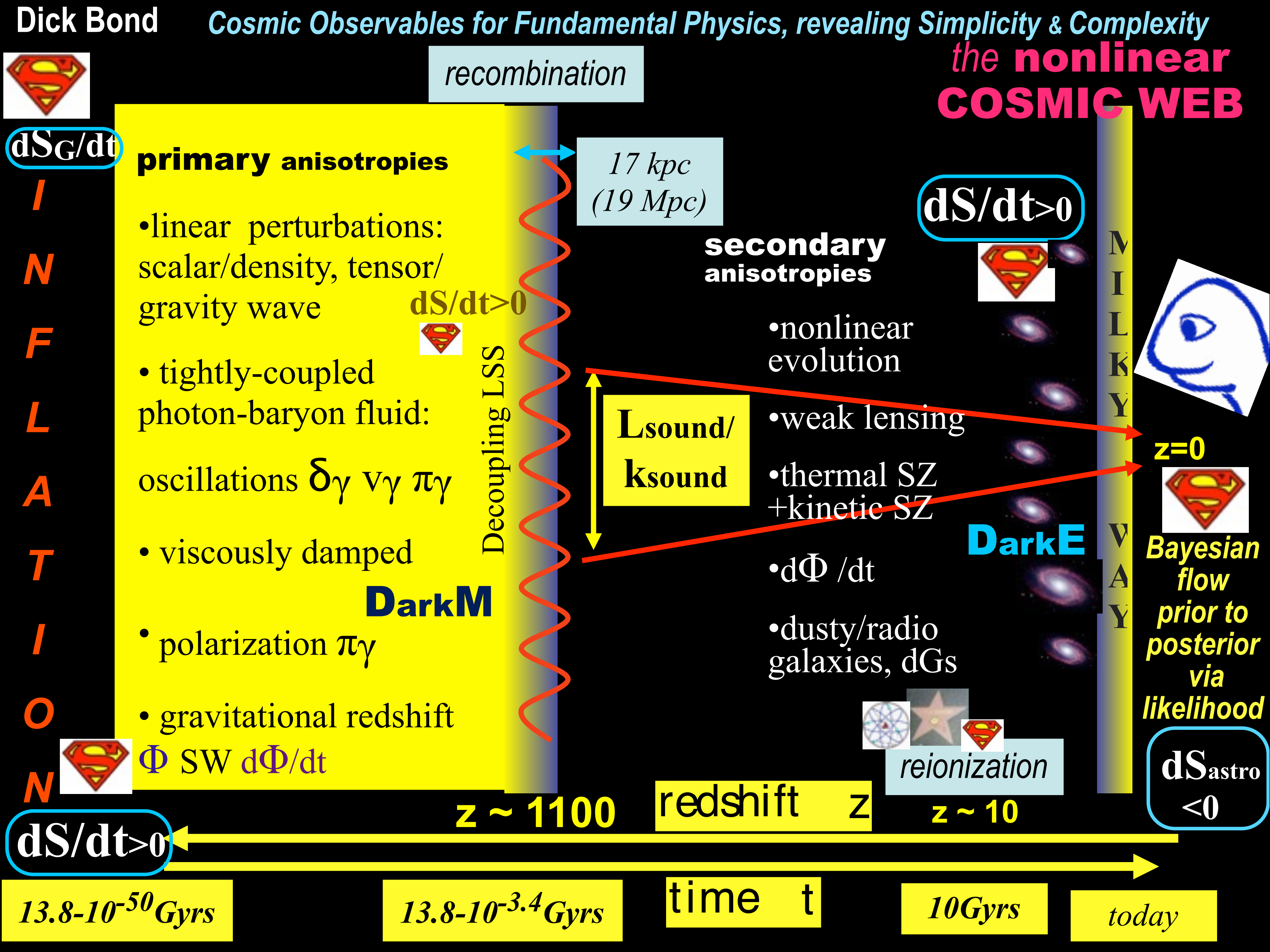
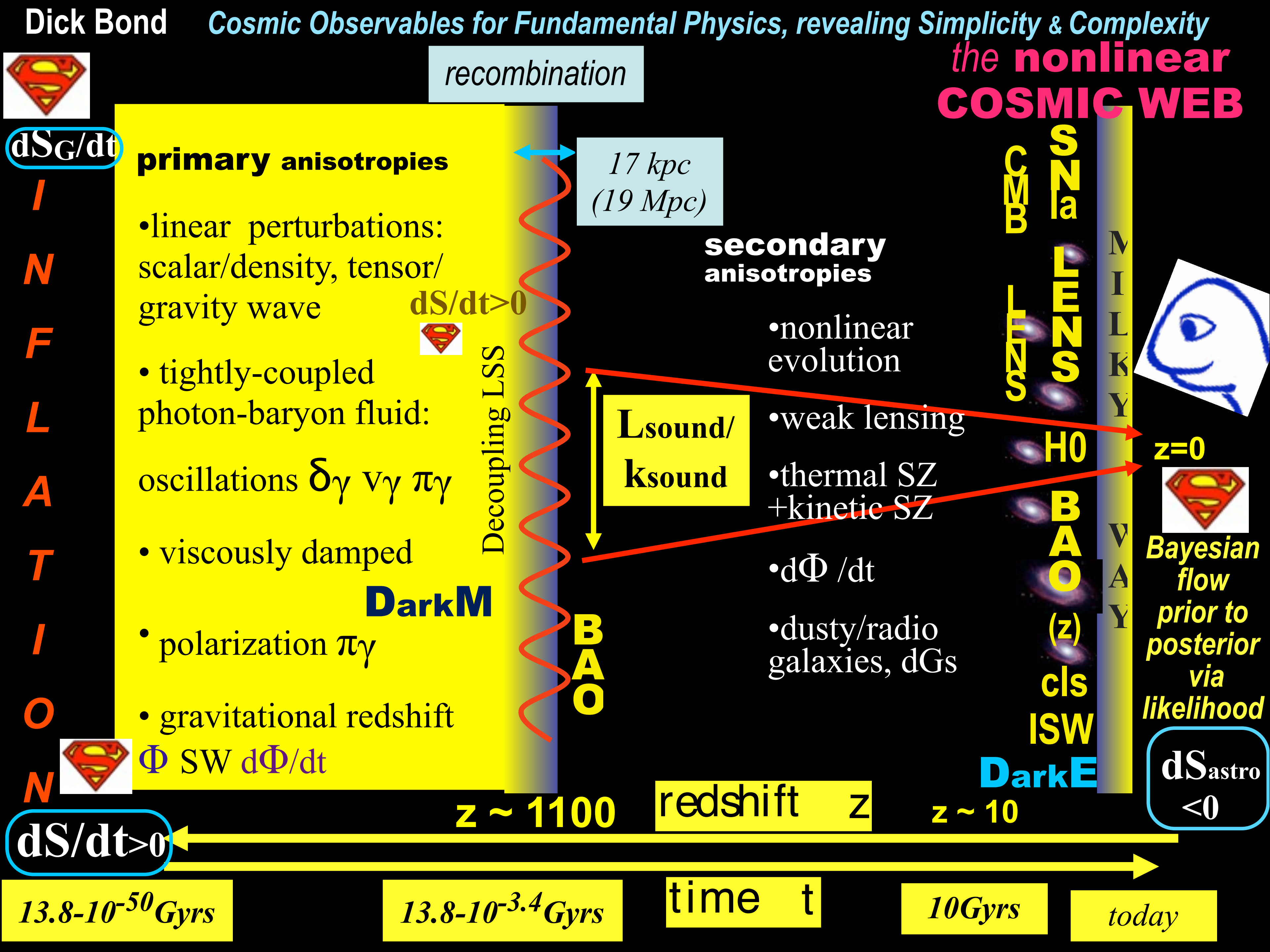

Dick Bond
Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity
the nonlinear COSMIC WEB
recombination
dS_G/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid:
oscillations δγ vγ πγ
• viscously damped
DarkM
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
Decoupling LSS
17 kpc (19 Mpc)
Lsound/ ksound
dS/dt>0
secondary anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
DarkE
•dΦ /dt
•dusty/radio galaxies, dGs
reionization
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
dS_astro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.8-10^-50 Gyrs
13.8-10^-3.4 Gyrs
10Gyrs
today



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LENS
SN Ia
LENS
H0
BAO
(z)
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dS/dt>0
time t
13.8-10^-50 Gyrs
13.8-10^-3.4 Gyrs
10Gyrs
today

SIMPLICITY

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

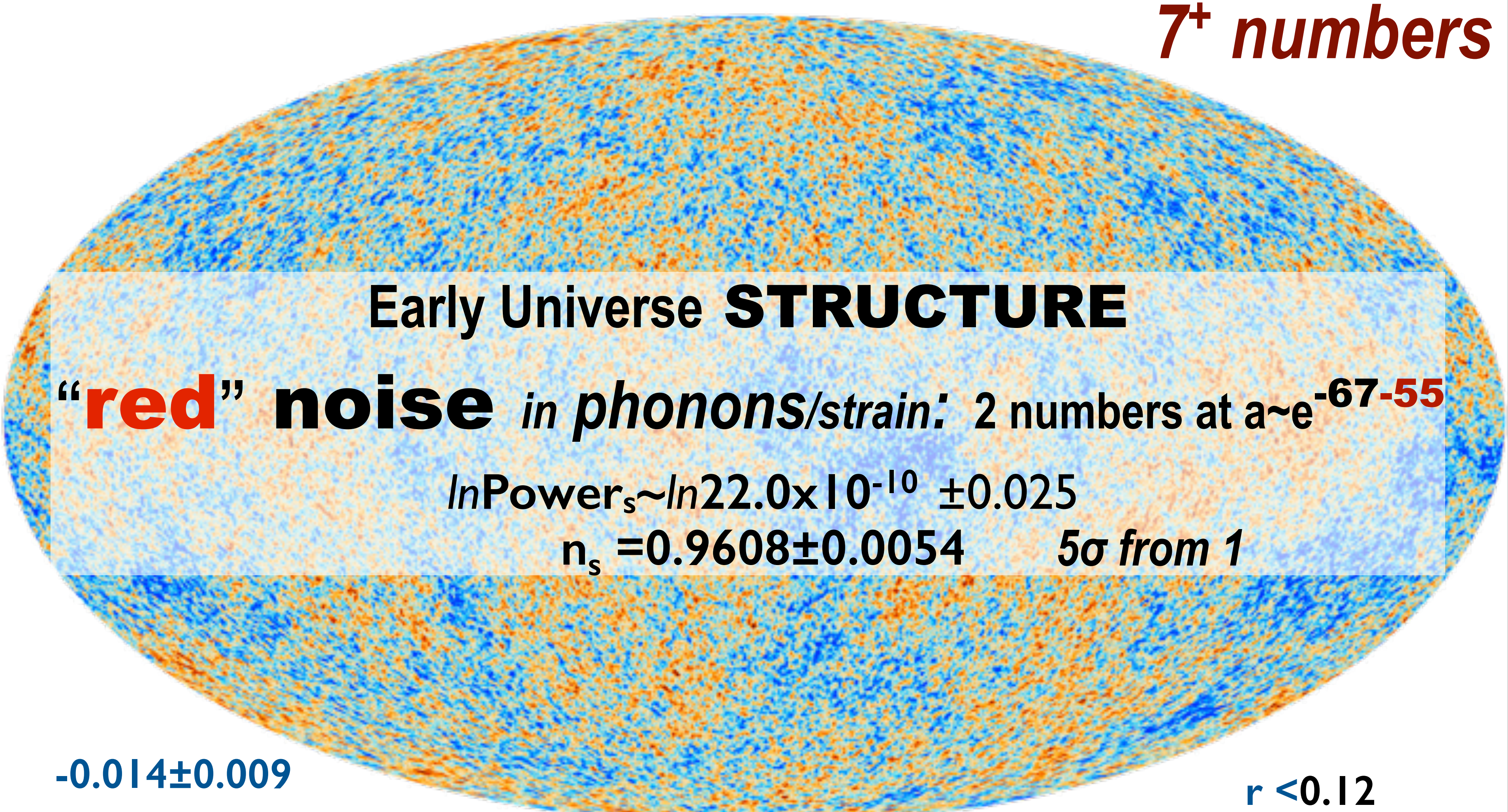
at $a \sim e^{-67-60} \sim 1/10^{30+25}$

reveals ***primordial sound waves in matter***

=> *learn* ***contents*** & ***structure*** *at 380000 yr,* $a \sim e^{-7}$

=> *infer the structure far far earlier* $a \sim e^{-67-60}$

7⁺ numbers



Early Universe STRUCTURE

"**red**" **noise** *in* ***phonons****/strain:* 2 numbers at $a \sim e^{-67-55}$

