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

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

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

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

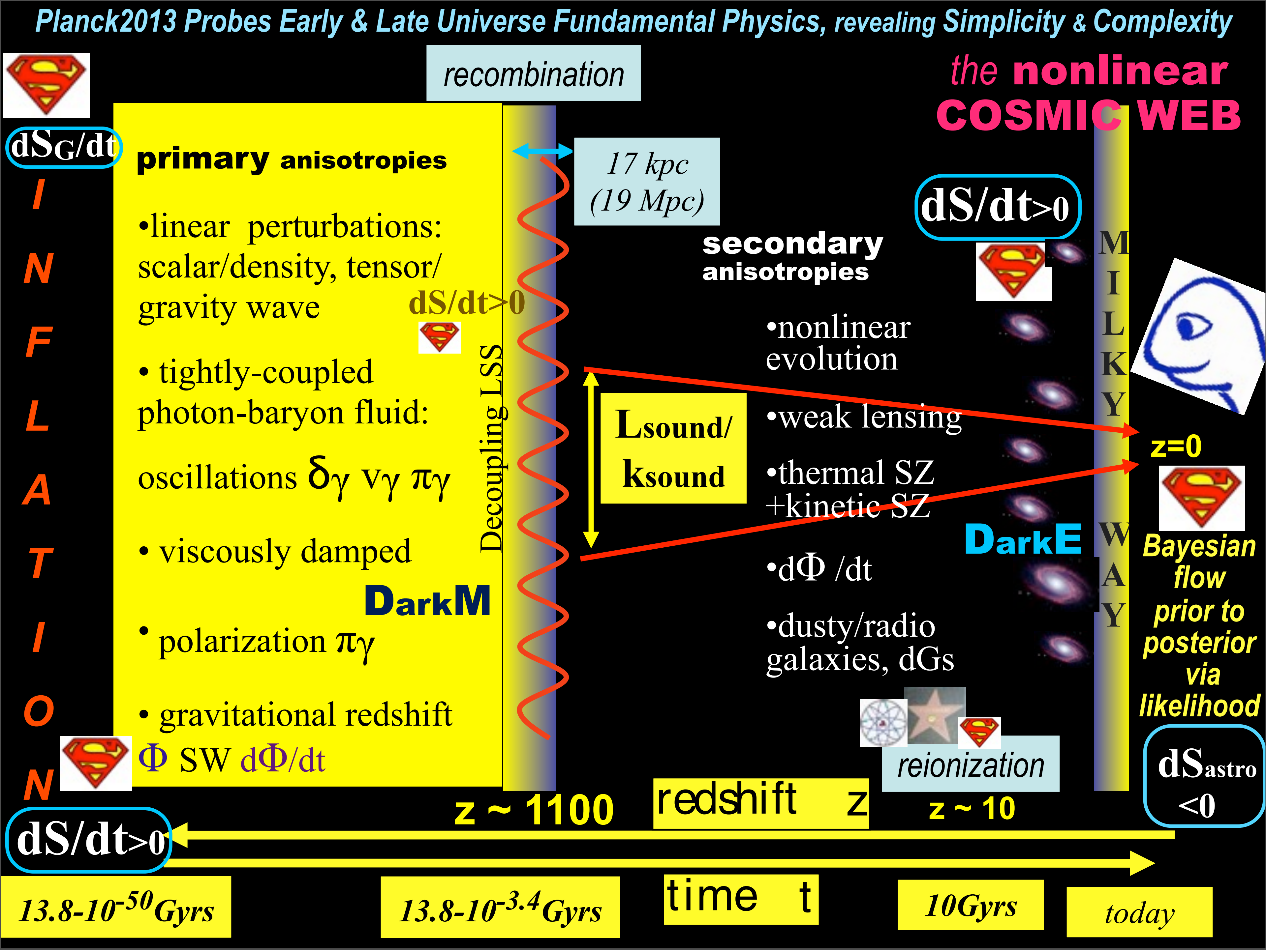
Planck 2013 results. XV. CMB power spectra and likelihood

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


Planck2013 Probes Early & Late Universe Fundamental Physics, revealing Simplicity & Complexity
recombination
the nonlinear COSMIC WEB
dSG/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
secondary anisotropies
dS/dt>0
•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
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
13.8-10^-50 Gyrs
13.8-10^-3.4 Gyrs
time t
10Gyrs
today

Fundamental Physics from the *Planck* Satellite

Early & Late Universe: from Simplicity to Complexity

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

Dick Bond

25 years cifar

∃ *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} ≲ ($10^{25.3}$ ev)^4 & now V_{de} ~ ($10^{-2.9}$ ev)^4*

∃ *dark kinetic energy then K_{de} ≲(.003)V_{de} & now? K_{de} ~ (-0.1 !! to 0) V_{de}*

modified gravity = de: conformally equivalent to Einstein gravity + late-time inflaton + fifth forces matter-de interaction (~ ρ_m - 3p_m=TraceT_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*

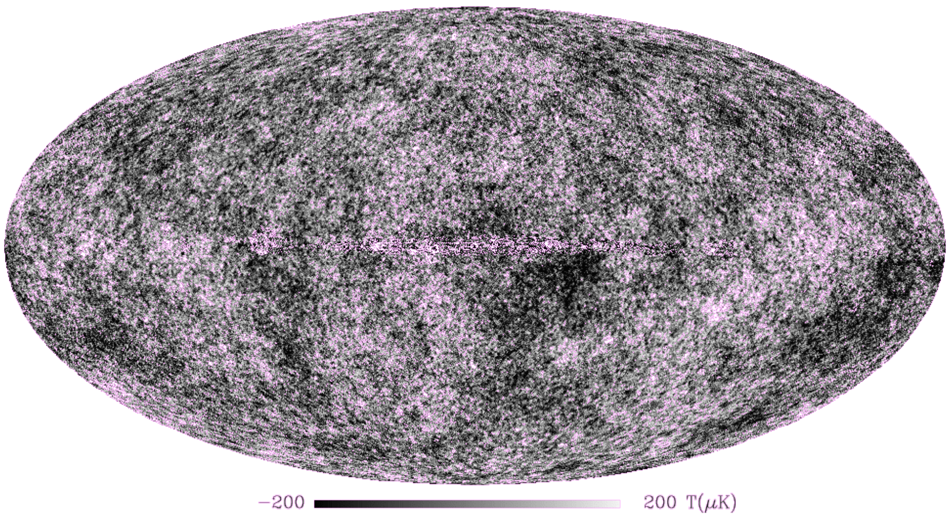
the driven "vacuum" accelerates. but differentially? yes, both then & now

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!!

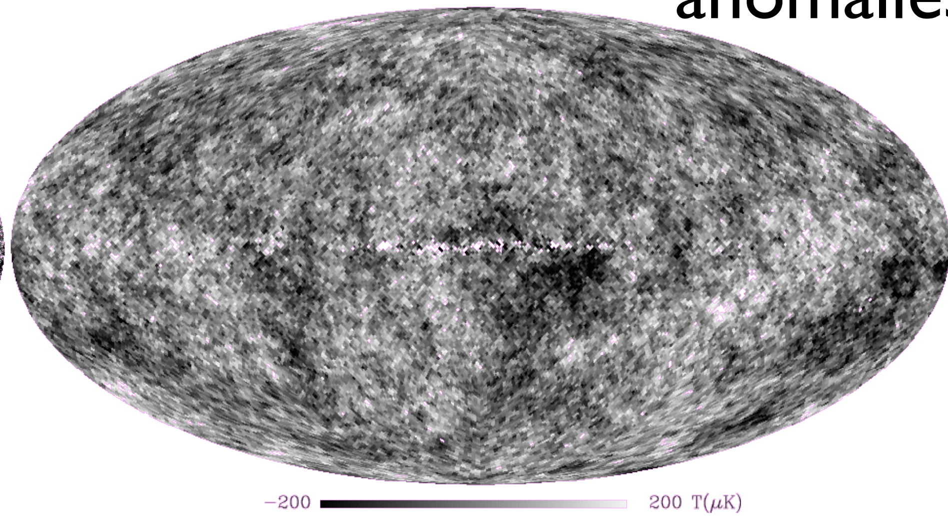
10 e-folds then cf. 1 e-fold now: because resolution (comoving wavenumber k) is related to dynamics (Ha) then, but not now

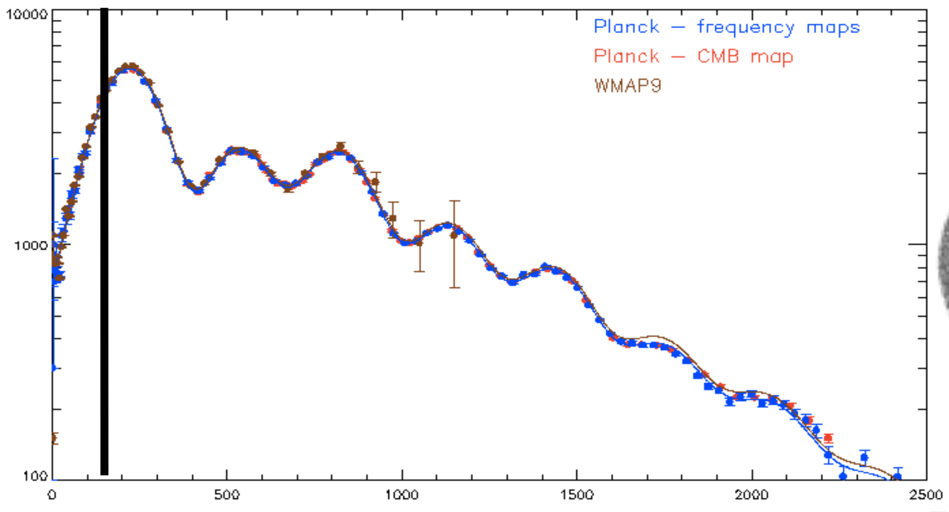
the quantum fluctuations here & now are not important for cosmic structure *full Planck resolution*



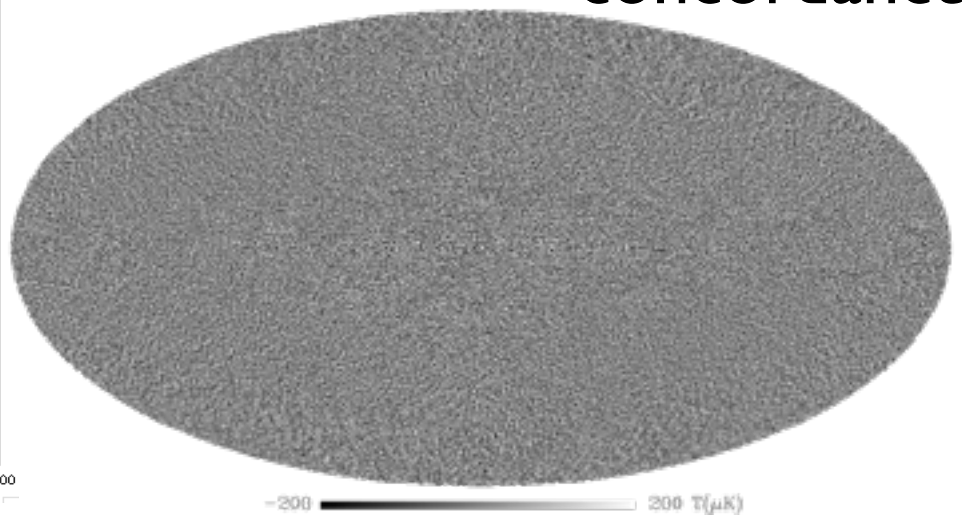
Planck smoothed to 1deg fwhm

L<134 anomalies





L>134 concordance



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

SIMPLICITY

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

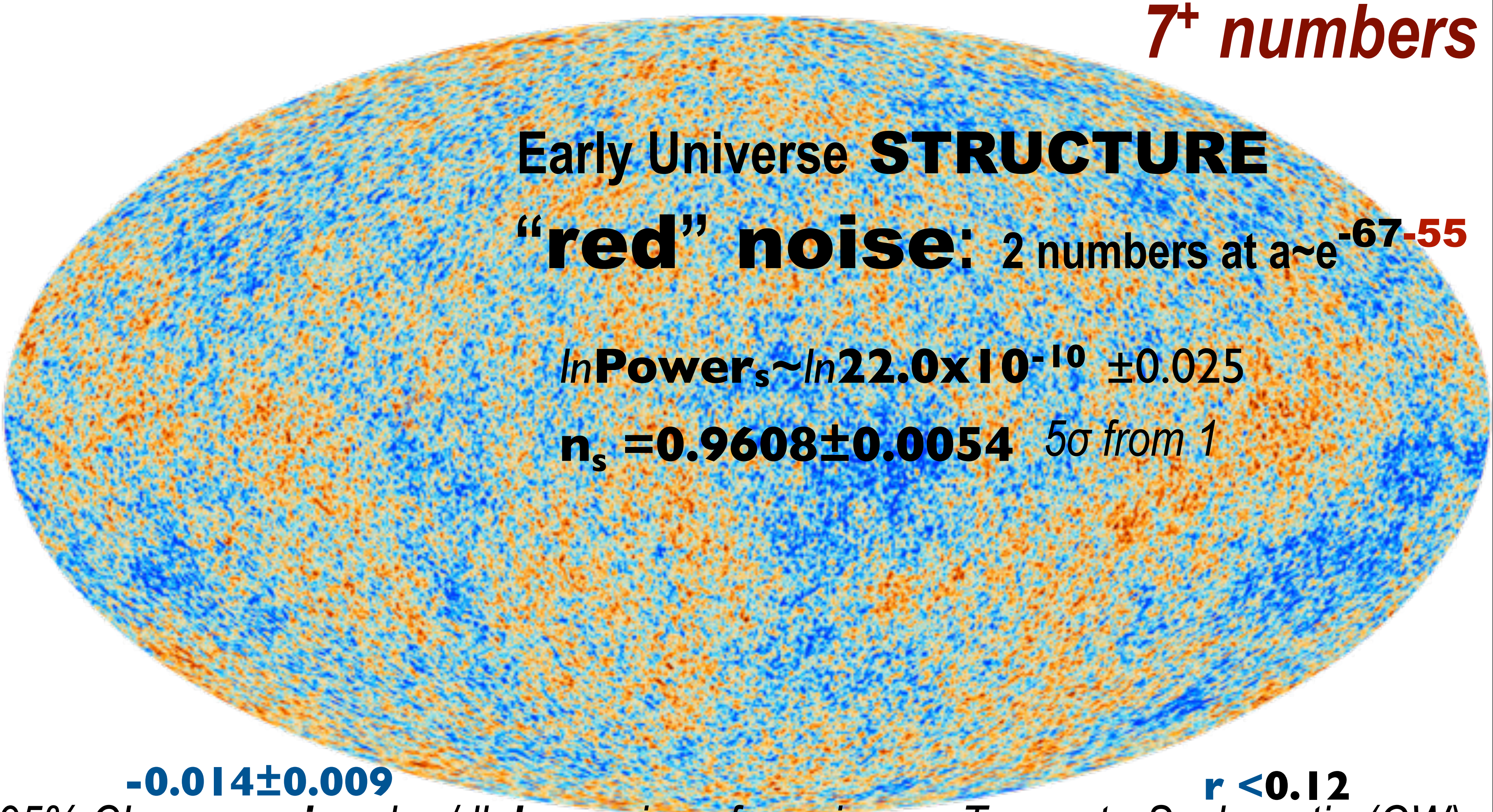
at $a \sim e^{-67-60} \sim 1/10^{30+25}$

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: 2 numbers at $a \sim e^{-67-55}$

$ln\mathbf{Power_s} \sim ln\mathbf{22.0 \times 10^{-10}} \pm 0.025$

$\mathbf{n_s = 0.9608 \pm 0.0054}$ *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%)*

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\Omega_{er}h^2$ $\Omega_{m\nu}h^2$

T_{cmb} $m_{neutrinos}$ $\theta \sim \ell_s^{-1}$

n_s $r = A_t/A_s$

$\ln A_s$ $dn_s/d\ln k$ n_t

$\sim \ln \sigma_8^2$

Inflation Histories
(CMBall+LSS+SN+WL)

***P1.3** like, **ACT**12 final spectra & params, 1500 sq deg, ~600 for params, **SPT**12 2540 sq deg*

Calabrese+13 ACT12+SPT12+WMAP9

standard inflation space: n_s $dn_s/d\ln k$ r =T/S @k-pivots f_{nl}

*ln***Power**$_s$~*ln***22.0x10^{-10}** ±0.025 **P**1.3+ *ln***22x10^{-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) -0.028 ± 0.010 SPT12+

