Dick Bond @ CIFAR17

all cosmic structure from **entropy! ~ζ**

adiabatic trajectories +d*bar*S

stochastic "coarse grain" S

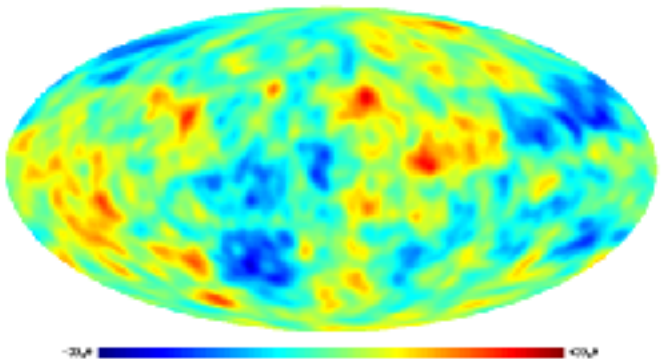
ballistics => caustics

=> corrugated shock-in-time

=> S intermittent nonG

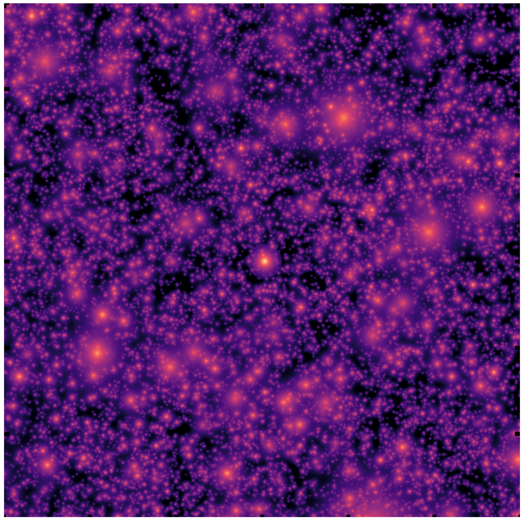
uncorrelated nonG cf. usual correlated nonG

CMB+LSS: std Gaussian inflaton ζ + subdominant uncorrelated ζ from modulated preheating by isocons

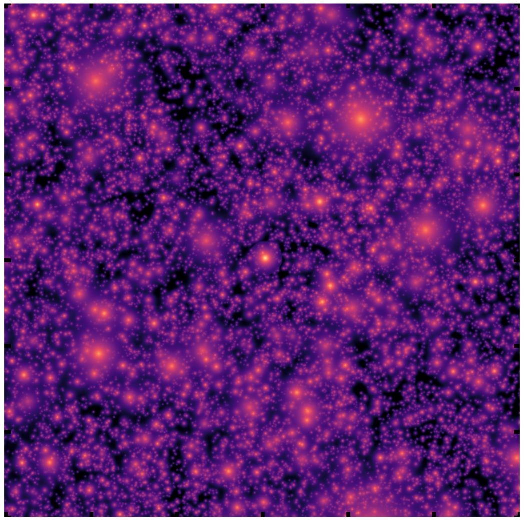


B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std



LSS tSZ: Gaussian std + subdominant uncorrelated ζ



ABSB+FH, alvarez+b+stein+frolov+huang

Dick Bond @ CIFAR17

all cosmic structure from **entropy! ~ζ**

adiabatic trajectories + dS

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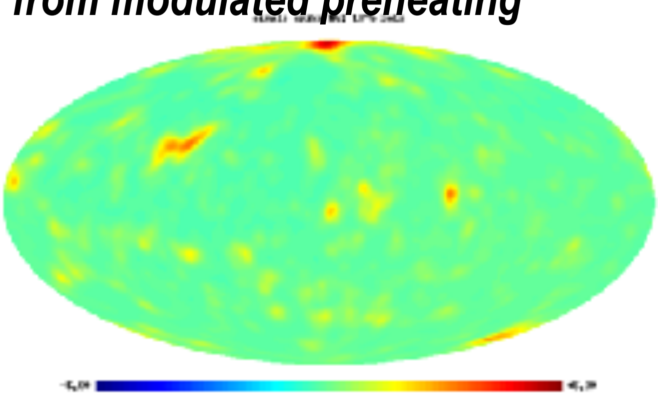
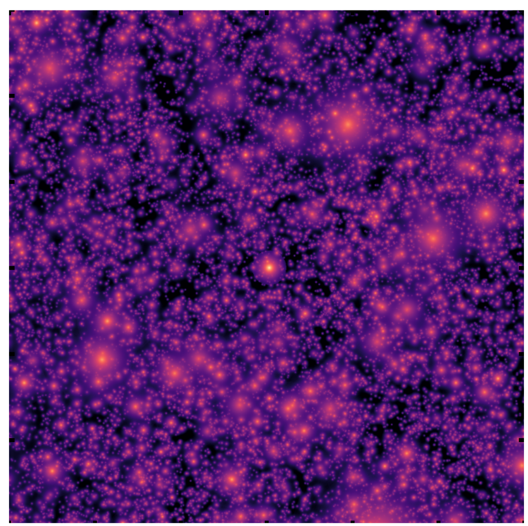
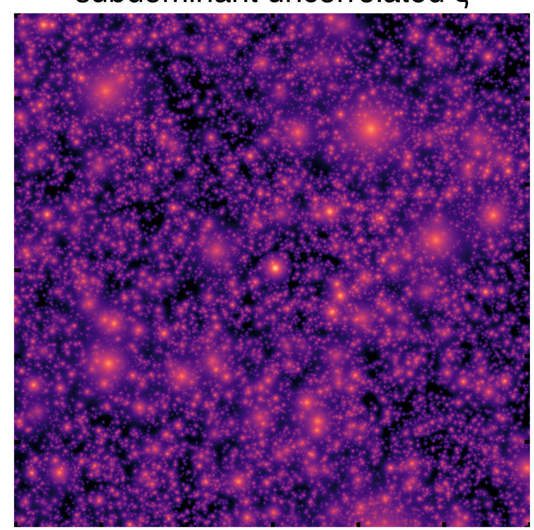


B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std



LSS tSZ: Gaussian std + subdominant uncorrelated ζ



ABSB+FH, alvarez+b+stein+frolov+huang

the **Super-WEB** aka the primordial **3-curvature web** aka the **phonon**/isotropic **strain** = *volume deformation* **web**

$\ln \rho(x,t)/\langle\rho\rangle|_V$ $\quad$ $\ln V/\langle V\rangle|_\rho = 3 \ln a(x,t)/\langle a\rangle|_\rho$ $\quad$ $d\zeta \sim dS\; T/3(E+PV)$

$\zeta(x,t) = \int (dE+pdV)/E \quad /\langle 3(1+p/\rho)\rangle(t)$ — *BST83, SBB89, SB90,91, B95, Bond+Braden2017 ζ for preheating*

$\zeta(x,t) = \ln \rho(x,t) /\langle 3(1+p/\rho)\rangle(t) + \int (1+p/\rho)(x,t)\, d\ln a(x,t) /\langle 1+p/\rho\rangle(t)$

or: $\zeta(x,t) = \ln \rho(x,t)/\rho_b / 3(1+p_b/\rho_b) + \ln a(x,t)/a_b$

gradient / Morse flow *+stochastic jitter*, simple Hamilton principle function $S \sim H(\phi_b)$

along coarse-grain trajectories $d\zeta = d\ln \rho/\rho_b /3(1+p/\rho) + d\ln a/a_b = [d\bar{\zeta}](fg\text{->}cg)$

early preheating: **gradient / Morse flow,** complicated Hamilton principle function S

ballistic /caustic **phase => ΔS nonlinear** ζ lattice sims

cf. late-time **density web ~ strain web** - $\ln \rho/\langle\rho\rangle$ = Trace $\ln e_J{}^j = \ln V/\langle V\rangle|_\rho$

cold $\langle p/\rho\rangle \sim 0 \Rightarrow \zeta(x,t\,|cdm)$ *conserved before shell crossing (preheating)*

quadratic map of the ζ-**scape**

(radical) **compression** ***in quadratic space, using Planck likelihood rather than linear Wiener compression*** (**<ζ** | *Temp, E pol*> +**$\delta\zeta$**) *maps,*

e.g., onto ***12 bands in k-space*** *(LM projection)* *Planck15 inflation B+Huang 13-15-17..*

=> fully includes lensing & BB from BKP & cosmic param marginalization

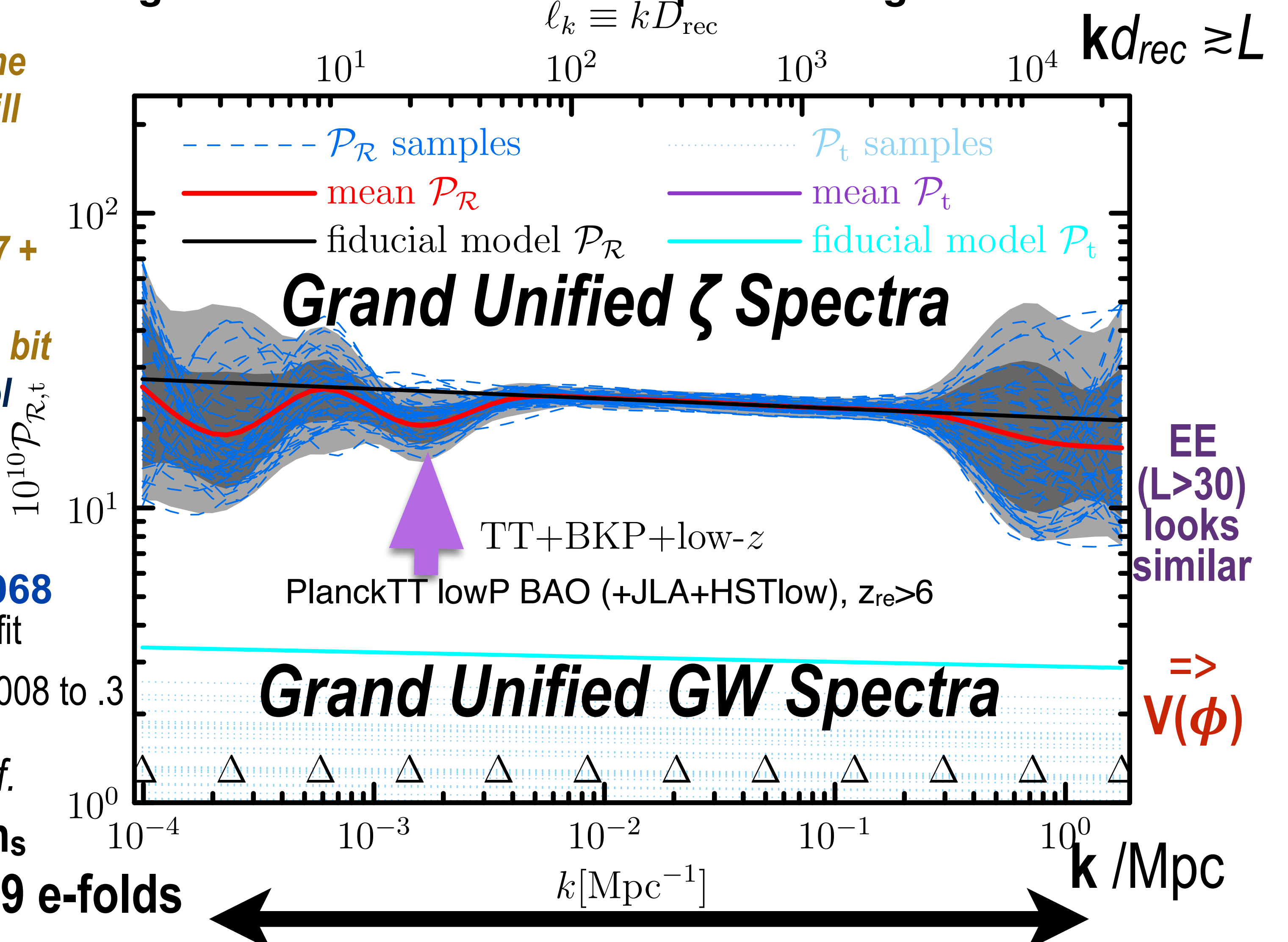
the exploration of the L=20-30 anomaly will improve in Planck2017
+ BICEP/KECK2017 + Spider 201x, x=7
lower tau helps a bit
+ highL AdvACTPol

