Random Fields in Early Universe Cosmology

Dick Bond @
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique
25 years cifar

What was the Universe made of & how was it distributed?

Are there primordial non-Gaussian compenents - subdominant inflation-induced, preheating - induced or cosmic-string induced?

THEN: coherent inflaton /**"vacuum" energy +** **zero-point fluctuations** in all fields (*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium soup

very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic
$V_{eff}(\psi_{inf})$?
$K_{eff}(\psi_{inf})$?
trajectory probability

baryogenesis dark matter BBN γdec **dark energy**
$V_{eff}(\psi_{inf})$?
$K_{eff}(\psi_{inf})$?

$-d\ln\rho_{tot}/d\ln a\ /2$
$=\varepsilon(k)=1+q,\ k\sim Ha$

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de}\sim H^2M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

mid 80s + ~ Chaotic inflation $\lambda\phi^4$, $m^2\phi^2$; 90s cos(ϕ/f)

INFLATION

Inflaton Drifts & stochastic kicks@k=Ha ⇒ structure (x,t)

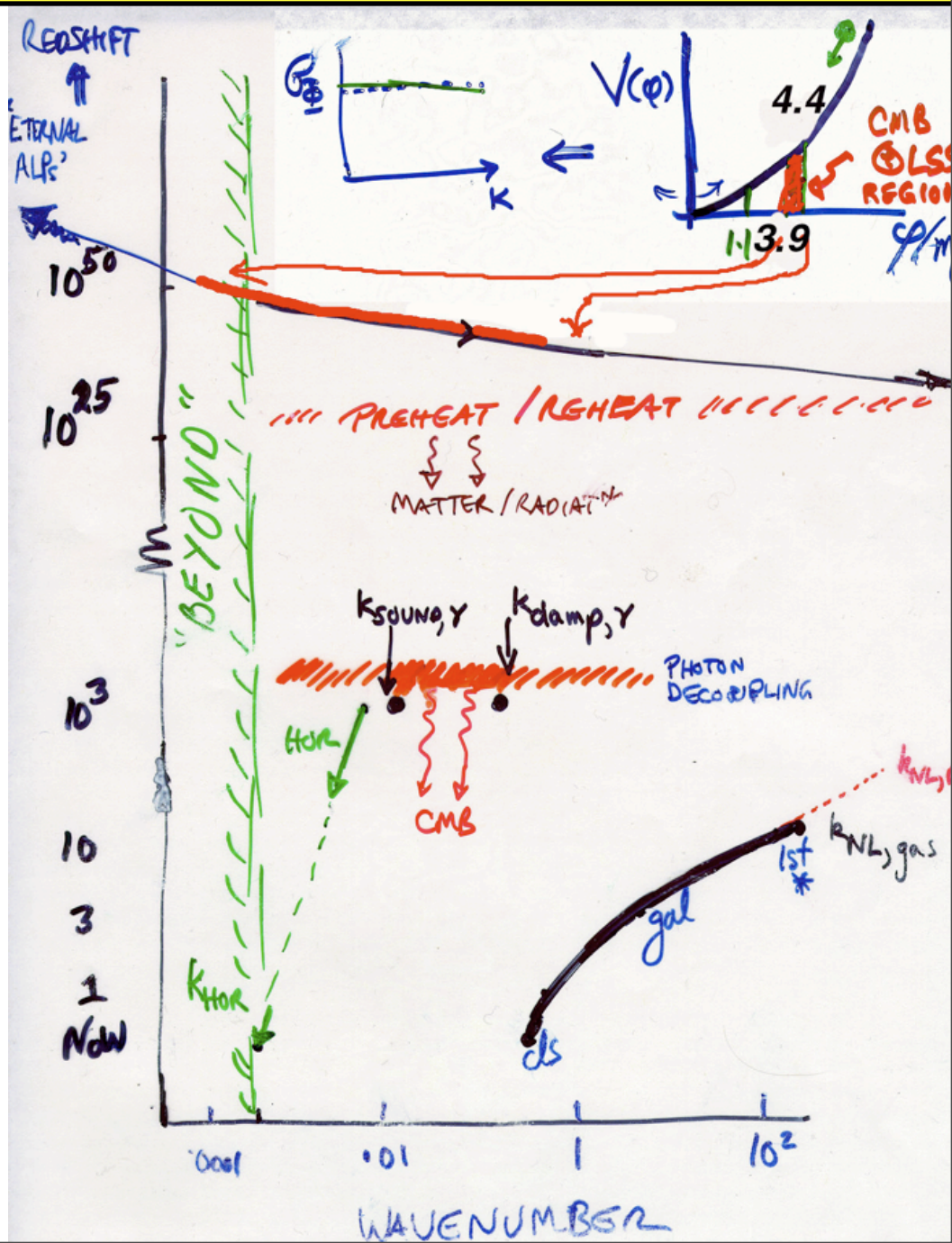
our Hubble patch: smooth + Gaussian fluctuations observable scales are a narrow window on potential surface ⇒

featureless (?) P_Φ & P_{GW}

UUU...ULSS:

non-Gaussian "eternal alps"

a veryVERYBIG U



Old view: Theory prior = delta function of THE correct one and only theory

New: Theory prior = probability distribution of late-flows on an energy LANDSCAPE

