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 théorique **Dick Bond** 25 years cifar

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 loL, unclear if any at hiL. Doppler dipole modulation exists

P13 hiL nonG pattern constraints are restrictive, but open up with decoupled ζ_{NL}, support$(\zeta_{NL})^3$
& 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.*** $\zeta_{NL}(x)$ 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

KITP 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
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

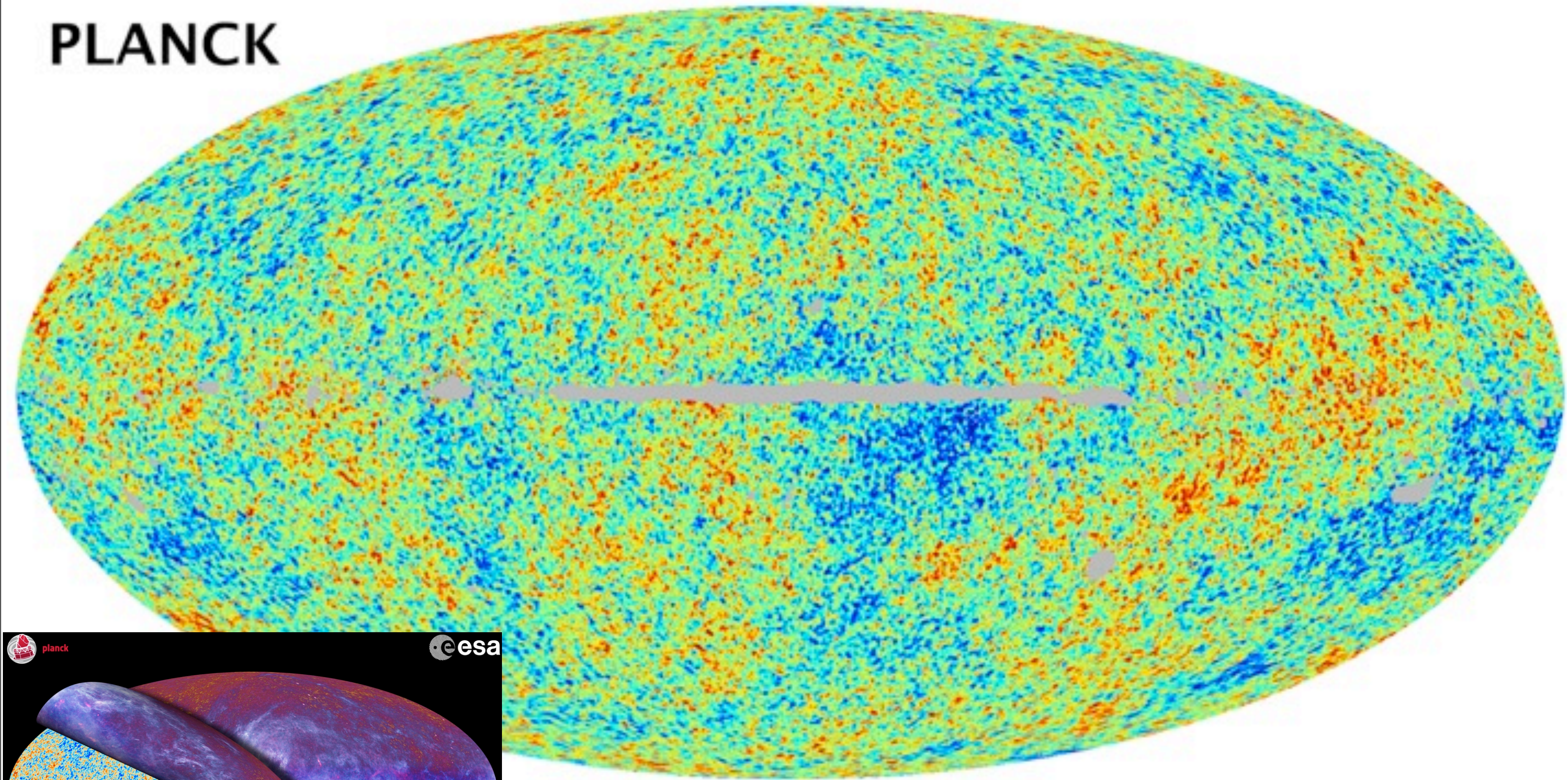
May: much nonG from LSS observability discussion

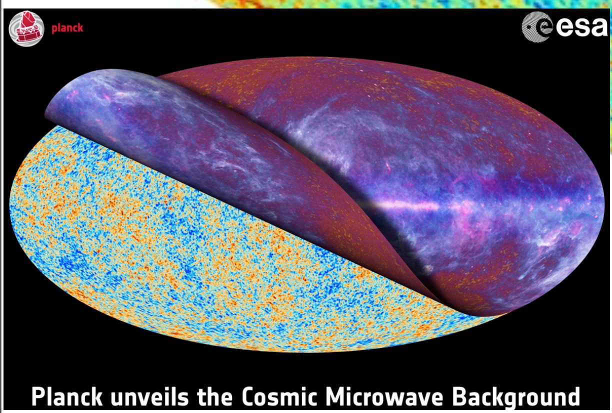
5/02, Marilena LoVerde Non-Gaussian Mode Coupling and the Statistical Cosmological Principle
5/14, Dmitri Pogosyan Geometrical measures for (mildly) non-Gaussian cosmological fields
6/13, Matias Zaldarriaga The effective theory of Large Scale Structure

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

Planck SMICA Map

CMB-data Concordance

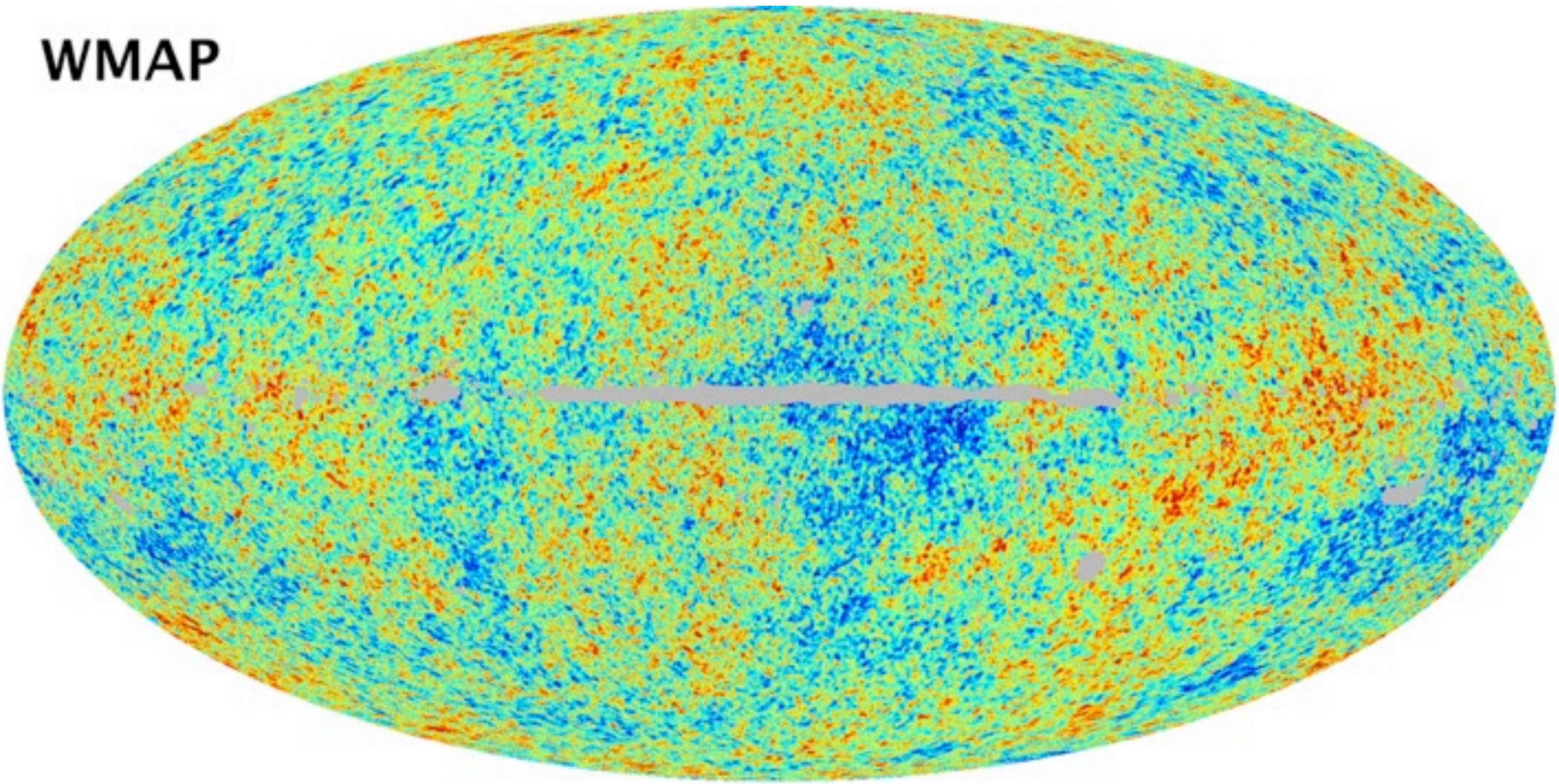




Planck/SMICA map, 5′ resolution.

WMAP W–band, Template Cleaned

CMB-data Concordance



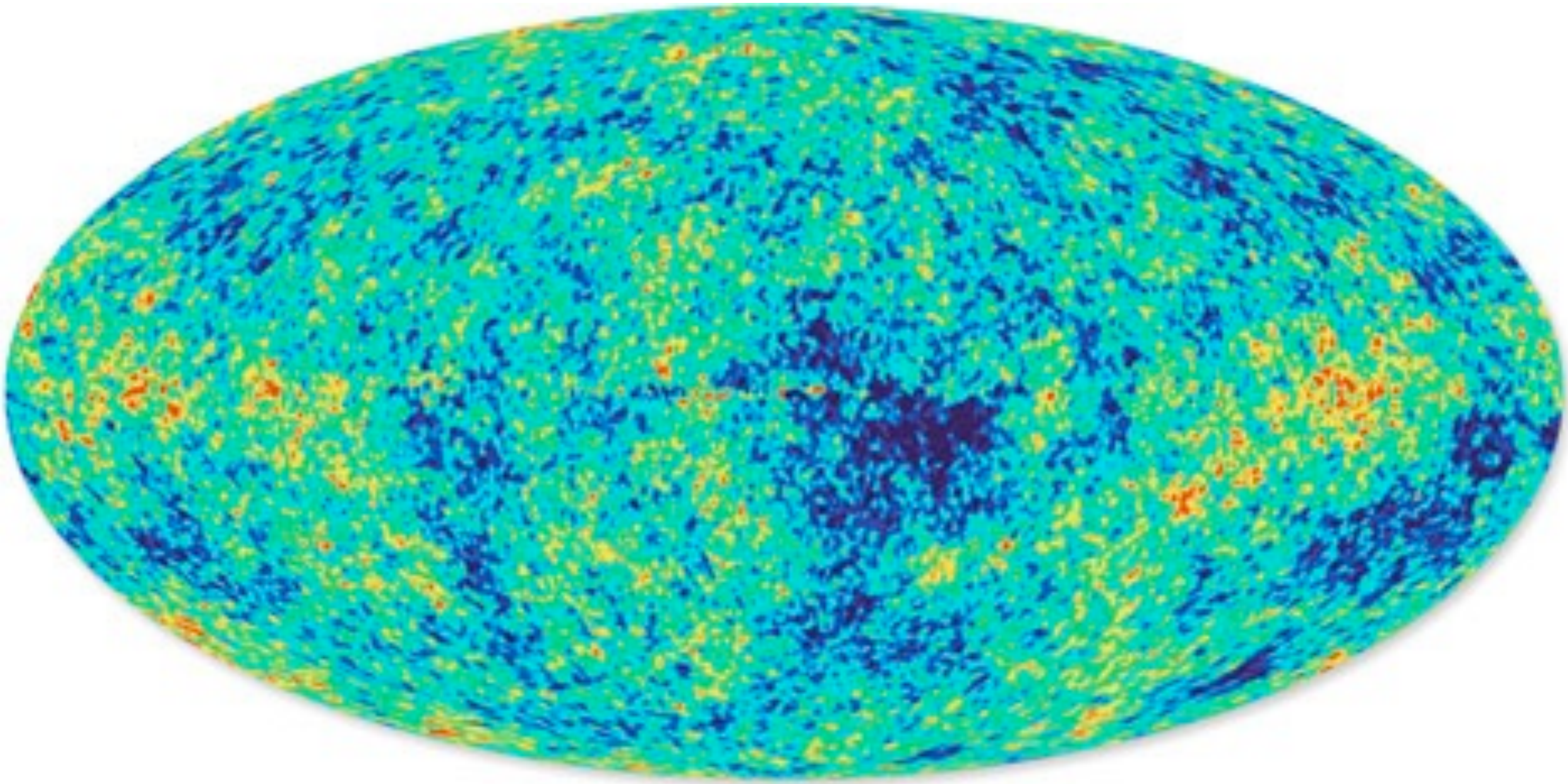
Cleaned with Planck 353 GHz dust map and low-frequency templates. 12′ resolution.

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

WMAP W-band, Template Cleaned

CMB-data Concordance



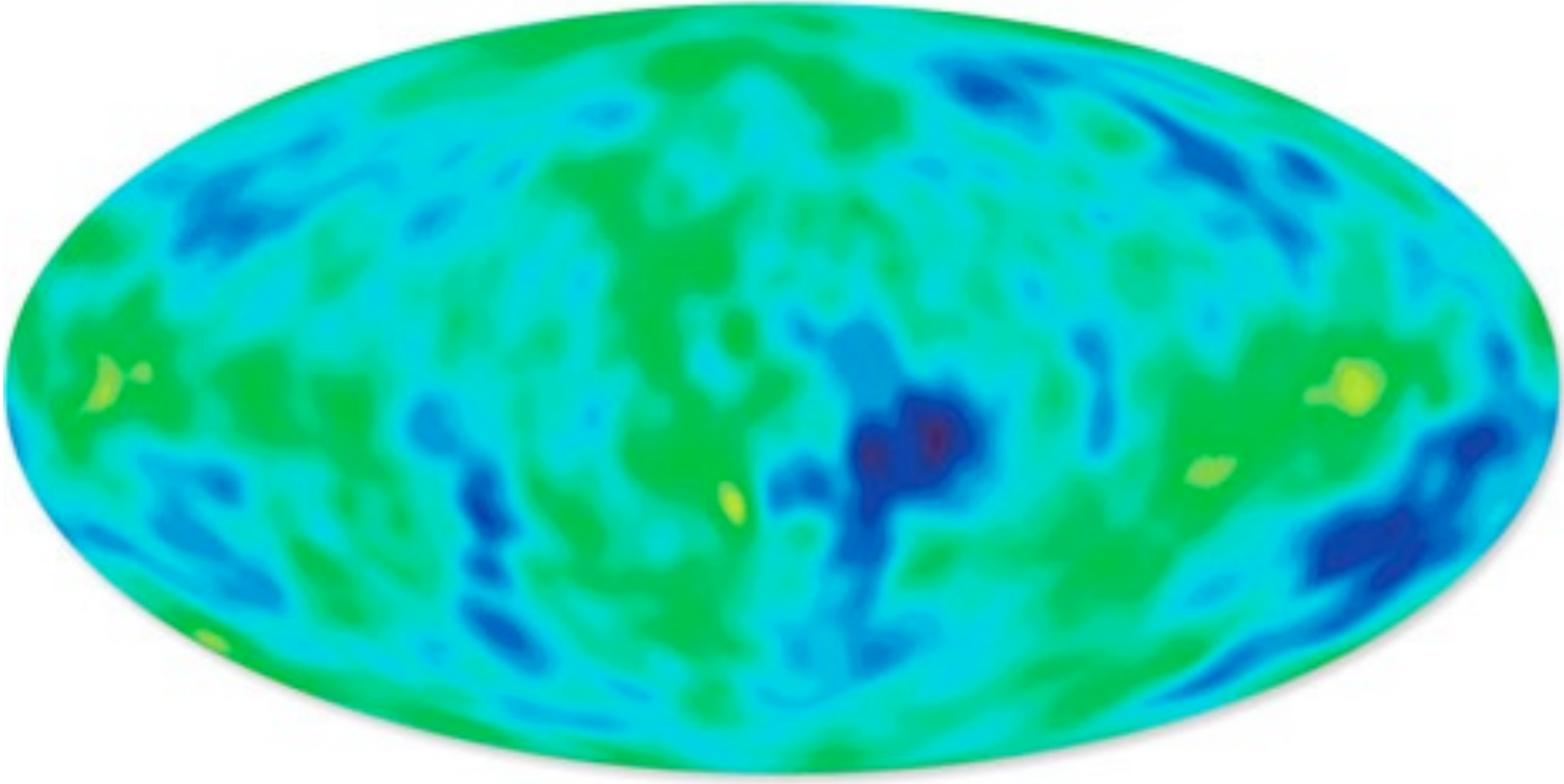
Cleaned with low-frequency templates only.

