CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

25 years cifar

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

Universe=System+Res =Data+Theory ***en-TANGO-ment***

Dick Bond CIAR

the **Cosmotician's** *Agenda:* ***Statistical Paths*** *in Cosmic Theory & Data*

Entropy/Information Generation *in Post-inflation Preheating:* ***A Shock-in-Time***

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Entropy/Information Generation in Post-inflation Preheating: A Shock-in-Time

we compress the Petabit++ observed cosmic info into a precious few bits encoding 6+ parameters of the Minimal Cosmic Standard model (LCDM)

ρ_{dm}/ρ_b=5.1 ρ_m/ρ_{de} =.30 Ω_m=0.268 ±.012 Ω_Λ=0.736 ±.012

$Power_s$=25x10^{-10} $Tilt_s$ =0.963±0.013 **running=-0.024 ± 0.015 r=T/S<0.19**

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CMB*ology* **uses WMAP7+ACT** (SPT), **past: Boom, CBI, Acbar,..** (QuAD, ...). **LSS*ology*** **BAO H0** ***SN lens, clusters***. coming: ***Planck*** **cosmology** Jan2013,14 **cosmic parameters** Jan11(25p), Feb12 **SZ,CIB,ISM** ***ACTpol, ABS, Spider,*** *Quiet-2, .. CARMA, Mustang2 on GBT, CCAT, ALMA, ..*

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WMAP: 1.15 Tbits in 9yrs, cf. MyLifeBits, Gordon Bell, 1.28 Tbits in 9yrs, Planck 36 Tbits, ACT 304 Tbits. Terabit=10^{12}bits=125 GigaBytes. e.g., Compress e.g., ΔS_{1f} (r) = -3.7 Spider+Planck cf. ACT1

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How Structure in the Universe Arose?: *fluctuation generation in curvature from an early inflaton: isocurvature, Gravity Wave, non-Gaussianity signatures*

(coherence + quantum noise => incoherence via entropy/information generation)
morphs *into the nonlinear* ***Cosmic Web: clusters, filaments, voids; galaxies*** **(SZ)**

the fate of the U?: dark energy properties driving late inflation, ***S in asymptotic dS?***

Studying the Cosmic Tango

Cosmotician

P(cosmic parameters|D,T), P(D|T)
D=CMB,LSS,SN,..,complexity, life
T=baryon, dark matter, vacuum mass-energy densities,...,early and late inflation,structure of manfolds (extra compactifying 7 + 3+1), holes, branes, fibres, strings,vacuua landscape, physical coupling 'constants'

Anthrostatician=superHorizon measurer

Studying the Cosmic Tango

en-Tango-ment, the dance of S+R=U
Universe=System(s)+Reservoir,
=Signal(s)+Residual *noise*,
=Effective Theory+*Hidden variables,*
observer(s)+observed,
ruled by (information) entropy, entangled. *the fine grains in the coarse grains*

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

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

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

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information in **nearly-Gaussian** random **fields** of U: spatial coarse-grained **CMB entropy** & how we capture it. **dark matter entropy, cluster & protocluster & cosmic web entropy. MHD turbulence entropy** with cooling & grain polarized emission - a CMB fgnd. *How Shannon info-entropy flows from CMB bolometer timestreams to marginalized cosmic parameters via **Bayesian chains from prior to posterior.***

Shannon entropy ~ von-Neumann entropy
= Trace $\varrho \ln \varrho^{-1}$ = full non-equilibrium S
$\varrho(U) = \varrho(S,R) = \varrho(R|S)\, \varrho(S)$ entanglement of phase & probability

Studying the Cosmic Tango

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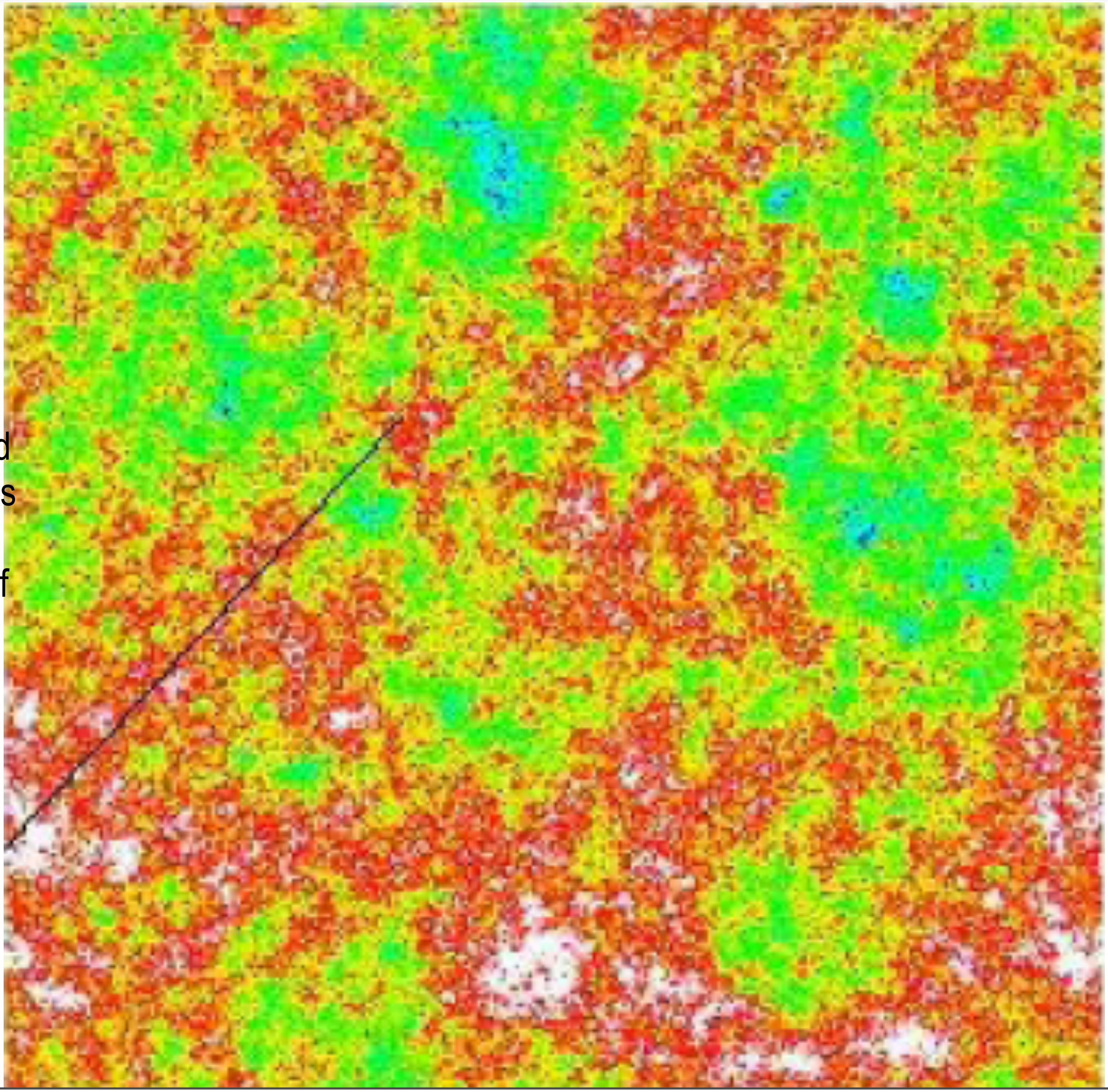
resolution dimension **λ = -*ln* r/r_0**
S(λ |coarse-grained-measures) deals with the **non-equilibrium & non-thermal S** in clusters, includes DarkMatter coarse-grained S - and **of preheating configurations**.

gravitational entropy remains a **mystery, horizon needed? gravo-thermal catastrophe** = negative specific heat, what gravity wants is to localize concentrating mass into black holes and make accelerating voids to straighten out U.

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

χ



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

pre-heating patch (~1cm)

evolve from early U vacuum potential and vacuum noise

10 Gpc

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χ

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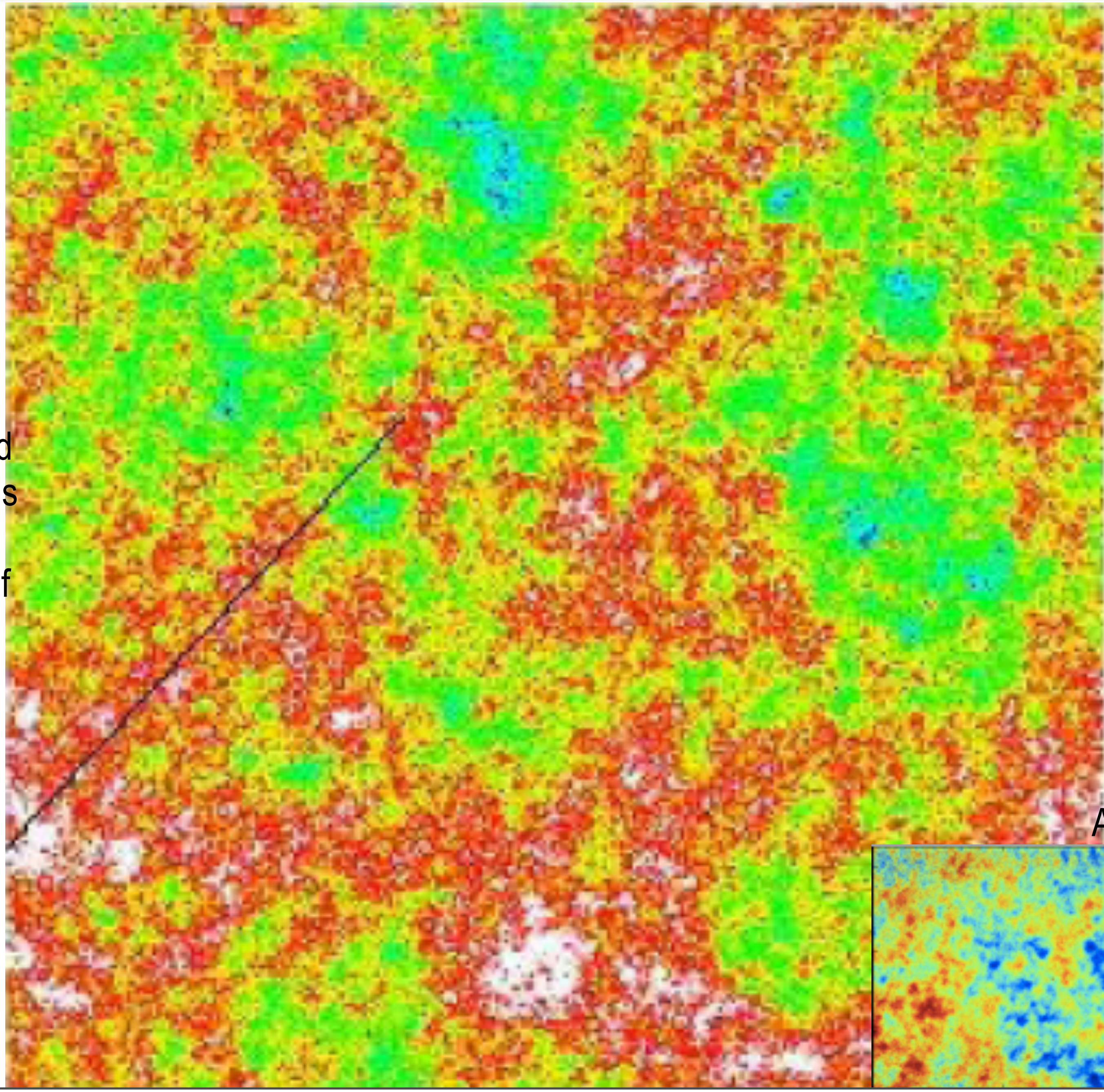
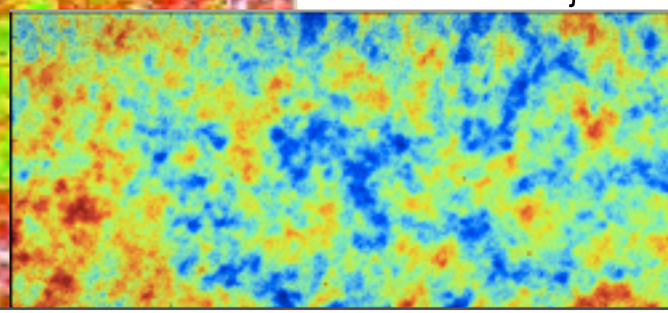


evolve from early U vacuum potential and vacuum noise

ACT+WMAP7 hajian+10



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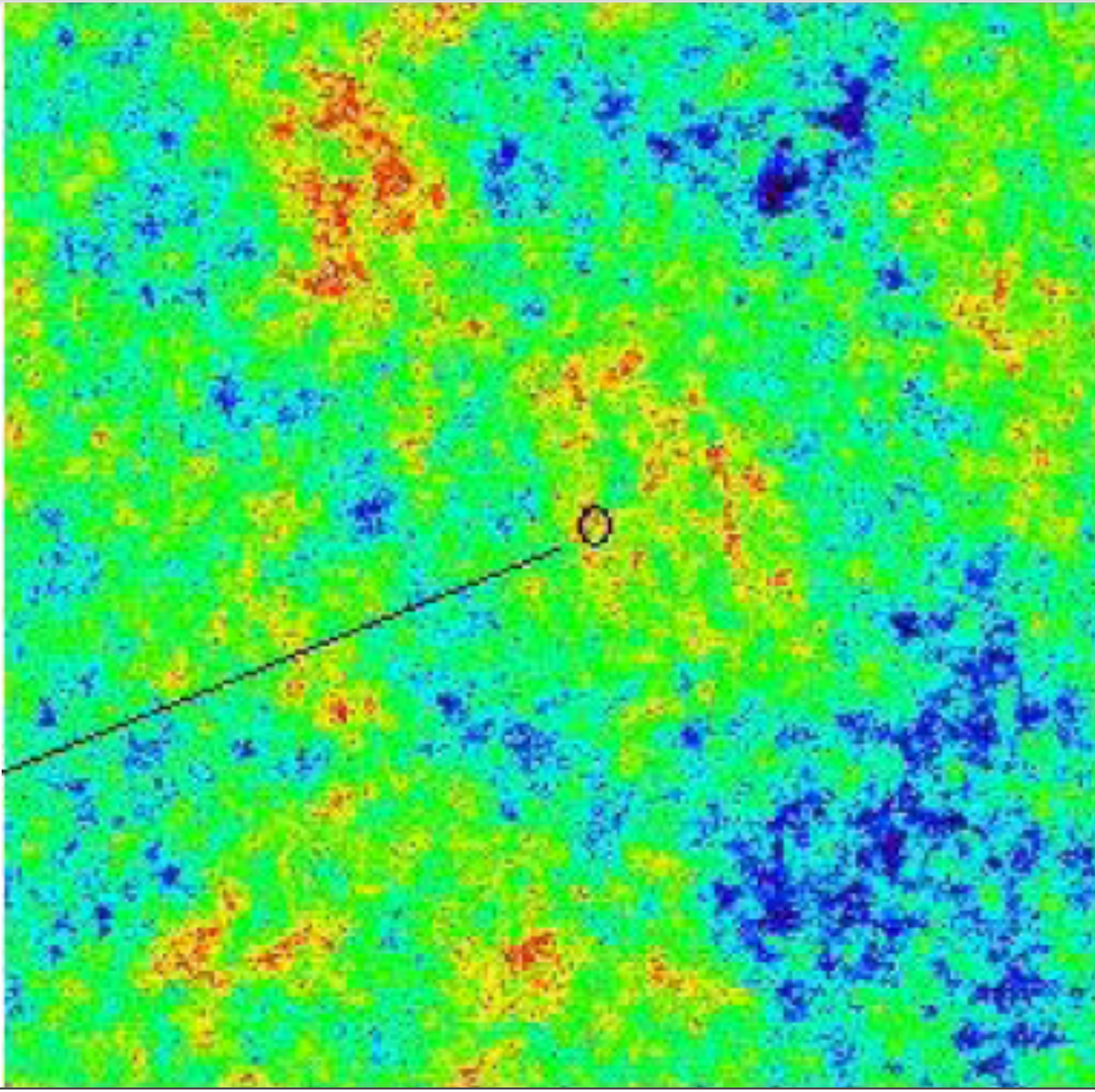


