Intermittent non-Gaussianity & Anomalies: rare patchy subdominants from Modulated Heating, Bubble Collisions & Oscillons

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

Dick Bond

CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH

Grand Unified Theory of Anomalies TBD *Anomalies in Polarization? TBD*

anomalies are nonG, non-statistical-isotropy. just from broken Gaussianity?

WMAP *cold spot anomaly: coherent in scale space 1:497 @826', 1:9 @360'*

power spectrum asymmetry: 7% at lowL, unclear if any at hiL. Doppler dipole modulation exists

P13 hiL nonG pattern constraints are restrictive, but open up with decoupled ζ_{NL}, support(ζ_{NL})^3 & need further exploration of nonG with a built-in scale, related to radically broken scale invariance

$\zeta_{NL}(x)$ from ***"isocon" degrees of freedom cf.*** $\zeta_{inf}(x)$ from ***inflaton***

modulated heating, ***ballistic chaos, caustics, shock-in-time,***

modulators isocon $\chi(x)$, ***axionic-isocon***(x) ***couplings*** $g(x)$ super-horizon accessible

quantum tunneling landscape, inflating bubbles & bubble-bubble collisions

aka ***theory of nonlinear multi-field dynamics using lattice simulations. symplectic defrost++ code + new spectral code.***

intermittent nonG: ∃ a statistical landscape of possibilities.

allowed level highly constrained, but as observed anomalies?

unknown, ∃ much to explore

Bond, Huang 13a,b
Bond, Frolov, Huang, Kofman 09
Bond, Braden 13
Bond, Braden, Frolov, Huang 13
Bond, Braden, Frolov, Huang, Nolta 13
Bond, Braden, Mersini 13a,b,c

KITP13 Primordial Cosmology talks of relevance: nonG, Anomalies, ...

4/08, Christopher Hirata The CMB power asymmetry

4/08, Eiichiro Komatsu Making sense of the "north-south" asymmetry

4/09, Jonathan Braden Density perturbations from preheating caustics and the Shock-in-time

4/16, Dick Bond Lunch discussion, p(reheating), perturbations and structure of models

4/17, Mustafa Amin Nonlinear field dynamics after inflation

Observations and Theoretical Challenges in Primordial Cosmology

Paul Shellard, James Fergusson Non-Gaussian Inflation and Planck

Ben Wandelt Non-Gaussianity

Kris Gorski Erikson Isotropy

Kendrick Smith panel

Leonardo Senatore Bottom up overview

Daniel Green Two Interpretations of the Bounds on Non-Gaussianity

Matthew Kleban Fundamental Physics from Cosmology

Antony Lewis, Duncan Hanson Primordial and kinematic power modulation from Planck

Discussion: Cosmology: Where we go from here? Frolov, Contaldi

May: much nonG from LSS observability discussion

5/02, Marilena LoVerde Non-Gaussian Mode Coupling and the Statistical Cosmological Principle

5/14, Dmitri Pogosyan Geometrical measures for (mildly) non-Gaussian cosmological fields

6/13, Matias Zaldarriaga The effective theory of Large Scale Structure

6/25 Dick Bond Intermittent non-Gaussianity and Anomalies: rare patchy subdominants from Modulated Heating, Bubble Collisions & Oscillons ***take 1***

SIMPLICITY

at $a \sim e^{-7} \sim 1/1100 \Rightarrow$

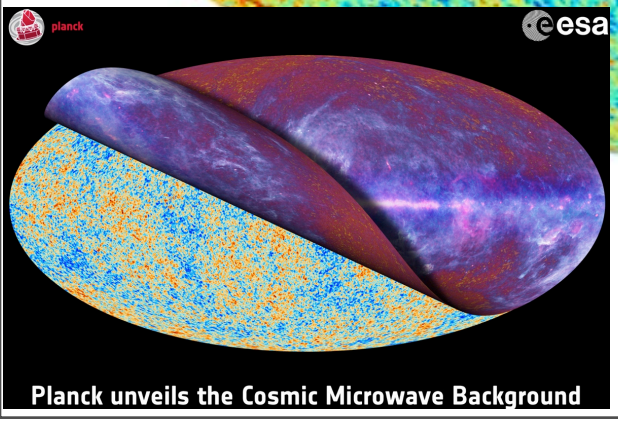
at $a \sim e^{-67+60} \sim 1/10^{30+25}$

"red" noise: 2 numbers

PLANCK

Planck SMICA Map

CMB-data Concordance



Planck CMB/SMICA map, ~5' resolution
+ NILC, SEVEM, C-R 3 independent component separated CMB maps show the same features

SIMPLICITY

at $a \sim e^{-7} \sim 1/1100 \Rightarrow$

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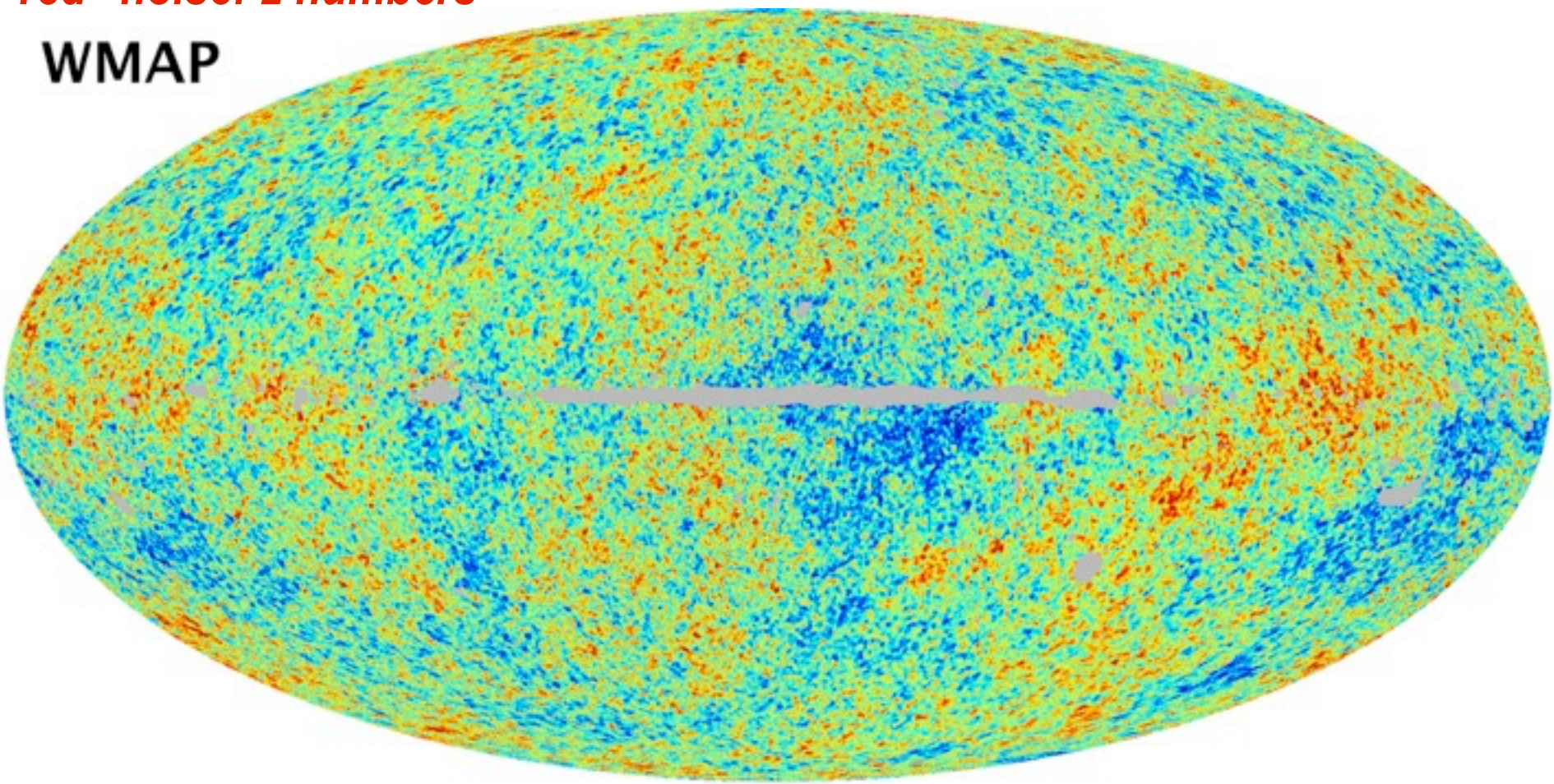
WMAP W-band, Template Cleaned

CMB-data Concordance



Cleaned with Planck 353 GHz dust map and low-frequency templates. 12′ resolution.

similar tremendous agreement with the much higher (5X) resolution ACT & SPT maps

total focus on the 1.2% difference in "calibration" between P13 (HFI &LFI) & WMAP9

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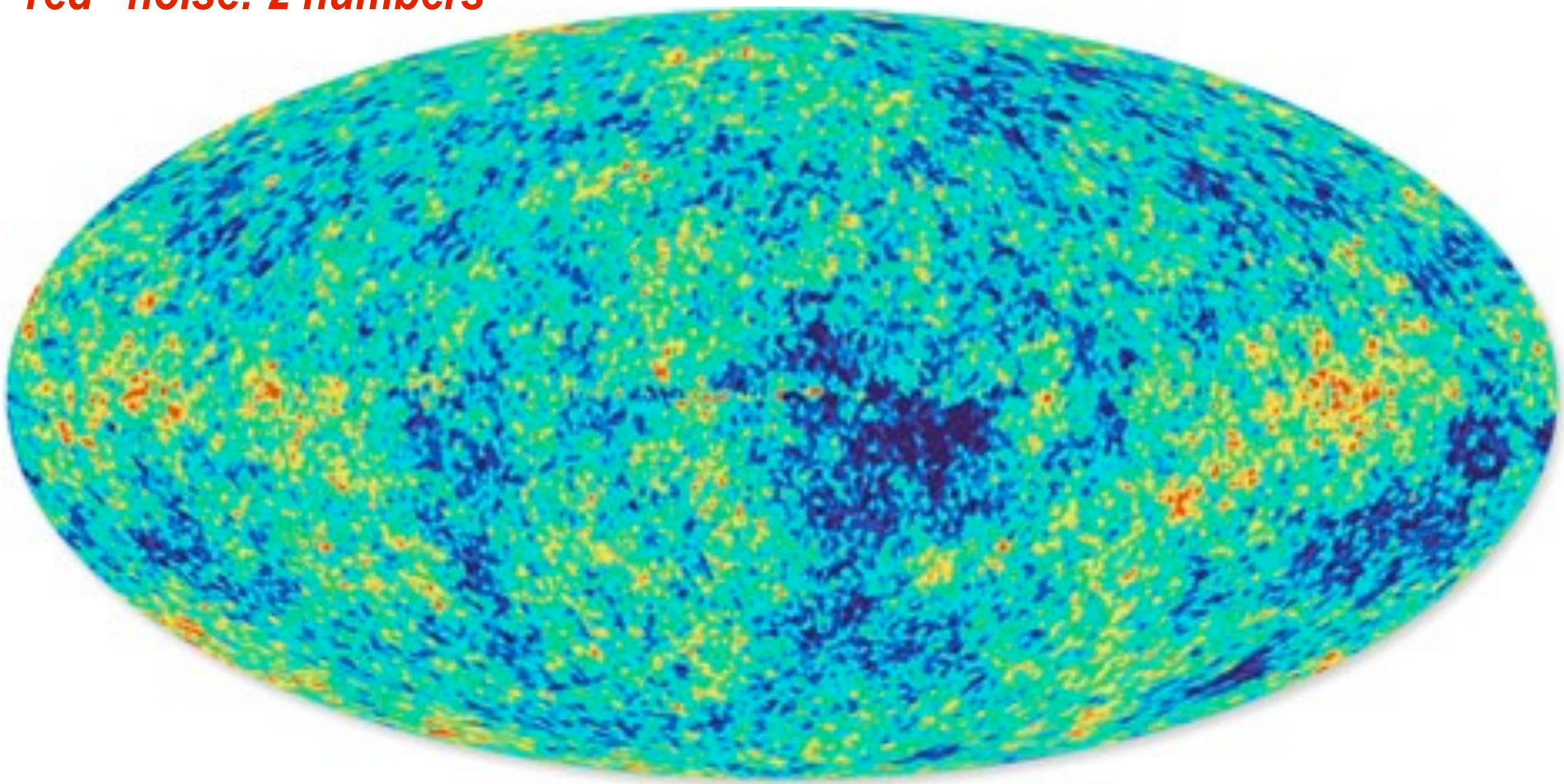

Cleaned with low-frequency templates only.