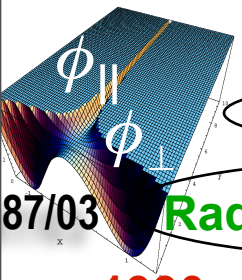
6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation



New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03 Radical BSI inflation

variable M_P inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

SUSY F-term inflation

SUSY D-term inflation

Assisted inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

2003 KKLT

N-flation

ekpyrotic/ cyclic

D3,D7 brane inflation

DBI inflation

moving brane separations

Warped Brane inflation

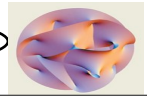
Tachyon inflation

Racetrack inflation

moduli fields

monodromy

Roulette inflation Kahler moduli/axion



Old view: Theory prior = delta function of THE correct one and only theory

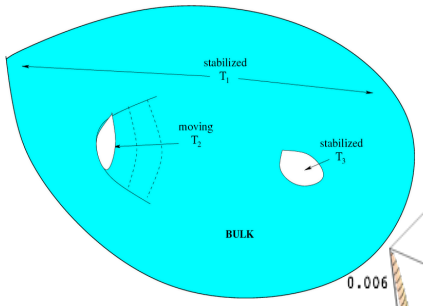
New view: Theory prior = probability distribution on an energy landscape whose features are at best only glimpsed,

huge number of potential minima, inflation the late stage flow in the low energy structure toward these minima. Critical role of collective coordinates in the low energy landscape:

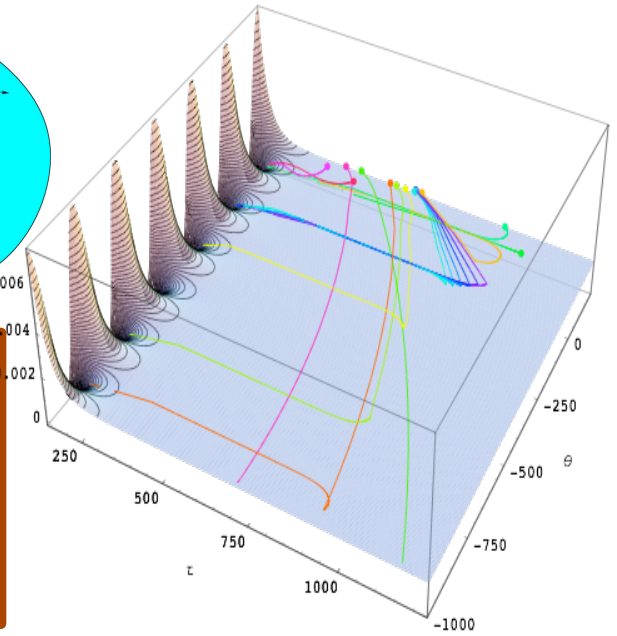
moving brane/antibrane separations (D3,D7) moduli fields, sizes and shapes of geometrical structures such as holes in a dynamical extra-dimensional (6D) manifold approaching stabilization

Roulette inflation Kahler moduli/axion

The 'house' does not just play dice with the world.



{Number of Efolds:, 29, 211, 4, 12, 2, 285, 105, 8, 11, 18, 30, 53, 106, 0, 0, 0



theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial conditions

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

1+w0, wa

$\theta \sim \ell_s^{-1}$

ne(a)

$\sim \ln \sigma_8^2$

primordial non-Gaussianity

$\Phi(x) = \Phi_G(x) + f_{NL} (\Phi_G^2(x) - \langle\Phi_G^2\rangle)$

local smooth

DBI inflation: non-quadratic kinetic energy
cosmic/fundamental strings/defects
from end-of-inflation & preheating

$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL}\rangle$

resonant preheating

$\ln P_s(\ln k)$ & $r(k_p)$

& $\ln P_t(\ln k)$

+ subdominant isocurvature/ cosmic string/ tSZ ...