ln$Power_s \sim$ *ln*22.0×10^{-10} ±0.025

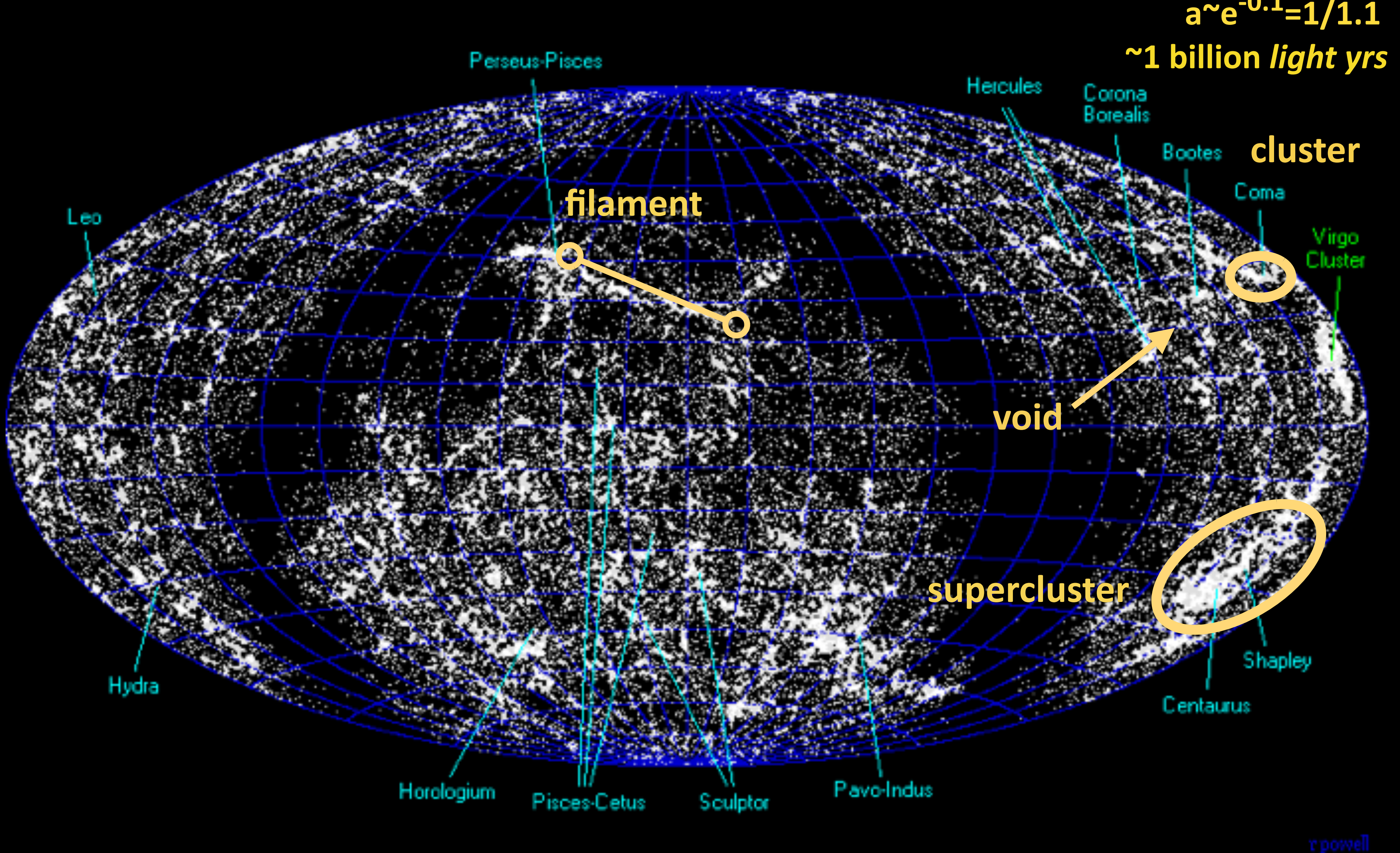
$n_s = 0.9608 \pm 0.0054$ *5σ from 1*

-0.014±0.009

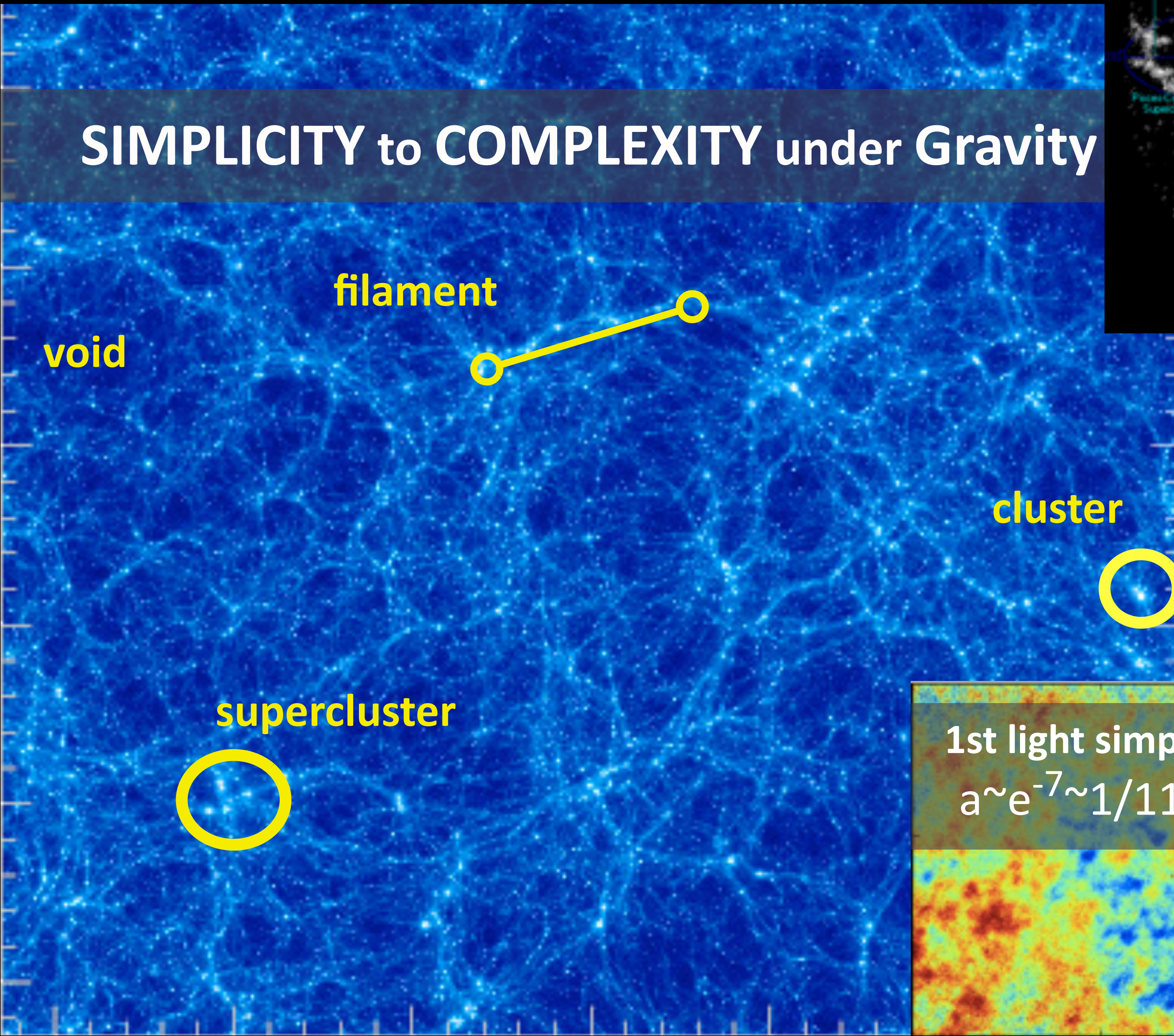
r <0.12

95% CL on ***running*** *d*$\mathbf{n_s}$*/dln****k****, running of running,* ***r*** *=Tensor-to-Scalar ratio (GW),*
isocurvature modes *for axions (<3.9%), baryons, neutrinos, curvatons (<0.25%)*

Cosmic Web of 60,000 nearby galaxies: exhibits "local" **COMPLEXITY**



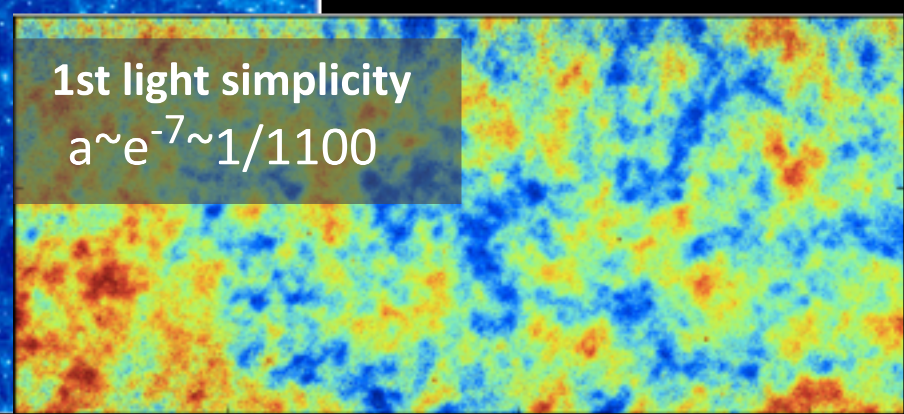
Simulation of the 7^+ numbers begets the Cosmic Web of clusters now a~1 & galaxies then a~1/4



~ billion light years

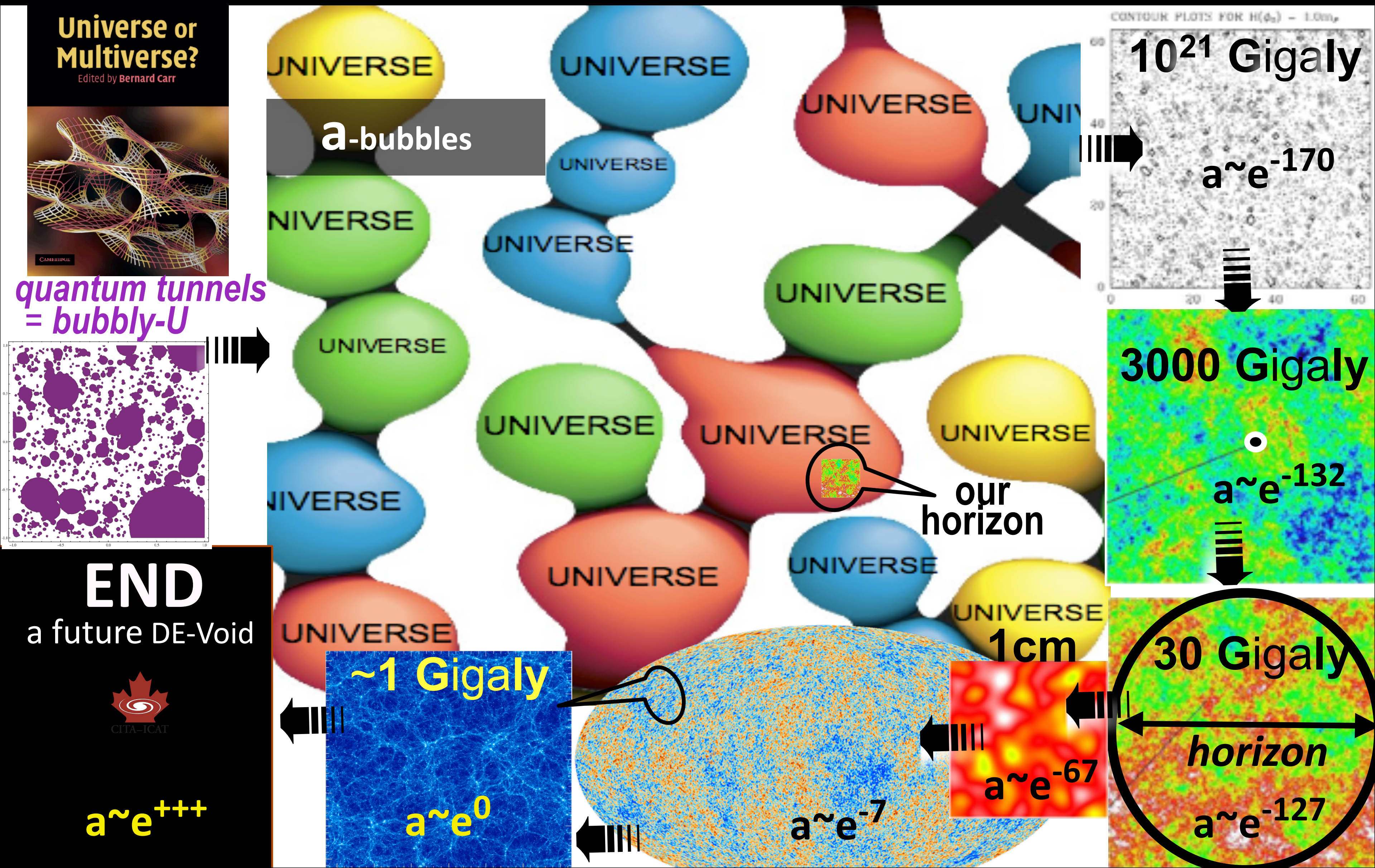
state of the art simulations
a~1 to 1/1.1

ordinary matter
dark matter
dark energy



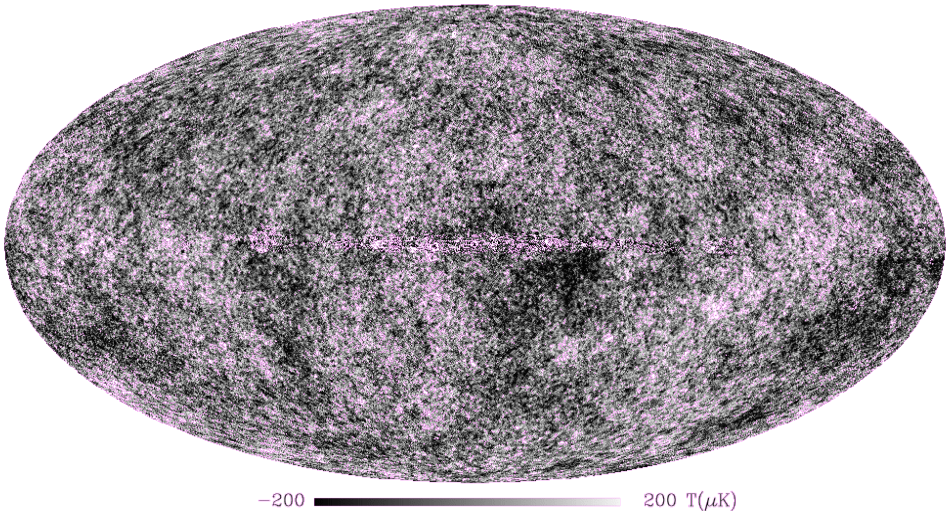
ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information

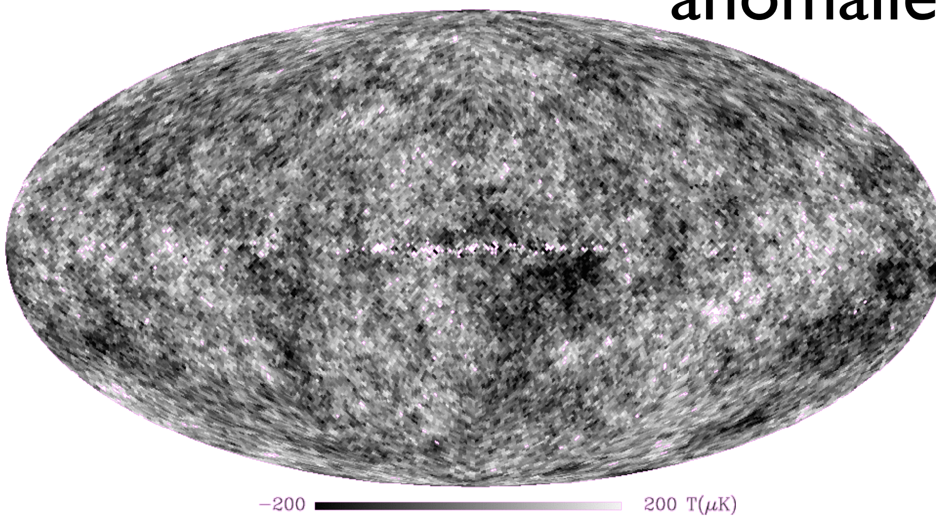


L<134
anomalies

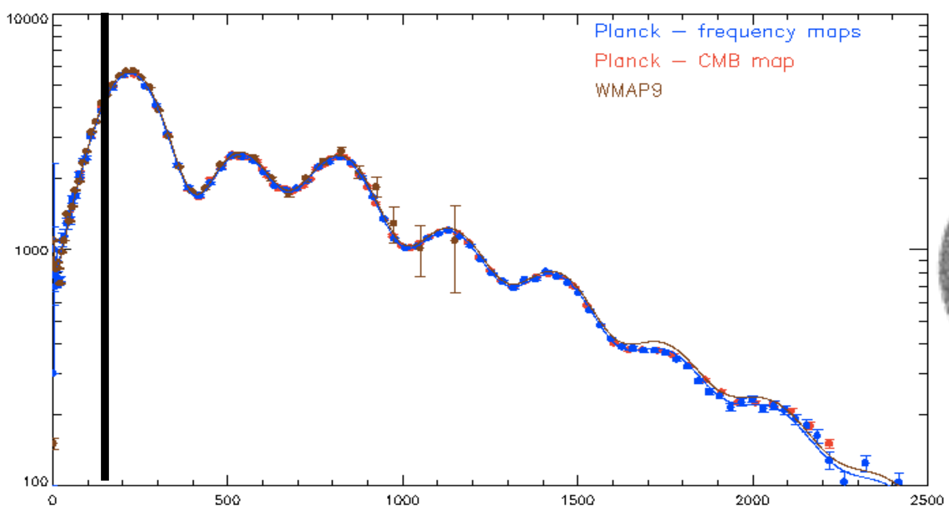
full Planck resolution

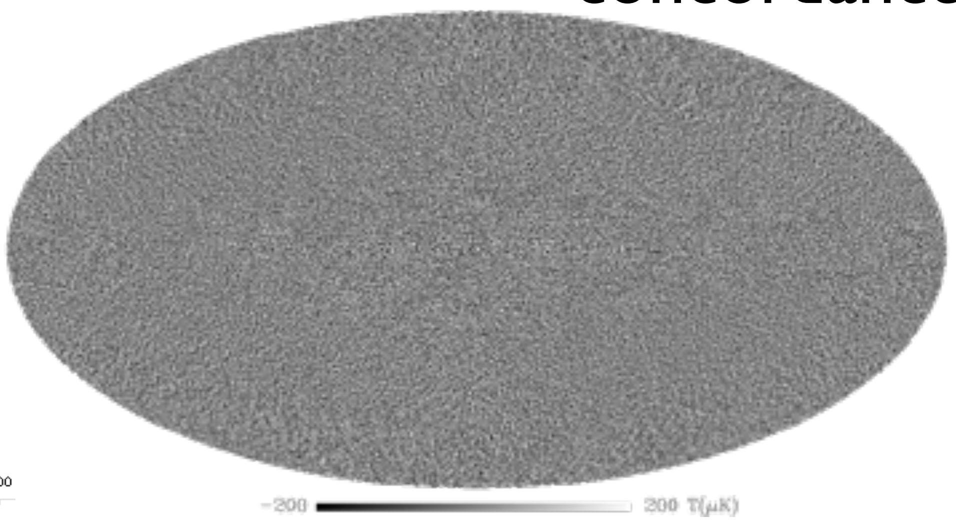


Planck smoothed to 1deg fwhm



L>134
concordance





small scale leftover = where most of Planck's information resides> 120X, > 4X WMAP9

Fundamental Physics from the Planck Satellite

Planck 2013 results. XXII. Constraints on inflation

Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity

Planck 2013 results. XXIII. Isotropy and Statistics of the CMB

Planck 2013 results. XXV. Searches for cosmic strings and other topological defects

Planck 2013 results. XXVI. Background geometry and topology of the Universe

CMB in Canada: @CITA Boomerang, Acbar, CBI1,2, WMAP, **Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET2; GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA, CCAT. CMB@CIFAR:+ APEX, SPT, SPTpol, EBEX**

the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Planck 2013 results. XII. Component separation

