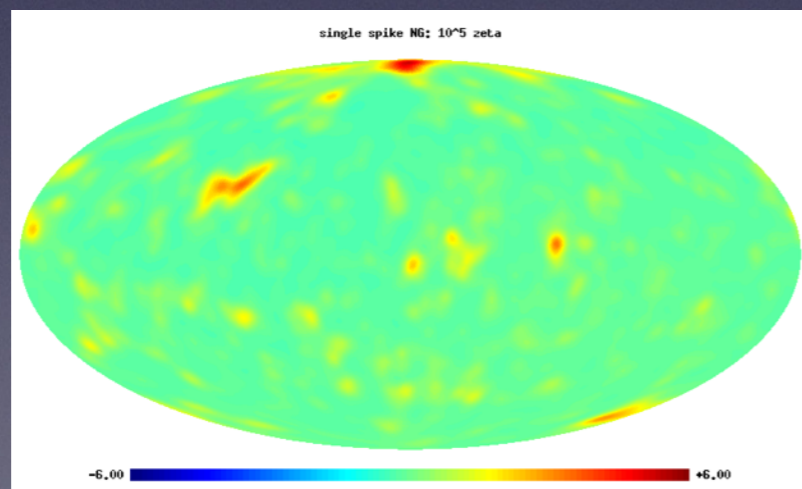


# NonGaussian Curvature Perturbations from Entropy Generation on Cosmic Trajectories

**JONATHAN BRADEN**

CITA (Canadian Institute for Theoretical Astrophysics)

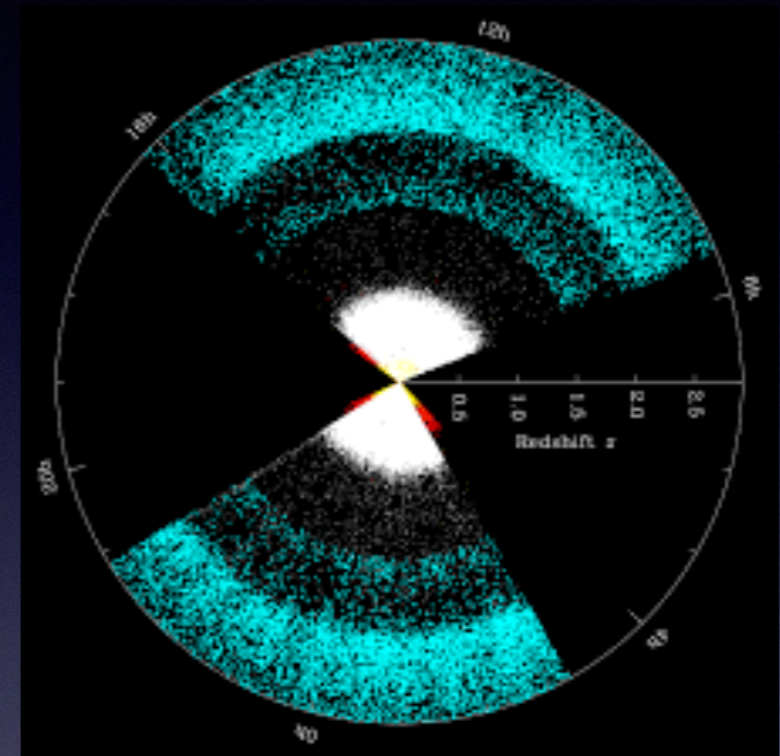
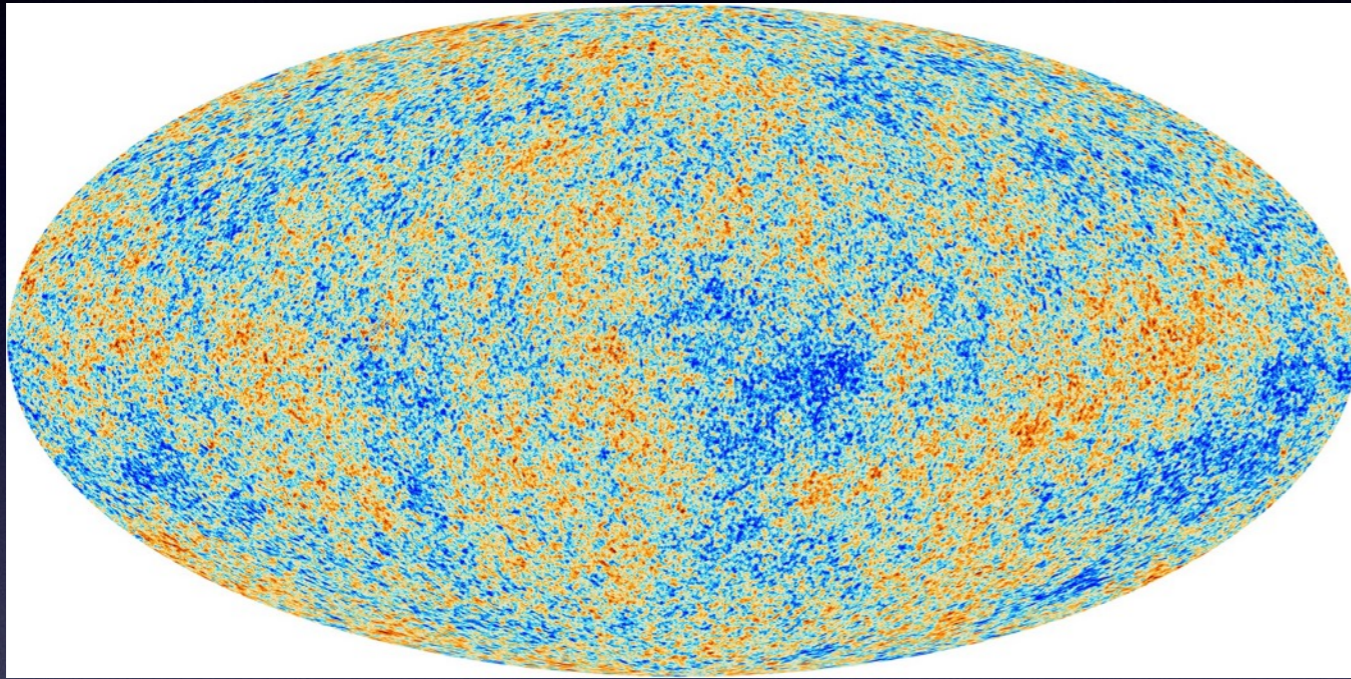
[www.cita.utoronto.ca/~jbraden](http://www.cita.utoronto.ca/~jbraden)



Work with  
*Dick Bond, Andrei Frolov,  
Zhiqi Huang, Thomas Morrison*

COSMO 19, Aachen, Germany, September 2, 2019

# Inflation and Cosmology



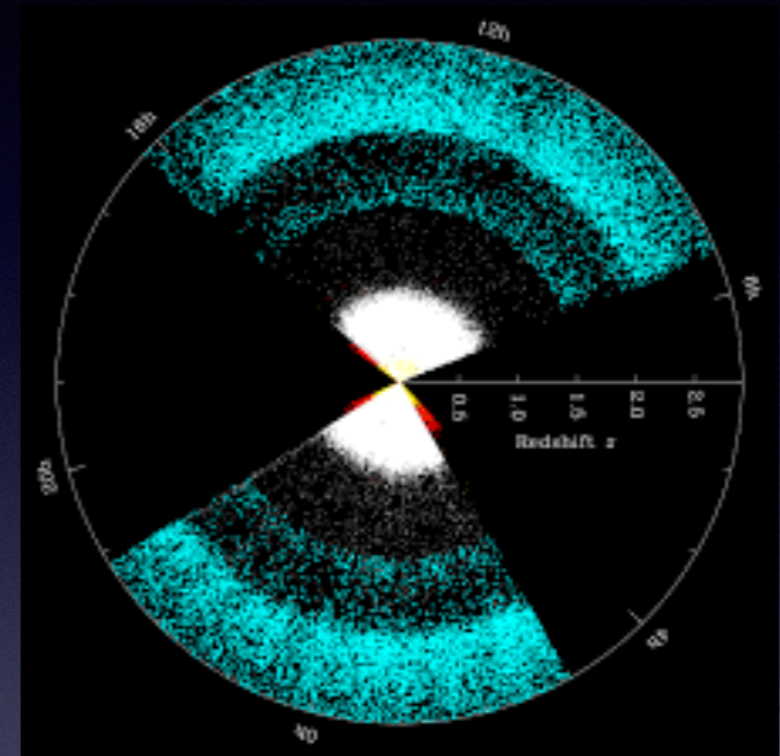
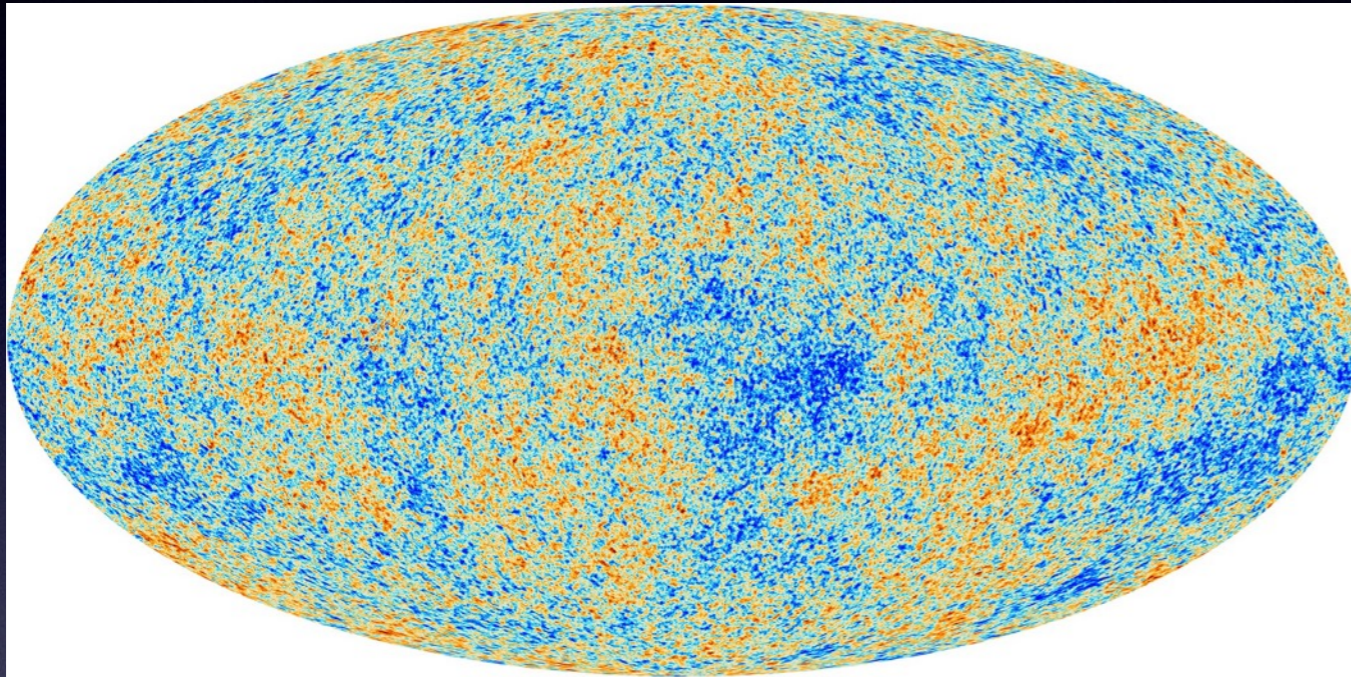
**Standard Inflation: Models a few parameters**

$$P_s(k) = A_s k^{n_s - 1}$$

$$r = 16\epsilon$$

$$f_{\text{NL}}$$

# Inflation and Cosmology



**Standard Inflation: Models a few parameters**

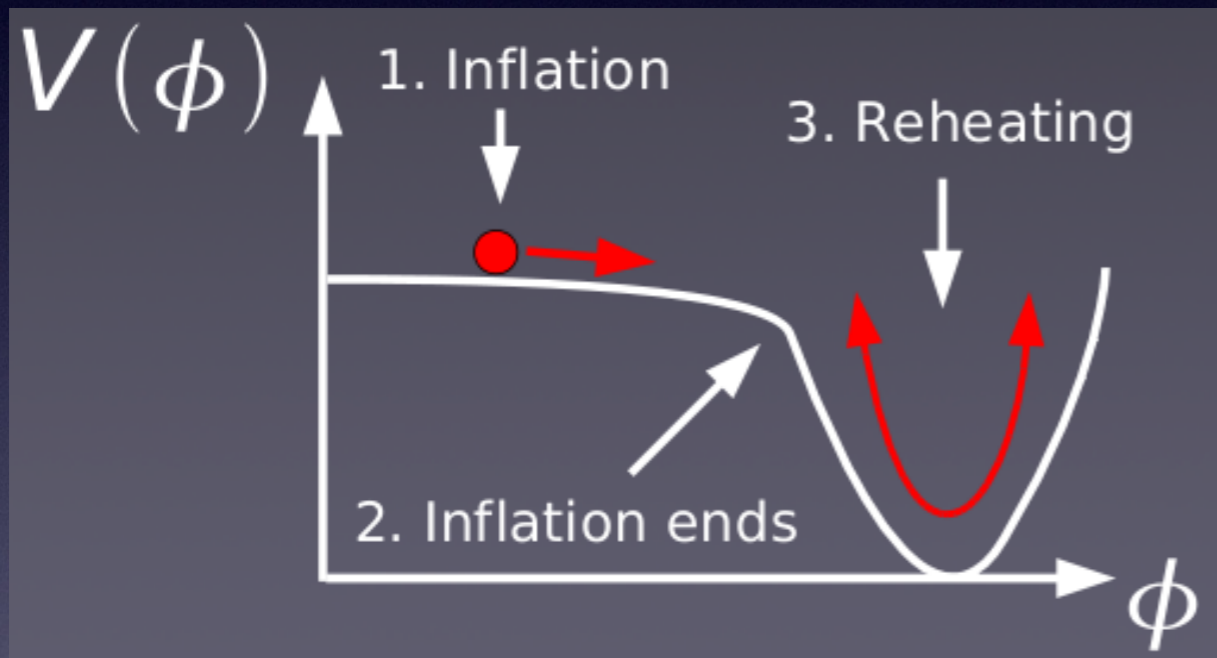
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$$r = 16\epsilon$$