INFLATION THEN

PROBES NOW

"standard inflation space": n_s $dn_s/d\ln k$ r @k-pivots

$n_s(kp) = .962 \pm .013$ ($\pm .005$ Planck1) $.959 \pm .011$ all data

$r = P_t/P_s(kp') < 0.40_{cmb}$ 95% CL ($\pm .03$ P1, $\pm .01$ Spider+P2.5)

$dn_s/d\ln k\,(kp) = -.016 \pm .019$ ($\pm .005$ Planck1)

(*partially*) *blind trajectories* e.g., $n_s(k)$ and $r(kp)$, *are better*

local quadratic non-G constraint: $-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$ WMAP5 ($\pm$ 5-10 Planck1yr)

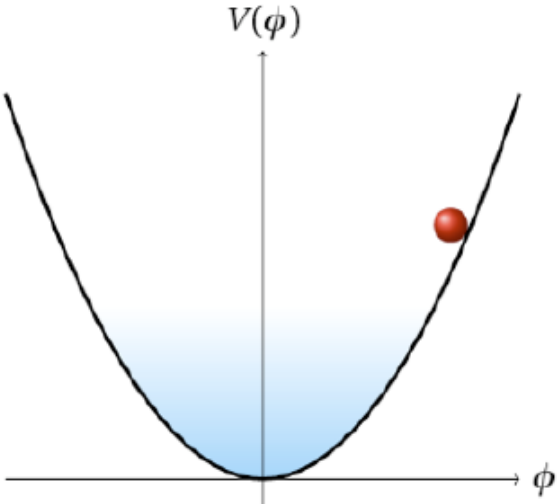
preheating

Parametric resonance

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

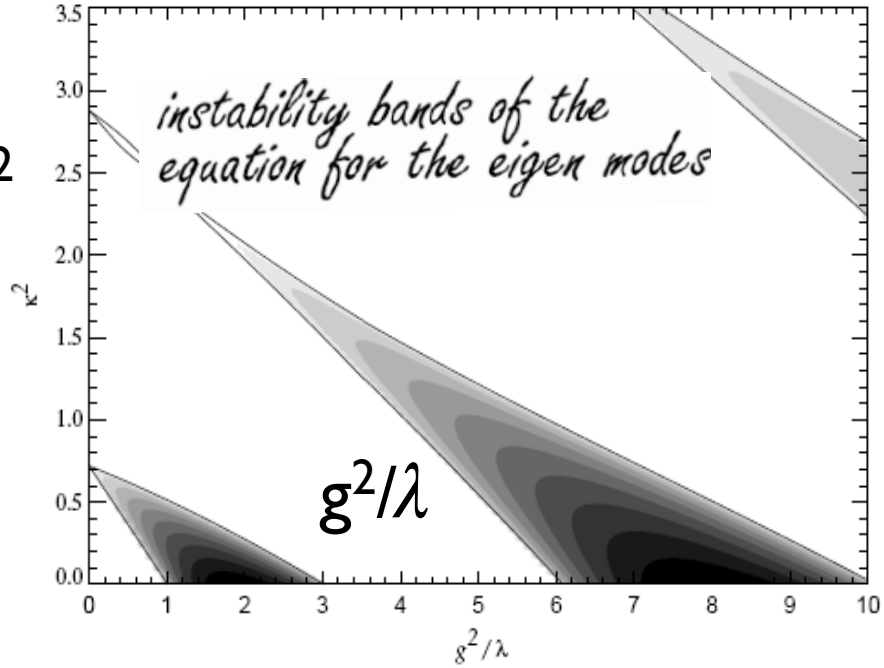
90s Kofman, Linde, Starobinsky, .., Greene, Felder, Frolov, ... 00s

$$\ddot{\chi}_k + 3\frac{\dot{a}}{a}\dot{\chi}_k + \left(\frac{k^2}{a^2} + g^2\phi^2\right)\chi_k = 0$$



The oscillating inflaton modulates the mass of the fields coupled to it, and becomes unstable through parametric resonance.

