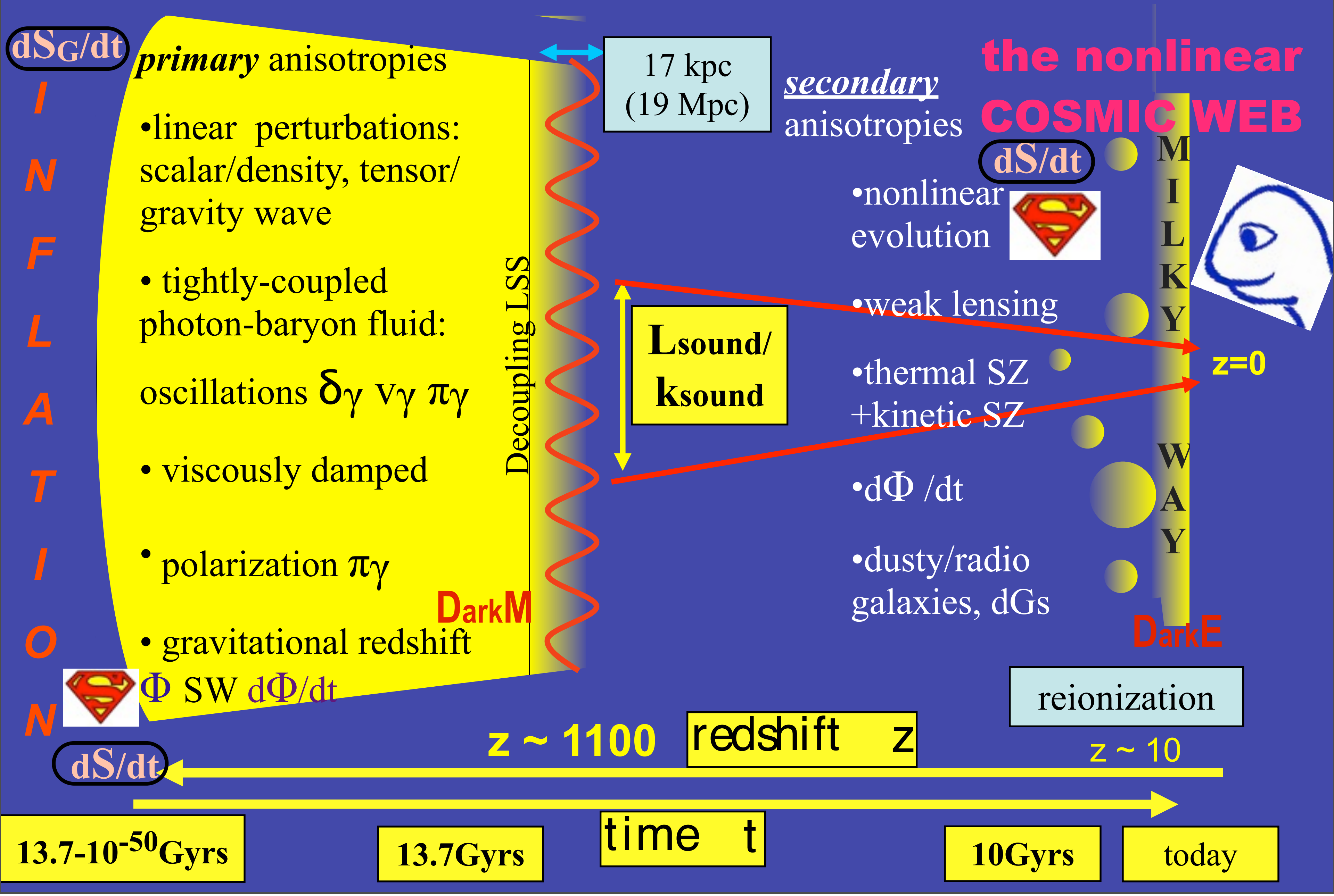
the Shock-in-Times of Entropy/Information Generation in Post-inflation Preheating

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



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

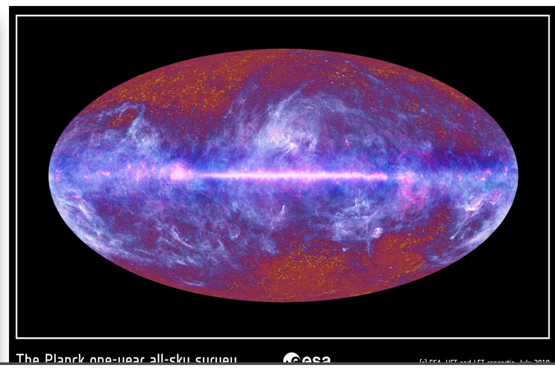
new interaction channels ***g, χ_a*** ***ultimately to***

standard model degrees of freedom

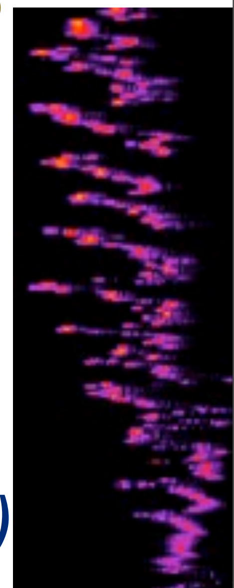
∃ a role for *decaying particles, 1st order phase transitions?*

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

χ(**x**)

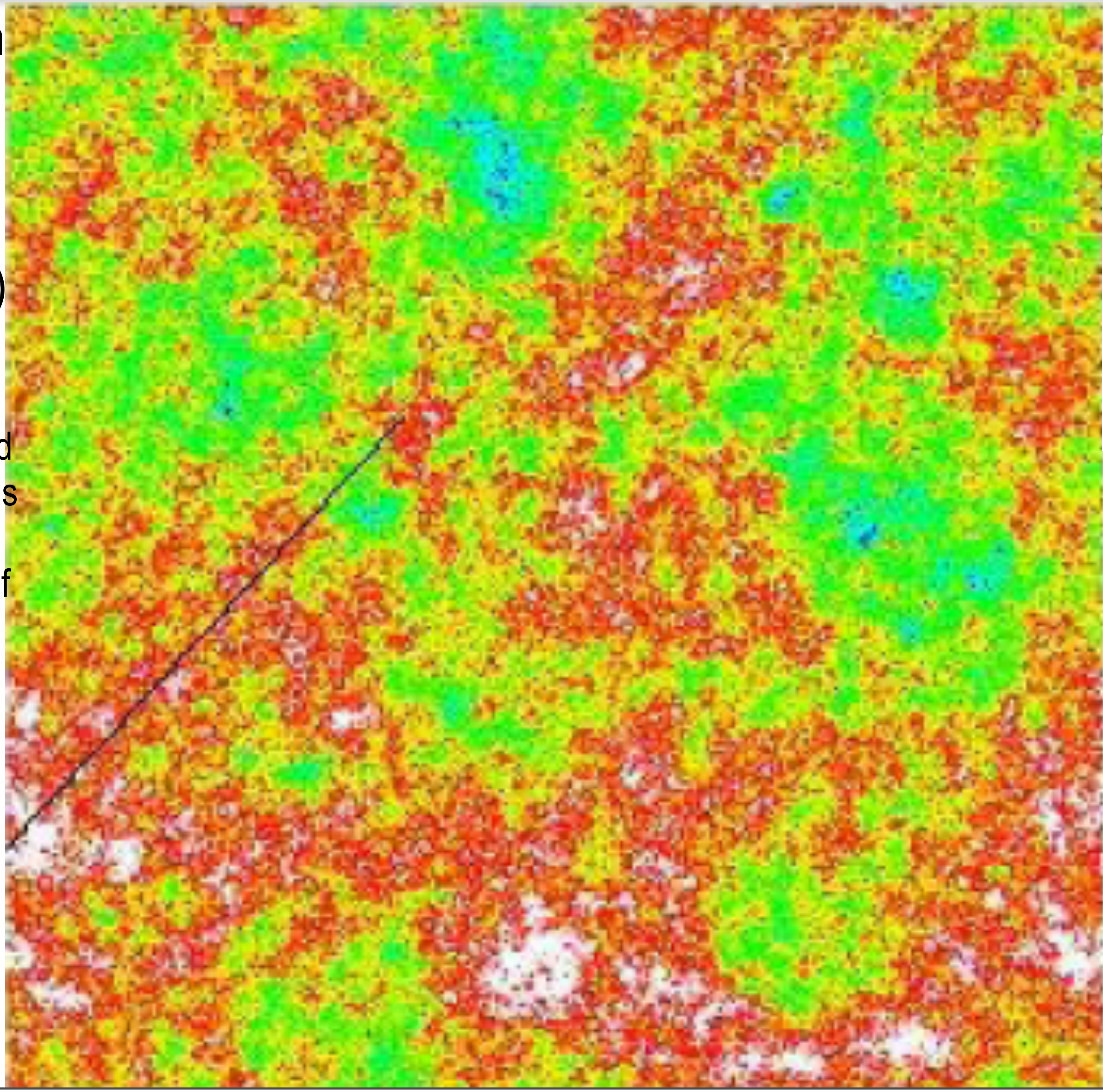
or

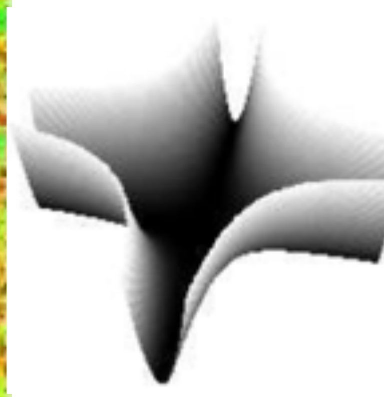
g(σ(**x**)

or..

scalar field fluctuations in the vacuum of the ultra-early Universe

pre-heating patch (~1cm)





