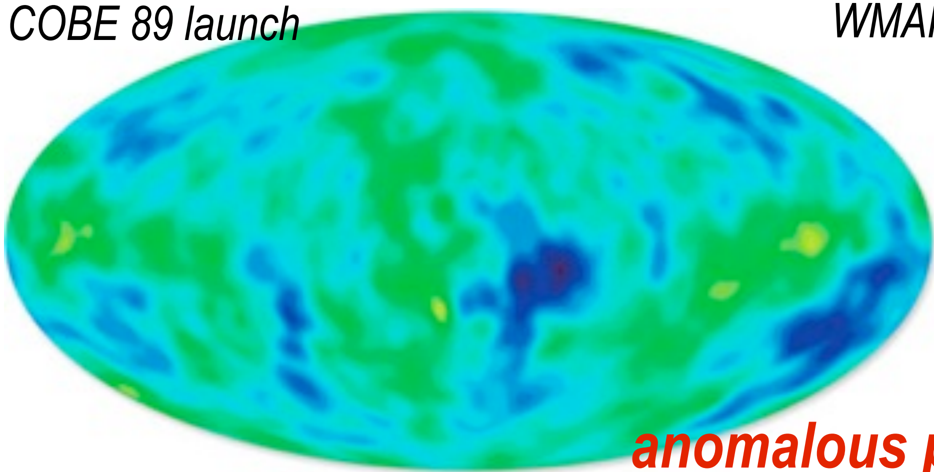
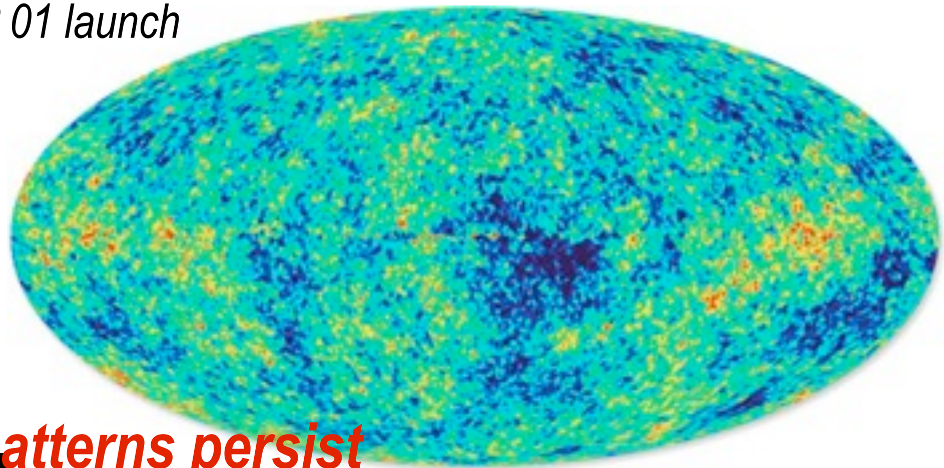
COBE 89 launch

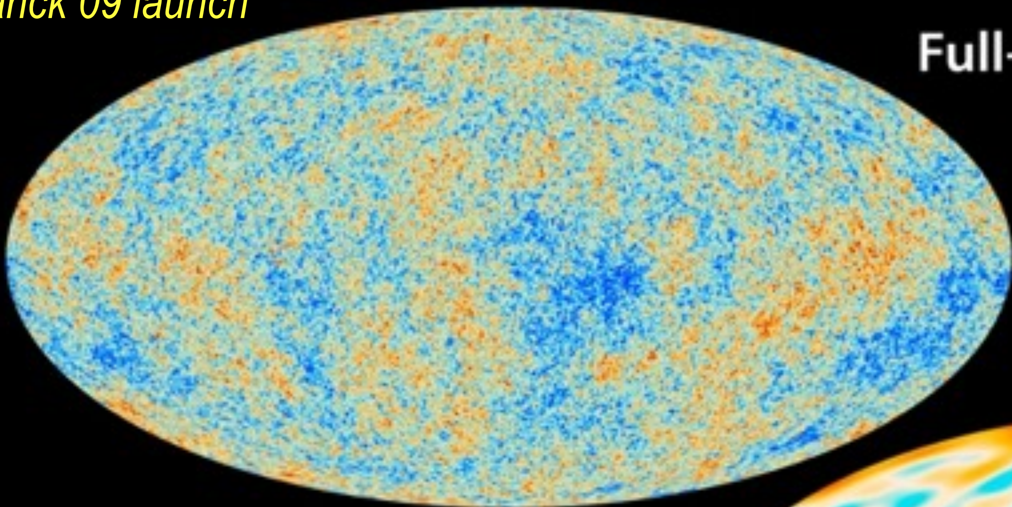


WMAP 01 launch



anomalous patterns persist

Planck 09 launch



Full-Sky Map

NonGaussian 3-point-pattern measure

f_{nl}: 2.7 ± 5.8 local => ± 5 (Pext)

-f_{nl}: 42.3 ± 75.2 equil

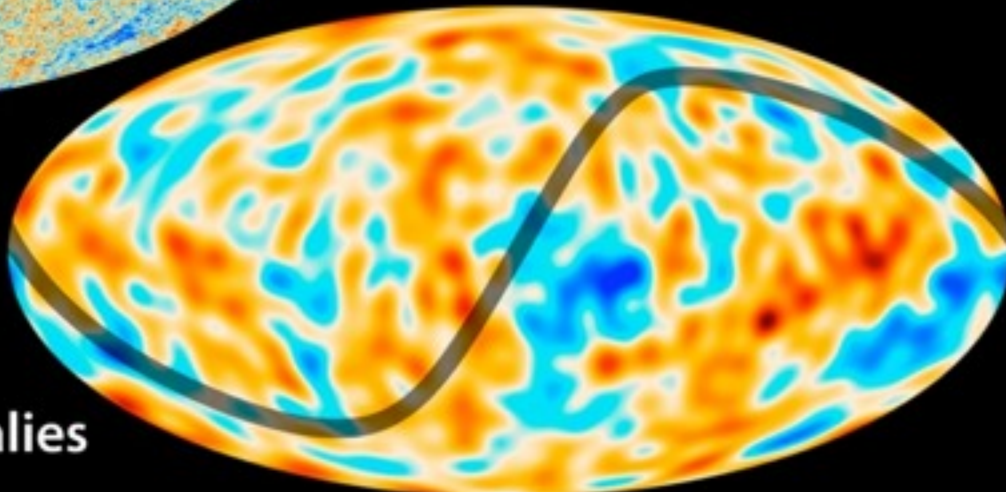
-25.3 ± 39.2 ortho & f_{NL}^{eff}

the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

planck

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

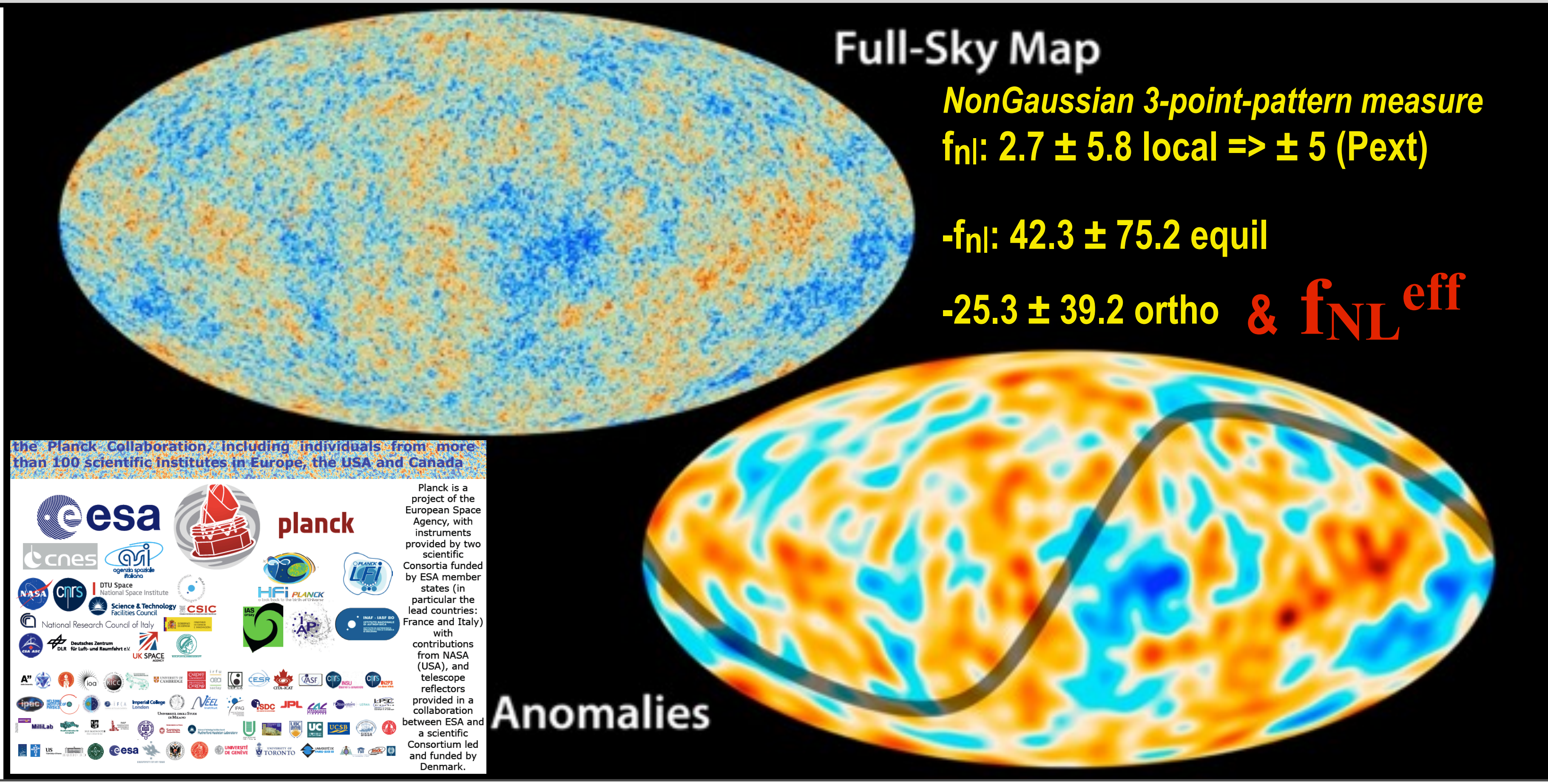
Anomalies



Dick Bond@CITA ***Non-Gaussianity from Modulations of the Shock-in-Times of Post-inflation Preheating***

Are LargeScale anomalies statistically significant? no said WMAP7 Bennett+
Seem to be says Planck1.3, so theorists should look again

*Planck1.3 says **Size of the Universe > 2*distance to recombination** for a variety of flat, plus and minus curved topologies, as did COBE and WMAP. Inflation models prefer a super-big universe, with nothing special just beyond our Hubble volume leaking in - maybe. Thus, can anomalies relate to inflation, given the strong non-G pattern-constraints from the 3-point function coded in f_{NL}*
*e.g., from **LS-intermittency** due to an **ultraLS modulating field** remembering*
***post-inflation entropy generation** BondFrolovHuangKofman09, BBraden13, B[2]FH13*



