ζ *all cosmic structure from* **entropy**!

linear ***(bst1983)*** **=>nonlinear** $\zeta(x,t) = \int_{\text{field-path}} (dE+pdV) / 3(E+pdV)$

SBB89, SB90,91, B95, B+Braden17 ***coarse-grained*** *horizon scale cf. fine-grained fluctuations*

system / signal *reservoir / noise*

BB, B2FH, b+braden+frolov+huang

Dick Bond @Harvard17_4

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coarse-grained *horizon scale cf. fine-grained fluctuations*

$\ln V / \langle V\rangle|_\rho = 3 \ln a(x,t) / \langle a\rangle|_\rho = \ln \det A^i{}_j(x,t) / \langle a\rangle|_\rho \sim 1/2 \ln \det {}^{(3)}g^i{}_j$

***volume deformation* = isotropic strain**

SBB89, SB90,91, B95

-> Sasaki+ δN 'formalism'

B2FH, b+braden+frolov+huang

Dick Bond @Harvard17_4

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volume deformation **= isotropic strain**

$\ln \rho(x,t) / \langle\rho\rangle|_V$ **phonon**

SBB89, SB90,91, B95, B+Braden17

B2FH, b+braden+frolov+huang

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volume deformation = isotropic strain

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along coarse-grain trajectories $d\zeta = [\mathbf{d}bar\ \zeta](fg\text{->}cg)$ $(- [\mathbf{d}bar\ \zeta](cg\text{->}fg))$

regimes: 1. stochastic inflation non-adiabatic $[\mathbf{d}bar\ \zeta](fg\text{->}cg)$

reduction of Langevin network for all fields, Fokker-Planck probability evolution

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$\ln \rho(x,t)/\langle\rho\rangle|_V$ **phonon**

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regimes: 1. stochastic inflation non-adiabatic $[\mathbf{d}bar\ \zeta](fg\text{->}cg)$

gradient flow ***+stochastic jitter,*** **simple Hamilton principle function** $S \sim H(\phi_{cg})$

origin of all cosmic structure from quantum noise story - nonGaussianity feedback of cg on fg

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ζ *all cosmic structure from* **entropy**!

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regimes: 1. stochastic inflation non-adiabatic $[\mathbf{d}bar\ \zeta](fg\text{->}cg)$

gradient flow *+stochastic jitter,* simple Hamilton principle function S~H(ϕ_{cg})

classical dynamical system theory, chaos

2. ballistic phase adiabatic thru EoI, but caustics & Kolmogorov-Sinai entropy

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2. ballistic phase adiabatic thru EoI, but caustics & Kolmogorov-Sinai entropy

3. shock-in-time, *cg <=> fg, origin of almost all entropy* $S_{U,m+r} \sim 10^{88.6}$

non-equilibrium S burst, slow evolution to quark/gluon plasma *cf.* $S_G \sim 10^{121.9}$ *asymptotic DE*

Dick Bond *@Harvard17_4*

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cf. $S_G \sim 10^{121.9}$ *asymptotic DE*

further S generation in early Unioverse: phase transitions, out-of-equilibrium decays?

further **d***bar S: reionization epoch & beyond via nuclear/accretion, gravitational collapse* ***CIB***

Dick Bond @Harvard17_4

ζ all cosmic structure from **entropy**!

linear (*bst1983*) =>**nonlinear** $\zeta(x,t) = \int_{\text{field-path}} (dE+pdV) / 3(E+pdV)$

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cf. $S_G \sim 10^{121.9}$ *asymptotic DE*

..7.. *cf.* late-time **density web ~ strain web ln ρdetA** /3

if cold DM $p/\rho \sim 0$ => $\zeta(x,t\,|cdm)$ *is conserved before shell crossing (preheating)* esa

planck

Feb17: 145 papers; >24,000 (ADS) citations

cnes

asi agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA — MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

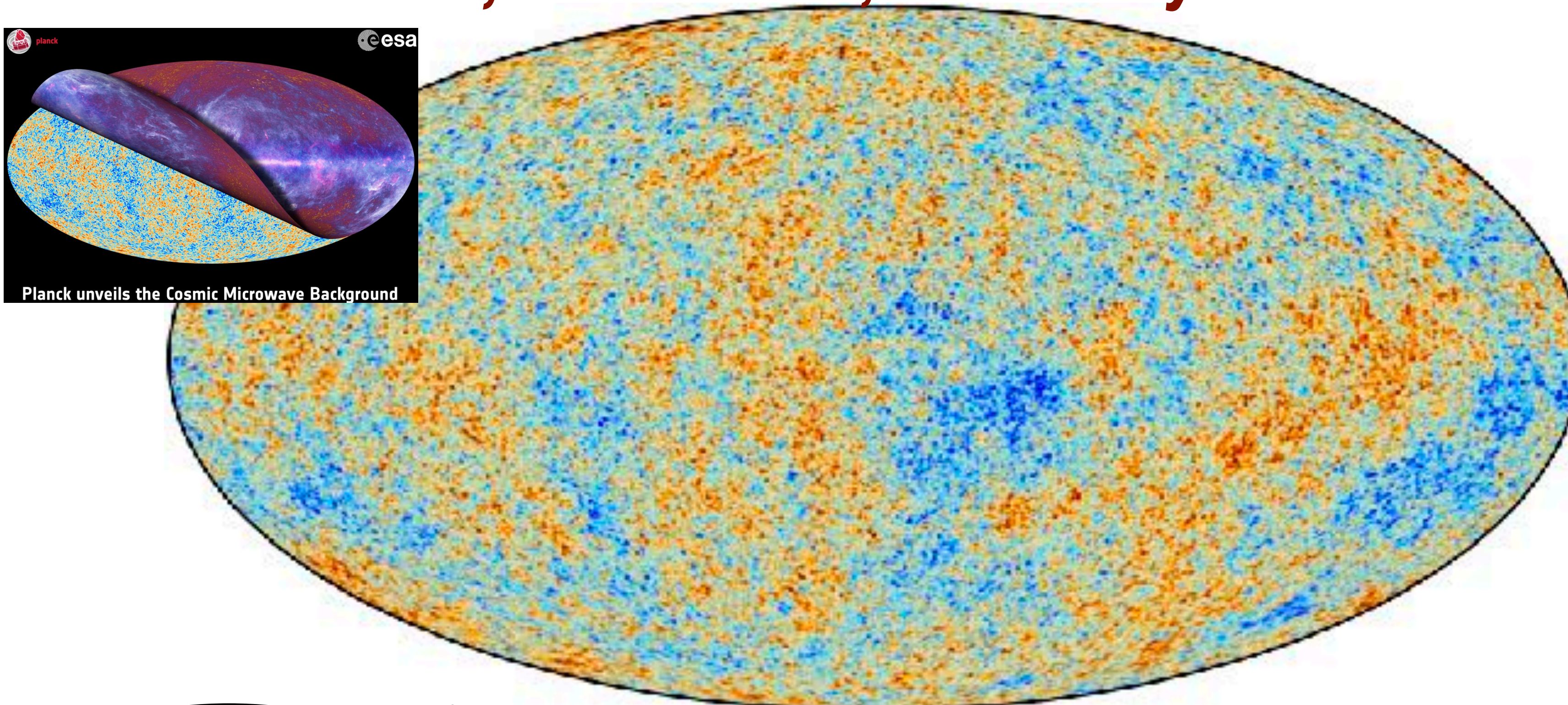
INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

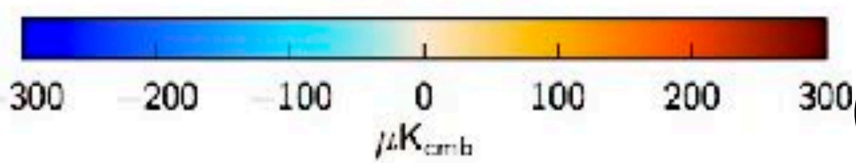
Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-16, 16-17-

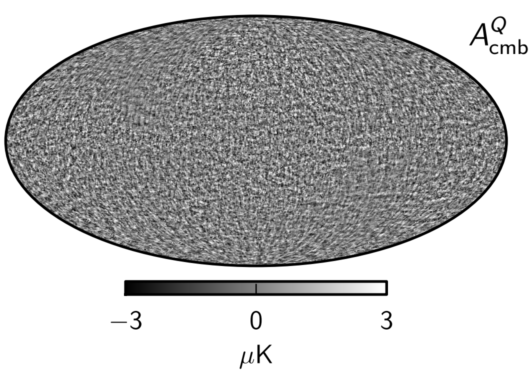
Planck's primordial light unveiled, *Mar 2013 => **Feb 2015** => pre-2016 => >jun 2017 final*

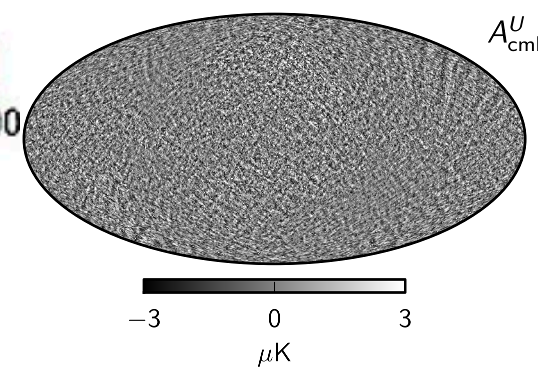
reveals the SIMPLICITY of primordial cosmic structure

7⁺ numbers, 3 densities, 2+1 early-Universe inflation









Temperature changes in micro-degrees

ζ- TOPOGRAPHY & CARTOGRAPHY

of our Hubble-patch bit of the early universe

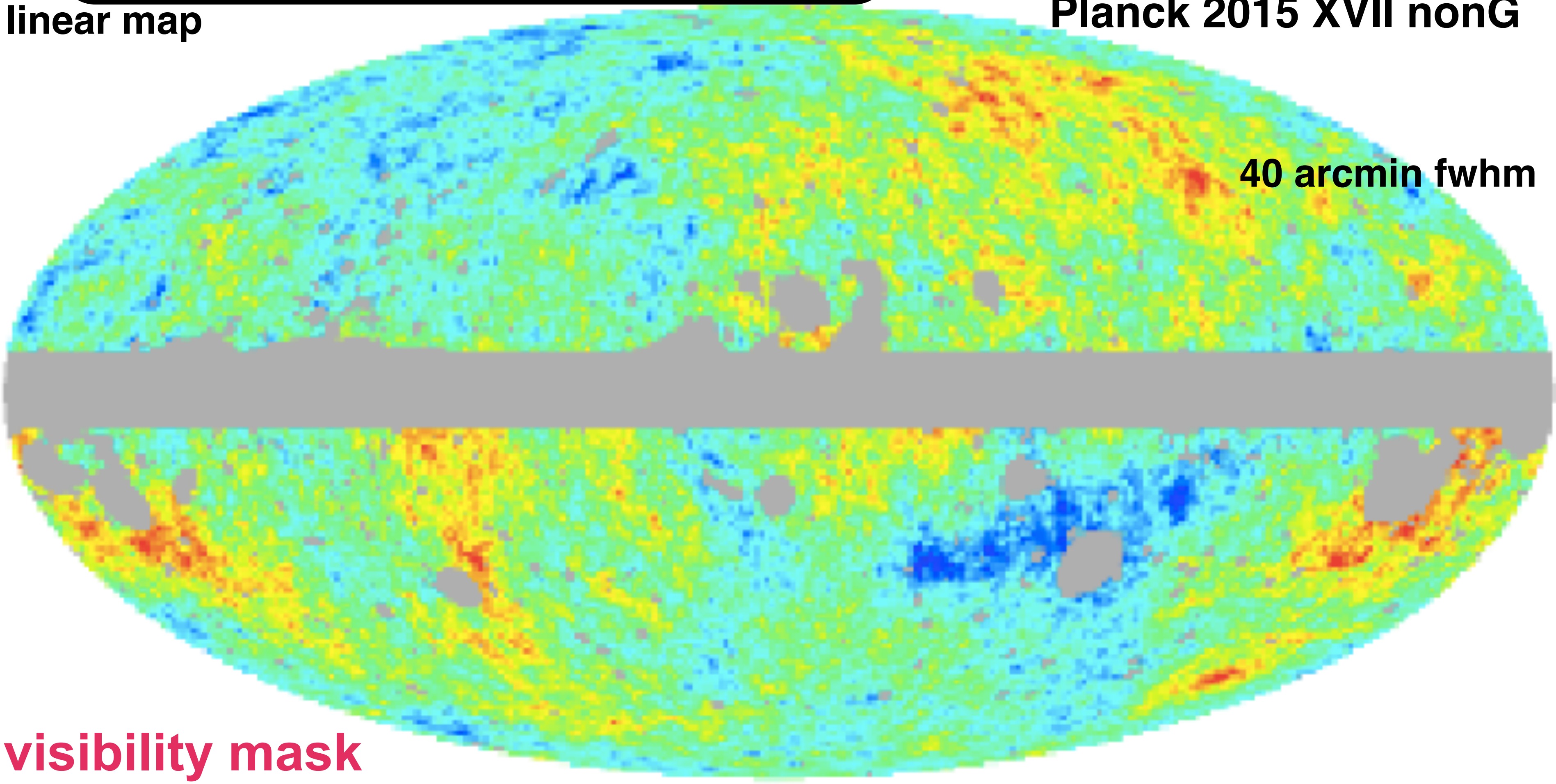
<ζ|Temp, E pol>

caution: not de-lensed, but the Wiener filter does partially de-lens

linear map

Planck 2015 XVII nonG

40 arcmin fwhm



visibility mask

$\int$d ***visibility***(*distance*) <ζ|Temp, E pol> *(angles, distance)*

$\langle \zeta_{LM}(\chi) | T_{LM} E_{LM} \rangle$

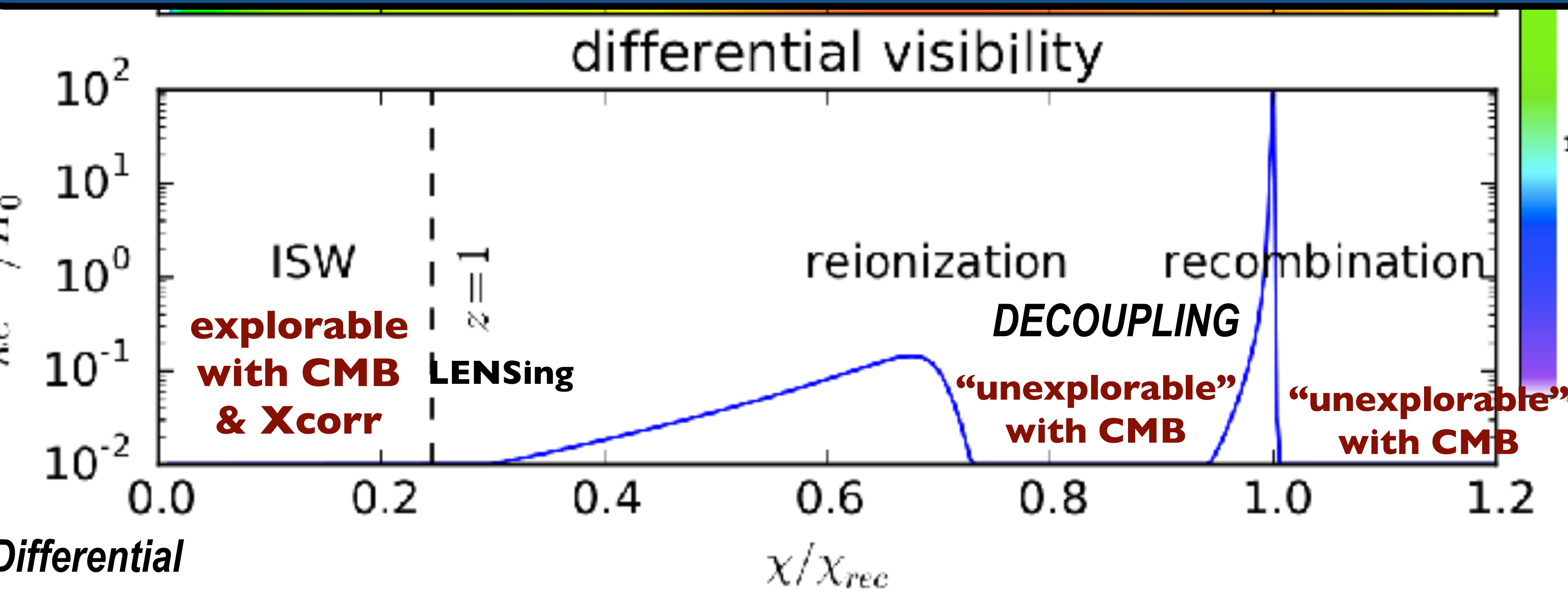
the unexplorable ζ-scape, explore with landscape++ ideas

our Hubble Bit will reveal all?