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

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

10 Gpc

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or

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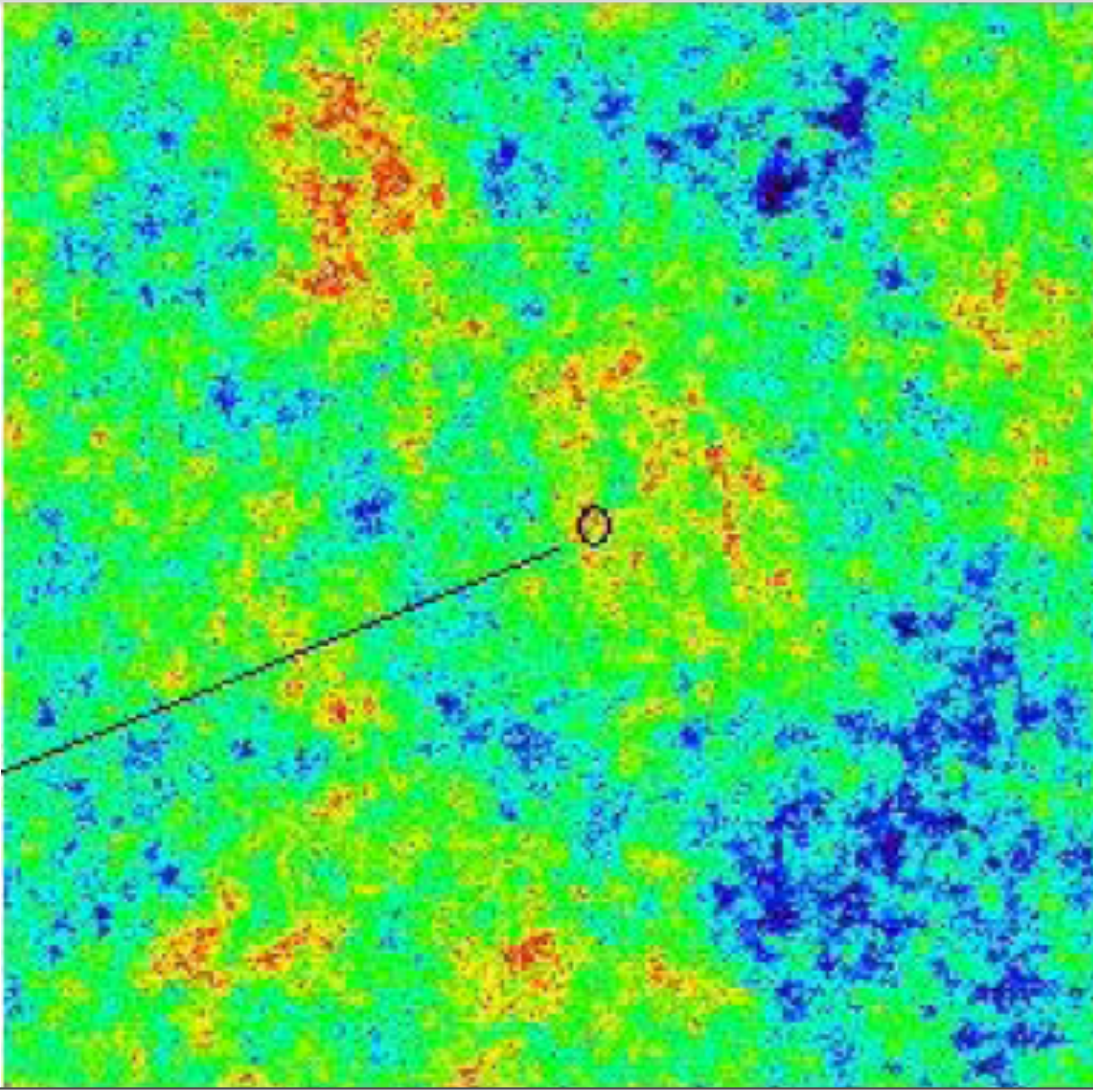
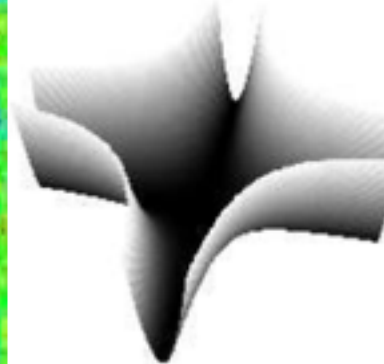


current Hubble patch ~10 Gpc

speed limit horizon



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

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

1000 Gpc

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

isocon

$\chi(\mathbf{x})$

or

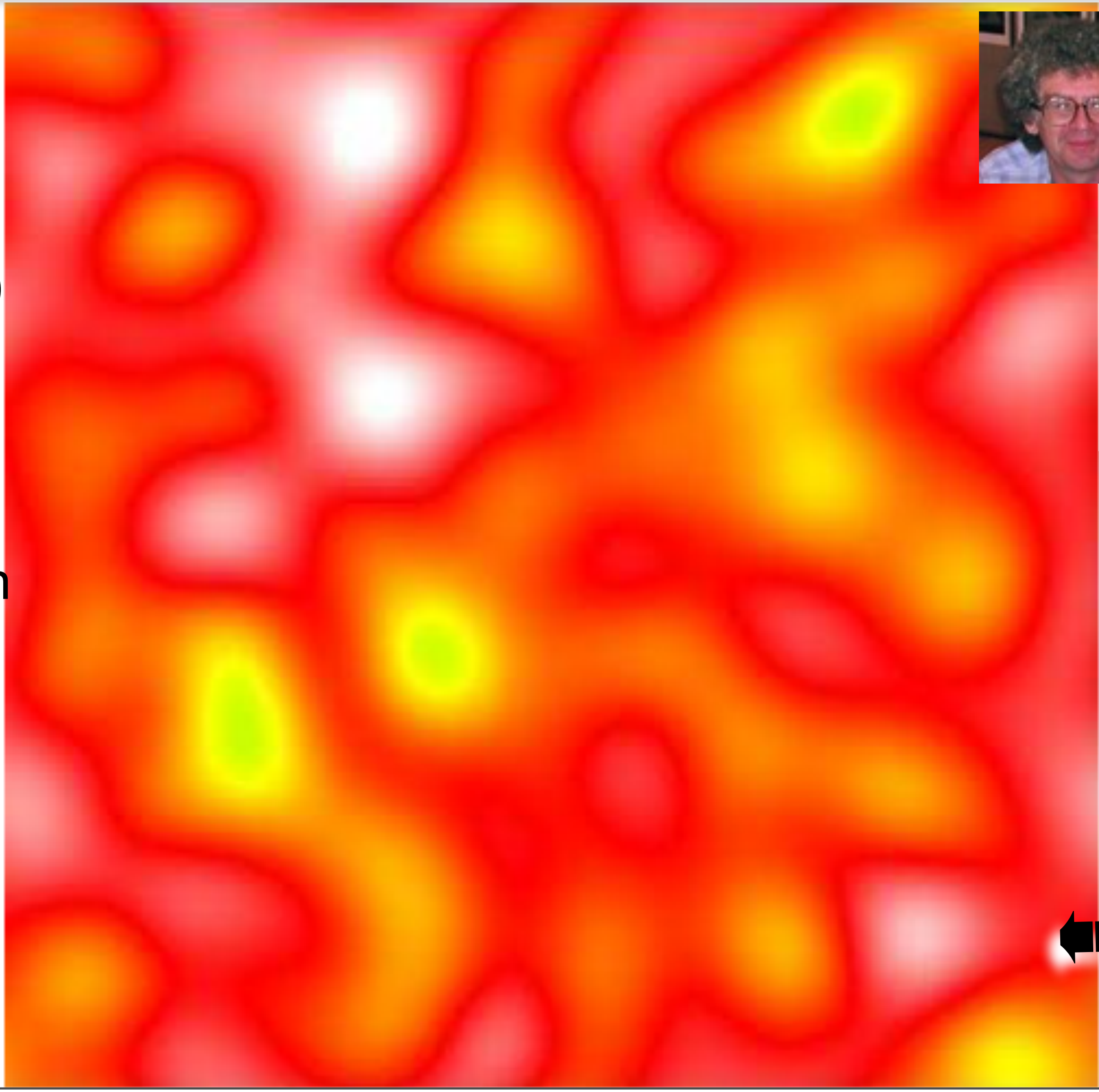
$\mathbf{g}(\sigma(\mathbf{x}))$

or..

