
담배
닭 도 리 탕
아 구 탕
부 대 찌 개
조기매운탕
동태매운탕
Chilsung
Coca-Cola

Let There Be Heat: the Shock-in-Times of Post-inflation Preheating

dS_G/dt

INFLATION

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave dS/dt>0
- tightly-coupled photon-baryon fluid: oscillations δγ vγ πγ
- viscously damped
- polarization πγ
- gravitational redshift Φ SW dΦ/dt

DarkM

17 kpc (19 Mpc)

Decoupling LSS

Lsound/ ksound

secondary anisotropies dS/dt>0

- nonlinear evolution
- weak lensing
- thermal SZ +kinetic SZ
- dΦ /dt
- dusty/radio galaxies, dGs

DarkE

the nonlinear COSMIC WEB

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

reionization

dS_astro <0

dS/dt>0

z ~ 1100

redshift z

z ~ 10

time t

13.7-10^-50 Gyrs

13.7Gyrs

10Gyrs

today

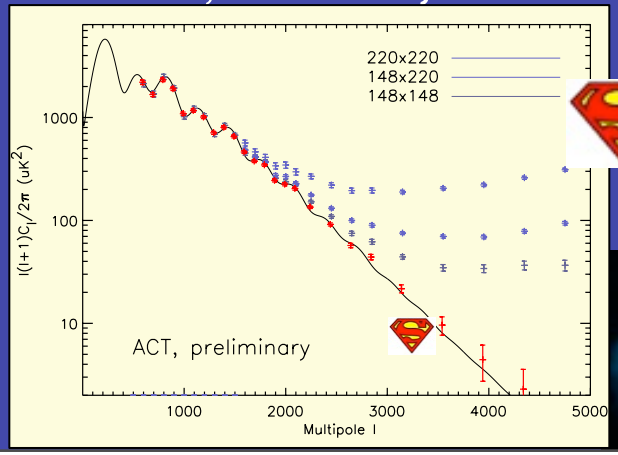
Dick Bond@GC2012 CIFAR@CITA with CITA aka **Cosmic Information Theory & Analysis**

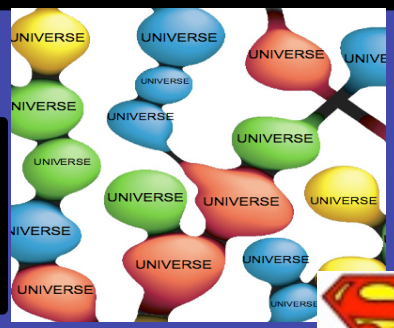
Let There Be Heat: the Shock-in-Times of Post-inflation Preheating

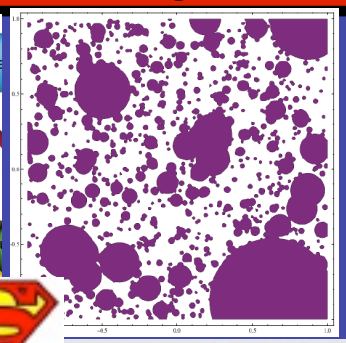
Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity

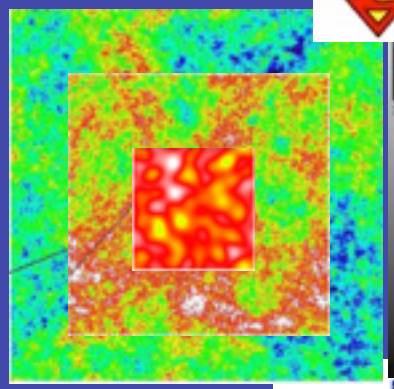
IT from BIT from BITs in IT
information quantity = entropy Shannon 1948
information quality = IQ essence

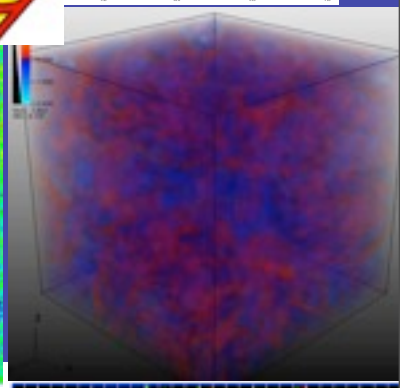
info& primarily-**earlyU**
=Bond@IAP 12.09.28
info& primarily-**clusters/SZ**
=Bond@IAS 12.10.04
info& primarily-**primaryCMB**
=Bond@APC 12.10.30; @Imperial 12.11.02
Damping Tail & Recombination History
new SPT12+,ACT12+,Planck13

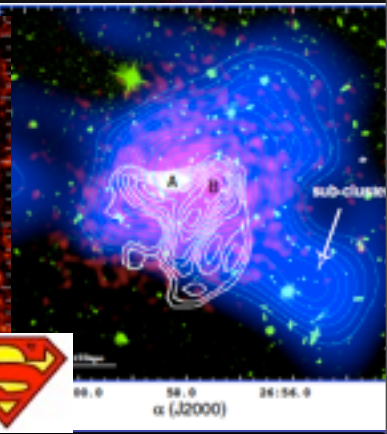


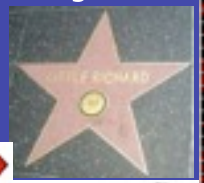












the coherent & the entropic, in all its forms, from the ultra-early-U to Now to the ultra-late-U

Dick Bond CIFAR@CITA with CITA aka *Cosmic Information Theory & Analysis*

Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity

the **nonlinear COSMIC WEB**

dS$_G$/dt

I N F L A T I O N

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z ~ 1100 redshift z z ~ 10

13.7-10^{-50}Gyrs | **13.7Gyrs** | time t | **10Gyrs** | today

Universe = System(s)+Reservoir
~ Signal(s)+Residual *noise*
~ Effective Theory+*Hidden variables*
~ *Data+Theory*
~ observer(s)+observed

the coherent and the entropic, in all its forms, from ultra-early-U to ultra-late-U

$S_{U,m+r} \sim 10^{88.6}$ *cf.* $S_G \sim 10^{121.9}$ *asymptotic DE*

$S_{th,cl} \sim 10^{76}$ *Studying the* **Cosmic Tango**
en-TANGO-ment the dance of U=R∪S

our **Cosmoticians' Agenda:** *Statistical Paths in Cosmic Theory & Data via the Bayesian chain drawing what we know of It from Its Bits*

$P(q|D,T) = P(D|q,T)P(q|T)P(T)/P(D|T)$ *D=CMB,LSS,SN,..,complexity, life*
T=baryon, dark matter, vacuum mass-energy densities,...,
early & late inflation as low energy flows/trajectories on a (string) landscape

entropy =<information-content> Quantity Shannon 1948

generalized parameter space {q} ~phase space

$$S_f(D,T) = \int dq\, P_f \ln[P_f^{-1}]$$

relative Shannon entropy = - *Kullback Leibler divergence*

$$S_{fi}(D,T) = \int dq\, P_f \ln[P_f^{-1} P_i] \quad \text{cf. } S_f - S_i$$

= relative RENYI entropy of order 1; use order n for clustering & clumping

IQ=information quality

IQ~{minimal length messages/codes | error tolerance} *Planck(E/T), genetic code, recipes, axioms, algorithms, IC/BC/evolution eqⁿs*

cat information_overload.txt | grep fundamental | grep physics > exec_summary.tex

filter, compress, reduce, marginalize

early U applications of "CITA" to cosmic-complexity

☆ ***the superhorizon measure problem & the Lambda-scape***

☆ ***the emergence of the collective from the random!***
coherence from driven zero-point vacuum fluctuations ⇨ V
inflaton, gravity waves; decohere

☆ ***let there be heat:*** entropy generation in **preheating** from the coherent inflaton (origin of all "matter")

$S_{U,m+r} \sim 10^{88.6}$

cf. $S_G \sim 10^{121.9}$

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Studying the Cosmic Tango

some non-early U applications of "CITA" to cosmic-complexity

☛ information in **nearly-Gaussian** density/potential random **fields** of U, & in weakly and strongly non-linear fields. *ergodic theorem & constrained fields*

☛ spatial coarse-grained **CMB entropy** & how we capture it

☛ **dark matter entropy, cluster & *protocluster* & *cosmic web* entropy**

MHD turbulence entropy with cooling & grain polarized emission - CMB fgnd

☛ ***How Shannon info-entropy flows from CMB bolometer timestreams to marginalized cosmic parameters via Bayesian chains from prior to posterior. 1D & 2D & ... $\Delta S(q,DT)$*** *(cf. ACT10),* ***q=r, w, n_s, ...***

early U applications of "CITA" to cosmic-complexity

☆ ***the superhorizon measure problem & the Lambda-scape***

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Studying the Cosmic Tango

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T=baryon, dark matter, vacuum mass-energy densities,...,
early & late inflation as low energy flows/trajectories on a (string) landscape

Old: Theory prior = delta function of THE correct one&only

New: Theory prior = probability distribution of **late-*ish*-flows** on a **LANDSCAPE**

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

isocon

$\chi(\mathbf{x})$

or

$\mathbf{g}(\sigma(\mathbf{x}))$

or..

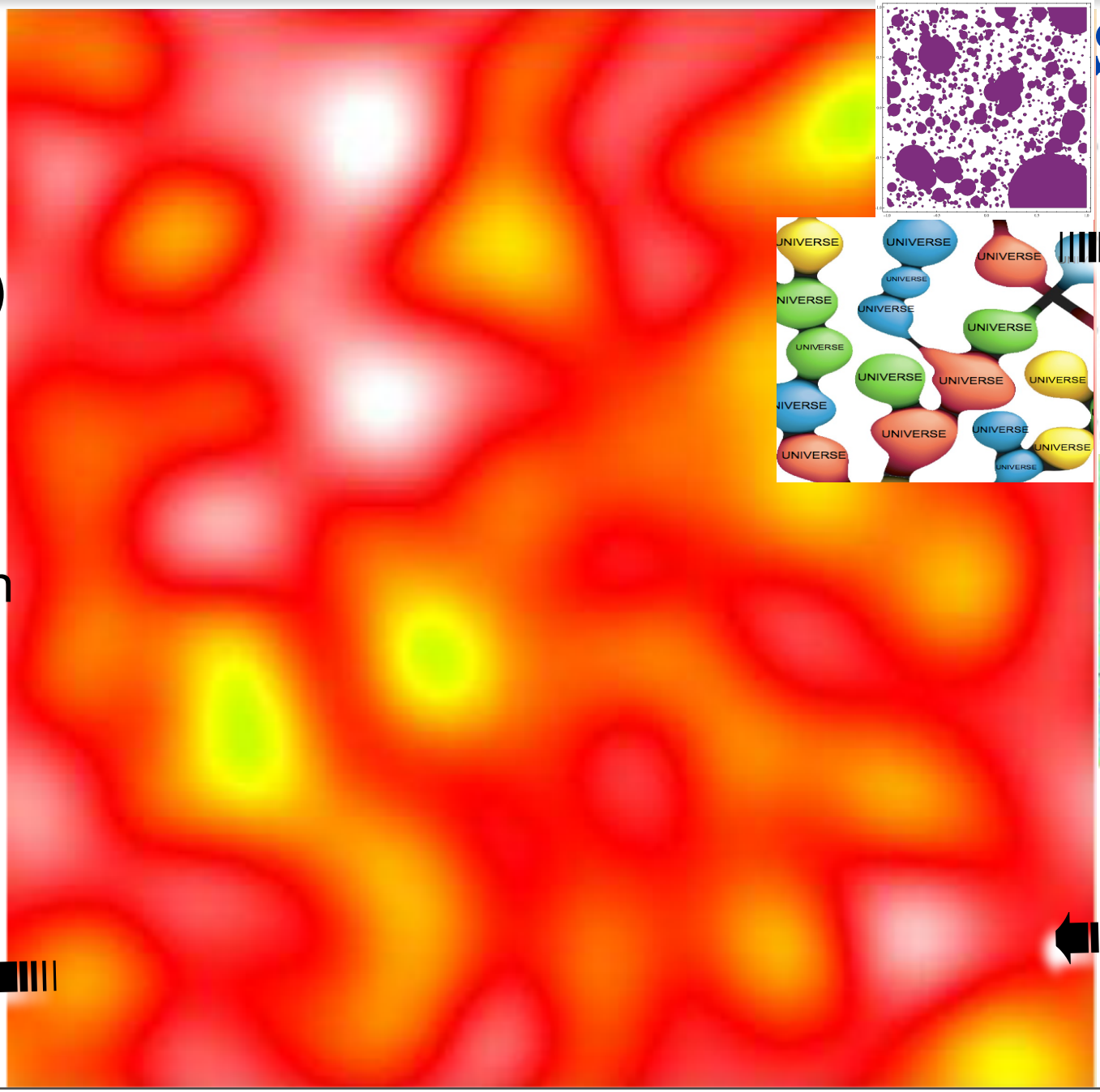
ϕ

inflaton

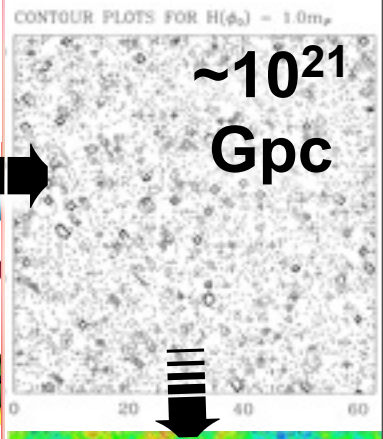
pre-heating patch (~1cm)