CMB *~10,000,000 T/E modes of tΛCDM*
≲500 modes of anomaly
≲100 modes reionization history

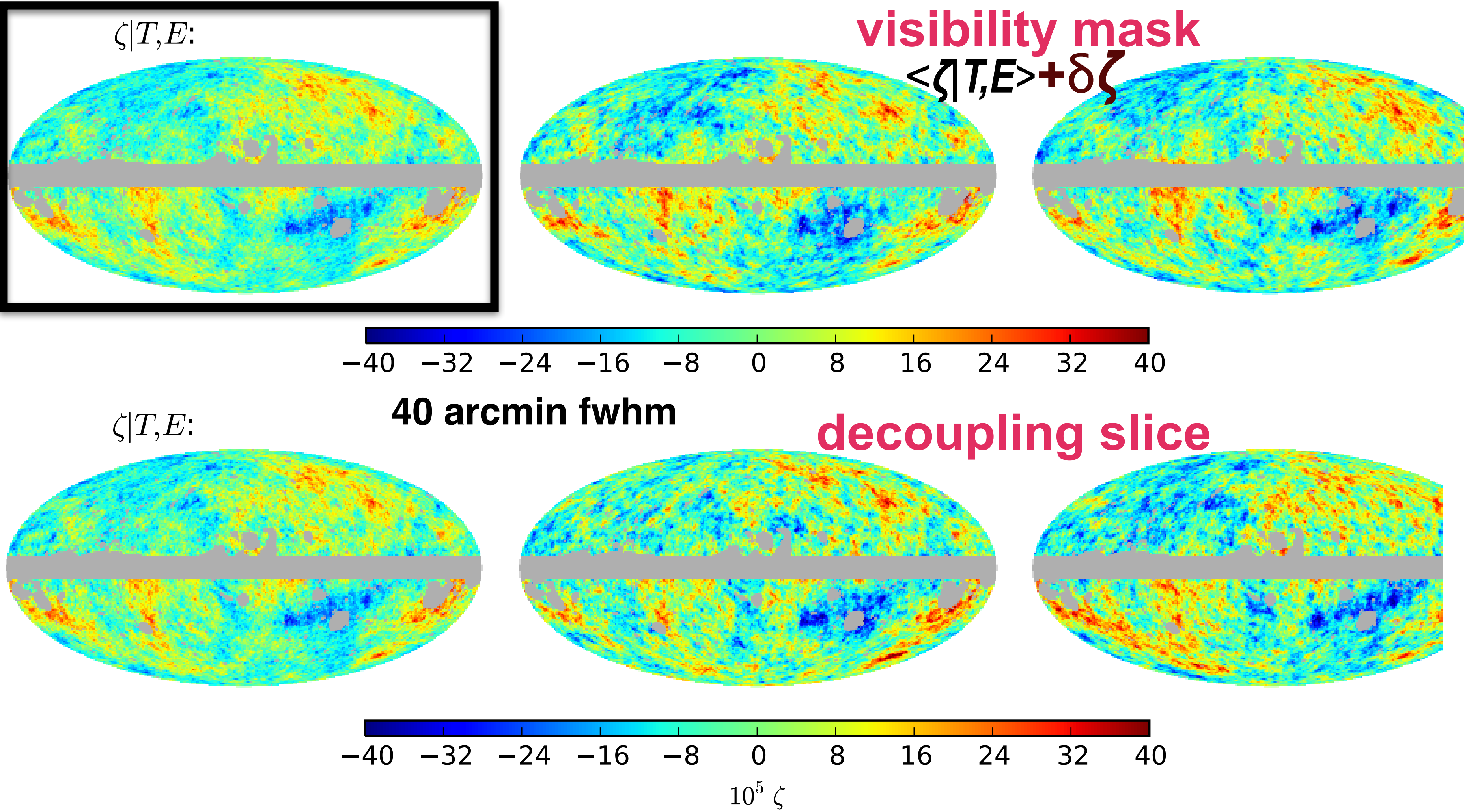
CMB modes
~ $f_{sky} L_{max}^2$

LSS tomography
X k_{max} d_{max}



Differential Visibility

limits to our knowledge



Maps = *(radical)* **compressions** *of the* ***time ordered information* ToI** ***onto***

a parameterized space q^A: *Linear maps, Quadratic maps (power), cosmic parameter maps*

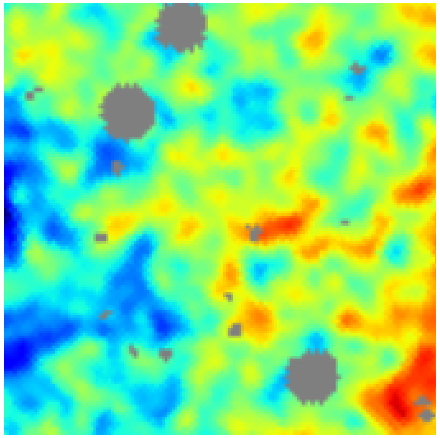
*a **Map** is an **ensemble = mean-map + fluctuation-maps**, **encoding correlated errors***

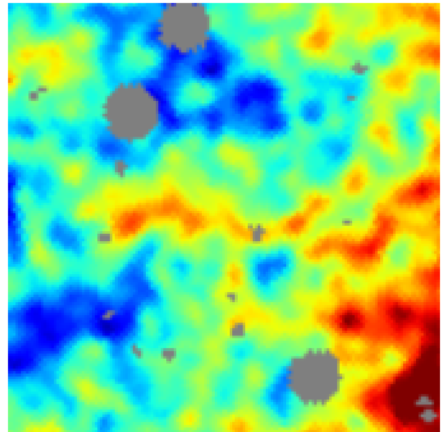
allowed fluctuations are less noisy with T +E-pol (extra mode/LM)

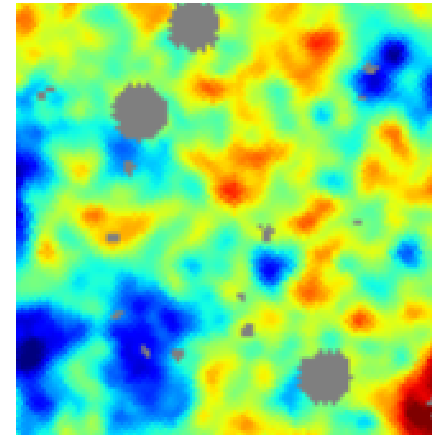
Planck 2015 XVII nonG

$\zeta|T,E$:

visibility mask





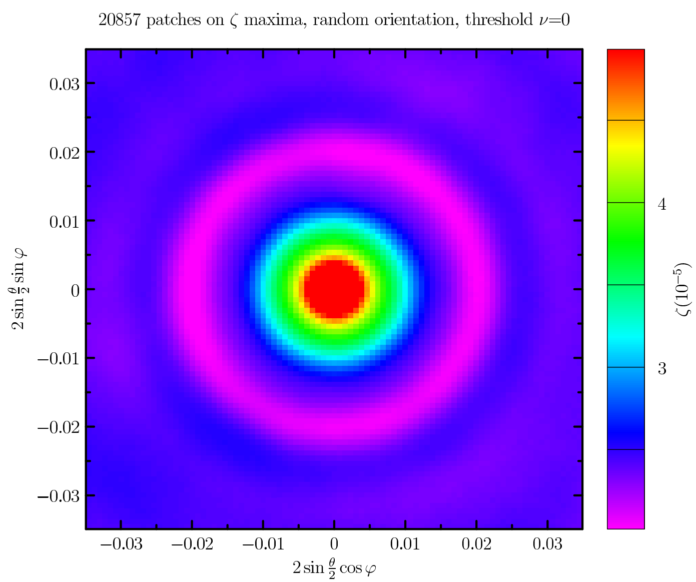


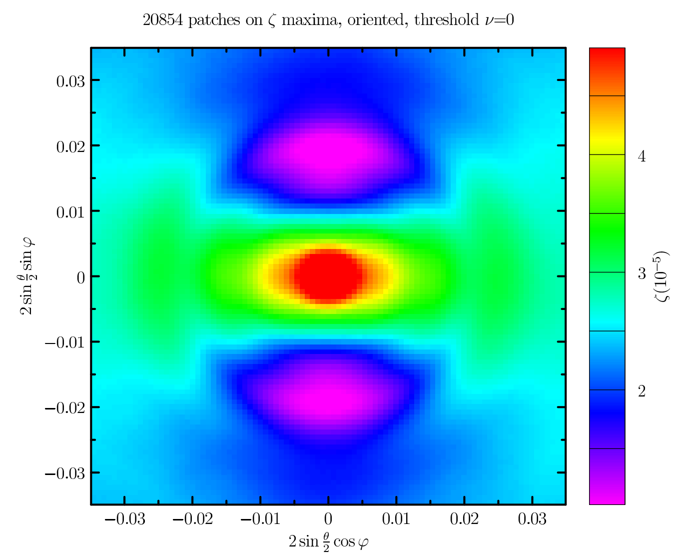
20x20 sq deg

zoom in, higher res: 20 arcmin fwhm

stack to damp fluctuations

$<\zeta|\zeta_{pk}>|_{dv}$



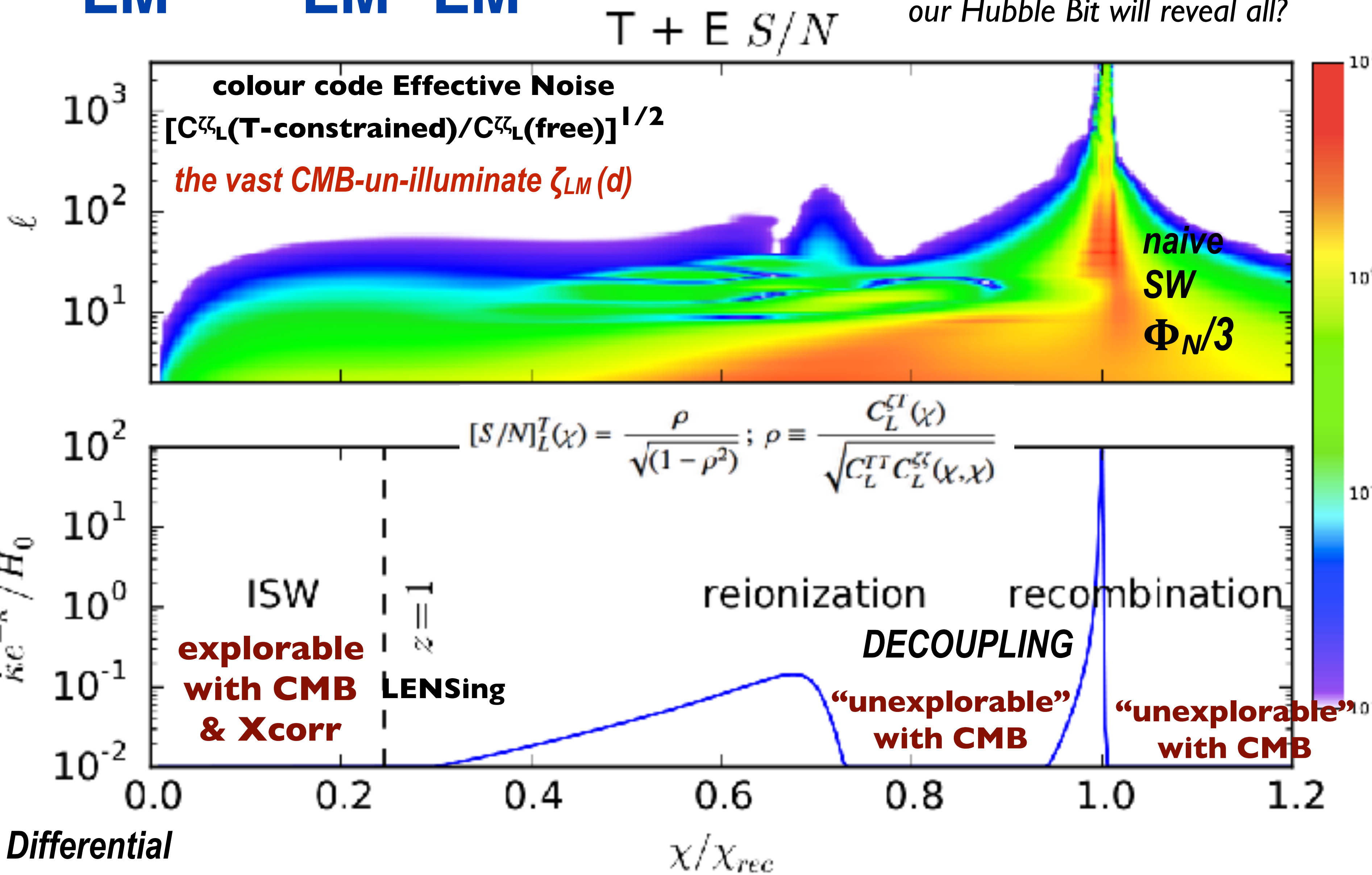


oriented stacks, etc.

$\langle \zeta_{LM}(\chi) | T_{LM} E_{LM} \rangle$

the unexplorable ζ-scape, explore with landscape++ ideas

our Hubble Bit will reveal all?



limits to our knowledge

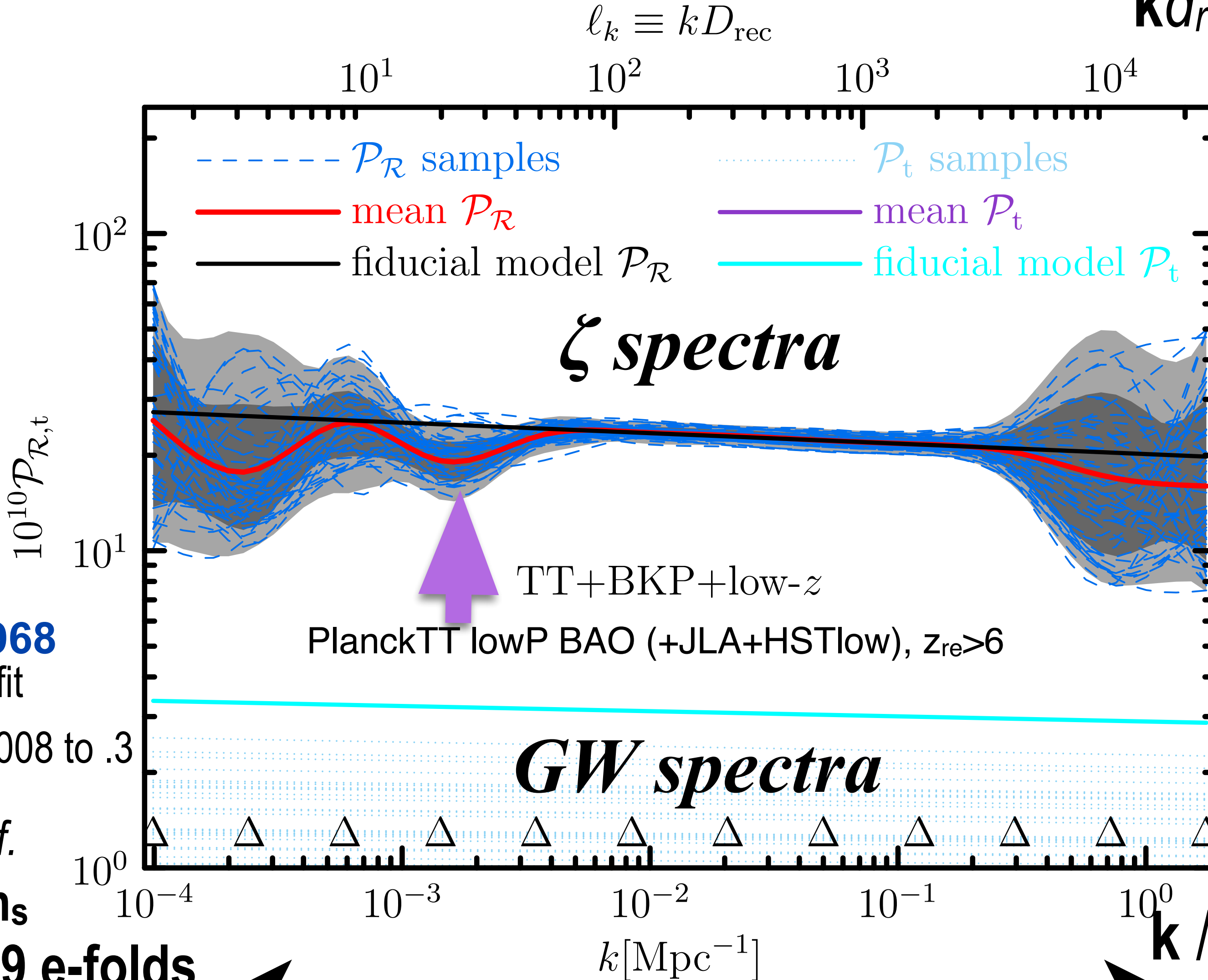
Planck 2015 XVII nonG

quadratic map of the ζ-**scape**

Planck 2015 XX inflation

CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip; *includes CMB lensing, parameter marginalization*

kd_{rec} ≳ L



EE (L>30) looks similar

=> V(*ϕ*)

uniform **n_s=0.968**
P15+LSS best fit

superb 12-knot fit k~ .008 to .3

r<.11 95%CL *cf.*
r<0.09 uniform n_s

9 e-folds

k /Mpc

Beyond the Standard Model of cosmology? SMc = *tilted*ΛCDM +r (ζ, h_{+x})

BSMc = SMc + primordial anomalies

std nonG $\zeta = \zeta_G + f_{NL}*(\zeta_G^2 - \langle\zeta_G^2\rangle)$ local & equilateral pattern & orthogonal
non-std nonG $\zeta = \zeta_{inflaton}$ + ***uncorrelated*** $\zeta_{[GRF\}}$ modulated heating intermittent?

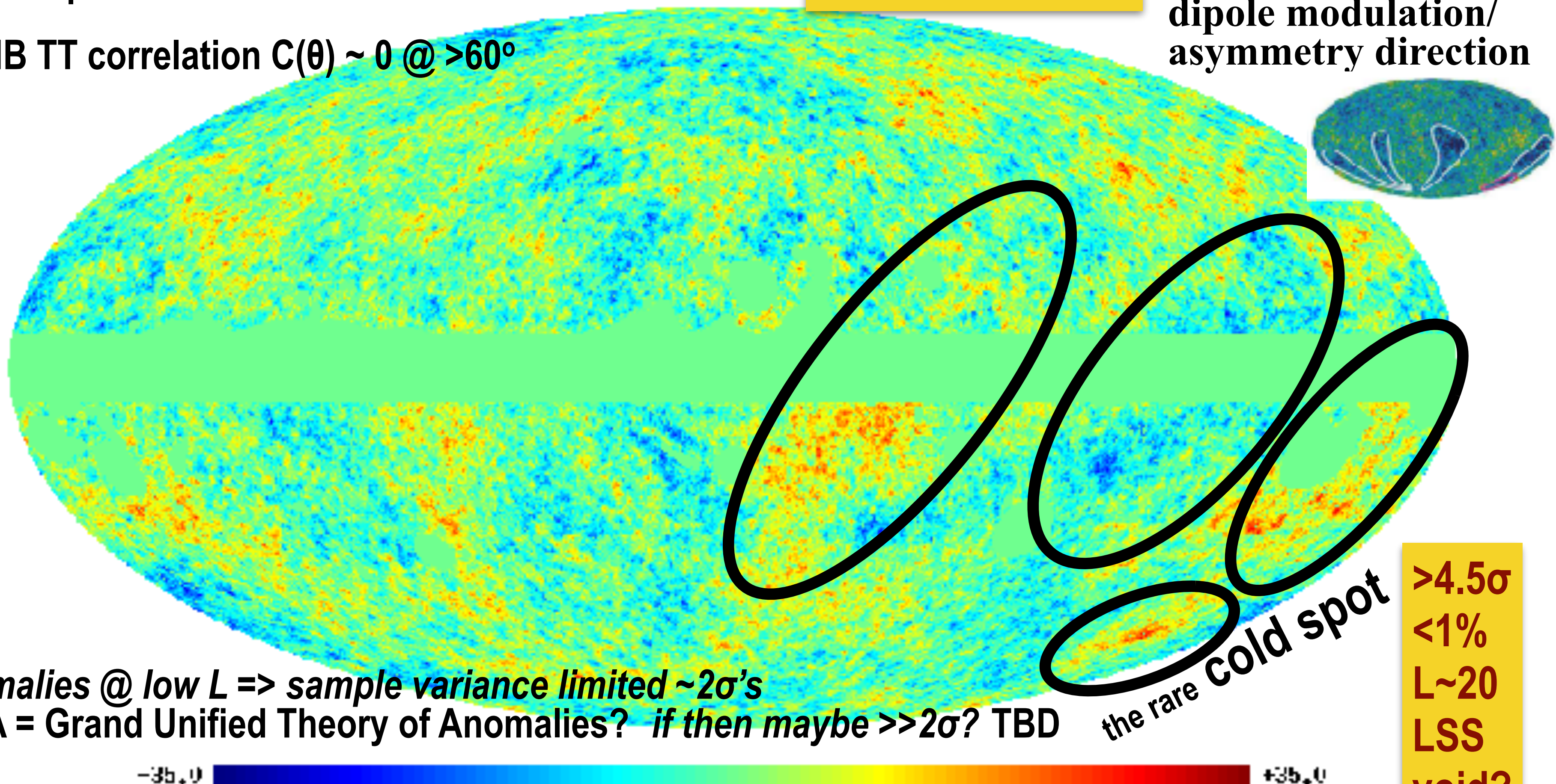
CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip
hemisphere difference ~7% at low resolution