$f_{\text{NL}}$

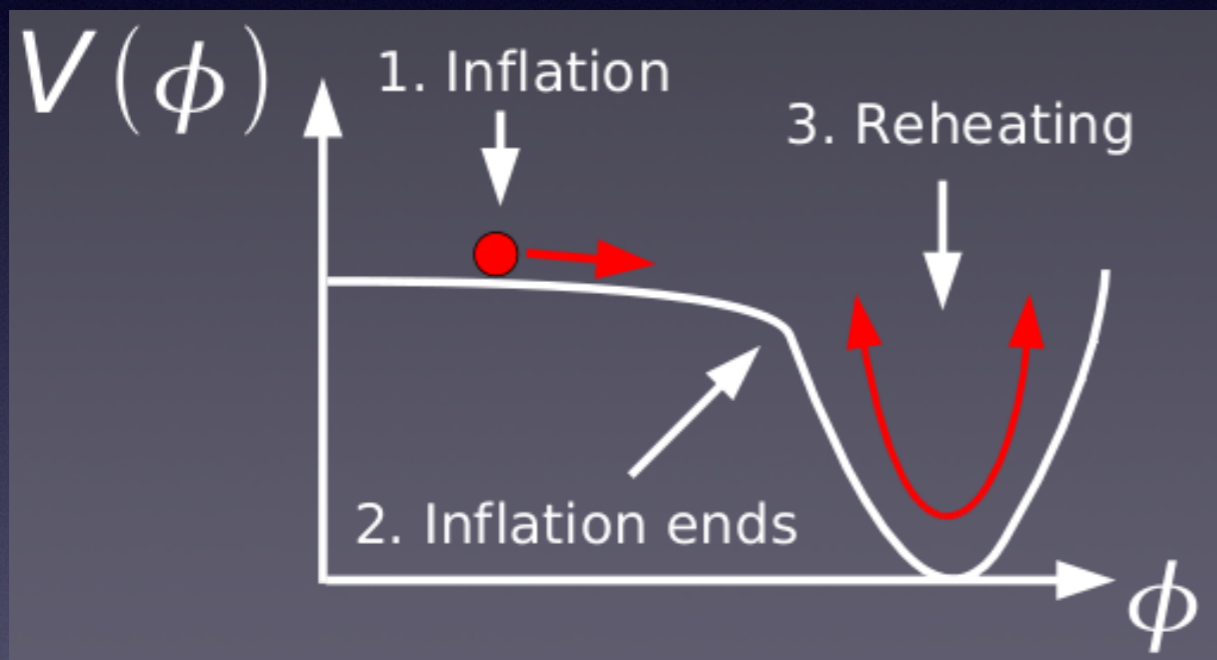
**Perturbative  
NonGaussianity**

# What is the Inflaton?



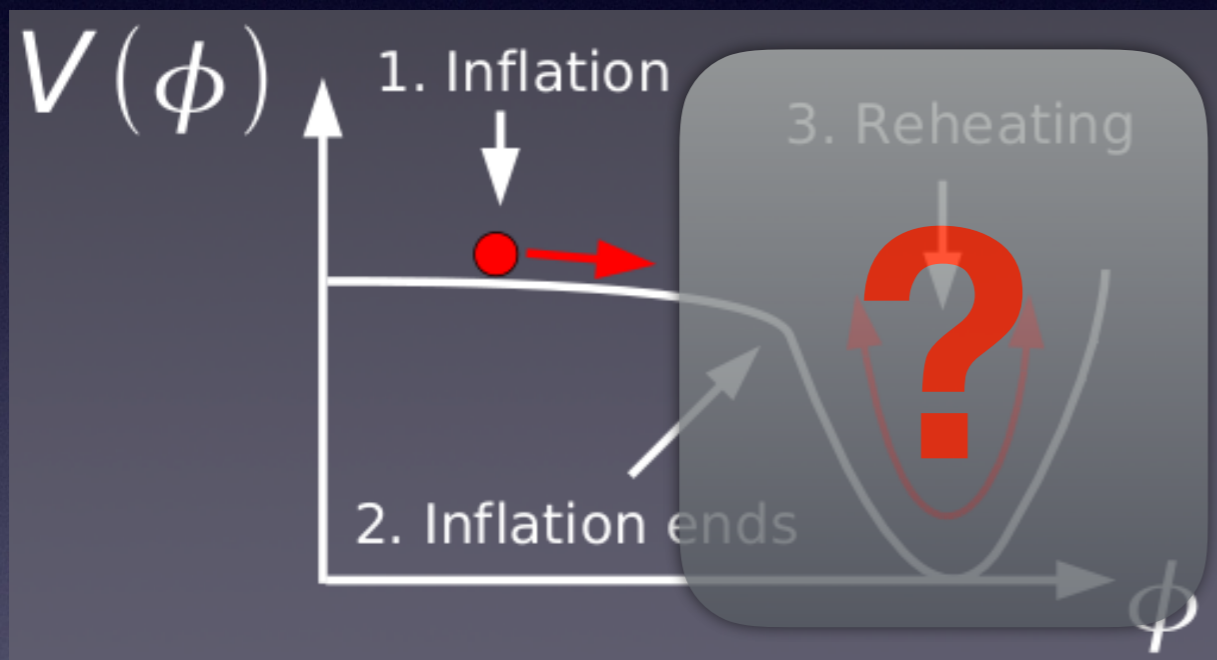
# What is the Inflaton?

Observations



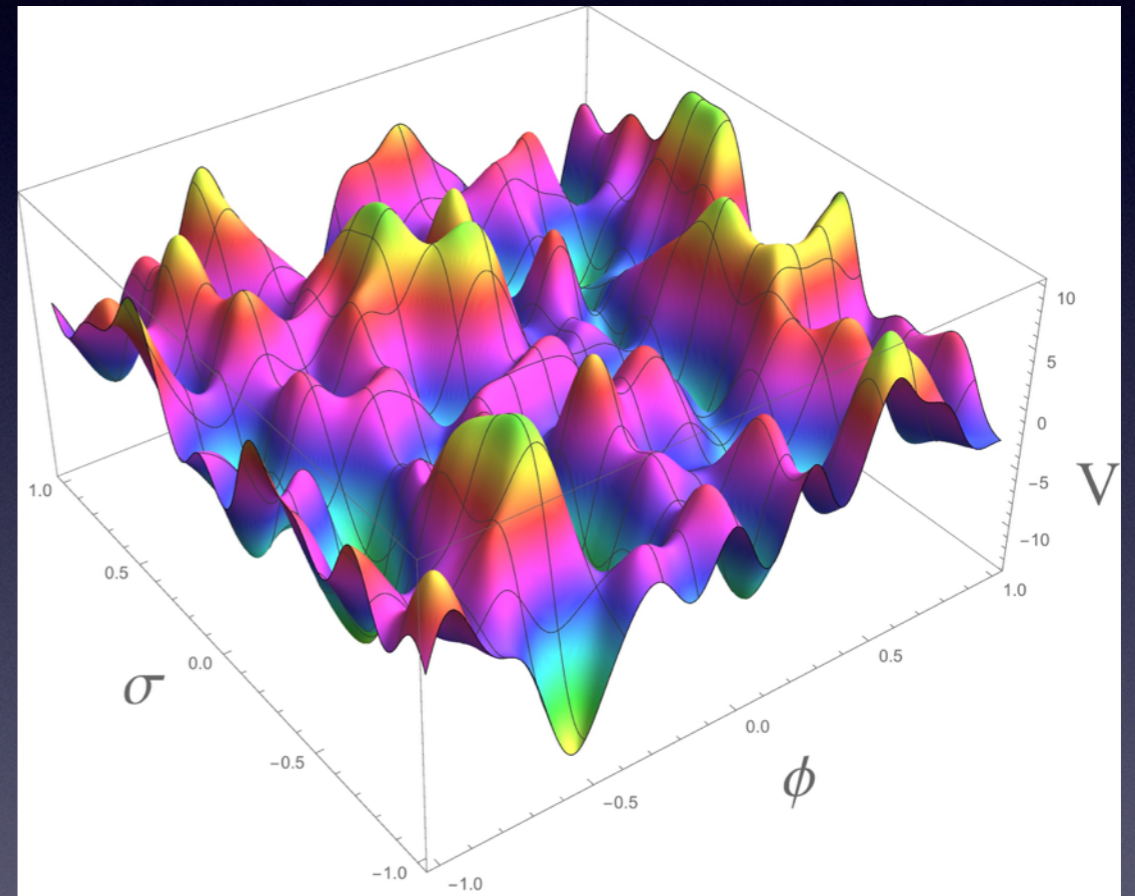
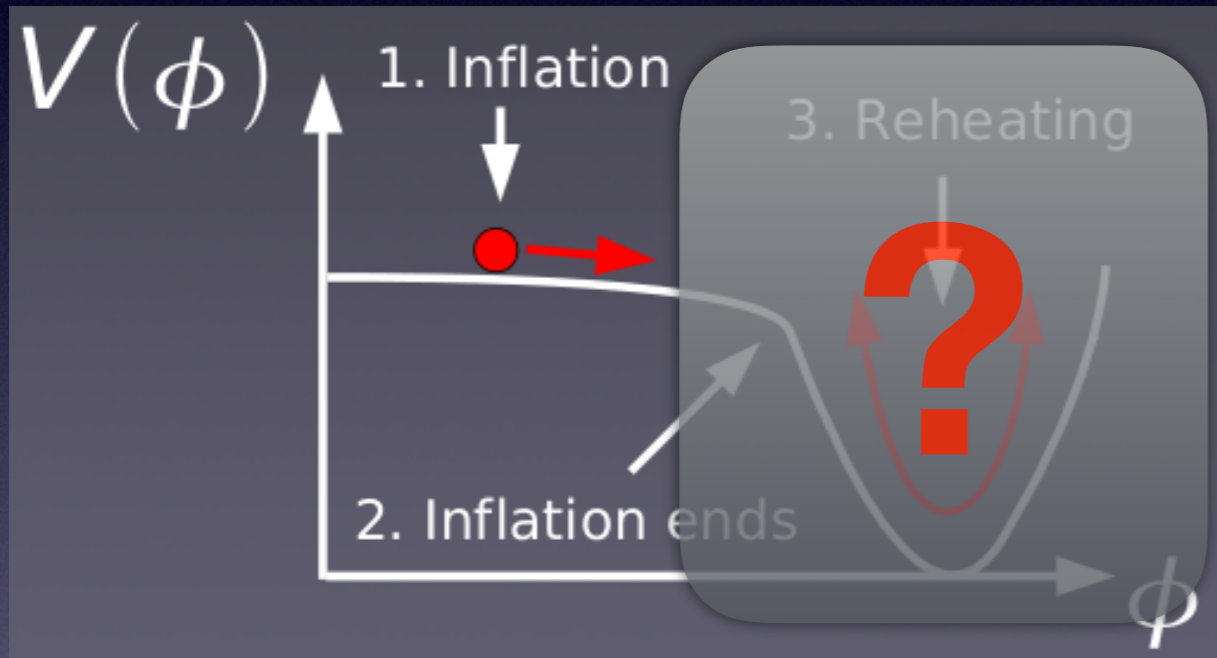
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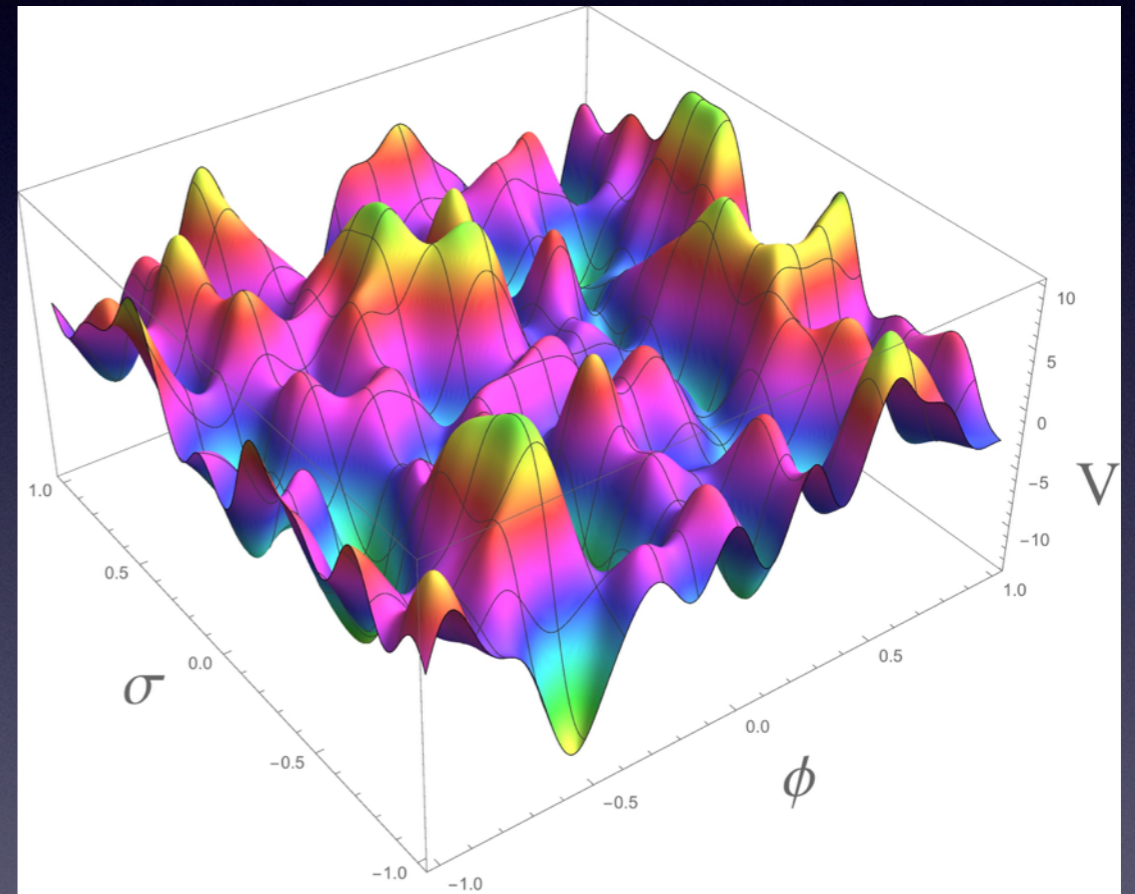
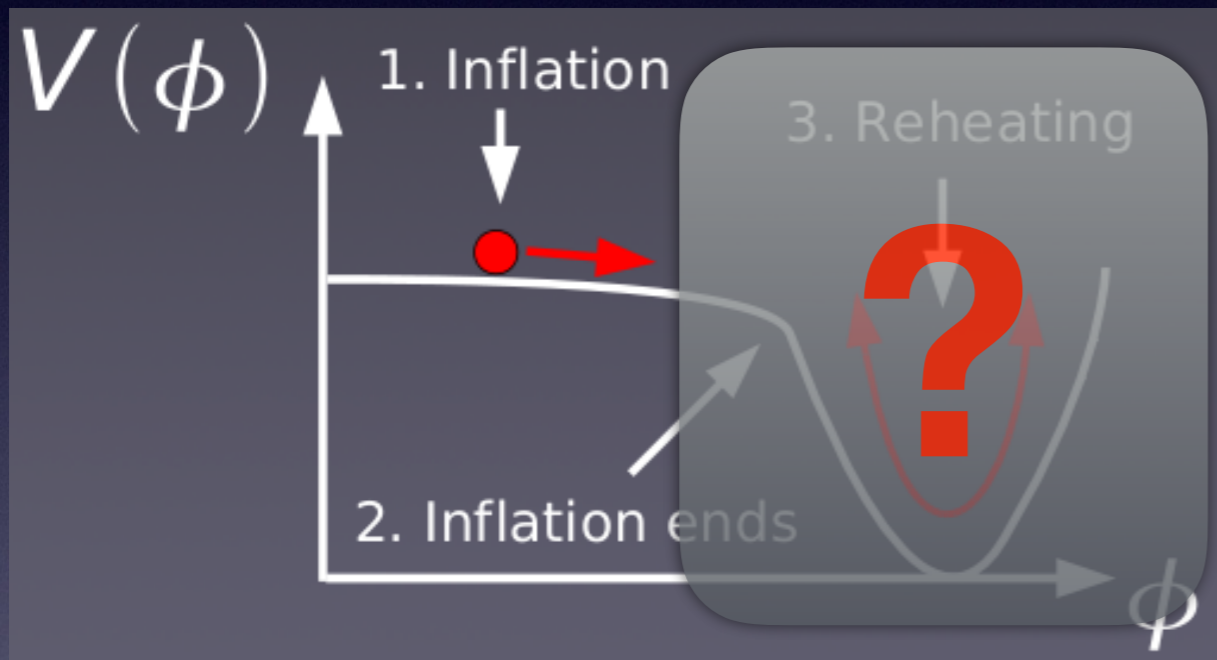
# What is the Inflaton?