primordial non-Gaussianity

$\zeta(x) = \zeta_G(x) + f_{NL*}\,(\zeta_G^2(x) - \langle \zeta_G^2 \rangle)$

local smooth. use optimal pattern estimator

cf. DBI inflation: non-quadratic kinetic energy

cosmic/fundamental strings/defects

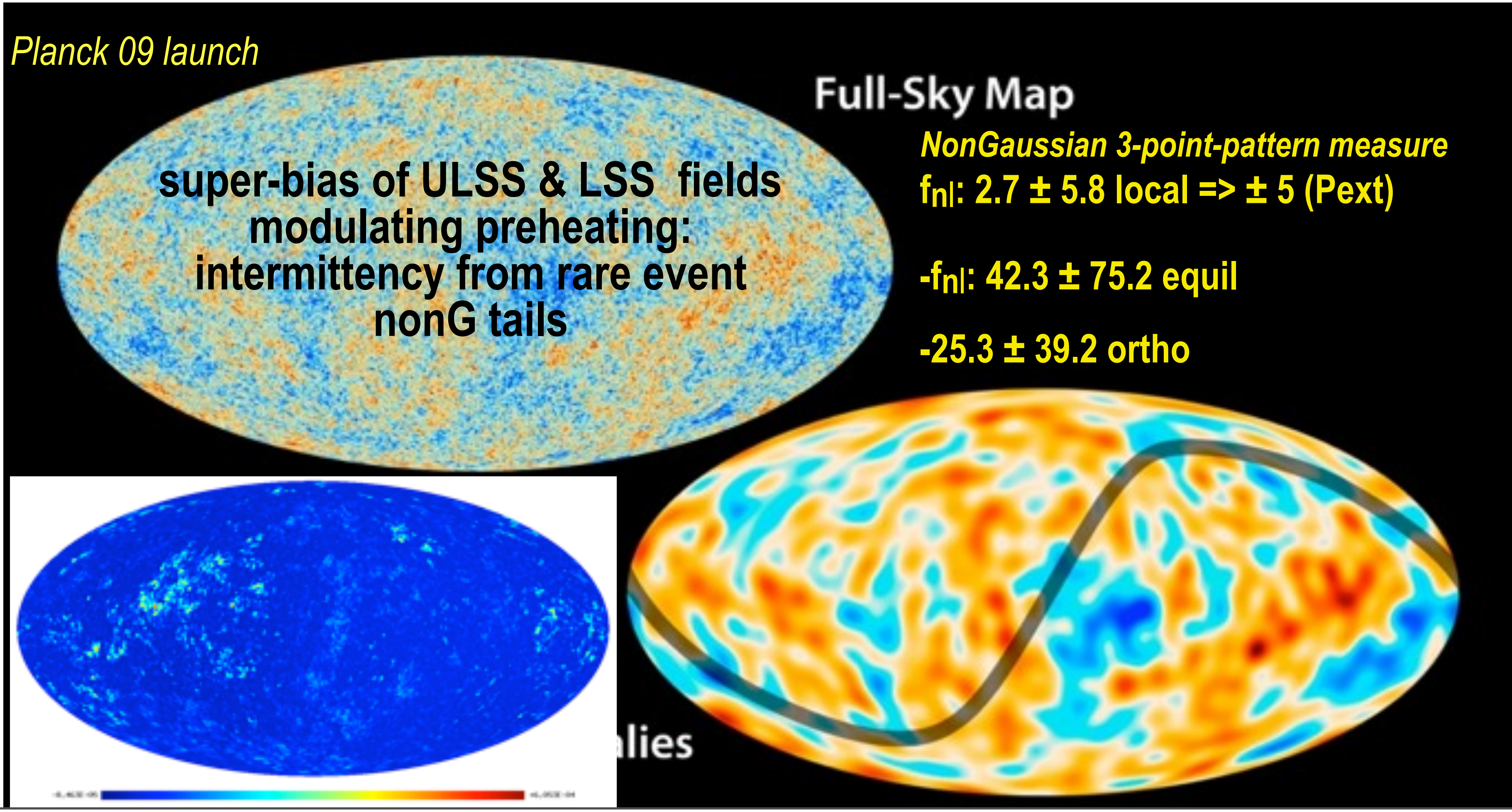
from end-of-inflation & preheating

$\zeta(x) = \zeta_G(x) + F_{NL}(\chi_b(x))$

modulating preheating

f_{NLeff} + cold spots

$\zeta(x) = \zeta_G(x) + F_{NL}(g_b(x))$



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

isocon

$\chi(\mathbf{x})$

or

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

or..

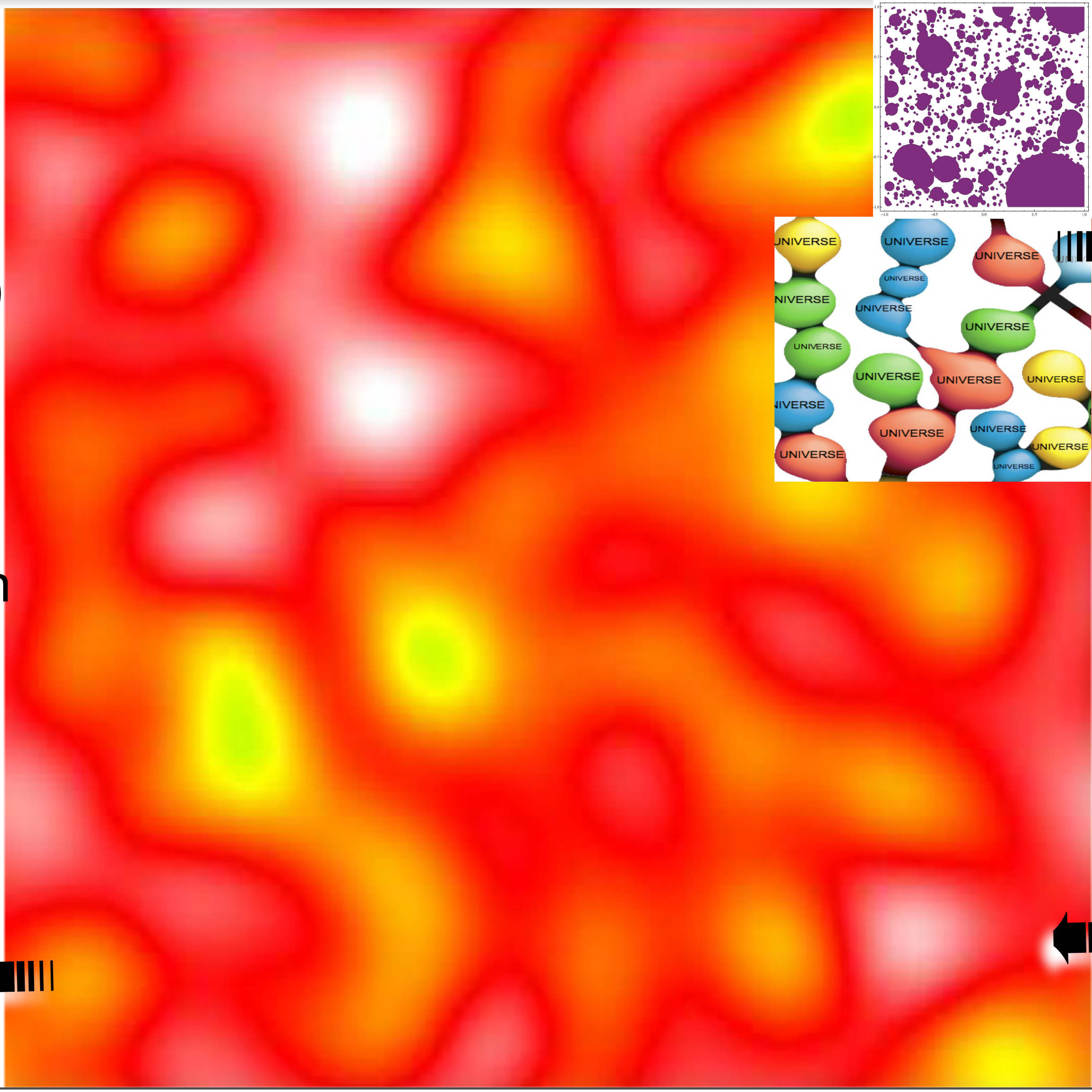
ϕ

inflaton

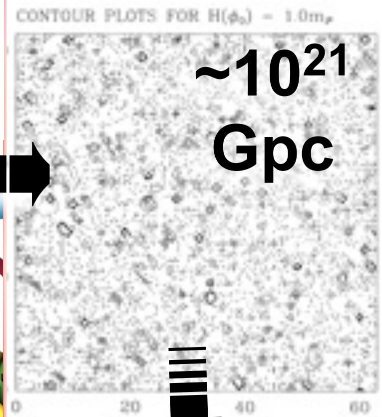
pre-heating patch (~1cm)

$S_{U,m+r}$

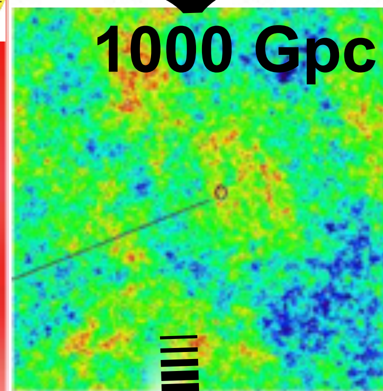
$\sim 10^{88.6}$



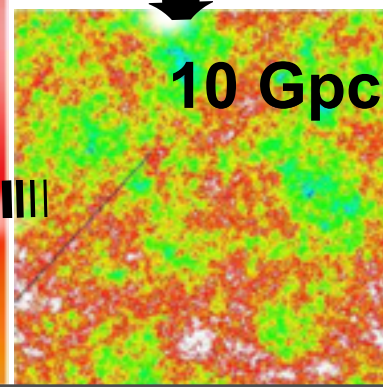
$S_{U,uuUULSS}$



~10[21] Gpc



1000 Gpc



10 Gpc

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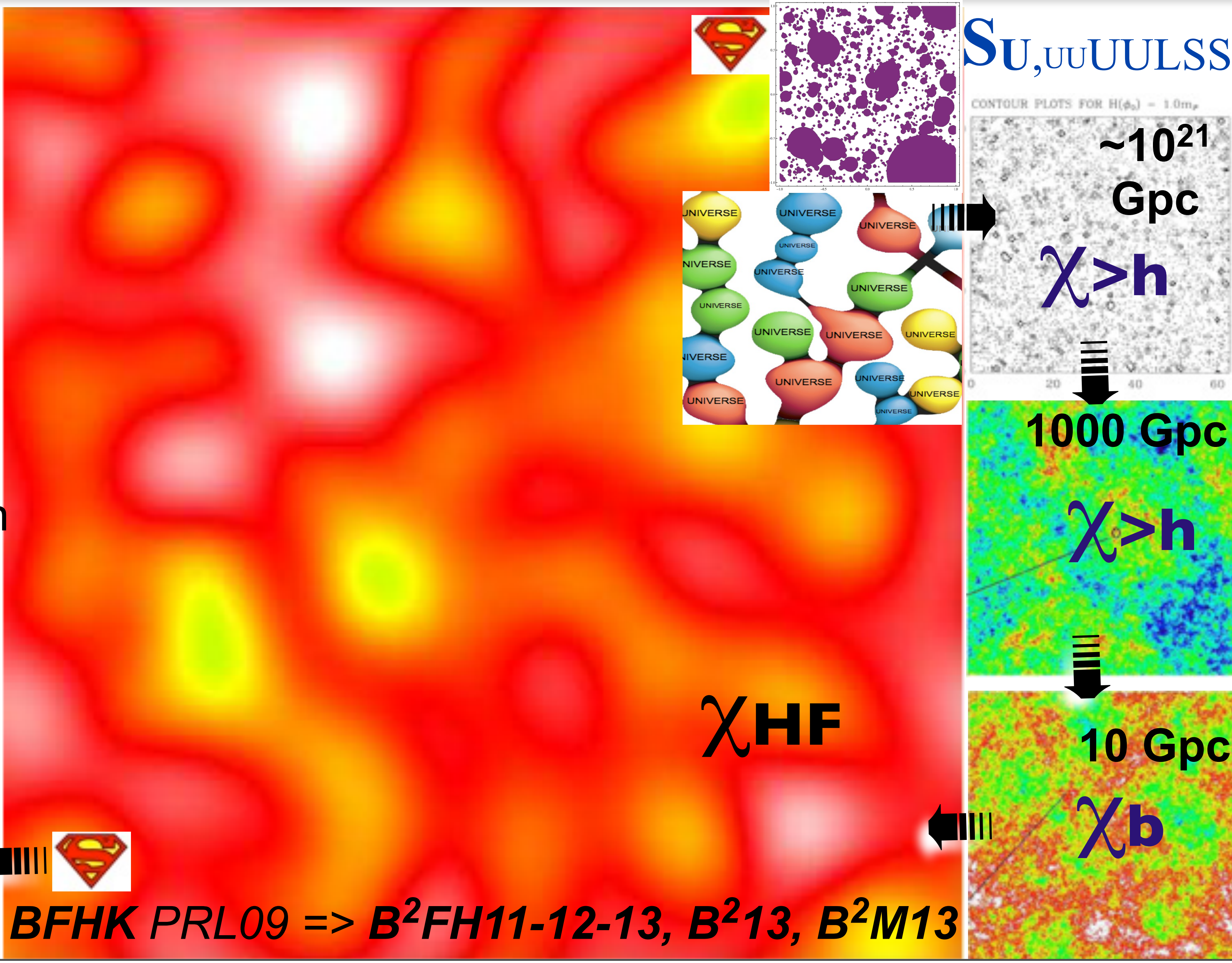

