Extending stochastic inflation to include coherent pulses to explain instability-driven multi-field simulation ensembles of concentrated primordial non-Gaussianity

Dick Bond *@simons eU 22 04 26* Tom Morrison (GS), Jonathan Braden, Tomas Galvez

$3\boldsymbol{\zeta}(x,t) = \int_{\text{field-path}} (dE+pdV)/(E+pV) \sim dS/\beta(E+pV)$ ***the* entropic structure measure**

$\zeta(x,t) \sim \int \Delta\zeta_{nG}\text{-}Prominences(x-x_c)\, dN_c(x_c R_c) +$ Gaussian *random* ζ*-flucs*

$\zeta(x,t) \sim \sum_p \Delta\zeta_{nG}(\boldsymbol{\chi}_p(x,\boldsymbol{\alpha}_e)) +$ Gaussian *random* ζ*-flucs*, $\boldsymbol{\chi}_p(x,\boldsymbol{\alpha}_e) =$ Gaussian *random*

nonG from instabilities during inflation as well as **modulated heating nonG**

- Inflation probes fundamental physics in the CMB/LSS and higher k scales through ζ. Major effort: linear transfer / nonlinear transport $\zeta_G+\zeta_{nG}$ from early U through neutrino decoupling and photon decoupling through the gravitational instability of DM and baryons into the entangled cosmic web (x,t) and its luminous observables - and component separate /disentangle non-G ζ-forms /templates to measure. We use Webskys. Deep Learning approaches are underway, Seljak, Wandelt + @MIC2022 meeting

- NonG = from nearly G aka perturbative nonG everywhere distributed - Planck well-constrained, LSS measures just beginning (via MIC+) - to **space (x) and resolution (k) confined nonG extreme peaks** aka concentrations to wall, string, etal ζ-memories => complex, so let simulations be our guide to what's possible, what may be generic, and how to measure the forms.

- Conclude: with m_{AB}^2 temporarily < 0 we find localized concentrations of NonG is a generic feature of breaking/restoring symmetry during inflation for a wide range of potential parameters. Superposed almost statistically independently (?) on a relatively Gaussian base. => **In search of Buried Treasure in LSS/CMB**

varieties of primordial nonG and how to search for them

perturbative: the nonG component is strongly correlated with the dominant Gaussian

see Planck2018 IX (nonG) for an exhaustive study and current constraints - using both T+Epol

Planck2018 IX arxiv 1905.05697 correlated nonG
nonG 3-point-correlation-pattern measure
f_{nl}: -0.9 ± 5.1 local for -Newton potential
=> f_{NL^*} =-1.54 ± 3.0 for phonons/V-strain $f_{NL^*} \sigma_\zeta$ < .0006
f_{nl}: -26 ± 47 equilateral
-38 ± 24 orthogonal
SO to .0003

cf. ***Planck2015 XVII***
nonG 3-point-correlation-pattern measure
f_{nl}=0.8 ± 5.0 local for -Newton potential
=> f_{NL^*} =-0.52 ± 3.0 for phonons/V-strain
-f_{nl}: -4 ± 43 equilateral
-26 ± 21 orthogonal

f_{nl}: *to ± 0.5 ! SphereX ~2023 - all-sky near-IR satellite 6 arcsec resolution 96 bands*

Planck 2015/2018 VII (Isotropy & Statistics) arxiv 1906.02552. **blind nonG stats in scale space => no *strong* evidence**
e.g., ***Kolmogorov-Sinai test on n(T, E | Prominences) at 2 scales.*** **rare low-L anomalies,** ***cold spot in T not E***

beyond Planck2018: **higher res CMB (SO,S4) ~ $f_{sky} L_{max}^2$** *cf.* **LSS $f_{sky} L_{max}^2$ X k_{max} d_{max}** ***z-space, LIM more modes***

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cf. ***BOSS bispectrum+power spectrum MIC22***
nonG 3-point-correlation-pattern measure
f_{nl}=-30 ± 29; -33 ± 28 local
=> .. *Senatore+; Zaldarriaga, Philcox+*
f_{nl}: 2 ± 212; 940 ± 600 equilateral
126 ± 72; 170 ± 170 orthogonal

f_{nl}: to ± 0.5 ! SphereX ~2023 - all-sky near-IR satellite 6 arcsec resolution 96 bands

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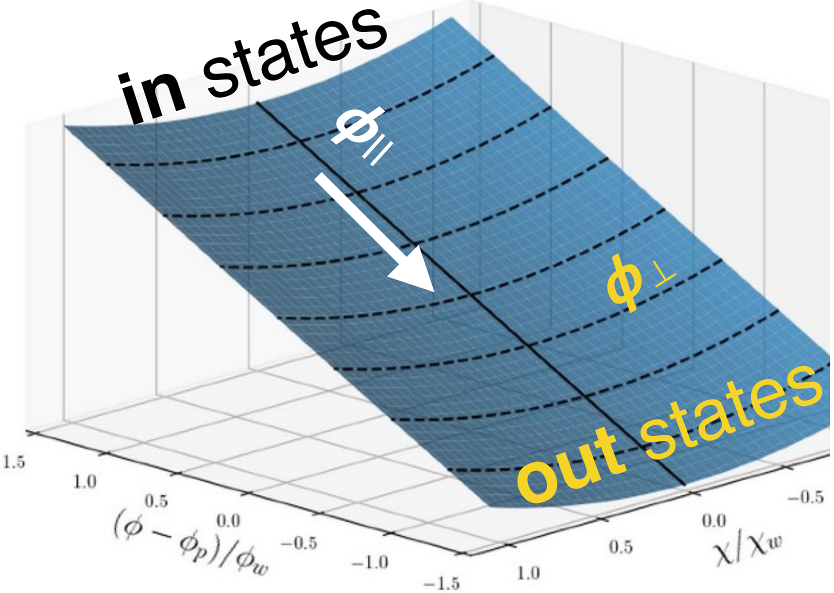
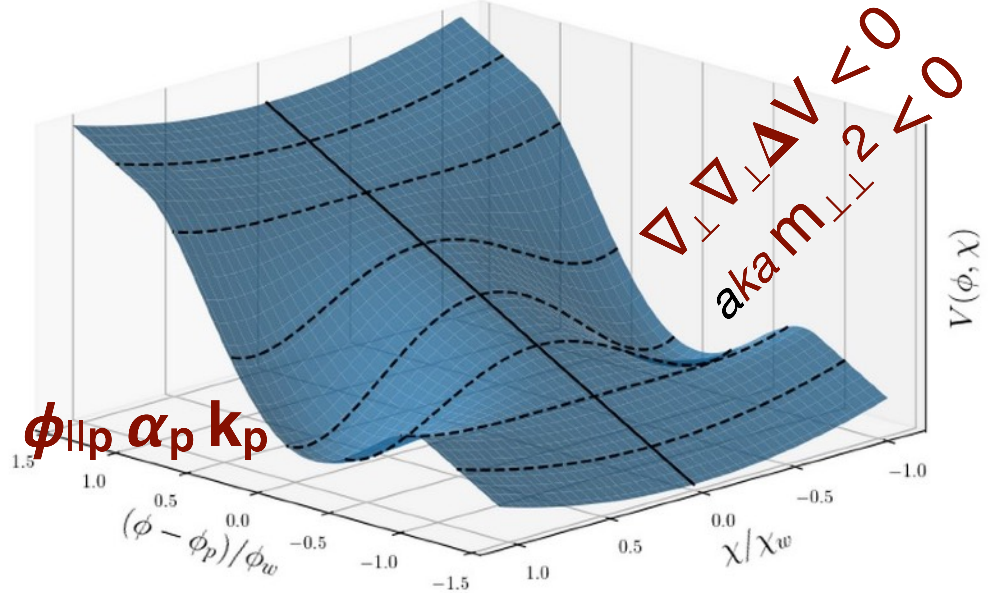




We get to choose k_p and instability strength & V0
k_p may be high and buried or - with heavy constraints - in the CMB+LSS range. There could be many k_p instability events

experiments:
χ-light -> χ-heavy
ΔV wide -> ΔV narrow
weak -> strong instability

unperturbed inflation flow +:

$$\Delta V = 1/4\lambda(\phi)[(\chi^2 - v^2)^2 - v^4];$$

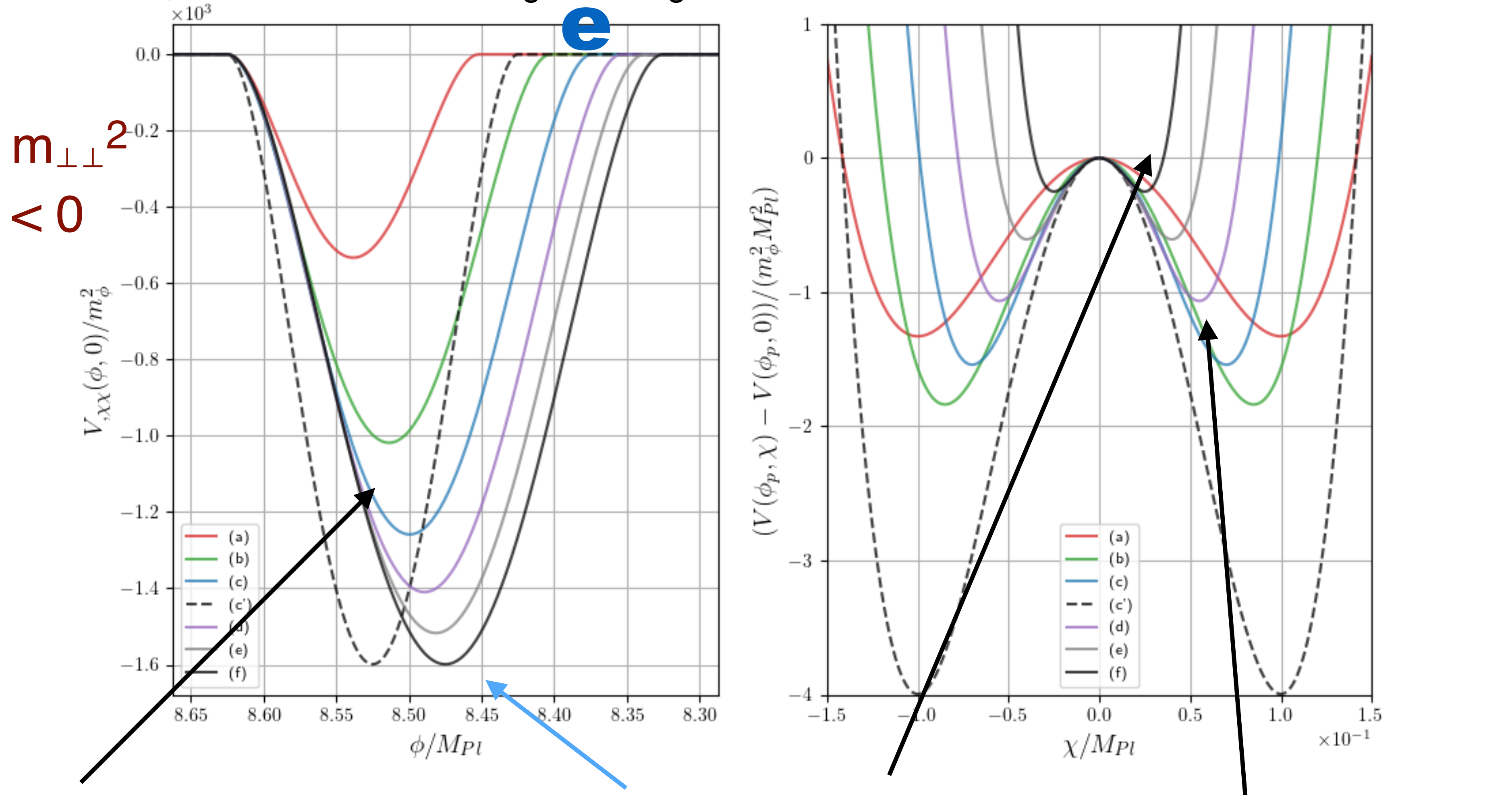
controls strength & on-off   vev

an ensemble of symmetry breaking/restoration potentials

$$\Delta V = 1/4\lambda(\phi)[(\chi^2 - v^2)^2 - v^4],$$

X U, U= 0 to 1 overall strength scaling

- a deep breath in the downward flow
- U makes differential templates easier to compute



leads to ζ peaks - common

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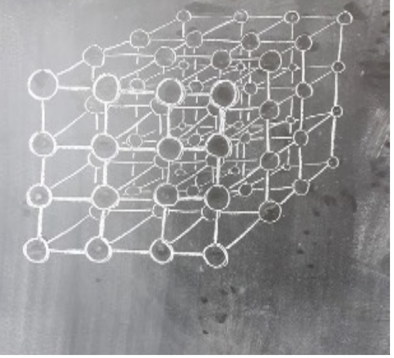
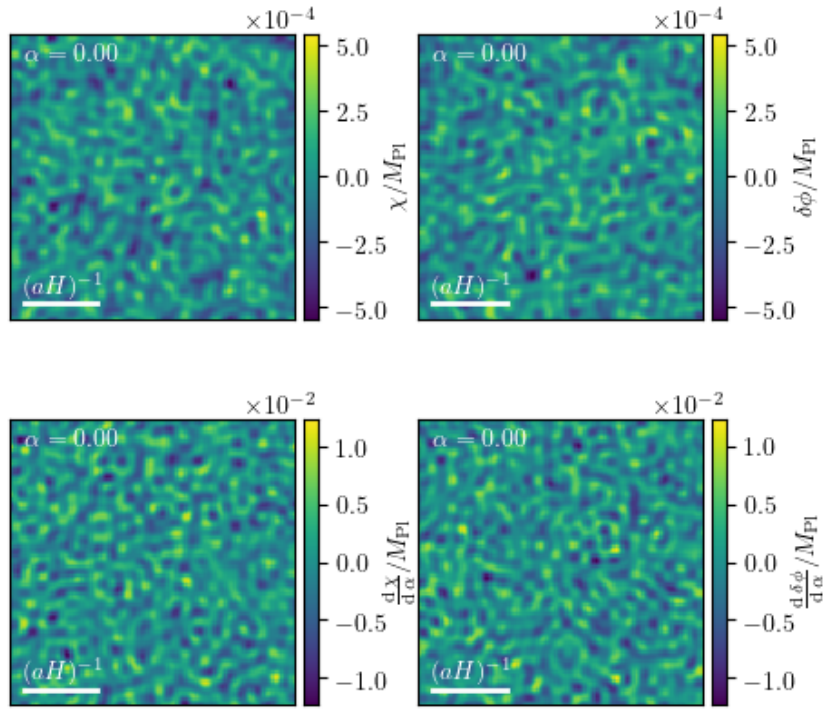


in state
in the native phase space variables

Discretizing space onto a lattice recasts PDEs as many coupled ODEs, which can be integrated numerically.



$$\frac{d\phi^A}{d\tau} = a^{-2}\Pi^A,$$

$$\frac{d\Pi^A}{d\tau} = -\nabla^2\phi^A - a^4\frac{\partial V}{\partial \phi^A},$$

$$\frac{d\alpha}{d\tau} = \frac{-1}{6M_{Pl}}\Pi^a,$$

$$\frac{d\Pi^a}{d\tau} = -\left\langle -a^{-3}\Pi^A\Pi^A + a\nabla\phi^A\cdot\nabla\phi^A + 4a^3V\right\rangle$$