$S_{U,m+r}$

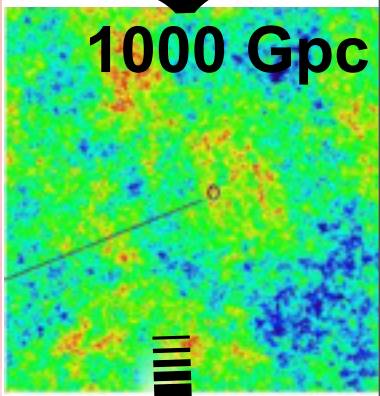
$\sim 10^{88.6}$



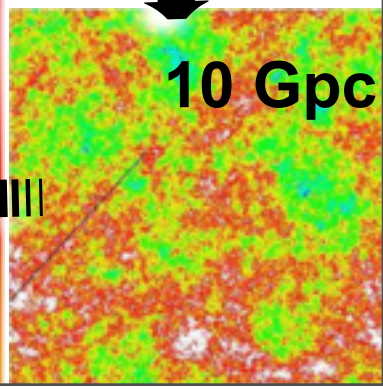
$S_{U,UUULSS}$



$\sim 10^{21}$ Gpc



1000 Gpc



10 Gpc

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

how (most of) the entropy in matter

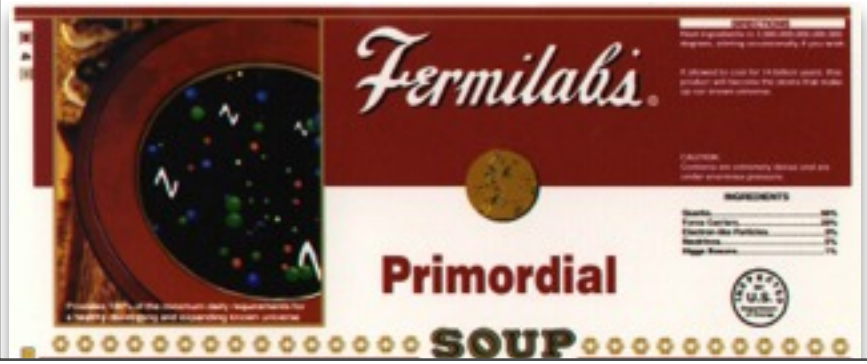
=> *GUT plasma/quark soup* => $S(\gamma,\nu)$ was generated *(through a shock-in-time)*

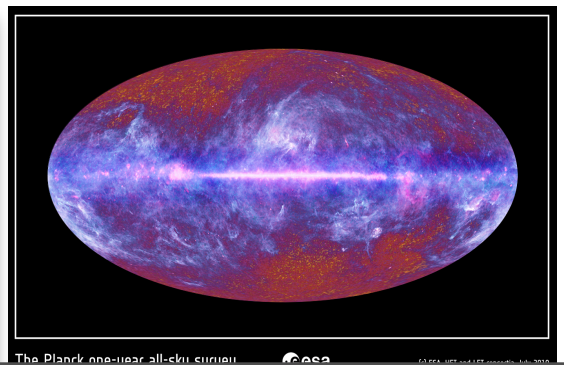
via nonlinear coupling of the inflaton to new interaction channels g,χ_a *ultimately to standard model degrees of freedom*

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

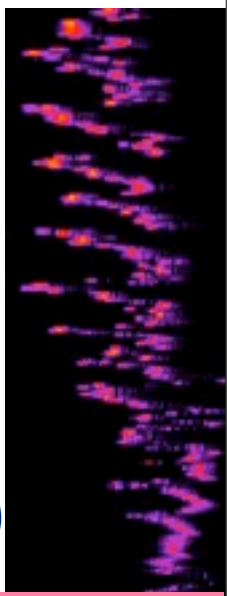
exactly who, what, where, when, why?

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





$a_{Shock}(g)$



non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

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

isocon

$\chi(\mathbf{x})$

or

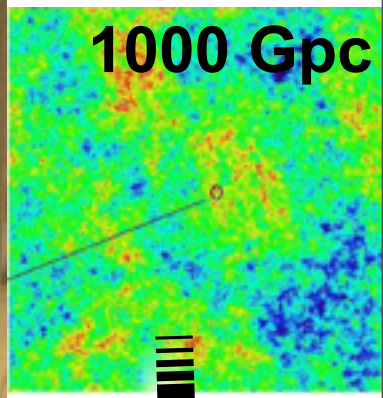
$\mathbf{g}(\sigma(\mathbf{x}))$

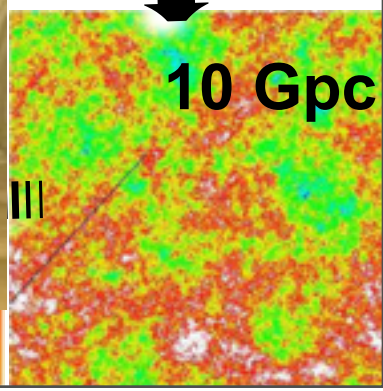
or..

pre-heating patch (~1cm)

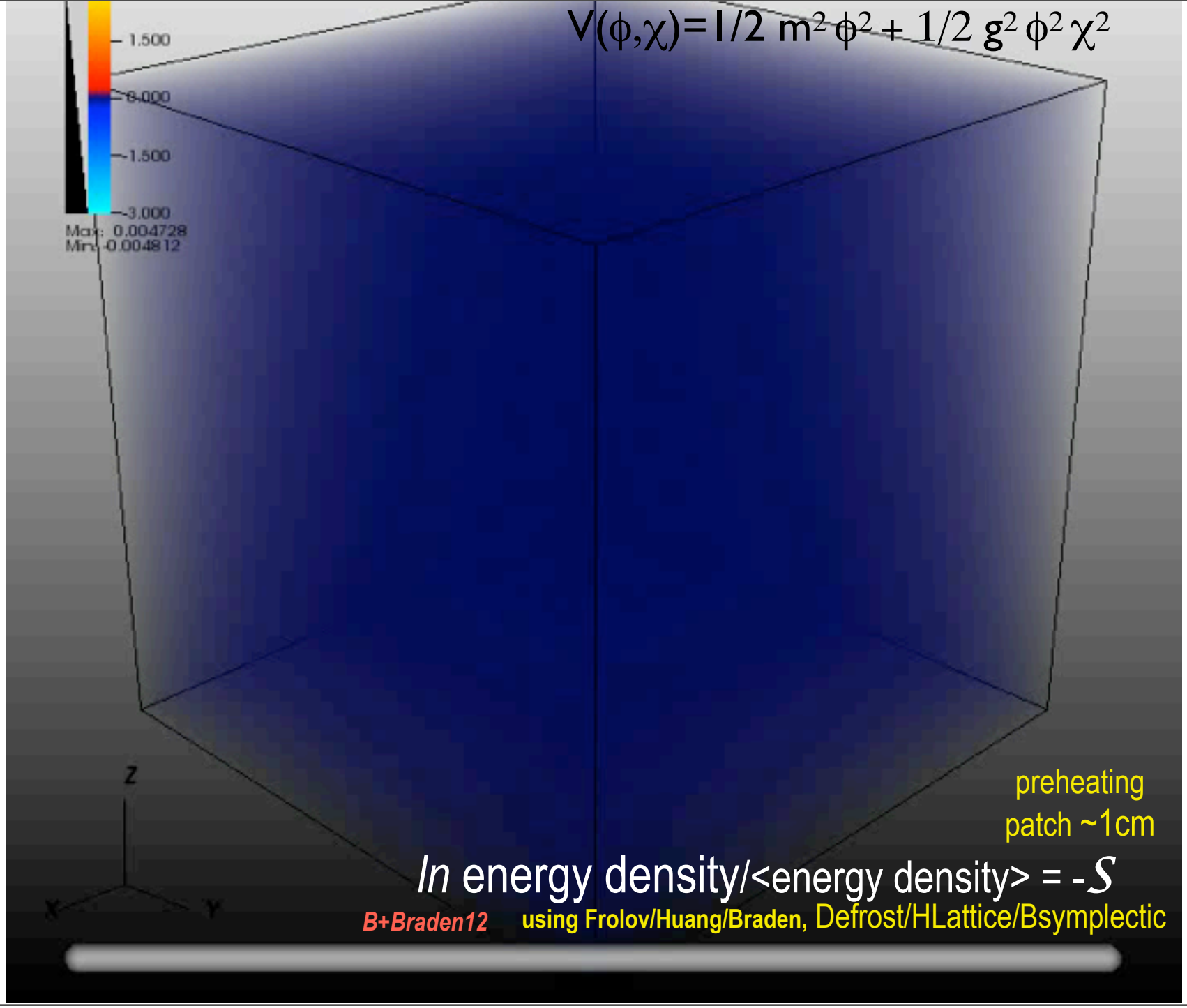
Parametric Resonance

$g^2/\lambda \sim 1$





B^2FH12 @ifaUH aka Waikiki Feb12


$V(\phi,\chi)=1/2\ m^2\phi^2+1/2\ g^2\phi^2\chi^2$
1.500
0.000
-1.500
-3.000
Max: 0.004728
Min: -0.004812
Z
X
Y
preheating
patch ~1cm
ln energy density/<energy density> = -S
B+Braden12 using Frolov/Huang/Braden, Defrost/HLattice/Bsymplectic

$T^a{}_b = \rho_{(c)} U^a U_b + U^a J_{(e)b} + U_b J_{(e)}{}^a + p_{(c)}(\delta^a{}_b + U^a U_b) + \Pi^a{}_b$

spatial complexity** but ∃ **statistical simplicity (1-pt, 2-pt)

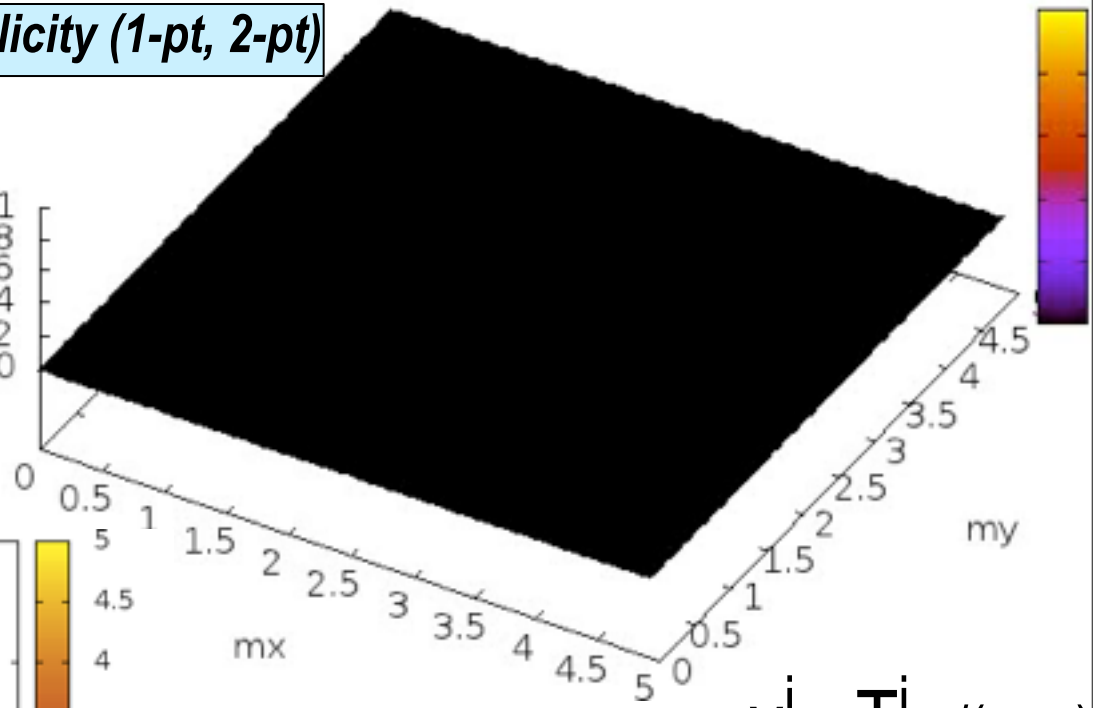
post-shock ⇒ total stress-energy $T^a{}_b$