Planck 2013 results. XV. CMB power spectra and likelihood

Planck 2013 results. XVI. Cosmological parameters

Planck 2013 results. XVII. Gravitational lensing by large-scale structure

Planck 2013 results. XXVII. Doppler boosting of the CMB: Eppur si muove

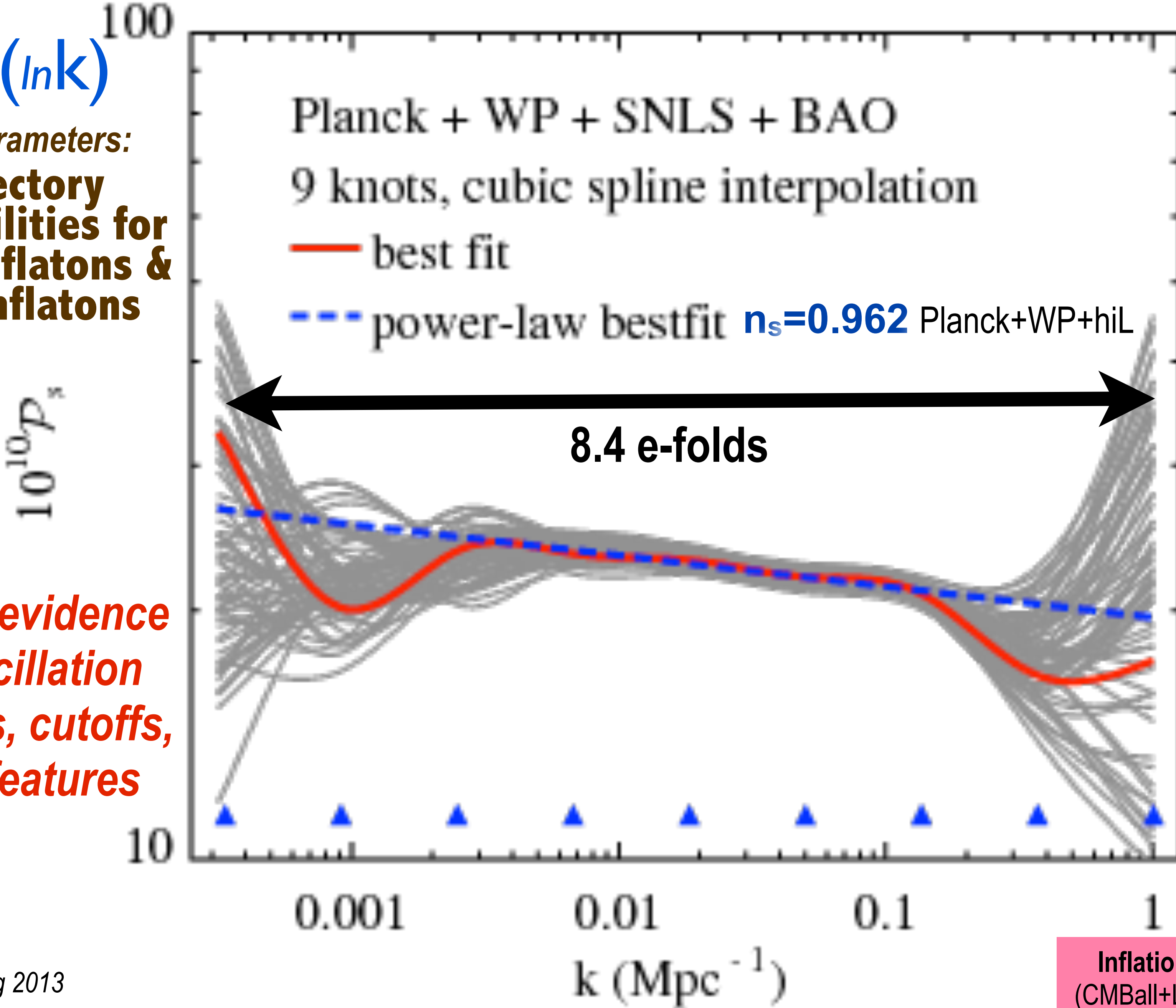
Planck 2013 results. XIX. The integrated Sachs-Wolfe effect

Planck 2013 results. XIa. Profile likelihoods for cosmological parameters *frequentist cf. Bayesian of XVI* *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* $\varepsilon(\ln Ha)$, $V(\psi)$

$\ln P_s(\ln k)$

new parameters:

trajectory probabilities for early-inflatons & late-inflatons



no** strong **evidence for oscillation patterns, cutoffs, local features

Bond, Huang 2013

Inflation Histories (CMBall+LSS+SN+WL)

NO TENSIONS

Planck HFI cf. Planck LFI *"P13 Comparison Paper"*

Planck HFI cf. ACT *Calabrese+13, TBD*

Planck cf. BAO z-surveys, compatible with tLCDM

lnPower_s~*ln*22.0×10^{-10} ±0.025 P1.3+ *ln*22×10^{-10} ±0.028 A12+S12+w9

n_s =0.9608±0.0054 (P1.3+WP+hiL+BAO) 0.9678±0.0088 A12+S12+w9

± 0.002 (P2.5ext)

$dn_s/d\ln k$=-0.014±0.009 (P1.3+WP, P1.3+WP+hiL+BAO)

-0.003 ± 0.013 (ACT12+ WMAP7+BAO+H0)

r <0.12, 0.11,0.16,0.11,0.13 (95% CL: P1.3+WP, P1.3+WP+hiL+BAO, A12,S12, W9)

< 0.007-0.013 (P2.5ext) 2015?

nonGaussianity f_{nl}: 2.7 ± 5.8 local => ± 5 (Pext) f_{nl}: -42.3 ± 75.2 equil -25.3 ± 39.2 ortho

TENSIONS

Planck cf. WMAP9 *"P13 Comparison Paper", still ~1% amplitude difference, map level by eye agreement spectacular*

Planck cf. SPT *not really, in overlap region*

$dn_s/d\ln k$=-0.014±0.009 (P1.3+WP, P1.3+WP+hiL+BAO) **-0.028 ± 0.010 SPT12+**

Planck primary cf. Planck SZ ncl & y-maps, gastrophysics, neutrino mass?

Planck primary cf. PlanckSZ/WMAP9 X ROSAT cross spectra
Hajian, Battaglia+13, slightly less tension

Planck primary cf. H0 Reiss+, Freedman+ systematic errors GPE reanalysis H0 from 74 to 70

Planck primary cf. SN1a w<-1 but CFHT-SNLS relative calibration change

Planck primary cf. maser H0. changed before the ESLAB mtg

Planck primary cf. CFHT-LENS

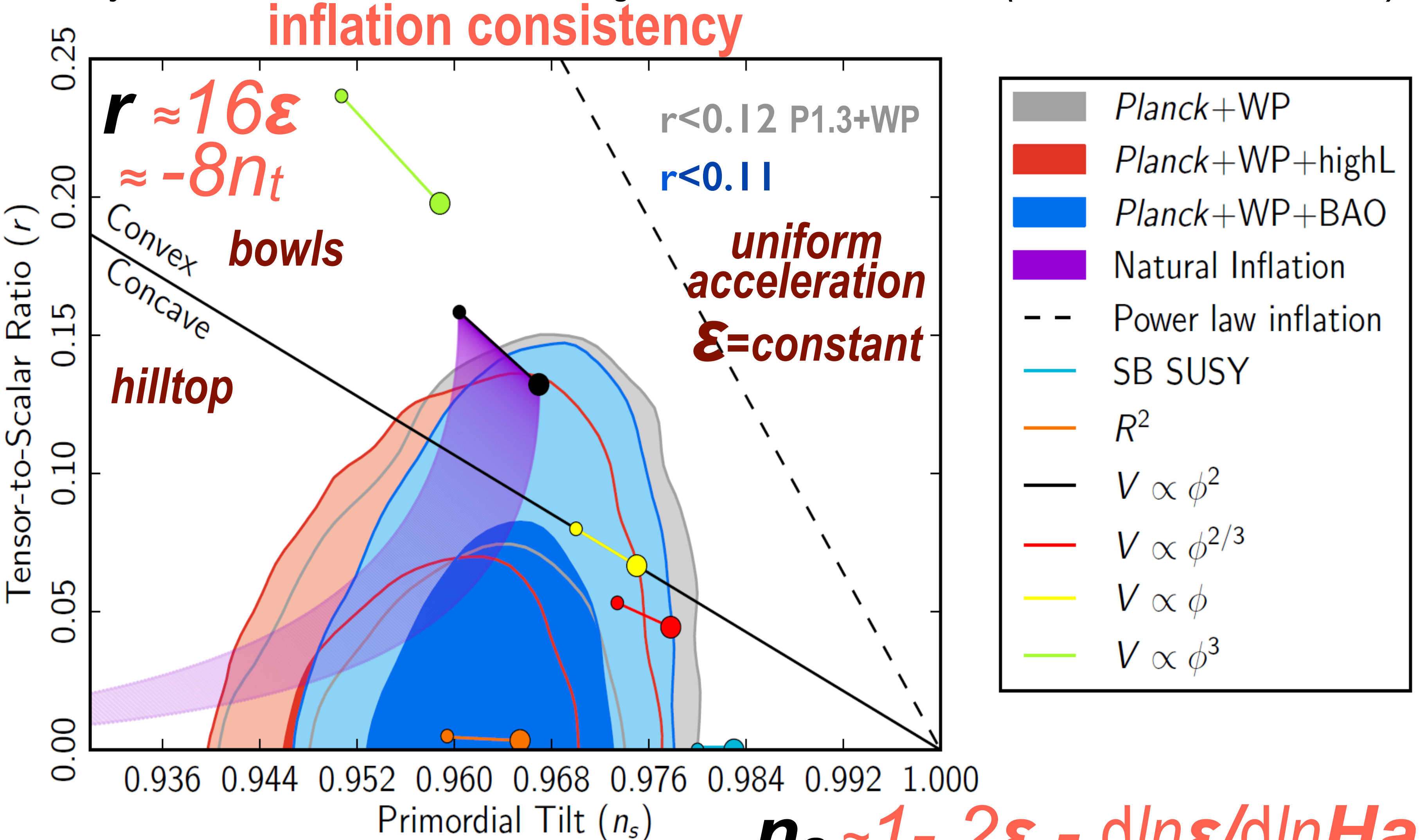
Planck non-G f_{NL} cf. non-G large-scale Planck/WMAP anomalies. *consistent*

Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits)

uniform acceleration** line $\varepsilon \equiv 3KE/(KE+PE)$ = constant is **strongly ruled out

=> *early universe acceleration must change over observable scales (as well as to end inflation)*

inflation consistency



$n_s \approx 1 - 2\varepsilon - d\ln\varepsilon/d\ln Ha$

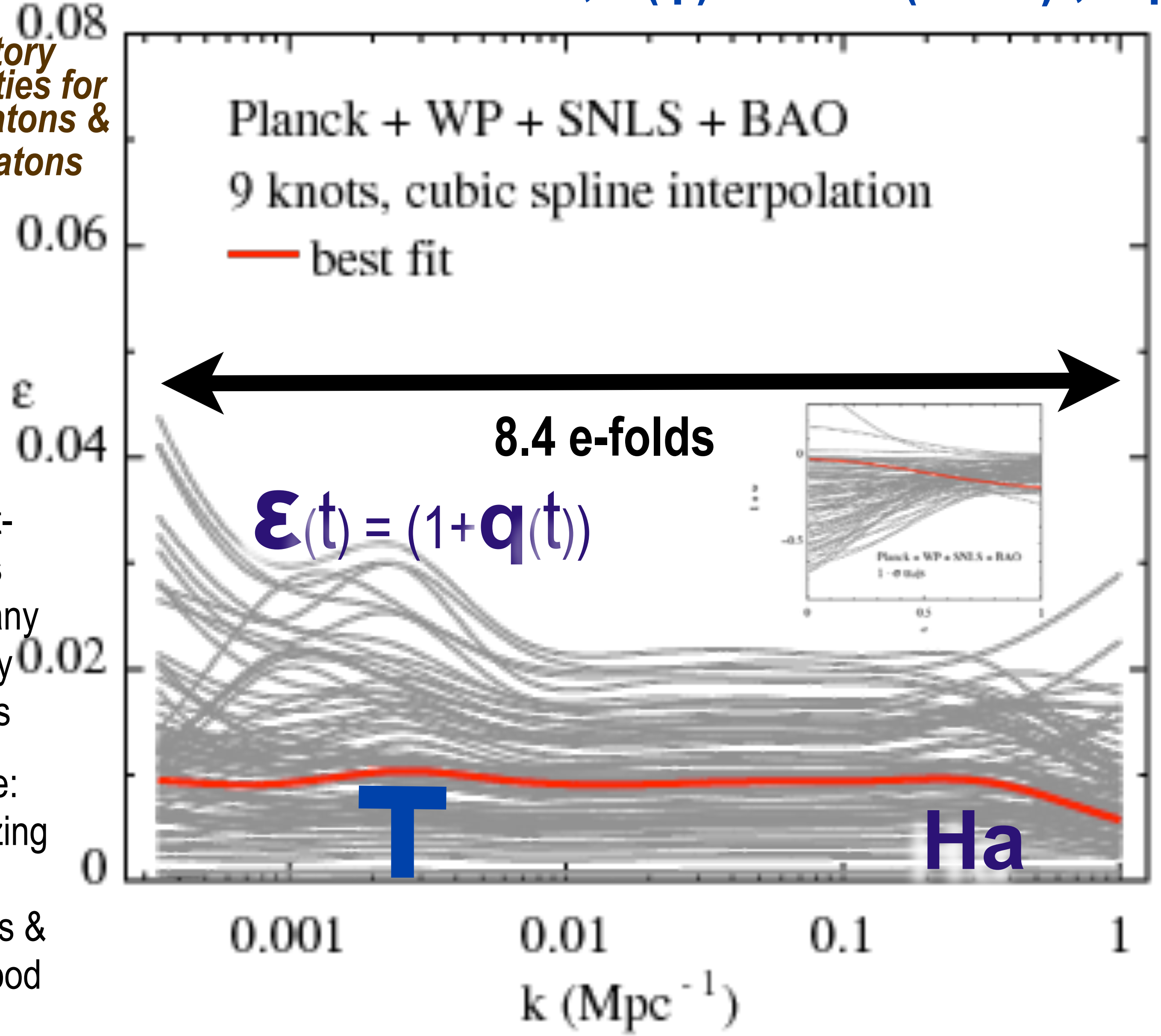
r without B-mode pol is delicate **rule out: exponential potential models(power-law inf)**, the simplest hybrid inflationary models (Spontaneously Broken SUSY) & **Φ^n, n >2 monomial potentials of chaotic inflation** ***some* popular *inflation survivors:* Natural = pNGB, monodromy =driven pNGB, Roulette (shrinking holes in extra-dim), brane (separation), Higgs, flattened potentials** *= non-monomial, ...*

early-inflaton DE acceleration trajectories then

Bond, Huang 2013

$\varepsilon = -\, d\ln H / d\ln a$; $V(\psi) \approx 3 M_P^2 H^2 (1-\varepsilon/3)$; $d\psi / d\ln a = \pm\sqrt{\varepsilon}$

trajectory probabilities for early-inflatons & late-inflatons



aka

$(1+w_{de})3/2$

then

(hydro)

resolution
lnk ~ lnHa
dynamics

$\varepsilon \approx r/16$

can post-process bands in any trajectory variables

key issue: characterizing the correlations & the likelihood surface

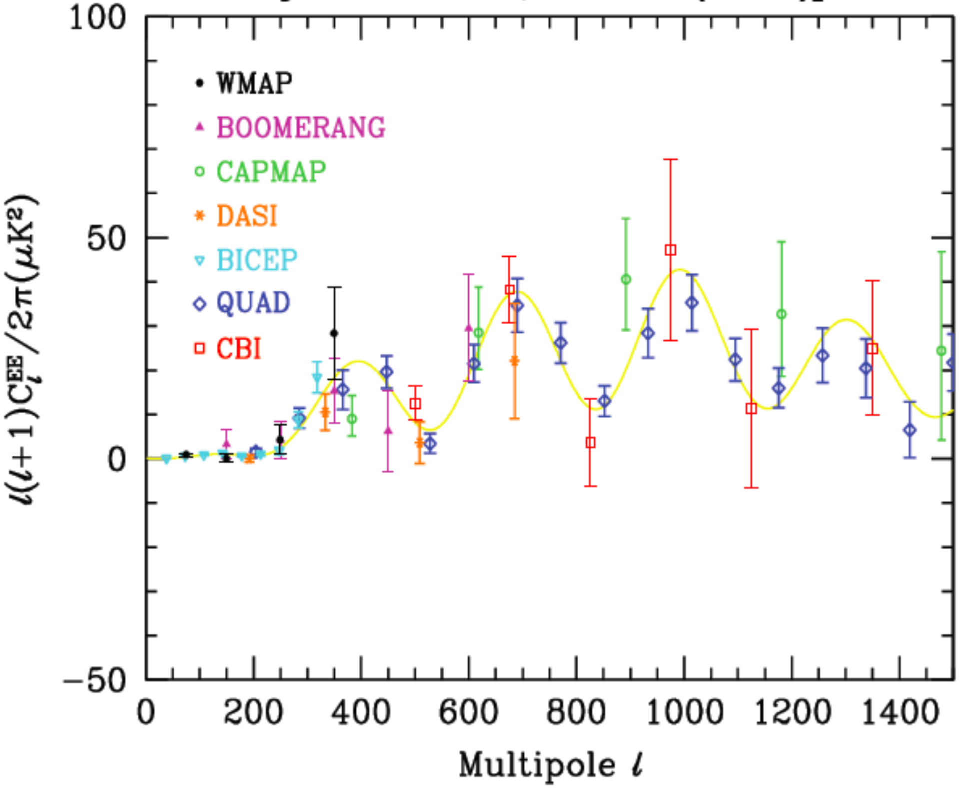
$\varepsilon \approx V$ / $0.0005\ (10^{16}\mathrm{Gev})^4$

best-fit P1.3yr TT model predicts the polarization. works perfectly at all frequency cross correlations strengthens the case for the Galactic/extragalactic nuisance parameter model being accurate