CMB TT correlation C(θ) ~ 0 @ >60°

<ζ |*T,E-pol*>

octupole/quadrupole alignment

dipole modulation/ asymmetry direction

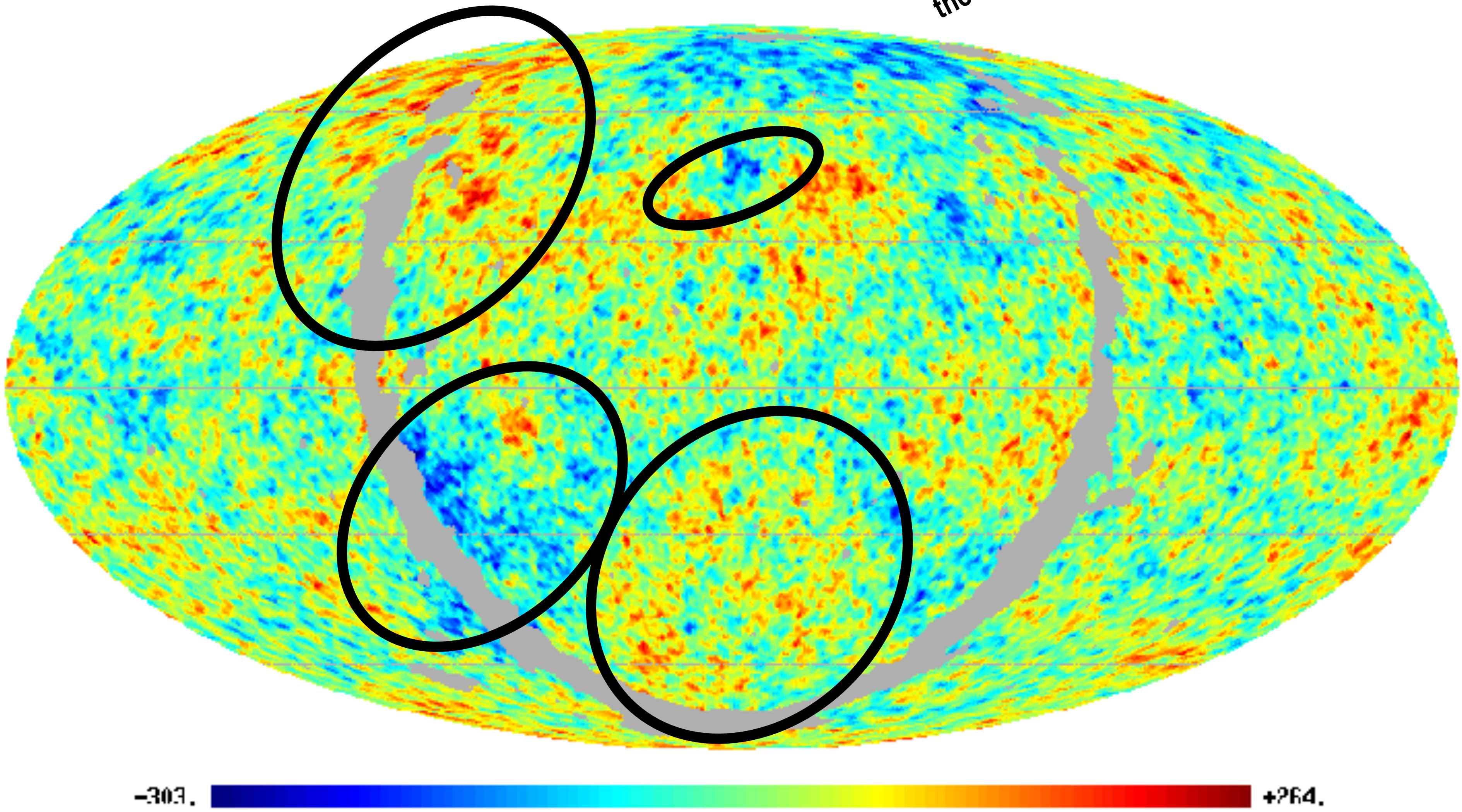


anomalies @ low L => sample variance limited ~2σ's
GUTA = Grand Unified Theory of Anomalies? *if then maybe >>2σ? TBD*

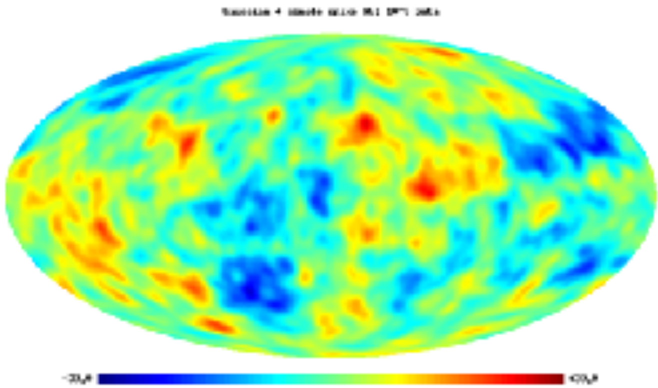
>4.5σ
<1%
L~20
LSS
void?

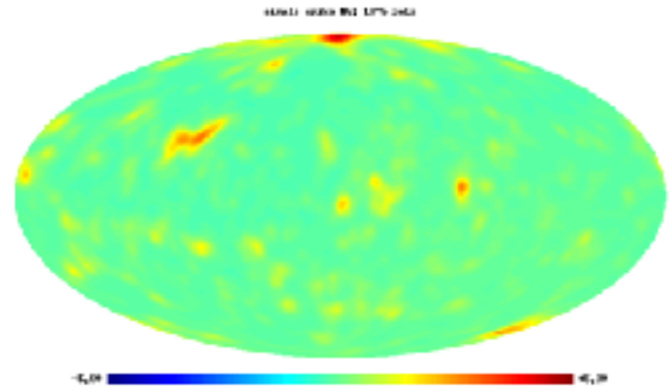
BFH, b+frolov+huang

the rare **cold spot**



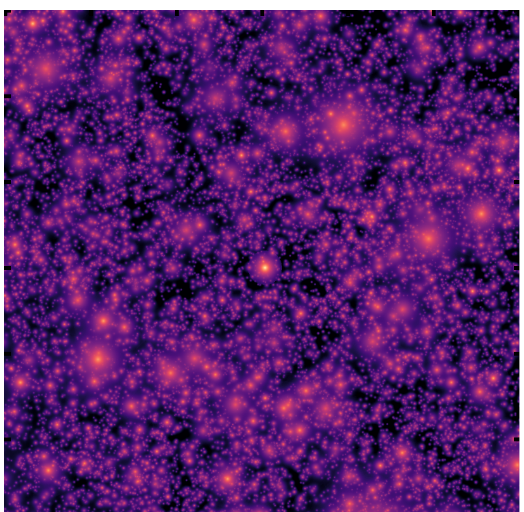
CMB+LSS mocks to test: standard Gaussian inflaton ζ_{inf}+ subdominant uncorrelated ζ_{isoc}
e.g., ***from modulated preheating by isocons***





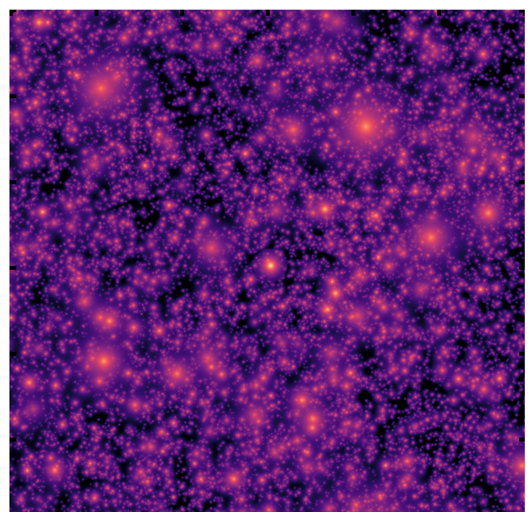
uncorrelated nonG ‘wide open’ cf. usual correlated highly constrained nonG

LSS tSZ: Gaussian std



B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std +
subdominant uncorrelated ζ



ABSB+FH, alvarez+b+stein+frolov+huang

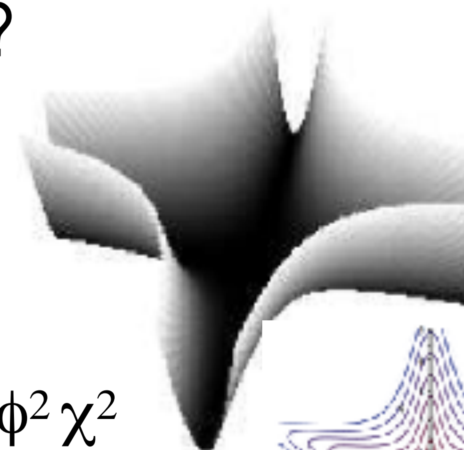
what is the **inflaton's potential**?

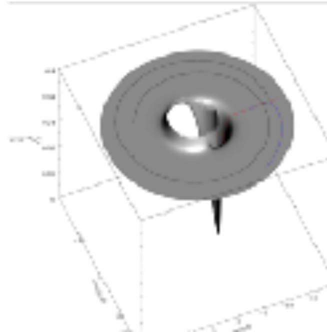
around a minimum is the heating question

how was *matter & entropy* generated at the end of *acceleration = inflation*?

Relate to Higgs & standard model?

2 filament?

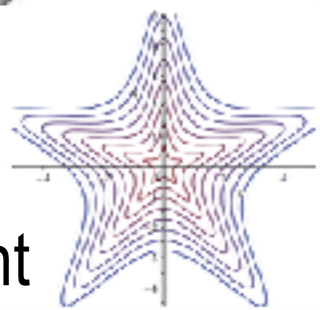




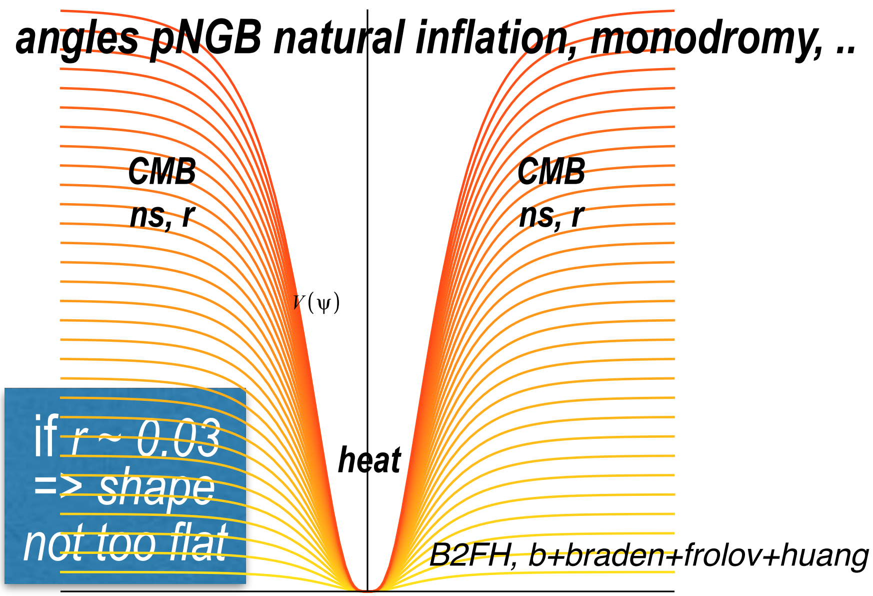
4 filament

$1/4\lambda\phi^4 + 1/2 g^2 \phi^2 \chi^2$

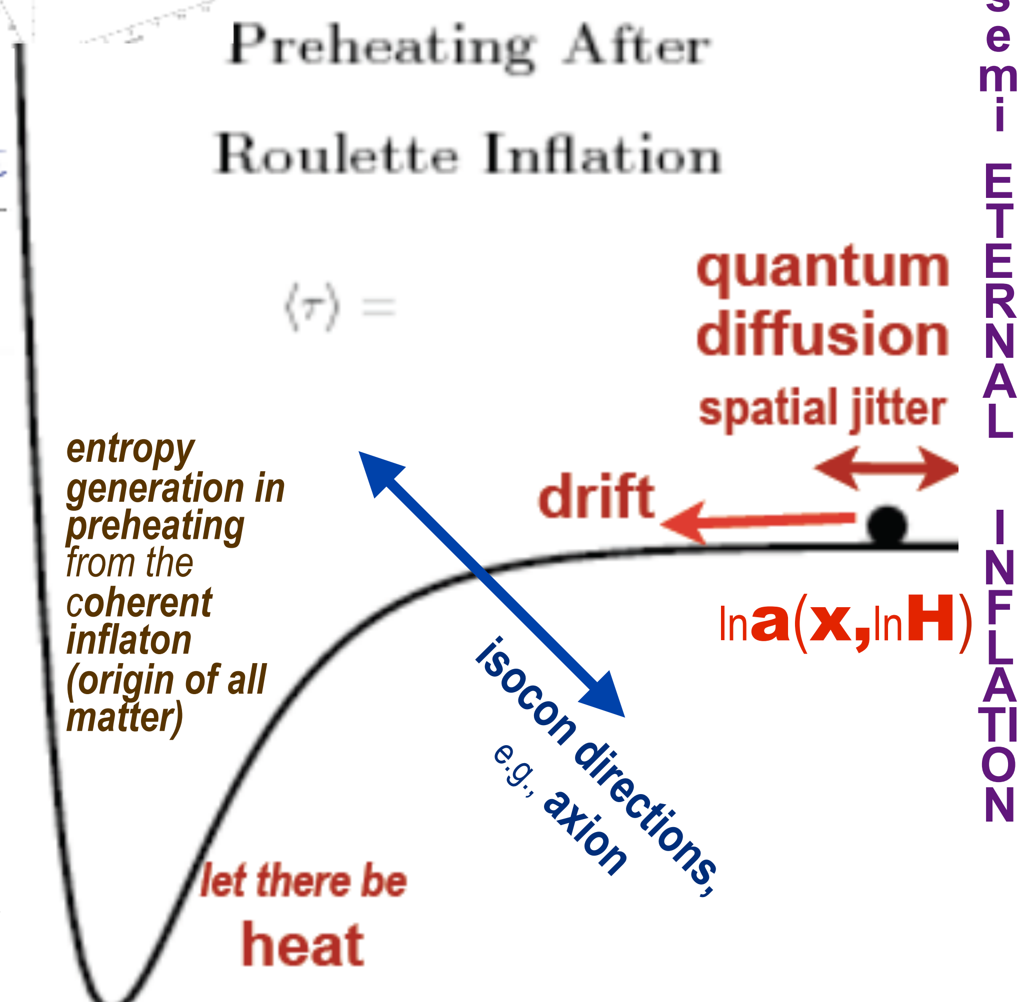
3-filament   5-filament

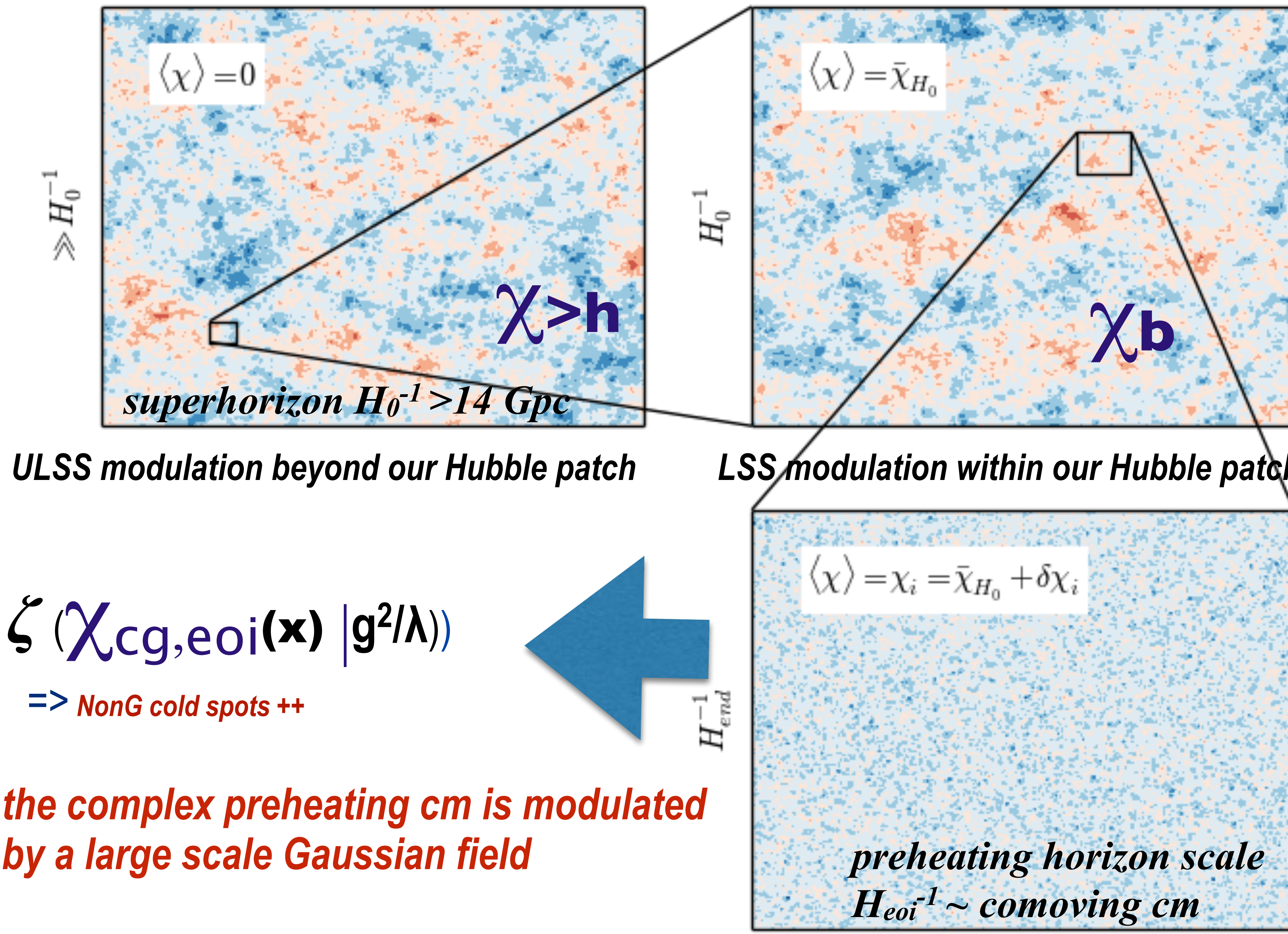


angles pNGB natural inflation, monodromy, ..