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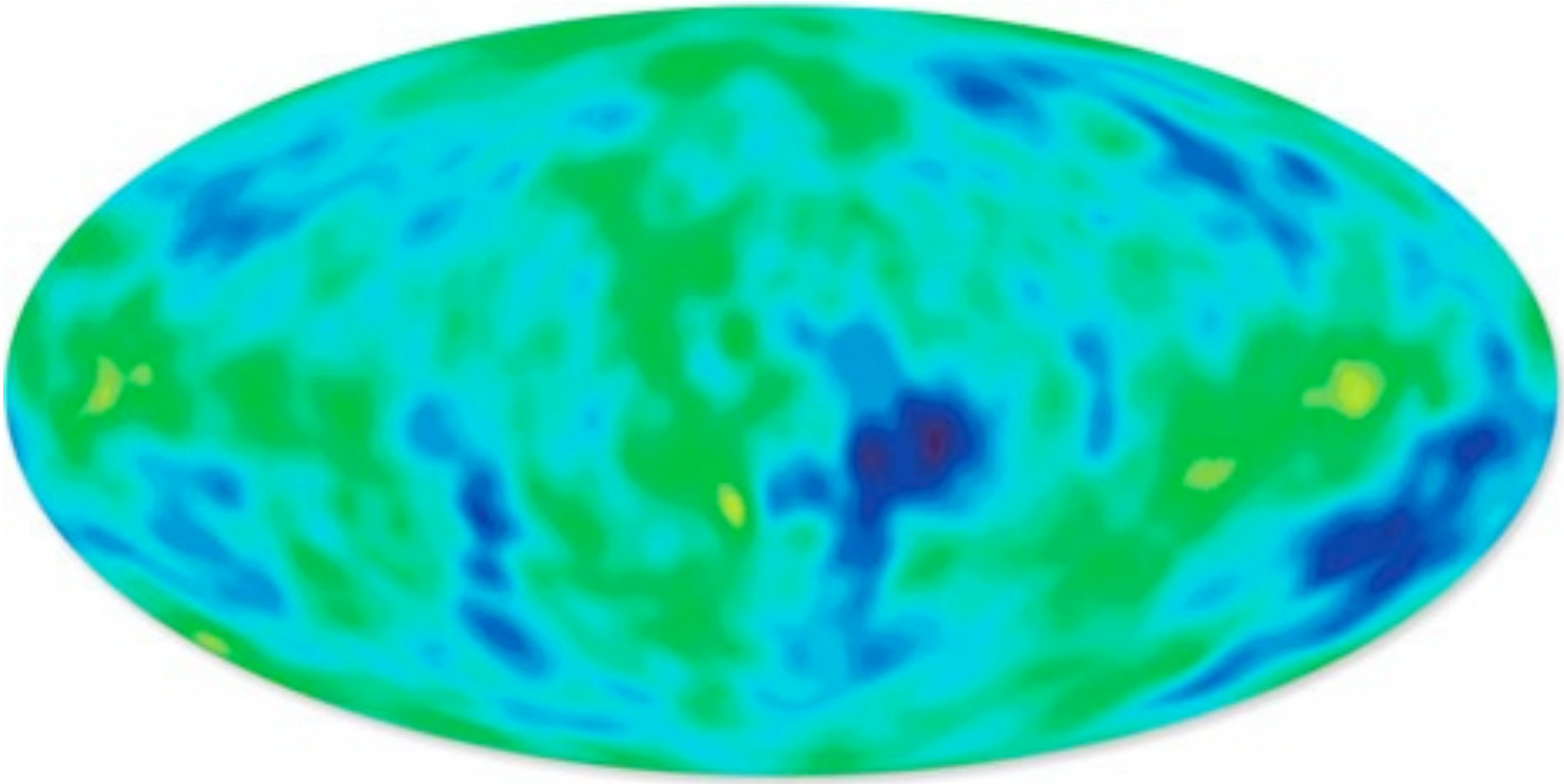
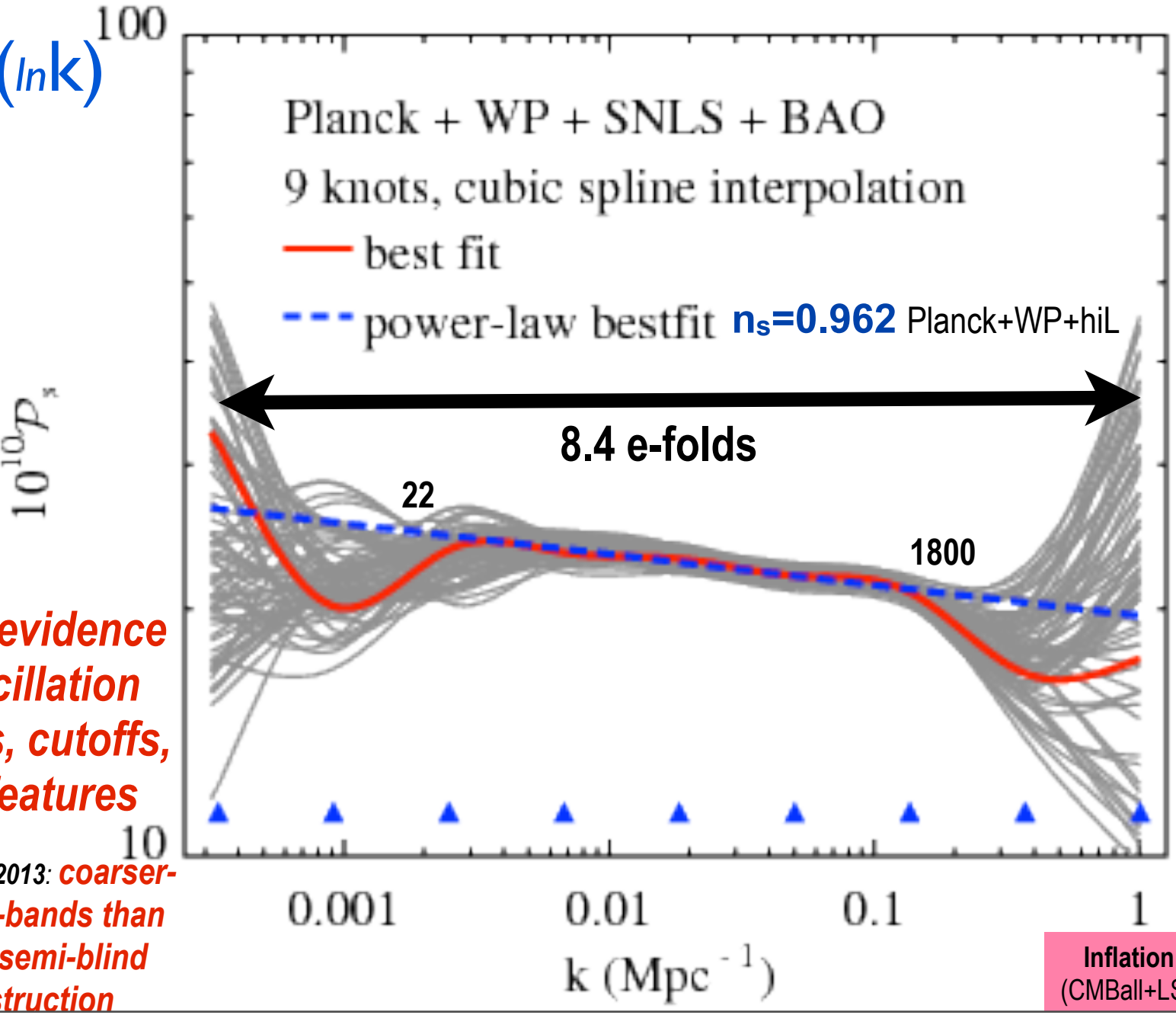
COBE

CMB-data Concordance



scan $ln\mathbf{P_s}(ln k)/A_s$, $ln\mathbf{A_s}=ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$; *consistency => reconstruct* $\boldsymbol{\varepsilon}(ln\mathbf{Ha})$, $\mathbf{V(\psi)}$

$ln P_s(ln k)$



no strong evidence for oscillation patterns, cutoffs, local features

Bond, Huang 2013: coarser-grained k-bands than **P13 XXII** ***semi-blind reconstruction***

Inflation Histories
(CMBall+LSS+SN+WL)

primordial nonGaussianity

$\zeta_{NL}(x) = \zeta_G(x) + f_{NL}^* (\zeta_G^2(x) - \langle \zeta_G^2 \rangle)$
local smooth.
use optimal pattern estimators

nonG 3-point-correlation-pattern measure

f_{nl}: 2.7 ± 5.8 local for Newton potential *cf.* ± 5 (Pext)

=> f_{NL^*} =0.44 ± 3.5 *for phonons/3-curvature*

-f_{nl}: 42.3 ± 75.2 equil

-25.3 ± 39.2 ortho

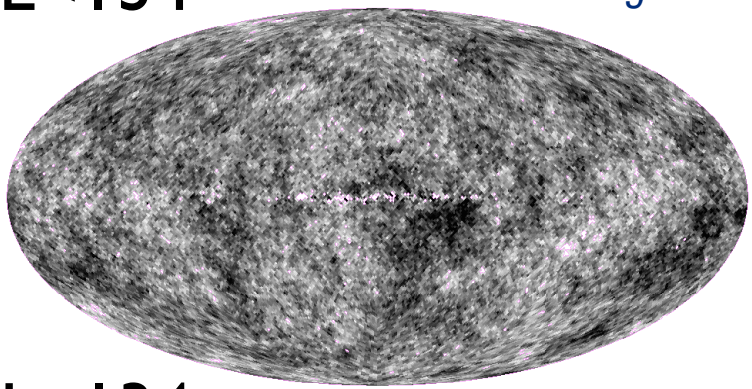
cf. DBI inflation: non-quadratic kinetic energy

phonon ~ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ => $f_{NL}^* = 3/5\, f_{NL} - 1$

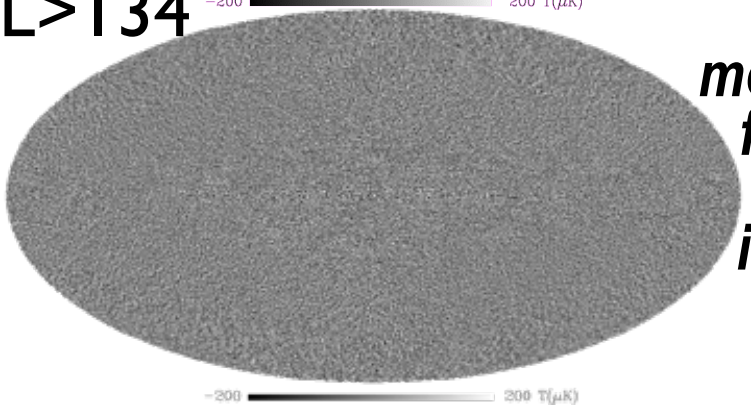
$\zeta_{NL}(x)$=
equilateral pattern &
orthogonal pattern

P13 XXIV, XXII

L<134 *Planck smoothed to 1deg fwhm*



L>134



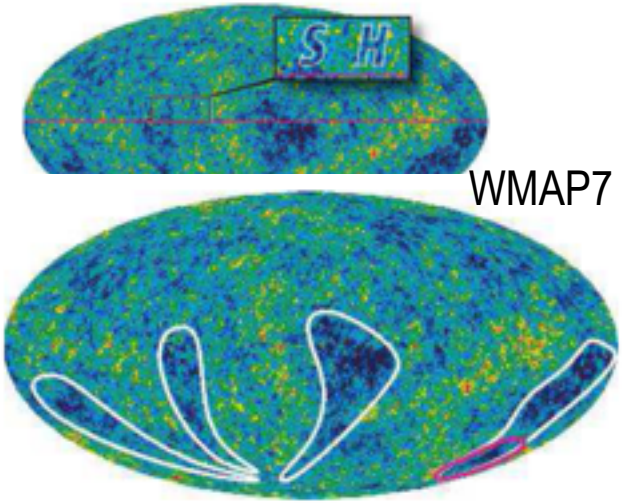
scale (k) dependent patterns: connecting to power spectrum broken scale invariance. hint?

cosmic/fundamental strings/defects *P13 XXV*

most nonG info from high L: why Planck improved so much over WMAP9

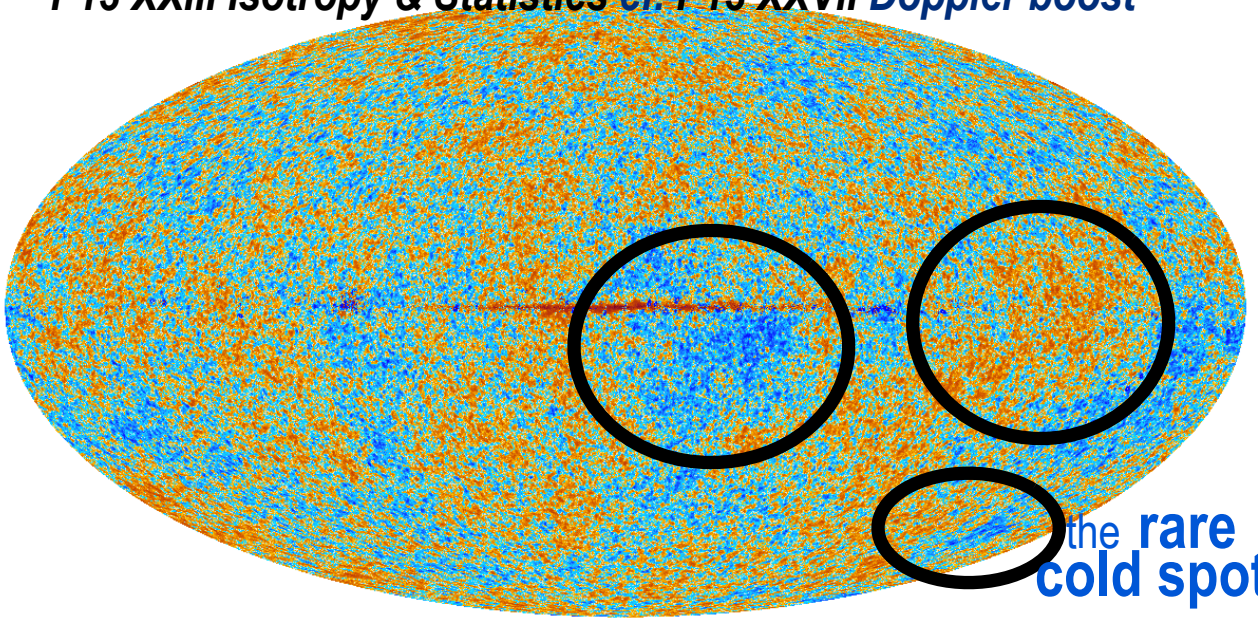
COMPLEXITY

at a~e^{-67}?



WMAP7

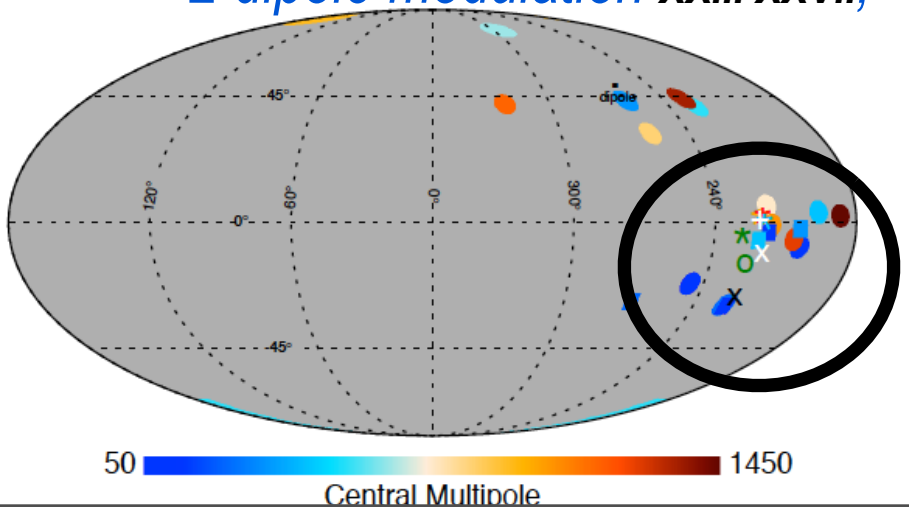
P13 XXIII Isotropy & Statistics cf. P13 XXVII Doppler boost

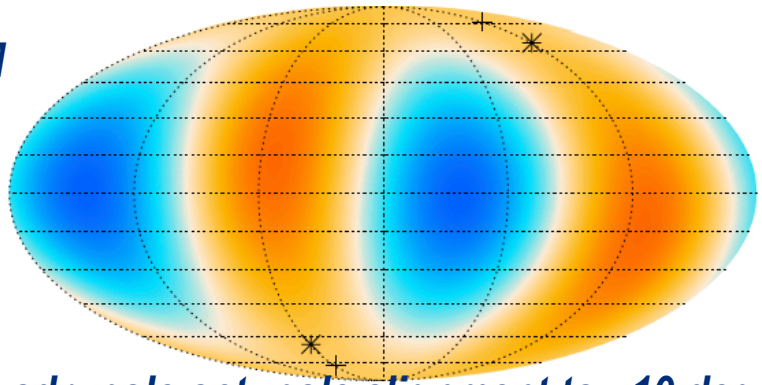


the **rare cold spot**

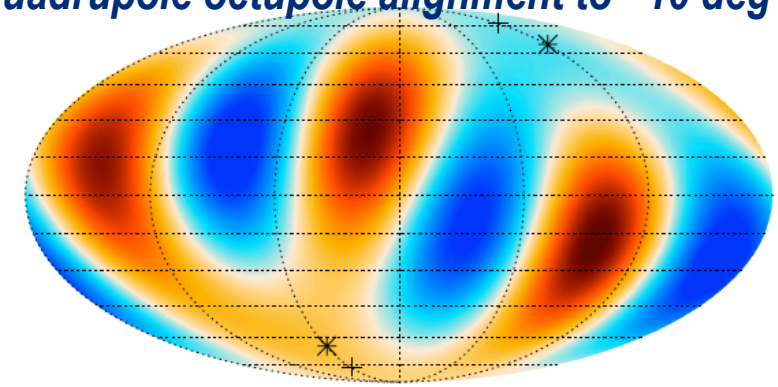
C_L @L<200 is low cf. L~200-2000 forecast for tilted LCDM

