Coherent Inflation *with* **Quantum Jitter to Hot Big Bang, an Incoherent Particle Soup**

how (most of) the entropy in matter =>

GUT plasma/quark soup => $S(\gamma,\nu)$ was

generated *(through a* **shock-in-time***)*

via nonlinear coupling *of the* ***inflaton*** *to* ***new***

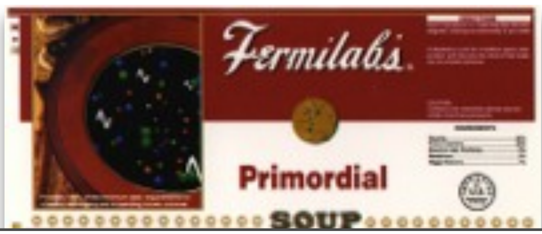
interaction channels g,χ_a $V_{eff}(\varphi,\chi_a \,|\, g,\ldots)$ *aka*

$V_{eff}(r,\theta_a \,|\, g,\ldots)$ *ultimately to* ***standard model degrees of freedom***

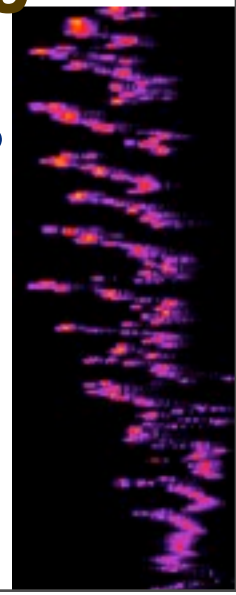
∃ a role for *decaying particles, 1st order phase transitions?*

exactly who, what, where, when, why?

we search for fossil "non-Gaussian" structures from this period with Planck +WMAP9



$a_{Shock}(g)$



Potentials at the End of Inflation with Physical Motivation

HEATING: *how to damp coherent ballistic trajectories into high-k entropy.*

old, eg SBB89 Γ (KE+PE). still used! e.g., warm inflation

$$J_j = \Gamma_j \dot{\phi}_j, \quad \dot{\phi}_j \equiv \mathrm{sgn}(\dot{\phi}_j)|\partial_\mu \phi_j \partial^\mu \phi_j|^{1/2}$$

$$\Gamma_j = f_j M_j \,. \qquad \frac{1}{a^4}\frac{da^4\rho_r}{dt} = \sum_i \Gamma_j \dot{\phi}_j^2$$

decay rates (Feynman diagrams) and transport theory difficult to make accurate through preheating

rather fundamental scalar field nonlinear evolution equations (inflaton, isocons) & effective potentials & kinetic energies

*post KLS93: via inflaton self-couplings; isocon-inflaton field couplings, fermion-bar fermion, gauge fields, pseudo-scalar*FFdual,*

$$V(\phi_1,\phi_2) = \frac{m_2^2\phi_2^2}{2} + \frac{\lambda_2\phi_2^4}{4} + \frac{m_1^2\phi_1^2}{2} + \frac{\lambda_1\phi_1^4}{4} - \frac{\nu\phi_1^2\phi_2^2}{2} + V_0 \,. \quad -\mu_1\phi_1\phi_2^2$$

tachyonic instability: m_{eff}^2 <0 single field can preheat fast with only a few oscillations, eg roulette in the groove, trilinear

*Stochastic inflation works: ballistic trajectories for fields q_X with kicks from sub-horizon waves dW_X causing nearby trajectories to deviate, ζ_{NL} like dE+pdV a near-adiabatic invariant, sourced by stress*strain-rate & energy currents (regularizer between nearby positions X).*

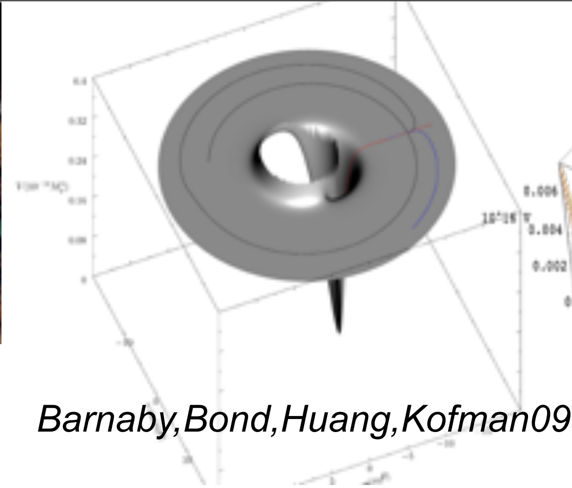
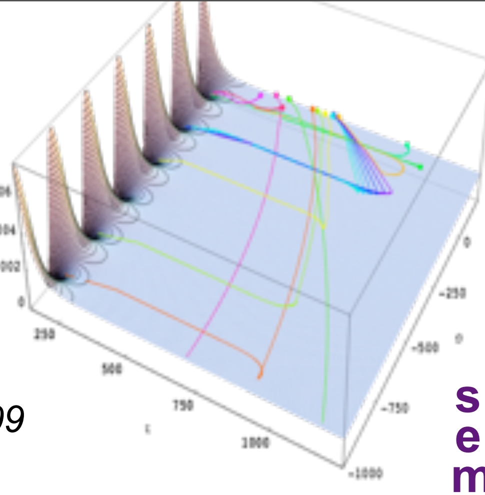
$\varepsilon = -3/2\, d\ln\rho / d\ln a^3 = 1$ defines End of Inflation (cf. ε <.0075 now!), but it is not a magic boundary, dragged trajectories break into (spatially independent) oscillations. weak point-to-point coupling until ...

new picture: ballistic until the shock-in-time = huge time-localized non-eq entropy generation; slow S-evolution after which is V-dependent. only weak-coupling of nearby points before. ULSS & LSS & SSS modulator field ζ_{NL}(modulator(x)), e.g. modulator = χ_i(x), g(x)

***entropy generation in preheating** from the*
coherent inflaton (origin of all matter & radiation)

nonG from post-inflation but pre-entropy generation (B²FH13) drift trajectories can lead to pre-shock-in-time caustics and other phase space convergences in the deformations

$\partial \ln a / \partial \chi_i(x)$, $\partial \ln a / \partial g(x)$ =>

Barnaby,Bond,Huang,Kofman09

NL,nonG curvature distribution($\chi_i(x)$, g(x),..)

semi ETERNAL INFLATION

quantum diffusion

spatial jitter

drift

roulette oscillations highly damped => no-non-G

if redirect by χ_i, **g**

=> non-G

let there be
heat

www.youtube.com/watch?v=FW__su-W-ck&NR=1

***entropy generation in preheating** from the*
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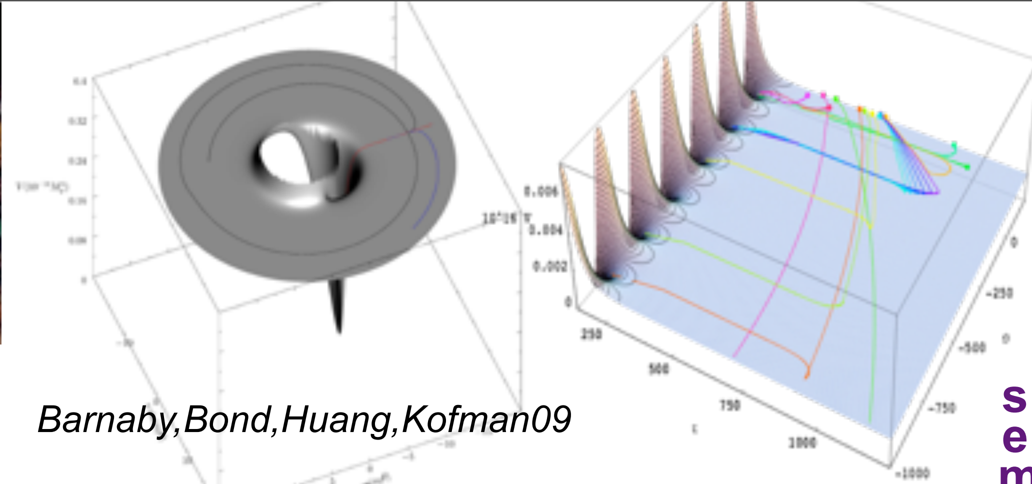
$\partial \ln \mathbf{a} / \partial \chi_i(\mathbf{x})$, $\partial \ln \mathbf{a} / \partial g(\mathbf{x})$ =>

$a =\quad 1$

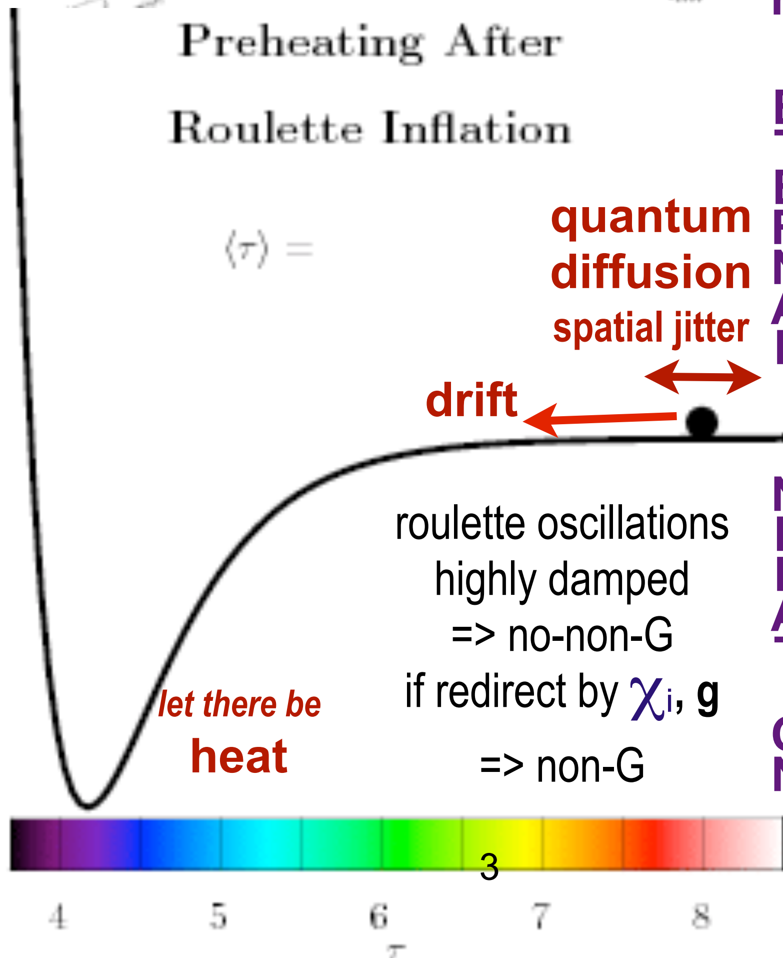
NL,nonG curvature distribution($\chi_i(x)$, g(x),..)



Barnaby,Bond,Huang,Kofman09

A visualized 2D slice

in lattice simulation



semi ETERNAL INFLATION

www.youtube.com/watch?v=FW__su-W-ck&NR=1

modulating post-inflation entropy generation shocks *via* long range fields

isocon

χ(**x**)

or

g(σ(**x**)

or..