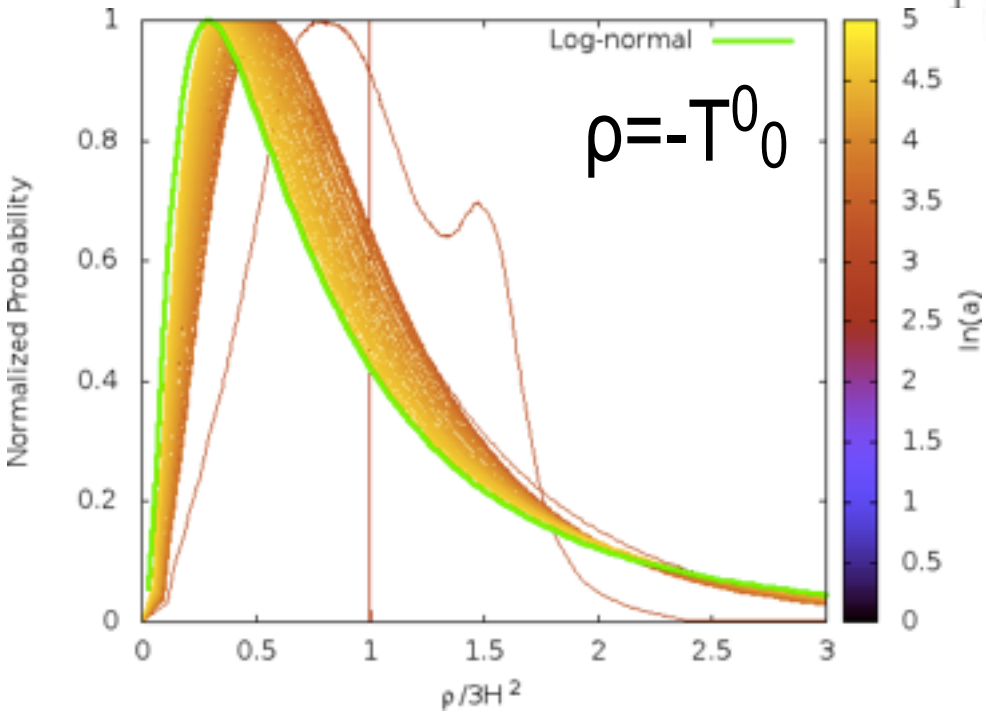
hydrodynamics description phonons

entangled primary fields $(\varphi, \Pi_\varphi, \chi, \Pi_\chi)$

=> not good post-shock descriptors

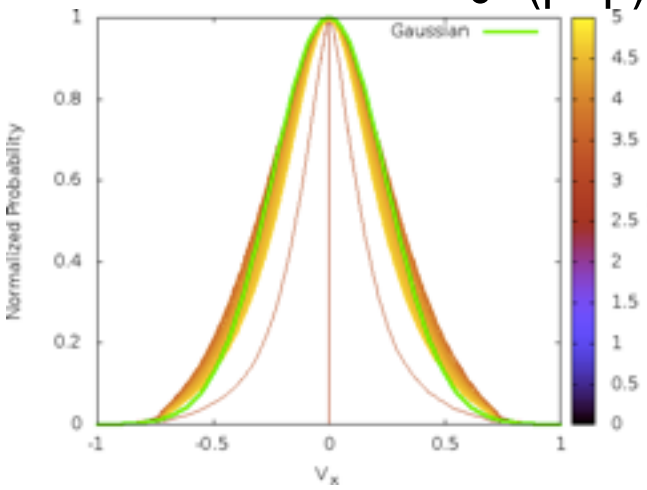
$V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2$





$\rho = -T^0{}_0$

$v^i = a T^i{}_0 / (\rho + p)$



nearly Gaussian in ln ρ/<ρ> & in k-bands! B+Braden12 ***nearly Gaussian in v***

CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT,*

Studying the Cosmic Tango *en-TANGO-ment* ***Universe=System+Res=Data+Theory*** =Signal(s)+*noise*=EFT+*Hidden variables*

Shannon entropy $S_f(D,T) = -\int dq\, P_f \ln P_f$ **=information with no Quality measure on the bits IQ**

~ von-Neumann entropy= Trace ϱ ln ϱ^{-1} , ϱ(U) = ϱ(S,R) = ϱ(R|S) ϱ(S) entanglement of phase & probability

Gaussian random field *with correlation function* ***C*** *weight matrix* C^{-1}

$S = (\text{Trace } \ln C + N_{dof} \ln 2\pi + N_{dof})/2 = \langle \ln V_{phase\text{-}space} \rangle + N_{dof}/2$

=Shannon entropy subject to the constraint $\int dq\, P_f\, \delta q^i \delta q^j = C^{ij}$

relative Shannon entropy $S_{fi} = \text{Tr}\{\ln C_f\, C_i^{-1} + 1 - C_f\, C_i^{-1}\}/2$

cf. ***grand canonical ensemble: constrained*** E_{tot} ***&*** N_A ***&*** V

Lagrange multipliers (conjugate variables) $\beta = 1/T$ & $-\beta\mu_A$ & β^**pressure; in LTE, functions of (x)*

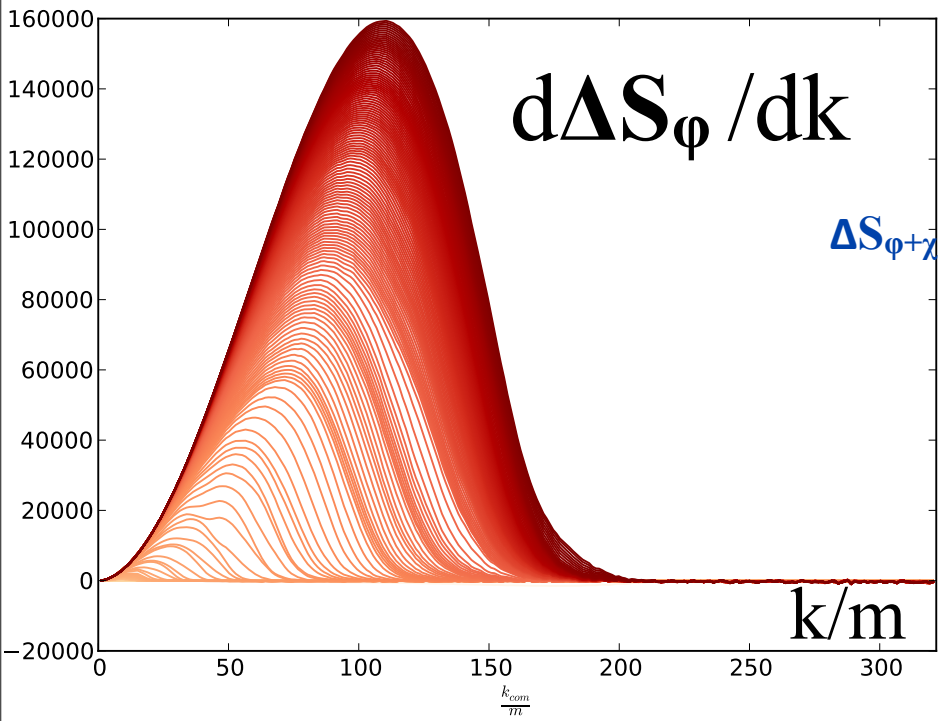
non-eq thermodynamics*: flux* $J_{(e)}^{\ i}(x)$ $J_{(N)}^{\ Ai}(x)$ *conjugate thermodynamical forces* B_i $(\sim \partial_i \beta)$

more constraints (e.g., higher point correlations & more complexity) reduce entropy by limiting the freedom of the degrees of freedom q: ***non-Gaussian distributions have lower S***

Lagrange multipliers: out-of-equilibrium drivers κ_i *for* $\langle \delta q^i \rangle$ *and* K_{ij} *for* $C^{ij} \langle \delta q^i \delta q^j \rangle$

problem: ***Dimensional Reduction*** *when eigenvalues of C ~ 0, S ~* $-\infty$*: but cold degrees of freedom should have S=0 (3rd). Bose-Einstein & Fermi-Dirac statistics - indistinguishable cf. distinguishable. Condensates form when too much N for E.*

eU S: Δs =Δ 1/2Tr $C_{\ln\rho \ln\rho}$ **info-content in phonons** $\mathcal{S} = -\ln[\rho\, V/E]$



$\Delta S_\varphi \sim 1/2 \sum_k \ln \det \langle (\varphi, \Pi_\varphi)\,(\varphi, \Pi_\varphi)^\dagger \rangle$

$\Delta S_\chi \sim 1/2 \sum_k \ln \det \langle (\chi, \Pi_\chi)\,(\chi, \Pi_\chi)^\dagger \rangle$

$\Delta S_{\varphi+\chi} \sim 1/2 \sum_k \ln \det \langle (\varphi, \Pi_\varphi, \chi, \Pi_\chi)\,(\varphi, \Pi_\varphi, \chi, \Pi_\chi)^\dagger \rangle$

Gaussian entropies for the "fundamental" interacting fields, φ, χ, subject to correlated 2-point measurements: $4N^3$ dof. $\varphi_A = \varphi_{Ab} + \varphi_{Af}$

how good are $M^2_{AB}(\varphi_{Ab}(x))$-*f*-quasiparticles?

post-shock fields become well-entangled,

hydrodynamic conserved quantities: N^3 dof in S

S_k = *phonons*

$\Delta S_{\ln\rho} \sim 1/2 \sum_k \ln \det \langle S\, S^\dagger \rangle$,

$S = \ln \rho^{-1}$ E/V = an **information content**

$D..S/dt = \nabla_U ..S \sim -(1+w)..\mathrm{Tr}\ \delta\sigma$ + higher

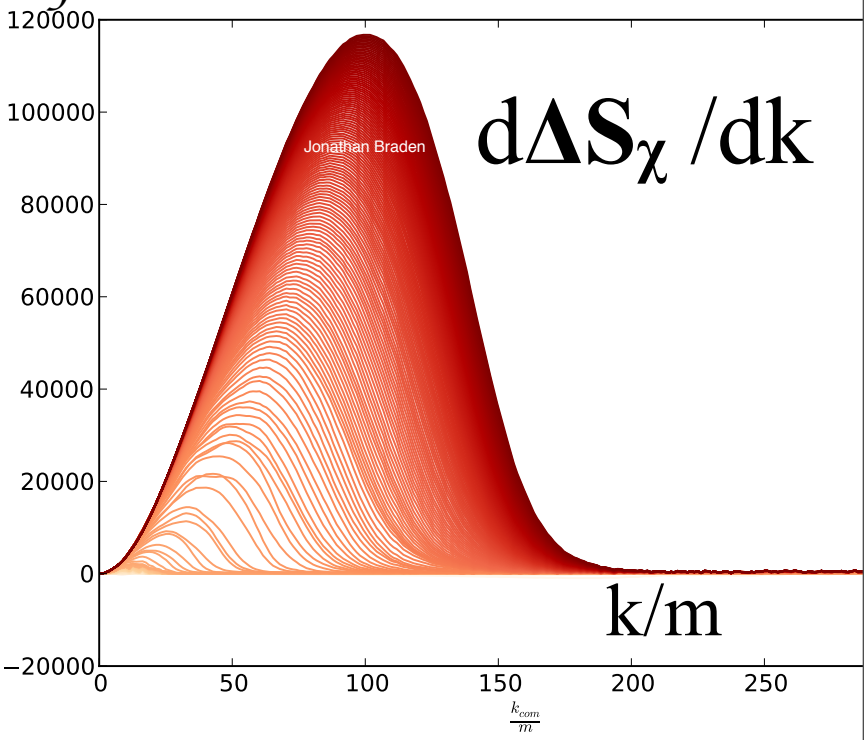
$\sigma_{a;b}$ = shear = $1/2\,(U_{a;b} + U_{b:a})$