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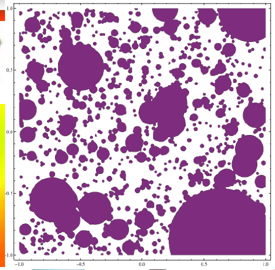
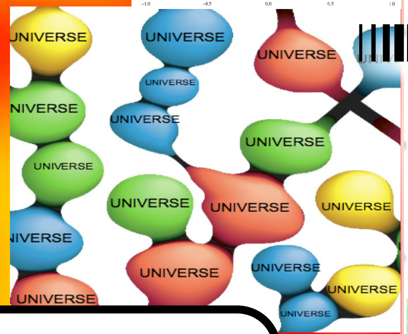
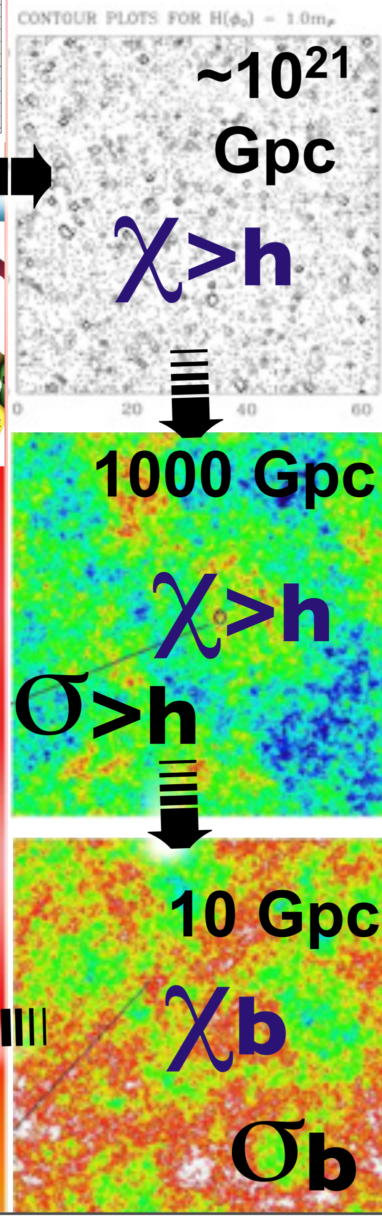




$S_{U,uuUULSS}$



$$\frac{\sigma^2_{>h}}{\sigma^2_b} \sim \frac{\ln(k_h/k_{uuUULSS})}{\ln(k_b/k_h)}$$

~ 5 ? => a "*landscape*" of $\chi_{>h}$

marginalize σ_{HF}

over ~50 e-folds of HF structure

χ_{HF}

BFHK *PRL09* => ***B^2FH11-12-13, $B^2$13, B^2M13***

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isocon

$\chi(\mathbf{x})$

or

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

or..

ϕ

inflaton

pre-heating patch (~1cm)

$S_{U,m+r}$

~$10^{88.6}$

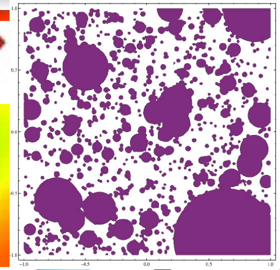
$$\frac{\sigma^2_{>h}}{\sigma^2_b} \sim \frac{\ln(k_h/k_{uuUULSS})}{\ln(k_b/k_h)}$$

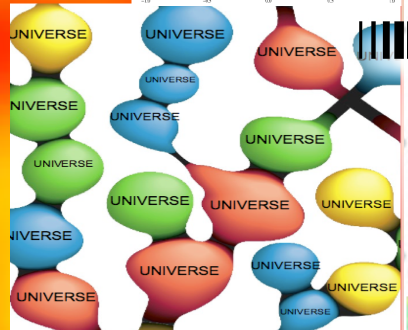
~ 5 ? => a "*landscape*" of $g_{>h}$

marginalize σ_{HF}

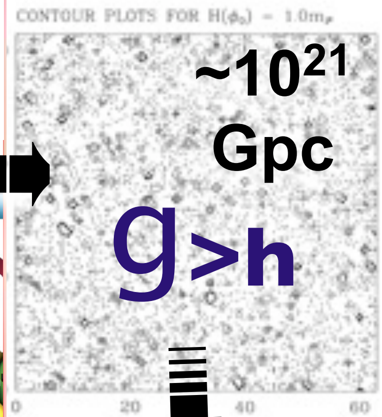
over ~50 e-folds of HF structure

g_{HF}



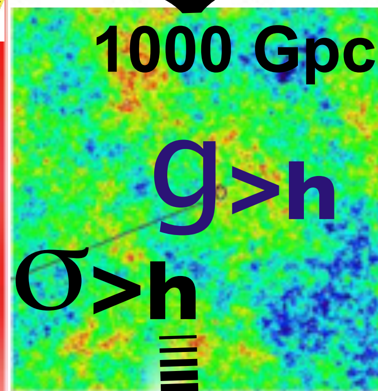


$S_{U,uuUULSS}$



~10^{21} Gpc

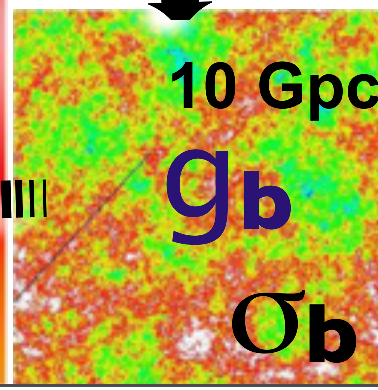
$g_{>h}$



1000 Gpc

$g_{>h}$

$\sigma_{>h}$



10 Gpc

g_b

σ_b

BFHK** PRL09 => **B^{2}FH11-12-13, B^{2}13, B^{2}M13

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isocon

χ**(x)**

or

g(σ(**x**))

or..

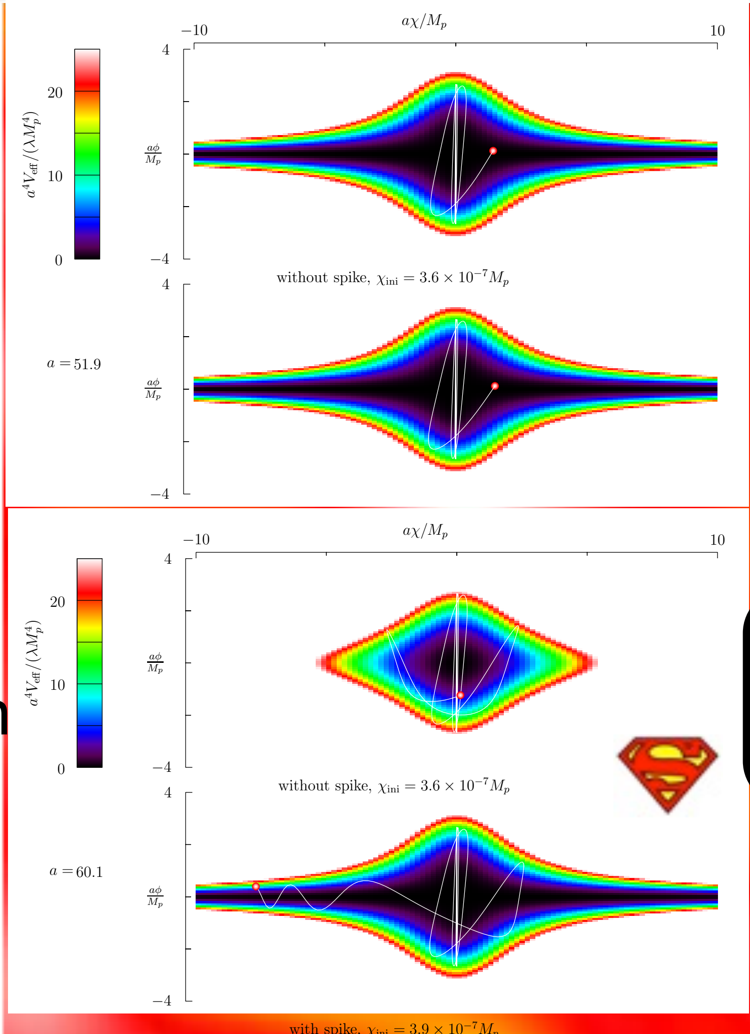
ϕ

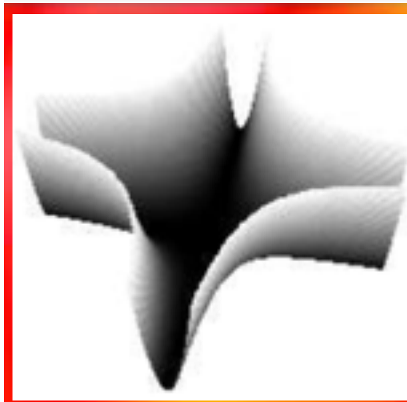
inflaton

pre-heating patch (~1cm)

$S_{U,m+r}$

~$10^{88.6}$

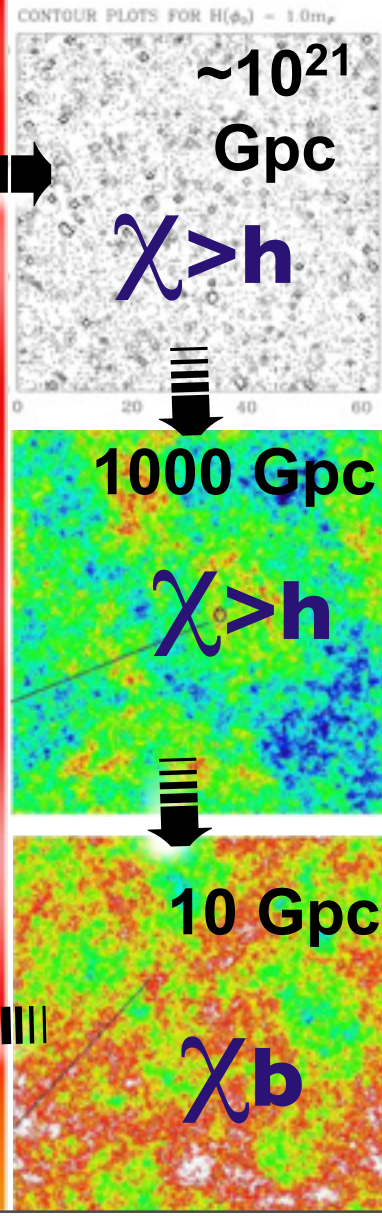




Parametric Resonance

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

$S_{U,uuUULSS}$



~10^{21} Gpc

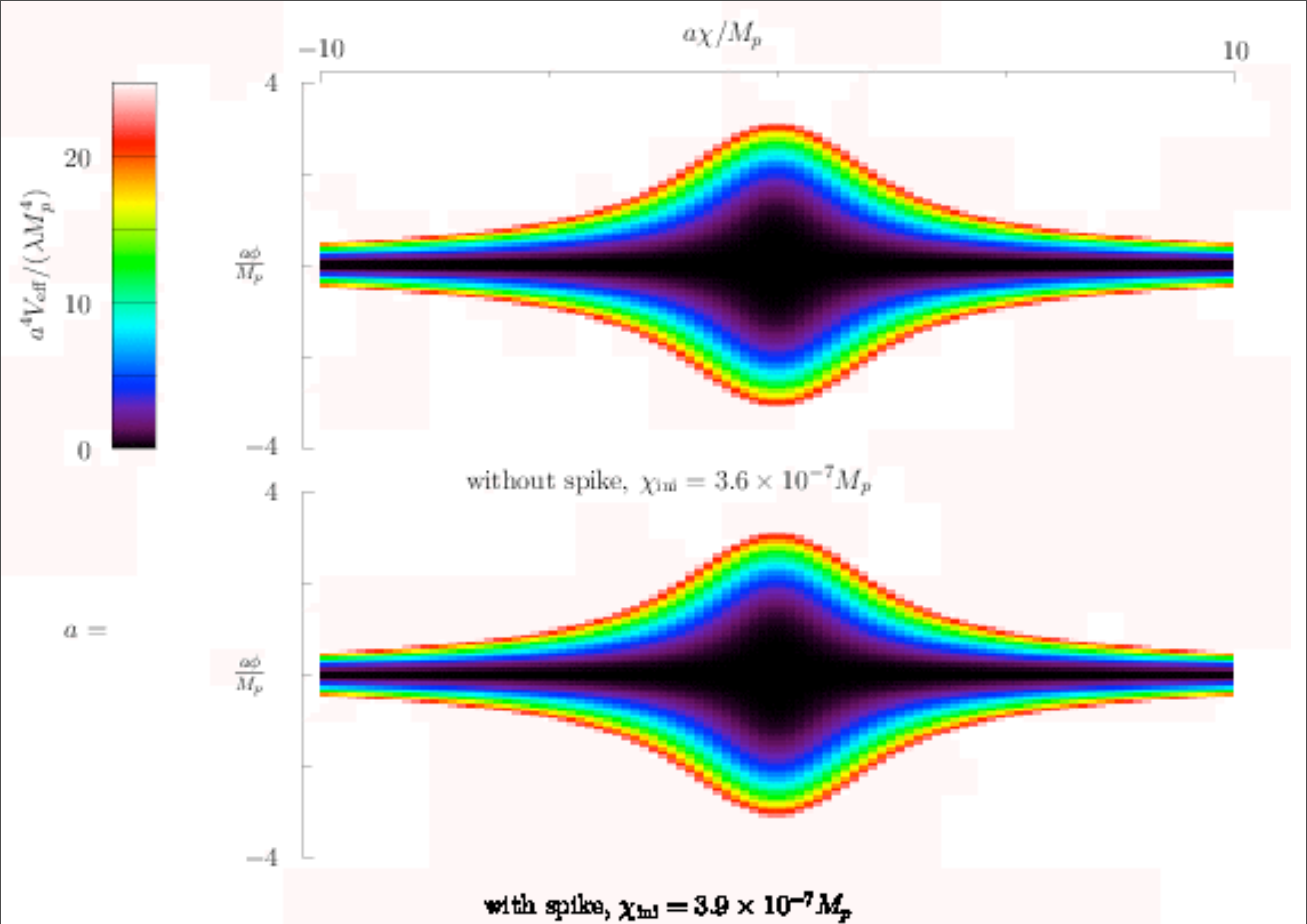
χ**>h**

1000 Gpc

χ**>h**

10 Gpc

χ**b**



V_{eff} is trajectory dependent

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

isocon

χ(**x**)