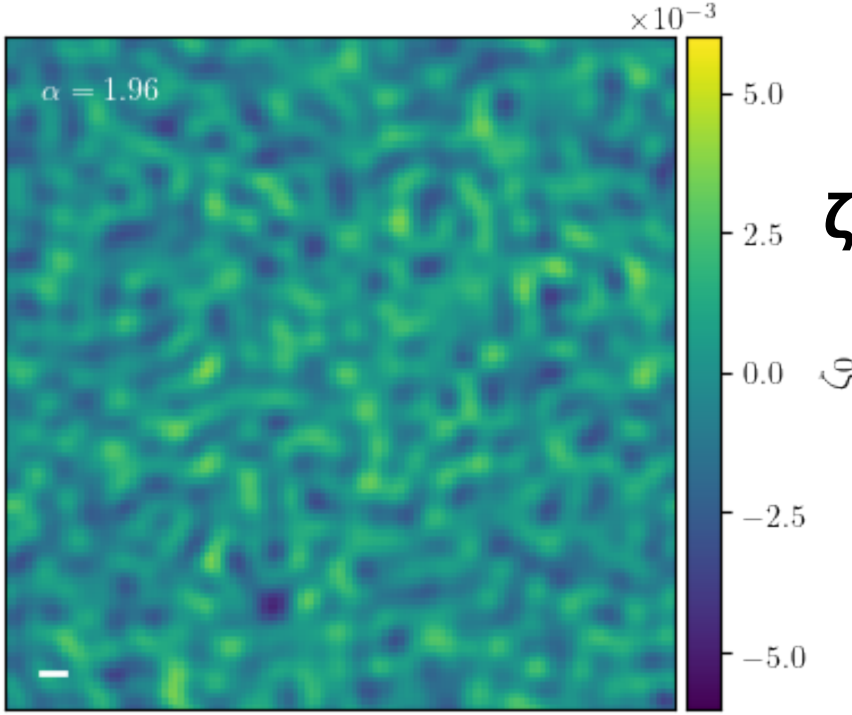
Very high accuracy **pseudospectral code with symplectic integrator** *(developed by Braden for preheating)* => extract very small nonG from full nonlinear dynamics, including all stochastic inflation effects

$$\dot\zeta = \frac{\dot\phi\nabla^2\phi + \nabla\dot\phi\cdot\nabla\phi + \dot\chi\nabla^2\chi + \nabla\dot\chi\cdot\nabla\chi}{3a^2(\rho+P)}$$

Energy conservation to 10^{-13}

out state

$\zeta_f(x\ t_f \mid V_0\ ;$ *Bunch-Davies GRF IC*$)$

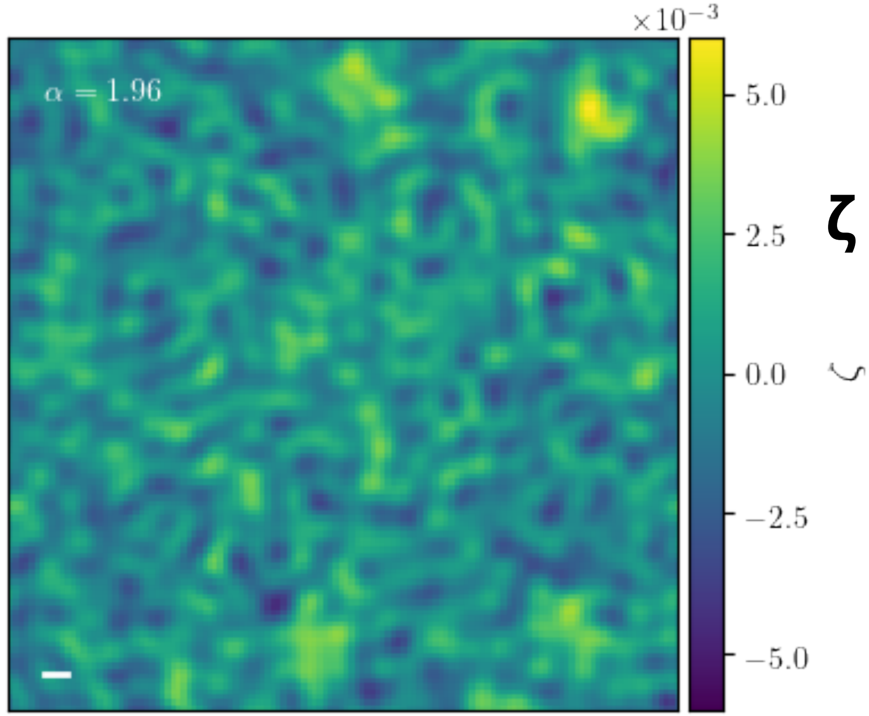


ζ_0

V0 control of amplitude

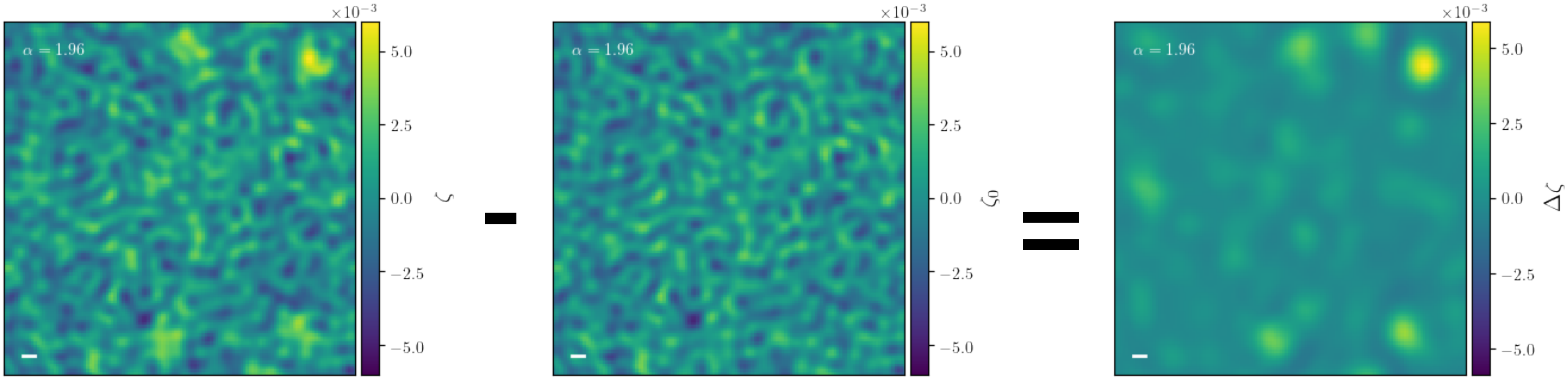
out state

$\boldsymbol{\zeta_f}$(x | $\boldsymbol{\Delta}$V +V_0 ; *Bunch-Davies GRF IC*)



out state

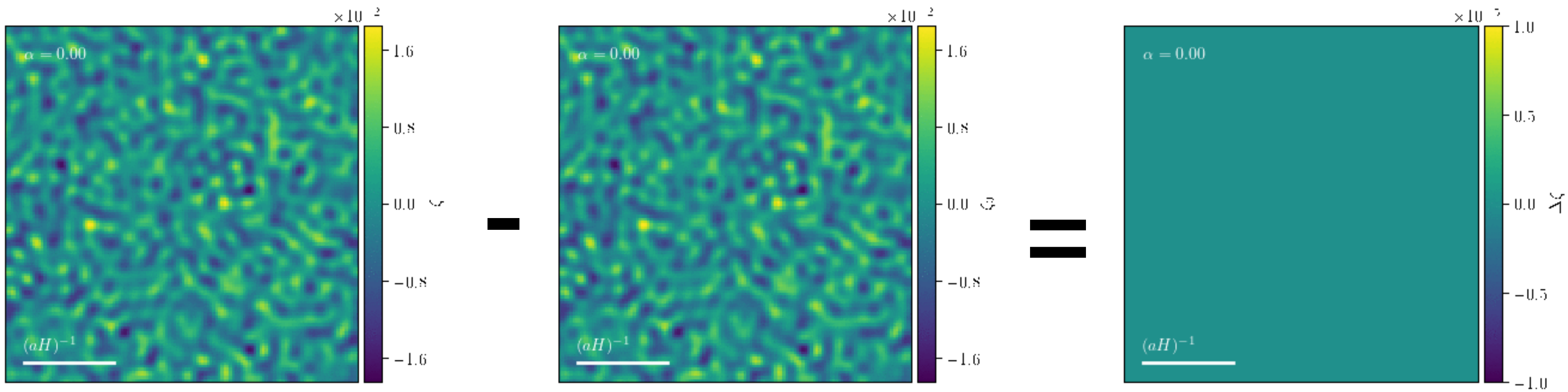
$\zeta_f(x \mid \Delta V + V_0)$ $\quad$ $\zeta_f(x \mid V_0)$ $\quad$ $\Delta\zeta$



Subtracting off a baseline sim using V_0 gives $\Delta\zeta = \zeta - \zeta_0$, this removes nearly Gaussian 'noise' V_0 generates from the NonG signal.

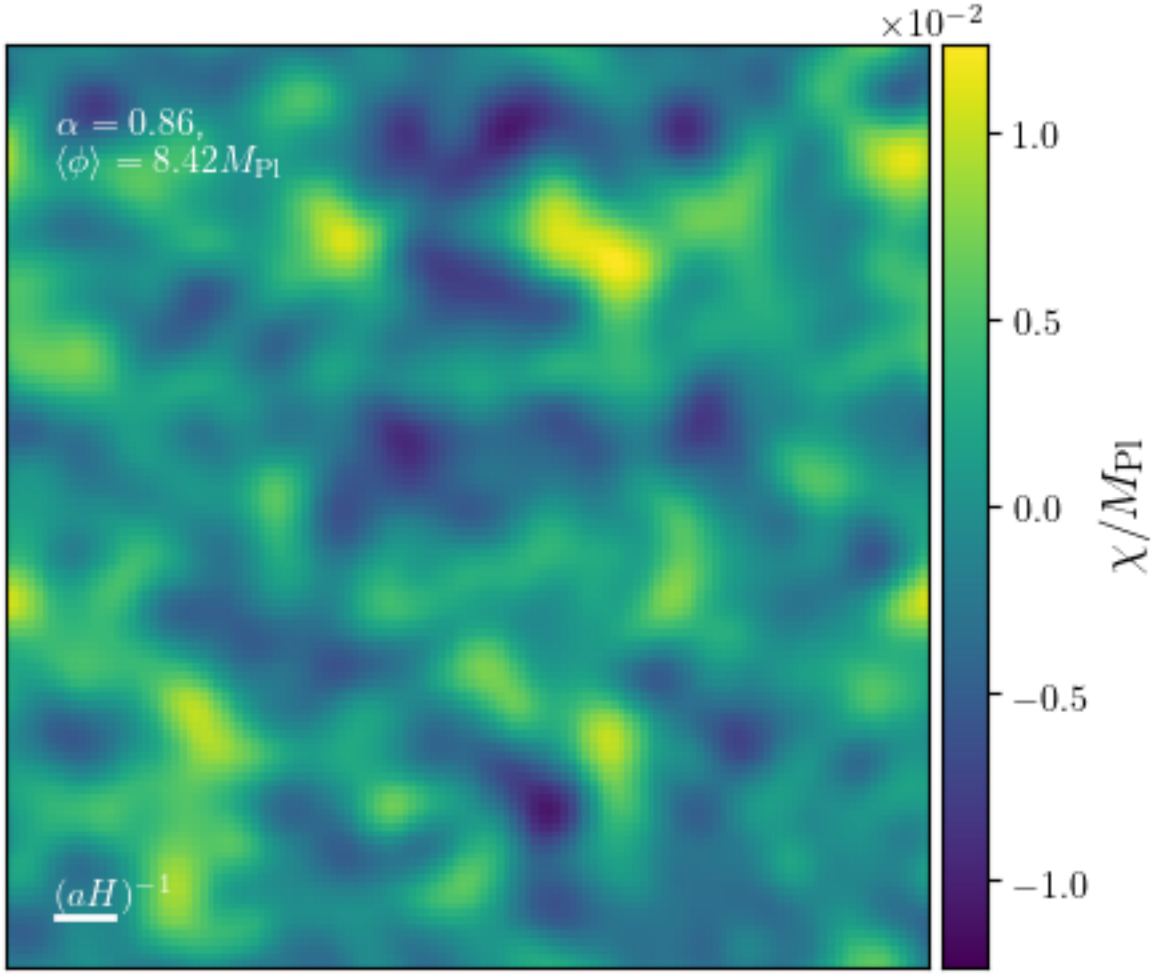
=> $\Delta\zeta$ has strong local NonG concentrations. Convolved with transfer function to get the gravitational potential for N-body/gas, linear to nonlinear cosmic web. How to unravel the $\Delta\zeta$ from the gastrophysical dynamics. Subtle effects in CMB/LSS => Top down is easier than bottom up 'backward' unravelling.

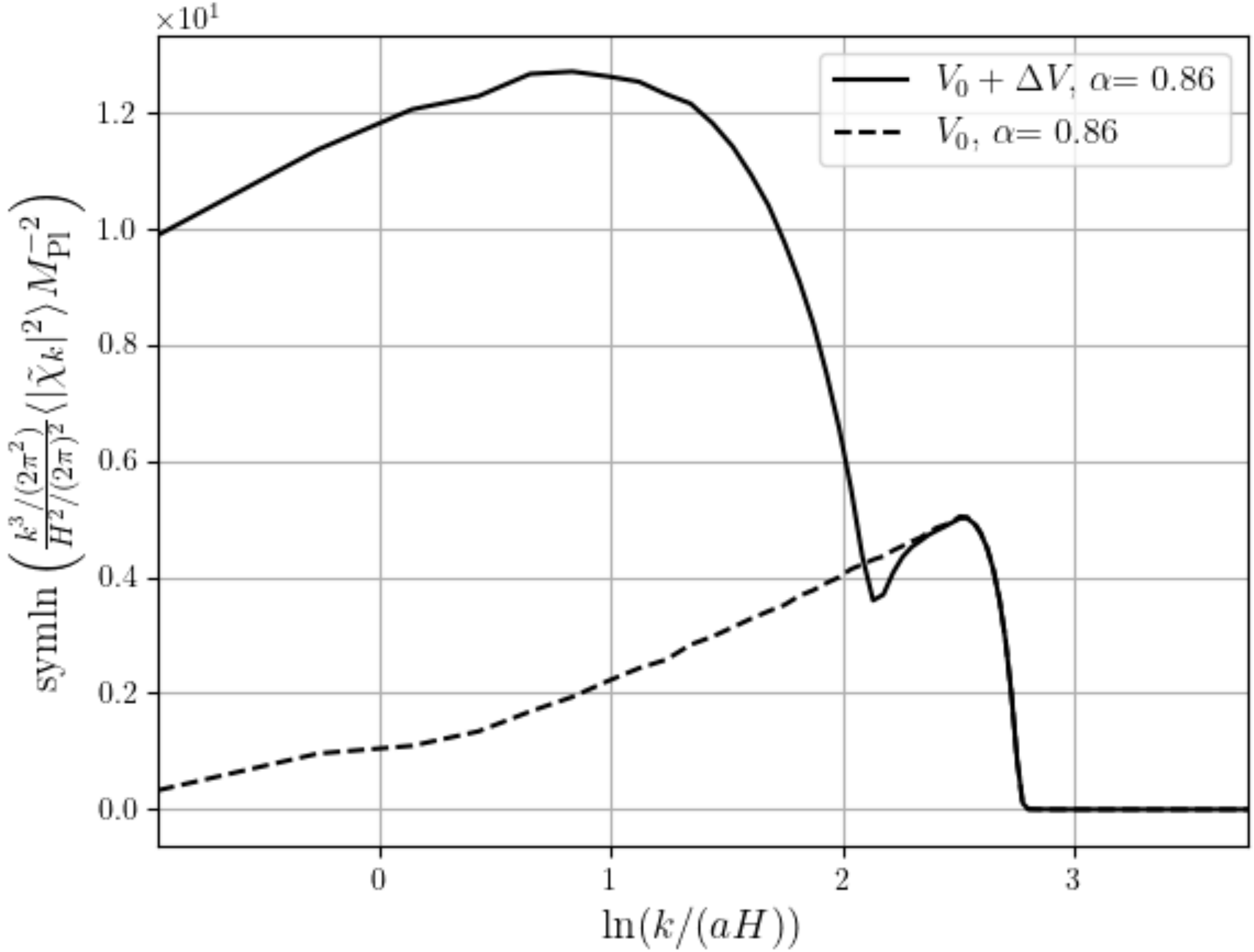
in state => **out** state, the movie



$\Delta\zeta_f > 0$ in the final state. Shorter arrested dynamics can lead to $\Delta\zeta_f < 0$