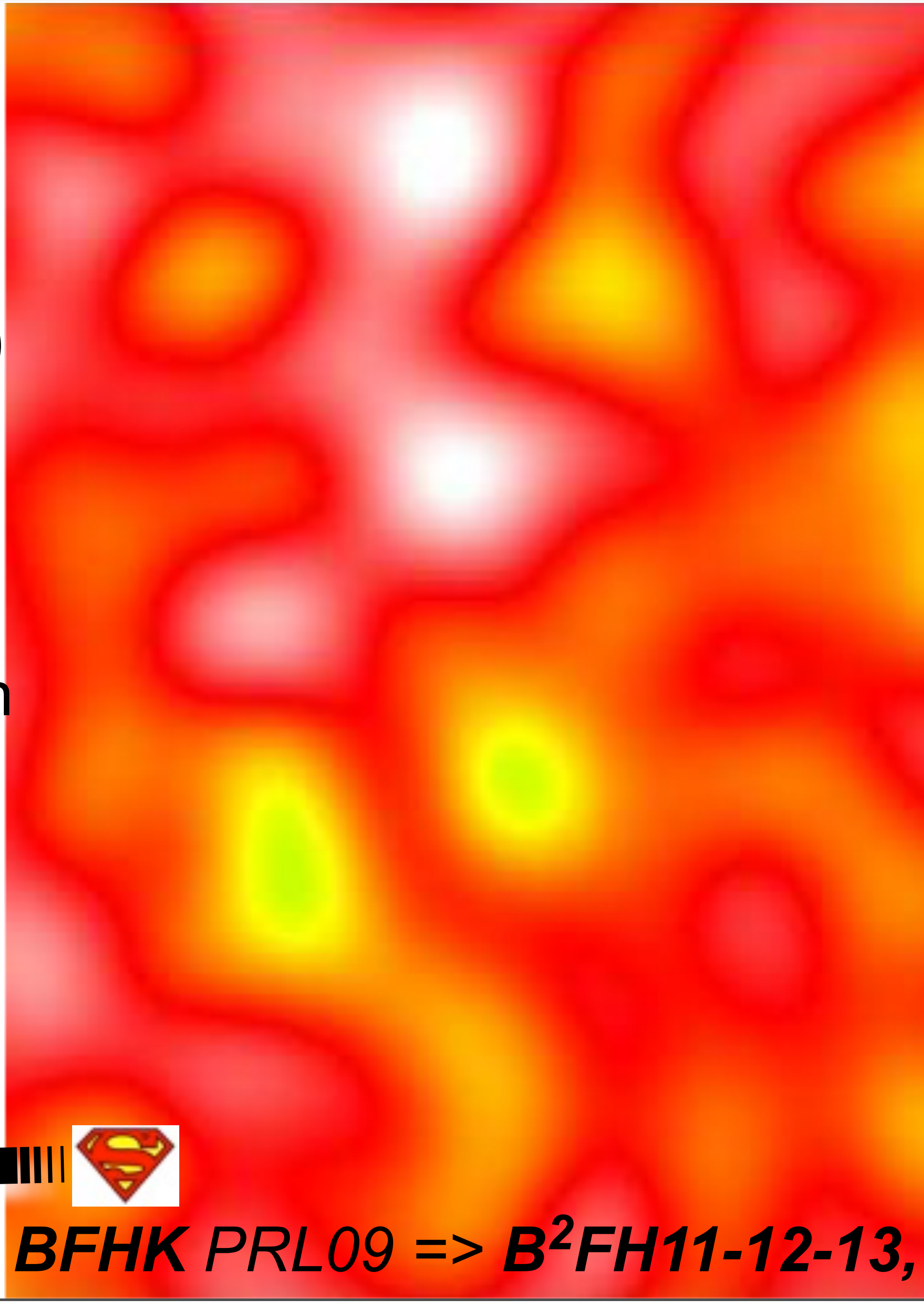
ϕ

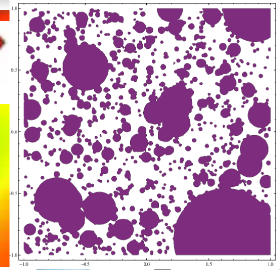
inflaton

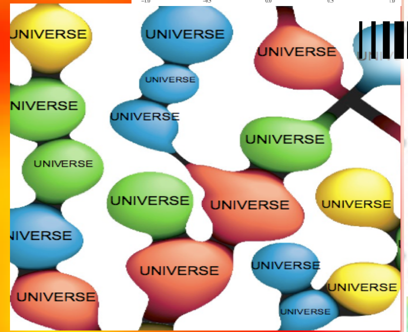
pre-heating patch (~1cm)

$S_{U,m+r}$

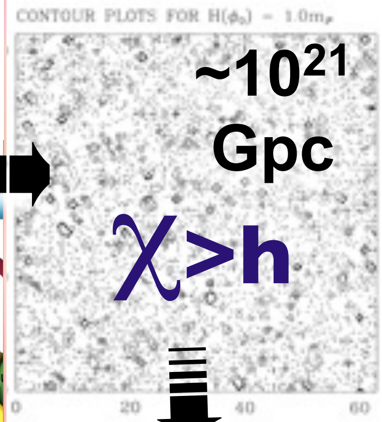
~$10^{88.6}$

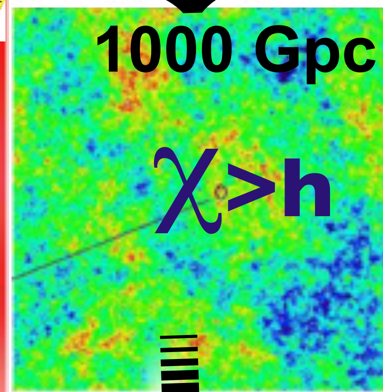


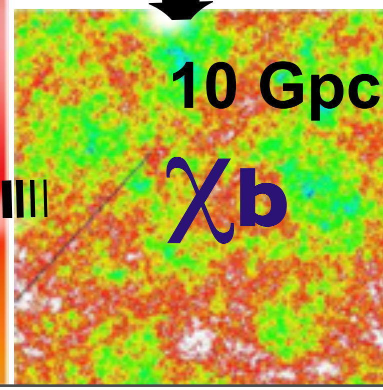




$S_{U,uuUULSS}$







modulating post-inflation entropy generation shocks *via* long range fields

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$\chi(\mathbf{x})$

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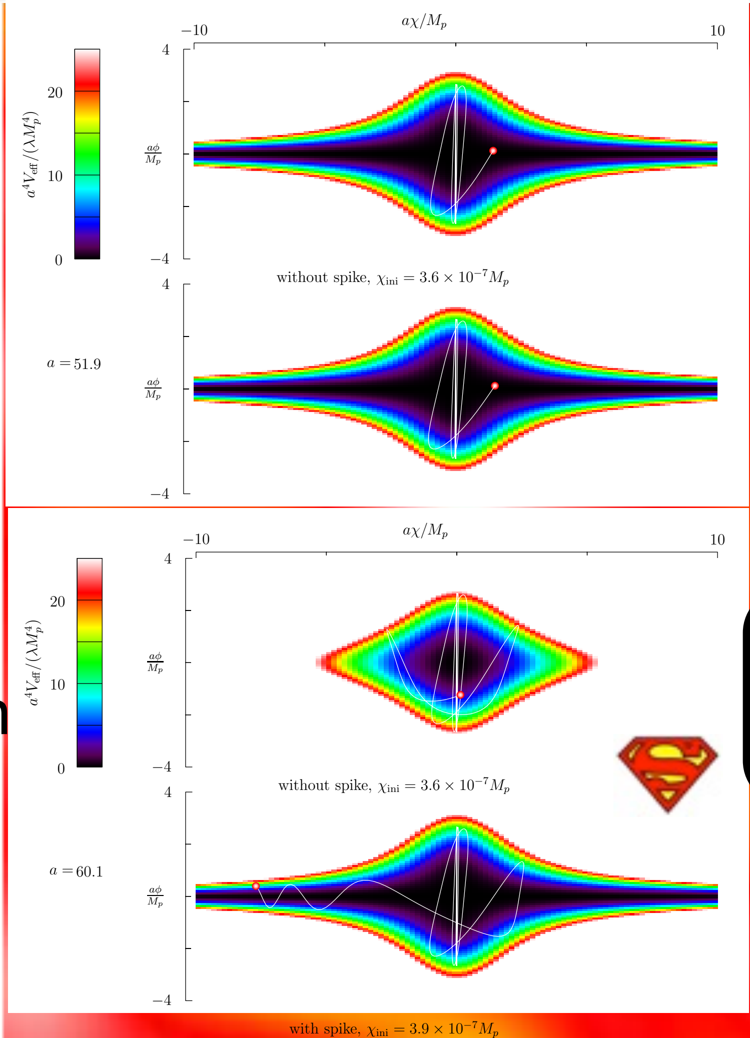
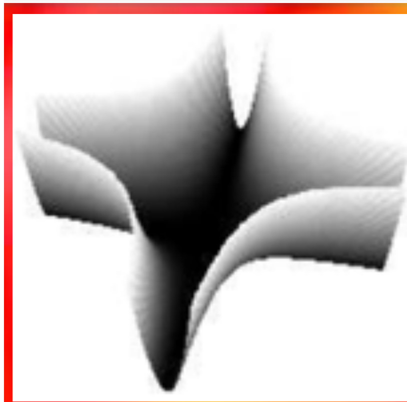