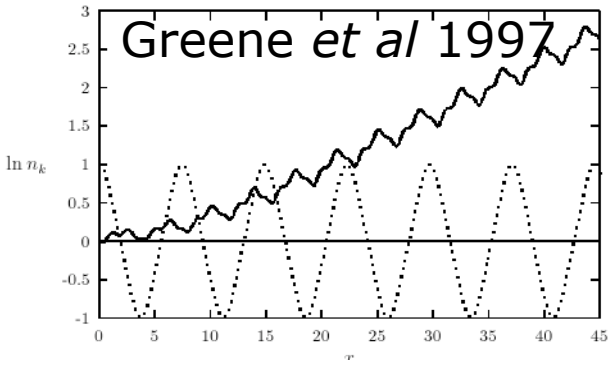
$\sim k^2$



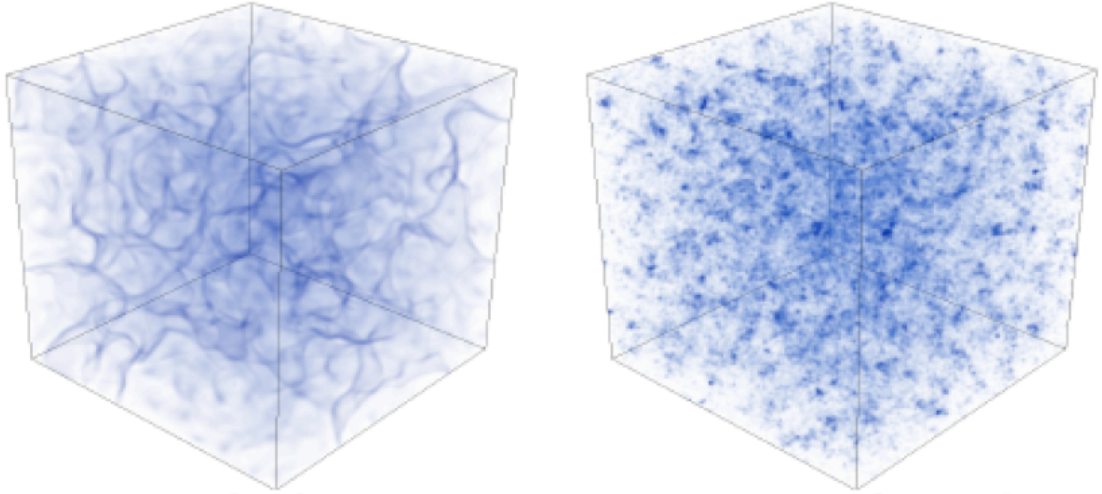
Formation of Structure

Linear instability amplifies seed fluctuations and creates structure; its non-linear evolution looks like LSS but is driven by repulsion!

Frolov 2008 DEFROST code ≈ Felder's LatticeEasy



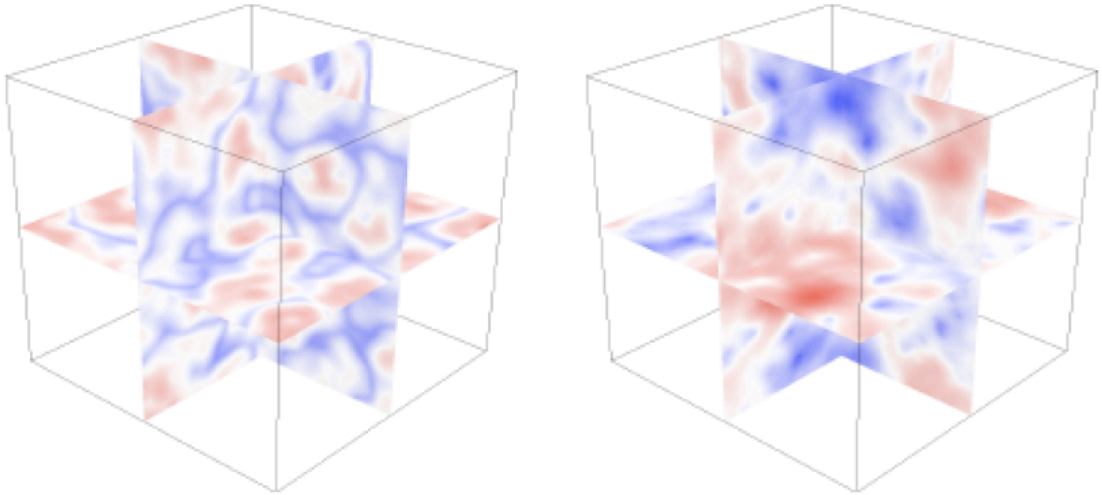
total density



bubbles form...

... then break into blobs

gravitational potential



potential traces dense bubble walls and empty interiors...

... the structure grows larger due to repulsive field interactions

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

results depend upon the input value of a uniform χ_b, a random Gaussian variable with variance $\sim H_b/2\pi$

(uncorrelated with inflaton $\delta\phi \sim H_b/2\pi$ fluctuations)