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

COBE

CMB-data Concordance

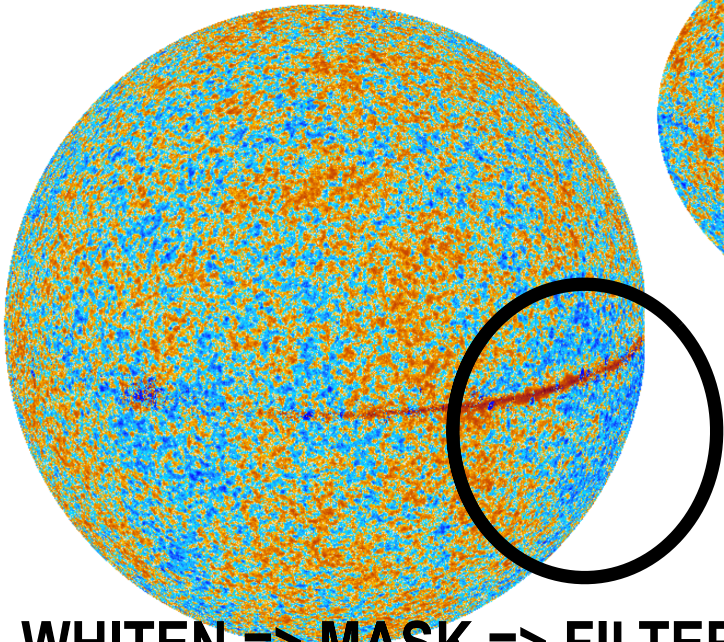


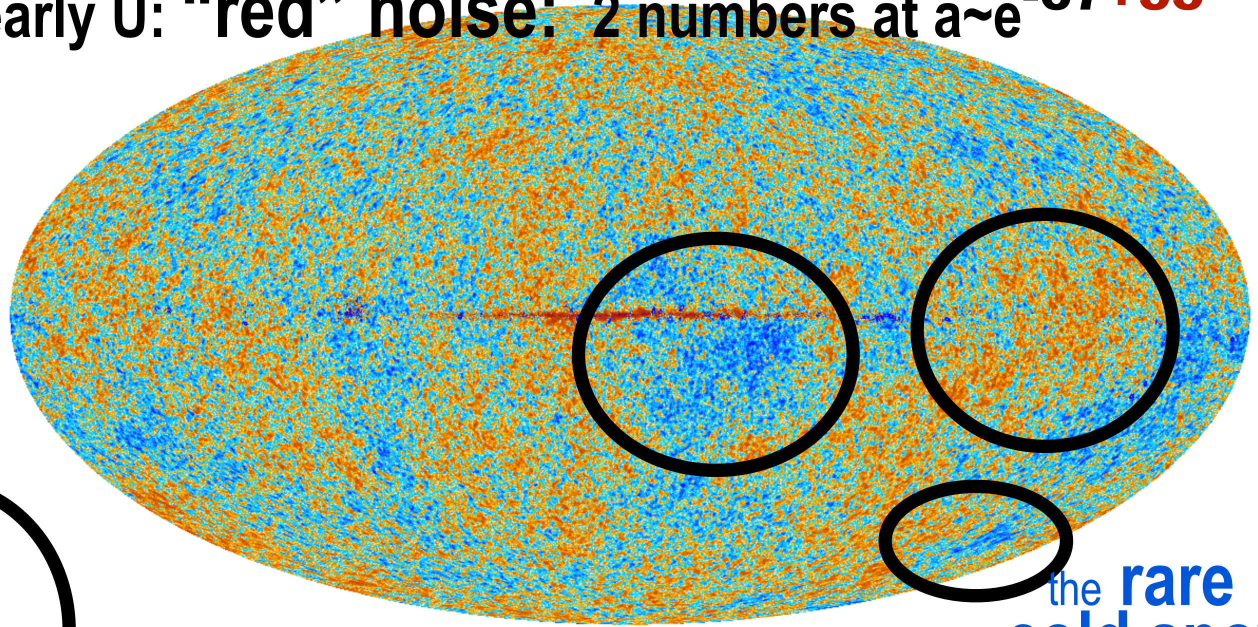
SIMPLICITY

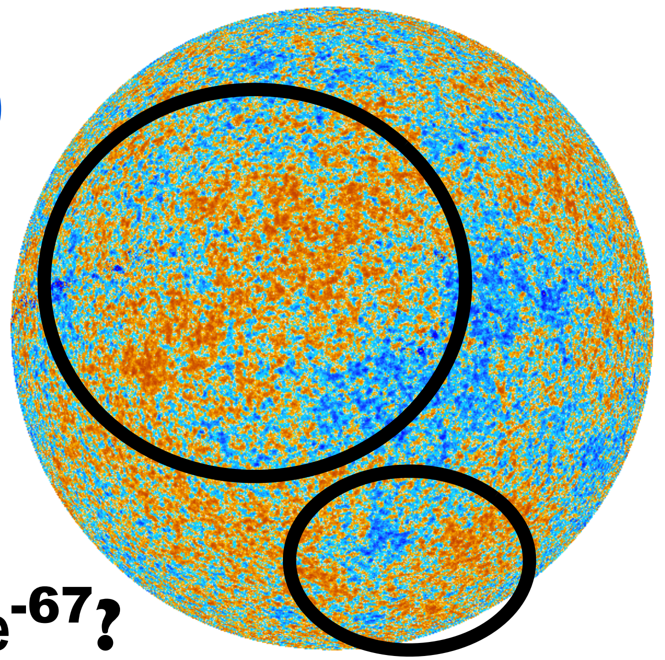
early U: "red" noise: 2 numbers at $a \sim e^{-67+55}$

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

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







WHITEN => MASK => FILTER BANK *(SSG42 filter)*

=> EXTRACT PEAKS *(hierarchical peak patches)*

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

***hot & cold spots** 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

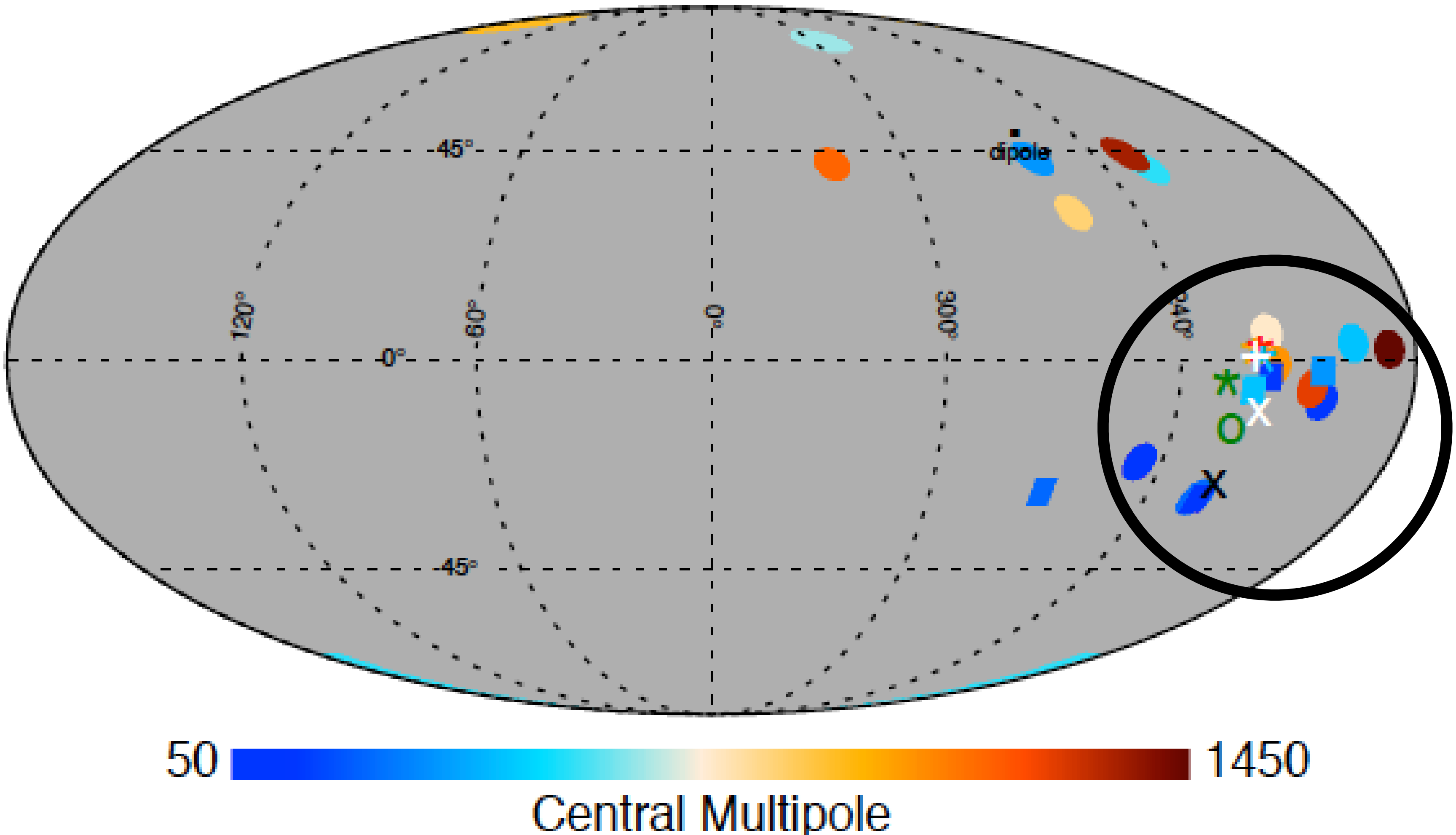
Anomalies in Polarization? TBD

+ anomalies = COMPLEXITY *at* $a \sim e^{-67}$?

power spectrum @L<400 is low cf. L>400 forecast for tilted LCDM model

***power spectrum asymmetry**: dipole near Galactic Equator points towards LSS anomaly*

L<400 ~7% anomaly firm (P13&WMAP), L>400 <0.2% with L_{max}=2000? (***Doppler boost of P13 XXVII cf. P13 XXIII Isotropy & Statistics TBD***) dipole modulation (1-(xcoth(x/2)-1) **q.v**) ΔT(**q**), x=hν/T (it works, amp~.003 to ~4σ) aberration **q** => **q**+**∇**(**q.v**) - *5σ detection of kinematic dipole effects*



also: octupole quadrupole alignment within ~10 deg; correlation function consistent with zero beyond 60 deg

primordial nonGaussianity

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

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

local smooth.

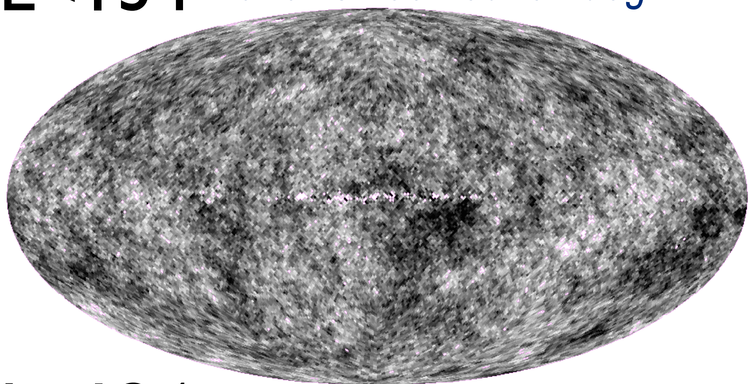
use optimal pattern estimators

cf. DBI inflation: non-quadratic kinetic energy

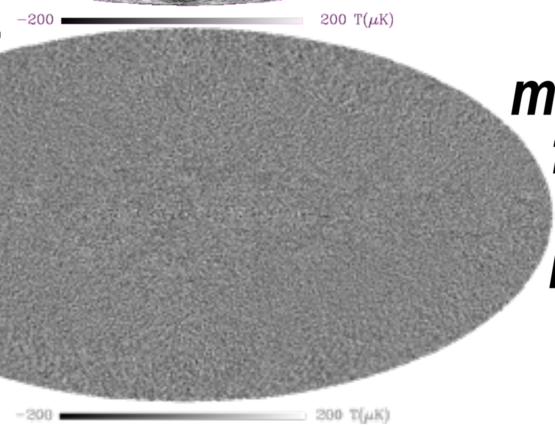
phonon ~ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ => $f_{NL^*} = 3/5\, f_{NL} - 1$

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

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

from end-of-inflation & preheating chaos

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

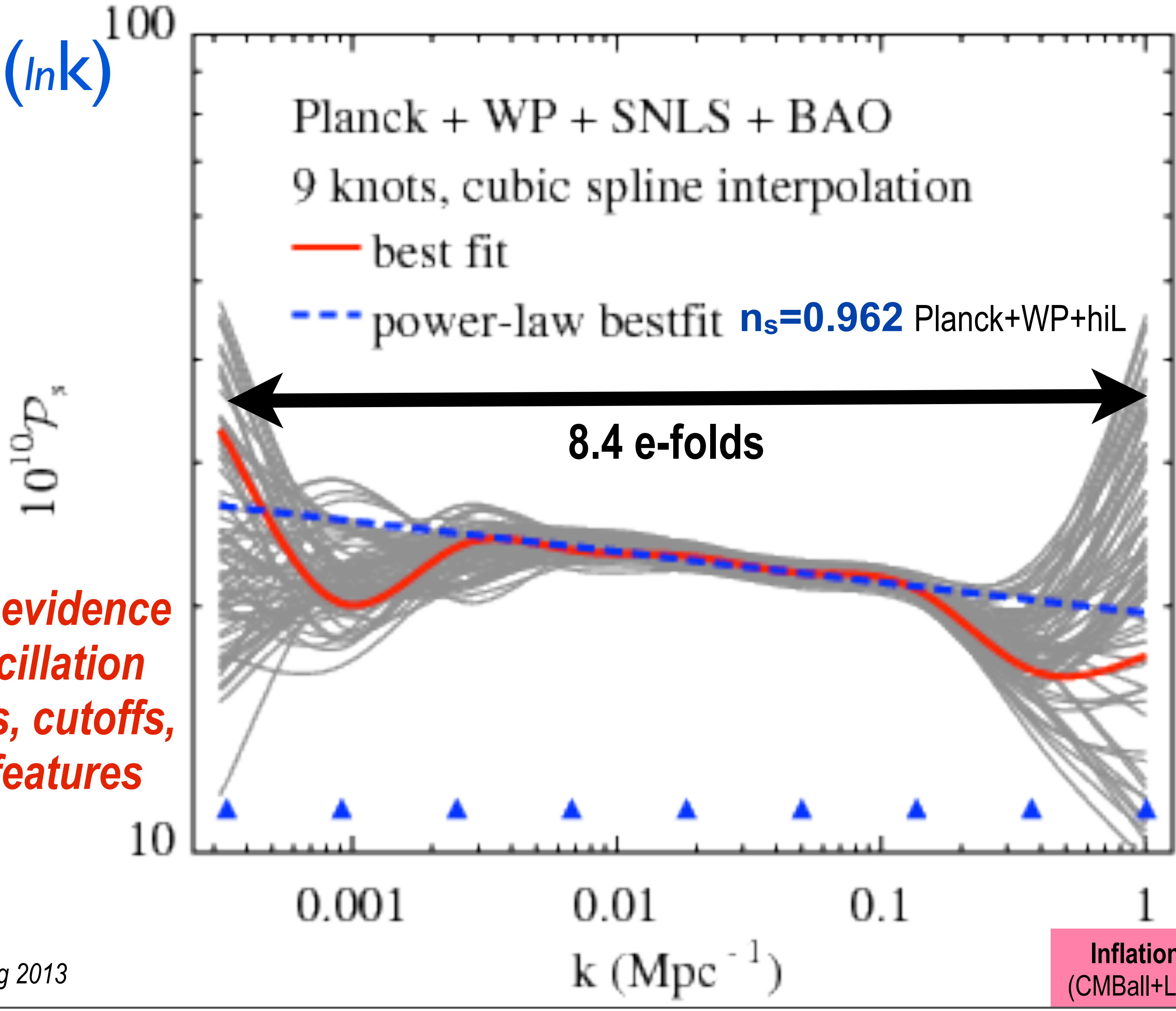
intermittent ***CMB power bursts from super-bias of a GRF modulating field landscape scan***

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

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

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

$\ln P_s(\ln k)$

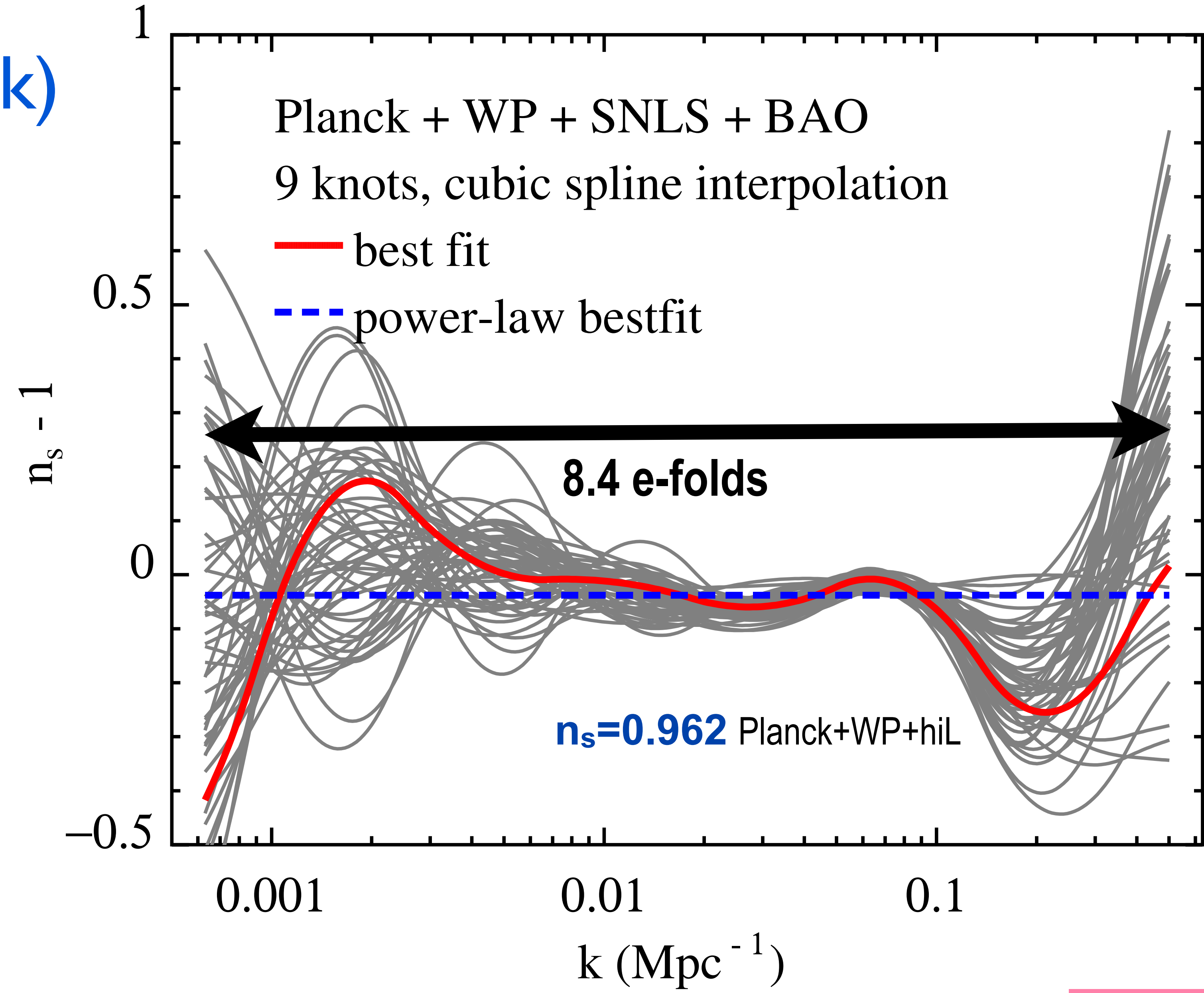


no strong evidence for oscillation patterns, cutoffs, local features

Bond, Huang 2013

Inflation Histories (CMBall+LSS+SN+WL) *scan* $ln\mathbf{P_s}(ln\mathrm{k})/A_s$, $ln\mathbf{A_s}=ln\mathrm{P_s}(k_{pivot,s})$, $\boldsymbol{r}(k_{pivot,t})$; *consistency => reconstruct* $\boldsymbol{\varepsilon}(ln\mathbf{Ha})$, $\mathbf{V}(\boldsymbol{\psi})$