uniform **n_s=0.968**
P15+LSS best fit

superb 12-knot fit k~ .008 to .3

r<.11 95%CL *cf.*

r<0.09 uniform n_s

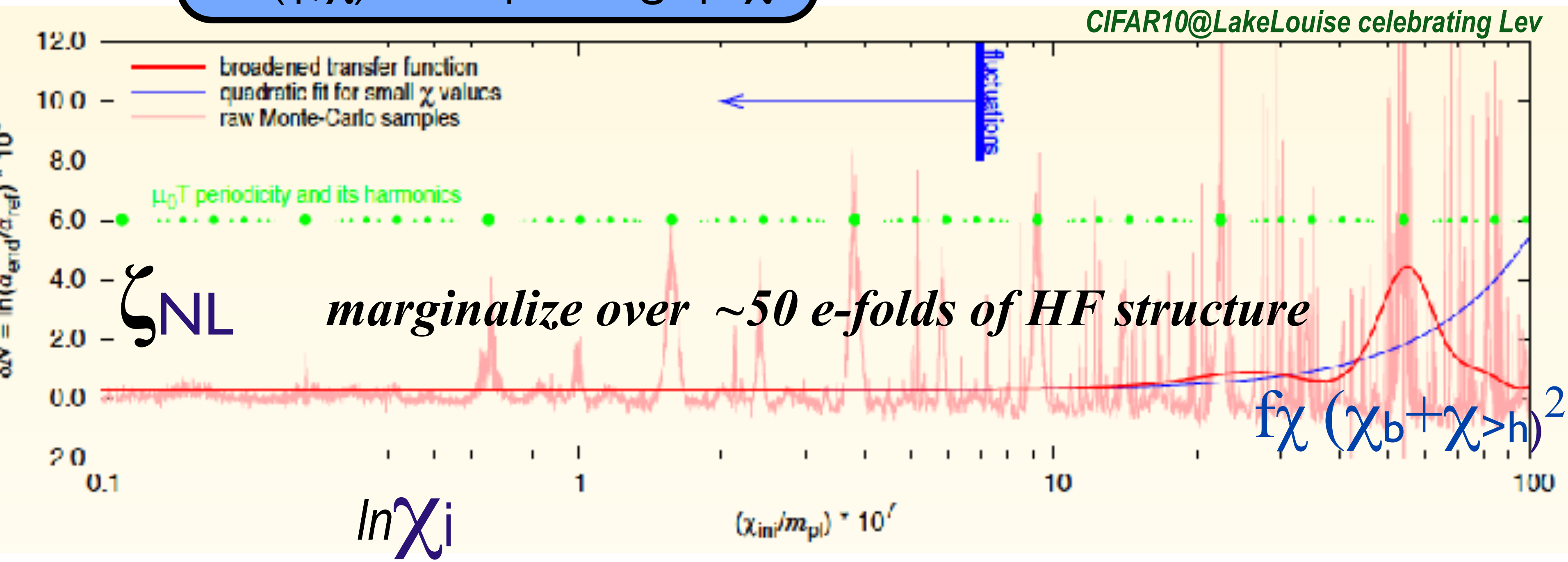


Local nonG: correlated quadratic $\zeta(x) = \zeta_G(x) + f_{NL}\, \zeta_G^2(x)$

Chaotic Billiards: NonG from Parametric Resonance in Preheating

B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 17

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



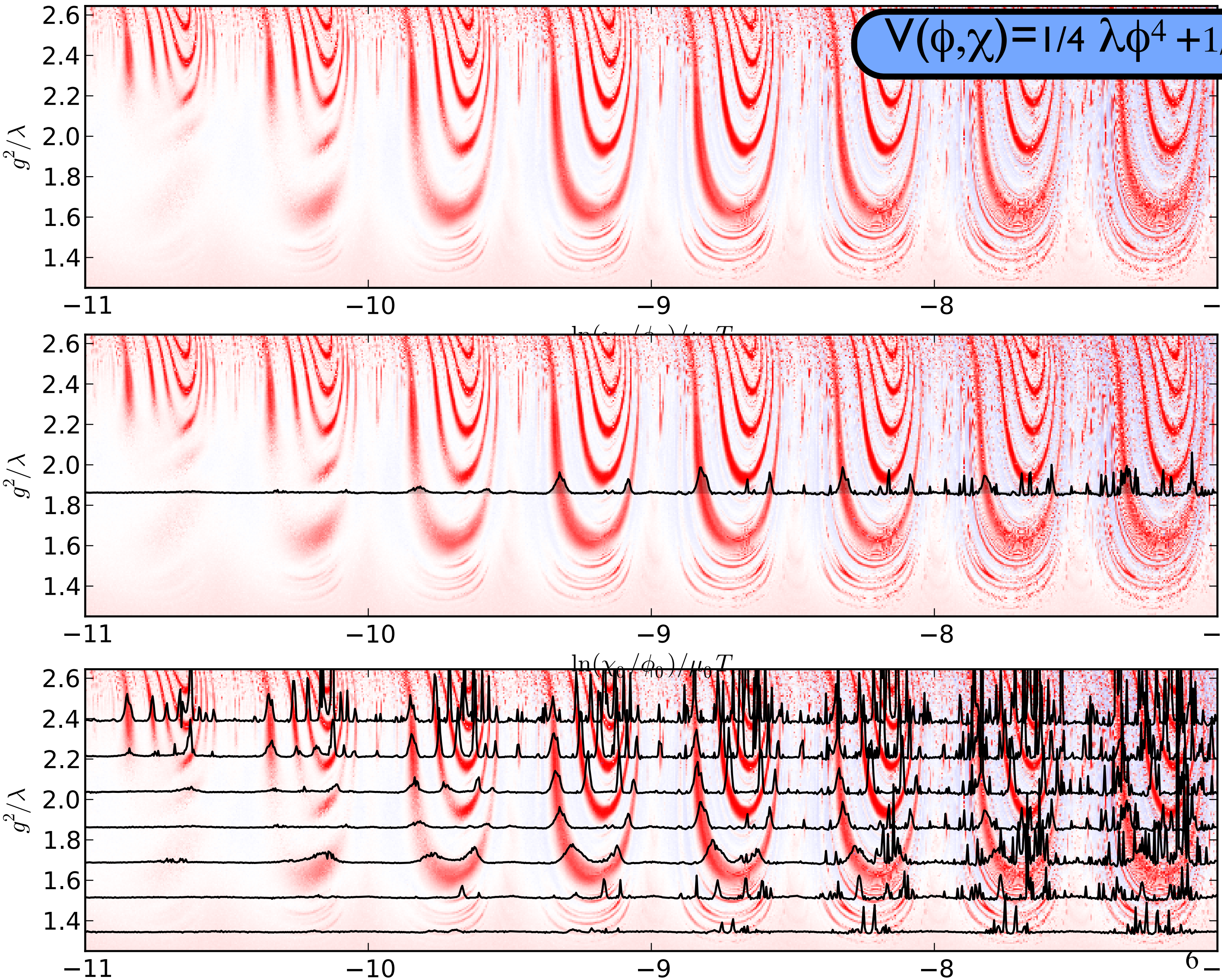
$< \zeta_{NL} | \chi_b + \chi_{>h} > \quad \sim \beta(\chi_{>h})\, \chi_b + f(\chi_{>h})\, \chi_b^2 + \ldots$

$f_{NL}^{equiv} = \beta^2 f_\chi\, [P_\chi / P_\phi]^2 (k_{pivot})$

nonG 3-pt f_{nl}: 0.8 ± 5.0 local for Φ_N
=> f_{NL^*} = -0.52 ± 3.0 for ζ phonons

=> constrain $f_\chi^3\ \chi_{>h}^2$ *($P_\chi/P_\phi \sim 2\varepsilon$ => very relaxed limit)* *gigafigure of **lattice** simulations* *computational tour de force* *BBFH, b+braden+frolov+huang*