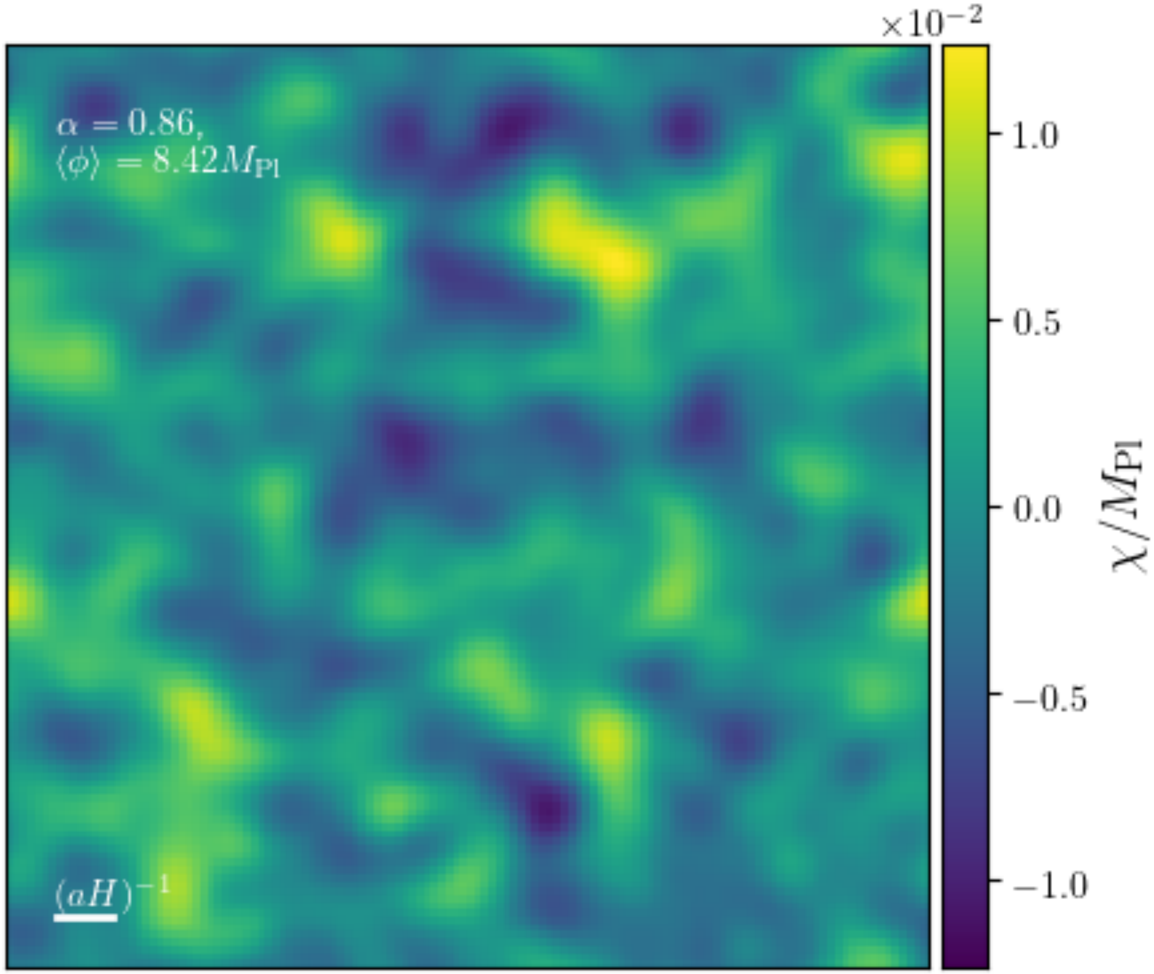
slice_chi_e_cp



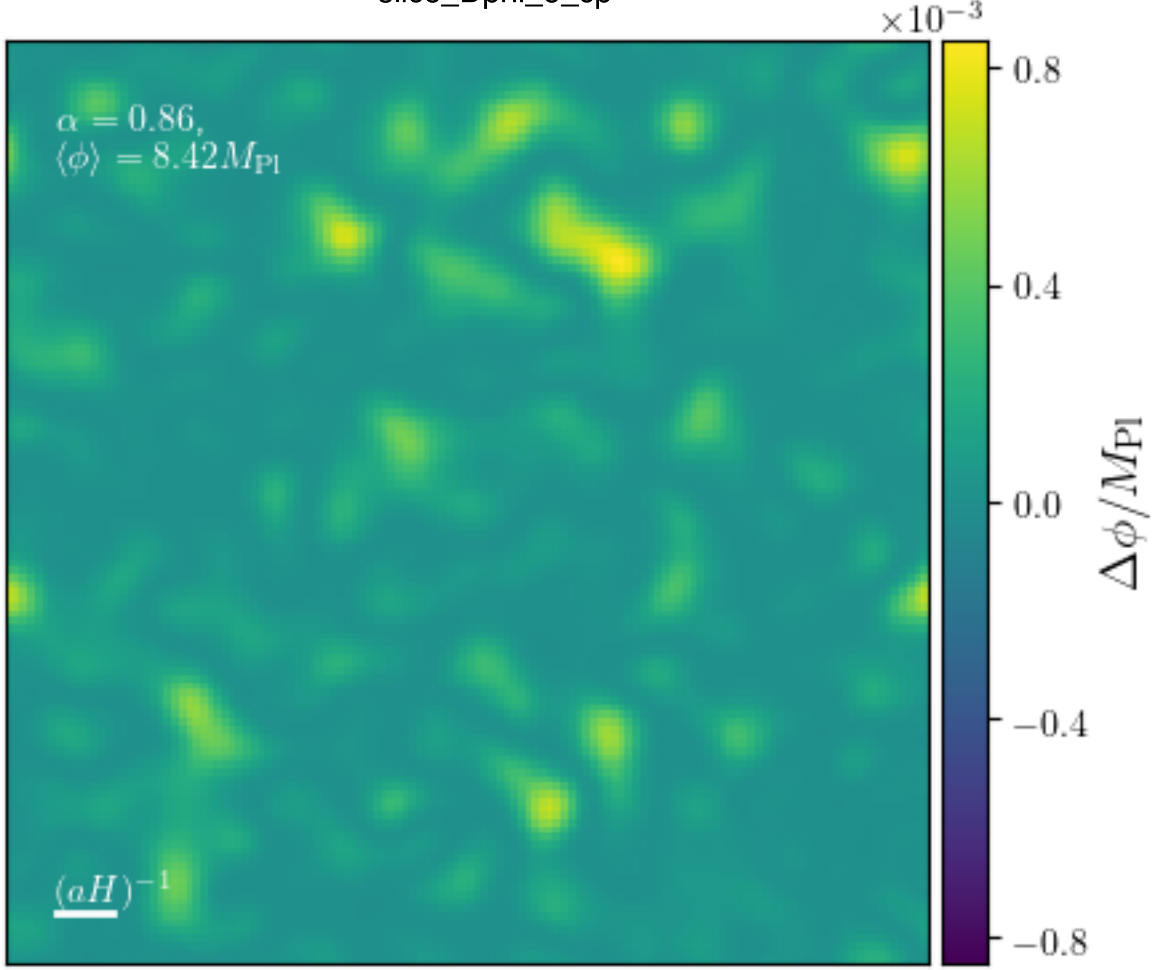


$\times 10^1$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
$\ln(k/(aH))$
$\mathrm{symln}\left(\frac{k^3/(2\pi^2)}{H^2/(2\pi)^2}\langle|\tilde{\chi}_k|^2\rangle M_{\rm Pl}^{-2}\right)$
$V_0 + \Delta V$, α= 0.86
V_0, α= 0.86

slice_chi_e_cp

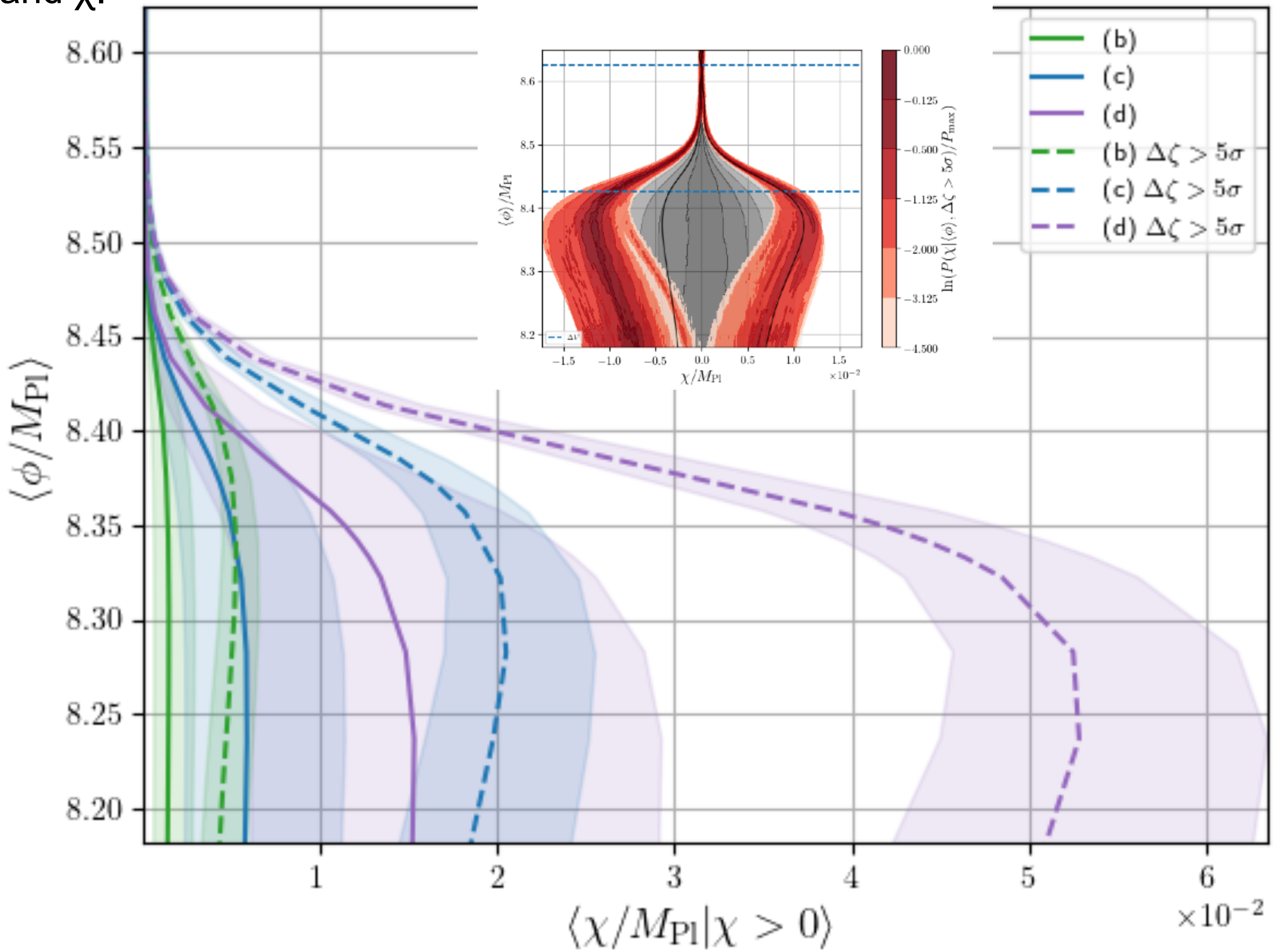


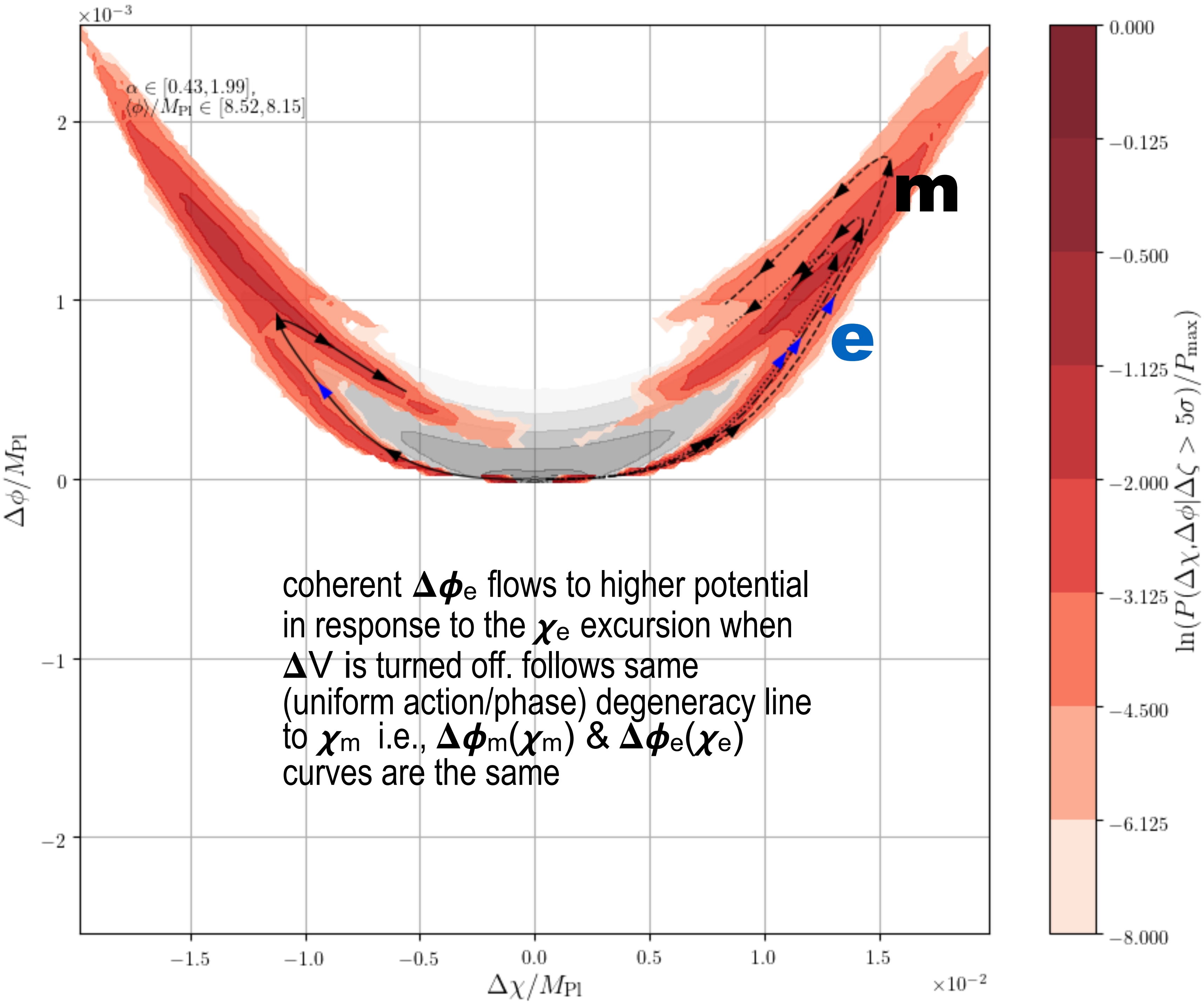
slice_Dphi_e_cp



post select trajectories with Δζ>5σ.