$n_s(ln\mathrm{k})$

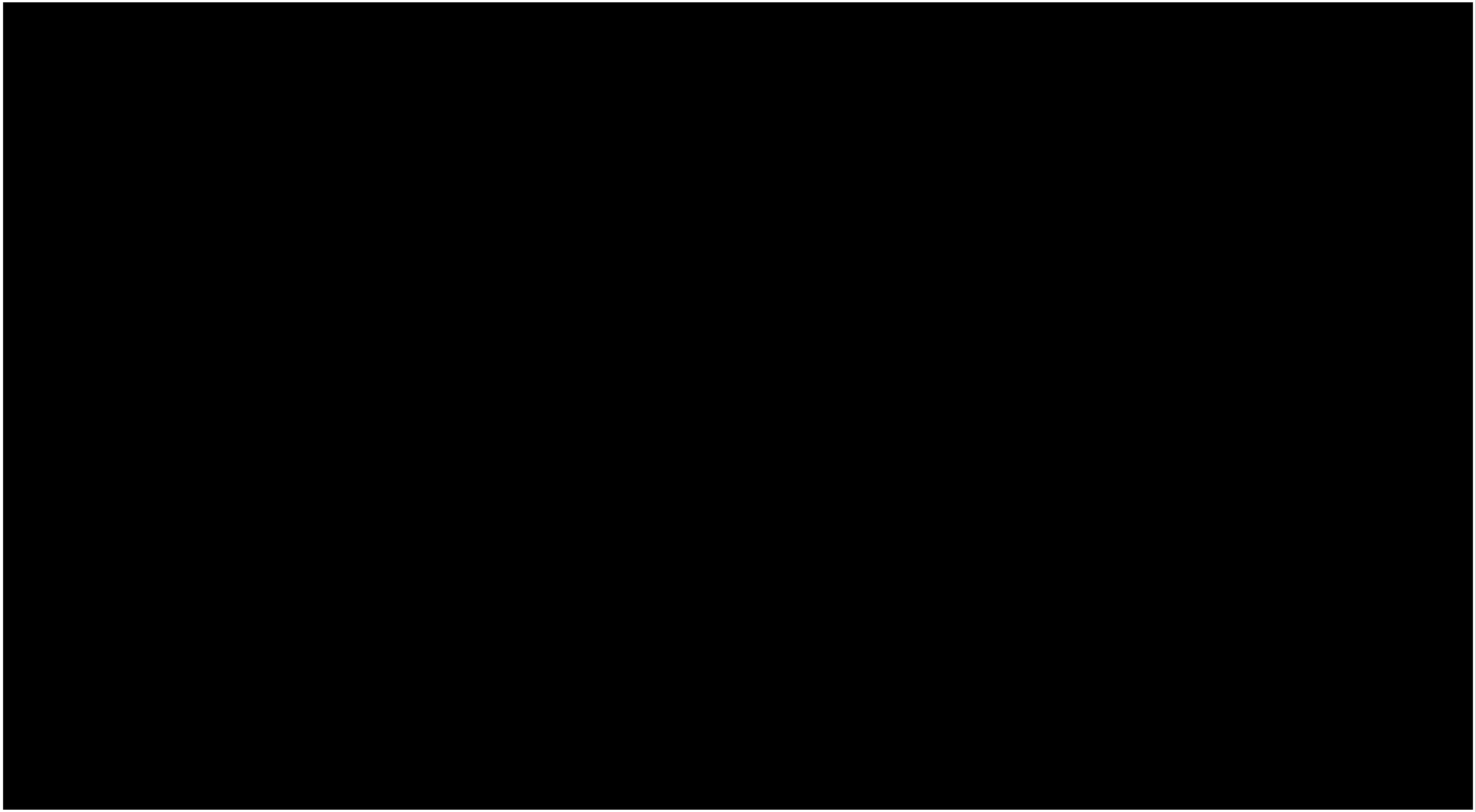


Bond, Huang 2013

Inflation Histories
(CMBall+LSS+SN+WL)

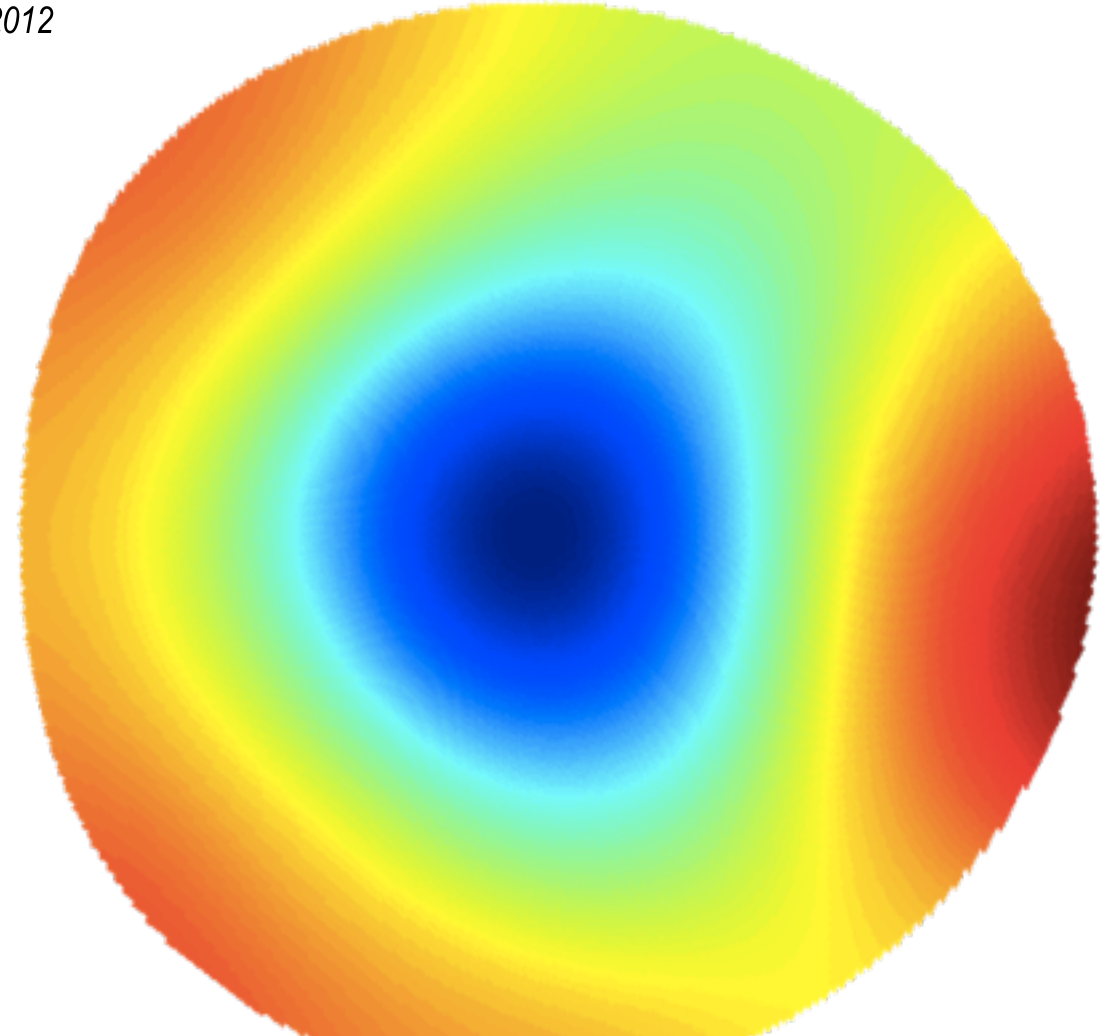
SSG42 FILTER SWEEP

WMAP7



closing in on cold spot structure *(the resolution dimension)*

Bond, Frolov, Nolta, 2012



PLANCK2013 & WMAP7: hot & cold spots agree with BE87 Gaussian stats $n_{pk}(<\nu)$

except for one cold outlier out of Galactic plane (& others near the plane)

PLANCK2013: 826’, 105 peaks, coldest -4.97σ

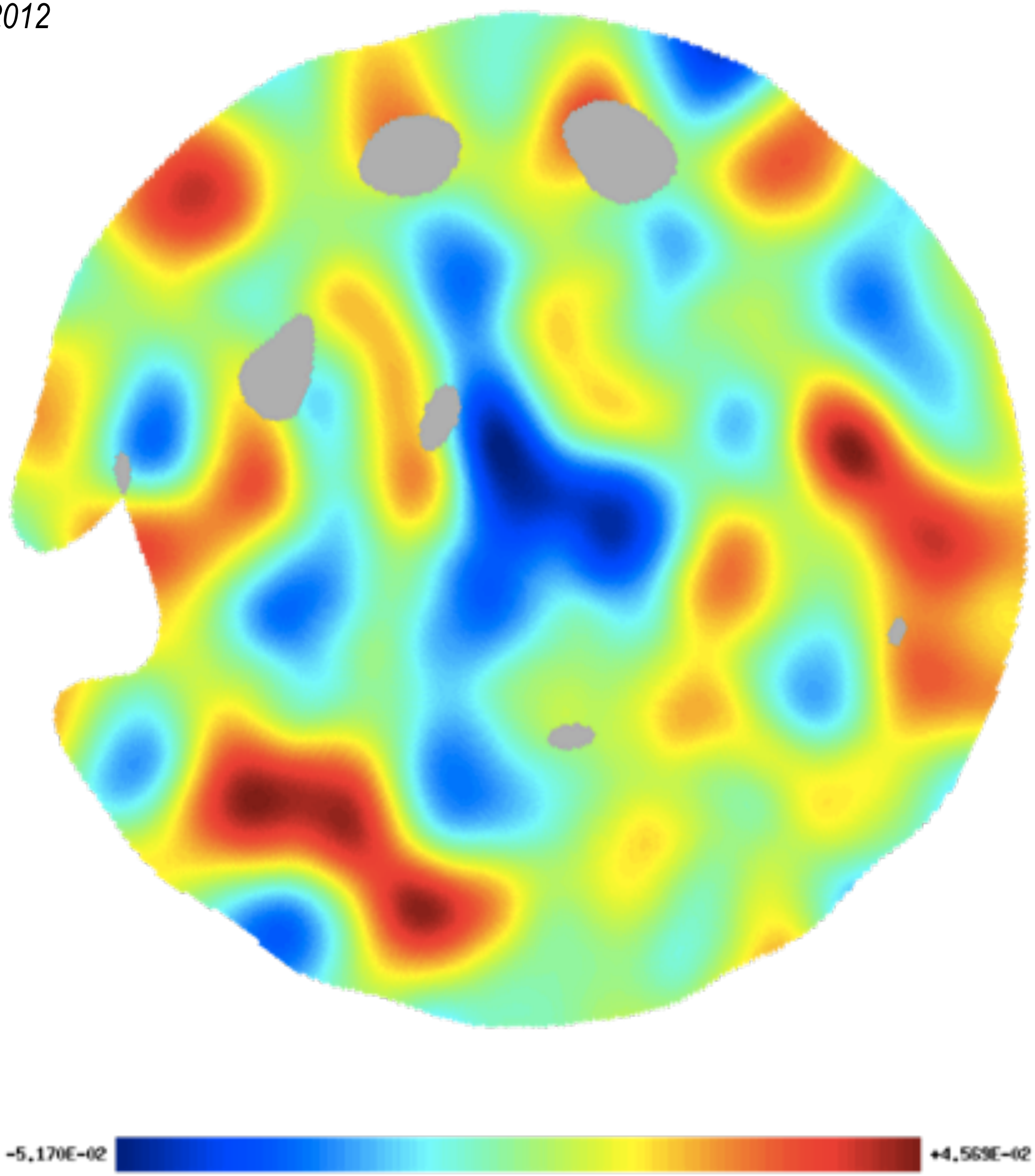
WMAP7: 800’, 105 peaks, coldest -4.87σ significance 1:300