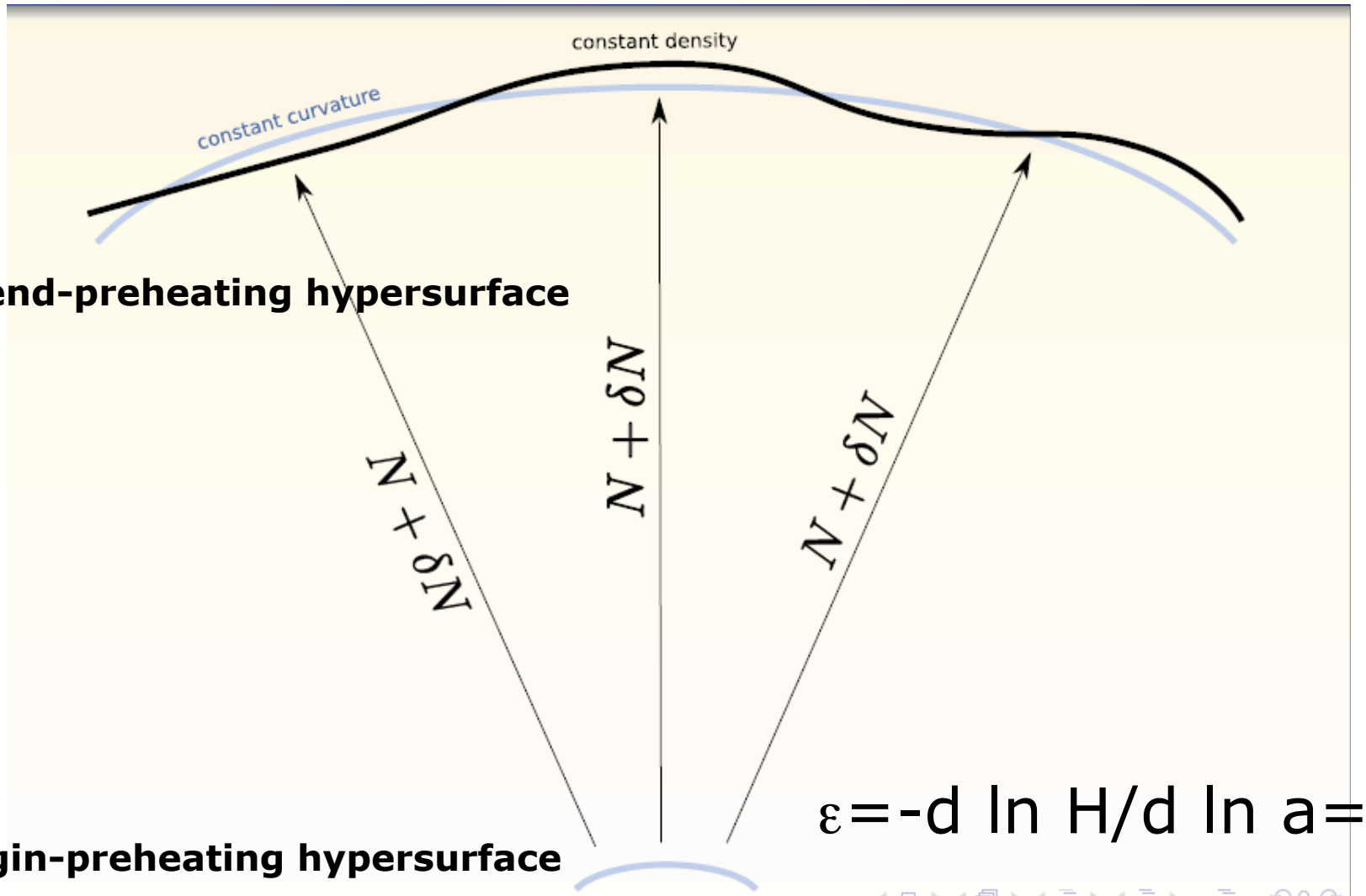
non-Gaussianity from preheating

$\chi_b(x,t)$ $+\chi_f$

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

calculate how the time from the end of accelerated expansion (end of inflation) to the onset of thermal equilibrium depends on $\chi_b(x,t)$

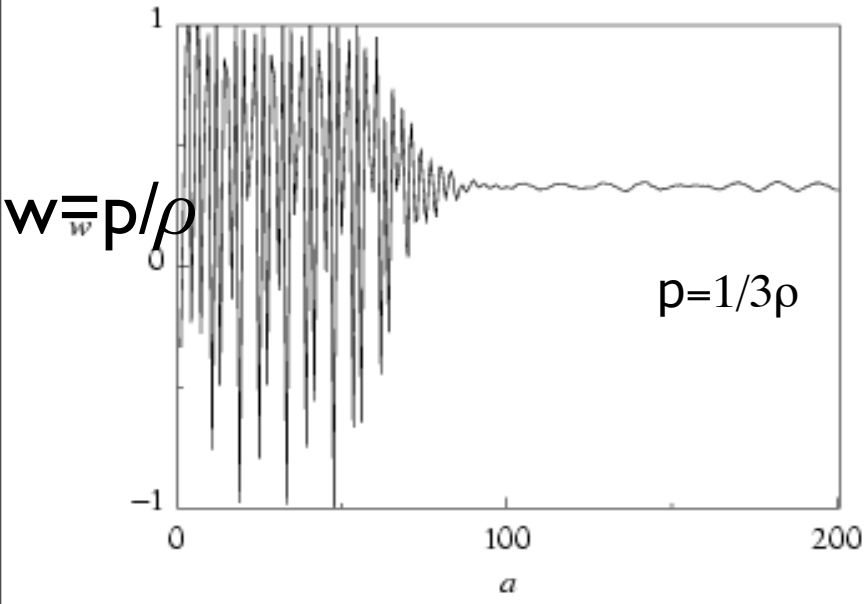
$$-\delta N = \delta \ln a|_H = \textit{curvature fluctuation}$$