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

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c $\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$\Omega_{er}h^2$ $\Omega_{m\nu}h^2$ X_{He}

T_{cmb} $m_{neutrinos}$ $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

Inflation Histories
(CMBall+LSS+SN+WL)

new parameters: **trajectory probabilities for early-inflatons & late-inflatons (partially) blind cf. informed "theory" priors**

P1.3 *like,* ***ACT****12 final spectra & params, 1500 sq deg, ~600 for params,* ***SPT****12 2540 sq deg*
Calabrese+13 ACT12+SPT12+WMAP9

standard inflation space: n_s $dn_s/d\ln k$ r =T/S @k-pivots f_{nl}

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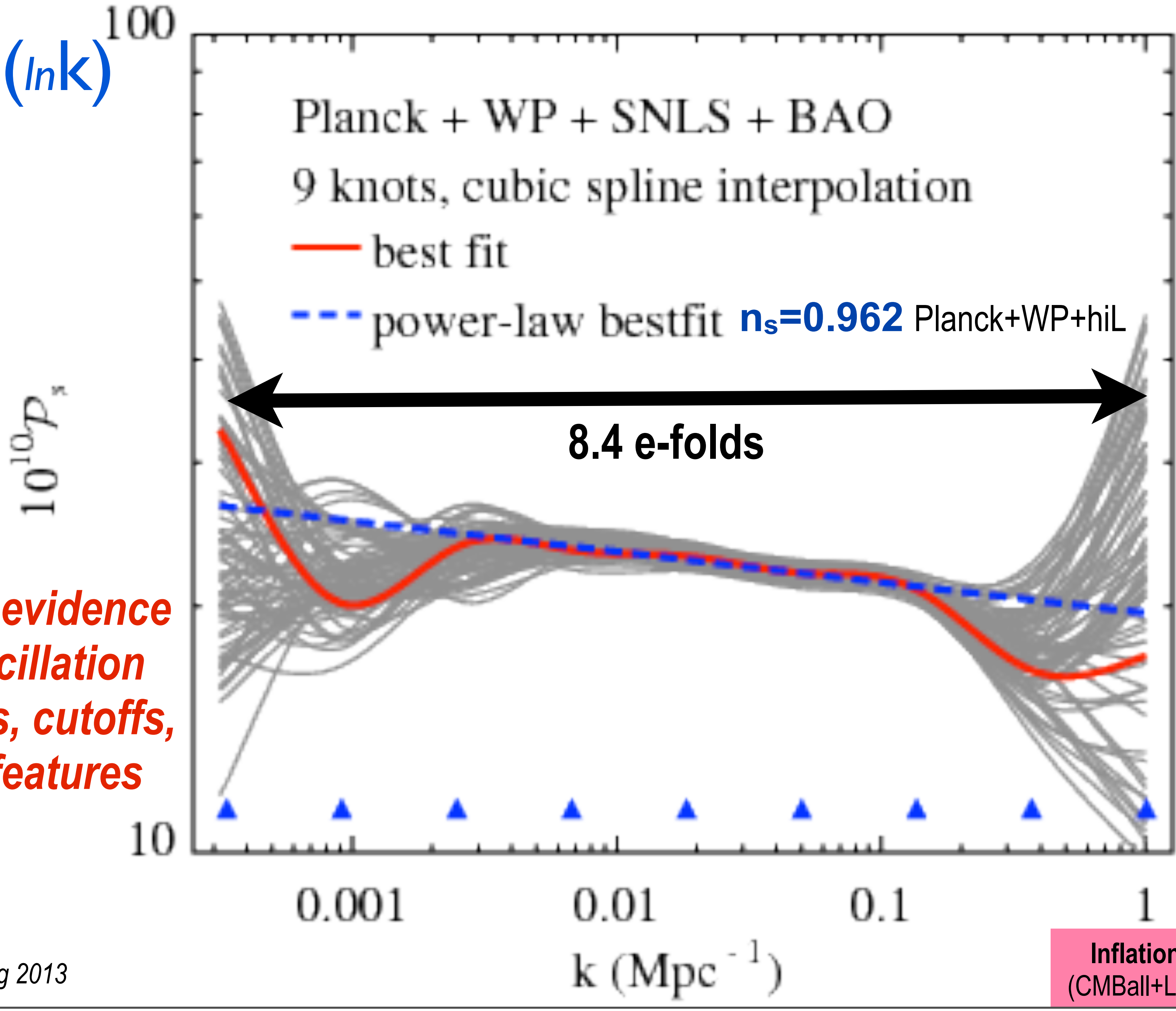
trajectories: ln **Primordial power spectra** *(ln***k***)*, **n_s***(***k***)*, **ε**(Ha)=3/2(1+w_t), V(ψ), ψ(a) scan $\ln \mathbf{P_s}(\ln k)/A_s$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$; consistency => reconstruct $\boldsymbol{\varepsilon}(\ln \mathbf{Ha})$, $\mathbf{V}(\psi)$

$\ln P_s(\ln k)$

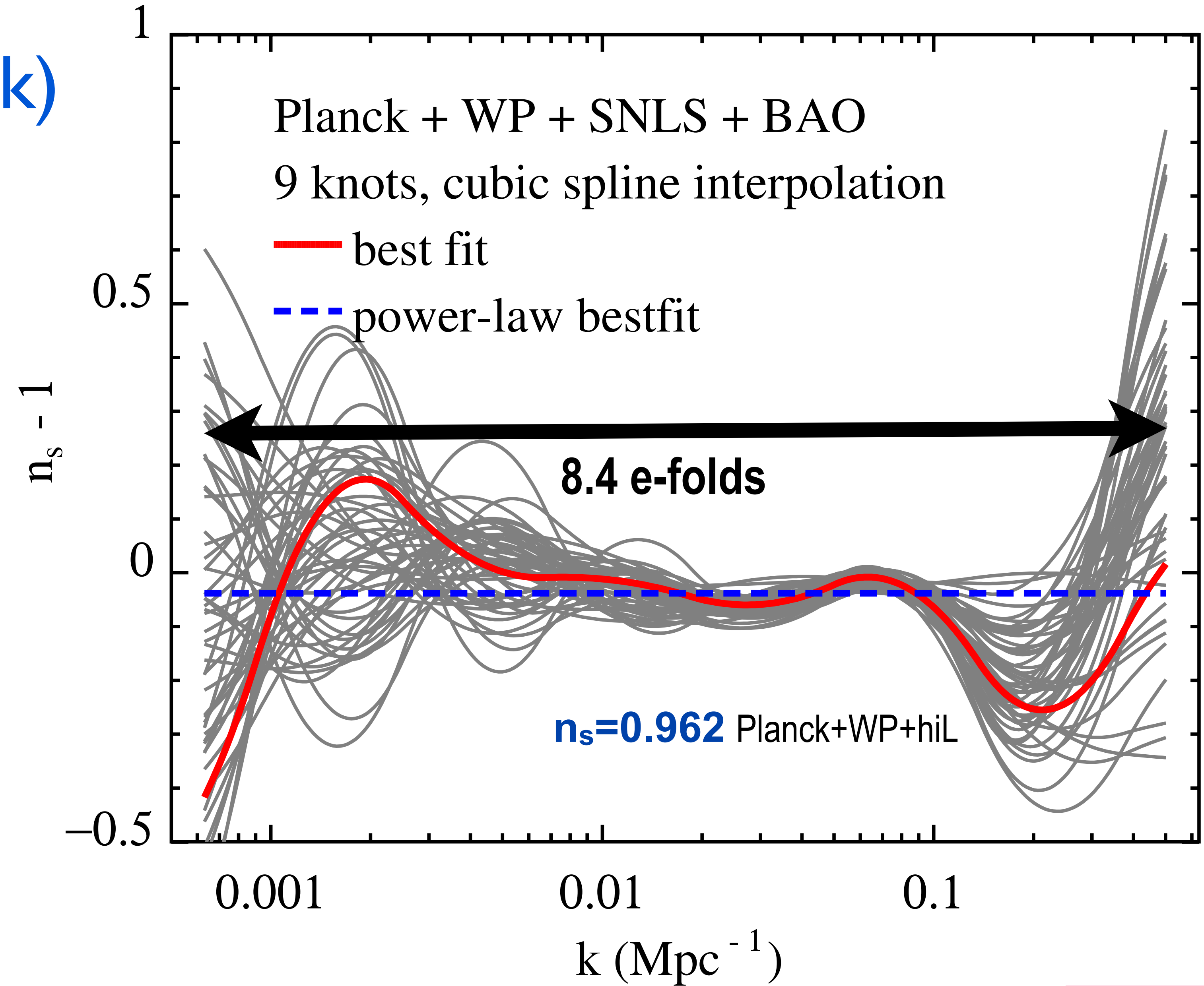


no strong evidence for oscillation patterns, cutoffs, local features

Bond, Huang 2013

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

$n_s(ln\mathrm{k})$

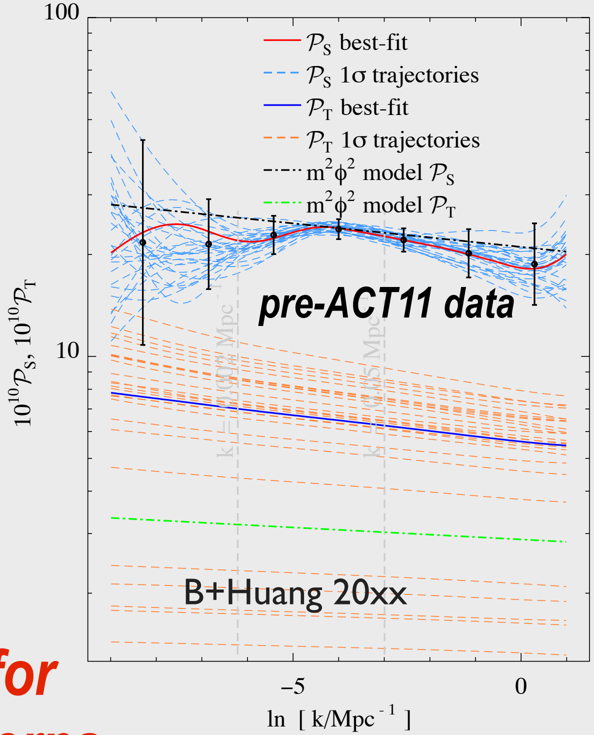


Bond, Huang 2013

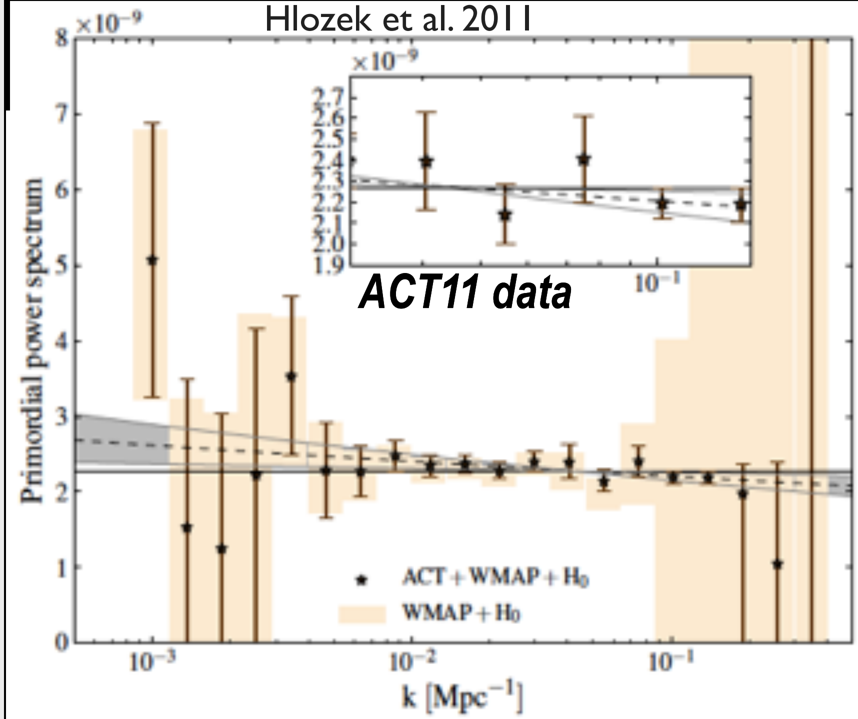
Inflation Histories
(CMBall+LSS+SN+WL)

early-U, NOW

semi-blind & informed reconstruction of Scalar / Tensor power spectra, acceleration histories