WMAP7: 360’, 528 peaks, coldest -4.25σ significance 1:9.1

closing in on cold spot structure *(the resolution dimension)*

Bond, Frolov, Nolta, 2012

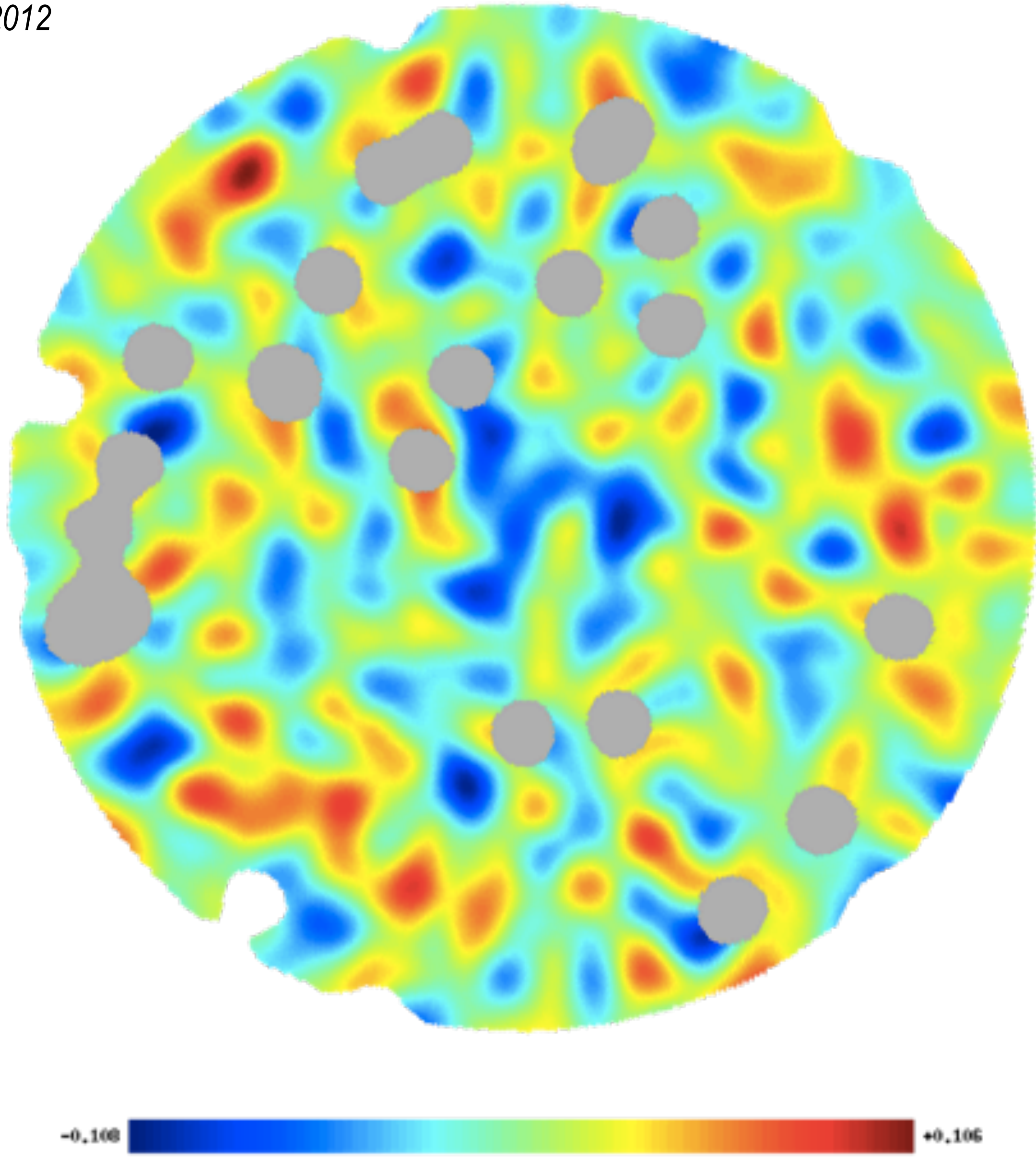
4 deg



closing in on cold spot structure *(the resolution dimension)*

Bond, Frolov, Nolta, 2012

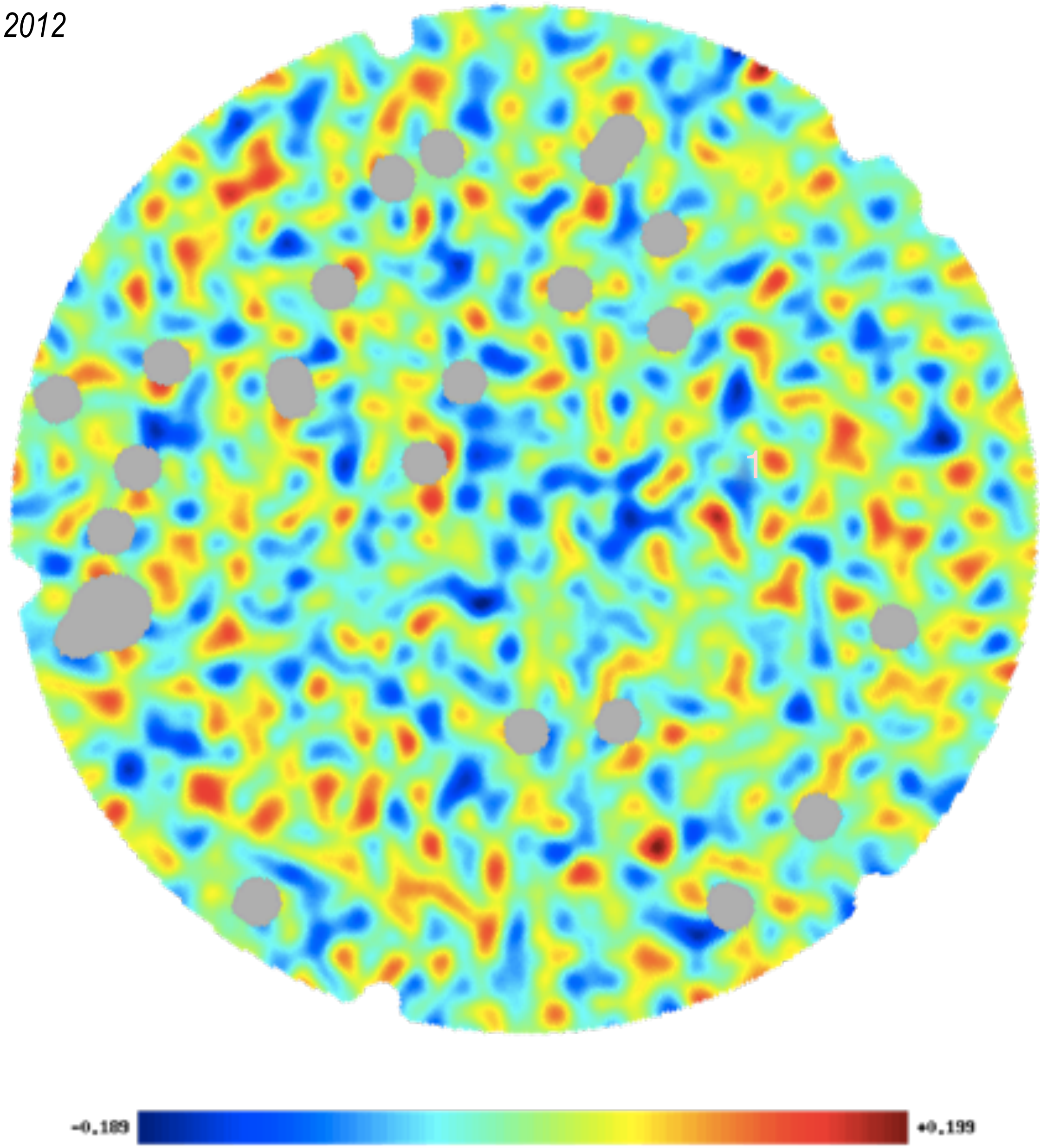
2 deg



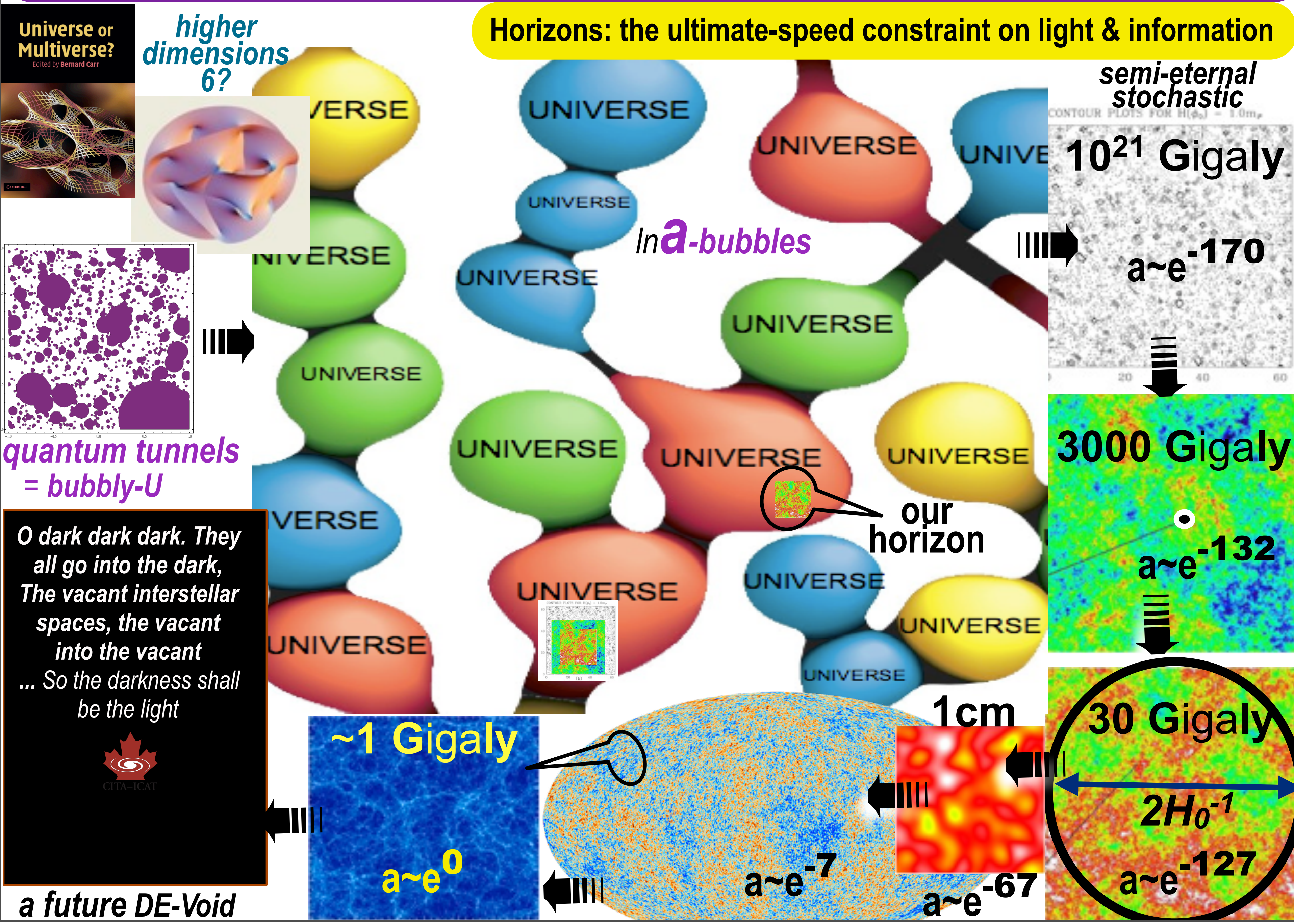
closing in on cold spot structure *(the resolution dimension)*

Bond, Frolov, Nolta, 2012

1 deg



UltraUltraUltraLargeScaleStructure beyond our Horizon to our Hubble patch and below

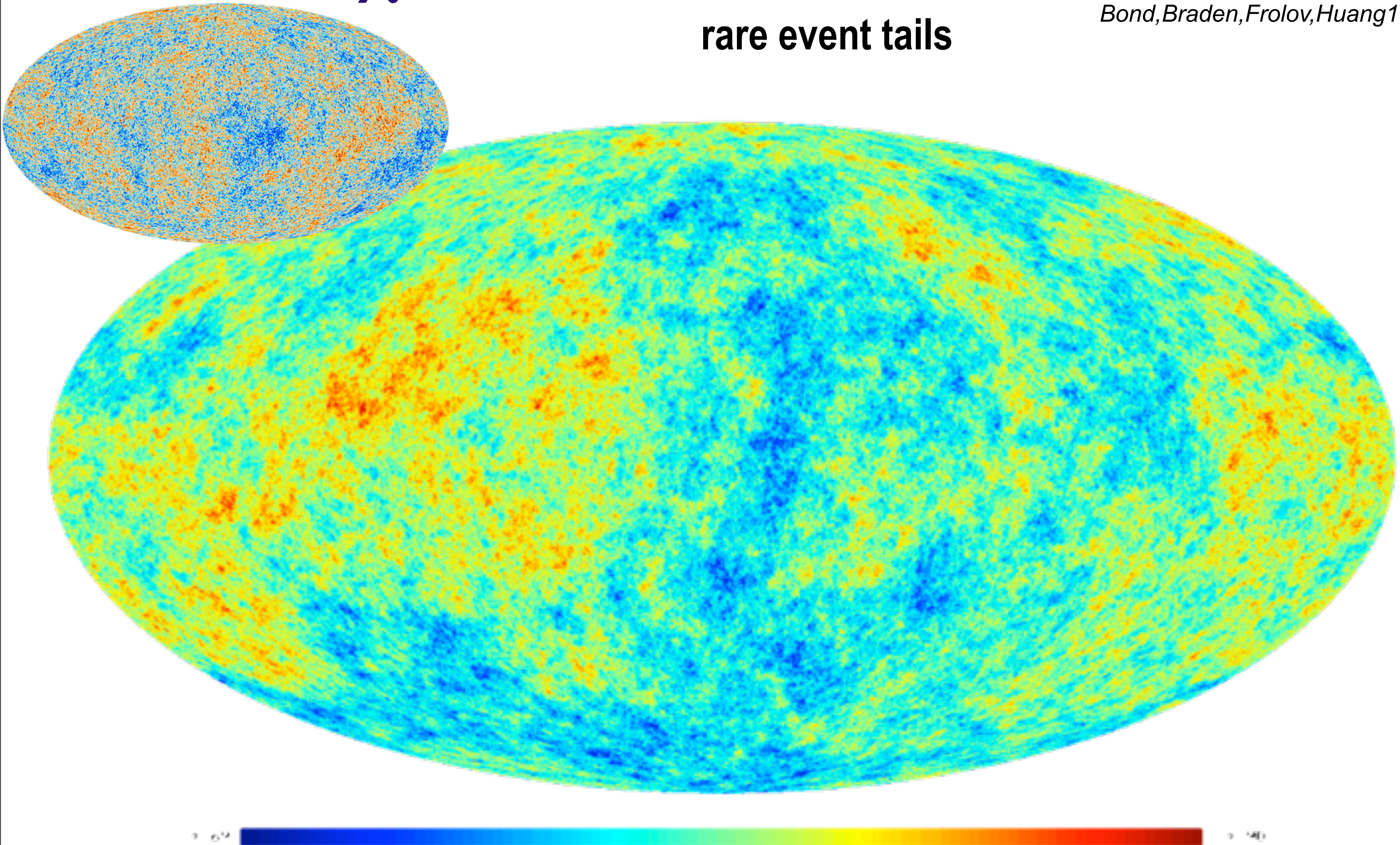


simulated sky with Gaussian inflaton-induced + **uncorrelated subdominant non-Gaussian isocon-modulated preheating**. Landscape-accessing super-horizon

control variable = χ **>h** => ***super-bias, intermittent, extended source-like***

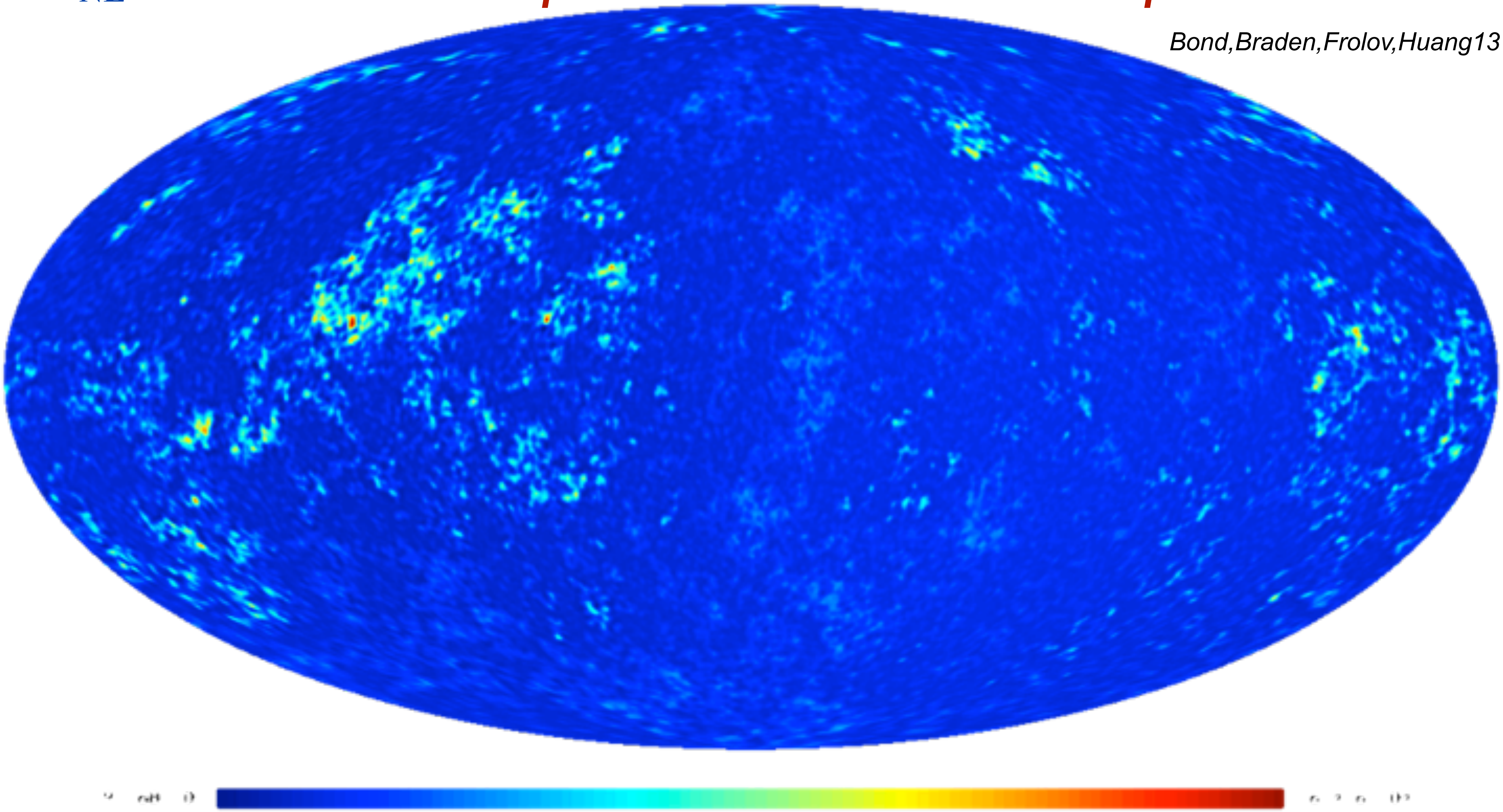
Bond,Braden,Frolov,Huang13

rare event tails



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

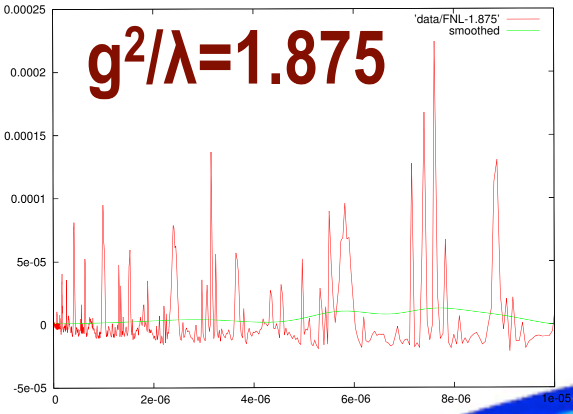
f_{NL} method is ***not how to pattern-search for intermittent power bursts***



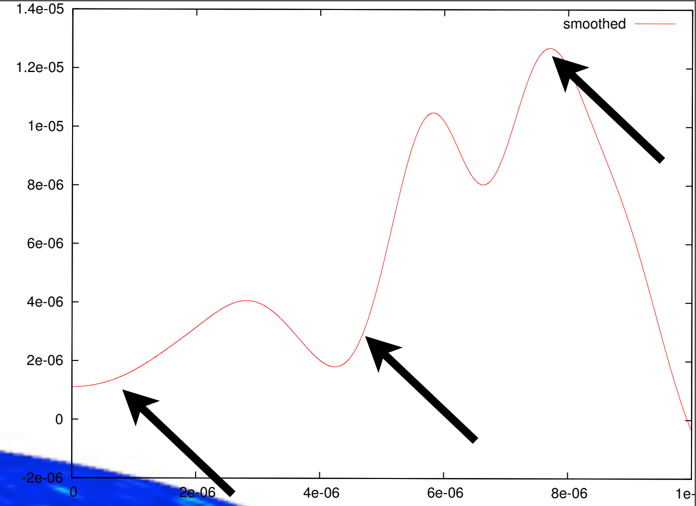
for some $\chi_{>h}$ there is a perturbative regime:

