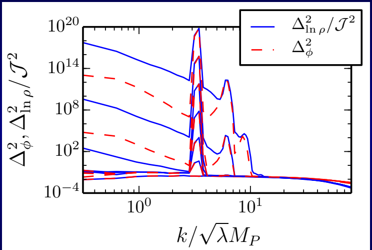
$$[\hat{A},\hat{B}] \equiv \hat{A}\hat{B} - \hat{B}\hat{A} \text{ and } \{\hat{A},\hat{B}\} = \hat{A}\hat{B} + \hat{B}\hat{A}$$

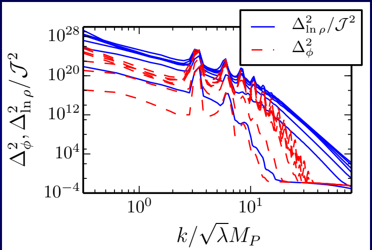
Semi-Classical Limit $\hbar \to 0$

$$C^S \to C^{\text{classical}}_{\vartheta,\varphi}$$

$$C^A \to \left\langle \left\{ \hat{\vartheta}, \hat{\varphi} \right\}_{PB} \right\rangle = \left\langle \left| \frac{\partial(\varphi)}{\partial(\varphi_{\text{can}})} \right|^2 \right\rangle$$

Accounting for NonCanonical Nature





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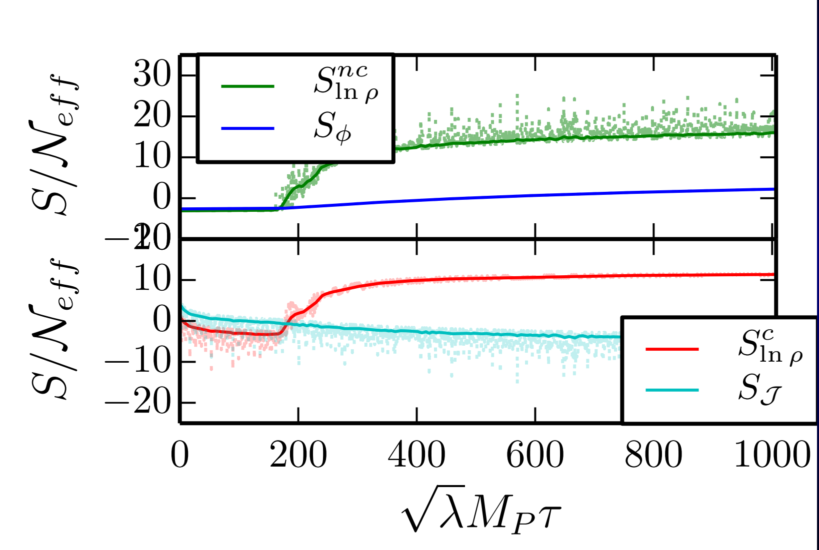
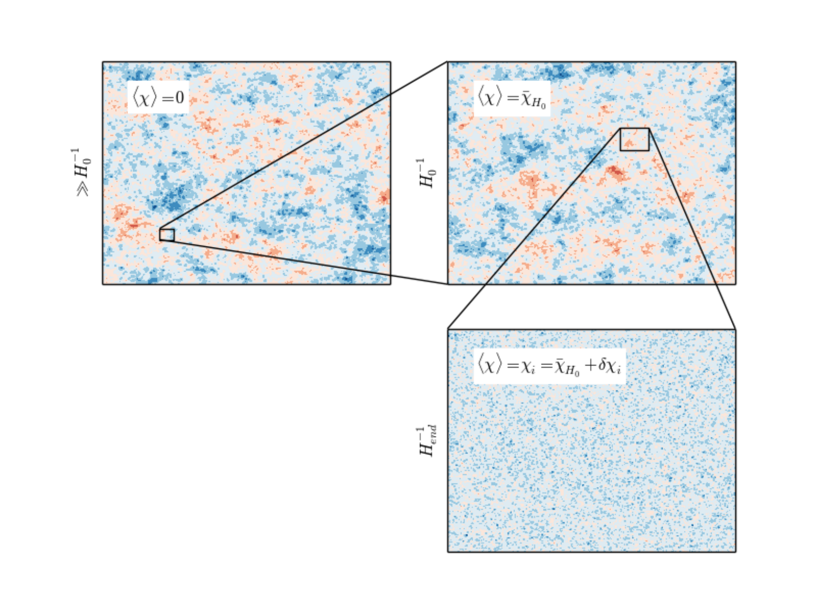
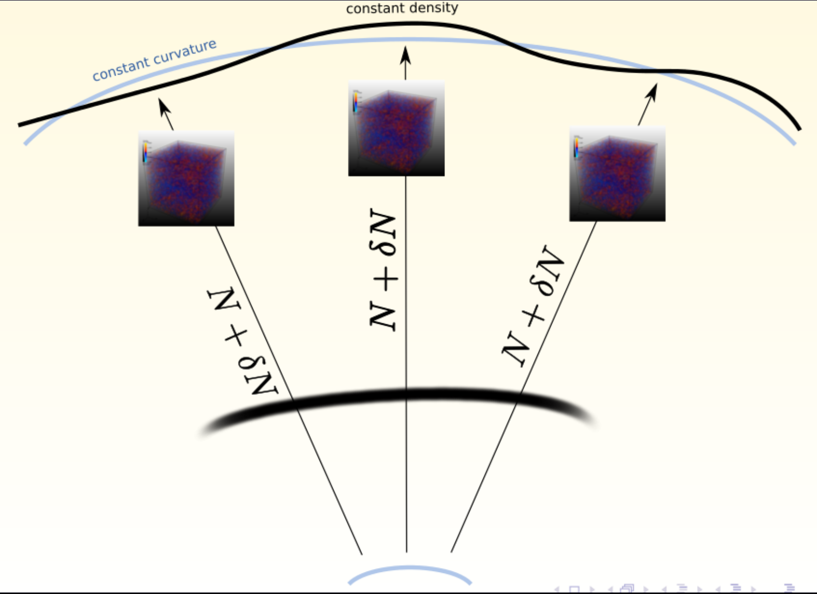