ϕ

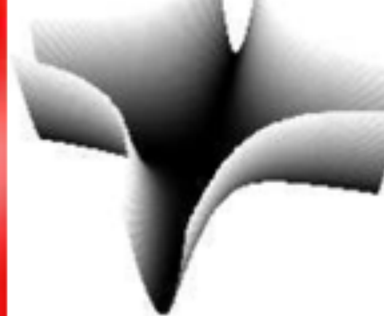
inflaton

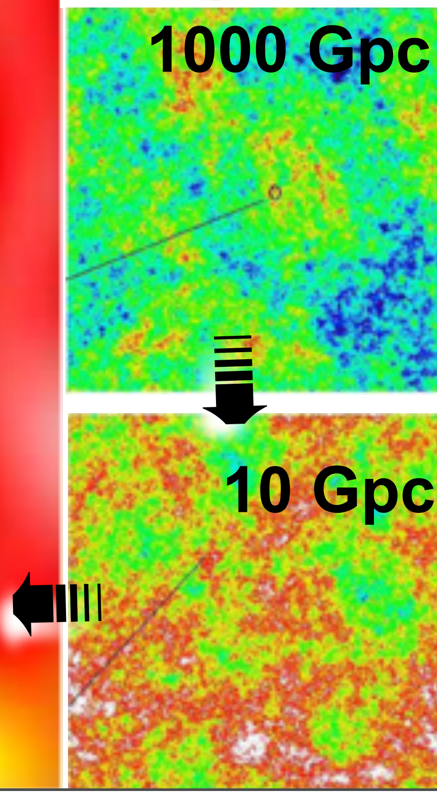
pre-
heating
patch
(~1cm)



Parametric
Resonance

$g^2/\lambda \sim 1$





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

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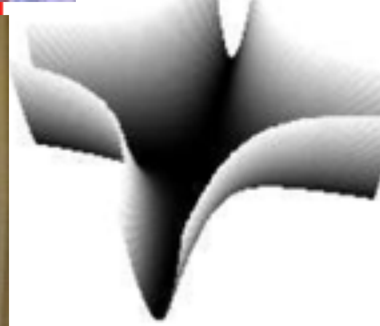
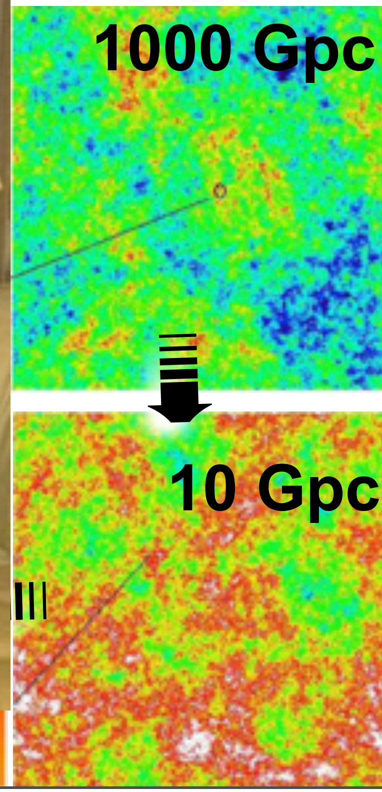




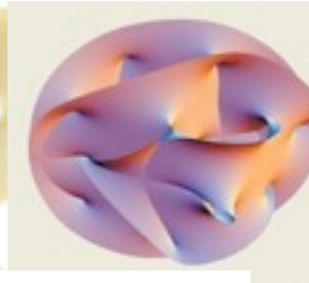
pre-heating patch (~1cm)

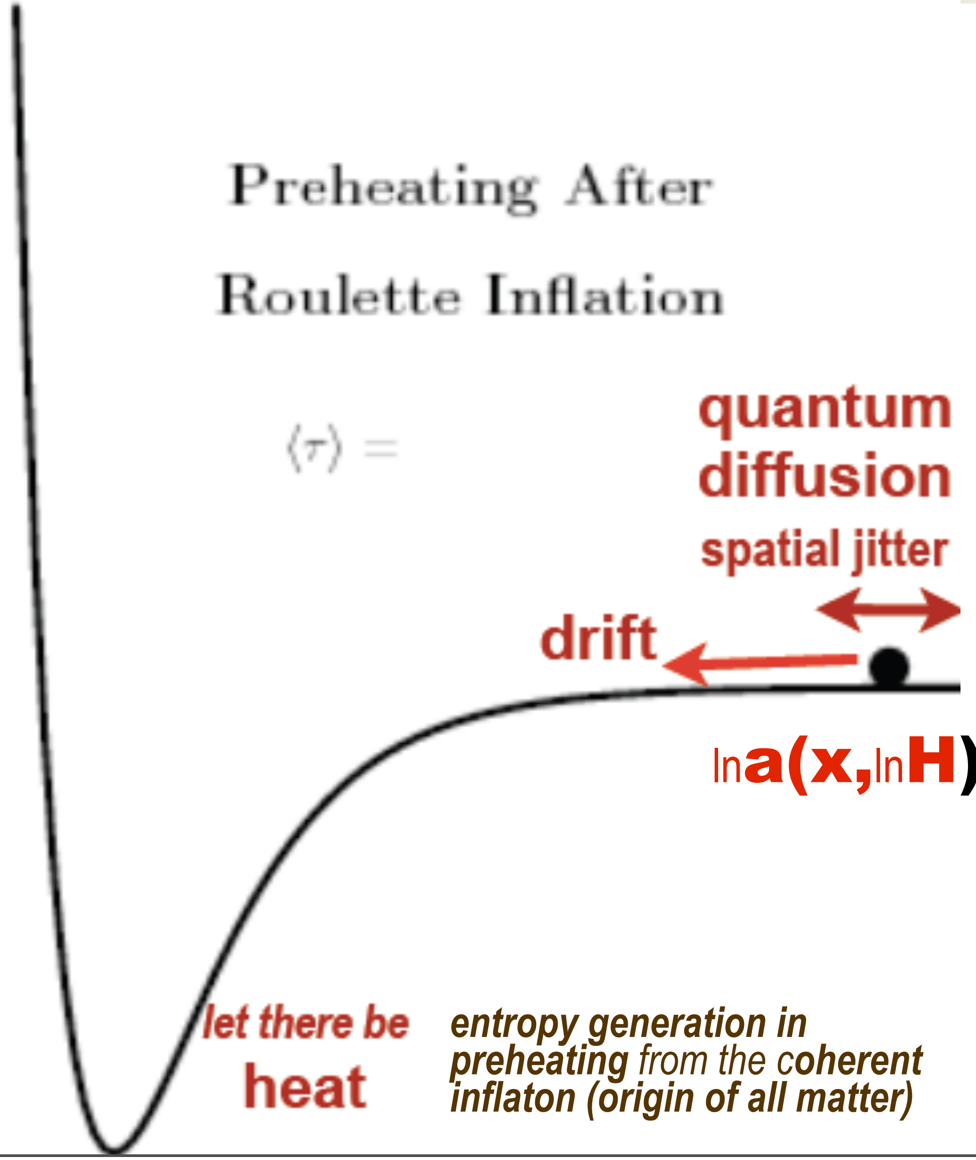
***B^2FH12 @ifaUH aka Waikiki** Feb12*

Roulette Inflation: ***a statistical mini - landscape (one of very many) of the early U origins of observed cosmic structure:***

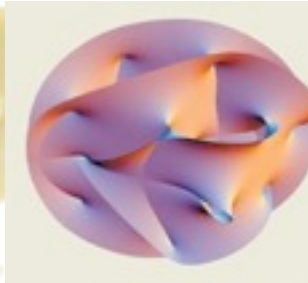
holey U: sizes/shapes of geometrical structures such as holes in a dynamical extra-dimensional (6-7D) space settling into a stable bit of extra-dim at each point in our 3D space;

braney U: *motions of lower-dimension subspace…*





Roulette Inflation: *a statistical mini - landscape (one of very many) of the early U origins of observed cosmic structure:*



holey U: sizes/shapes of geometrical structures such as holes in a dynamical extra-dimensional (6-7D) space settling into a stable bit of extra-dim at each point in our 3D space;

braney U: *motions of lower-dimension subspaces*

Barnaby, Bond, Huang, Kofman 2009

pre-heating patch (**<1cm**-now, **<10^{-30} cm**-then)

semi ETERNAL INFLATION

quantum diffusion

spatial jitter

drift

let there be

heat

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

Roulette Inflation: ***a statistical mini - landscape (one of very many) of the early U origins of observed cosmic structure:***

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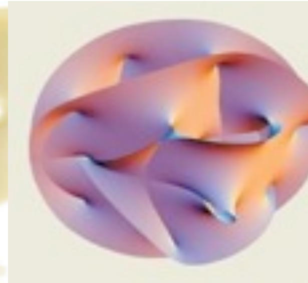
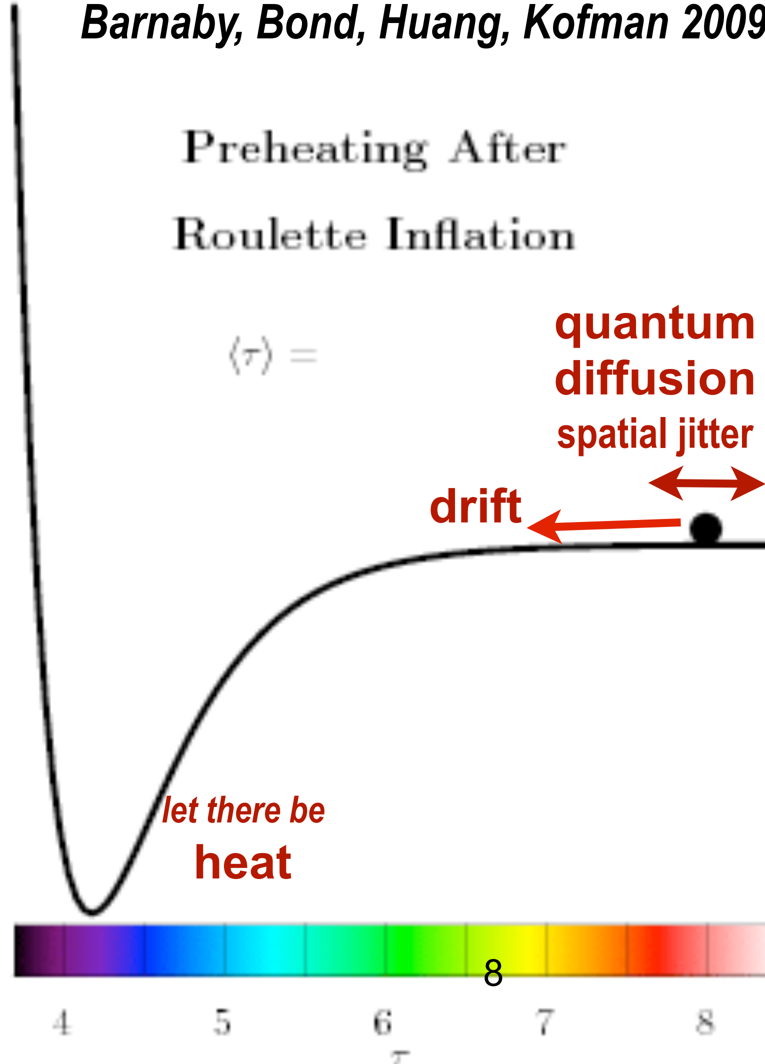


pre-heating patch (**<1cm**-now, **<10^{-30} cm**-then)