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



colour coded

ζNL

many 64^3 sims to show the wondrous complexity of

*ln*a(χ_i, g^2/λ)

nonlinearly-arrested caustic structure of ballistic k=0 trajectories

k~0 “ballistic” trajectories

become **entangled** *with*

non-zero **k-modes** *in a coarse-grained*

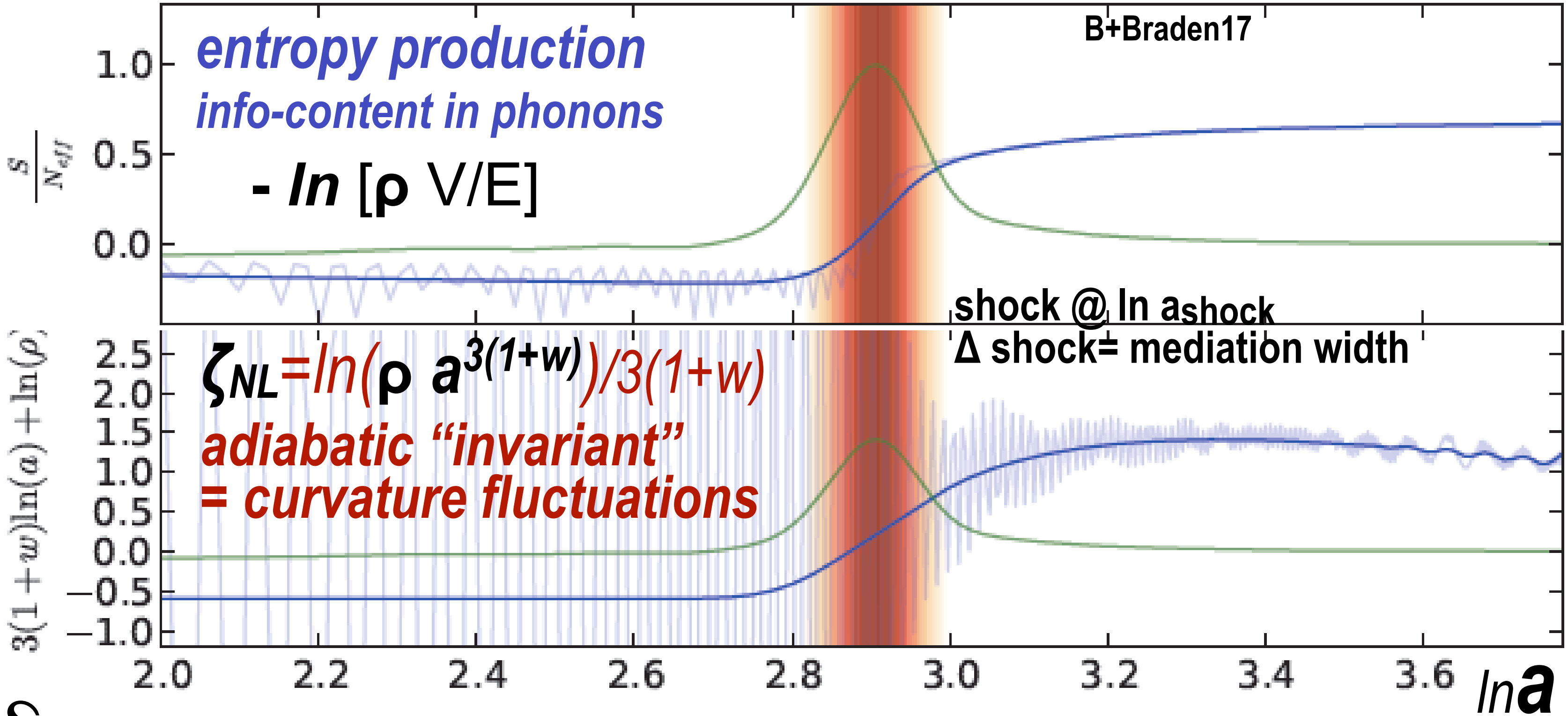
non-equilibrium **entropy** *generating*

shock-in-time

whence to the **StdModel-pp**

- ***ln*** [ρ V/E] & ζ_{NL}**=ln(ρ $a^{3(1+w)}$)/3(1+w)** *are* **nearly Gaussian within a preheating horizon (~ cm)** *shown by* **BB lattice sims for pdf in k-bands, smallness of the 3 pt,** *etc.* **(!!!)**

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

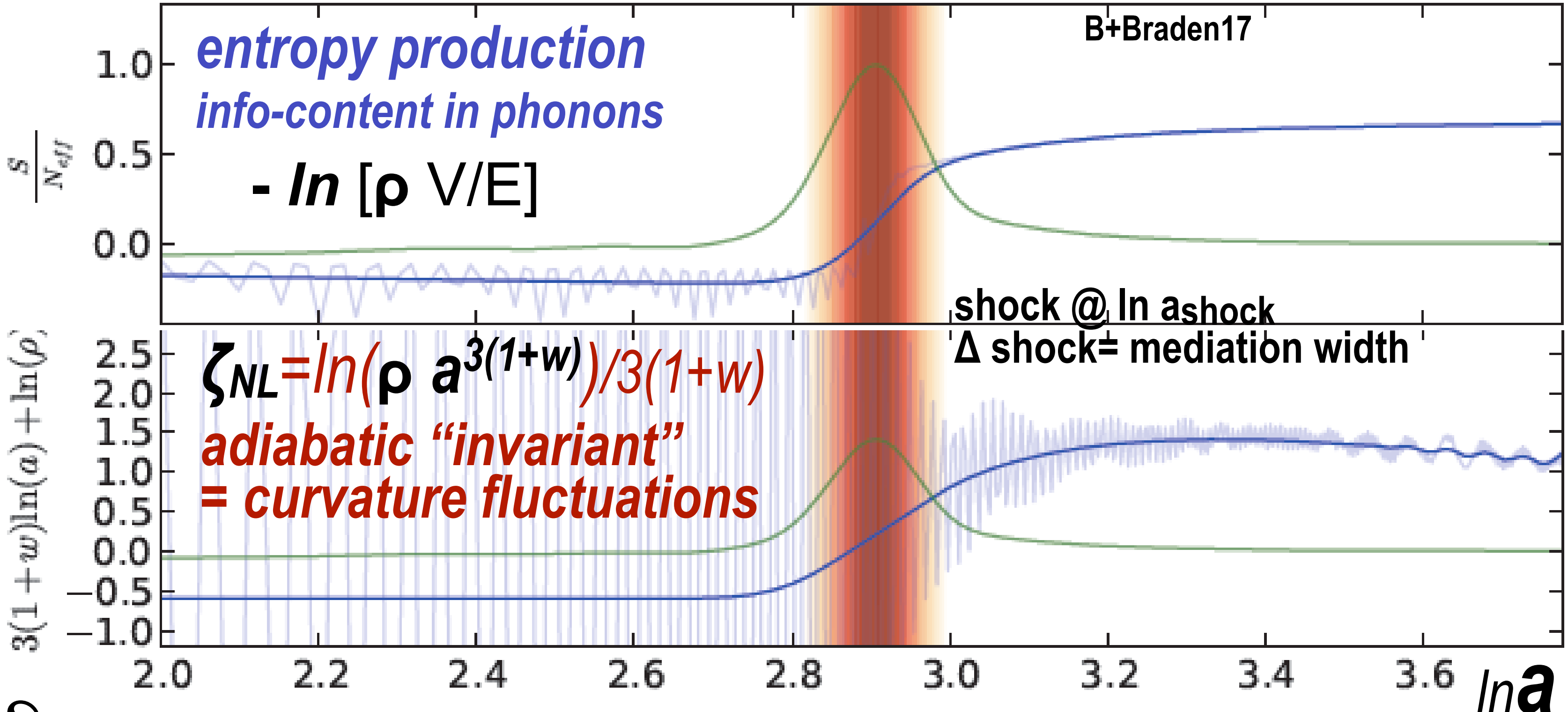


true thermal equilibrium far off ➤ & on to coupling to standard model degrees of freedom

$$\delta\zeta_{NL\,\mathrm{shock}}(\mathrm{tf}\ |\chi_i(\mathbf{x}),\, g^2/\lambda))$$

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

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

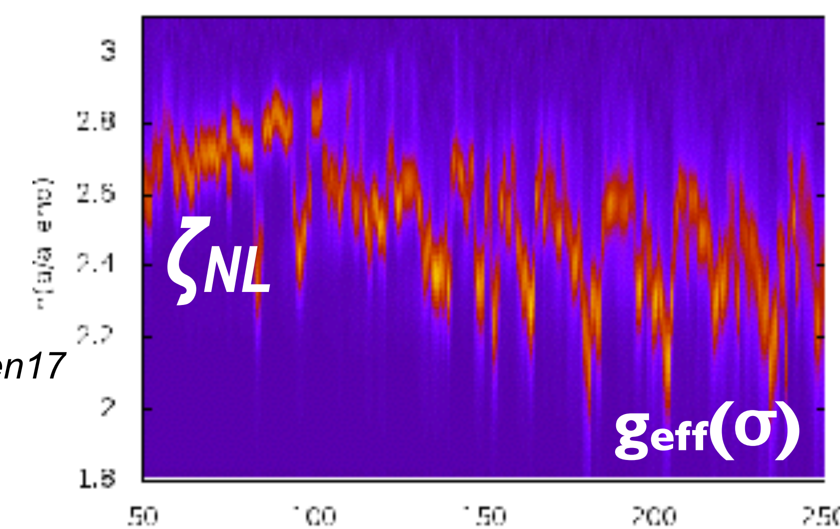
$$\delta\zeta_{NLshock}(\mathrm{tf}\,|\chi_i(\mathbf{x}), g^2/\lambda))$$

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

$$\delta\zeta_{NLshock}\ (\mathrm{tf}\ |\ \mathbf{g}(\sigma(\mathbf{x}))$$ => modulated

$$V(\phi,\chi) = 1/2\ m^2\phi^2 + 1/2\ g_{eff}(\sigma)^2\phi^2\chi^2$$ Bond,Braden17