Density Perturbations from the Shock-in-Time

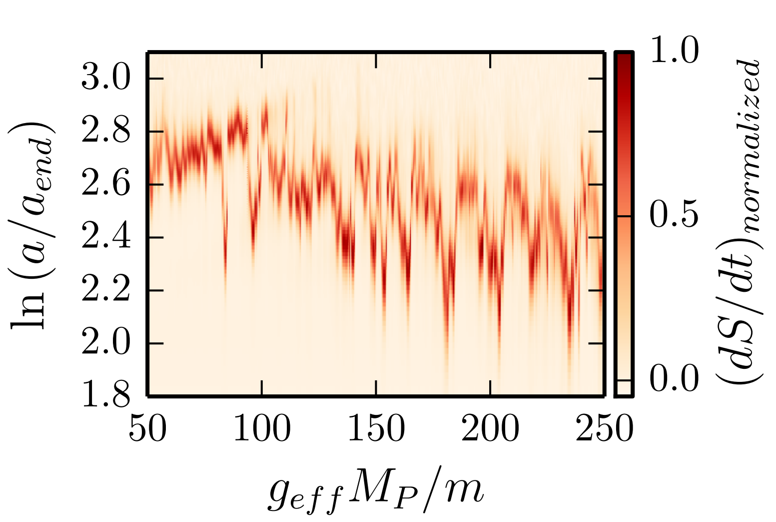
Ultra Large Scale Modulating Isocurvature Field



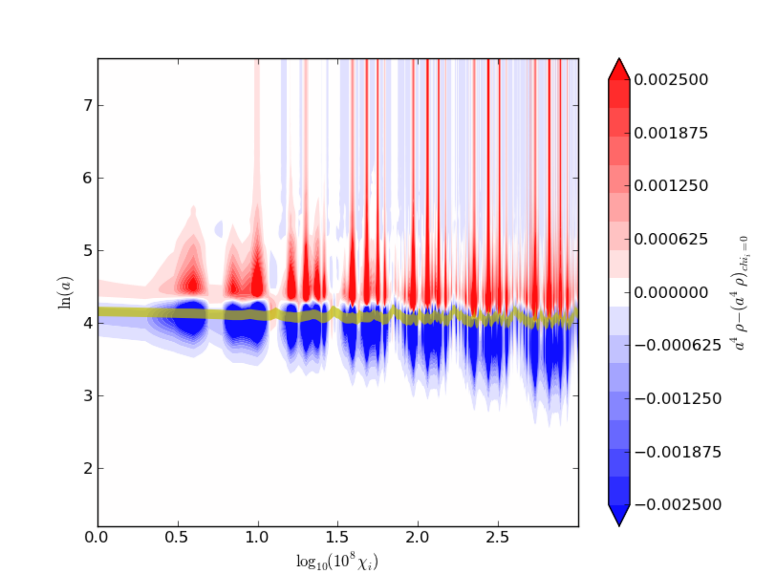
$$\zeta = \zeta_{\text{inf}} + F_{NL}(\chi) \qquad \zeta = (\delta \ln a)\,|_{\rho}$$