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# What is the Inflaton?

Observations



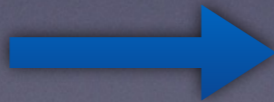
How do potential features imprint themselves on the cosmos?

$$\zeta(\mathbf{x}, t)$$
$$h_{ij}^{\text{TT}}(\mathbf{x}, t)$$



# $\zeta$ and Entropy [JB and Bond, in progress]

$$\begin{aligned}\frac{d\zeta}{dt} &= \frac{1}{3(1+w)} \frac{d \ln \rho}{dt} + \frac{d \ln a}{dt} \\ &= \frac{T}{3V(\rho + P)} \frac{dS}{dt}\end{aligned}$$

Entropy Production   $\zeta$  Production

# Possible Effects

- Potential features during inflation [JB, Bond, Morrison]
  - Nonlinear superhorizon evolution
  - Particle production during inflation
- End-of-inflation dynamics [JB, Bond, Frolov, Huang]
- Initial Conditions [JB, Johnson, Peiris, Aguirre]

# Possible Effects

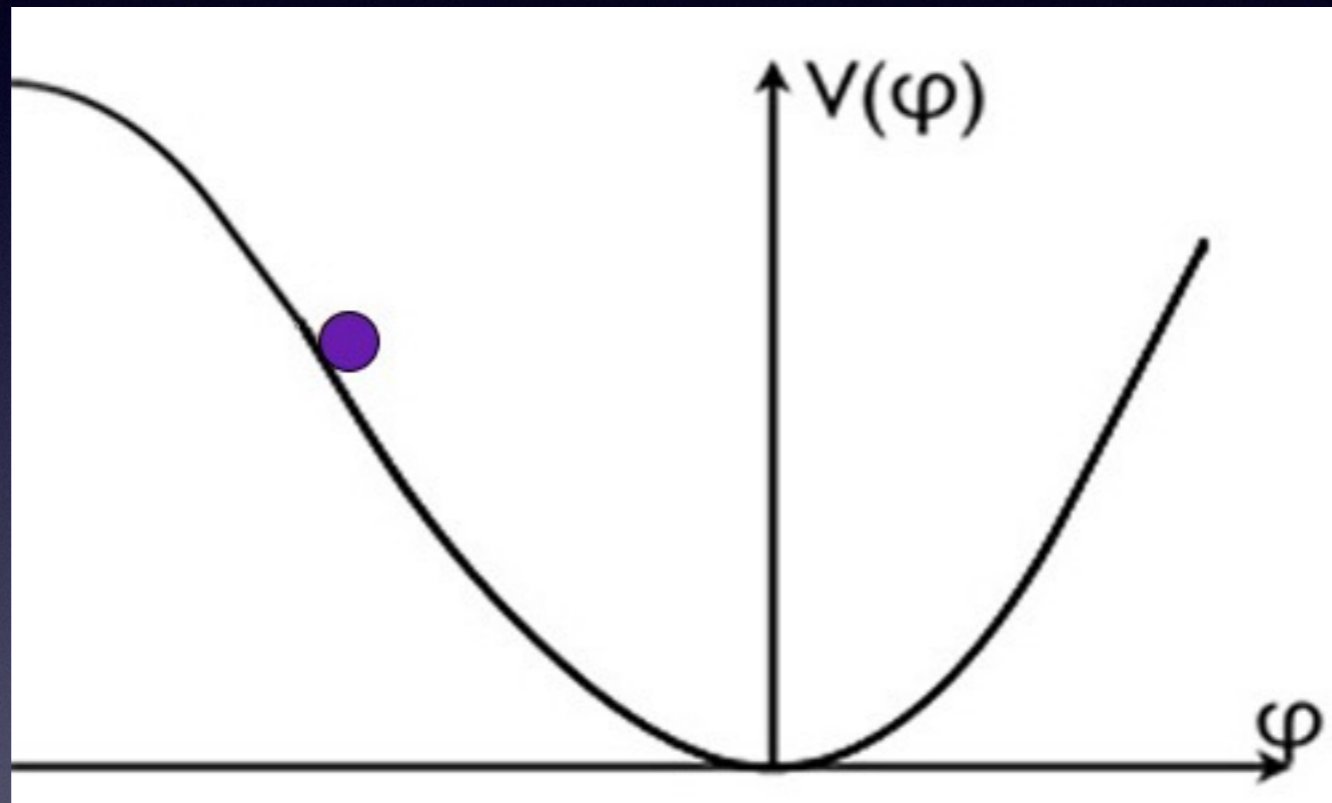
- Potential features during inflation [JB, Bond, Morrison]
  - Nonlinear superhorizon evolution
  - Particle production during inflation
- **End-of-inflation dynamics** [JB, Bond, Frolov, Huang]
- Initial Conditions [JB, Johnson, Peiris, Aguirre]

# NonGaussian Curvature Perturbations From End-of-Inflation

[JB, Bond, Frolov, Huang]

# End-of-Inflation

[JB, Bond, Frolov, Huang]



Few degrees of freedom  
Cold ( $T=0$ )  
Low entropy

# End-of-Inflation

[JB, Bond, Frolov, Huang]

**QUICK & EASY DIRECTIONS**

**JUST ADD DARK MATTER**

COOKING TIMES MAY VARY. MULTIVERSES WITH EXCESS DARK ENERGY WILL FAIL.



**CONDENSED**



**A QUICK MEAL IN 13.8 BILLION YEARS!**

**PRIMORDIAL SOUP FOR THE PURIST**

**\*\*EVERYTHING YOU NEED TO GET LIFE STARTED IN YOUR  $SU(3) \times SU(2) \times U(1)$  UNIVERSE.**

**\*\*GRAVITY, PRIMORDIAL FLUCTUATIONS, AND DARK MATTER SOLD SEPARATELY.**



Nutrition Facts	Amount/serving	%DV	Amount/serving	%DV
Protein		0%	Metal sulfides	0%
Fat		0%	Hydrogen	100%
Carbohydrate		0%	Ammonia	0%
Fiber		0%	Methane	0%
Calories	0.0		Carbon monoxide	0%
Fat Calories	0.0		Formaldehyde	0%
			High MW PAHs	0%
			NP-40	0%

Questions or comments? email [bullock@uci.aedu](mailto:bullock@uci.aedu)  
Allow up to  $10^{33}$  years for refund.



Always recycle



your atoms

**Primordial**

**SOUP**

NET WT.  $10 \frac{3}{4}$  OZ. (305g)

INGREDIENTS: HYDROGEN AND HELIUM.