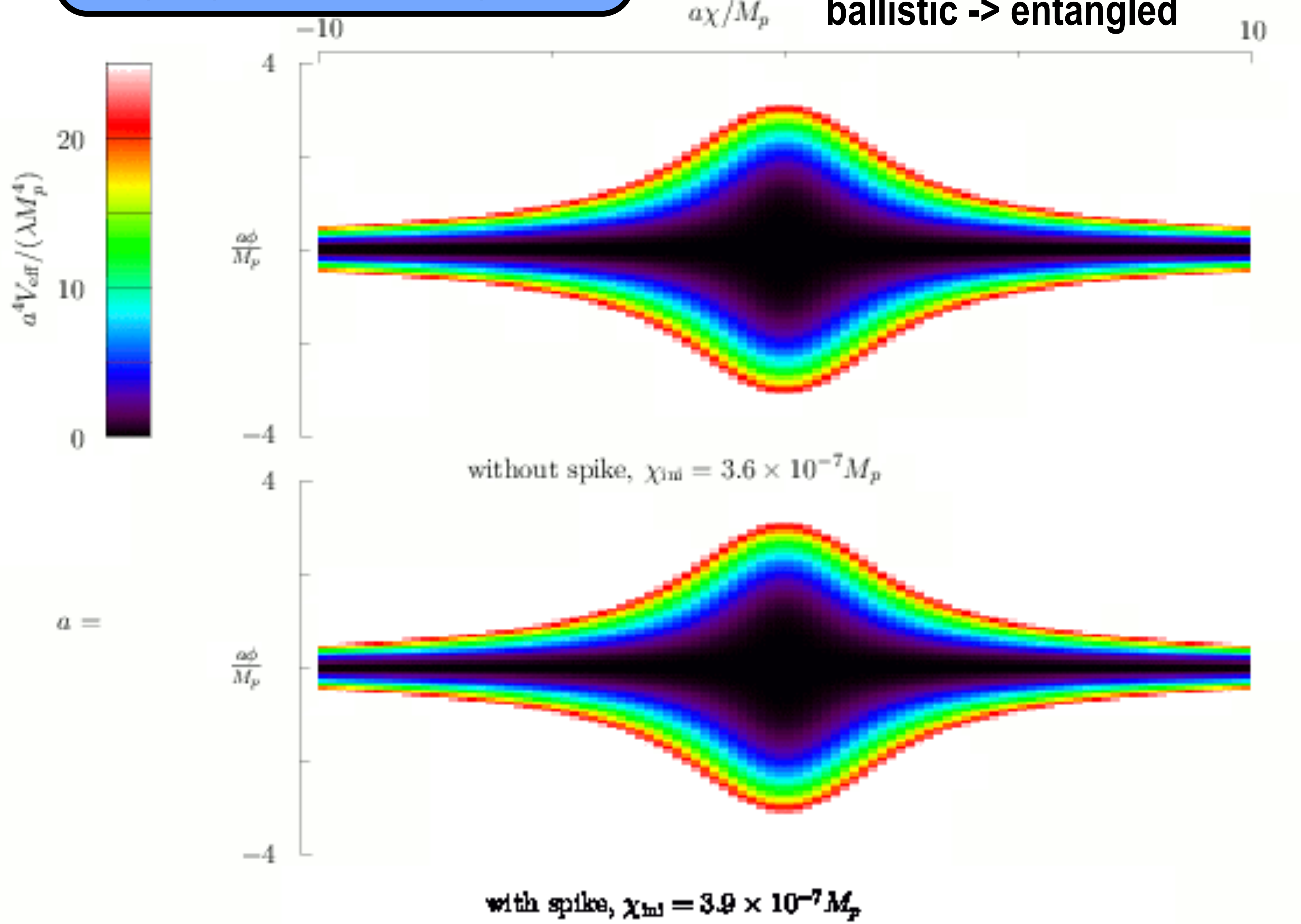
$g_0 + g_1\ \sigma/M_P,\ g_0 \exp[\gamma_1\ \sigma/M_P], ..$



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

full lattice simulations of k~0 trajectories (χ_i)

ballistic -> entangled



(nonlinear) **V_{eff} is trajectory-bundle dependent**

caustics in ballistic orbits

$<\delta q^A\ t2 \ | \ \delta q^B\ ti> \sim \exp(\mathcal{E}(t2 \,|\, t1)) <\delta q^A\ t1 \ | \ \delta q^B\ ti >$

early U parameters: final *ln* **a**, ln ρ, ϕ, χ, Π_ϕ, Π_χ, initial χ_i , *couplings* g, λ, ..

parameter strain tensor $\mathcal{E}(t2 \,|\, t1)$

$d\mathcal{E}/dt$ strain rate ~ local Lyapunov coefficients *Floquet instability charts*

instability to have nearby parameters diverge => chaotic billiards

small $\mathcal{E}$ eigenvalues => coherent trajectory bundles (for a time) =

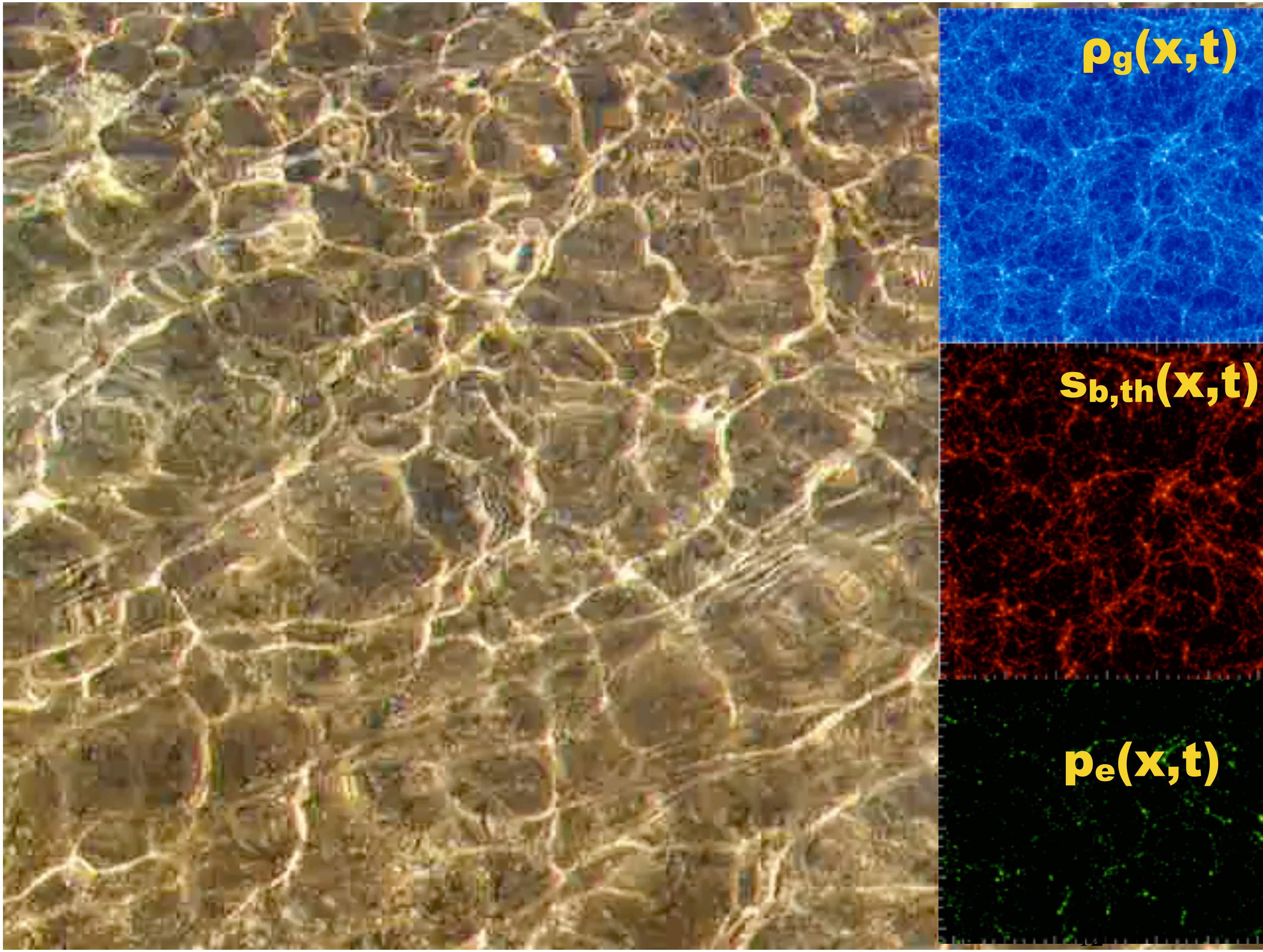
caustics (inverse -> ∞) $1/ [\partial \ln \mathbf{a} / \partial \chi_i(\mathbf{x})]$; caustics => peaks in *ln* **a** (χ_i)

stopping time **tstop** (χ_i) when $\mathcal{E}$ evalues get large <=> local gradients ⇑

cf. LSS parameters: **final Eulerian position <= initial Lagrangian position**

1LPT aka Zeldovich: $\partial x/\partial r = \exp(\mathcal{E})$ -> 0 density $\rho \sim \exp(-\mathrm{Tr}(\mathcal{E}))$ -> ∞

caustics are ubiquitous: **LSS/cosmic web & preheating**

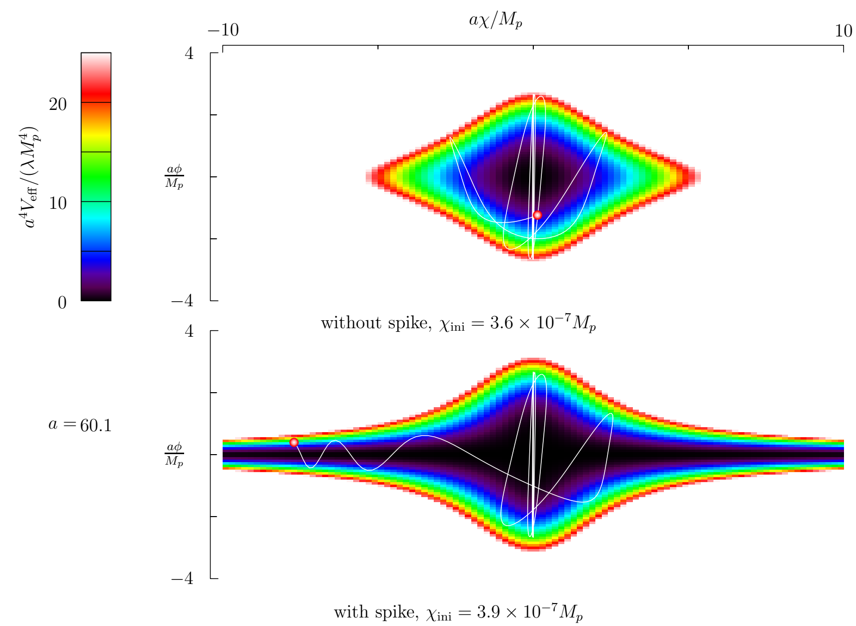


understanding the ζ -spike structure, qualitatively YES and quantitatively MAYBE B^2FH 17

arresting the orbits via a shock-in-time, incoherent cf. coherent (caustic) trajectory bundles