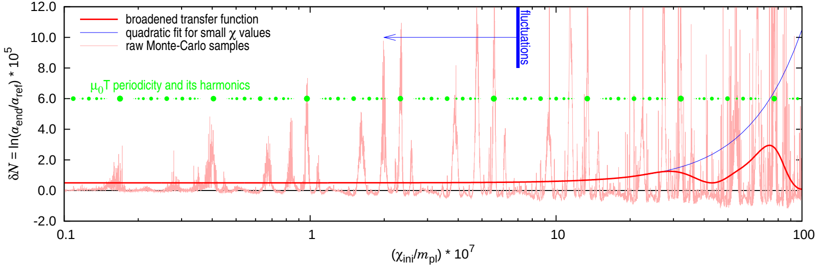
Dependence of Shock on Model Parameters: Coupling Constants



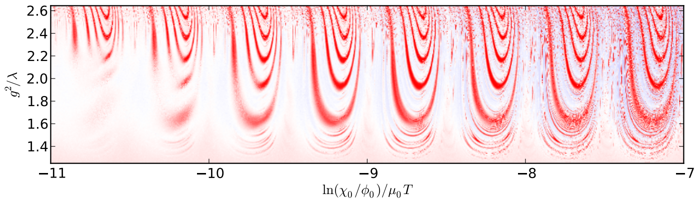
Dependence of Shock on Model Parameters: Initial Fields



Density Perturbations



Dependence of Density Perturbations on Parameters



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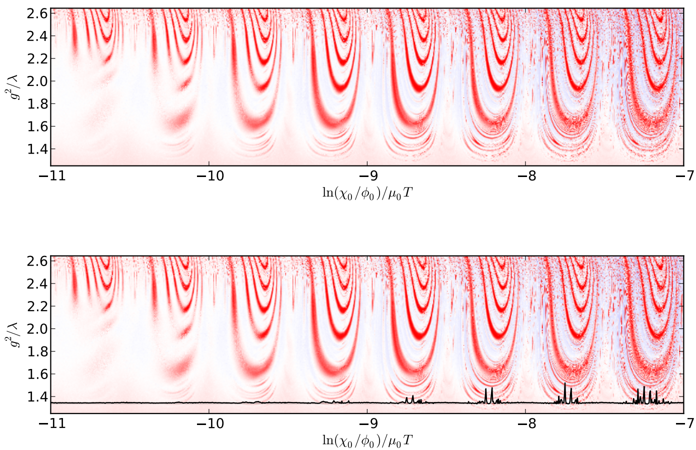

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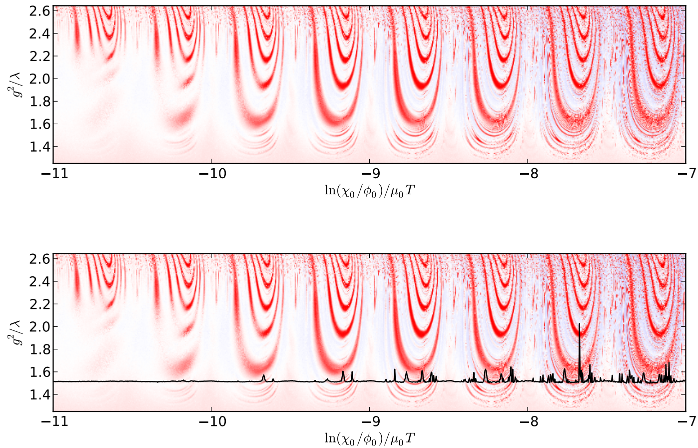

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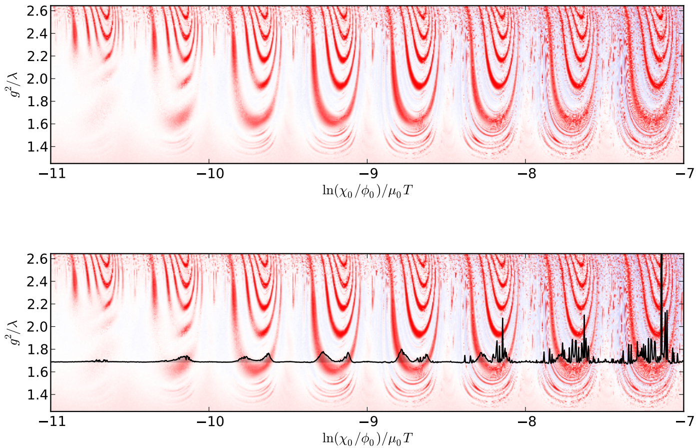