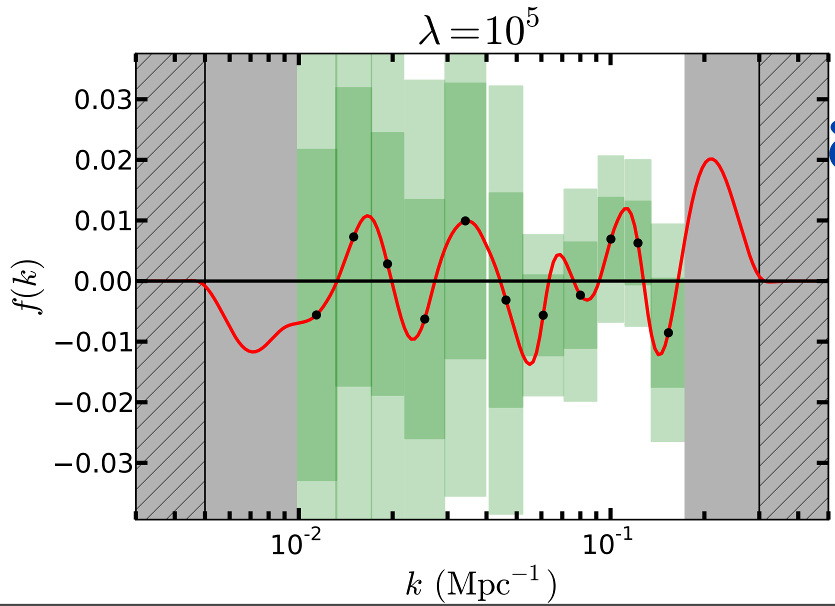


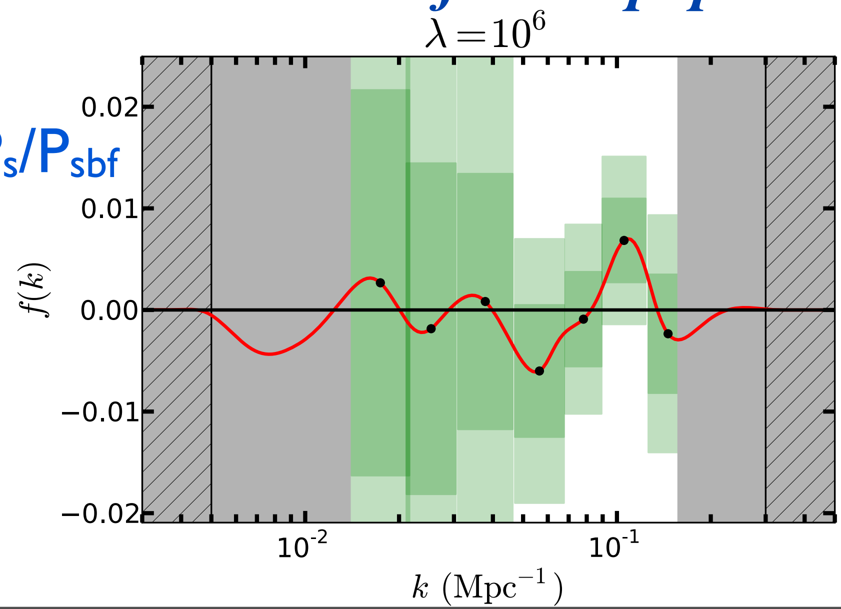
no evidence for oscillation patterns



Planck1.3 inflation paper

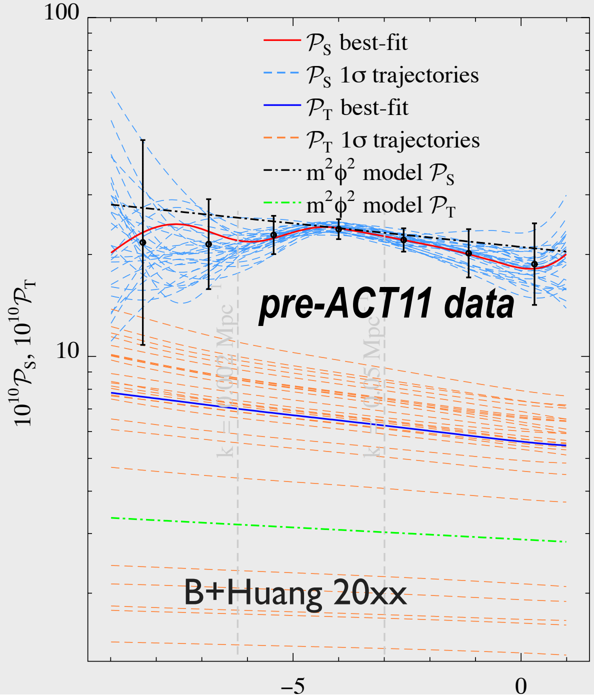
$\delta P_s/P_{sbf}$

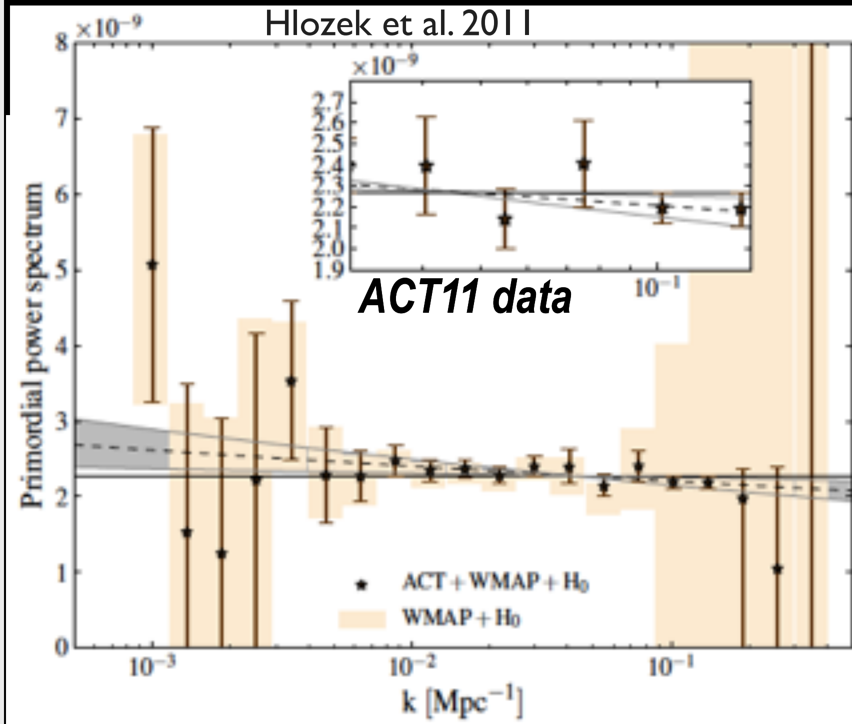


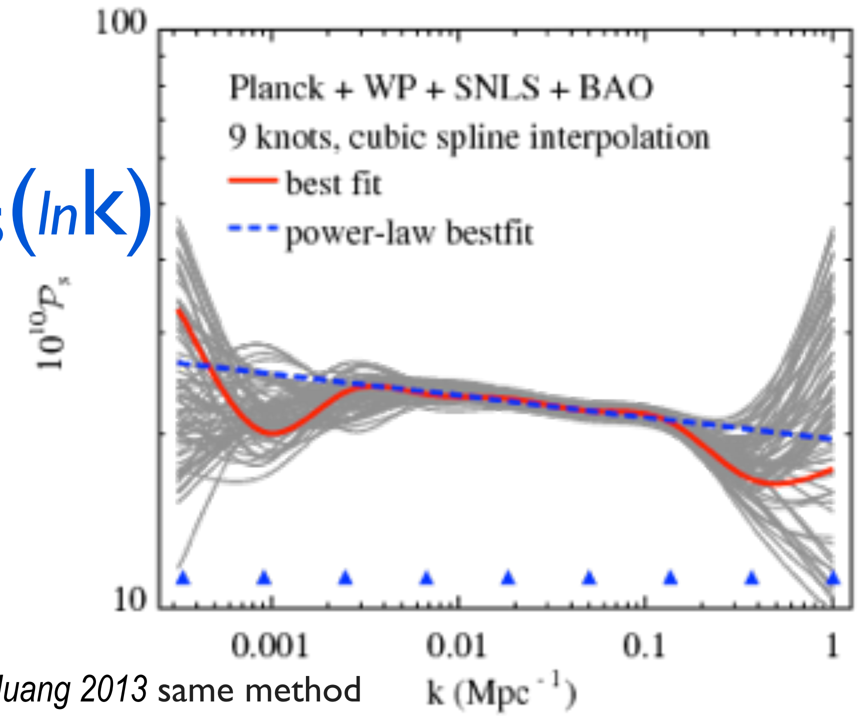


early-U, NOW

semi-blind & informed reconstruction of acceleration histories & S/T power spectra





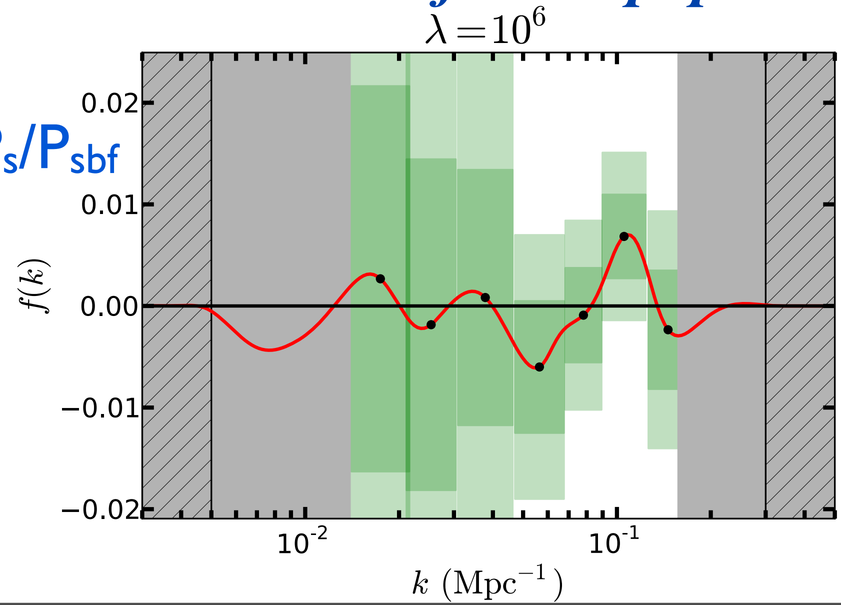


$\ln P_s(\ln k)$

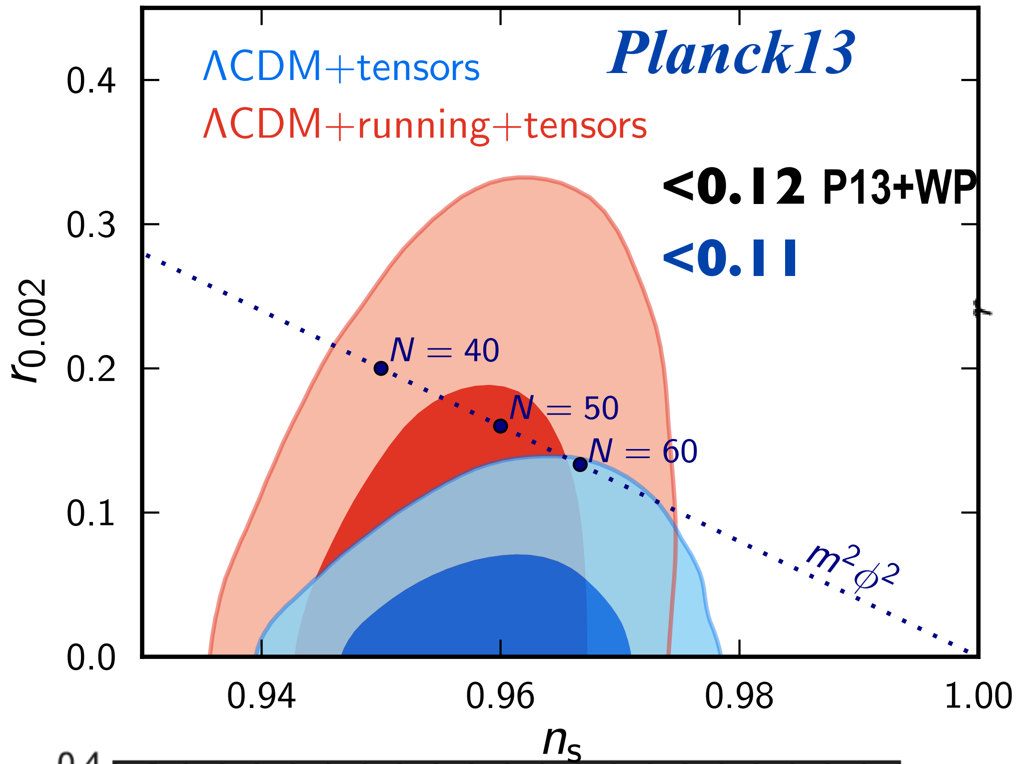
Bond, Huang 2013 same method

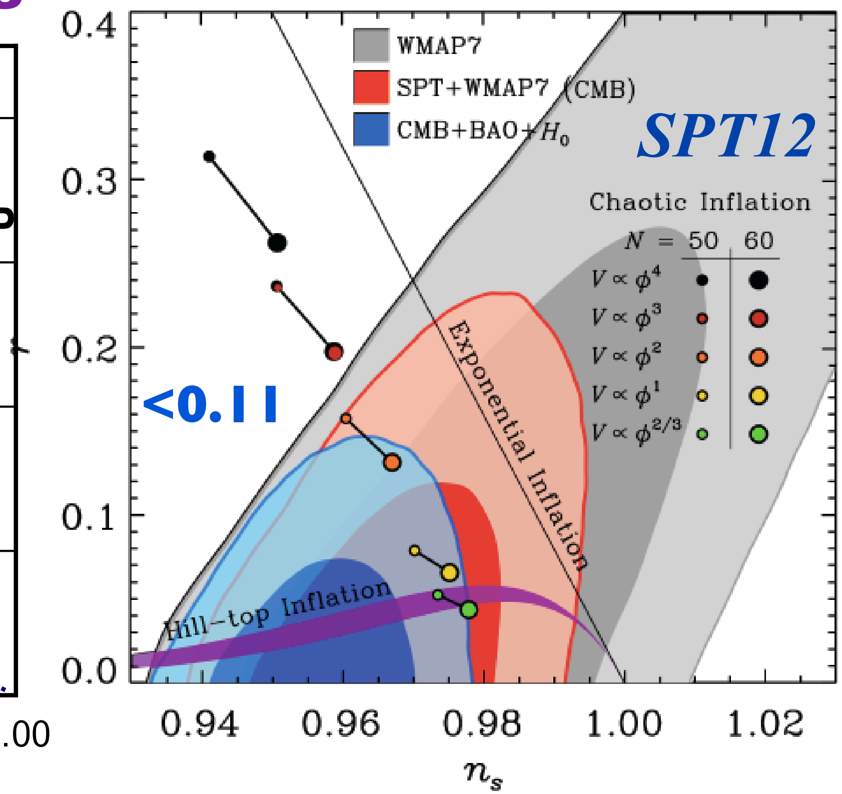
Planck1.3 inflation paper

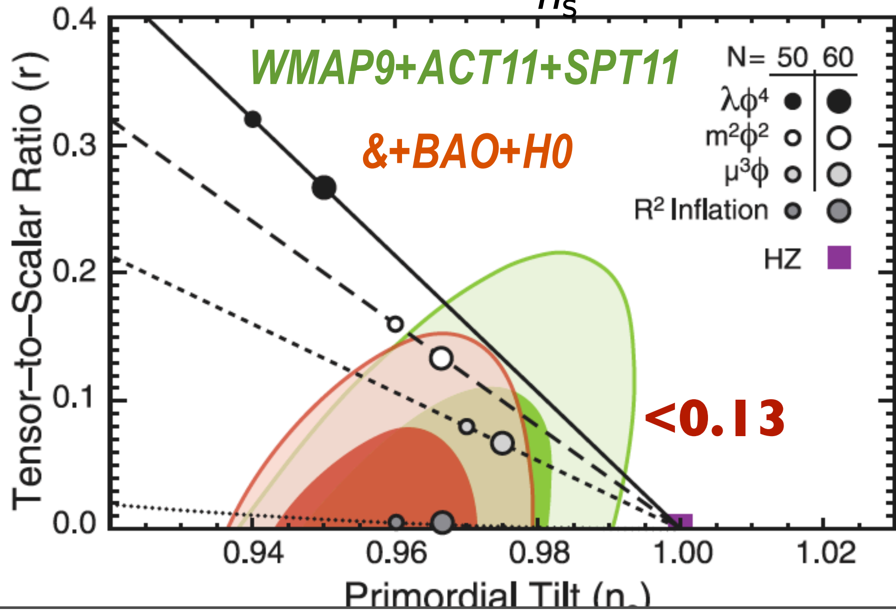
$\delta P_s / P_{sbf}$

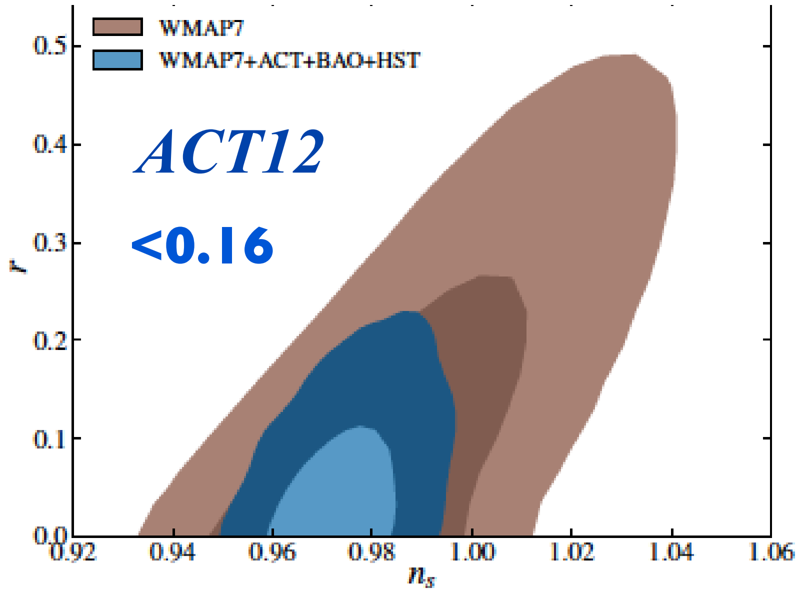


early-U **Gravity Wave Constraints**







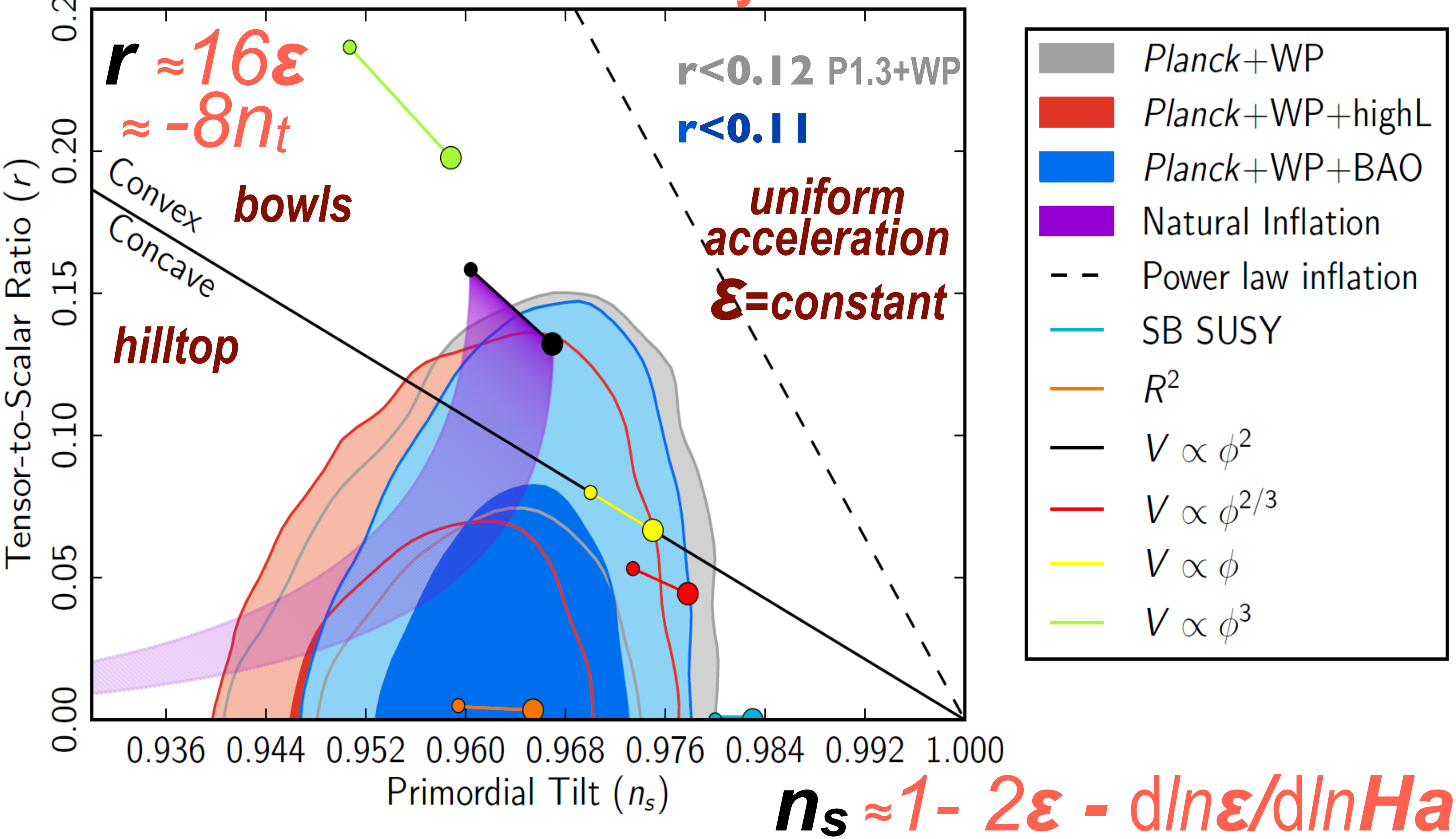


Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits)

uniform acceleration *line* ***ε ≡ 3KE /(KE+PE)*** *= constant is* ***strongly ruled out***