MAY CONTAIN TRACE AMOUNTS OF LITHIUM

Many degrees of freedom  
Hot ( $T > 10 \text{ MeV}$ )  
High entropy

# Lattice Simulations

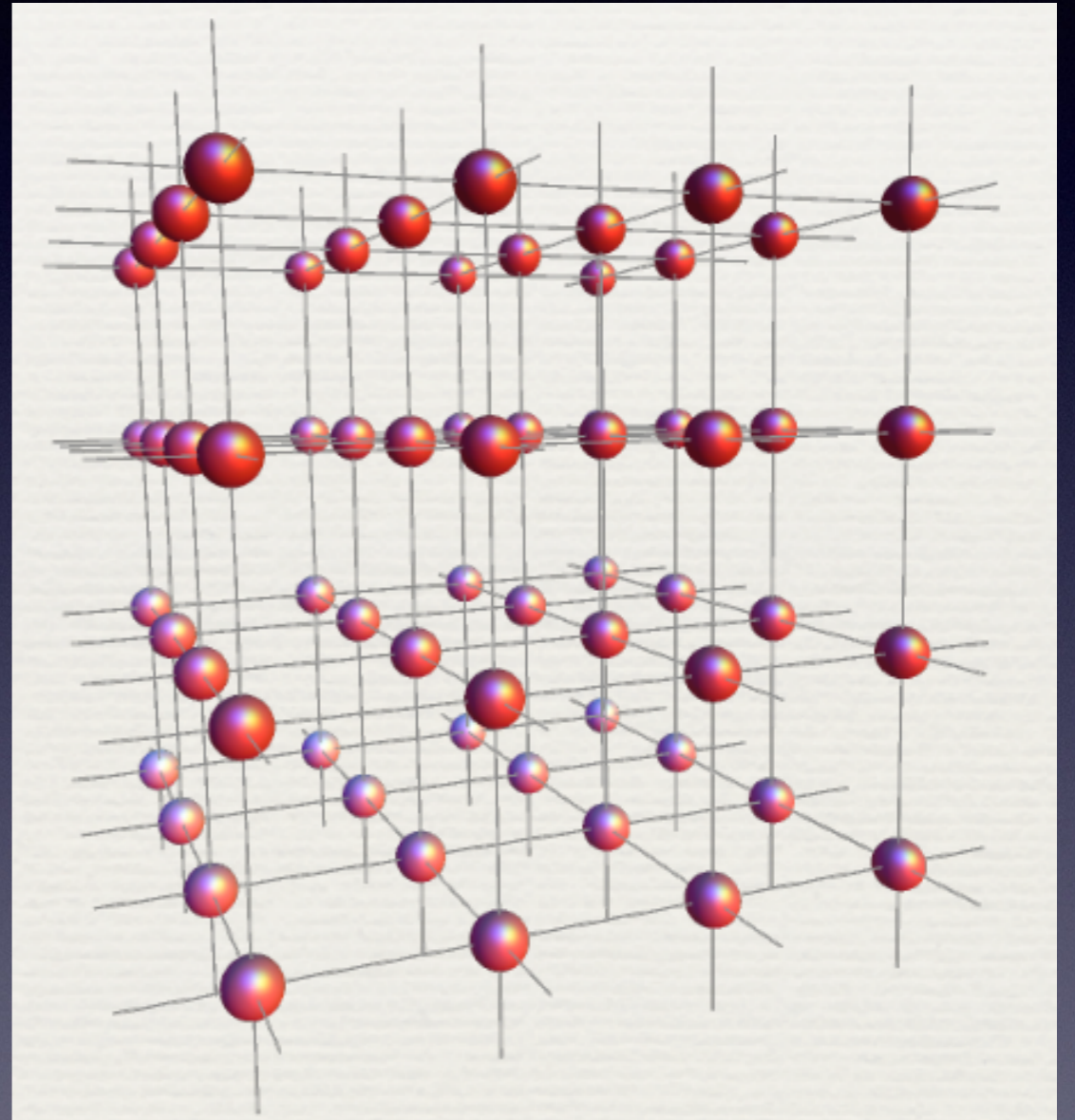
[Braden]

- Solve field equation

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

$$H^2 = \frac{\rho}{3M_P^2}$$

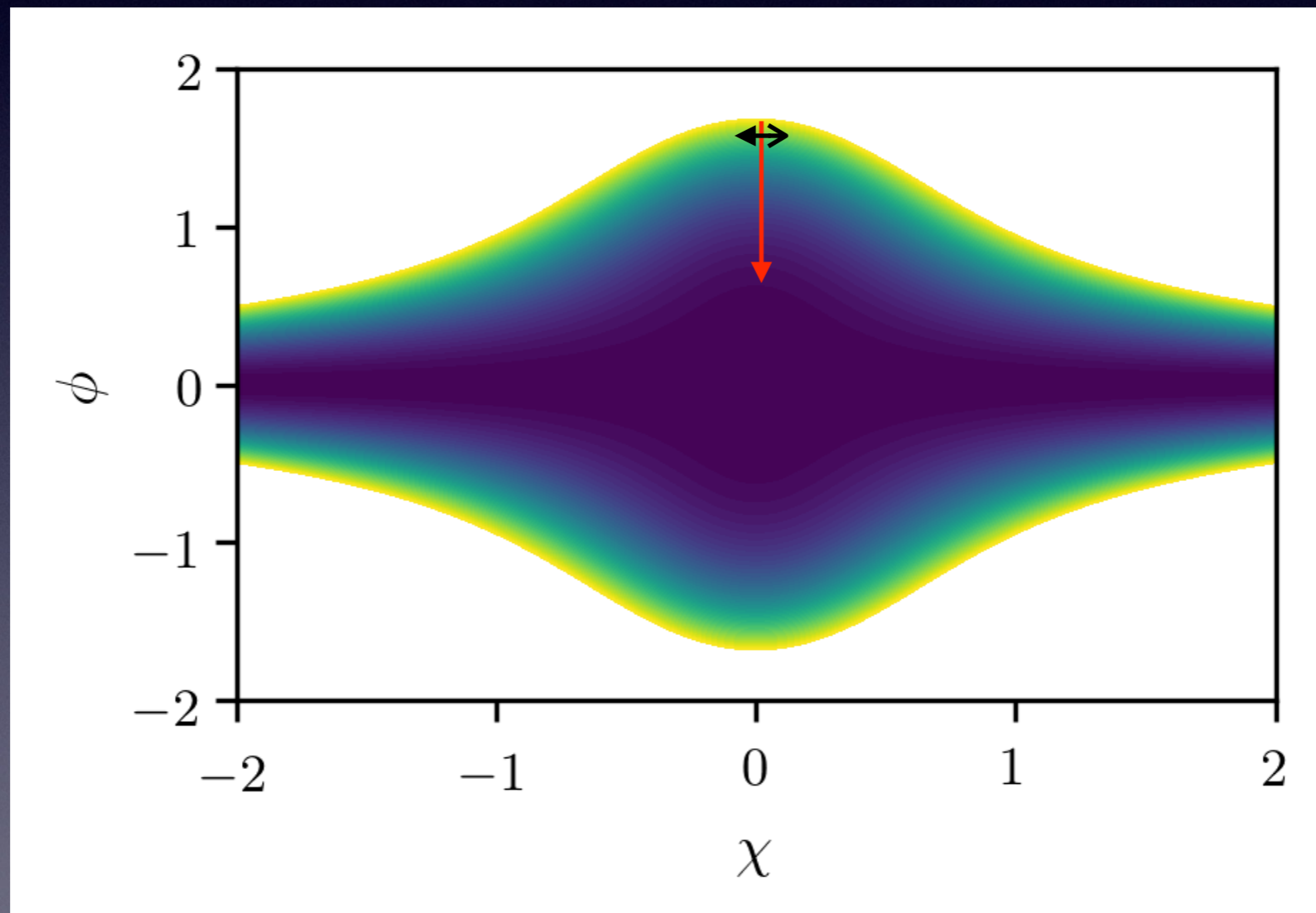
- Finite-difference or pseudospectral
- 10th order Gauss-Legendre (general) or 8th order Yoshida (nonlinear sigma model)
- Quantum fluctuations  $\longrightarrow$  random field realization



$\mathcal{O}(10^{-15})$  convergence

# Simple Model

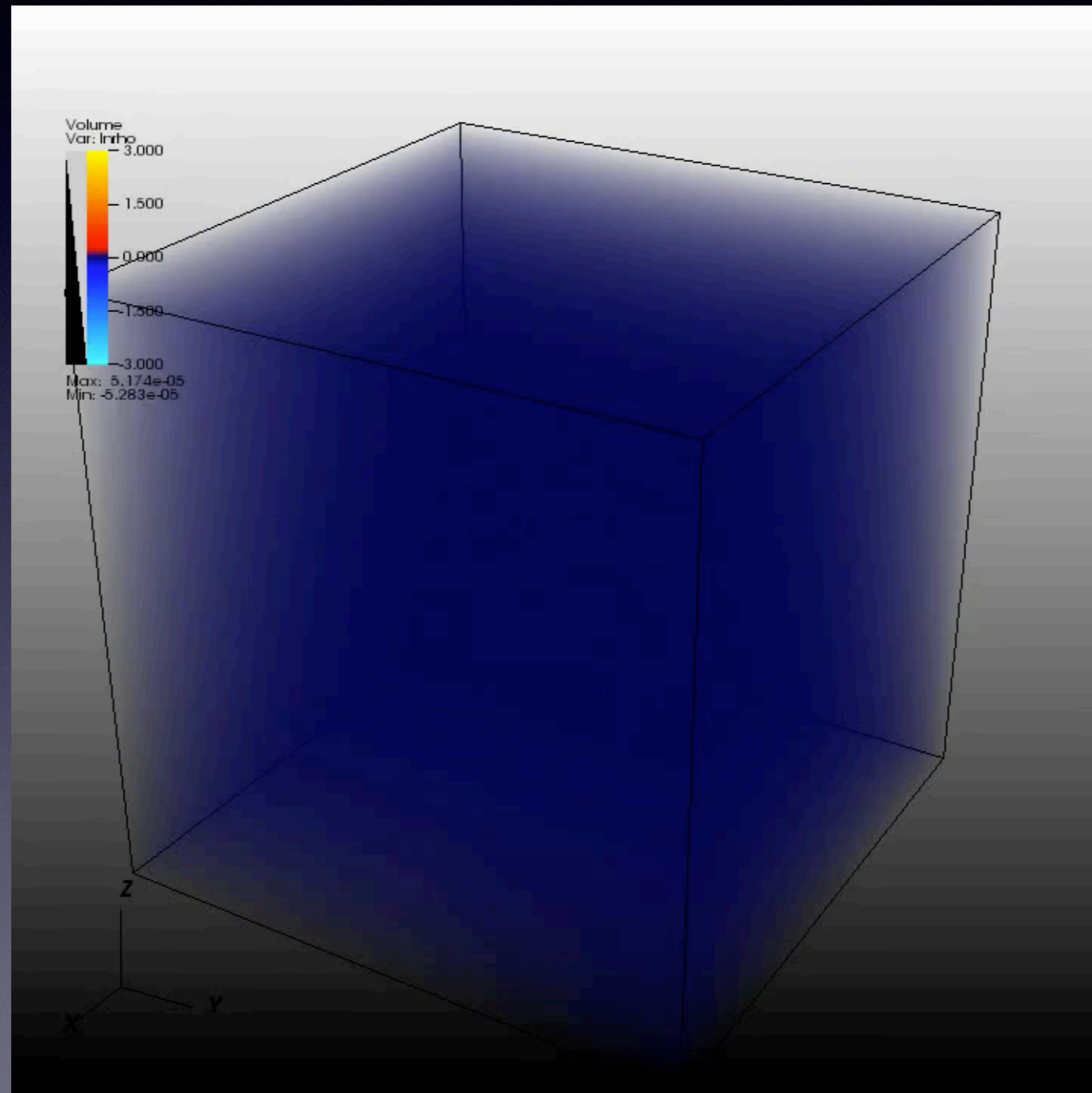
$$\mathcal{L} = \frac{M_{\text{P}}^2}{2} (1 + \xi \phi^2) R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{\lambda}{4} \phi^4 - \frac{g^2}{2} \phi^2 \chi^2$$