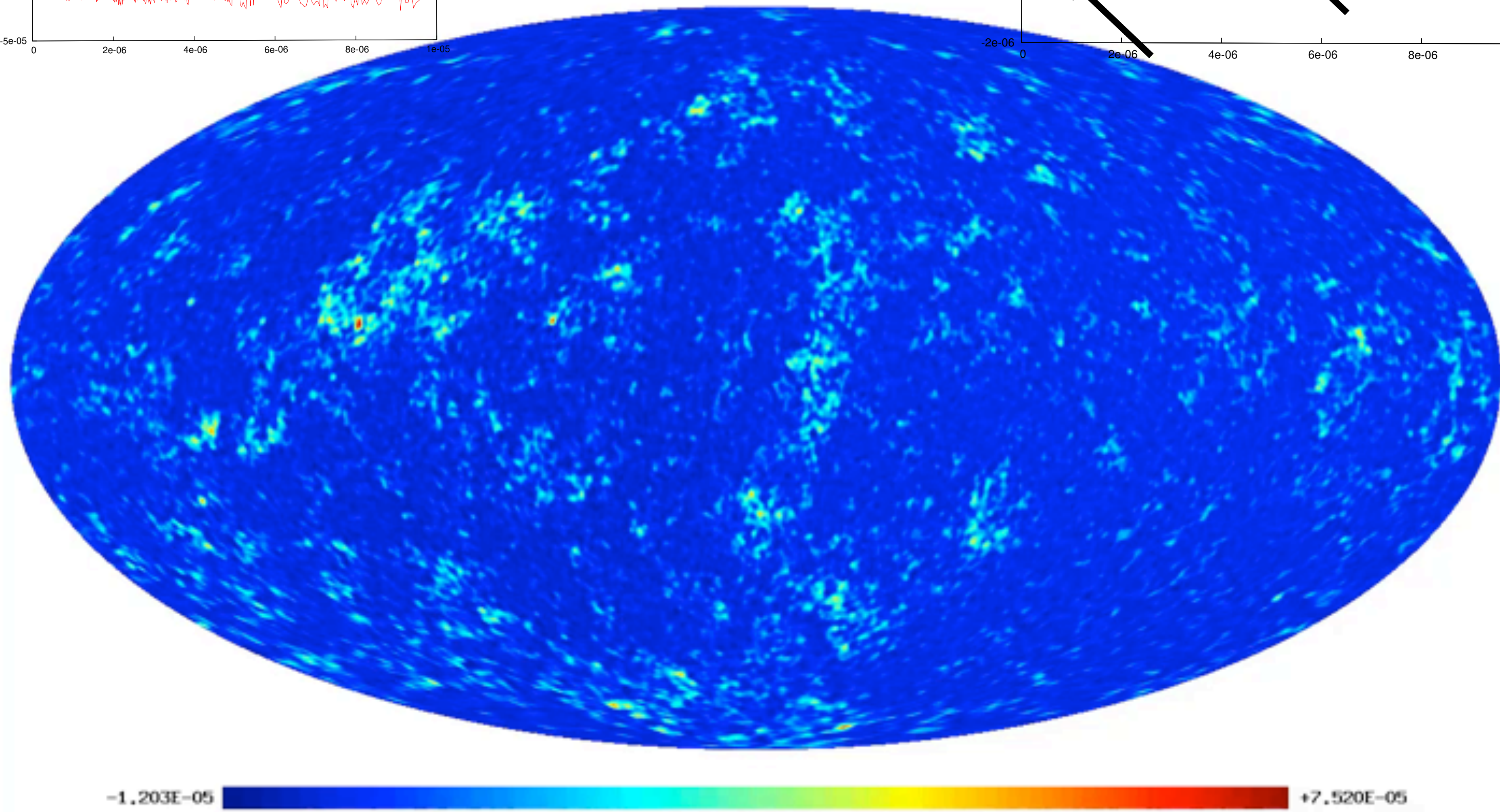
$$f_{NL}^{equiv} = \beta_\chi^2 f_\chi \, [P_\chi/P_\phi]^2(k_{pivot})$$ => constrain $f_\chi^3 \, \chi_{>h}^2$

subdominant structure change as we scan χ>h



Bond,Braden,Frolov,Huang13





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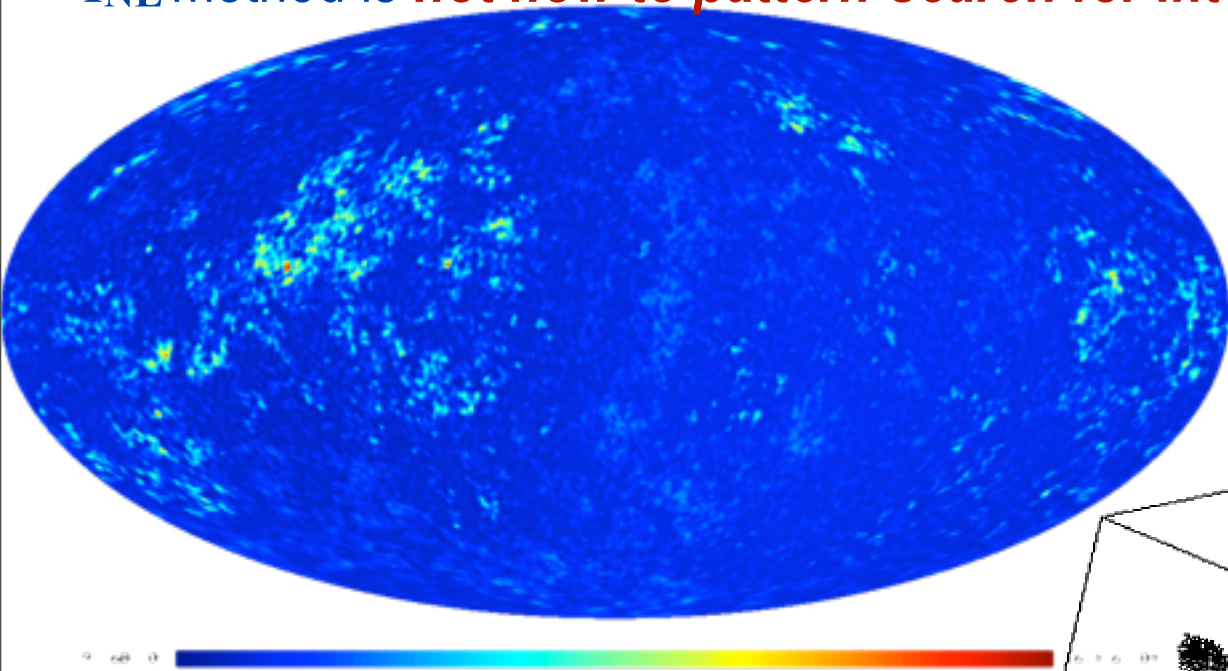
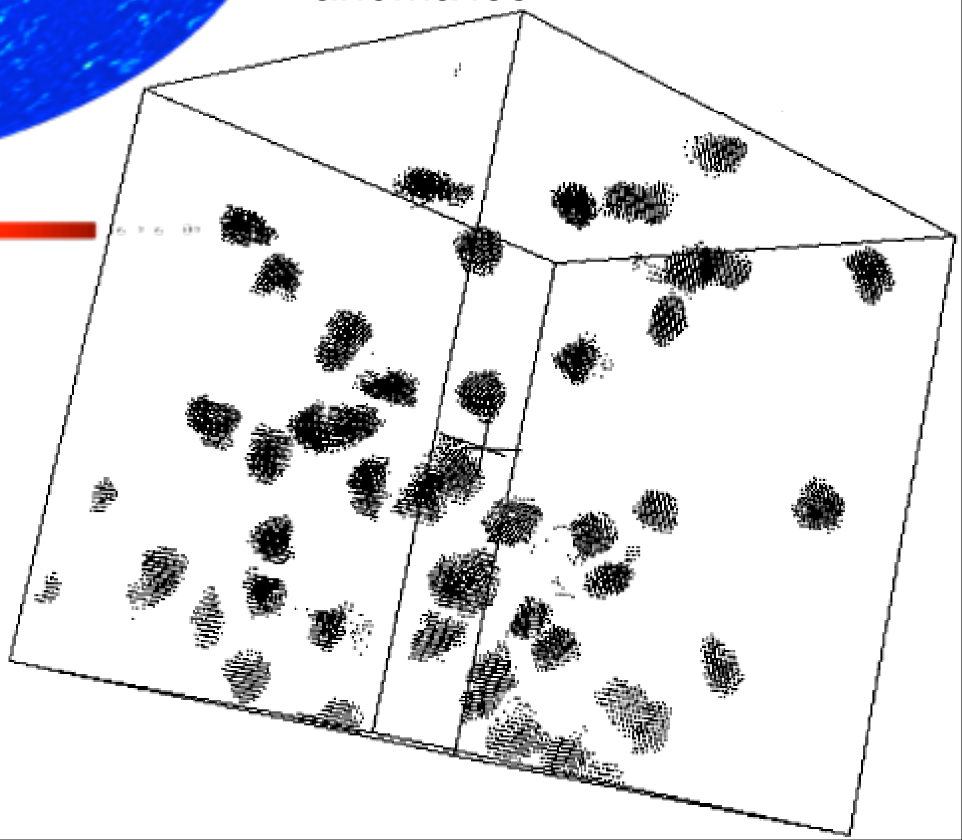
Bond,Braden,Frolov,Huang13

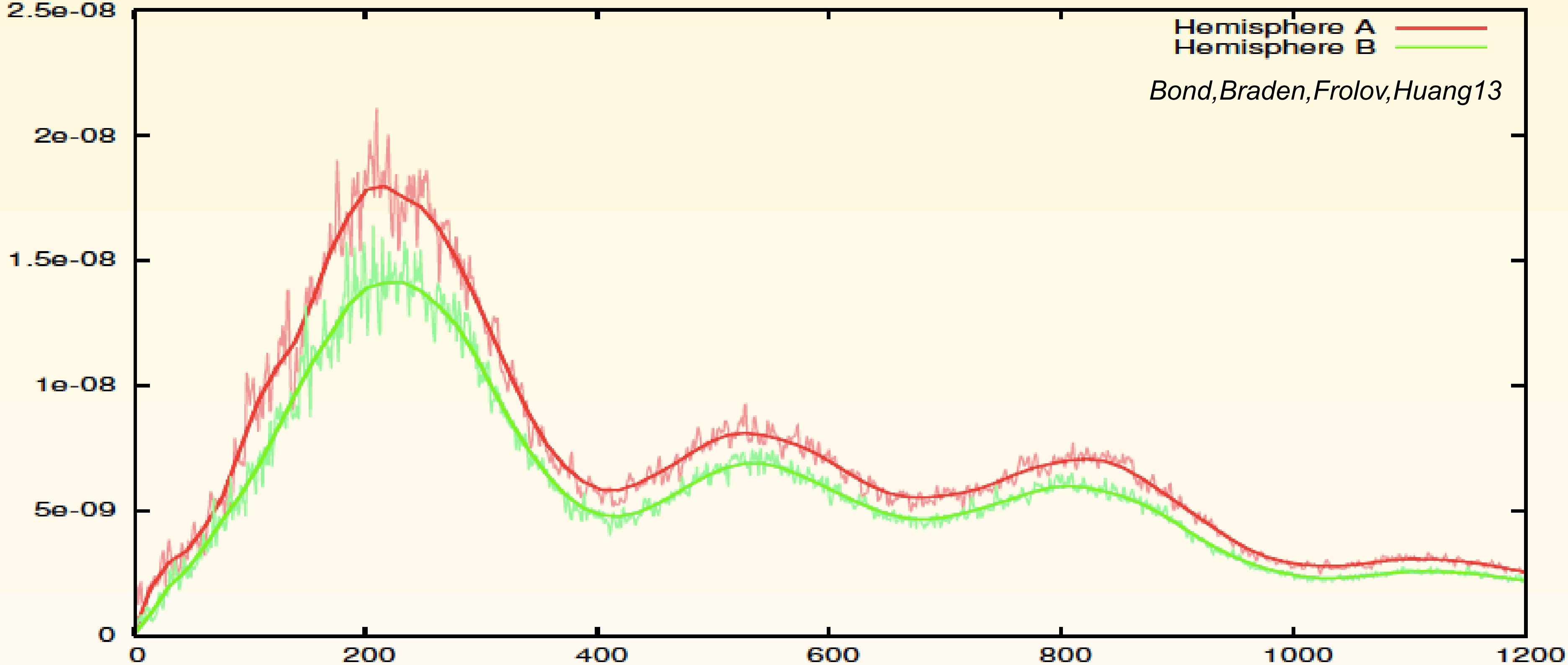


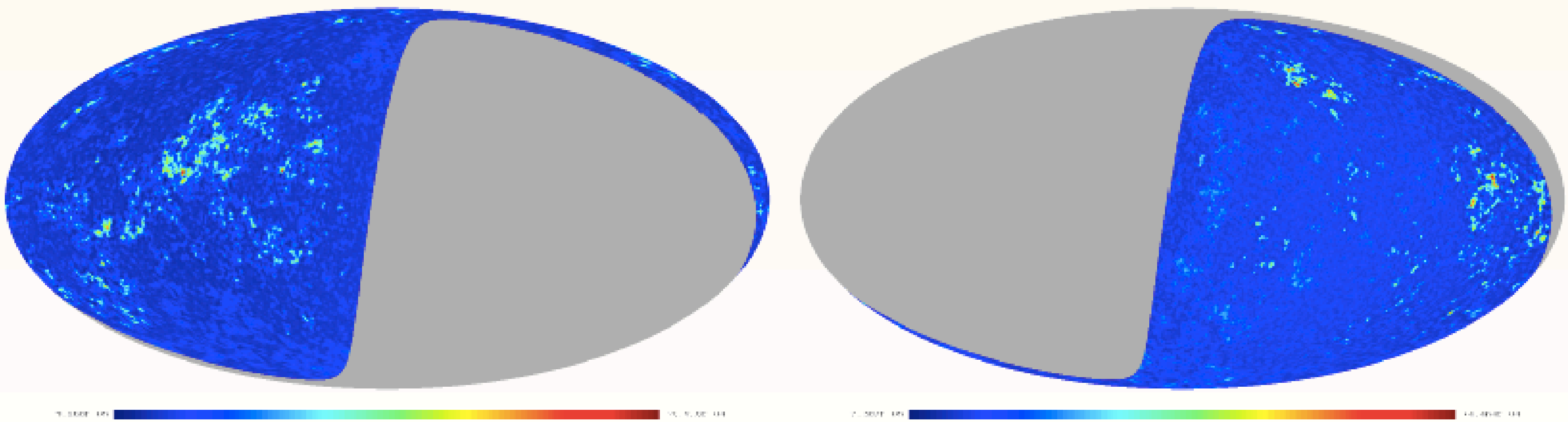
intermittency from steep threshold functions acting on a slightly red curvature field (gravitational potential) lead to very-large-scale splotch "anomalies"



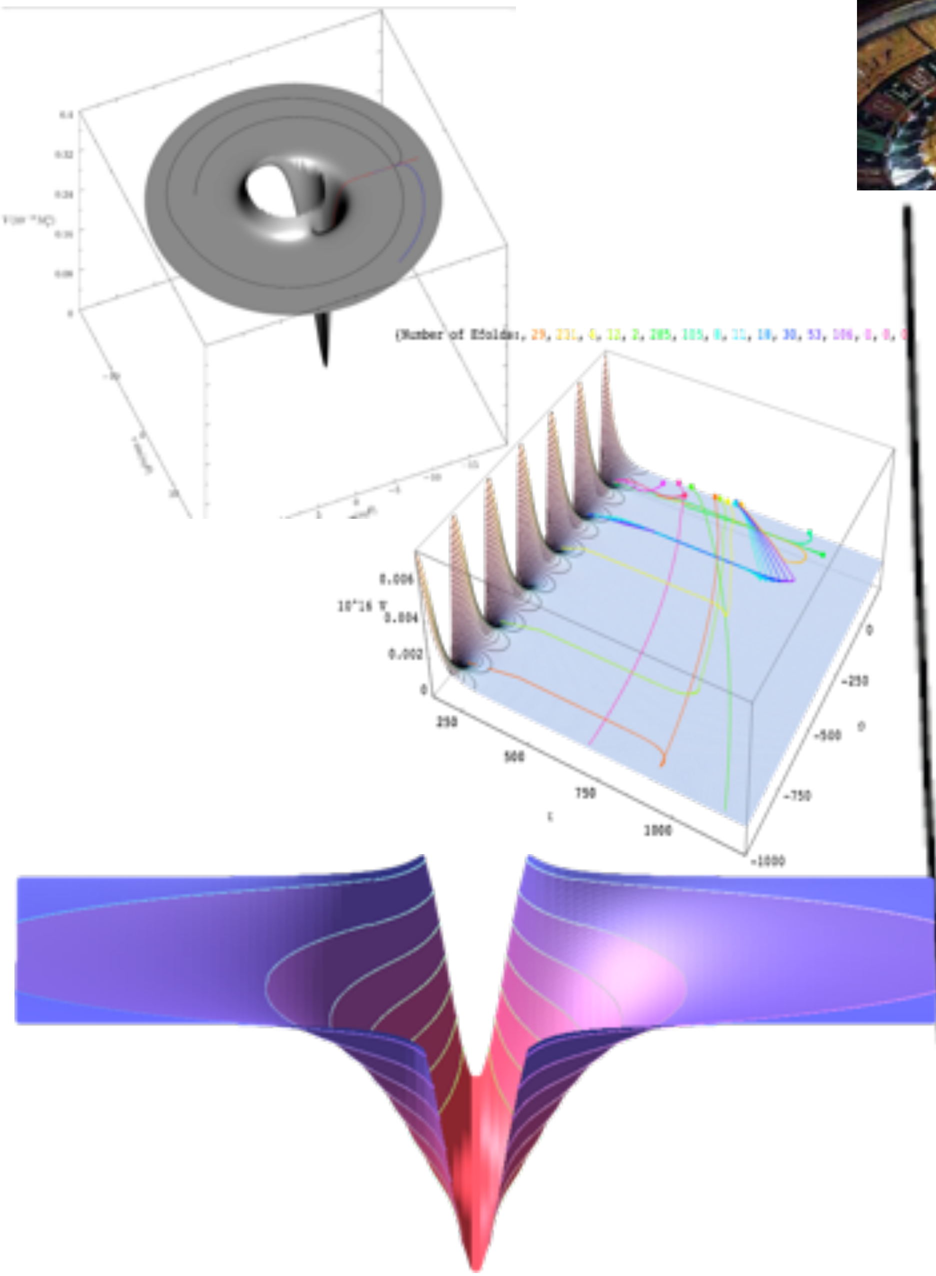
cf. the more localized Lagrangian space **intermittency** from steep cluster-threshold functions acting on the **density field**. **Cluster-patches** lead to pressure intermittency and SZ sources in the CMB