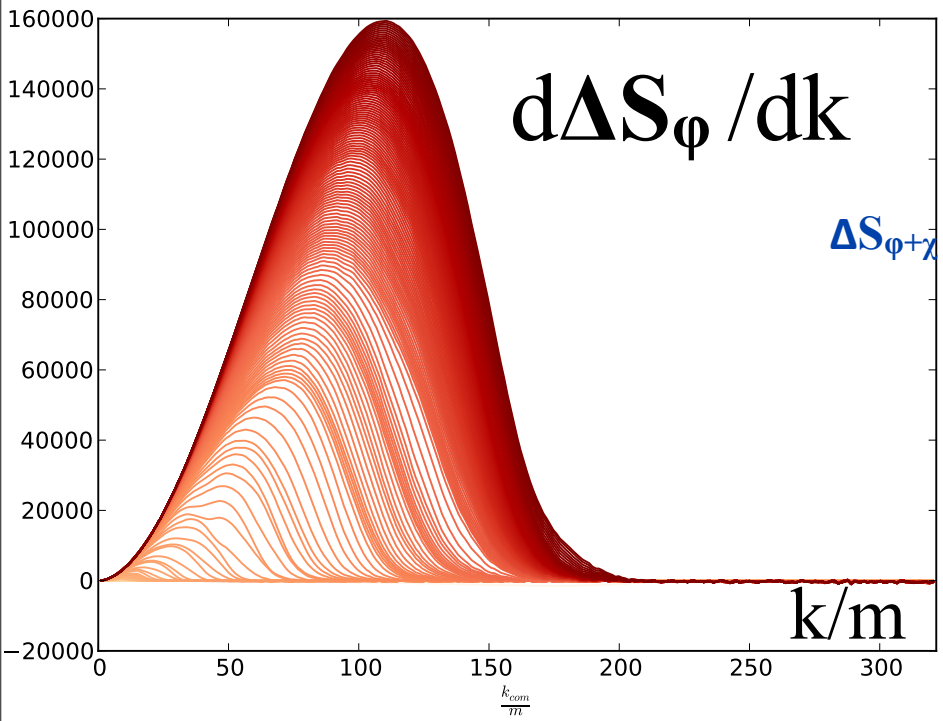
TBD: identify ***shear viscosity, thermal conductivity*** *&* *bulk viscosity* ***via correlation function measures***

$\Pi = -2\eta\,\sigma'$, $J_{(e)} = -C\,\nabla S$

phonons *=****isotropic-shear*** *waves=longitudinal velocities*

anisotropic-shear waves: viscous damping





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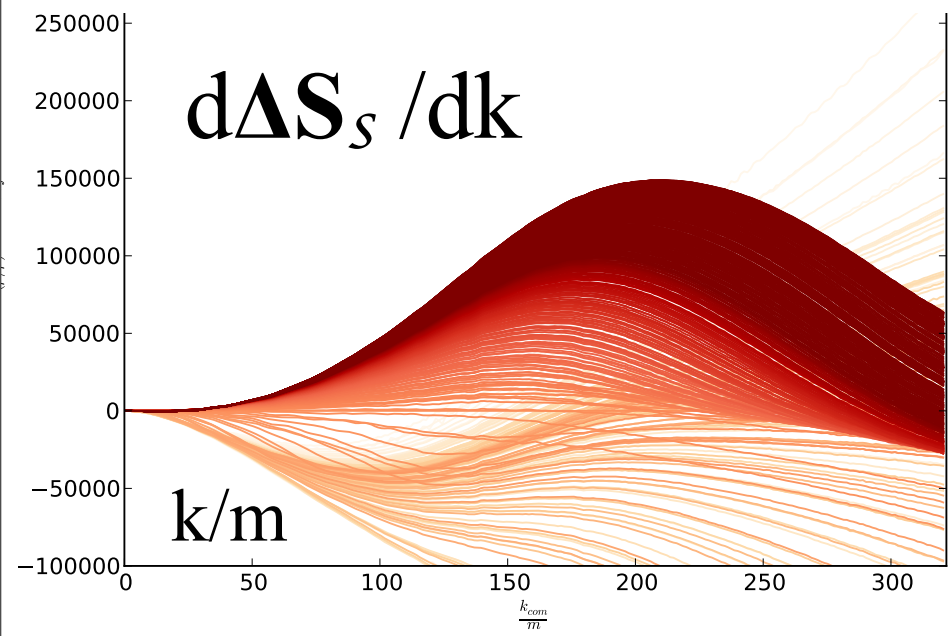
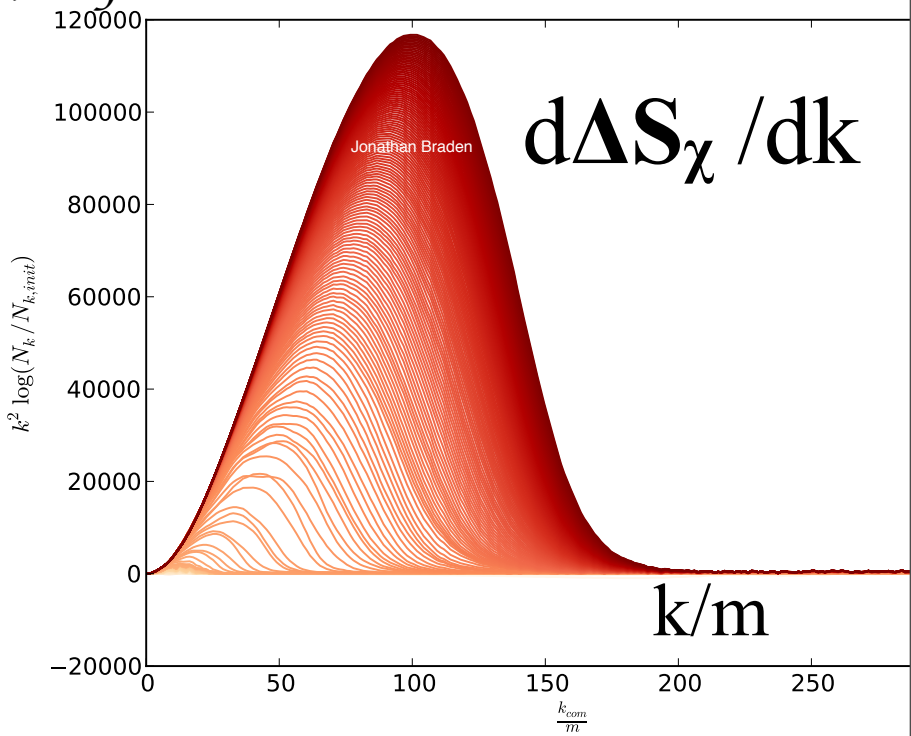
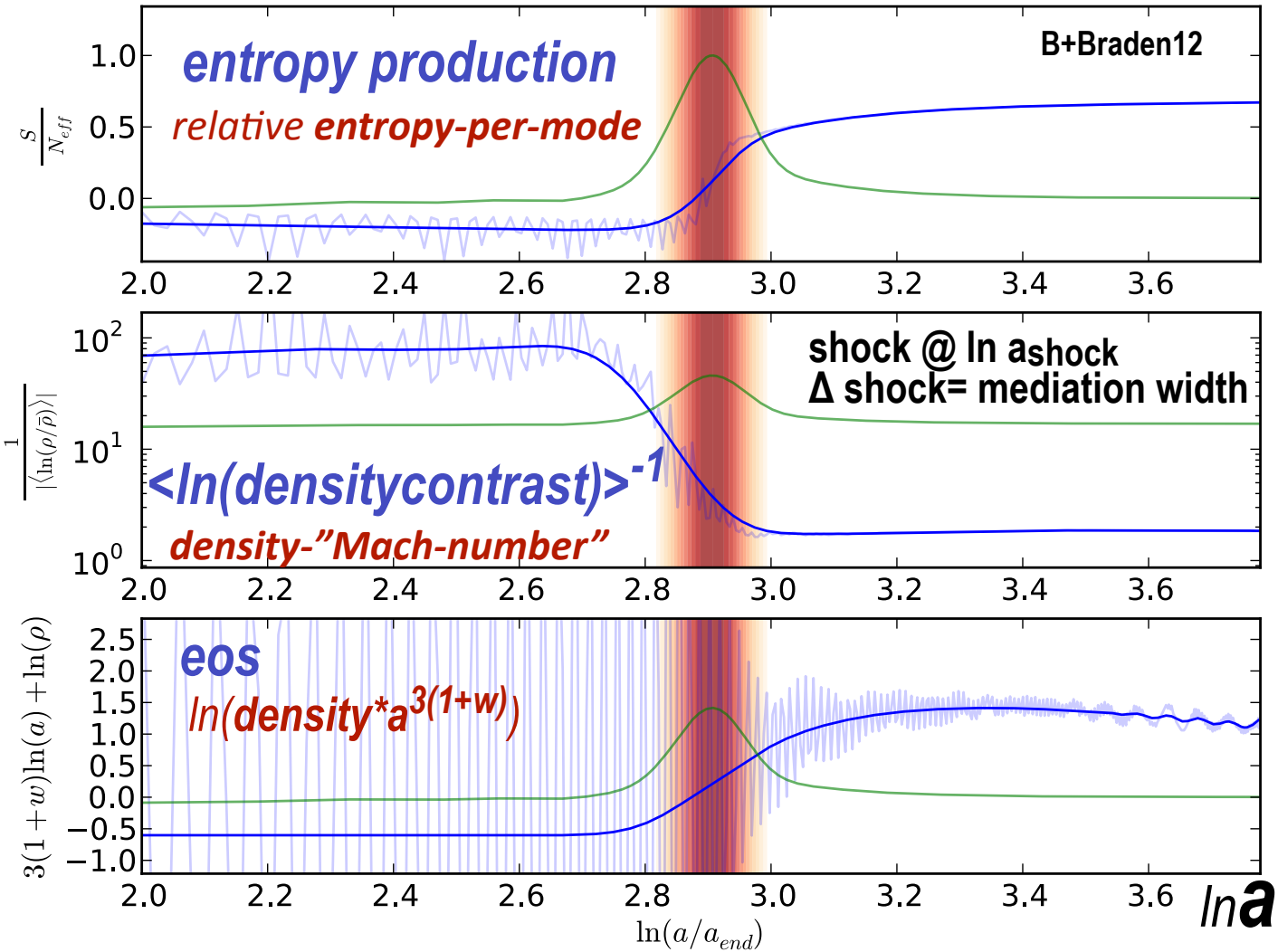




eU S: Δs =Δ 1/2Tr C*ln*ρ*ln*ρ info-content in phonons σ = - *ln* [ρ V/E]



true thermal equilibrium far off

➤

& on to coupling to standard model degrees of freedom

the **Shock-in-time:** constrained coarse-grained ***Shannon-entropy(ln a)*** minus the initial Gaussian random field entropy (from band-limited quantum fluctuations)

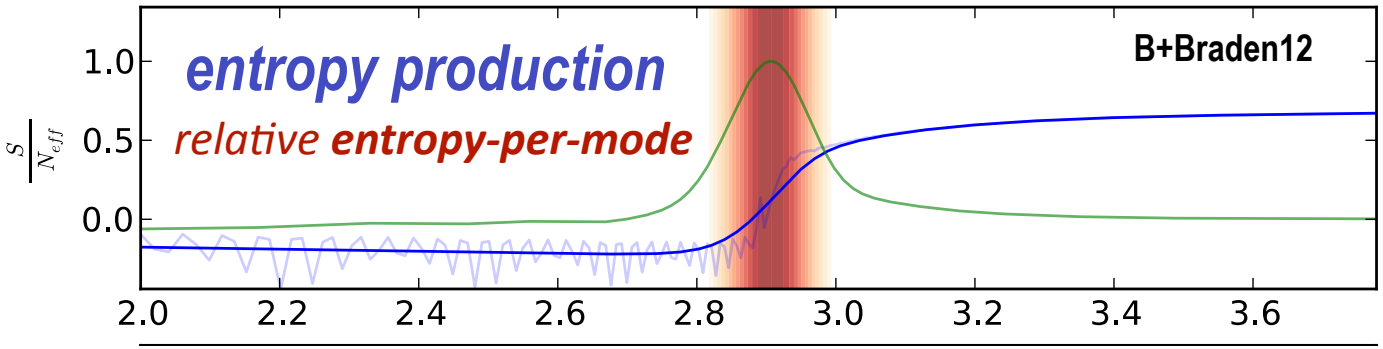
there is indeed a spike of entropy production at the shock front.