conformal potential-flattening eg Higgs inflation *SBB89 etc*



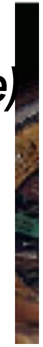


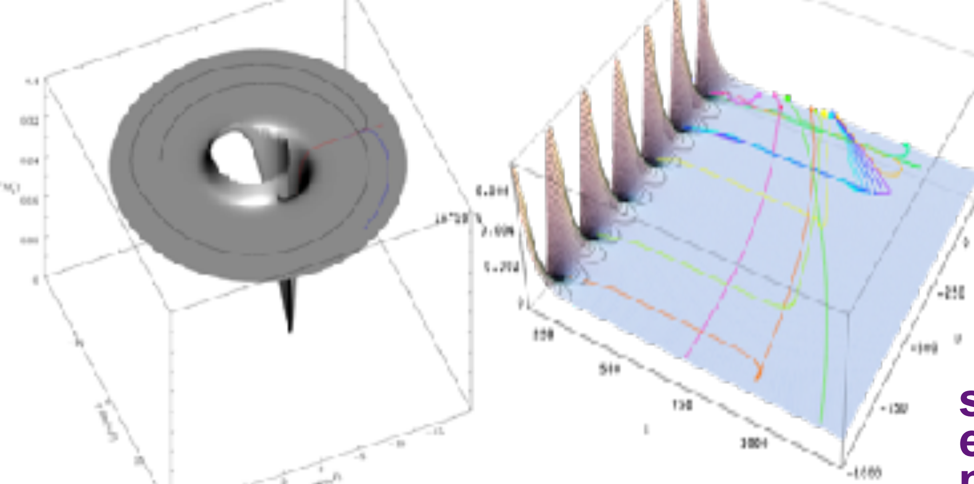
$\langle\chi\rangle = 0$
$\gg H_0^{-1}$
χ>h
superhorizon H_0^{-1} >14 Gpc
ULSS modulation beyond our Hubble patch
$\langle\chi\rangle = \bar{\chi}_{H_0}$
H_0^{-1}
χb
LSS modulation within our Hubble patch
$\langle\chi\rangle = \chi_i = \bar{\chi}_{H_0} + \delta\chi_i$
H_{end}^{-1}
preheating horizon scale
H_{eoi}^{-1} ~ comoving cm
$\zeta\,(\chi_{cg,eoi}(\mathbf{x})\ |g^2/\lambda))$
=> NonG cold spots ++
the complex preheating cm is modulated
by a large scale Gaussian field

single field V heating slow, oscillating

but shaped V can give rapid heating (roulette)

Barnaby,Bond,Huang,Kofman09

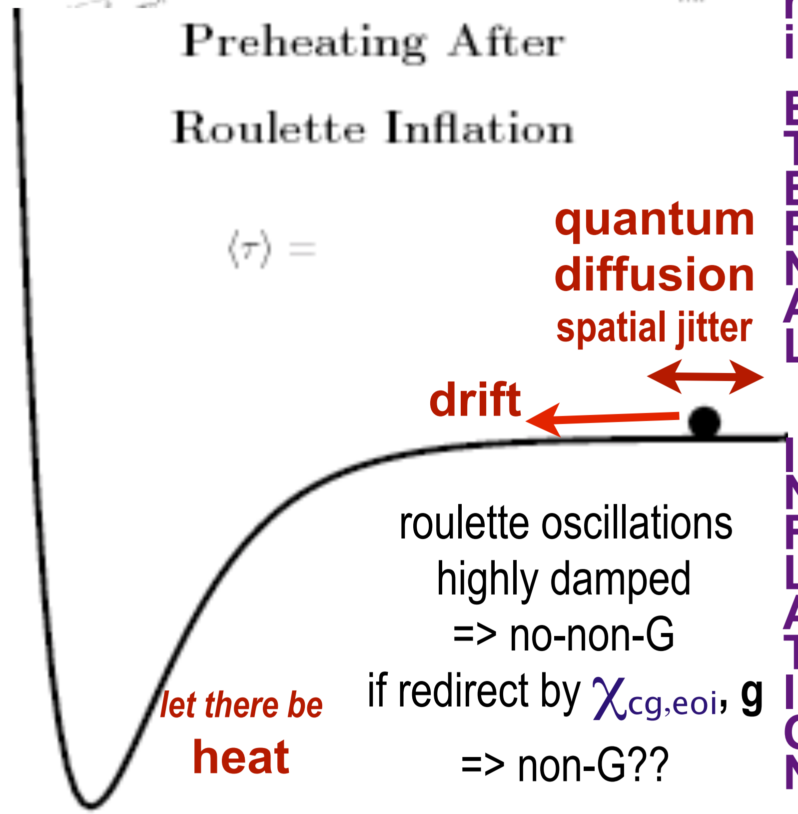


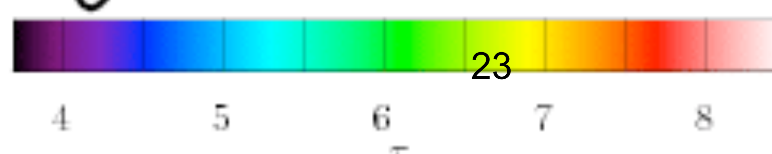


$a = \quad 1$

A visualized 2D slice

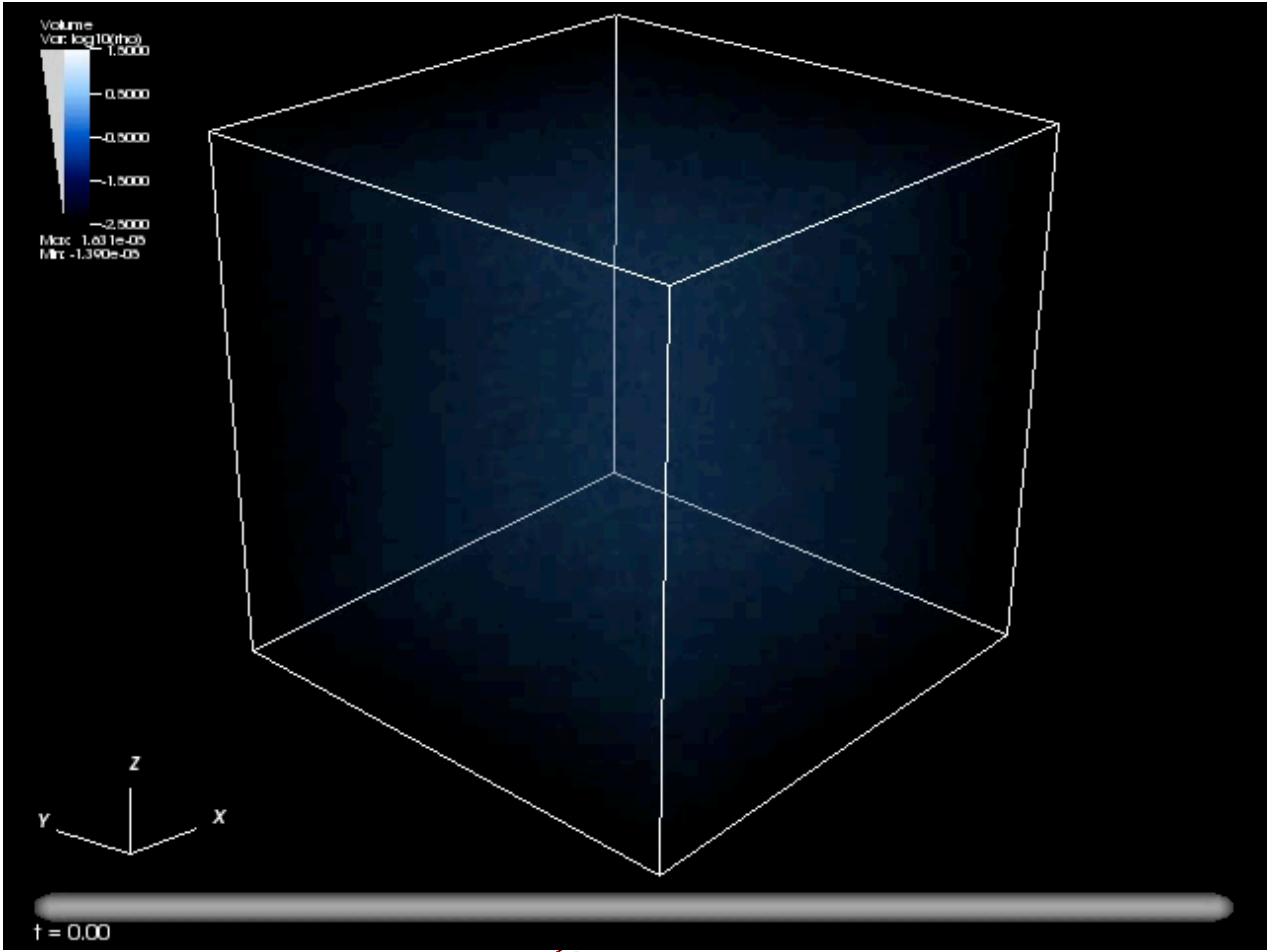
in lattice simulation





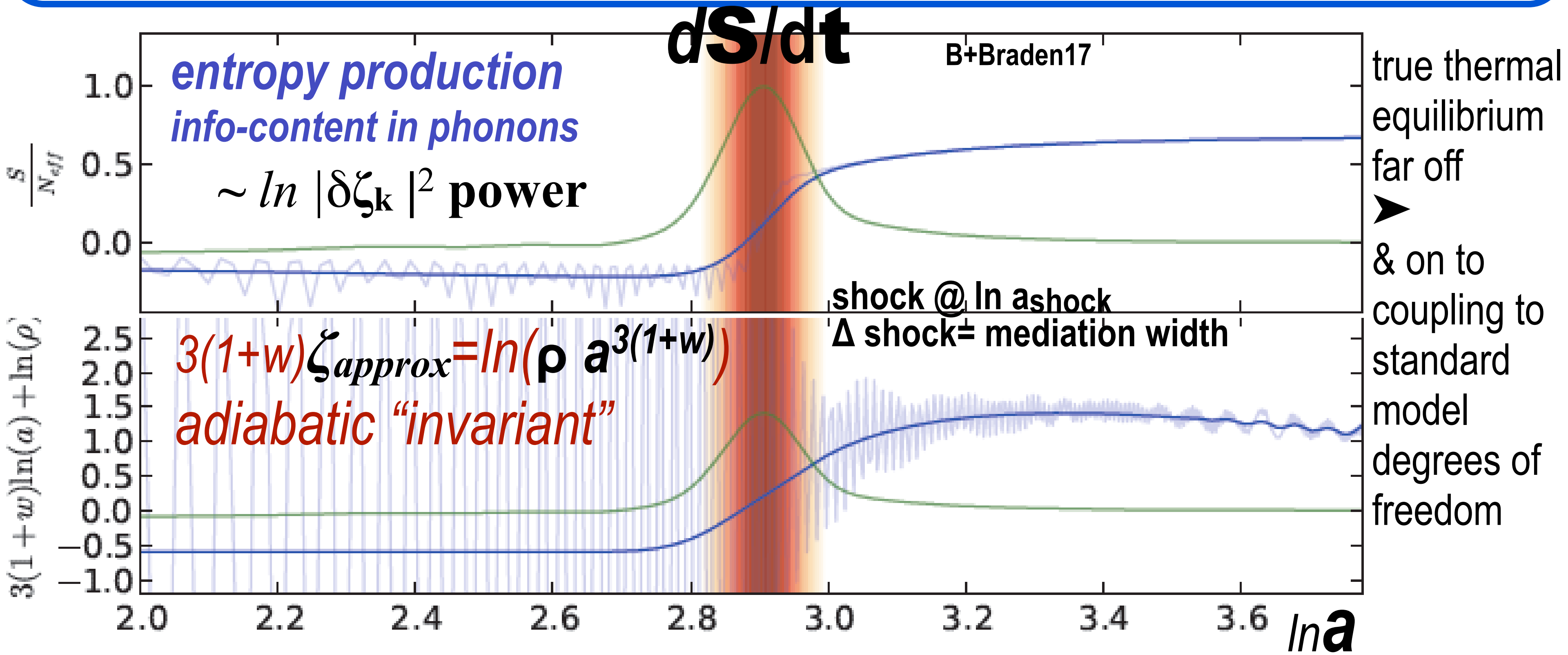
www.youtube.com/watch?v=FW__su-W-ck&NR=1

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



***log-normal pdf (density** aka ζ**)**, in k-bands too; normal pdf (velocity)*

nonG from large-scale modulations of the shock-in-times of preheating



coarse-grain $\langle\zeta\rangle$ <=> fine-grain $\delta\zeta_k$ gradients, δV

$$\zeta_{final}(x,t_f\,|\chi_{cg,eoi}(x),g^2/\lambda) \sim \zeta_{shock}$$

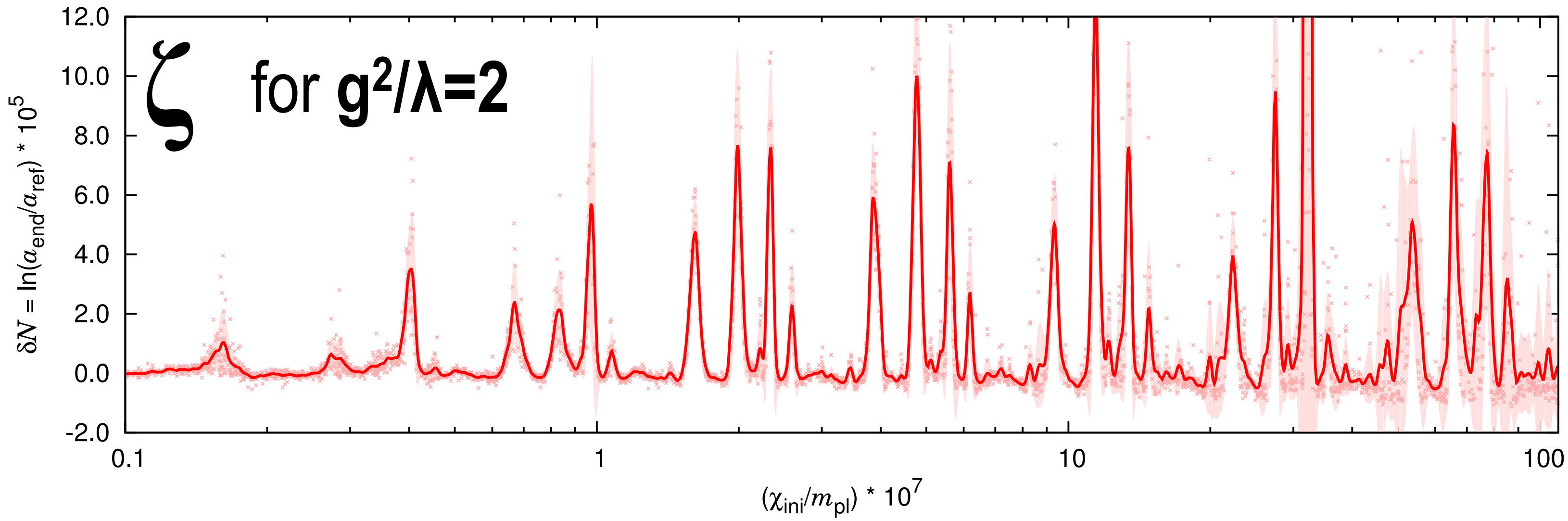
$$V(\phi,\chi)=1/4\,\lambda\phi^4+1/2\,g^2\phi^2\chi^2$$

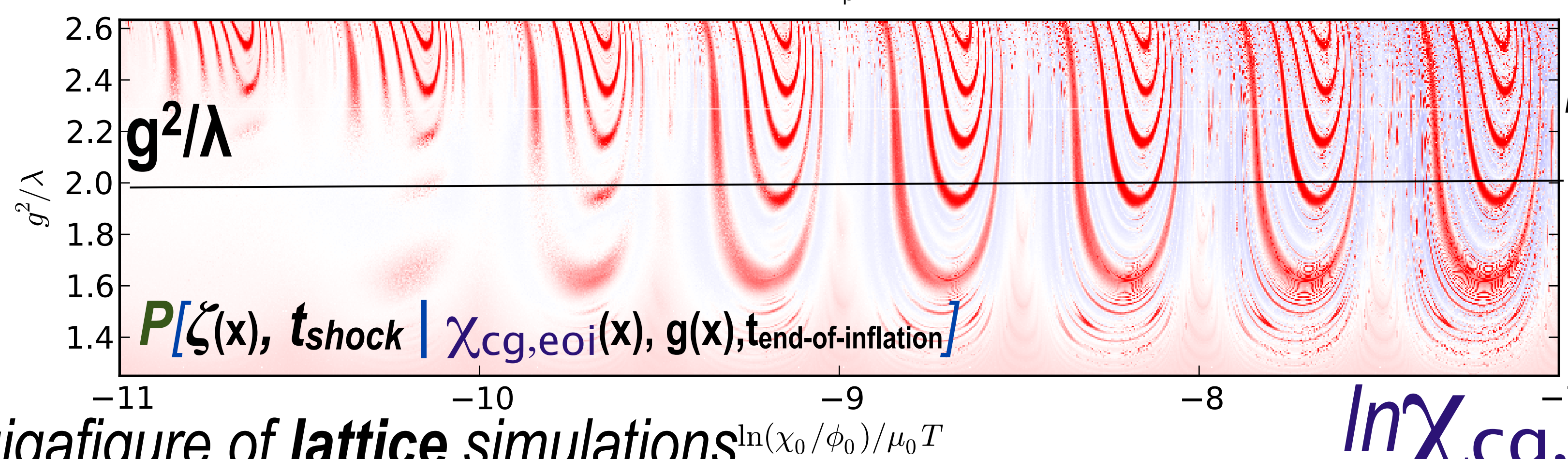
$dS/dt(t,g)$ => *the Shock-in-time: entropy production rate*

$\zeta_{shock}(\chi_{cg,eoi}(x) \,|\, g^2/\lambda)$ => ***Chaotic Billiards: NonG from Parametric Resonance in Preheating***