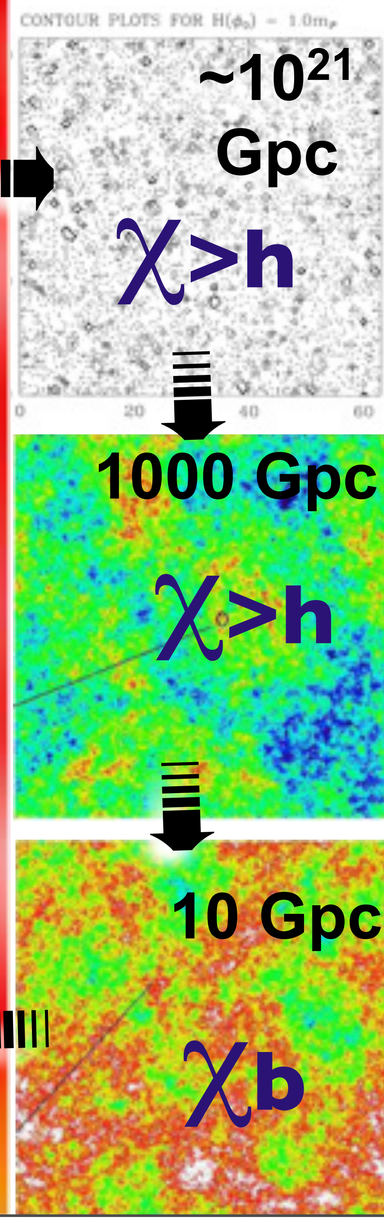


Parametric Resonance

$V(\phi,\chi)$

$= 1/4\, \lambda\phi^4 + 1/2\, g^2 \phi^2 \chi^2$

$S_{U,uuUULSS}$



$\sim 10^{21}$ Gpc

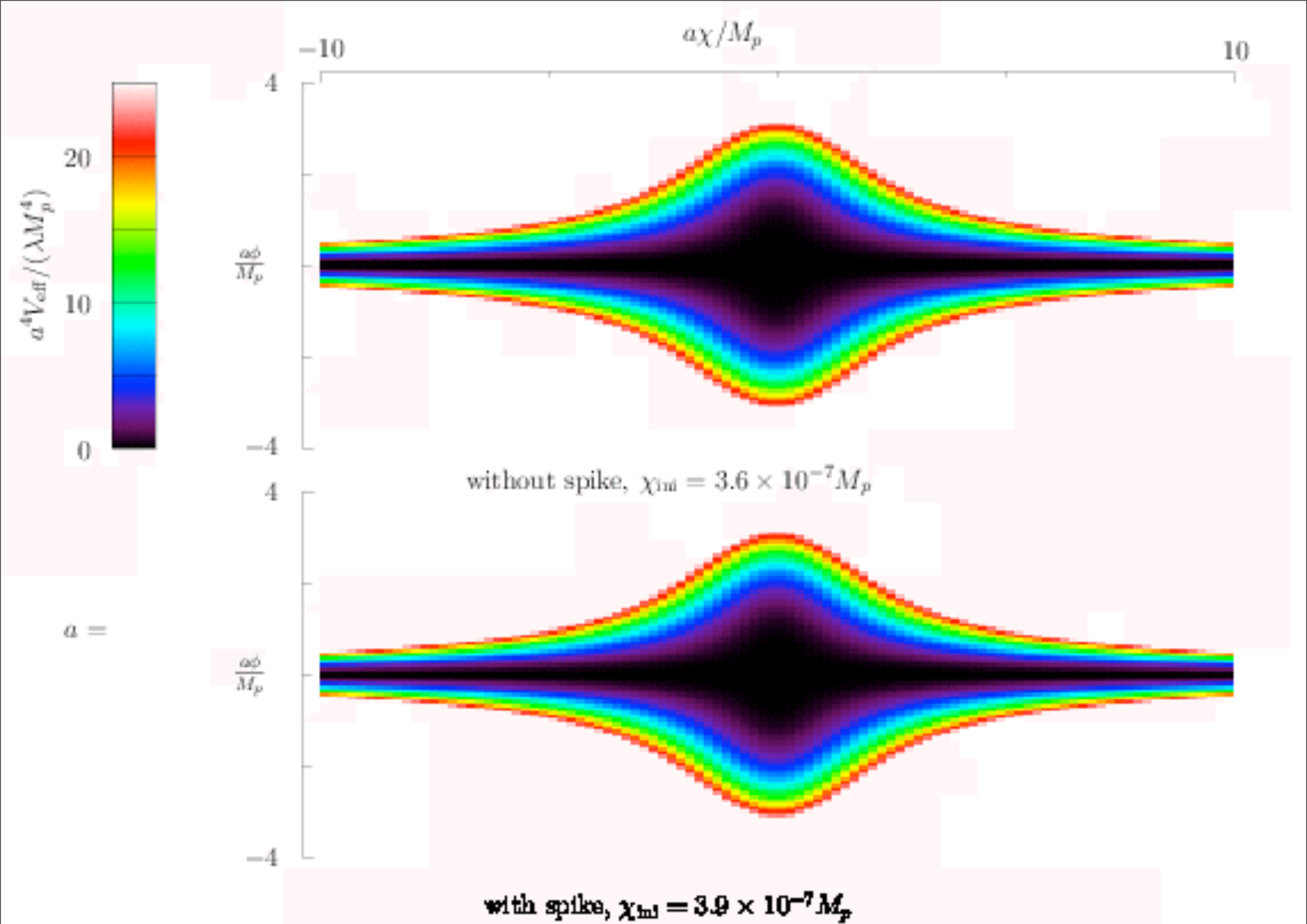
$\chi > h$

1000 Gpc

$\chi > h$

10 Gpc

χb



V_{eff} is trajectory dependent

modulating post-inflation entropy generation shocks *via* long range fields

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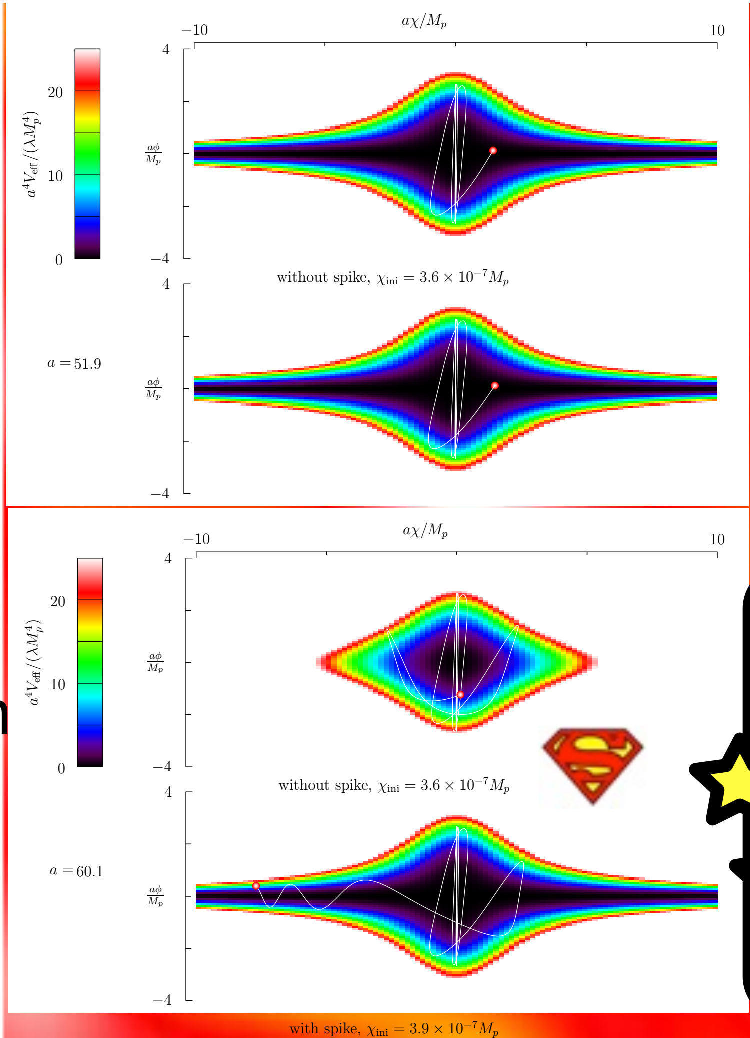
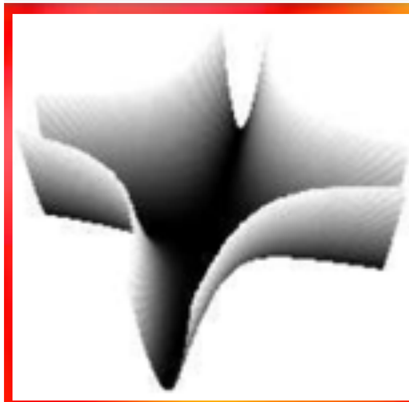
pre-heating patch (~1cm)





How general? We now think very - basins at the end of inflation

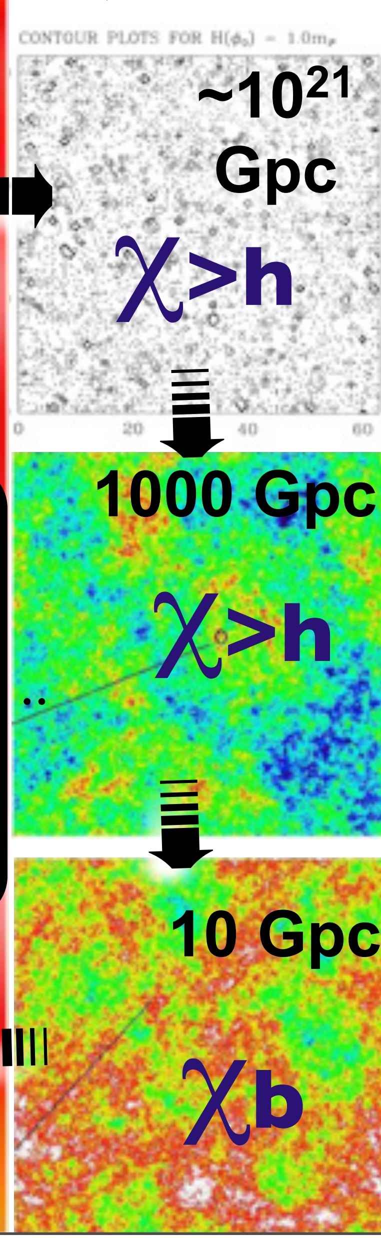
$V(\phi,\chi)$

$= 1/4\ \lambda\phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$,

$1/2 m^2\phi^2 + 1/2\ g^2(\sigma)\phi^2\chi^2$

$= 1/4\ \lambda\ (r^2 - v^2)^2\ U$

$V(r)U(\cos\theta),\ r^2 = \phi^2+\chi^2$



$V(r,\theta) = \sum_M V_M(r)\cos(m\theta)$ *pNGB, Roulette r~hole size*

3D $\varphi\ \chi\ \sigma$ fields $V(r,n) = \sum_{LM} V_{LM}(r) Y_{LM}(n)$

$S_{U,m+r}$

~$10^{88.6}$

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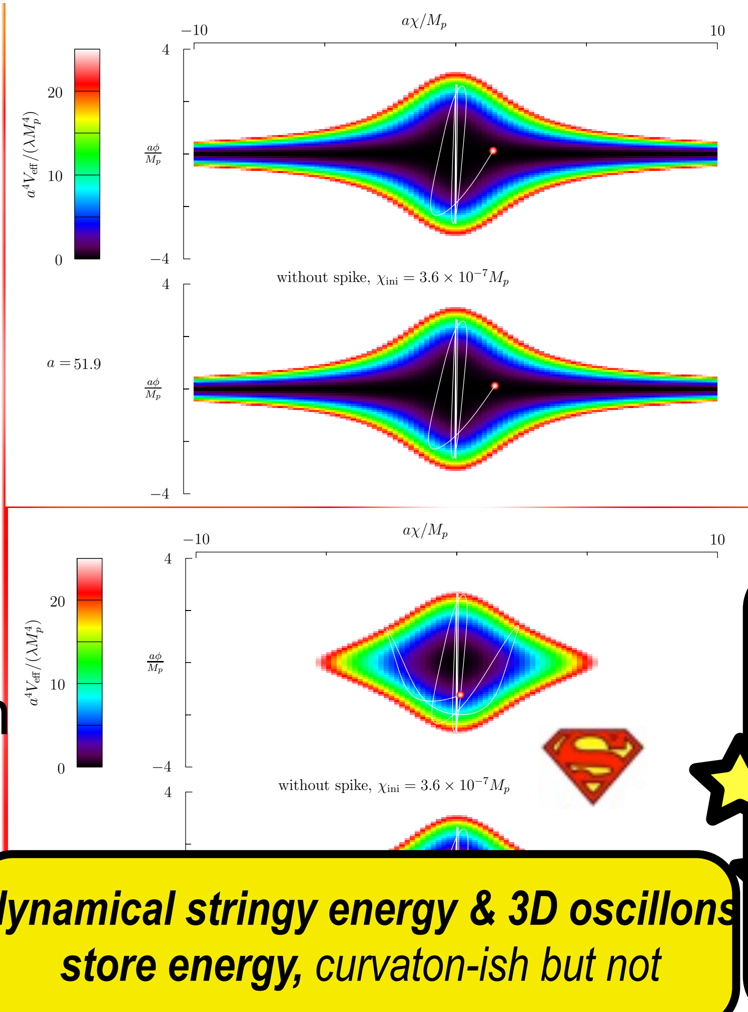

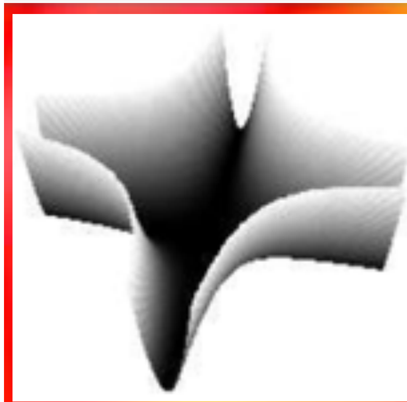

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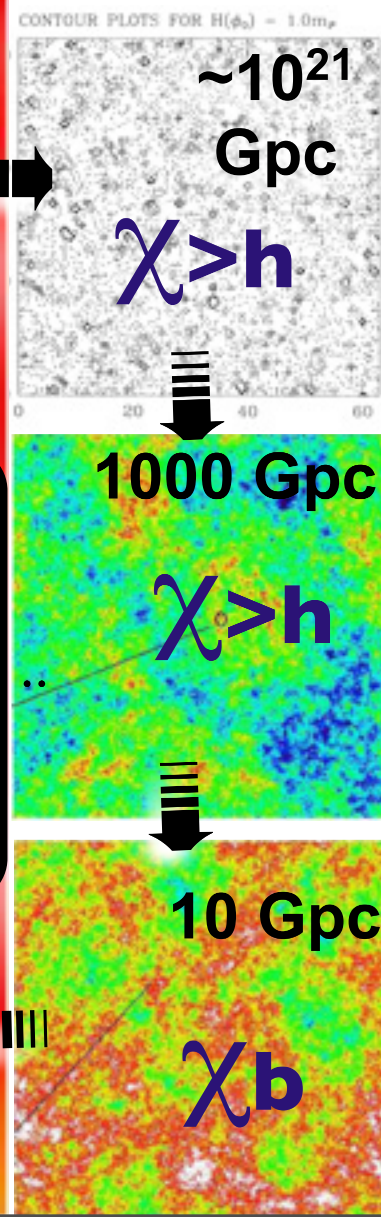
$= 1/4\, \lambda\, (r^2 - v^2)^2\, U$