or

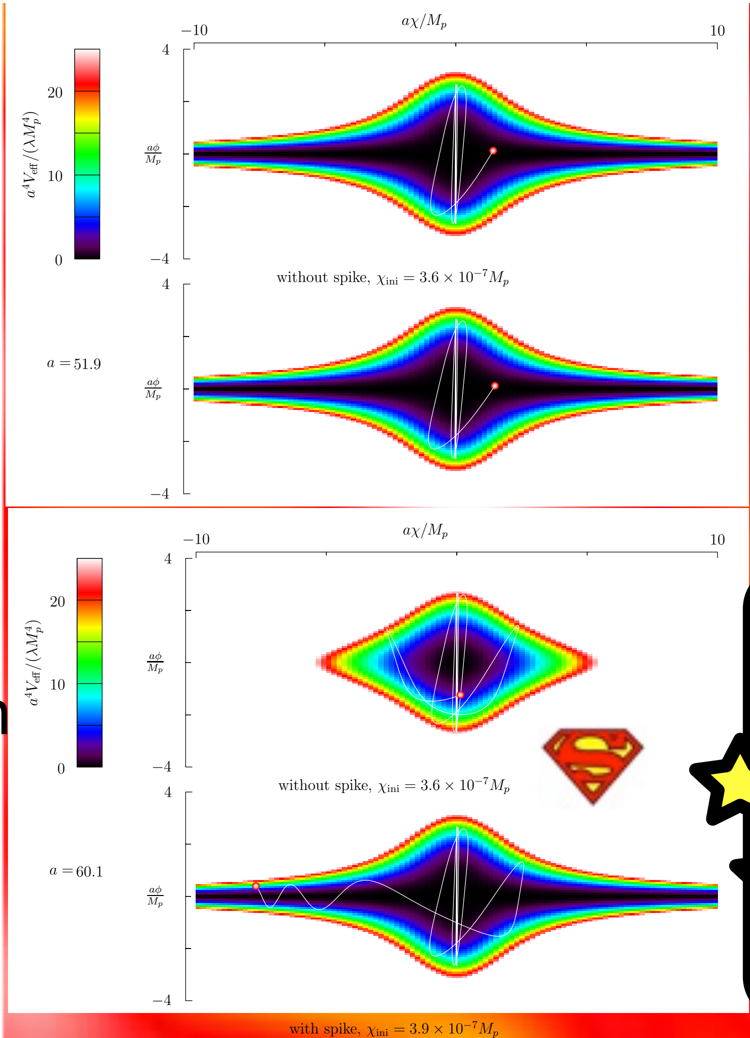
g(σ(**x**))

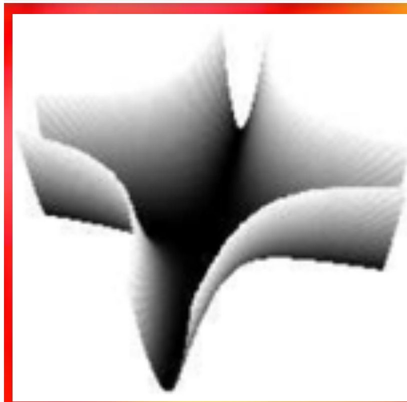
or..

ϕ

inflaton

pre-heating patch (~1cm)





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

$V(\phi,\chi)$

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

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

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

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

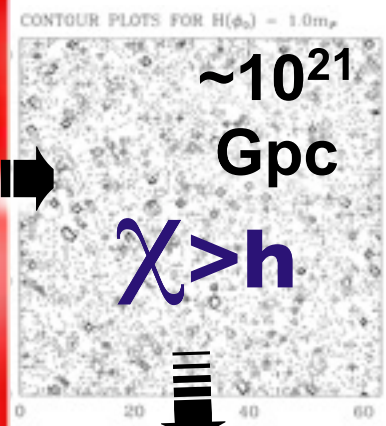
$V(r,\theta) = \sum_M V_M(r) \cos(m\theta)$ *pNGB, Roulette r~hole size*

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

$S_{U,m+r}$

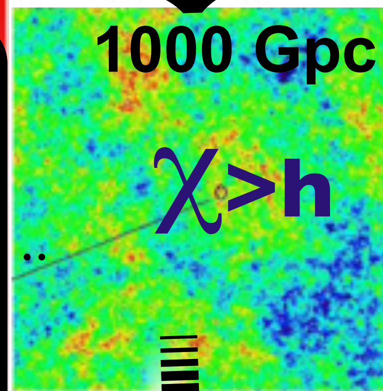
$\sim 10^{88.6}$

$S_{U,uuUULSS}$



$\sim 10^{21}$ Gpc

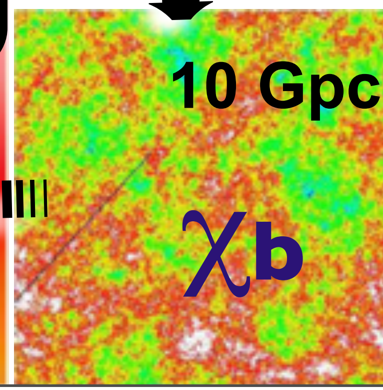
χ>h



1000 Gpc

χ>h

..



10 Gpc

χb

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isocon

$\chi(\mathbf{x})$

or

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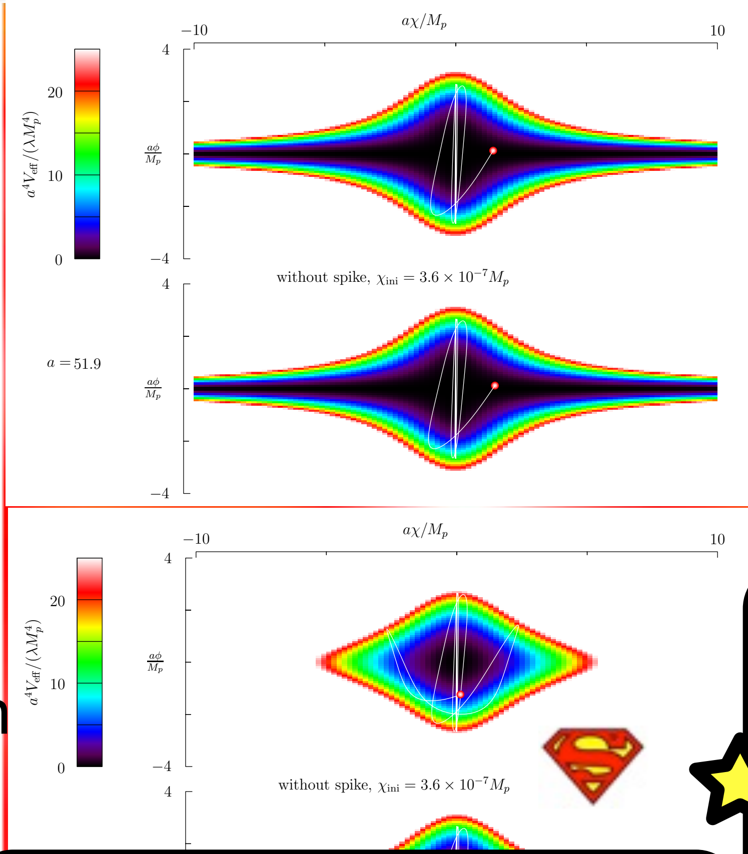
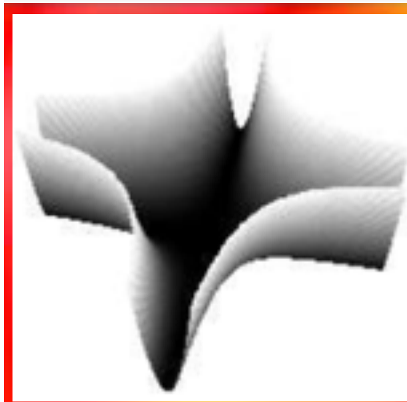
or..

ϕ

inflaton

pre-heating patch (~1cm)





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

$$V(\phi,\chi)$$

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

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

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

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

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

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

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

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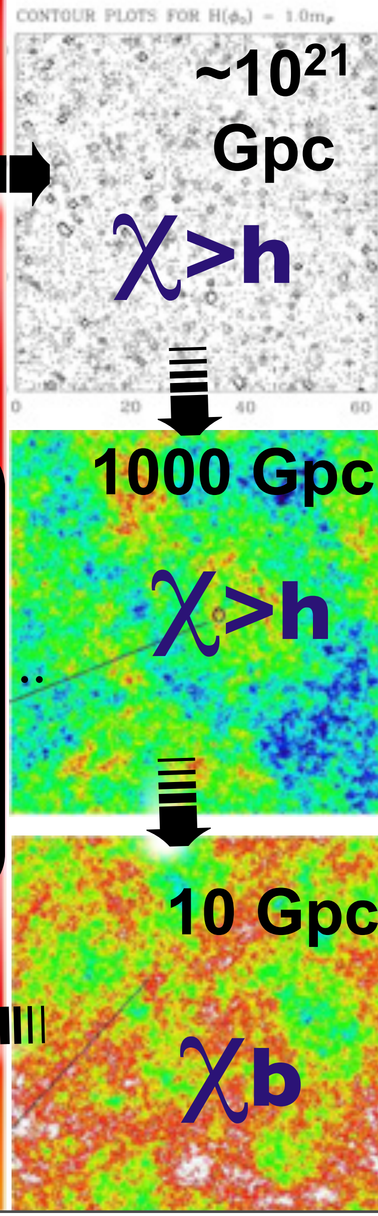

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isocon

χ(**x**)

or

g(σ(**x**))

or..

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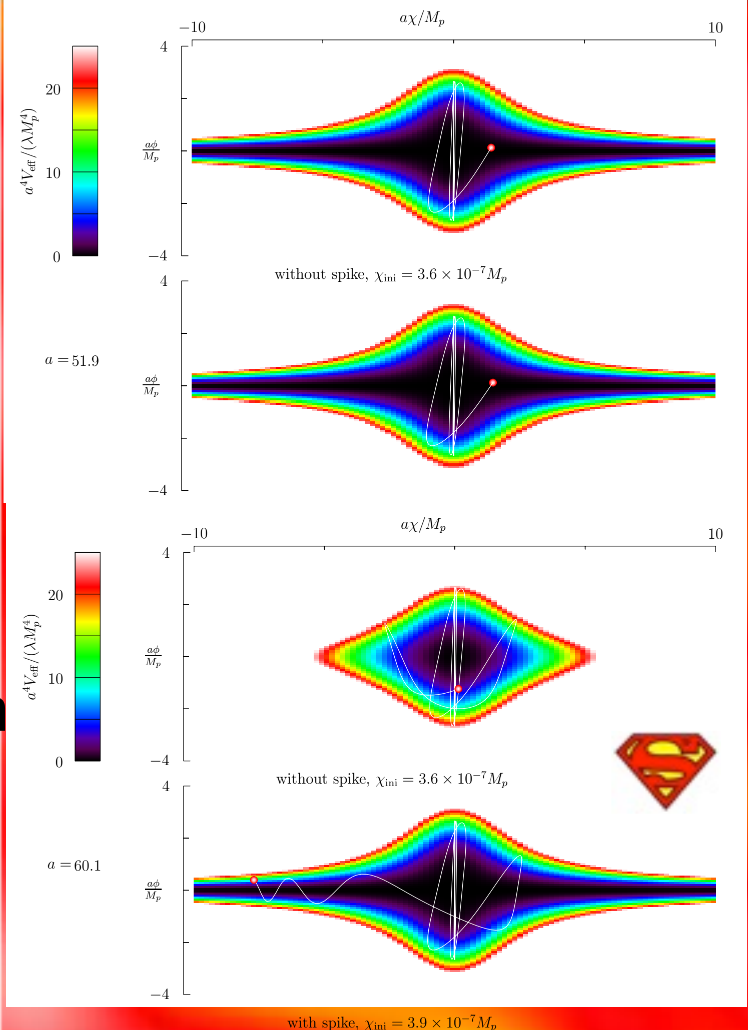
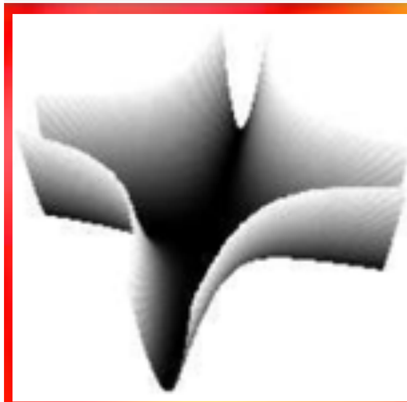
pre-heating patch (~1cm)





