Gaussian & non-G Random Fields in Early Universe Cosmology: Then and Now

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25 years cifar

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

NOW: baryons/leptons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy

(+photons+light neutrinos + *gravity waves*). *??a bit of strings/textures/PBHs??*

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

nonlinear & non-G web of galaxies/clusters

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

$-d\ln\rho_{tot}/d\ln a\ /2$

$=\varepsilon(k)=1+q,\ k\sim Ha$

dark energy

$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?

trajectory probability

cosmic mysteries

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

brief history of bond's non-Gaussian exploration in inflation: THEN

early 80s: hot, warm & **cold** collisionless **dark matter** + inflation

$\Rightarrow$ ***x**CDM*: *86 extra power dilemma* $\Rightarrow$ vary x: k_{Heq} k_{mn} $k_{features}$

87: X = s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / Λ+b / Op+b /τ /BSI /BSI2

90s-00s: data settled on *X* = Λ +tilt $\Rightarrow$ *dark-energy* +tilt

Linde & Kofman 87, clipped pNGB (1-cos(χ/f)) string issue single field Grinstein, Allen & Wise 87

SBB89: δH, δm^2_{ij}, moguls, waterfalls $\Rightarrow$ plateau/mountain/valley

$V=\lambda_\phi\phi^4/4+m_\phi^2\phi^2/2+\lambda_\chi\chi^4/4+m_\chi^2\chi^2/2-\nu\phi^2\chi^2/2$ + 3-leg HYBRID; inflaton + isocons

trajectory bifurcation at $m^2_{is,is} \leq 0$ TACHYONIC $\Rightarrow$ non-G with & without 3-leg,

avoid late domain walls ($\Rightarrow$modify $V_{late\ time}$)

SB90/91: nonG technology: $\mathbf{y}(\mathbf{r},t) = \mathbf{y}_f(\mathbf{r},t) + \mathbf{y}_b(\mathbf{r},t)$ (+ $\mathbf{y}_{>h}(\mathbf{r},t)$) full EE+ϕ/χ eqs, restricted to the nonlinear longitudinal gauge (NL-LG); fluctuation/background split $\Rightarrow$ *Langevin network*: $\mathbf{y}_f$ linearized (fn of $\mathbf{y}_b$); $\mathbf{y}_b(\mathbf{r},t)$ super-"horizon" k < u Ha,

drift+stochastic kicks; reduced Hamilton-Jacobi eqn; identify $\ln a|_{H^*}$ as the nonlinear generalization of φ_{com} or ζ

setup for eternal alps (semi-eternal inflation, nonG at UUULSS, but nearly Gaussian over current horizon scales or baroque-ish V)

B91 *full NL-LG nonG Langevin network:* $Y_{bi}(\mathbf{r},t) \in \{\phi,\Pi_\phi,\chi,\Pi_\chi,\ln a,H \mid T=\ln Ha\}$

brief history of bfhk09 non-Gaussian exploration in inflation: NOW

80-90s: arena for BSI & non-G near EOI, new fields coupling in

expected k~Ha rule would apply. ***pre-heating surprise!***

lna$[\chi_i(x,t)]$ **from "subgrid"** $\propto H_e^{-1}$ **lattice simulations of** ϕ_{UHF} χ_{UHF}

like stochastic f-b split, with no dropping of gradient or nonlinear terms

Why ***lna***$[\chi_i]$**?** **ingredient 1** **chaotic zero modes** **fill V arms, Lyapunov log-**χ_i **spacing, overtones as well; ingredient 2 arm flow shuts off when** $m_{\chi\chi}^2$ **rises sharply at vigorous preheating nonlinearity onset** $\Rightarrow$ **EOS change**

$P(\chi\,|\,\chi_{LF}) \sim \exp[-(\chi-\chi_{LF})^2/2\sigma_{HF}^2]$ builds a usable low-pass effective mean field

does it work? linear $\langle\chi\,|\,\chi_{LF}\rangle \sim \chi_{LF}$ is sharp-k filter f-b split BBKS86, BCEK90, BM96

fourier transform $(F_{NL} - \langle F_{NL}\,|\chi_{LF}\rangle)$ is small for $k<k_{LF}$ for quadratic, exponential & even Gaussian spikes (variance ~1% at k_{LF} 0.15 at $k_{LF}/10$)

$\langle F_{NL}\,|\chi_b(x,t)+\chi_{>h}\rangle$ regimes

contrast with $\phi_{>h}$**: may be way out there in eternal inflation land, but not in a preheated ε>1 patch**

LOW $\chi_{>h}$ $\beta_\chi\,\chi_b + f_\chi\,\chi_b^2$ **subdominant linear, (much) less constrained** f_χ **cf.** f_{NL}

MEDIUM $\chi_{>h}$ **encompass smoothed spikes,** ***to be rare*** **(for ΔT cold spot, potential well anomalies** ***or not to be rare*** **(and suffer constraints)**

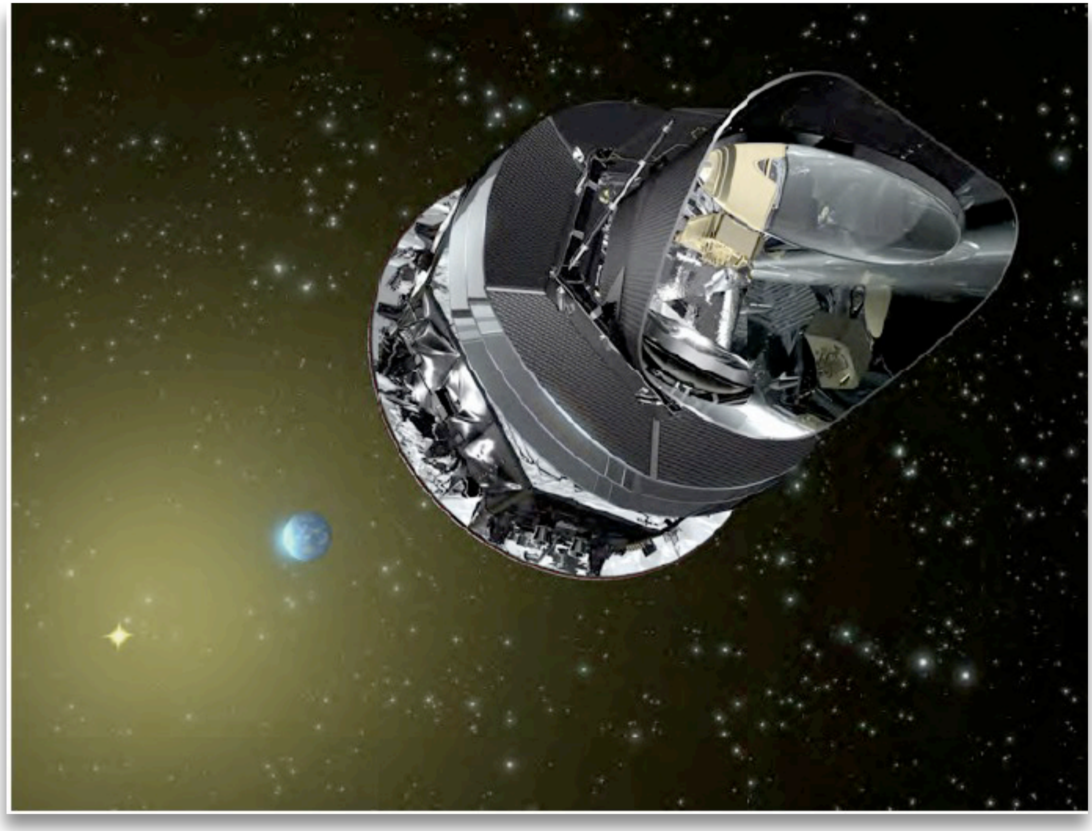
LARGE $\chi_{>h}$ **encompass part of a smoothed spike, upside, downside, topside**

Approaching the Planck Era in ≤ 1 month

status; impact of Planck on Planck era physics*, early inflation $n_s(k)$, GW: Tensor(k), subdominant isocurvature, cosmic strings, textures, *nonGaussian* F_{NL} *+late inflation w(z)

Launch planned for April 29, 2009 maybe (~10:30am Eastern) from Kourou, French Guiana 4°N

Herschel in Kourou Feb 11
Planck in Kourou Feb 18
Launch window: 1 hour per day; 2 days on, 2 weeks off to refill Herschel dewar



ESA /NASA /CSA Toronto HFI QLA/KST, TA, ... *Barth & Dick, Marc-Antoine Miville-Deschenes, Carrie MacTavish, Brendan Crill, Olivier Dore, Mike Nolta, Peter Martin* UBC LFI *Douglas Scott etal.*

CBI pol to Apr'05 @Chile
nonG

CBI2
QUaD @SP

Quiet1
@Chile

Quiet2
1000 HEMTs

Boom03@LDB +B98
nonG

Bicep @SP

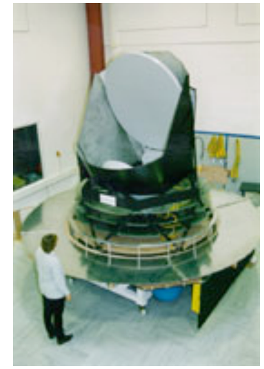
Bicep2

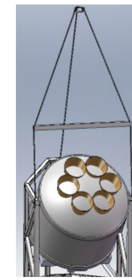
Keck/Spud

EBEX
@LDB

WMAP @L2 to 2010-20??
nonG

Planck09.3
nonG
(52 bolometers)
+ HEMTs @L2
9 frequencies





Spider
2312 bolos
@LDB

DASI @SP

CAPMAP

Herschel

CHIP

BLAST

2004 2006 2008 LHC 2011

2005 2007 2009

Bpol
@L2

Acbar to Jan'06, 08f @SP

SPT
1000 bolos
@SPole

BLASTpol

Clover
@Chile

SZA
@Cal

ACT
3000 bolos
3 freqs @Chile

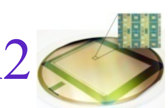
Polarbear
300 bolos
@Cal/Chile

SPTpol

AMI

APEX
~400 bolos
@Chile

SCUBA2

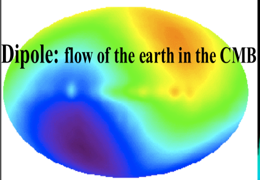


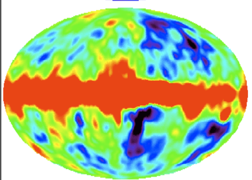
12000 bolos
JCMT @Hawaii

ALMA
@Chile

GBT

LMT@Mexico

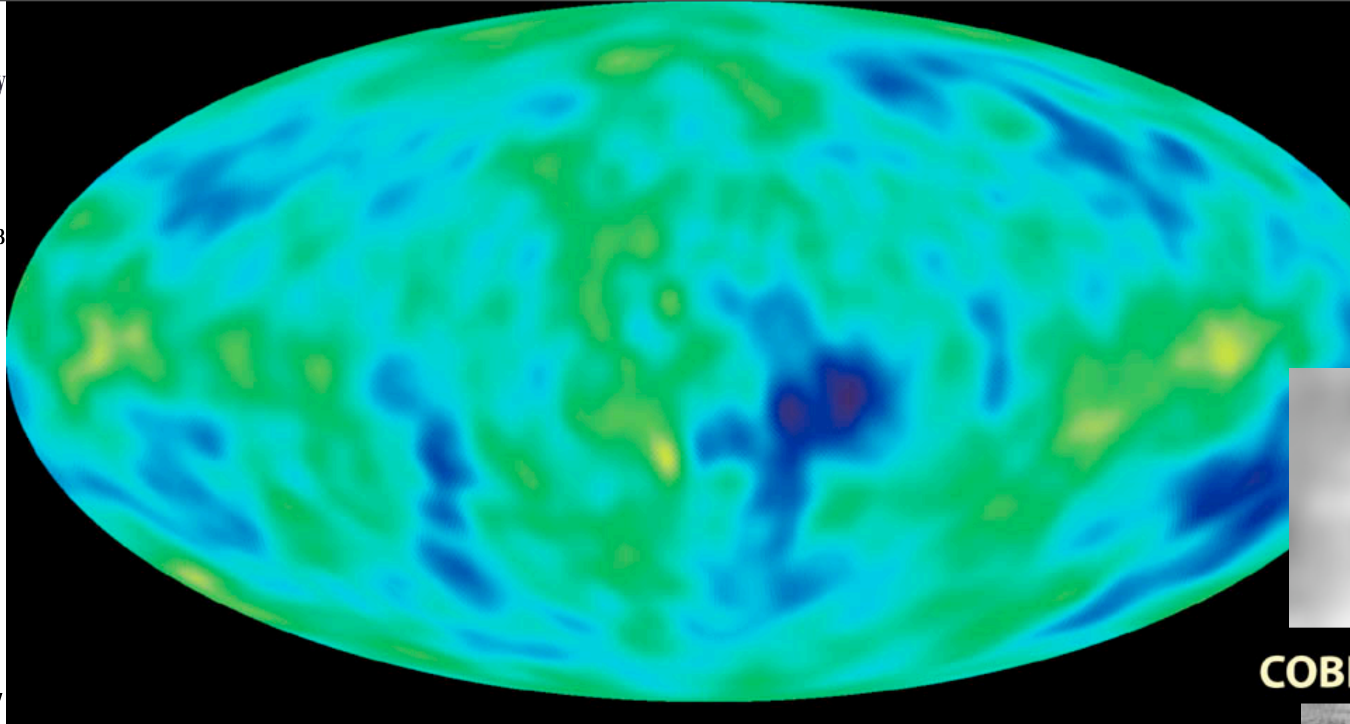


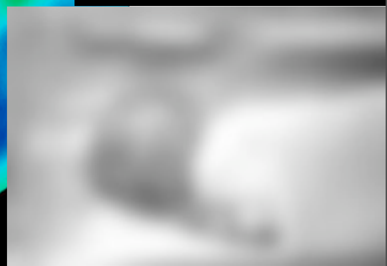


COBE/DMR:
CMB + Galactic @7^0

is this a statistically isotropic Gaussian random field, when account is taken of the Milky Way emissions & extra-galactic sources?

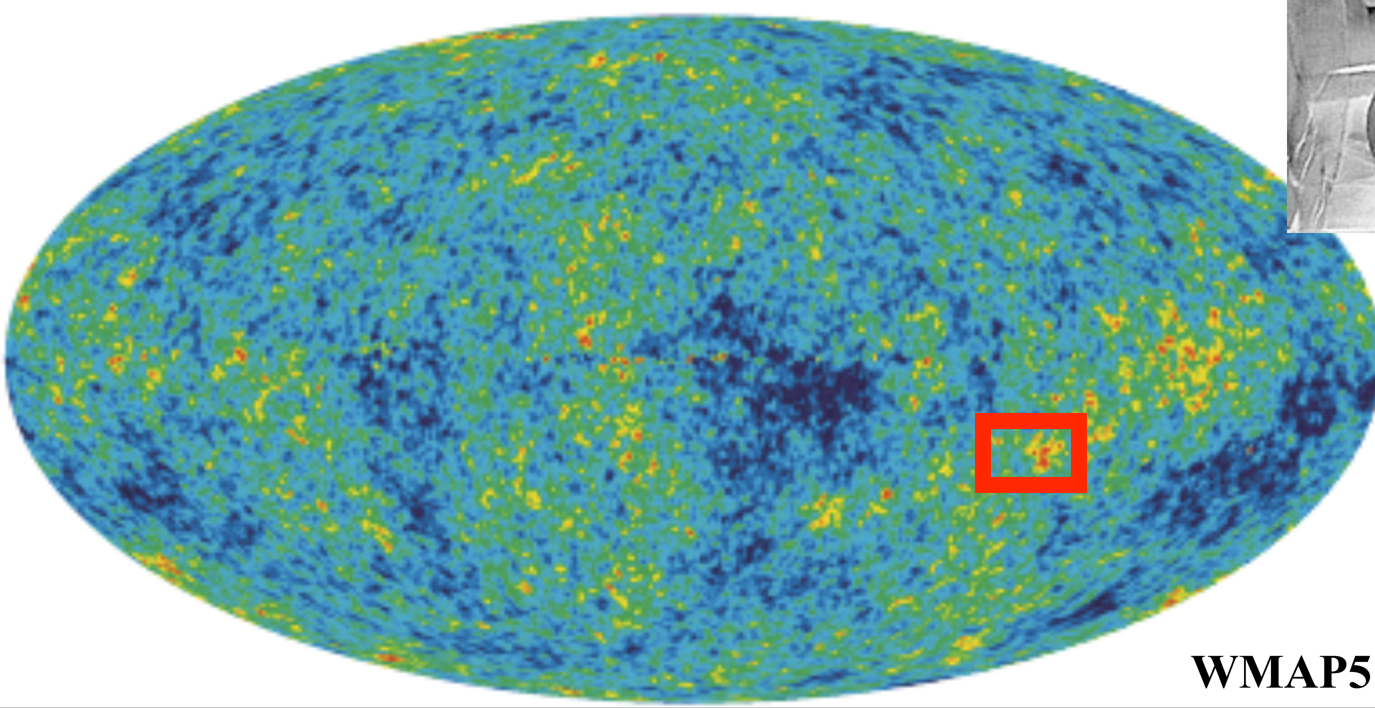
yes! maybe?

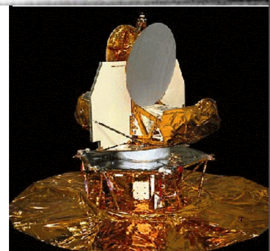




COBE

1992/96



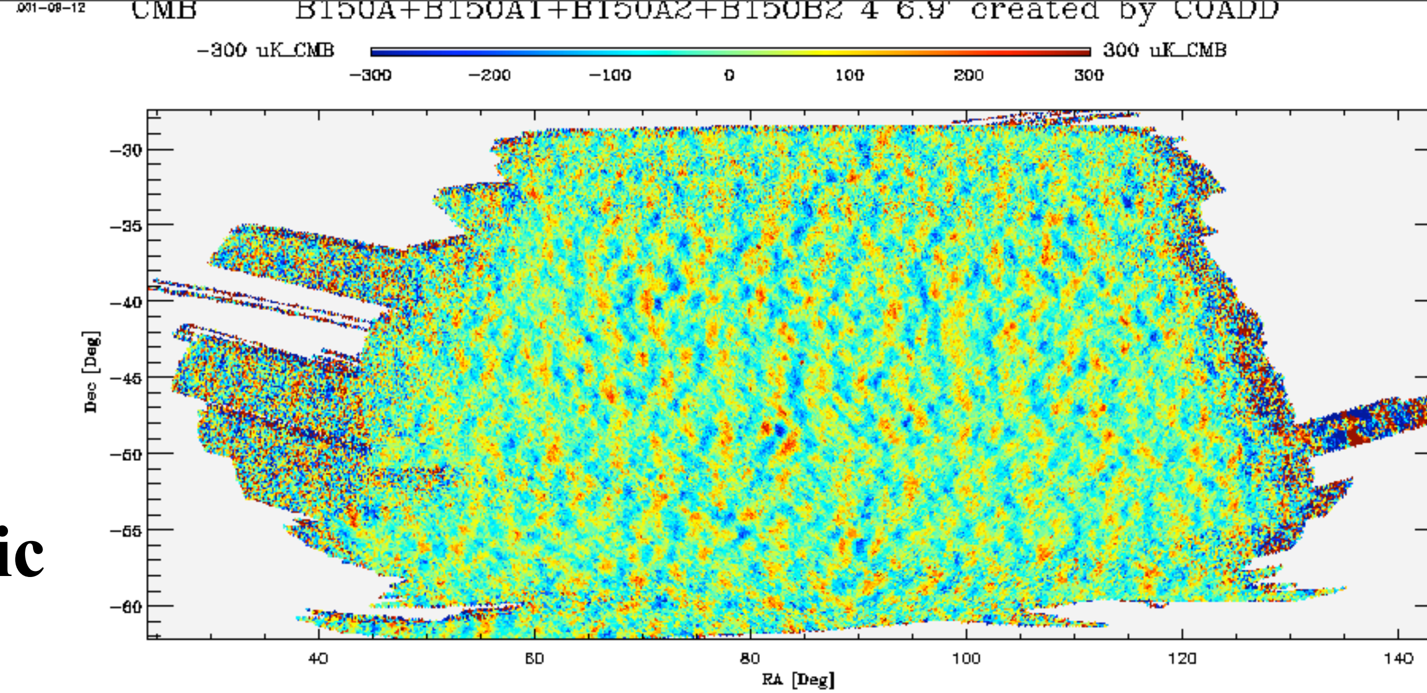


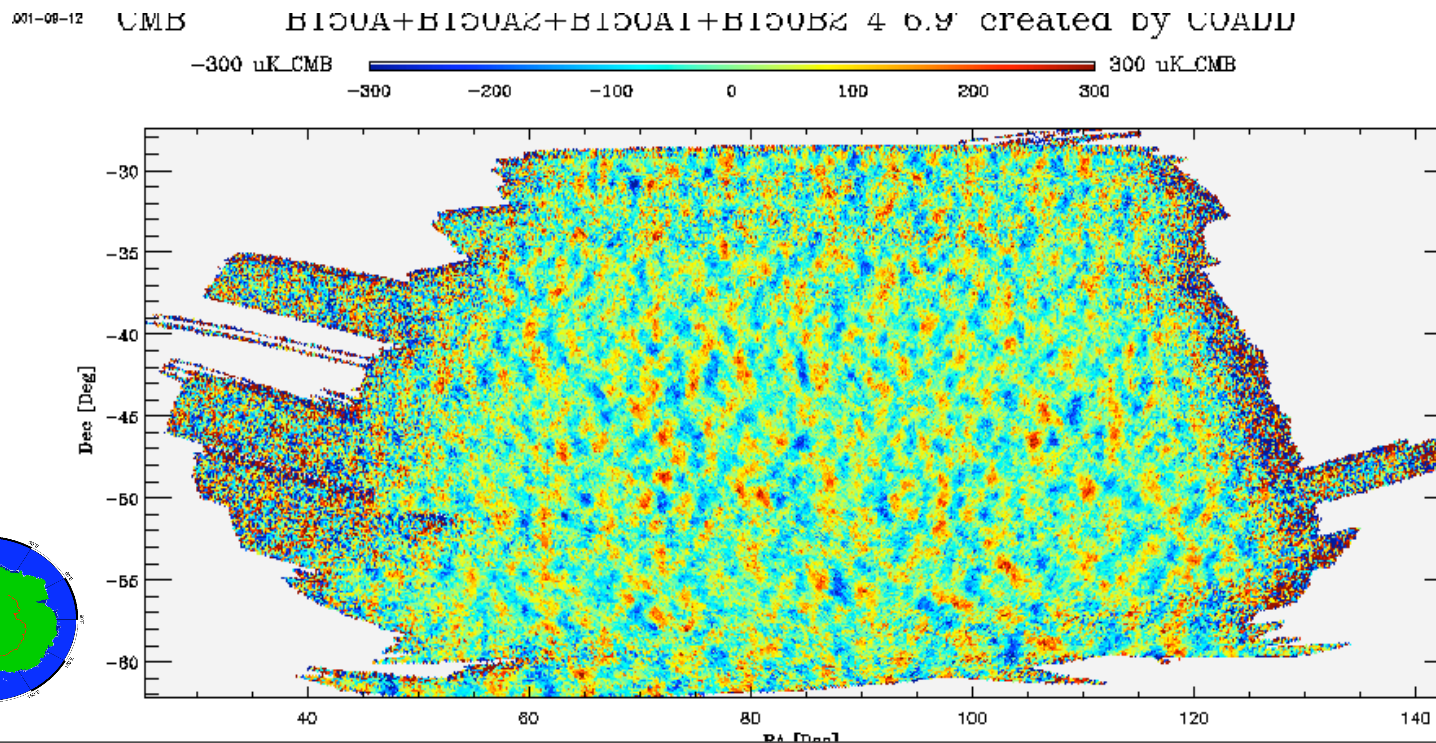
WMAP5

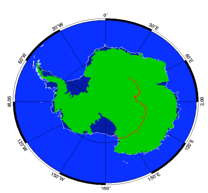
Feb03
Mar06
Mar08

Boomerang @150GHz is (nearly) Gaussian: Simulated vs Real

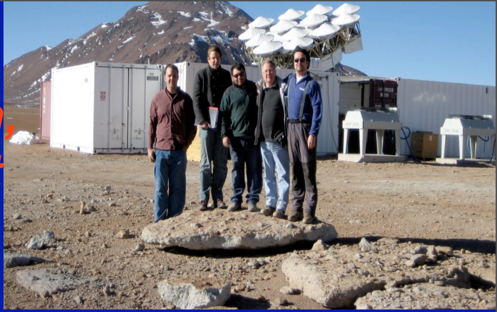
thermodynamic CMB temperature fluctuations
2.9% of sky
ΔT~30 ppm