A visualized 2D slice

in lattice simulation

Barnaby, Bond, Huang, Kofman 2009



semi ETERNAL INFLATION

8

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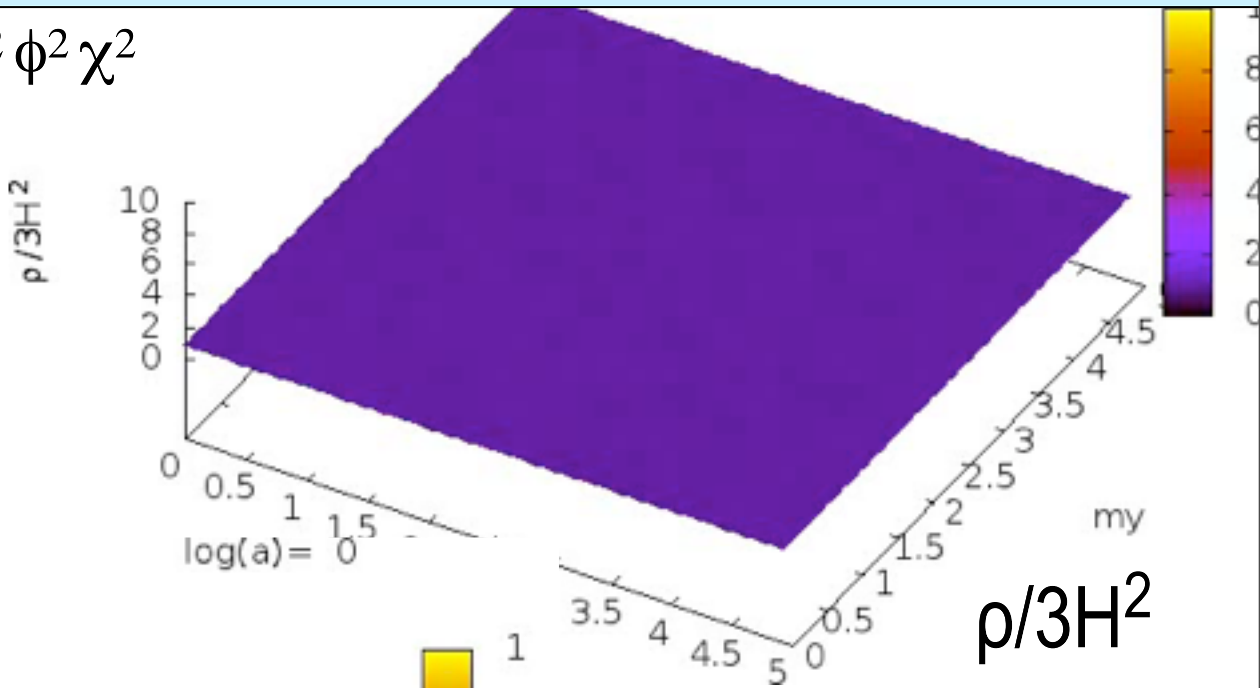
coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

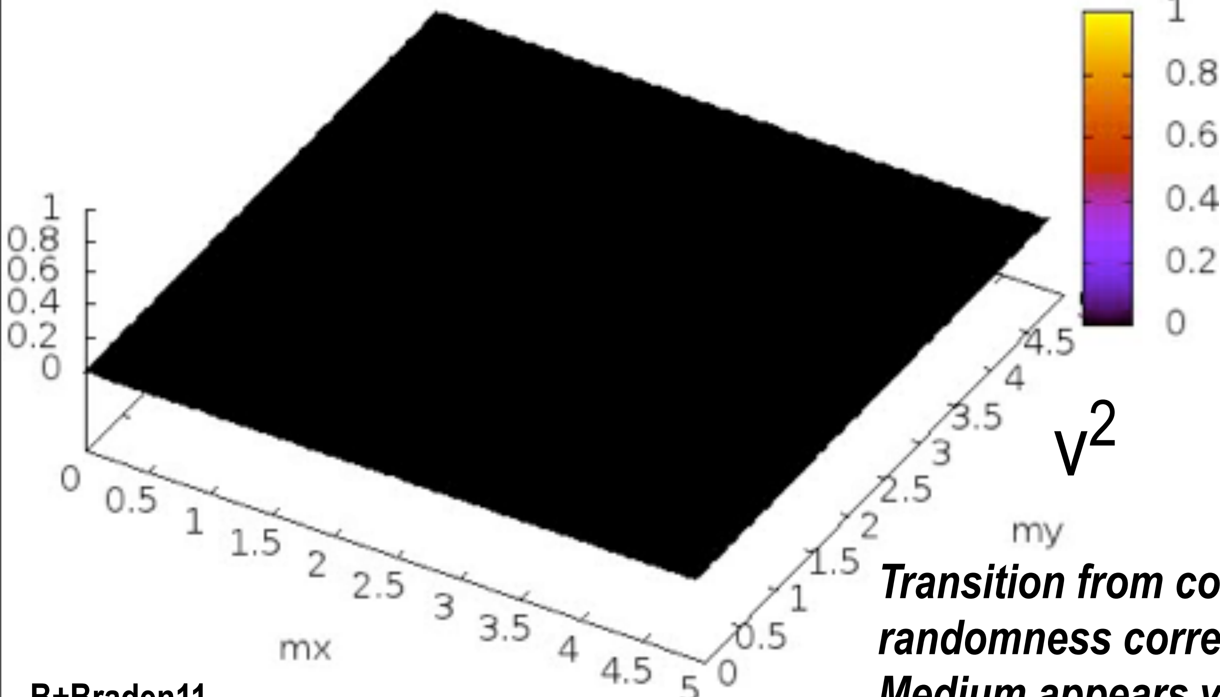
$V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2 \phi^2 \chi^2$



Slow Dynamics of IR Modes
⇒ Hydrodynamic Description

$\rho = -T^0{}_0 \quad P = -T^i{}_i$

$v^i = aT^i{}_0 / (\rho + P)$

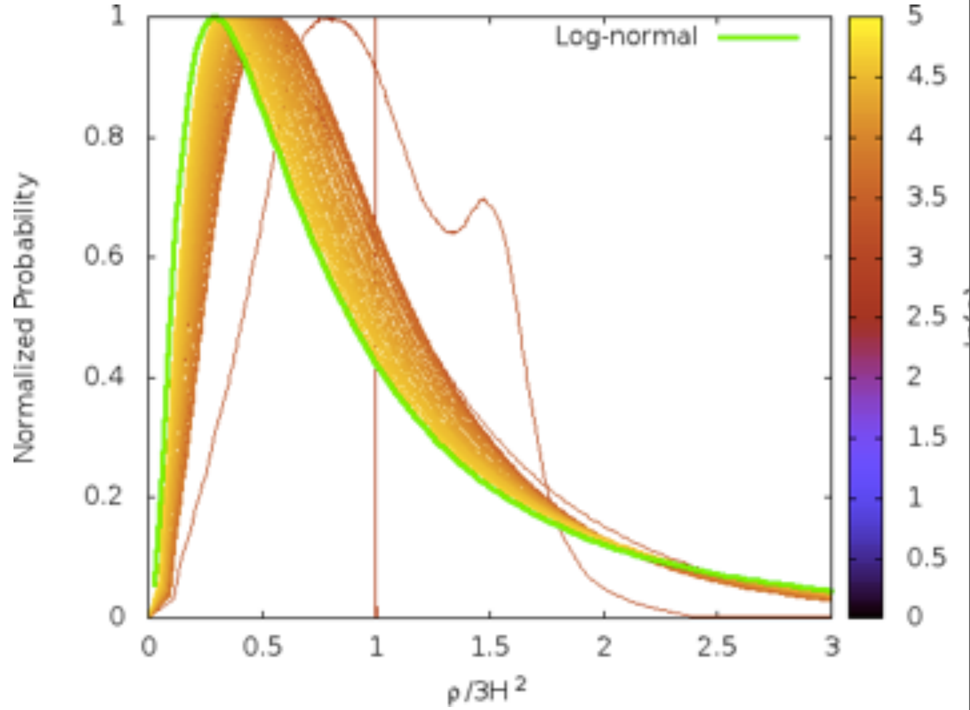


non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

Transition from coherent wall-like structures to randomness corresponds to the shock-in-time. Medium appears very complex in space and time, but ...