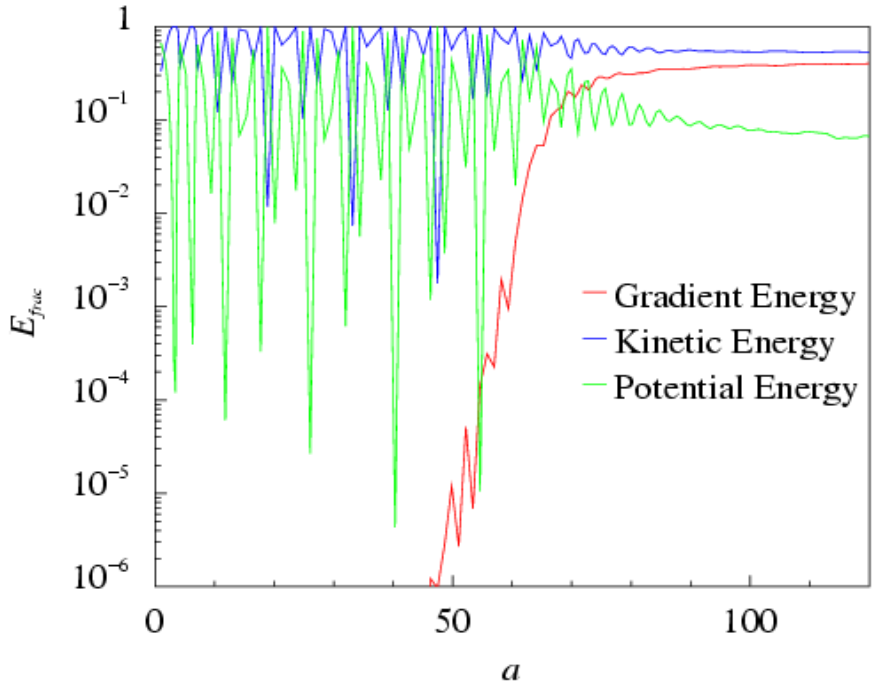


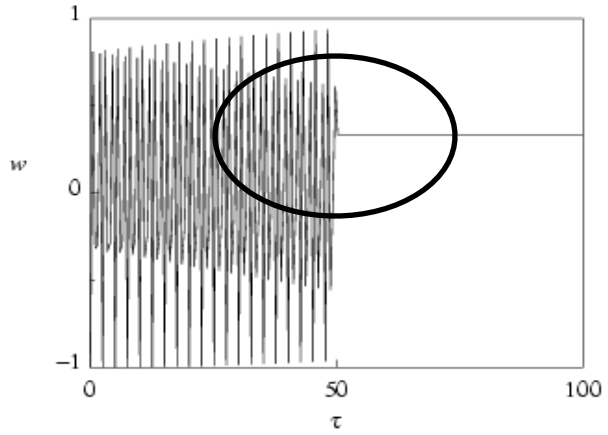
$\varepsilon = -d \ln H / d \ln a = 1$

equation of state evolution via simulation: pass from w ≈ -1 potential-dominated coherence via oscillation & mode cascade to w=1/3 thermal equilbrium

simulation size 128^3 $\chi_b = 0$







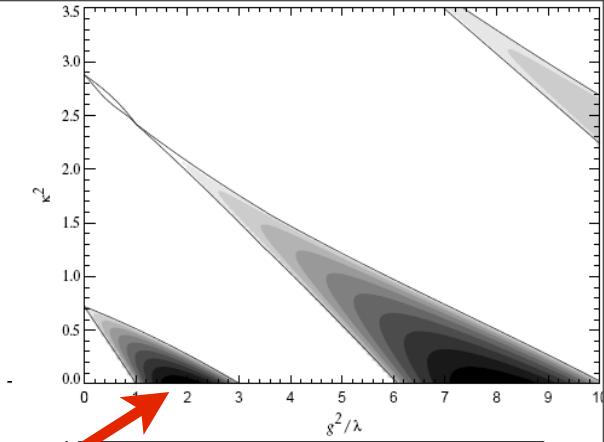
We search for ppm effects

⇒ Symplectic DEFROST:

energy conservation ~10^{-13} level!!