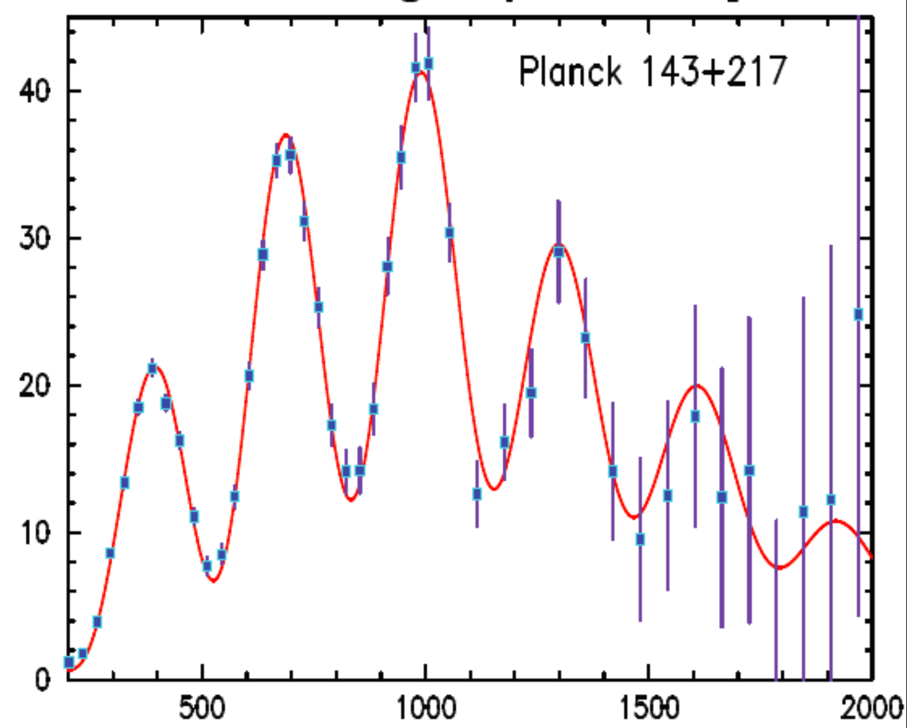
teaser for 2014

EE polarization

[J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)]



[Planck 2013 results. XVI. Cosmological parameters]



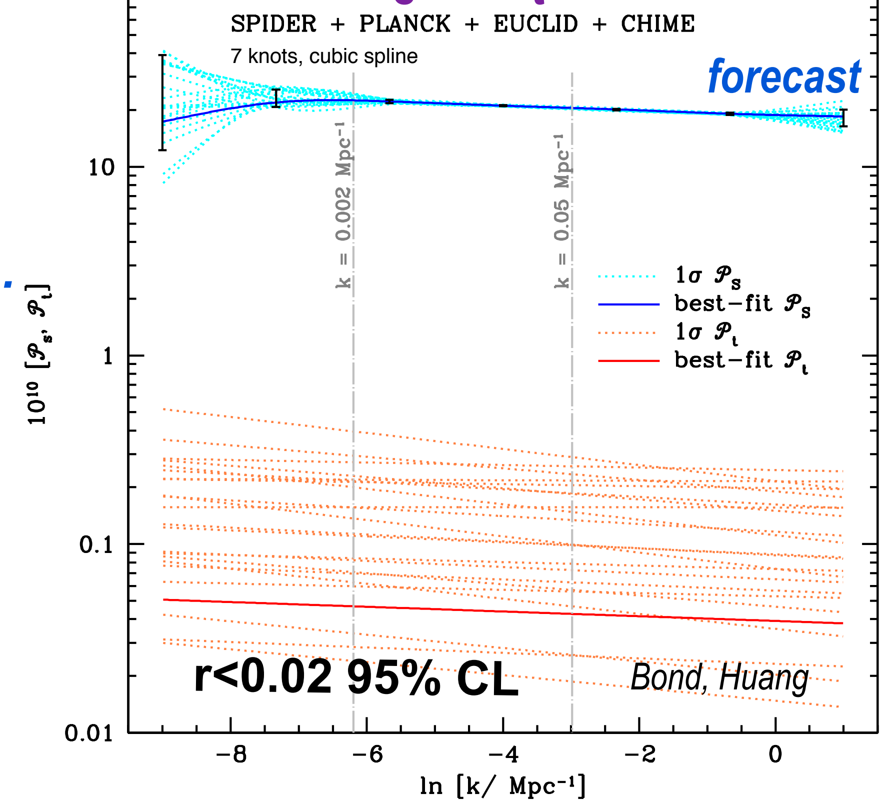
a long path to constrain** the **B-mode of polarization** at the **r =.02 to .05 level of P2.5 forecasts

CMB Lensing induces B-mode of polarization from E-mode: *Detection of **B**-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope* **Hanson+13 using Herschel sub-mm+SPT-E-mode x SPT B-mode to confirm detection at 7.7sigma**

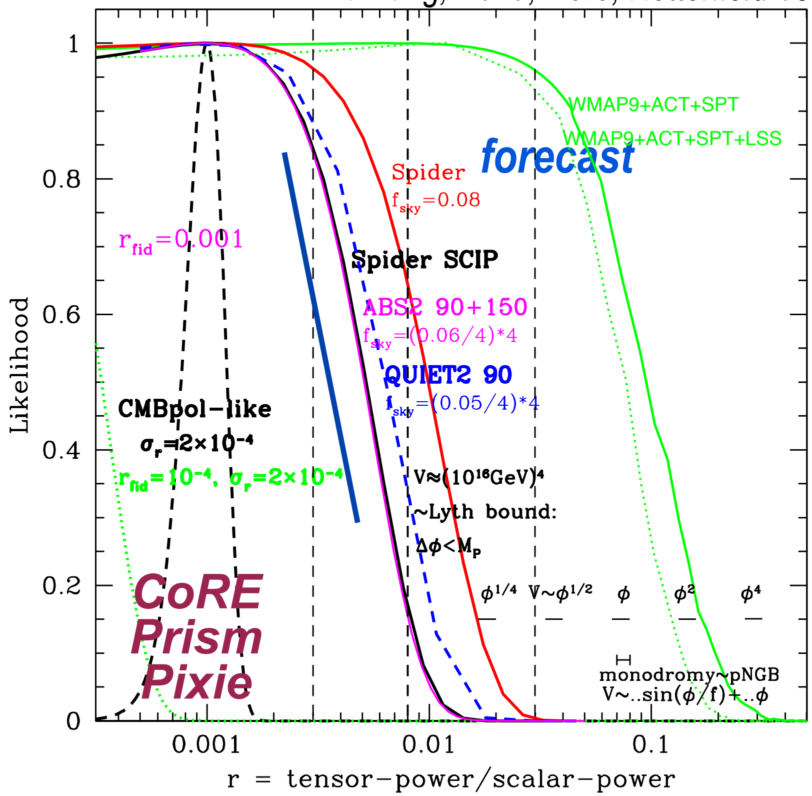
Spider24days+Planck2.5yr: r-n_t *matrix*-forecast for r=0.12 input for $m^2\varphi^2$ ($2\sigma_r$ ~0.02 including fgnds)

similar r-forecasts for ***ABS+, Quiet2, Keck, ..***

7 knot $\ln P_s$ +r-n_t for r=0



Farhang, Bond, Dore, Netterfield 13

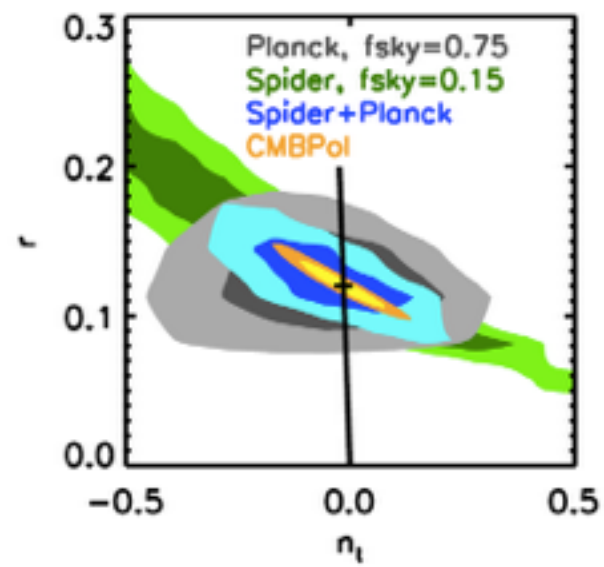


can get B-mode shapes but without the precision needed to check

$-n_t \approx r/8$

consistency

COBE-like errors on tilt



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

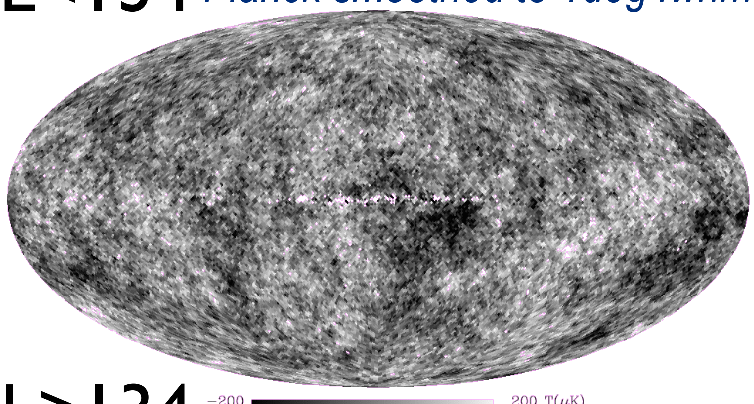
cf. *DBI inflation: non-quadratic kinetic energy*