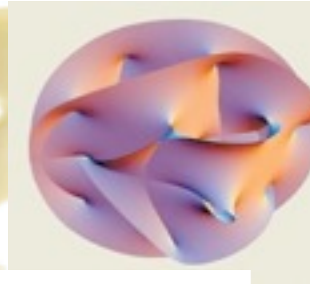
associated hemispherical power asymmetry extends to high L, though diminished. the symmetric inflaton-induced power swamp the power bursts

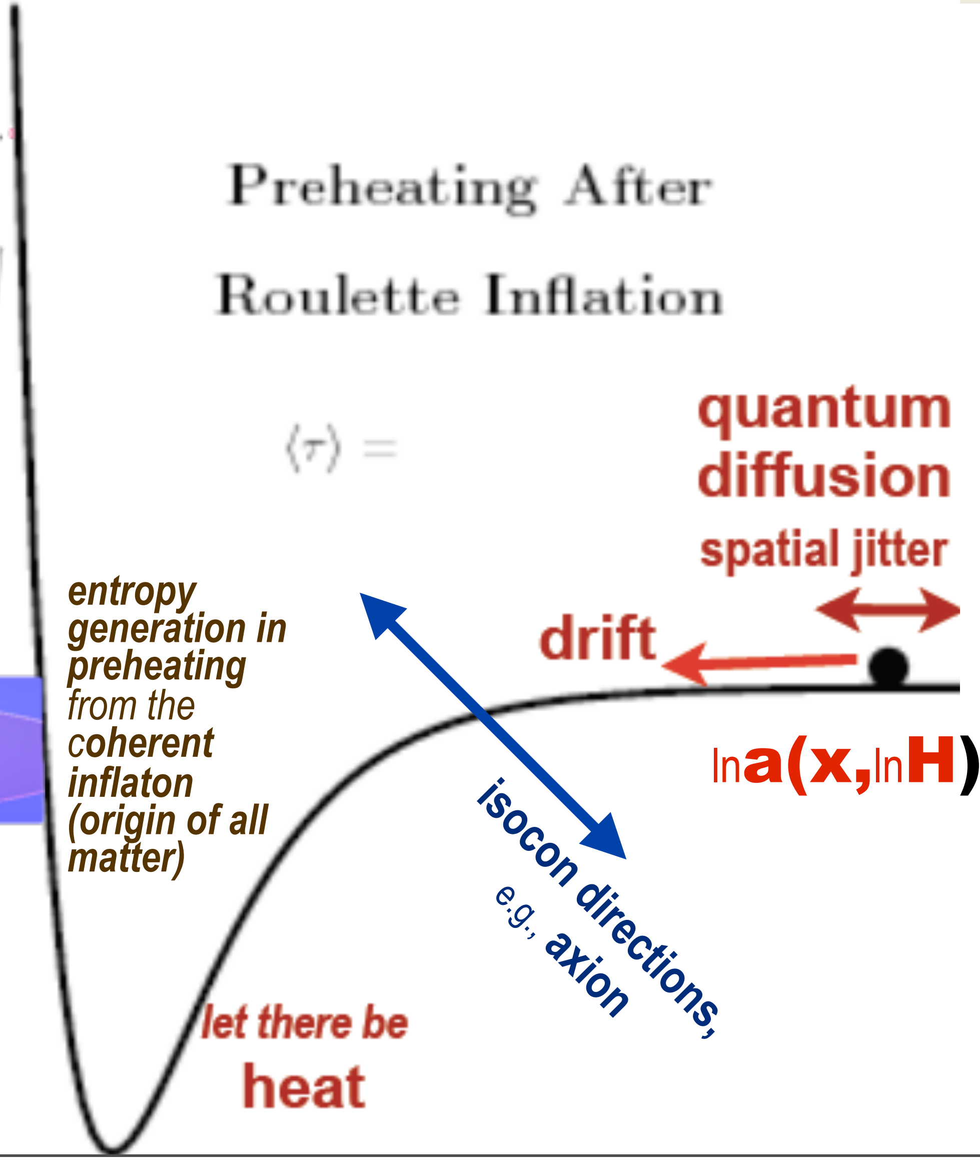




non-Gaussianity





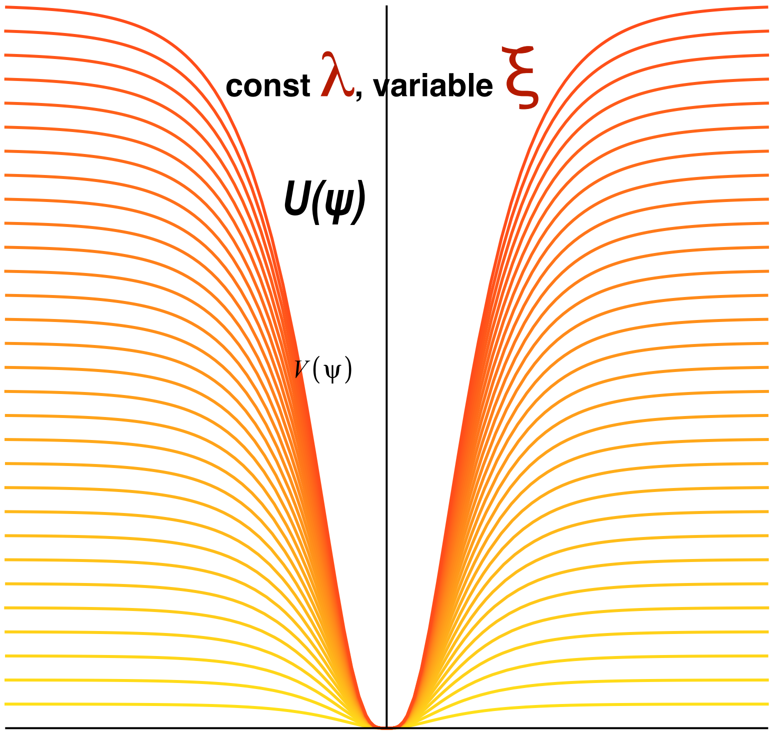


s e m i ETERNAL INFLATION

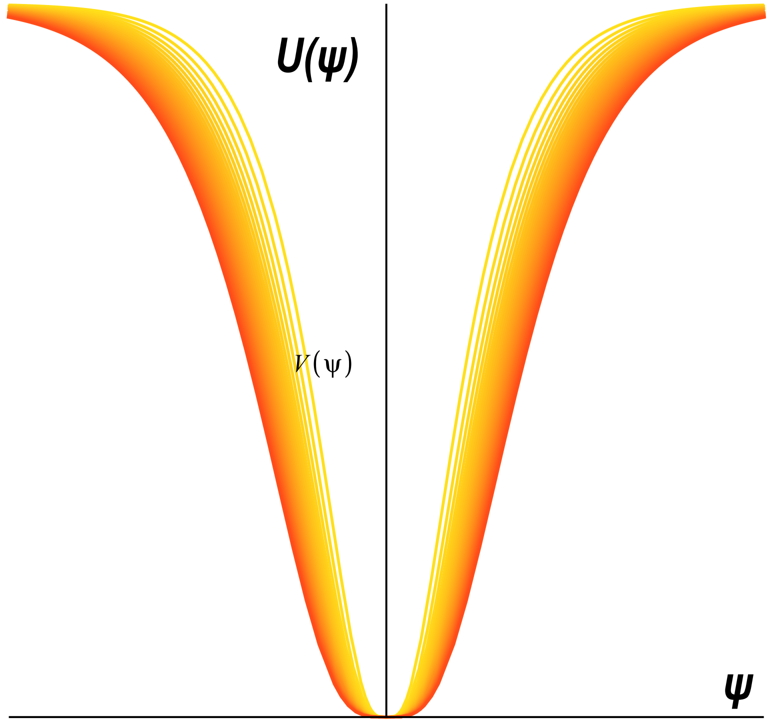
flattened V to satisfy P13

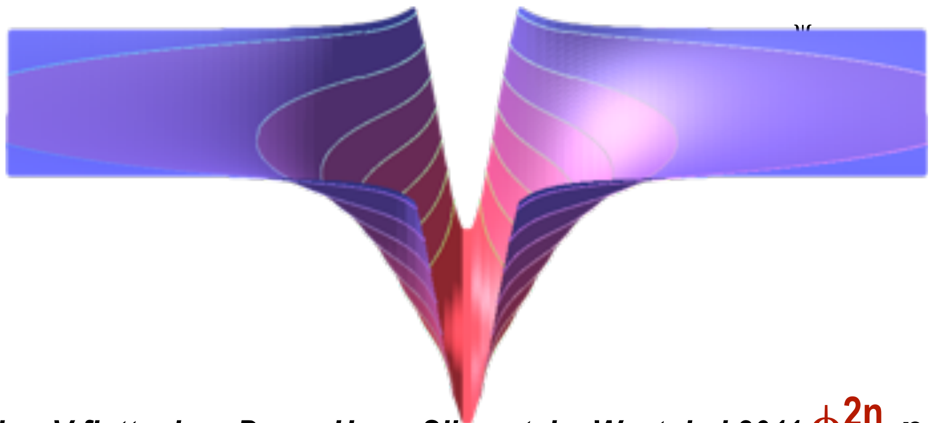
$V(\phi,\chi) = 1/4\, \lambda \phi^4 - 1/2\, \xi\, \phi^2 R + 1/2\, g^2 \phi^2 \chi^2$

in Einstein frame for new (canonically normalized) field $\boldsymbol{\psi}$



const λ/ξ^2, variable ξ





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

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

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

conformal V-flattening of SBB89,

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

other V-flattening: Dong, Horn, Silverstein, Westphal 2011 ϕ^{2n}, n<1 =>

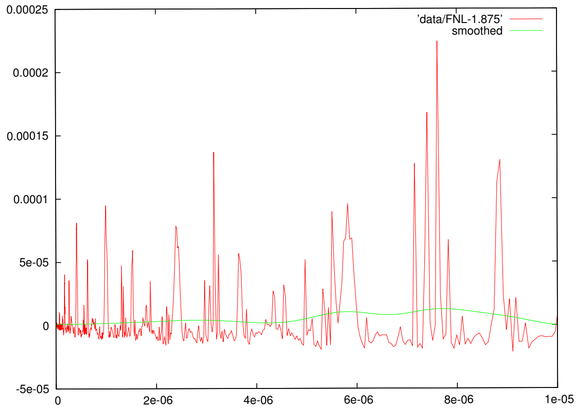
r = 8n/(N_I+n/3) 1-n_s = (n+1)/(N_I-n/6)

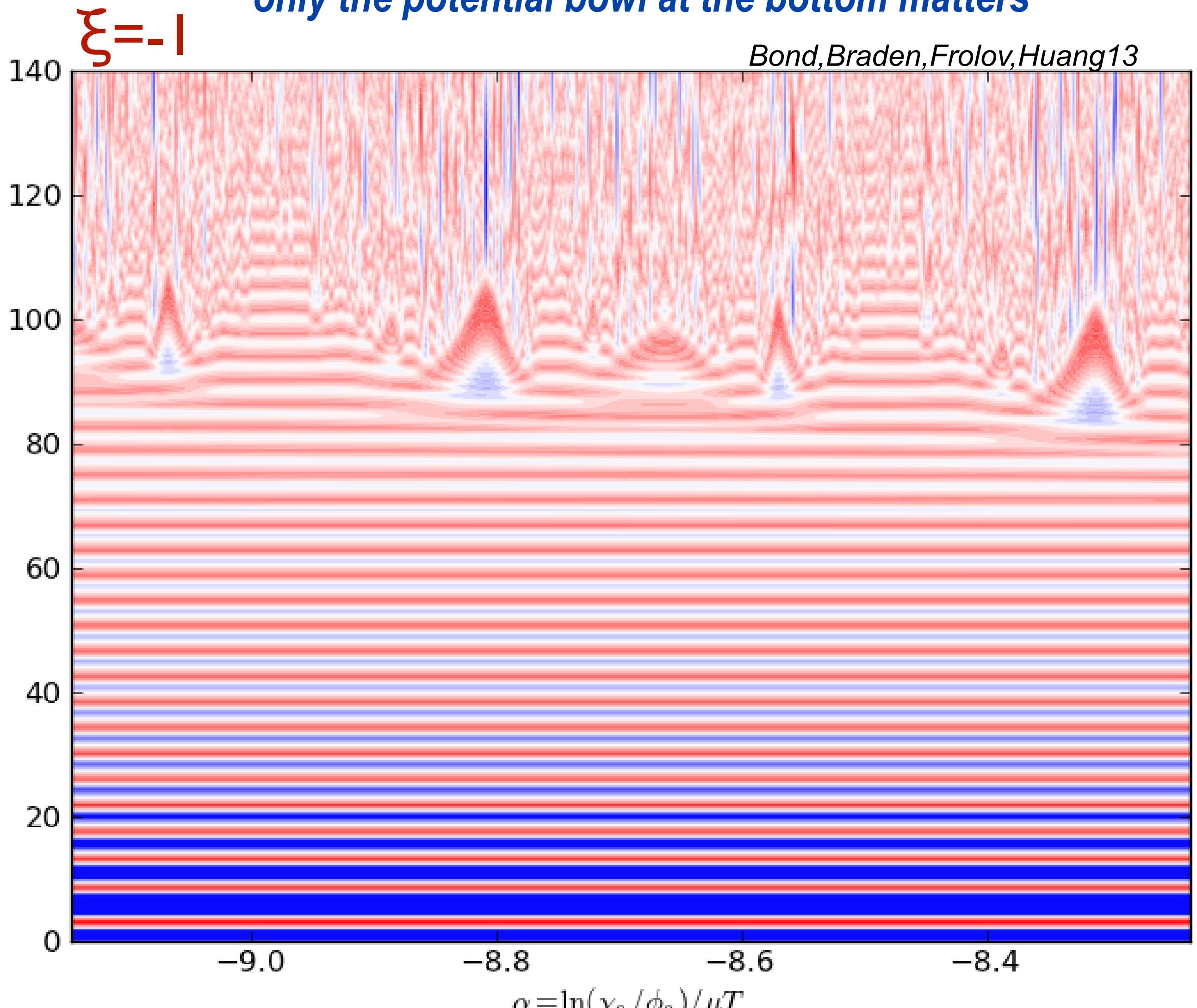
e.g., ***monodromy*** SW08 p=1/3, MSW08 p=1/2 & cos = shift symmetry

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





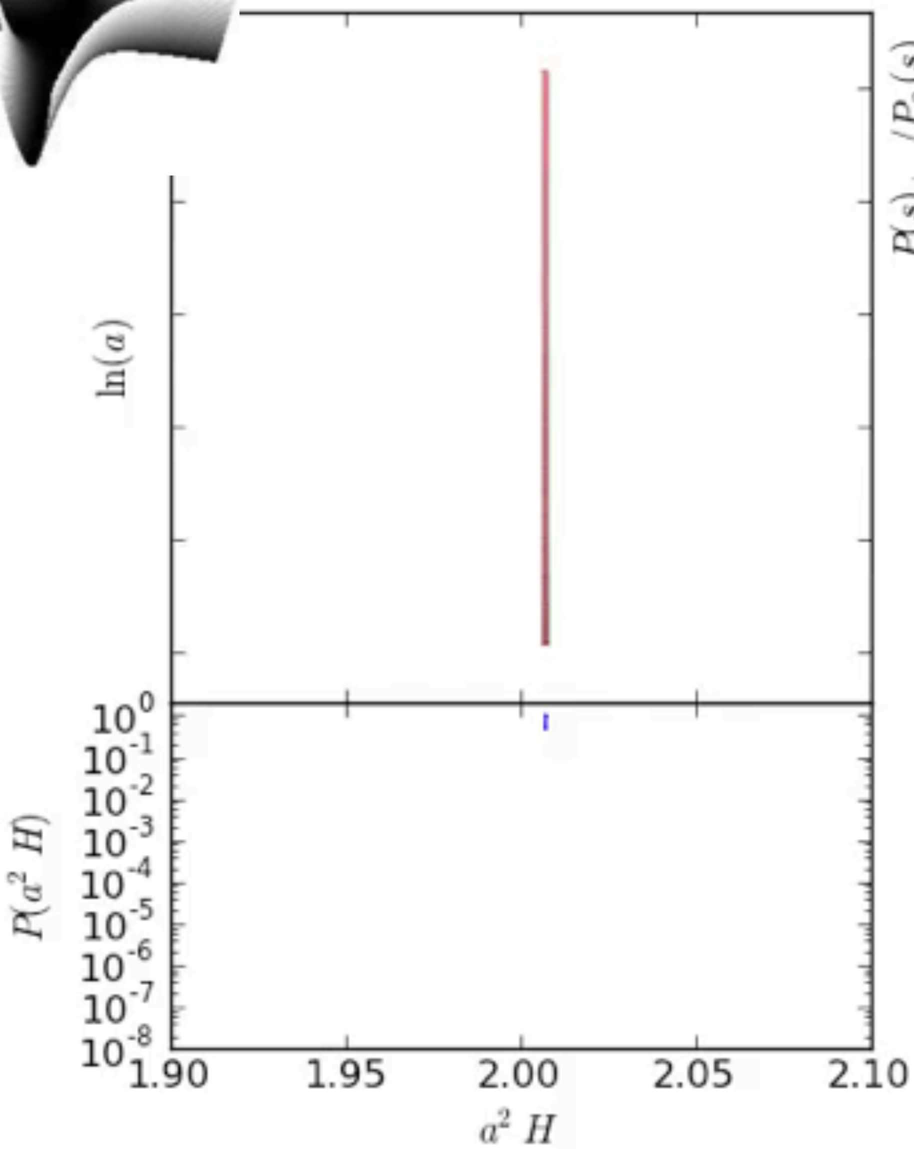
calculating ballistic evolution to caustics gives the spikes in perfect agreement with full nonlinear lattice simulations