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

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

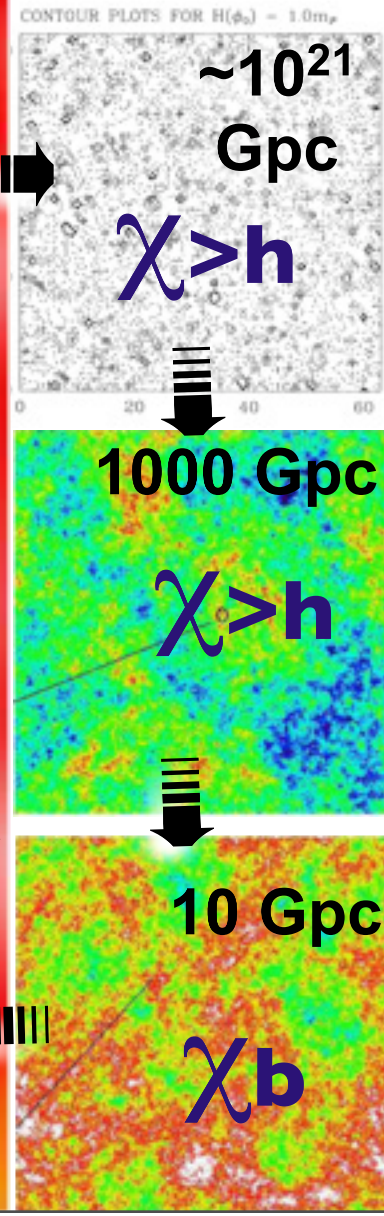
$\mathbf{V(r,\theta)= \sum_M V_M(r)\cos(m\theta)}$ ***pNGB, Roulette r~hole size***

3D φ χ σ fields $\mathbf{V(r,n)= \sum_{LM} V_{LM}(r) Y_{LM}(n)}$

$\mathbf{S_{U,m+r}}$

$\mathbf{\sim 10^{88.6}}$

$\mathrm{S_{U,uuUULSS}}$



Inflation = phenomenology of a collective mode, the phonon, fundamental field but composed of many *fundamental* **fields. in linear theory phonon~∑** *fundamental;*

in nonlinear theory, **phonon~** $\ln(\rho\, a^{3(1+w)})/3(1+w)=\zeta_{NL}$

Geometrical view, a theory of condensed strain & strain waves $\varepsilon_{ij}=[1/2 \ln^{(3)} g]_{ij}$**, phonons~Trace (ε), gravity waves** ε^{TT}**.**

Inflaton = phonon condensate, fluctuations are phonons. *relativistic negative-pressure EOS.*

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 X).**

fundamental **scalar fields (inflaton, isocons) & effective potentials & kinetic energies**

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

HEATING: how to damp coherent ballistic trajectories into high-k entropy. old, *eg SBB87* **Γ (KE+PE). still used! post KLS93: via inflaton self-couplings; isocon-inflaton field couplings, gauge fields FFdual, fermion-bar fermion**

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 $\zeta_{NL}(\text{modulator}(x))$**, e.g. modulator =** $\chi_i(x)$, $g(x)$

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

for caustics and other features in the varieties of effective potentials, extra field dimensions seem to be needed

post-shock $\Rightarrow$ conserved energy-momentum current defines important collective variables => total stress-energy $T^a{}_b$ => density

the shock-in-time = randomization front, an efficient entropy source

nearly Gaussian PDF for $\ln \rho_x / \langle\rho\rangle$ $\ln \rho/\langle\rho\rangle(k)$ **& V hydro/phonon regime.**

Observable preheating nongaussianities can be encoded in the spatial structure

of the shock-in-time, characterized by $\ln\, a_{shock}(x)/a_{end}$ &

the mediation width. ~ $\ln\, a_{final}(x)/a_{end}$

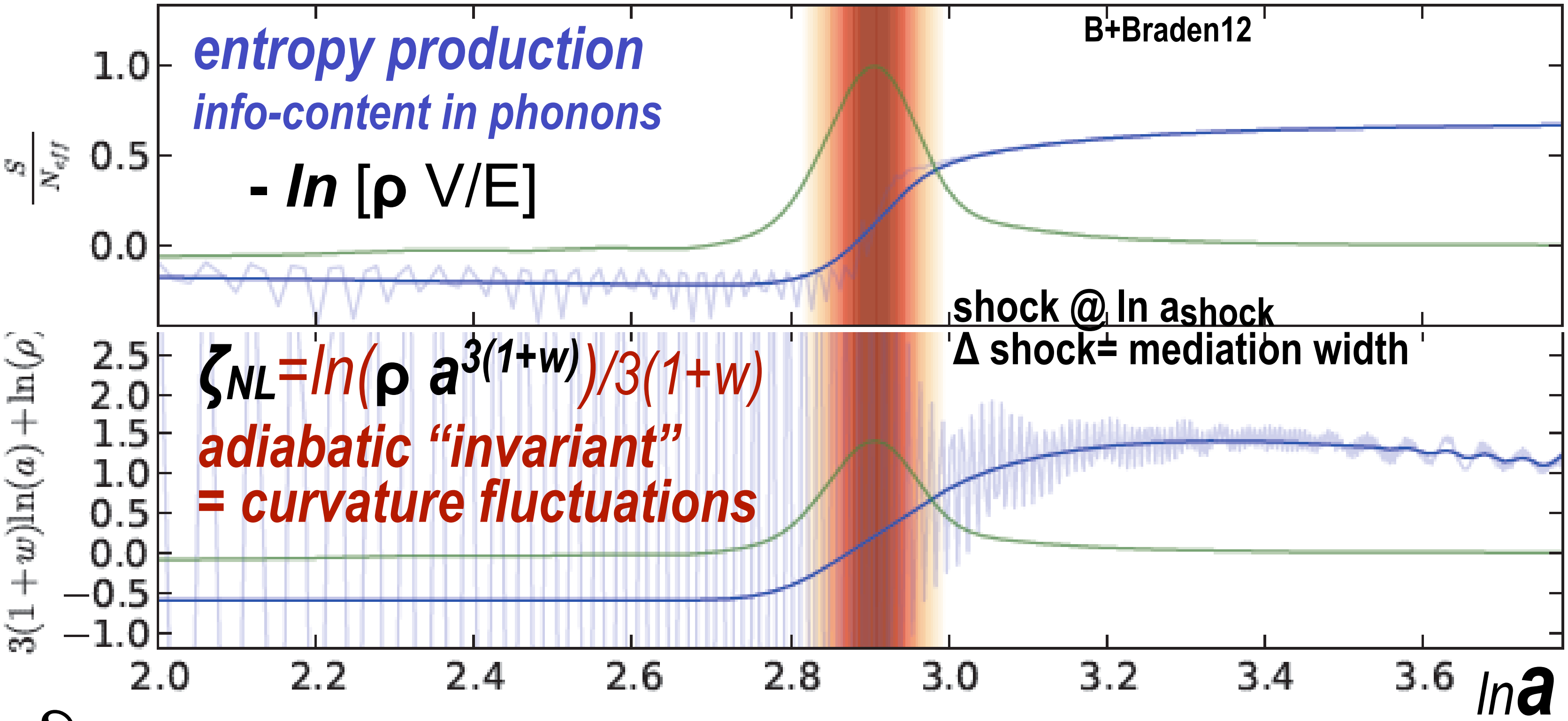
entangled primary fields $(\varphi, \Pi_\varphi, \chi, \Pi_\chi)$ **=>** ***not good post-shock descriptors***

Final State = Thermal Equilibrium

= maximum spreading of information in modes subject to energy & particle number constraints.

How to couple to standard model degrees of freedom *to accelerate the power spectrum evolution to a thermal bose-einstein distribution function?*

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



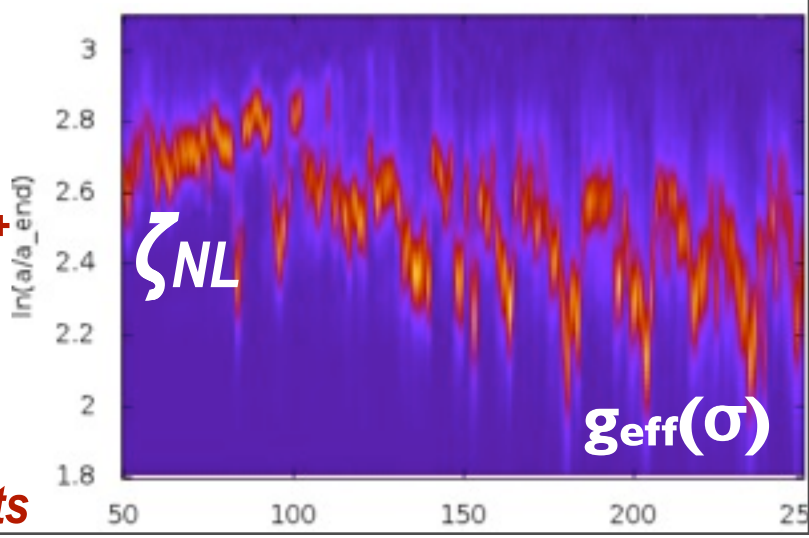
true thermal equilibrium far off ➤ & on to coupling to standard model degrees of freedom

$\delta\zeta_{NL\mathrm{shock}}\,(\mathbf{g}(\sigma(\mathbf{x}))$ => modulated non-G

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

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

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

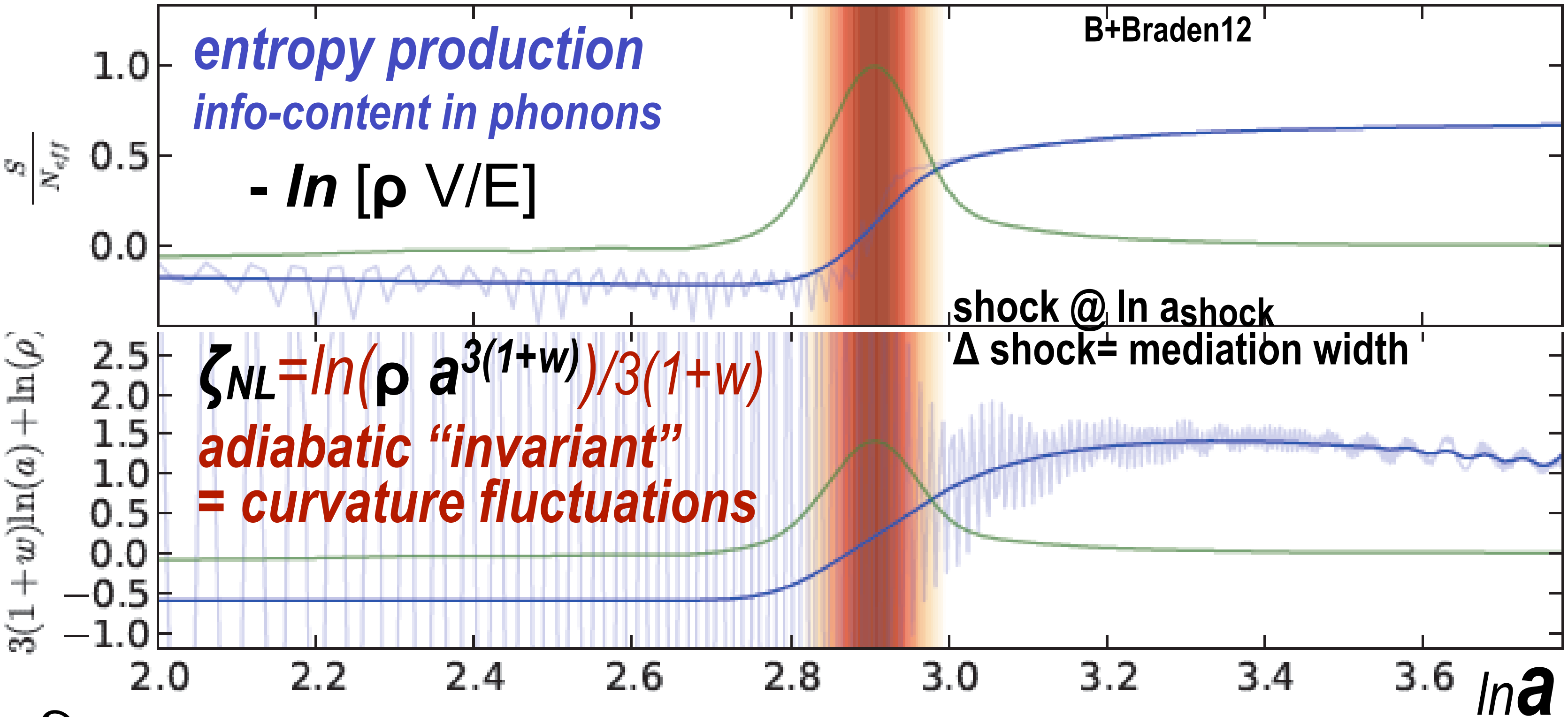


V_{eff} is dynamical *Bond,Braden,Frolov,Huang13*

unconventional local non-G: no scale built into V;

perturbative isocon-based f_{NL}; rare event cold spots

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

$\delta\zeta_{NLshock}$ ($\mathbf{g}(\sigma(\mathbf{x}))$ => 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 ++*