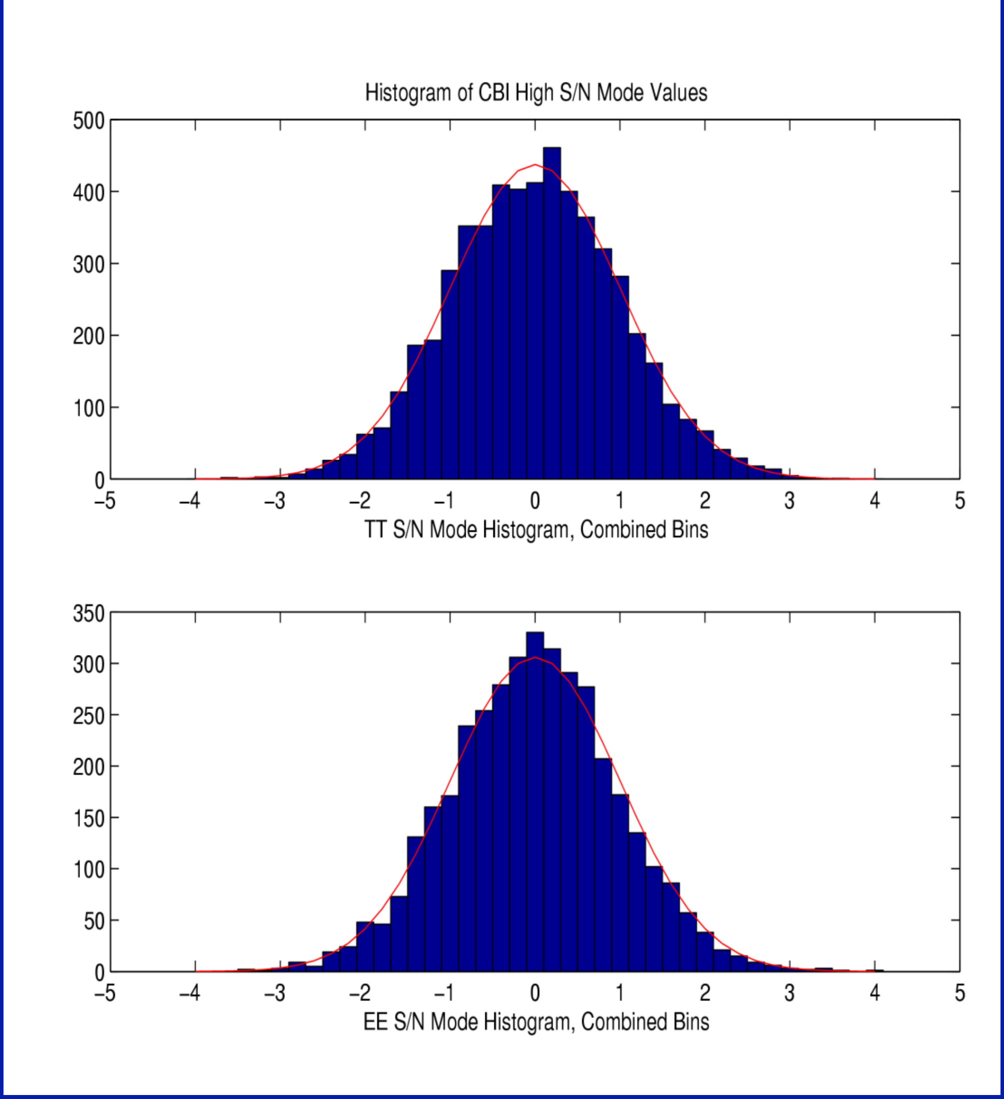


All non-primary CMB components are non-Gaussian: extragalactic radio and submm sources; Galactic synchrotron, bremsstrahlung & dust emission, CMB-upscattering from hot gas in clusters, gravitational lensing of the CMB, ...

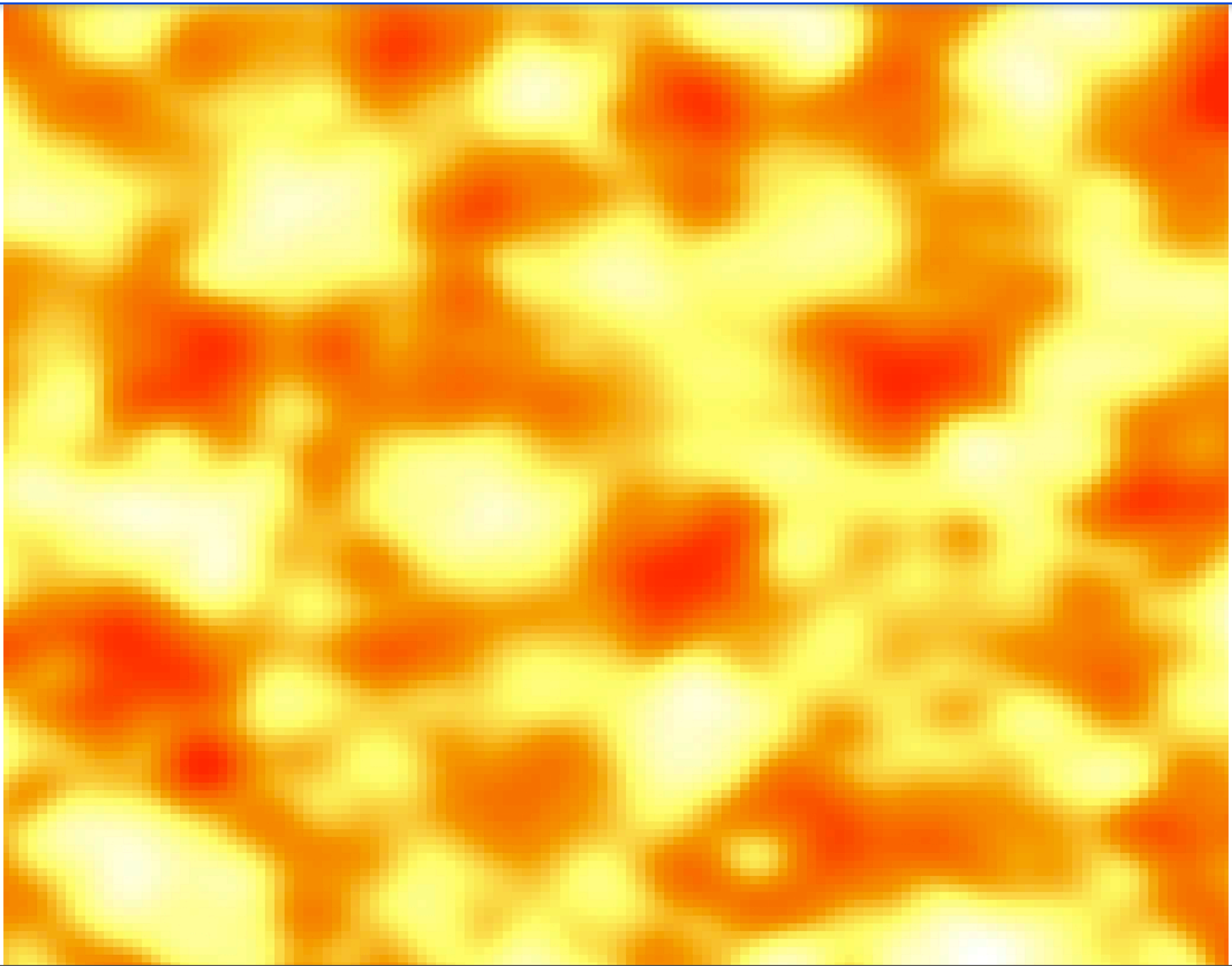


even the high resolution Cosmic Background Imager ΔT is ~ Gaussian, & so is its CMB polarization signal

- Method: Decompose data (with extragalactic radio sources removed) into uncorrelated S/N eigenmodes for each bin; Pick out modes expected to have signal; Check distribution for non-Gaussianity
- We kept 5500 modes for TT ΔT, 3800 for EE polarization
- all are consistent with Gaussian
- first check of EE polarization



nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web "now", the galaxy/dwarf system "then"



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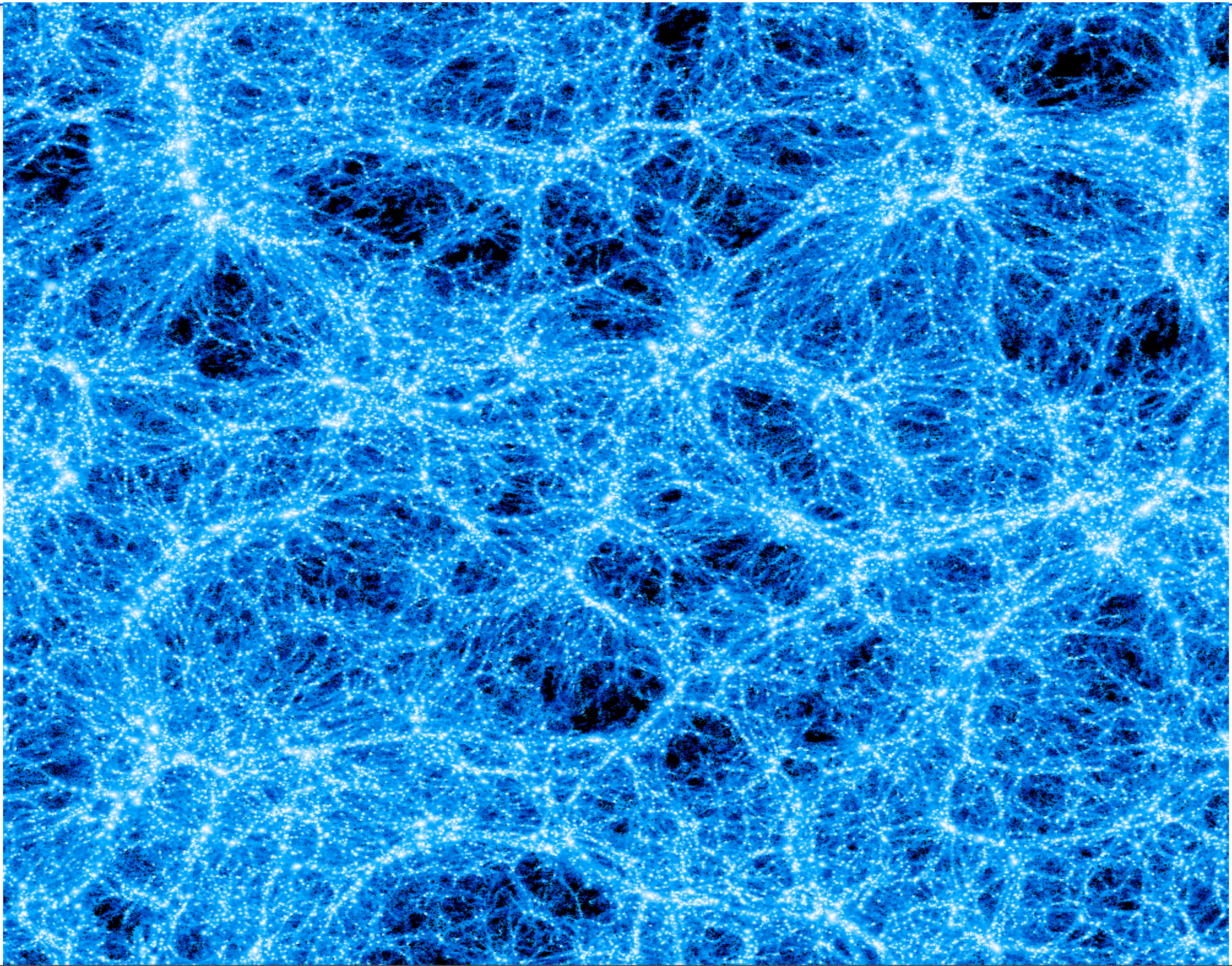
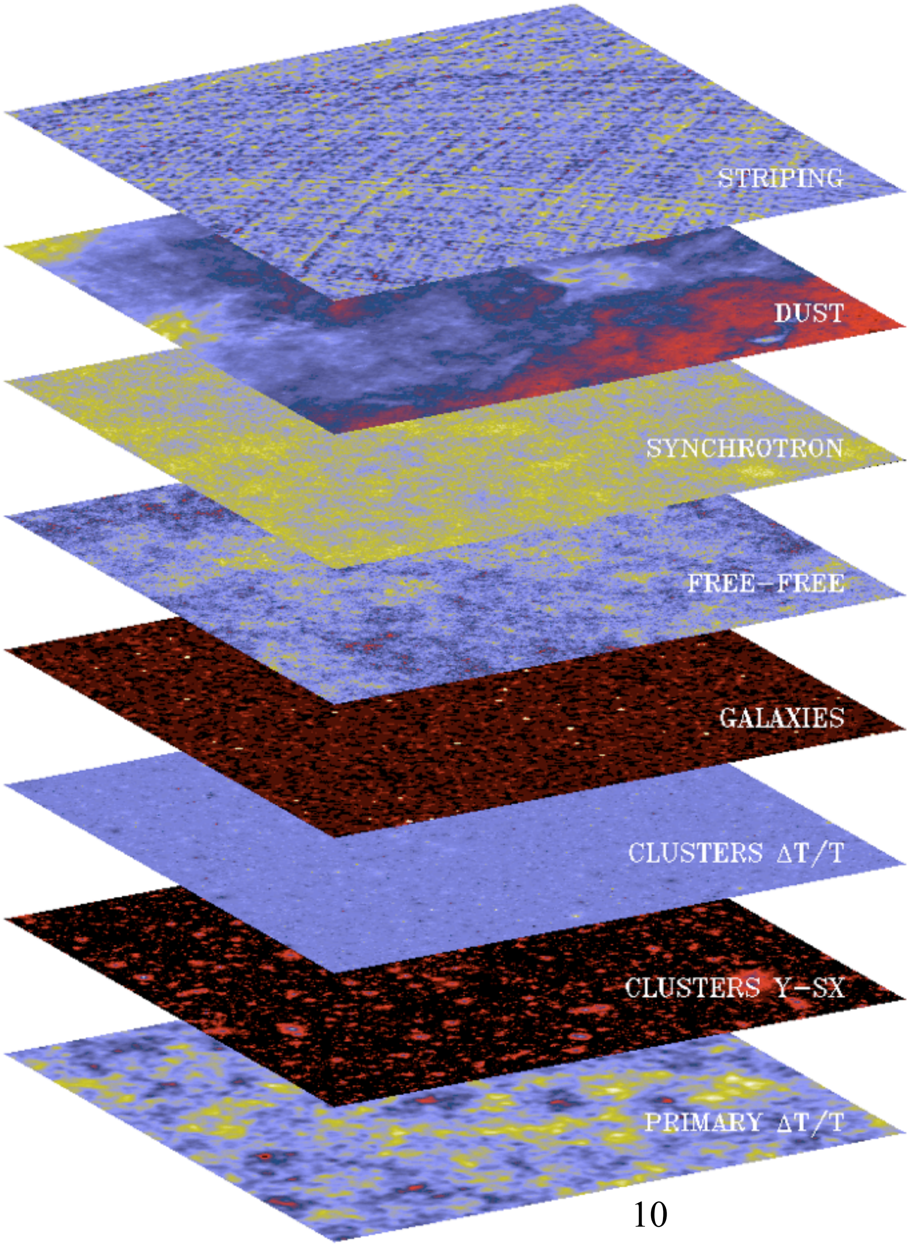


the quest for primordial non-Gaussianity within the primary CMB requires exquisite foreground removal, whether inflation-induced or cosmic-string-induced, ...

striping
dust
synchrotron
bremsstrahlung
dusty galaxies
kinetic SZ
thermal SZ
PRIMARY



F.R. BOUCHET & R. GISPERT 1998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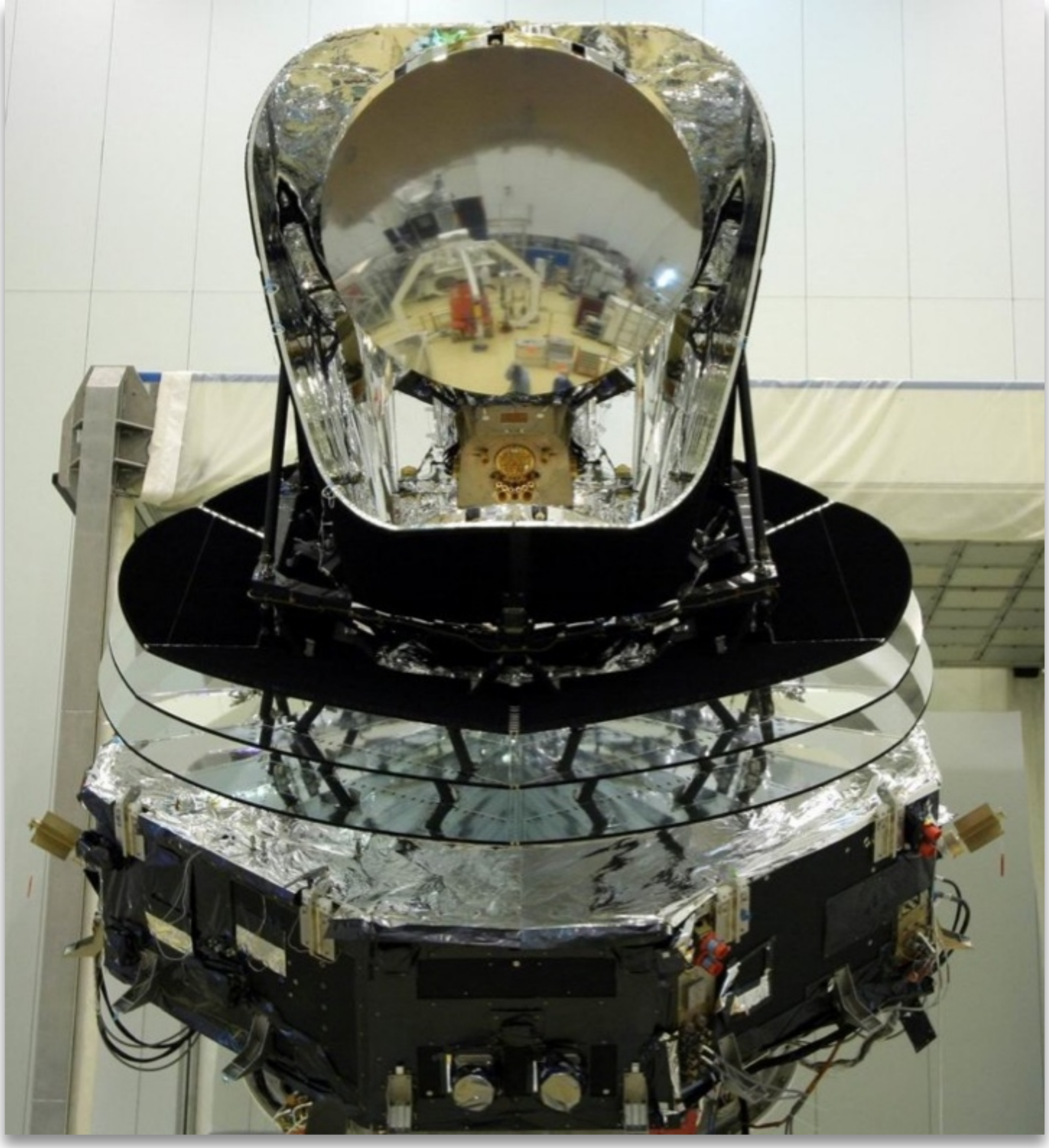
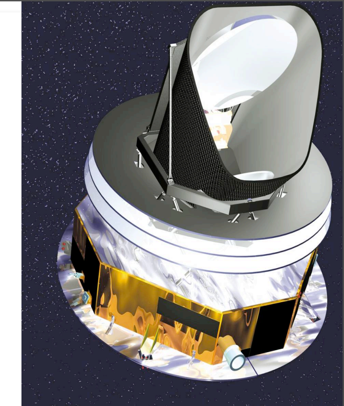
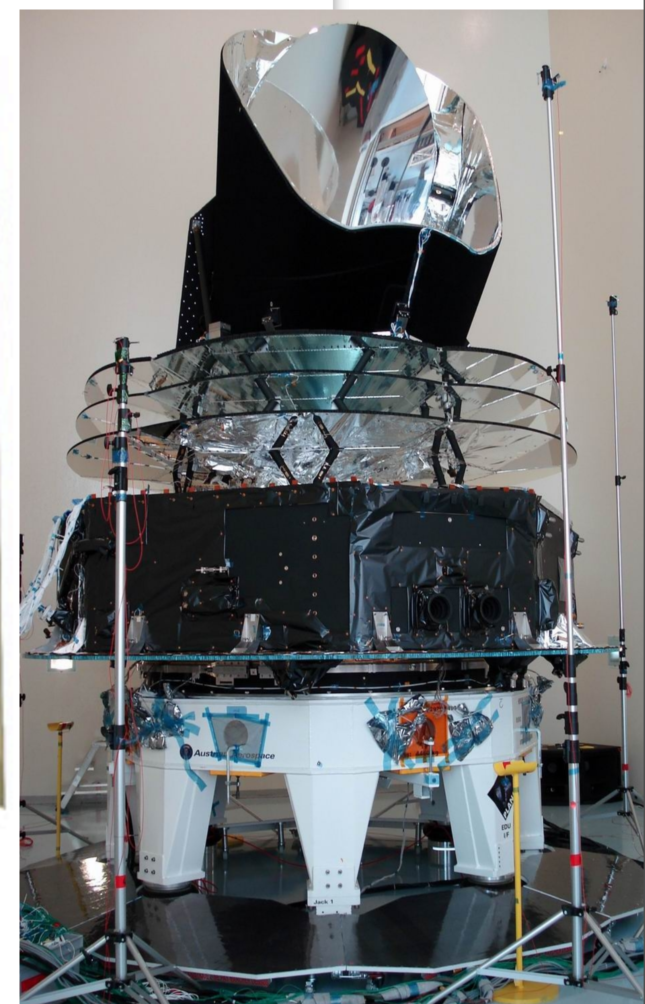