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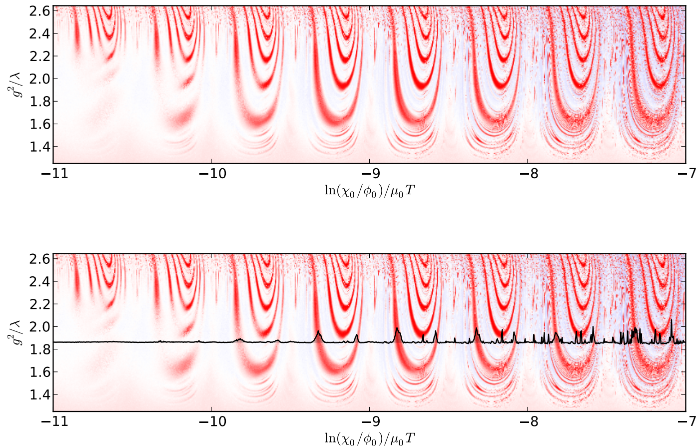

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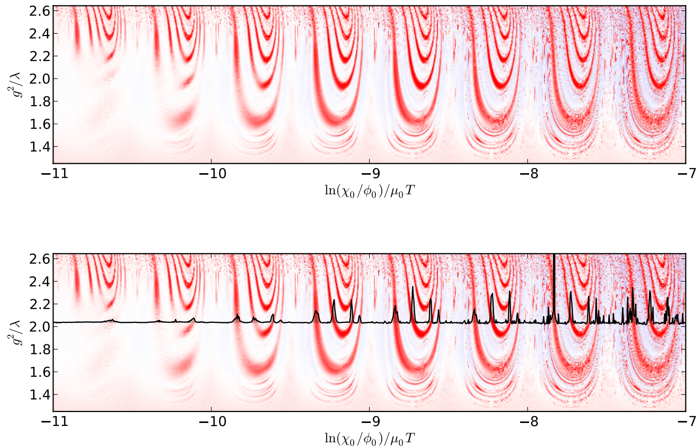

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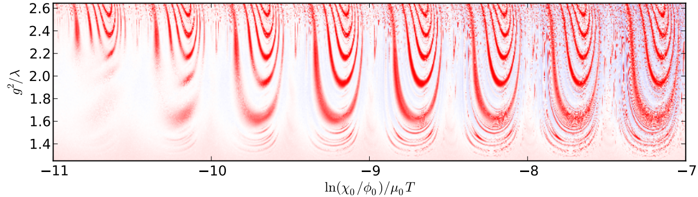