$\Delta C_L / C_L$ @L<400 ~7% (P13 XXIII & WMAP9),
high L C_L asymmetry small <0.2% with L_{max}=1500?
∃ *dipole modulation* ***XXIII XXVII****, +?*





quadrupole octupole alignment to ~10 deg



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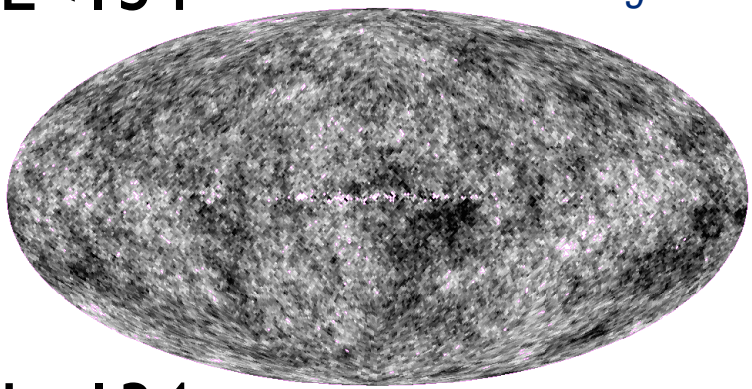

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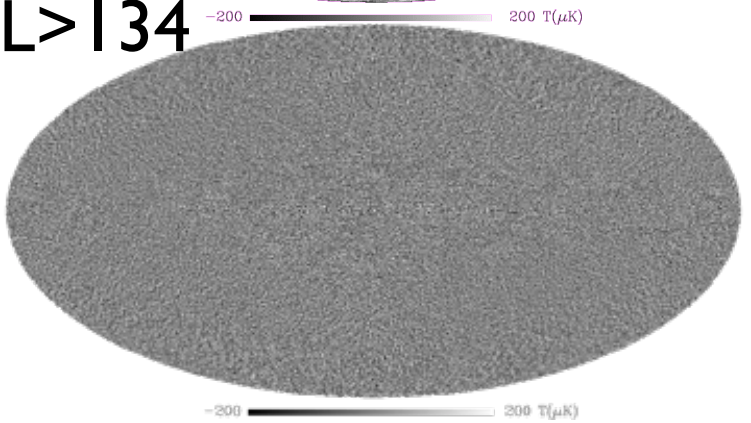


scale (k) dependent patterns: connecting to power spectrum broken scale invariance. hint? *P13 XXIV*

from end-of-inflation & preheating chaos

$f_{NL}(\chi_b(x))$

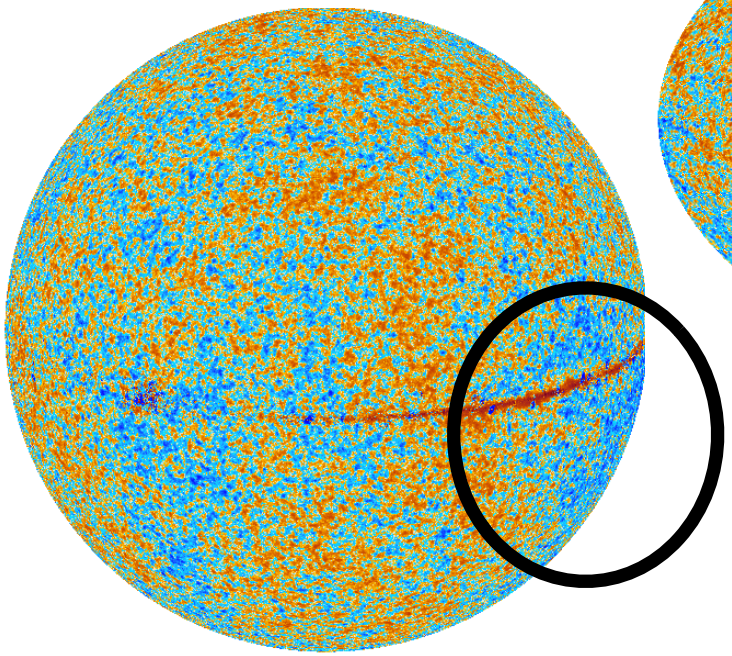
intermittent *CMB power bursts from super-bias of a GRF modulating field landscape scan*

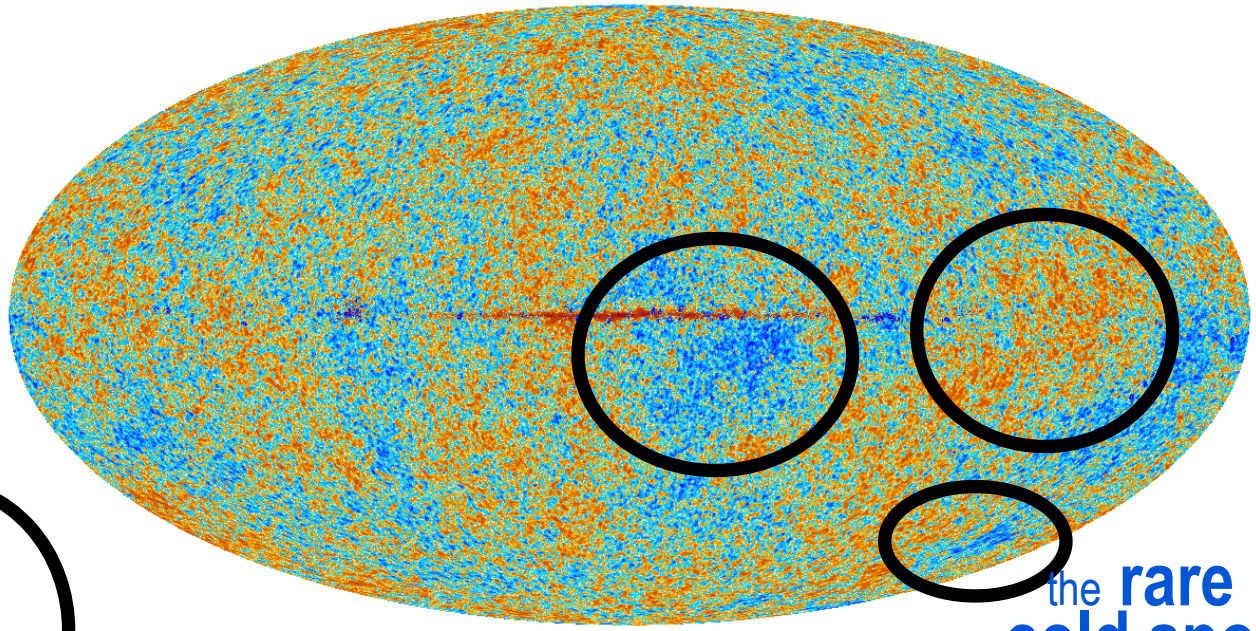
cosmic/fundamental strings/defects **@EoI**

bubble collisions *CMB Euclidean SO(4) => real SO(3,1) => SO(2,1) collisions, oscillon broken*

COMPLEXITY

at $a \sim e^{-67}$?





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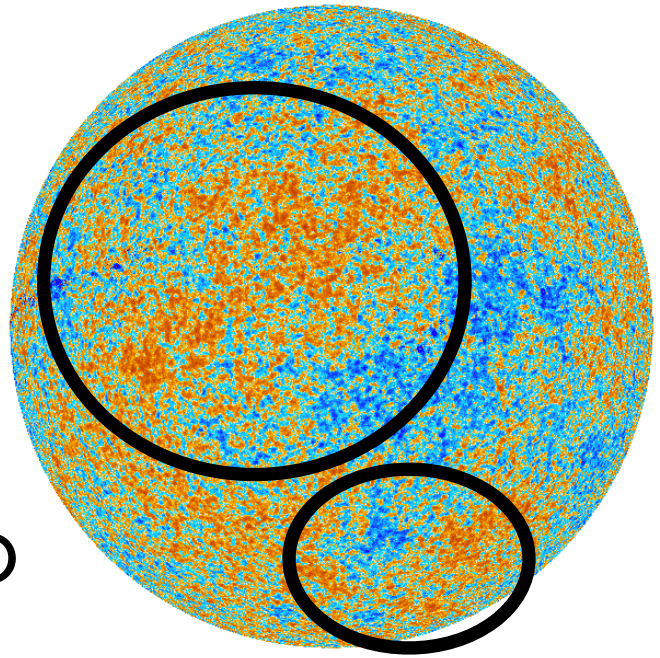


WHITEN => MASK => FILTER BANK *(SSG42 filter)*
=> EXTRACT PEAKS *(hierarchical peak patches)*

filter = extra dimension: **scale space** analysis ADS of our CFT

hot & cold peaks *agree with BE87* ***Gaussian stats*** $n_{pk}(<\nu)$

PLANCK2013: 826', 105 peaks, coldest -4.97σ 1:497

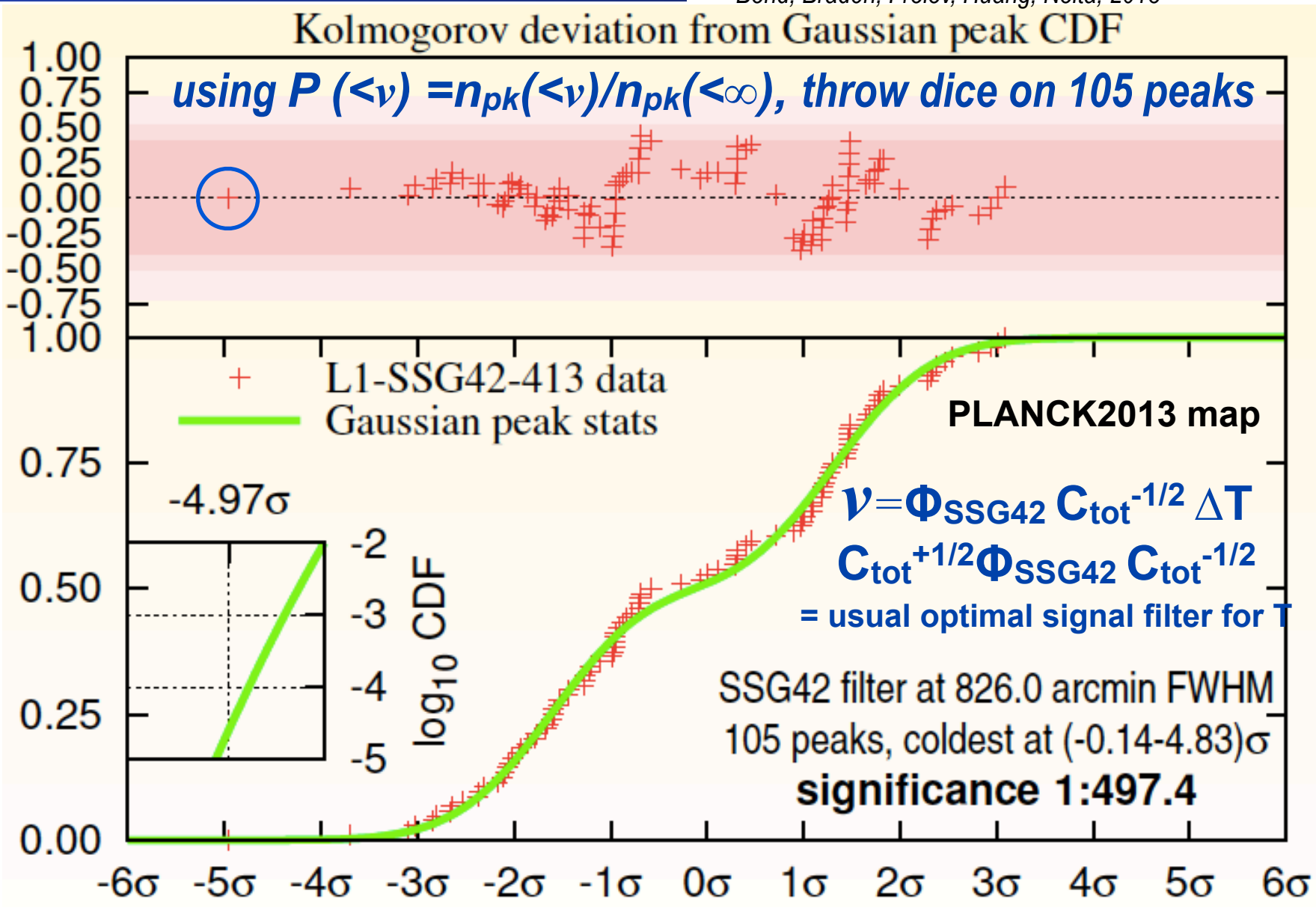
WMAP7: 800', coldest -4.87σ significance 1:300

Grand Unified Theory of Anomalies TBD

Anomalies in Polarization? TBD

TESTING CMB PEAK STATISTICS

Bond, Crittenden 2001
Bond, Braden, Frolov, Huang, Nolta, 2013



P13 XXIII Spherical Mexican Hat Wavelets, 3 filters, kurtosis & excursion areas $\nu > 4$, .3% significance