$V(r)U(\cos\theta)$, $r^2 = \phi^2+\chi^2$

dynamical stringy energy & 3D oscillons store energy, *curvaton-ish but not*

$S_{U,UUULSS}$



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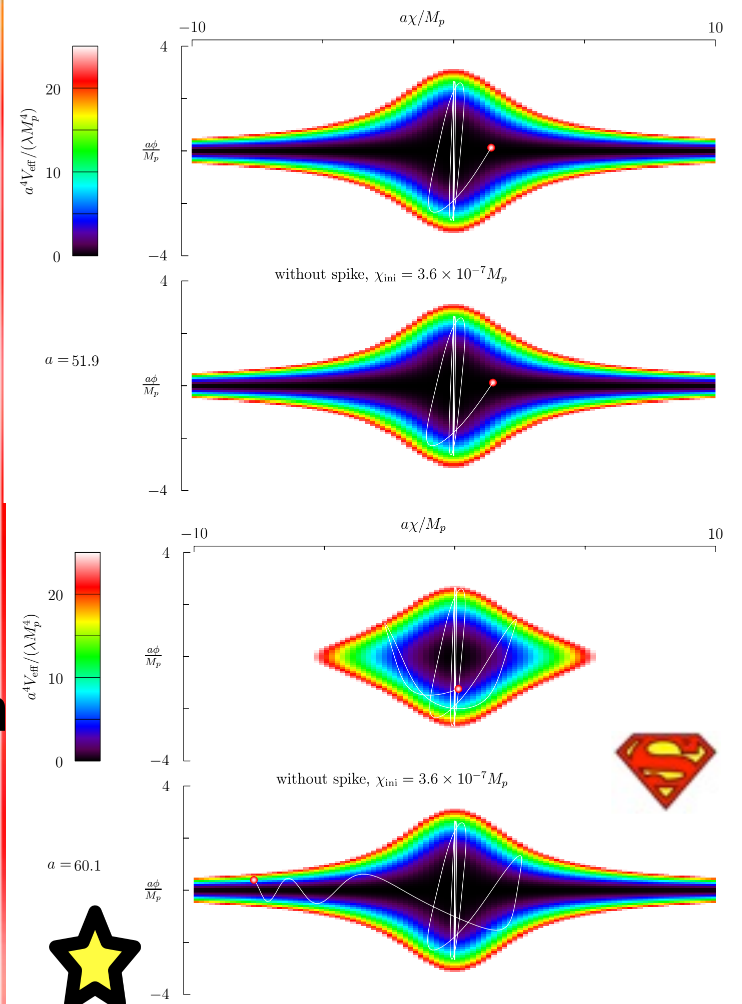
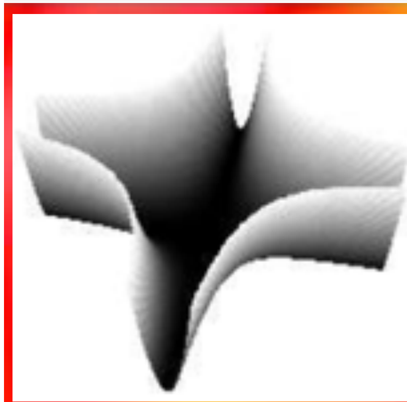
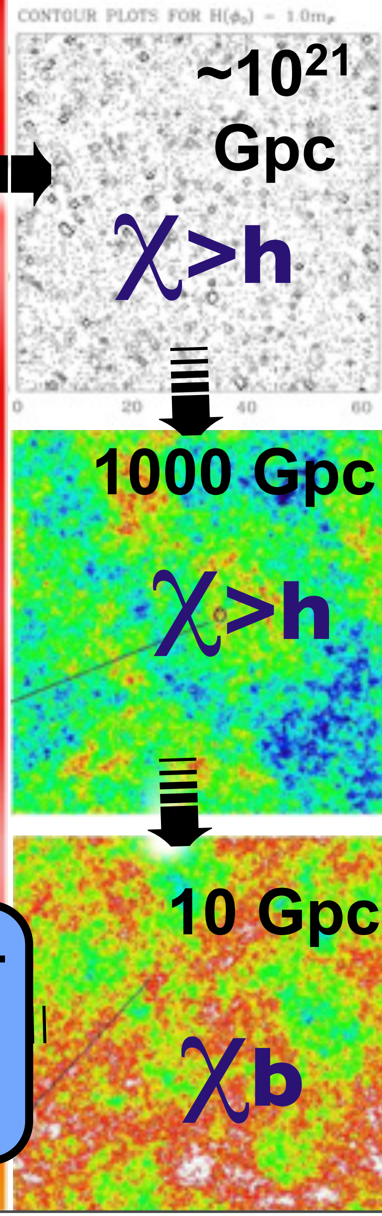




How general? We now think very - basins at the end of inflation

$V(r)U(\cos\theta)$, $r^2 = \phi^2 + \chi^2$

$S_{U,uuUULSS}$

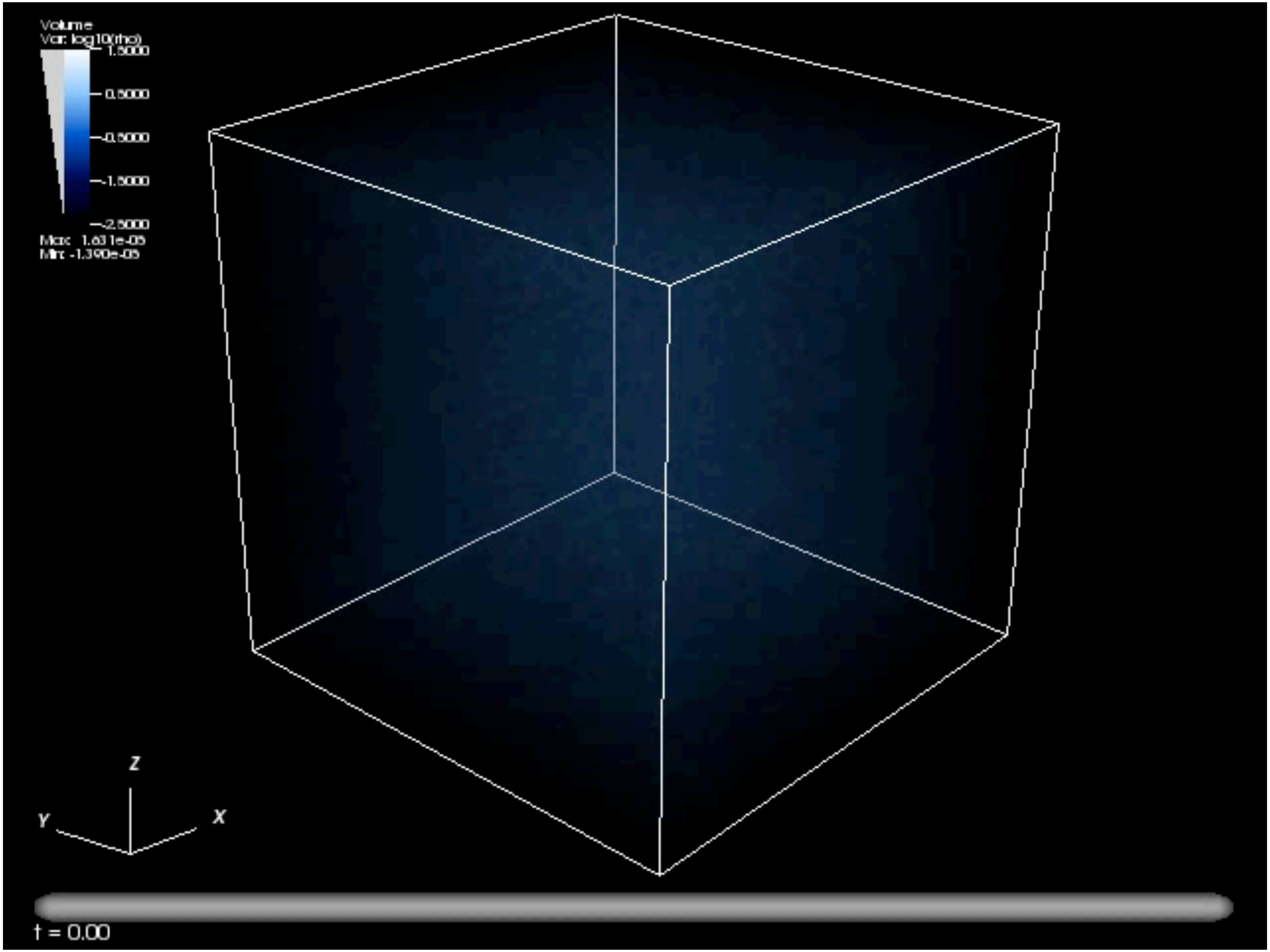


angular variables pNGB natural inflation, racetrack, monodromy, ..

$V(r,\theta) = \sum_M V_M(r) \cos(m\theta)$ *pNGB, Roulette r~hole size*

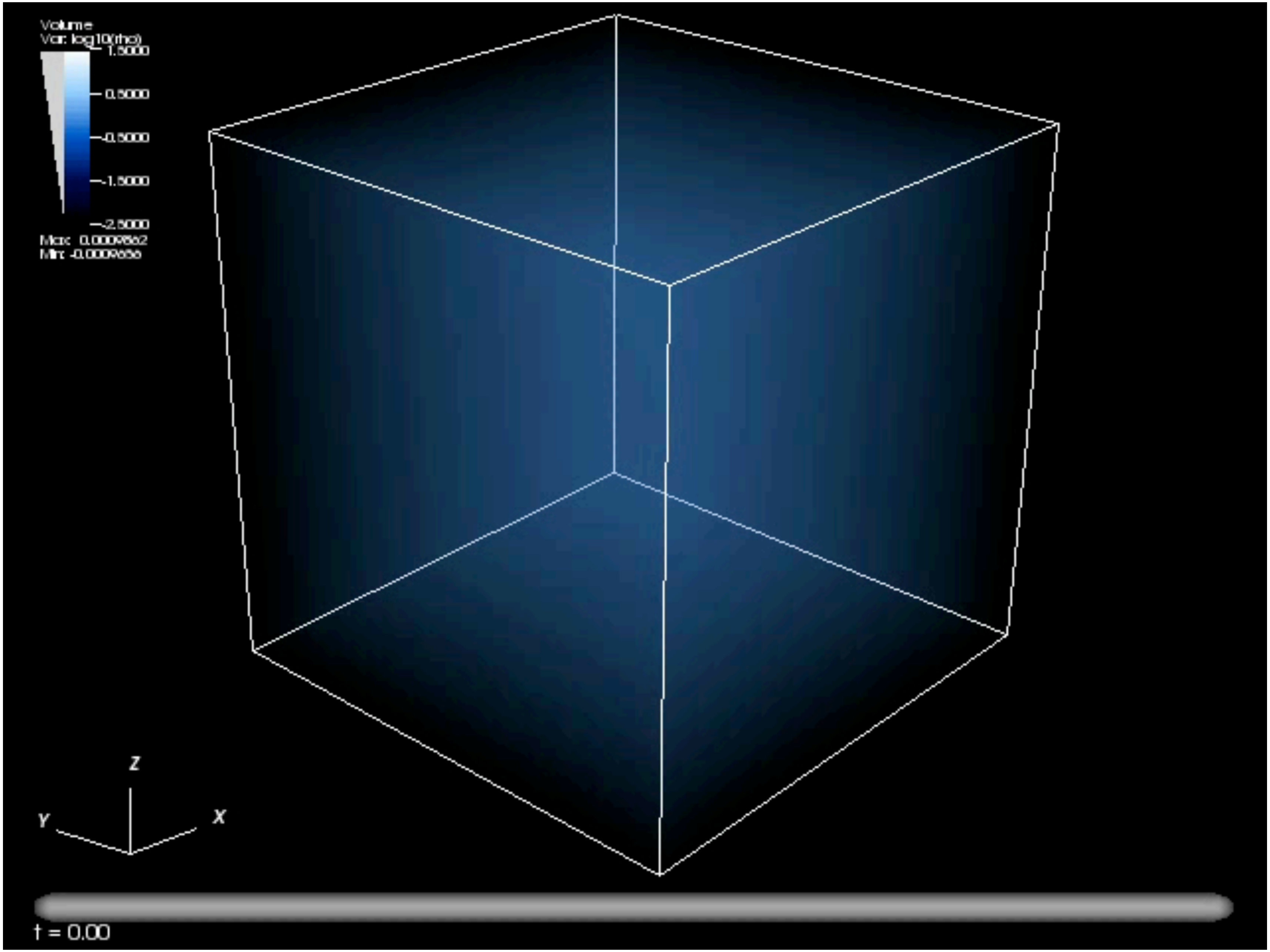
3D $\varphi\ \chi\ \sigma$ fields $V(r,n) = \sum_{LM} V_{LM}(r) Y_{LM}(n)$