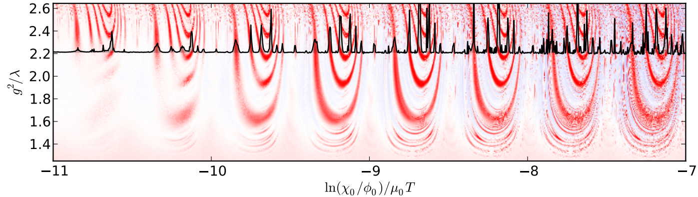

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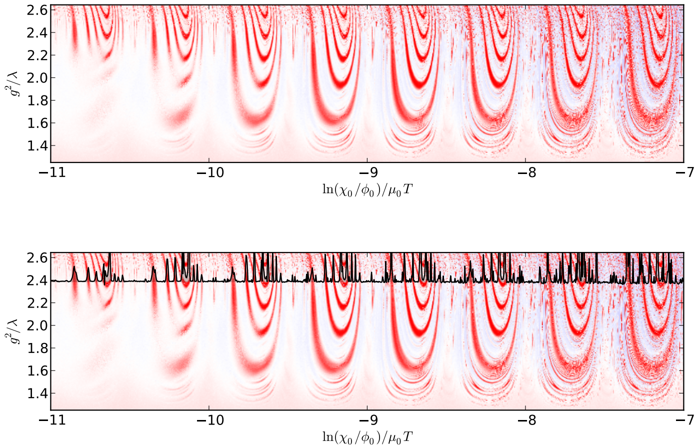
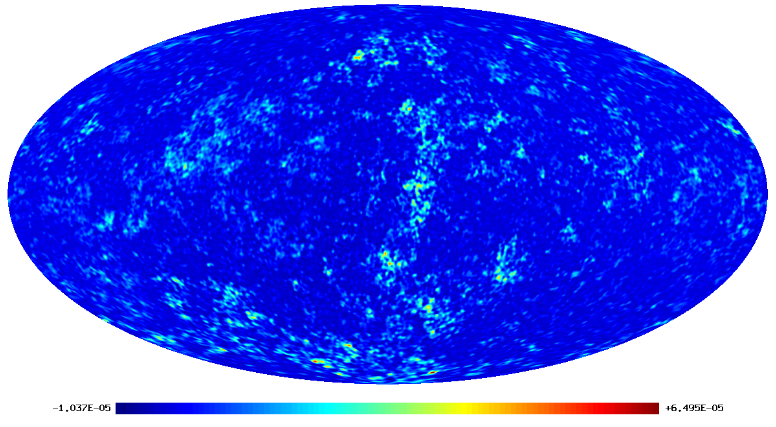
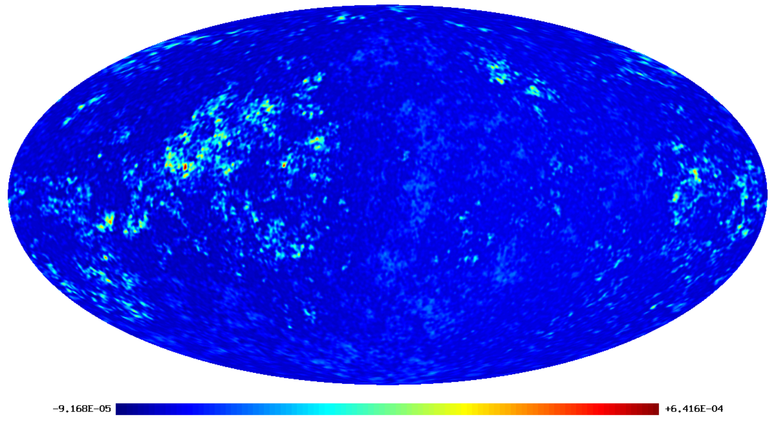


The Shock-in-Time on the CMB Sky



The Shock-in-Time on the CMB Sky



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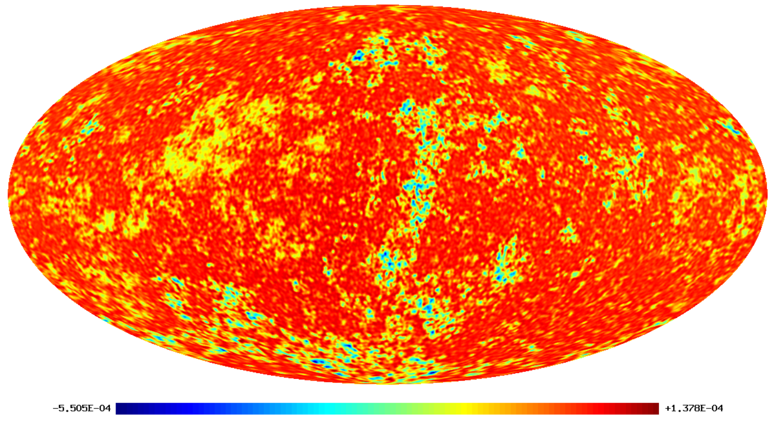

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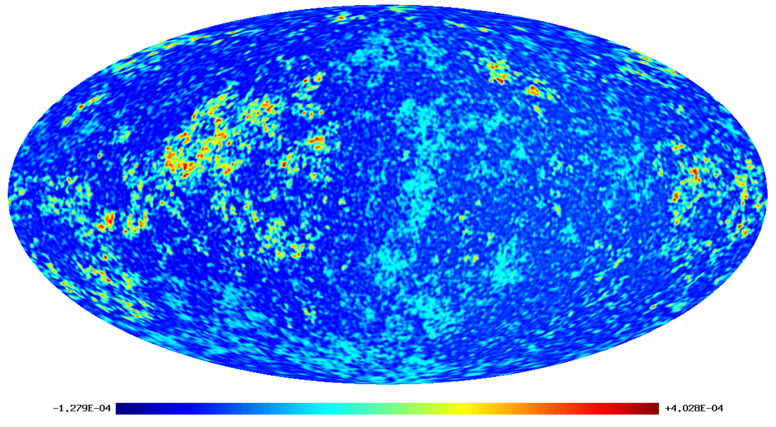

Conclusions

- Inflation is a crucial ingredient in modern cosmology, confirmed by CMB observations
- The inflationary phase *must* end, the stage of (p)reheating
- Leads to highly nonthermal slowly evolving state
- Transition characterised by short burst of entropy production
- Many interesting dynamical phenomena