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

inflation consistency



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, ...*

Old view: Theory prior = delta function of THE correct one and only theory

New: Theory prior = probability distribution of late-flows on an *action* LANDSCAPE

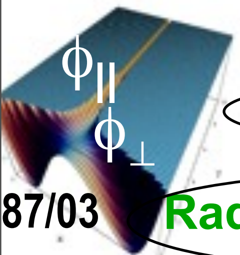
6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation



New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03

Radical BSI inflation

running (nee variable M_P) inflation

Higgs inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

KLS94 preheating

SUSY F-term inflation

SUSY D-term inflation

Assisted inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

ekpyrotic/cyclic

2003 KKLT

N-flation

D3,D7 brane inflation

DBI inflation

moving brane separations

Racetrack inflation

Tachyon inflation

Warped Brane inflation

moduli fields

monodromy

Higgs inflation

Roulette inflation Kahler moduli/axion

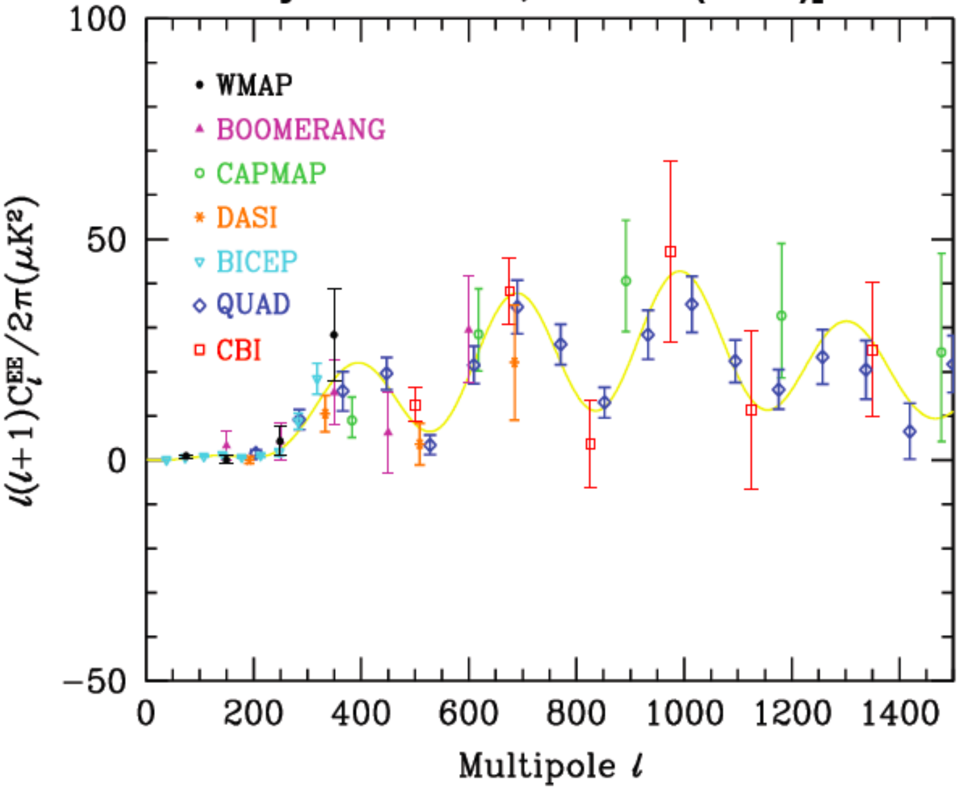
fibre inflation

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

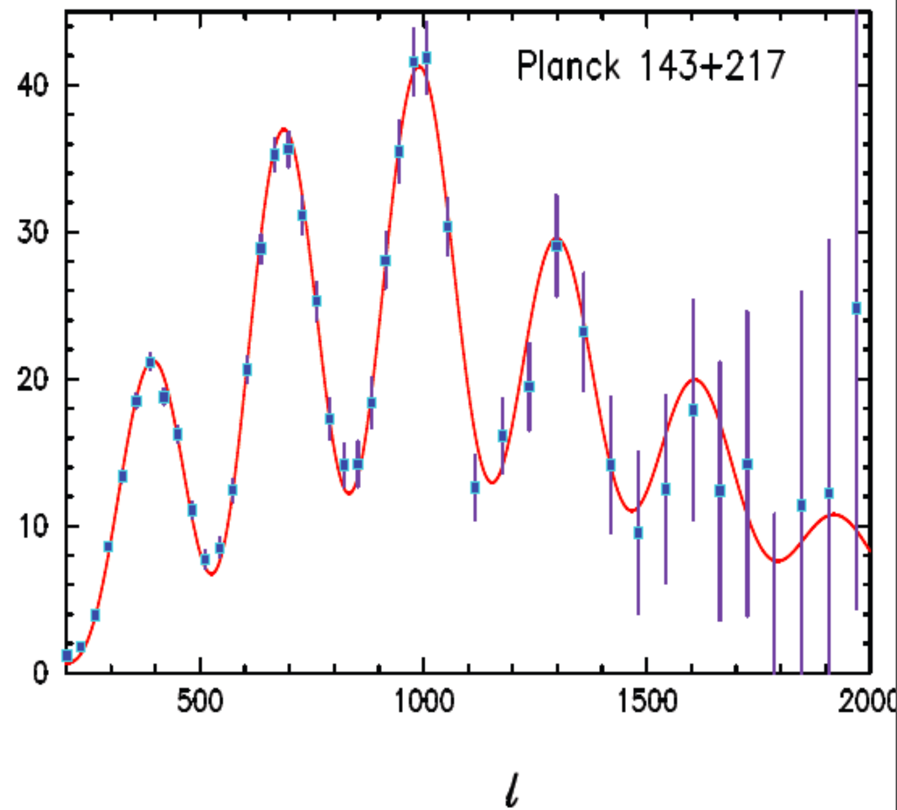
teaser for 2014

EE polarization

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



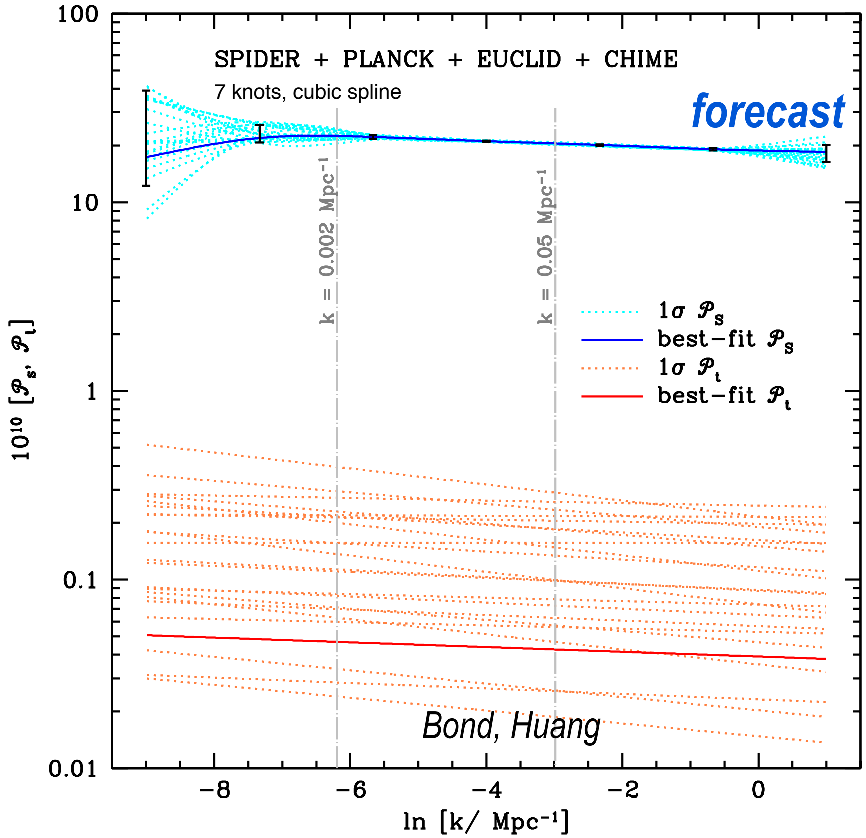
[Planck 2013 results. XVI. Cosmological parameters]

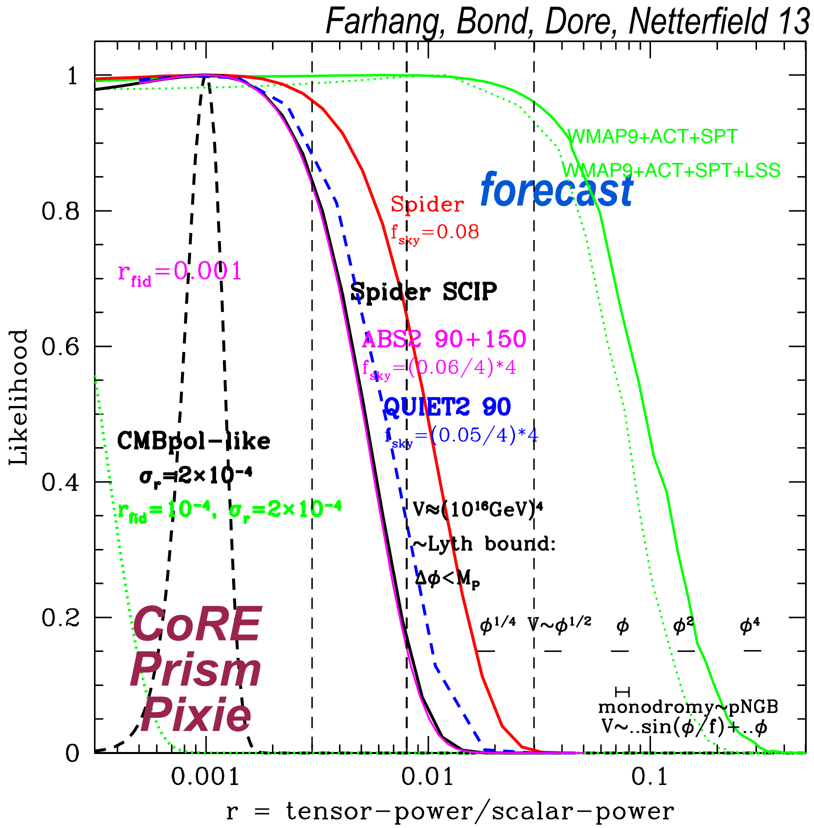


a long path to constrain** the **B-mode of polarization** at the **r =.02 to .05 level of P2.5 forecasts

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, ..***

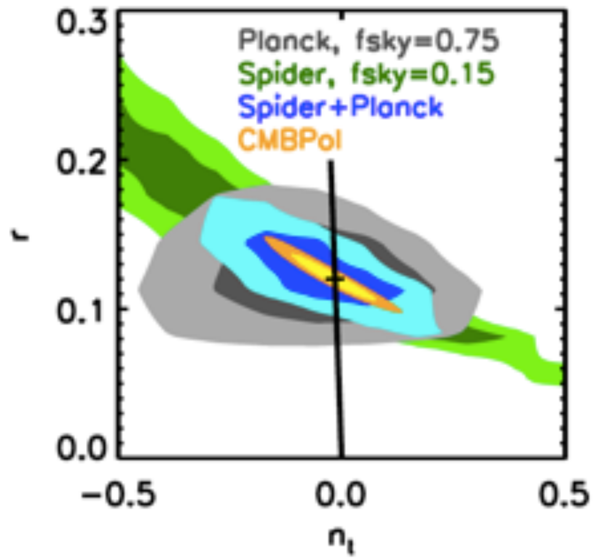




can get B-mode shapes but without the precision needed to check

$-n_t \approx r/8$

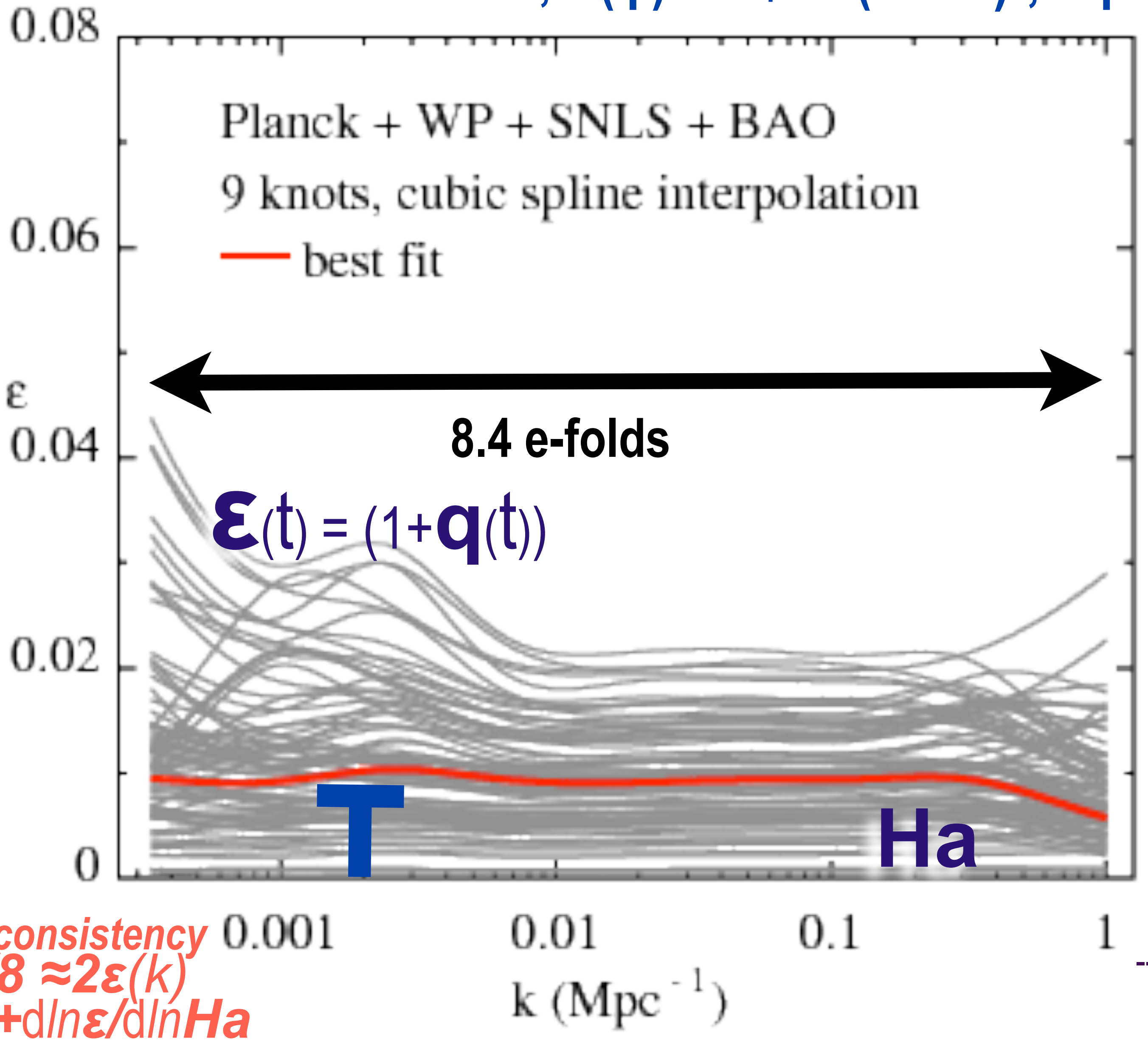
consistency



early-inflaton DE acceleration trajectories then

Bond, Huang 2013

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



aka

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

then

(hydro)