χ

current Hubble patch ~10 Gpc

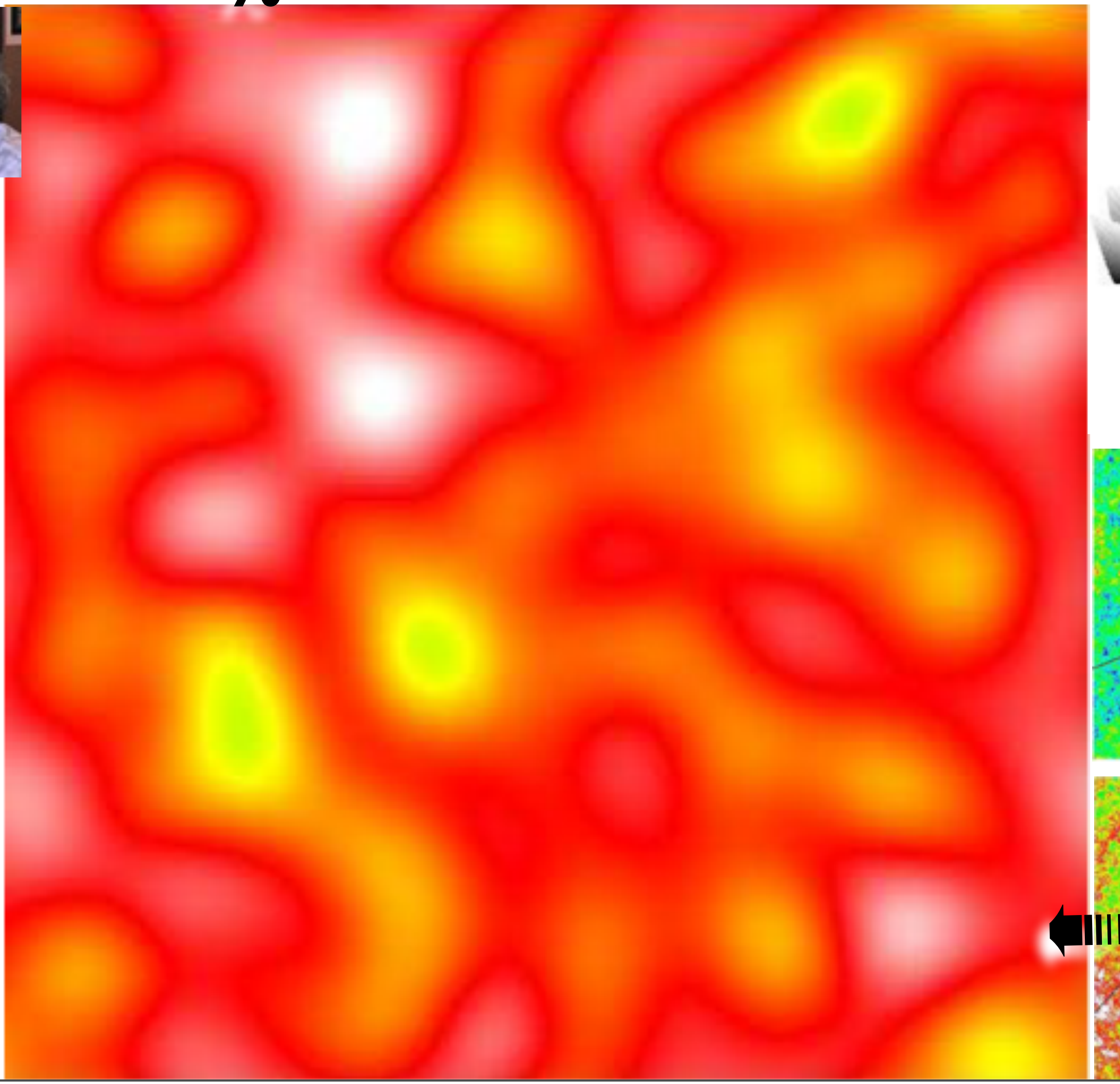
speed limit horizon

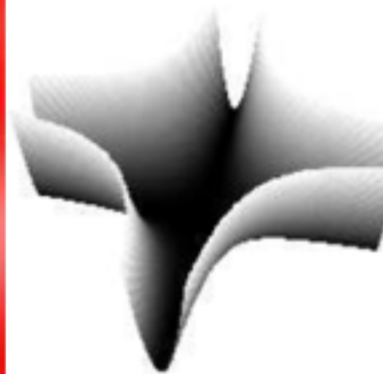
patterns in the quantum jitter evolve under gravity

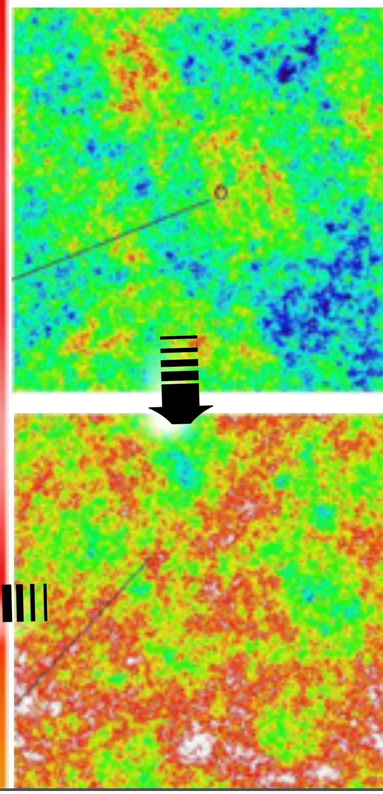
(& gas dynamics)

1000 Gpc

ϕ inflaton χ isocon $V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$ **Parametric Resonance** $g^2/\lambda \sim 1$







pre-heating patch (~1cm)

end of inflation @ε=1

through **preheating**

(linear resonance, nonlinear backreaction $\delta\psi,\delta\chi$)

to thermal equilibrium

$ln(n_k^{-1}+1) \Rightarrow k/T,\ \rho_k \sim E_k(n_k+1/2)$

from coherent "background" field with nearly-Gaussian linear fluctuations to incoherent heat bath through a not-that-turbulence-like cascade: development of complexity: information (multi-scale entropy) *b+**braden** 11*

@ $k > H_{end}^{-1}$

=> no effect on k-observed? MAYBE:

relics (e.g., strings, isocons), HF gravity waves (kHz-GHz cf. 10^{-19}Hz),

isocon modulation & non-Gaussianity

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

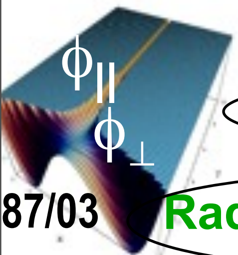
1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation



Double Inflation

Power-law inflation

SUGRA inflation

87/03

Radical BSI inflation

running (nee variable M_P) inflation

Higgs inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

KLS94 preheating

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

Racetrack inflation

Tachyon inflation

Warped Brane inflation

moduli fields

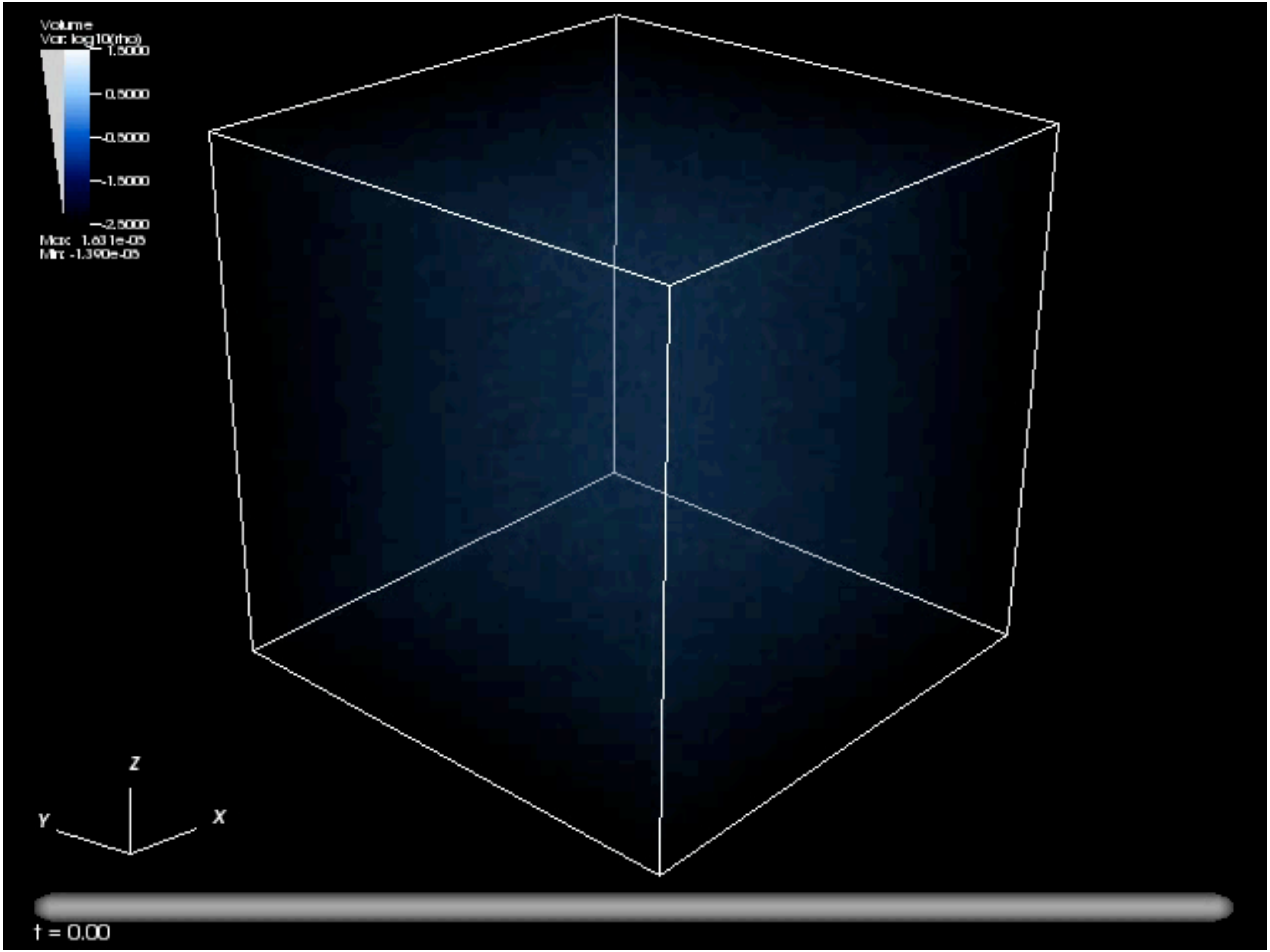
monodromy

Higgs inflation

Roulette inflation Kahler moduli/axion

fibre inflation

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



Preheating = Shock-in-time Jonathan Braden + B 2011

Initial State = Nearly Homogeneous Inflaton

Low entropy (vac fluc.), information encoded in a few parameters

Preheating

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

Transition Regime

Complex slowly evolving nonlinear, nonequilbrium state e.g. Micha and Tkachev 2004, turbulence analogy??? not quite

the shock-in-time is the sharp mediator between the linear & the highly nonlinear transition
a fascinating non-Gaussianity through a

Thermal Equilibrium

Maximum spreading of information in modes subject to energy and particle number constraints.

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

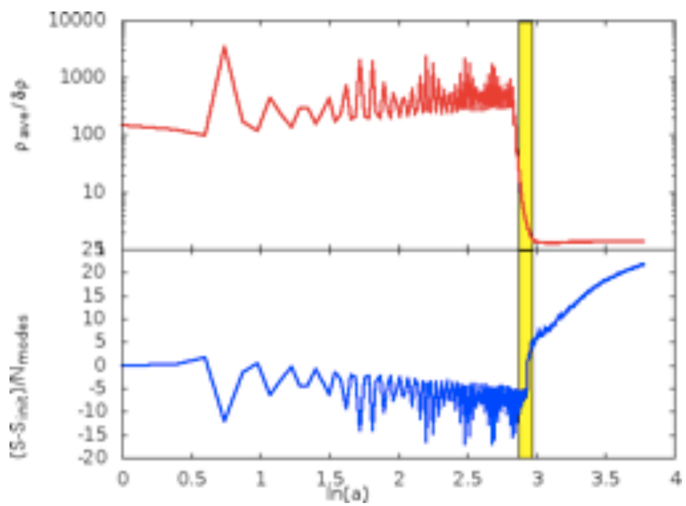
Characteristic temporal scale

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

nonequilibrium Shannon (~von Neumann) entropy

$S = -\mathrm{Tr}\, P[f\,] \ln P[f\,] \Leftarrow -\mathrm{Tr}\, \rho \ln \rho$

$P[f\,]$: probability density functional, ρ density matrix

classical $\Leftarrow$ quantum

$\varrho(U) = \varrho(S,R) = \varrho(R|S)\, \varrho(S)$ **entanglement of phase & probability**

Coarse Graining & Entropy Production

we have explored many ways of treating non-eq S. max S constrained by measurements we theorists make on the medium

Field ⇒ Correlation Functions

Measurements: Constraints (information) on Correlators
Maximize entropy subject to given constraints
Generation of higher order correlators ⇒ entropy generation

Entropy & Correlator Constraints & Gaussian Distributions

if only power spectrum is constrained ⇒ multivariate Gaussian maximizes S

$$S/N = 1/2N\, \mathrm{Tr} \ln P(k) + 1/2 + 1/2 \ln(2\pi)$$

$\ln = \log_e$ measure info in nats, $\mathrm{lb} = \log_2$ measure info in bits

$P(k)$ dimensionful, so ΔS relative to a S_i, counting states ⇒normalize to =1 state