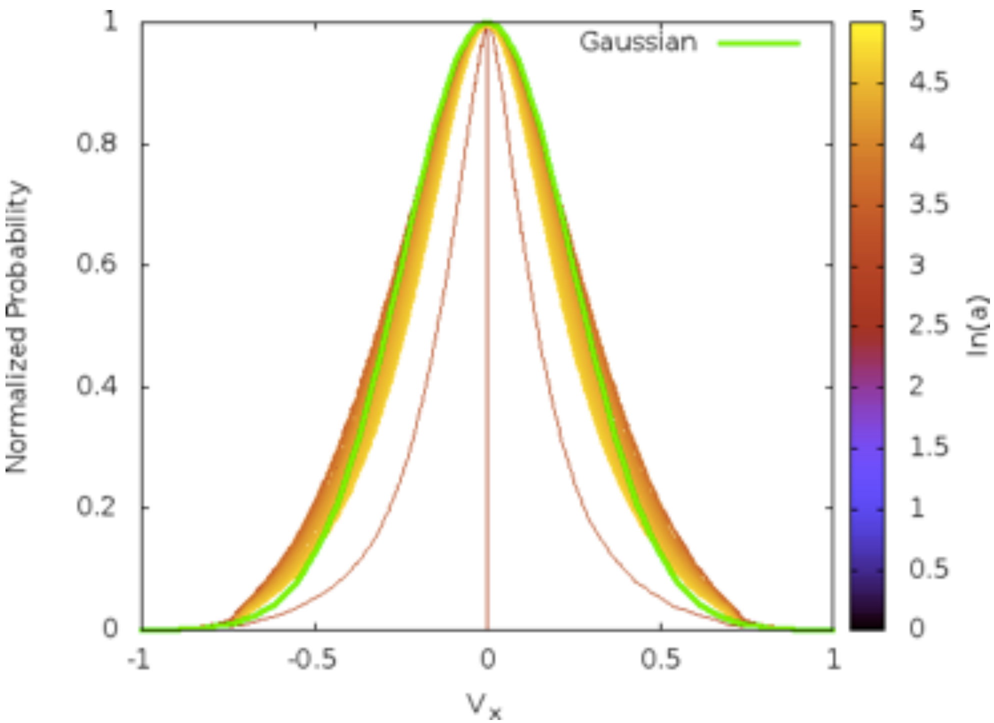
B+Braden11

but Statistical Simplicity



Density PDF~ log-normal after initial transient Frolov10

Velocity components ~ Gaussian PDF



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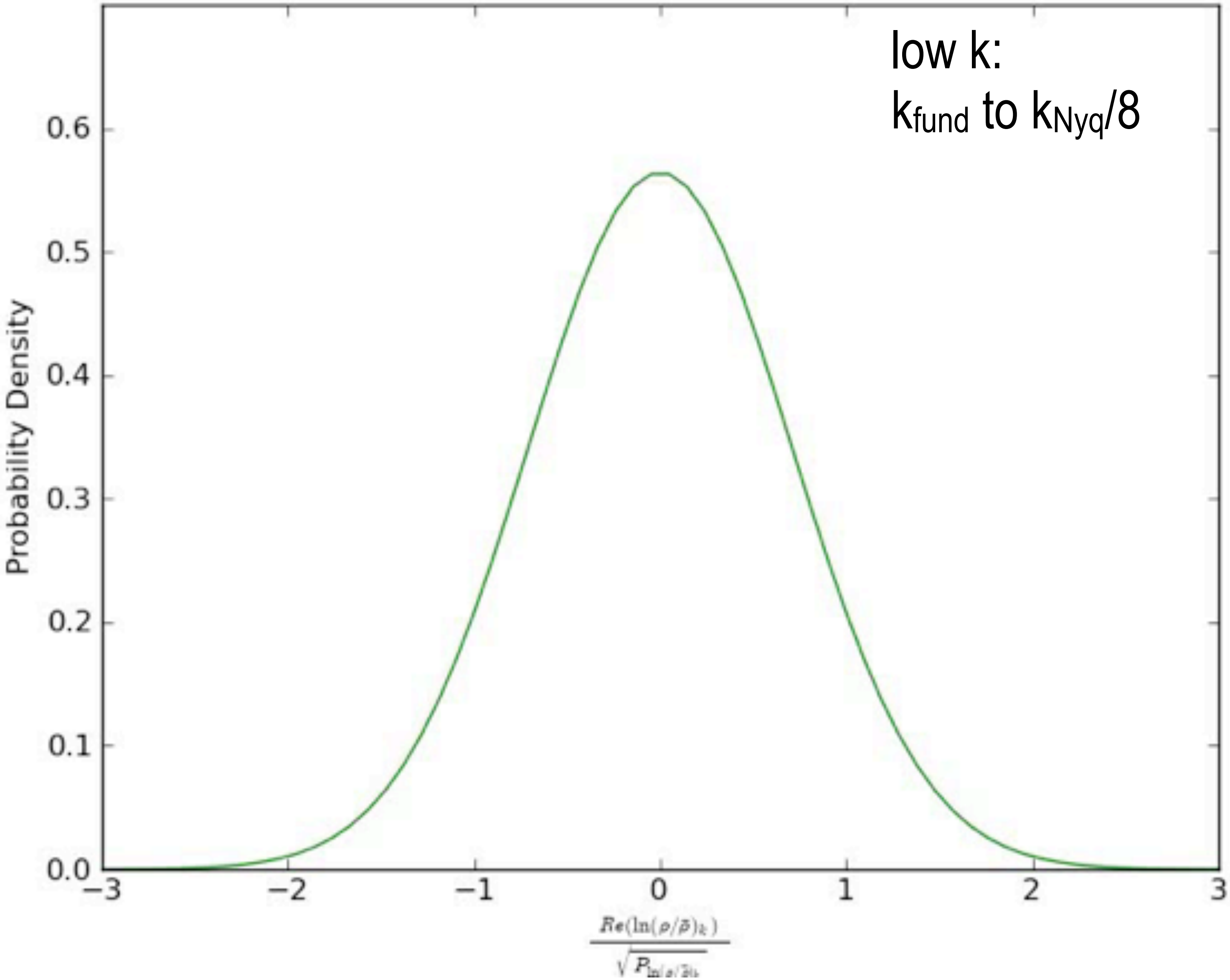
(WMAP, **Planck**, LSS)
spiky nG preheating

B+Braden11

box L=10m and N=1024^3

but Statistical Simplicity

FT(*ln* density) PDF ~ log-normal after initial transient



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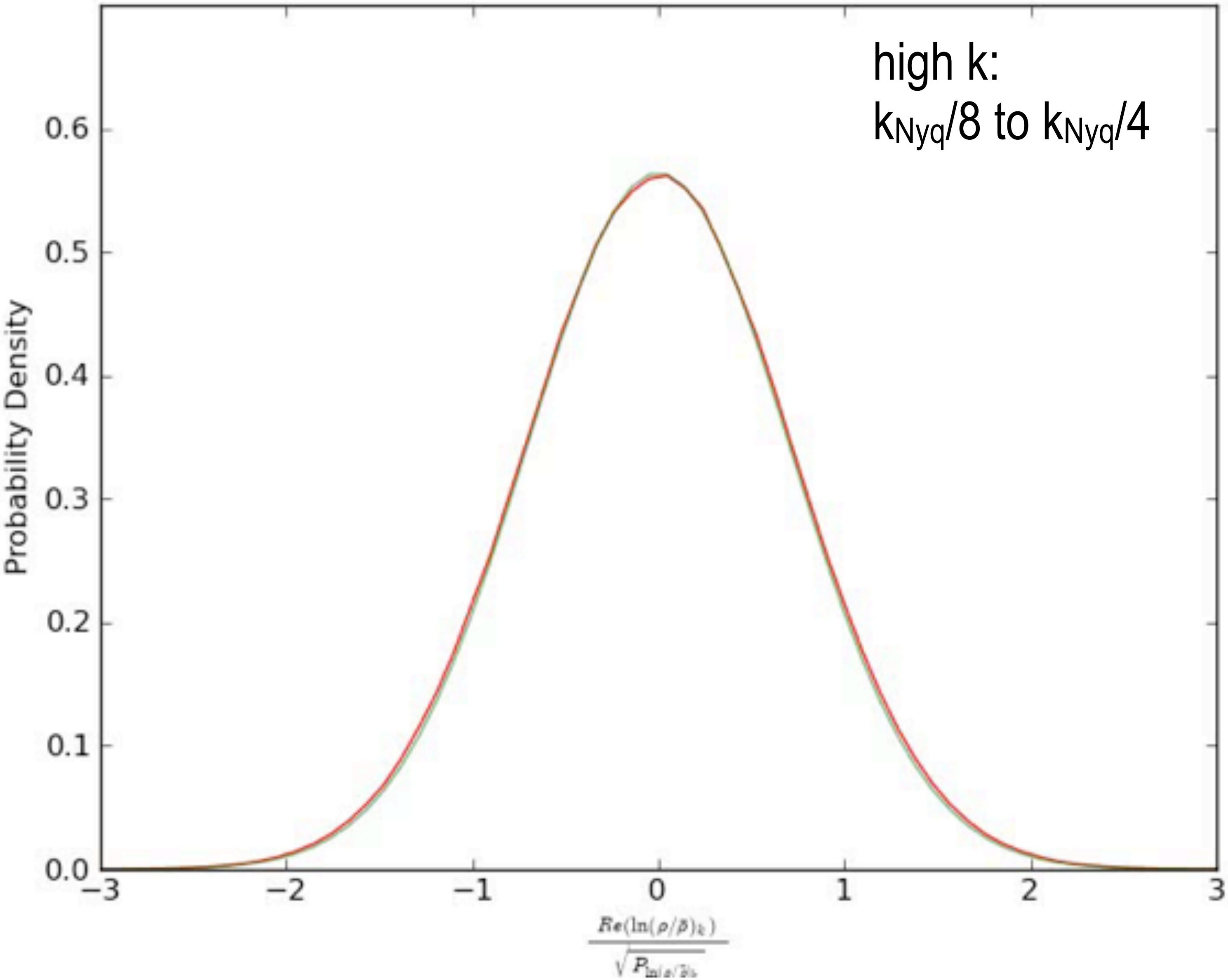