quartic inflaton $V(\phi,\chi) = 1/4\ \lambda\phi^4 + 1/2\ g^2 \phi^2 \chi^2$



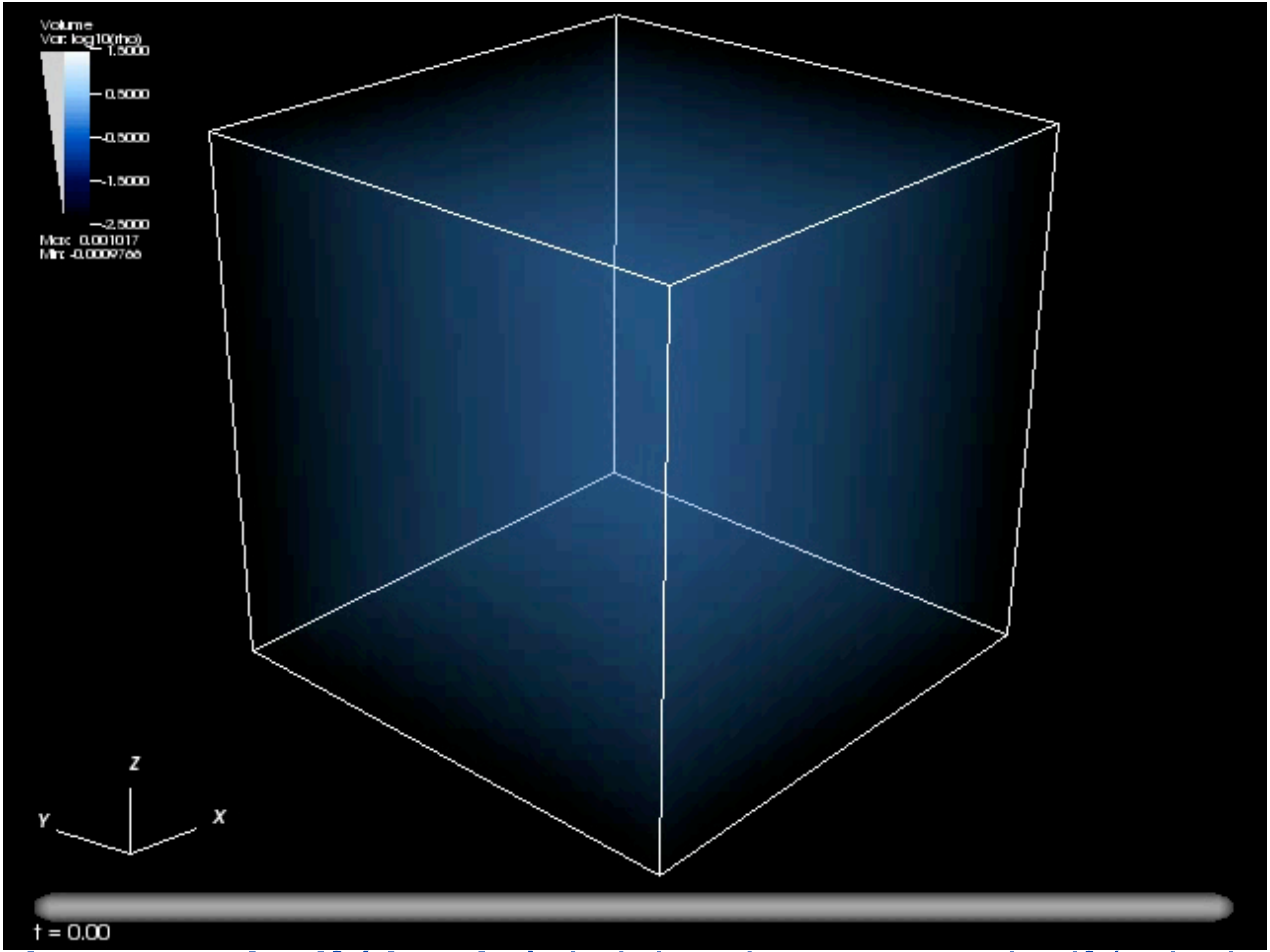
log-normal pdf (density)*, in k-bands too; normal pdf (velocity)*

quadratic inflaton $V(\phi,\chi) = \ 1/2\ m^2\phi^2 + 1/2\ g^2(\sigma)\phi^2\chi^2$ ..



log-normal pdf (density)*, in k-bands too; normal pdf (velocity)*

quadratic inflaton **trilinear coupling** $V(\phi,\chi) = 1/2\, m^2\phi^2 + 1/2\, \sigma\, \phi\chi^2 + 1/4\, \lambda\, \chi^4$



log-normal pdf (density)*, in k-bands too; normal pdf (velocity)*

Designing density fluctuation spectra in inflation

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obeying Gaussian statistics independently of initial conditions. Since observations only probe a narrow patch of the potential surface, it is possible that it is littered with moguls, leading to arbitrarily complex "mountain range" spectra that can only be determined phenomenologically. We also construct an inflation model which houses the chaotic inflation picture within the grand unified theory (GUT) framework. The standard chaotic picture requires an unnaturally flat scalar field potential, $\lambda \approx 5\times 10^{-14}$, and a strong curvature coupling parameter bound, $\xi < 0.002$. By allowing the Higgs field to be strongly coupled to gravity through a large negative curvature coupling strength, $\xi \sim -10^4$, so the Planck mass depends on the GUT Higgs field, the Higgs field can be strongly coupled to matter fields [with $\lambda \sim (\xi/10^5)^2$]. This leads to both a flat Zeldovich spectrum of the "observed" amplitude and a high reheating temperature ($\sim 10^{15}$ GeV), unlike the $\lambda \sim 10^{-13}$ standard case. The large $-\xi$ would be related to the ratio of the Planck scale to a typical GUT scale. Although a single dynamically important Higgs multiplet gives flat spectra, a richer Higgs sector could lead to broken scale invariance.

APPENDIX B: INDUCED GRAVITY IN A GUT FRAMEWORK

In Sec. VII we claimed that if the curvature coupling constant was chosen to be $\xi = -2\times 10^4$, inflation could be incorporated within a grand unified theory. However, the simplified analysis of that section utilized a single complex scalar field coupled to a U(1) gauge field, and we now wish to consider the physically more interesting case of non-Abelian gauge fields. We concentrate on the well-studied minimal SU(5) model, although any gauge group could be incorporated. In SU(5), the Higgs field, H, and the gauge field, A_μ, both in the adjoint representation,

We now consider the cosmological consequences of the four fields that parametrize the diagonal Higgs field, $H = \sqrt{2}\phi_i \tau^i$. It proves convenient to choose the diagonal basis

$$\begin{aligned}
\tau^1 &= \mathrm{diag}[2,2,2,-3,-3]/\sqrt{60}\ ,\\
\tau^2 &= \mathrm{diag}[0,0,0,1,-1]/2\ ,\\
\tau^3 &= \mathrm{diag}[1,-1,0,0,0]/2\ ,\\
\tau^4 &= \mathrm{diag}[1,1,-2,0,0]/(2\sqrt{3})\ ,
\end{aligned} \tag{B14}$$

and then express the ϕ_i in hyperspherical coordinates, $\phi,\theta_1,\theta_2,\theta_3$:

angle variables in SU(5)

$$\begin{aligned}
\phi_1 &= \phi\cos\theta_1\ ,\\
\phi_2 &= \phi\sin\theta_1\cos\theta_2\ ,\\
\phi_3 &= \phi\sin\theta_1\sin\theta_2\cos\theta_3\ ,\\
\phi_4 &= \phi\sin\theta_1\sin\theta_2\sin\theta_3\ .
\end{aligned} \tag{B15}$$

We find that the scalar field part of the Lagrangian density, (B2), is

$$\begin{aligned}
\mathcal{L}_\phi = -\tfrac{1}{2}\chi_{,\mu}\chi^{,\mu} - \frac{1}{2}\frac{m_P^2\phi^2}{16\pi f}(\theta_{1,\mu}\theta_1^{;\mu} + \sin^2\theta_1\theta_{2,\mu}\theta_2^{;\mu}\\
+\sin^2\theta_1\sin^2\theta_2\theta_{3,\mu}\theta_3^{;\mu})\\
-\left[\frac{m_P^2}{16\pi f}\right]^2 V(H)\ ,
\end{aligned} \tag{B16a}$$

where

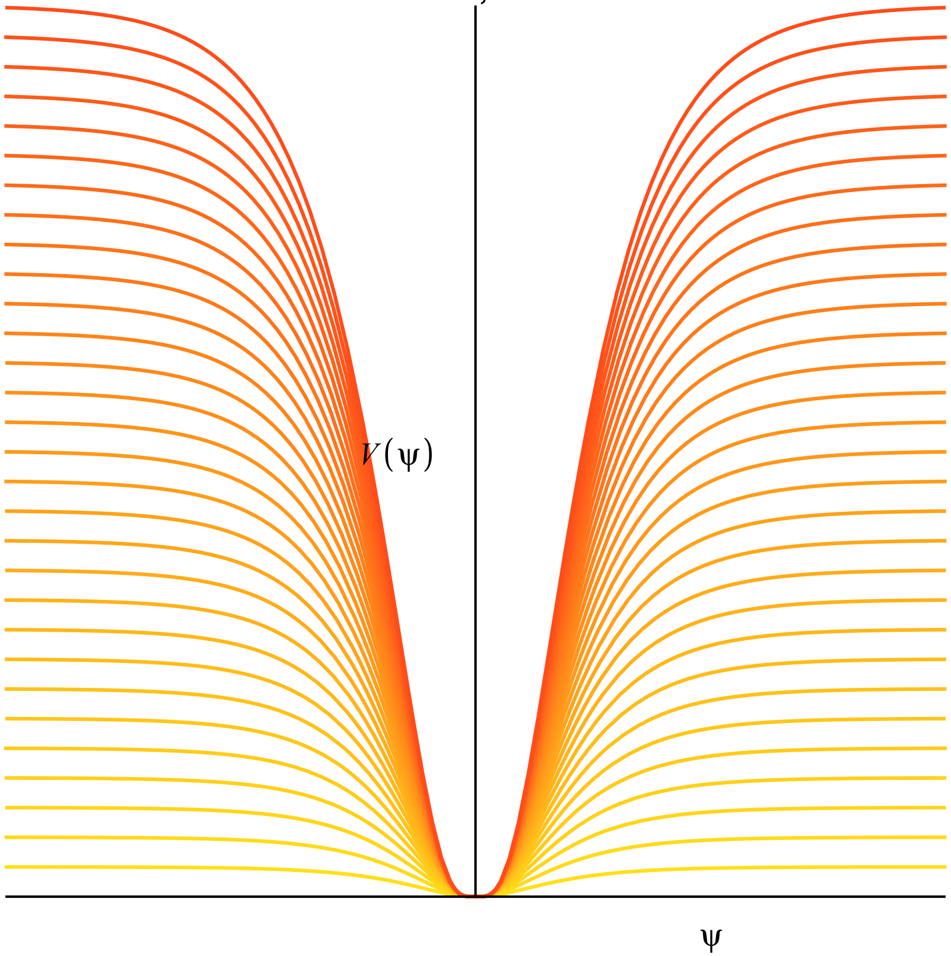
$$V(H) = -m_1^2\phi^2 + \phi^4[\lambda_1 + \lambda_2 g(\theta_i)]\ , \tag{B16b}$$

$$\begin{aligned}
g(\theta_i) = \tfrac{7}{30} + \tfrac{4}{3}\sin^2\theta_1 - \tfrac{16}{15}\sin^4\theta_1 + \sin^2\theta_1\sin^2\theta_2\\
\times\left[-1 + \sin^2\theta_1\sin^2\theta_2\right.\\
\left. + \frac{4\sqrt{5}}{15}\cos\theta_1\sin\theta_1\sin\theta_2\sin(3\theta_3)\right]\ ,
\end{aligned} \tag{B16c}$$