incoherent

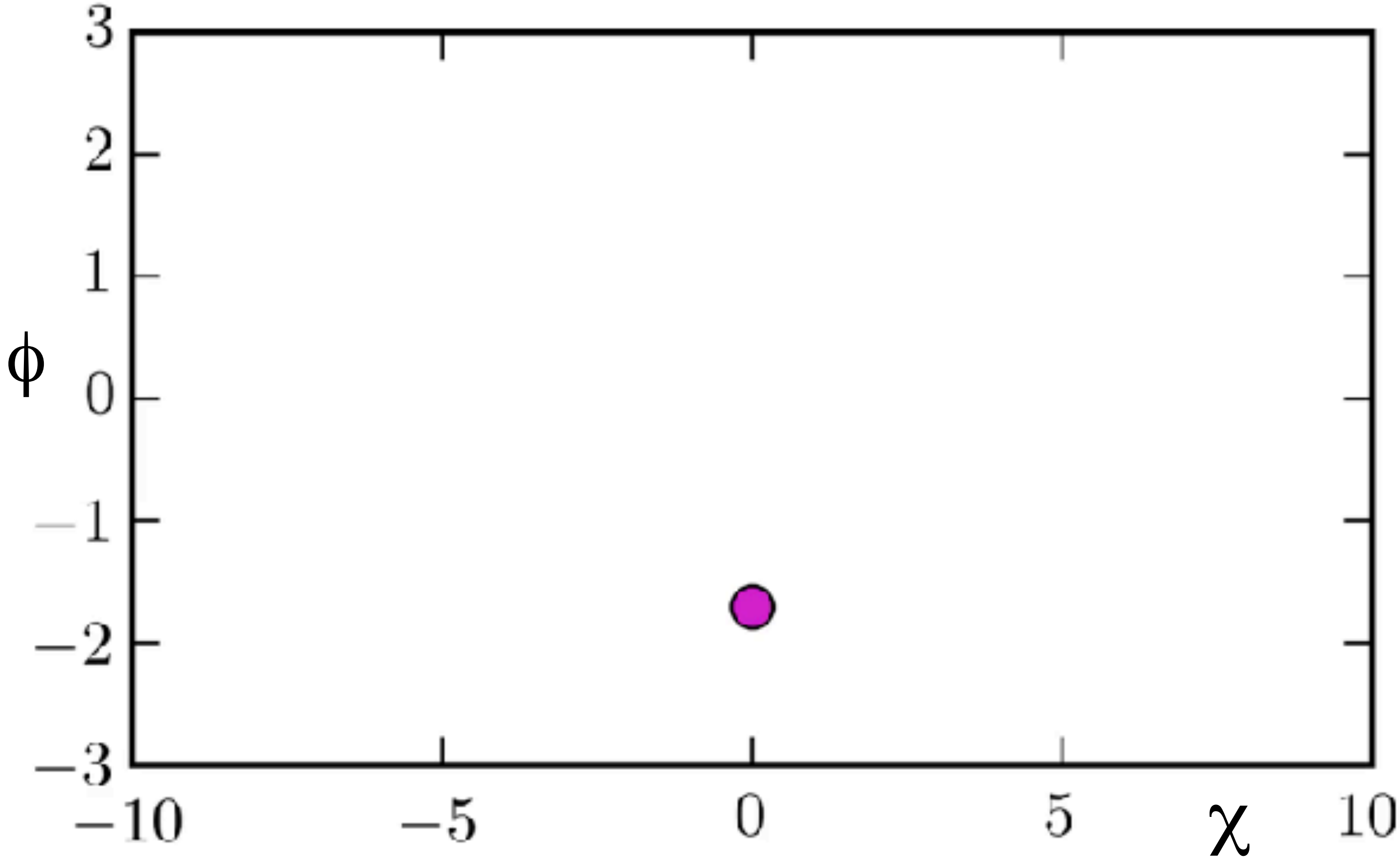
coherent



ballistic billiards k=0 mode **phase space string** **evolution**

2D constrained distribution functions

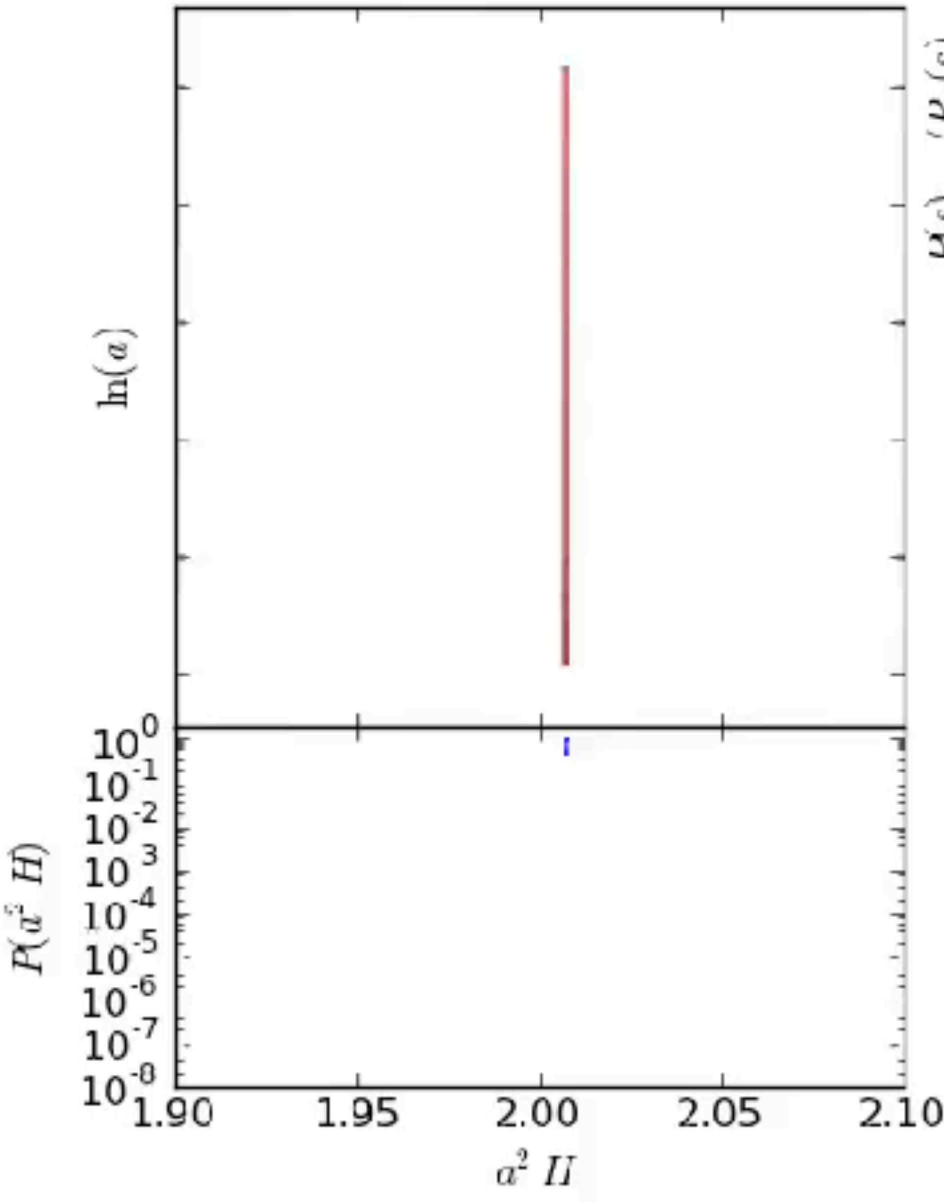
stopping criterion when coarse-grained entropy of field variables rises <=>strain high

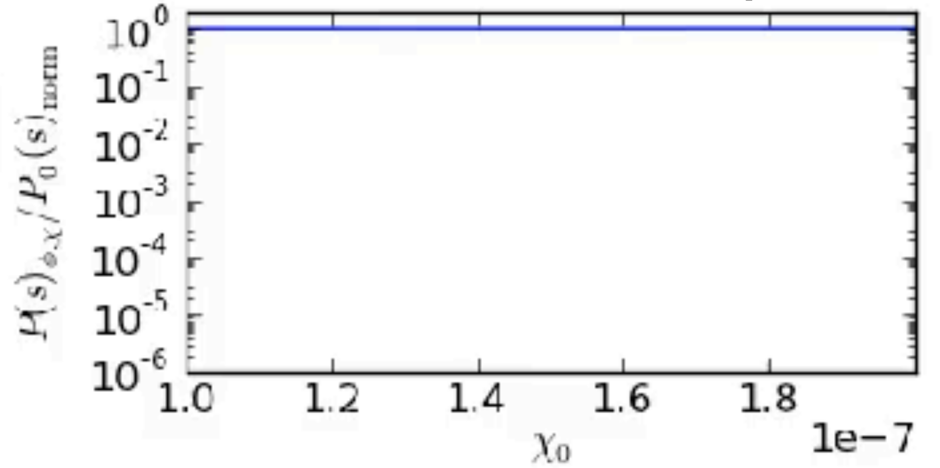


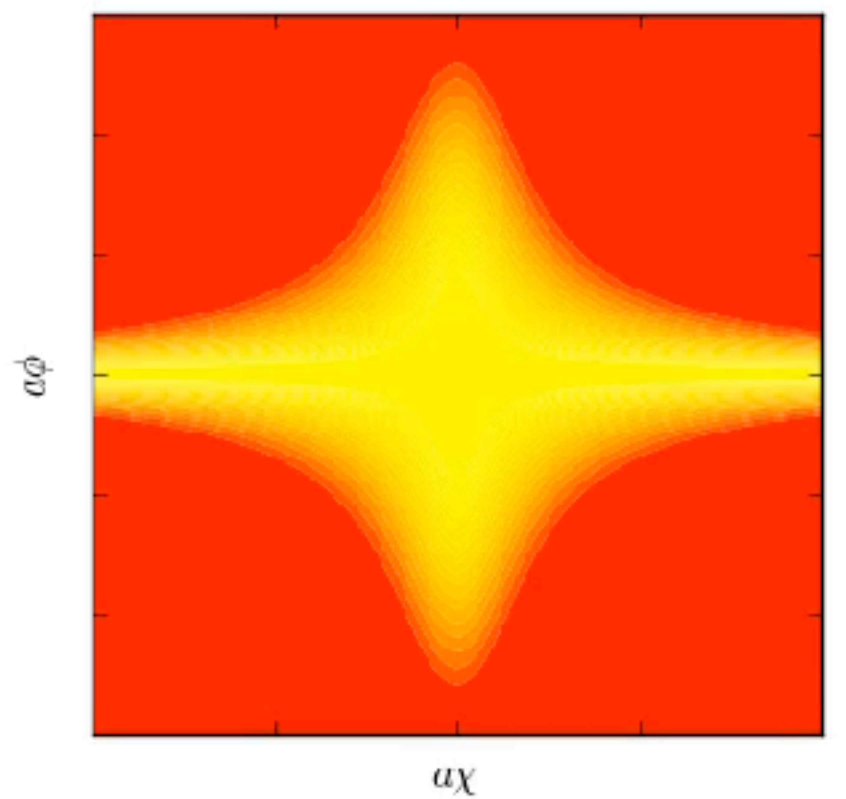
$$V = 1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$$