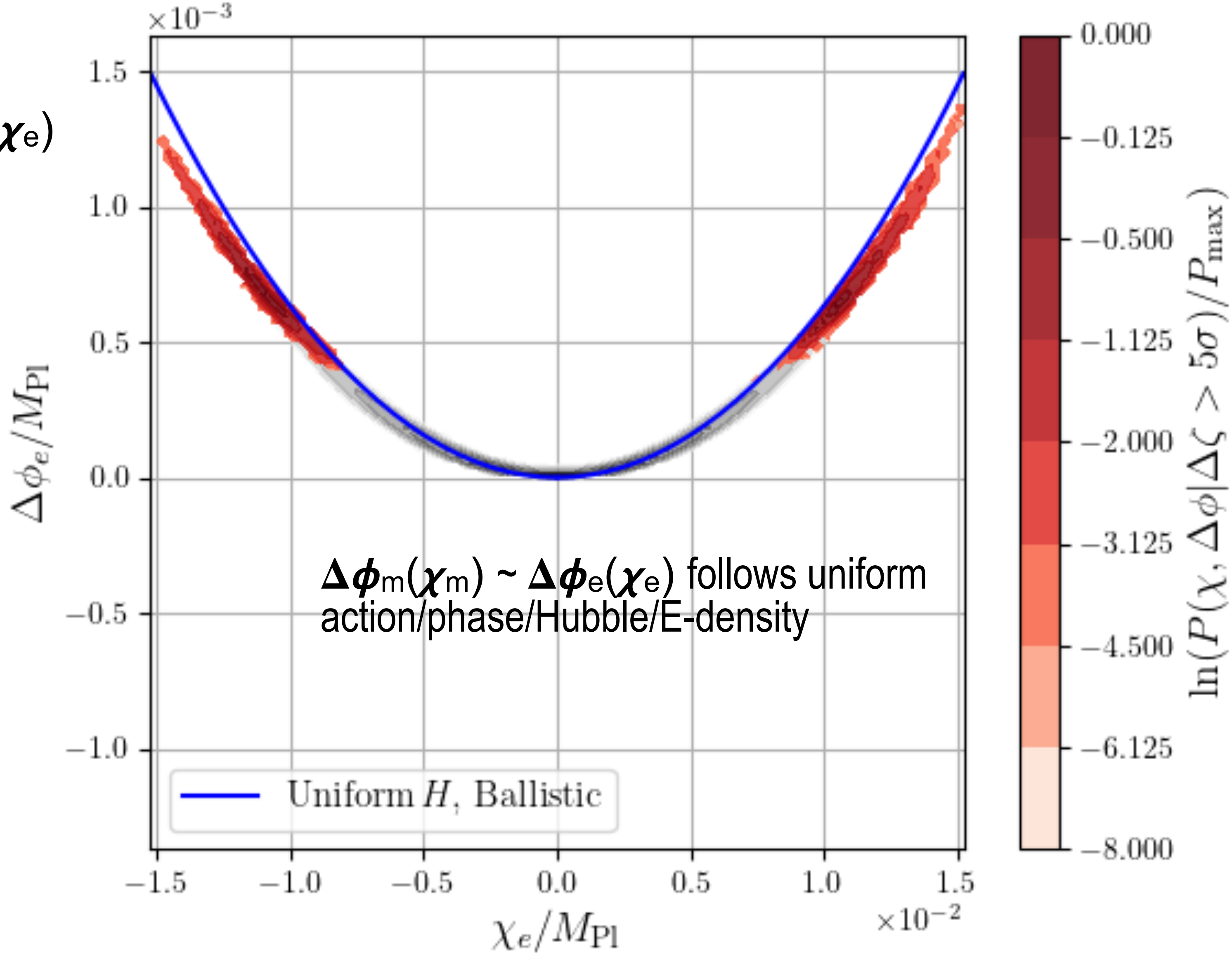
Trajectories leading to Δζ concentrations are those which undergo the maximum excursion during the ΔV instability, leading to strongest nonlinear interactions between ϕ and χ.





×10⁻³
α ∈ [0.43,1.99],
⟨φ⟩/M_Pl ∈ [8.52,8.15]
Δφ/M_Pl
2
1
0
−1
−2
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
×10⁻²
Δχ/M_Pl
m
e
0.000
−0.125
−0.500
−1.125
−2.000
−3.125
−4.500
−6.125
−8.000
ln(P(Δχ,Δφ|Δζ > 5σ)/P_max)
coherent Δϕe flows to higher potential
in response to the χe excursion when
ΔV is turned off. follows same
(uniform action/phase) degeneracy line
to χm i.e., Δϕm(χm) & Δϕe(χe)
curves are the same

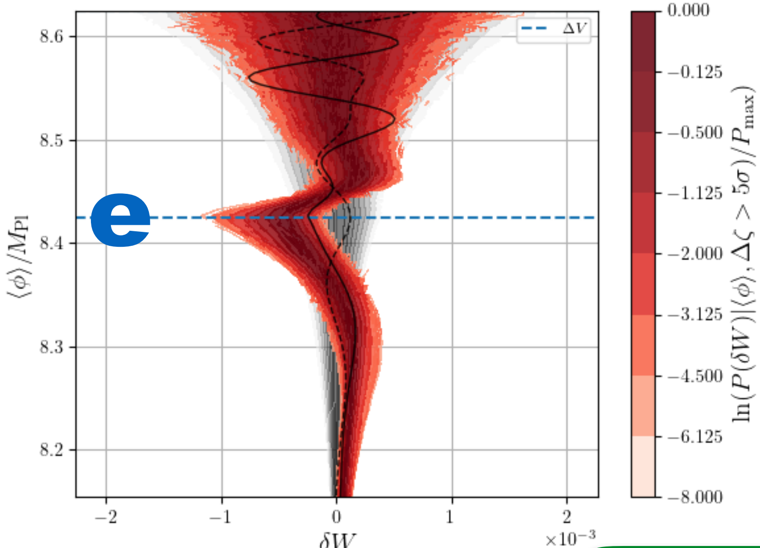
$\Delta\boldsymbol{\phi}_e(\boldsymbol{\chi}_e)$

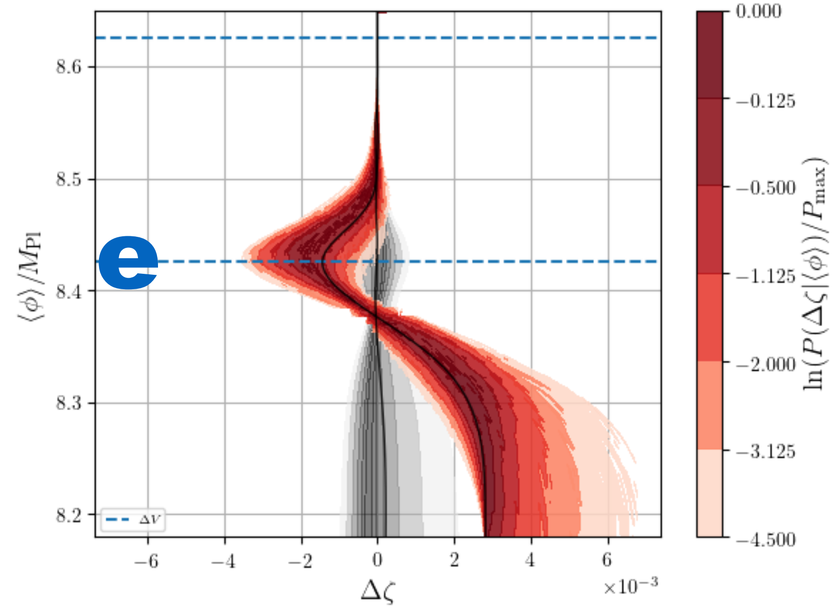


post – burst final : $\Delta\zeta_p \approx \Delta\phi_p(\chi_e)/\sqrt{2M_P\epsilon_e}$ *or* $\Delta\zeta_p \approx \Delta\phi_p(\chi_m)/\sqrt{2M_P\epsilon_m}$, *i.e., function of* χ_e

post select trajectories with Δζ>5σ.

Trajectories leading to Δζ concentration
maximum excursion during the ΔV insta
nonlinear interactions between ϕ and χ.

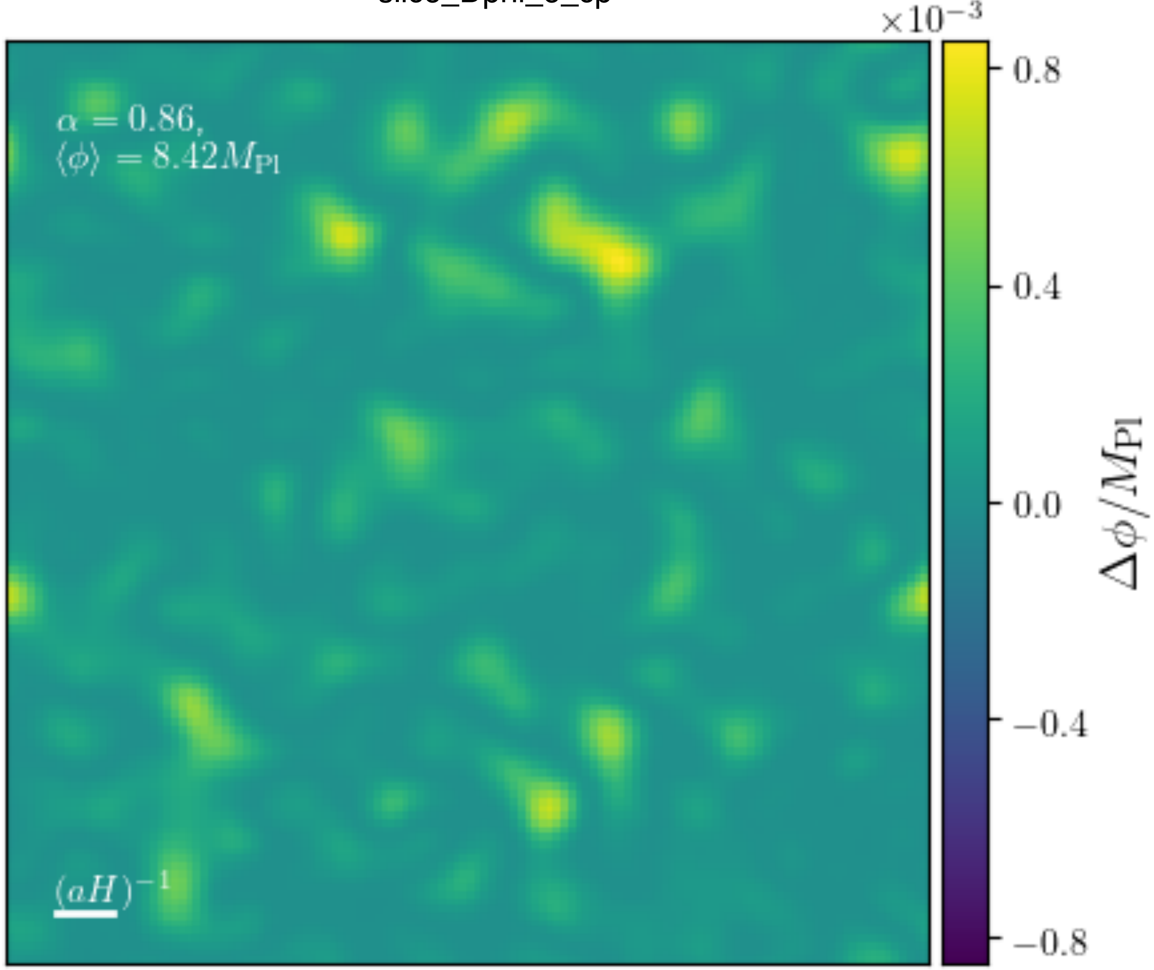




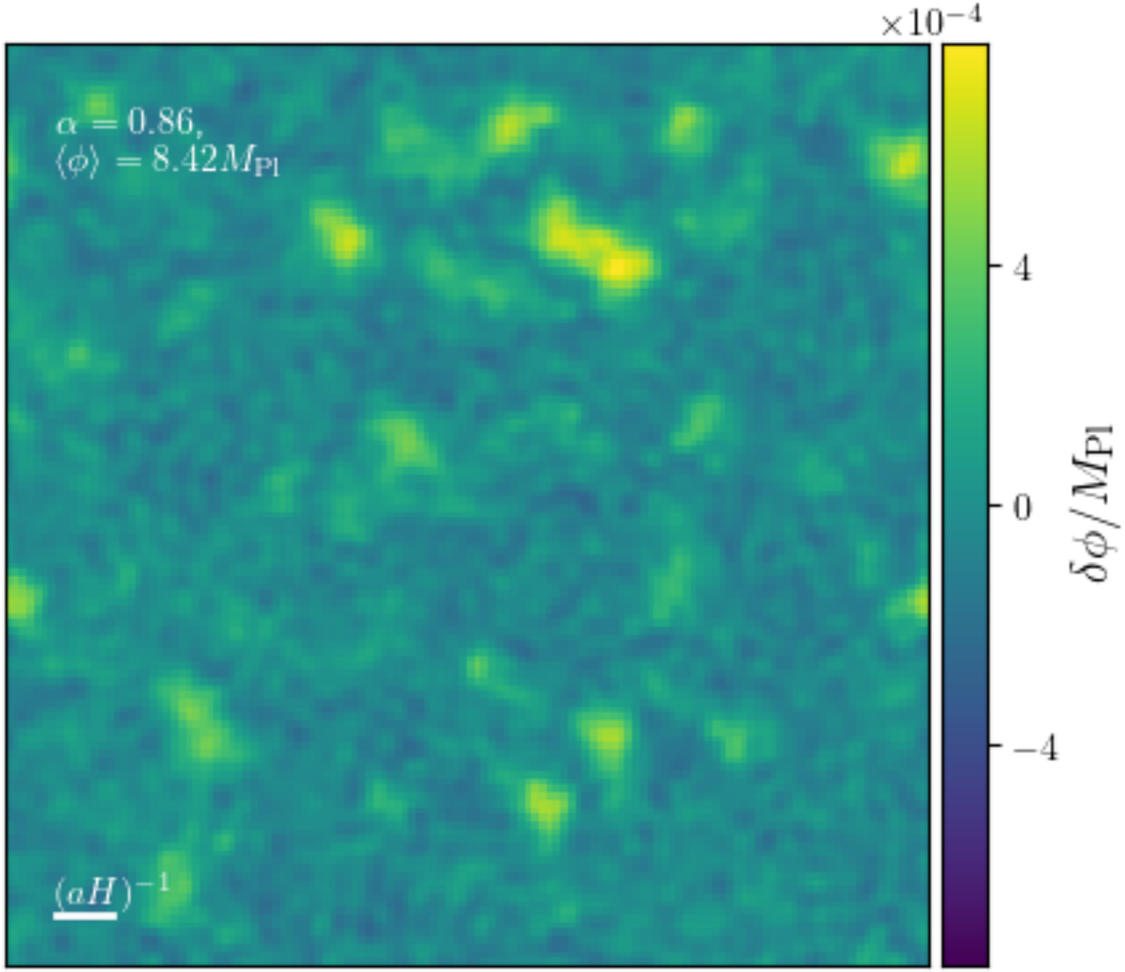
$$d\zeta = \left\{ \nabla^2\delta\phi_A \cdot d\bar{\phi}^A + \nabla\delta\phi_A \cdot \nabla d\delta\phi^A + \nabla^2\delta\phi_A \cdot d\delta\phi^A \right\}/3(\rho+p)_{tot}$$

$$\text{Stochastic framework}: d\zeta_{cg} = d\zeta_{fg->cg,Linear} + d\zeta_{cg,NL} + d\zeta_{fg->cg,NL} = -d\ln\epsilon$$