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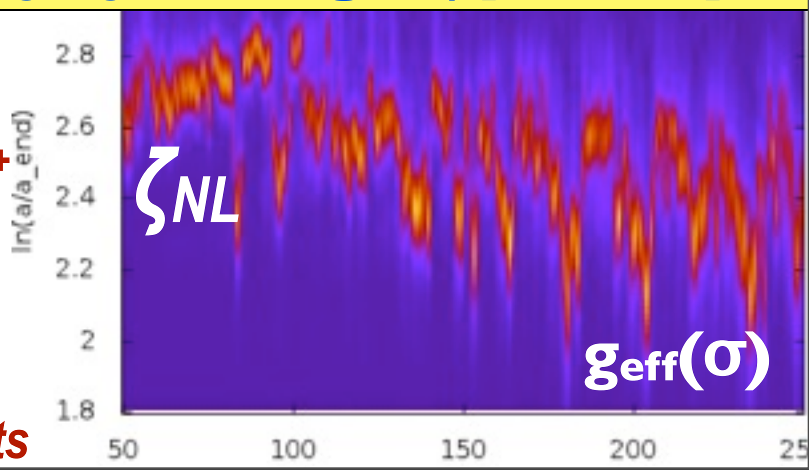

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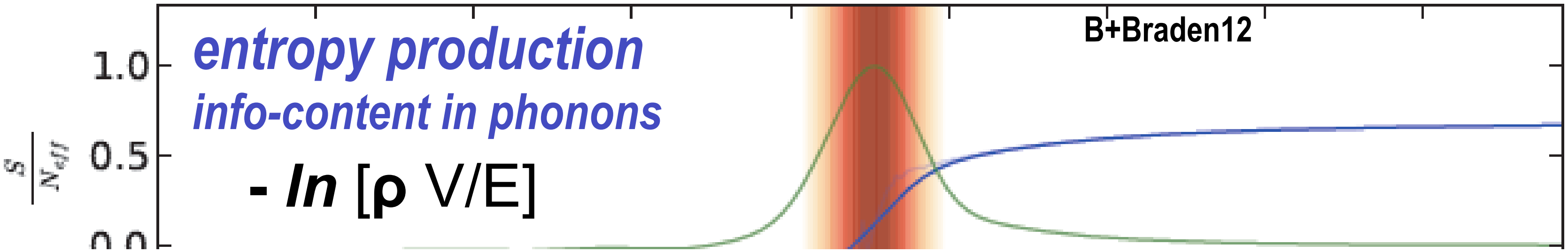
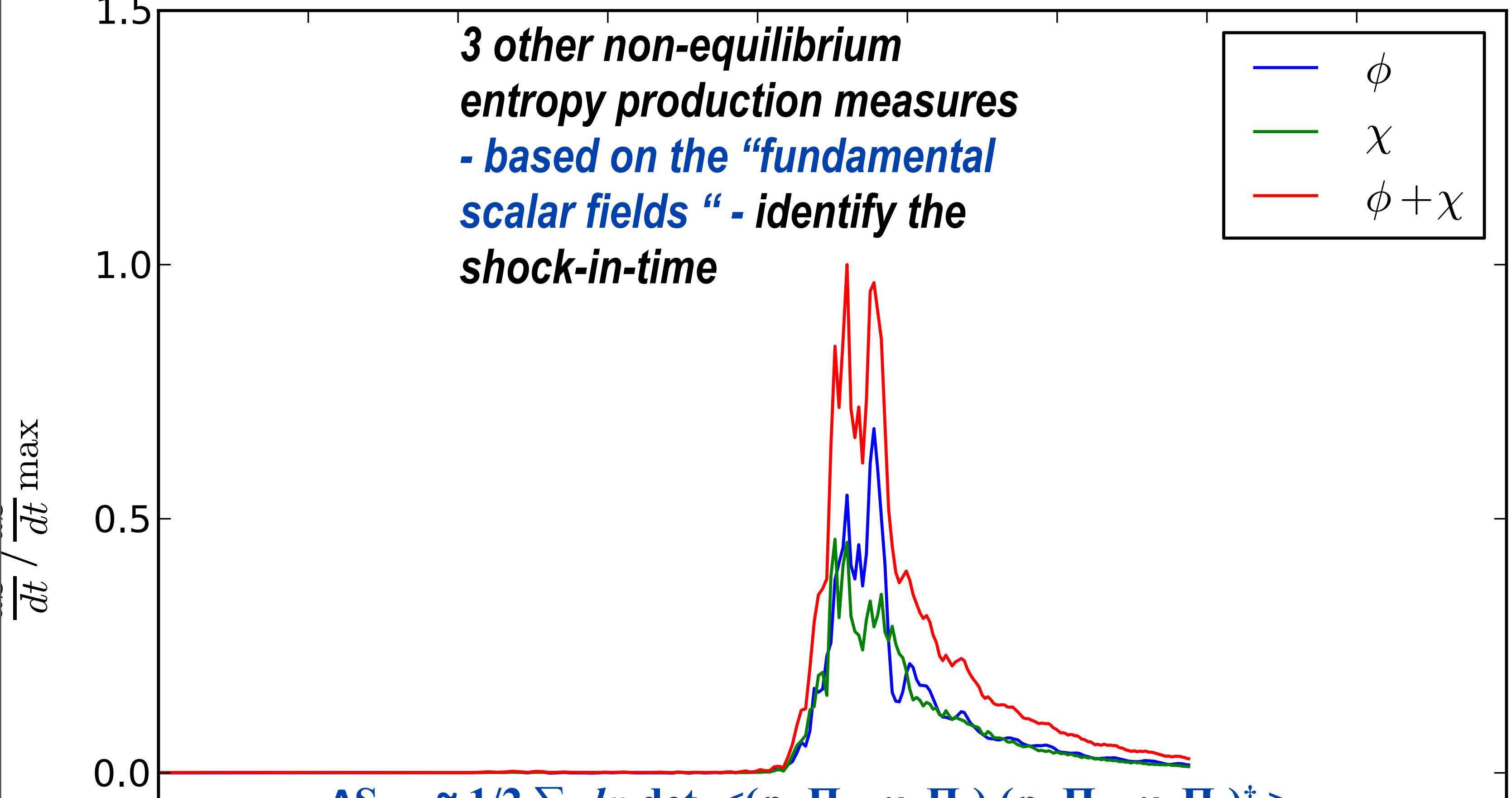


true thermal equilibrium far off ➤

to

of



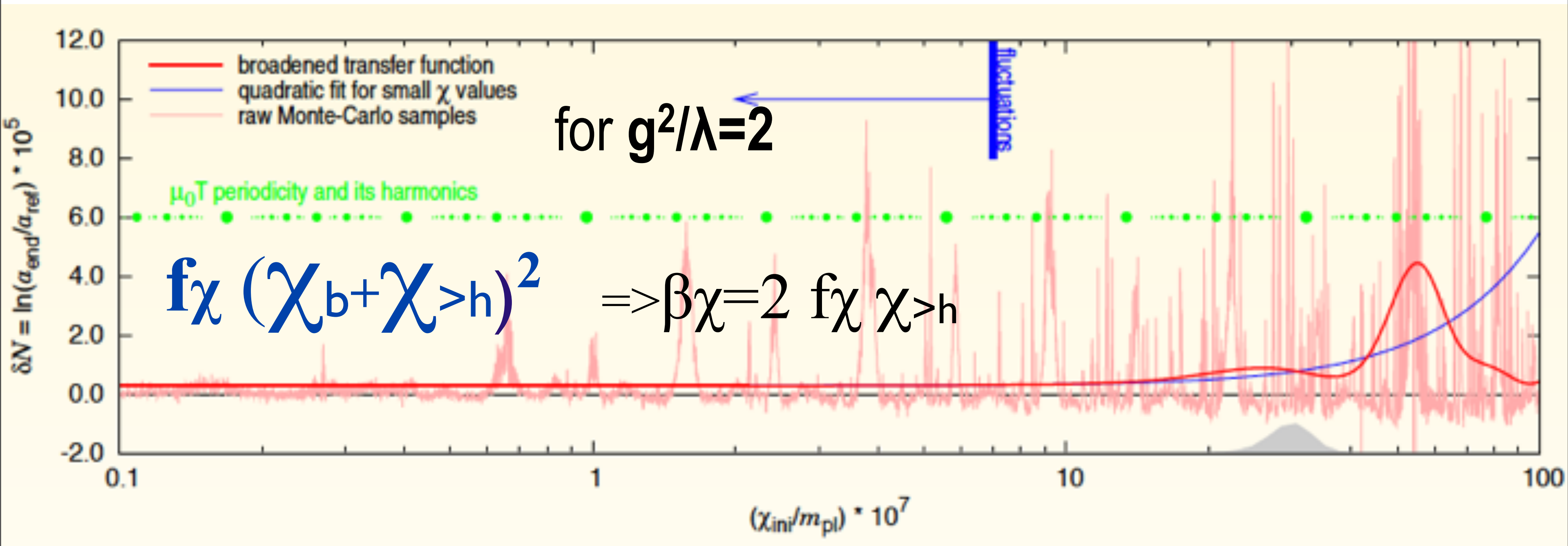
$\Delta S_{\varphi+\chi} \sim 1/2 \sum_k \ln \det \langle(\varphi, \Pi_\varphi, \chi, \Pi_\chi)(\varphi, \Pi_\varphi, \chi, \Pi_\chi)^\dagger\rangle$

field smoothing over χ_{HF} over ~50 e-folds of HF structure

$$\langle F_{NL} | \chi_b + \chi_{>h} \rangle \sim \beta_\chi(\chi_{>h})\, \chi_b + f_\chi(\chi_{>h})\, \chi_b^2 + \ldots$$

cf. $F(x) = F_G(x) + f_{NL*}\, F_G^2(x)$

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



for $g^2/\lambda=2$

$f_\chi\, (\chi_b + \chi_{>h})^2 \quad \Rightarrow \beta_\chi = 2\, f_\chi\, \chi_{>h}$

$f_{NL}^{equiv} = \beta_\chi^2 f_\chi\, [P_\chi/P_\phi]^2 (k_{pivot})$ Local $f_{NL}=2.7 \pm 5.8$ Planck1.3

$\Rightarrow$ constrain $f_\chi^3\, \chi_{>h}^2$ ($P_\chi/P_\phi \sim 2\varepsilon \Rightarrow$ ***relaxed limit***)