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

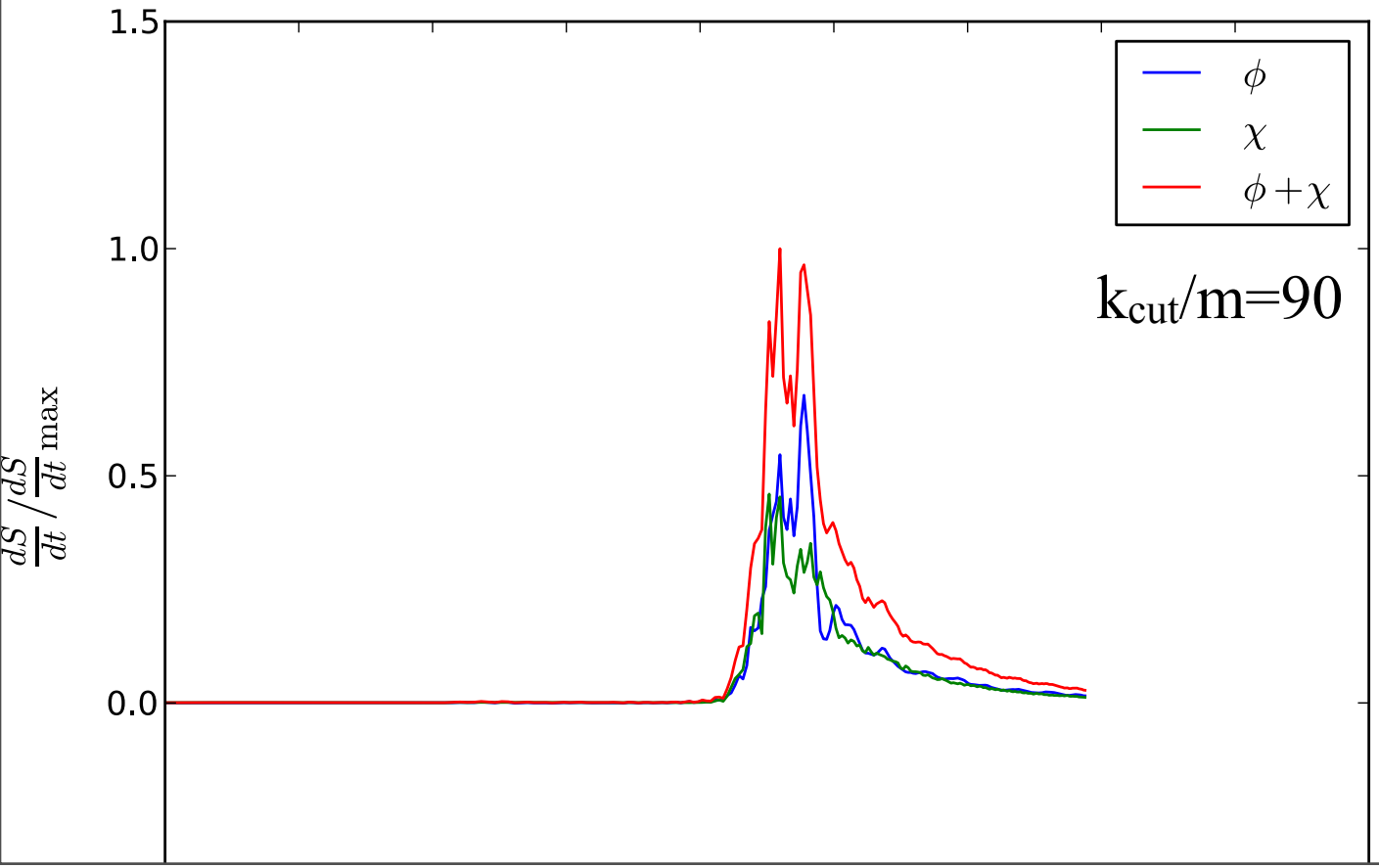
post-shock ⇒ Hydrodynamics phonon description

nearly Gaussian in ln ρ/<ρ>(x) ln ρ/<ρ>(k)& v

eU S: Δs =Δ 1/2Tr C*ln*ρ*ln*ρ info-content in phonons σ = - *ln* [ρ V/E]



ln a/a$_{end}$



true thermal equilibrium far off

➤

& on to coupling to standard model degrees of freedom

non description ρ>(k)& v

the Shock-in-Times of Post-inflation Preheating B+Braden12

Initial State = Nearly Homogeneous Inflaton

low entropy (coherent φ + vac fluctuations), *information encoded in a few parameters*

Preheating

Instabilities result in nonlinear transition to an incoherent state, resonances?
KLS 94, 97,e.g. Tkachev, Felder, Garcia-Bellido, ...

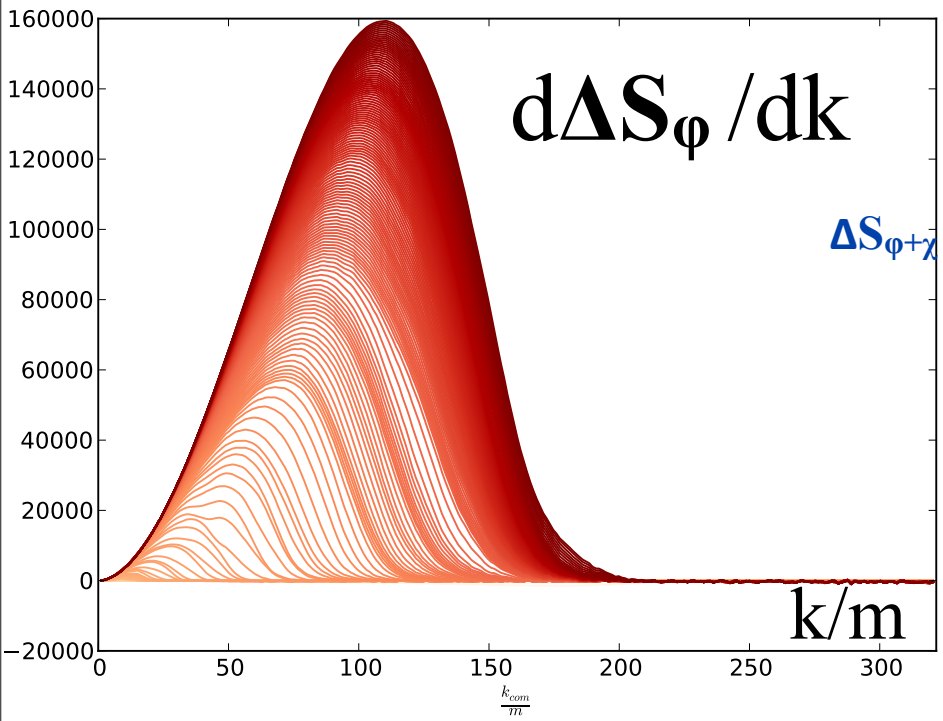
the shock-in-time is the sharp mediator between the linear & the highly nonlinear transition
a fascinating non-Gaussianity can arise if there is a spatial modulator field varying the shock time

(Near Adiabatic) *Transition Regime*

Complex slowly evolving nonlinear, nonequilbrium state e.g. Micha and Tkachev 2004,
turbulence analogy??? ***the evolution is NOT a Kolmogorov-like turbulent cascade to higher modes***

Final State = Thermal Equilibrium

= maximum spreading of information in modes subject to energy & particle number constraints. *How to couple to standard model dofs to accelerate the power spectrum evolution to a thermal bose-einstein distribution function?*



$\Delta S_\varphi \sim 1/2 \sum_k \ln \det \langle(\varphi, \Pi_\varphi)\,(\varphi, \Pi_\varphi)^\dagger\rangle$

$\Delta S_\chi \sim 1/2 \sum_k \ln \det \langle(\chi, \Pi_\chi)\,(\chi, \Pi_\chi)^\dagger\rangle$

$\Delta S_{\varphi+\chi} \sim 1/2 \sum_k \ln \det \langle(\varphi, \Pi_\varphi, \chi, \Pi_\chi)\,(\varphi, \Pi_\varphi, \chi, \Pi_\chi)^\dagger\rangle$

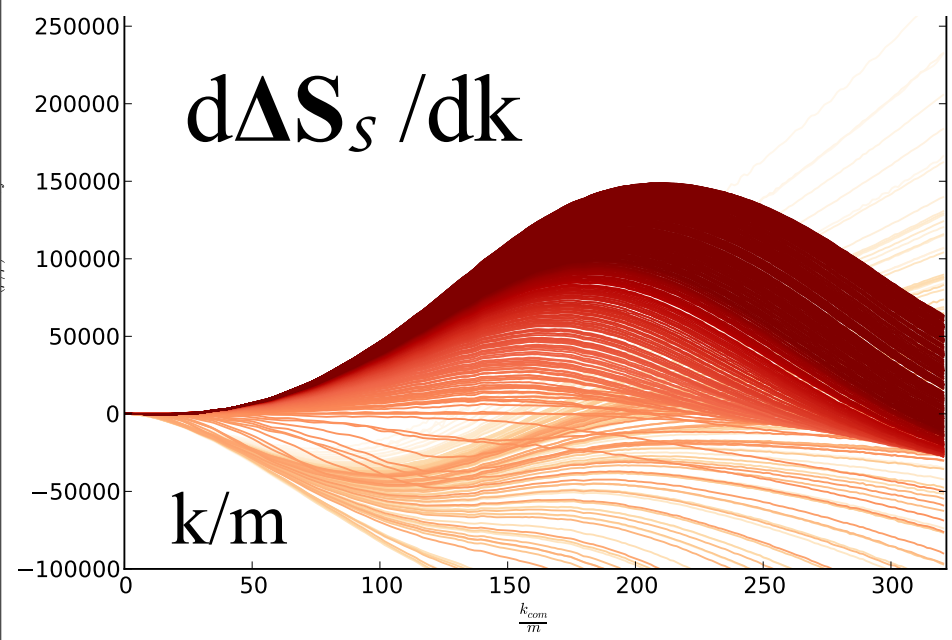
Gaussian entropies for the "fundamental" interacting fields, φ, χ, subject to correlated 2-point measurements: $4N^3$ dof. $\varphi_A = \varphi_{Ab} + \varphi_{Af}$

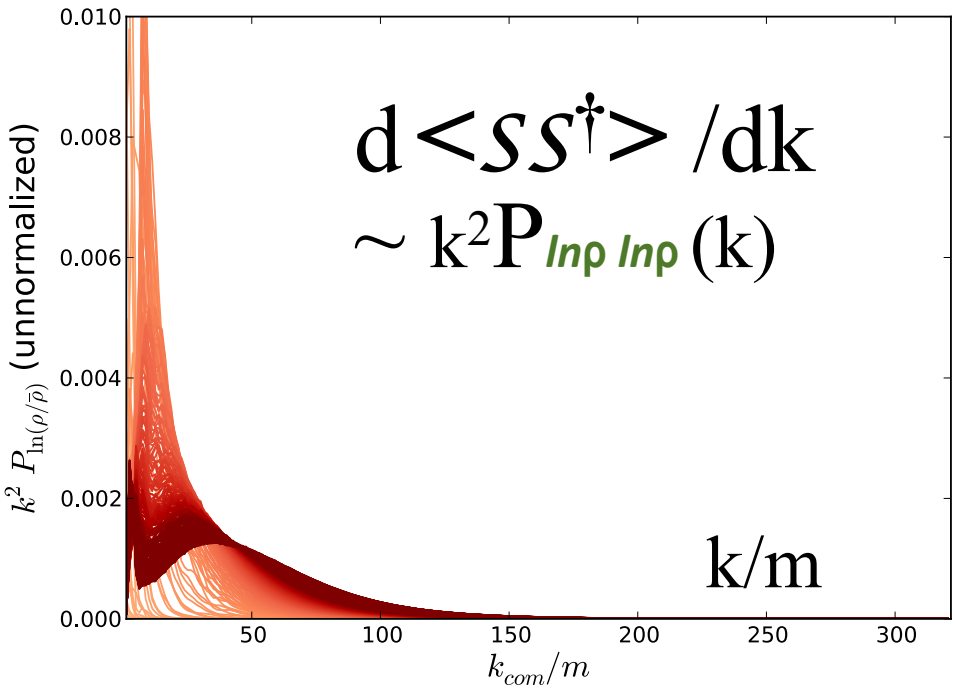
how good are $M^2_{AB}(\varphi_{Ab}(x))$*-f*-quasiparticles?