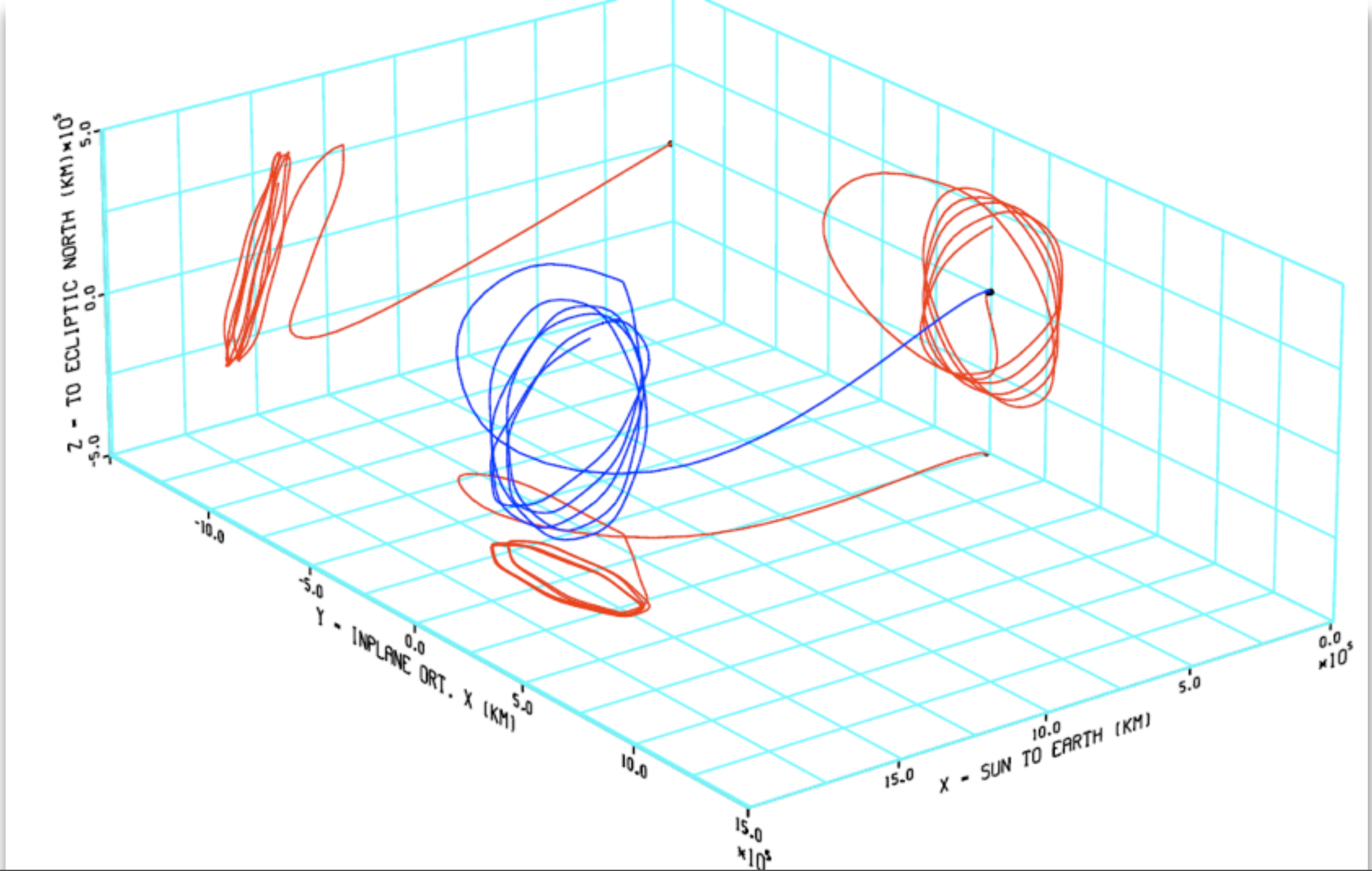


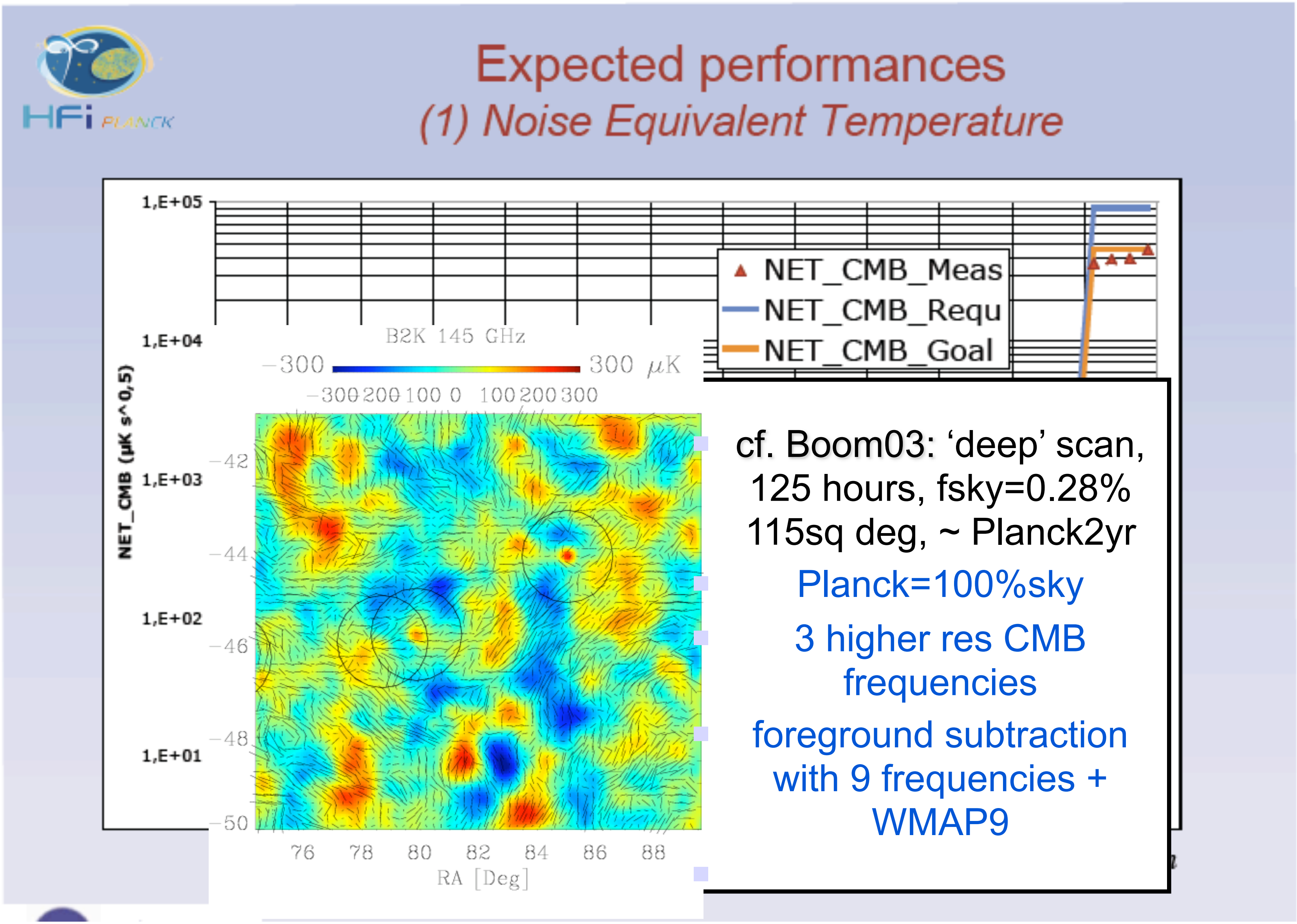
Planck's Journey

Trip to L2: ~ 30 days

- *Decontamination & Cooldown ~ 45 days*
- *Detectors at 100mK at L2 around June 18*
- *CPV (Checkout & Performance Verification) thru end-Jul*



NET requirement vs. NET measurement vs NET goal: very close to goal, better than requirement in all channels: 100 GHz_P 143 GHz_P 143 GHz 217 GHz_P 217 GHz 353 GHz_P 545 GHz 857 GHz



cf. Boom03: 'deep' scan, 125 hours, fsky=0.28% 115sq deg, ~ Planck2yr

Planck=100%sky

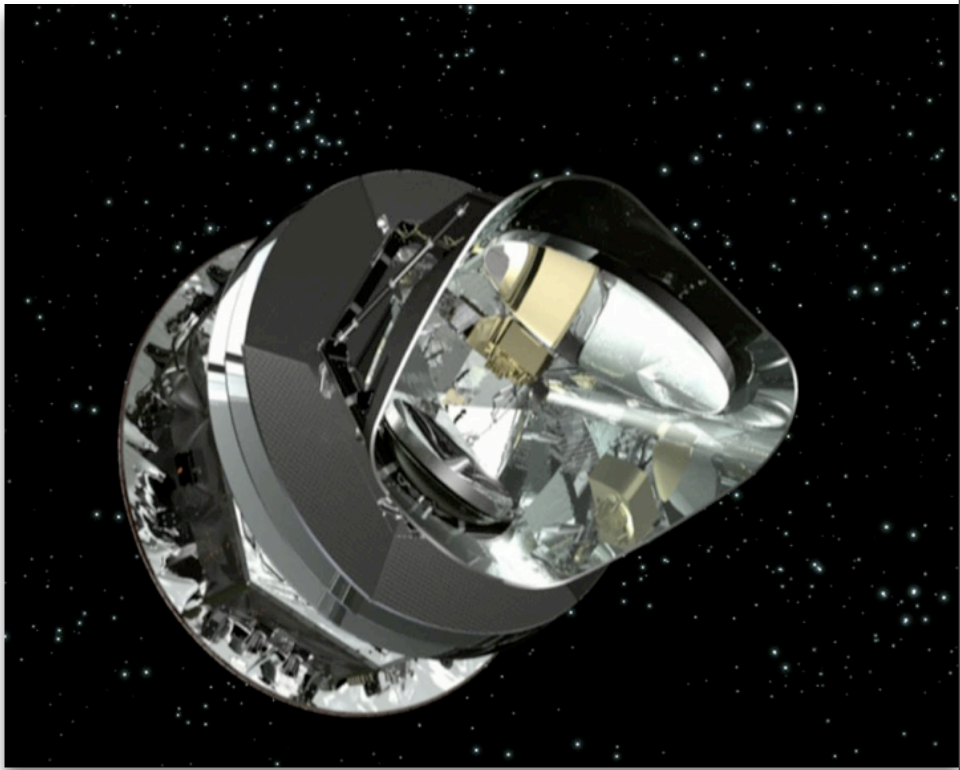
3 higher res CMB frequencies

foreground subtraction with 9 frequencies + WMAP9

Schedule

Launch: April 2009

- *Cruise & CPV ends July 2009*
- *Two sky surveys finished July 2010*
- *Early Release Compact Source Catalog ~Dec 2010*
- *Four sky surveys finished: July 2011*
- *Public release of 1yr data, papers: July 2012*



brief history of bond's non-Gaussian exploration in inflation: THEN

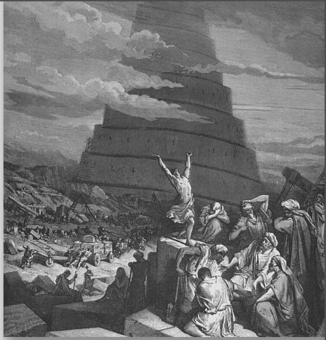
early 80s: hot, warm & **cold** collisionless **dark matter** + inflation

⇒*xCDM*: *86 extra power dilemma* ⇒ vary x: k_{Heq} k_{mn} $k_{features}$

87: ***X*****=** **s /H0 /** Λ **/ Open/ is /is+ad/ h-c/ h+/ b/ b /** Λ**+b / Op+b /**τ **/ BSI /BSI2**

90s-00s: data settled on ***X*****=** Λ **+tilt ⇒ *dark-energy* +tilt**

COSMIC PARAMETERS THEN



e.g., BBE1987 vary *x* in *x*CDM

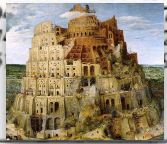
for *x*CDM, predict CMB (6deg, 5min); LSS cluster-cluster, cluster-galaxy, bulk flows, σ_8: redshift of "galaxy formation"

14 Gyr, Ω_Λ=0.8, H0=75, b~c,
50μK cf 30μK cobe, σ_8~0.72

x= s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / Λ+b / Op+b /τ /BSI /BSI2

Predictions for Models

Parameter	OBS	CDM	C40	VAC/C	OP/C	ISO/C	ISO/AD	HOT	HC	C + B	B + C	BCV	BCO	CDM + dec	(CDM + X)$_3$ (k_u^{-1} = 300)	(CDM + X)$_2$ (k_u^{-1} = 200)
Ω, Ω_B, H_0	...	1, 0.1, 50	1, 0.1, 40	1, 0.03, 50	0.2, 0.03, 50	1, 0.1, 50	1, 0.1, 50	1, 0.1, 50	1, 0.1, 50	1, 0.2, 40	1, 0.5, 50	1, 0.1, 75	0.2, 0.1, 75	1, 1, 50	1, 0.1, 40	1, 0.1, 50
$\Omega_X(\Omega_\nu)$, Ω_{vac}	...	0.9, 0	0.9, 0	0.17, 0.8	0.17, 0	0.9, 0	0.9, 0	(0.9), 0	0.5 (0.4), 0	0.8, 0	0.5, 0	0.1, 0.8	0.1, 0	1, 0	0.9, 0	0.9, 0
b	...	1.7	1.8	1	1	1.7	1.7	0.53	1.7	1.8	1.7	1	1	1.7	1.8	1.7
t_0 (by)	GC: 14–22 NC: 13–26	13	17	22	17	13	13	13	13	17	13	14	11	13	17	13
$\sigma_0(R_g = 0.35)$ ...	...	2.9	2.4	2.7	2.7	1.6	2.5	2.0	1.3	2.2	1.9	2.4	2.4	6.8	2.2	2.7
z_g	...	3.7	2.9	2.3	4.0	1.3	3.1	1	1.1	2.5	2.0	1.3	2.0	13	2.6	3.4
$\sigma_0(R_{cl} = 5)$	...	0.42	0.39	0.75	0.75	0.43	0.42	1.4	0.44	0.40	0.44	0.72	0.72	0.47	0.41	0.43
$\langle v \rangle_c$	...	3.2	3.1	3.1	3.1	3.0	3.2	3.1	2.9	3.1	3.0	2.8	2.8	2.7	3.1	3.1
$\xi_{cc}(20)$	1.5	0.15	0.26	1.7	1.7	0.70	0.35	1.1	1.0	0.49	1.3	2.2	2.2	1.8	1.0	0.85
$\xi_{cc}(25)$	1.0	0.08	0.15	1.2	1.2	0.42	0.21	0.45	0.51	031	0.93	1.7	1.7	0.92	0.83	0.68
$\xi_{cc}(30)$	0.72	0.03	0.07	0.85	0.85	0.25	0.11	0.20	0.24	0.20	0.61	1.4	1.4	0.49	0.64	0.51
$\xi_{cc}(50)$	0.29	−0.01*	−0.006*	0.24	0.24	0.02	−0.01*	−0.009*	−0.02*	0.04	0.23	0.59	0.59	0.16	0.28	0.21
$\xi_{cc}(100$	0.08	−0.002*	−0.003*	0.02	0.02	−0.003*	−0.003*	−0.003*	−0.009*	−0.007*	−0.01*	036	0.36	0.02	0.08	0.06
$\xi_{cg}(20)$	0.49	0.13	0.17	0.57	0.57	0.32	0.19	0.96	0.44	0.23	0.50	0.76	0.76	0.70	0.39	0.32
$\xi_{cg}(25)$	0.33	0.04	0.06	0.37	0.37	0.16	0.08	0.35	0.23	0.11	0.32	0.54	0.54	0.42	0.26	0.20
$\xi_{cg}(30)$	0.24	0.01	0.02	0.25	0.25	0.09	0.03	0.12	0.11	0.06	0.22	0.41	0.41	0.24	0.19	0.15
$\xi_{cg}(40)$	0.14	−0.003	0.002	0.13	0.13	0.03	0.006	−0.001	0.02	0.03	0.13	0.26	0.26	0.09	0.12	0.10
$v(R_f = 3.2)$	610 ± 50	136–654	134–650	166–797	157–752	172–824	148–709	594–2850	185–889	149–714	208–1000	232–1120	218–1050	293–1399	280–1331	241–1151
$v(R_f = 15)$	599 ± 104	71–340	76–365	134–639	126–601	114–544	86–409	387–1850	124–587	95–450	154–735	206–987	[illegible]	[illegible]	250–1190	202–970
$v(R_f = 25)$		53–250	56–269	115–550	108–516	89–421	64–309	419–1350	91–435	71–342	119–573	186–894	[illegible]	[illegible]	233–1106	185–882
$v(R_f = 40)$	970 ± 300	35–180	40–192	95–456	90–430	66–315	47–221	200–958	65–311	52–251	87–419	160–771	[illegible]	[illegible]	214–1016	165–787
$\Delta T/T$ (4′.5)	<25	5	6	20	70	...	...	20	...	6	8	10	[illegible]	[illegible]	...	...
× 10^6 (6°)	<48	7	8	20	40	60	30	20	8	8	15	25	[illegible]	[illegible]	72 (98)	40 (64)

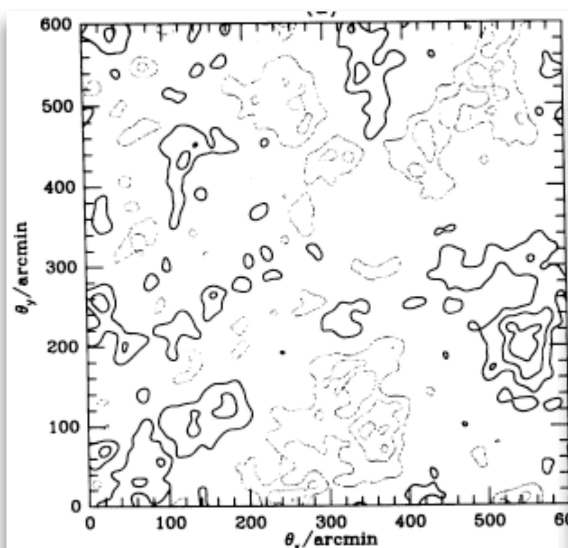


Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary $\Delta T/T$

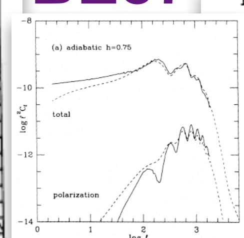
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle|\Delta T(LM)|^2\rangle$ *with target* C_L *shapes*

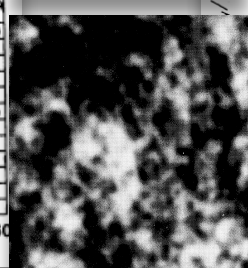
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

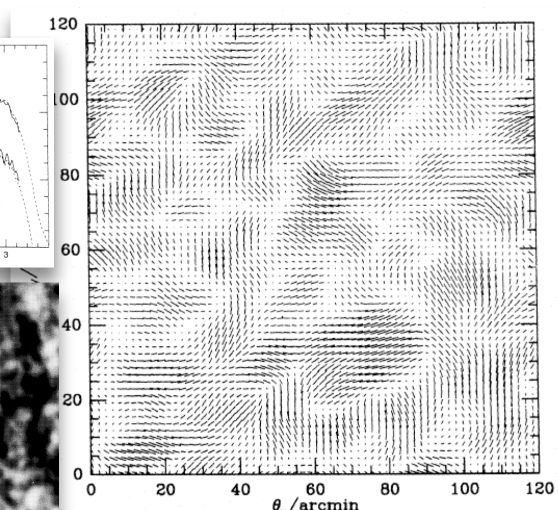
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



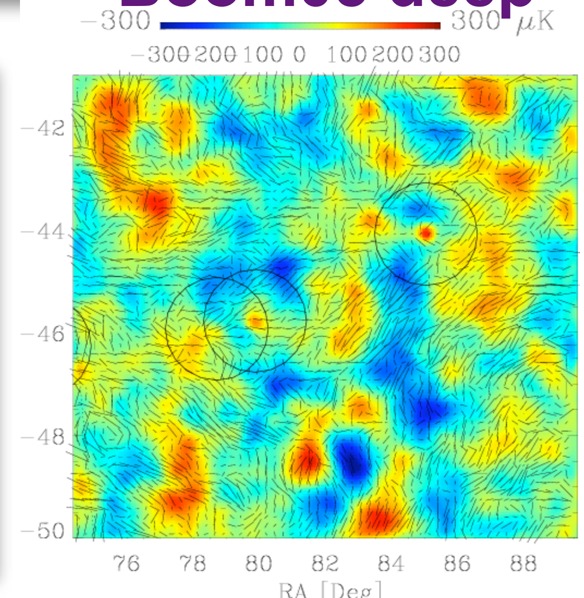
BE87







Boom05 deep



brief history of bond's non-Gaussian exploration in inflation: THEN

Linde & Kofman 87, clipped pNGB ($1-\cos(\chi/f)$) string issue single field Grinstein, Allen & Wise 87

SBB89: δH, δm^2_{ij}, moguls, waterfalls ⇒ plateau/mountain/valley

$V=\lambda_\phi \phi^4/4+m_\phi^2\phi^2/2+\lambda_\chi \chi^4/4+m_\chi^2\chi^2/2-\nu\phi^2\chi^2/2$ + 3-leg HYBRID; inflaton + isocons

trajectory bifurcation at $m^2_{is,is} \leq 0$ TACHYONIC ⇒ non-G with & without 3-leg,

avoid late domain walls (⇒modify $V_{\text{late time}}$)