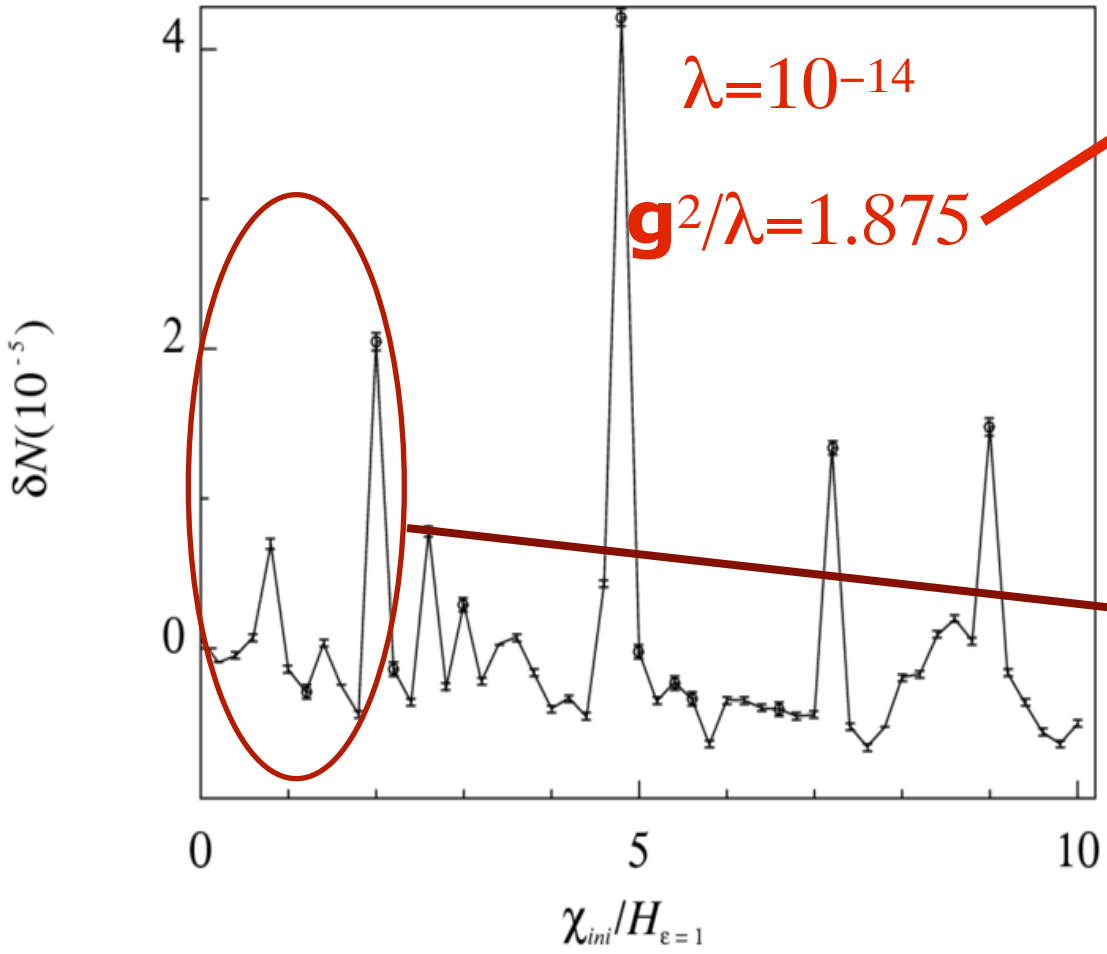
cf. DEFROST ~10^{-5} level & Felder's LatticeEasy ~10^{-4} level.