post-shock fields become well-entangled,

hydrodynamic conserved quantities: N^3 dof in S

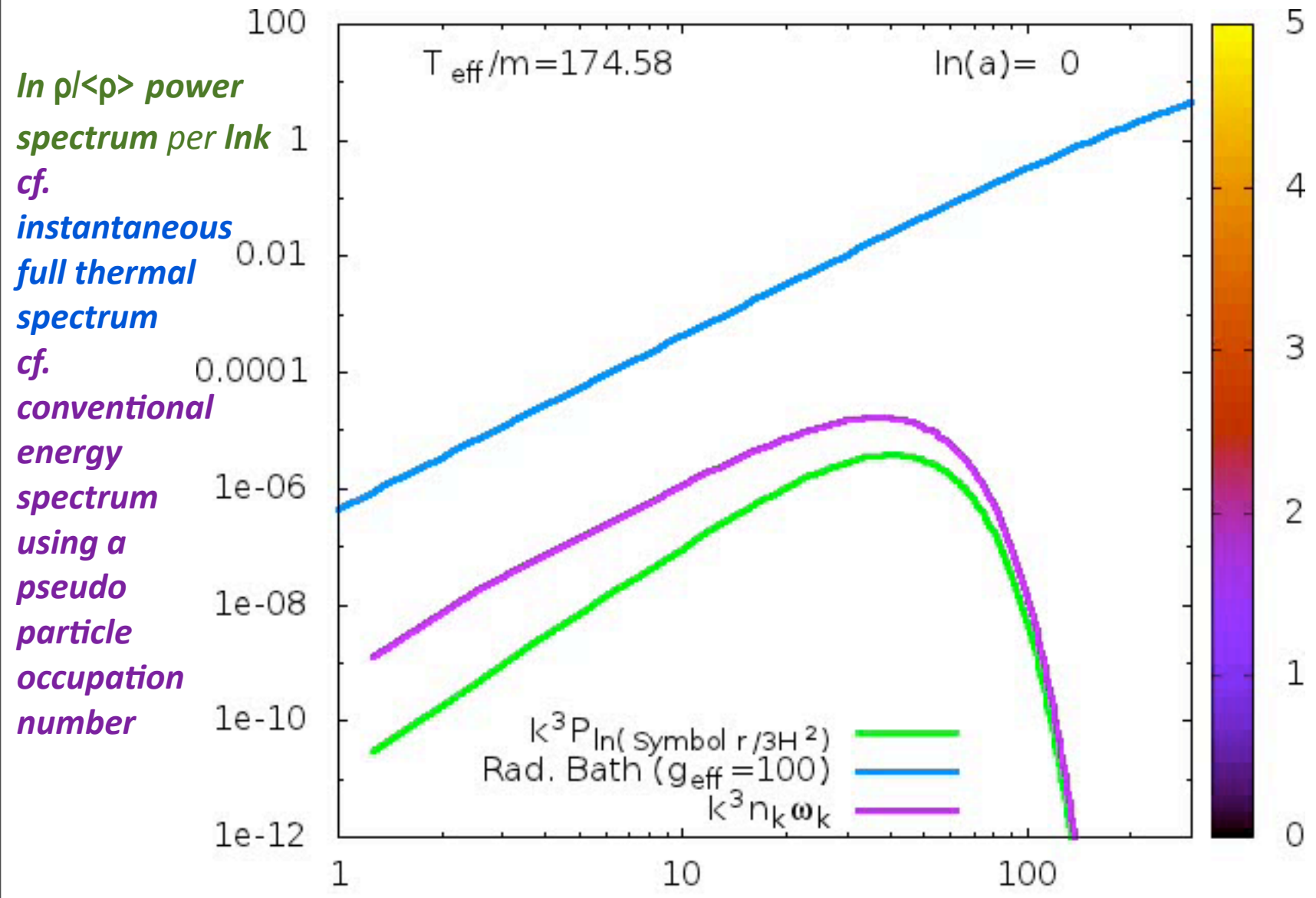
s_k = *phonons*





coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

$s_{Ui\sim 0}$; $s_{Utot,m+r}/n_b \sim 1.66\times10^{10}$ bits/b; $s_\gamma/n_\gamma = 5.2$ bits/$\Upsilon = 2130/411$; $s_\nu = 21/22\ s_\gamma$



ln ρ/<ρ> power spectrum per lnk

cf. instantaneous full thermal spectrum

cf. conventional energy spectrum using a pseudo particle occupation number

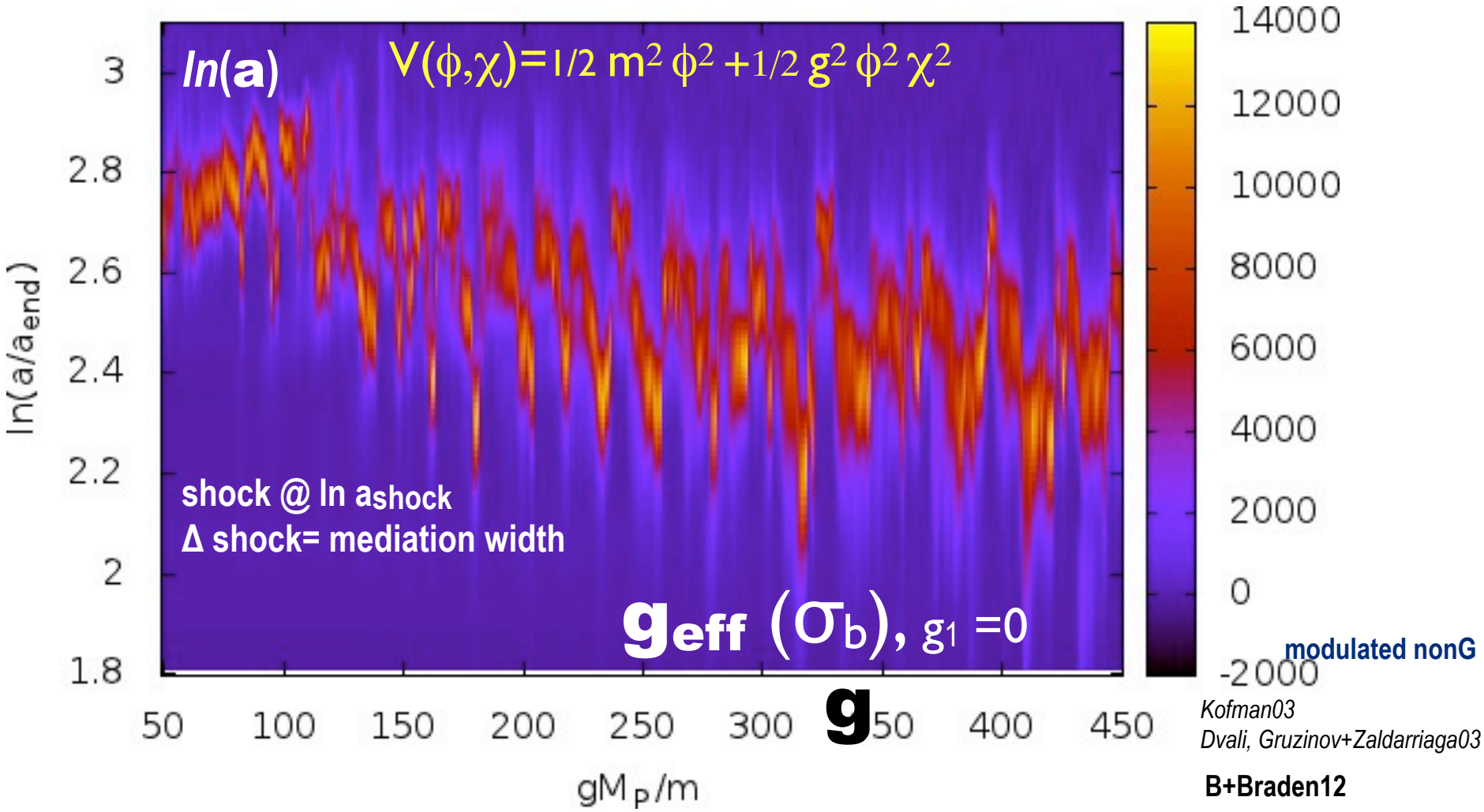
$V(\phi,\chi) = 1/2\ m^2\phi^2 + 1/2\ g^2\phi^2\chi^2$

B+Braden12

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

non-Gaussianity (WMAP, **Planck**, LSS) spiky nG preheating

$\delta ln a_{shock}$ (**g**(σ(**x**)) => modulated non-Gaussianity from preheating!



Kofman03
Dvali, Gruzinov+Zaldarriaga03

B+Braden12

$$\mathbf{g} = \mathbf{g_{eff}}(\boldsymbol{\sigma}_{\mathbf{b}}(\mathrm{x})) \textit{ with } \textbf{frozen } \textit{large scale } \boldsymbol{\sigma}_{\mathbf{b}}(\mathrm{x})$$

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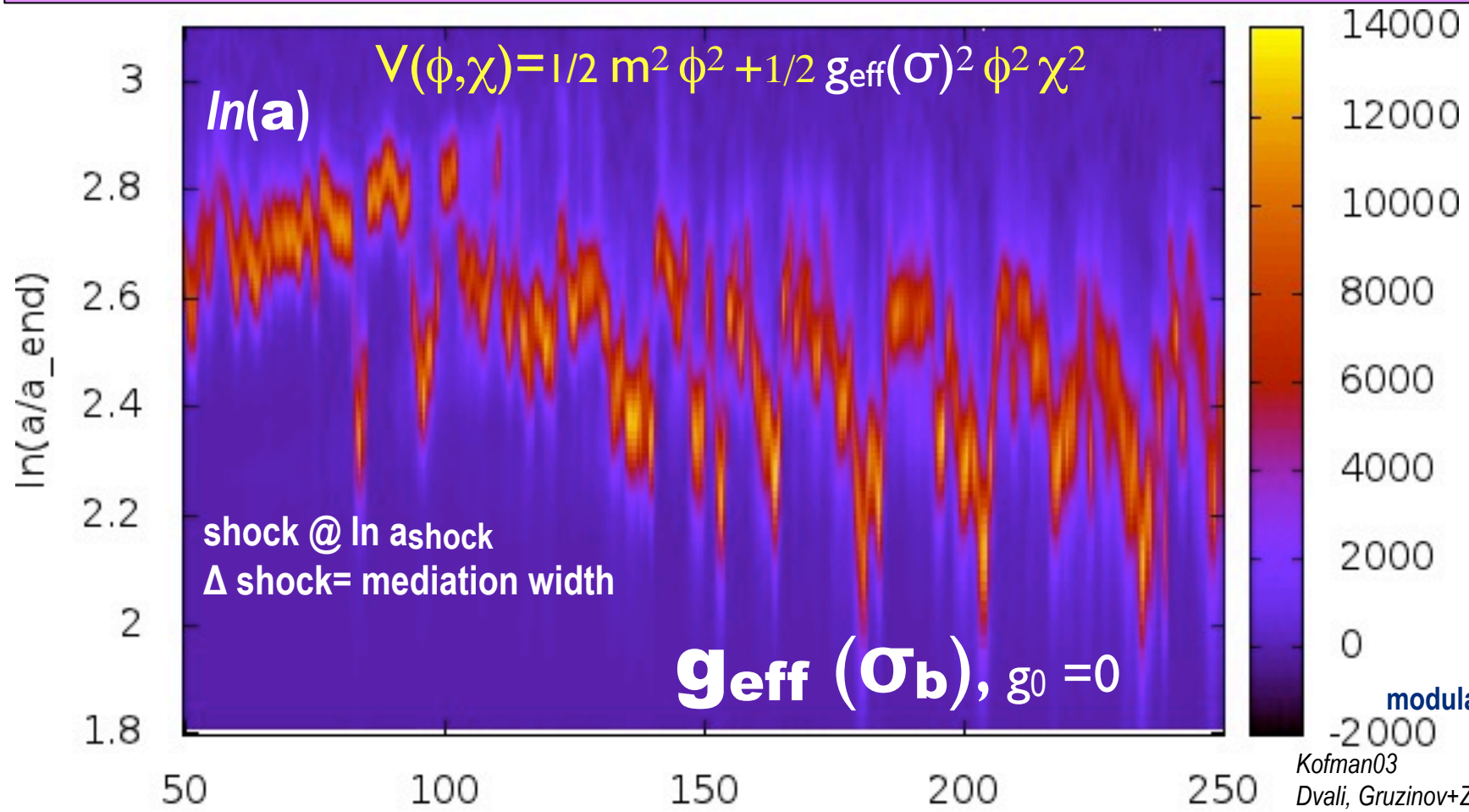

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$g_{eff}(\sigma) = g_0 + g_1\ \sigma/M_P$, $g_0 \exp[\gamma_1\ \sigma/M_P]$, ..

dynamical $\sigma_b(x,t) = \sigma - \sigma_f$ *cf.* **frozen $\sigma_b(x)$** *cf.* $\chi_b(x) = \chi_i$