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

P13 XXIV, XXII

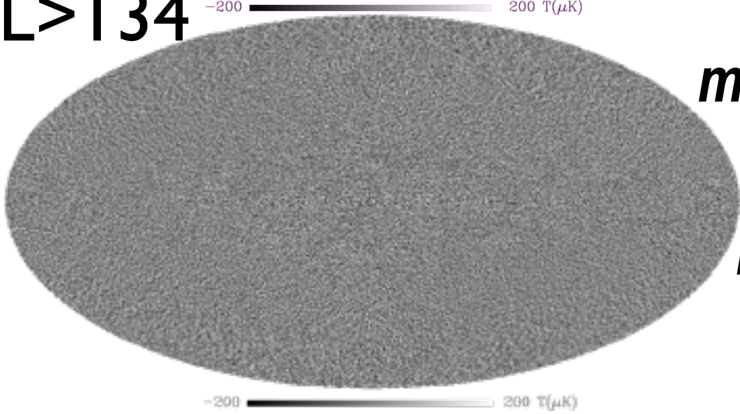
L<134 *Planck smoothed to 1deg fwhm*



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

cosmic/fundamental strings/defects *P13 XXV*

L>134



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

SIMPLICITY

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

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

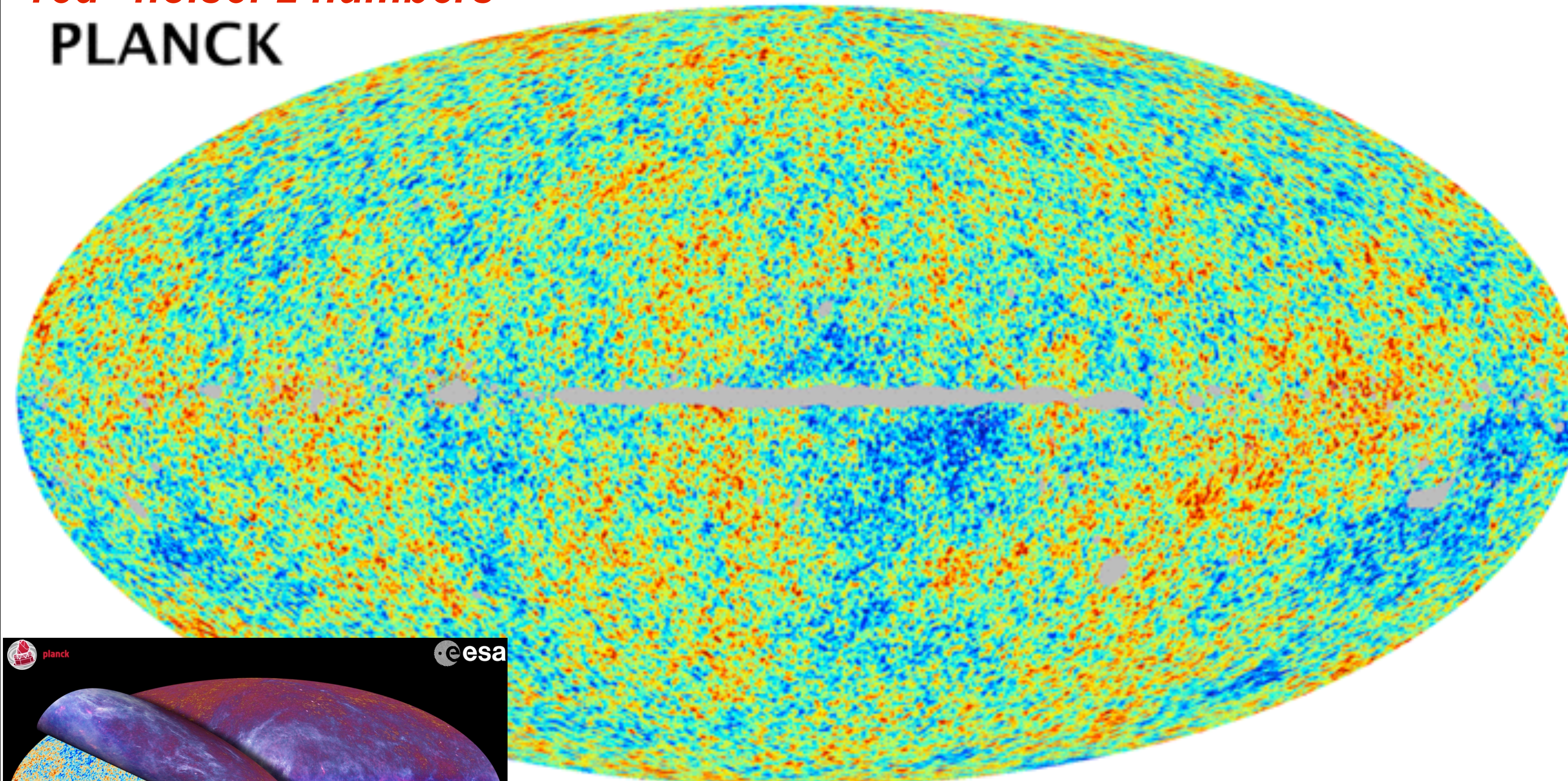
"red" noise: 2 numbers

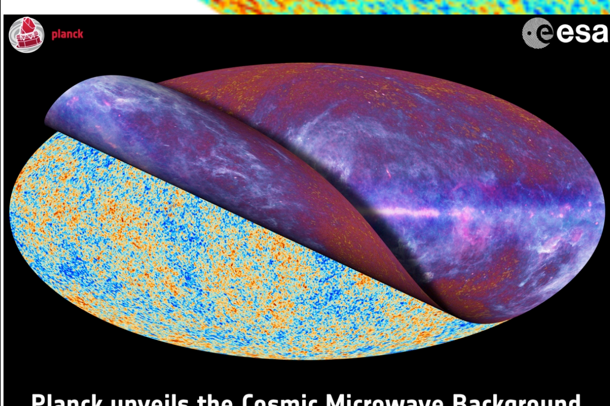
PLANCK

Planck 09 launch

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

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

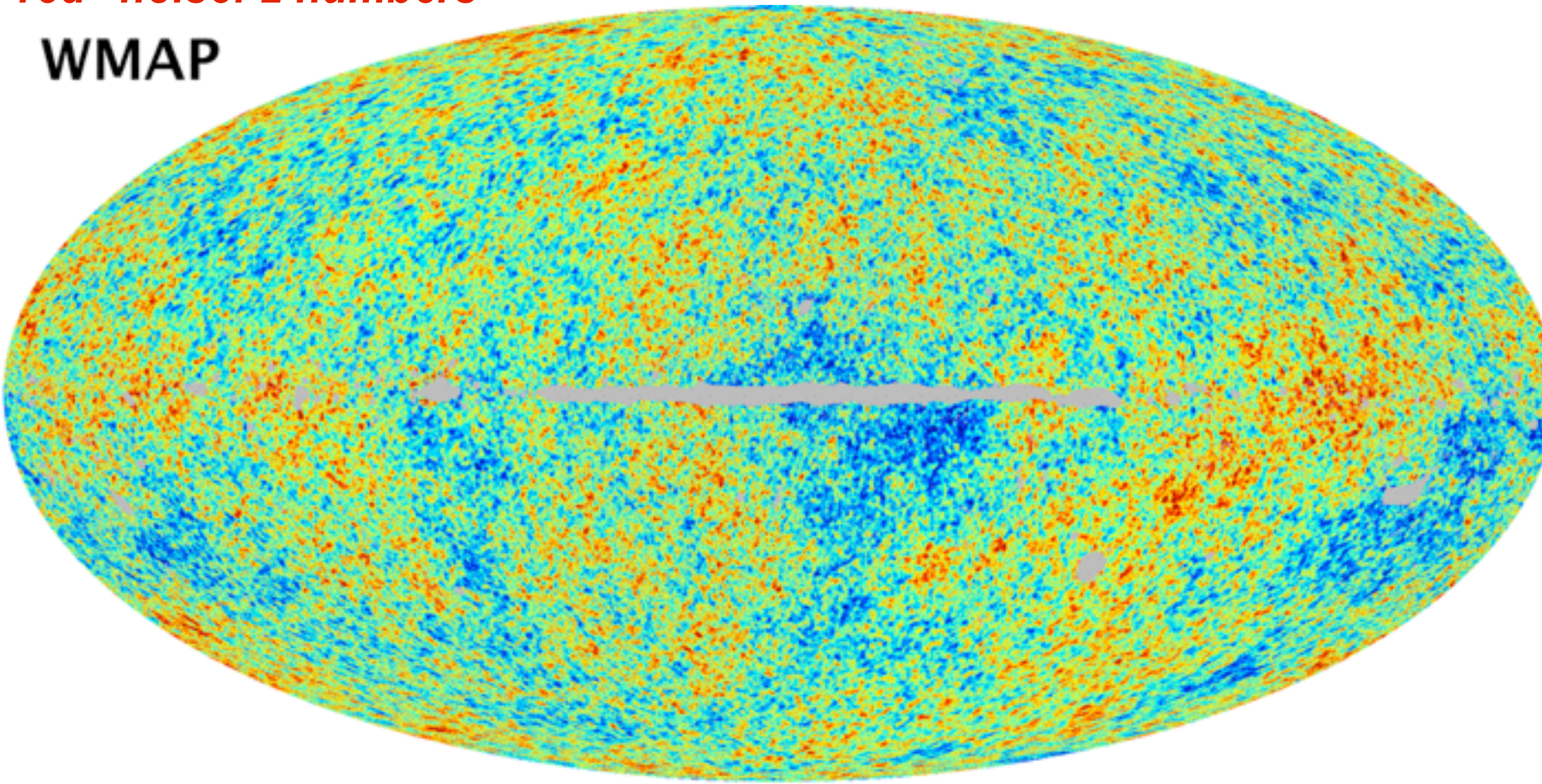
"red" noise: 2 numbers

WMAP

WMAP 01 launch

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

SIMPLICITY

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

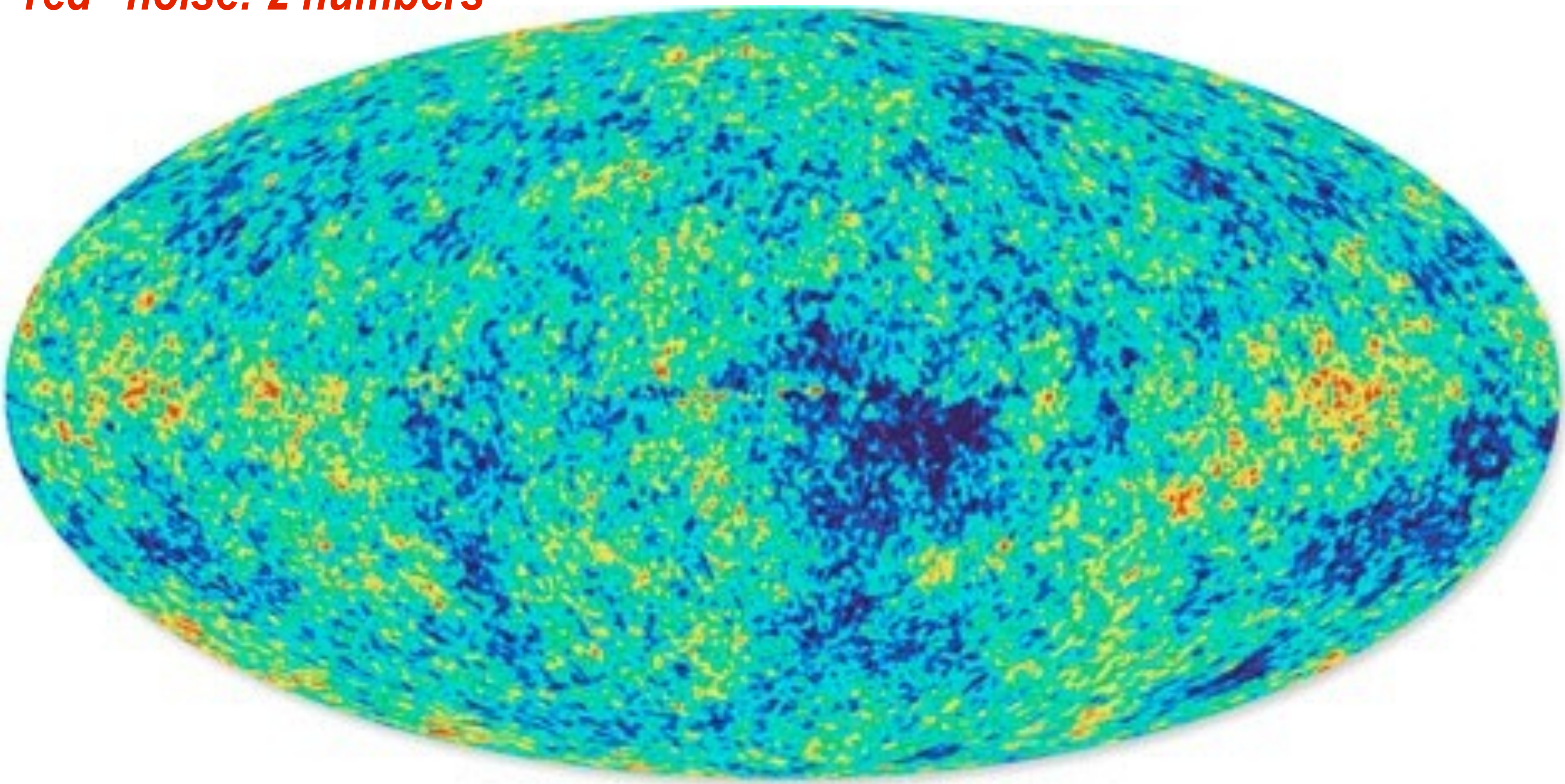
at $a \sim e^{-67+60} \sim 1/10^{30+25}$

"red" noise: 2 numbers

WMAP 01 launch

WMAP W-band, Template Cleaned

CMB-data Concordance



Cleaned with low-frequency templates only.

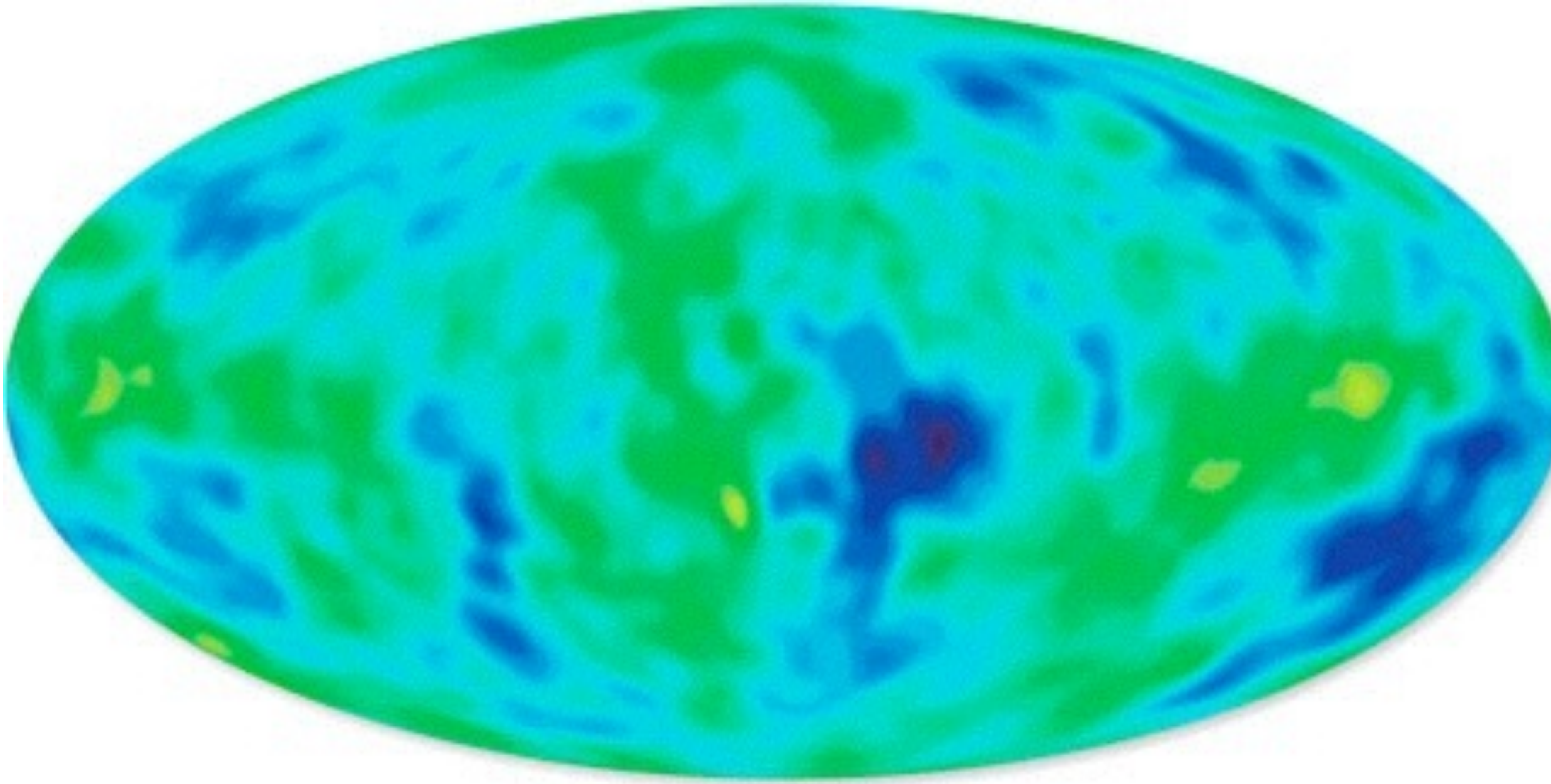
similar tremendous agreement with the much higher (5X) resolution ACT & SPT maps

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

COBE 89 launch

COBE

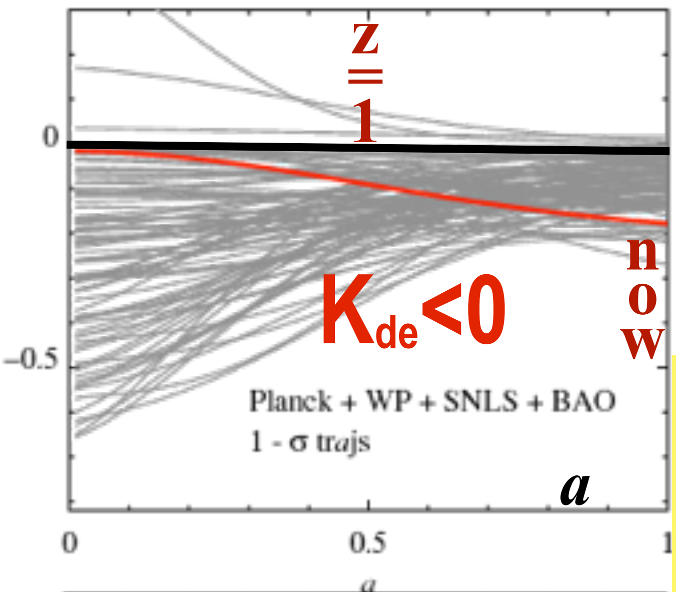
CMB-data Concordance

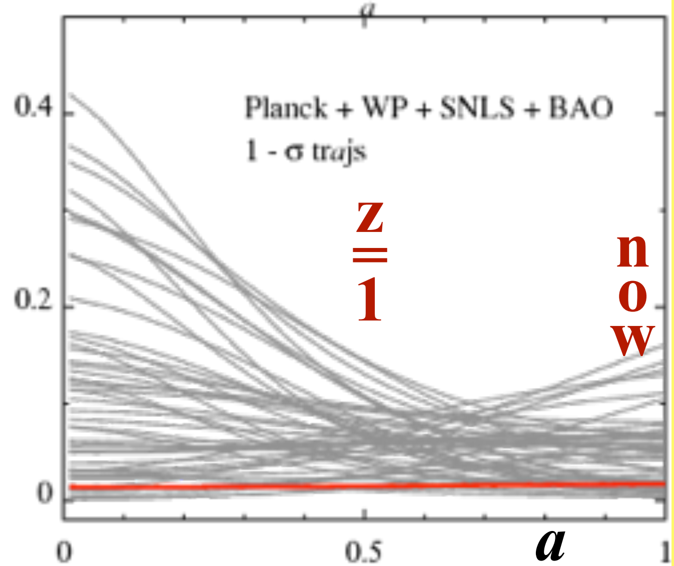


late-inflaton DE trajectories

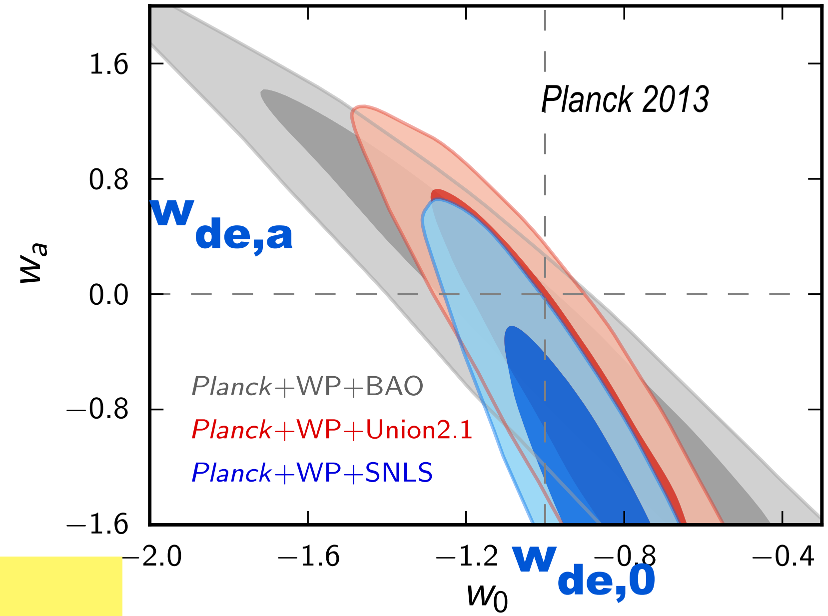
***informed* = 3-parameter $W_{de}(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)$**

Bond, Huang 2013





$1+W_{de} = -\, d\,ln\rho_{de} / d\,ln a^3$



$1+w_{de,0}$
$= -0.13\pm0.12$

if $w_{de,a}$

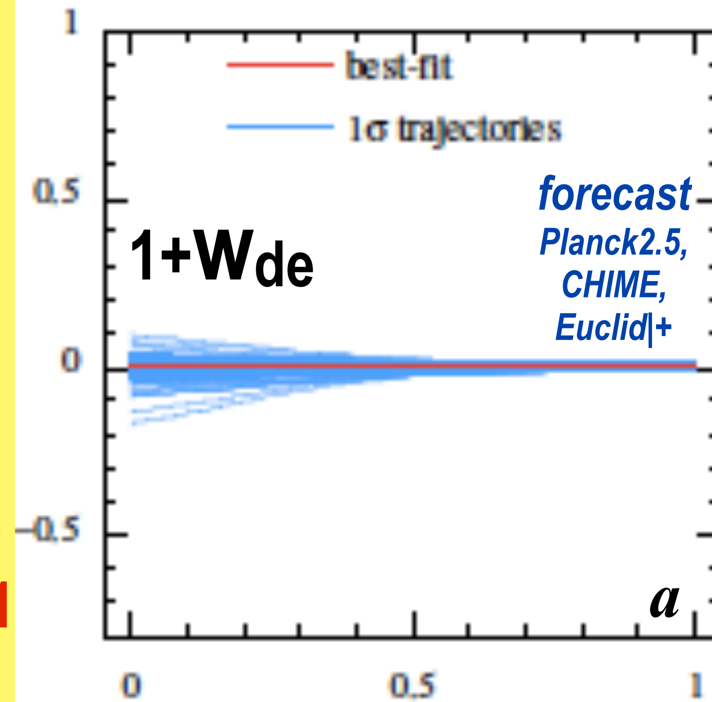
V_{de}, $\varepsilon_{de\infty}$

$\varepsilon_s = (d\ln V/d\psi)^2/4$
@pivot a_{eq}

= −0.25 +.20 −.26

P1.3+SNLS3 =0.0 +.21

future .005 +.031 −.025

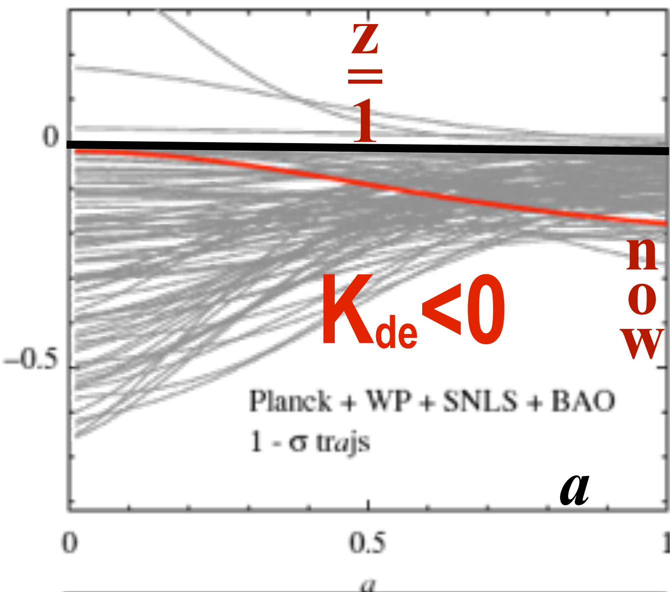


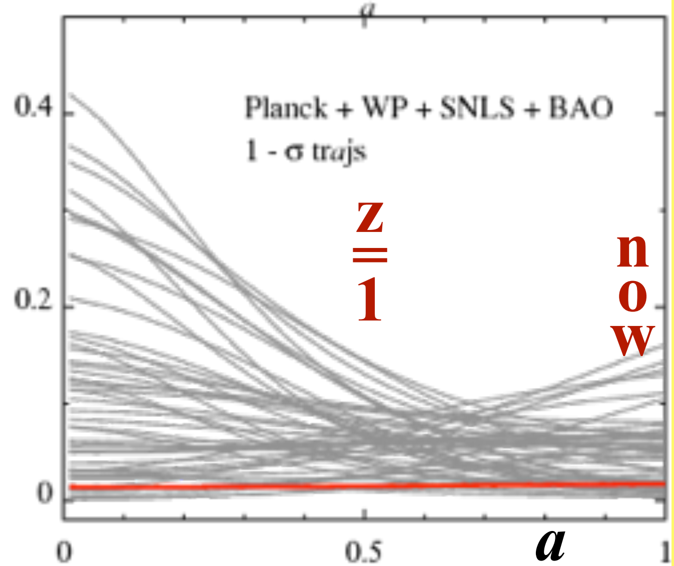
late-inflaton DE trajectories

***informed* = 3-parameter $W_{de}(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)$**

$1+W_{de} = -\, d\ln\rho_{de} / d\ln a^3$

Bond, Huang 2013





1+w=KE/PE <0!!