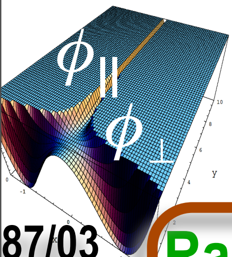
Old view: **Theory prior = delta function of THE correct one and only theory**

1980

R^2-inflation

Old Inflation

Chaotic inflation



New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03

Radical BSI inflation
& non-Gaussianity
& baroqueness of V

variable M_P inflation

Extended inflation

1990

Hybrid inflation

Natural pNGB inflation

resonant preheating @ end-of-inflation

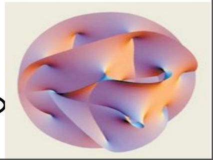
2000

2003 KKLT

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

moduli fields

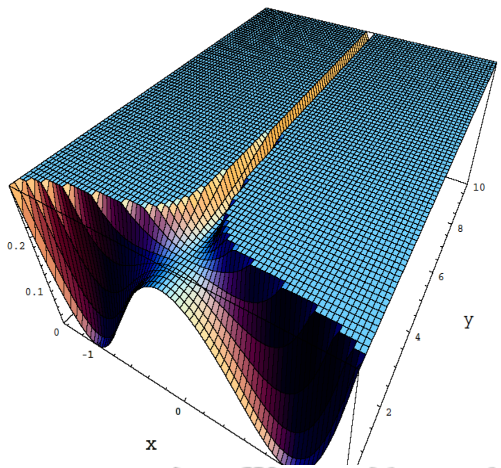
Roulette inflation Kahler moduli/axion



Radical BSI inflation

1987

2003



SBB89: multi-field, the hybrid inflation prototype, with curvature & isocurvature & **P_s(k) with any shape possible** & P_t(k) almost any shape (mountains & valleys of power), gorges, moguls, waterfalls, $m^2_{eff} < 0$, i.e., tachyonic, **non-Gaussian, baroqueness,** radically broken by variable braking **ε(k); SB90,91 Hamilton-Jacobi formalism to do non-G (& Bardeen pix of non-G) ε(k) - H(ϕ)**

cf. gentle break by smooth brake in the slow roll limit.

than flat spectra give. We consider a wide variety of models based on the chaotic inflation paradigm and sketch the effects that varying the expansion rate, structure of the potential surface, and the curvature coupling constants have on the quantum fluctuation spectra. We calculate in detail the quantum generation of fluctuation spectra by numerically solving the linearized perturbation equations for multiple scalar fields, the metric, and the radiation into which the scalars dissipate, following the evolution from inside the horizon through reheating. We conclude that (1) useful extended nonflat power laws are very difficult to realize in inflation, (2) double inflation leading to a mountain leveling off at a high-amplitude plateau at long wavelengths is generic, but to tune the cliff rising up to the plateau to lie in an interesting wavelength range, a special choice of initial conditions and/or scalar field potentials is required, and (3) small mountains (moguls) on the potential surface lead to mountains of extra power in the fluctuations added on top of an underlying flat spectrum. For quadratic and quartic couplings, the mountain fluctuations may obey Gaussian statistics but the spectral form will be very sensitive to initial conditions as well as potential parameters; non-Gaussian mountain fluctuations which depend upon potential parameters but not on initial field conditions will be the more likely outcome. However, adding cubic couplings can give mountains obeying Gaussian statistics independently of initial conditions. Since observations only probe a narrow patch of the potential surface, it is possible that it is littered with moguls, leading to arbitrarily complex "mountain range" spectra that can only be determined phenomenologically. We also construct an inflation model which houses the chaotic inflation picture within the grand unified theory

Blind power spectrum analysis cf. data, then & now

measures matter

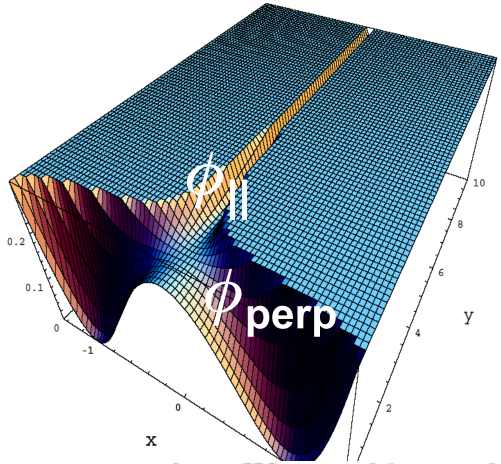
"theory prior"

informed priors?

Radical BSI inflation

1987

2003



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Blind power spectrum analysis cf. data, then & now

measures matter

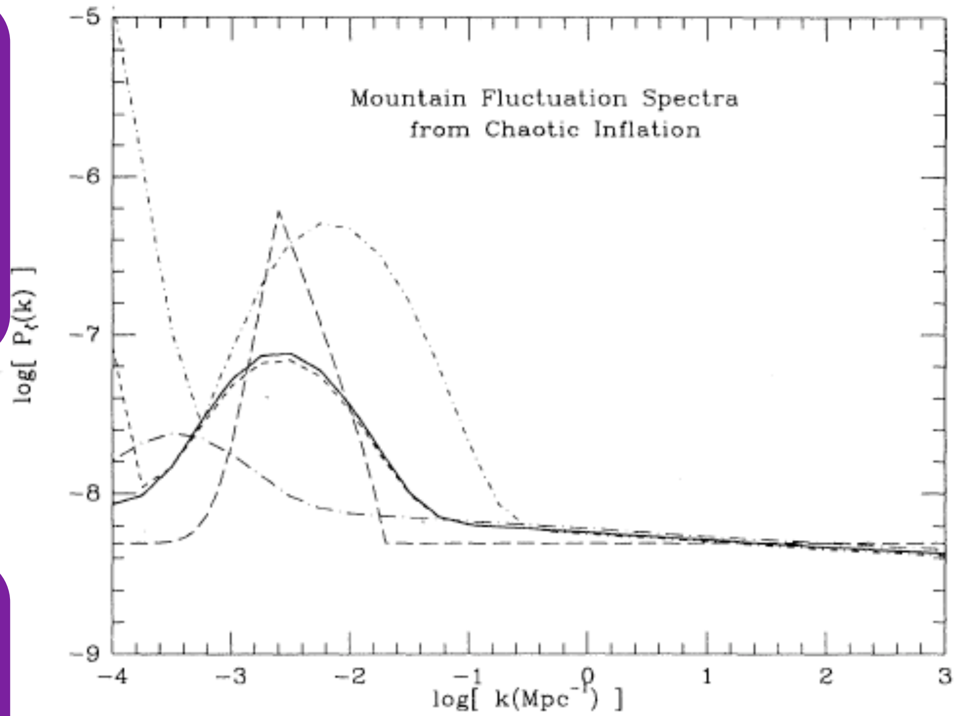
"theory prior"

informed priors?

The net result would be non-Gaussian fluctuations in ϕ_2. If the field ϕ_1 does not enter into a prolonged $m_{11}^2>0$ phase after the $m_{11}^2<0$ phase, significant non-Gaussian isocon fluctuations would survive. Thus the generic case for moguls centered about a $\phi_{1ri}(\phi_2)$ ridge line which is continuous with the incoming $\phi_{1tr}(\phi_2)$ trough line, as in the $\nu<0$, $\mu_1=0$ case of Sec. VI C, is a non-Gaussian "mountain," provided

$$\langle(\delta\phi_1)^2(\mathbf{x},t)\rangle^{1/2} \gtrsim |\bar{\phi}_1-\phi_{1ri}| \ . \tag{6.13}$$

In this expression, the quantum fluctuations $\langle(\delta\phi_1)^2(\mathbf{x},t)\rangle$ are assumed to have the short-distance rapidly oscillating $k^{-1} \lesssim (Ha)^{-1}$ waves filtered out. Note that starting from $\phi_1=0$ with a symmetric mogul leads to bifurcation of the field, which can lead to domain walls. To avoid a domain-wall density problem, we must suppose that either the mogul is localized in ϕ_2 or another interaction is present at lower energies to destroy the walls. In either case, the large-scale non-Gaussian metric perturbations will survive intact.



addition of cubic interaction terms to the potential (6.3) can also give $m_{11}^2<0$ over a short range. If they are symmetric about ϕ_{1tr}, the induced ϕ_2 fluctuations would again be non-Gaussian. [redacted] The nonlinear interaction of $\delta\phi_1$ with $\delta\phi_2$ generates adiabatic perturbations whose primordial amplitude ζ is quadratic in the Gaussian field $\delta\phi_1$ as evaluated at the end of the $m_{11}^2<0$ period. The spectrum has a mountain centered on the comoving wave number leaving the horizon at the beginning of the $m_{11}^2<0$ period. [redacted]

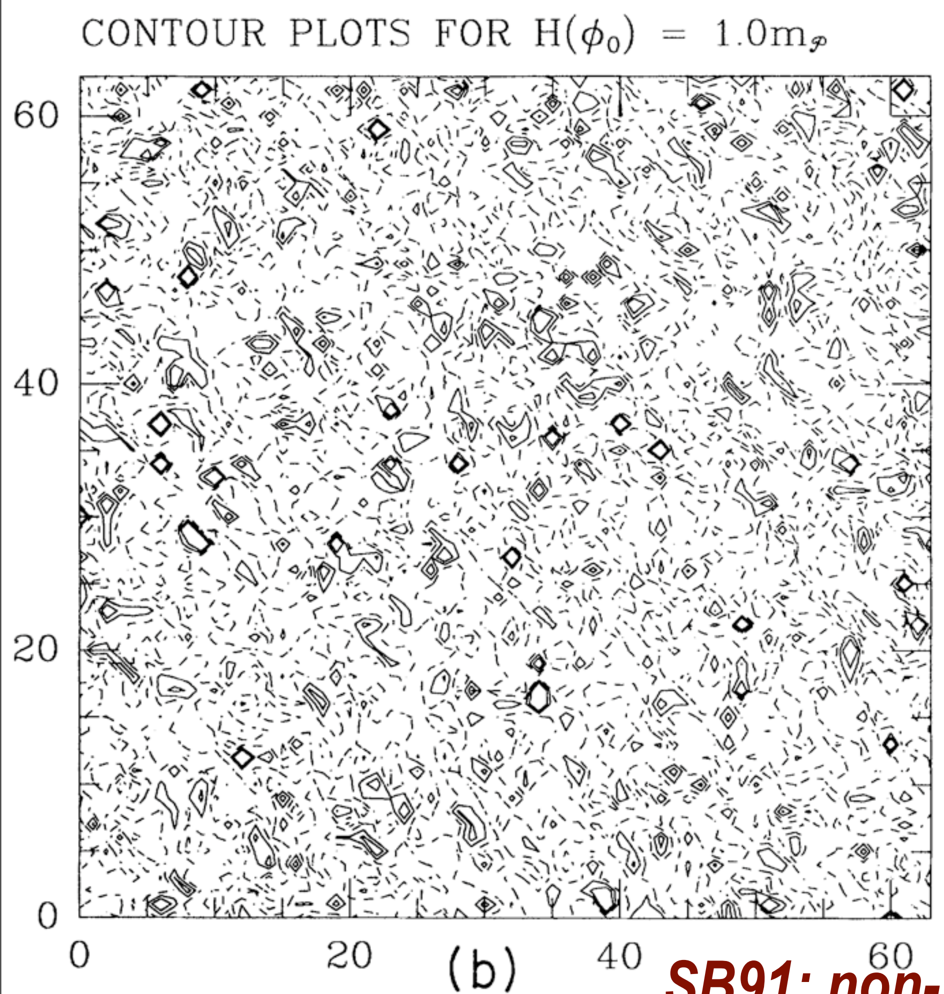
brief history of bond's non-Gaussian exploration in inflation: THEN

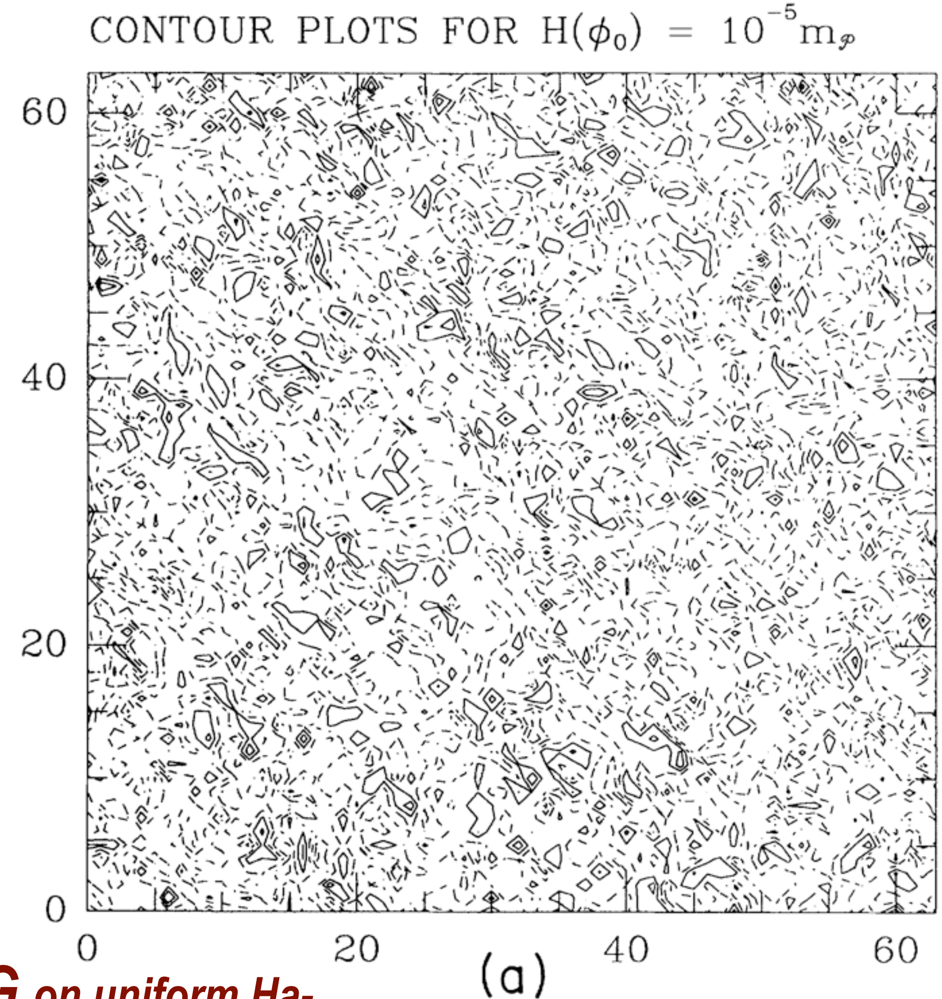
SB90/91: nonG technology: $\mathbf{y}(\mathbf{r},t) = \mathbf{y}_f(\mathbf{r},t) + \mathbf{y}_b(\mathbf{r},t)$ (+ $\mathbf{y}_{>h}(\mathbf{r},t)$) full EE+ϕ/χ eqs, restricted to the nonlinear longitudinal gauge (NL-LG); fluctuation/background split ⇒ *Langevin network*: $\mathbf{y}_f$ linearized (fn of $\mathbf{y}_b$); $\mathbf{y}_b(\mathbf{r},t)$ super-"horizon" $k < u\, Ha$,

drift+stochastic kicks; reduced Hamilton-Jacobi eqn; identify $\ln \mathbf{a}|_{H^*}$ as the nonlinear generalization of φ_{com} or ζ

setup for eternal alps (semi-eternal inflation, nonG at UUULSS, but nearly Gaussian over current horizon scales or baroque-ish V)

B91 *full NL-LG nonG Langevin* *network:* $\mathbf{Y}_{bi}(\mathbf{r},t) \in \{\phi, \Pi_\phi, \chi, \Pi_\chi, \ln a, H \mid T = \ln Ha\}$

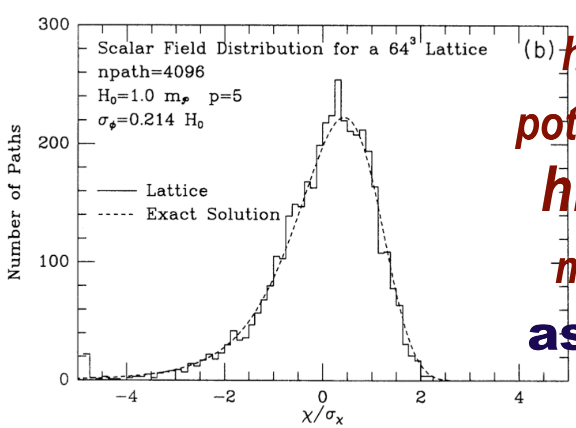


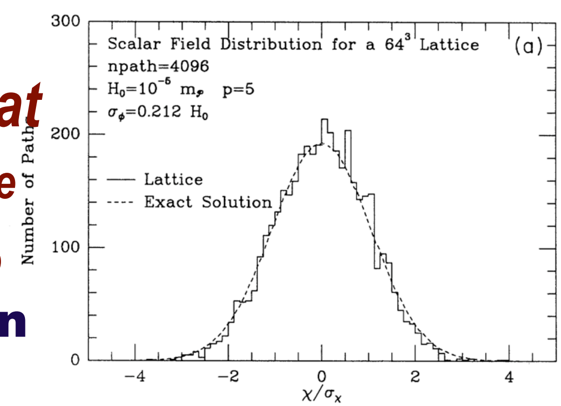


SB91: non-G on uniform Ha-hypersurfaces from a simple exponential potential **via quantum kicks > drift at high H_I~m_p uuUULSS** cf. observable nearly-**Gaussian at low H_I~$10^{-5}m_p$**

asymptotic flat eternal inflation

V has similar behaviour





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

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 ⇒

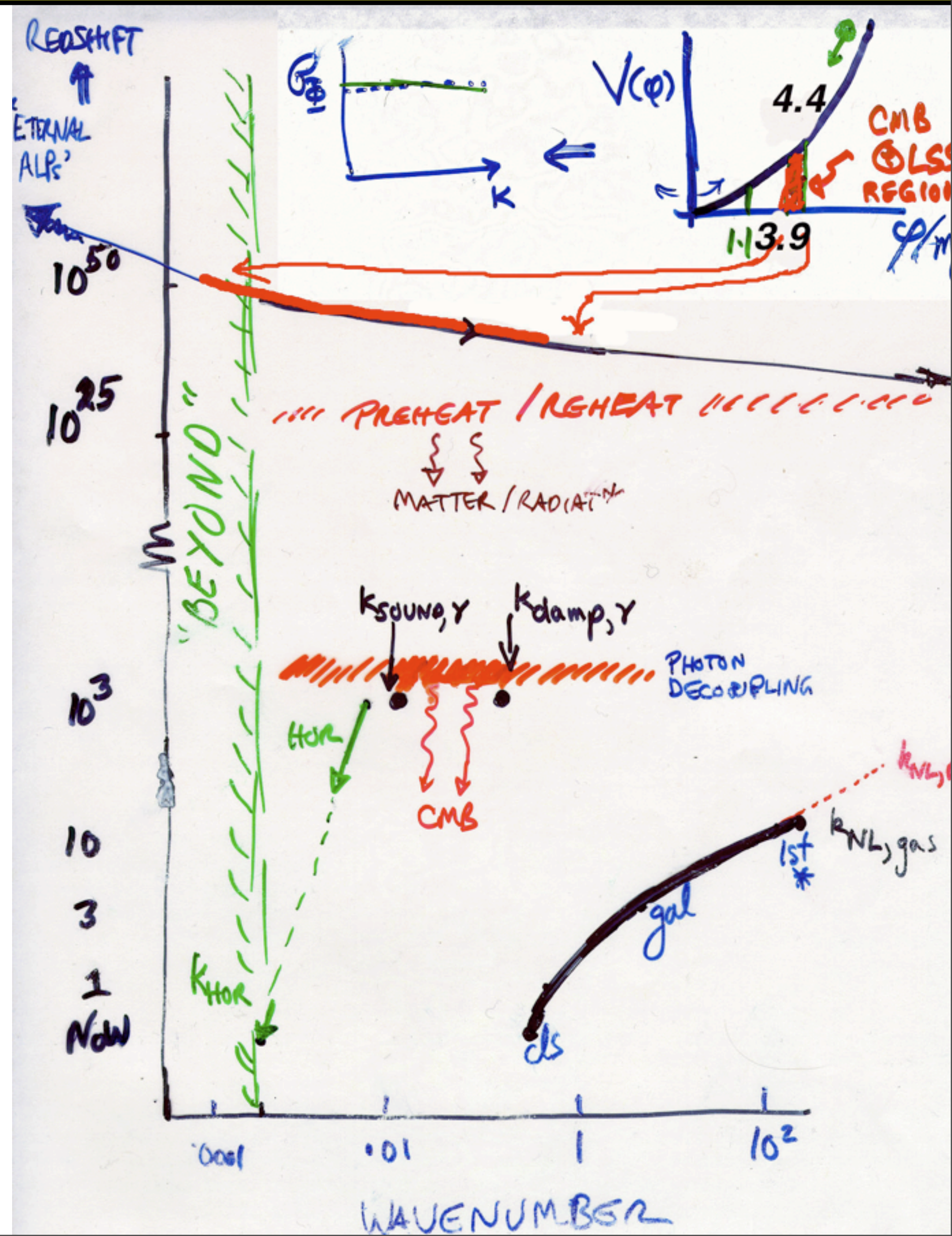
featureless (?) $P_{\varphi com}$ & P_{GW}

UUU...ULSS:

non-Gaussian

“eternal alps”

a veryVERYBIG U



brief history of bond's non-Gaussian exploration in inflation: THEN

B91 *full NL-LG nonG Langevin network:* $Y_{bi}(\mathbf{r},t) \in \{\phi, \Pi_\phi, \chi, \Pi_\chi, \ln a, H \mid T = \ln Ha\}$

NL-LG time is stochastic: $N_b dt = f_t \, d\ln k_H + f_t q_t \, dW(\ln k_H)$

resolution dimension ~ $\ln k_H$; ***Wiener increment*** $dW(\ln k_H)$ ***obeys***

$$\langle dW(\ln k_{H1}) \, dW(\ln k_{H2}) \rangle = \delta(\ln k_{H1} - \ln k_{H2}) \, d\ln k_H$$

mean drift: $d \langle Y_{bi} \rangle = \langle f_t \; F_{bi} \rangle \, d\ln k_H$

bgnd-fluctuations about mean: $d\delta Y_{bi} = \delta(f_t F_{bi}) d \ln k_H + [q_i + f_t F_{bi} q_t] \, d\ln k_H$

e.g., q_ϕ, $q_\chi = u \, H_b / 2\pi$

generally: **n** ***scalar fields at*** **m** ***spatial points*** $\Rightarrow$ **nm** ***independent Wiener increments***