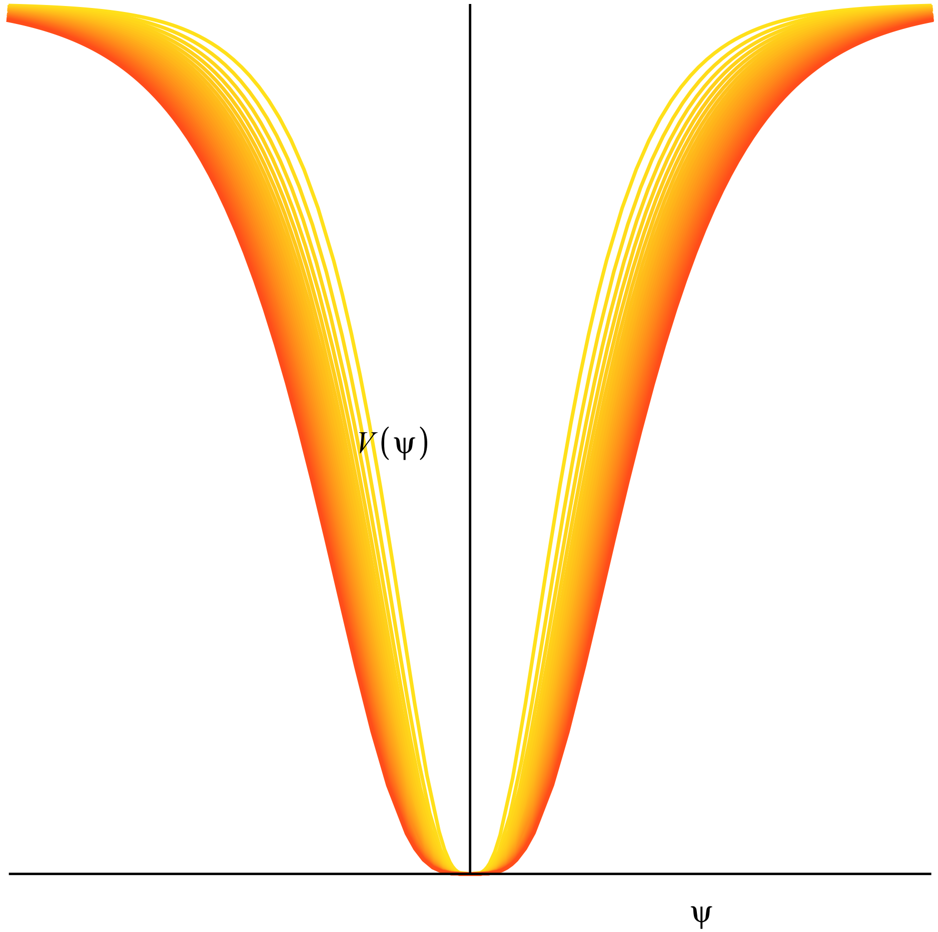
L = (1-xi phi^2) R/2 - (nabla phi)^2/2 - lambda phi^4/4

in Einstein frame and for new (canonically normalized) field psi

const lambda, variable xi



const lambda/xi^2, variable xi



$$\chi = \int [K^{11}(\phi)]^{1/2} d\phi \,,$$

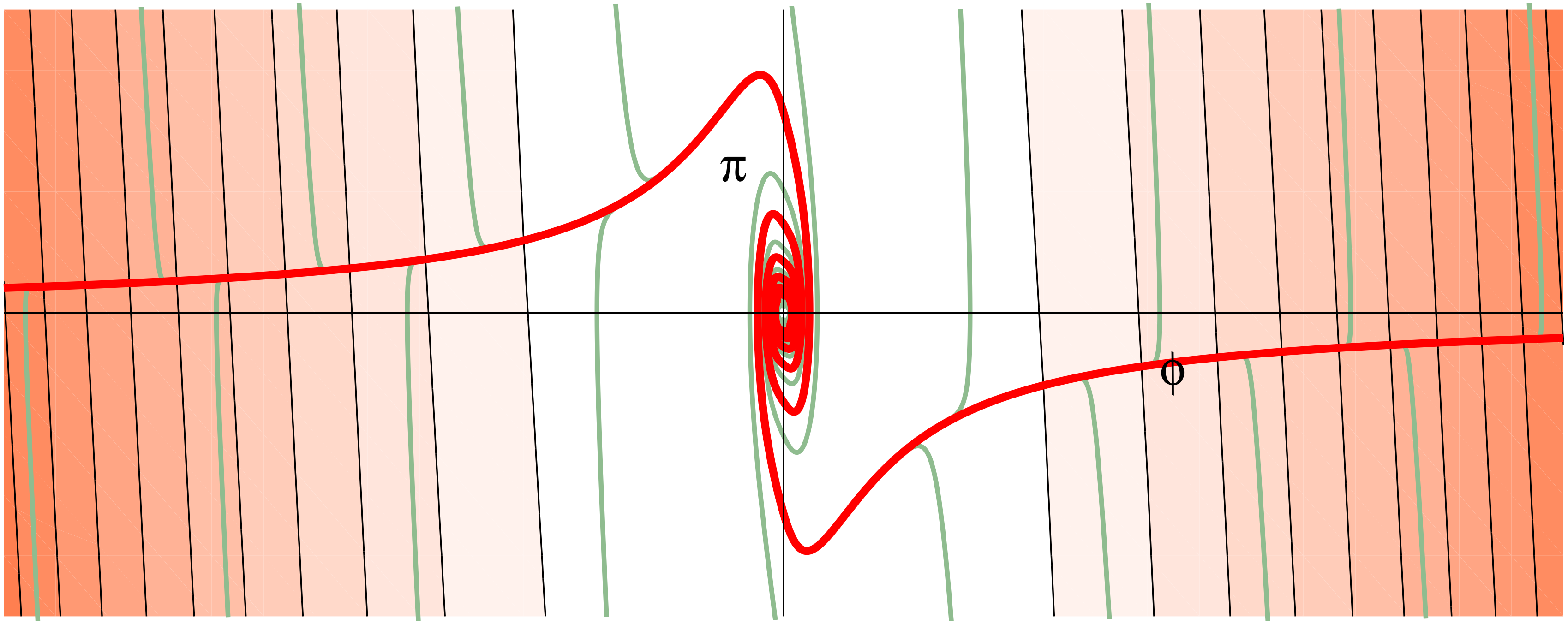
$$U(\chi) = \left[\frac{m^2}{m_P^2} + 8\pi|\xi| \frac{\phi^2(\chi)}{m_P^2} \right]^{-2} V(\phi(\chi)) \,.$$

$$K^{11} = \frac{\dfrac{m^2}{m_P^2} + 8\pi|\xi|(1+6|\xi|)\dfrac{\phi^2}{m_P^2}}{\left[\dfrac{m^2}{m_P^2} + 8\pi|\xi| \dfrac{\phi^2}{m_P^2} \right]^2} \,.$$

quartic inflaton variable Planck mass $V(\phi,\chi) = 1/4\, \lambda\phi^4 - 1/2\, \xi\, \phi^2 R + 1/2\, g^2 \phi^2 \chi^2$

$\xi = -1$

shading = *ln* a (φ,π)