P13+SN1a w<-1 but CFHT-SNLS relative calibration change

$1+w_{de,0}$ = -0.13±0.12

if $w_{de,a}$

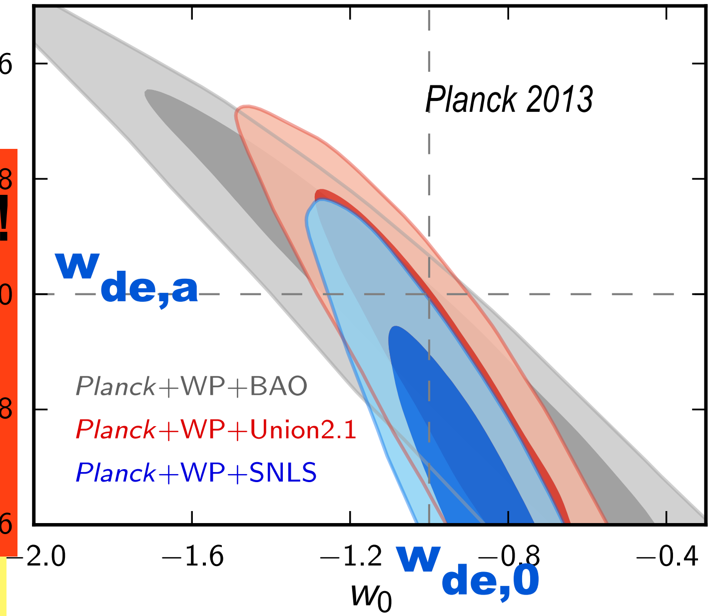
V_{de}, $\varepsilon_{de\infty}$

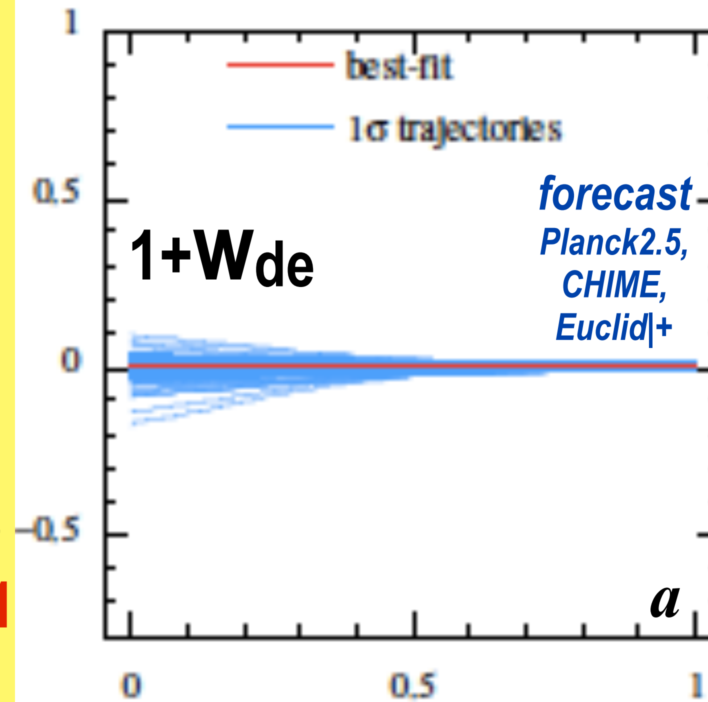
$\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

= -0.25 +.20 -.26

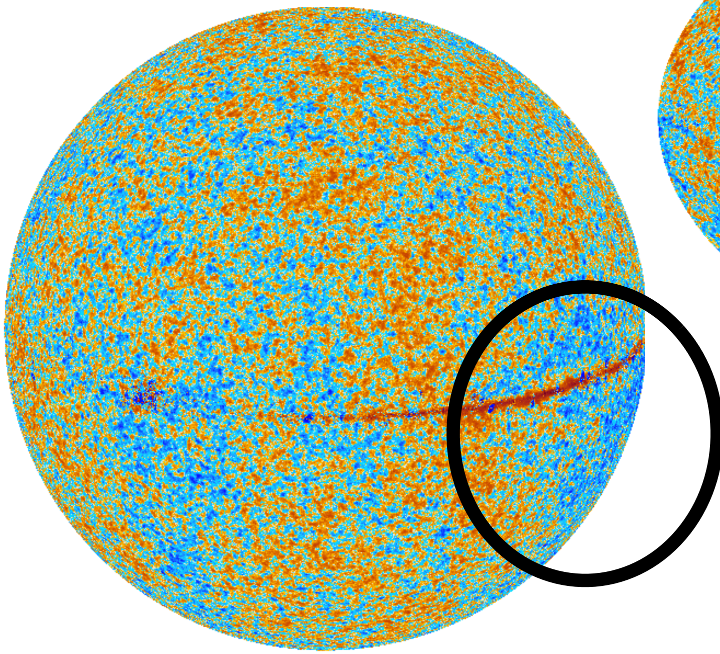
***P1.3+SNLS3* =0.0 +.21**

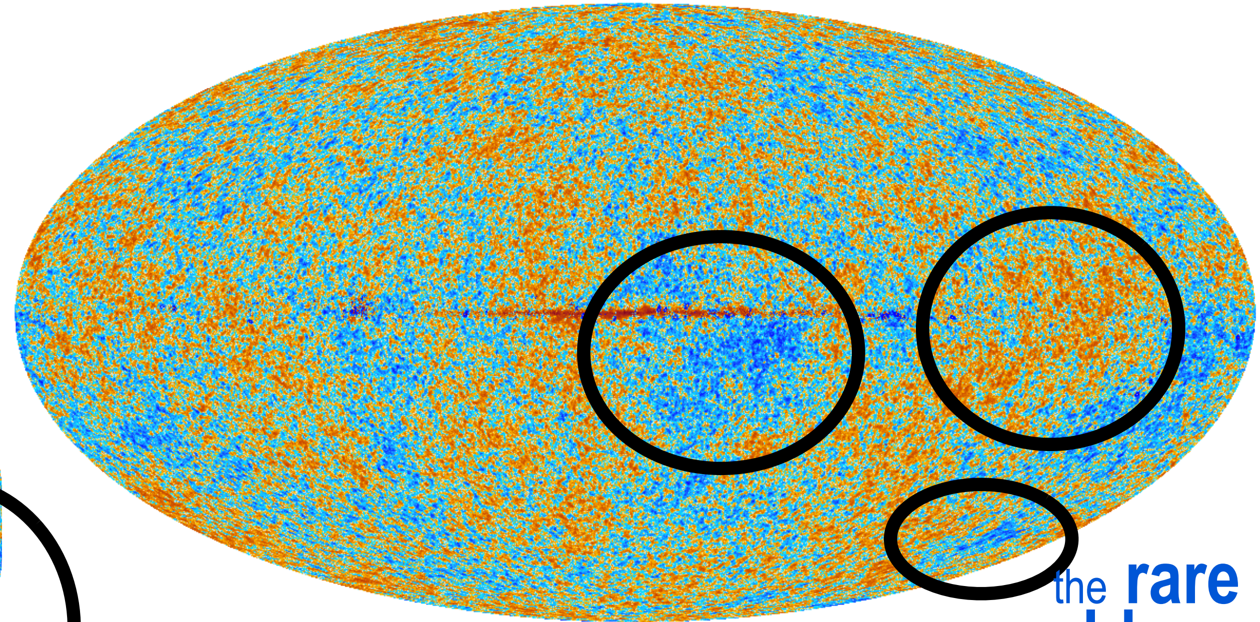
***future* .005 +.031 -.025**



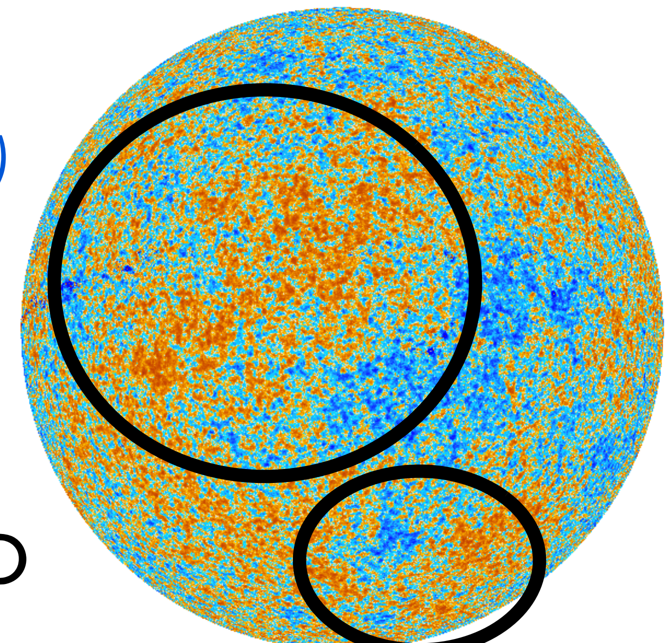


COMPLEXITY ***at***
$a \sim e^{-67}$?





the **rare cold spot**

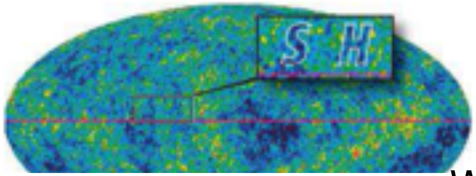


WHITEN => MASK => FILTER BANK *(SSG42 filter)*
=> EXTRACT PEAKS ***(hierarchical peak patches)***
filter **= extra dimension: scale space analysis ADS of our CFT**
hot & cold peaks ***agree with BE87*** ***Gaussian stats*** $n_{pk}(<\nu)$
PLANCK2013: 826', 105 peaks, coldest -4.97σ 1:497
WMAP7: 800', coldest -4.87σ significance 1:300

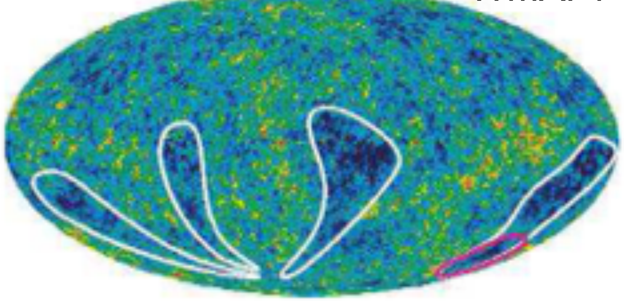
Grand Unified Theory of Anomalies TBD
Anomalies in Polarization? TBD

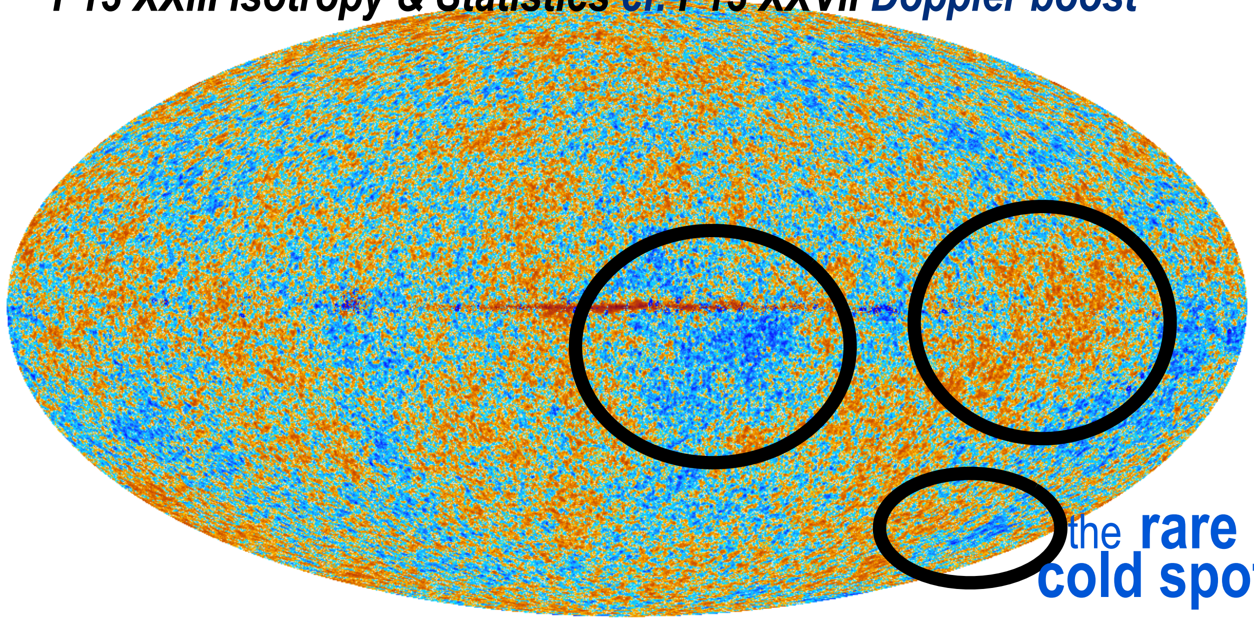
COMPLEXITY *at* a~e^{-67}?

P13 XXIII Isotropy & Statistics cf. P13 XXVII Doppler boost



WMAP7



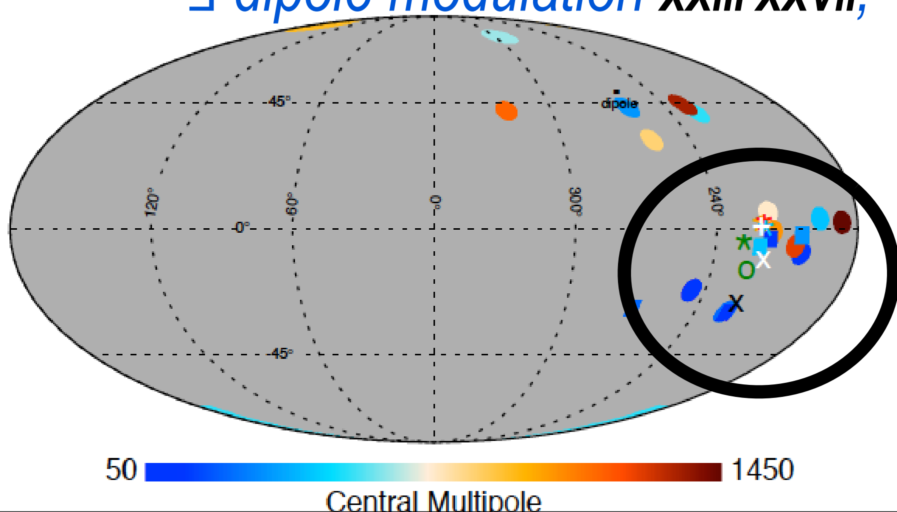


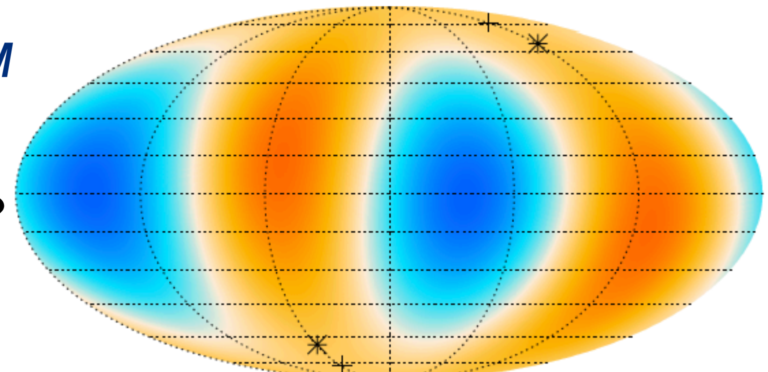
***C_L @L<200* is low cf. L~200-2000 forecast for tilted LCDM**