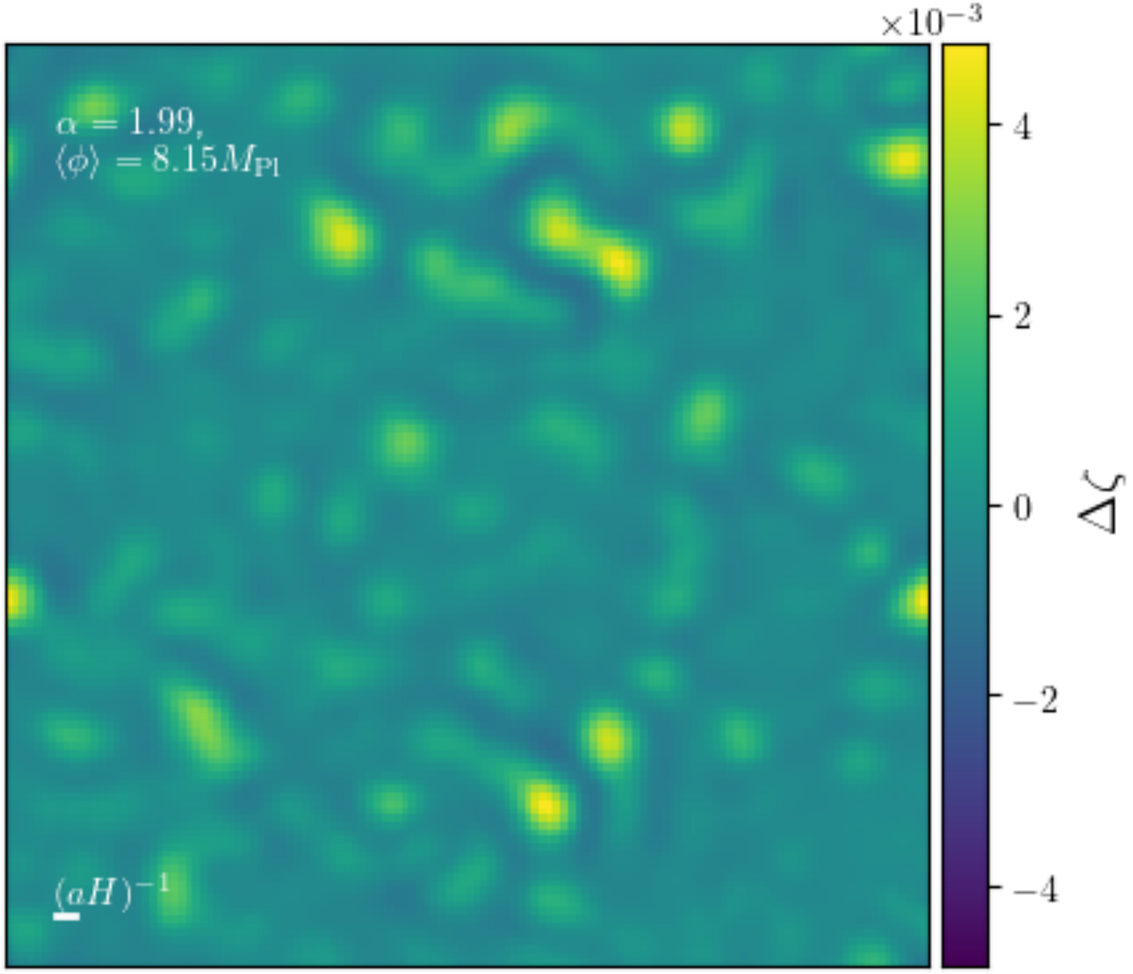
slice_Dphi_e_cp



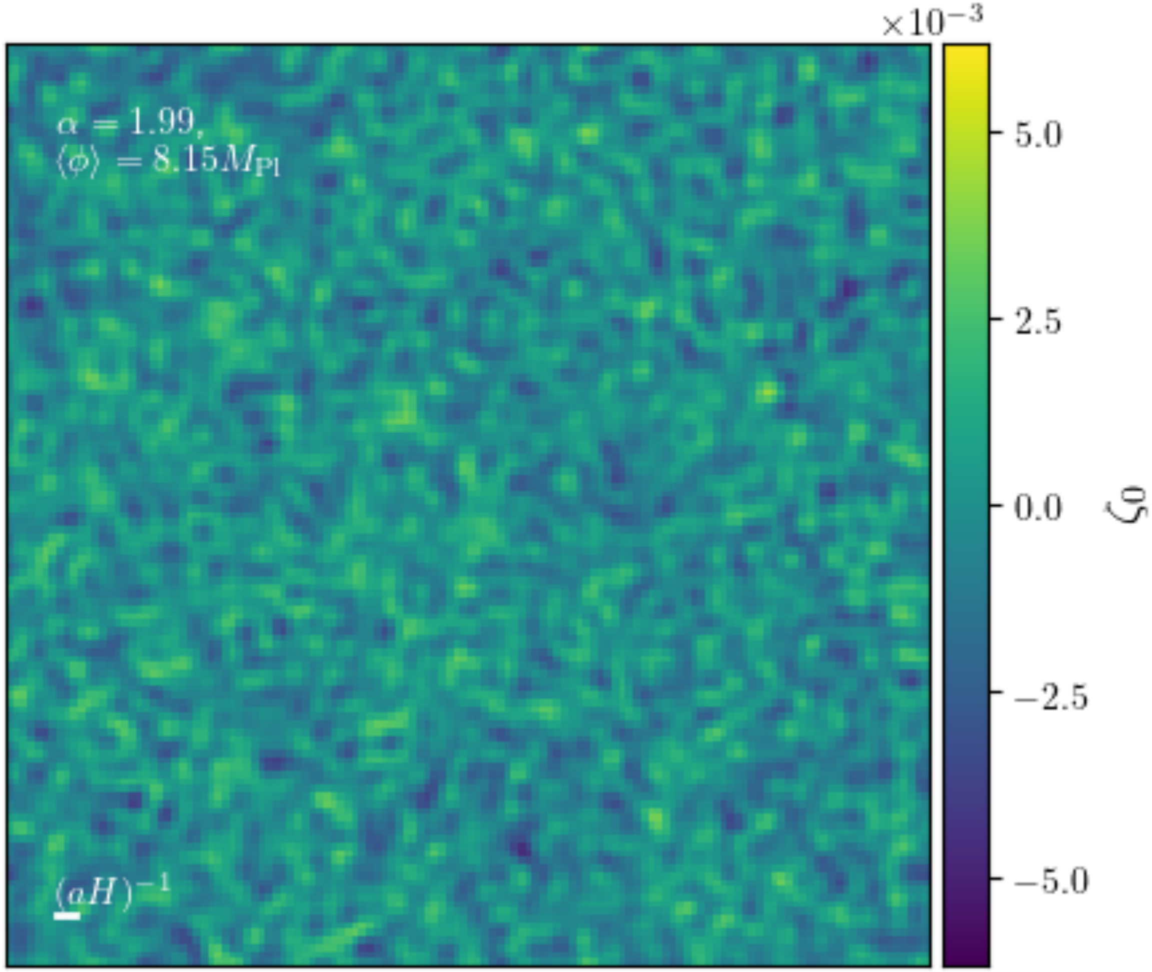
slice_phi_e_cp

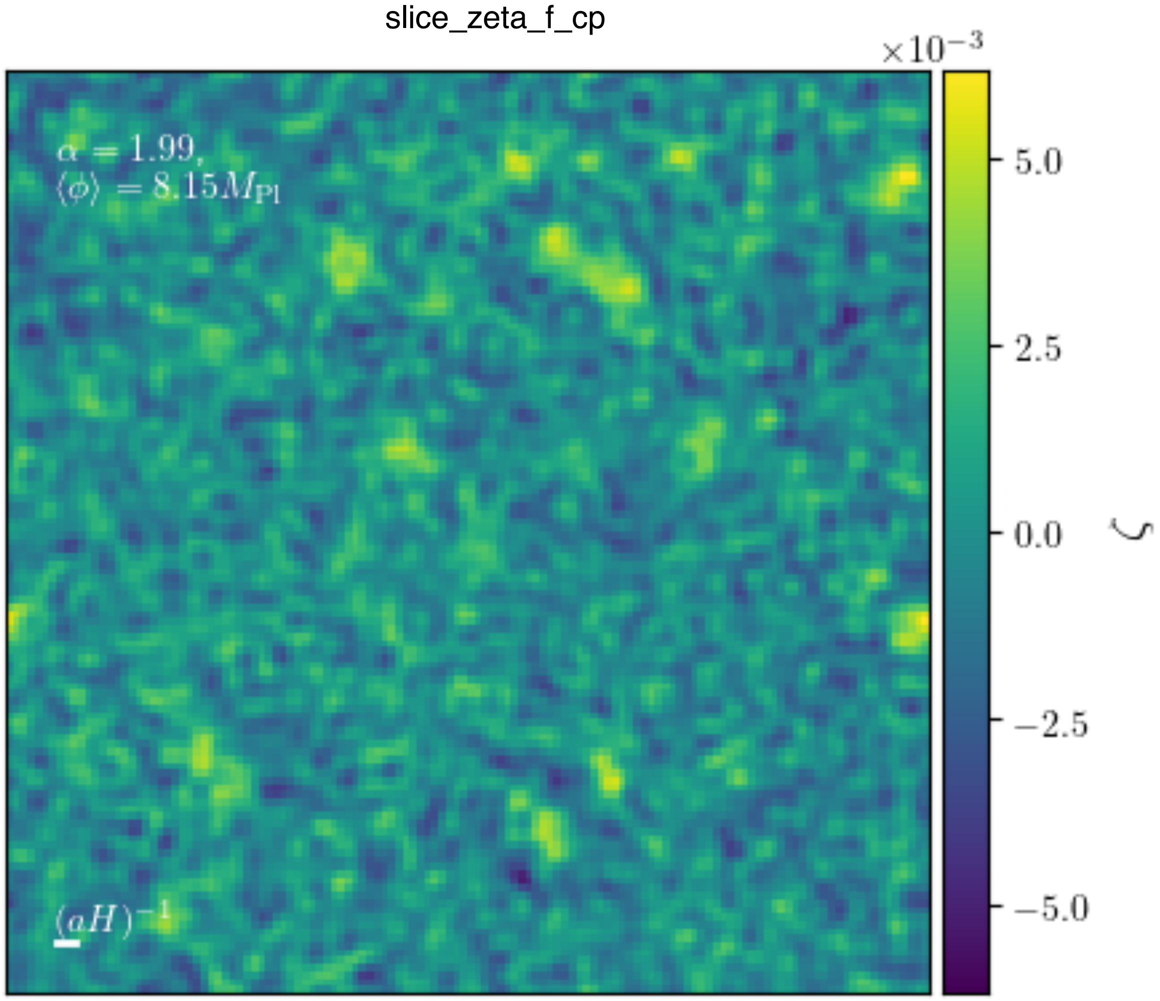


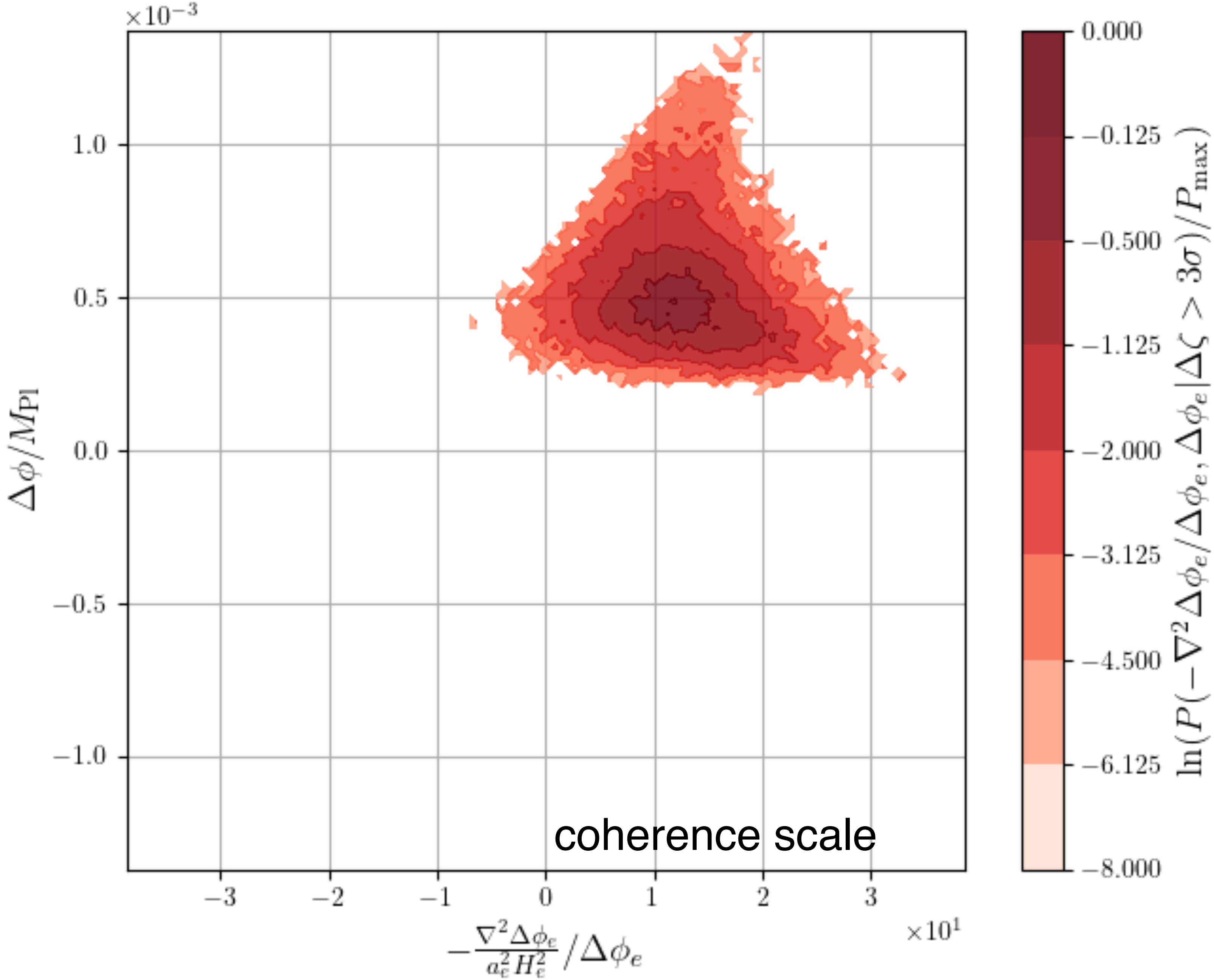
slice_Dzeta_f_cp



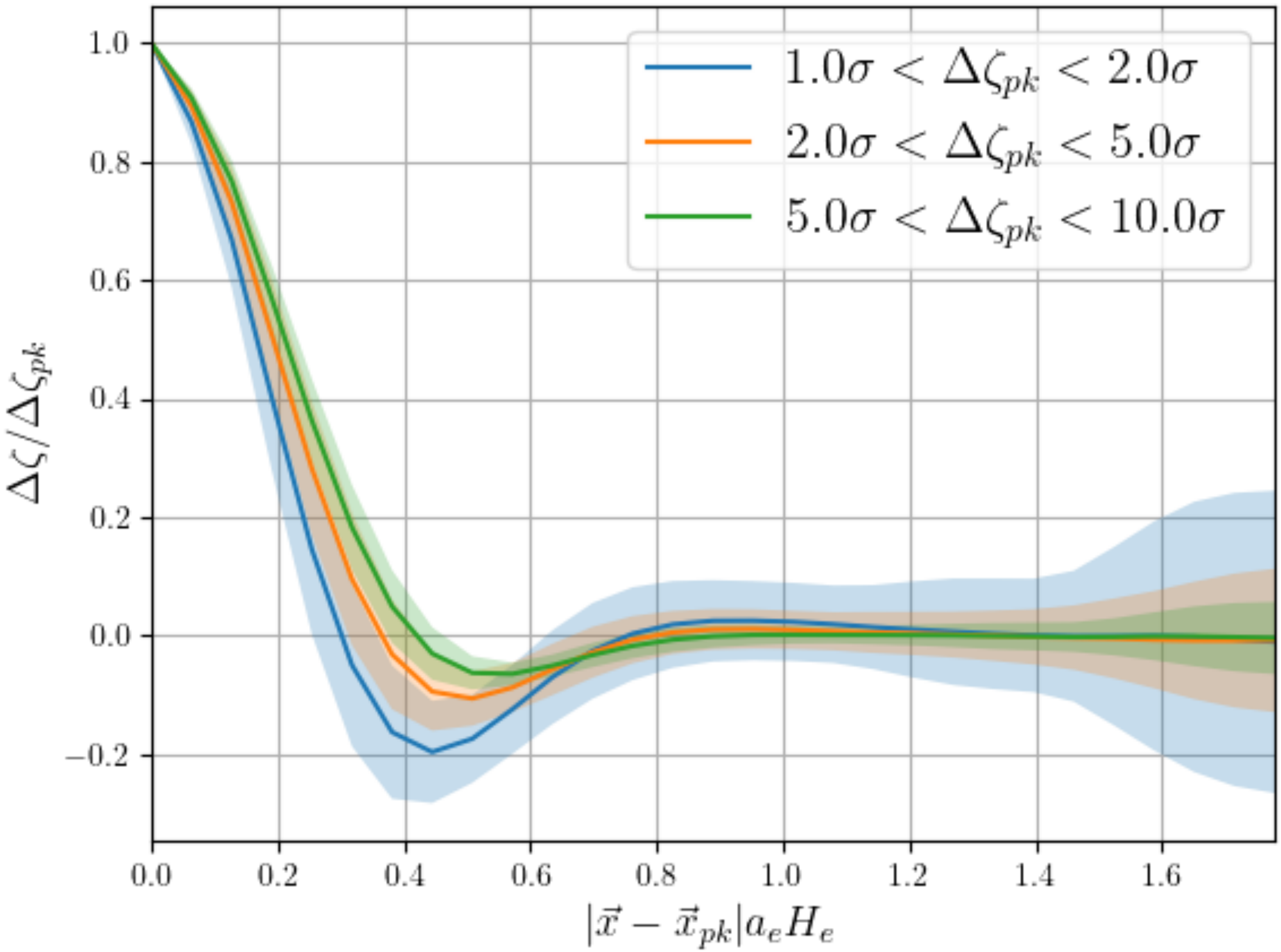
slice_zeta0_f_cp



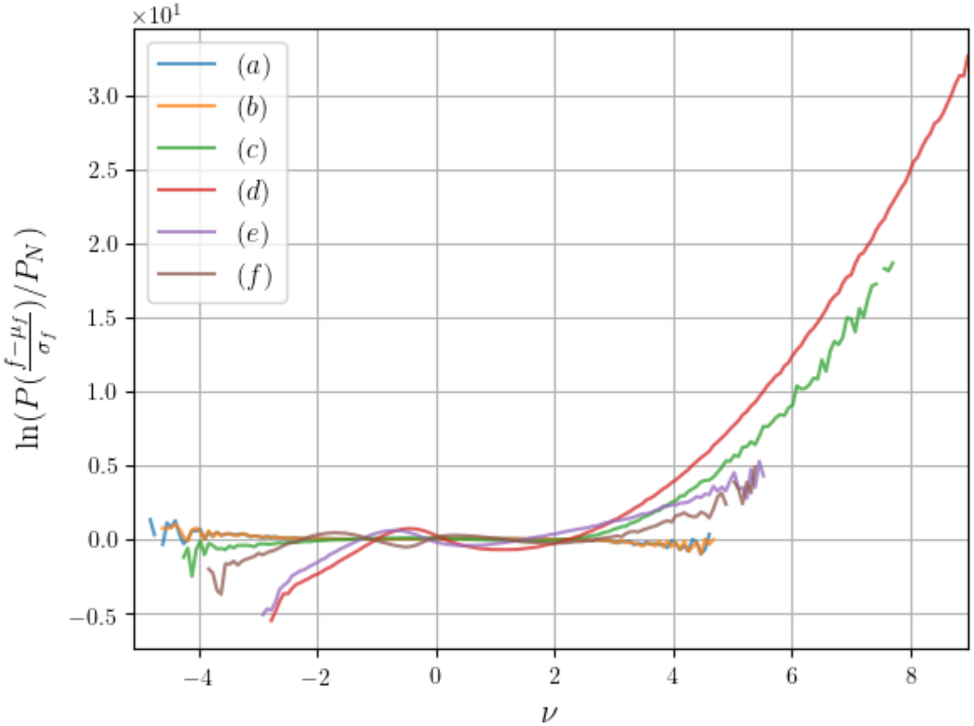

slice_zeta_f_cp
$\alpha = 1.99$,
$\langle\phi\rangle = 8.15 M_{\rm Pl}$
$(aH)^{-1}$
$\times 10^{-3}$
5.0
2.5
0.0
−2.5
−5.0
ζ

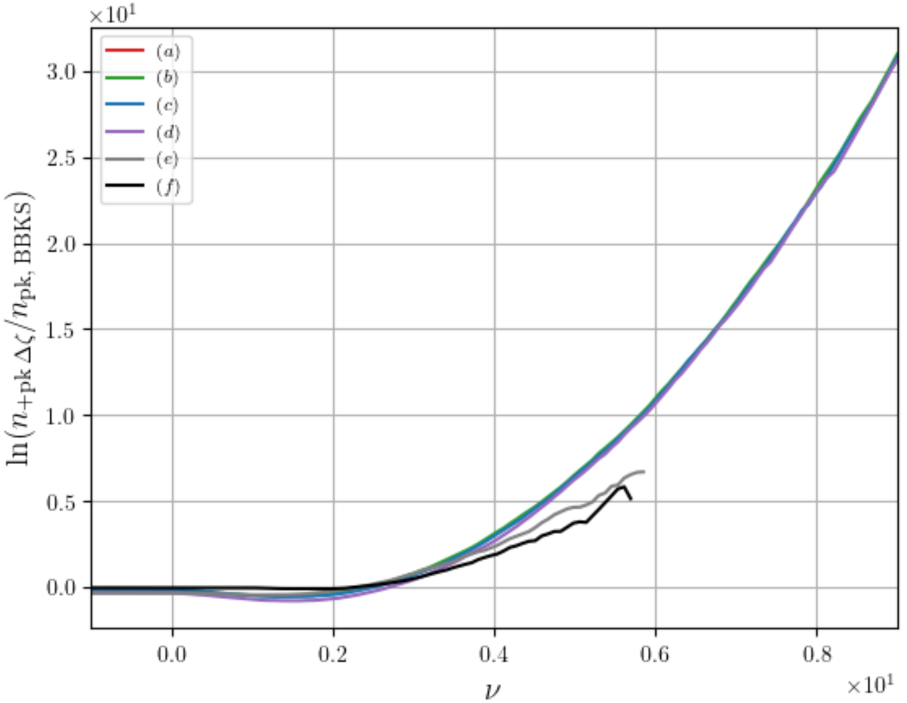


$\times 10^{-3}$
1.0
0.5
0.0
−0.5
−1.0
$\Delta\phi/M_{\rm Pl}$
−3
−2
−1
0
1
2
3
$\times 10^{1}$
$-\frac{\nabla^2 \Delta\phi_e}{a_e^2 H_e^2} / \Delta\phi_e$
coherence scale
0.000
−0.125
−0.500
−1.125
−2.000
−3.125
−4.500
−6.125
−8.000