80-90s: arena for BSI & non-G near EOI, new fields coupling in

expected k~Ha rule would apply. ***pre-heating surprise!***

ln a$[\chi_i(x,t)]$ **from "subgrid"** $\propto H_e^{-1}$ **lattice simulations of** ϕUHF χUHF

like stochastic f-b split, with no dropping of gradient or nonlinear terms

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

$1+w_0$, w_a $\theta \sim \ell_s^{-1}$ $\sim \ln \sigma_8^2$

+ subdominant isocurvature/ cosmic string ***& fgnds, tSZ,kSZ, ...***

+ primordial non-Gaussianity

$\varphi(x) = \varphi_G(x) + \mathbf{f_{NL}}\,(\varphi_G^2(x) - \langle\varphi_G^2\rangle)$

local smooth

$\varphi(x) = \varphi_G(x) + F_{NL}(\chi_b + \chi_{>h}) - \langle F_{NL}\rangle$

resonant preheating

DBI inflation: non-quadratic kinetic energy

$-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$

WMAP5 (± 5-10 Planck1yr)

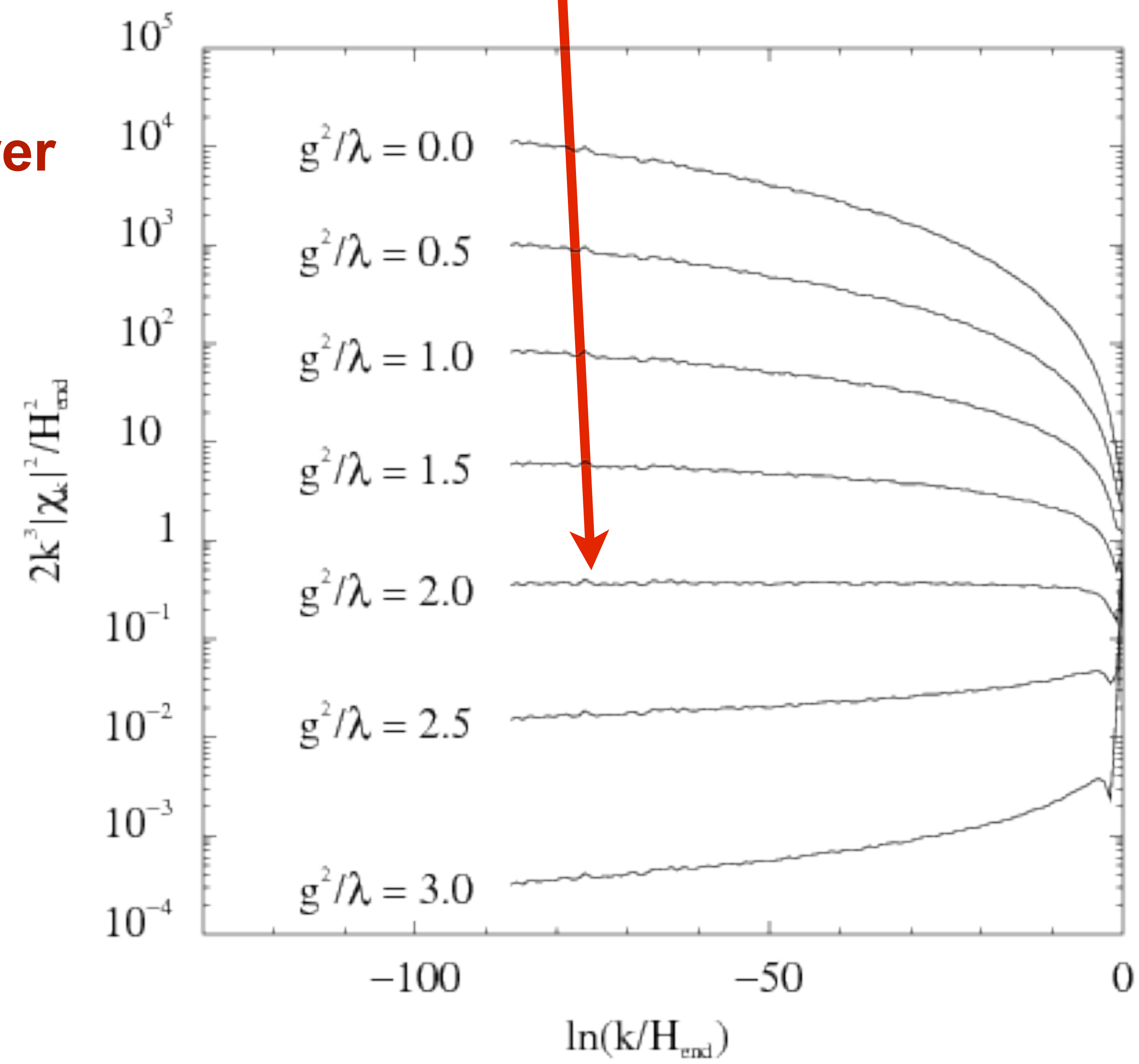
cosmic/fundamental strings/ defects from end-of-inflation & preheating

new parameters: **trajectory probabilities for early-inflatons & late-inflatons**

(partially) blind cf. informed "theory" priors

isocon power spectra are sensitive to g^2/λ

$\chi_i(x,t)$ power



characteristic smoothing scales

χ_{HF} $\sigma_{HF} \sim 7\text{x}10^{-7}$ ~50 e-folds

field smoothing over χ_{HF} $P(\chi|\chi_{LF}) \sim \exp[-(\chi-\chi_{LF})^2/2\sigma_{HF}^2]$

χ_{LF} *sqrt(*$\sigma_b^2 + \sigma_{>h}^2$*) SSS ~20 e-folds*

LSS χ_b $\sigma_b \sim 3\text{x}10^{-7}$ **~10 e-folds**

super-horizon $\chi_{>h}$ $\sigma_{>h} \sim$ *sqrt(*$N_{>h}$*)*x10^{-7}

~ $N_{>h}$ **e-folds** $N_{>h}$ **~100 to >10^4?**

"observed" $\chi_{>h}$ a random throw of the dice

dictates the nature of $< F_{NL}|\chi_b+\chi_{>h}>$

$P(\chi_{>h}) \sim \exp[-\chi_{>h}^2/2\sigma_{>h}^2]$

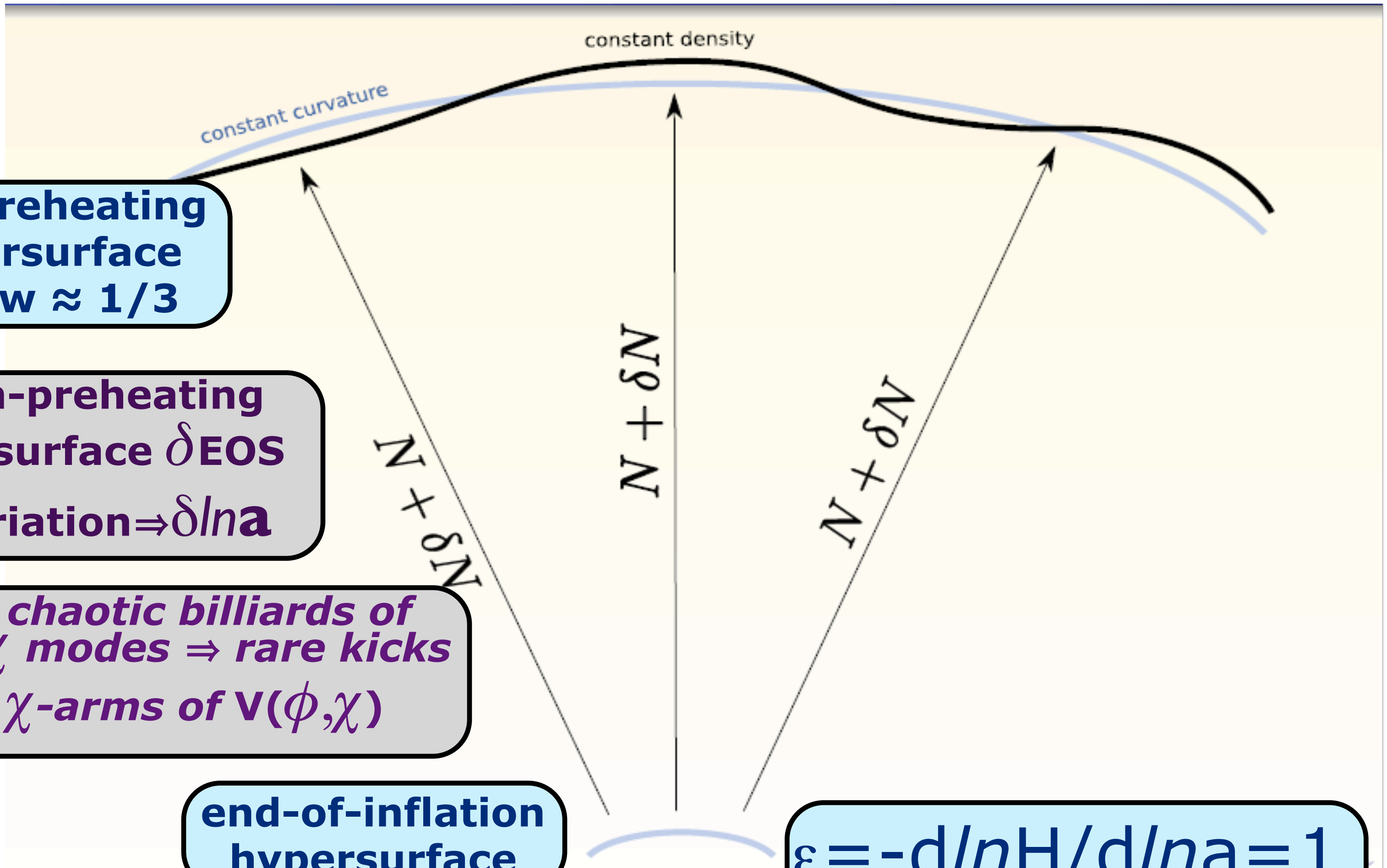
brief history of bfhk09 non-Gaussian exploration in inflation: NOW

Why $\ln a[\chi_i]$? ingredient 1 chaotic zero modes fill V arms, Lyapunov log-χ_i spacing, overtones as well; ingredient 2 arm flow shuts off when $m_{\chi\chi}^2$ rises sharply at vigorous preheating nonlinearity onset ⇒ EOS change

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

calculate how the expansion factor from the end of accelerated expansion (end of inflation) through preheating (copious mode-mode-coupling aka particle creation) to the onset of thermal equilibrium depends on $\chi_i(x,t)$

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



end-preheating hypersurface EOS w ≈ 1/3

begin-preheating hypersurface δEOS w-variation ⇒ $\delta \ln a$

linear chaotic billiards of k≈0 ϕ,χ modes ⇒ rare kicks into χ-arms of V(ϕ,χ)

end-of-inflation hypersurface

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

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

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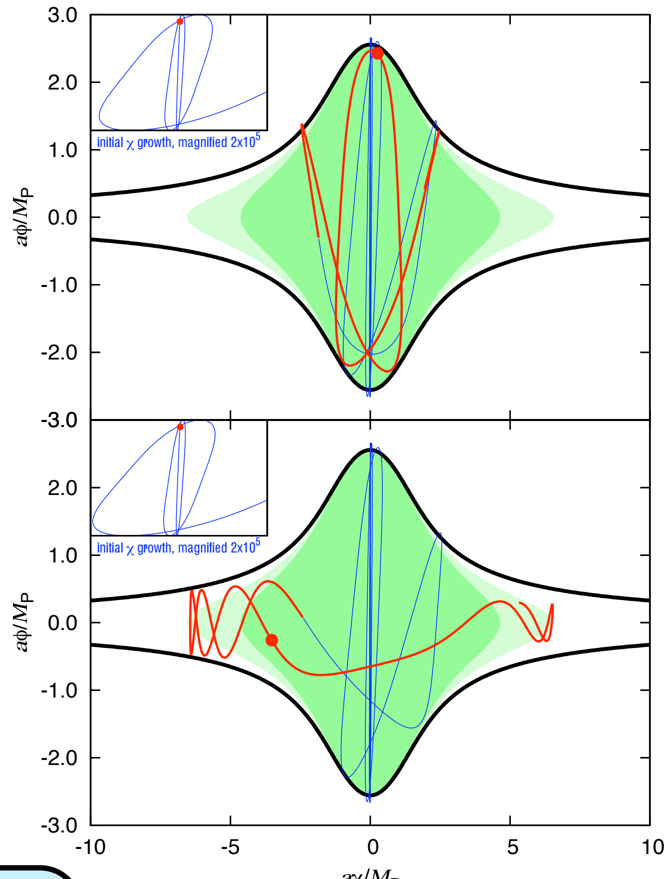
$\delta N = \delta \ln a|_H$ = *curvature fluctuation*



linear regime of zero-modes:

$\phi_0(t+T) = \phi_0(t)$

$\chi_0(t+T) = \chi_0(t) \exp[\mu_0 T]$

$\Rightarrow$ ***spikes are log*** χ_i ***spaced***

end-preheating hypersurface EOS w ≈ 1/3

begin-preheating hypersurface δEOS w-variation$\Rightarrow \delta \ln a$

linear chaotic billiards of k≈0 ϕ,χ modes ⇒ rare kicks into χ-arms of V(ϕ,χ)

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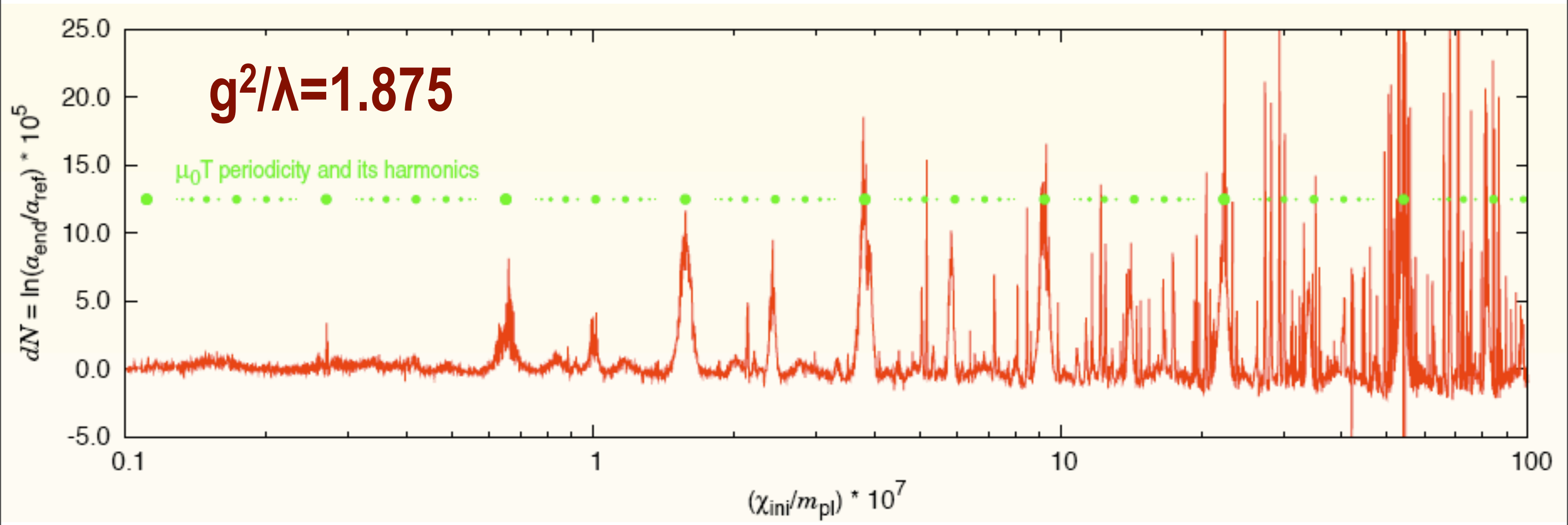
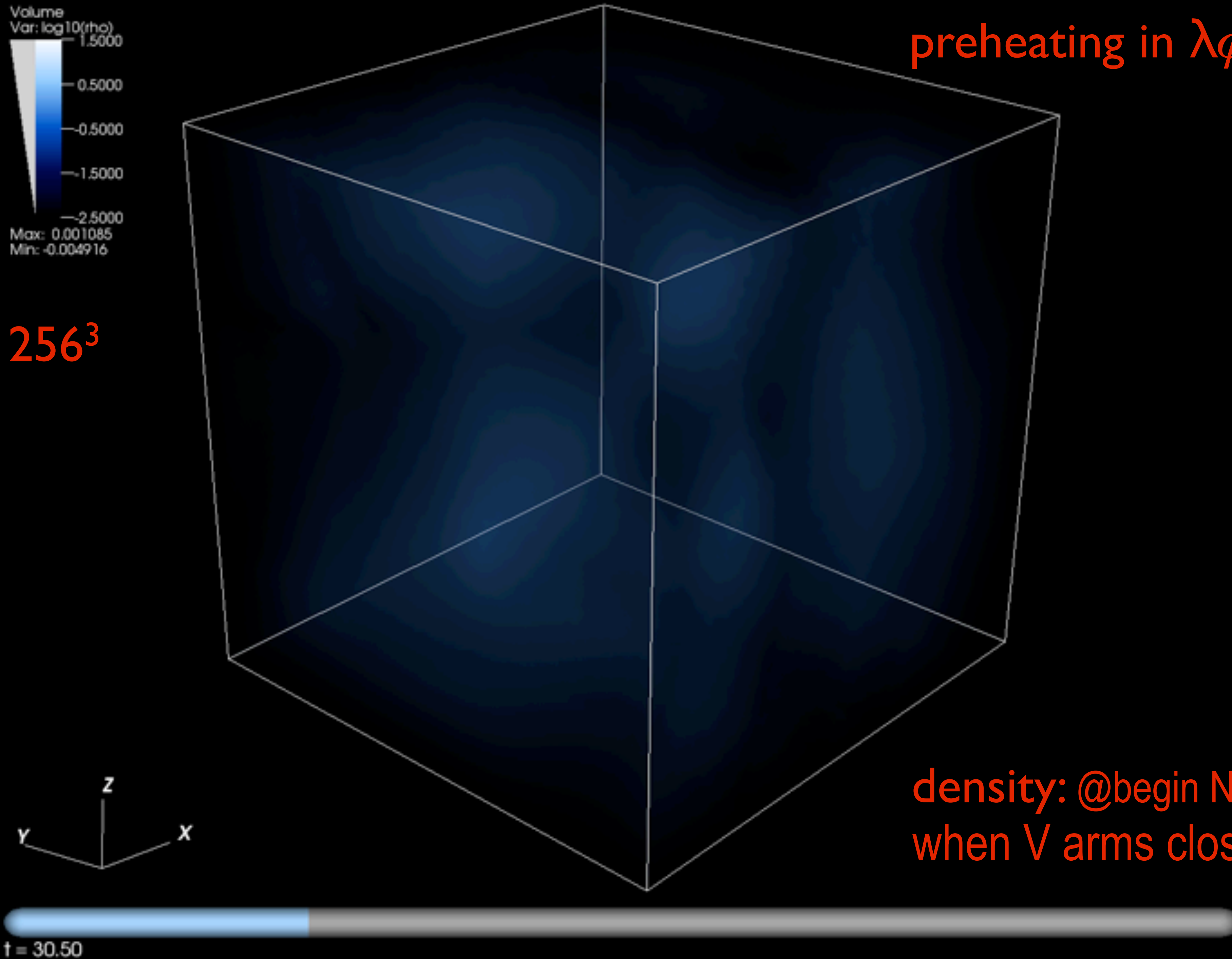

g²/λ=1.875
μ₀T periodicity and its harmonics
dN = ln(a_end/a_ref) * 10^5
(χ_ini/m_pl) * 10^7
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
0.1
1
10
100