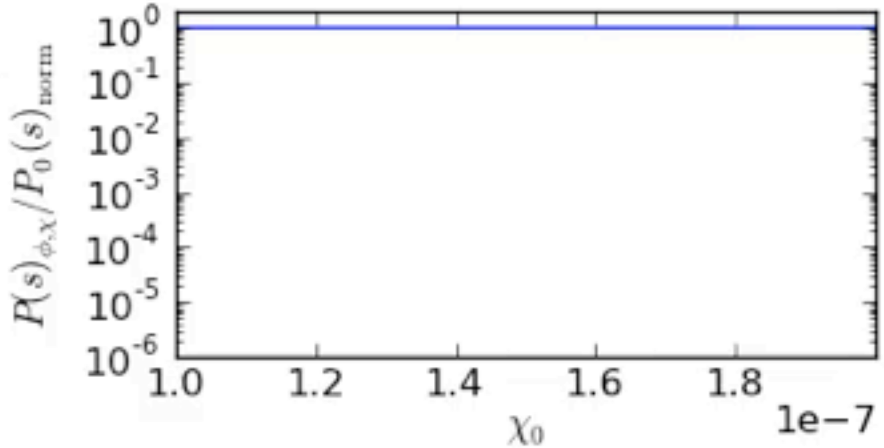
(now being done for a suite of flattened potentials to better deal with the shock-in-time)

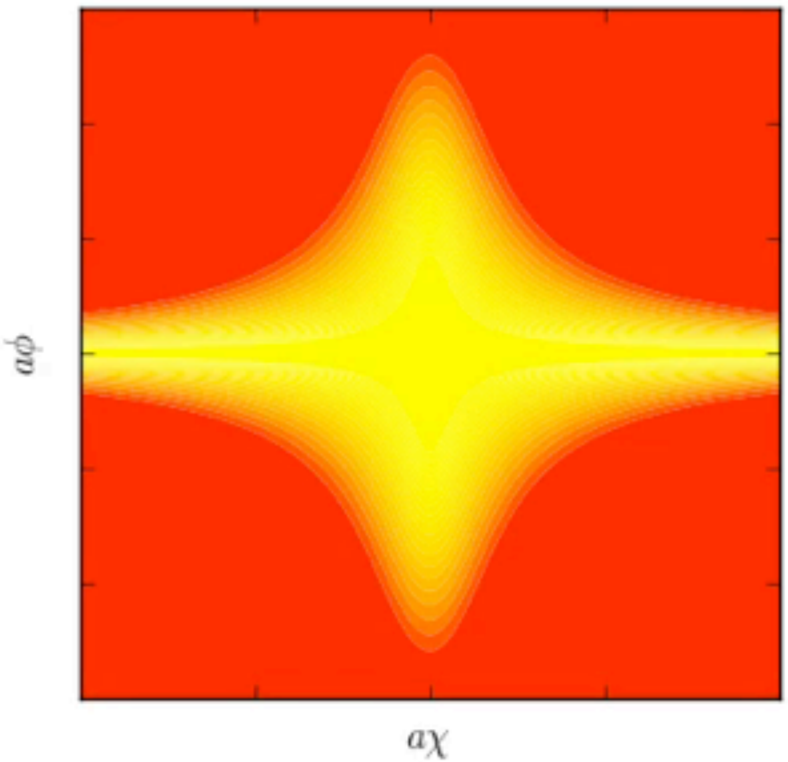
nonG from post-inflation but pre-entropy generation ballistic trajectories can lead to pre-shock-in-time caustics and other phase space convergences in the deformations (!) Zeldovich map-ish

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

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







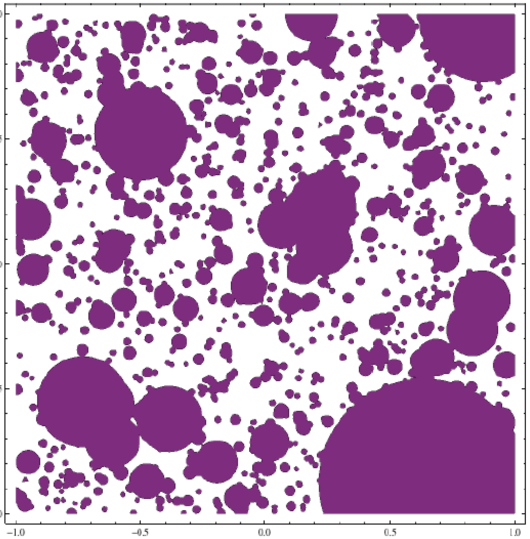
distribution functions & trajectory caustics

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)

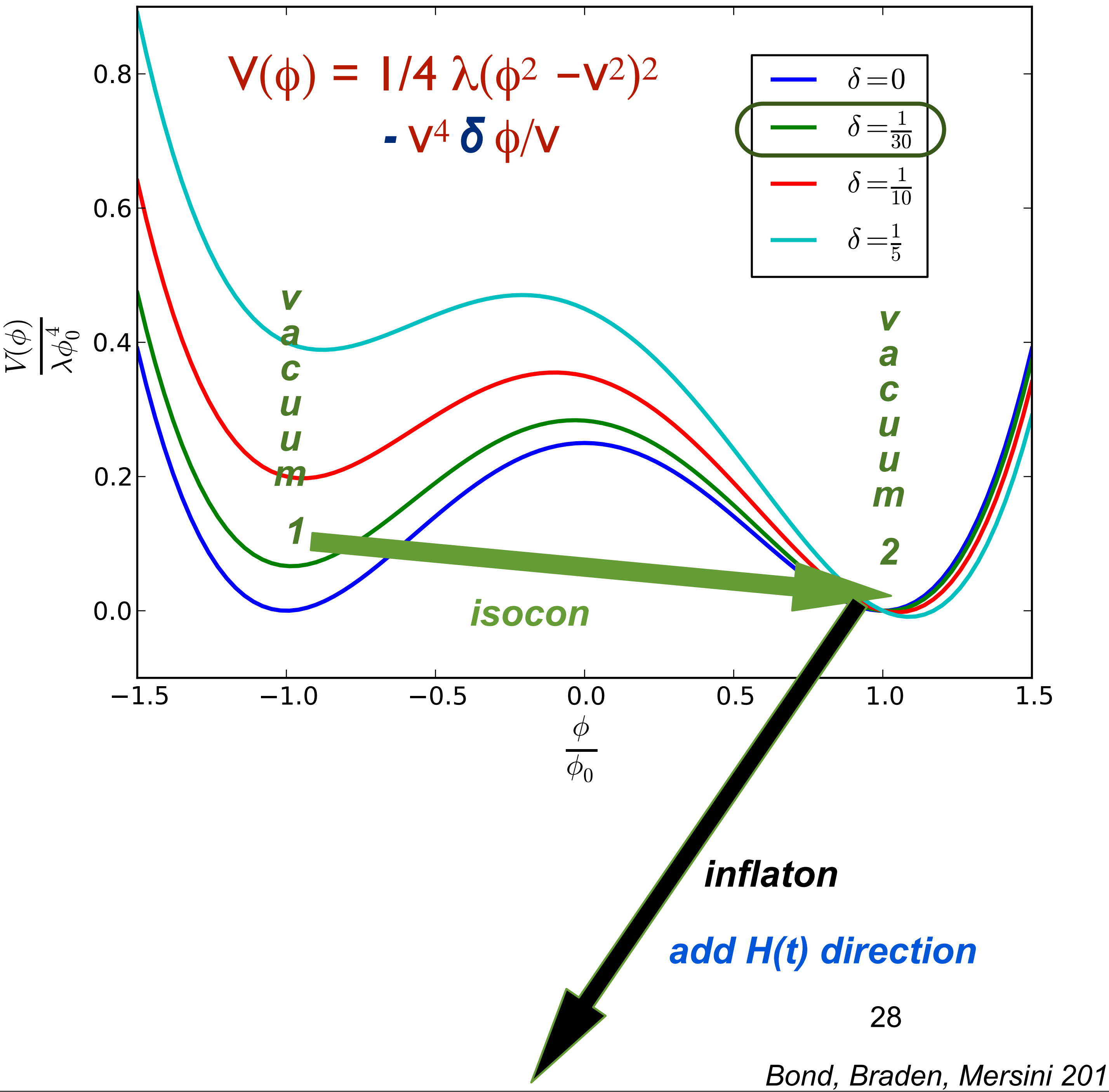
+ long-lived oscillons, size related to the mass

cf. 1D work that dominates the subject

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

an oscillon phenomenon is possible in preheating Easther+

CMB+ observables?



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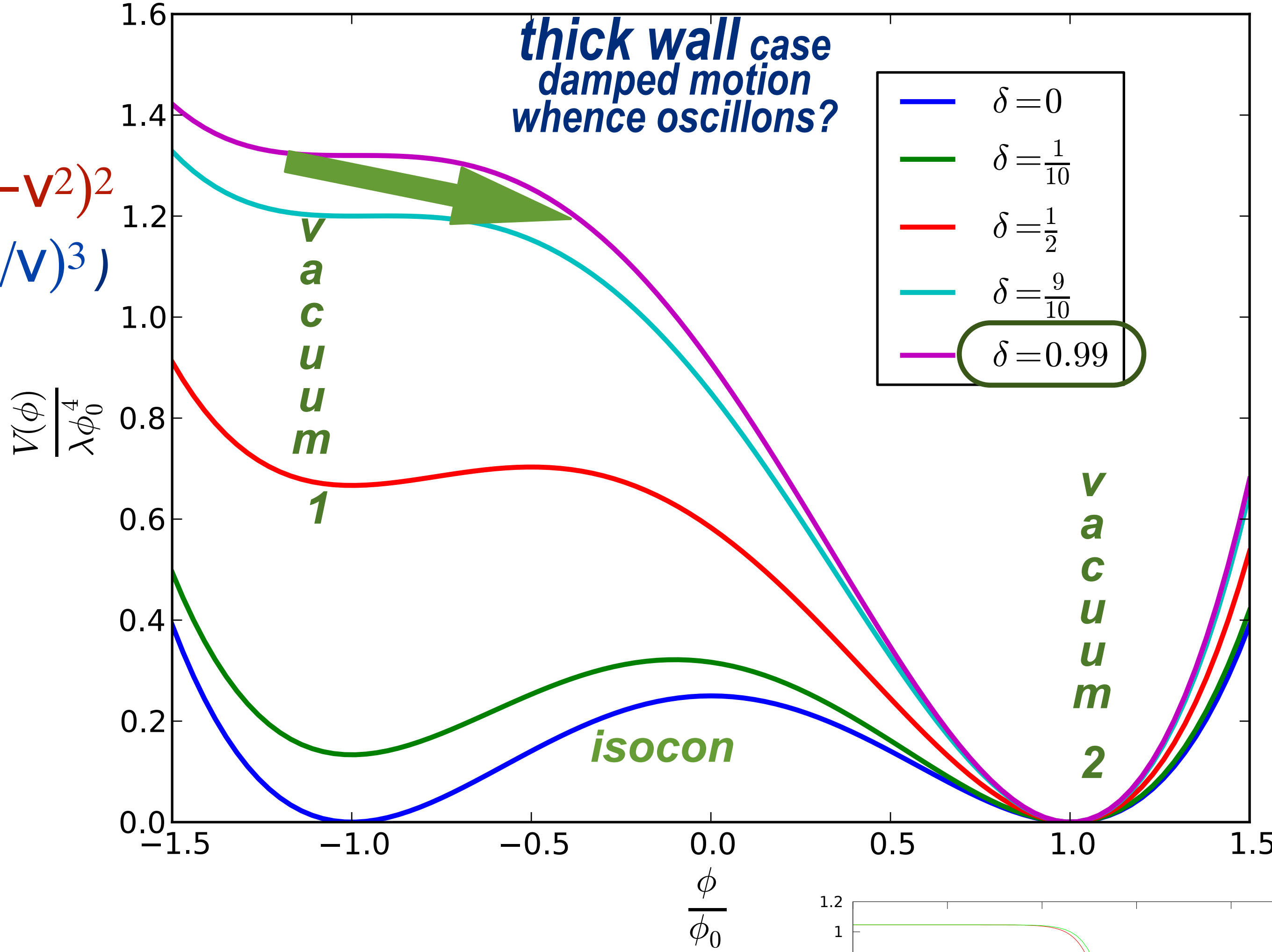
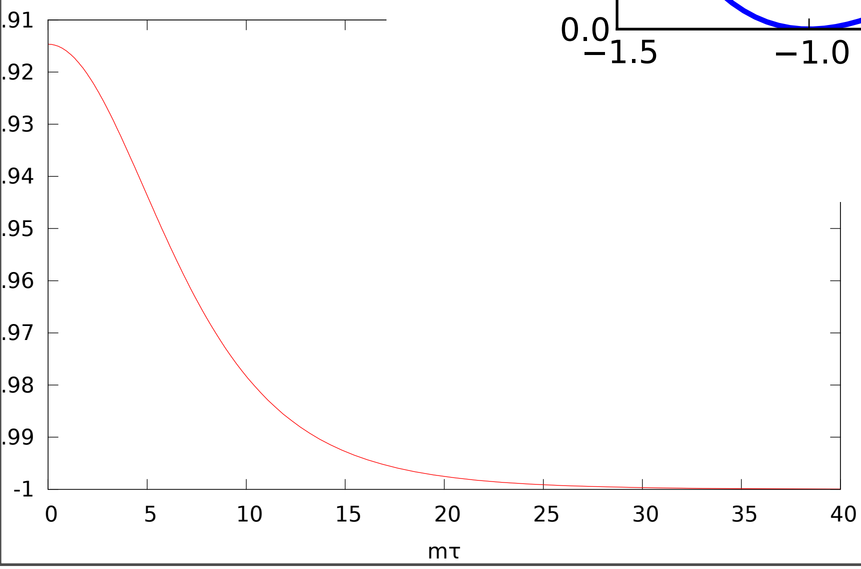
$$V(\phi) = 1/4\ \lambda(\phi^2 - v^2)^2 - v^4\delta\ (\phi/v - 2(\phi/v)^3)$$



large δ

thick wall
instanton

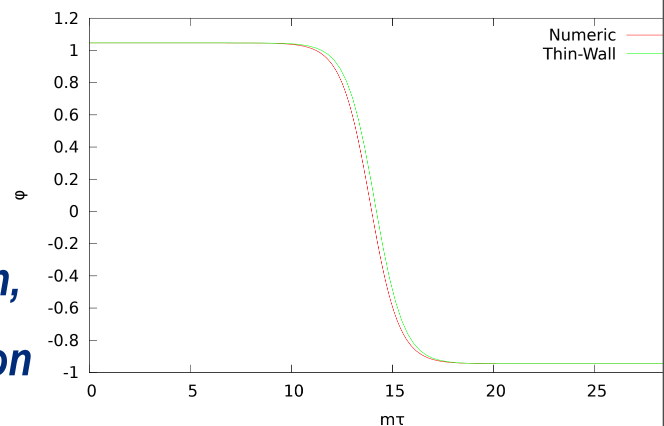
how important are fluctuations in the Euclidean trajectory from the (classical) instanton



small δ

thin wall
instanton

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



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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 Qballs?
small amp conditions
$(m^2 - \omega^2)\varphi + (-\nabla^2 \mathrm{Phi}) + (\partial V/\partial\varphi - m^2 \varphi) \sim 0$ freq (>0) curvature (>0) nonlinear (must be <0)

BUT no theorems (so far) for when oscillons arise. V shallow at large phi *BUT not for bubbles*
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*
shallow flattened V for preheating oscillons *BUT not for nearly symmetric bubble potentials*

energy fraction in oscillons > 80%. Farhi etal 08 Amin+ >> 50% *BUT not in our sims ~10%, 90% scalar radiation*
preheat with pspectre pseudo spectral code Easther, Finkel, Roth 256^3 defrost (Frolov) LatticeEasy (Felder +Tkachev) *BUT defrost++ with symplectic integration + radiation boundary conditions + new (much) faster spectral code*
oscillons overdense by a few *BUT we see higher, 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*

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

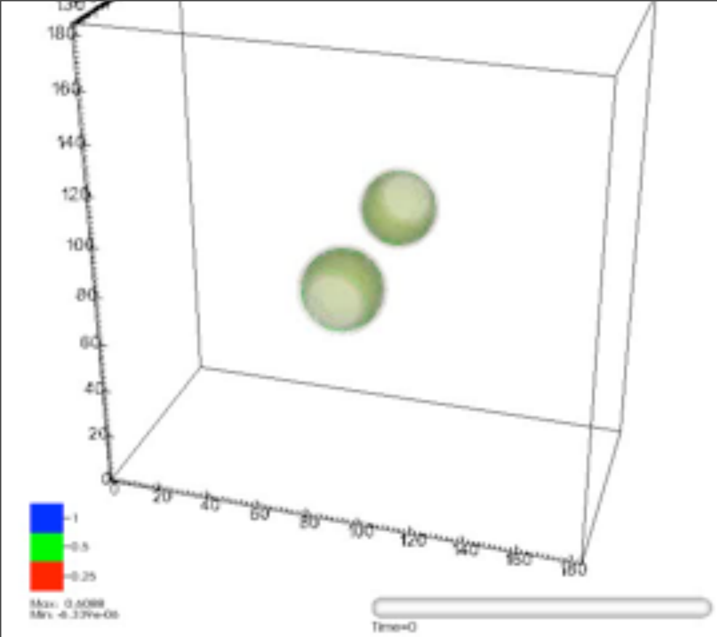
with tiny zero point & wall fluctuations

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

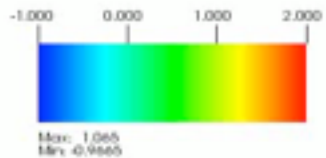
+ long-lived oscillons, size related to the mass

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

an oscillon phenomenon is possible in preheating CMB+ observables?