$\ln(P(-\nabla^2\Delta\phi_e/\Delta\phi_e, \Delta\phi_e | \Delta\zeta > 3\sigma)/P_{\rm max})$



1.0σ < Δζ_pk < 2.0σ
2.0σ < Δζ_pk < 5.0σ
5.0σ < Δζ_pk < 10.0σ
Δζ/Δζ_pk
|x⃗ − x⃗_pk|a_e H_e
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6



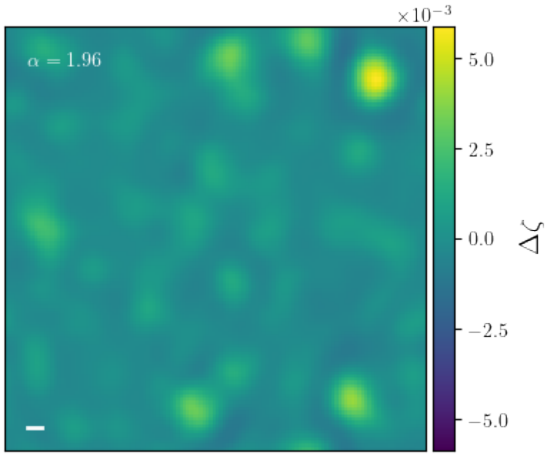


1-point prob dist function measures NonG induced by ΔV.

NonG shows up as a long tail of high excursions in excess of the expectation for a Gaussian field, which is close to what V_0 gives.

peak density relative to BBKS

ν = field/sigma_field



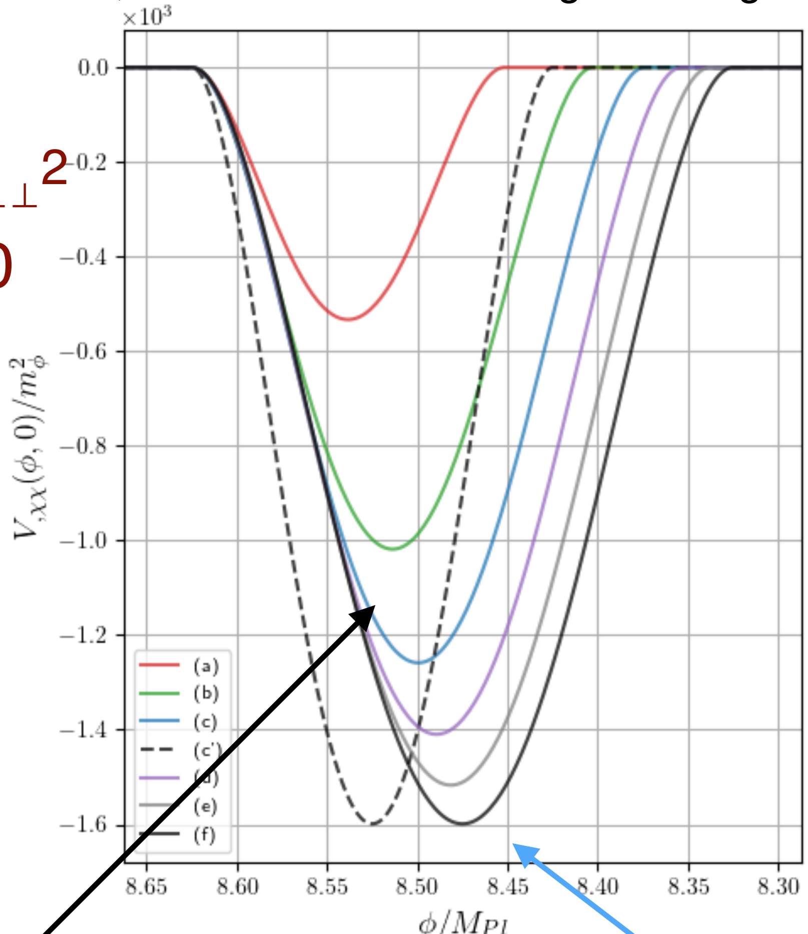
an ensemble of symmetry breaking/restoration potentials

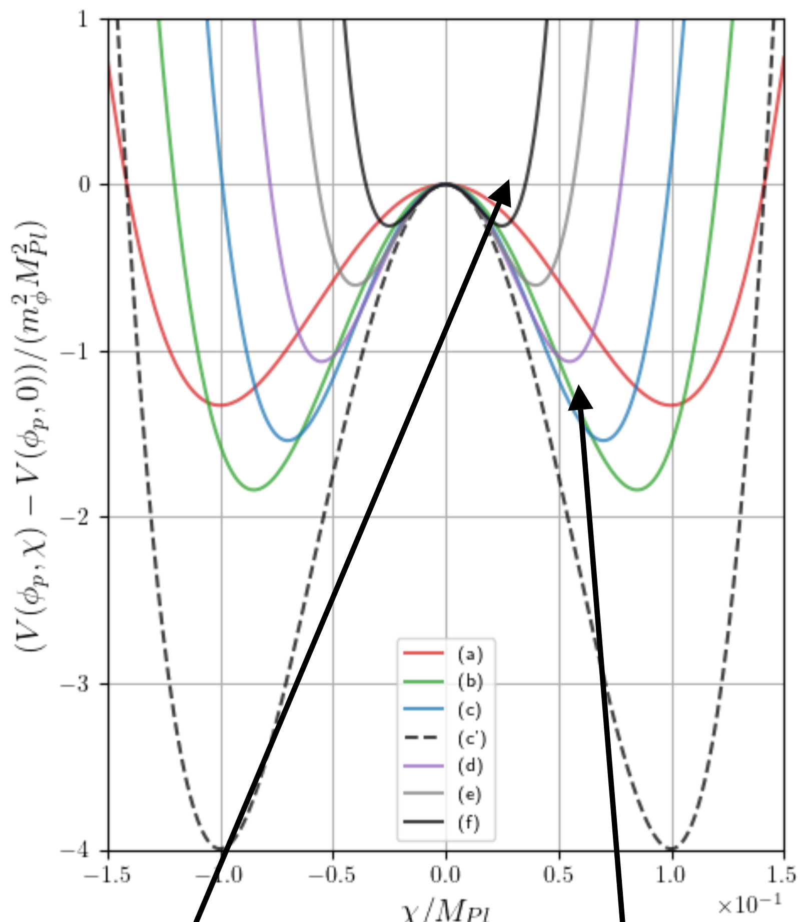
$$\Delta V = 1/4\lambda(\phi)[(\chi^2 - v^2)^2 - v^4],$$