spikes persist with flattened effective potential

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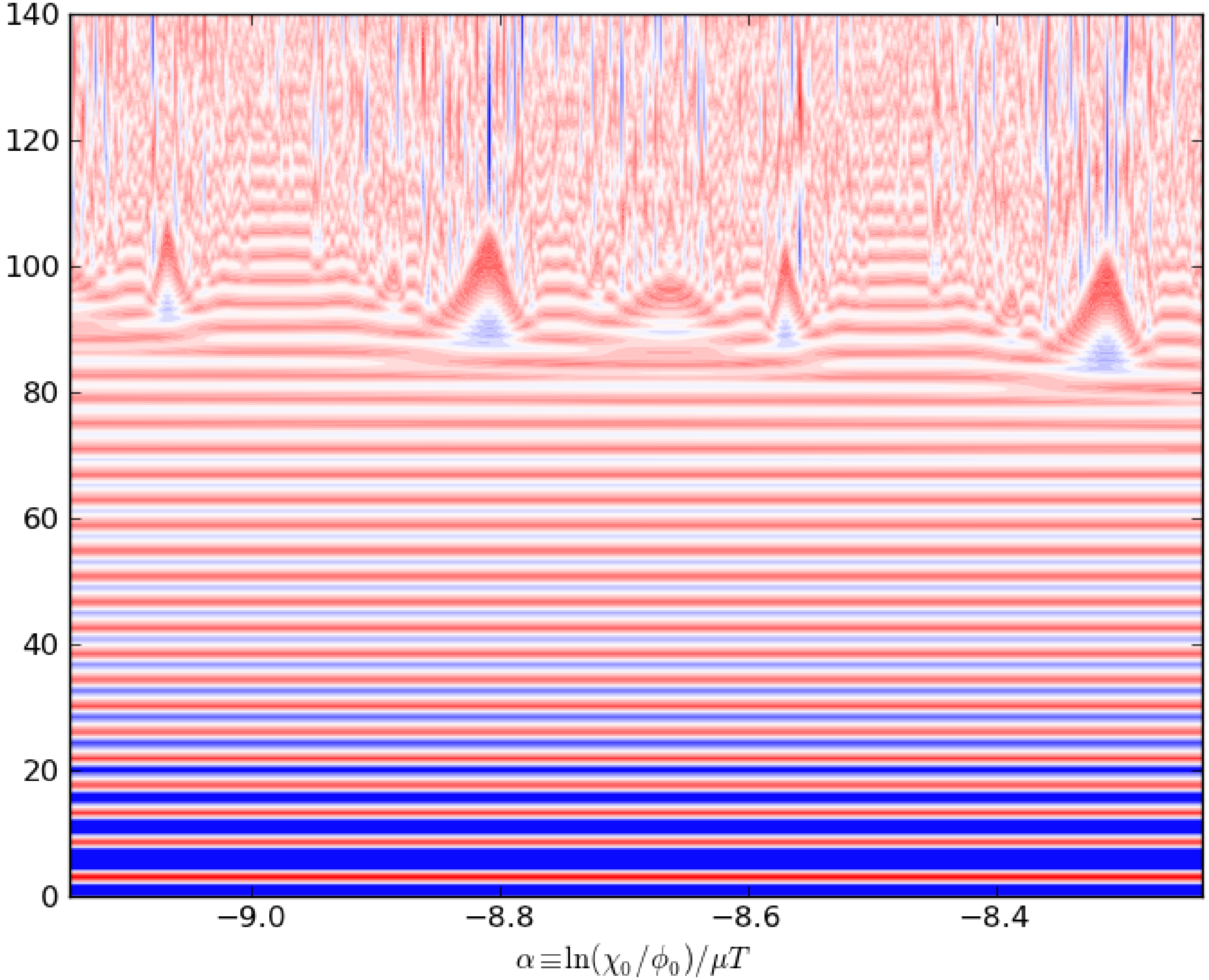
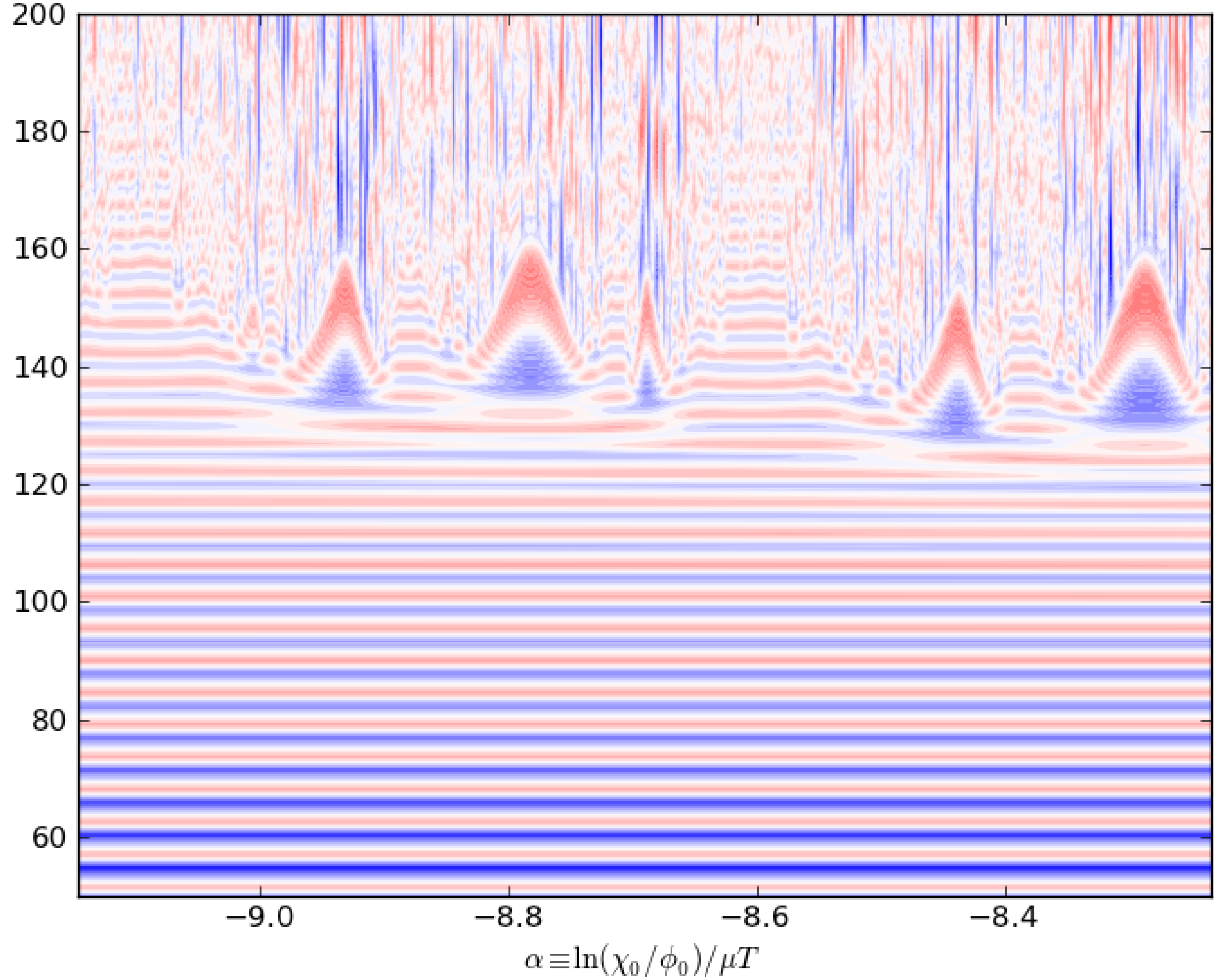


spikes persist with flattened effective potential

quartic inflaton variable Planck mass $V(\phi,\chi) = 1/4\ \lambda\phi^4 - 1/2\ \xi\ \phi^2 R + 1/2\ g^2 \phi^2 \chi^2$

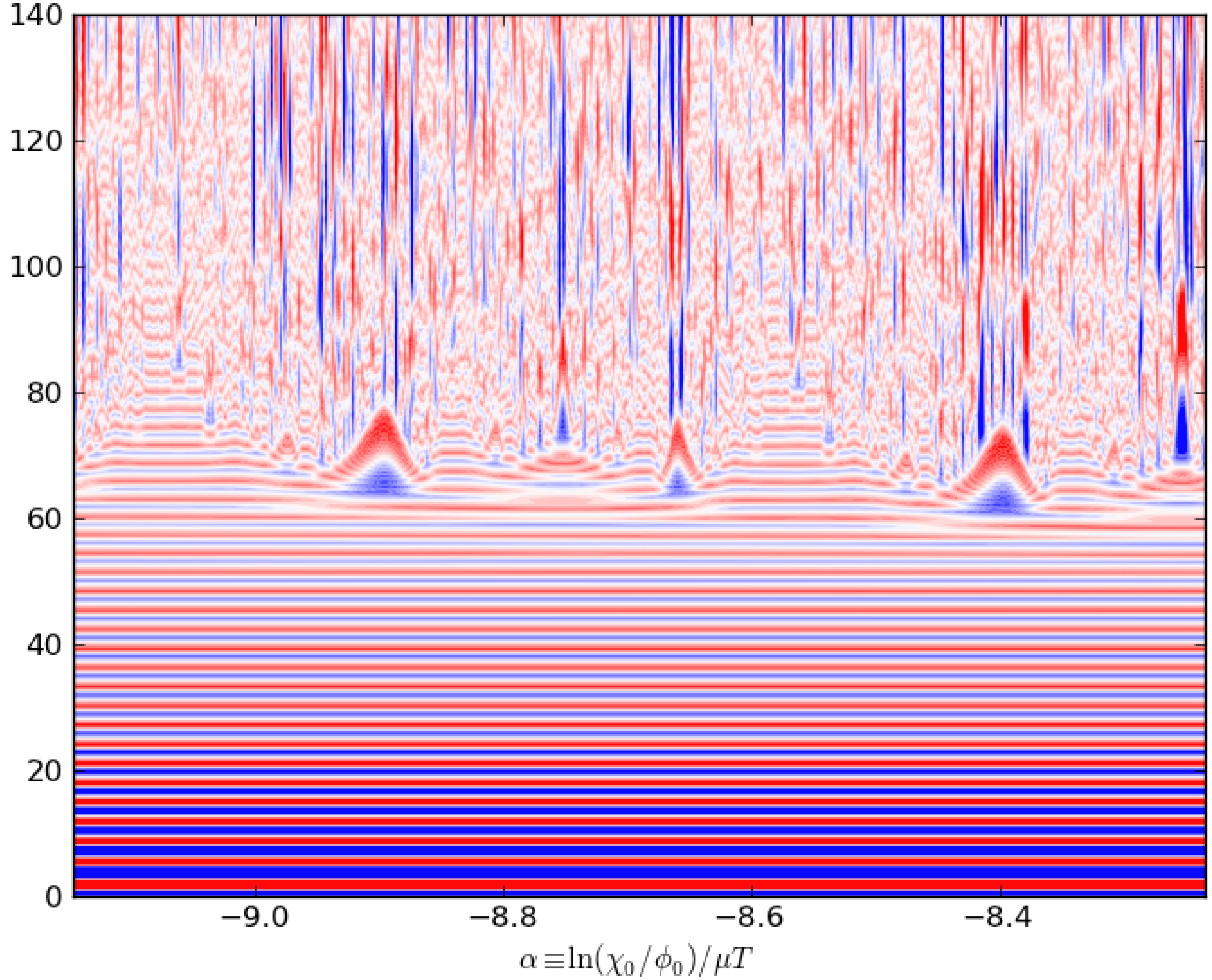
$\xi=-2$



spikes persist with flattened effective potential

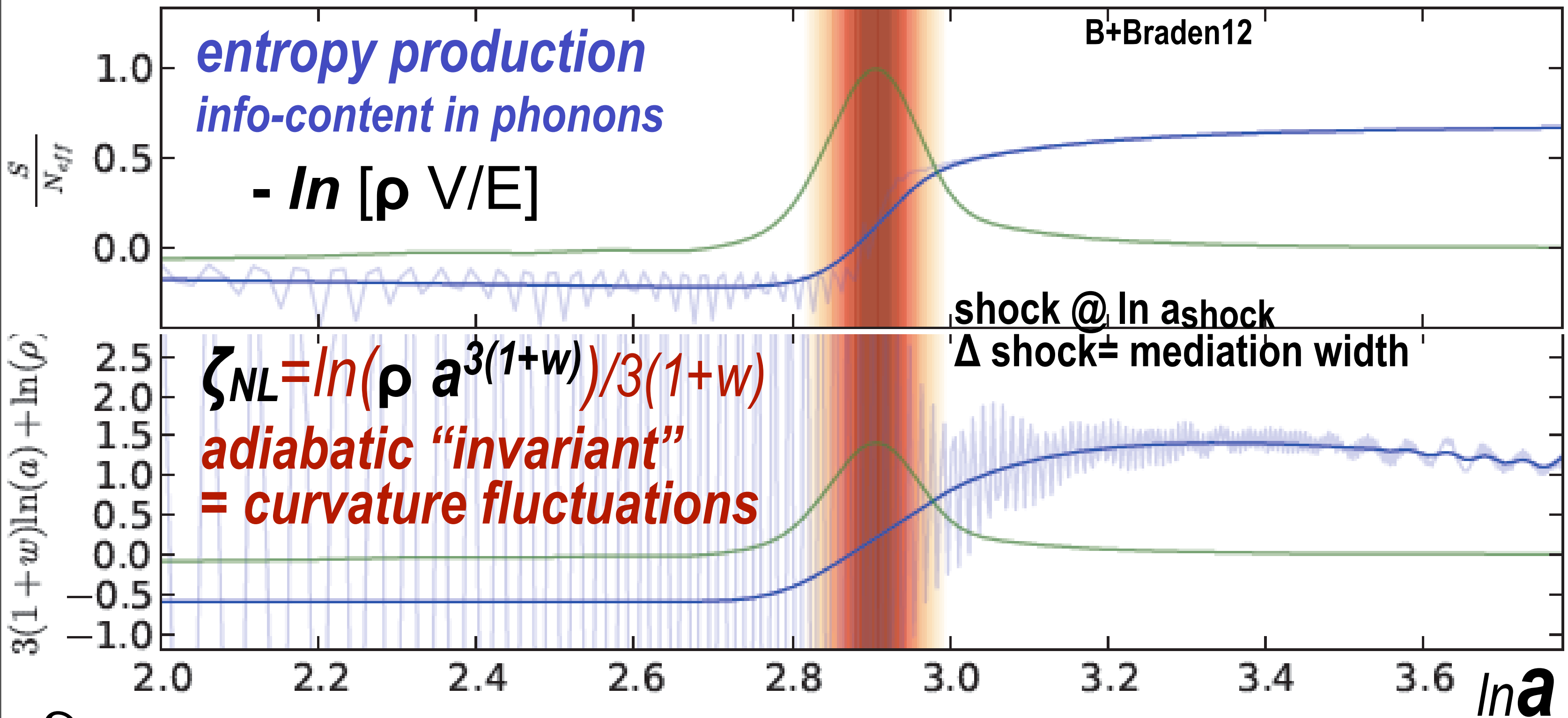
quartic inflaton variable Planck mass $V(\phi,\chi) = 1/4\, \lambda\phi^4 - 1/2\, \xi\, \phi^2 R + 1/2\, g^2 \phi^2 \chi^2$