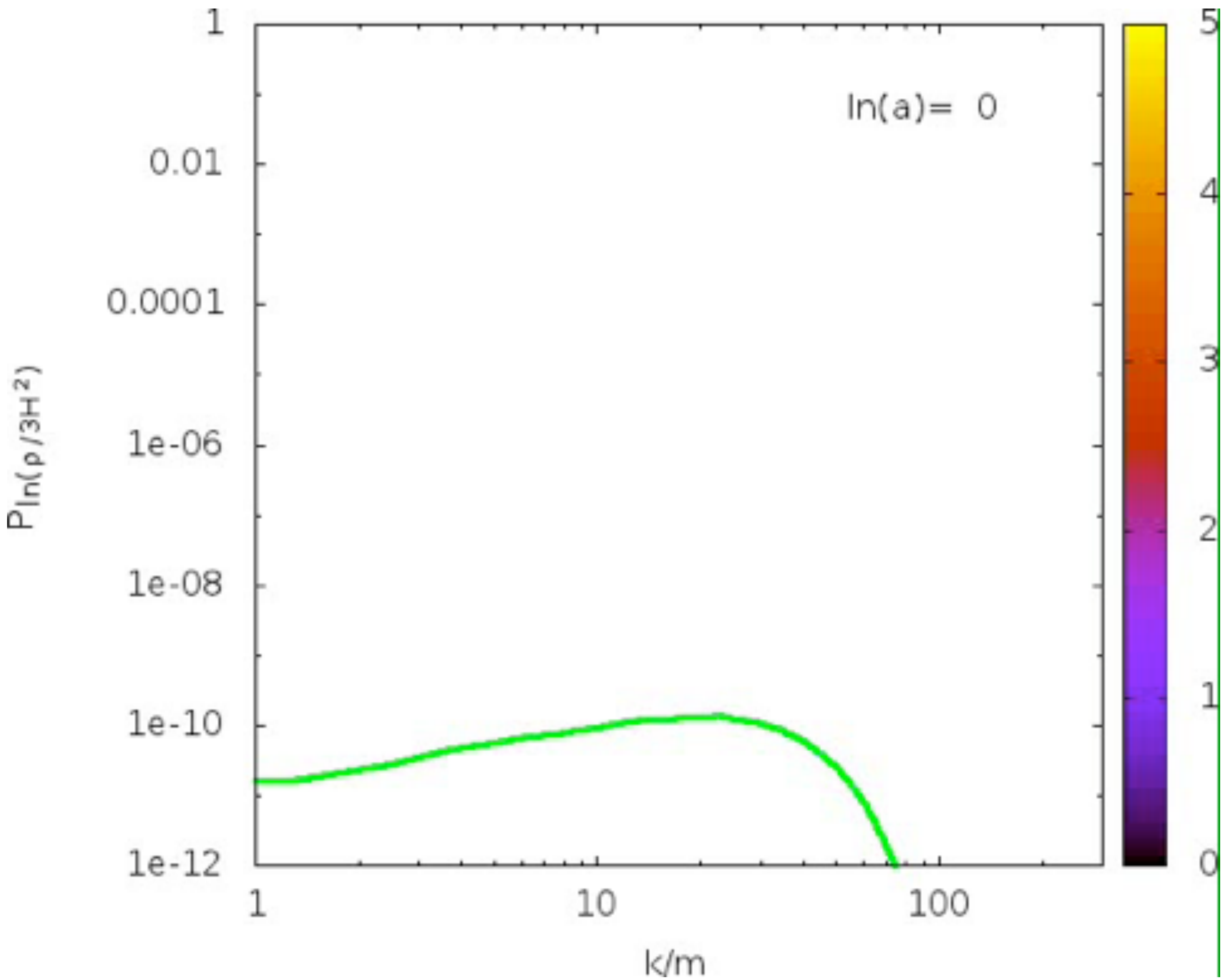
Power Spectrum

Nonlinear dynamics via large parallel lattice simulations using modified version of DEFROST Frolov 2008

log is more Gaussian

ln(ρ/3H²)~ ln(ρ/<ρ>) as the dynamical random field.

$$V = \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\chi^2$$

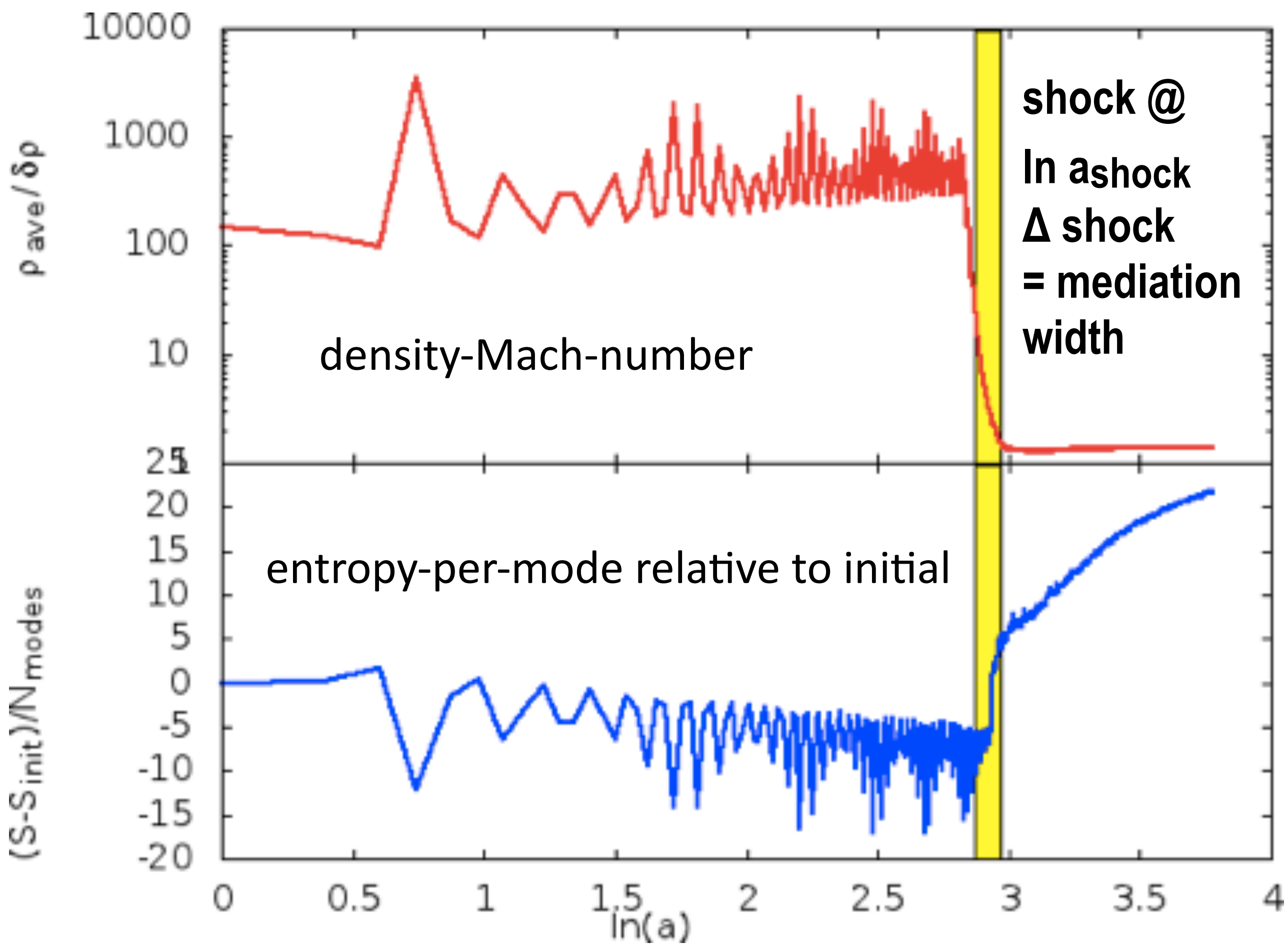


$m/M_P=10^{-6}$, $g^2=10^{-5}$

low entropy initial state: uniform inflaton + simulated vacuum aka quantum fluctuations, initial isocon field rapid classical increase in nonlinear fluctuation power through mode-mode coupling ⇒ shock-in-time.

post shock evolution of power is relatively slow *(coupling to standard model?? accelerates particle production at very high k? subgrid phenomenology a la eddy viscosity.)*

Entropy Production & the Shock-in-time

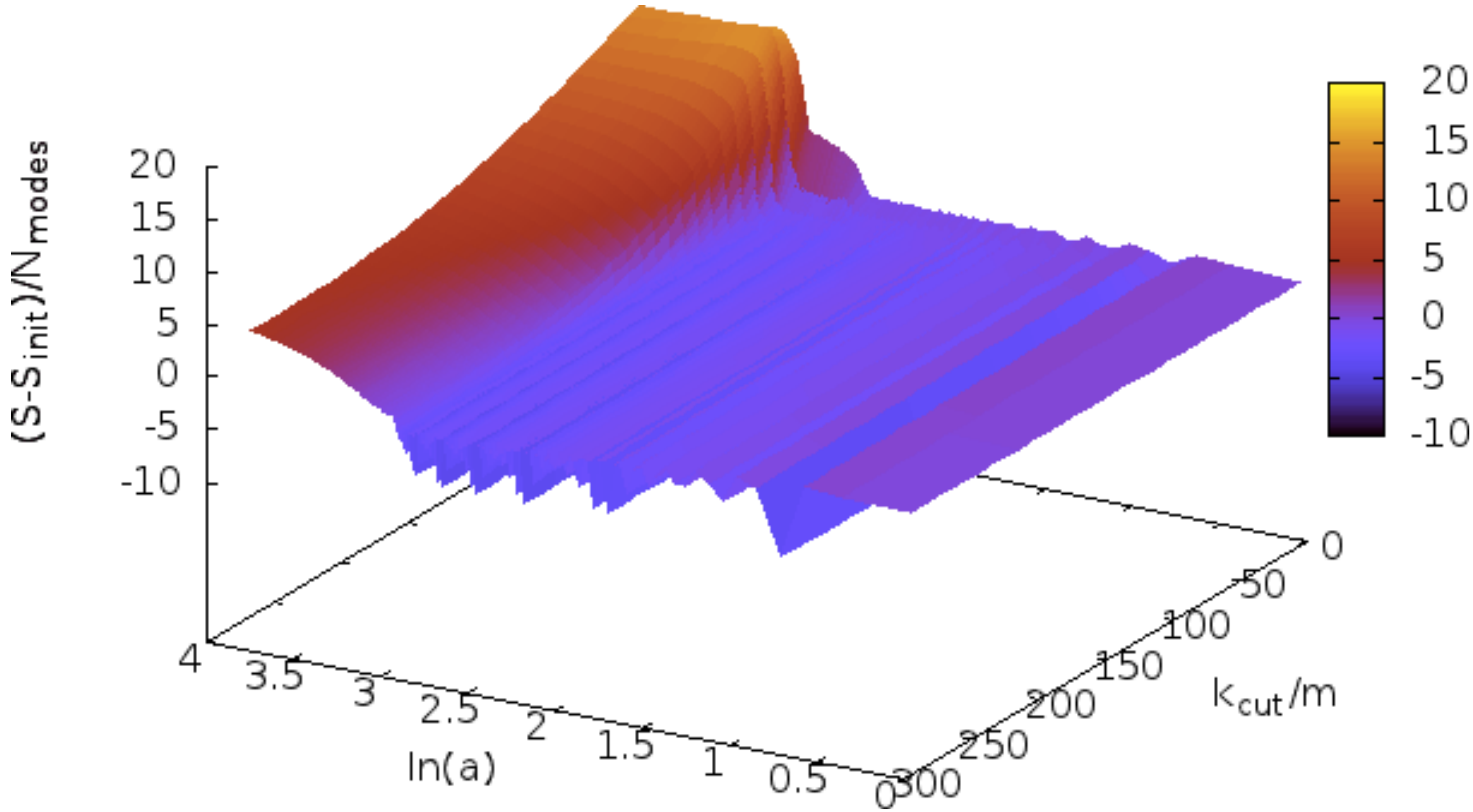


true
thermal
equil.
far off
➤
& to std
model

constrained coarse-grained Shannon entropy is taken relative to the initial entropy with its Gaussian random field entropy from band-limited quantum fluctuations

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

Scale Dependence of Shock-in-Time



entropy production is not scale-localized. resolution of the field = kcut (sharp k space cut). Rapid spread in k, but not a turbulence-like cascade, slower movement to high k. Suggests ***Renormalization Group Flow picture***.