X U, U= 0 to 1 overall strength scaling

- a deep breath in the downward flow
- U makes differential templates easier to compute

$m_{\perp\perp}{}^2 < 0$



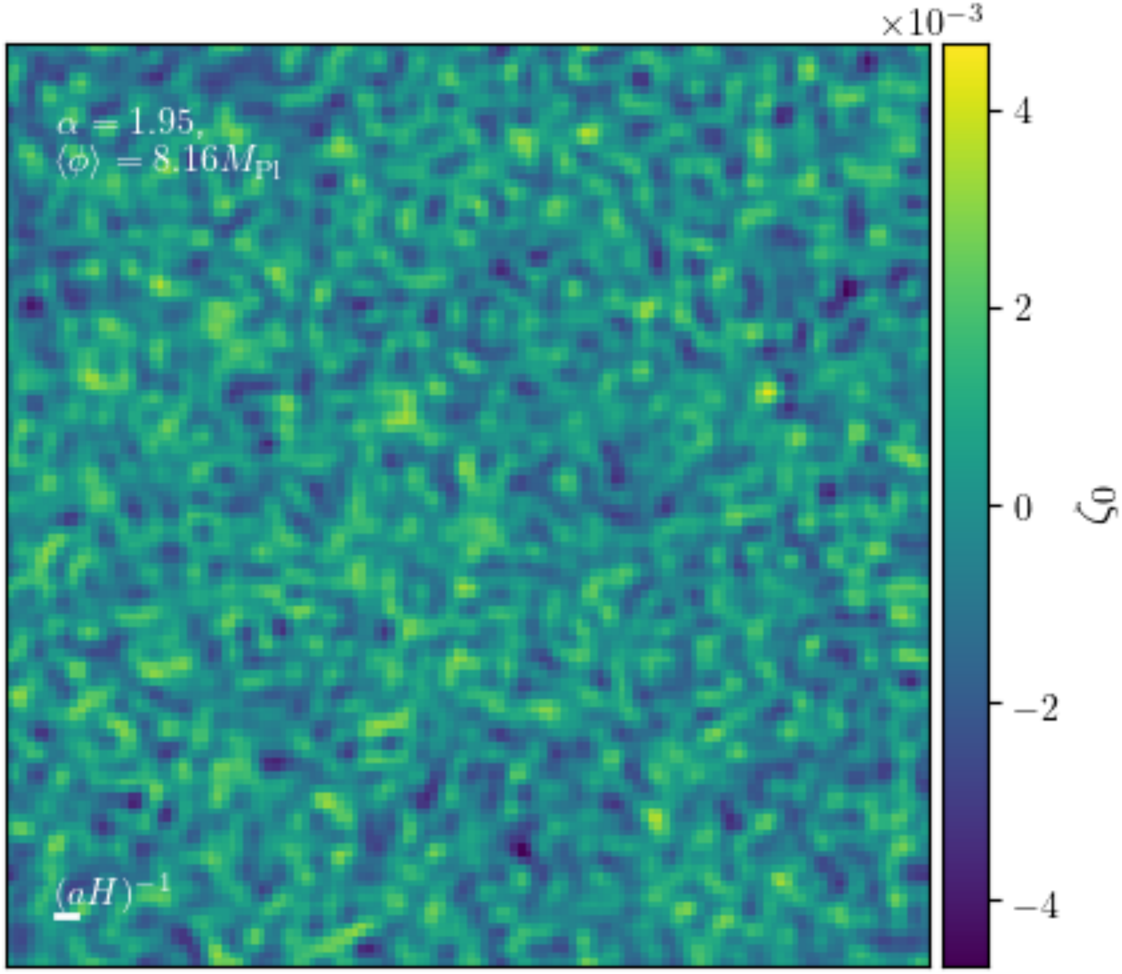


leads to ζ peaks - common

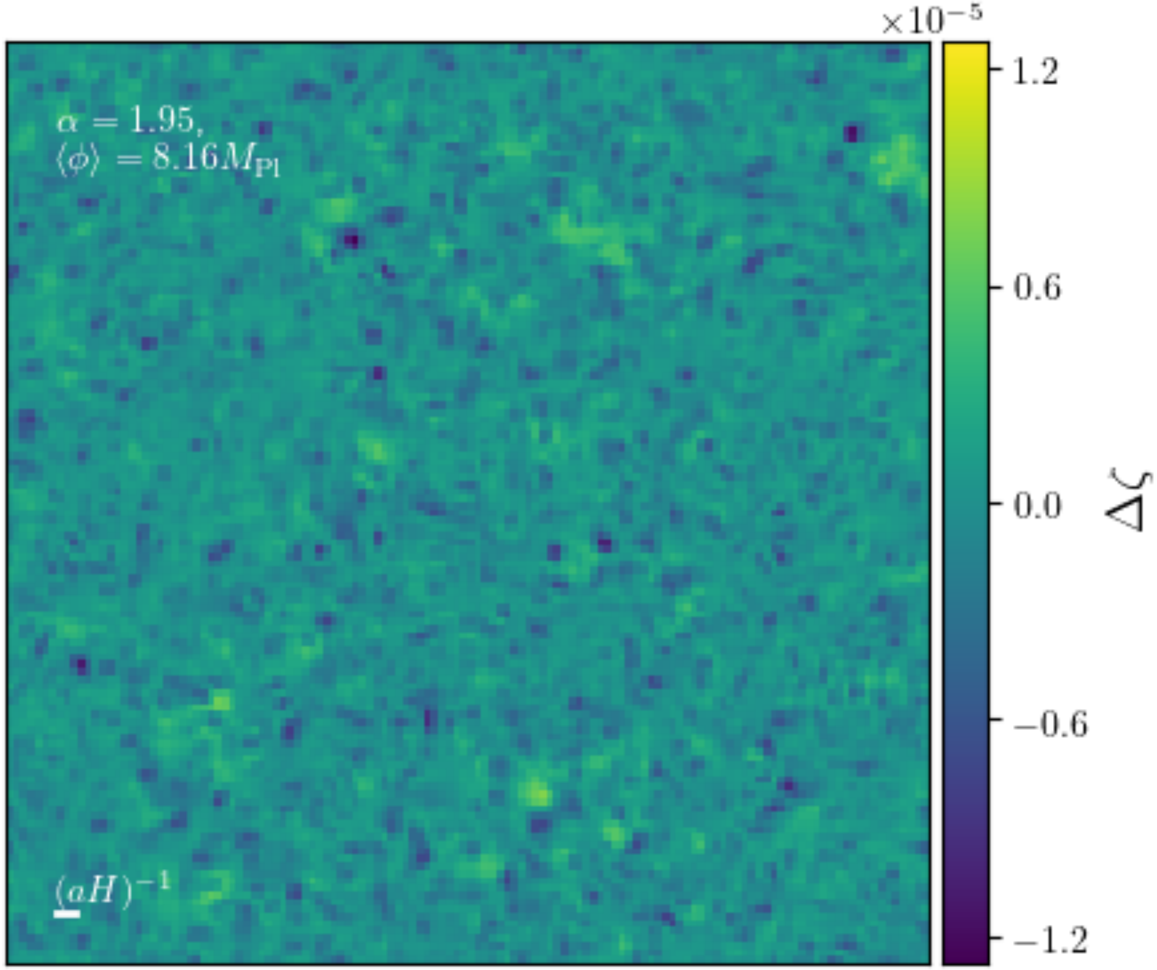
leads to wall memory in ζ

leads to ζ peaks - common

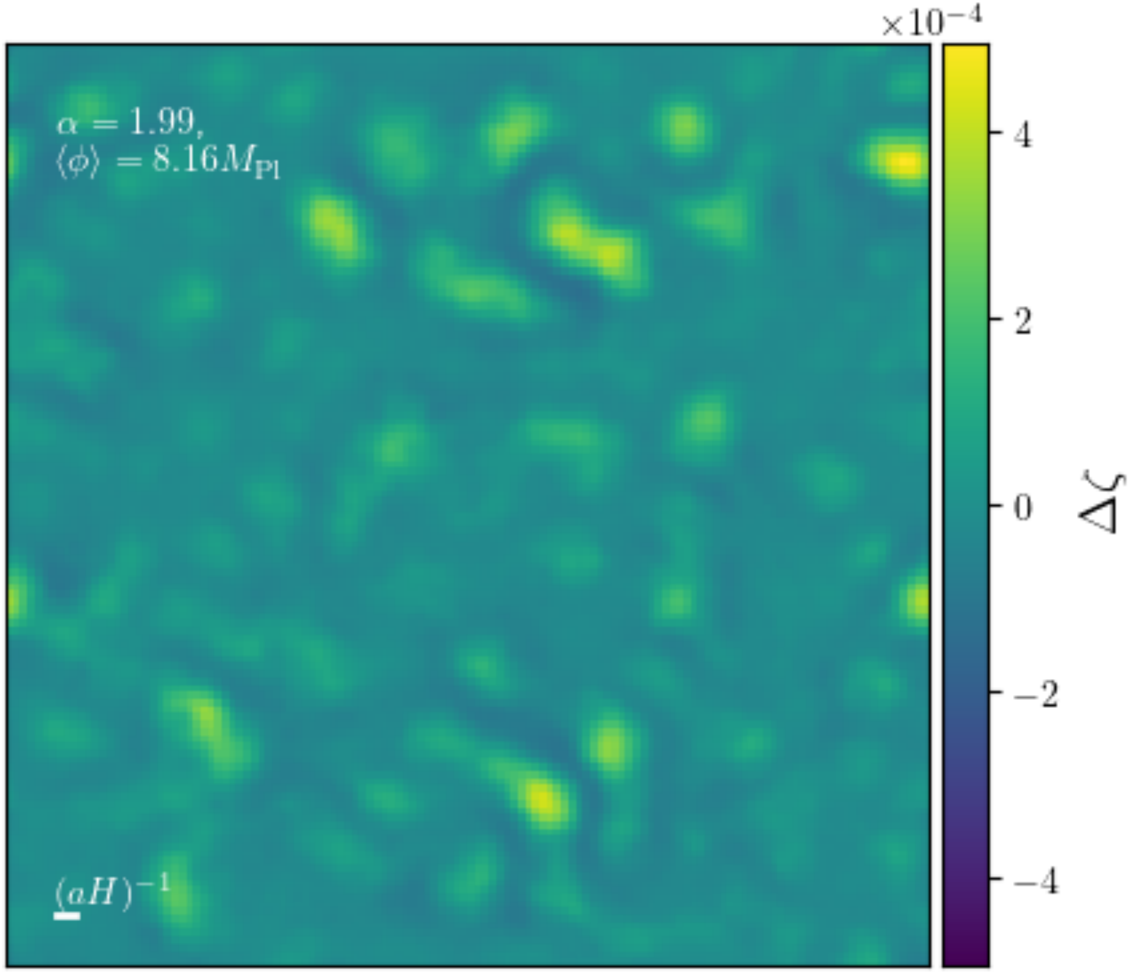
zeta0_slice_a



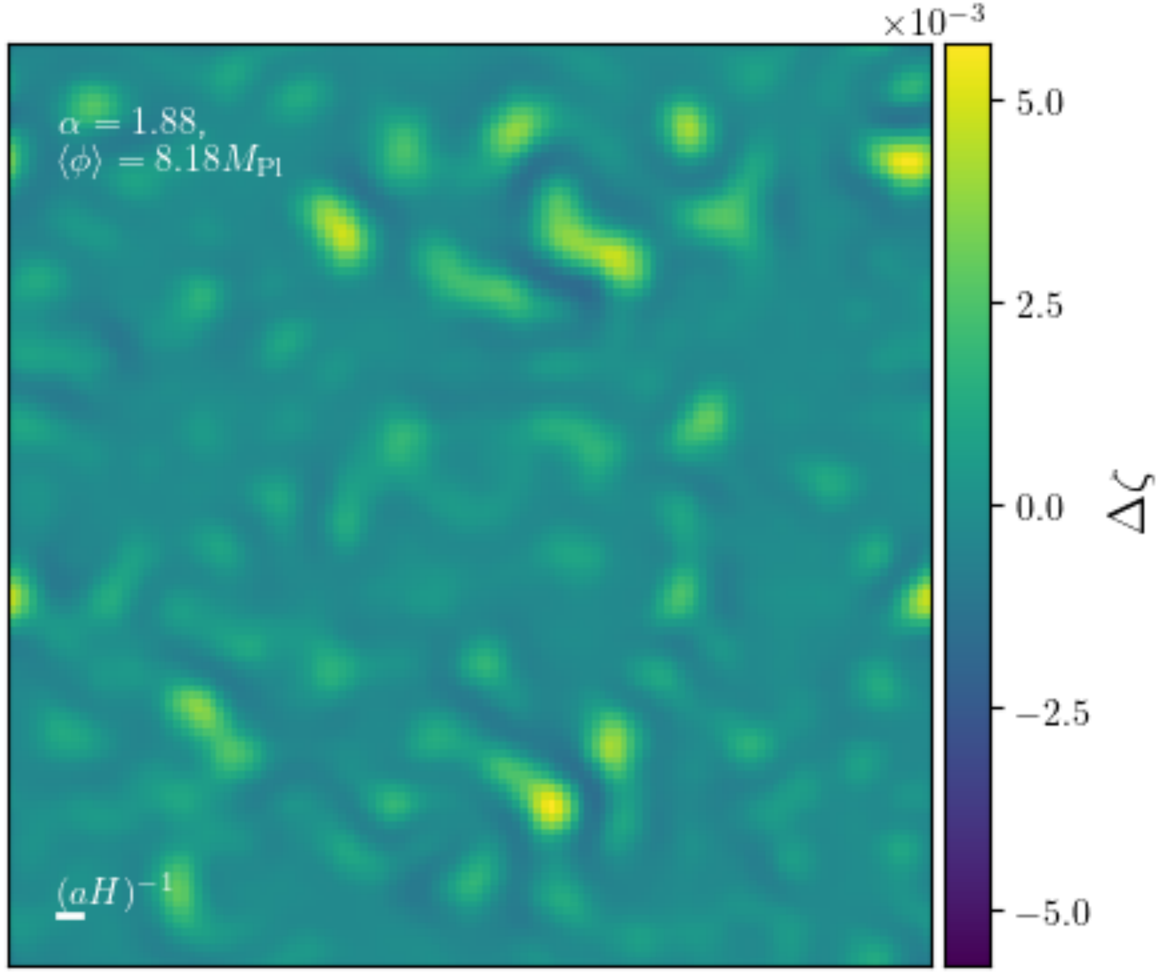
Dzeta_slice_a



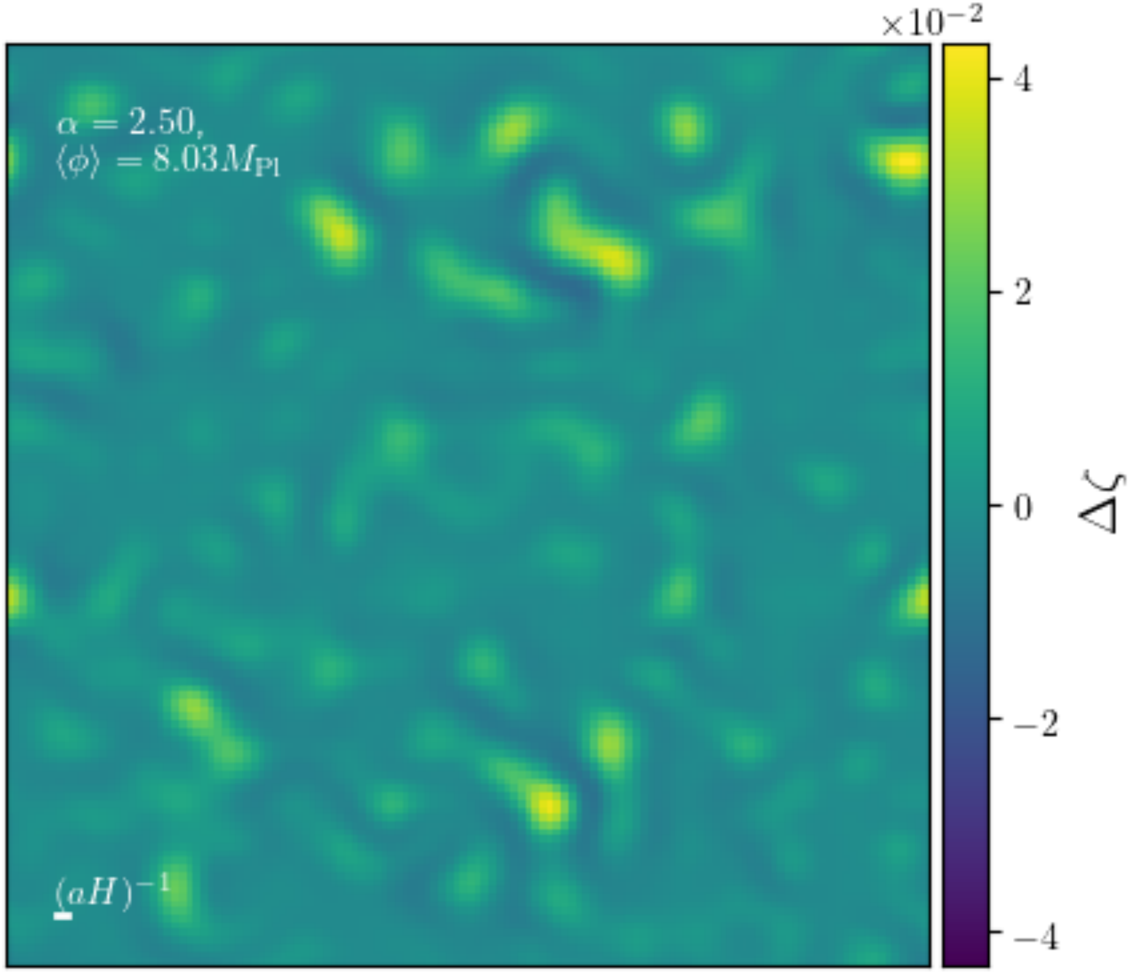
Dzeta_slice_b



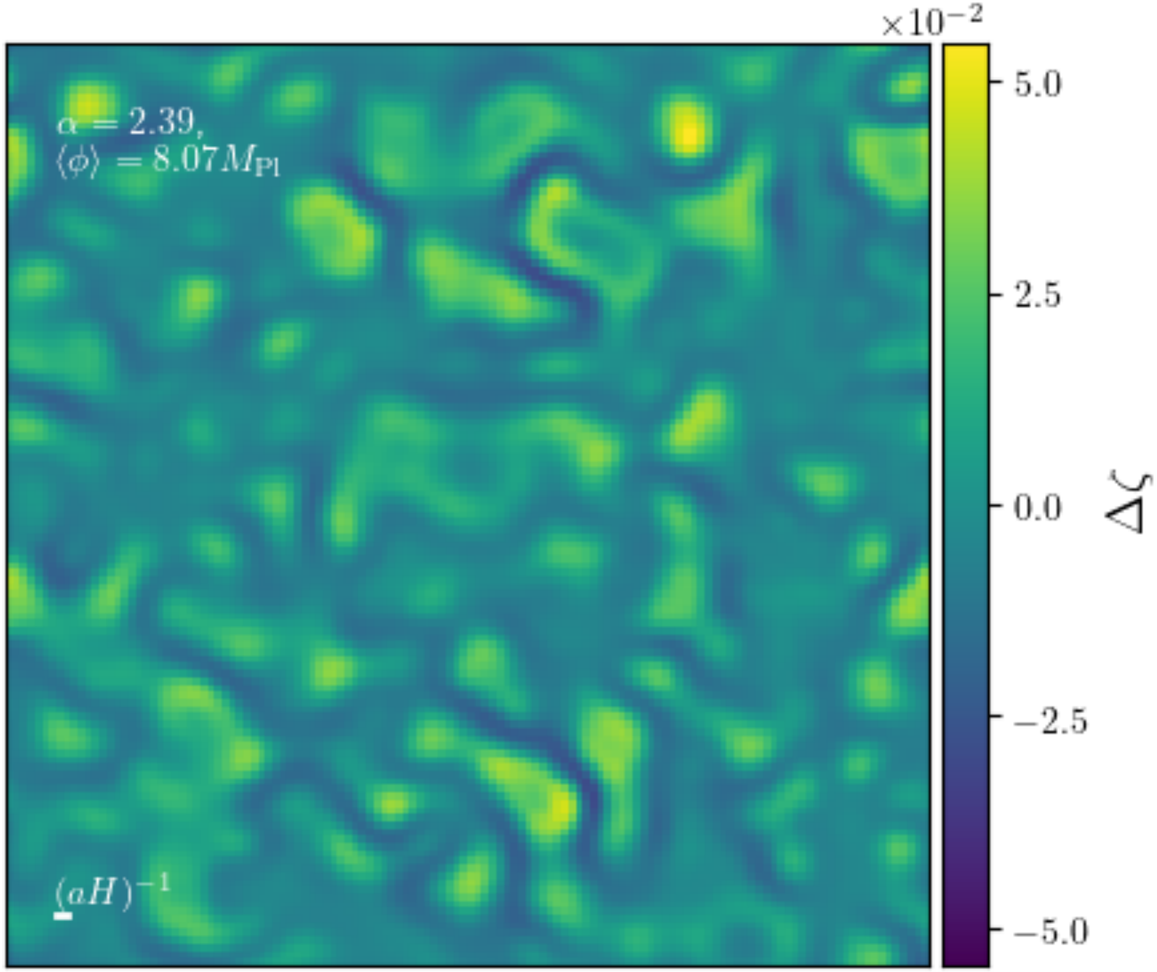
Dzeta_slice_c



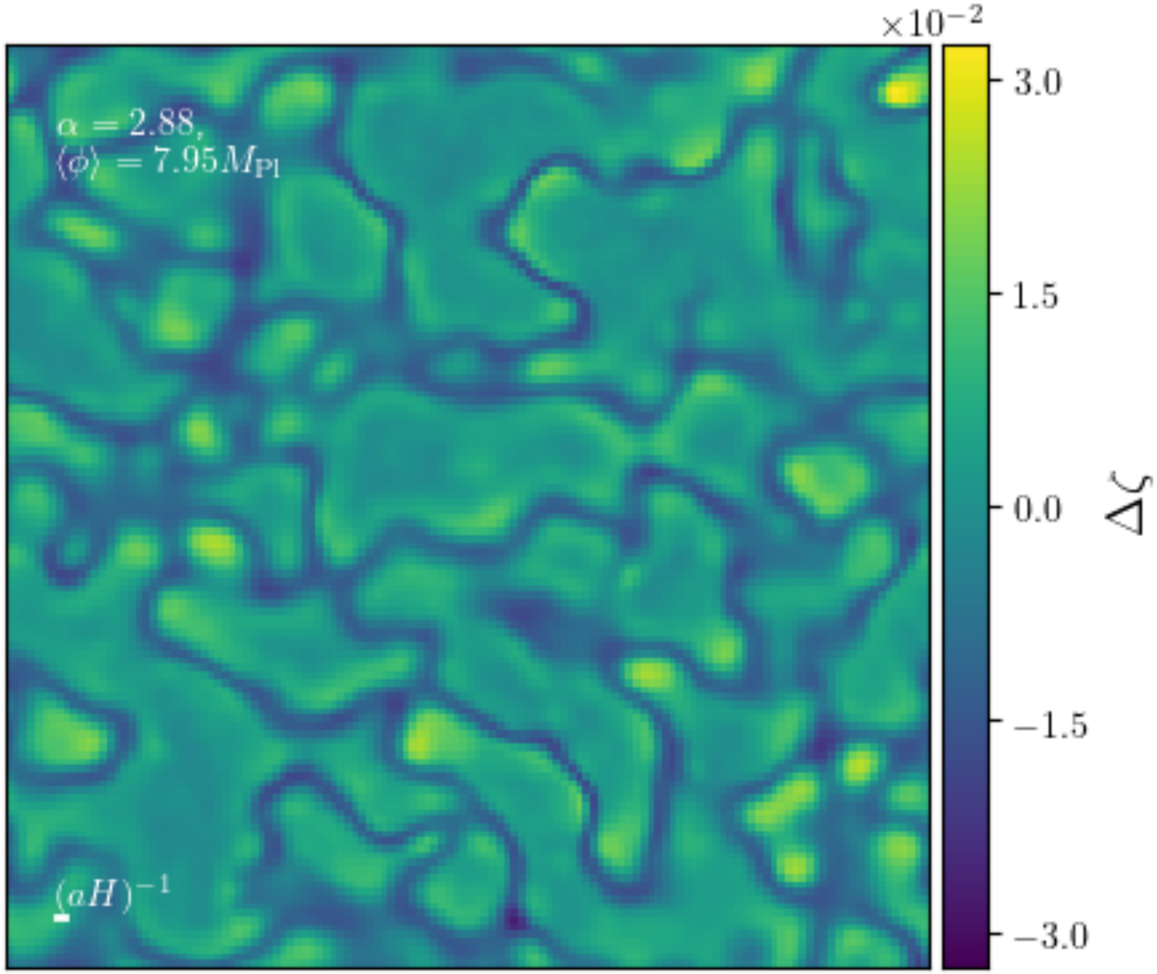
Dzeta_slice_d



Dzeta_slice_e



Dzeta_slice_f



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$\zeta(x,t) \sim \int \Delta\zeta nG$-Prominences$(x-x_c)\, dN_c(x_c R_c)$+ Gaussian random ζ-flucs

$\zeta(x,t) \sim \sum_p \Delta\zeta nG(\chi(x,\alpha_e))$ + Gaussian random ζ-flucs, $\chi(x,\alpha_e)$= Gaussian random

nonG from instabilities during inflation as well as **modulated heating nonG**

$m^2 > 0$ Spin spectrum for cosmic collider of Arkani-Hamad & Maldacena but small response in power spectrum & nonG

$m^2 < 0$ why not, $m_{AB}{}^2$ eigenspectrum, instability & Spontaneous symmetry breaking, landscape etc. more spectacular nonG

- $$s_p(\zeta\,|\,\chi_e) = -\ln P(\zeta\,|\,\chi_e) = \frac{1}{2}(\zeta - \Delta\zeta_p)^T C_{\zeta\zeta}^{-1}(\zeta - \Delta\zeta_p)) + \frac{1}{2}\, Tr \ln C_{\zeta\zeta} + \frac{1}{2}\ln(2\pi)$$

$$s_p(\chi_e) = \frac{1}{2}\chi_e^T C_{\chi\chi}^{-1}\chi_e + \frac{1}{2} Tr \ln C_{\chi\chi} + \frac{1}{2}\ln(2\pi)$$

$$P_p(\zeta) = \int \exp[-s_p(\zeta\chi_e) - s_p(\chi_e)]d\chi_e \;\sim\; < \exp[\zeta C^{-1}\Delta\zeta_p] > \;\sim\; biased\ \zeta$$

nG-pulses **during inflation** $\quad \Delta\zeta_p(\chi_e) \approx \Delta\phi_p(\chi_e)/\sqrt{2M_P\epsilon_e} \;\; or \;\; \Delta\zeta_p(\chi_m) \approx \Delta\phi_p(\chi_m)/\sqrt{2M_P\epsilon_m}$

Concentrated nonG ζ-Prominences summary + future

CMB+LSS+ = one single vast entangled multi-messenger experiment probing the underlying BSMc