preheating in $\lambda\phi^4$

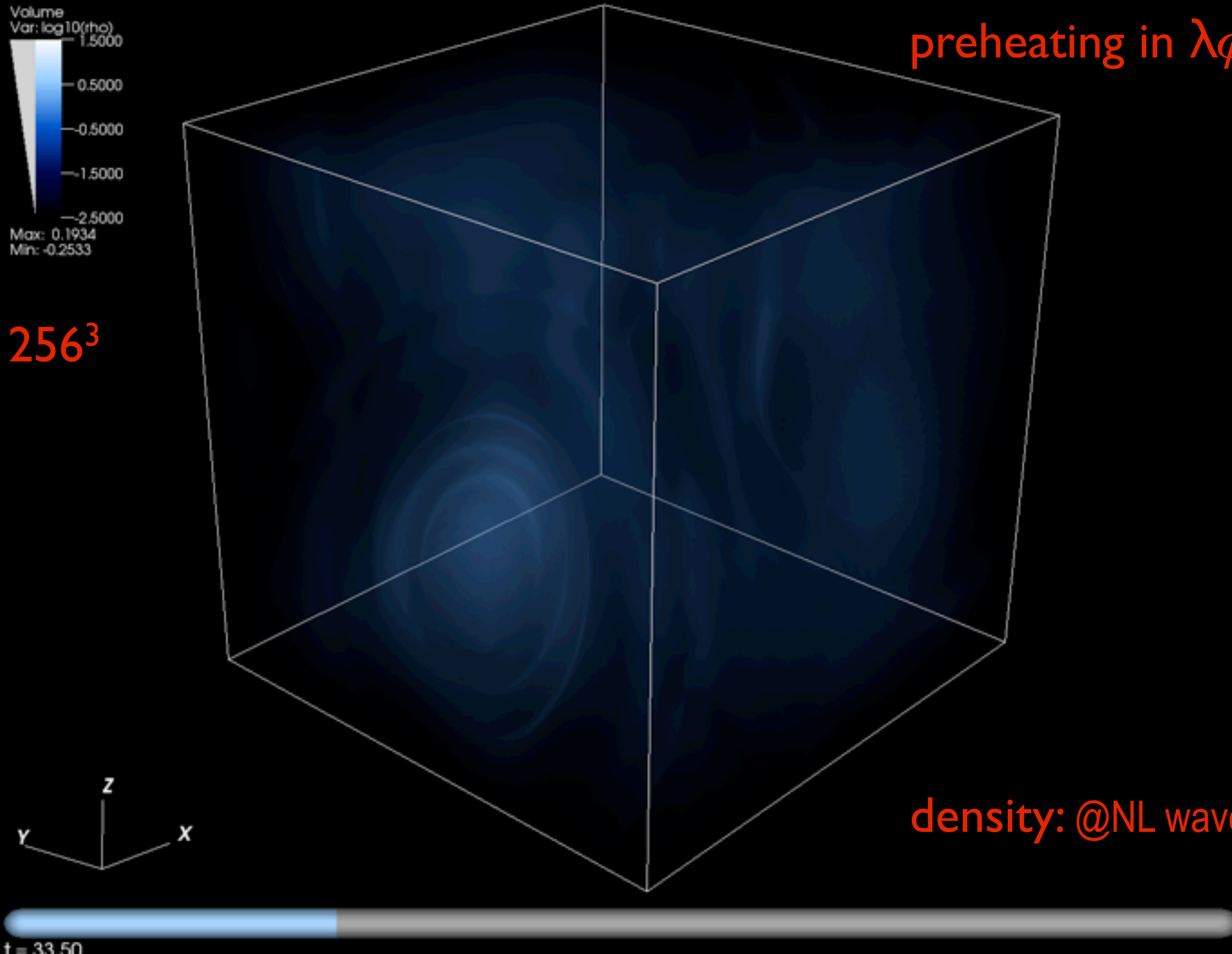
256^3



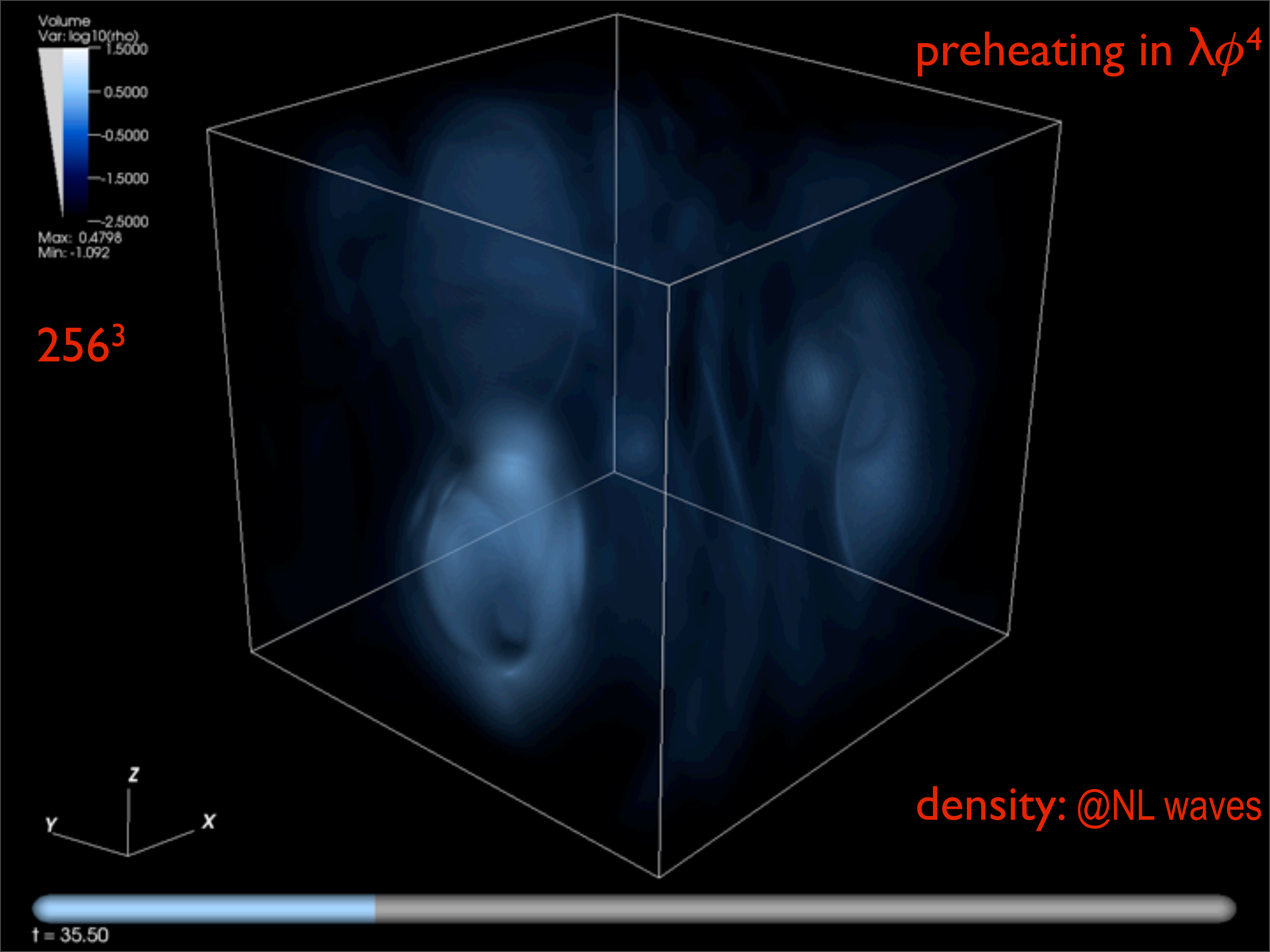
density: @begin NL, when V arms close

preheating in $\lambda\phi^4$

256^3



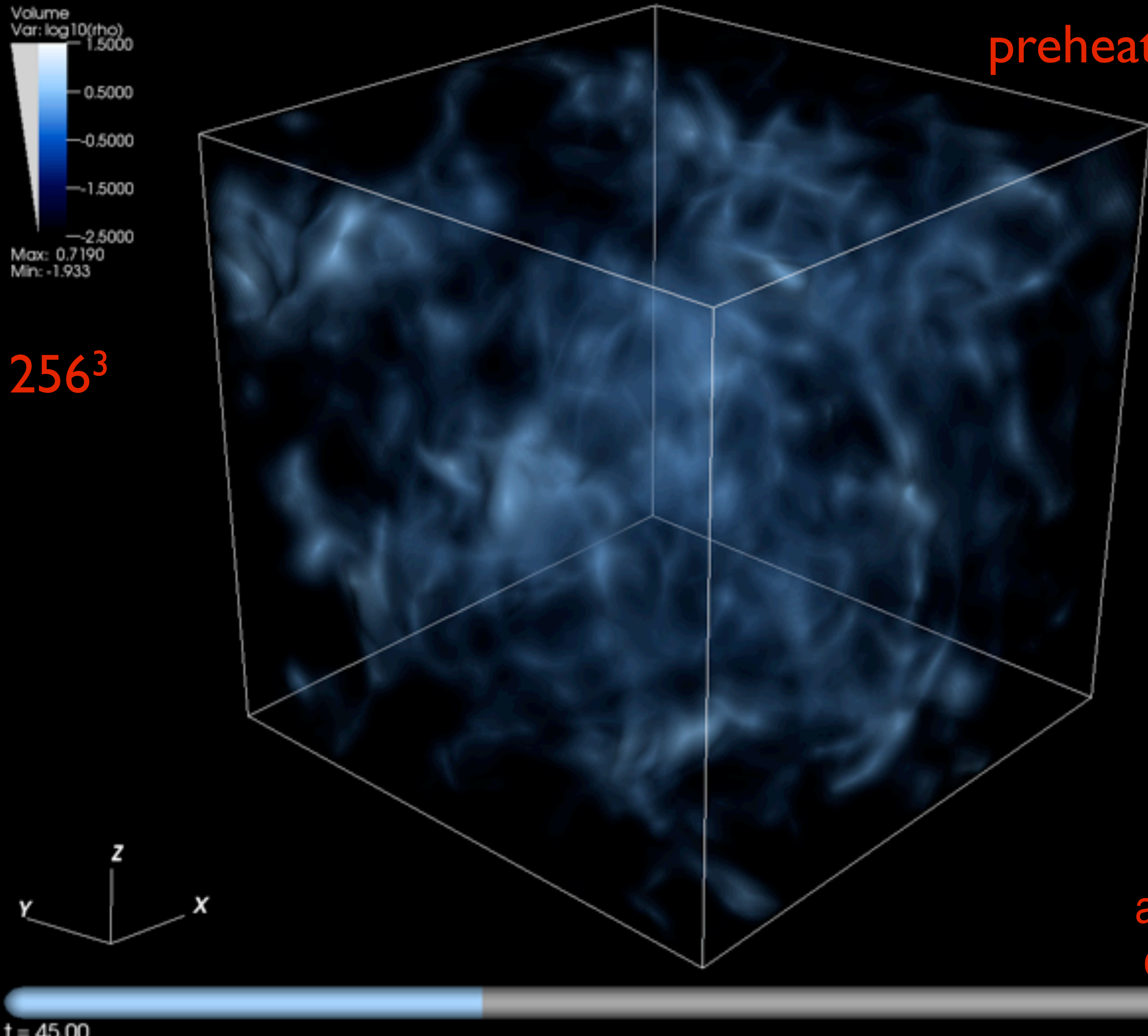
density: @NL waves



preheating in $\lambda\phi^4$
256^3
density: @NL waves
Volume
Var: log10(rho)
1.5000
0.5000
-0.5000
-1.5000
-2.5000
Max: 0.4798
Min: -1.092
Z
Y
X
t = 35.50

preheating in $\lambda\phi^4$

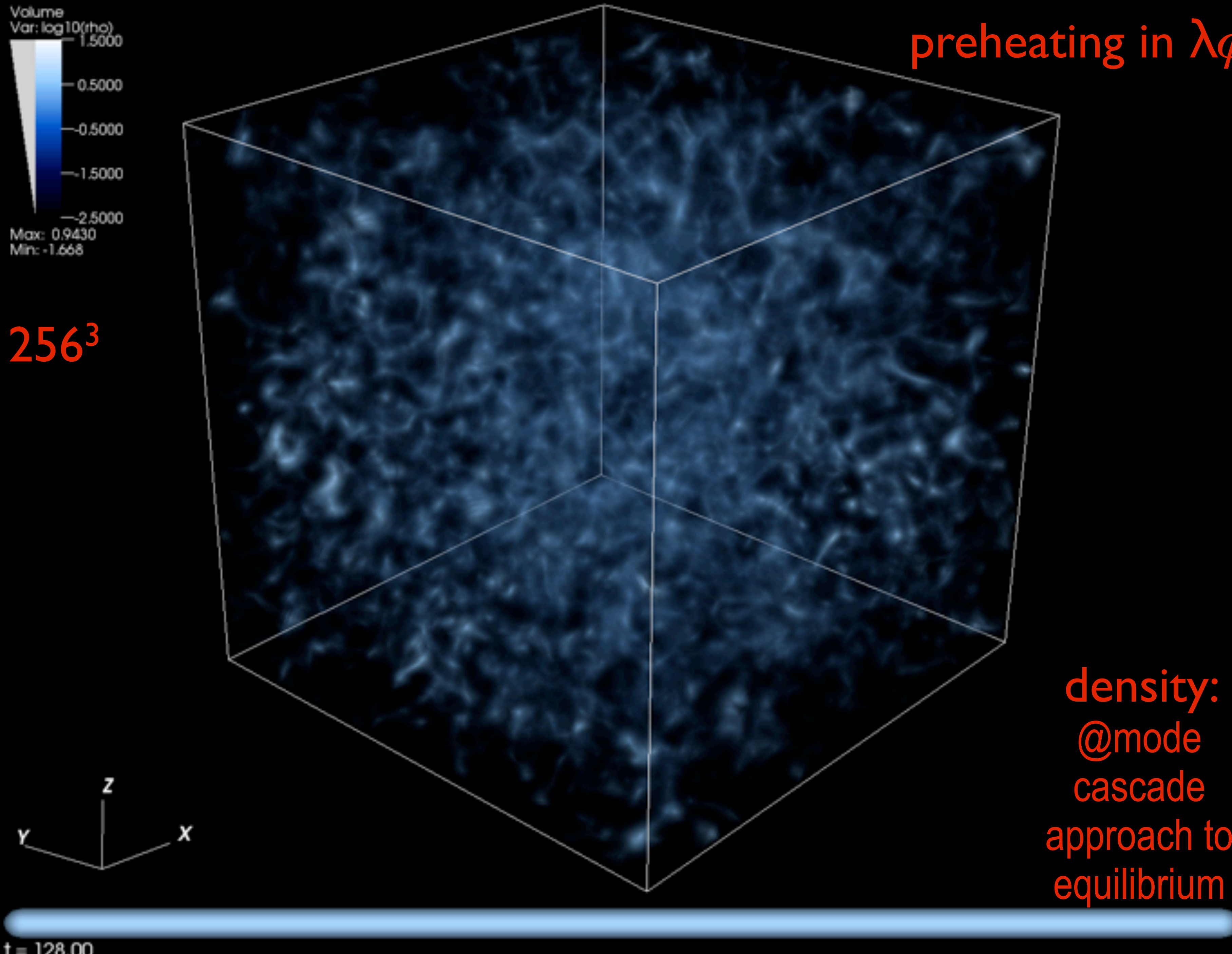
256^3



density:
@mode
cascade
approach to
equilibrium

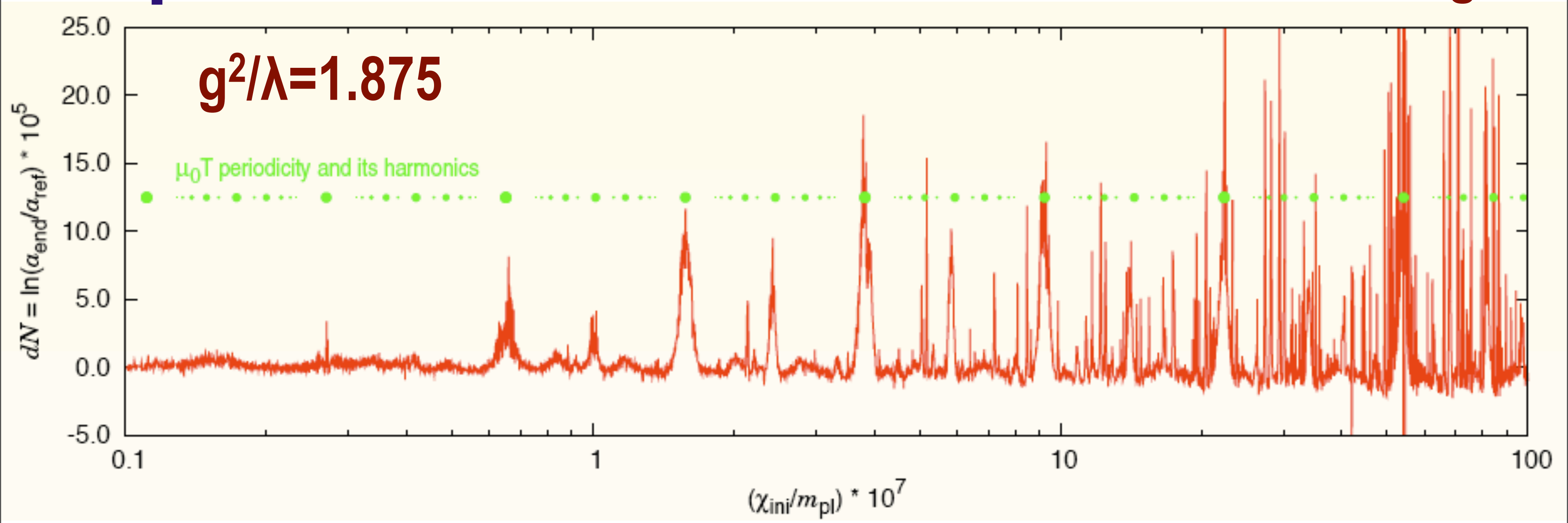
preheating in $\lambda\phi^4$

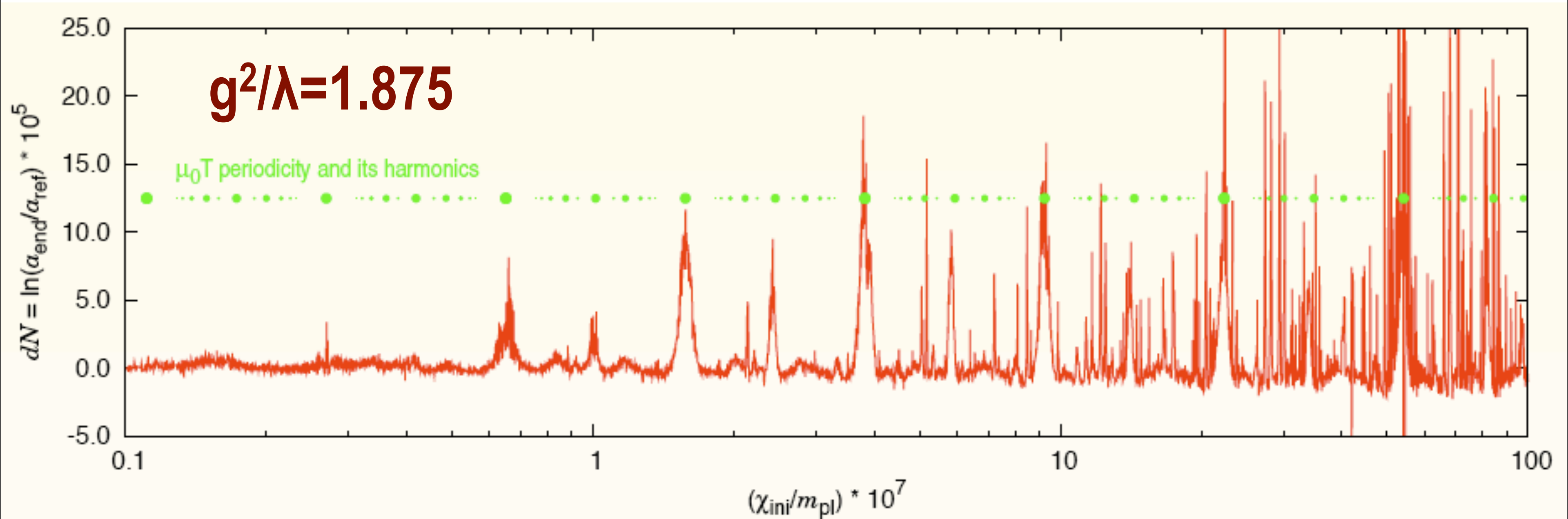
256^3



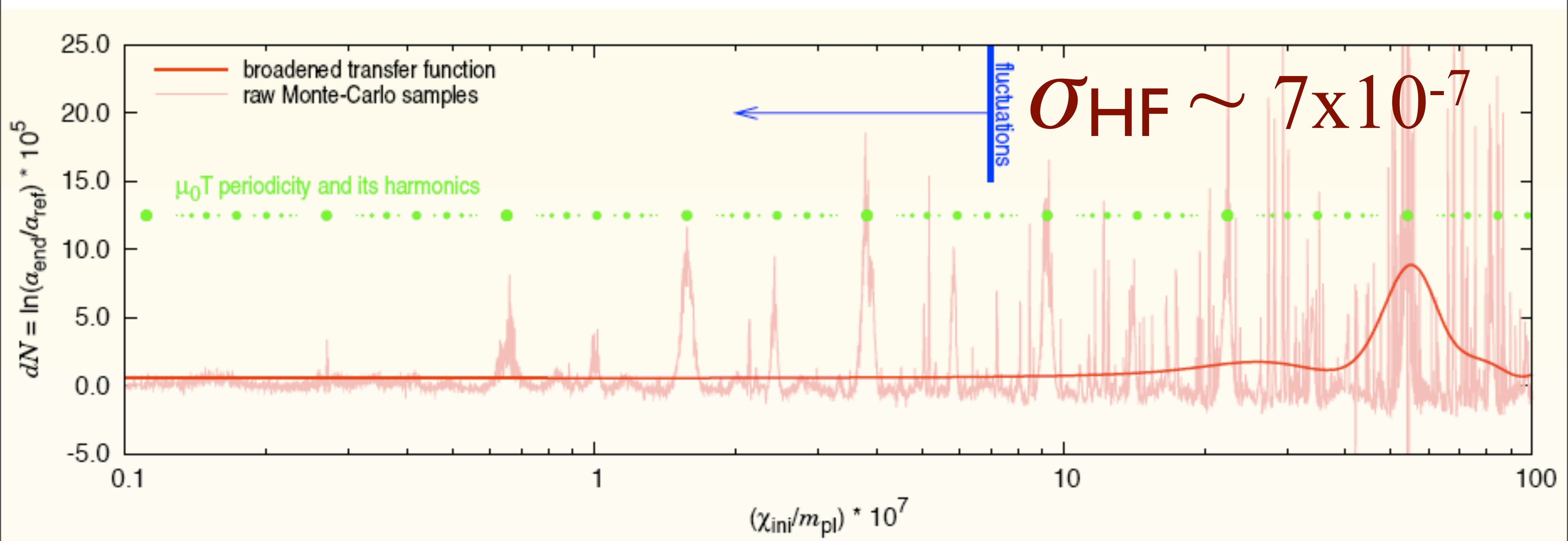
density:
@mode cascade
approach to equilibrium

to develop the $ln\,a(\chi_i)$ response curve, we perform > 10^4 lattice simulations for each g^2/λ





g²/λ=1.875
μ₀T periodicity and its harmonics
dN = ln(a_end/a_ref) * 10^5
(χ_ini/m_pl) * 10^7



broadened transfer function
raw Monte-Carlo samples
fluctuations
σ_HF ~ 7x10^-7
μ₀T periodicity and its harmonics
dN = ln(a_end/a_ref) * 10^5
(χ_ini/m_pl) * 10^7

brief history of bfhk09 non-Gaussian exploration in inflation: NOW

$P(\chi|\chi_{LF}) \sim \exp[-(\chi-\chi_{LF})^2/2\sigma_{HF}^2]$ builds a usable low-pass effective mean field

does it work? linear $\langle\chi|\chi_{LF}\rangle \sim \chi_{LF}$ is sharp-k filter f-b split BBKS86, BCEK90, BM96

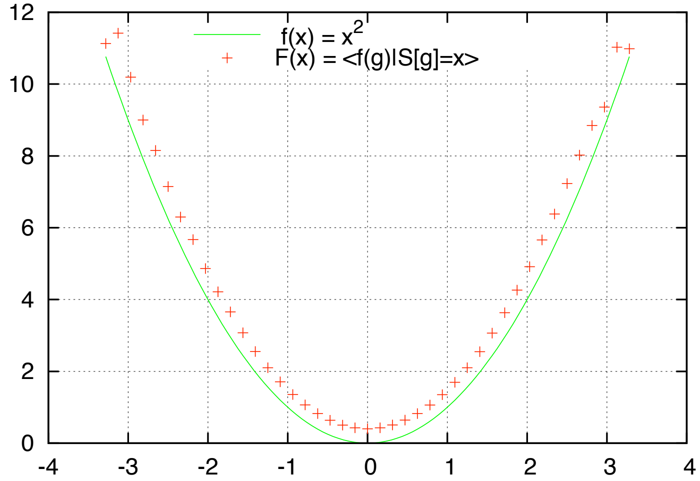
fourier transform (F_{NL} - $\langle F_{NL}|\chi_{LF}\rangle$) is small for $k<k_{LF}$ for quadratic, exponential & even Gaussian spikes (variance ~1% at k_{LF} 0.15 at $k_{LF}/10$)