B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 17

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





computational tour de force

huge number of 64^3 sims to show the wondrous complexity of

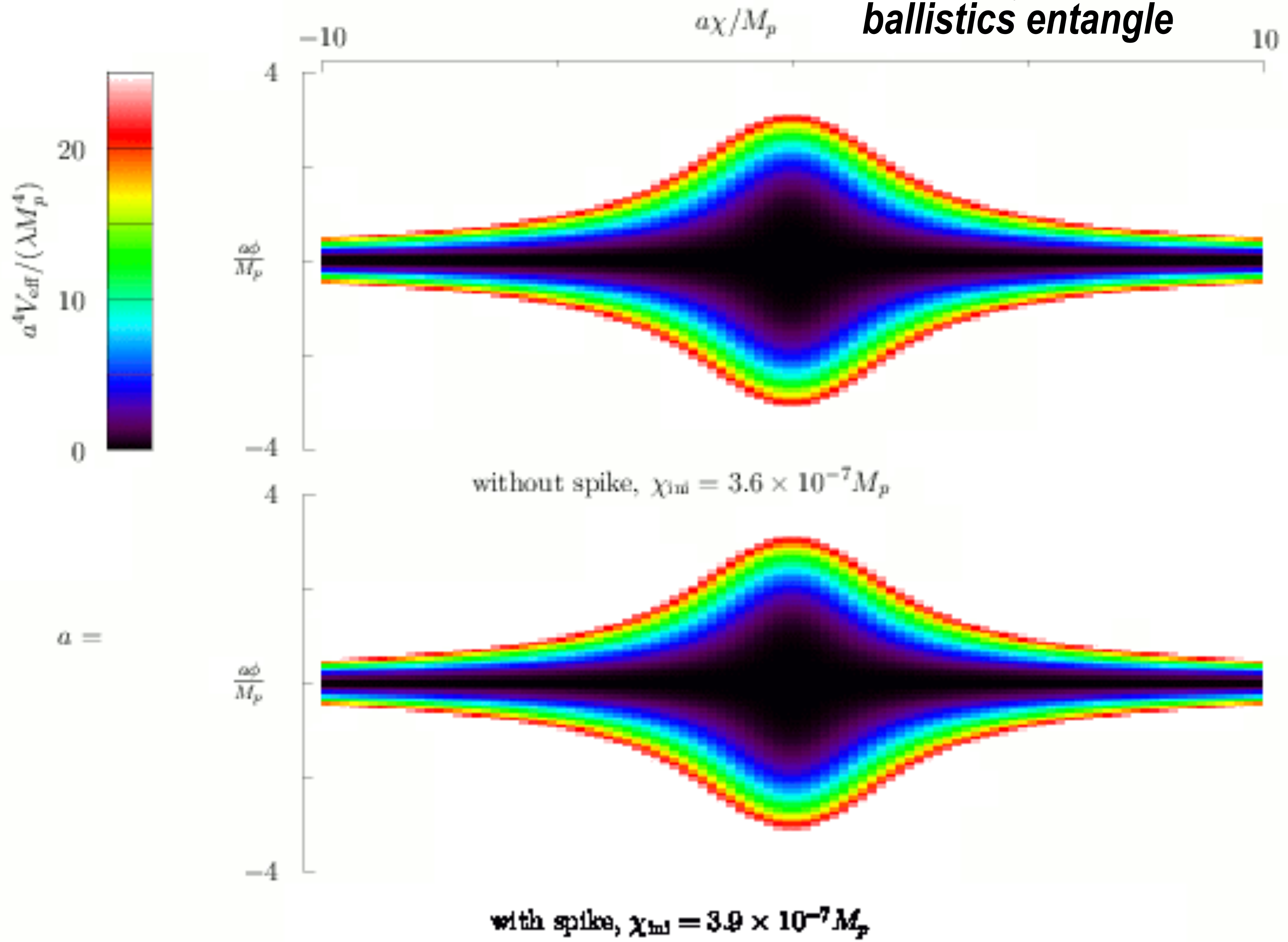
$\zeta(\chi_i, g^2/\lambda)$

*gigafigure of **lattice** simulations*

$\ln \chi_{cg,eoi}$

full lattice simulations of coarse-grained k~0 trajectories ($\chi_{cg,eoi}$)

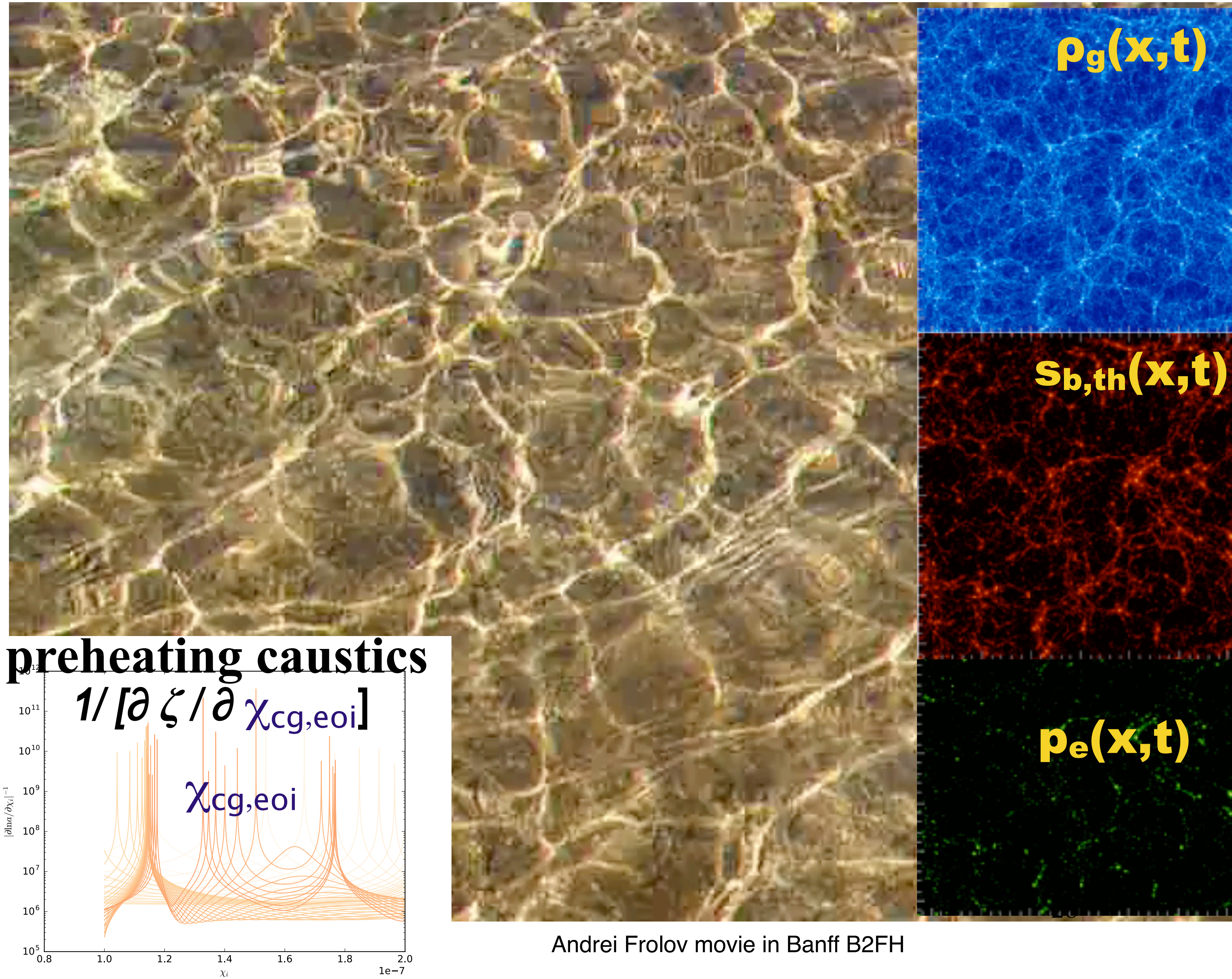
ballistics entangle



(nonlinear) **V_{eff} is trajectory-bundle dependent**

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

caustics are ubiquitous: **LSS/cosmic web & preheating**



Andrei Frolov movie in Banff B2FH

cm-scale **coarse-grained** k~0

“ballistic” trajectories

become **entangled** *with fluctuations*

aka sub-cm **k-modes** *in a coarse-grained*

*non-equilibrium-***entropy***-generating*

shock-in-time

& on to the quark/gluon plasma **StandardModel-pp**

$\delta\zeta_{\mathbf{k}}$ **&** $\mathit{ln}[\rho/<\rho>]_{\mathbf{k}}$ are **nearly Gaussian within a preheating horizon:** *shown by* **B+Braden17 lattice simulations for probability distribution functions in k-bands, and smallness of the 3 pt,** ***etc.*** (!!!)

caustics in $\langle q^A \rangle$ *ballistic* orbits

$\langle \delta q^A\ t2 \mid \delta q^B\ ti \rangle \sim \exp(\mathcal{E}(t2 \mid t1)) \langle \delta q^A\ t1 \mid \delta q^B\ ti \rangle$

early U parameters: **final φ, Π_φ, χ, Π_χ, *ln* a, ln ρ, initial $\chi_{cg,eoi}$, *couplings* g, λ, ..**

parameter strain tensor $\mathcal{E}(t2 \mid t1)$

d$\mathcal{E}$/dt strain rate ~ local Lyapunov coefficients *Floquet instability charts*

instability to have nearby parameters diverge => chaotic billiards

Kolmogorov-Sinai entropy: ~ Sum of positive evalues of d$\mathcal{E}$/dt

small $\mathcal{E}$ eigenvalues=> coherent trajectory bundles (for a time)

= caustics (inverse -> ∞) **1/ [$\partial \zeta / \partial \chi_{cg,eoi}$]**; => peaks in $\zeta(\chi_{cg,eoi})$

stopping time **tstop** ($\chi_{cg,eoi}$) when $\mathcal{E}$ evalues get large <=> local gradients $\Uparrow$

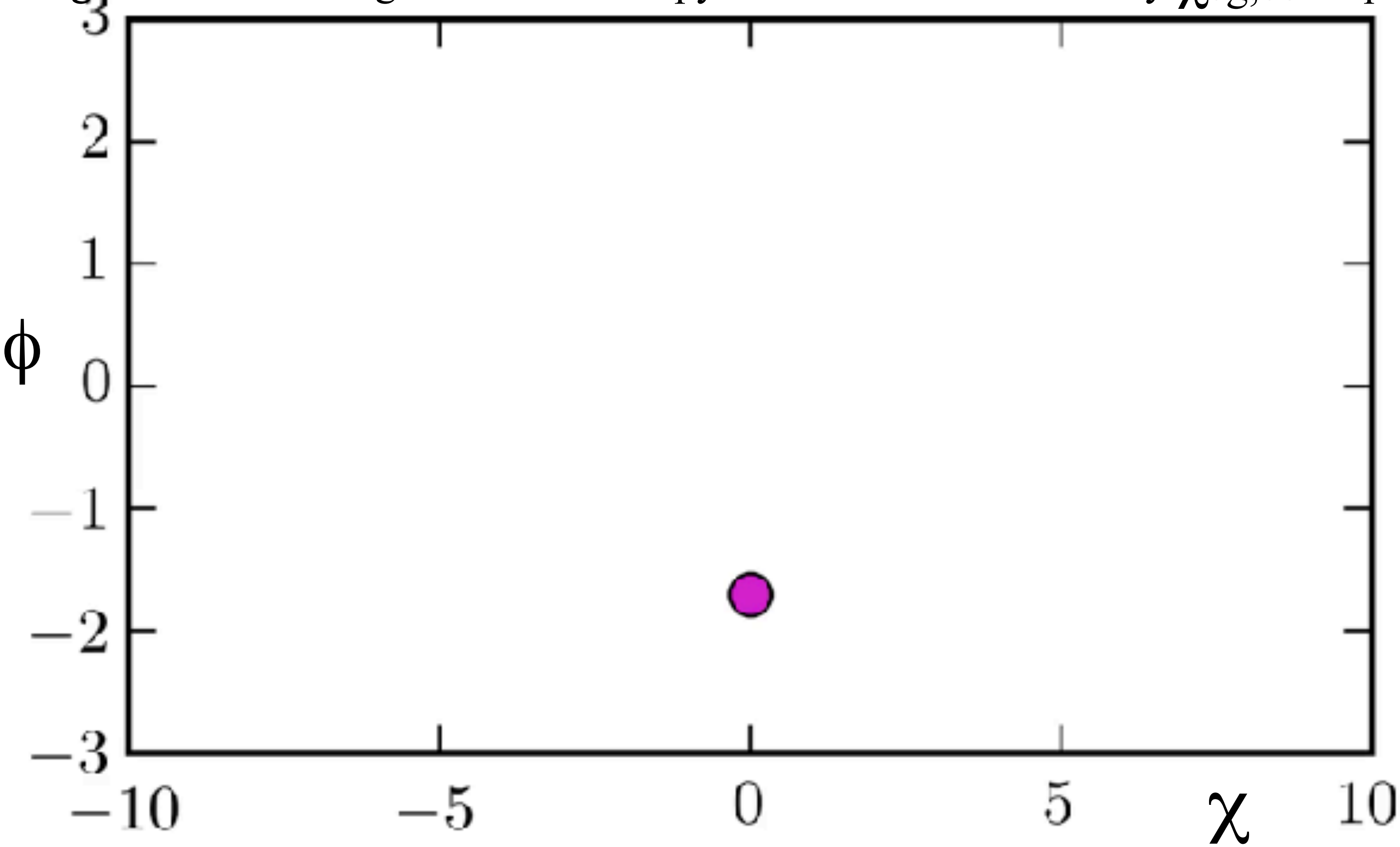
cf. LargeScaleStructure: final Eulerian position <= initial Lagrangian position

1LPT aka Zeldovich: $\partial x/\partial r = \exp(\mathcal{E})$ -> 0 density $\rho \sim \exp(-\mathrm{Tr}(\mathcal{E}))$ -> ∞

ballistic billiards k=0 mode phase space string evolution

2D constrained distribution functions

stopping criterion when coarse-grained entropy of field variables rises <=> strain ε high,
ie when integral of the Kolomgorov-Sinai entropy reaches a threshold - very $\chi_{cg,eoi}$ dependent

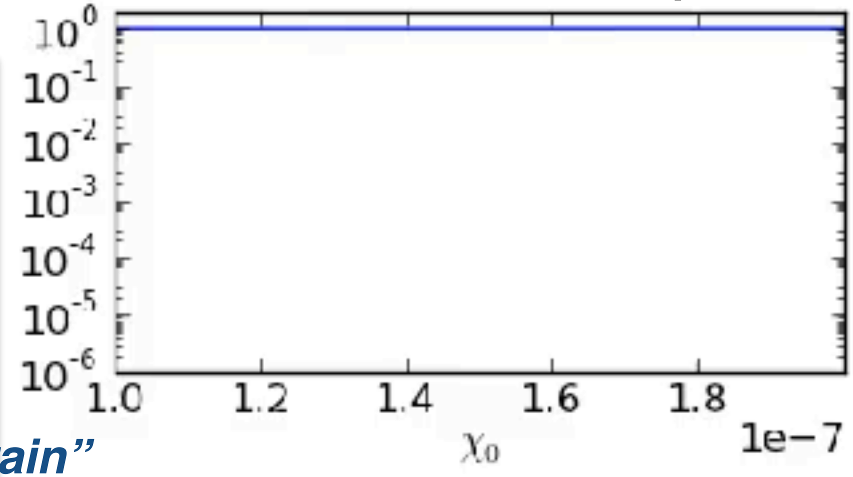


$V = 1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$

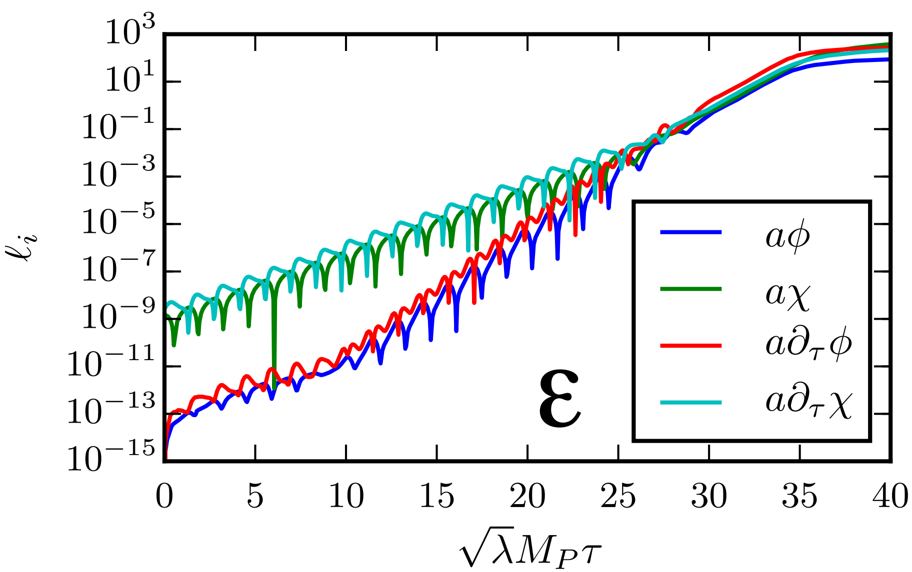
phase space strings

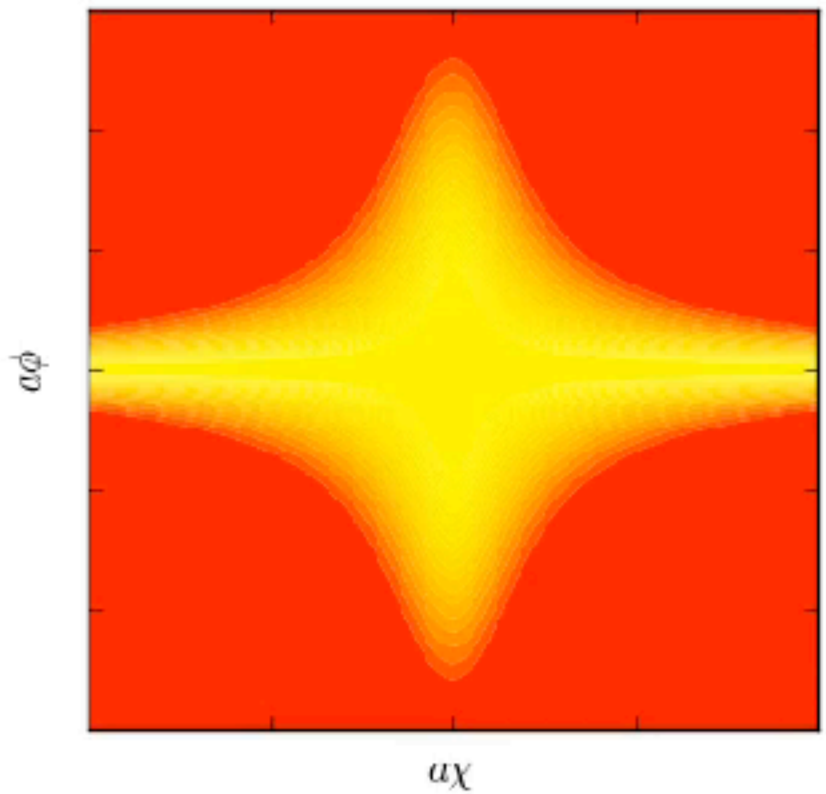
caustics are ubiquitous

2D constrained distribution functions



phase string growth in time "parameter strain"
integral of Kolmogorov-Sinai entropy