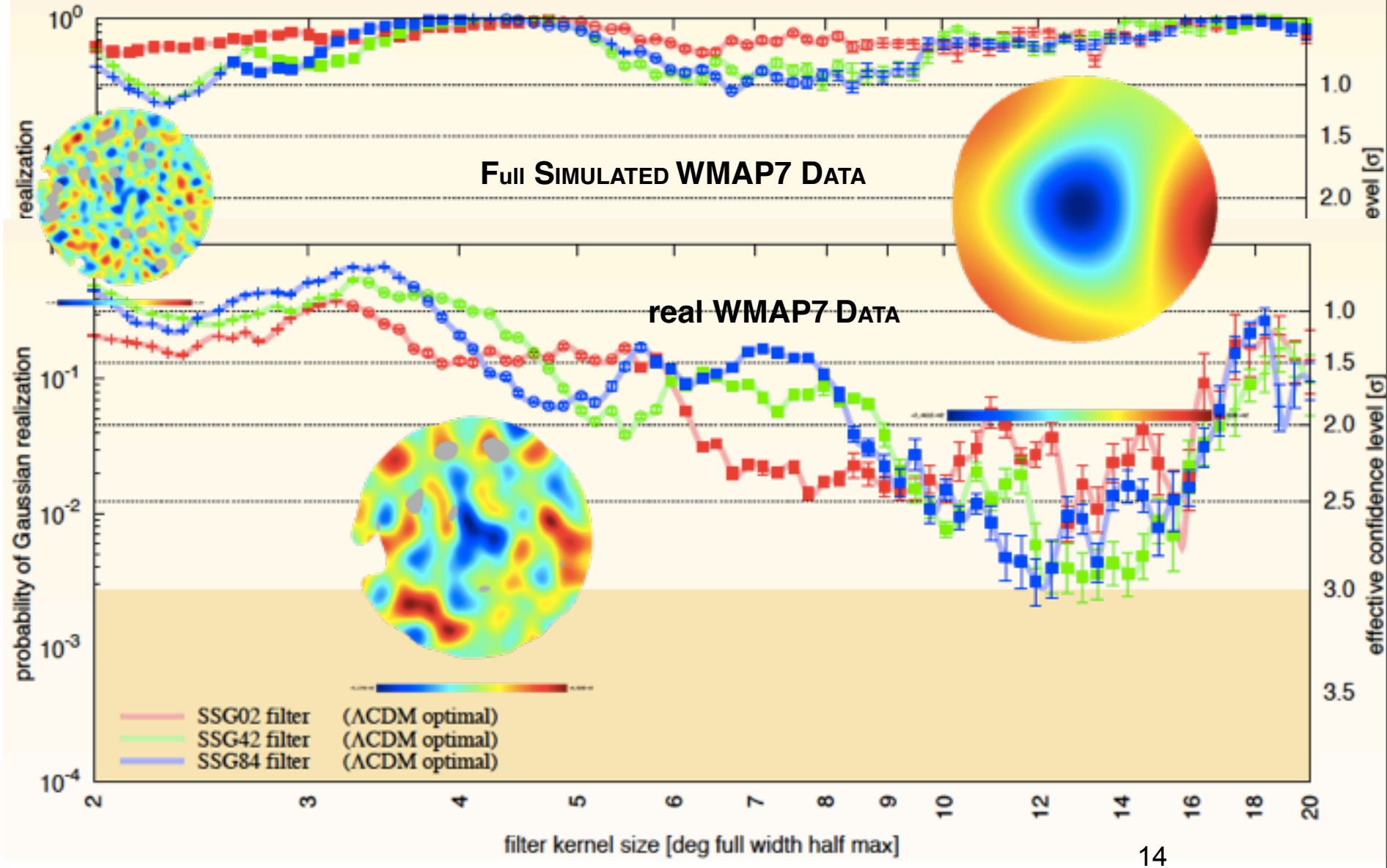
SSG42 Filter Sweep

WMAP7

Significance vs. Filter Size

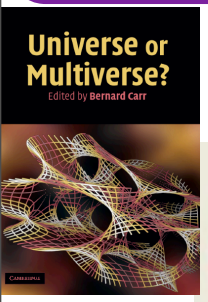
Bond, Braden, Frolov, Huang, Nolta, 2013

using $P(<\nu) = n_{pk}(<\nu)/n_{pk}(<\infty)$, throw dice on $N(R_f)$ peaks

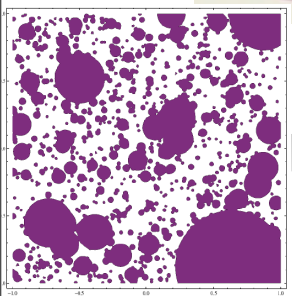


P13 XXIII Spherical Mexican Hat Wavelets, 3 filters, kurtosis & excursion areas $\nu > 4$, .3% significance

UltraUltraUltraLargeScaleStructure beyond our Horizon to our Hubble patch and below



higher dimensions 6?



quantum tunnels = bubbly-U

Horizons: the ultimate-speed constraint on light & information

ln a-bubbles

UNIVERSE

semi-eternal stochastic

10^{21} Gigaly

$a \sim e^{-170}$

Salopek, Bond91

3000 Gigaly

$a \sim e^{-132}$

our horizon

30 Gigaly

$2H_0^{-1}$

$a \sim e^{-127}$

1cm

$a \sim e^{-67}$

$a \sim e^{-7}$

~1 Gigaly

$a \sim e^{0}$

O dark dark dark. They all go into the dark, The vacant interstellar spaces, the vacant into the vacant ... So the darkness shall be the light

CITA–ICAT

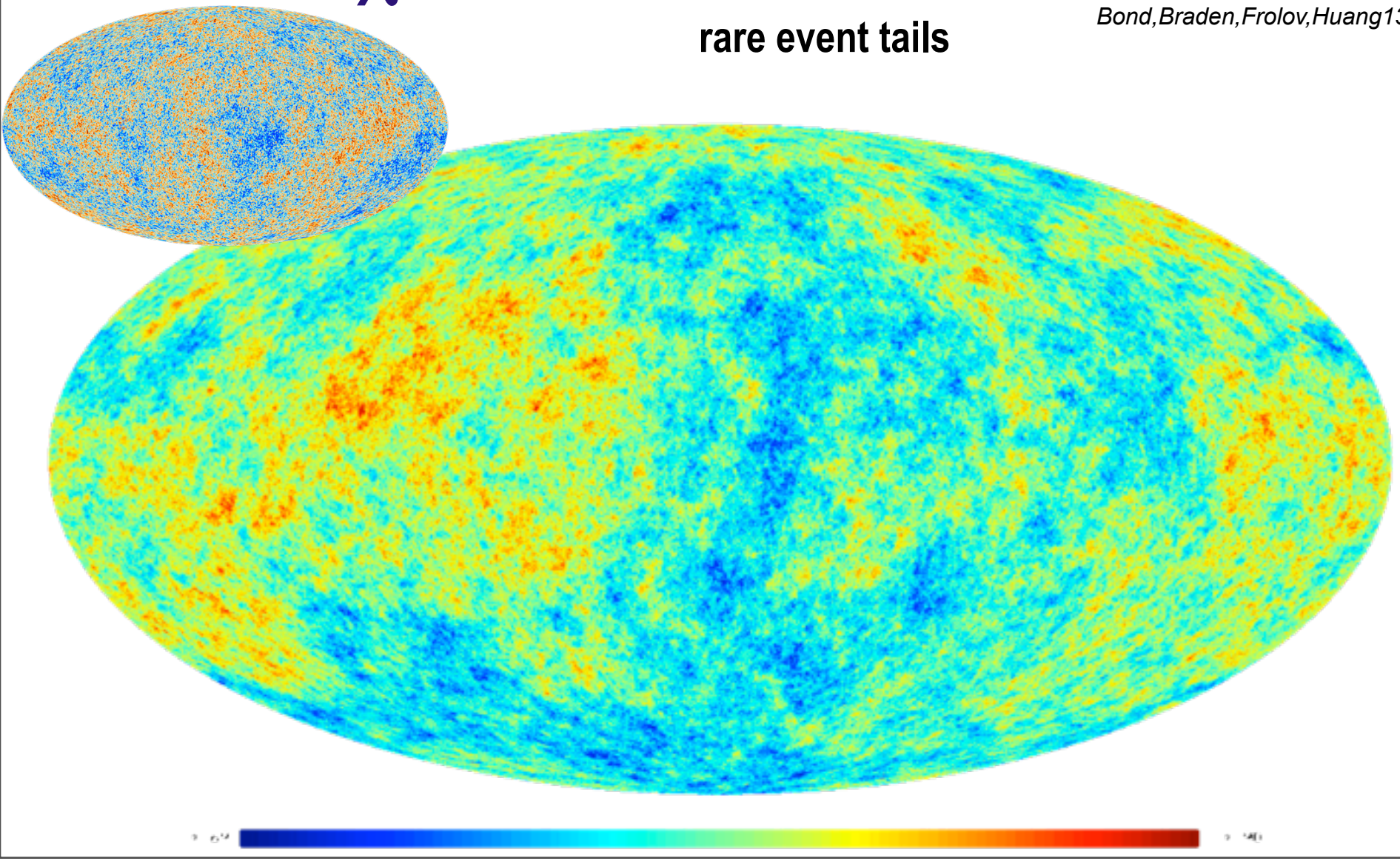
a future DE-Void

simulated sky with Gaussian inflaton-induced + **uncorrelated subdominant non-Gaussian isocon-modulated preheating**. Landscape-accessing super-horizon

control variable = $\chi_{>h}$ => ***super-bias, intermittent, extended source-like***

Bond,Braden,Frolov,Huang13

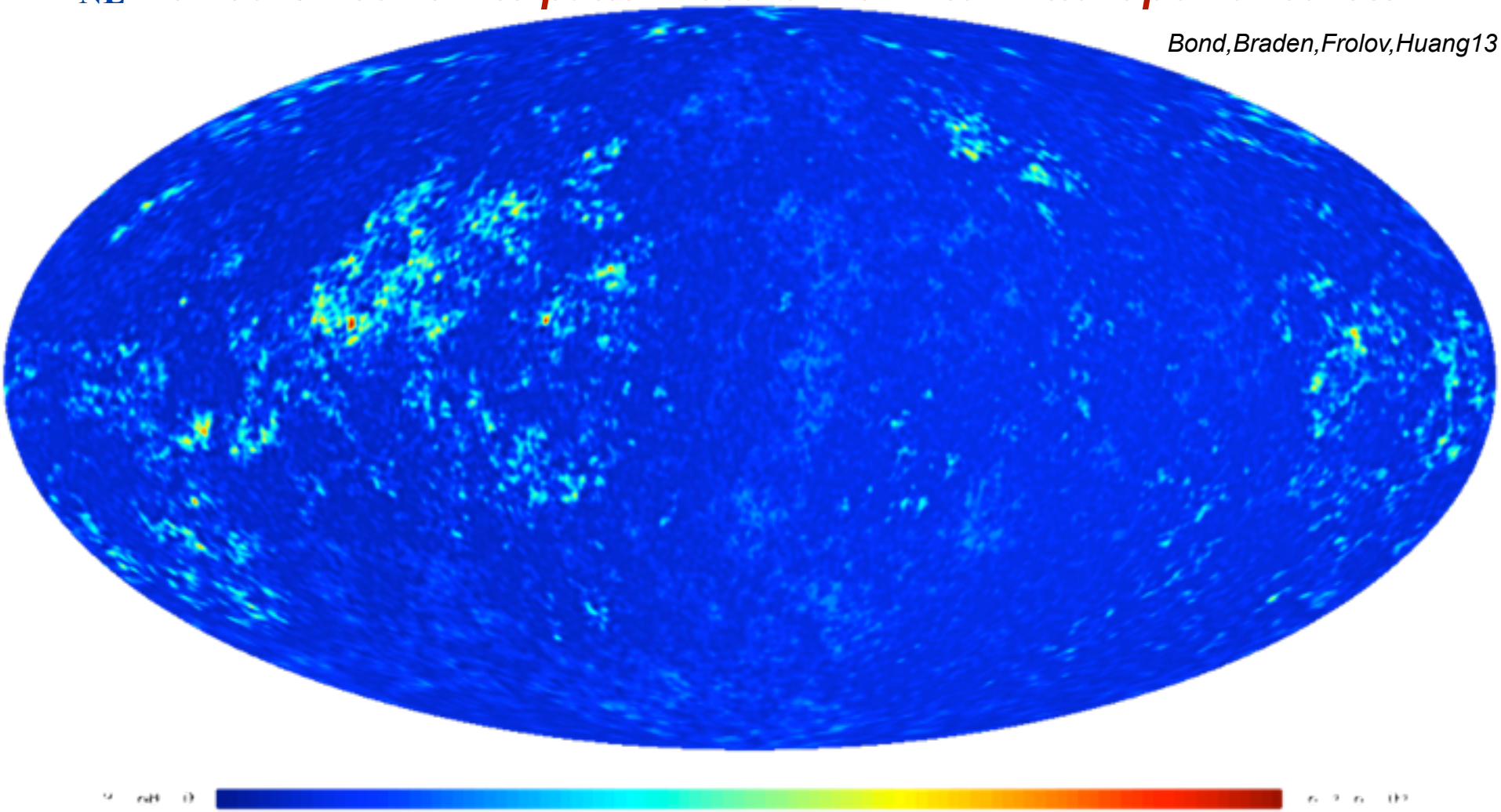
rare event tails



bispectrum & 3-point ~ $f_{sky,patches}^{3}$ => not overly constraining & standard

f_{NL} method is ***not how to pattern-search for intermittent power bursts***

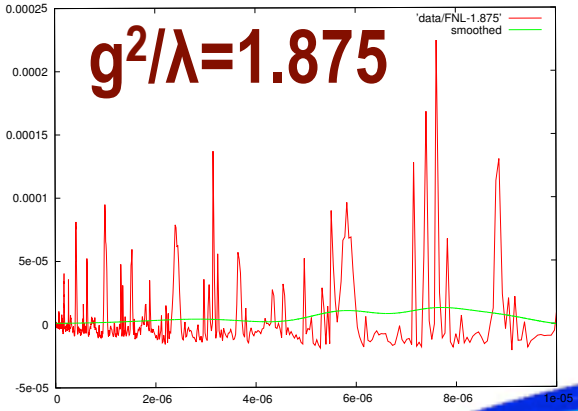
Bond,Braden,Frolov,Huang13



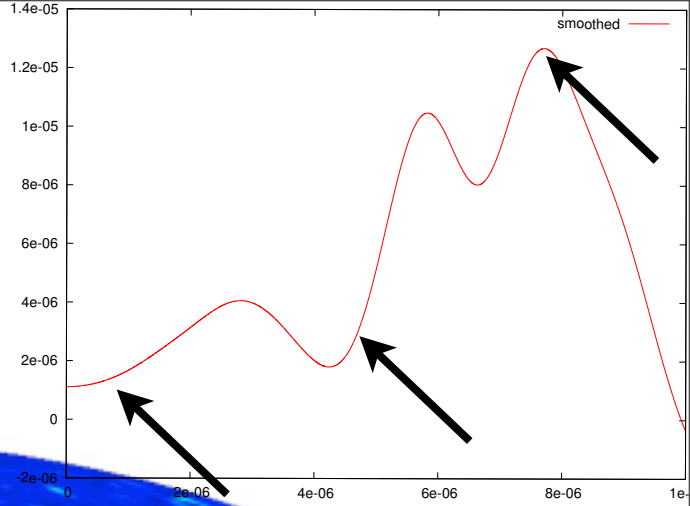
for some $\chi_{>h}$ there is a perturbative regime:

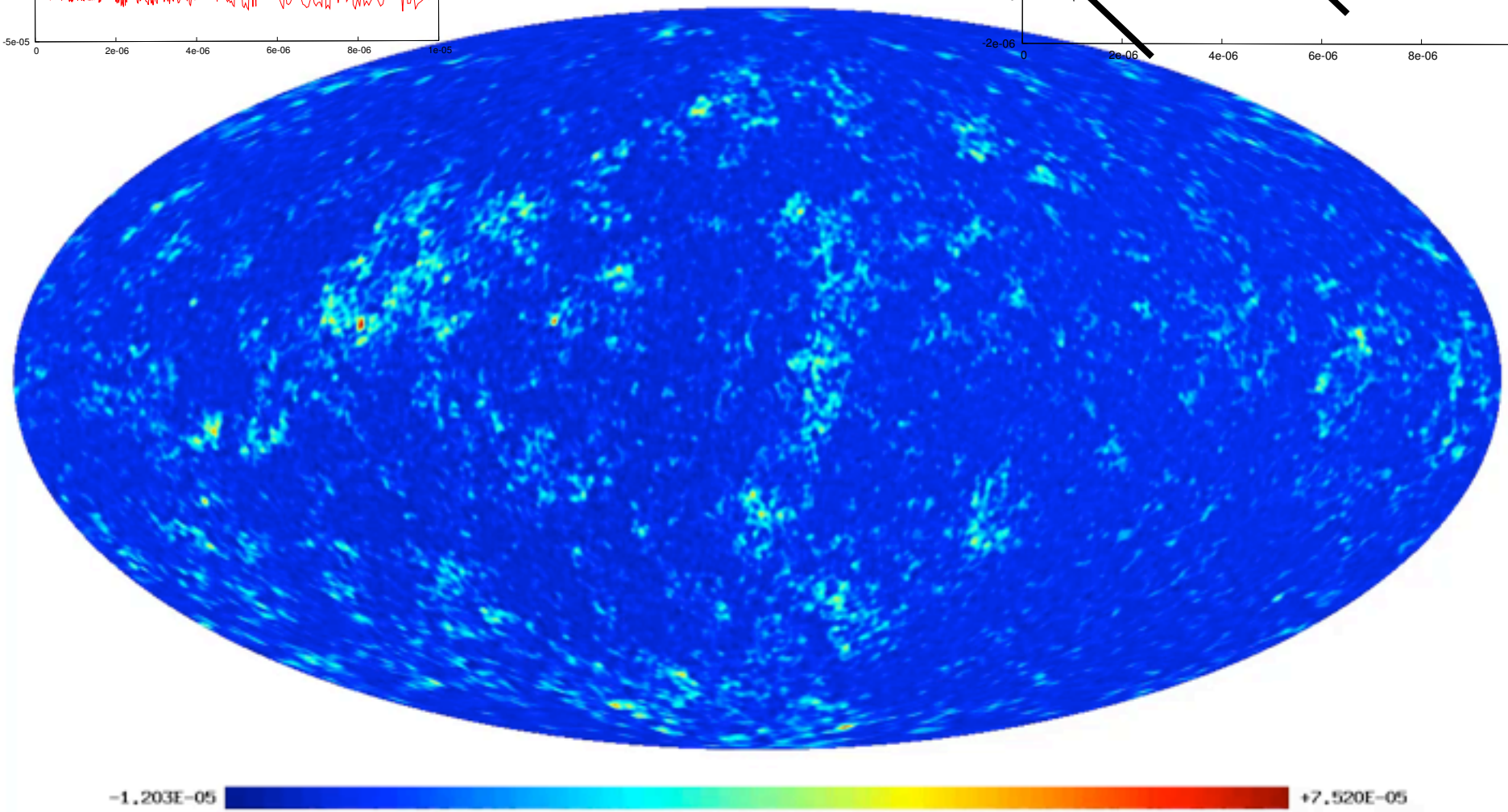
$$f_{NL}^{equiv} = \beta \chi^2 f_\chi \, [P_\chi/P_\phi]^2(k_{pivot}) \Rightarrow \text{constrain } f_\chi^3 \, \chi_{>h}^2$$

subdominant structure change as we scan χ>h



Bond,Braden,Frolov,Huang13





bispectrum & 3-point ~ $f_{sky,patches}^3$ => not overly constraining & standard f_{NL} method is *not how to pattern-search for intermittent power bursts*

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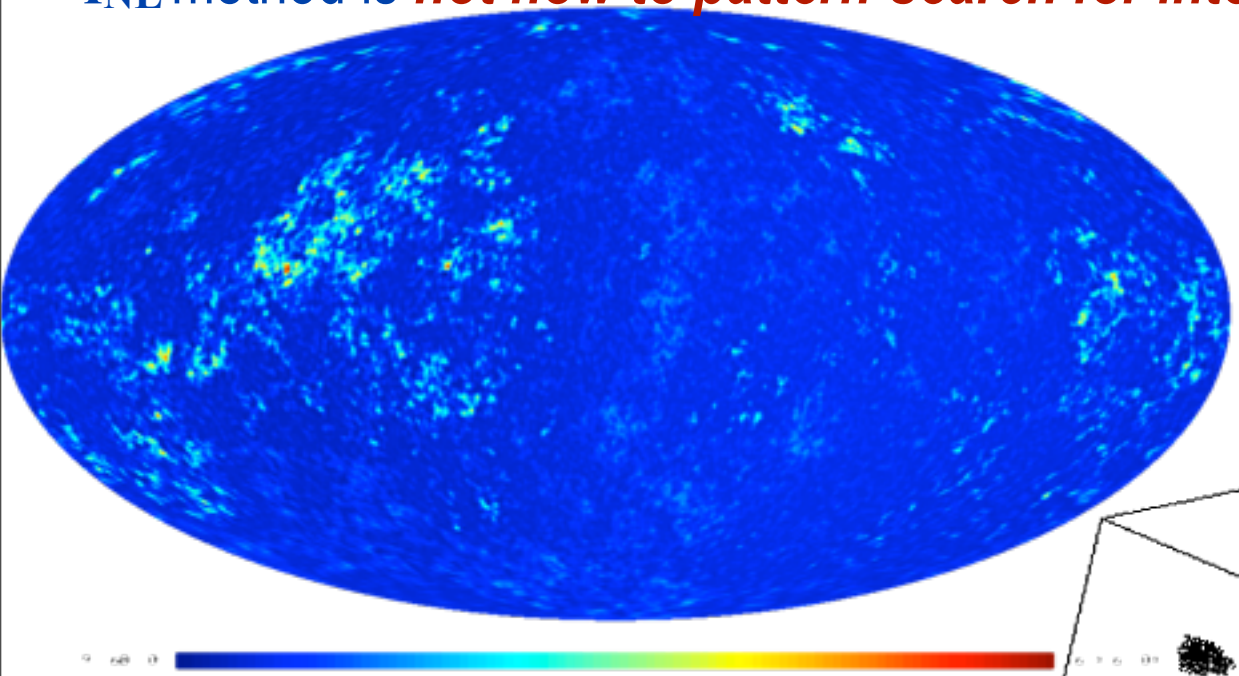
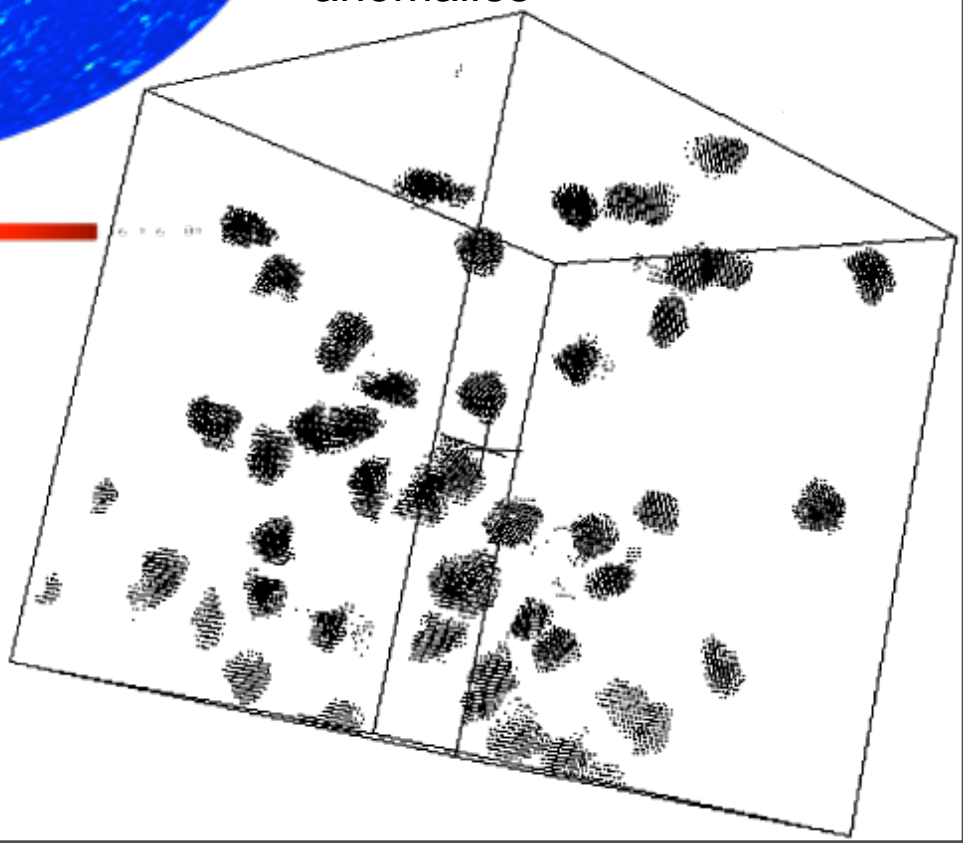
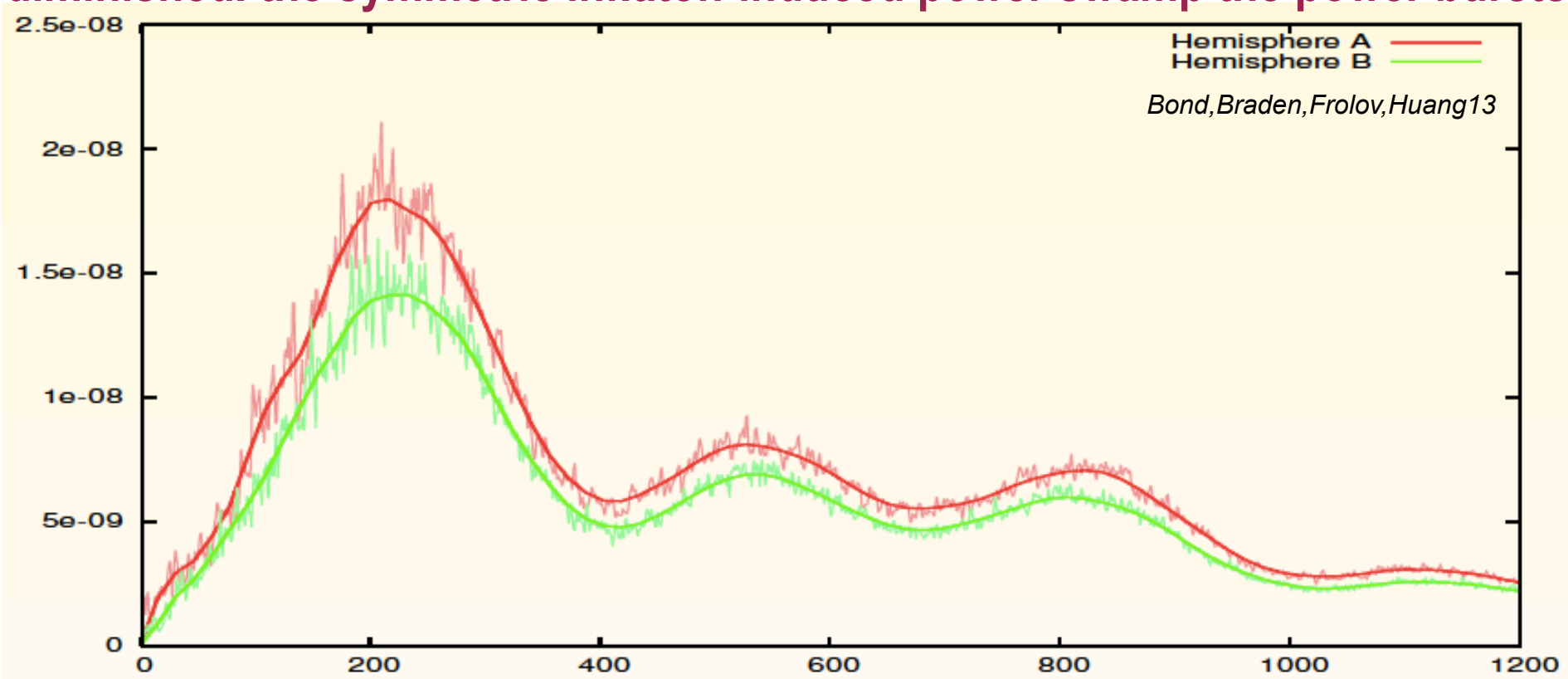


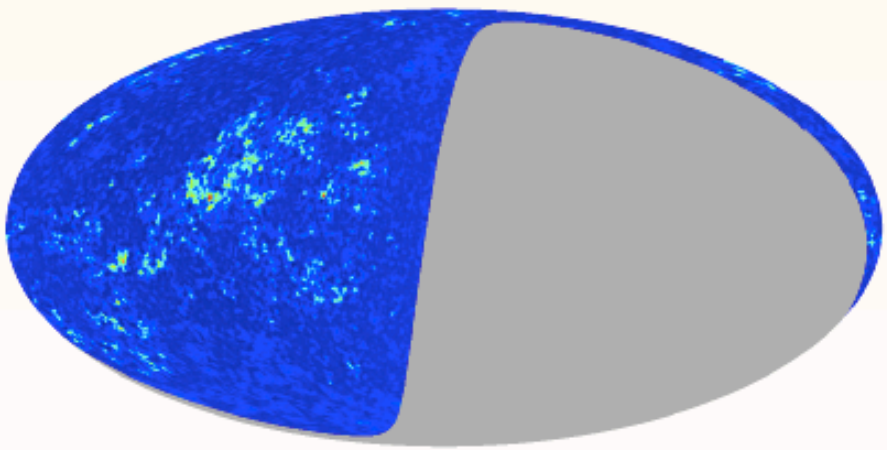
intermittency from steep threshold functions acting on a slightly red curvature field (gravitational potential) lead to very-large-scale splotch "anomalies"

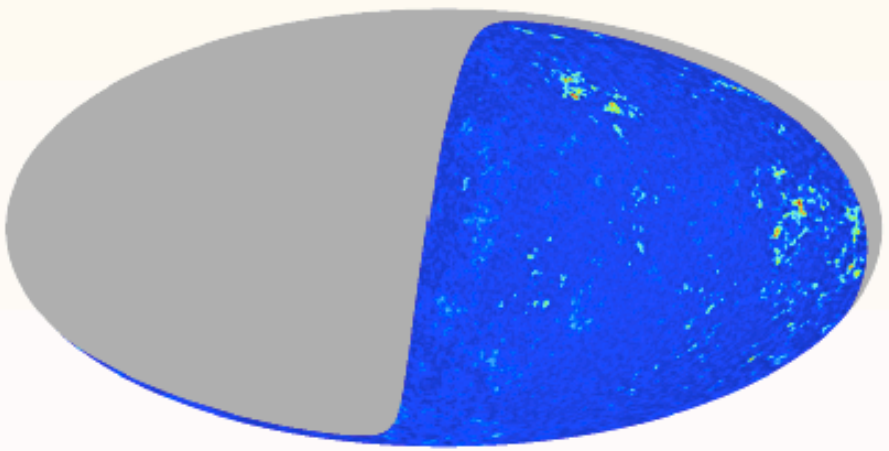


cf. the more localized Lagrangian space **intermittency** from steep cluster-threshold functions acting on the **density field**. **Cluster-patches** lead to pressure intermittency and SZ sources in the CMB

associated hemispherical power asymmetry extends to high L, though diminished. the symmetric inflaton-induced power swamp the power bursts