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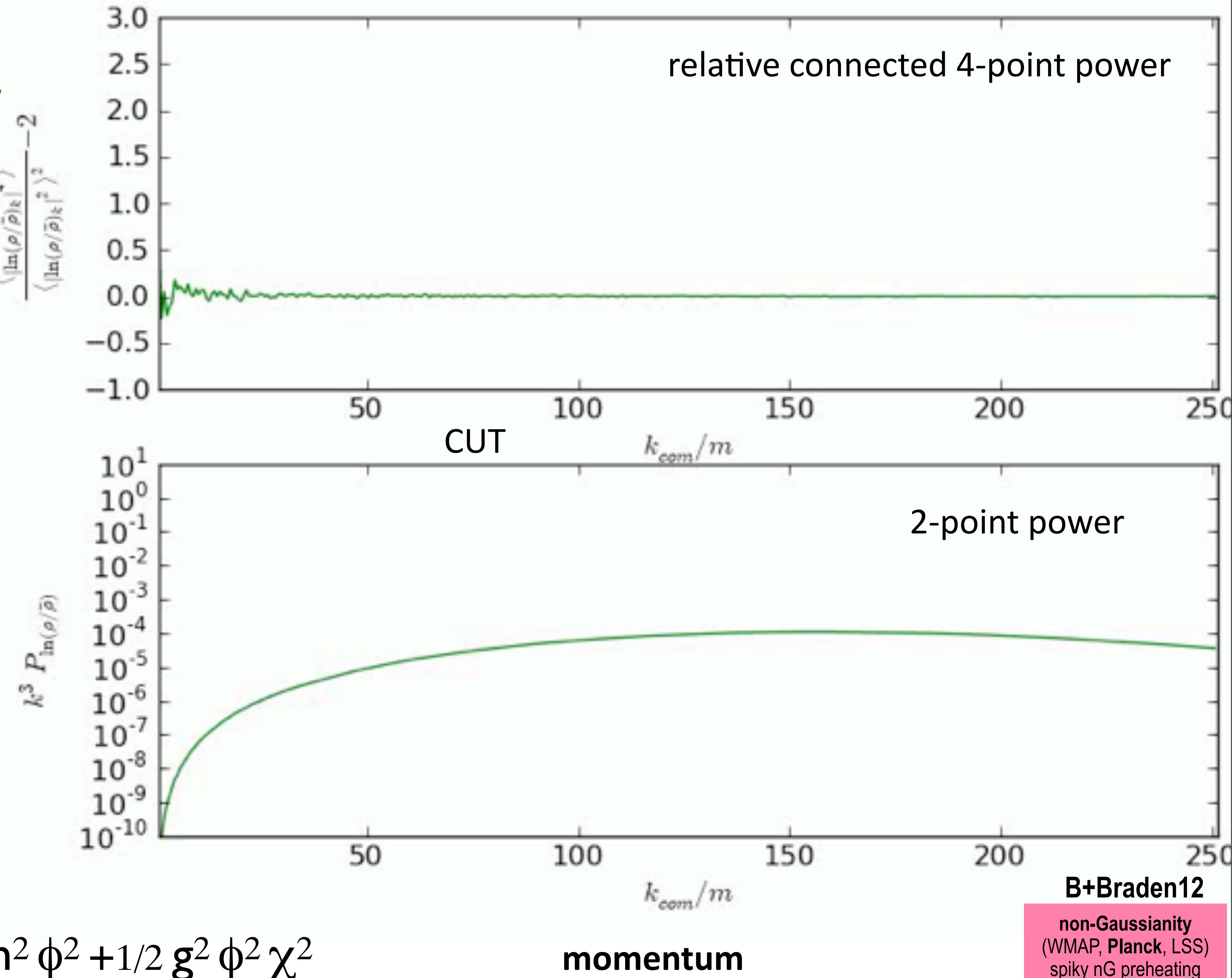
coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

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

ln ρ/<ρ> power spectrum cf. instantaneous full thermal spectrum cf. conventional energy spectrum using a pseudo particle occupation number



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

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

Thursday, 5 April, 12

Studying the Cosmic en-TANGO-ment the dance of $U=R\cup S$
of phase & probability: $\varrho(U) = \varrho(S,R) = \varrho(R|S)\,\varrho(S)$ *Universe*
=*System(s)*+*Reservoir* =Signal(s)+Residual *noise* =Effective (F) Theory+*Hidden variables*=*Data*+*Theory*, observer(s)+observed

$S/k_B = ln N_{states}$
$dS/dt > 0$

classical **nonequilibrium Shannon (relative) entropy**

$S_{fi} = -\int dq\, [P_f(q)\, ln\, P_f(q)\, /P_i(q)] + [P_f(q) - P_i(q)]$ **-KL divergence**

$P_f(q)$ probability density functional **distribution function**

$\Leftarrow$ *quantum* **(von Neumann)** $S = -Tr\, \rho\, ln\, \rho$ **density matrix**

coarse graining & entropy "production" ***(S=0 pure state)***

max S constrained by "measurements" of theorists on the medium

parameters q = Field variables ⇒ Correlation Functions

Measurements: e.g., constraints (information) on Correlators

marginalize higher order correlators (i.e., unknown)⇒ ***S*** ⬆

Bayes dS <0 as System knowledge ⬆ $P(q|D,T) = P(D|q,T)P(q|T)P(T)/P(D|T)$

Gaussian distribution=max-entropy $dist^n$ fn given 2-pt correlation fn

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

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

ln=log$_e$ measure info in nats, lb=log$_2$ measure info in bits

$C(k) = \langle |ln\rho|^2(k) \rangle$ but want discrete state counting or relative entropy

$S_{fi} = (Trace\ ln\ C_f\ C_i^{-1})/2 = \langle ln\ V_{p\text{-}space,f} / V_{p\text{-}space,fi} \rangle_f$

A Shocking End to Post Inflation Mean Field Dynamics

Shock-in-space t = const

$v_{bulk}^2 > c_s^2 \Rightarrow v_{bulk}^2 < c_s^2$

supersonic ⇒ subsonic

Characteristic spatial scale

Jump Conditions: $\Delta T^{\mu\nu}$

Randomizing Shock Front: ΔS

Mediation: width via viscosity or collisionless dynamics

post-shock evolution, slow, of temperature, etc.

Shock-in-time x = const (deviations for nonG)

$\langle\rho\rangle \gg \delta\rho \Rightarrow \langle\rho\rangle \ll \delta\rho$

Homogeneous ⇒ Fluctuations

Characteristic temporal scale

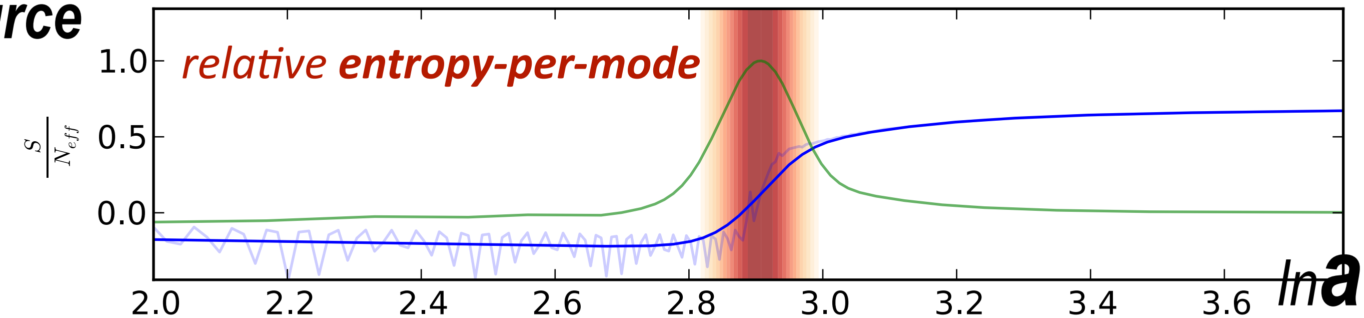
Jump Conditions: $\Delta T^{\mu 0}$

Randomizing mode cascade & Particle Production: ΔS

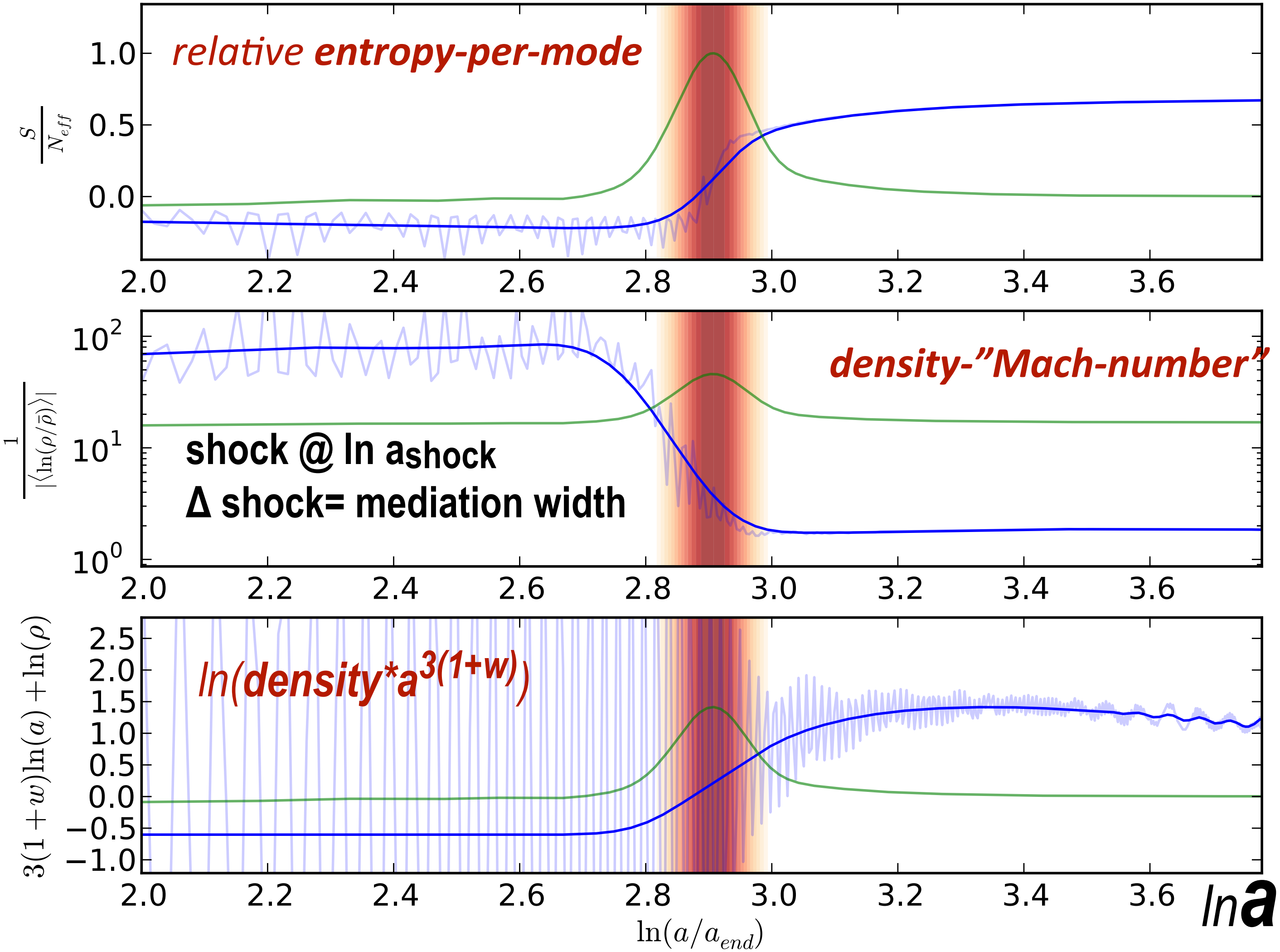
Mediation: width via gradients and nonlinearities