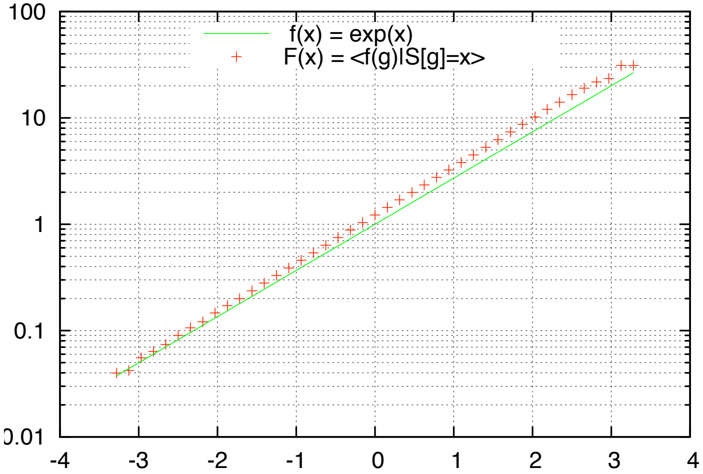
$\langle F_{NL}|\chi_b(x,t)+\chi_{>h}\rangle$ regimes

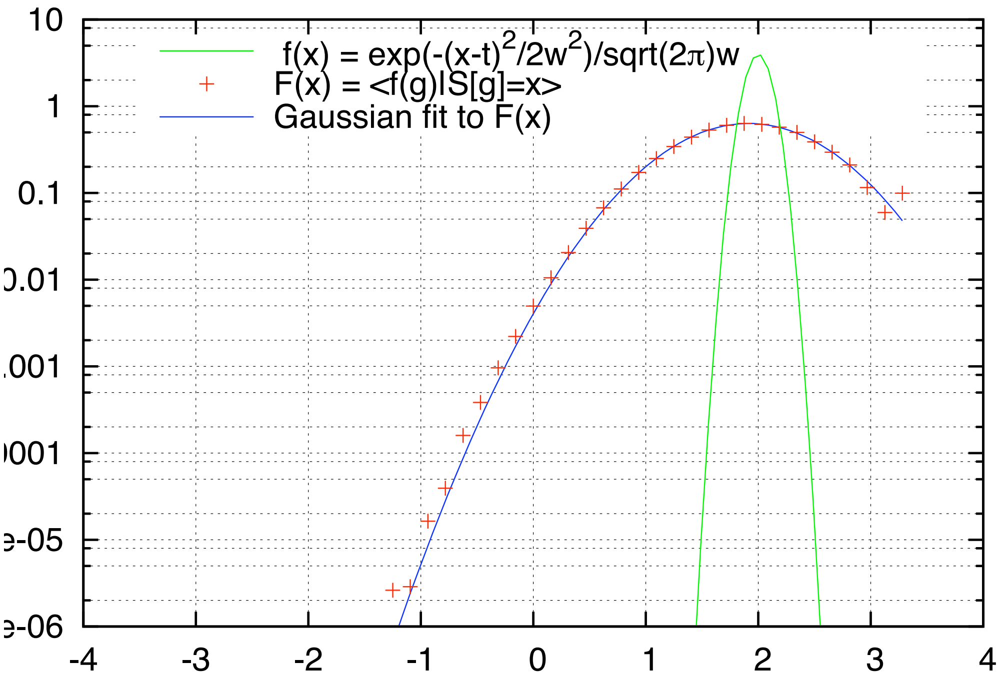
contrast with $\phi_{>h}$: may be way out there in eternal inflation land, but not in a preheated ε>1 patch

$F_{NL}(\chi_{HF}+\chi_b+\chi_{>h}) - F_{NL}(\chi_b+\chi_{>h})$

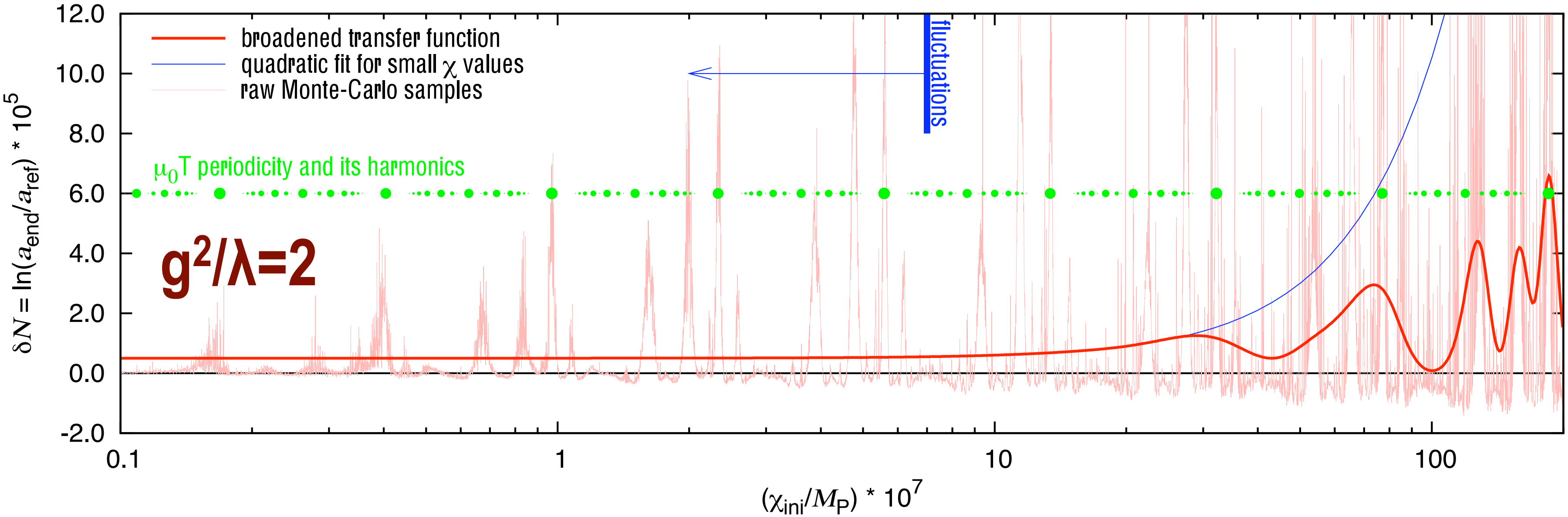
small for low k-filter

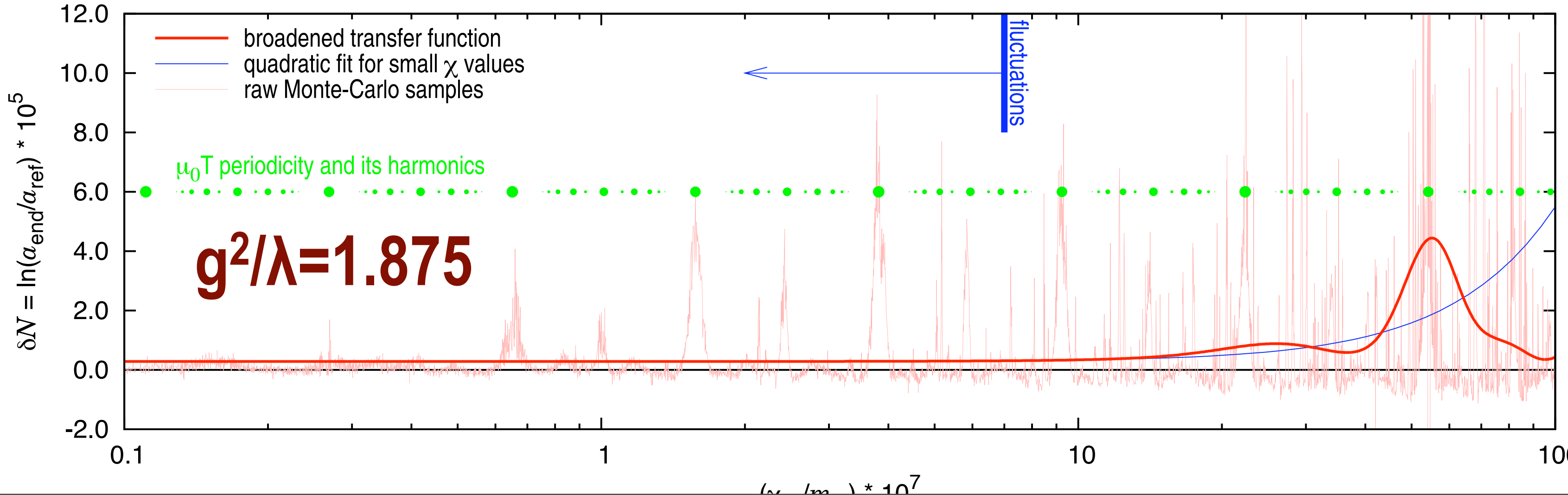






if the k=0 mode is in a parametric resonance band then *ln* **a**/a$_e$ is modulated by $\chi_{i}(x,t) = \chi_{HF} + \chi_{b} + \chi_{>h}$ with k<H$_e$a, treated as ~uniform over "subgrid" lattice sim determining χ_{UHF} & ϕ_{UHF}





brief history of bfhk09 non-Gaussian exploration in inflation: NOW

$\langle F_{NL} | \chi_b (x,t) + \chi_{>h} \rangle$ regimes

contrast with $\phi_{>h}$: may be way out there in eternal inflation land, but not in a preheated ε>1 patch

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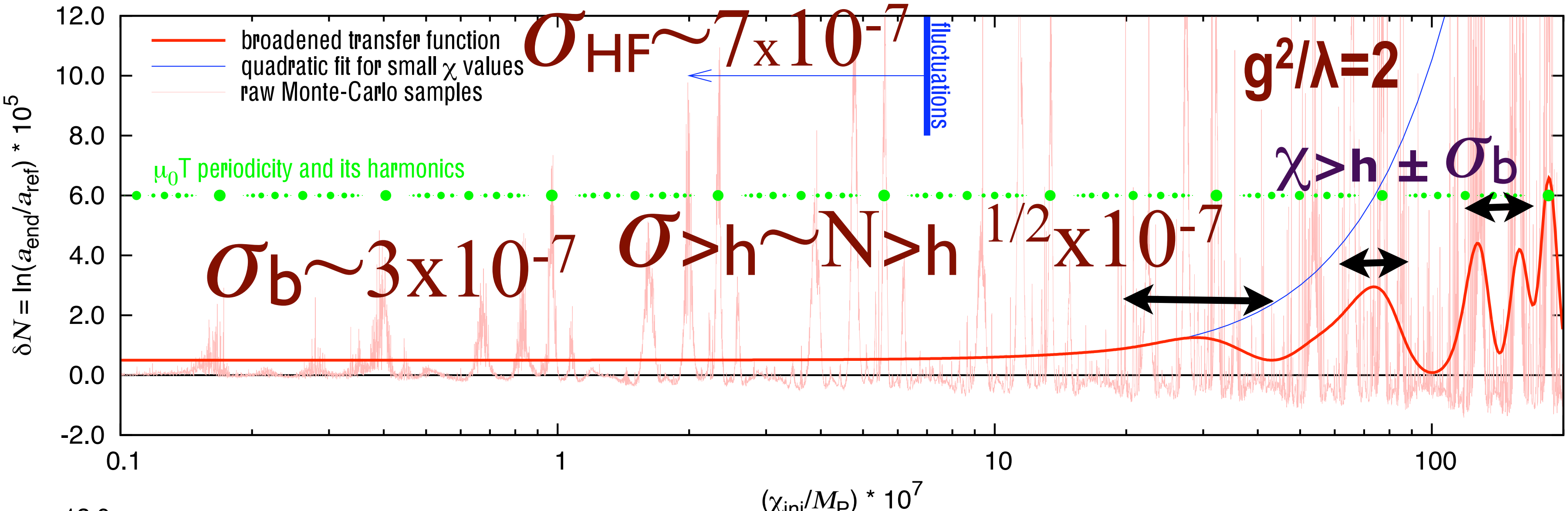
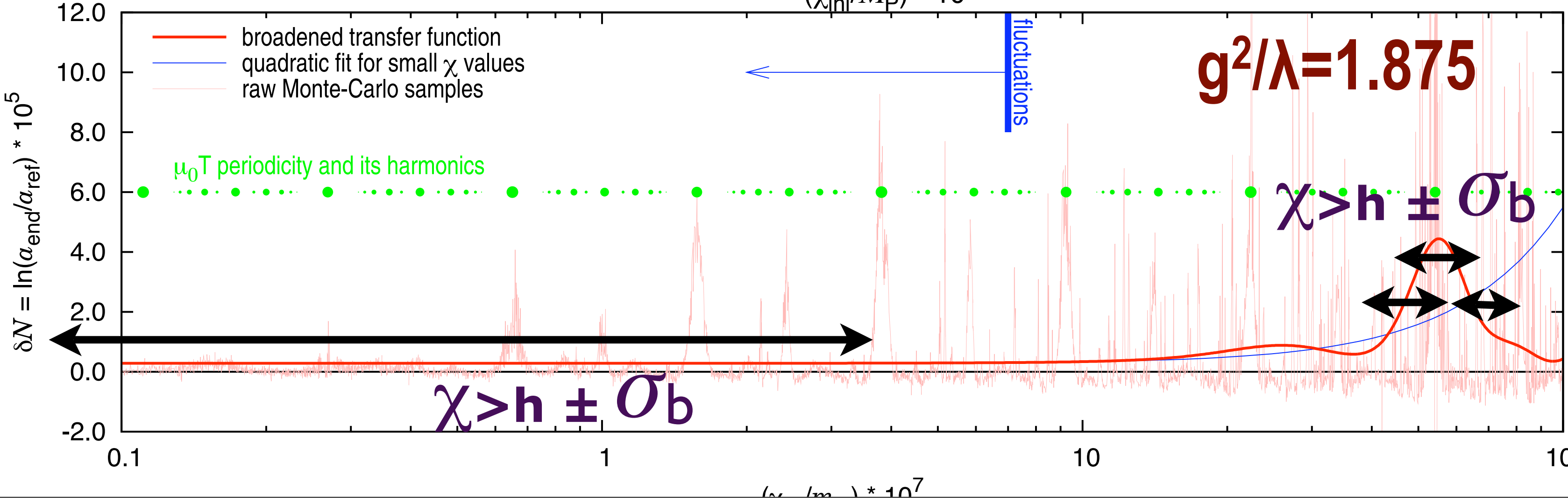
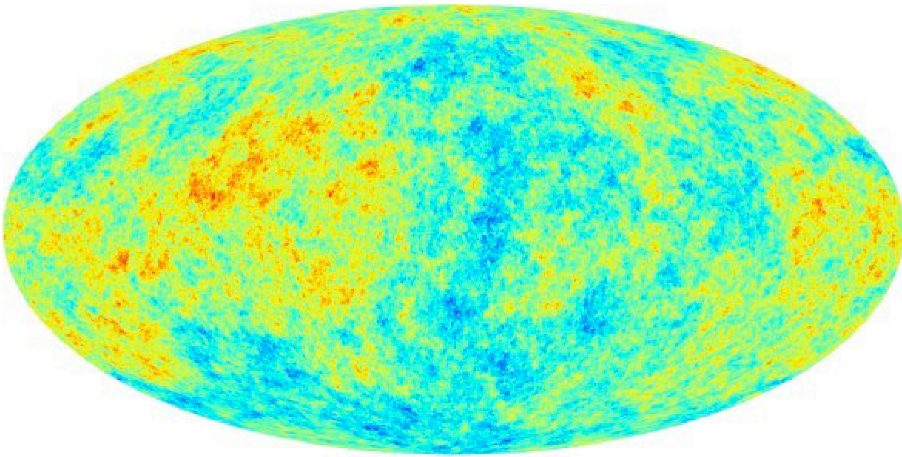


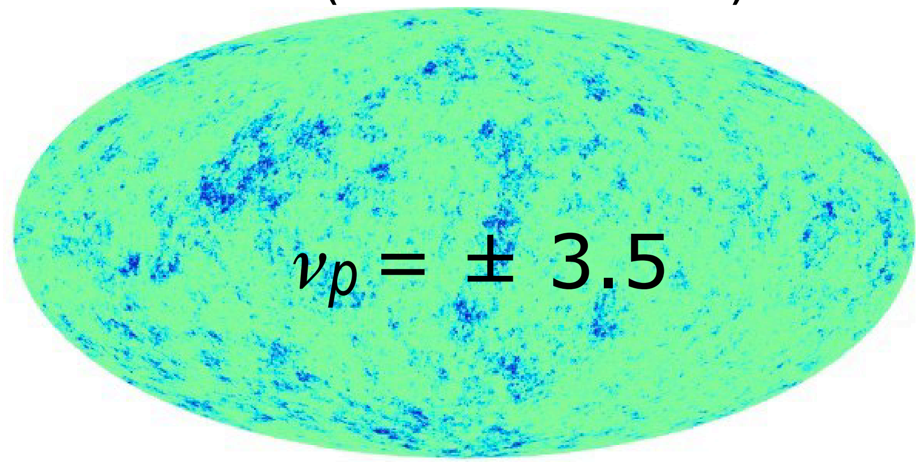


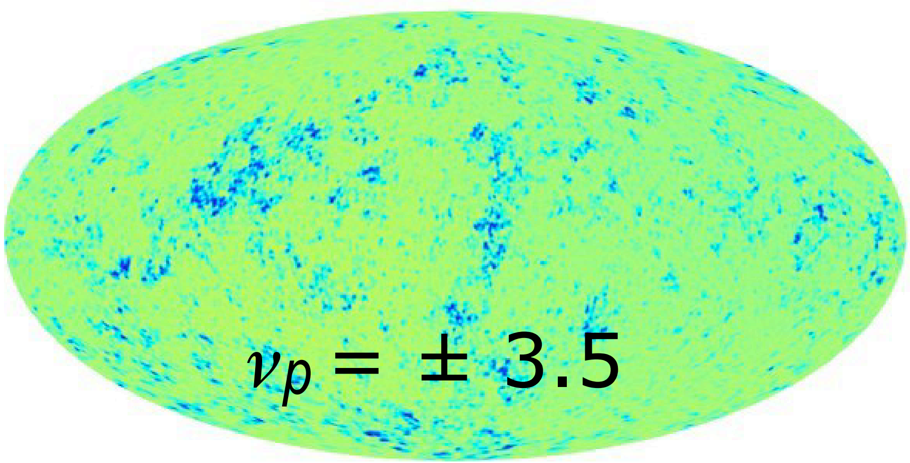
$\langle F_{NL} \mid \chi_b + \chi_{>h} \rangle \sim \pm \nu_p \, \sigma_b$ symmetrized Gaussian smoothed-spikes

scale invariant

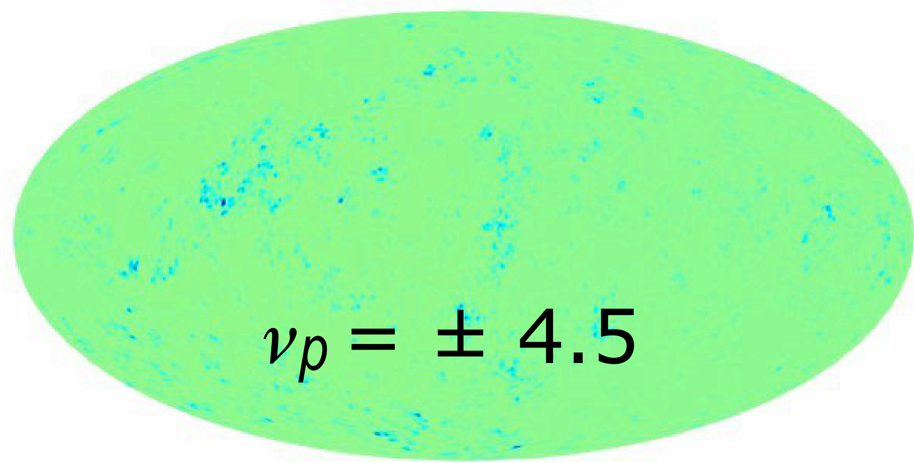


F_{NL} (scale invariant)