=> 3D constrained distribution functions

B2FH, b+braden+frolov+huang

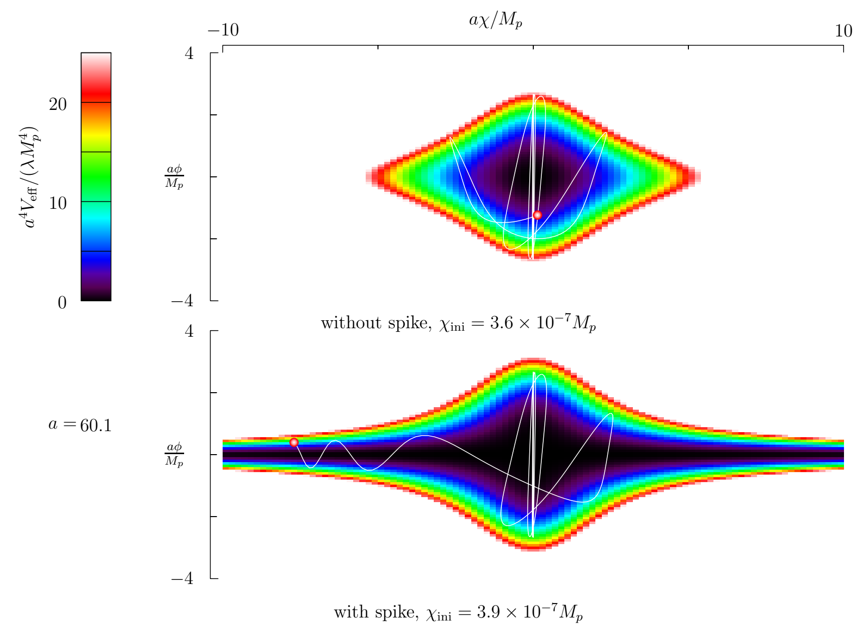
understanding the ζ -spike structure, qualitatively YES quantitatively in Progress

B[2]FH 17

arresting the orbits via a shock-in-time, incoherent cf. coherent (caustic) trajectory bundles

incoherent

coherent



how generic will caustic preheating be? structure around potential minima:

=> ‘filamentary’ potentials

=> ballistic flow channels

multi-filaments may lead to caustics

2 std inflaton, slow heating? roulette V is fast. 3-star

4 case workhorse. *the* ***5-star… ‘axionic' angles works with conformal flattening of V(ϕ_A) +***

cf. filaments that join at clusters in the LSS web

how modulated caustics in preheating could give observable intermittency

via isocon power on large & super-horizon scales

=>*light particles* (χ_{eoi} (x), couplings g(x), ...)

these isocons are active, NOT spectators

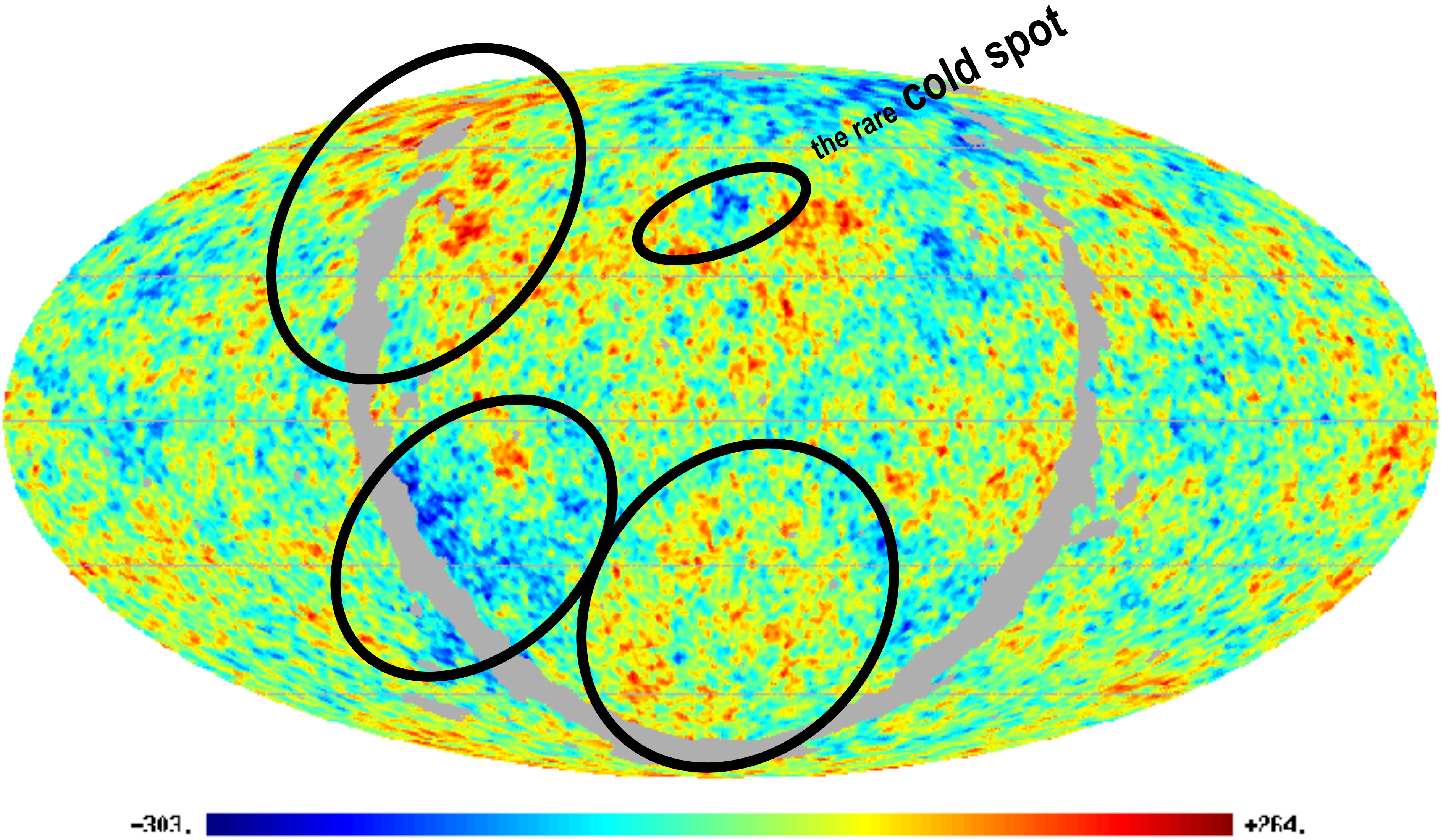
looking at the CMB cold spot again as an anomaly example

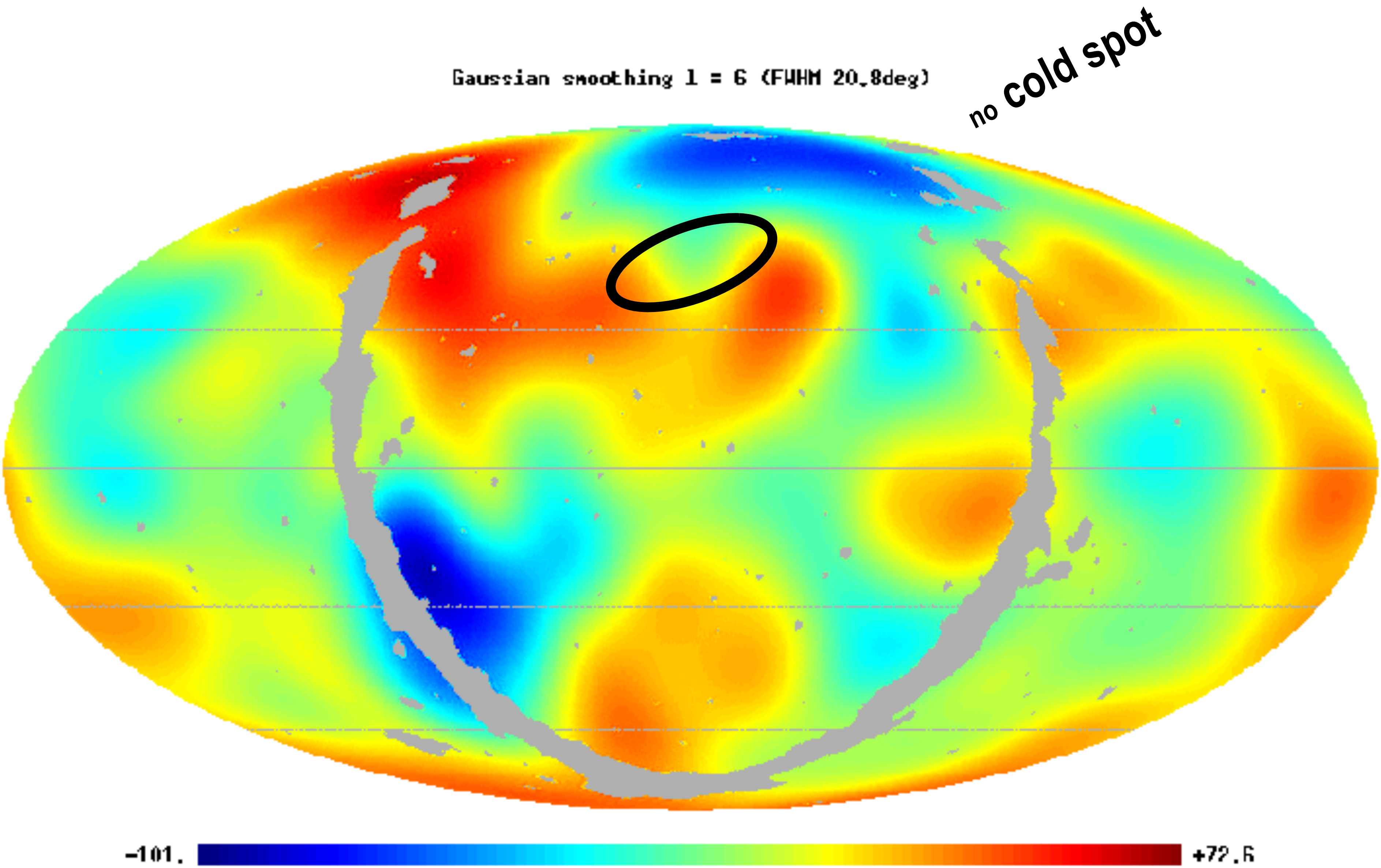
>4.5σ <1% L~20 ….. LSS void?

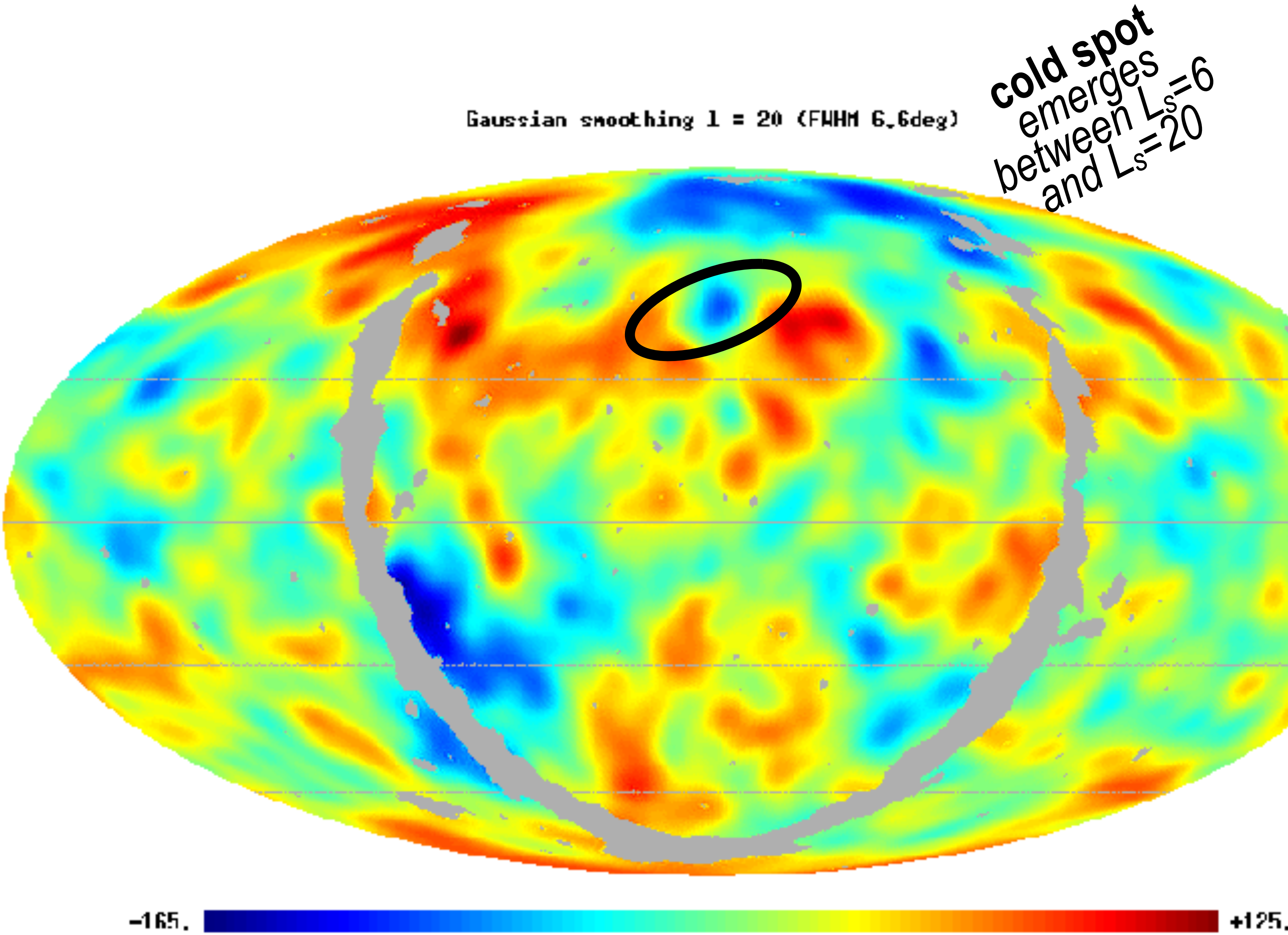
B+Huang tried hard to make a Grand Unified Theory of Anomalies? new ways of looking at the anomalies (comparing harmonic and real space in various ways) but no GUTA … TBD

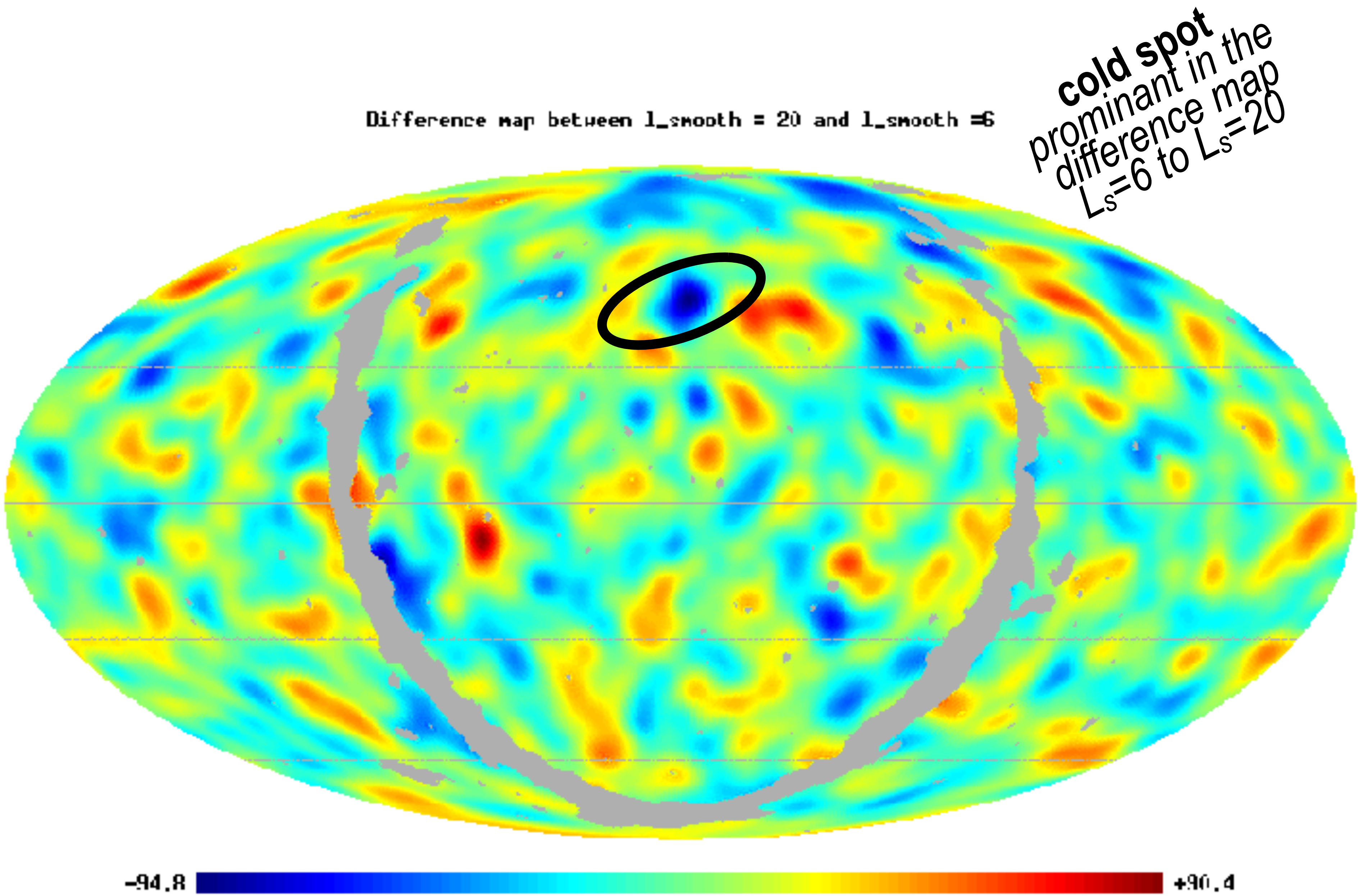
Cifar17 Lake Louise
Cosmology & Gravity

Cifar17 Lake Louise
Cosmology & Gravity


the rare cold spot
-303.
+264.


Gaussian smoothing l = 6 (FWHM 20.8deg)
no cold spot
-101.
+72.6


Gaussian smoothing l = 20 (FWHM 6.6deg)
cold spot
emerges
between L_s=6
and L_s=20
-165.
+125.