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

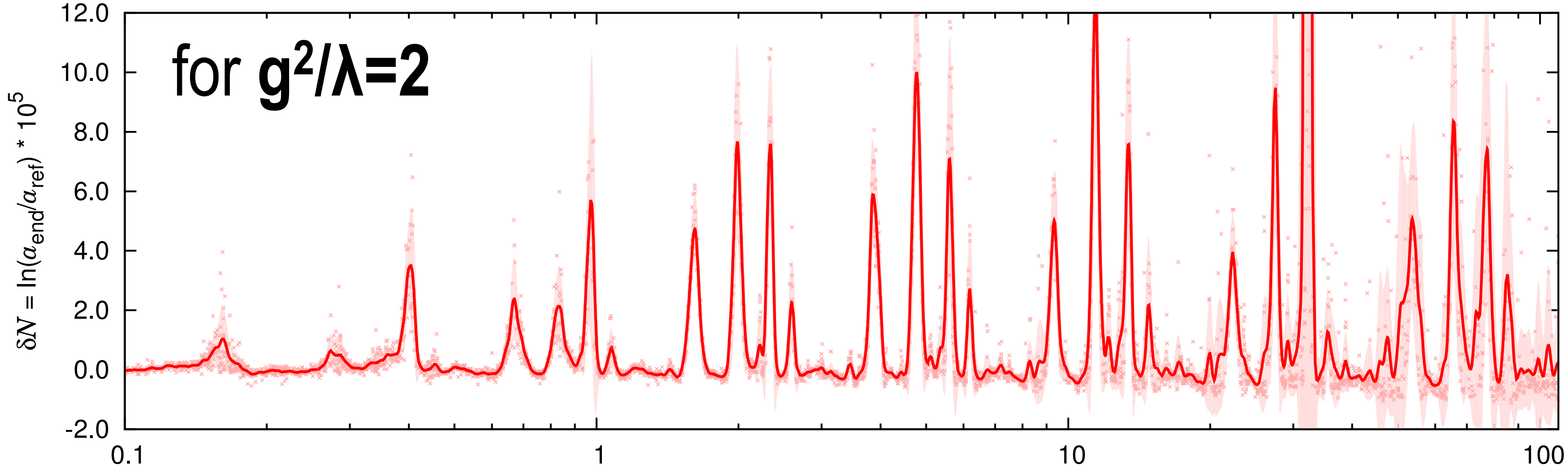
non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

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

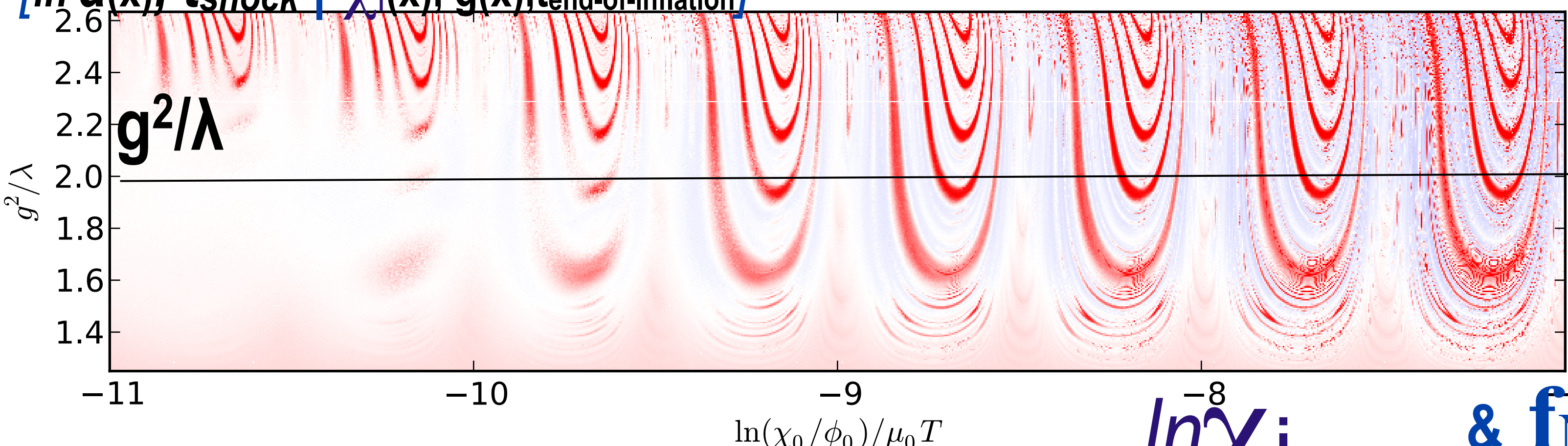
B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 12

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

*ln*a

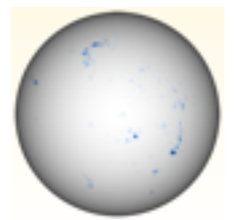


$P[\ln a(x),\ t_{shock} \mid \chi_i(x),\ g(x), t_{end\text{-}of\text{-}inflation}]$



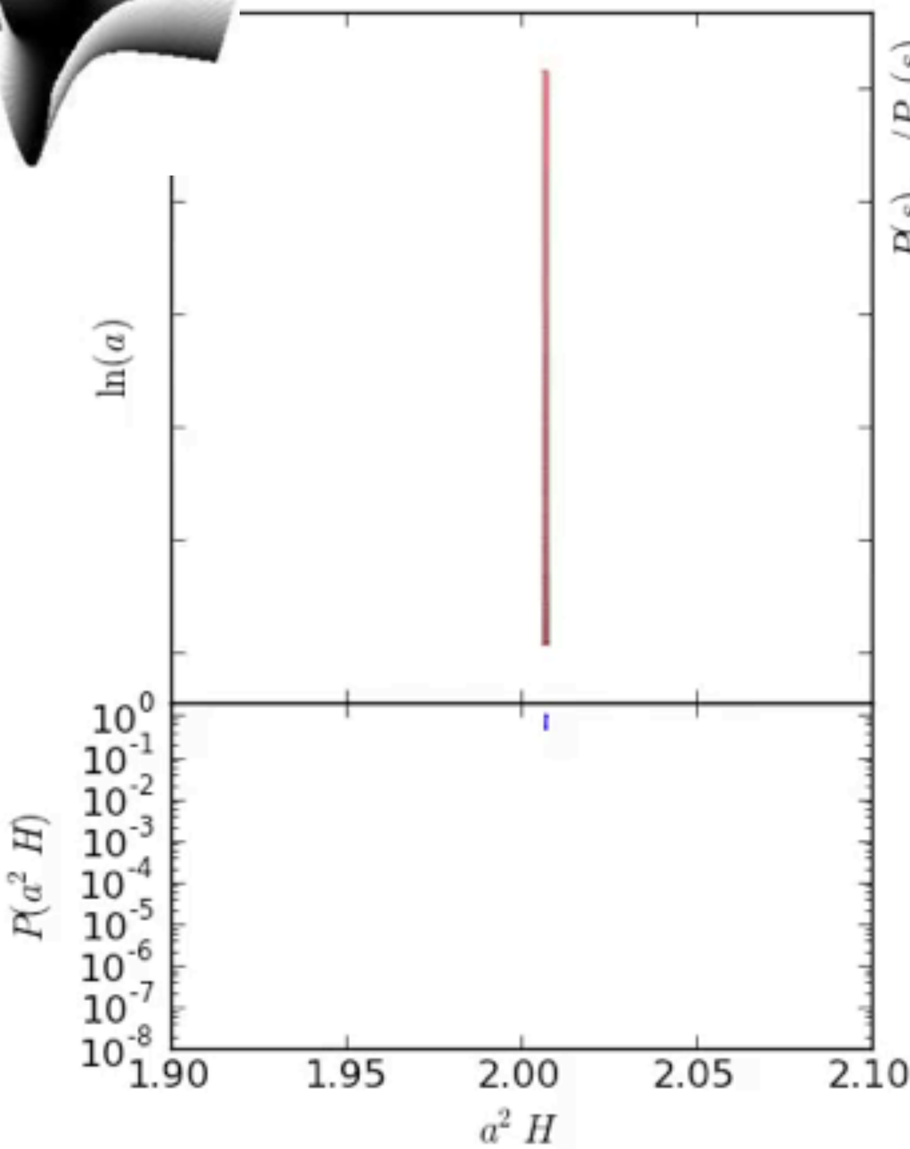
*ln*χi

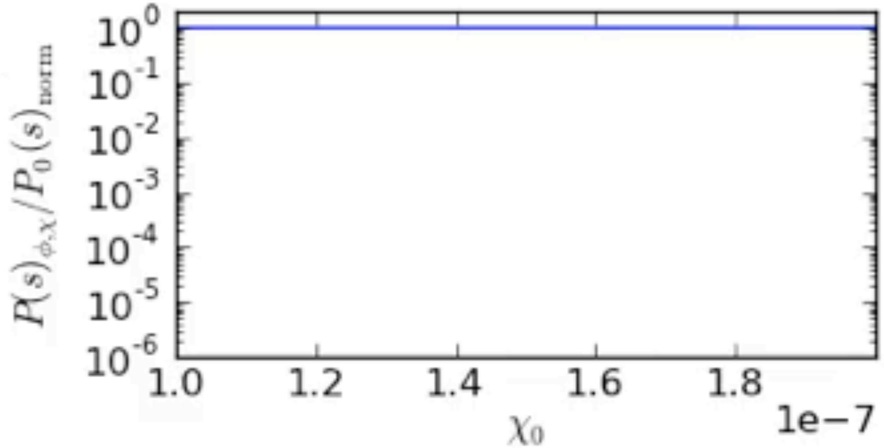
huge number of
64^3 ***sims to show the wondrous complexity of***
*ln*a(χi,g²/λ)

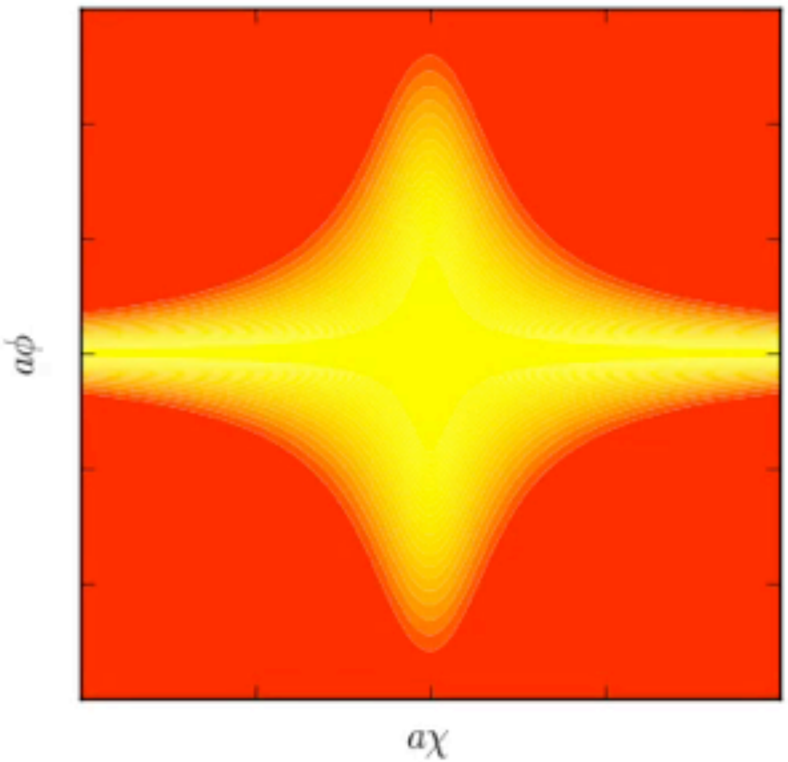


& f_{NL}^{equiv}

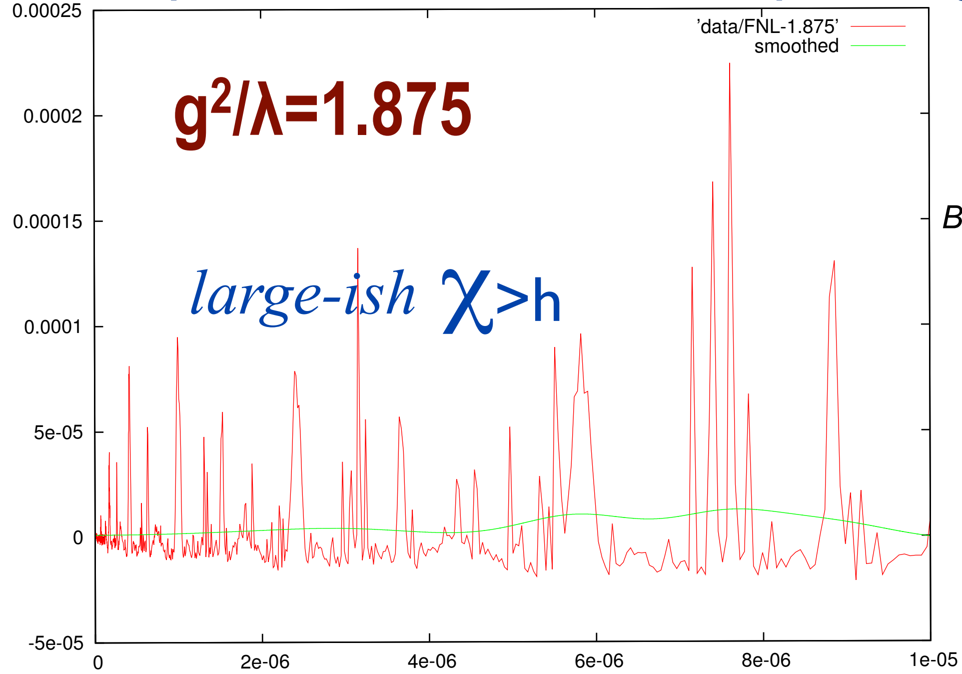
initial conditions spanning (roughly) a single period (ie. \mu_o T with \mu_0 the Floquet exponent of chi_0