***$\Delta C_L / C_L$ @L<400* ~7% *(P13 XXIII & WMAP9)*,**

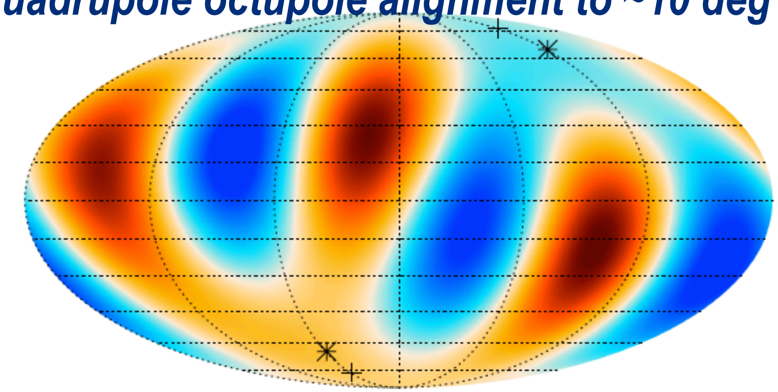
high L ***C_L*** asymmetry small **<0.2% with L_{max}=1500?**

∃ dipole modulation ***XXIII XXVII***, +?





quadrupole octupole alignment to ~10 deg



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*

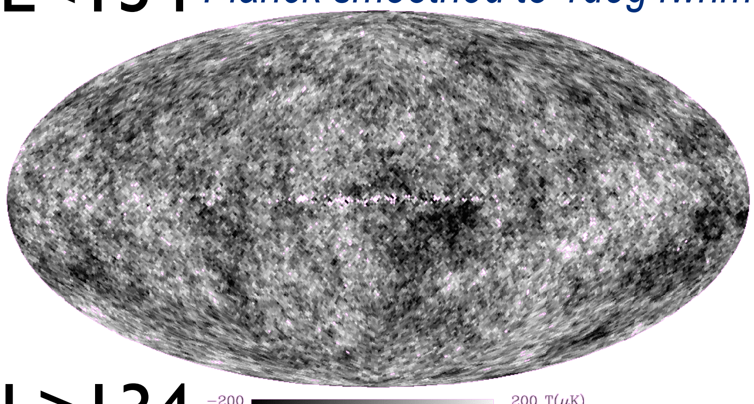
phonon ~ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ => $f_{NL*} = 3/5\, f_{NL} - 1$

$\zeta_{NL}(x)$=

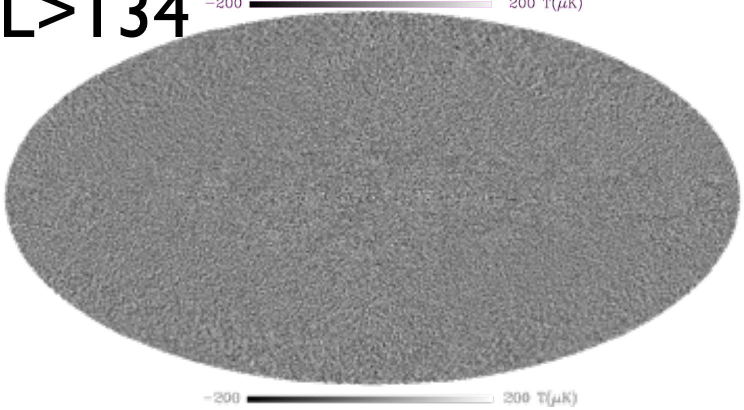
equilateral pattern &

orthogonal pattern

L<134 *Planck smoothed to 1deg fwhm*



L>134



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

from end-of-inflation & preheating chaos

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

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

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

bubble collisions ***CMB***

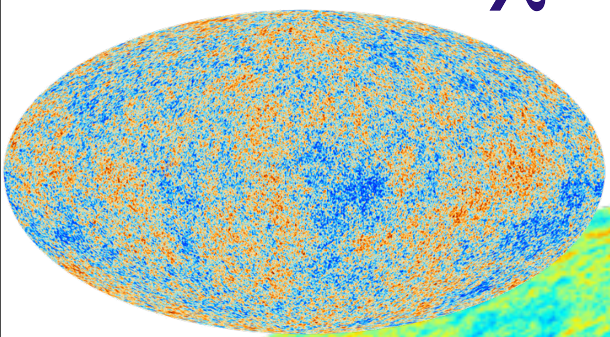
Euclidean SO(4) => real SO(3,1) => SO(2,1) collisions, oscillon broken

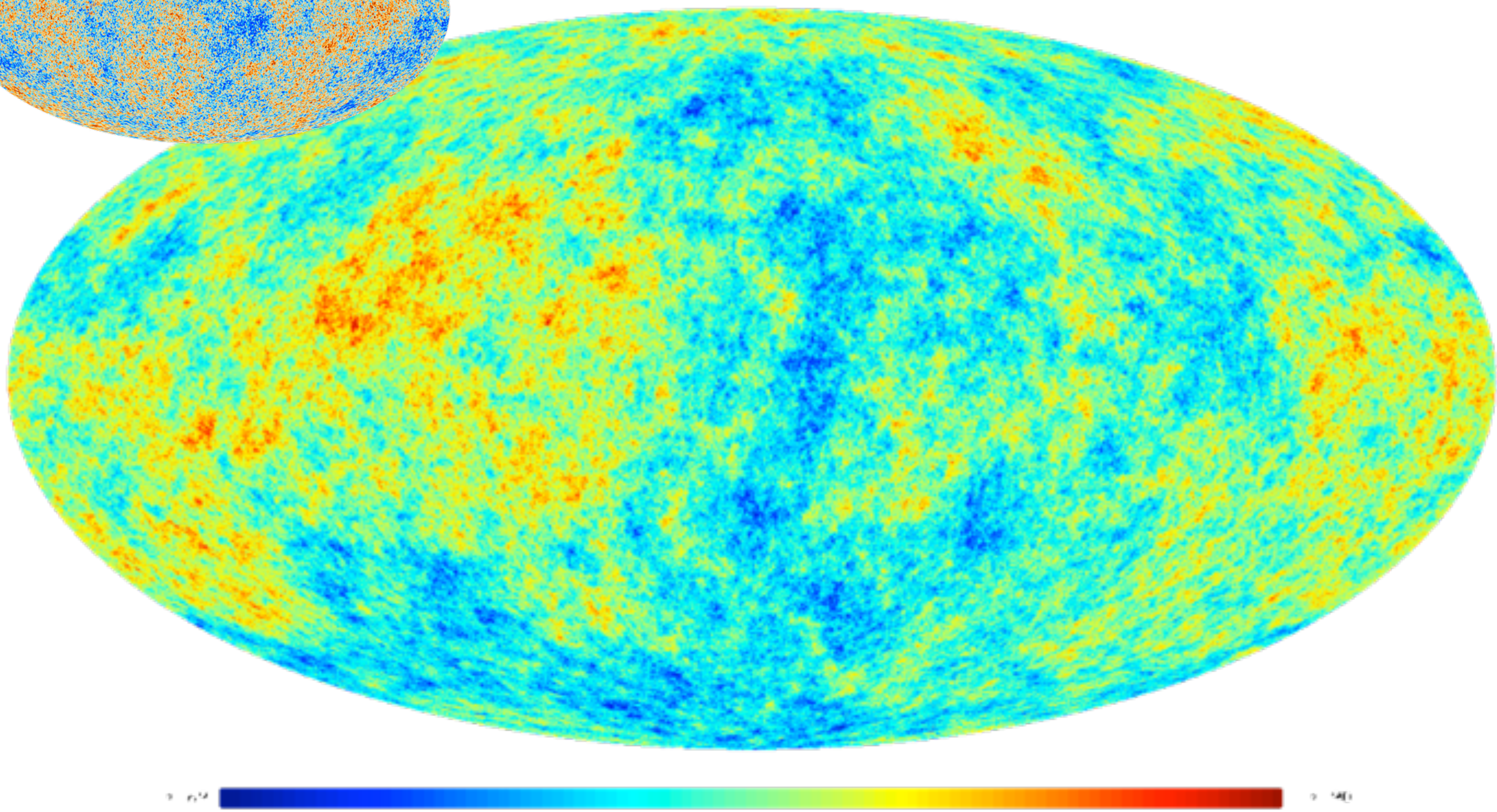
simulated sky with Gaussian inflaton-induced + **uncorrelated subdominant non-Gaussian isocon-modulated preheating**. Landscape-accessing super-horizon

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

Bond,Braden,Frolov,Huang13

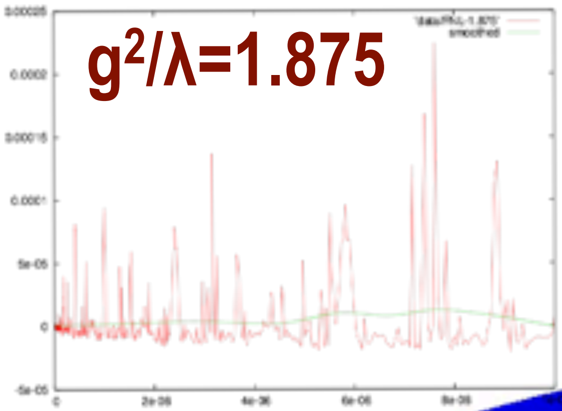
rare event tails

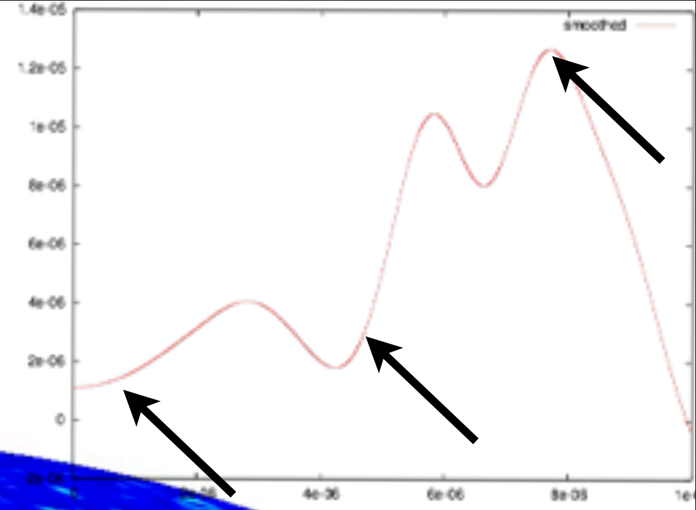


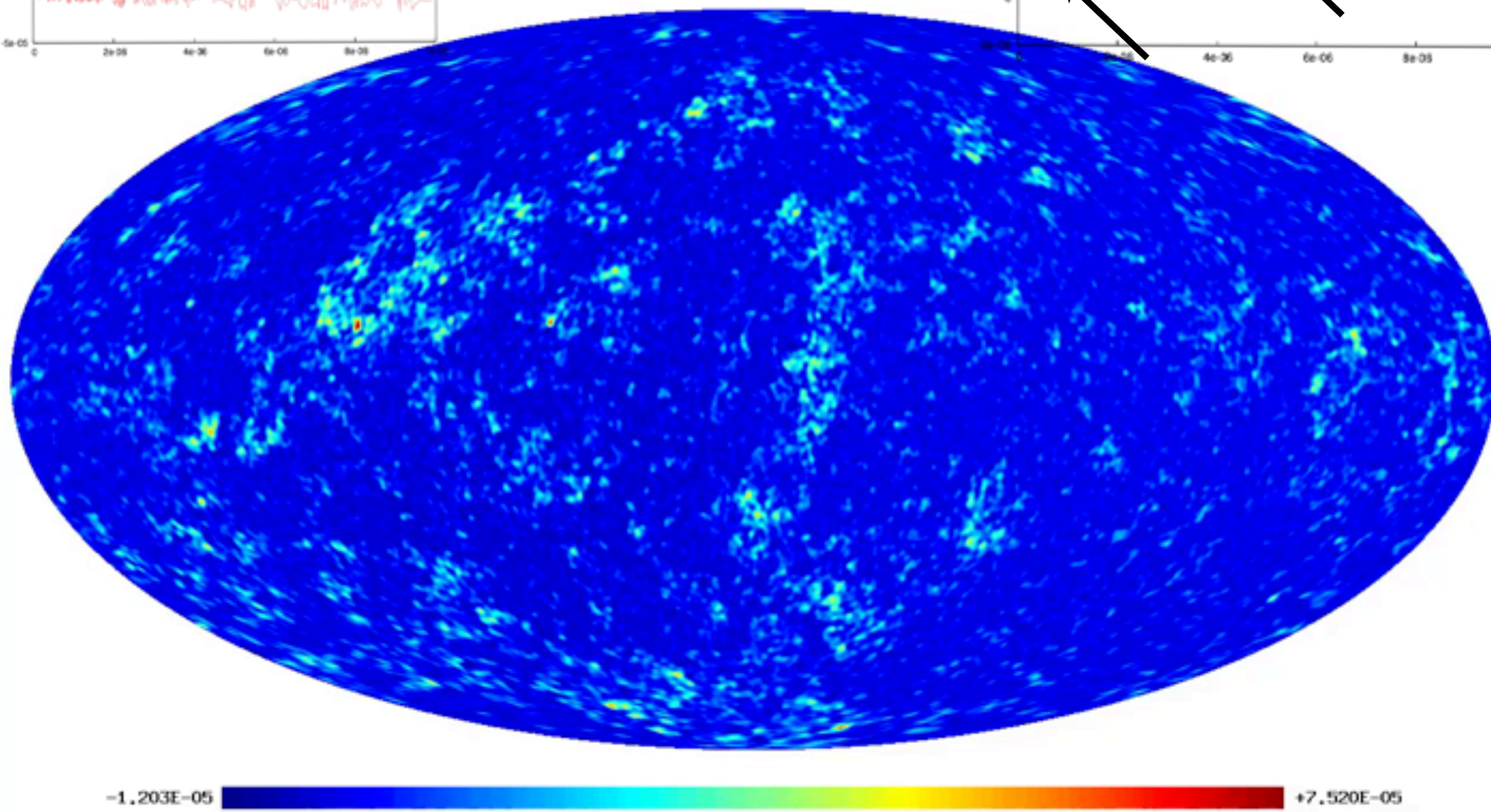


subdominant structure change as we scan $\chi > h$

Bond,Braden,Frolov,Huang13

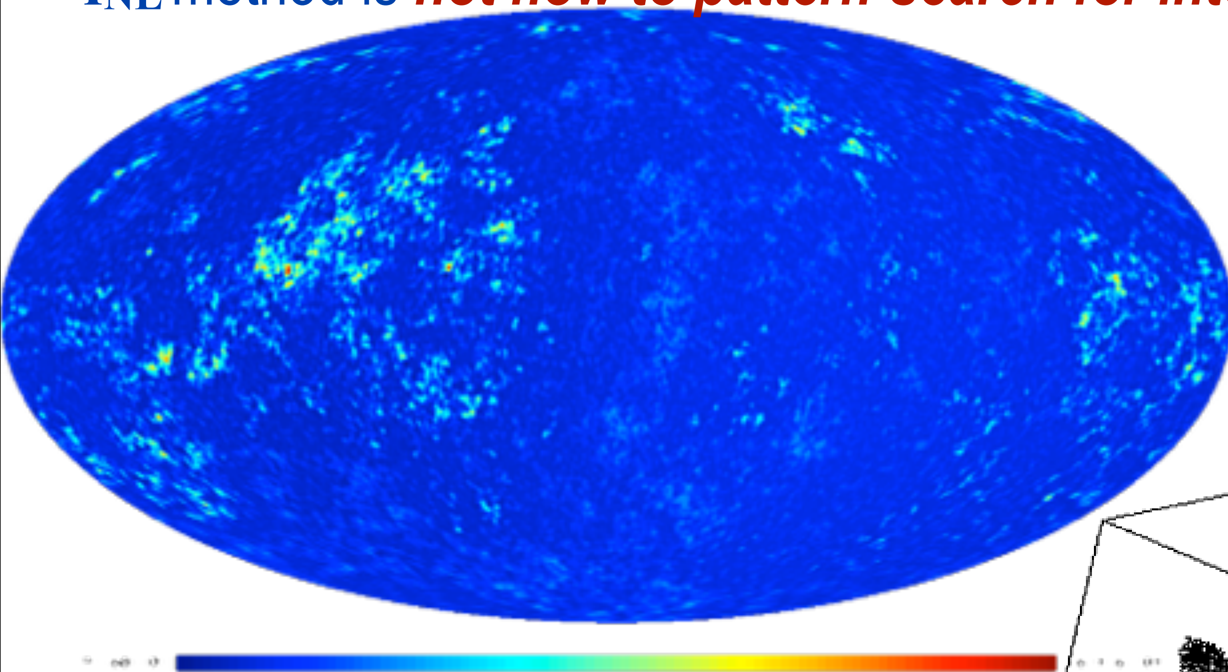




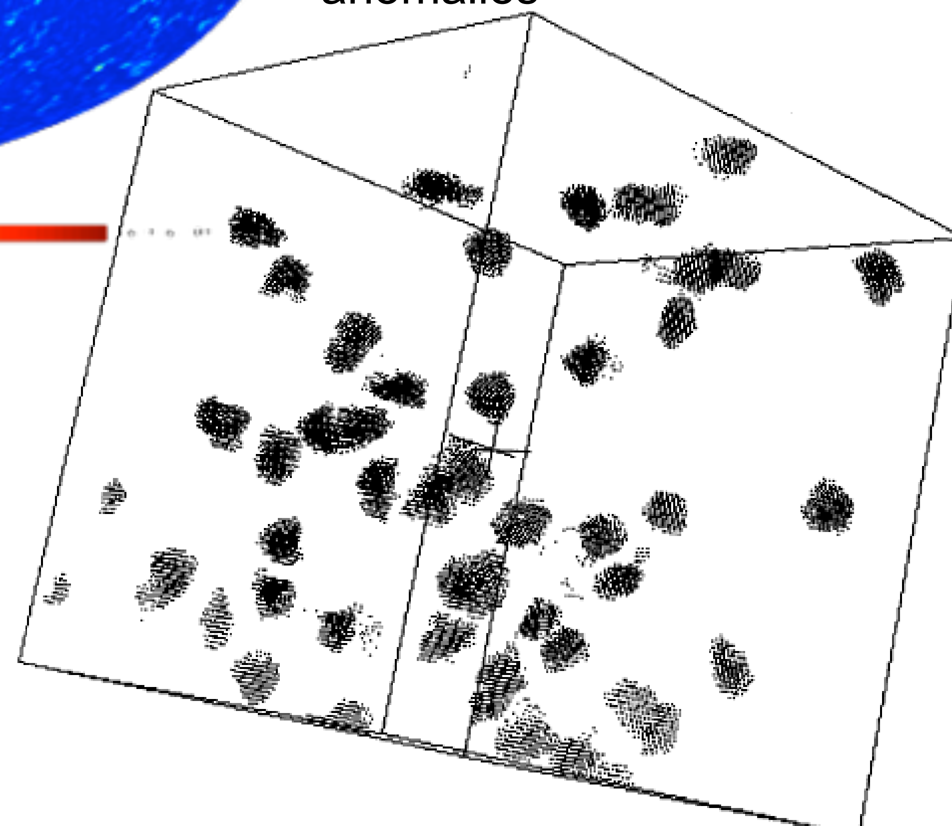


bispectrum & 3-point ~ $f_{sky,patches}^3$ => not overly constraining & standard f_{NL} method is ***not how to pattern-search for intermittent power bursts***