phase space strings

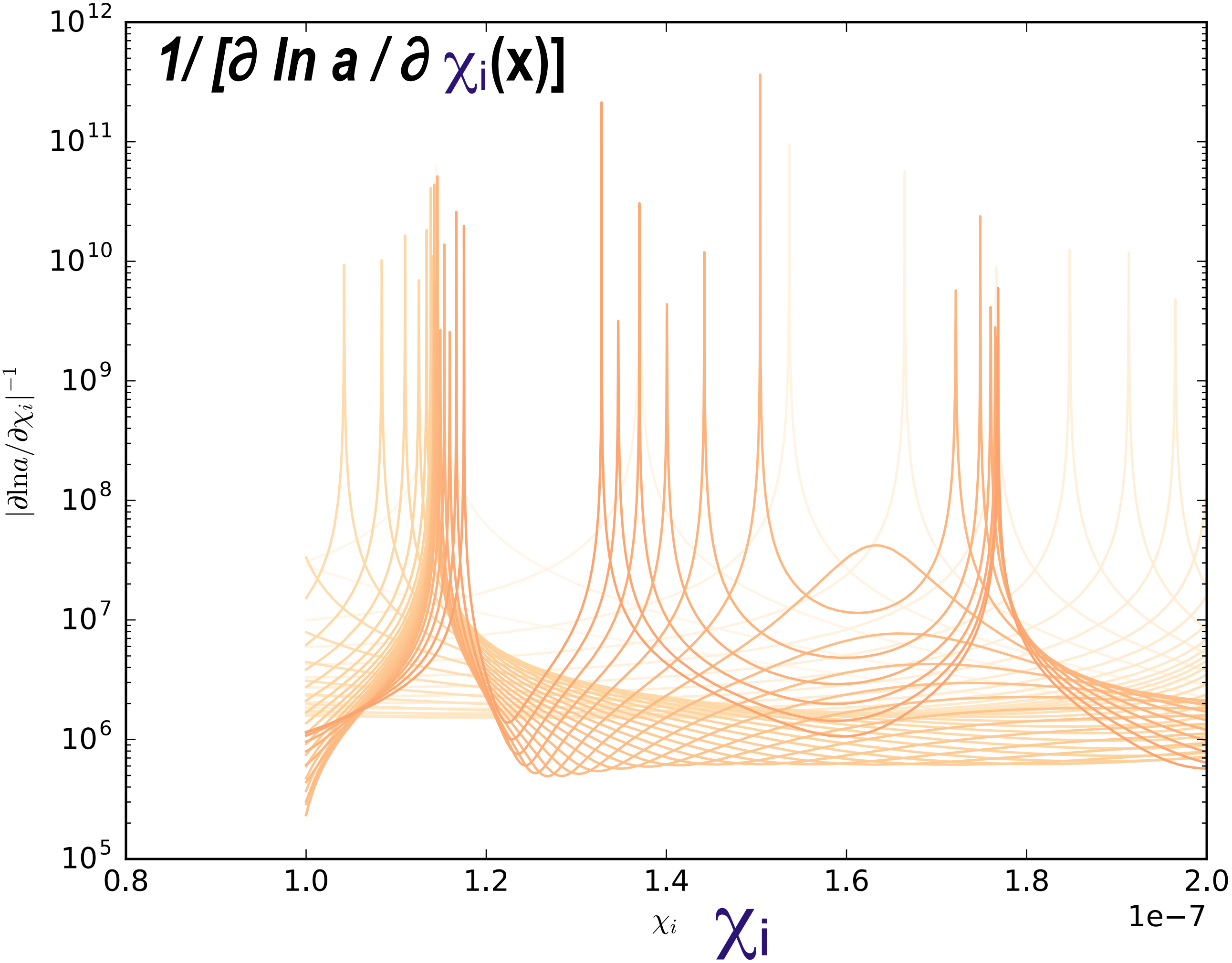
caustics are ubiquitous







calculating ballistic evolution to caustics gives the spikes in good agreement with full nonlinear lattice simulations ε^{-1}



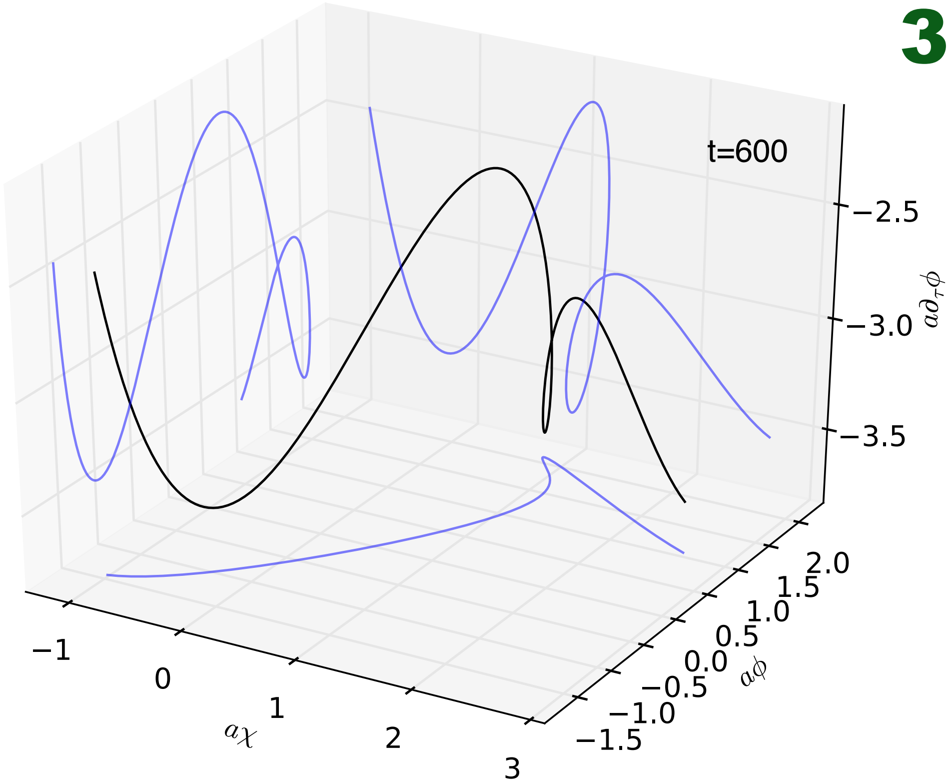
B2FH, b+braden+frolov+huang

***nonG from post-inflation but pre-entropy generation ballistic trajectories can lead to pre-shock-in-time caustics and other phase space convergences in the deformations (!)* Zeldovich map-ish**

eg $\partial \ln a / \partial \chi_i(x)$, $\partial \ln a / \partial g(x)$ => $P[\ln a(x),\ t_{shock}\ |\ \chi_i(x),\ g(x), t_{end\text{-}of\text{-}inflation}]$

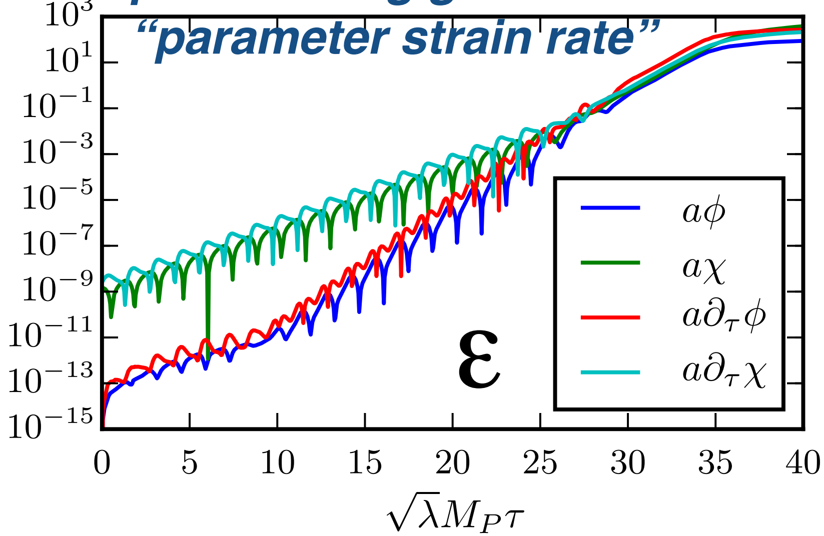
3D phase space strings

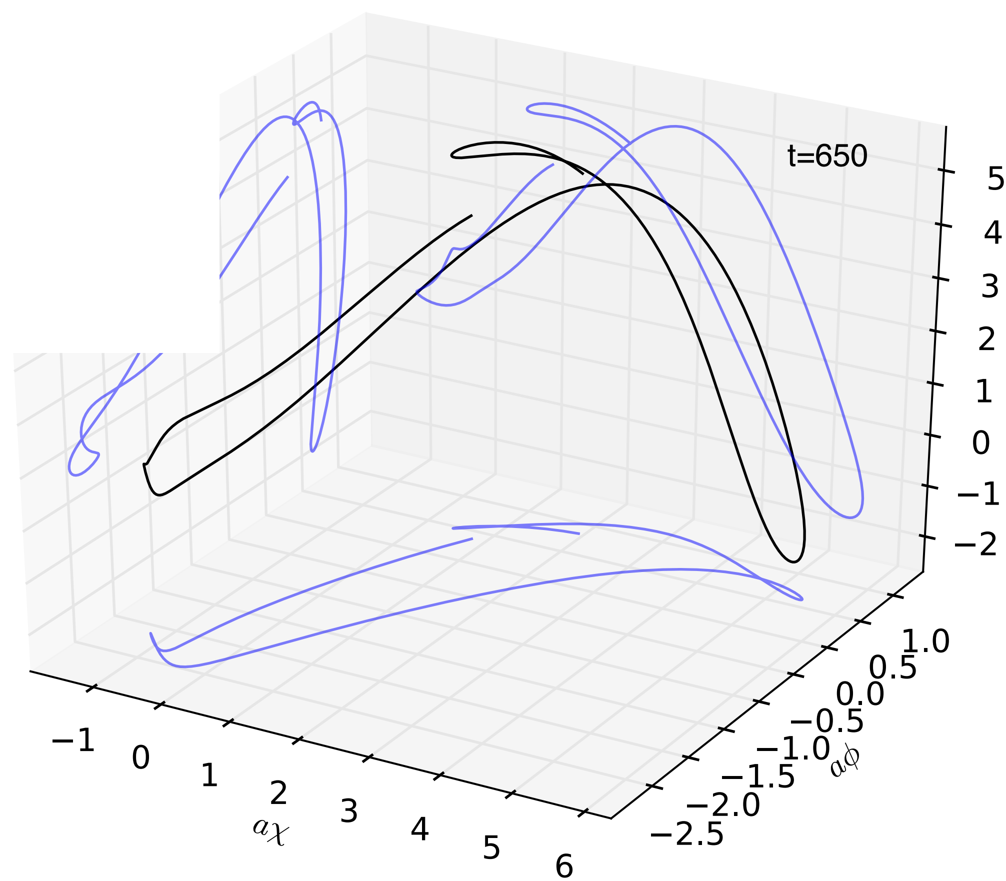
3D constrained distribution functions



phase string growth in time

“parameter strain rate”





how generic will caustic preheating be? structure around potential minima:

=> filamentary potentials

=> ballistic flow channels

multi-filaments may lead to caustics

2 std inflaton, slow heating? roulette V is fast. 3-star

4 case workhorse. *the* ***5-star... 'axionic' angles works with conformal flattening of V +***

cf. filaments that join at clusters in the LSS web isocon

χ(x)

or

g(σ(x)

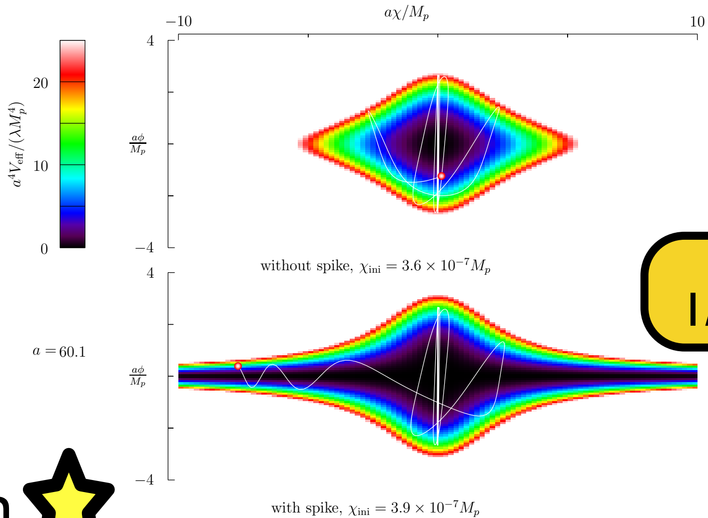
or..

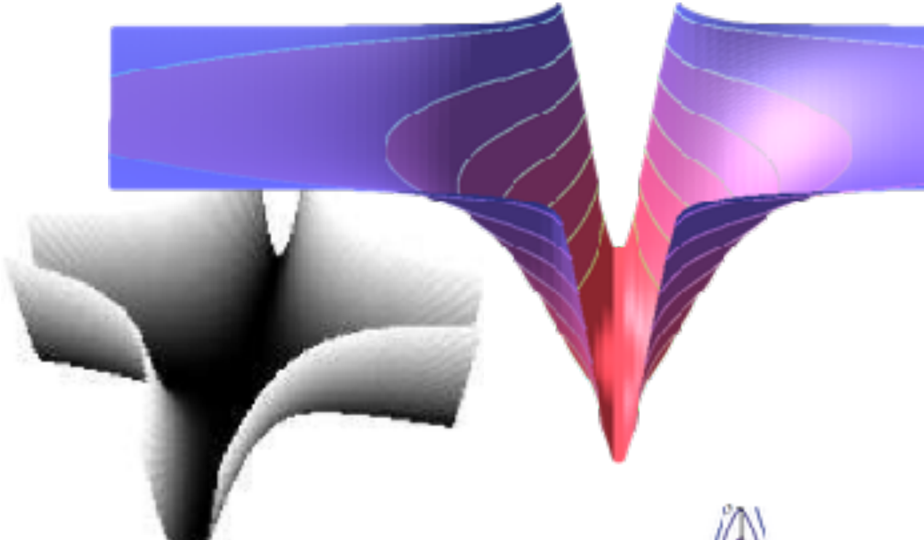
ϕ

inflaton

pre-heating patch (~1cm)

How generic is the intermittent caustic phenomenon? Holds for many basin potentials at the end of inflation. but not if rapid heating

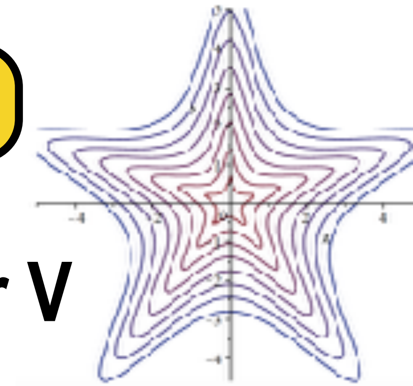




$1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$,

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

3-star => **5-star V**

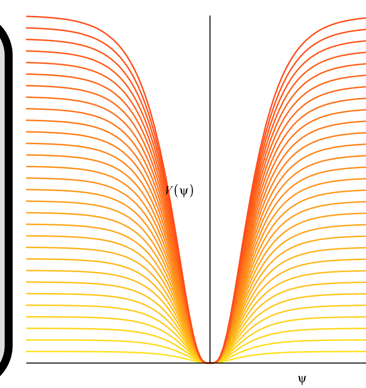


$1/4\ \lambda\ (r^2 - v^2)^2\ U$

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

filaments!

conformal transforms potential flatten



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 $V(r,n) = \sum_{LM} V_{LM}(r) Y_{LM}(n)$

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

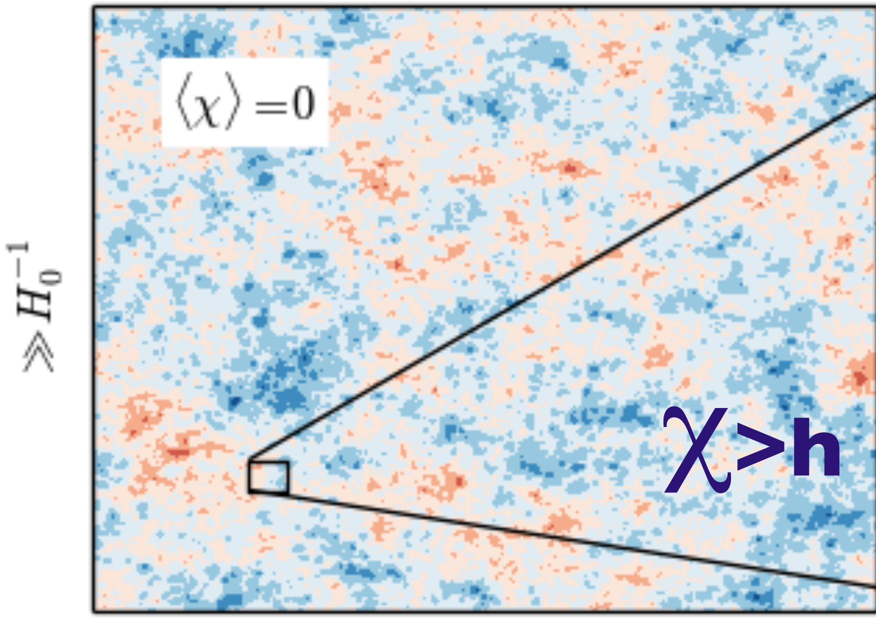
conformally transformed potentials a la Higgs/R², modified kinetic terms, flattened potentials of all sorts *B2FH, b+braden+frolov+huang*

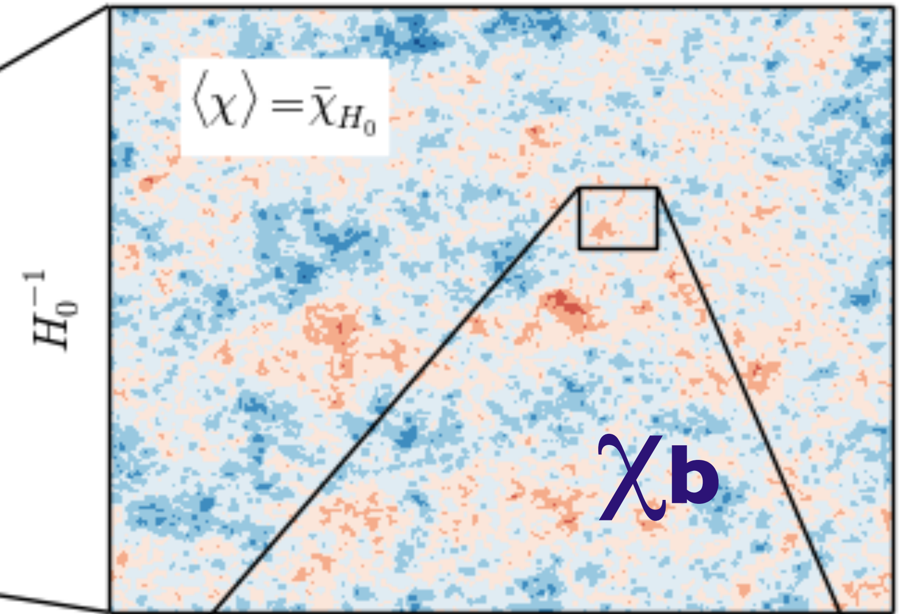
how modulated caustics in preheating could give observable intermittency

modulating the caustics on large scales & super-horizon scales via isocons

(coupling constat g modulation via isocon)