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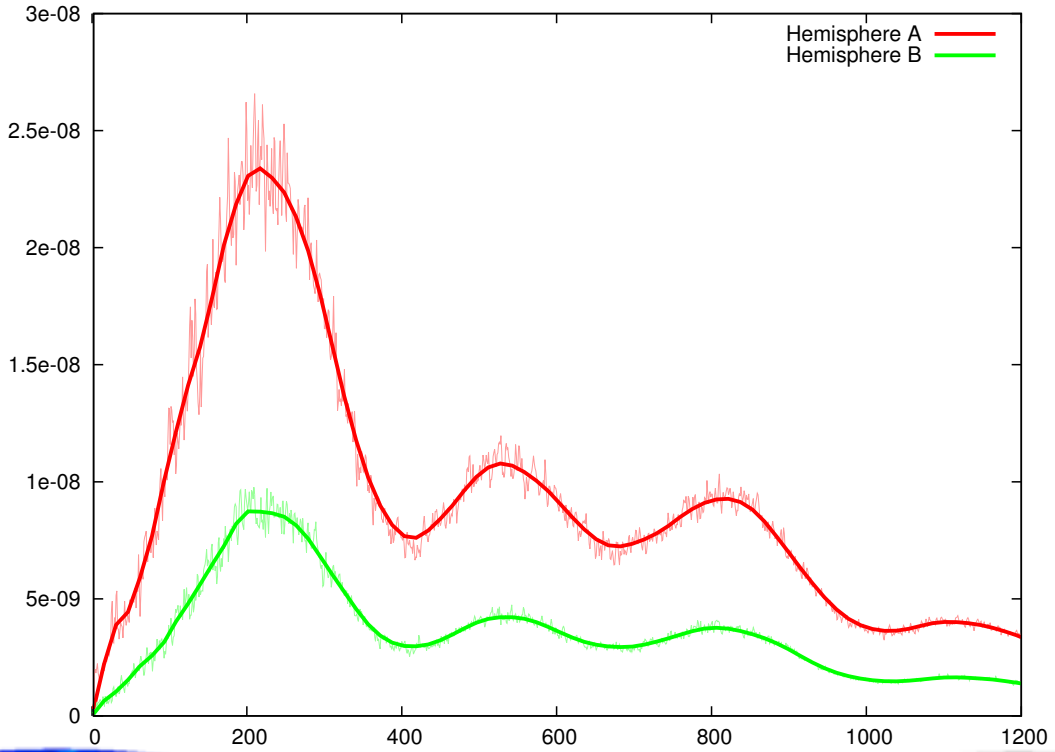
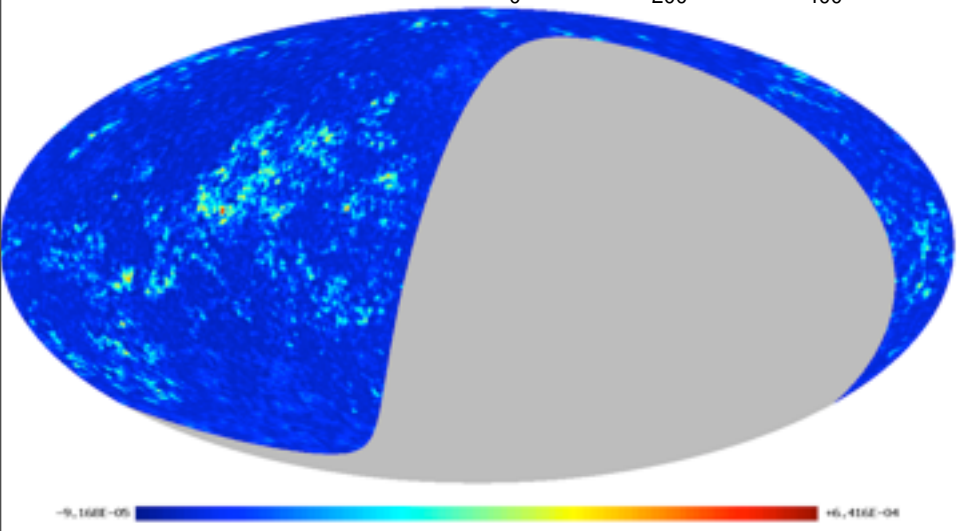
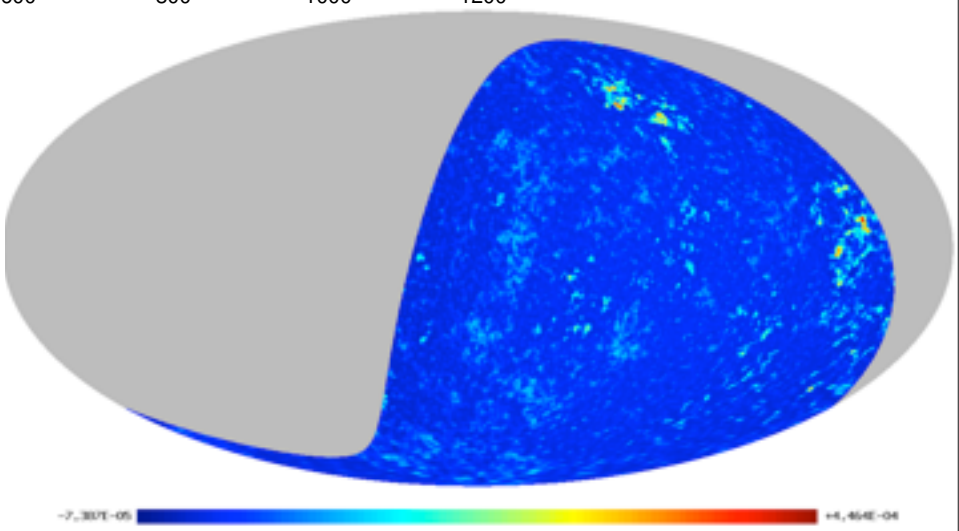


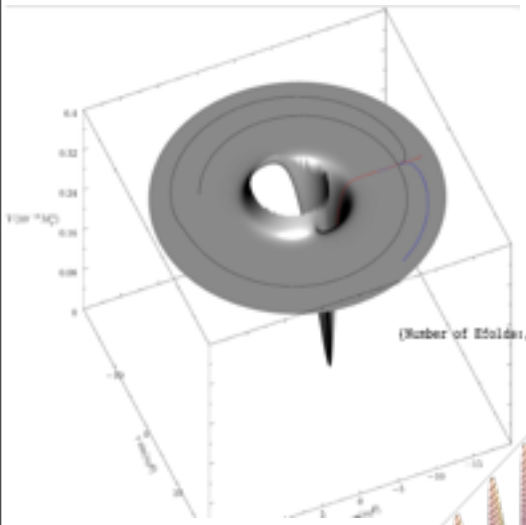
Bond,Braden,Frolov,Huang13

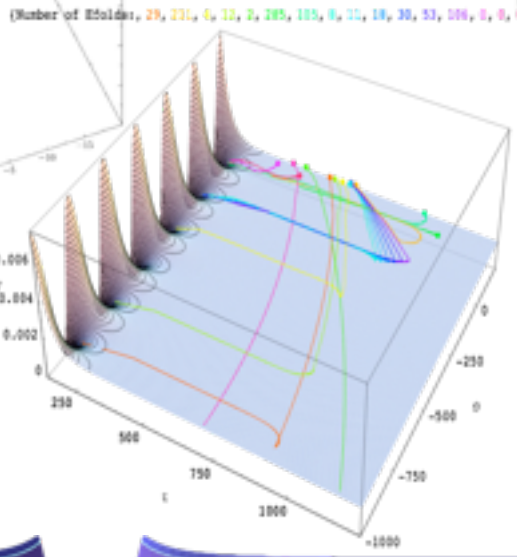
the achilles heel of intermittency models? TBD

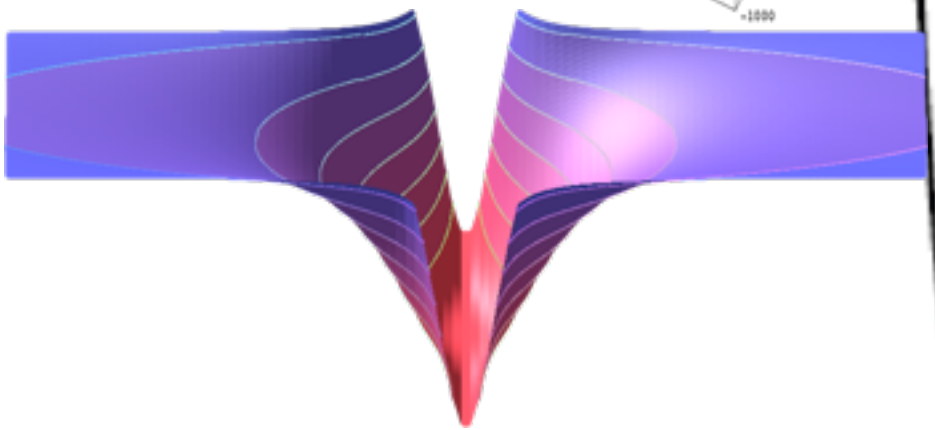


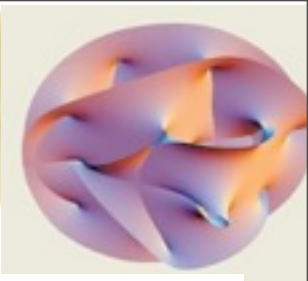


non-Gaussianity









moduli are complex fields => angular axion

Preheating After

Roulette Inflation

$\langle \tau \rangle =$

quantum diffusion

spatial jitter

drift

ln**a(x,**ln**H)**

isocon directions, e.g., axion

entropy generation in preheating from the coherent inflaton (origin of all matter)

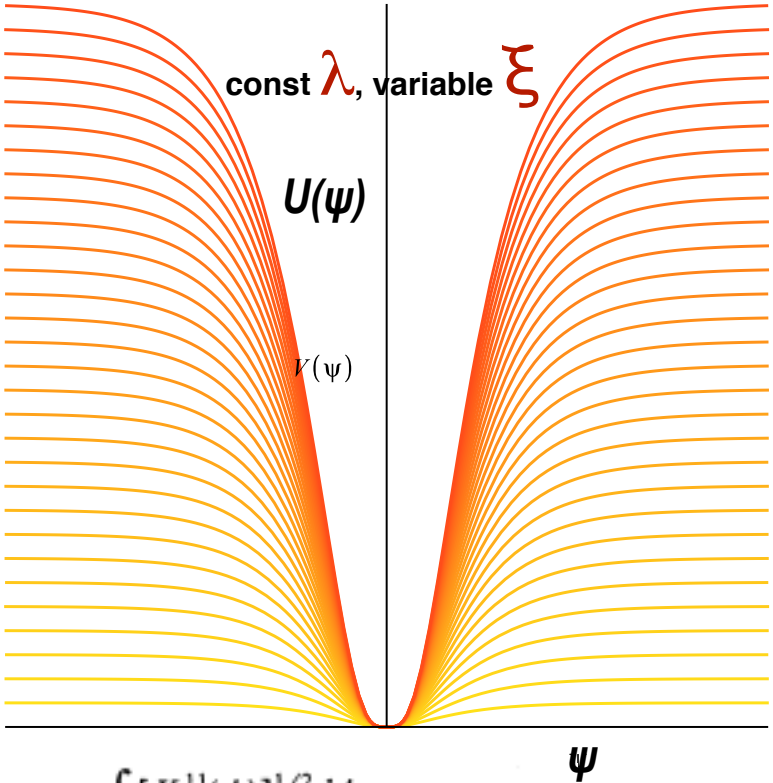
let there be **heat**

semi ETERNAL INFLATION

flattened V to satisfy P13 r-n_s

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

in Einstein frame for new (canonically normalized) field ψ



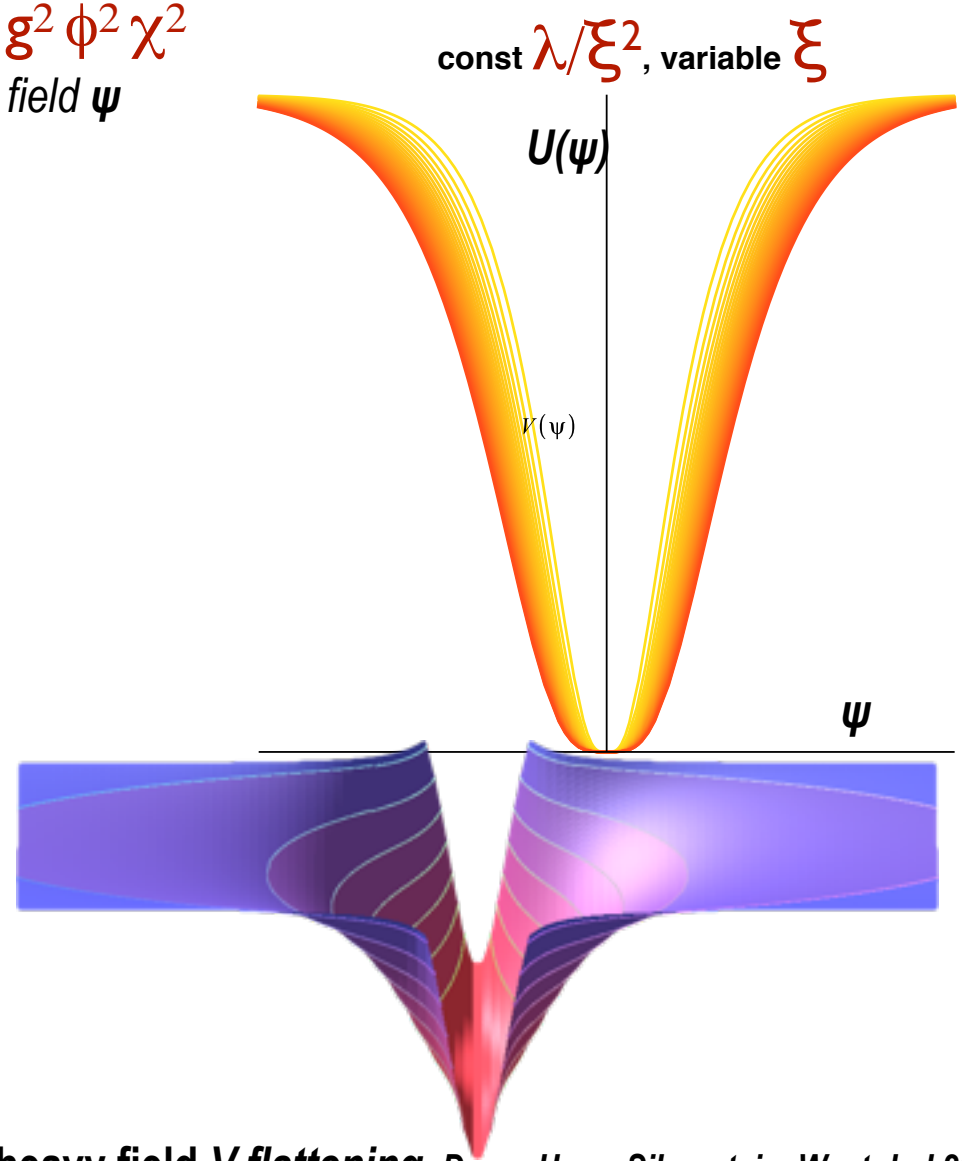
$$\psi\chi = \int [K^{11}(\phi)]^{1/2} d\phi\ ,$$

$$K^{11} = \frac{\frac{m^2}{m_P^2} + 8\pi|\xi|(1+6|\xi|)\frac{\phi^2}{m_P^2}}{\left[\frac{m^2}{m_P^2} + 8\pi|\xi|\frac{\phi^2}{m_P^2}\right]^2}\ .$$