Bond,Braden,Frolov,Huang13

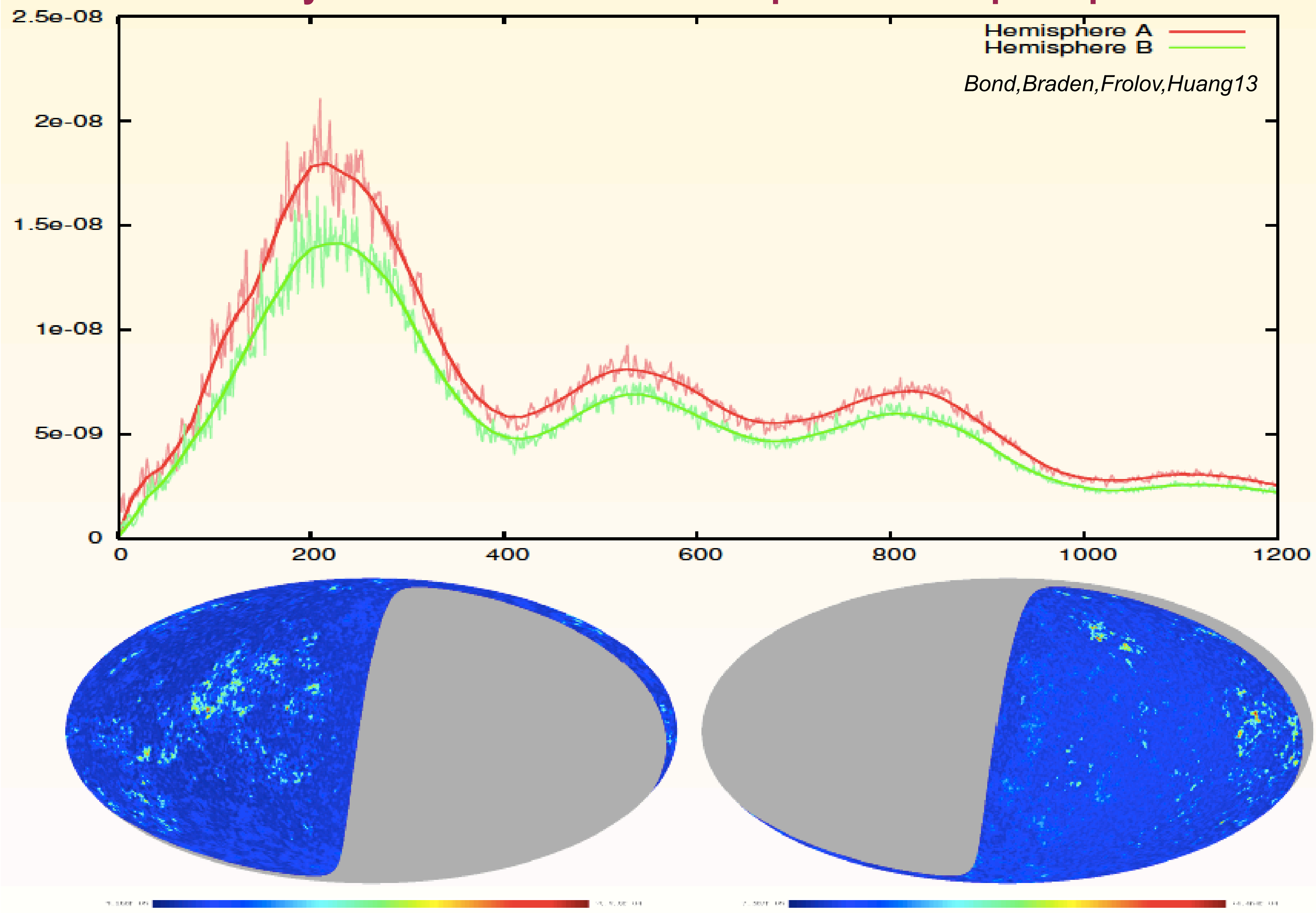


intermittency from steep threshold functions acting on a slightly red curvature field (gravitational potential) lead to very-large-scale splotch "anomalies"



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



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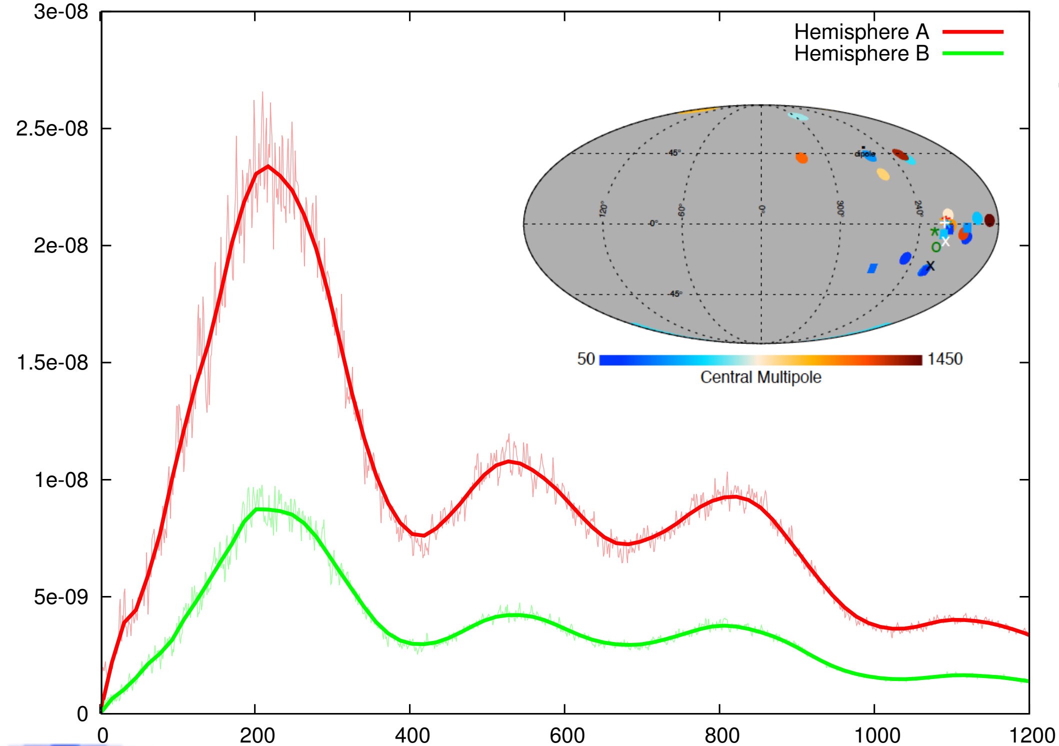
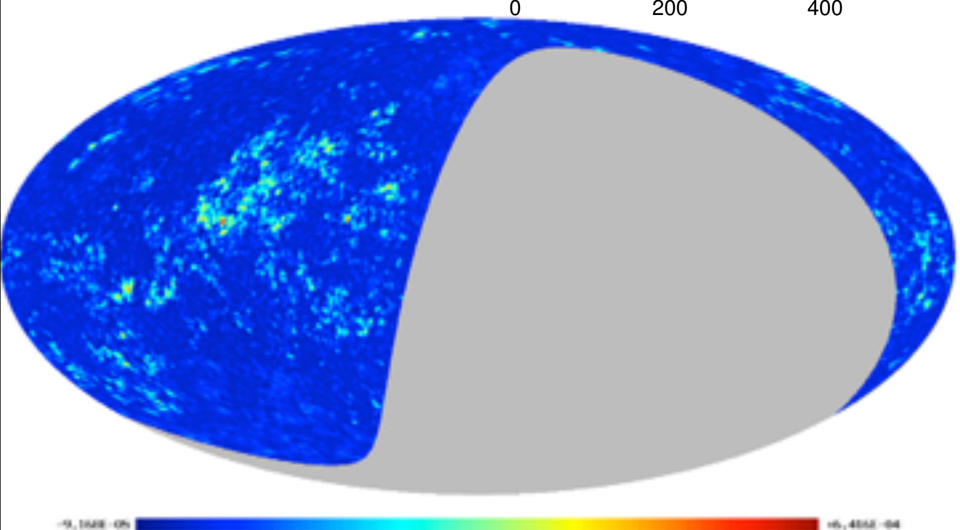
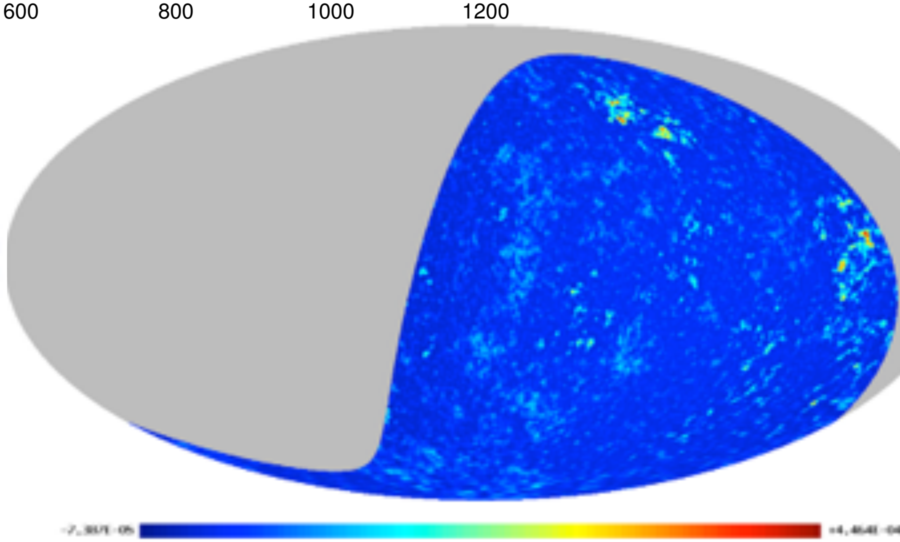


Bond,Braden,Frolov,Huang13

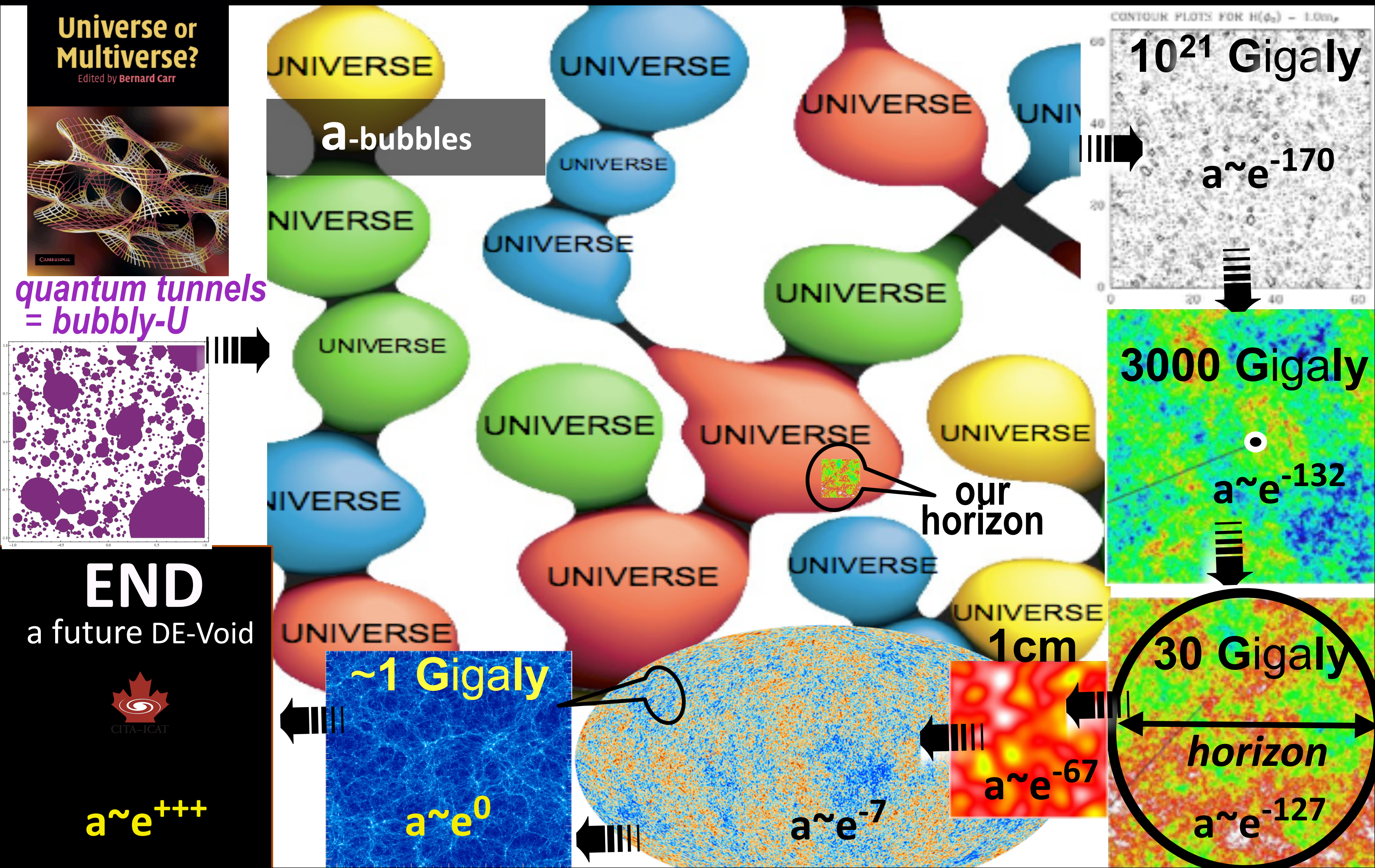
the achilles heel of intermittency models? TBD, *depends on damping & fuzziness, complicated computations B^2FH' are into*





ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information



Cosmic Observables for Fundamental Physics

Early & Late Universe: from Simplicity to Complexity

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

Dick Bond

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

∃ acceleration then & now {a, H ~$\rho^{1/2}/M_p$, ε=-dlnH/dlna =1+q=3/2(1+w)}

∃ inflation then (a ~ e^{-67} to $e^{-67-55++}$ < 10^{-35} s) & now (a ~1 to e^{-1+} 10^{17} s)

∃ dark potential energy then $V_{de} \lesssim (10^{25.3}\ ev)^4$ & now $V_{de} \sim (10^{-2.9}\ ev)^4$

∃ dark kinetic energy then $K_{de} \lesssim (.003)V_{de}$ & now? $K_{de} \sim$ (-0.1 !! to 0) V_{de}

modified gravity = de: conformally equivalent to Einstein gravity + late-time inflaton + fifth forces matter-de interaction (~ $\rho_m - 3p_m = Trace T_m$)

∃ (zero-point) quantum fluctuations => the origin of observed cosmic structure

∃ curvature fluctuations. scalar: adiabatic + isocons, tensor: gravity wave

∃ phonons in earlyU $\ln(\rho a^{3(1+w)})/3(1+w)$ = scalar adiabatic+ inflaton is a collective field

the driven "vacuum" accelerates. but differentially? yes, both then & now

we compute it, but we don't really understand it: vacuum tightly coupled to gravity

we know more about early-inflaton dynamics than late-inflaton dynamics!!

10 e-folds then cf. 1 e-fold now: because resolution (comoving wavenumber k) is related to dynamics (Ha) then, but not now

the quantum fluctuations here & now are not important for cosmic structure

END