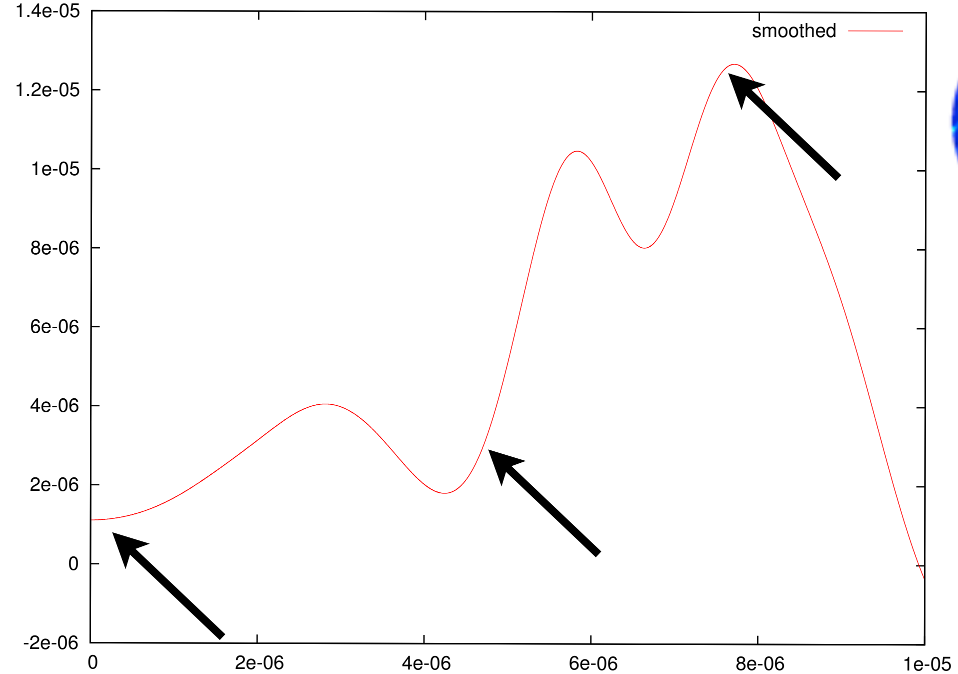






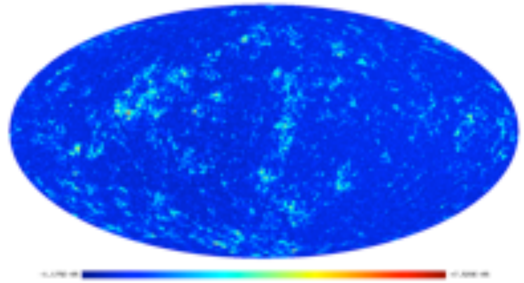
Samples of subdominant modulated preheating CMB*$\zeta_{NLshock}(\chi_i(x) \,|g^2/\lambda))$

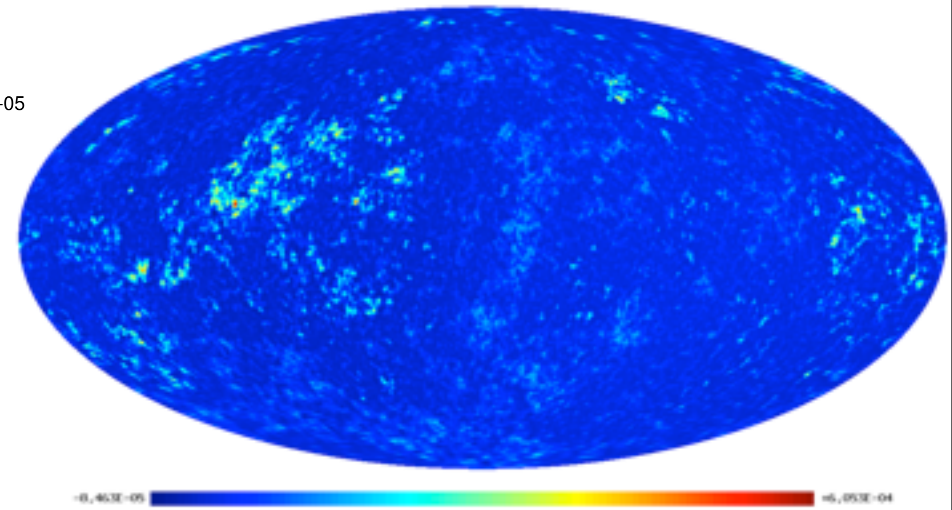


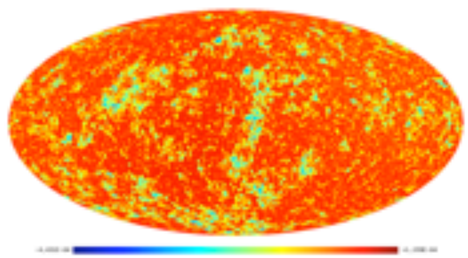


intermittent NL isocon χ map to be superposed upon nearly Gaussian inflaton-generated curvature fluctuation map

Bond,Frolov,Huang, Kofman09 => Bond,Braden,Frolov,Huang13



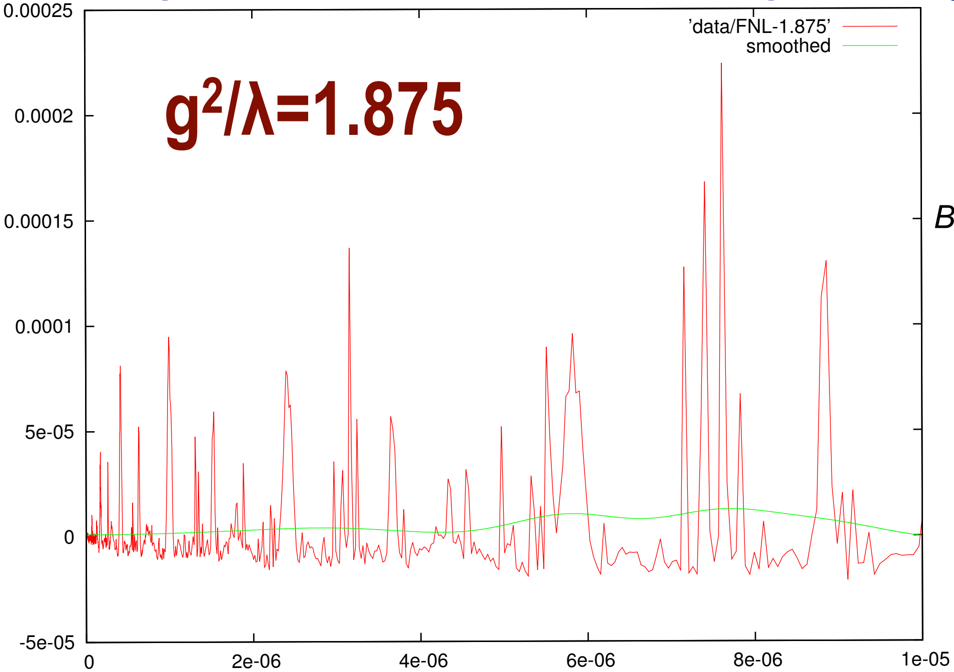


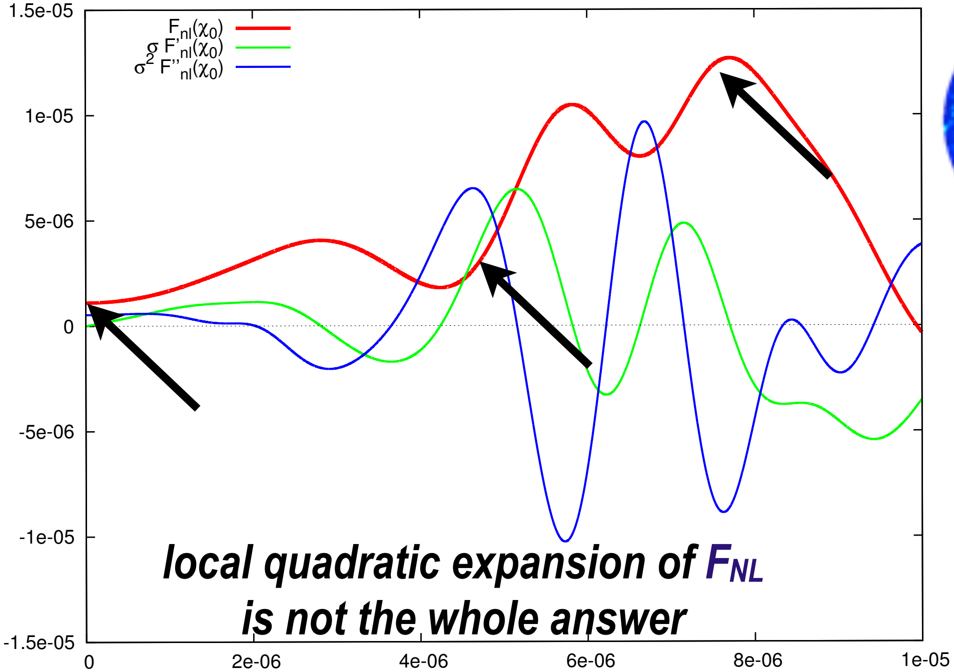


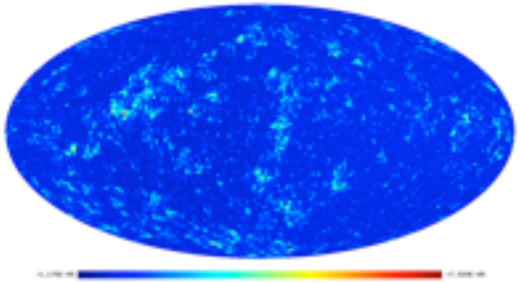
Samples of subdominant modulated preheating CMB $\cdot\zeta_{NLshock}(\chi_i(x)\,|g^2/\lambda)$

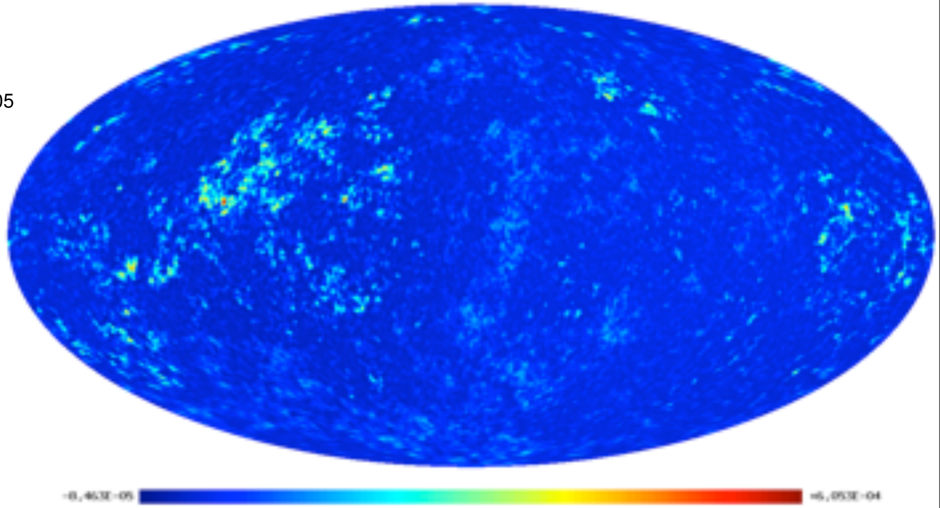
intermittent NL isocon χ map to be superposed upon nearly Gaussian inflaton-generated curvature fluctuation map

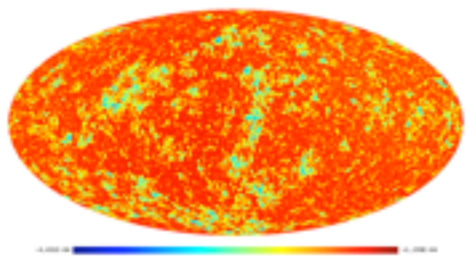
Bond,Frolov,Huang, Kofman09 => Bond,Braden,Frolov,Huang13











conclusions:

nothing definitive *yet* for anomalies, may just lead to potential & >horizon constraints

but amusing patterns do arise