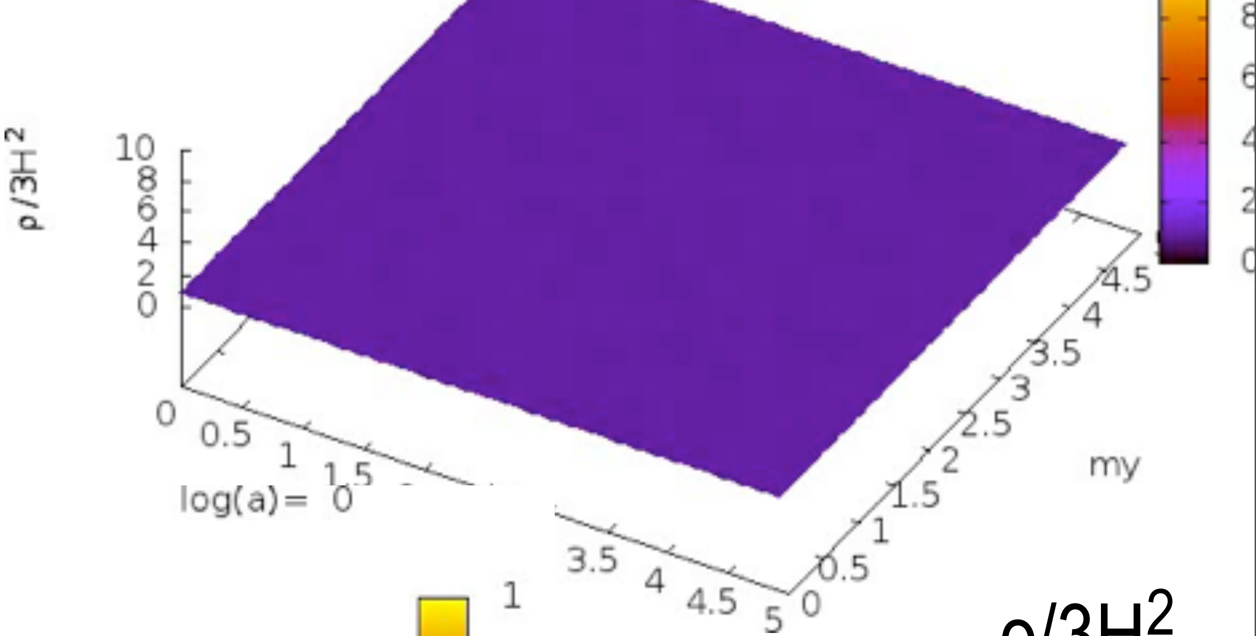
Post Shock Evolution

Slow Dynamics of IR Modes ⇒
Hydrodynamic Description

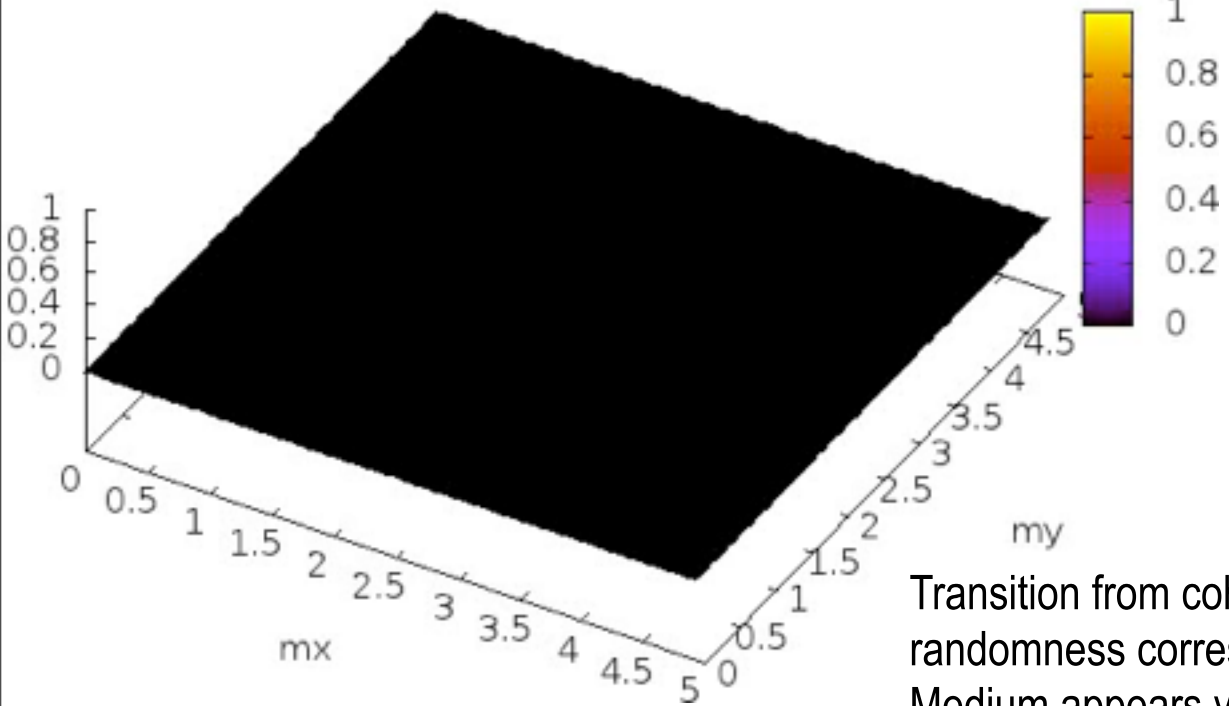
$\rho = -T^0{}_0$

$P = -T^i{}_i$

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



$\rho/3H^2$



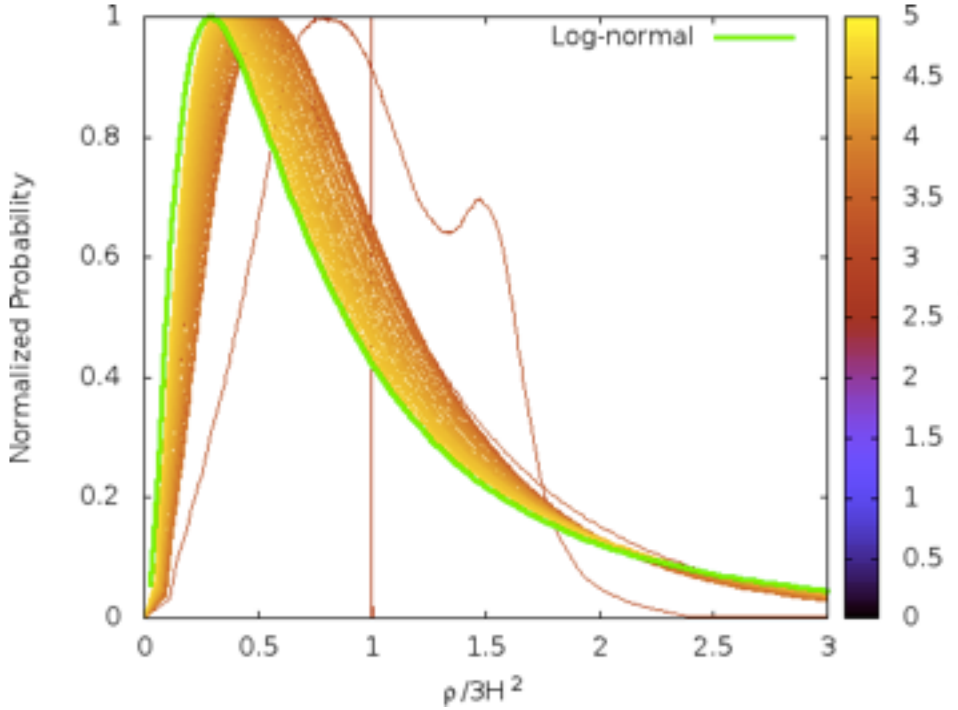
v^2

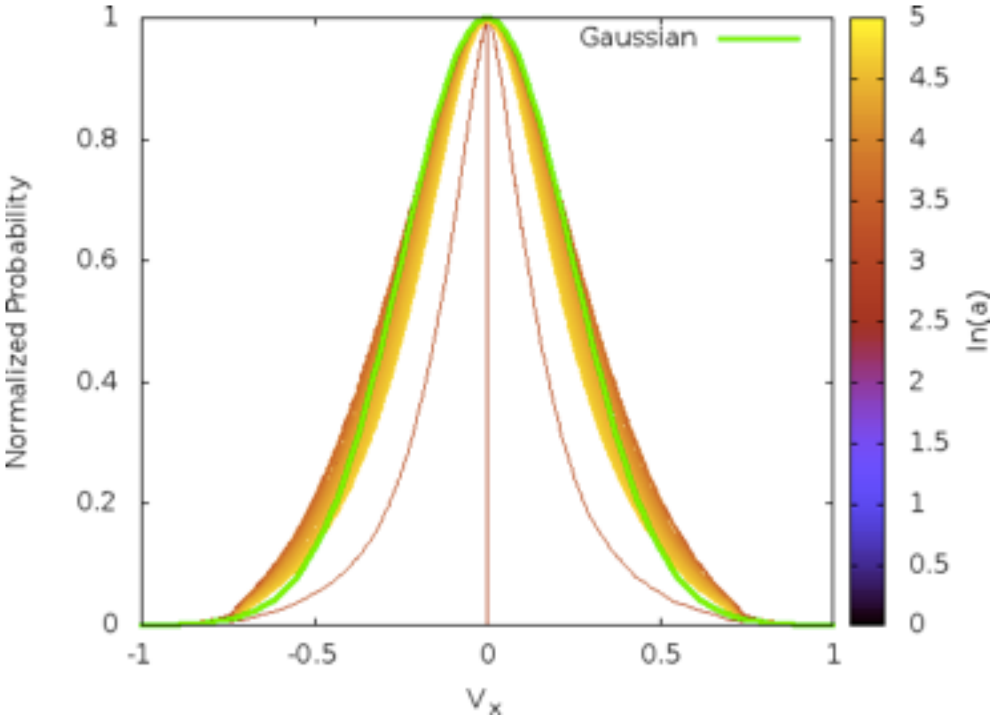
Transition from coherent wall-like structures to randomness corresponds to the shock-in-time. Medium appears very complex in space and time, but ...

but Statistical Simplicity

Density PDF~ log-normal after initial transient Frolov

Velocity components ~ Gaussian PDF





Renormalization and Scale Dependence via Wilsonian RG Blocking

Sequence of smoothed fields ρ_S defined by averaging over groups of 8 nearest neighbours with $r_S = 2^S \delta X_{lat}$ the smoothing scale.

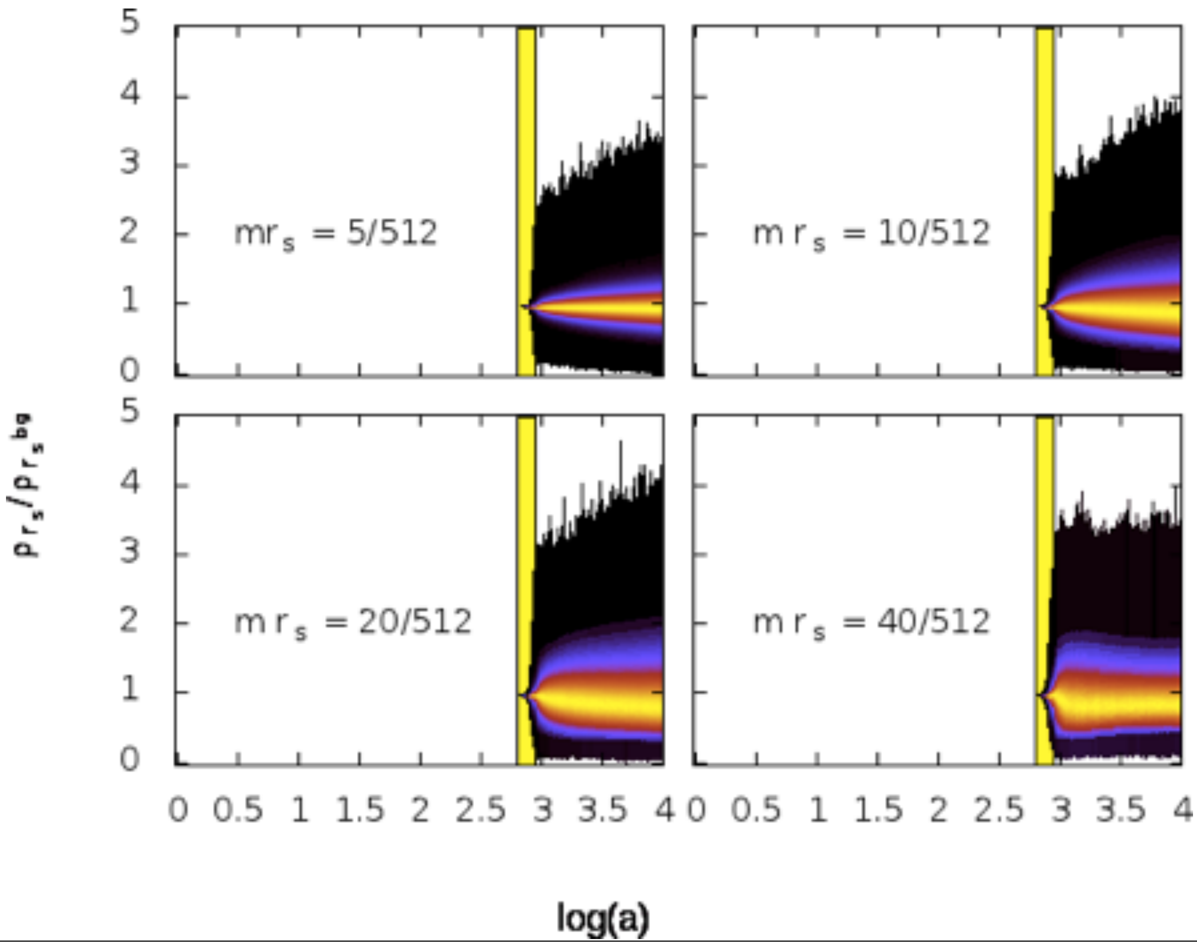
Define local background for $\rho_S(x)$ by ρ_{S+1}

idea: fluctuations *layered on* fluctuations *layered on* fluctuations ...

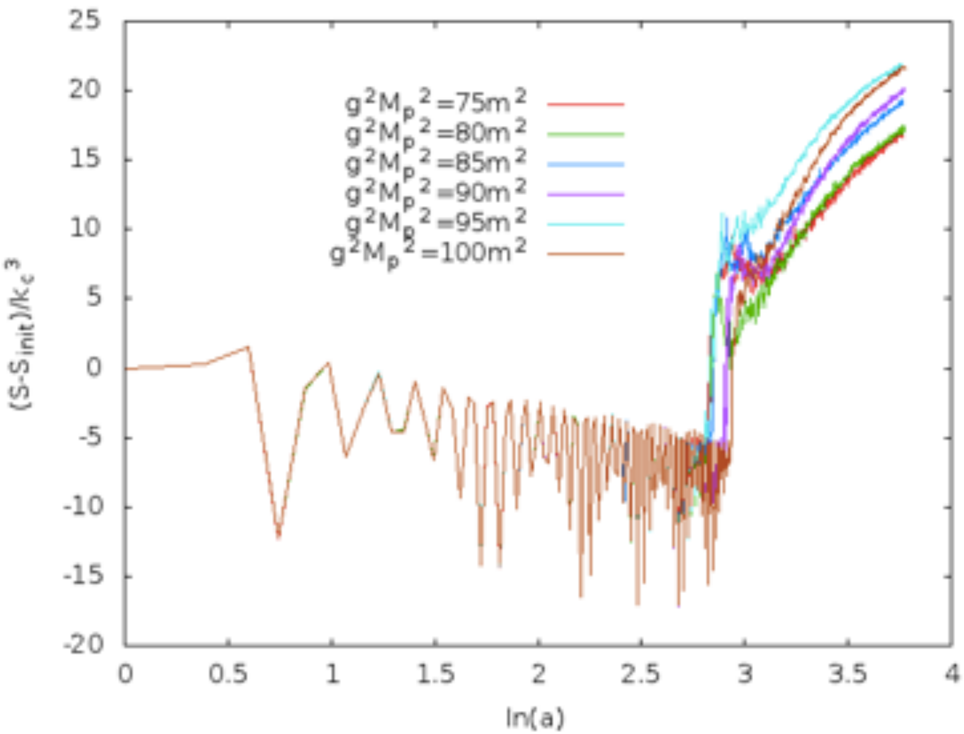
The shock-in-time has a more pronounced effect on larger scales

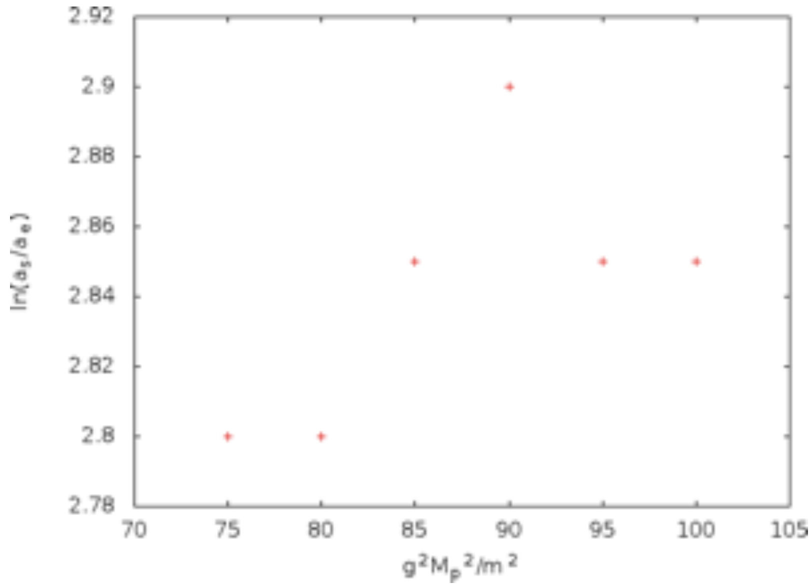
At late times, local fluctuation PDFs evolve more slowly on larger scales than on small

White bounds the extremal values in the simulation box.



Relation to Nongaussianities entropy change as coupling changes





dependence of $\ln(a_{shock}/a_{end})$ on parameters (coupling constants,<x_{init}>, ...)

relationship to nongaussianities from preheating

Bond,Frolov,Huang,Kofman (2009), and e.g. Chambers and Rajantie (2008)

The spatial structure of $\ln(a_{shock}/a_{end})$ (x) from modulated initial conditions encodes information about the perturbation spectra including nongaussianities.

a case with small post-shock nonG??