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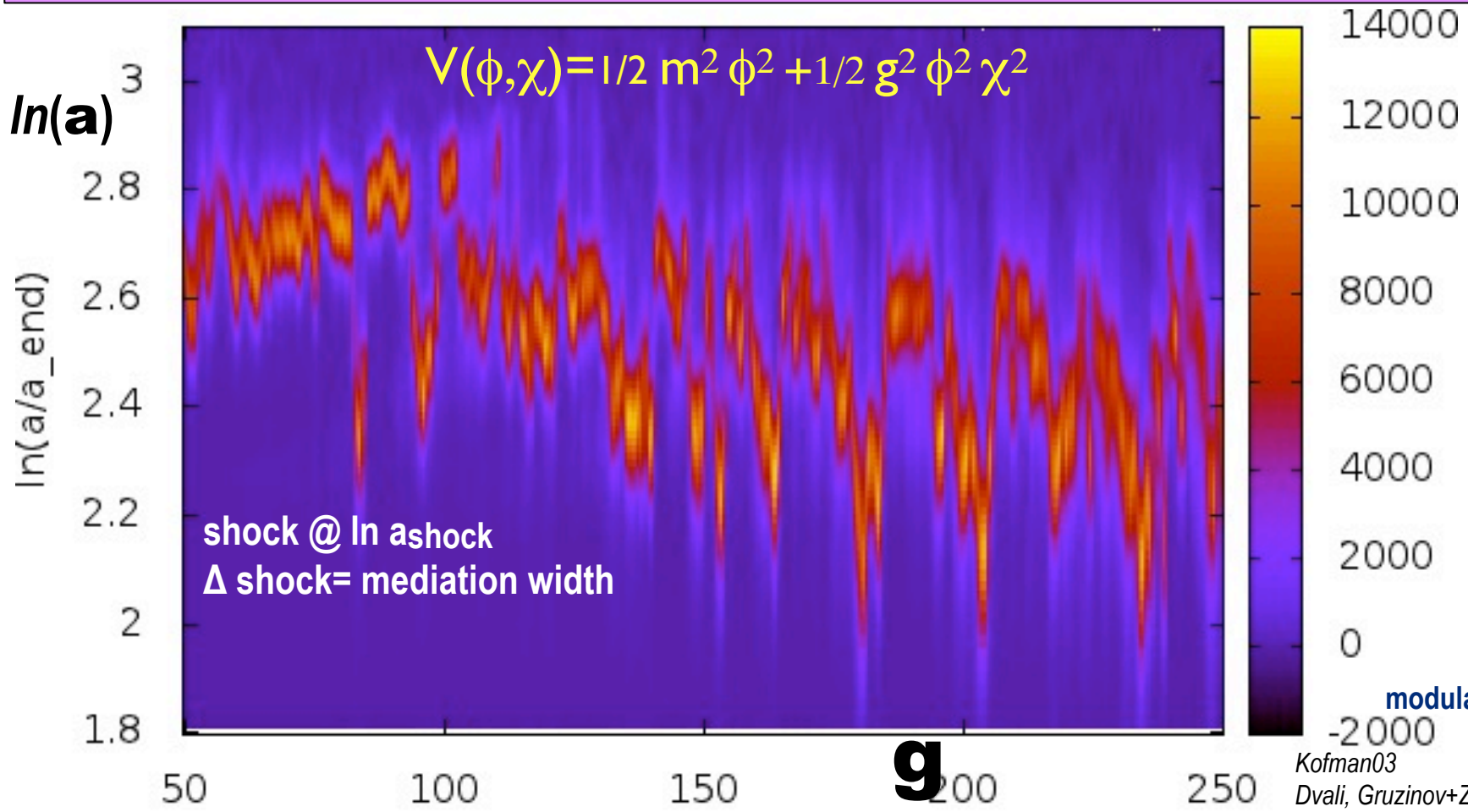


Kofman03
Dvali, Gruzinov+Zaldarriaga03

B+Braden12

Chaotic Billiards NonG $V(\phi,\chi)=1/4\ \lambda\phi^4 +1/2\ g^2\phi^2\chi^2$ *B+Frolov, Huang, Kofman 09*
B+Braden, Frolov, Huang 12

$\delta ln a_{shock}(\chi_i(x)\ |g^2/\lambda))$ => *NonG of cold spots ++*

B+Braden+Mersini 2012

BBM12: 3D Oscillons & Colliding Bubbles?

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

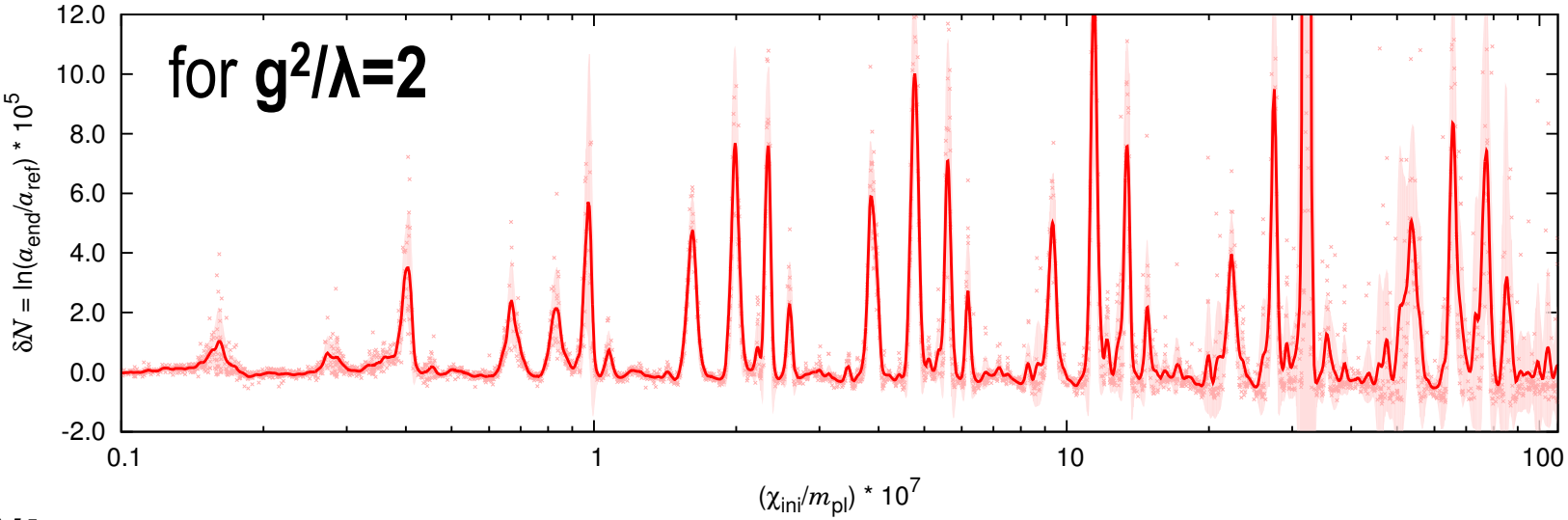
non-Gaussianity (WMAP, **Planck**, LSS) spiky nG preheating

δlna$_{shock}$(χ_i(x) |g²/λ)) => ***Chaotic Billiards: NonG from Parametric Resonance in Preheating***

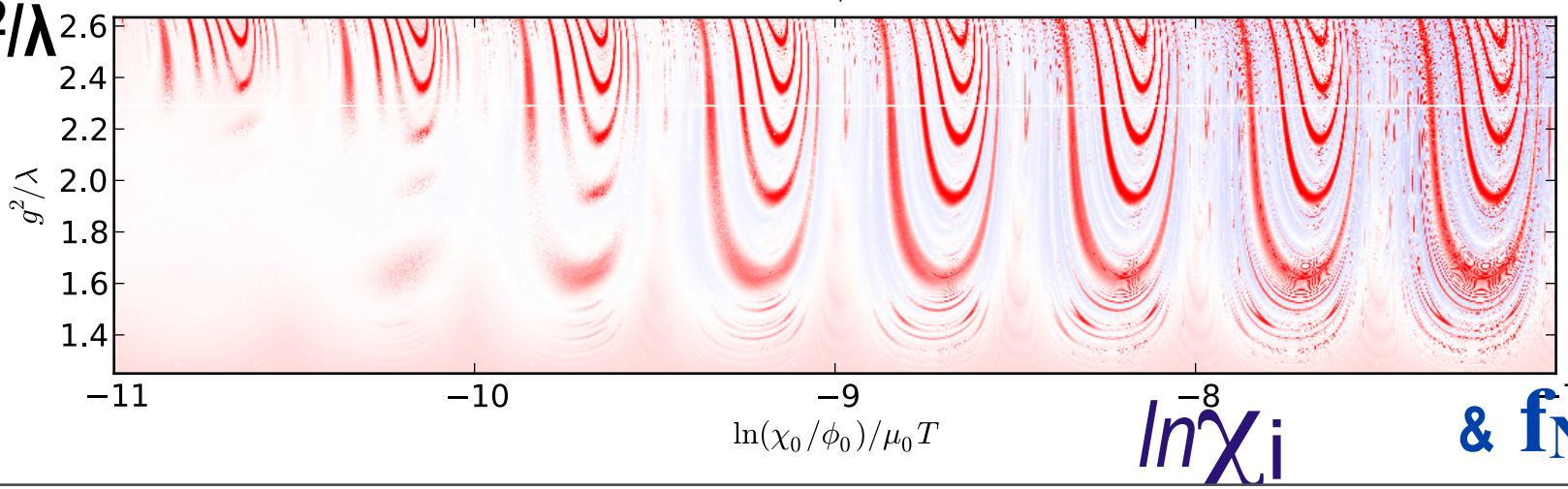
B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 12

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

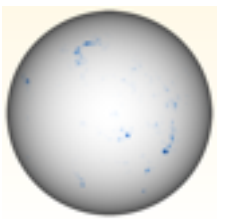
lna



g²/λ



huge number of 64^3 ***sims to show the wondrous complexity of*** $ln a(\chi_i, g^2/\lambda)$



$ln\chi_i$ **& f_{NL}^{equiv}**

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

non-Gaussianity (WMAP, **Planck**, LSS) spiky nG preheating

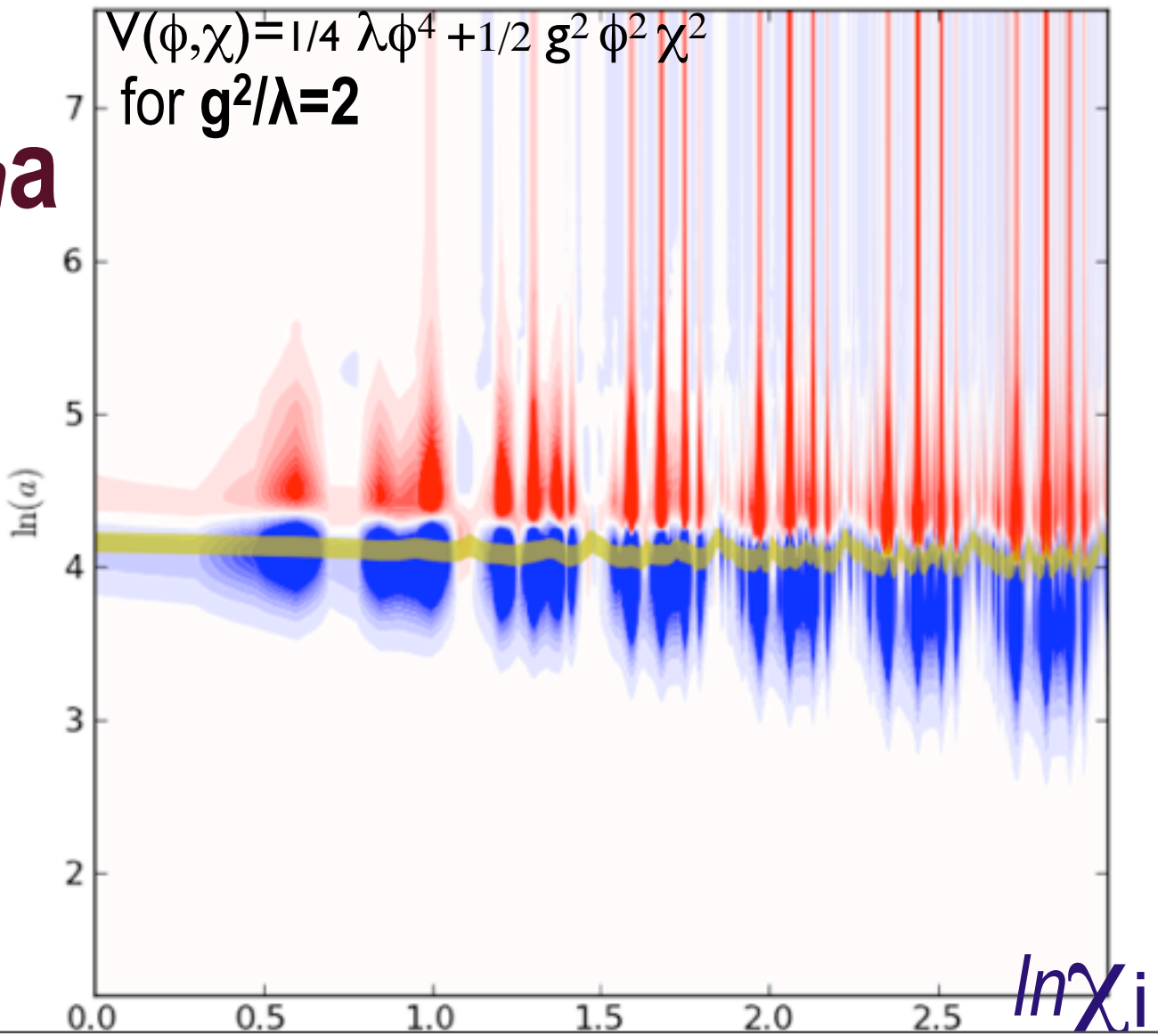
$\delta ln a_{shock}(\chi_i(x) | g^2/\lambda))$ => *Chaotic Billiards: NonG from Parametric Resonance in Preheating*