$$U(\chi) = \left[\frac{m^2}{m_P^2} + 8\pi|\xi|\frac{\phi^2(\chi)}{m_P^2}\right]^{-2} V(\phi(\chi))\ .$$

conformal V-flattening of SBB89*, Higgs inflation*

cf. Kallosh/Linde KITP 06/19 ξ = 1/6 -Δ, Δ small



heavy field *V-flattening**: Dong, Horn, Silverstein, Westphal 2011*

ϕ^{2n}, n<1 via heavy field trough driving light inflaton Veff =>

r = 8n/(N$_I$+n/3) 1-n$_s$ = (n+1)/(N$_I$-n/6) P13 OK

e.g., ***monodromy*** SW08 p=1/3, MSW08 p=1/2 & cos = shift symmetry

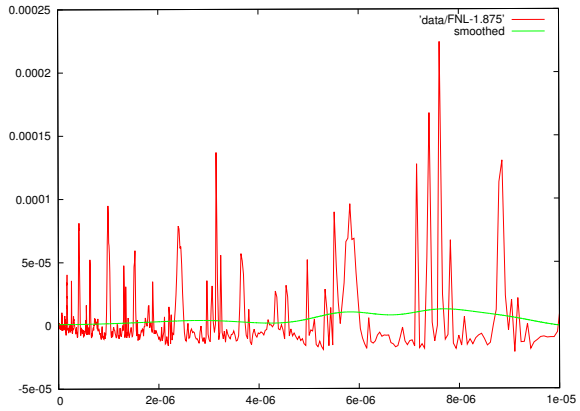
V-flat natural *in* ***roulette inflation*** *(Kahler moduli) BKKV*

quartic inflaton variable Planck mass $V(\phi,\chi) = 1/4\ \lambda\phi^4 - 1/2\ \xi\phi^2 R + 1/2\ g^2\phi^2\chi^2$

spikes persist with flattened effective potentials

only the potential bowl at the bottom matters

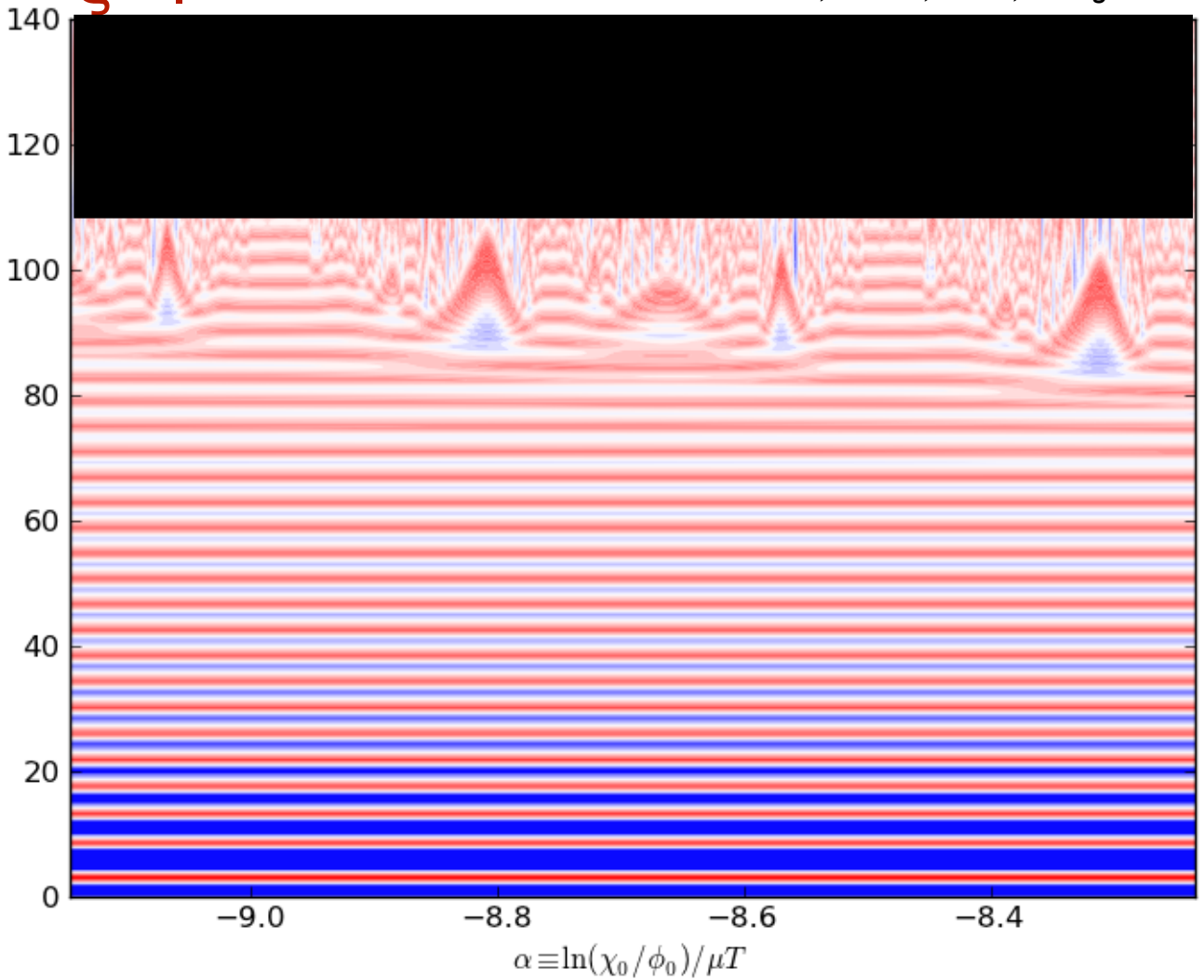
Bond,Braden,Frolov,Huang13



calculating ballistic evolution to caustics gives the spikes in perfect agreement with full nonlinear lattice simulations

(now being done for a suite of flattened potentials to better deal with the shock-in-time)

ξ=-1



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

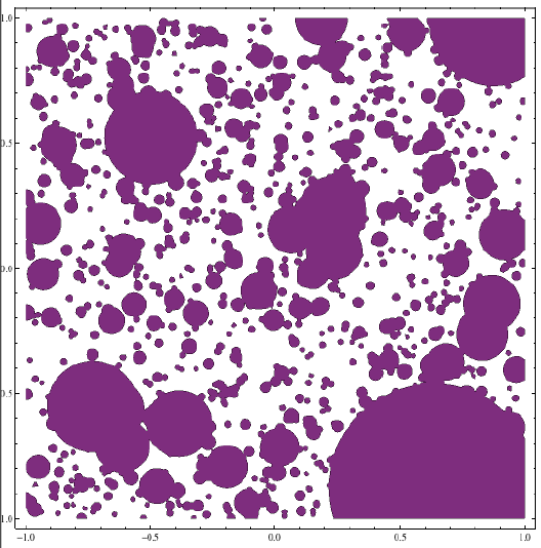
distribution functions & trajectory caustics

Bond,Braden,Frolov,Huang13

Bubbly U

Kleban11 review

+ KITP13 review



the **bubbly gospel**, a la Kleban11 + many

we live in a bubble, one among many, the nature of the universe *BUT stochastic semi-eternal inflation*

Coleman de Luccia instanton with SO(4) Euclidean symmetry => SO(3,1) real symmetry is gospel *BUT thick wall bubbles may be endemic in the landscape, depends upon V. bubble formation fluctuations about instanton. multiple field instantons, always one dof Euclidean-stochastic path?*

negative curvature, initially ~ initial bubble radius, diminished by subsequent inflation. if prob(N efolds) ~ $1/N^p$ p>>1 then N just enough => negative curvature likely observable *BUT it is not observed, our patch inflated alot if stochastic semi-eternal inflation*

all bubbles eventually collide *BUT with what probability: to see one seems quite unlikely*

look for SO(2,1) symmetric collision debris on the CMB sky ("cosmic wakes") as circular spots, scale TBD *BUT improbable. But if probable, why subdominant and not booming. BUT 3D instabilities from inevitable quantum fluctuations make complex interiors, oscillons etc. CMB smoothing fuzzes over this always? searches to prove landscape exists too naive?.*

bubble collisions make largescale modulations possible *BUT too large?*

here & in BBM13a,b,c we treat bubble creation and propagation as interesting nonlinear field theory problems in their own right, that may have a cosmological setting, still TBD. non-inflation domain walls and bubbles. now imbedding subdominant isocon-tunnels into an overall inflationary flow

when domain walls (big bubbles) collide in full 3D lattice sims

with tiny zero point & wall fluctuations

=> burst of scalar radiation at c

(with outgoing radiation BCs)

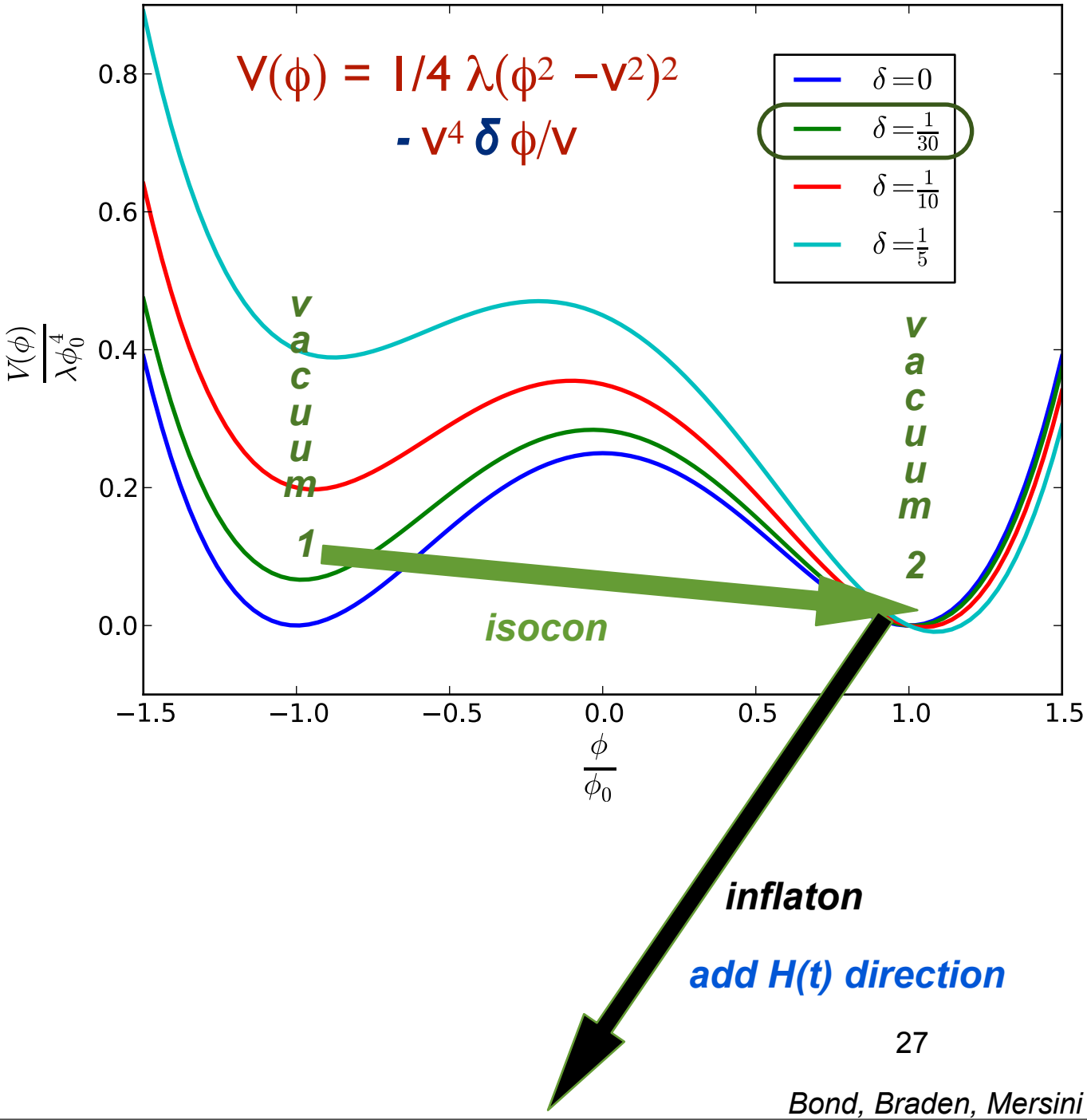
+ long-lived oscillons, size related to the mass

cf. 1D work that dominates the subject

Gleiser, Kleban+, Johnson,Peiris,Lehner,..

an oscillon phenomenon is possible in preheating Easther+

CMB+ observables?



Bond, Braden, Mersini 2013

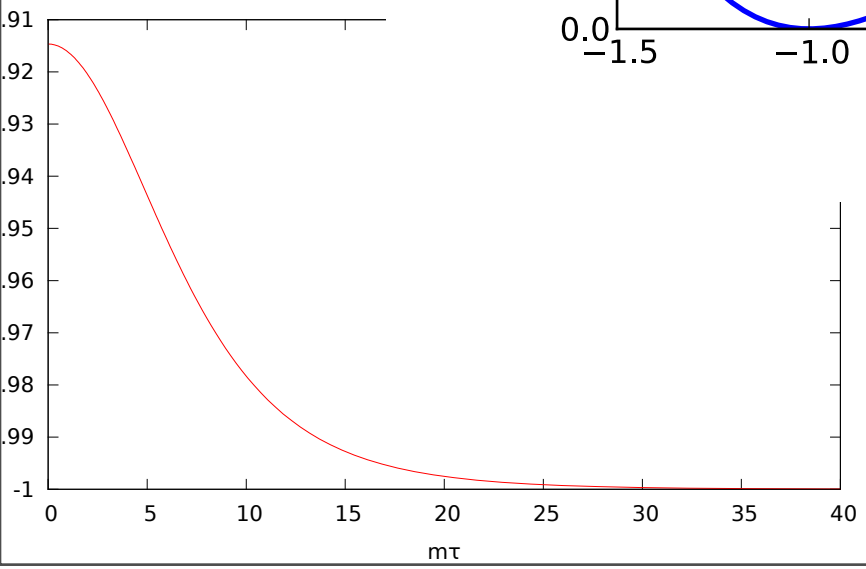
$V(\phi) = 1/4\ \lambda(\phi^2 - v^2)^2 - v^4\delta\,(\phi/v - 2(\phi/v)^3)$