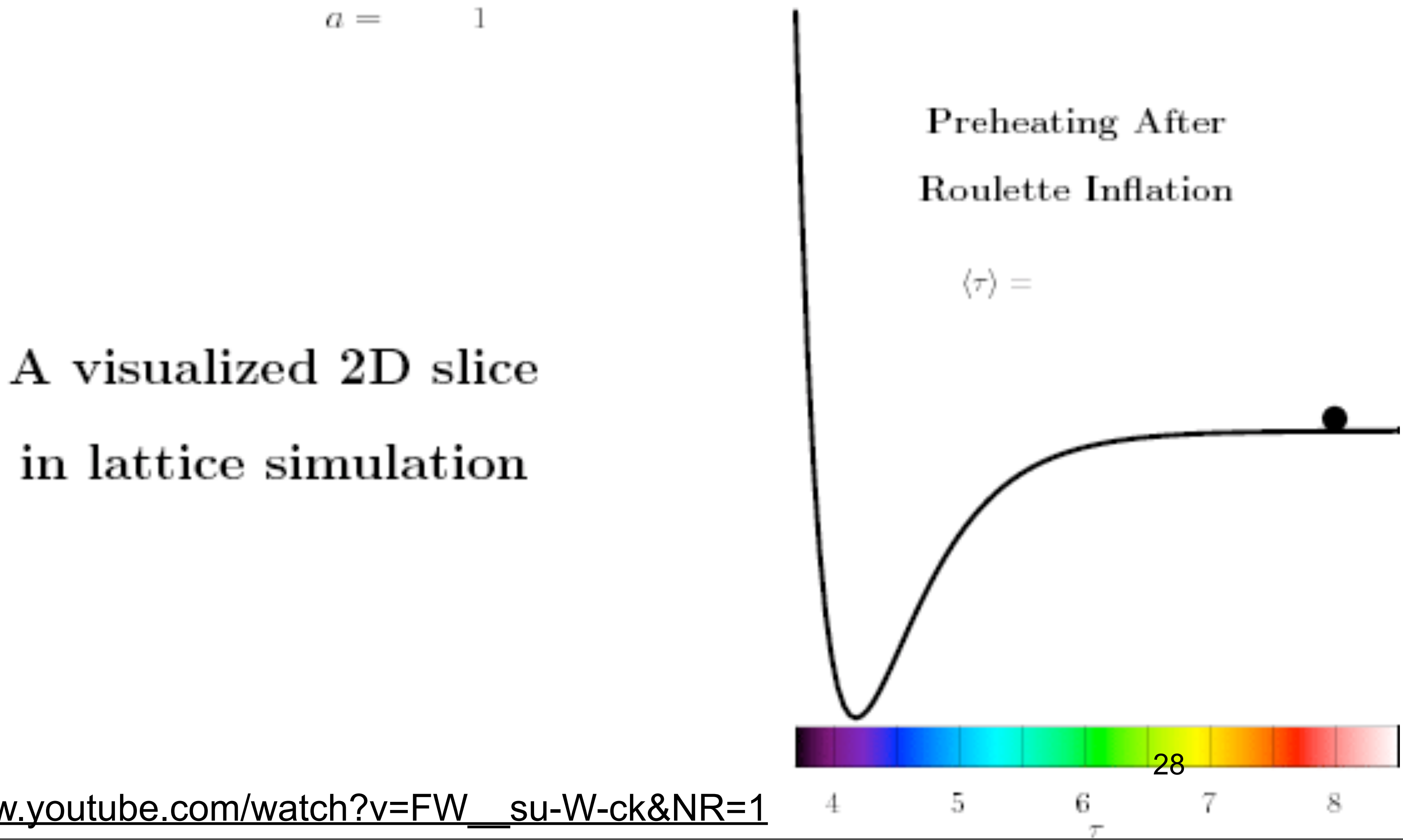
Barnaby, Bond, Huang, Kofman 2009

Preheating After Roulette Inflation

pre-heating patch (<1cm)

HLattice code: arbitrary number of fields, hybrid symplectic, to ~ trillionth accuracy!

Huang 2011 added full metric back action



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

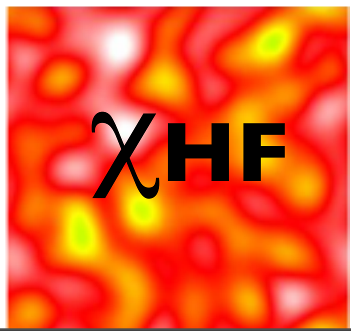
large post-shock nonG??

trying to prove that $\ln a_{final}/a_{end} \sim \ln a_{shock}/a_{end}$

curvature $F_{NL}(\chi(x,t)) = \delta \ln a|_H (\chi_i)$

highly nonlinear function of a Gaussian random 'isocon' field

$\chi(x,t) =$



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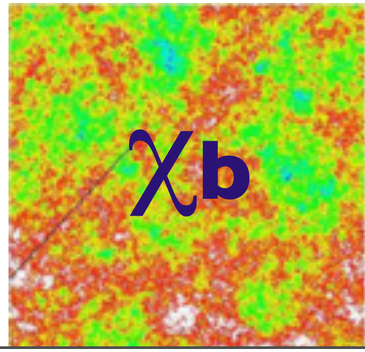

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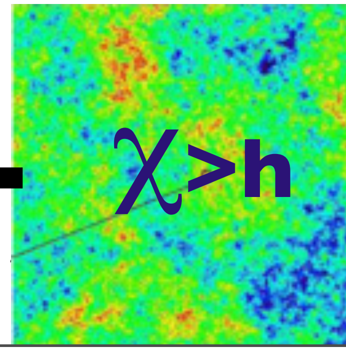
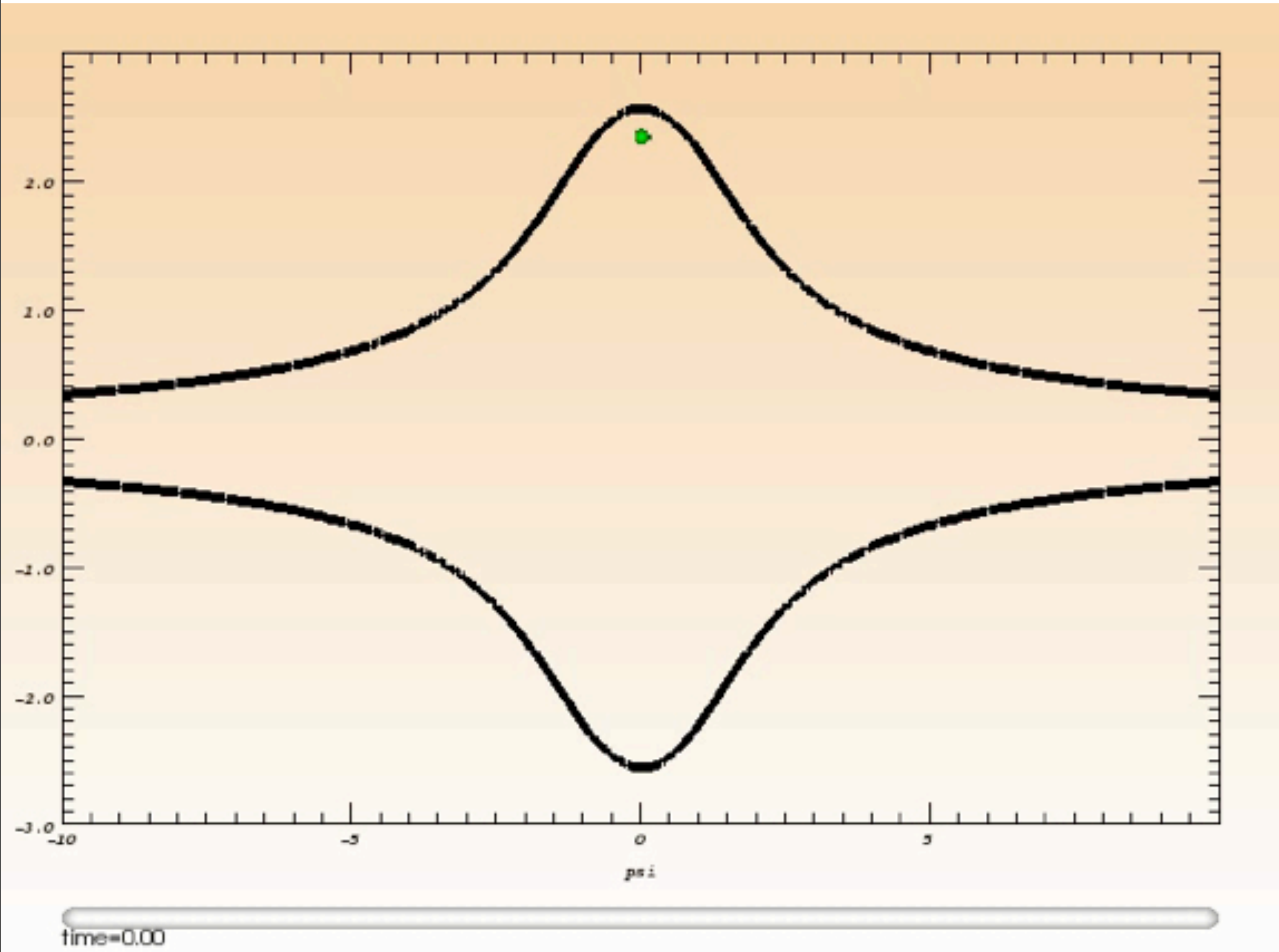


large post-shock nonG??

calculate $\delta \ln a\,[\chi_i(x,t)]$ *from* **ε=1** *(end of inflation)* ***through preheat***
(copious mode-mode-coupling aka particle creation) ***to thermal equilibrium***

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09



linear regime of zero-modes:

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

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

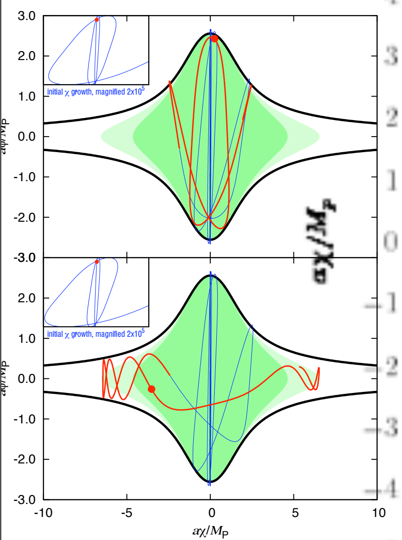
⇒ ***spikes are***

log χ_i ***spaced***

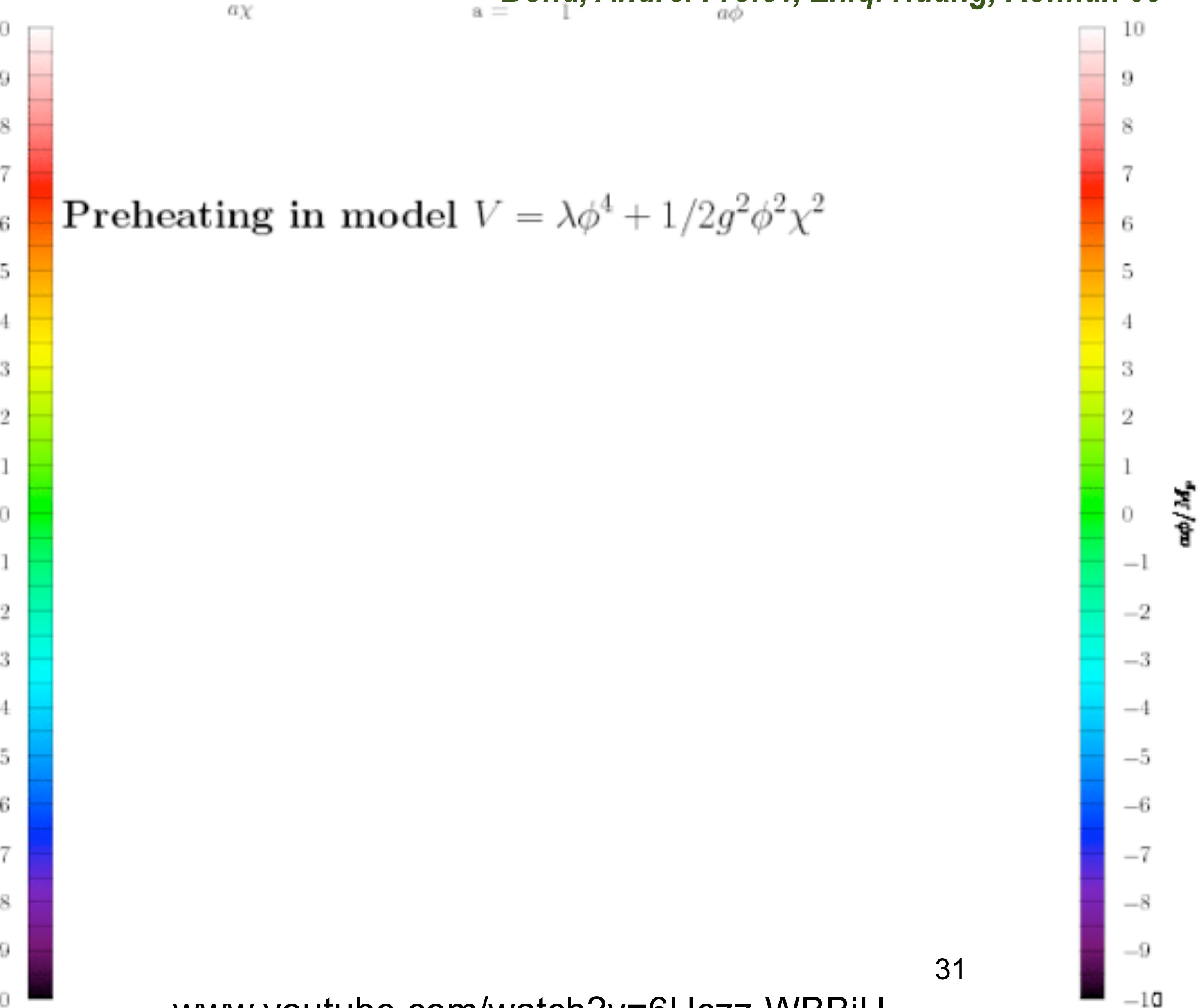
Cosmic Chaotic Billiards: NonGaussianity from Parametric Resonance in Preheating

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09

non-spike IC



spike IC



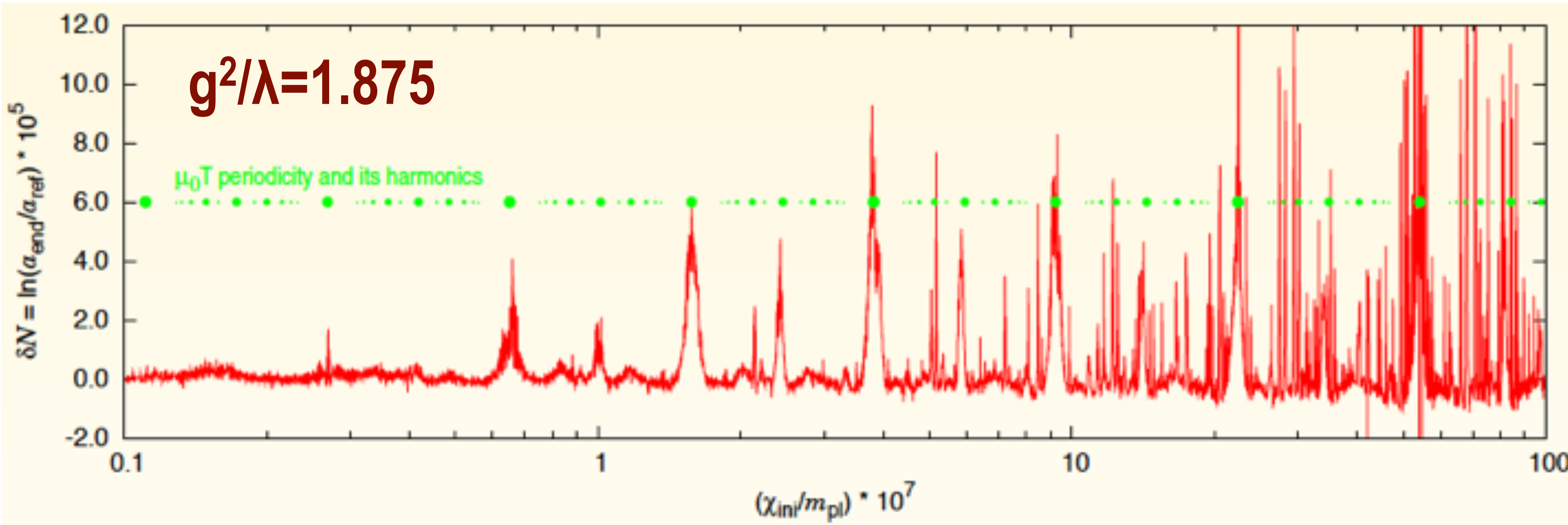
www.youtube.com/watch?v=6Uczz-WBBjU

large post-shock nonG??