post-shock evolution, slow, of fluctuations

Preheating is a shockingly efficient entropy source



the Shock-in-time: entropy production, <ln(density-contrast)>$^{-1}$,ln(density*a$^{3(1+w)}$)



true thermal equilibrium far off

➤

& on to coupling to standard model degrees of freedom

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.

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

non-Gaussianity
(WMAP, **Planck**, LSS)
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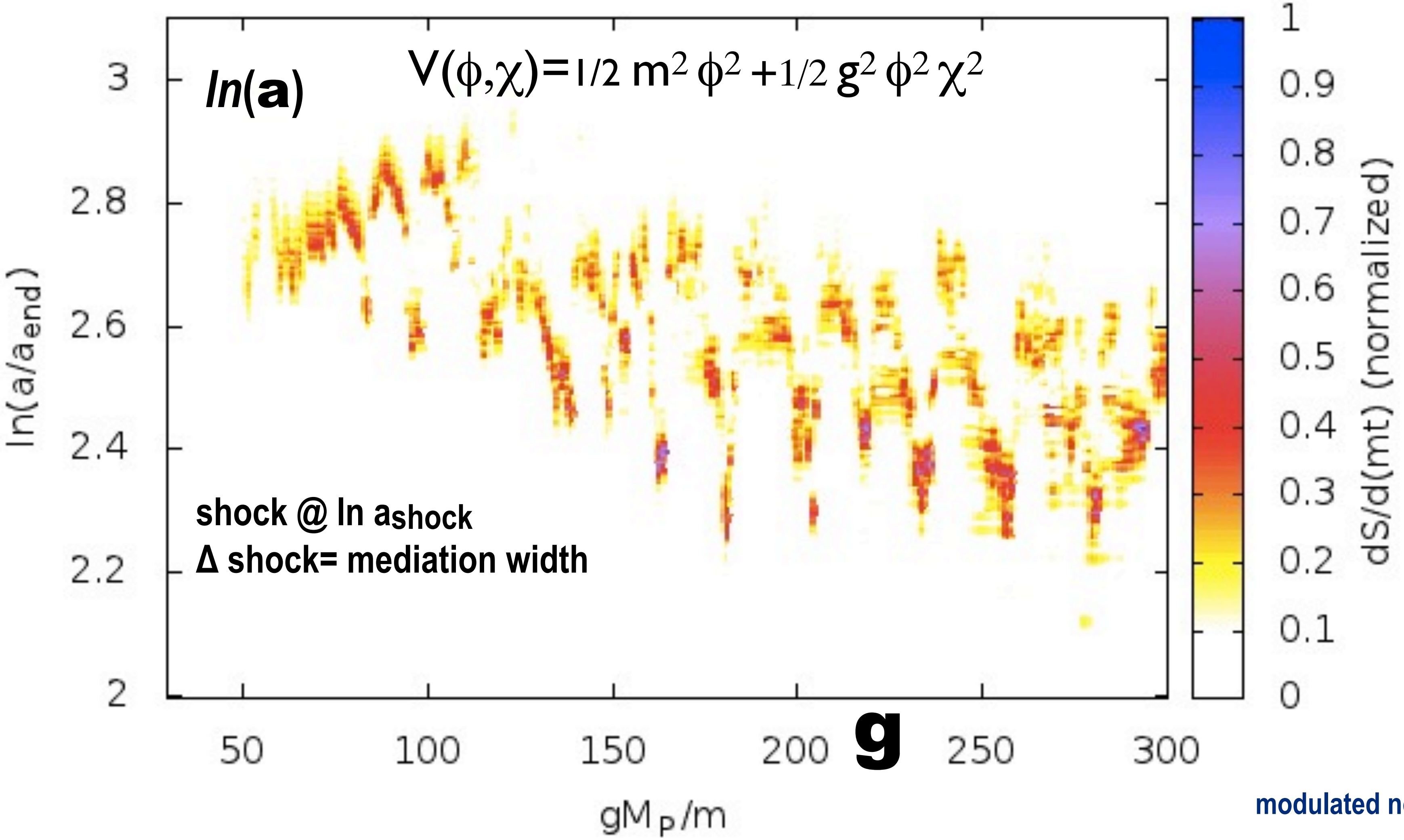
B+Braden11

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

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



modulated non-G

Kofman03
Dvali, Gruzinov+Zaldarriaga03
B+Braden12

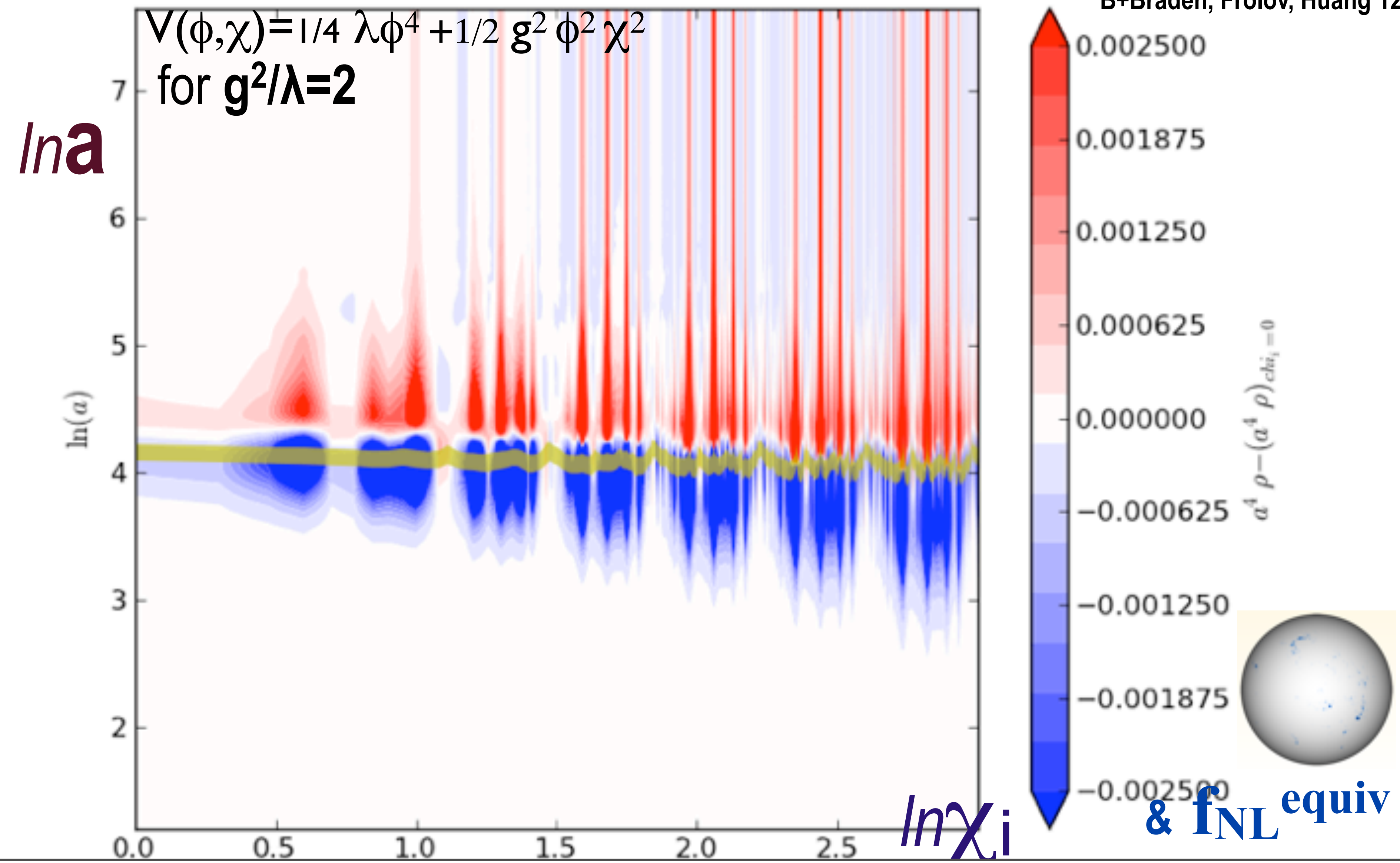
$V(\phi,\chi) = 1/2\, m^2 \phi^2 + 1/2\, g^2 \phi^2 \chi^2$