Difference map between l_smooth = 20 and l_smooth =6
cold spot
prominant in the
difference map
Ls=6 to Ls=20
-94.8
+90.4

$$W(\ell) = e^{-\frac{\ell(\ell+1)}{2(l_2+1/2)^2}} - e^{-\frac{\ell(\ell+1)}{2(l_1+1/2)^2}} \; (l_2 > l_1)$$

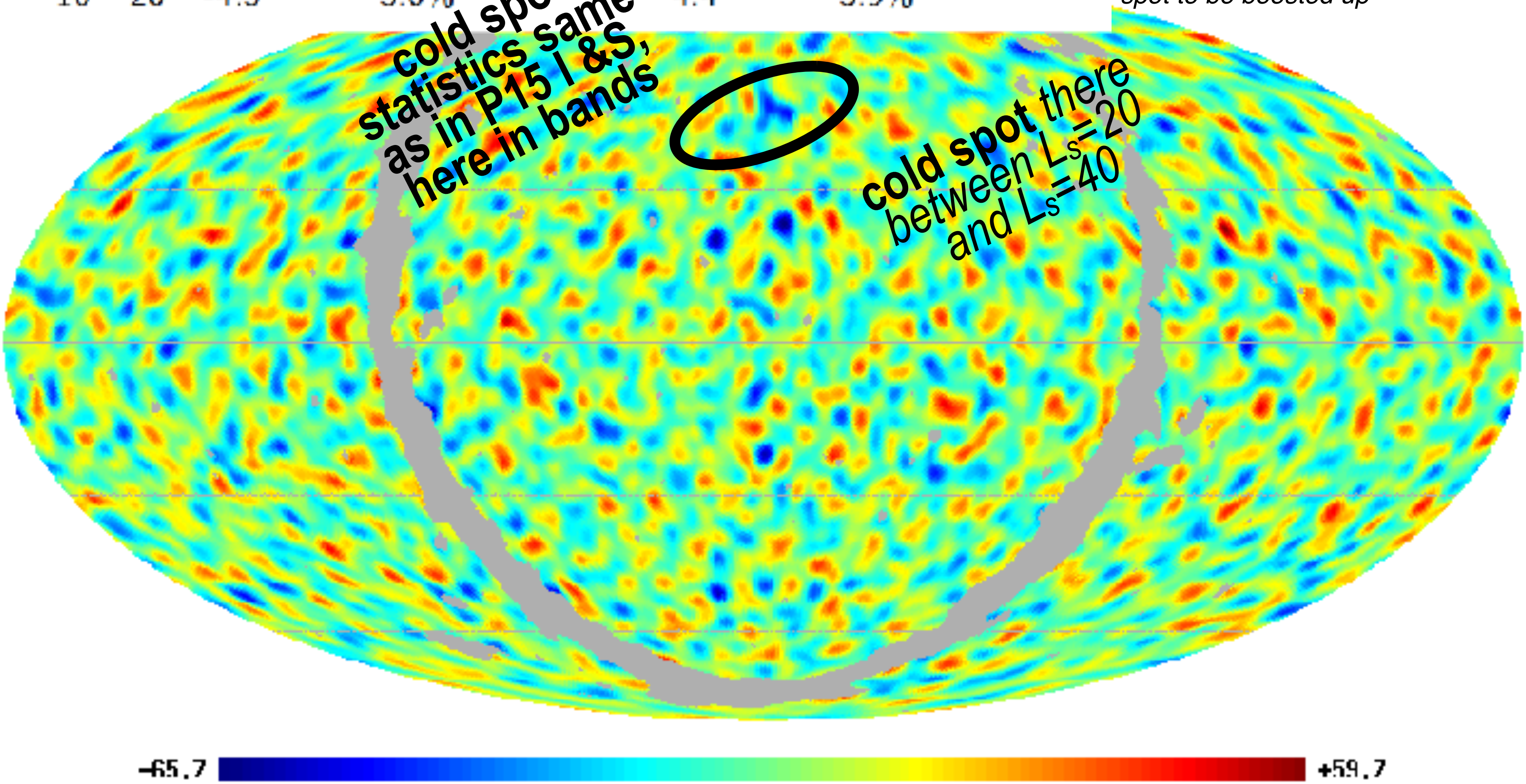
l_1	l_2	T_{cold}/σ_T	cold-spot p value	T_{hot}/σ_T	hot-spot p value
2	20	-3.5	29.9%	3.2	60.2%
4	20	-4.0	10.1%	3.9	13.9%
6	20	-4.5	2.0%	4.2	4.7%
8	20	-4.5	2.1%	4.3	4.5%
10	20	-4.5	3.0%	4.4	3.9%

tantalizing that the cold spot is the same L-band range as the L pspec dip, but all of our tools have not teased out a relation

B+Huang 2015

0

e.g. low L constrained fields do not make a nice low-L cavity for the cold spot to be boosted up



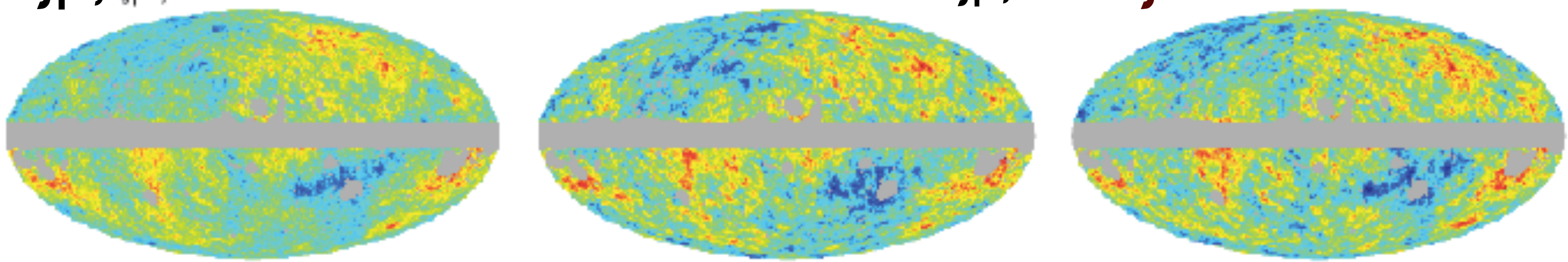
how intermittency could amplify the cold spot to statistical correctness

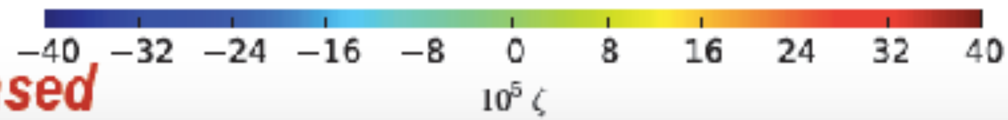
from >4.5σ Gaussian random field anomaly

Planck 2015 XVII nonG

<ζ|T,E>

<ζ|T,E>+δζ

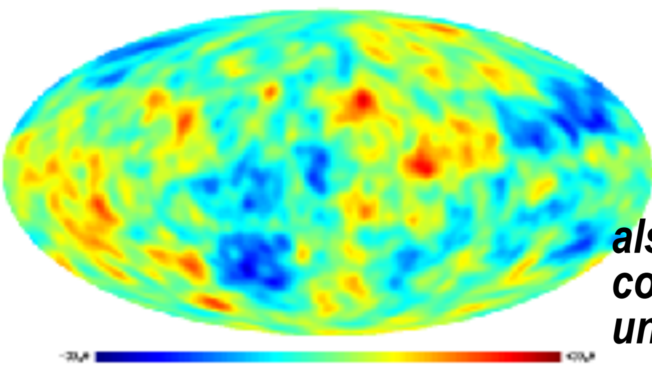




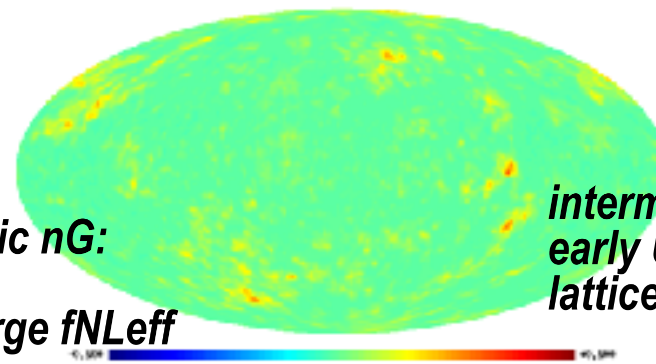
caution: not de-lensed

visibility mask

5deg fwhm



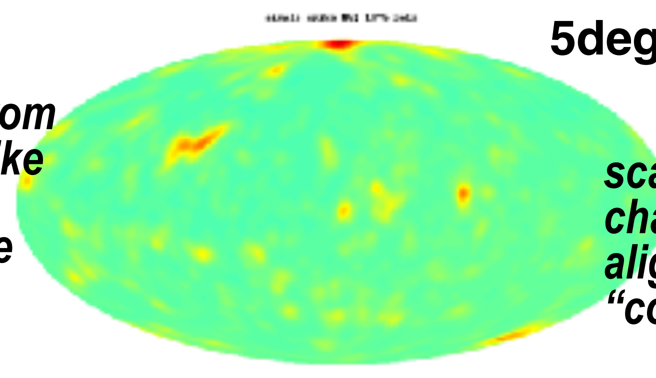
also cf. quadratic nG:
correlated fNL
uncorrelated large fNLeff



intermittent nG from early U preheating lattice sims - too small

5deg fwhm

intermittent nG from early U single spike sims - tunable amplitude, get the "cold spot"



scan sims to get chance intermittent alignment to get a "cold spot"

mocking heaven to explore 3D intermittency from **modulating preheating, bubble collisions**, etc

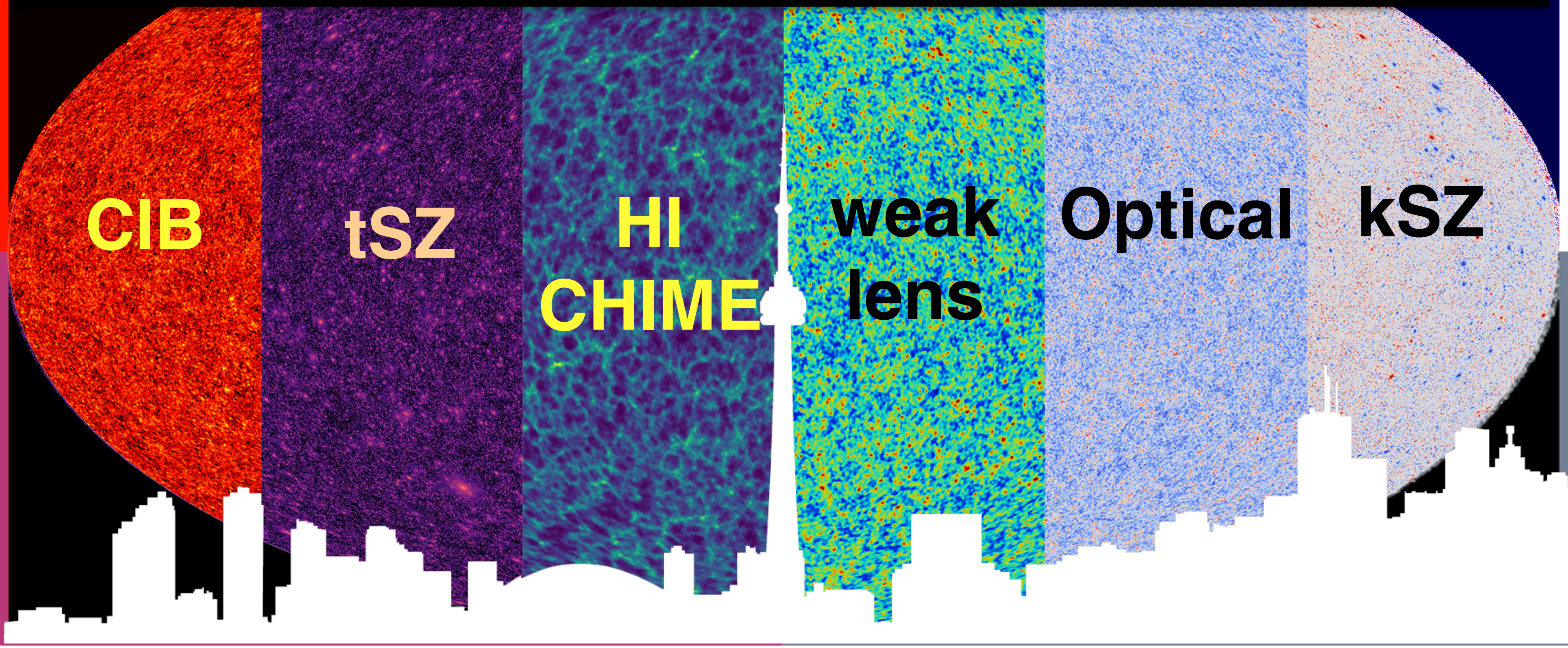
we are **in quest** of an **apparent breakdown of LSS homogeneity** - but NOT that

a nonlinear (large scale) bias response to the nearly scale invariant isocon field
cf. LSS bias of clusters/galaxies: threshold function acts on the linear density field

Mocking Heaven @ *CITA* *Alvarez Bond Stein Battaglia ..*

Peak Patch Full Sky Models for ***Planck, AdvACT, SO, CMB-S4, CCATp, CHIME, HIRAX, SKA, COMAP, EUCLID, LSST, …***

need ***End to End mocks, fully correlated to draw out:***
BSMc, DE/modG, Mnu, nonG (correlated, uncorrelated, intermittent),…

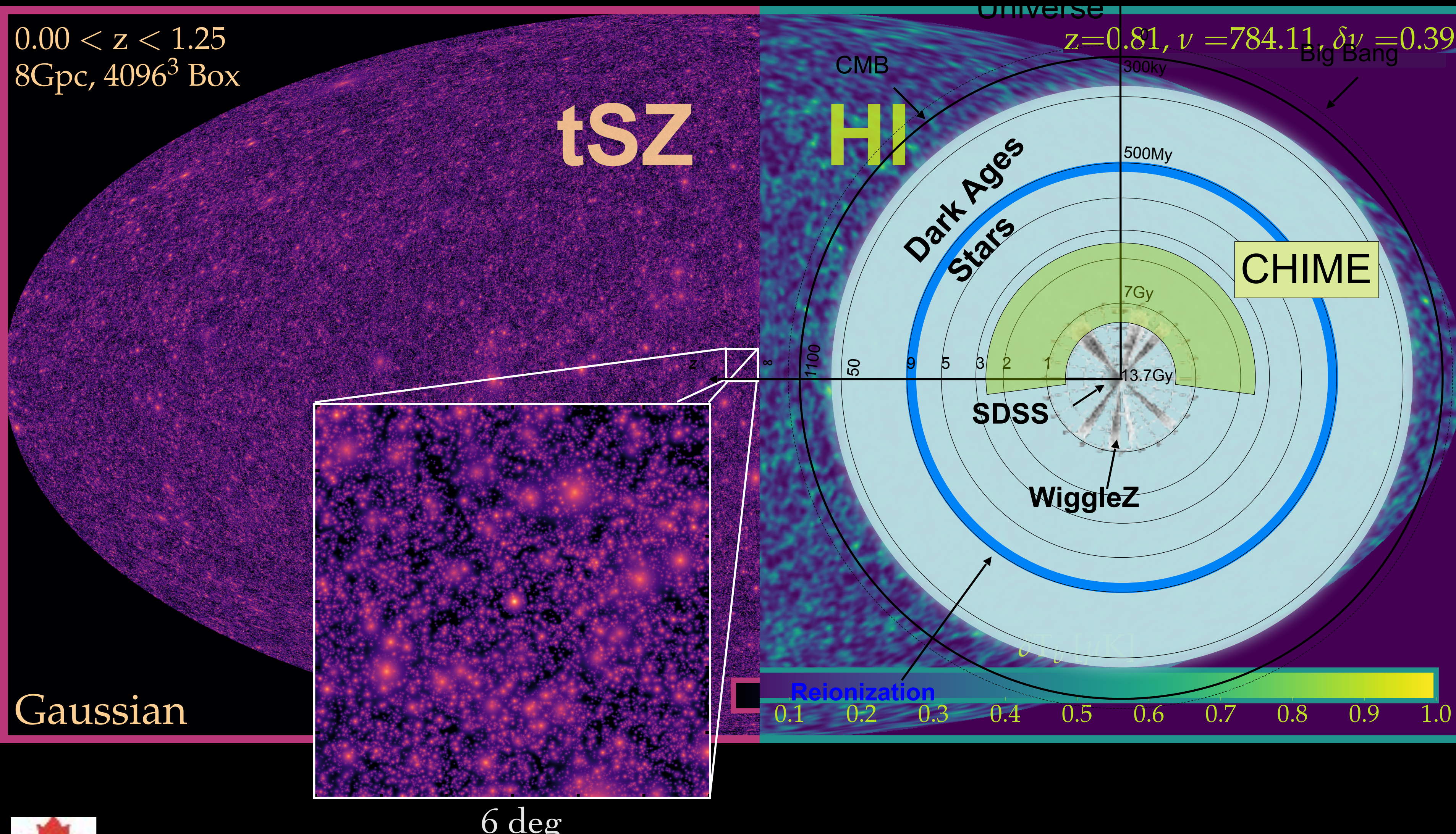


Planck 2015 XII: Full Focal Plane Sims (Nov): FFP8 ensemble of10K ***End****to****End*** *mission realizations in 1M maps. instrument noise + CMB + PSM + .. (25M NERSC CPU hrs)*

Compton Scattering (Sunyaev-Zeldovich) Simulations for ACT, Planck, Simons Obs &CMB Stage 4 Cluster Observations