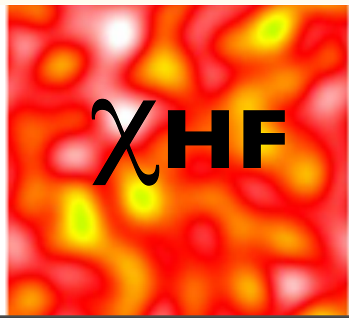
trying to prove that $\ln a_{final}/a_{end} \sim \ln a_{shock}/a_{end}$

curvature $F_{NL}(\chi(x,t)) = \delta \ln a|_H (\chi_i)$

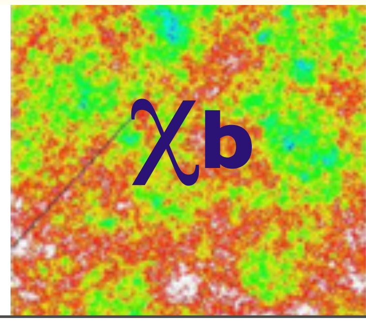
highly nonlinear function of a Gaussian random 'isocon' field



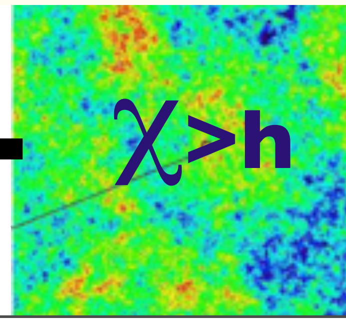
$\chi(x,t) =$



+



+

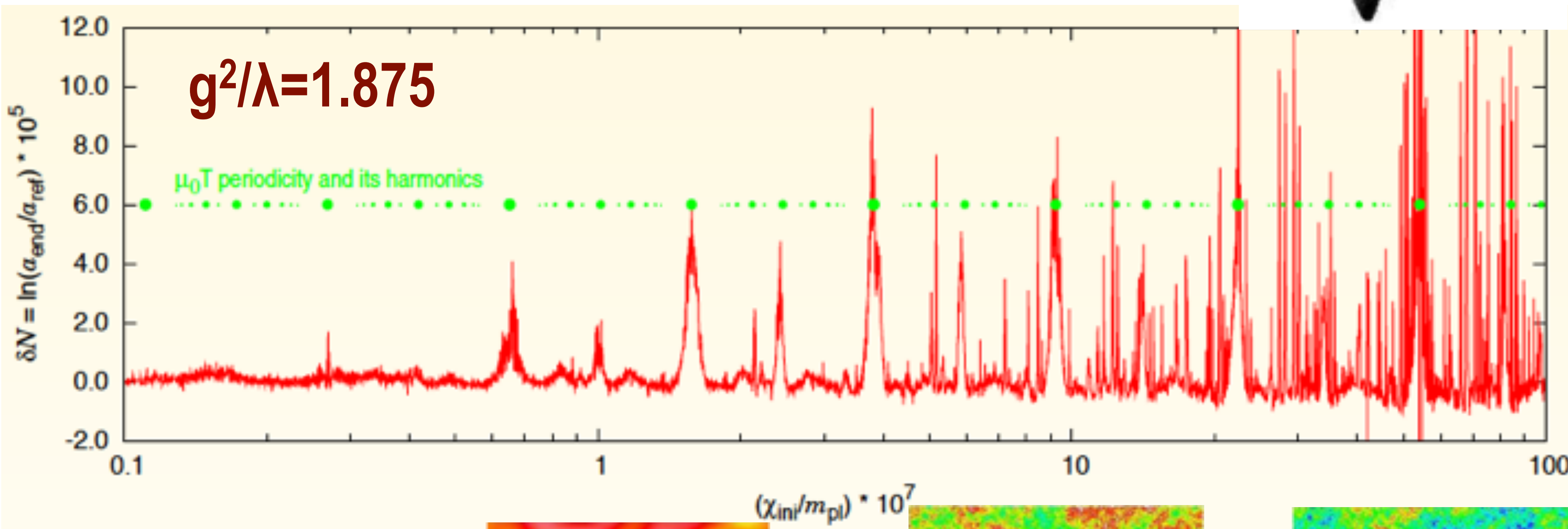


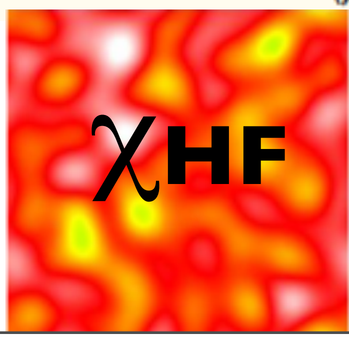
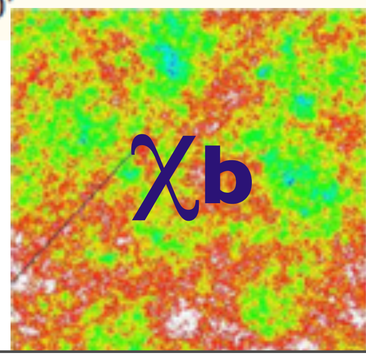
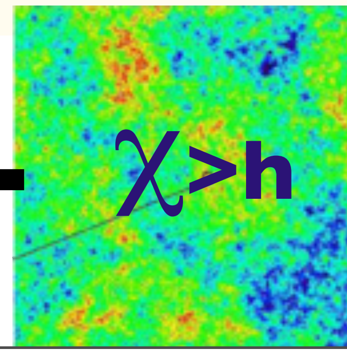
large post-shock nonG??

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

curvature $F_{NL}(\chi(x,t)) = \delta ln\,a|_H(\chi_i)$

highly nonlinear function of a Gaussian random 'isocon' field



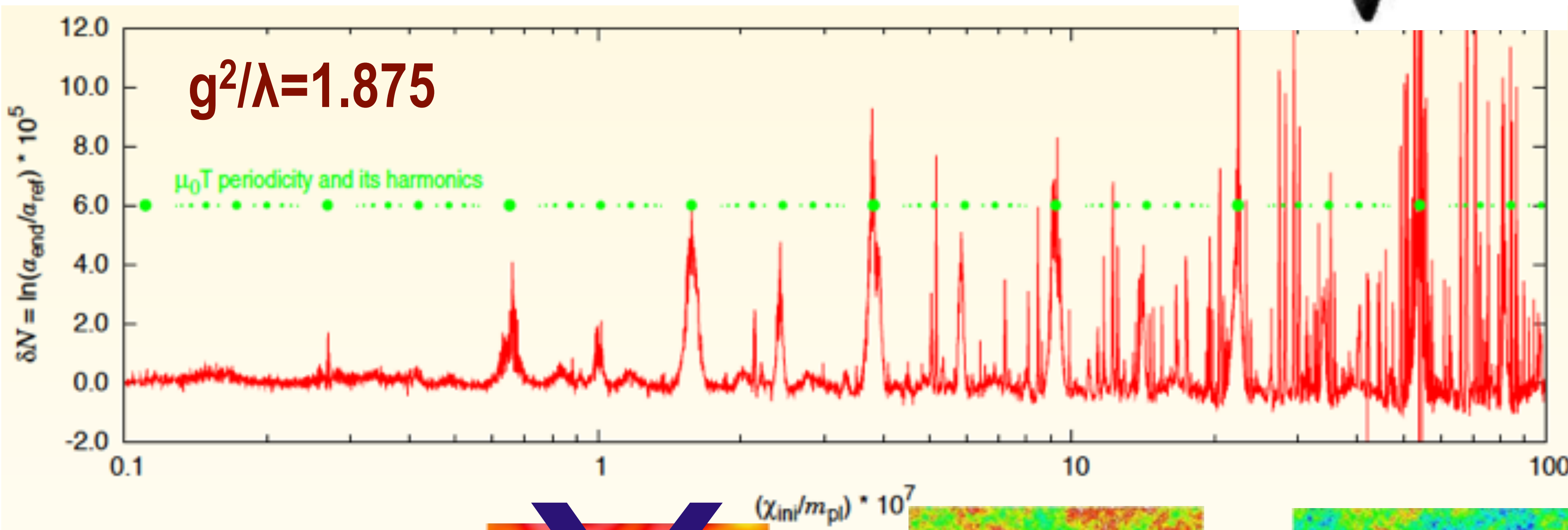
$\chi(x,t) =$  χ_{HF} +  χ_b +  $\chi_{>h}$

large post-shock nonG??

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

curvature $F_{NL}(\chi(x,t)) = \delta \, ln\, a|_H \, (\chi_i)$

highly nonlinear function of a Gaussian random 'isocon' field

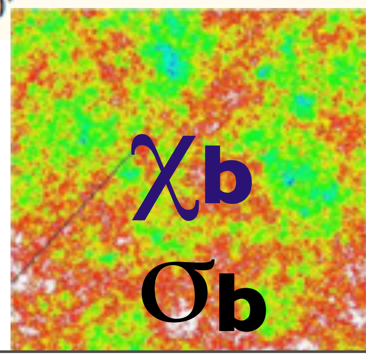


effective field theory

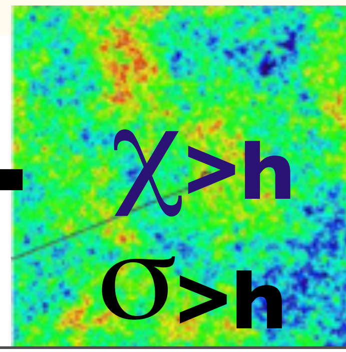
$\chi_{eff}(x,t) =$

field smoothing over χ_{HF}

+



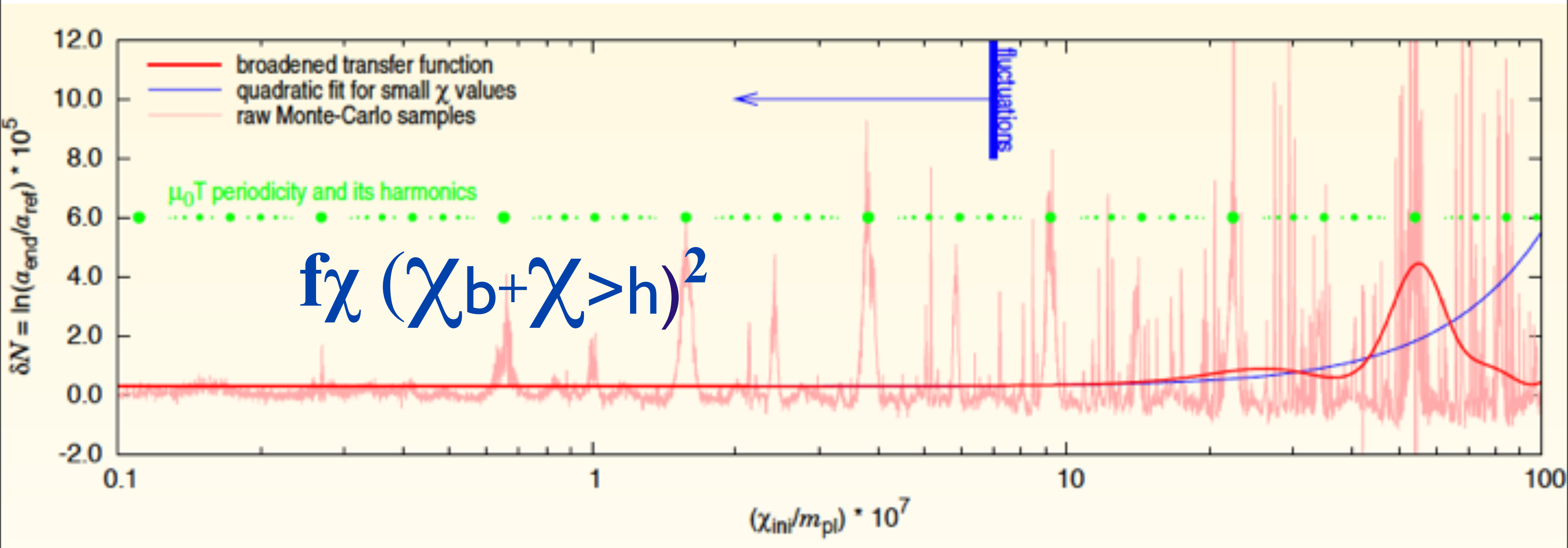
+



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

$$< F_{NL} | \chi_b + \chi_{>h} > \sim \beta(\chi_{>h})\, \chi_b + f(\chi_{>h})\, \chi_b^2 + \ldots$$

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



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

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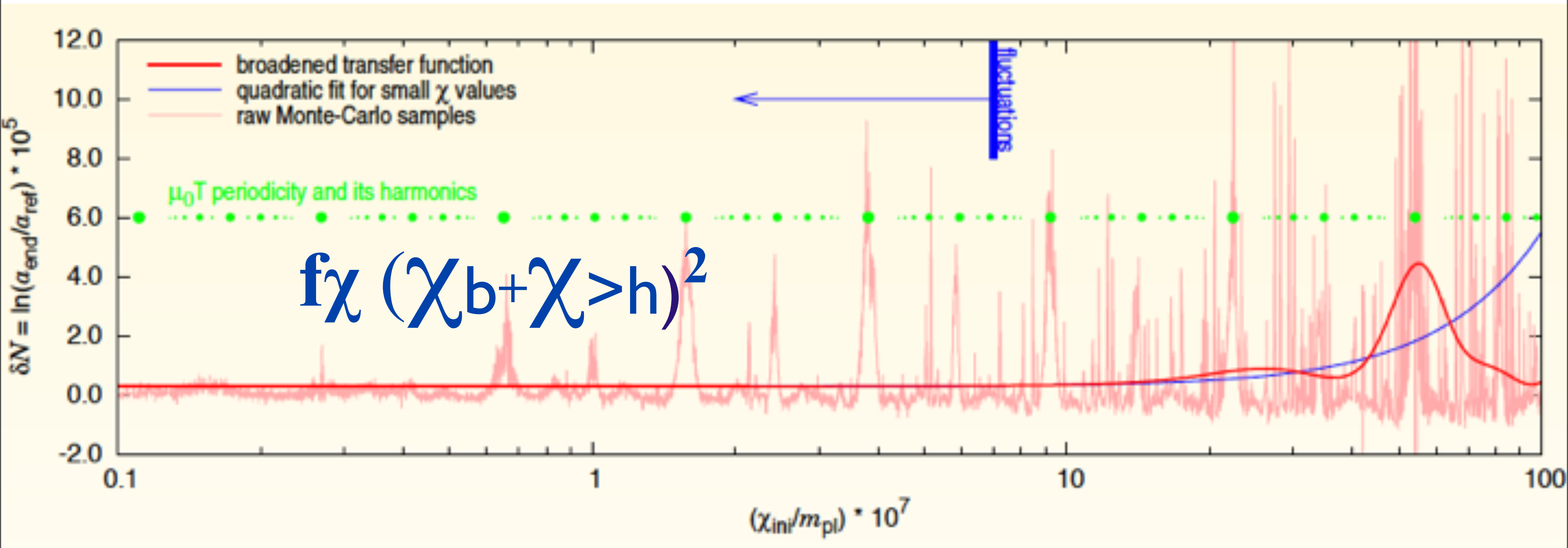