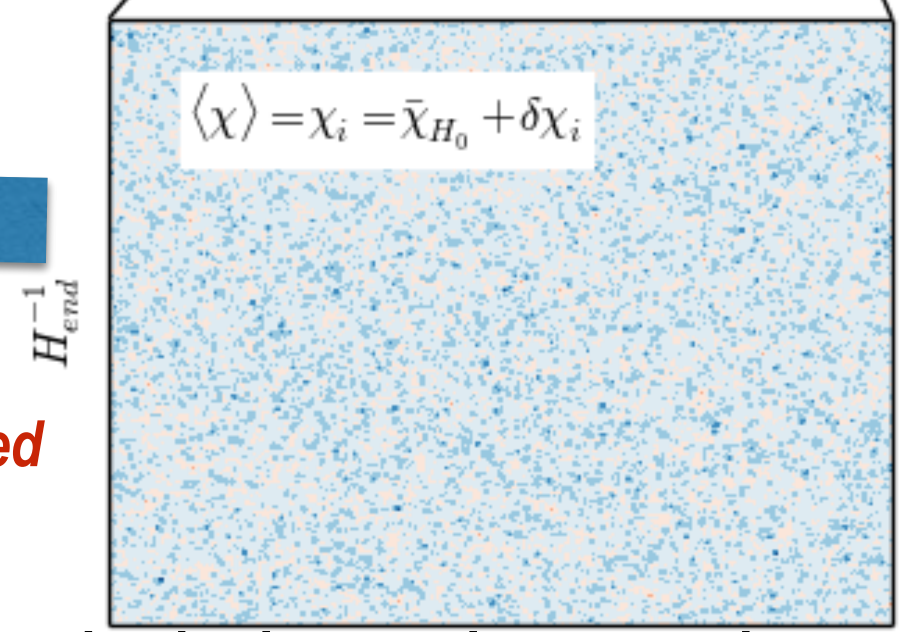
these isocons are NOT spectators





ULSS modulation beyond our Hubble patch

LSS modulation within our Hubble patch



$$\delta\zeta_{NL\,\mathrm{shock}}(\chi_i(\mathbf{x})\ |g^2/\lambda))$$

=> *NonG cold spots ++*

the complex preheating cm is modulated by a large scale Gaussian field

preheating horizon scale < comoving cm

Inflation ζ-Phenomenology *with* **CMB+LSS:** *Beyond the Standard Model of Cosmology*

highly nonlinear field evolutions happened (EoI caustics, bubble collisions)!

subdominant patterns do arise! => will any be observable as rare-event CMB/LSS 'GRF-biasing' anomalies?

or ***weak*** **constraints** *on* **multifield potentials, >horizon fields, nucleation rates**, *etc.*

b2fh17 ***progress in semi-analytic understanding of complex lattice sims with prob strings, caustics, trajectory stopping, shocks-in-time in the V-web***

light isocons cf. heavy isocons, the heavy can lighten up = original SBB nG

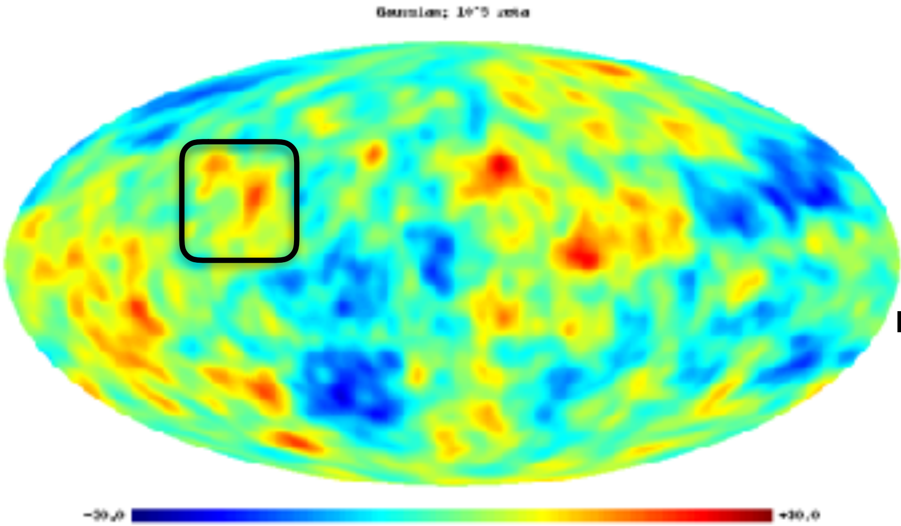
isocon modulators, coupling(isocon) modulators, isocon tunneling, isocon oscillons, isocon short-lived fuzzy-strings, + very long-lived strings

alas **a 2-number A_s-n_s early universe so far**

intermittency frustration: statistical variance is large cf. 2-3 parameter search

CMB ***restricts us to a*** **projected 2D ζ-scape to reconstruct phonon/isotropic-strain power,** ***the future may look much the same as now for*** **ζ=>potential V(ϕ)=>acceleration ε(a); r helps**

we **mock** the LSS future ***end-to-end*** *to probe the* **mode-rich 3D ζ-scape**



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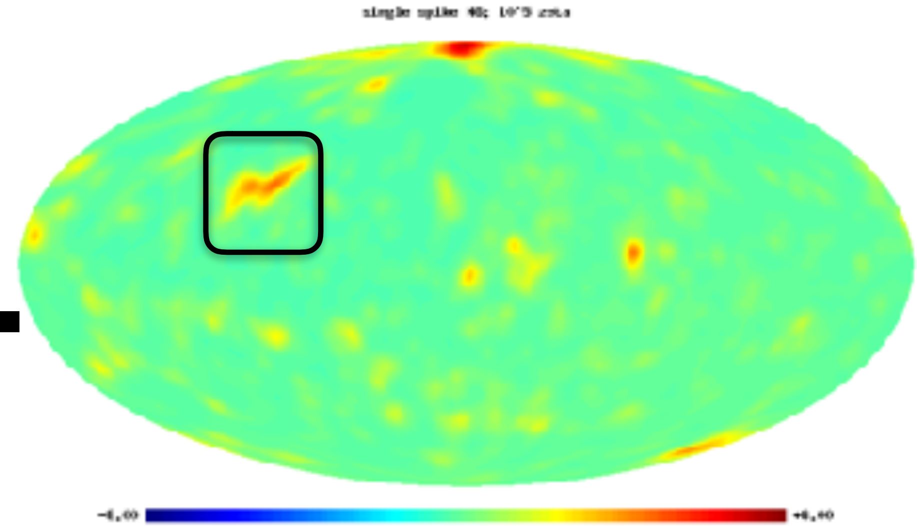
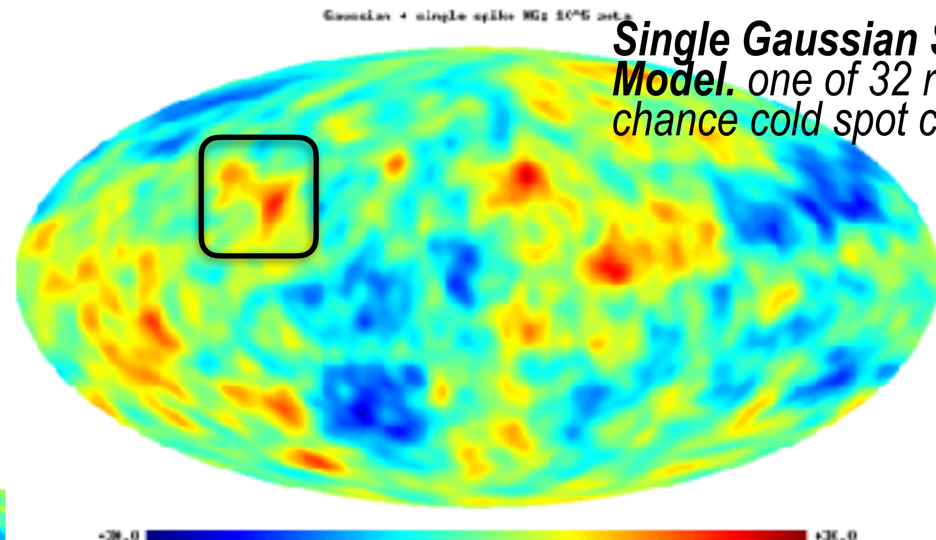


Single Gaussian Spike intermittent nonG Model. *one of 32 random choices to yield chance cold spot constructive interference.*

=



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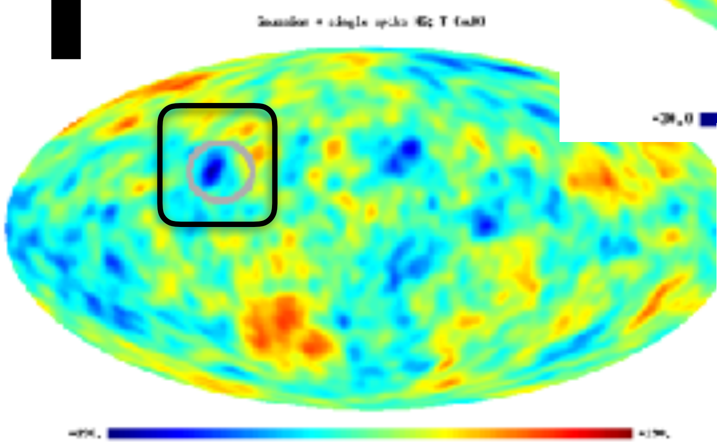

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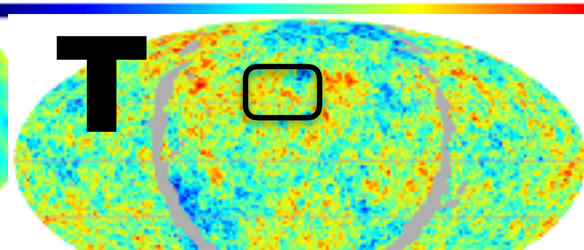
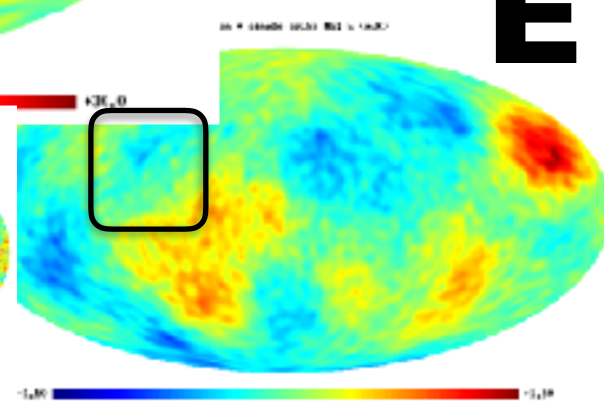


cf WMAP cold spot rotated

E



end