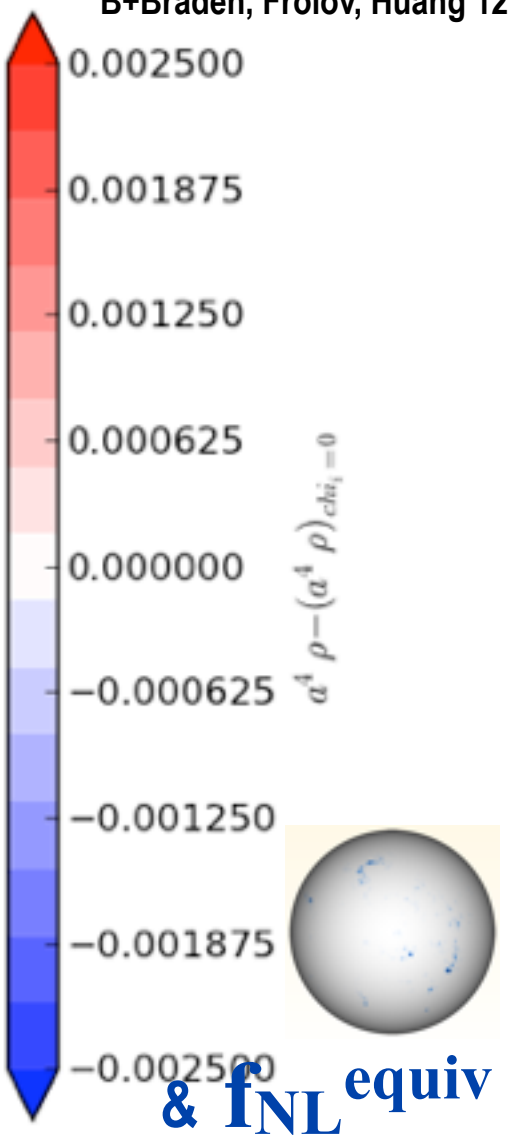
B+Frolov, Huang, Kofman 09

B+Braden, Frolov, Huang 12

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

for $g^2/\lambda=2$





& f_{NL}^{equiv}

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

non-Gaussianity (WMAP, **Planck**, LSS) spiky nG preheating

$\delta \ln a_{shock}(\chi_i(x) \,|\, g^2/\lambda)) =>$ *Chaotic Billiards: NonG from Parametric Resonance in Preheating*

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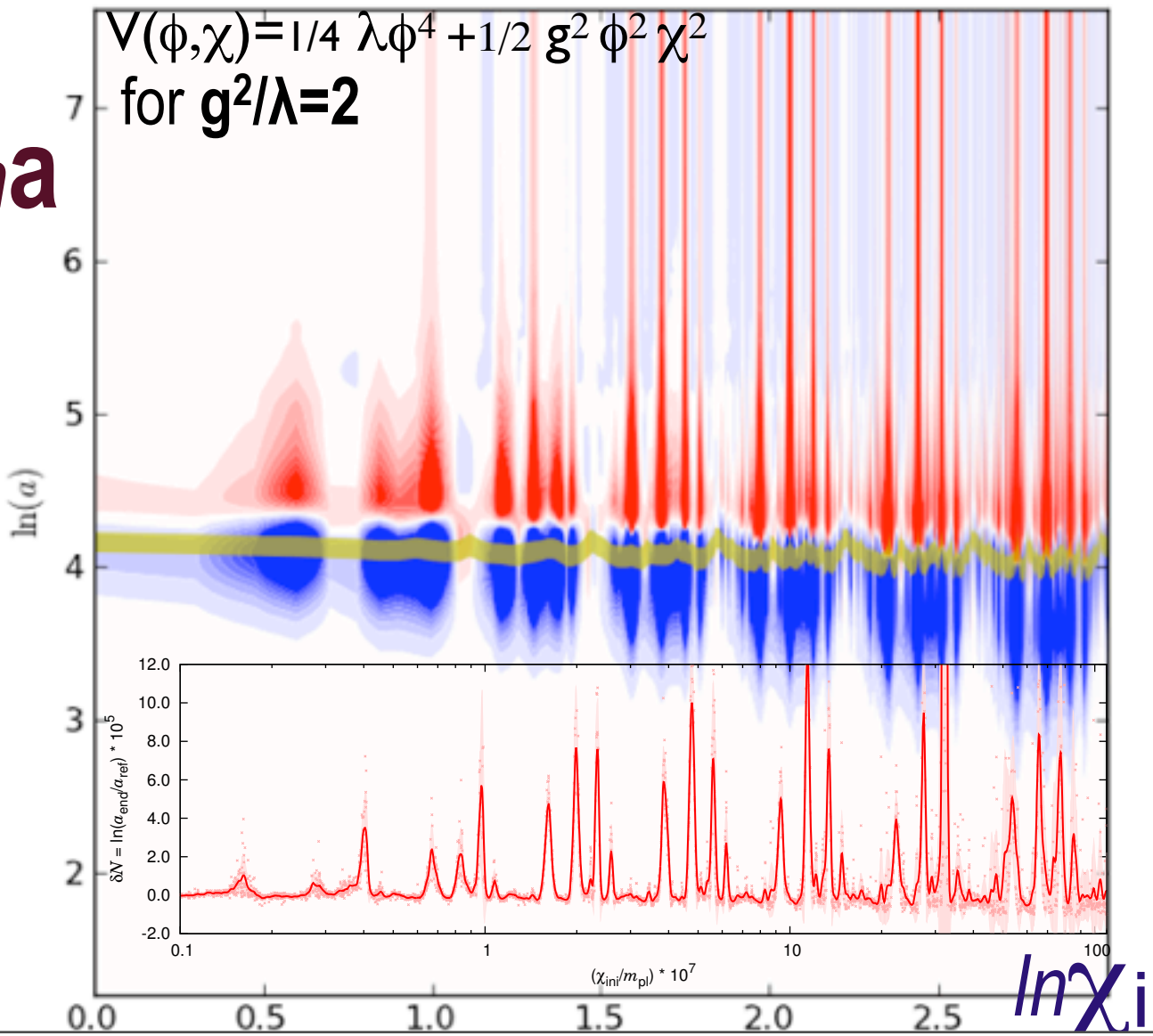
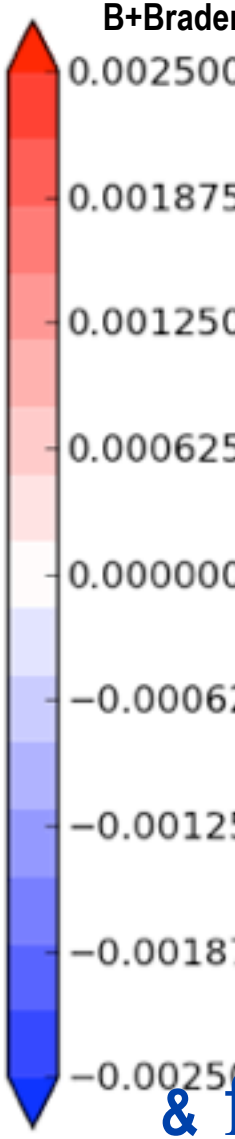
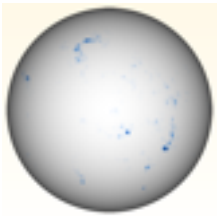


$\ln a$

$\ln \chi_i$





& f_{NL}^{equiv}

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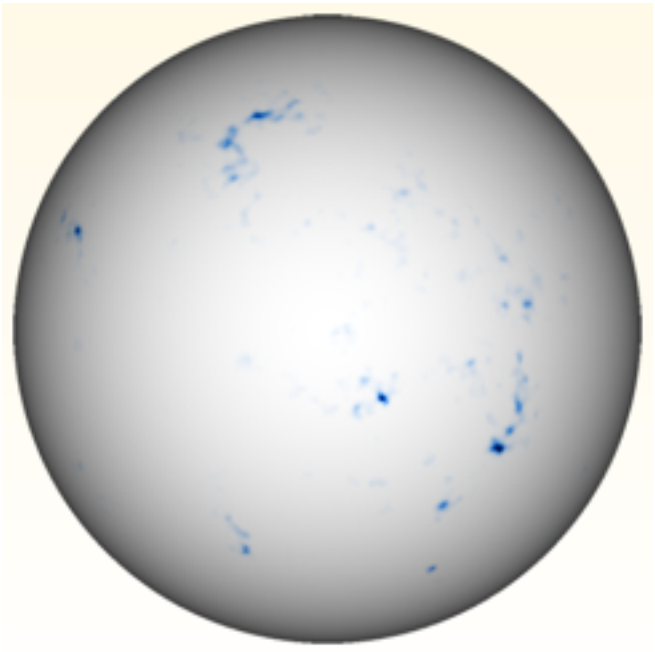
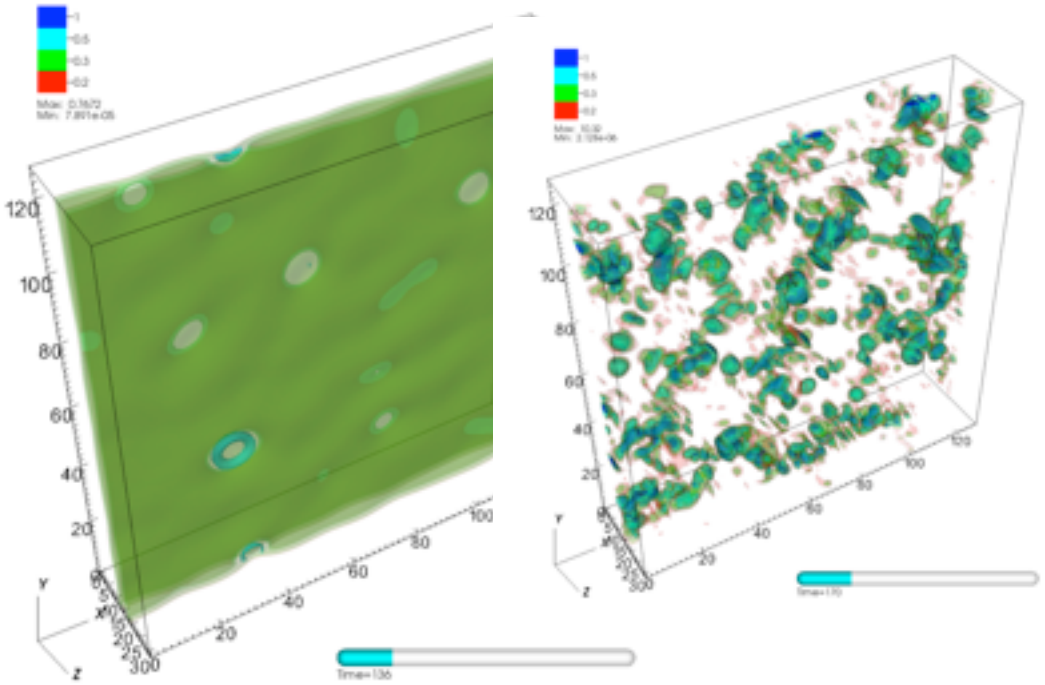


& f_{NL}^{equiv}

modulated nonG



when "vacuum" bubbles collide in full 3D lattice sims
with tiny zero point & wall fluctuations
=> burst of scalar radiation at c + long-lived oscillons, ~m^{-1}

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B+Braden+Mersini 2012

$\delta ln a_{shock}(\chi i(x)\ |g^2/\lambda))$ => *NonG of cold spots ++*

BBM12: 3D Oscillons & Colliding Bubbles?

Dick Bond CIFAR@CITA with CITA aka *Cosmic Information Theory & Analysis*

Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity

the **nonlinear COSMIC WEB**

dS$_G$/dt

I N F L A T I O N

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave **dS/dt>0**
- tightly-coupled photon-baryon fluid: oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$
- viscously damped
- polarization $\pi\gamma$
- gravitational redshift

Φ SW $d\Phi/dt$

DarkM

Decoupling LSS

17 kpc (19 Mpc)

Lsound/ ksound

secondary anisotropies **dS/dt>0**

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

DarkE

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

reionization

dS$_{astro}$ <0

dS/dt>0

z ~ 1100 redshift z z ~ 10

13.7-10^{-50}Gyrs | **13.7Gyrs** | time t | **10Gyrs** | today