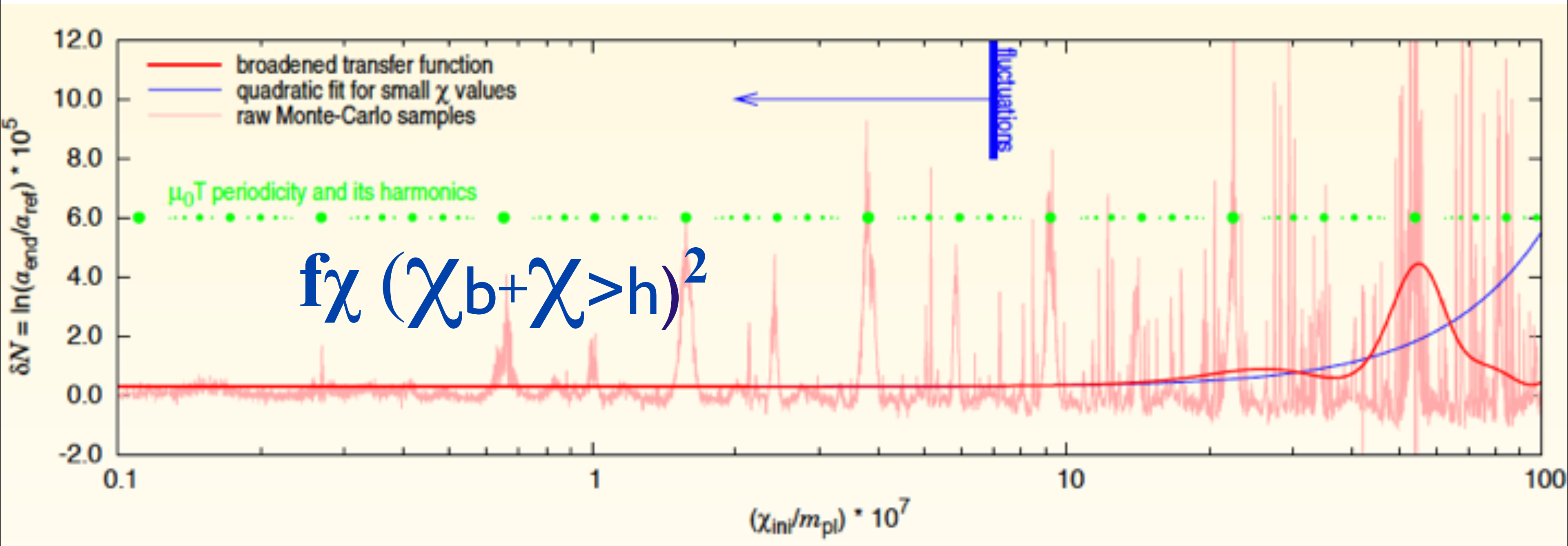
$$f_{NL}^{equiv} = \beta^2 f_\chi\, [P_\chi/P_\phi]^2 (k_{pivot})$$

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

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

$$< F_{NL}|\chi_b+\chi_{>h}> \;\sim \beta(\chi_{>h})\,\chi_b + f(\chi_{>h})\,\chi_b^2 + \ldots$$

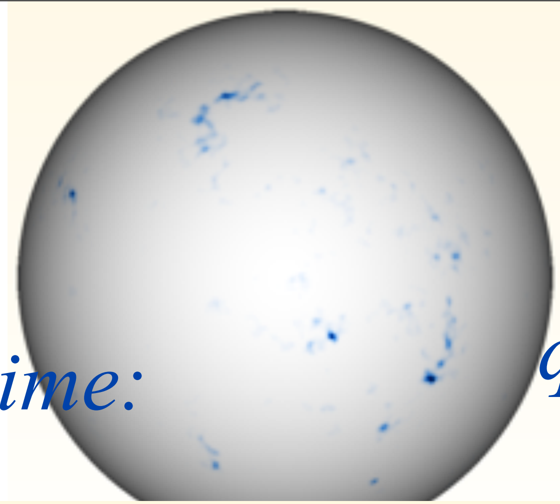
cf. $F(x)= F_G(x)+ f_{NL}\, F_G^2(x)$



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

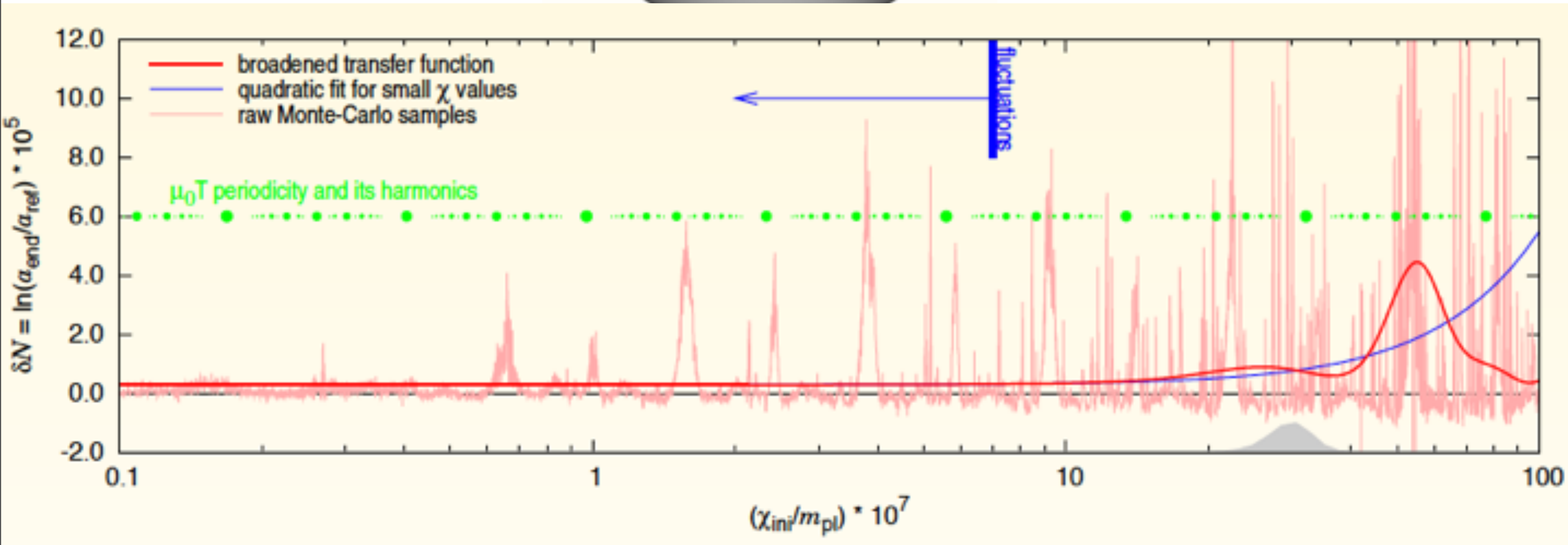
$f_{NL}^{equiv} = \beta^2 f_\chi\, [P_\chi/P_\phi]^2(k_{pivot})$ **-10< f_{NL}<74 WMAP5 (± 5 Planck)**

=> constrain $f_\chi^3\, \chi_{>h}^2$ ($P_\chi/P_\phi \sim 2\varepsilon$ => *relaxed limit*) *large-ish* χ>h *regime:*



*quadratic+***cold spot**

"rare events"



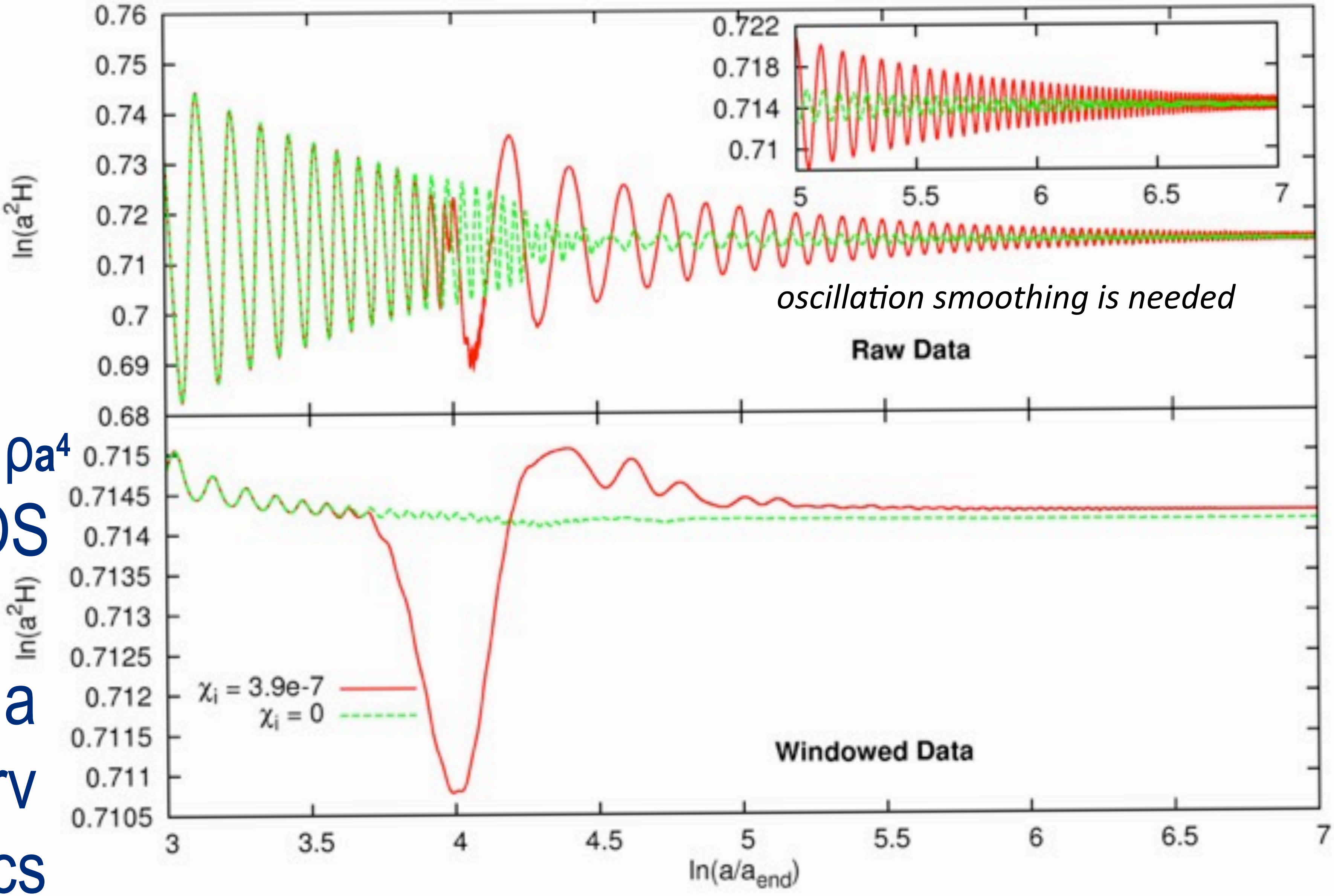
B+Frolov+Nolta, motivated by B+Braden+Frolov+Huang, B+Braden nonG

long aside: **novel ways of finding hot & cold spots in the CMB vs. resolution; probing their interior structures; their polarization & relation to anisotropic T-strain; use of L-statistics (L-mean, L-skewness, L-kurtosis, ..) less biased than conventional central moment estimators**

Relation to Nongaussianities smooth in time over oscillations gives EOS change ρa^4

looking for sub-parts-per-million deviations so high accuracy fundamental

$\delta\ln\rho a^4$ EOS ~ $\delta\ln a$ curv flucs



Relation to Nongaussianities smooth in time over oscillations gives EOS change ρa^4

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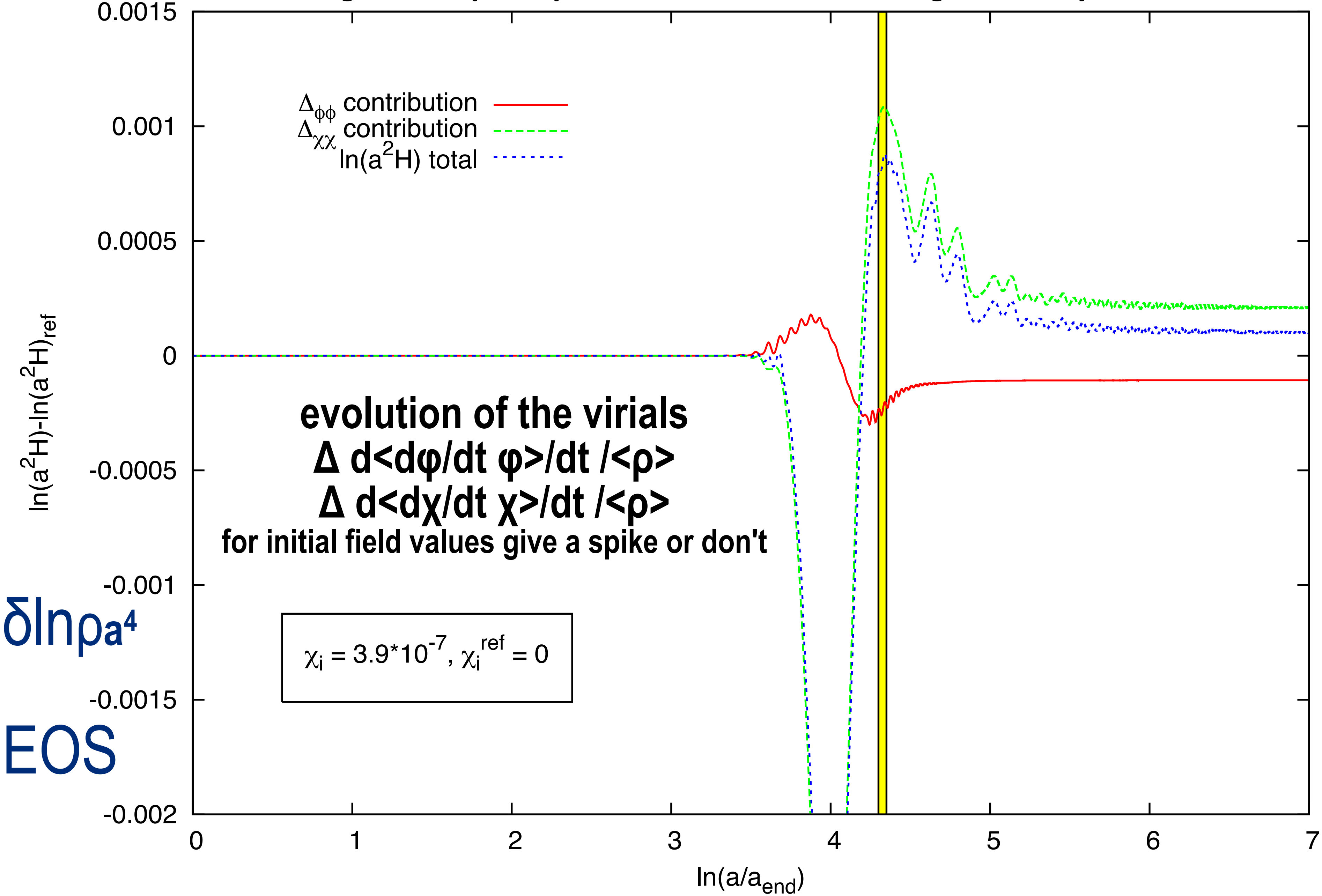
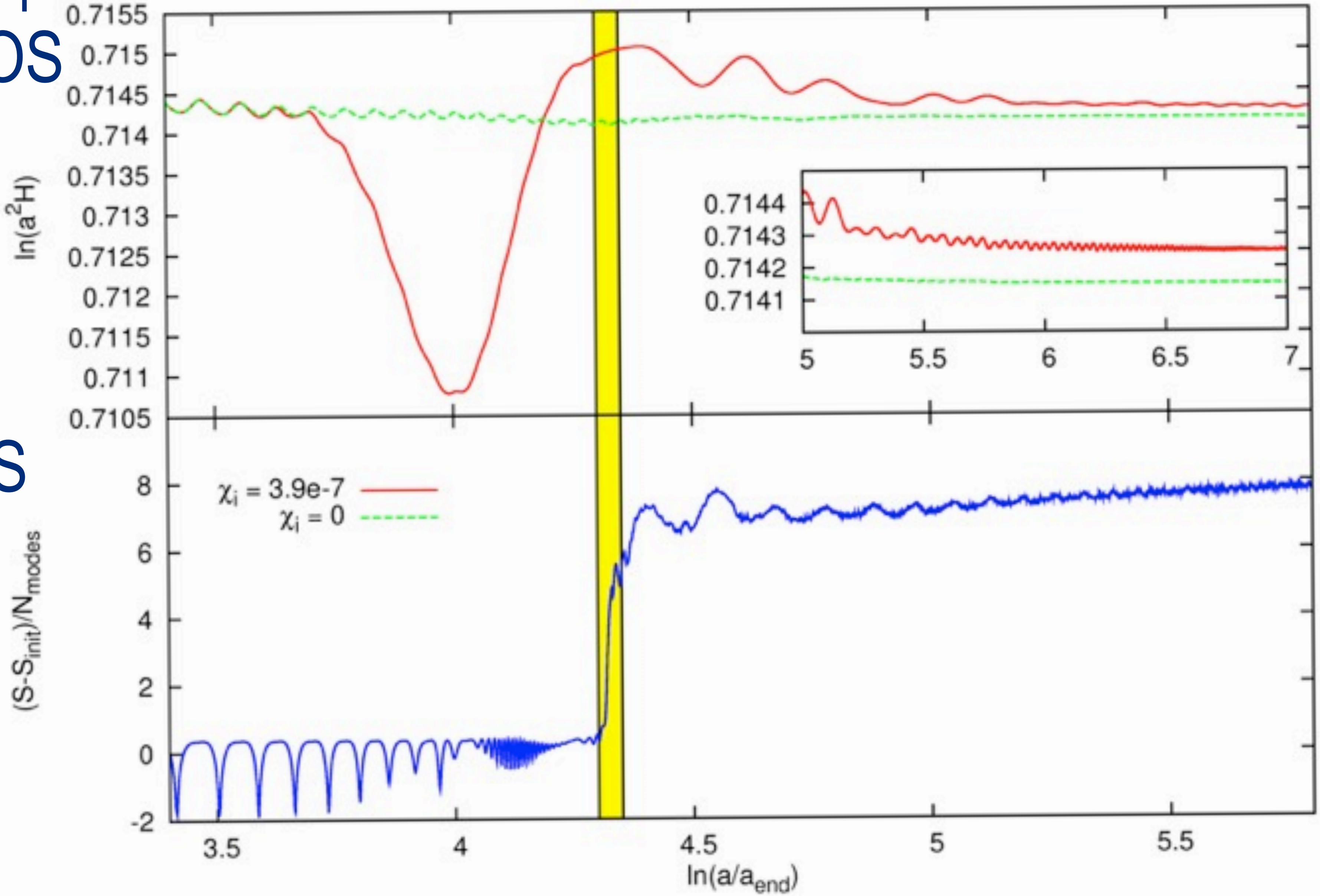