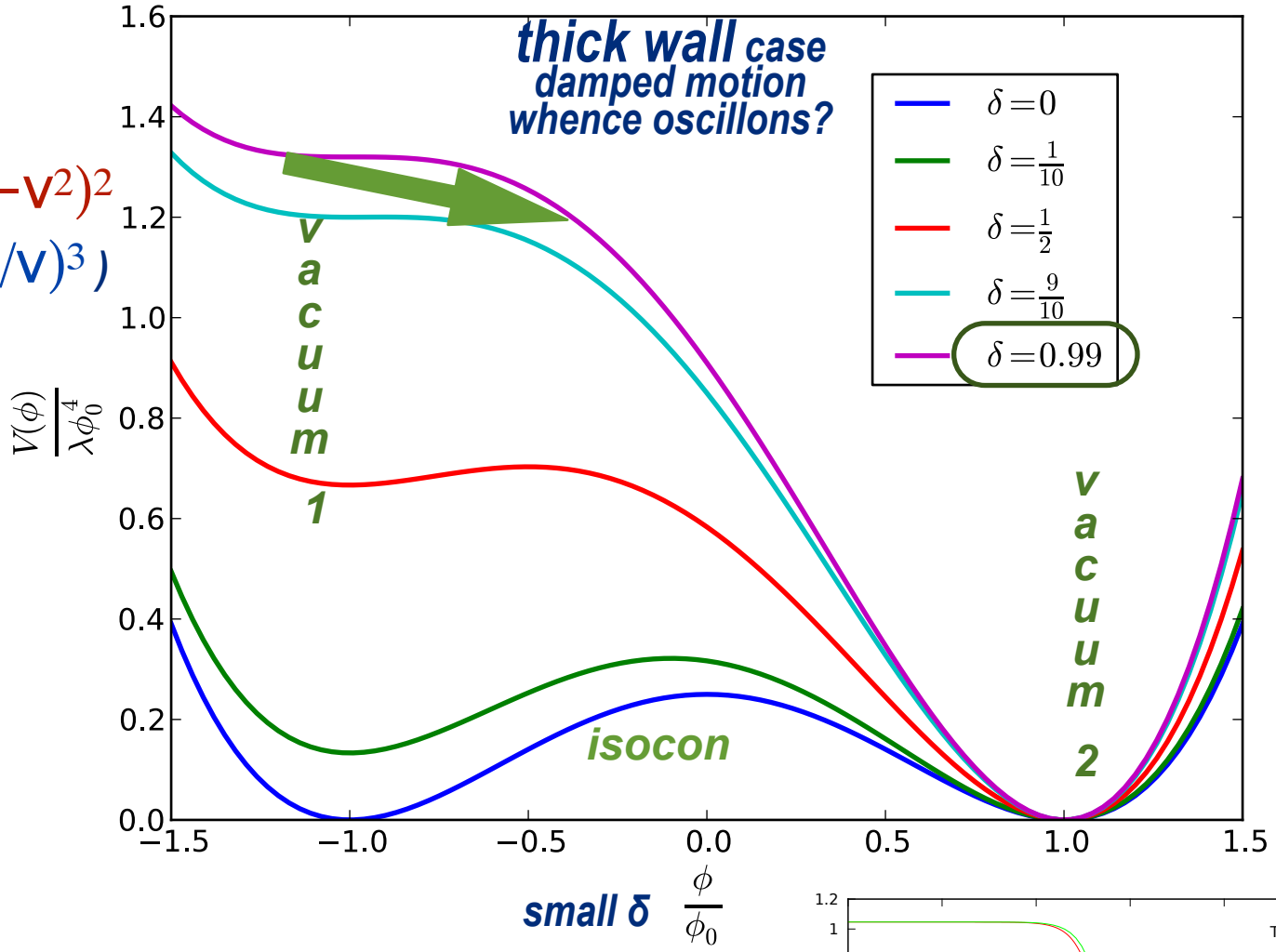
large δ

thick wall instanton

how important are fluctuations in the Euclidean trajectory from the (classical) instanton

JBraden spectral code



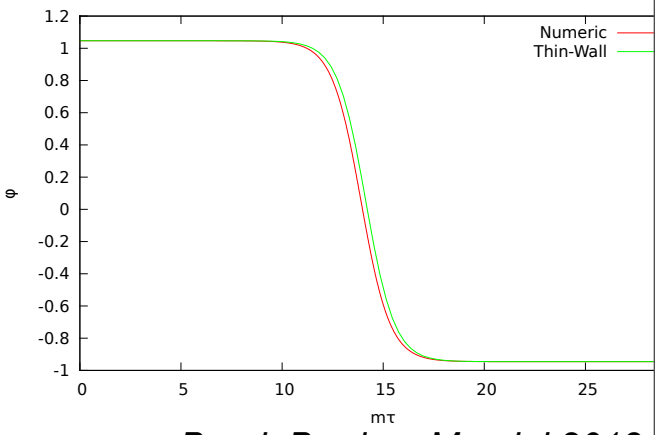


small δ

thin wall instanton

OK approximation, but accurate numerical instanton is needed for instability work

JBraden spectral code



Bond, Braden, Mersini 2013

oscillon in early universe, e.g., Amin++++, Gleiser, BBM13a,b,c

oscillatory, spatially local, long-lived, most work 1D, a few 3D sims for preheat + our bubbly sims

history: Bogolubsky+Makhankov76, Gleiser94, Copeland+95, ..., Amin+Shiokoff 10, Amin 13 - single 1D oscillon blob

relation to mulifield Qballs?

small amp conditions

$(m^2 - \omega^2)\,\varphi + (-\nabla^2\varphi) + (\partial V/\partial\varphi - m^2\varphi) \sim 0$ freq (>0) curvature (>0) nonlinear (must be <0)

BUT no theorems (so far) for when oscillons arise. V shallow at large φ *BUT how shallow for bubbles*

shallow flattened V for preheating oscillons *BUT not for nearly symmetric bubble potentials*

Floquet analysis of μ_k >>H, exponential instability *BUT modified for bubbles and domain walls BBM1*

want Re μ_k/H >10, M_P/m>>1, potential n <1 far out *BUT n varies*

energy fraction in oscillons > 80% Farhi etal 08 but 1D, E thresholding => non-oscillon pickup. Amin+ **>> 50%** ***BUT not in our bubble sims ~10%, 90% scalar radiation: 3D, rad propagates => no log-norm tail***

preheat with pspectre pseudo spectral code Easther, Finkel, Roth **256^3** checked with **defrost** (Frolov)

LatticeEasy (Felder+Tkachev) ***BUT defrost++ with symplectic integration + radiation boundary conditions (good for scanning many cases) + new (much) faster parallel spectral code (for bubbles++)***

oscillons overdense by a few *BUT we see higher ~10, though gravitational collapse not important*

Primordial Black Holes are hard to form *YES*

expansion history change *YES*

delayed preheating (store in oscillons) *YES*

number density modulation (using our nonG from preHeating ideas B+09) *YES, maybe*

characteristic oscillon 3D scale few/m, m curvature of V_{isoc} bottom, $(m/H)_{initial}$ inflate => expand to observable? In tunneling rate ~ height $(\nabla V)_{height}$ width $(\nabla\chi)_{height}$ of isocon barrier, maybe not so tiny?

when domain walls (big bubbles) collide in full 3D lattice sims

with tiny zero point & wall fluctuations

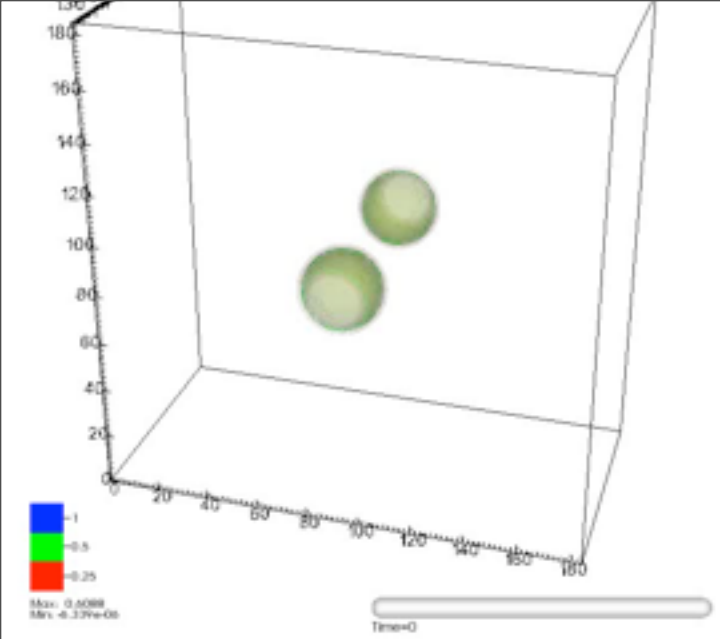
=> burst of scalar radiation at c (with outgoing radiation BCs)

+ long-lived oscillons, size related to the mass

cf. 1D work that dominates the subject Gleiser, Kleban+, Johnson,Peiris,Lehner,.

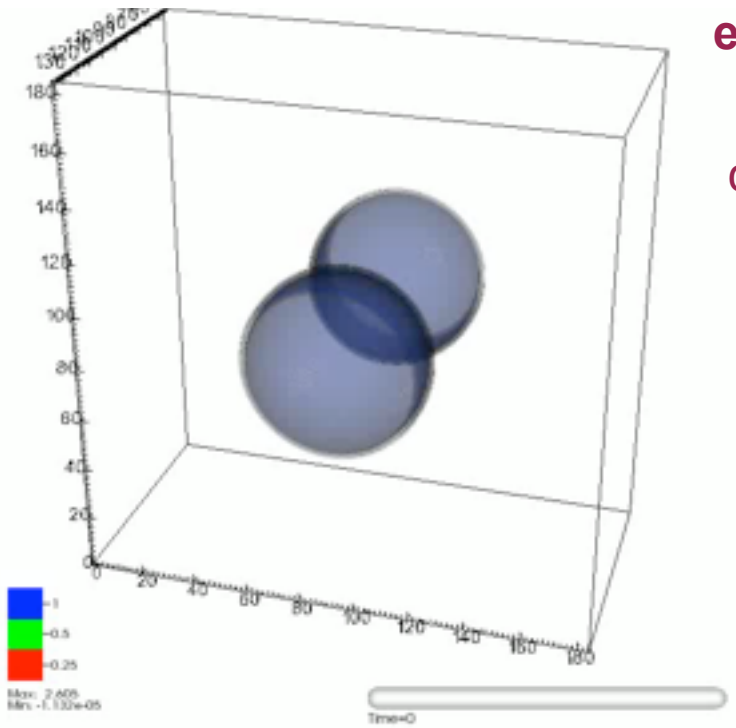
an oscillon phenomenon is possible in preheating CMB+ observables?

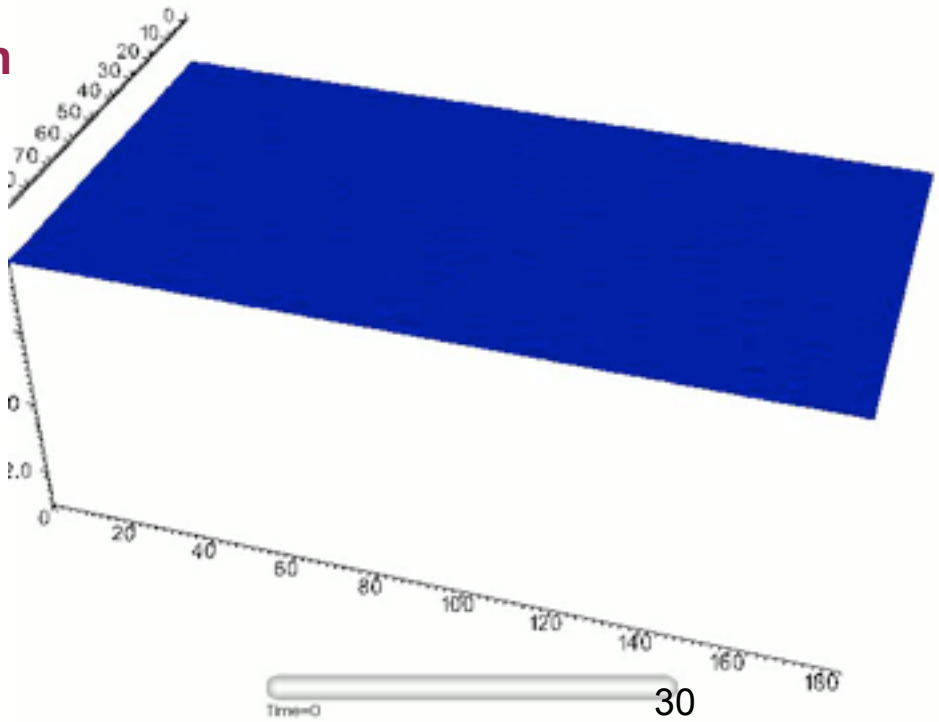
long-lived oscillon energy ~ 10%



energy density evolution

high contours





Bond, Braden, Mersini 2013

add H(t) = V_{inf} in inflaton direction

$R_{bubble,i} = 0.1\ H^{-1}$

$\Delta X_{bubble} = 0.25\ H^{-1}$

when domain walls (big bubbles) collide in full 3D lattice sims with tiny zero point & wall fluctuations

=> burst of scalar radiation at c (with outgoing radiation BCs) + long-lived oscillons, size related to the mass

energy density evolution

high contours

does the observable universe use double hubble bubble - iciousness? CMB intermittency?

Bond, Braden, Mersini 2013

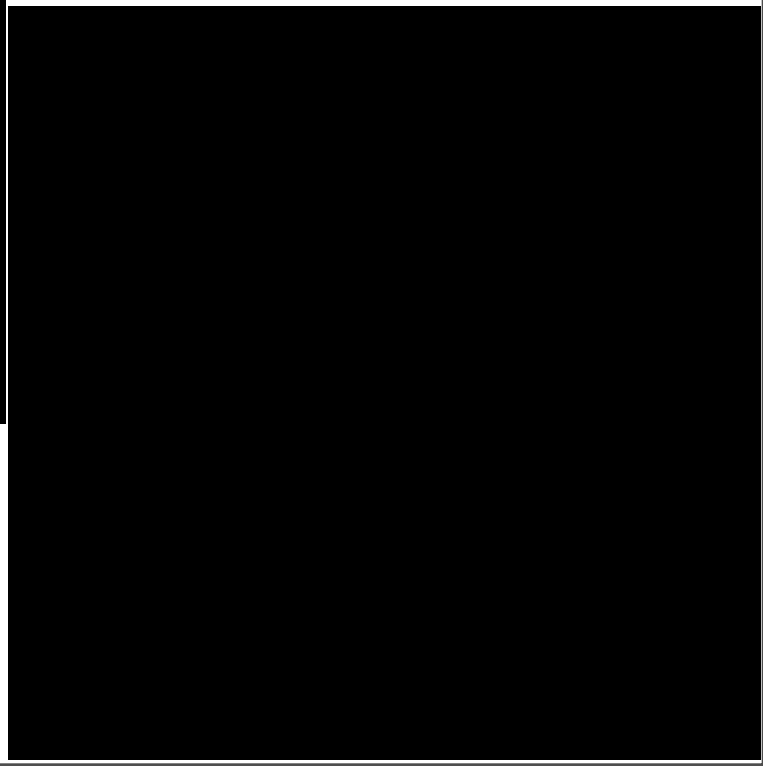
axionic potential

$V \sim 1-\cos(\theta)$

kink-antikink instanton = IC

continued wall collisions because of periodicity => amplification of quantum noise fluctuations

not quite applicable to Kleban+ unwinding inflation of D-branes



conclusions:

highly nonlinear field evolutions happened (EoI, bubble collisions).

do they lead to observable rare-event CMB or SSS/LSS/ULSS anomalies?

light isocons cf. heavy isocons, the heavy can lighten up = original SBB nG

isocon modulators, coupling(isocon) modulators, isocon tunneling, isocon oscillons, isocon short-lived fuzzy-strings, + very long-lived strings

or just *weak* constraints on multifield potentials, >horizon fields, nucleation rates, *etc.*

amusing subdominant patterns do arise!

END