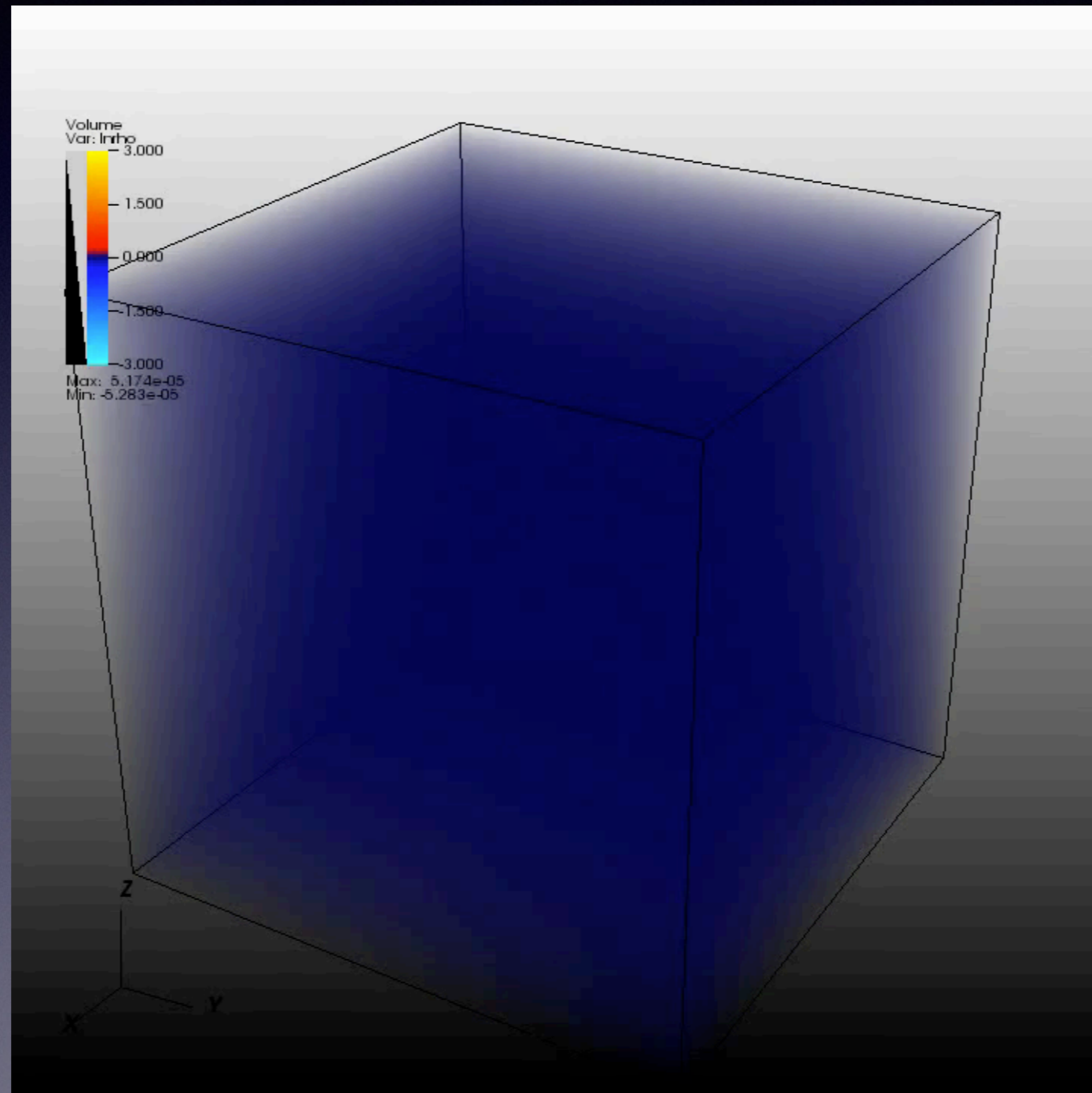
Precise Form Not Crucial



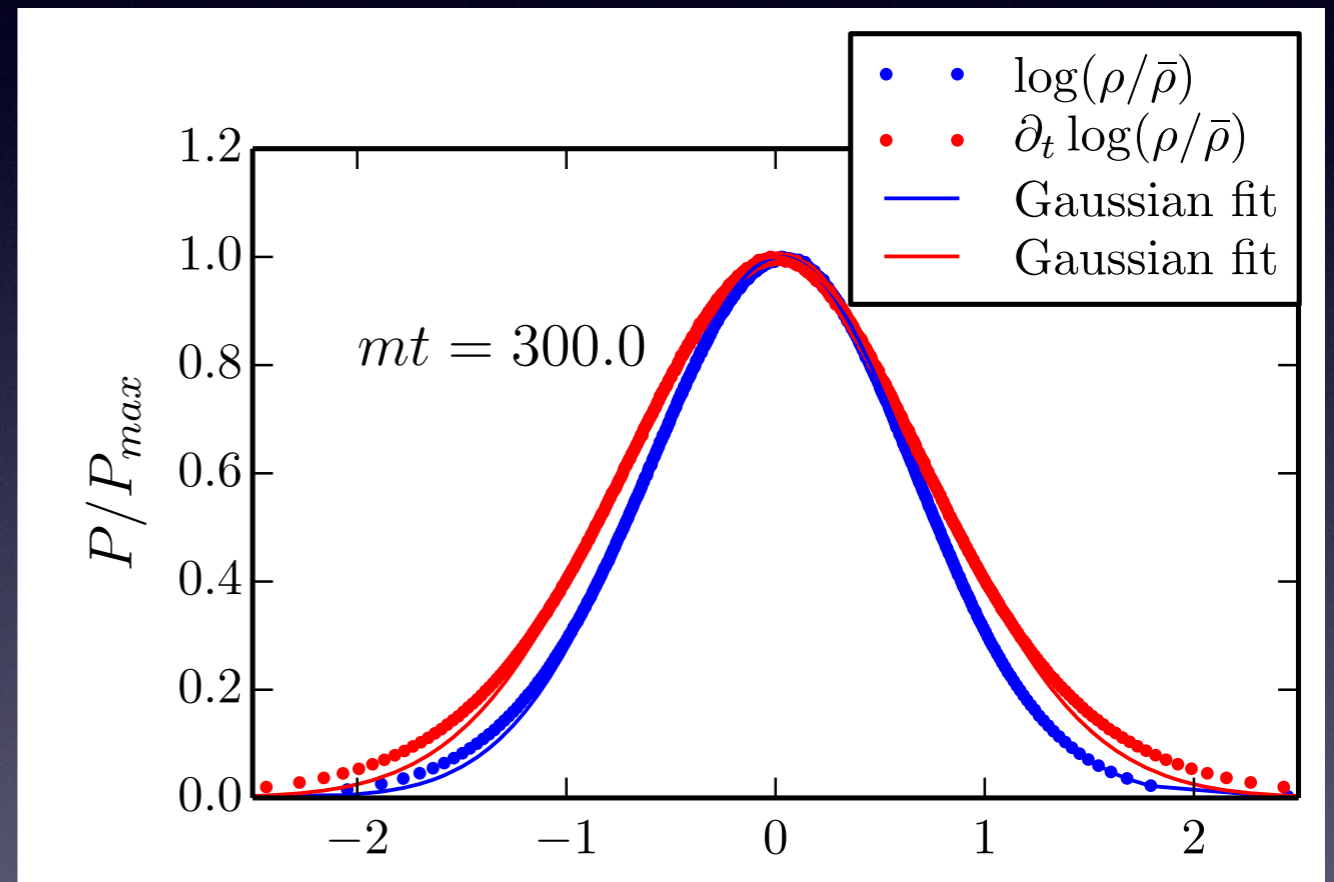
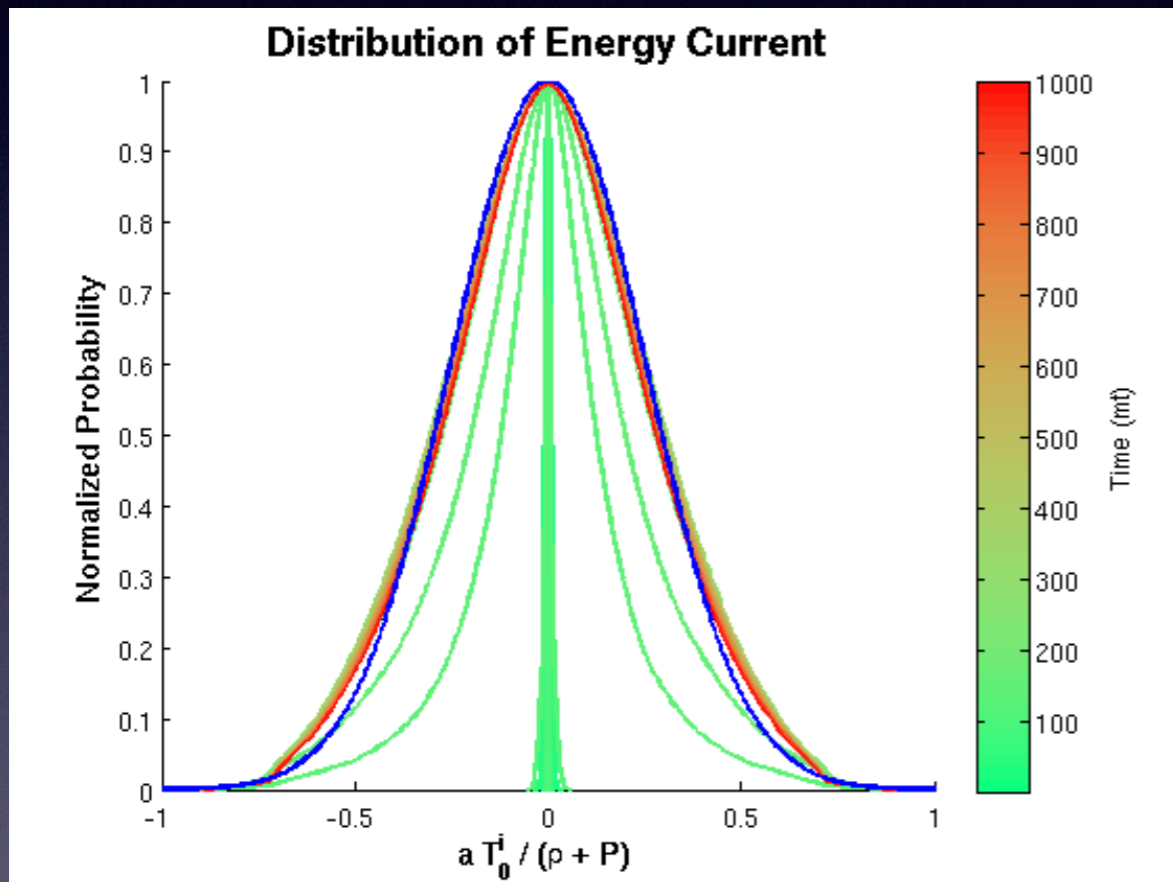
# Lattice Evolution