resolution
lnk ~ lnHa
dynamics

$\varepsilon \approx r/16$

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

inflation consistency

$-n_t \approx r/8 \approx 2\varepsilon(k)$

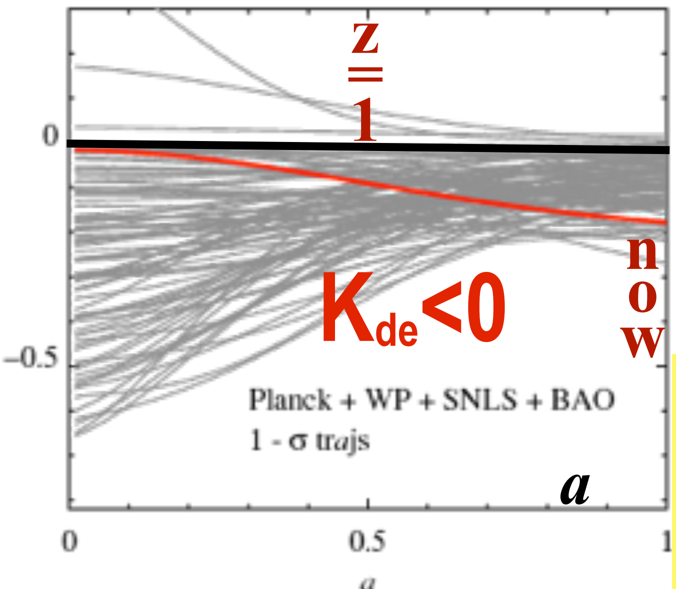
$1-n_s \approx 2\varepsilon + d\ln\varepsilon / d\ln Ha$

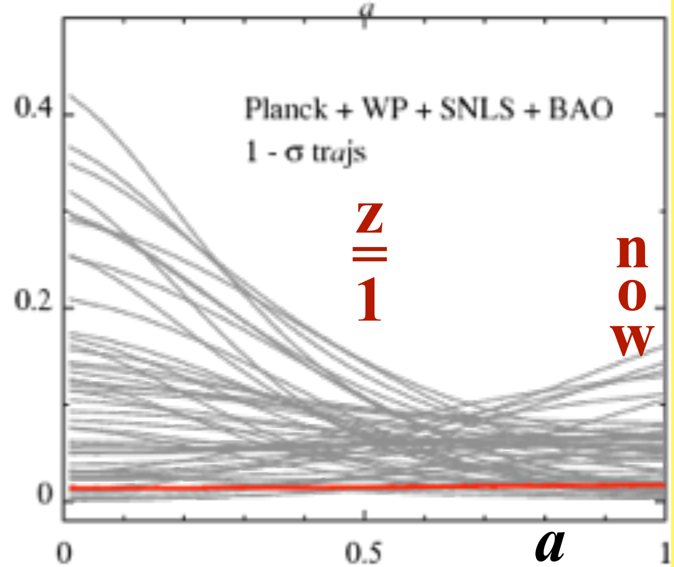
late-inflaton DE trajectories

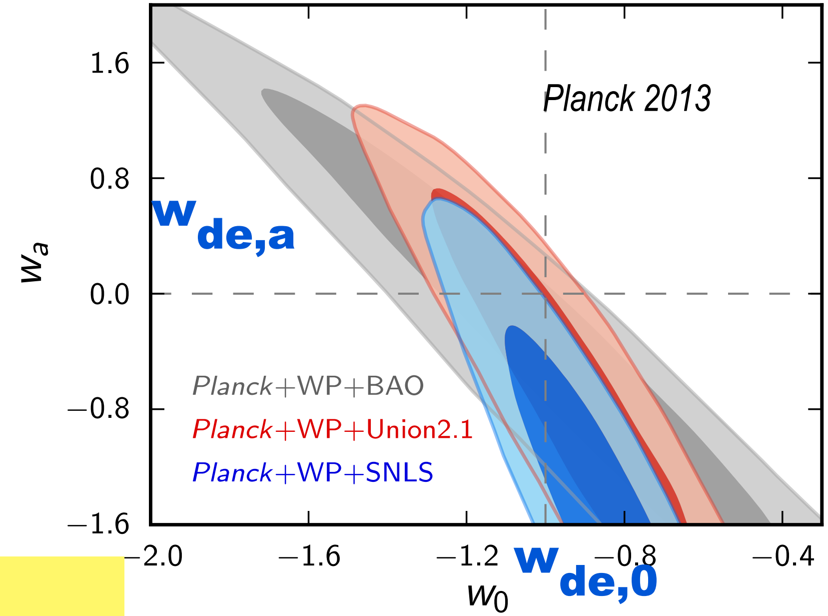
informed = *3-parameter* $W_{de}(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)$

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

Bond, Huang 2013







$1+w_{de,0}$

$= -0.13\pm0.12$

if $w_{de,a}$

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

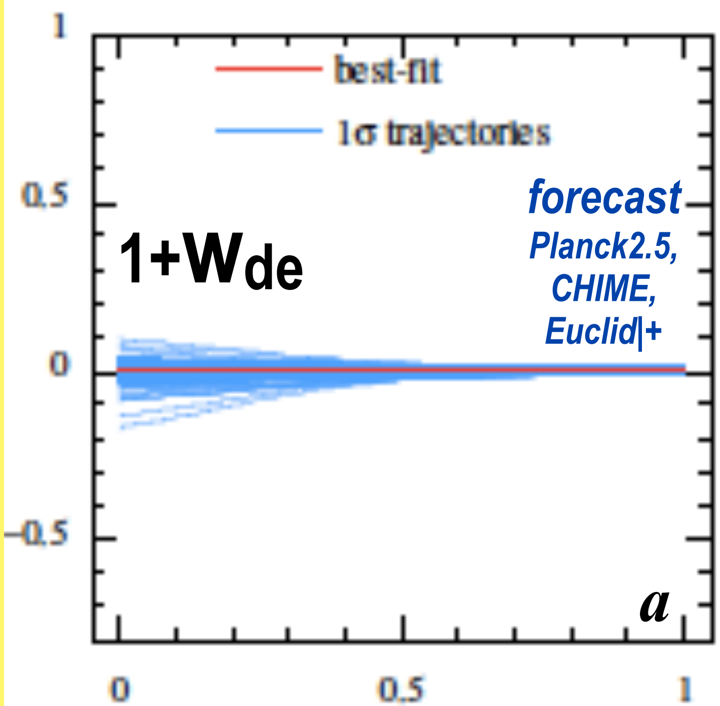
$\varepsilon_s = (d\ln V/d\psi)^2/4$

@pivot a_{eq}

$= -0.25 +.20 -.26$

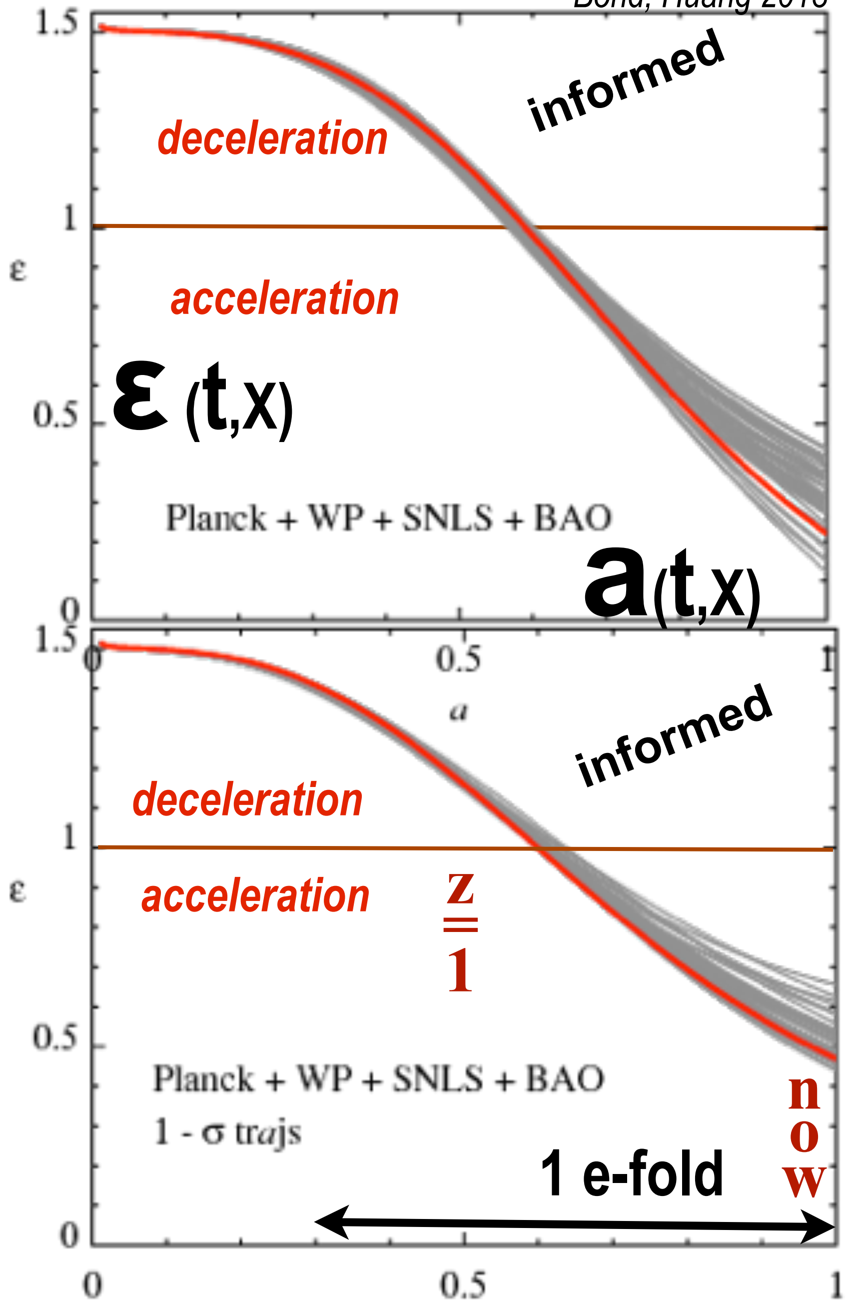
P1.3+SNLS3 $=0.0 +.21$

future $.005 +.031 -.025$



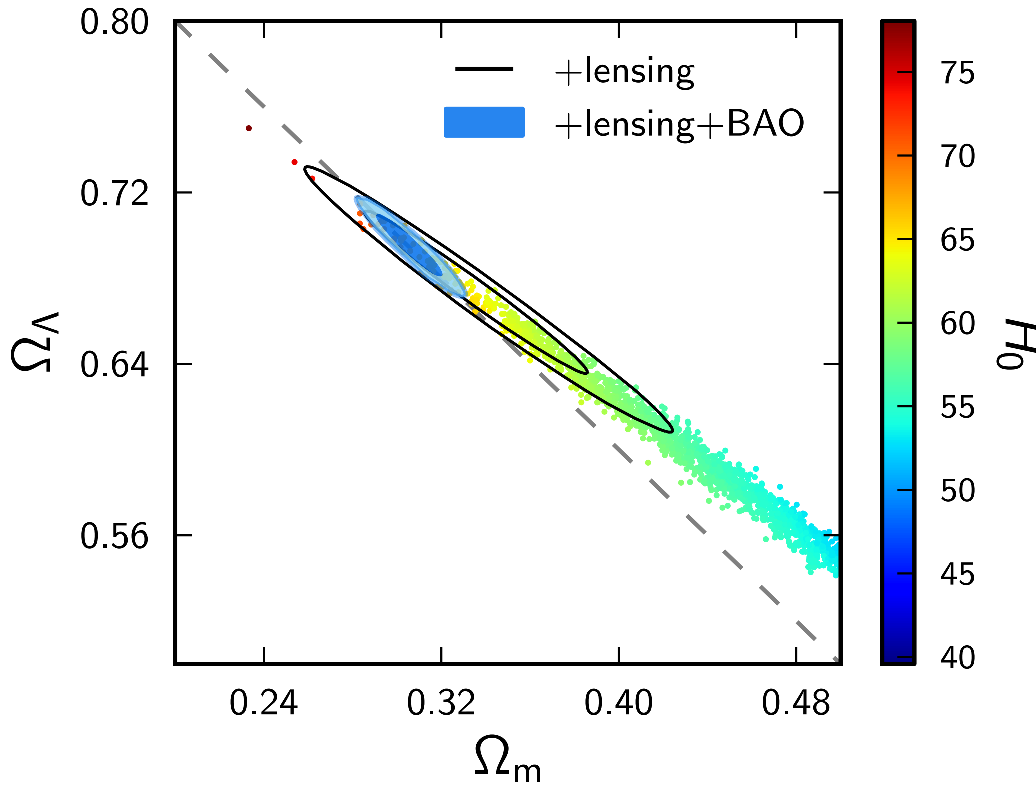
late-inflaton DE trajectories

Bond, Huang 2013

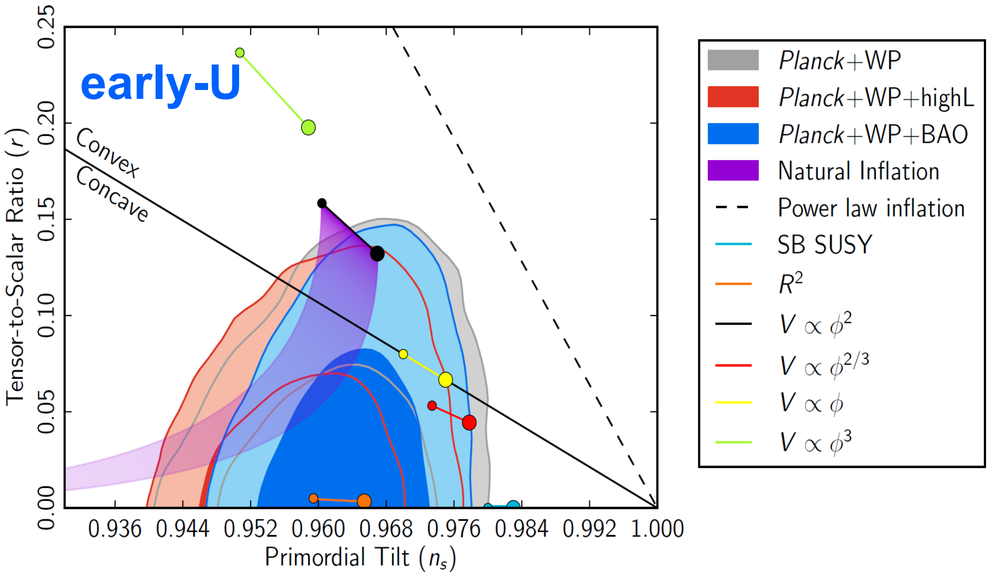


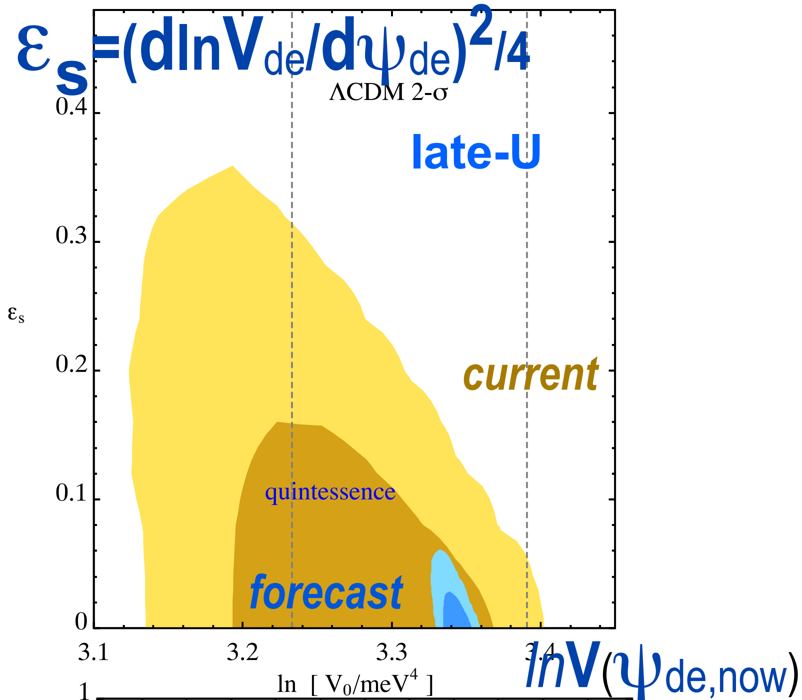
lensing breaks geometrical degeneracy:

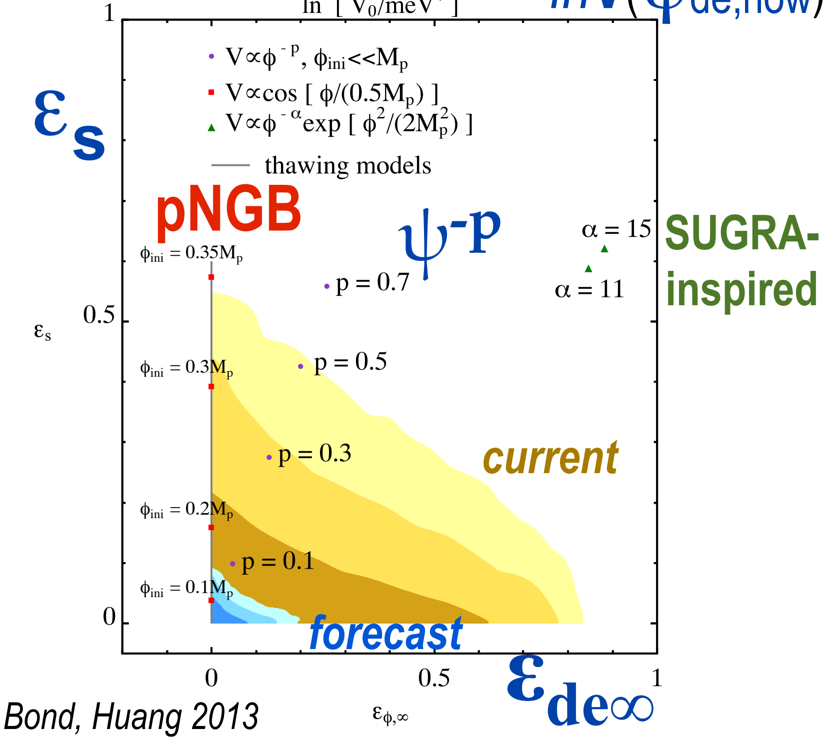
Planck alone gives dark energy cf. Planck+BAO



introduce a late-U DE plot littered with theory models similar to the early-U r-n_s plot. with HBK10/BH11 parameterization of the DE trajectories this can be done.

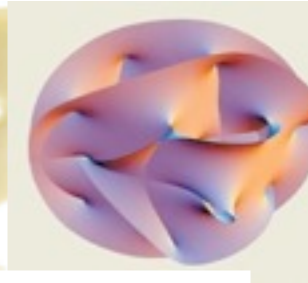


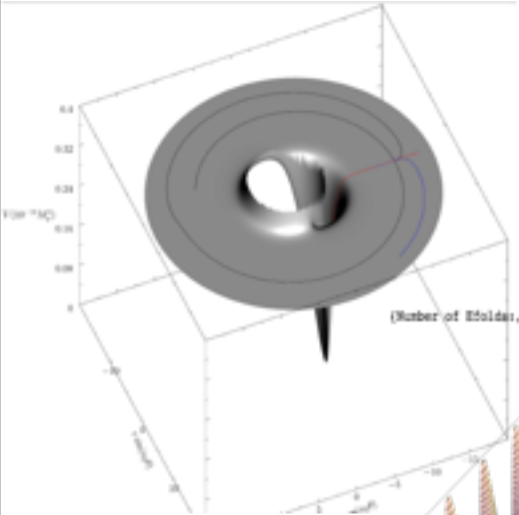


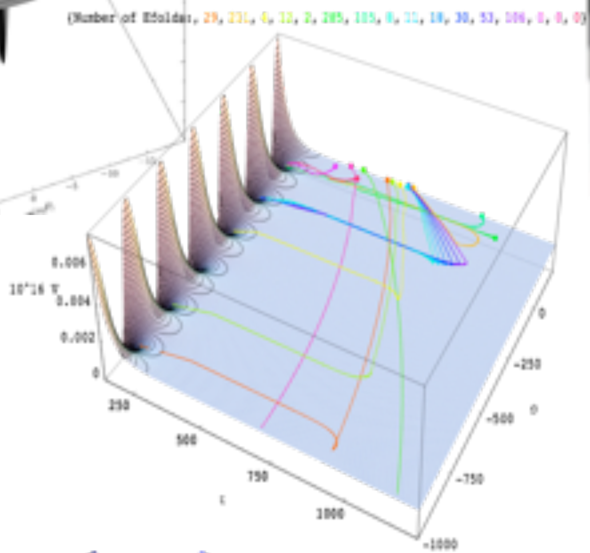


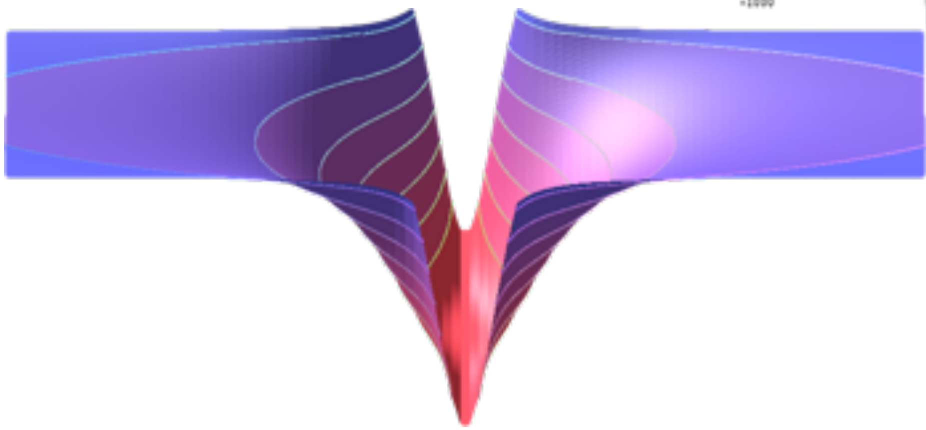
Bond, Huang 2013

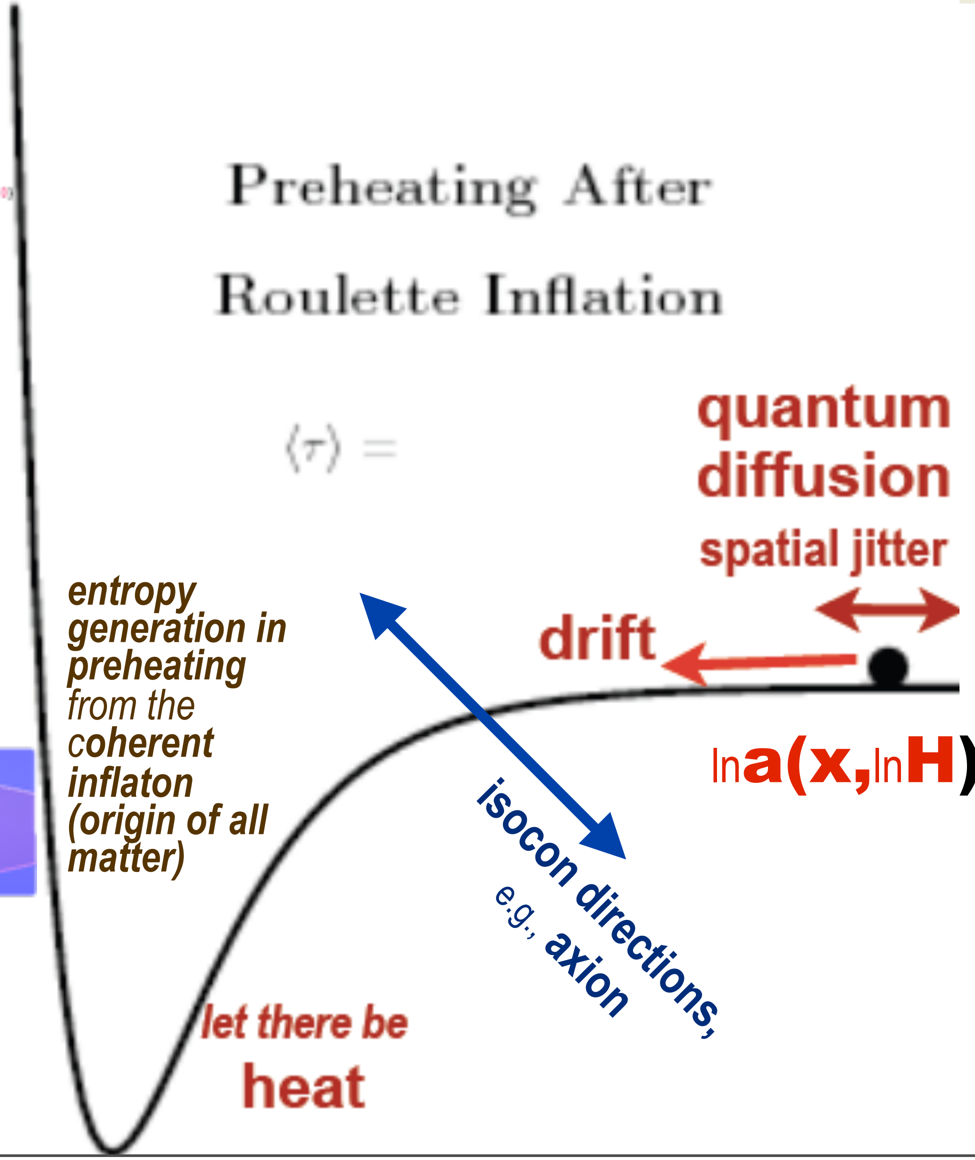
non-Gaussianity











semi ETERNAL INFLATION

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

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

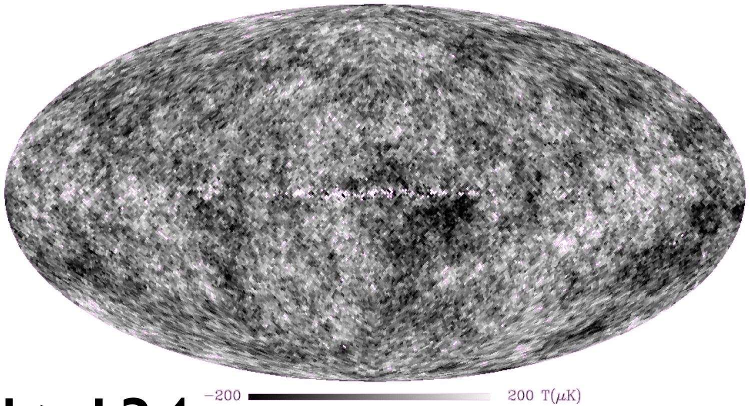
local smooth.

use optimal pattern estimators

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

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

& orthogonal pattern



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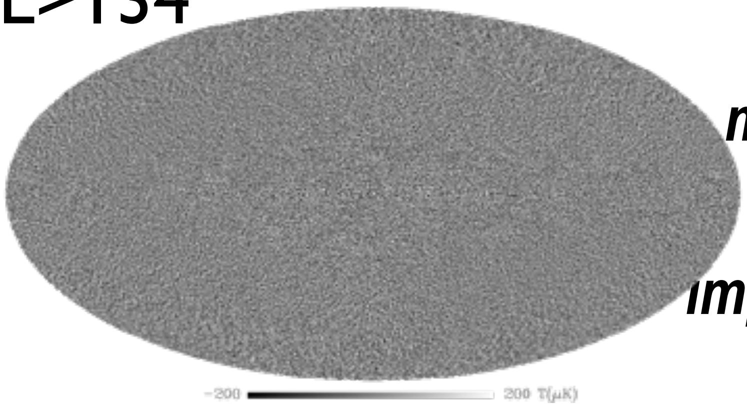


scale (k) dependent patterns: connecting to power spectrum broken scale invariance. hint?

cosmic/fundamental strings/defects

from end-of-inflation & preheating chaos

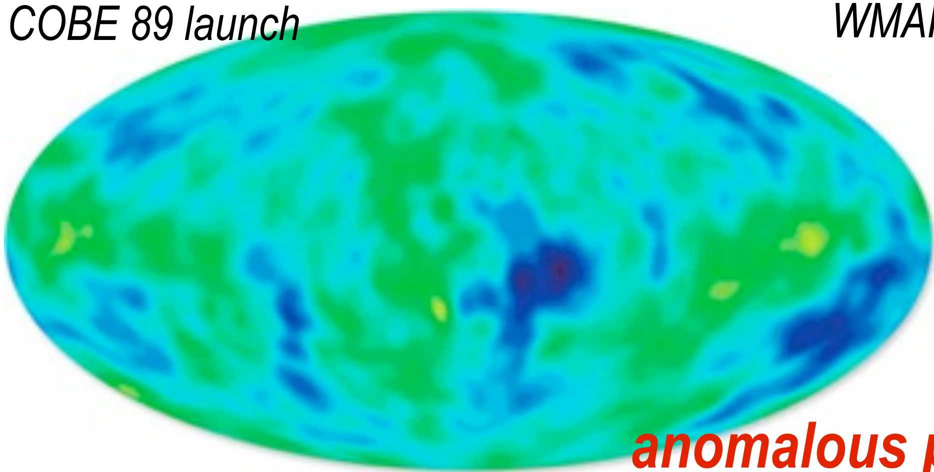
$F_{NL}(\chi_b(x))$

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

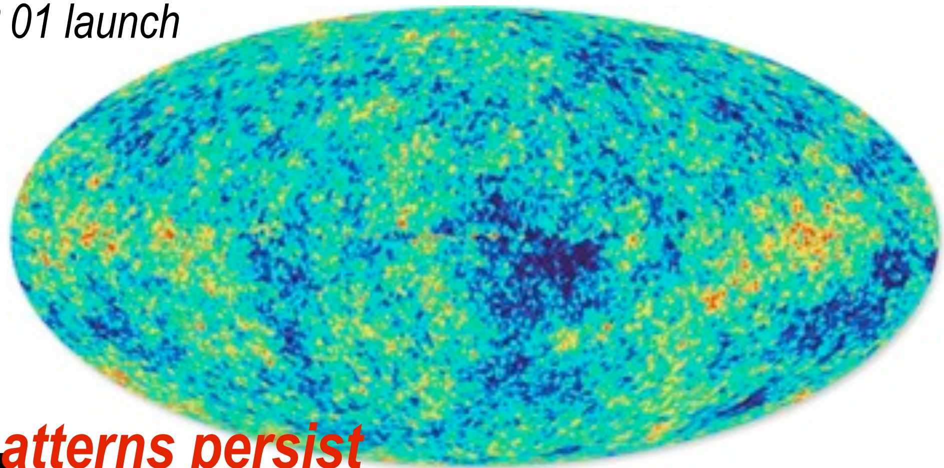
most nonG info from high L: why Planck improved so much over WMAP9