Using high res Gas Hydro Sims

HI Intensity Mapping simulations of CHIME / HIRAX .. z=0.8-2.5, ~(8 Gpc)^3



ABS Berger +FH

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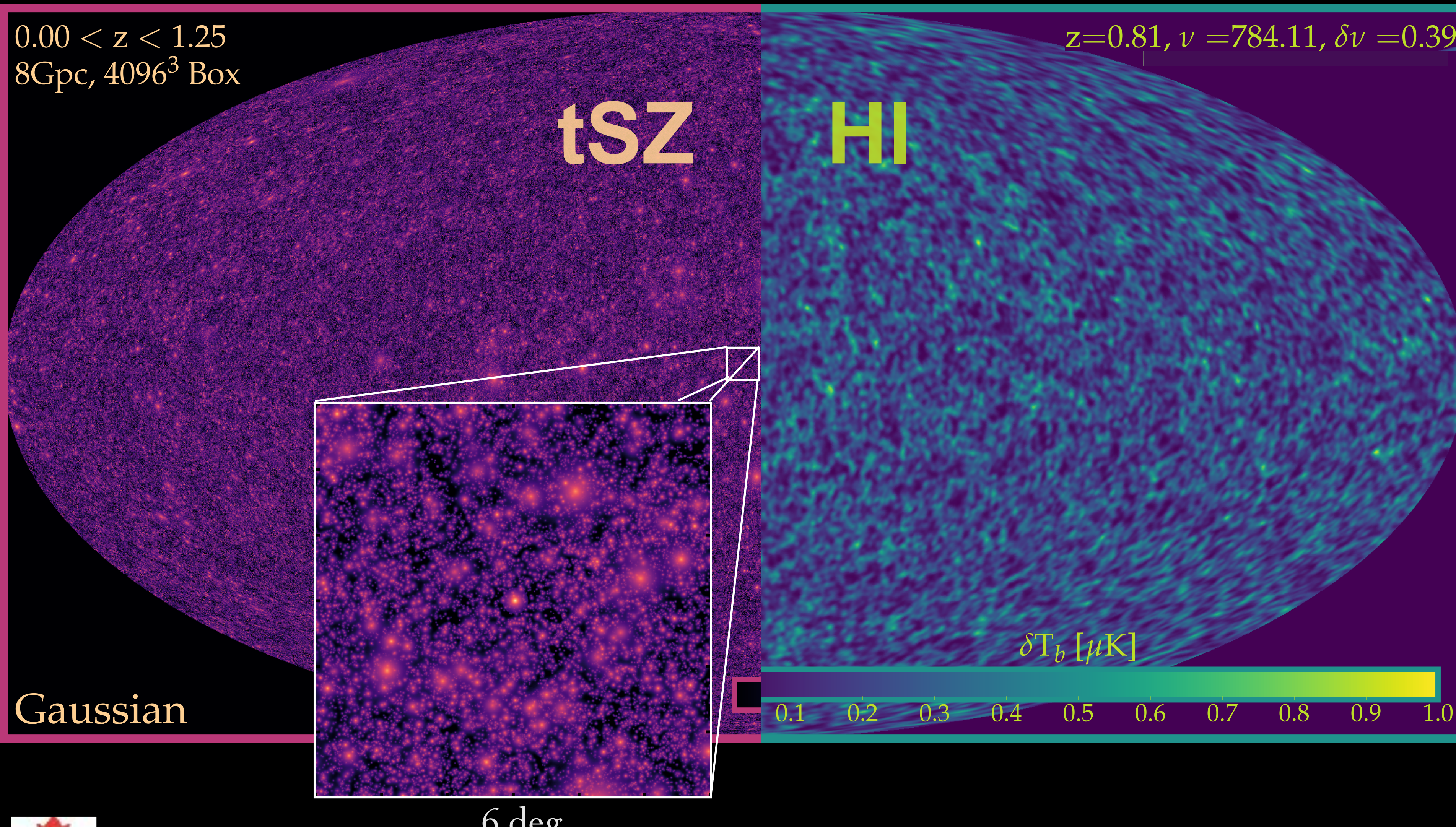

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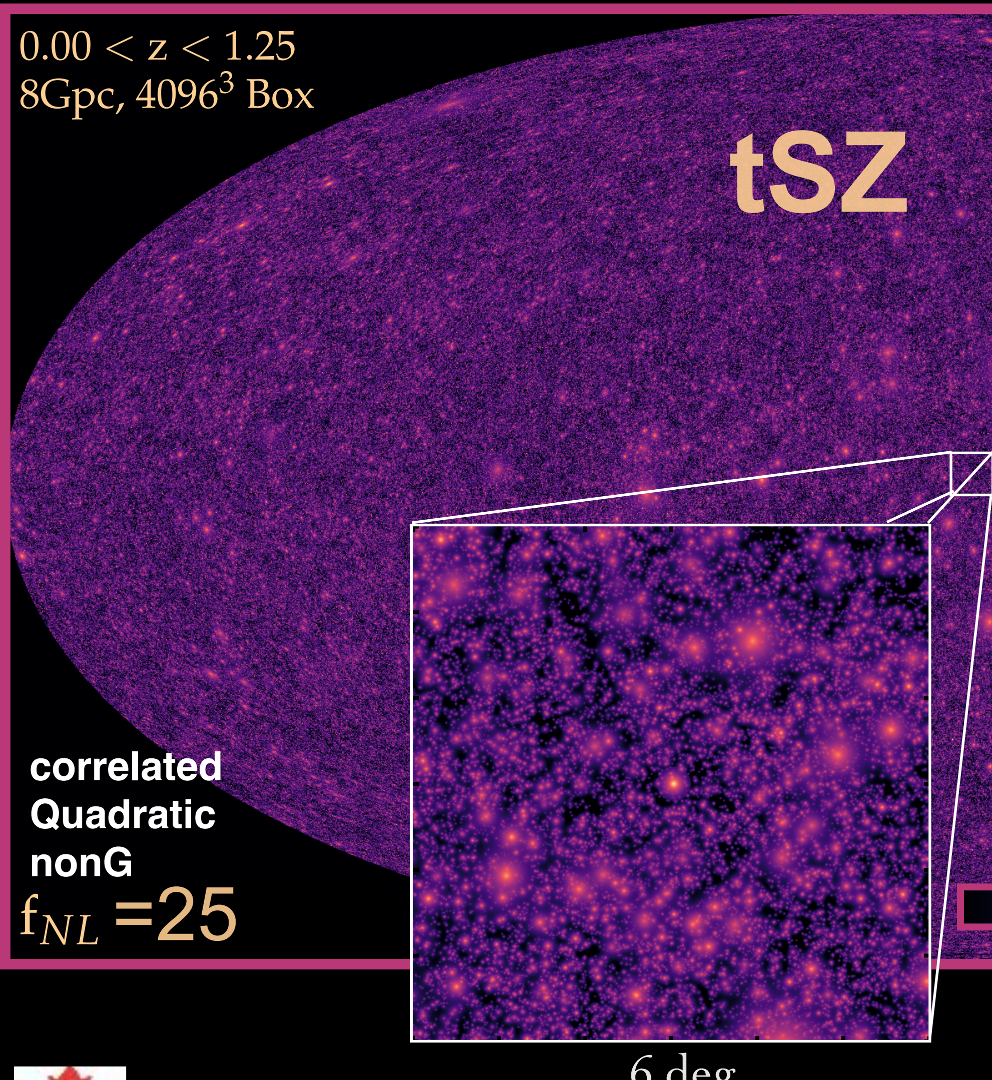

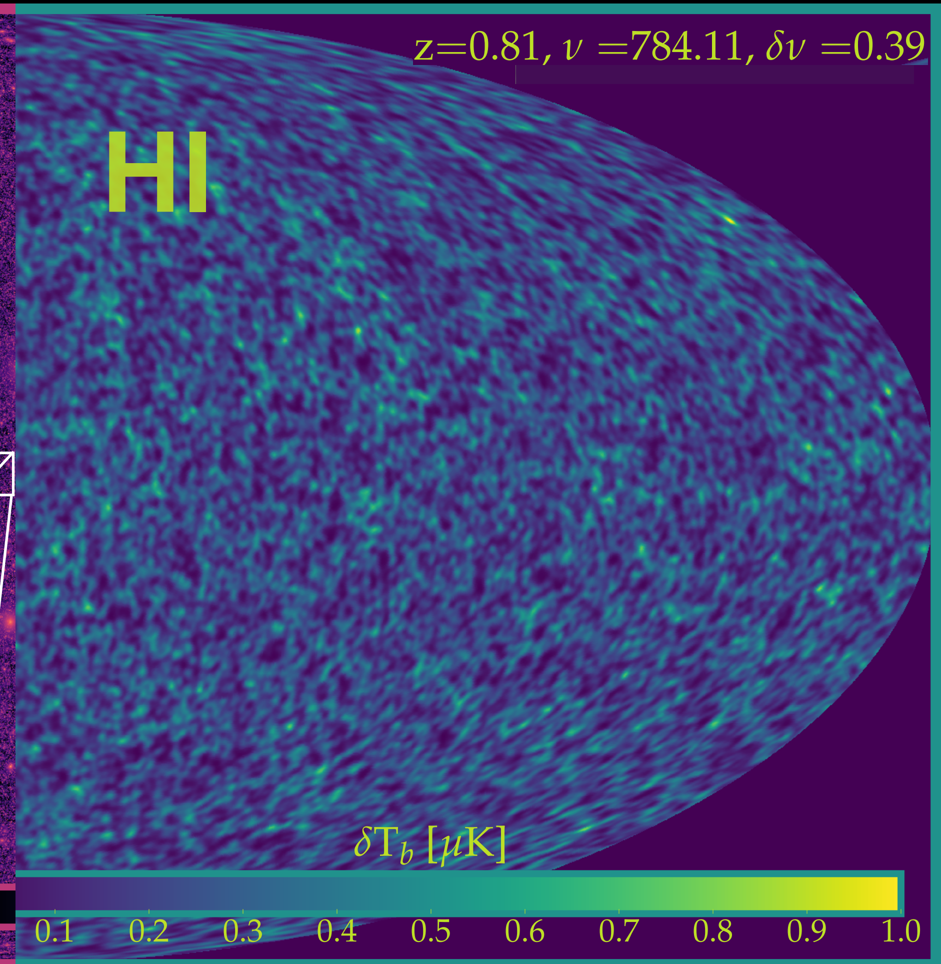

ABSB+FH, alvarez+b+stein+frolov+huang

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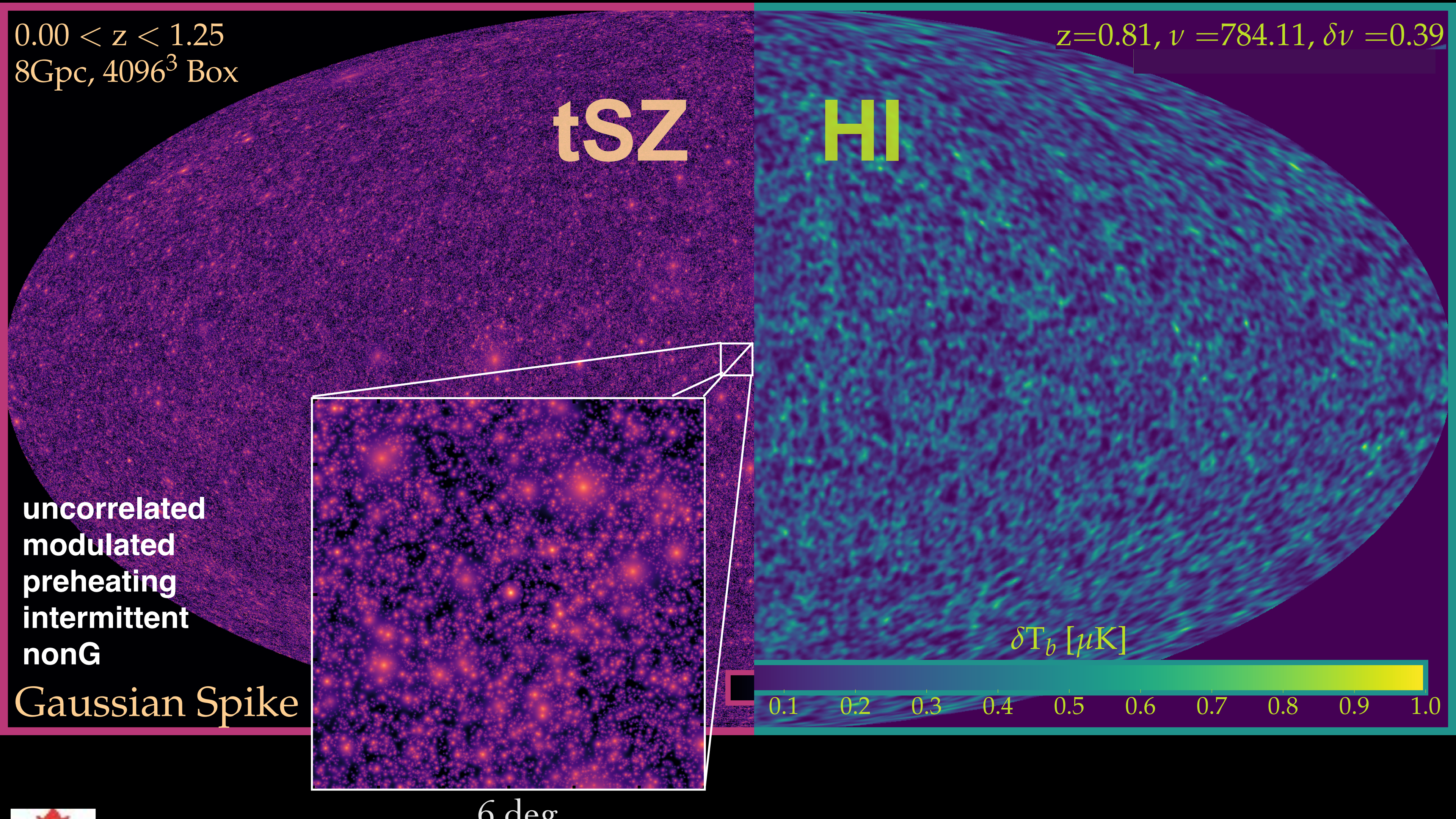
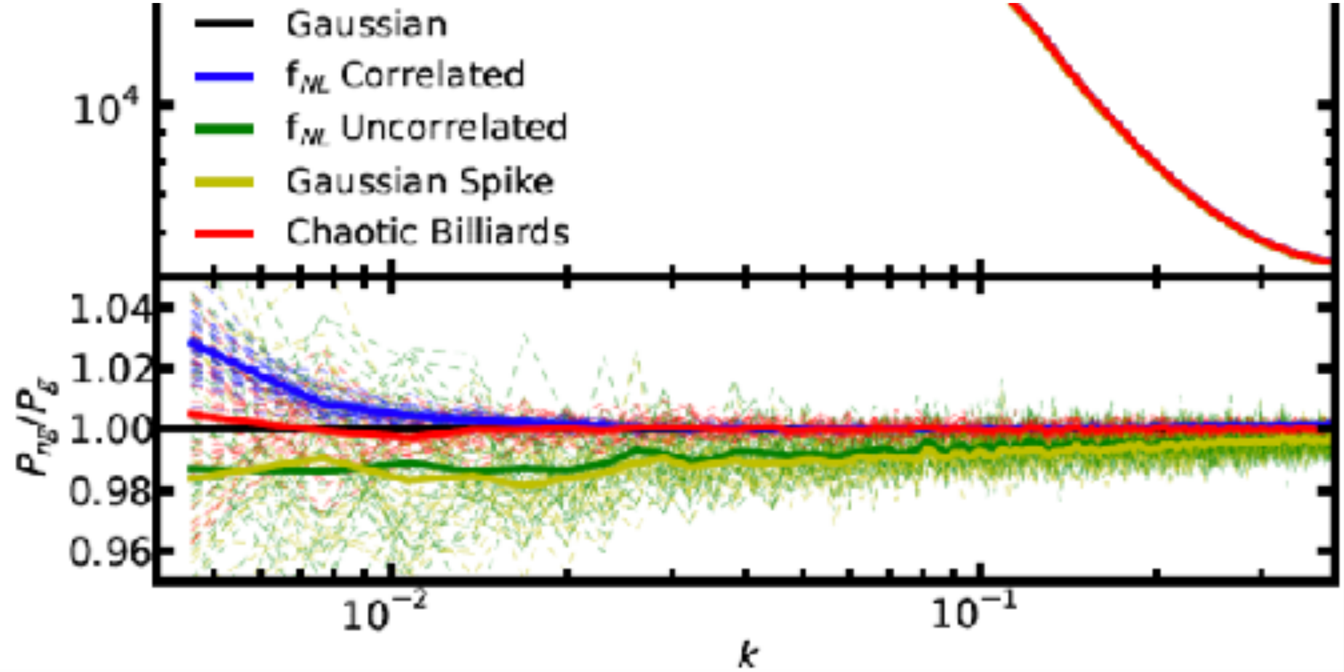


ABSB+FH, alvarez+b+stein+frolov+huang

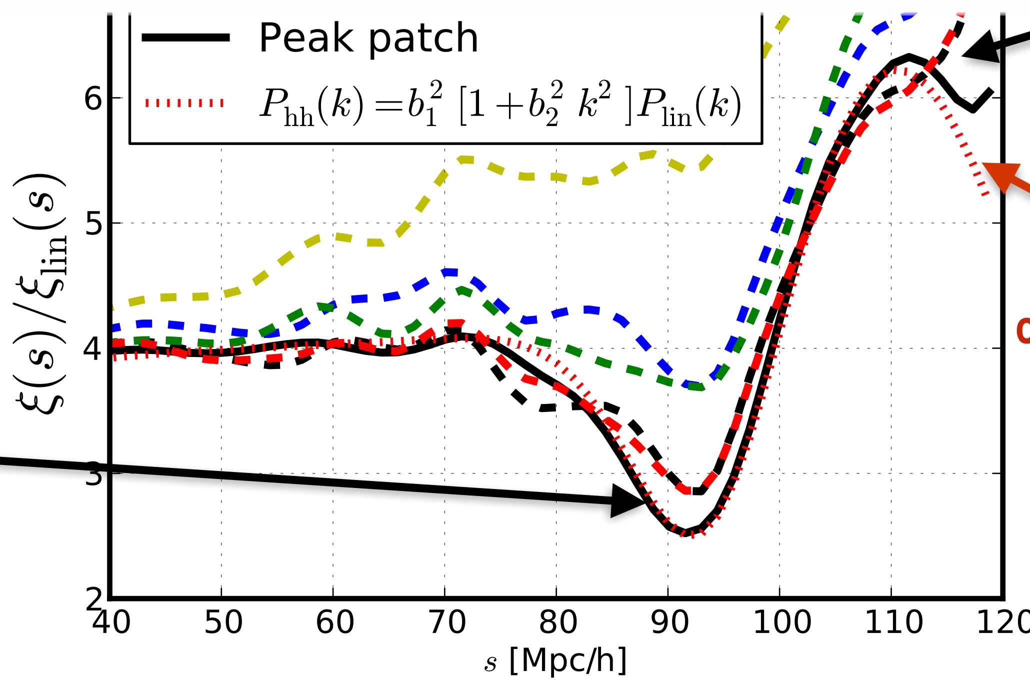
this is a quantitative exercise e.g.,

response of BAO & biasing of halos to forms of nonG - correlated cf. uncorrelated, intermittent cf. perturbative

e.g., **search for rare superBIAS events** >~ supercluster-scale



intermittent nG from early U single spike



Positive Curvature: Overabundance of Negative Extrema

Positive Curvature: Overabundance of Negative Extrema

cf. fit to N-body results: without any tuning it comes out from peak patches naturally

ABSB+FH, alvarez+b+stein+frolov+huang

highly nonlinear field evolutions happened

(EoI caustics, bubble collisions, non-eq entropy generation)

subdominant patterns do arise => will any be observable as rare-event CMB/LSS 'GaussianRandomField-biasing' anomalies?

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

B2FH17 ***progress in semi-analytic understanding of complex lattice sims with probability strings, caustics, trajectory stopping, shocks-in-time*** ***in the V(ϕ)-web***

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

alas **a 2-number A_s-n_s ζ-verse so far …** *r =+1?*

intermittency frustration: statistical variance is large - cf. a 2-3 parameter search

CMB ***restricts us to a*** **projected 2D ζ-scape to reconstruct ζ-maps & ζ-power,** ***the future may look much the same as now for ζ*** **=>potential V(ϕ)=>acceleration ε(a); constrained r helps**

we **mock** the LSS future ***end-to-end*** *to probe the* **mode-rich 3D ζ-scape**

end