# Lattice Evolution



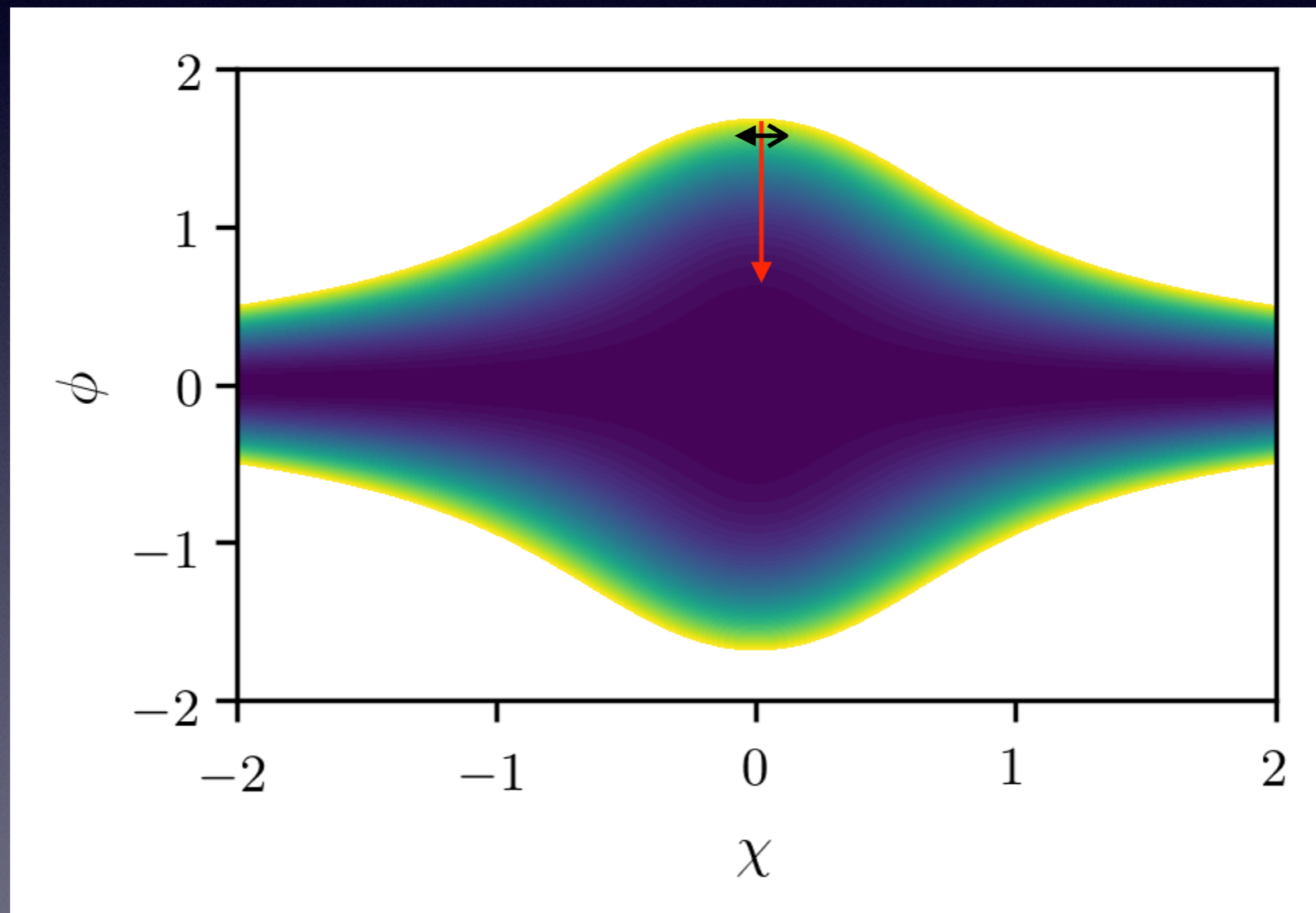
# Sources of $\zeta$



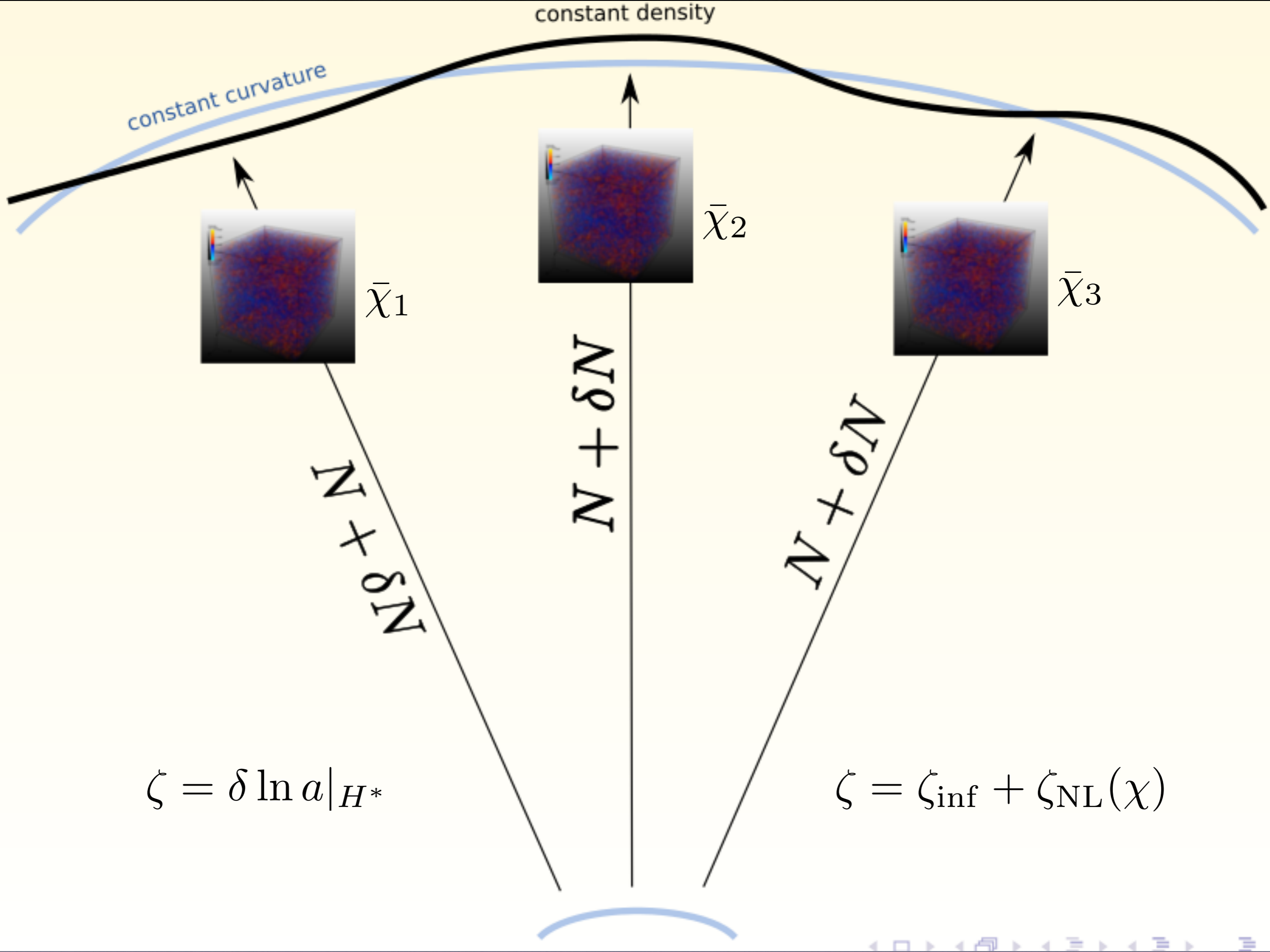
$$\frac{d\zeta}{dt} = \frac{\partial_i T^{i0}}{3(\rho + P)} = \sum_I \frac{\nabla \cdot (\dot{\phi}_I \nabla \phi_I)}{a^2(\rho + P)}$$

# Simple Model

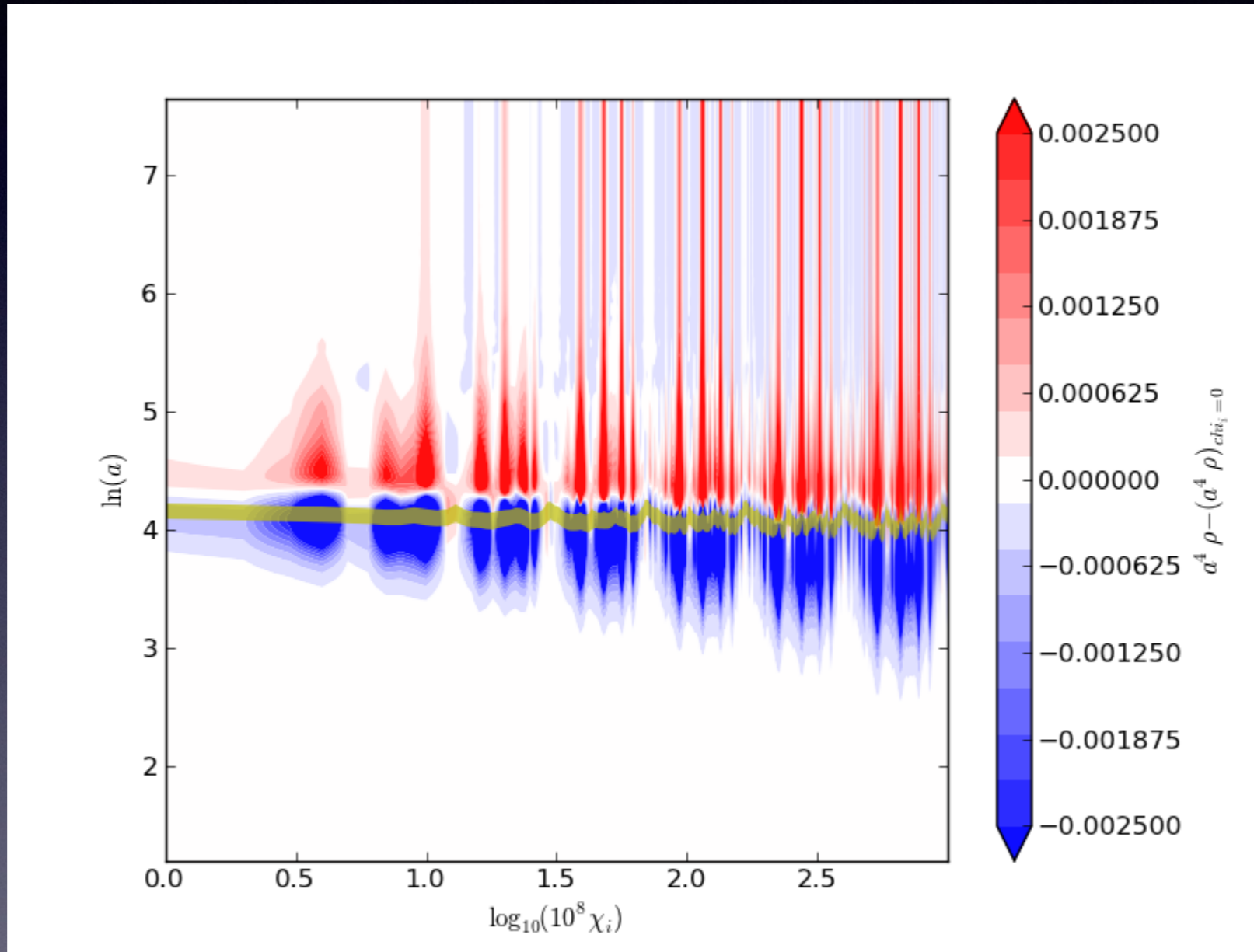
$$\mathcal{L} = \frac{M_{\text{P}}^2}{2} (1 + \xi \phi^2) R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{\lambda}{4} \phi^4 - \frac{g^2}{2} \phi^2 \chi^2$$