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

COBE 89 launch

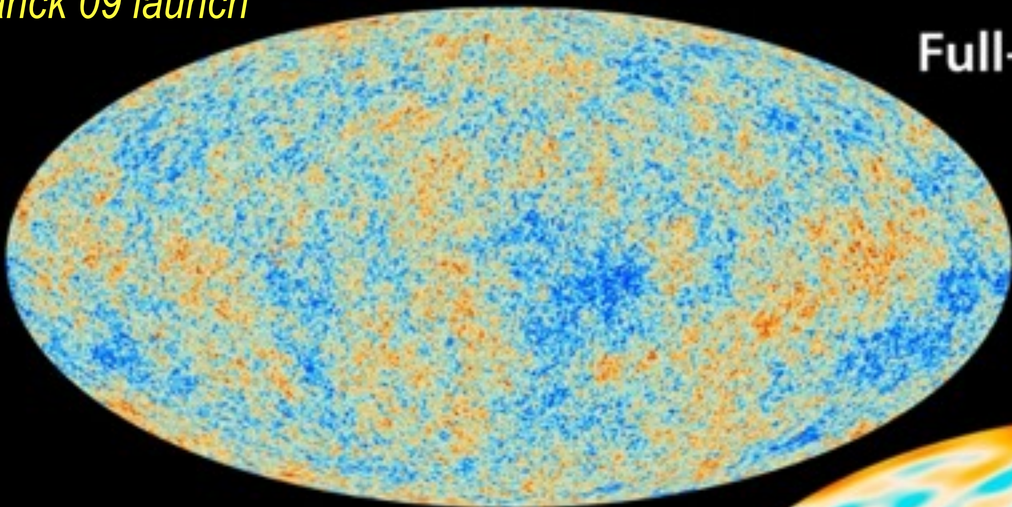


WMAP 01 launch



anomalous patterns persist

Planck 09 launch



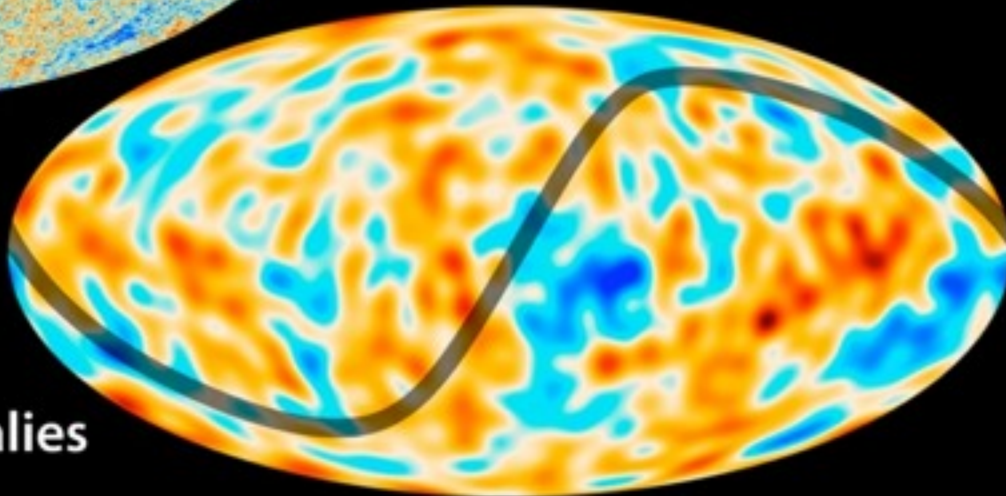
Full-Sky Map

NonGaussian 3-point-pattern measure

f_{nl}: 2.7 ± 5.8 local => ± 5 (Pext)

-f_{nl}: 42.3 ± 75.2 equil

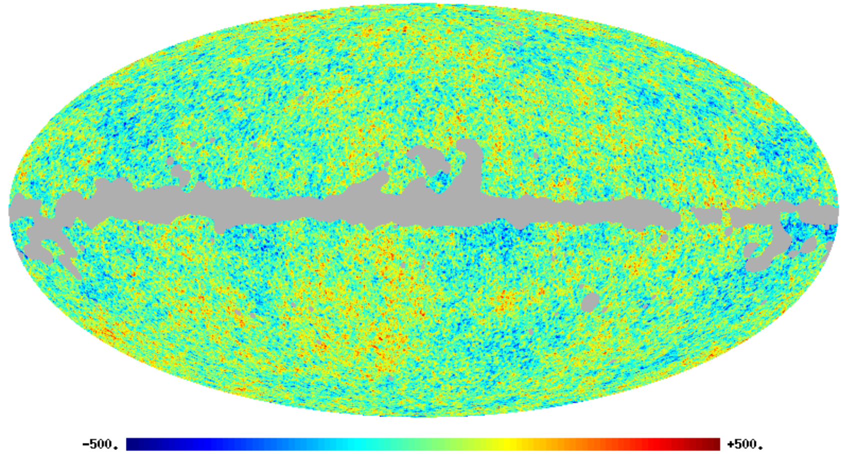
-25.3 ± 39.2 ortho **& f_{NL}^{eff}**



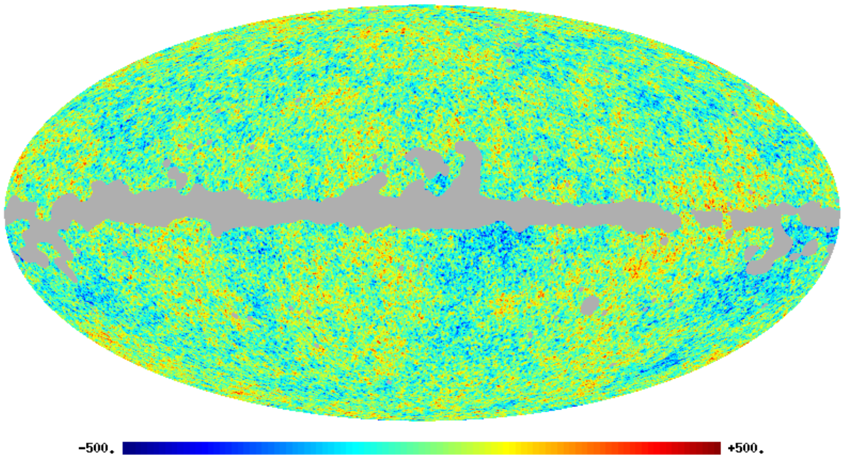
a homogeneous, anisotropic Bianchi VII_h model

Anomalies

Fluctuation CMB Sky



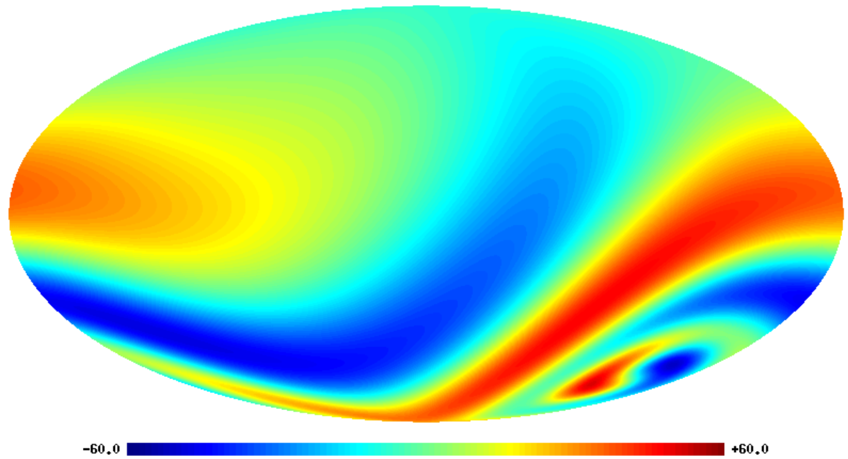
real CMB Sky



=

mean field CMB Sky

+



homogeneous, anisotropic Bianchi VII_h model: ultralarge scale rotation/vorticity and shear, *fit parameters violently disagree with Planck13 parameters. but maybe there is a grand unified theory of anomalies, as this tries to do.*

Grand Unified Theory of Anomalies TBD

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,* $a \sim e^{-7}$

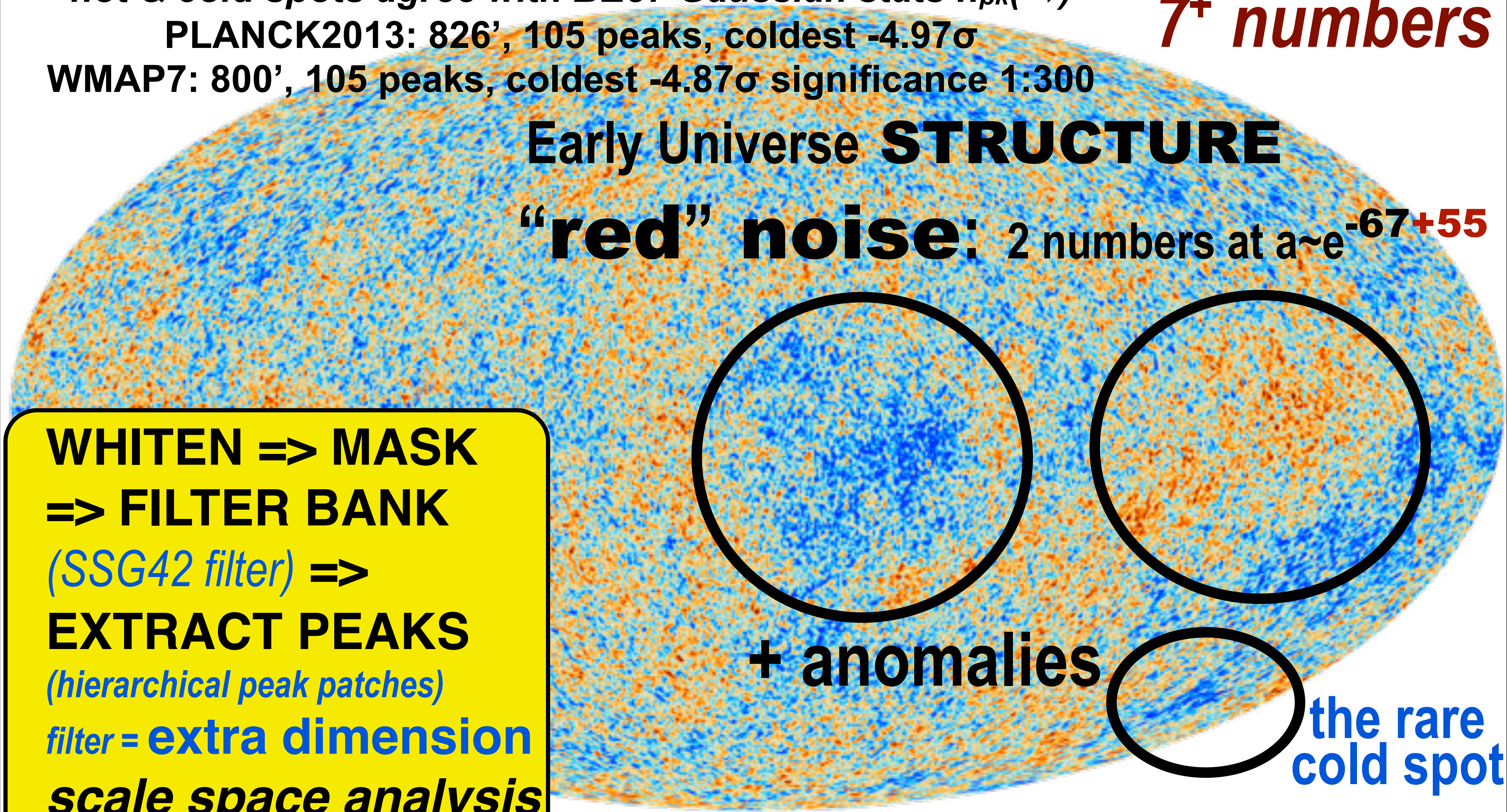
=> infer the structure far far earlier $a \sim e^{-67+60}$

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

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

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

7⁺ numbers



Early Universe STRUCTURE

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

+ anomalies

the rare cold spot

WHITEN => MASK

=> FILTER BANK

(SSG42 filter) **=>**

EXTRACT PEAKS

(hierarchical peak patches)