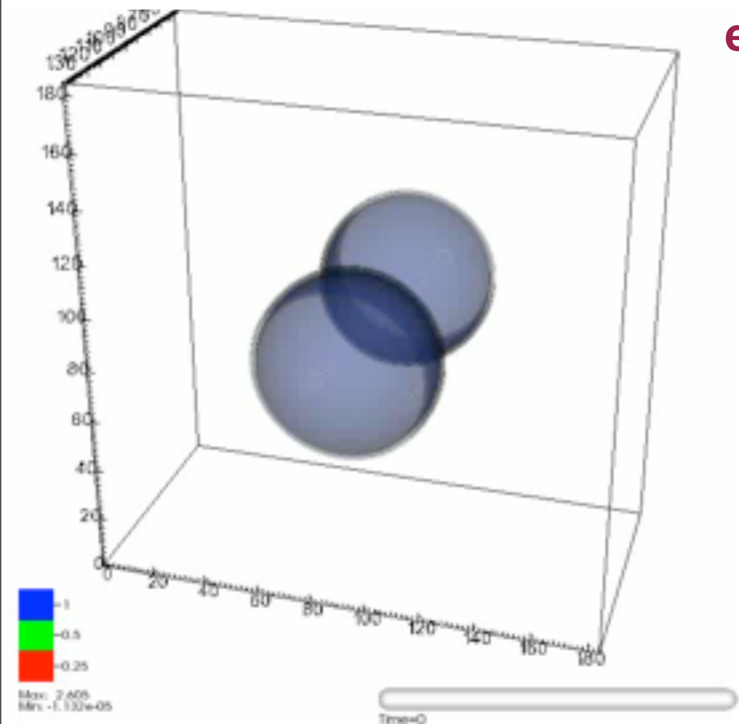


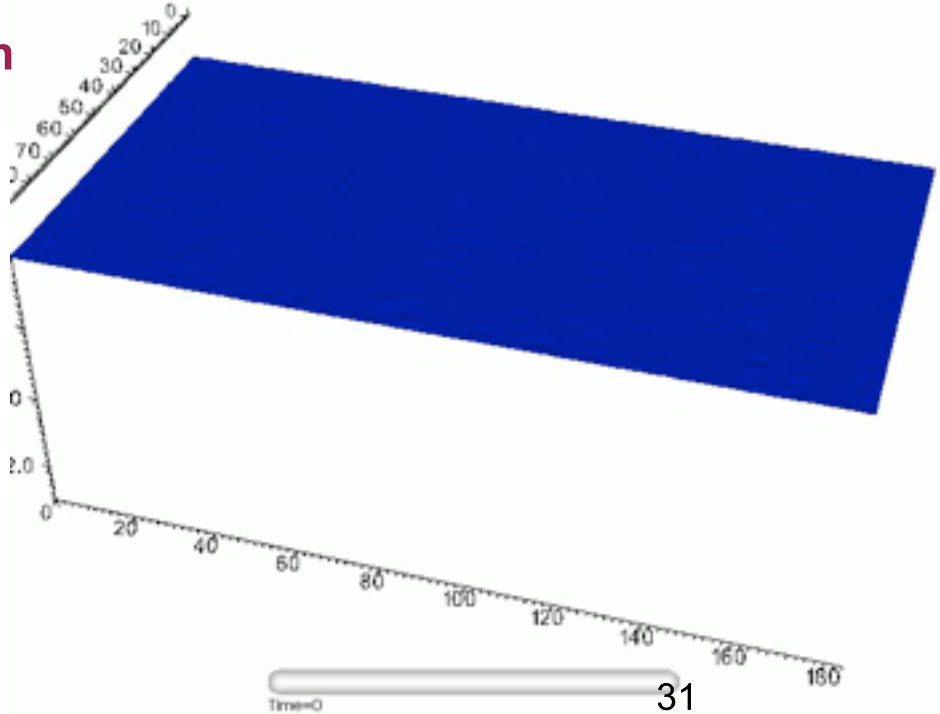
long-lived oscillon energy ~ 10%



energy density evolution

high contours





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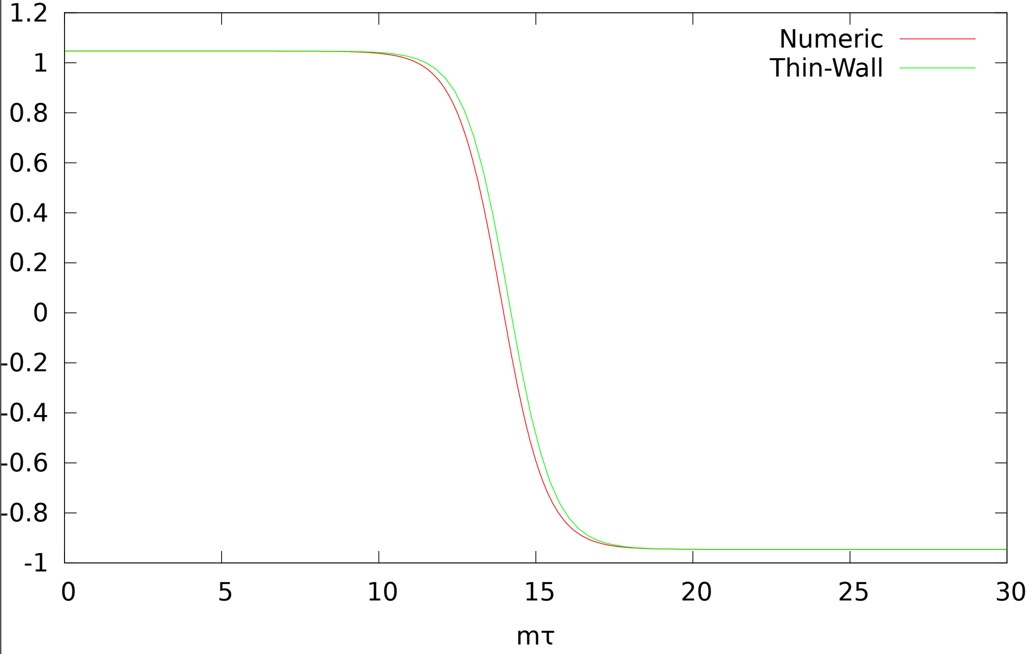
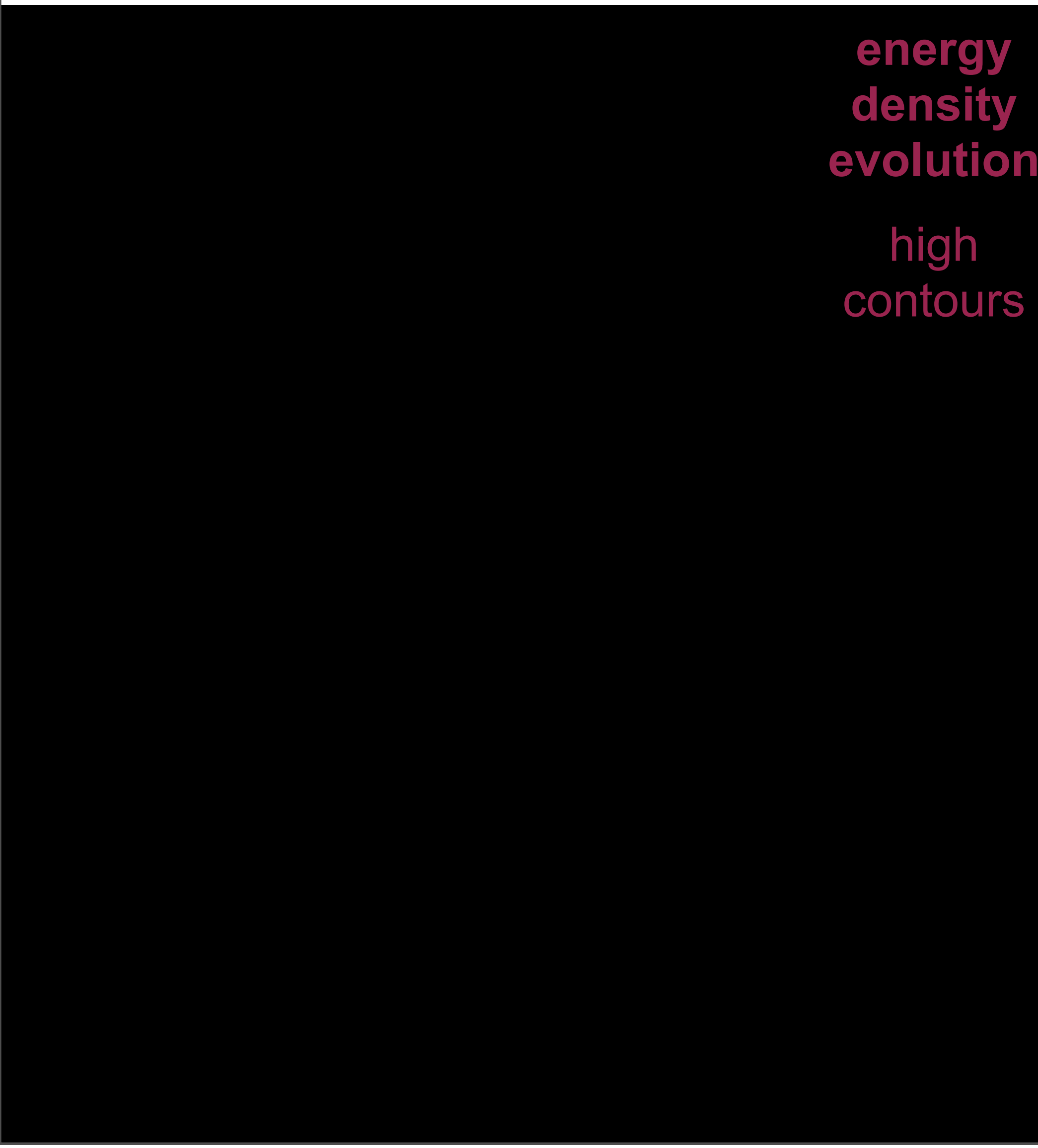


the oft-used thin wall approximation to instantons is not accurate enough. a full numerical instanton solution is required. especially so for thick wall scenarios *add $H(t) = V_{inf}$ in inflaton direction*

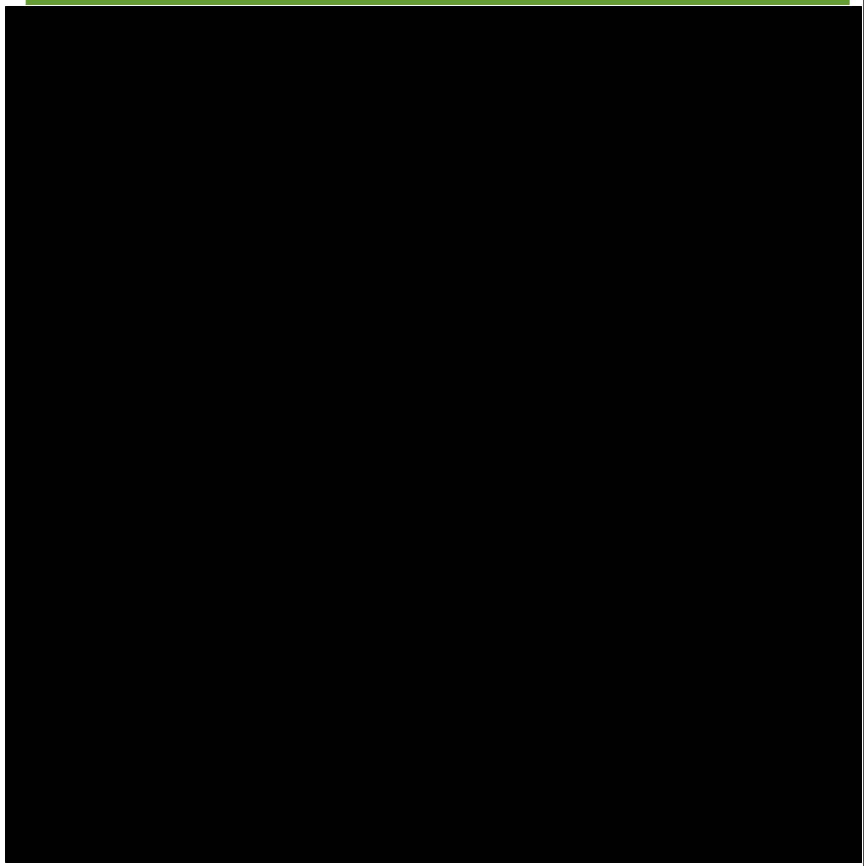
$R_{bubble,i} = 0.1\ H^{-1}$

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

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



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



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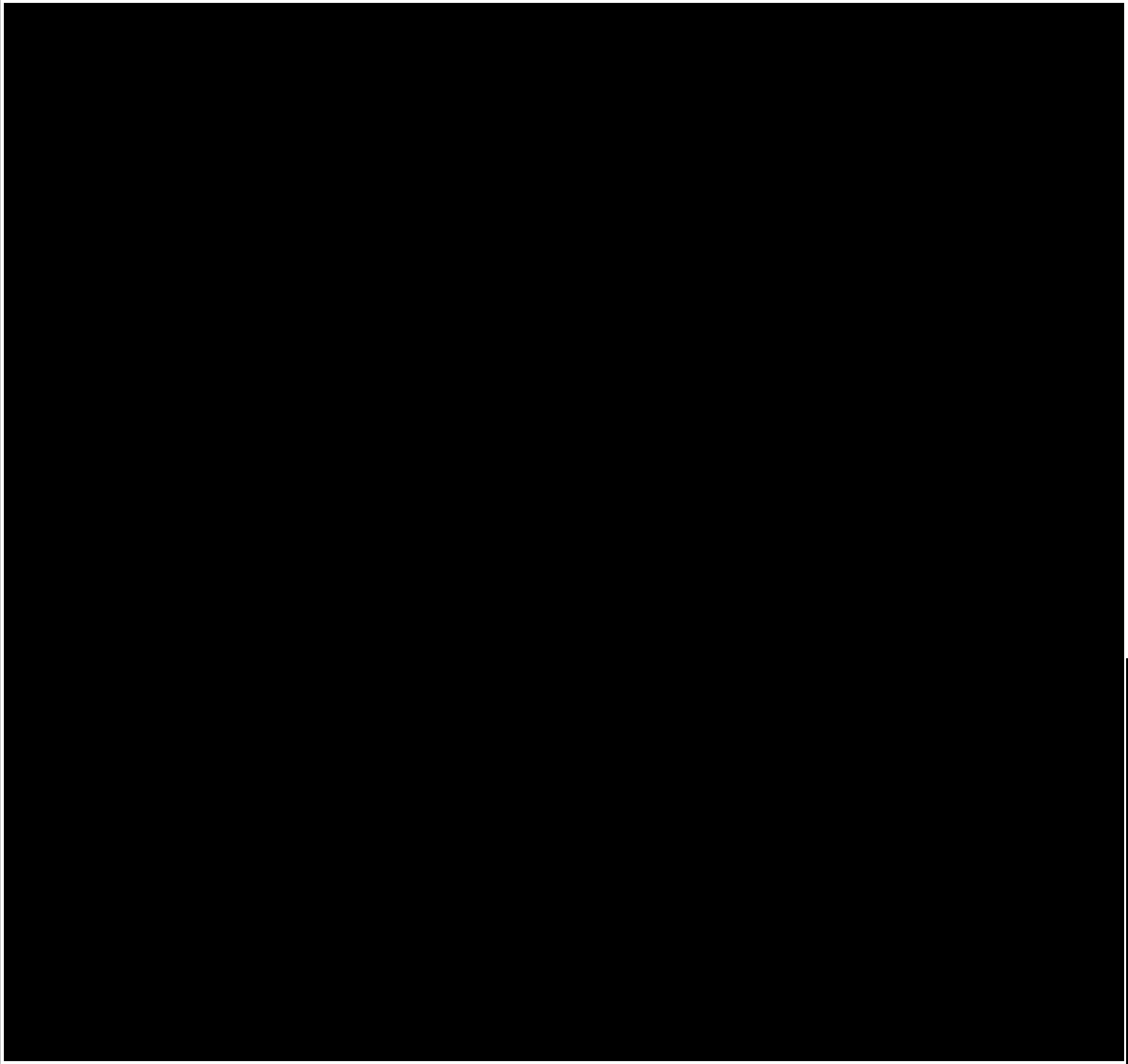
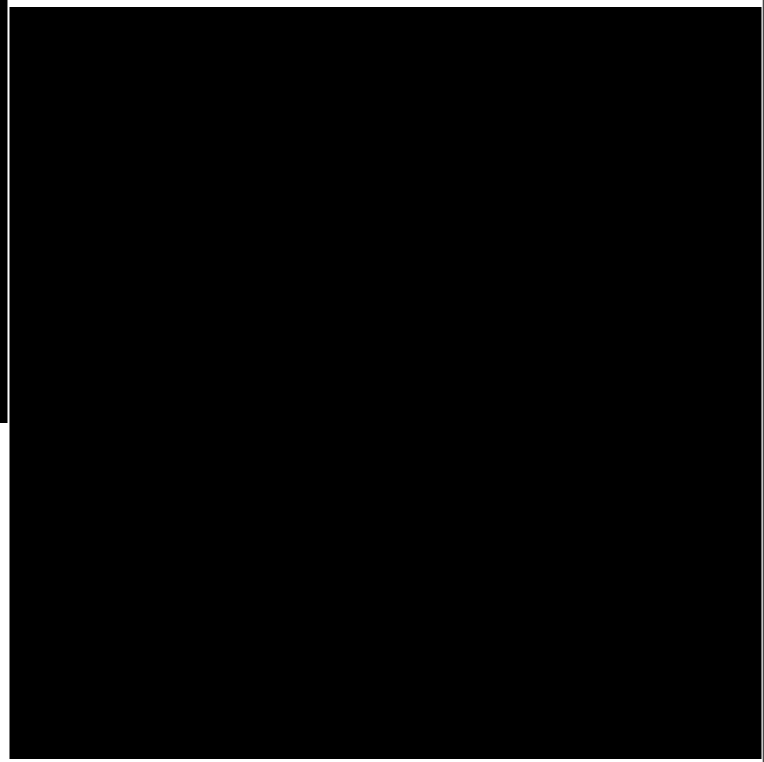


axionic potential

V~1-cos(θ)

kink -antikink instanton = IC

continued wall collisions
because of periodicity =>
amplification of quantum noise
fluctuations
not quite Kleban+ unwinding
inflation of D-branes



conclusions:

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

do they lead to observable rare-event anomalies?

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

amusing subdominant patterns do arise!

END