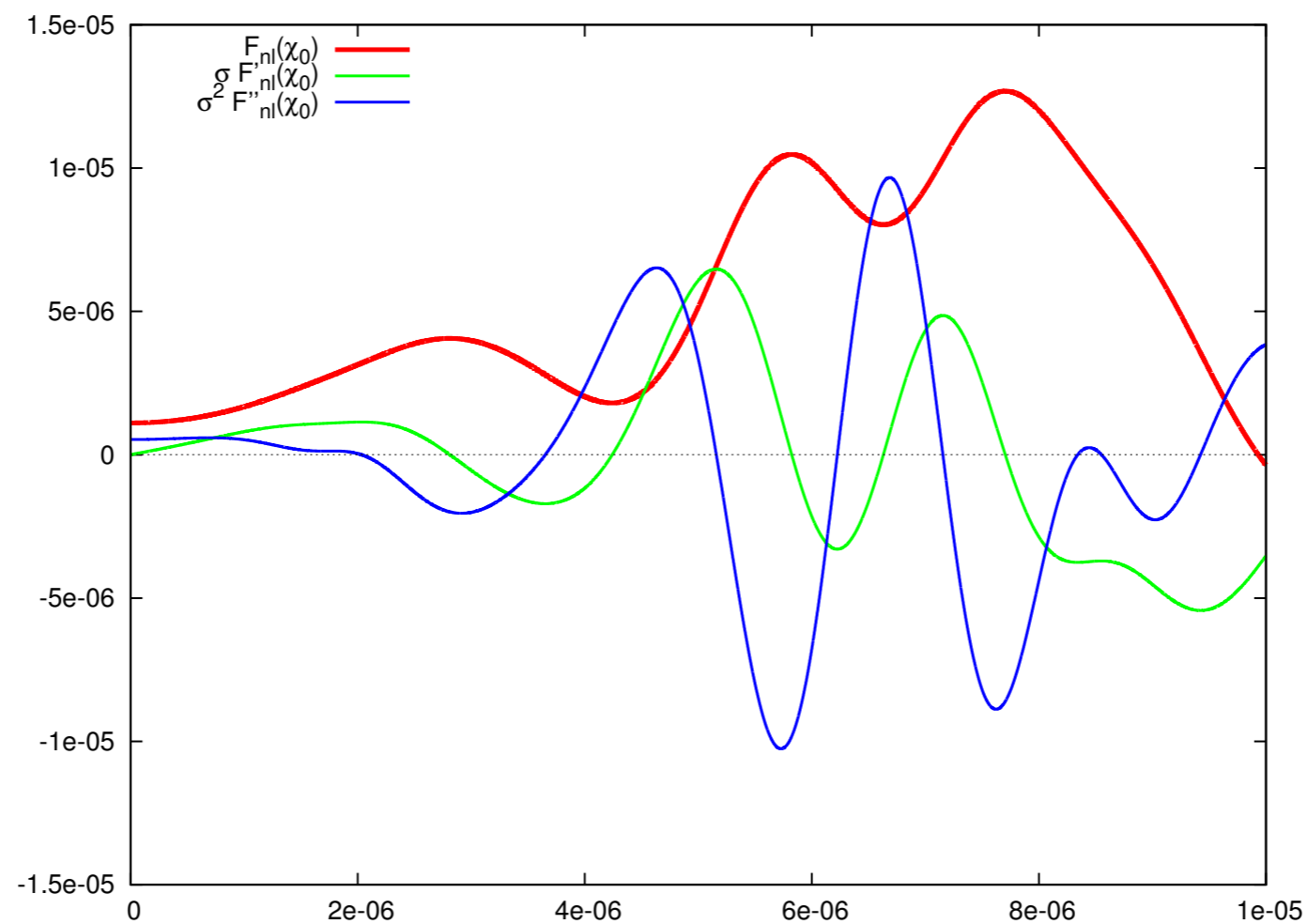
Precise Form Not Crucial



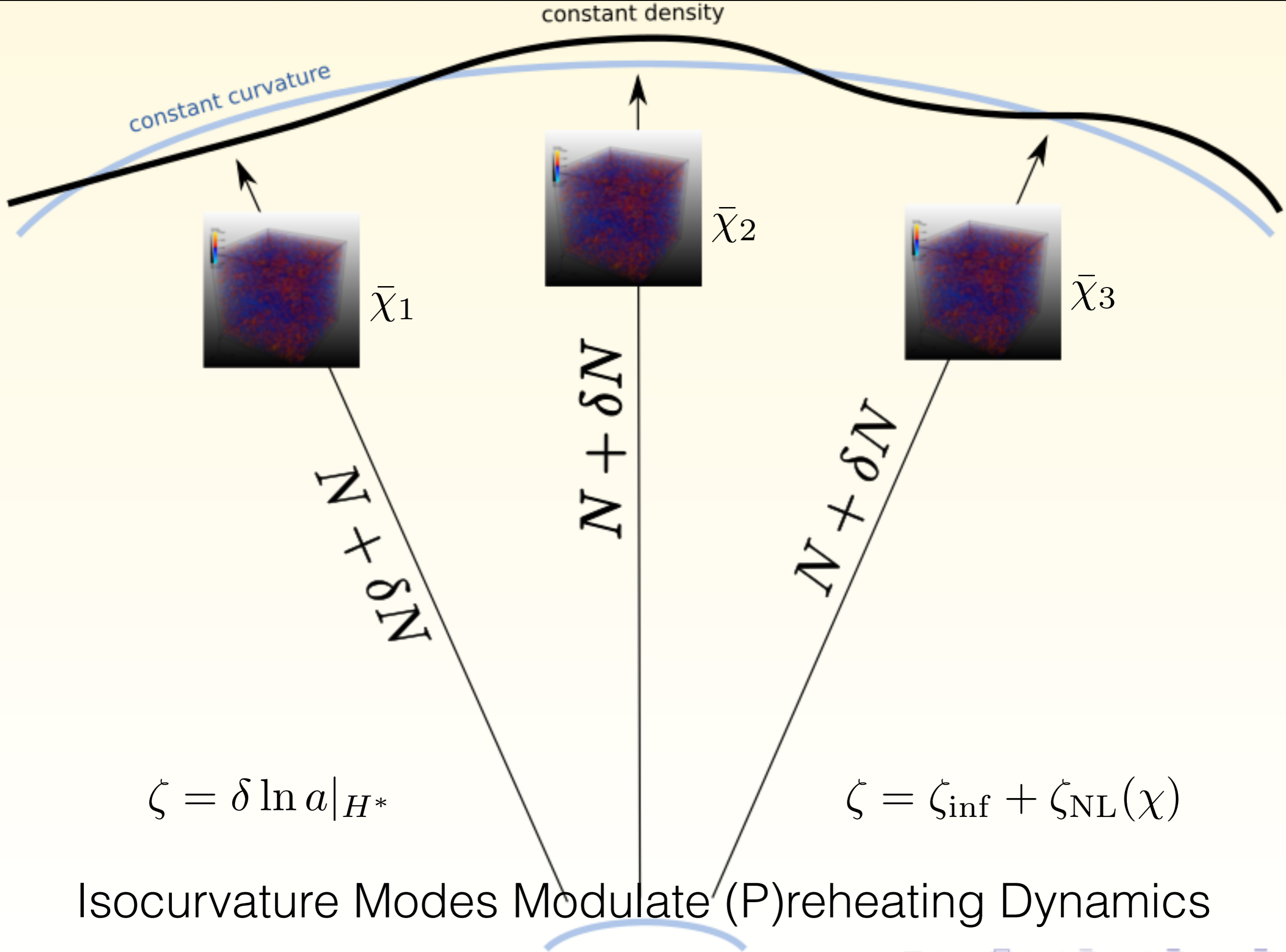
# Isocon Dependent Zeta



# Isocon Dependent Zeta

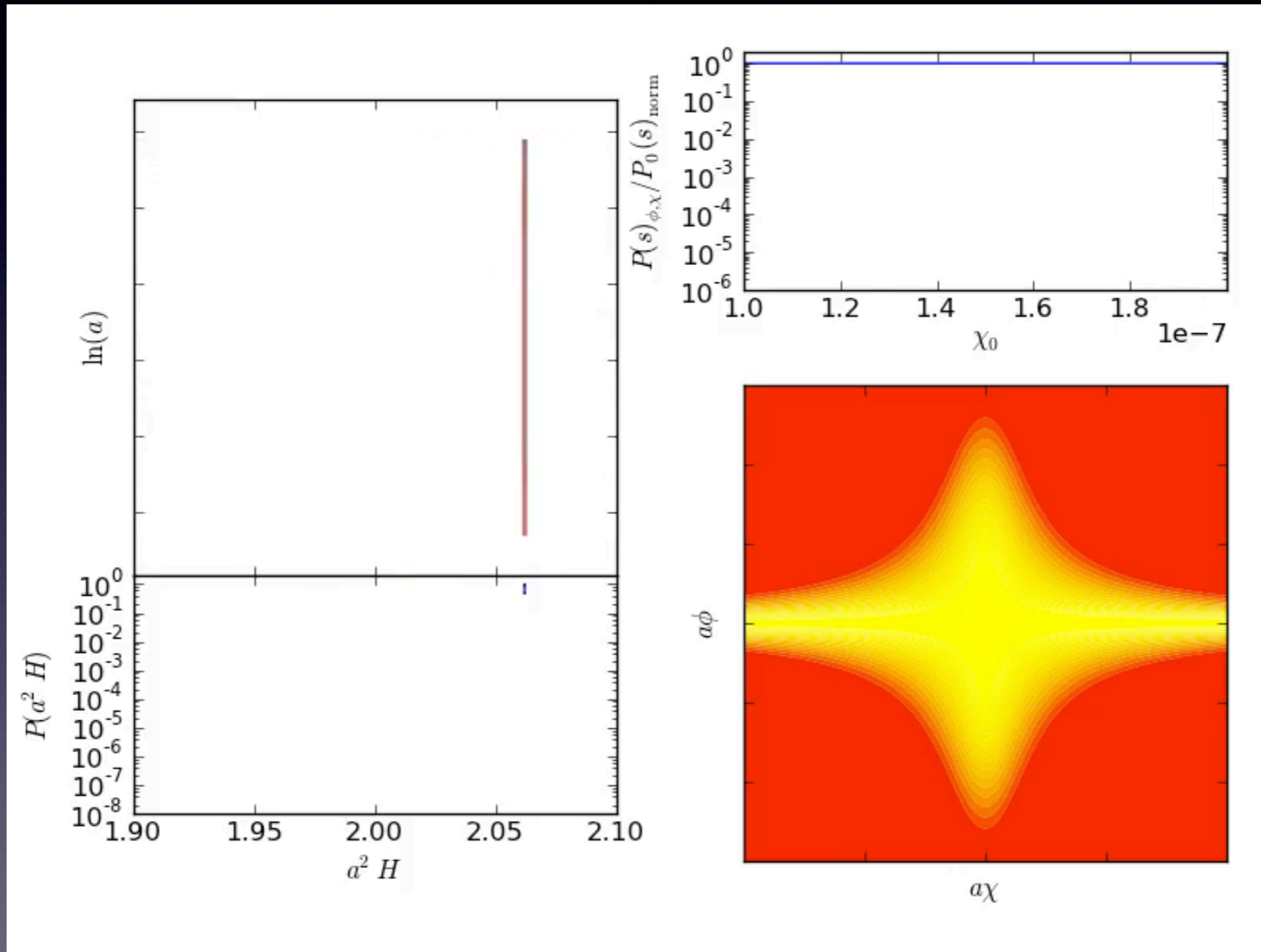


$$\zeta(\mathbf{x}) = \zeta_{\text{inf}}(\mathbf{x}) + F_{\text{NL}}(\chi(\mathbf{x}))$$