~ΔT[F_{NL} (scale invariant)] *1deg



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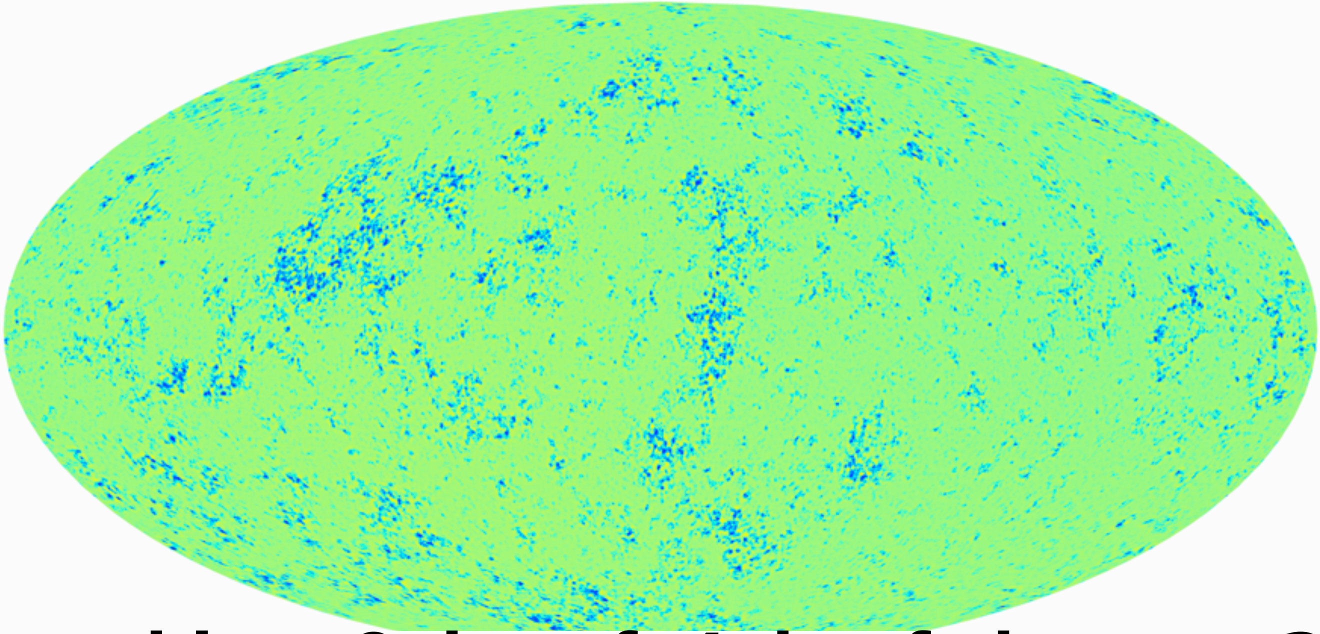
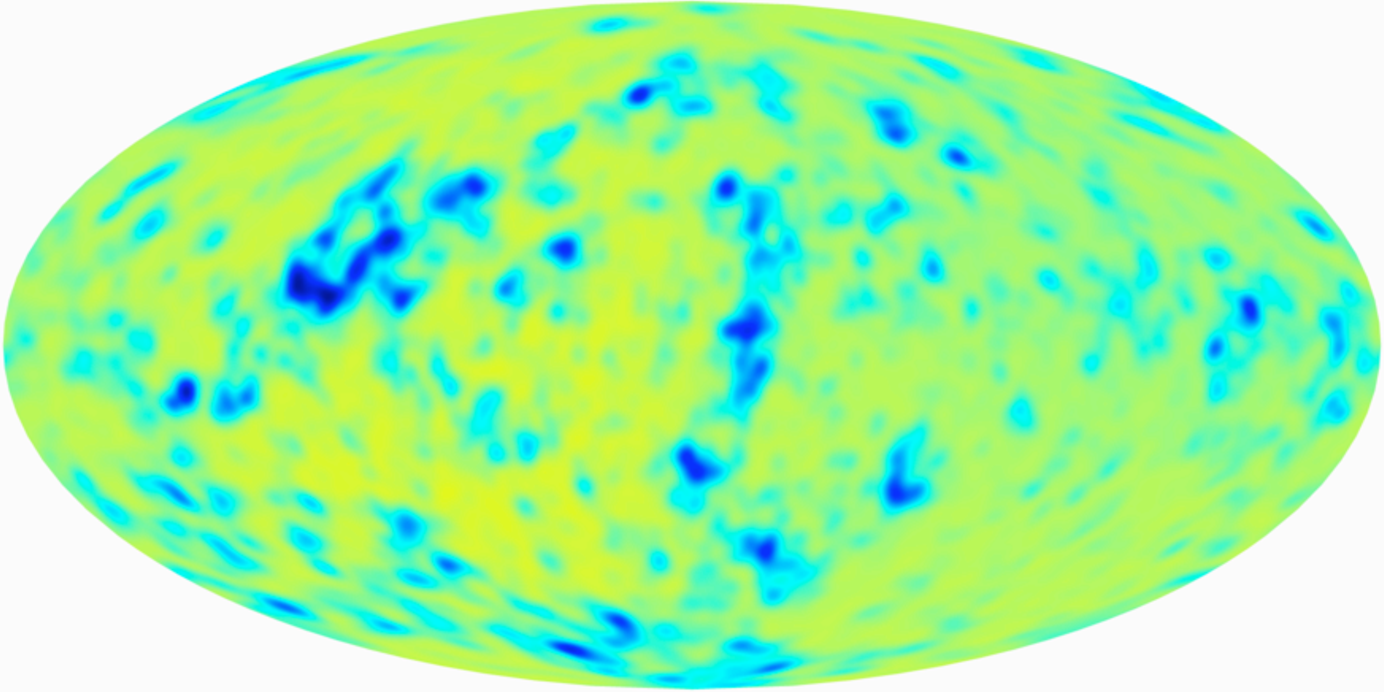
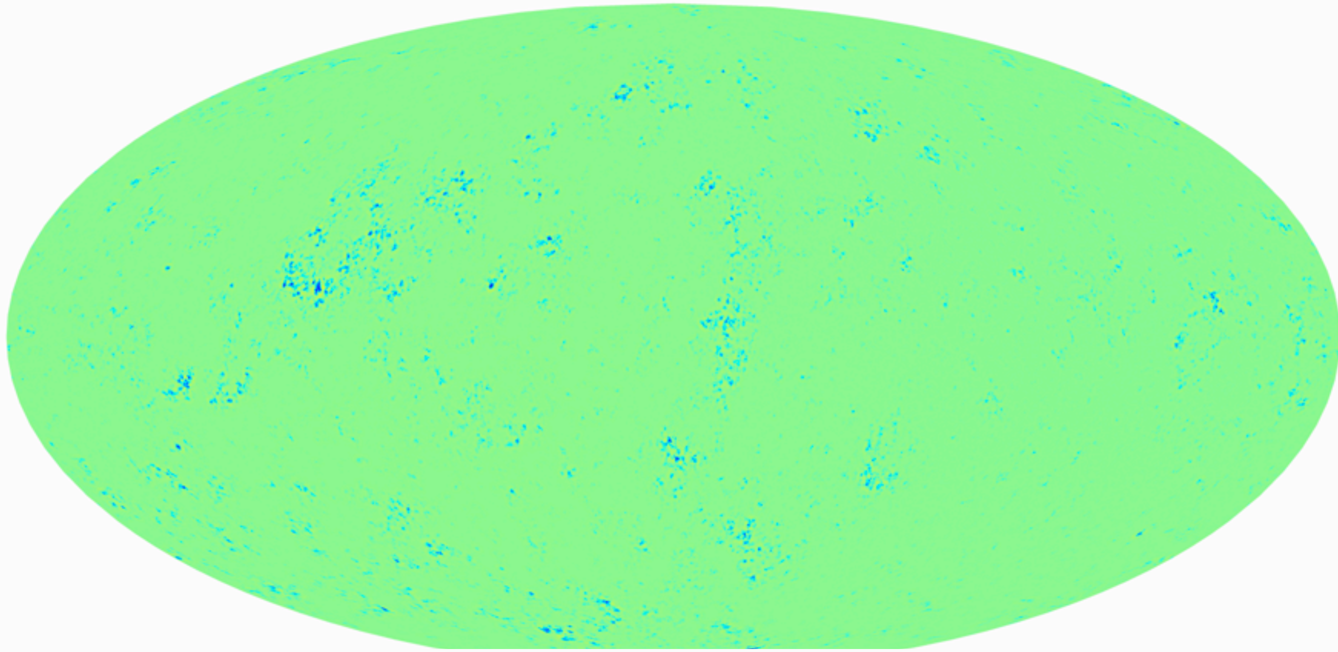


smoothing: 0 deg cf. 4 deg fwhm ν_p=3.5





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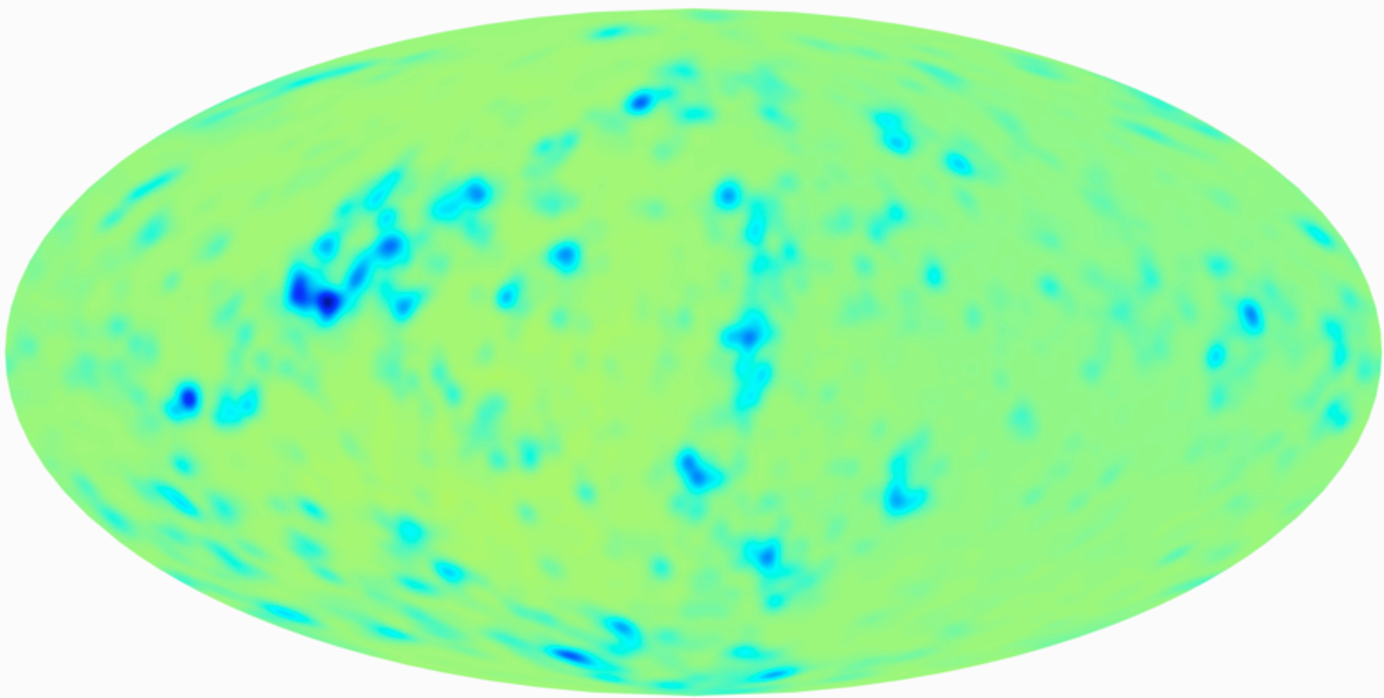
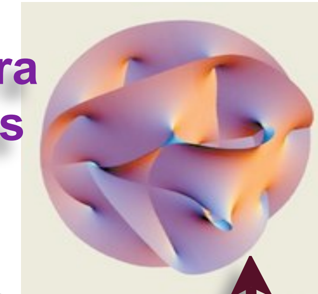


Old view: Theory prior = delta function of THE correct one and only theory

6/7 tiny extra dimensions



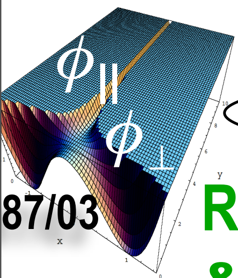
1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation



Double Inflation

Power-law inflation

SUGRA inflation

Radical BSI inflation

& non-Gaussianity

& baroqueness of V

variable M_P inflation

Extended inflation

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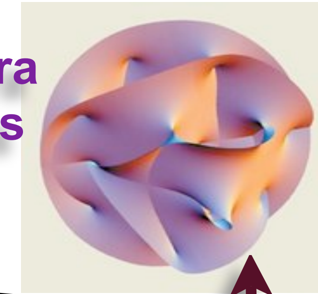

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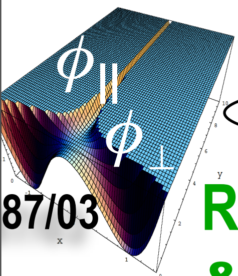

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87/03

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SUSY D-term inflation

Assisted inflation

Brane inflation

2000

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Super-natural Inflation

K-flation

2003 KKLT

N-flation

ekpyrotic/cyclic

D3,D7 brane inflation

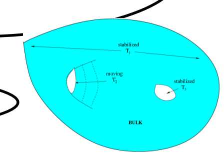
DBI inflation

moving brane separations

Warped Brane inflation

Tachyon inflation

Racetrack inflation

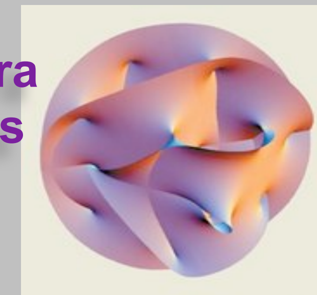


moduli fields

monodromy

Roulette inflation Kahler moduli/axion

6/7 tiny extra dimensions



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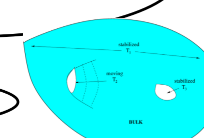


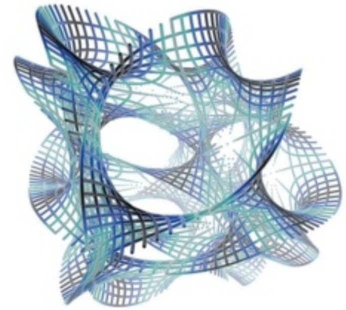
moduli fields

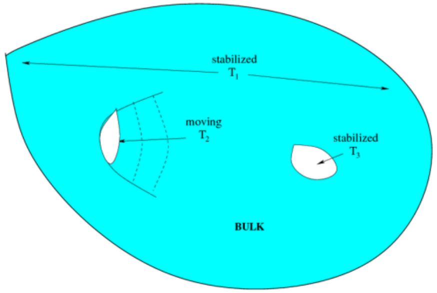
monodromy

Roulette inflation Kahler moduli/axion

Roulette:

which minimum for the rolling ball depends upon the throw; but which roulette wheel we play is chance too.

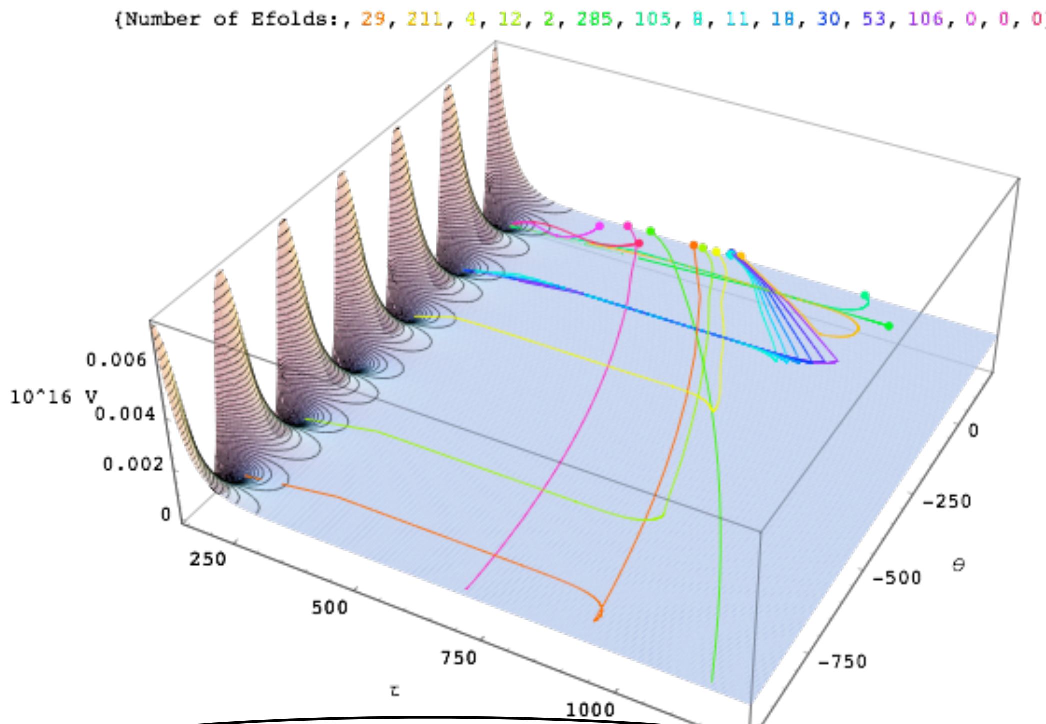




focus on "4-cycle Kahler moduli in large volume limit of IIB flux compactifications" Balasubramanian, Berglund 2004, + Conlon, Quevedo 2005, + Suruliz 2005

Real & imaginary parts are both important BKPV06

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



$$V \sim M_P^4 \, P_s \, r \quad (1-\varepsilon/3)\ 3/2$$

$$\sim (10^{16}\ \mathrm{Gev})^4 \quad r/0.1 \quad (1-\varepsilon/3)$$

$$\sim (\text{few } \times 10^{13}\ \mathrm{Gev})^4$$

$$n_s \sim -\, d\ln \varepsilon / d\ln k / (1-\varepsilon)$$

i.e., a finely-tuned potential shape

Roulette inflation Kahler moduli/axion

Trajectories in a Kahler modulus potential

τ_2 vs θ_2

$T_2=\tau_2+i\theta_2$

Fixed τ_i θ_i

i.e., **$i \neq 2$**

stabilized preheating

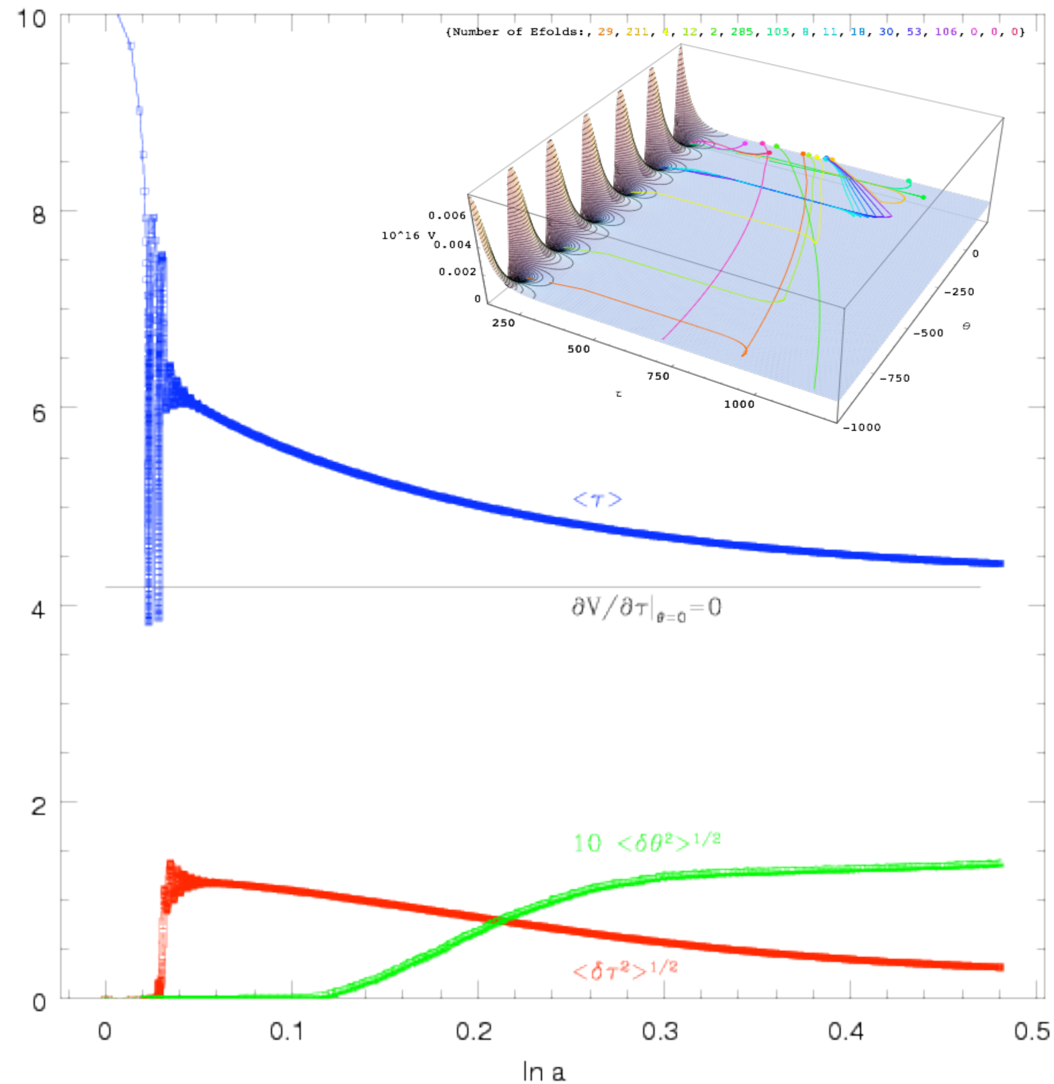
θ_2 settled in so approach pre-h in τ_2 trough

later nonlinear θ_2 is excited. **no $\delta \ln a$ but other modes should be important in endgame**

(stringy burst, SM coupling , ...)

$$V(\tau,\theta) = \frac{8(a_2A_2)^2\sqrt{\tau}e^{-2a_2\tau}}{3\alpha\lambda_2\mathcal{V}_m} - \frac{4W_0a_2A_2\tau e^{-a_2\tau}\cos(a_2\theta)}{\mathcal{V}_m^2} + \Delta V$$

& modified kinetic energy



80-90s: arena for BSI & non-G near EOI, new fields coupling in ***expected k~Ha rule would apply. pre-heating surprise!***

lna$[\chi_i(x,t)]$ **from "subgrid"** $\propto$ **H_e^{-1} lattice simulations of** ϕ_{UHF} χ_{UHF}

like stochastic f-b split, with no dropping of gradient or nonlinear terms

Why *lna*$[\chi_i]$? ingredient 1 chaotic zero modes fill V arms, Lyapunov log-χ_i spacing, overtones as well; ingredient 2 arm flow shuts off when $m_{\chi\chi}^2$ rises sharply at vigorous preheating nonlinearity onset ⇒ EOS change

$P(\chi\,|\,\chi_{LF}) \sim \exp[-(\chi-\chi_{LF})^2/2\sigma_{HF}^2]$ builds a usable low-pass effective mean field

does it work? linear $\langle\chi\,|\,\chi_{LF}\rangle \sim \chi_{LF}$ is sharp-k filter f-b split BBKS86, BCEK90, BM96

fourier transform $(F_{NL} - \langle F_{NL}\,|\chi_{LF}\rangle)$ is small for $k<k_{LF}$ for quadratic, exponential & even Gaussian spikes (variance ~1% at k_{LF} 0.15 at $k_{LF}/10$)

$\langle F_{NL}\,|\chi_b(x,t)+\chi_{>h}\rangle$ regimes

contrast with $\phi_{>h}$: may be way out there in eternal inflation land, but not in a preheated ε>1 patch

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LARGE $\chi_{>h}$ encompass part of a smoothed spike, upside, downside, topside

Observables and conclusions

$$\varphi(x)= \varphi_\phi(x)+ f_{NL}\,(\varphi_\phi{}^2(x)-<\varphi_\phi{}^2>)$$

local quadratic non-G constraint: $-9< f_{NL}<111 \Rightarrow -4< f_{NL}<80$ WM5 ($\pm$ 5-10 Planck1yr)

$$\Rightarrow \varphi(x)= \varphi_\phi(x)+ F_{NL}(\chi_{b+}\chi_{>h})-<F_{NL}>$$

resonant preheating form

modulated curvature fluctuations from preheating are superimposed on the usual curvature fluctuations from the inflaton. need $\delta\varepsilon$

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

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

As long as $g^2/\lambda \leq O(1)$ - SUSY-inspired is 2 - the χ field has very long wavelength perturbations (similar to, but uncorrelated with, the inflaton field)

Large & Small Scale Structure statistics of spiky F_{NL} map: under investigation

Rich possibilities in theory space & on the sky

e.g., $<\delta F_{NL}|\chi_{LF}> \sim$ linear+

e.g., $F_{NL}(\chi) \sim \Sigma_p F_p \exp(-(\chi\pm\chi_p)^2/2\gamma_p{}^2) \Rightarrow$ quadratic regime; **cold spot regime**: non-G ubiquitous