ξ=-1/2



spikes persist with flattened effective potential

nonG from large-scale modulations of the shock-in-times of preheating



true thermal equilibrium far off ➤ & on to coupling to standard model degrees of freedom

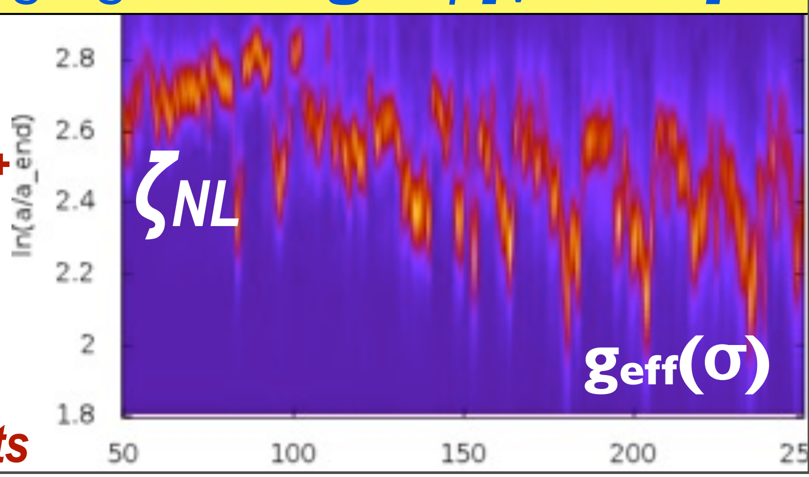
$\delta\zeta_{NLshock}$ (g(σ(x)) => modulated non-G

$g_0+g_1\,\sigma/M_P$, $g_0 \exp[\gamma_1\,\sigma/M_P]$, ..

$V(\phi,\chi)=1/2\; m^2\phi^2 + 1/2\; g_{eff}(\sigma)^2\phi^2\chi^2$

$\delta\zeta_{NLshock}(\chi_i(\mathbf{x})\; |g^2/\lambda)$) => NonG cold spots ++

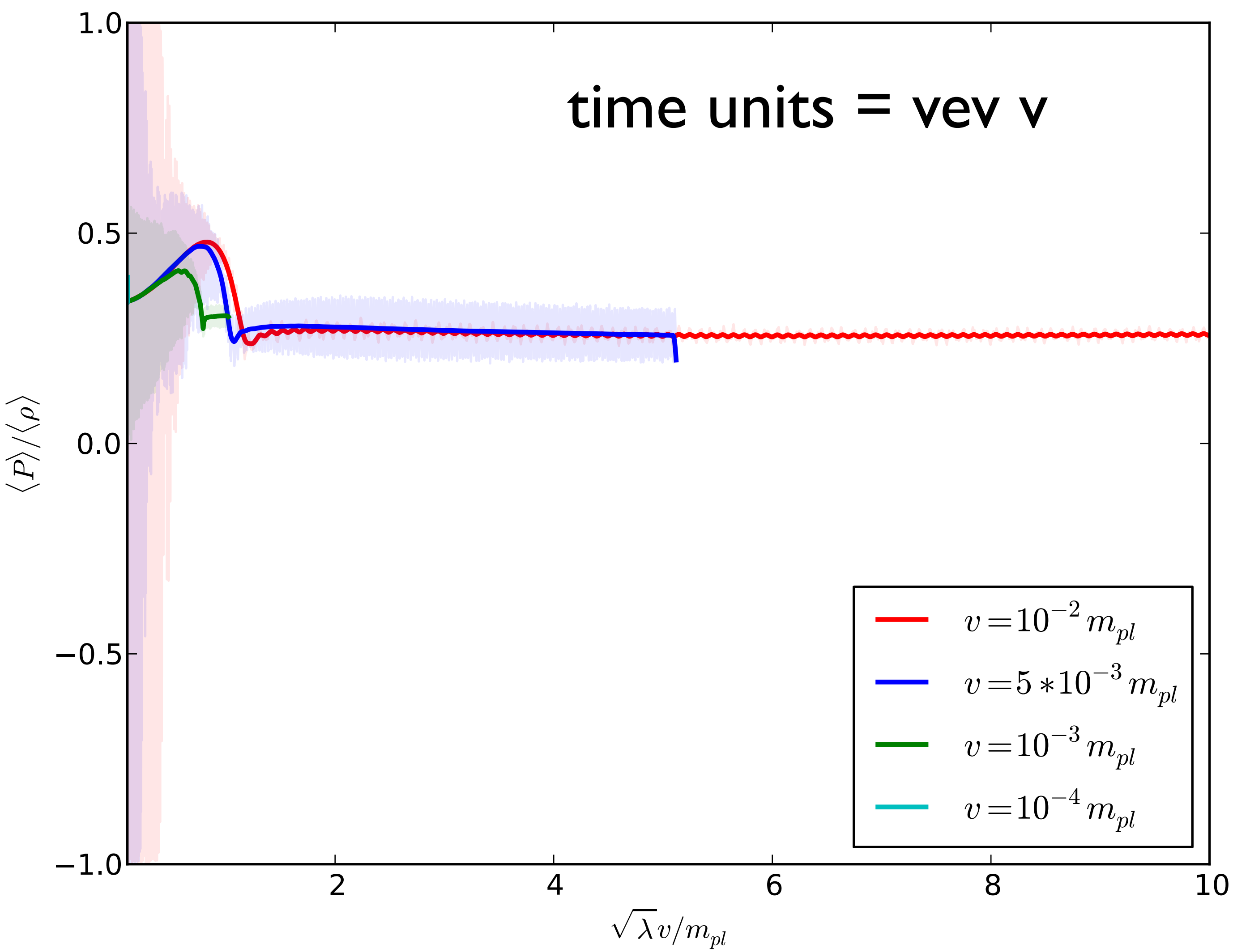
$V(\phi,\chi)=1/4\;\lambda\phi^4 + 1/2\; g^2\phi^2\chi^2$



V_{eff} is dynamical *Bond,Braden,Frolov,Huang13*

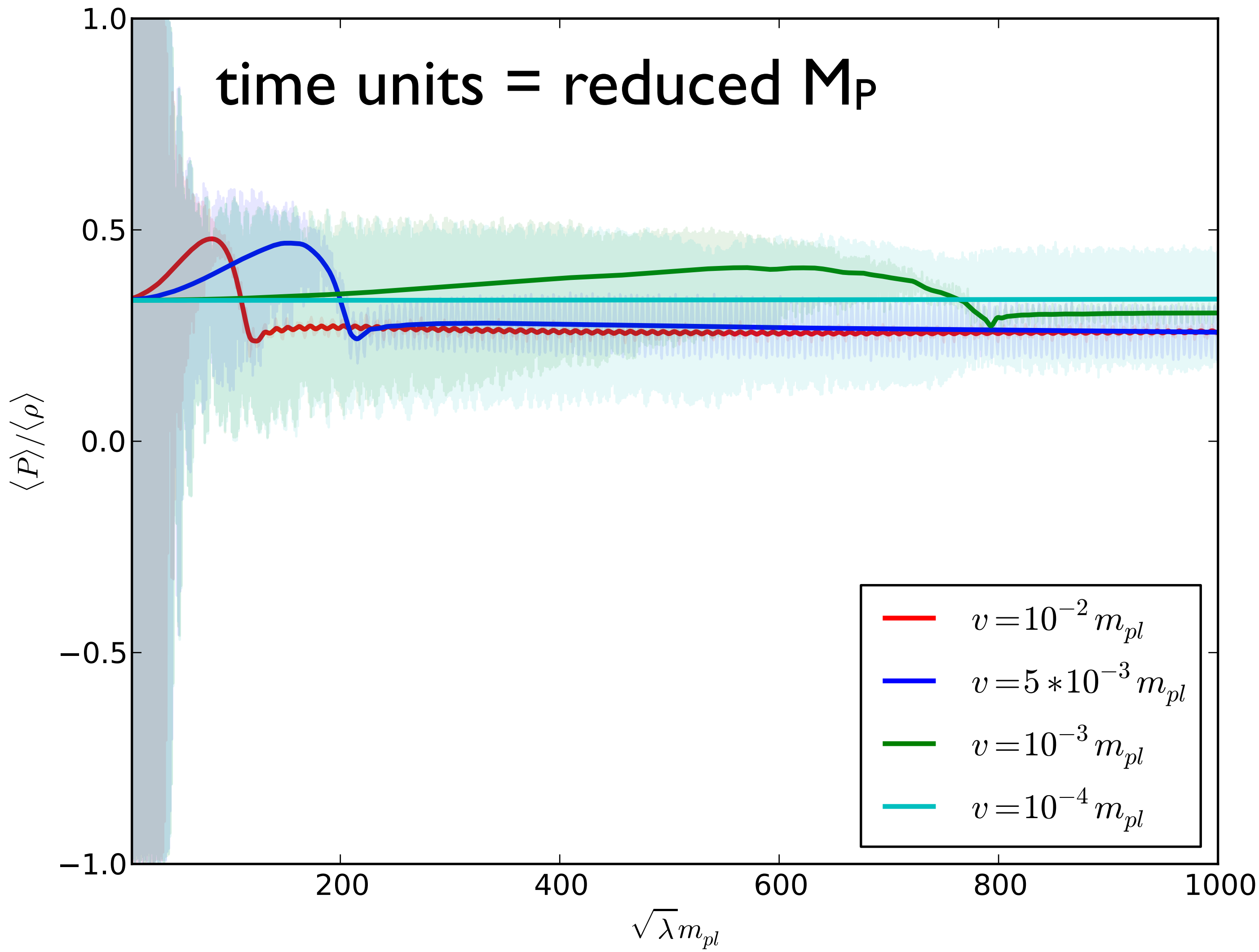
unconventional local non-G: no scale built into V;
perturbative isocon-based f_{NL}; rare event cold spots

$V(\phi,\chi) = 1/4\,\lambda\,(r^2 - v^2)^2\,U$ $\quad V(r)U(\cos\theta),\ r^2 = \phi^2+\chi^2$



string-like field configurations mediate the EoS for a long time

$V(\phi,\chi) = 1/4\ \lambda\ (r^2 - v^2)^2\ U \qquad V(r)U(\cos\theta),\ r^2 = \phi^2+\chi^2$



string-like field configurations mediate the EoS for a long time

from

quartic inflaton $V(\phi,\chi) = 1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$

quadratic inflaton $V(\phi,\chi) = 1/2\ m^2\phi^2 + 1/2\ g^2(\sigma)\phi^2\chi^2$ ..

quadratic inflaton trilinear coupling $V(\phi,\chi) = 1/2\ m^2\phi^2 + 1/2\ \sigma\ \phi\chi^2 + 1/4\ \lambda\ \chi^4$

quartic inflaton variable Planck mass $V(\phi,\chi) = 1/4\ \lambda\phi^4 - 1/2\ \xi\ \phi^2 R + 1/2\ g^2\phi^2\chi^2$

aka Higgs inflation. flattened effective potential in the Einstein frame

to

angular variables ***pNGB natural inflation, racetrack, monodromy, ..***

2 field: $V(r,\theta) = \sum_M V_M(r)\cos(m\theta)$ ***pNGB, Roulette r~hole size***

3 field: 3D $\varphi\ \chi\ \sigma$ fields $V(r,n) = \sum_{LM} V_{LM}(r) Y_{LM}(n)$

5 field: *angle variables in SU(5) & etc.*

to?

Simple exercises to flatten your potential

Xi Dong, Bart Horn, Eva Silverstein, and Alexander Westphal 2011