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

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

B+Frolov, Huang, Kofman 09

B+Braden, Frolov, Huang 12



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

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

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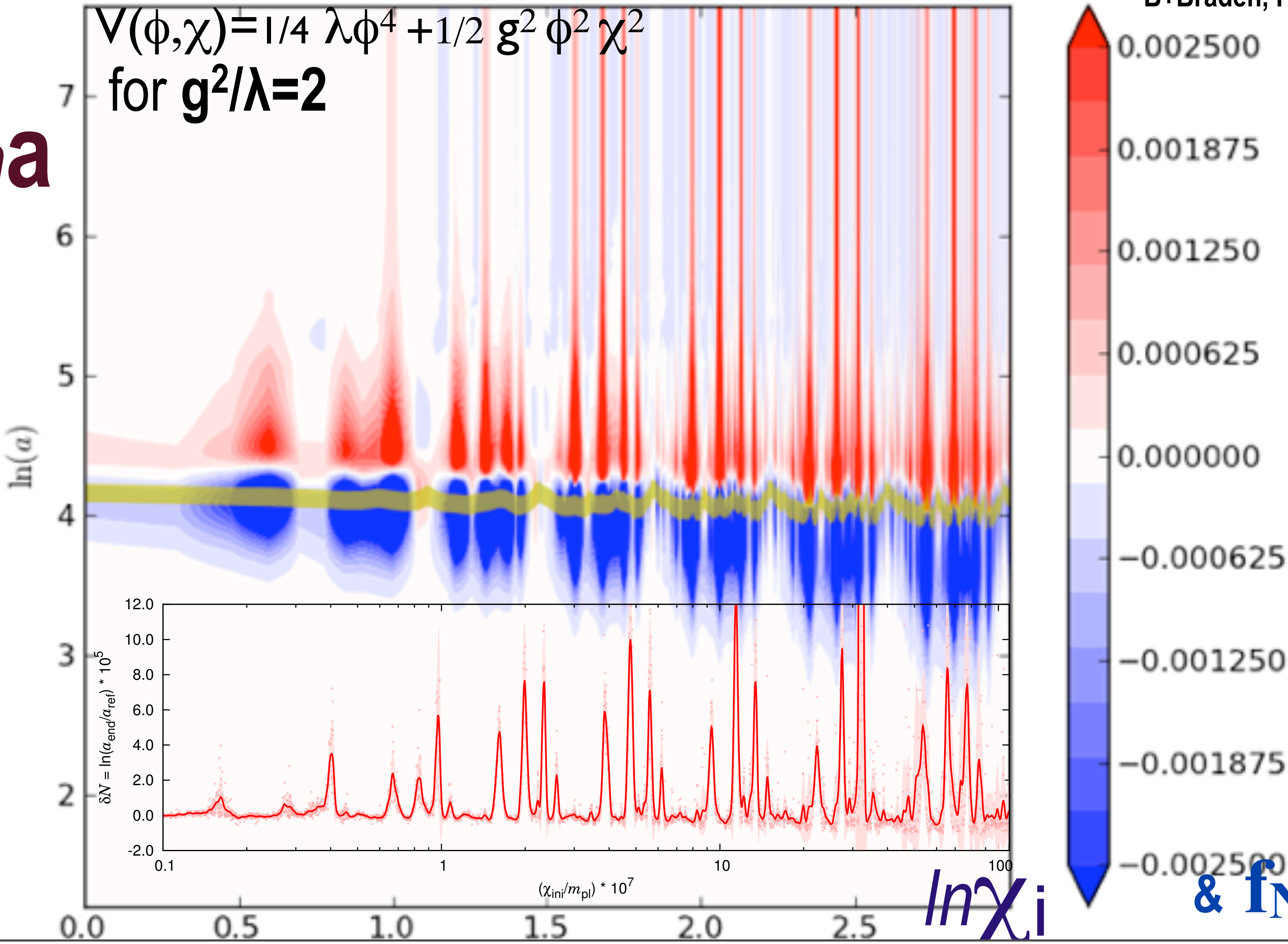
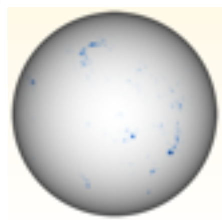




& f_{NL}^{equiv}

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?*

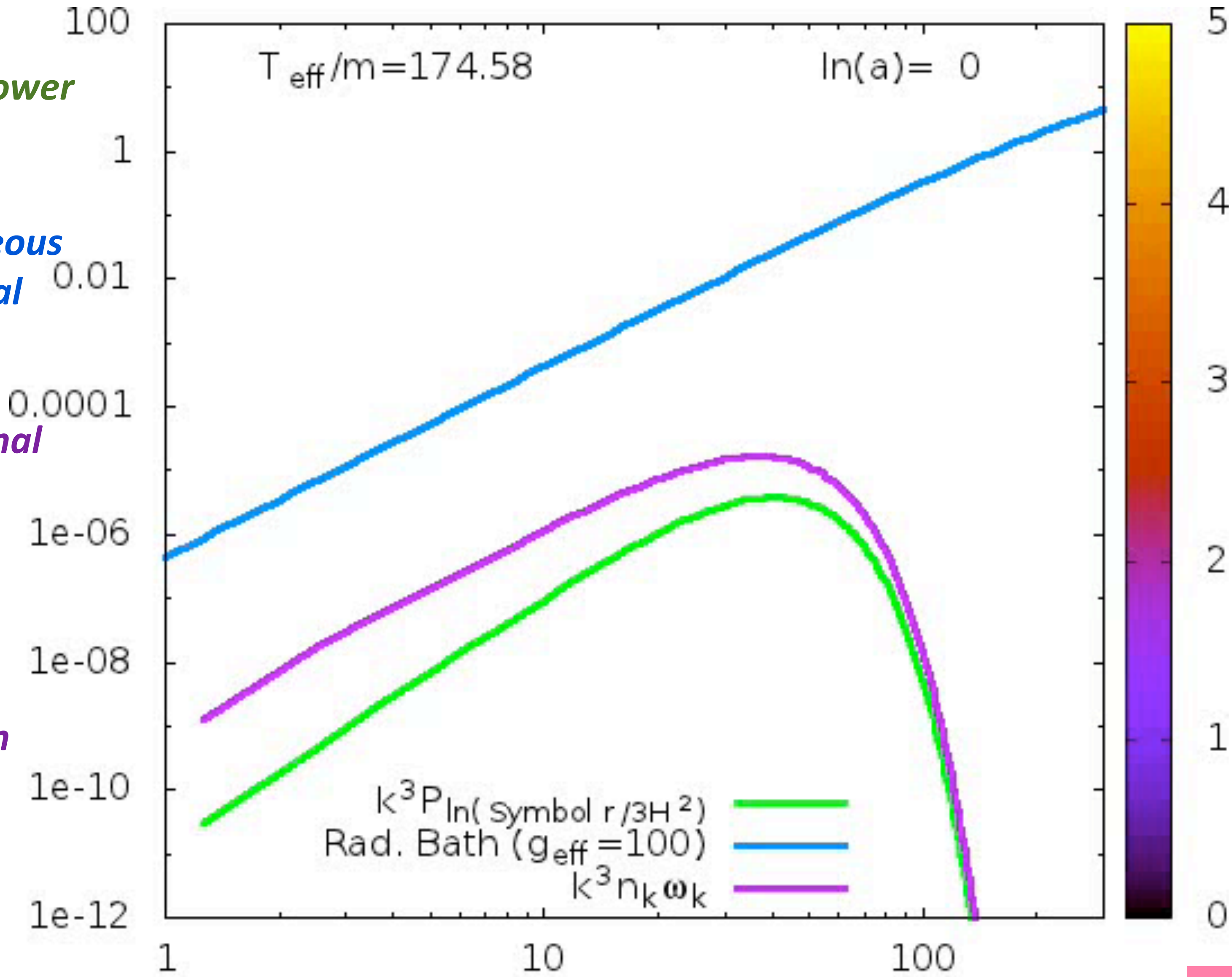
coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

s_{Ui}~*0*; $s_{Utot,m+r}/n_b$ ~*1.66x10*^{10} bits/b; s_γ / n_γ = *5.2 bits/Y* = *2130/411*; s_ν =*21/22* s_γ

ln ρ/<ρ> power spectrum

cf. instantaneous full thermal spectrum

cf. conventional energy spectrum using a pseudo particle occupation number



k/m **momentum**

B+Braden12

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Conclusions

BB12 **new language for preheating using complex information measures: the shock-in-time = randomization front, an efficient entropy source**

Spatial block RenormGp smoothing indicates that PDF's of fluctuations around local values evolve slowly post-shock

nearly Gaussian PDF for $\ln\rho_k$ **&** $\mathbf{v}_k$ **hydro/phonon regime**

Observable preheating **nonGaussianities** can be encoded in the spatial structure of the shock-in-time, characterized by $\ln\, a_{shock}(x)/a_{end}$

narrow mediation width. reasonable case made that ≈ $\ln\, a_{final}(x)/a_{end}$

generalized nonG from **shock-in-time(x | couplings, isocon, ...)** TBD fully explore the potential surface dependence => the **variety of preH nonG** ***B²FH12***

phenomenology CMB cold spot /quadratic constraints for preheating nG's; ***constrain/detect with PlanckEXT; explore more short-astro-distance exotica of high-k spiky potential pits***

whence opens up the large number of particle dofs & standard model? can this kick in earlier, aka warm inflation. anyway, we are having fun with the high k drain

end