δ*ln* a(χ_b) modulation: response to varying $\chi_b(x,t_e)$

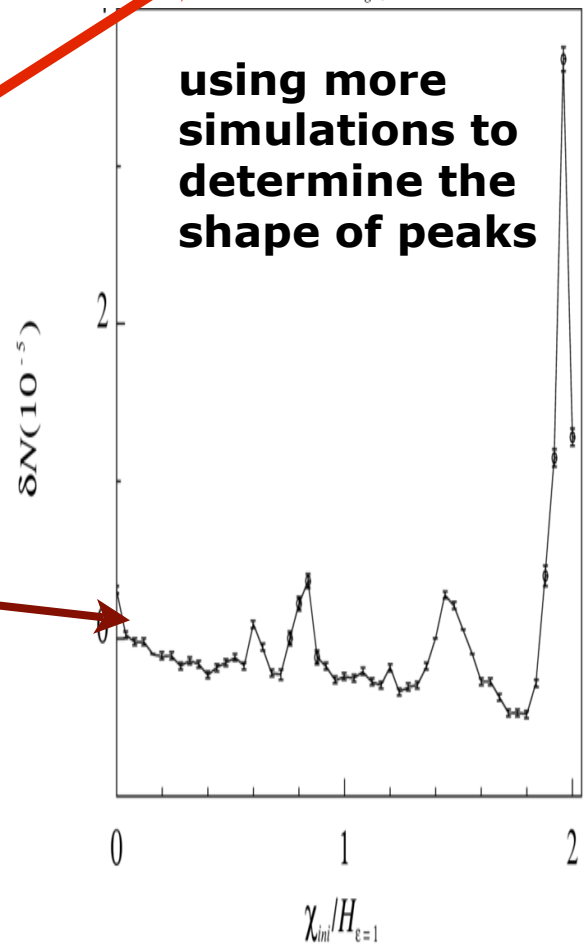


$\lambda=10^{-14}$

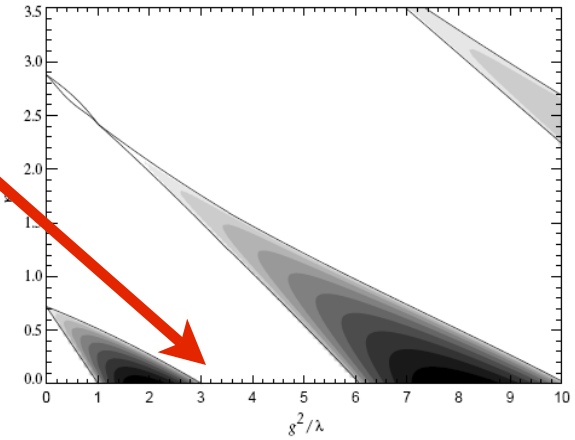
$g^2/\lambda=1.875$

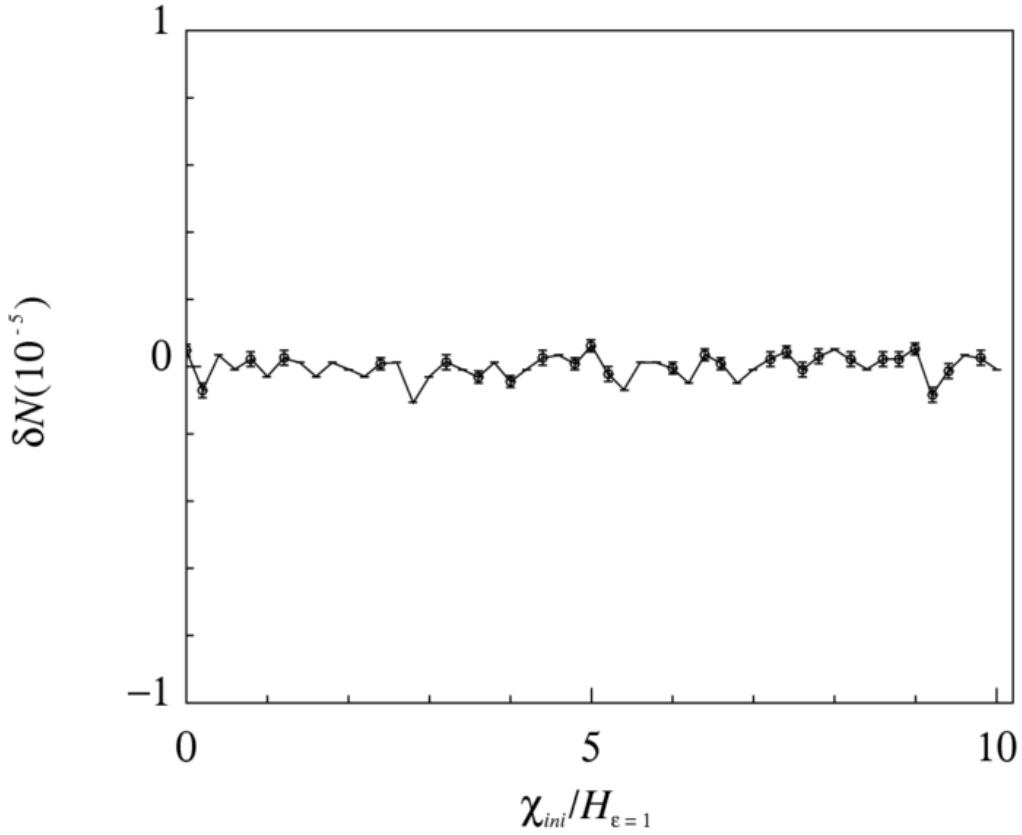


using more simulations to determine the shape of peaks



if the k=0 mode is not in the parametric resonance bands ($g^2/\lambda=3$ example) then $\delta ln\ a$ is not modulated by χ_b





Other tests: UV and IR cutoffs ok ➔

Observables and conclusions

$$\Phi(x) = \Phi_G(x) + f_{NL}\,(\Phi_G^2(x) - \langle\Phi_G^2\rangle)$$

local quadratic non-G constraint: $-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$ WMAP5 (± 5-10 Planck1yr)

$$\Rightarrow \Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL}\rangle$$

resonant preheating form

modulated curvature fluctuations from preheating are superimposed on the usual curvature fluctuations from the inflaton

the peak values have $\delta \ln a \sim 10^{-5} \Rightarrow$ *comparable to standard Gaussian*

temperature fluctuations, but spiky $F_{NL} \Rightarrow$ *non-Gaussian?*

As long as $g^2/\lambda \leq O(1)$, *the* χ *field has very long wavelength perturbations (similar to, but uncorrelated with, the inflaton field)*
Large Scale Structure statistics of spiky F_{NL} *mapping: under investigation*

Rich possibilities in theory space & on the sky

e.g., $F_{NL}(\chi) \sim \Sigma_p\, F_p \exp(-(\chi_p - \chi)^2/2\gamma_p^2) \Rightarrow$ e.g., $\langle \delta F_{NL} | \chi_{LF} \rangle \sim \Sigma_p\, \beta_p\, \chi_{LF}$,
but non-G is possible.

END