Relation to Nongaussianities EOS change ρa⁴ near the entropy jump

δlnρa⁴
EOS

looking for sub-parts-per-million deviations so high accuracy fundamental

δS



Conclusions

new language for preheating with complex information measures at its core: 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 $\ln\rho$ **& 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. reasonable case made for ~ $\ln a_{final}(x)/a_{end}$

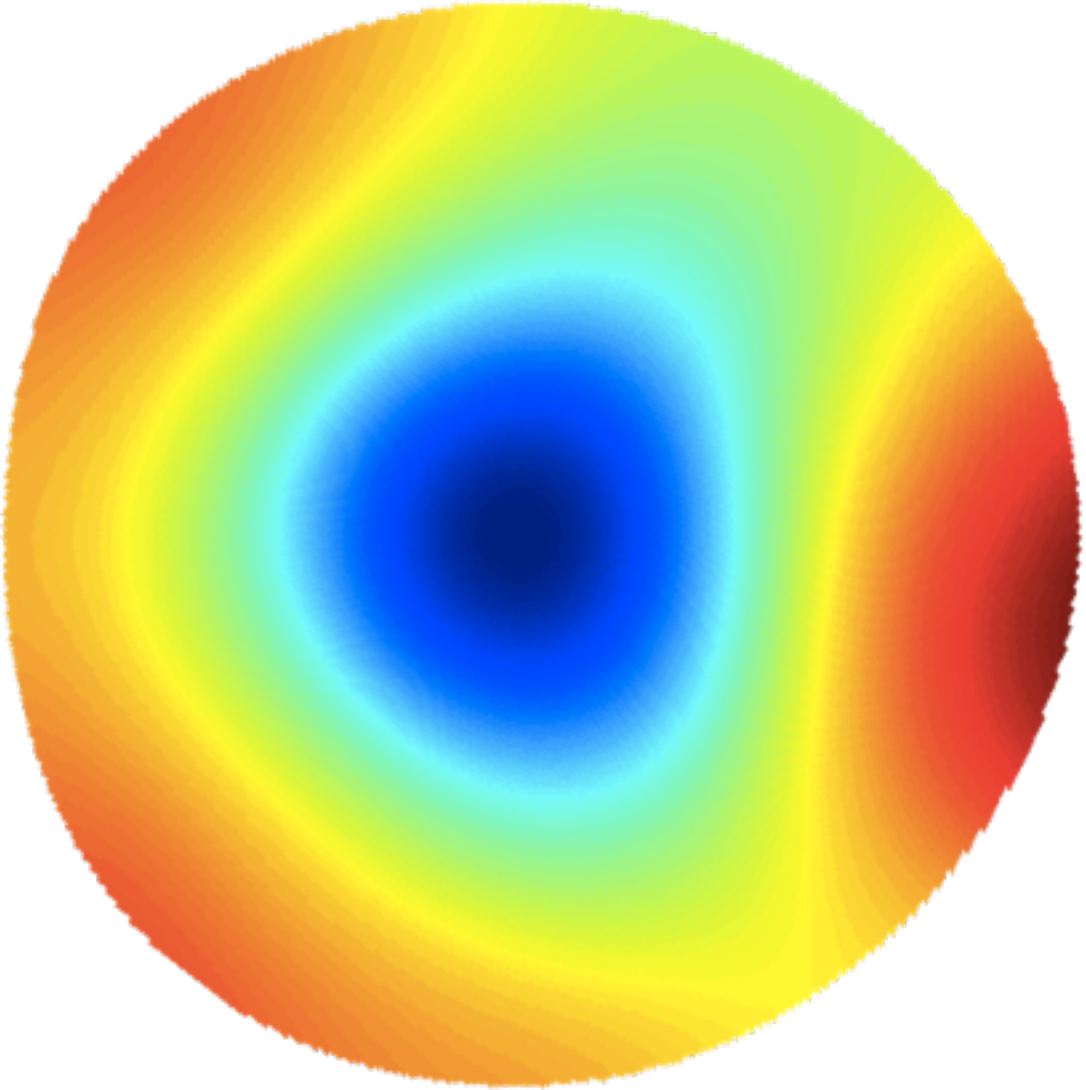
TBD: solidify the case for nonG from shock-in-time(x | couplings, isocon, ...) & explore the parameter dependence, and thus the **variety of nonG** that can arise. *constrain/detect with Planck.* ***explore more short-astro-distance exotica of spiky potential pits***

whence opening of 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

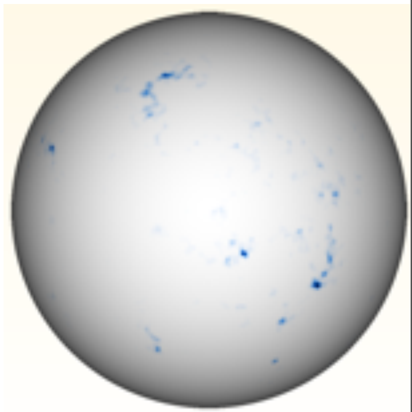
publish all of our cold spot /quadratic constraints nonG-S stuff

end

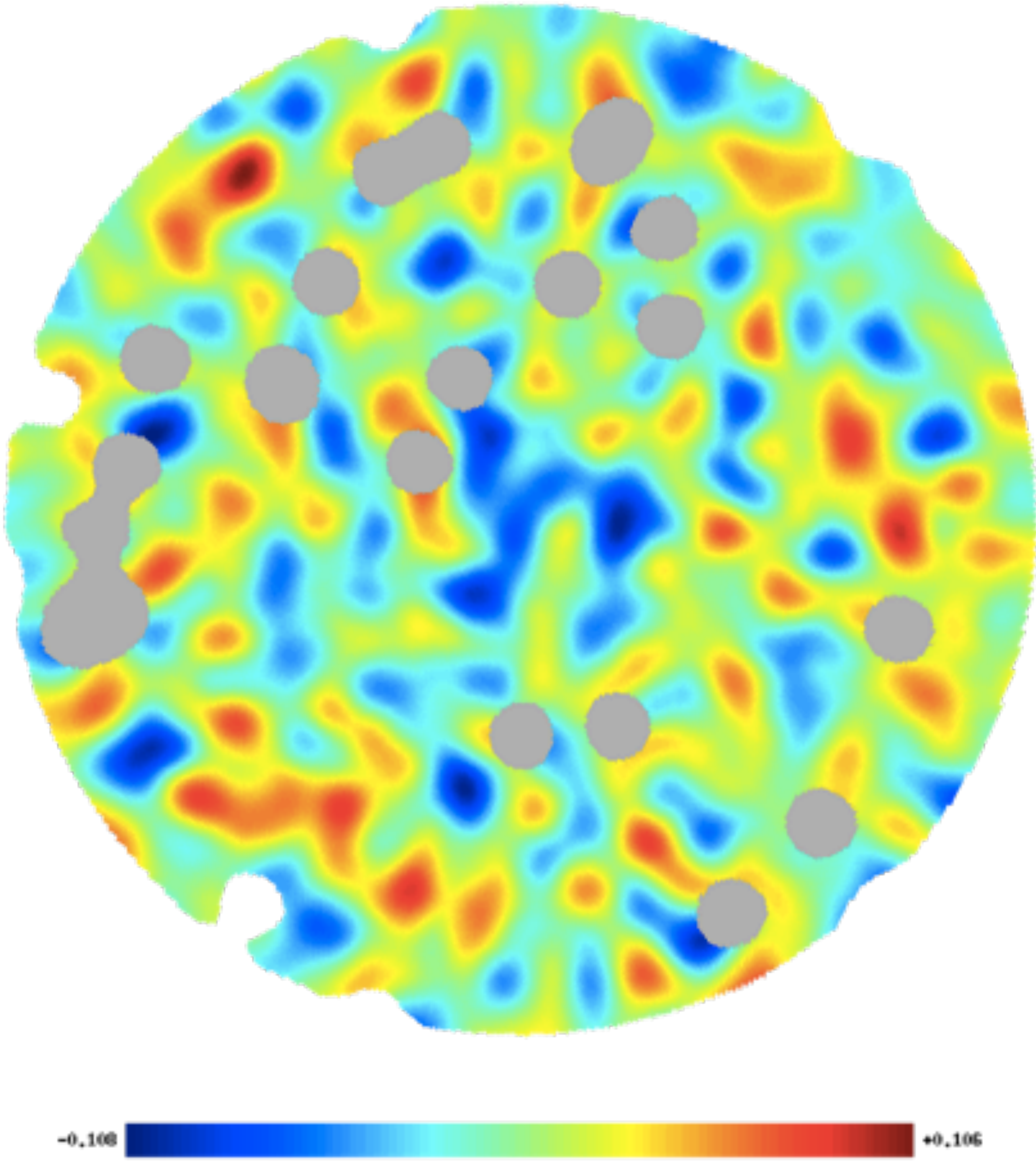
closing in on cold spot structure *(resolution)*



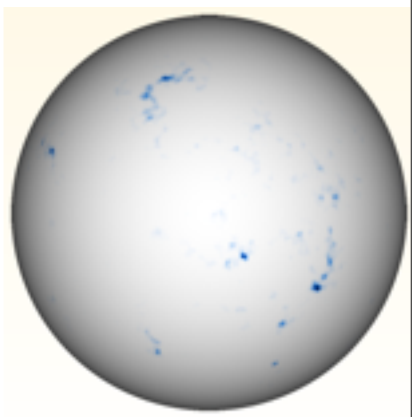
13 deg



closing in on cold spot structure *(resolution)*



2 deg

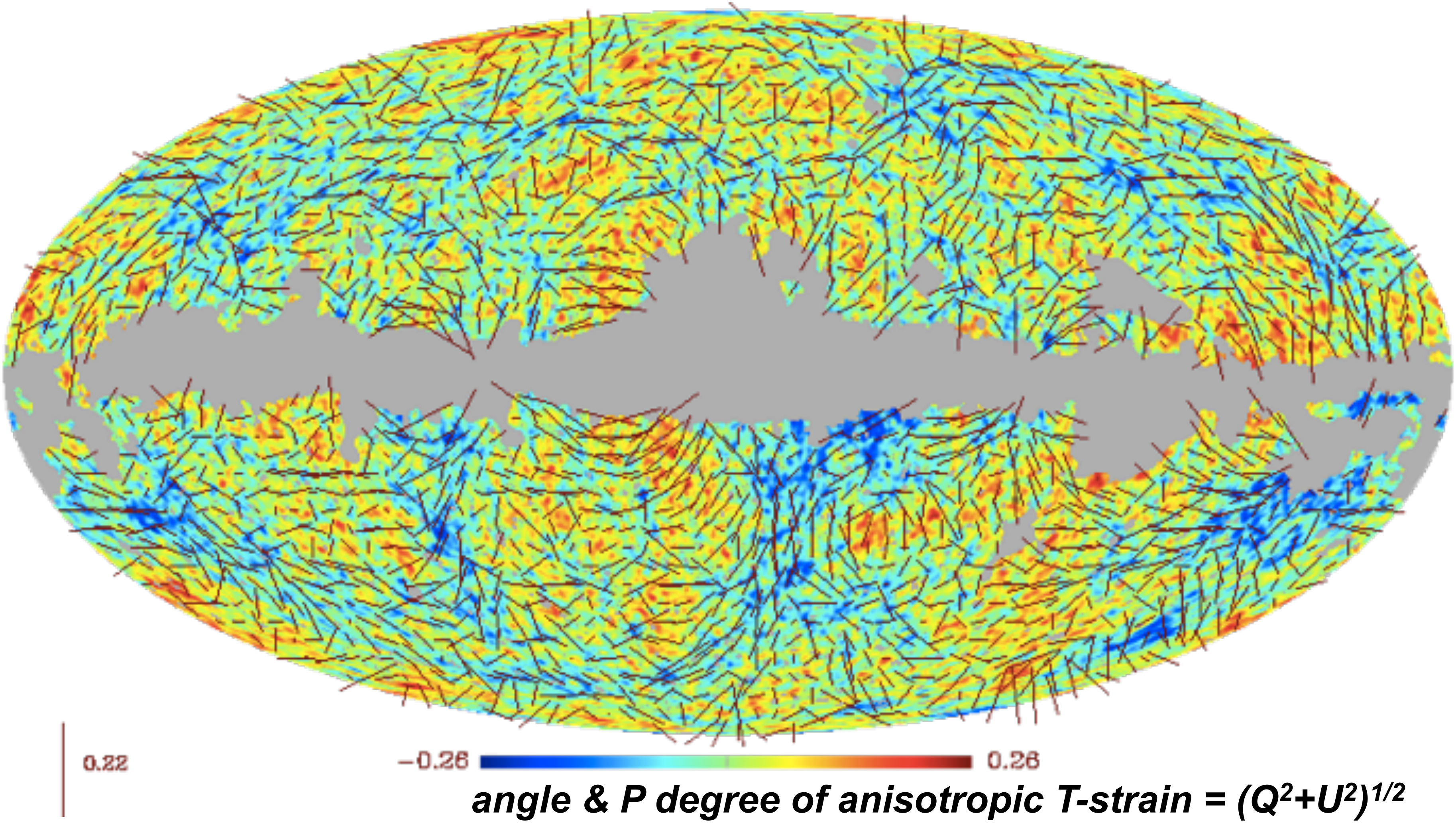


$$K_{ab} \equiv \Delta^{-1} \nabla_a \nabla_b T$$

isotropic T-strain: = I Stokes

anisotropic T-strain: K_{11}-K_{22} ~ Q E-like Stokes

anisotropic T-strain: K_{12}+K_{21} ~ U E-like Stokes



angle & P degree of anisotropic T-strain = $(Q^2+U^2)^{1/2}$

end