*MassPeakPatches+Hydro+eUsims .. A toolkit for CMB and LSS experiments creating t**op down** **websky-ensembles** to test BSMc theories (**nonG**, DM, DE,..) on the Universe: structure is coarse-grain halo+field & fine-grain response functions*

make early universe ζ_{tot} maps and characterize most prominent nonG structures: rank-ordered localized modes identification

embed these ζ_{tot} modes in phenomenological ζ_{tot} models to see how to unearth in LSS data - In search of Buried Treasure:

Independent ζ_{tot} components are entangled in gravitational collapse, emissions

10e-fold LSS (Planck, ACT, SO, S4, .., DES, DESI, Euclid, LSST, .., CIB, LIM HI, CII, CO) + 50e-fold & k>> k_{LSS} + (CMB distort, PBH,..)

- We simulated symmetry breaking/restoration during inflation.
- Comparing between two sims using potentials V and V_0 isolates the response Δζ to the potential feature ΔV, suppressing Gaussian subhorizon and normal (V_0) stochastic 'noise' from the NG signal. **Δ deformed vacua: *relative Casimir effect. Schwinger-like instability***
- We find the NonG of Δζ shows strong local concentrations, **ζ-condensates considered as sourcy with scale related to k_p. Final state post-selection shows the concentrations arise from phase-space trajectories undergoing large excursions during the instability leading to nonlinear interactions between ϕ and χ.**
- Nonlinear mode development is ~ particle creation but not a simple particle creation
- Strongest instability leaves **domain wall memory in ζ - a rather different nonG pattern that the sourcy patterns of less instability strength. No domain wall energy problem, just ghostly memory**
- Conjecture: Δζ could have hidden patterns reflecting other phase transition configurations, e.g., **fuzzy string memory, texture memory**, maybe oscillon memory. This can occur as well in preheating nonG.
- **Simple model of nonG as bias functions of hilly-spectrum GRFs allows for cosmic websky propagation to test cf. data**

$$\zeta(x,t) \sim \sum_p \Delta\zeta_{nG}(\chi_p(x,\alpha_e)) + \text{Gaussian random } \zeta\text{-flucs}, \ \chi_p(x,\alpha_e) = \text{Gaussian random}$$