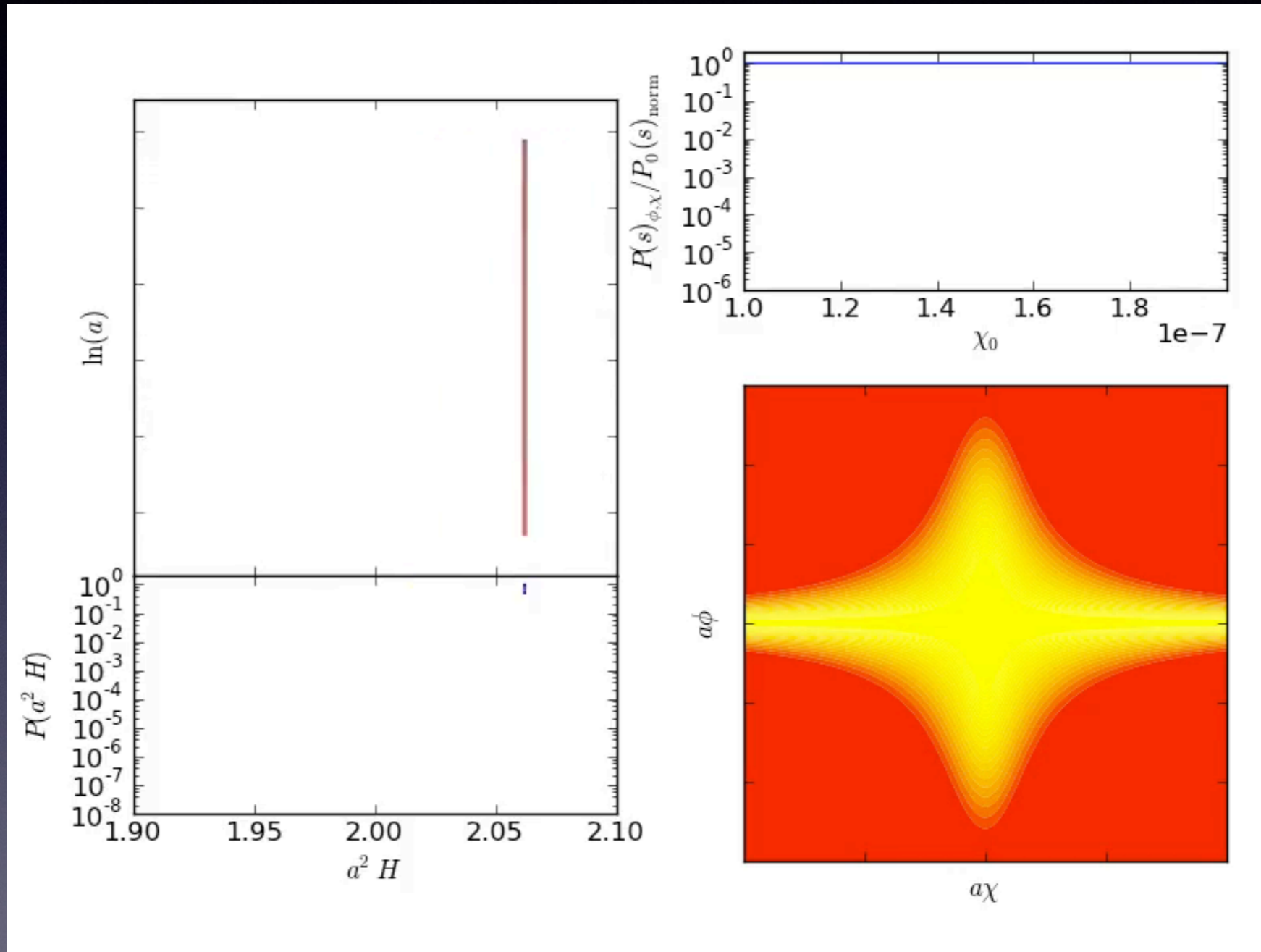


# Ballistics



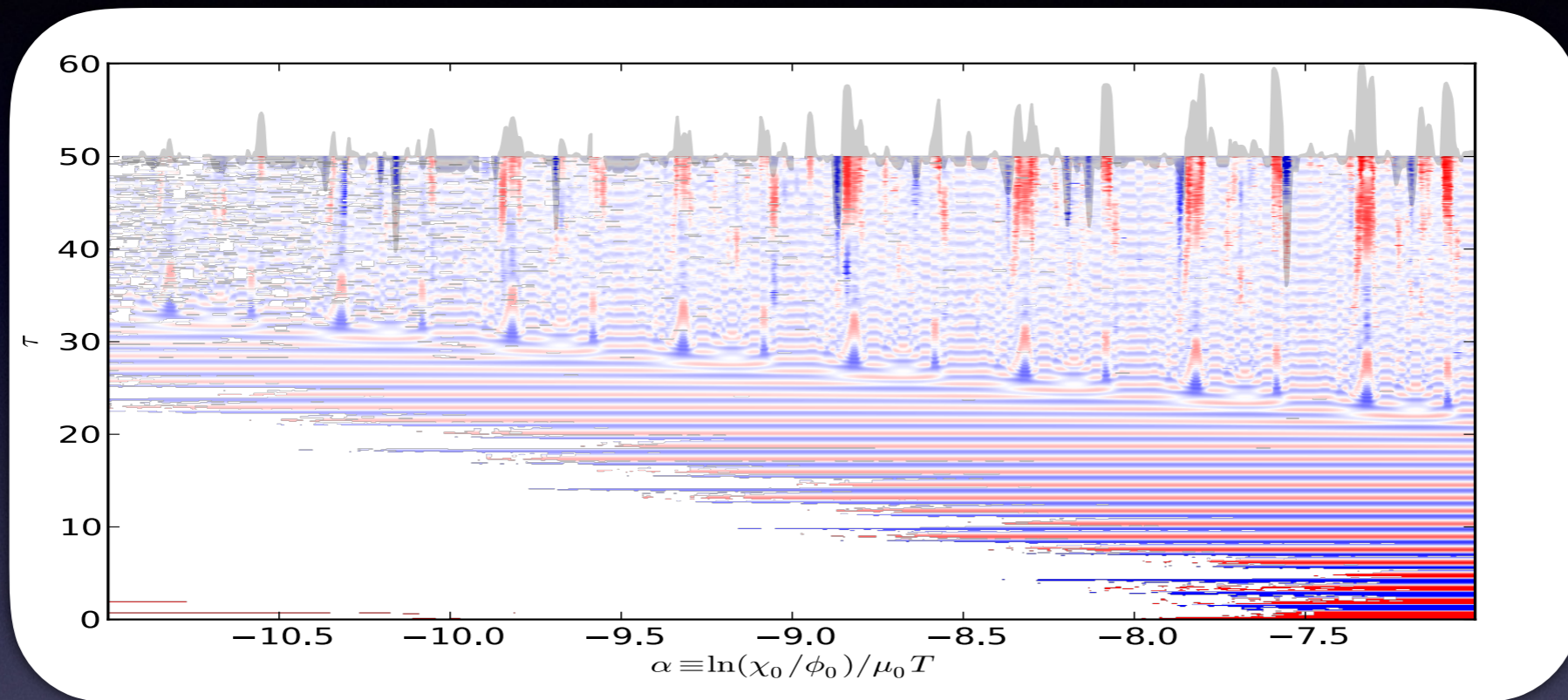
Drop gradients (reduced phase space)

# Ballistics

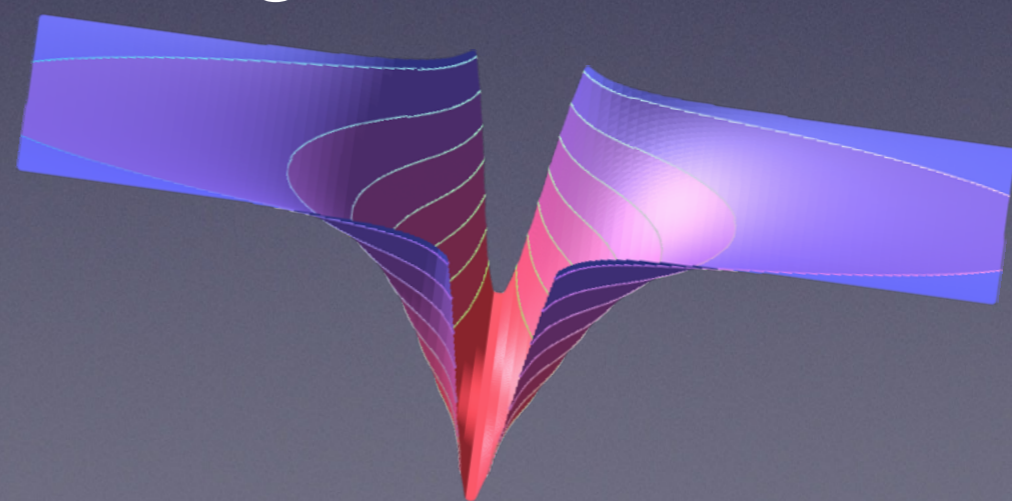
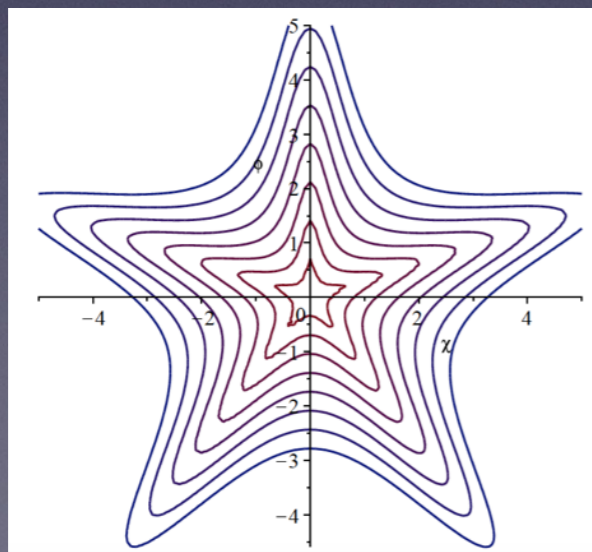


Drop gradients (reduced phase space)

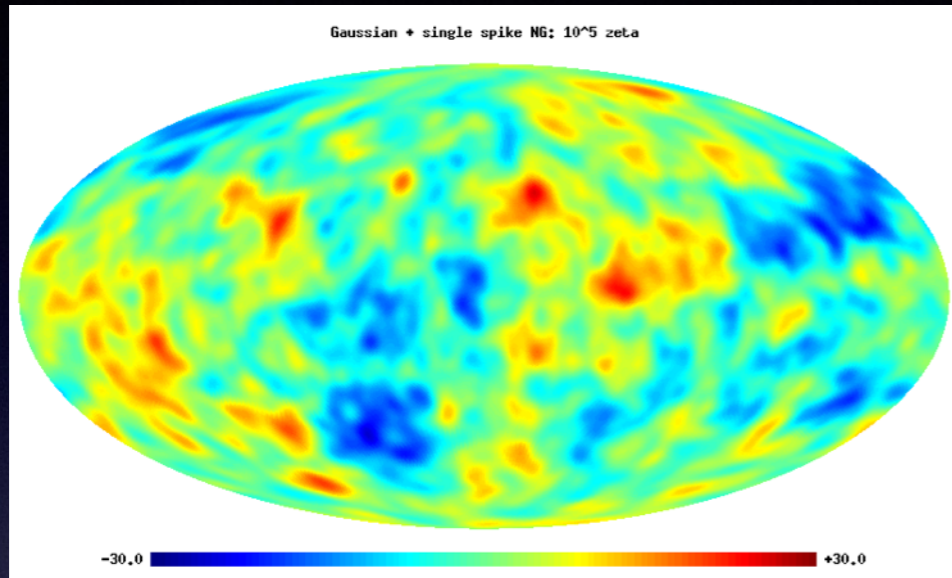
# Reproduce the Lattice



Billiard caustics ubiquitous  $\rightarrow$  generic mechanism

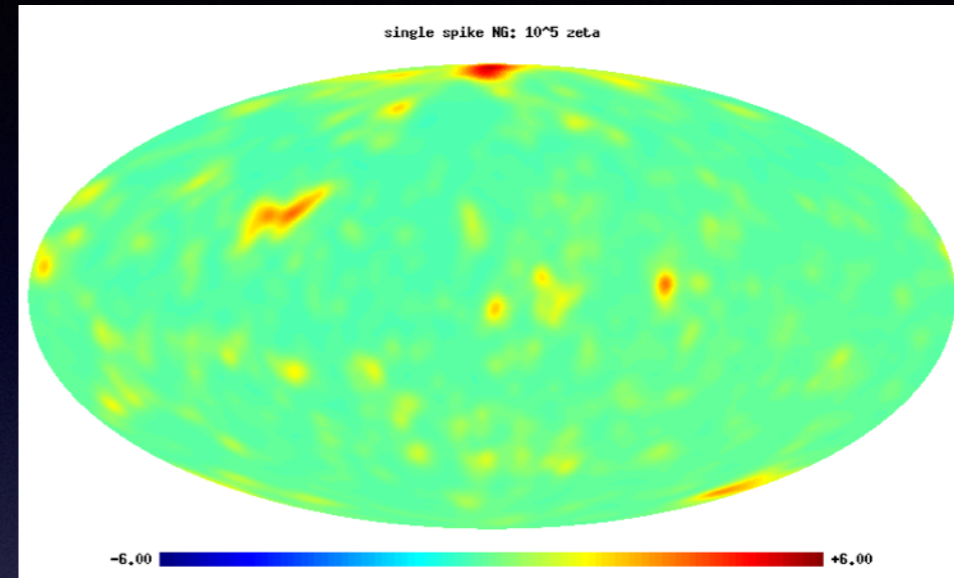


# Relation to Observations



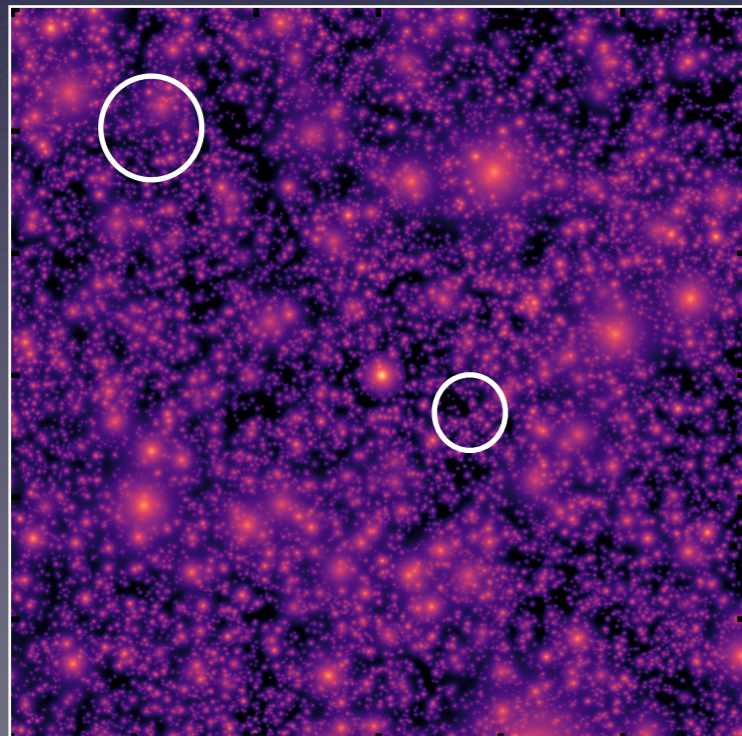
Perturbative NG

$$\zeta = \zeta_{\text{inf}} + f_{\text{NL}}^{\zeta} (\zeta_{\text{inf}}^2 - \langle \zeta_{\text{inf}}^2 \rangle)$$

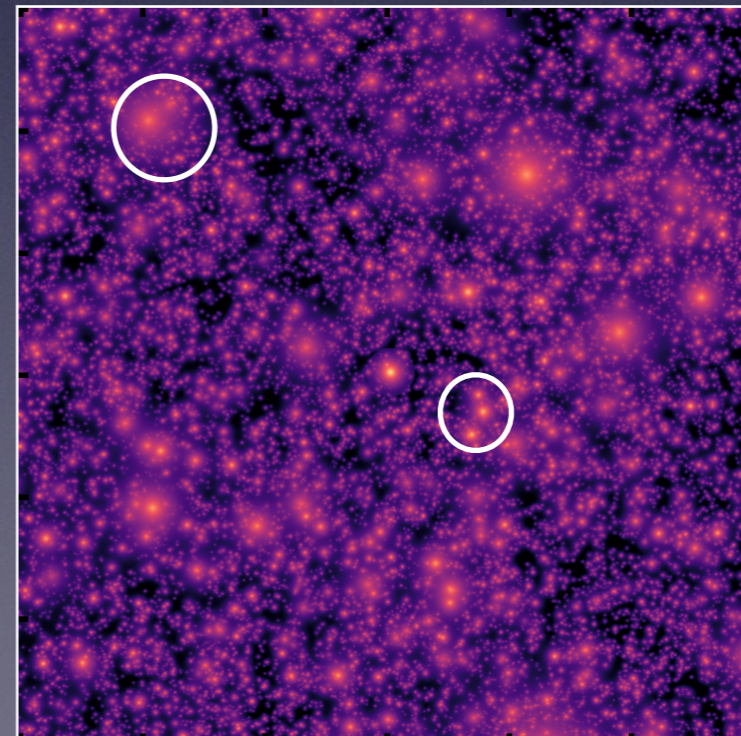


Intermittent NG

$$\zeta = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi)$$



*B2FH, bond+braden+frolov+huang*



*ABSB+FH, alvarez+bond+stein+braden+frolov+huang*

# Conclusions / Future Work

- Isocurvature fluctuations can modulate  $\zeta$  production via nonlinear evolution
- Generalized form of local nonGaussianity  $\zeta = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi)$
- Production of  $\zeta$  tied to entropy production
- General framework based on (smoothed) trajectory dynamics
- Detailed connection with CMB and LSS observations  
[Alvarez, Bond, JB, Frolov, Huang, Stein]