filter = **extra dimension**

scale space analysis

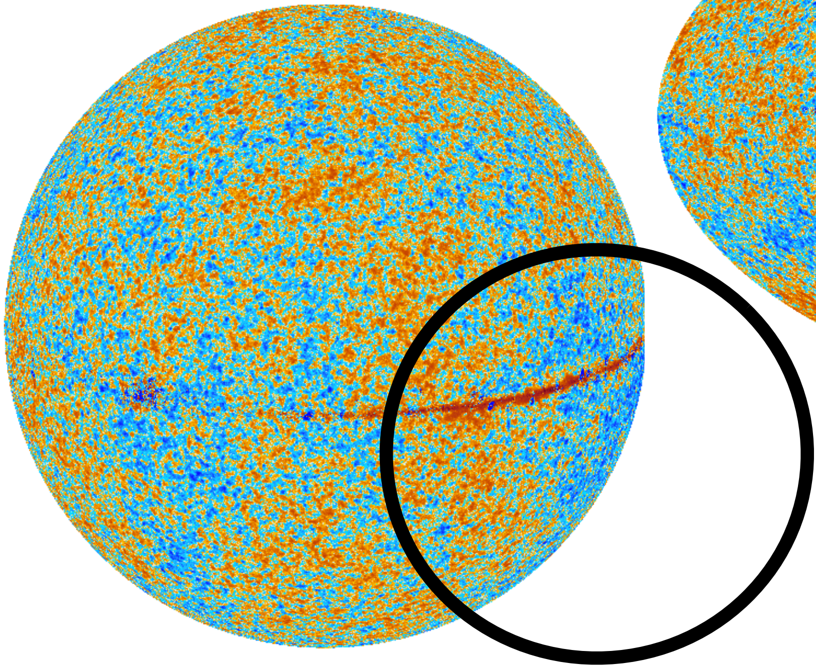
the ADS of our CFT

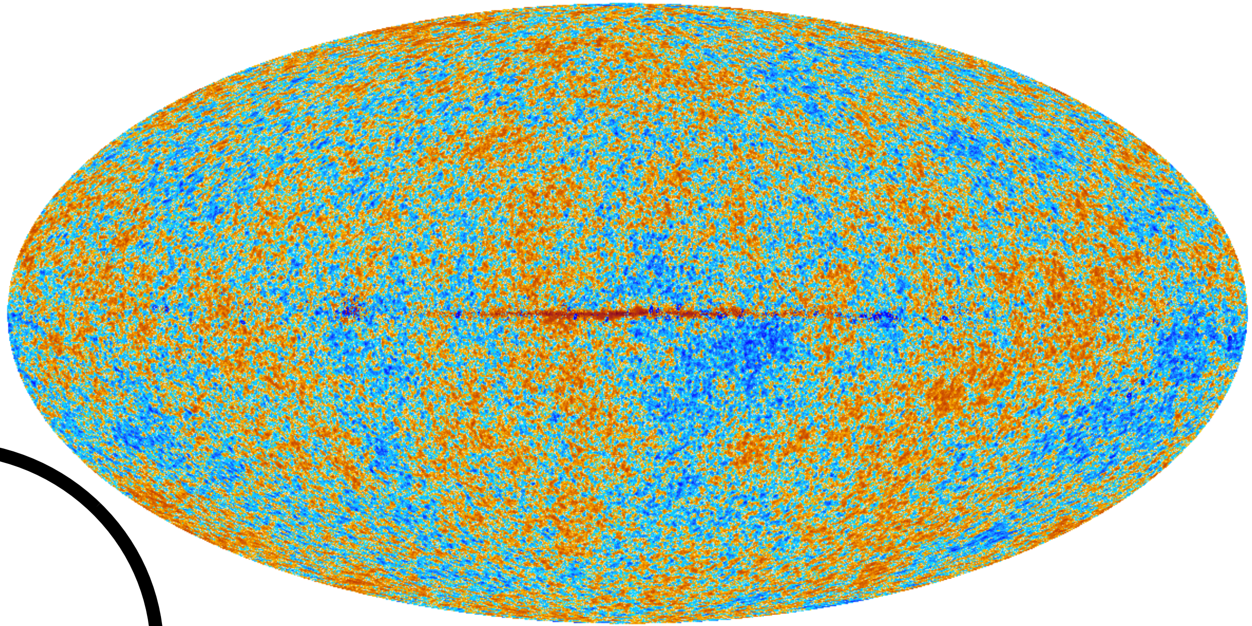
COMPLEXITY *at* $a \sim e^{-67}$**?**

SIMPLICITY

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

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

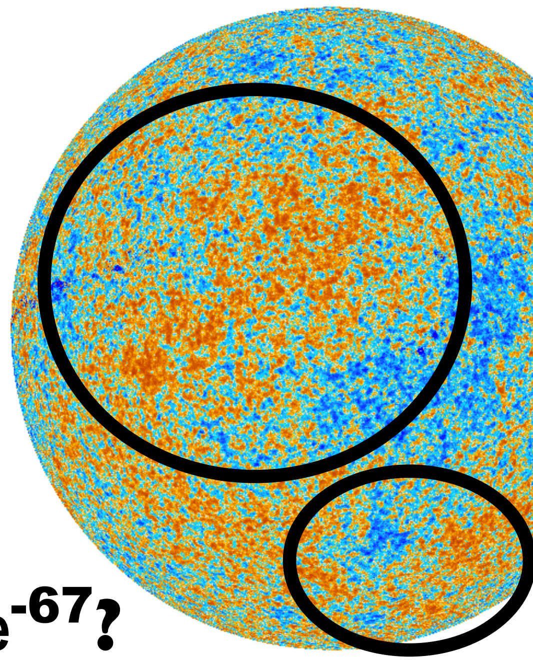




Anomalies in Polarization? TBD

+ anomalies

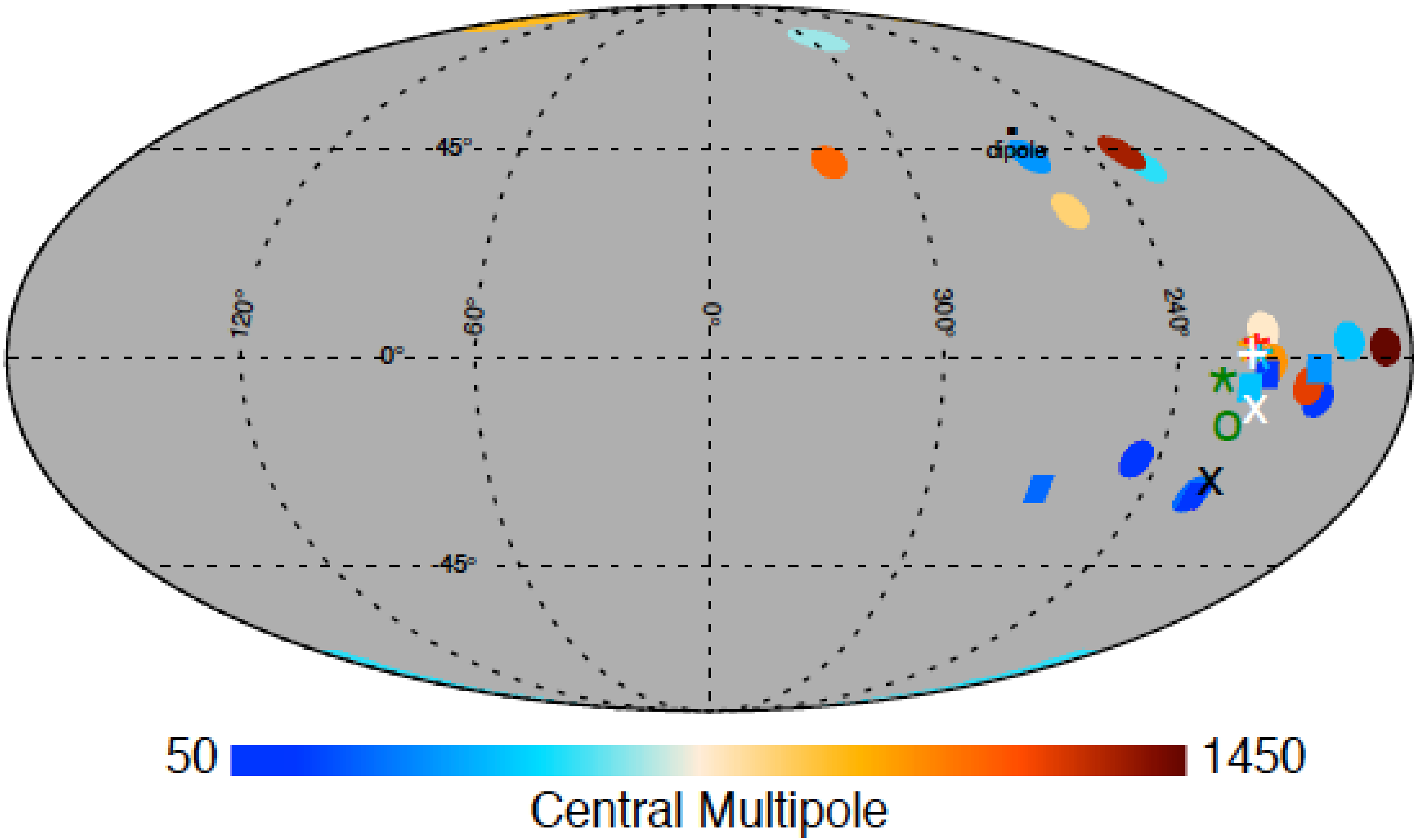
the rare
cold spot



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

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

L<400 ~7% anomaly, L>400 sub-percent (**maybe,** see Duncan Hanson's talk)



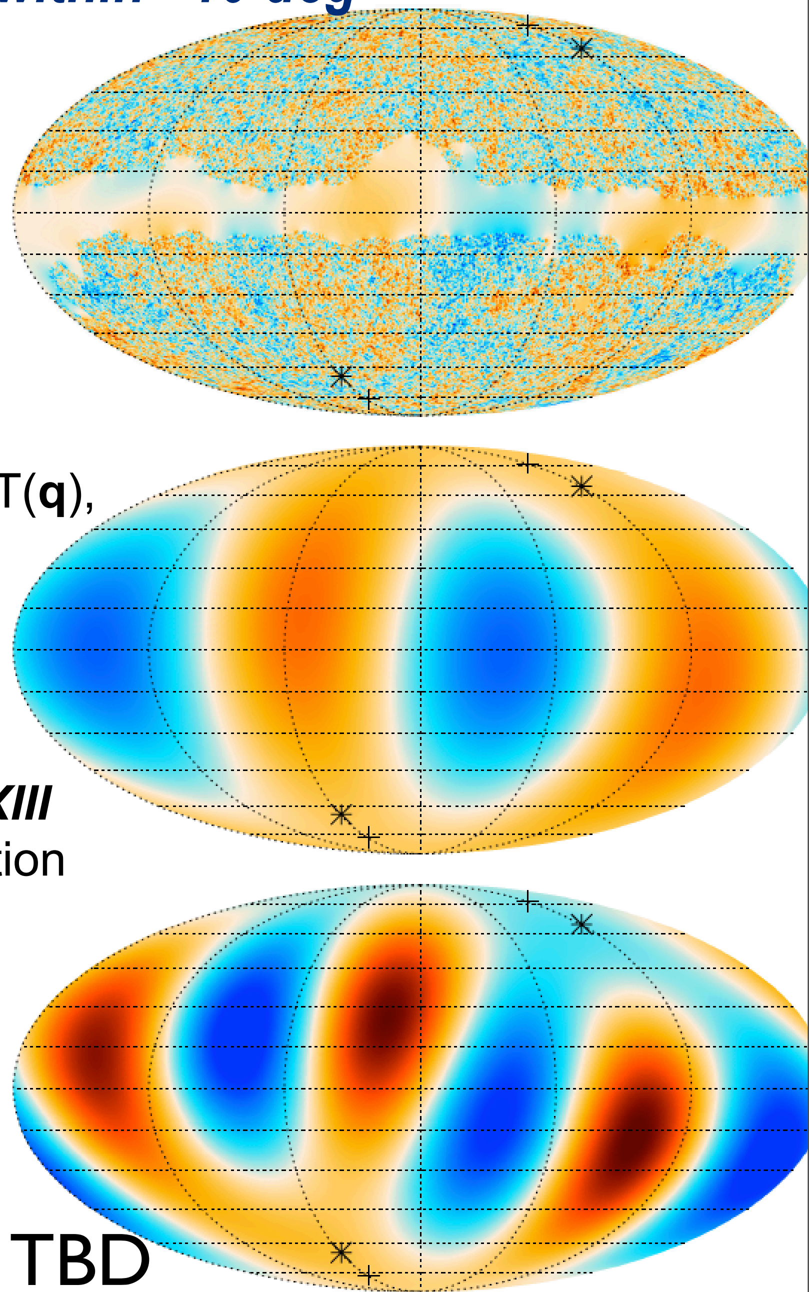
***power spectrum asymmetry*:**

dipole near Galactic Equator points towards LSS anomaly.

Low L asymmetry is firm P13 & WMAP, high L subject to Doppler boost correction

Challinor & Lewis 02, Hanson+ 09, ***Planck2103 XXVII, Doppler Boosting of the CMB***

octupole quadrupole alignment within ~10 deg



dipole modulation $\Delta T(\mathbf{q}) \Rightarrow (1-(x\coth(x/2)-1)\, \mathbf{q}.\mathbf{v})\, \Delta T(\mathbf{q})$, $x=h\nu/T$

aberration $\mathbf{q} \Rightarrow \mathbf{q}+\nabla(\mathbf{q}.\mathbf{v})$

5σ detection of kinematic dipole effects

influence on high L power asymmetry (cf. ***P13 XXIII Isotropy & Statistics*** TBD) dipole power modulation <0.2% with L_{max}=2000 ?

low L (<400) power asymmetry is robust

Anomalies in Polarization? TBD

Grand Unified Theory of Anomalies TBD

primordial non-Gaussianity

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

local smooth. use optimal pattern estimator

cf. DBI inflation: non-quadratic kinetic energy

cosmic/fundamental strings/defects

from end-of-inflation & preheating

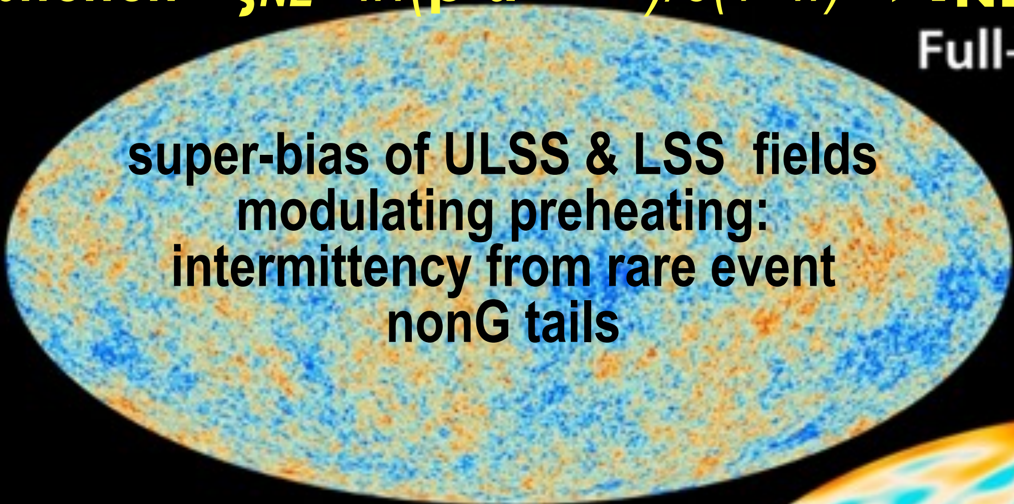
$\zeta_{NL}(x) = \zeta_G(x) + F_{NL}(\chi_b(x))$

modulating preheating

f_{NLeff} + cold spots

$\zeta_{NL}(x) = \zeta_G(x) + F_{NL}(g_b(x))$

phonon $\sim \zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ => $f_{NL*} = 3/5\, f_{NL} - 1 = 0.44 \pm 3.5$



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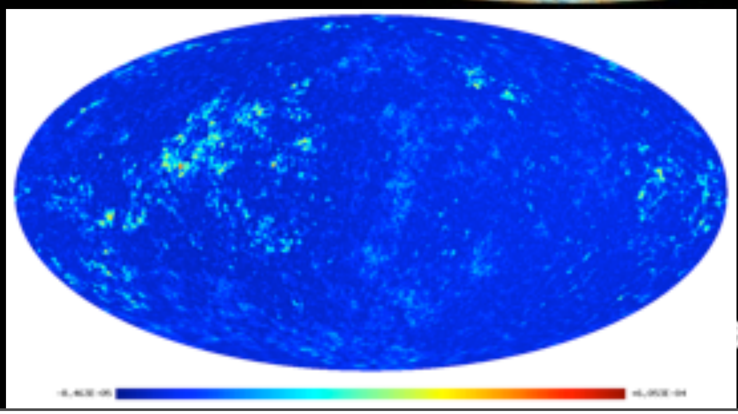
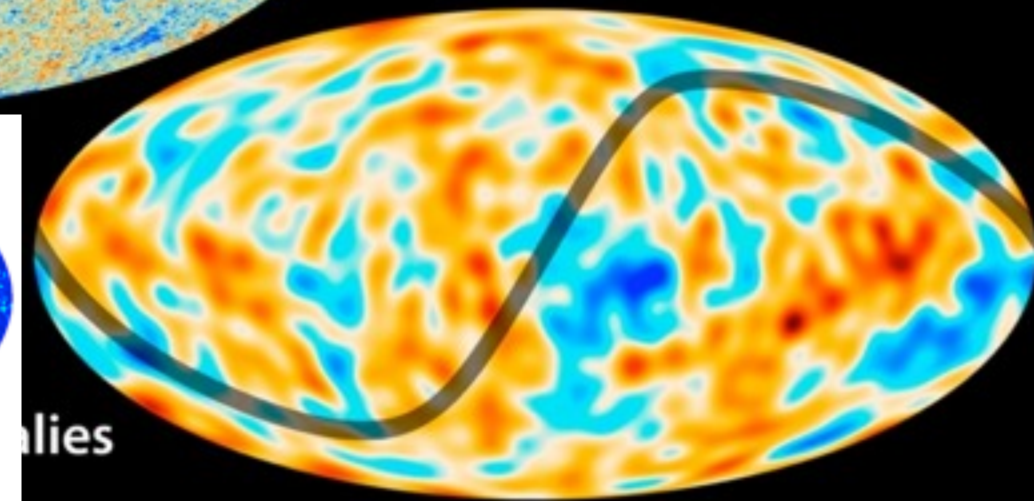
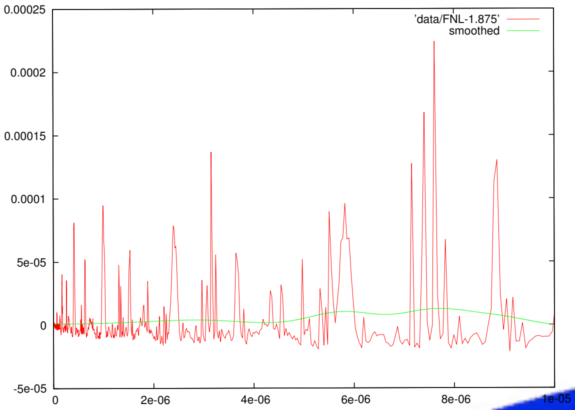
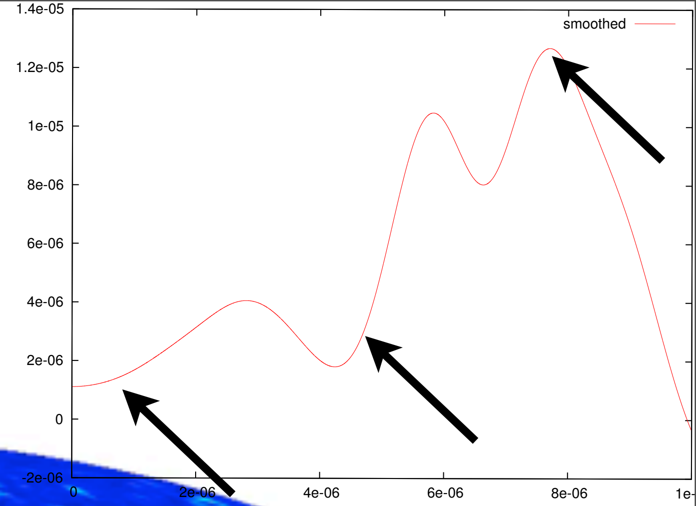


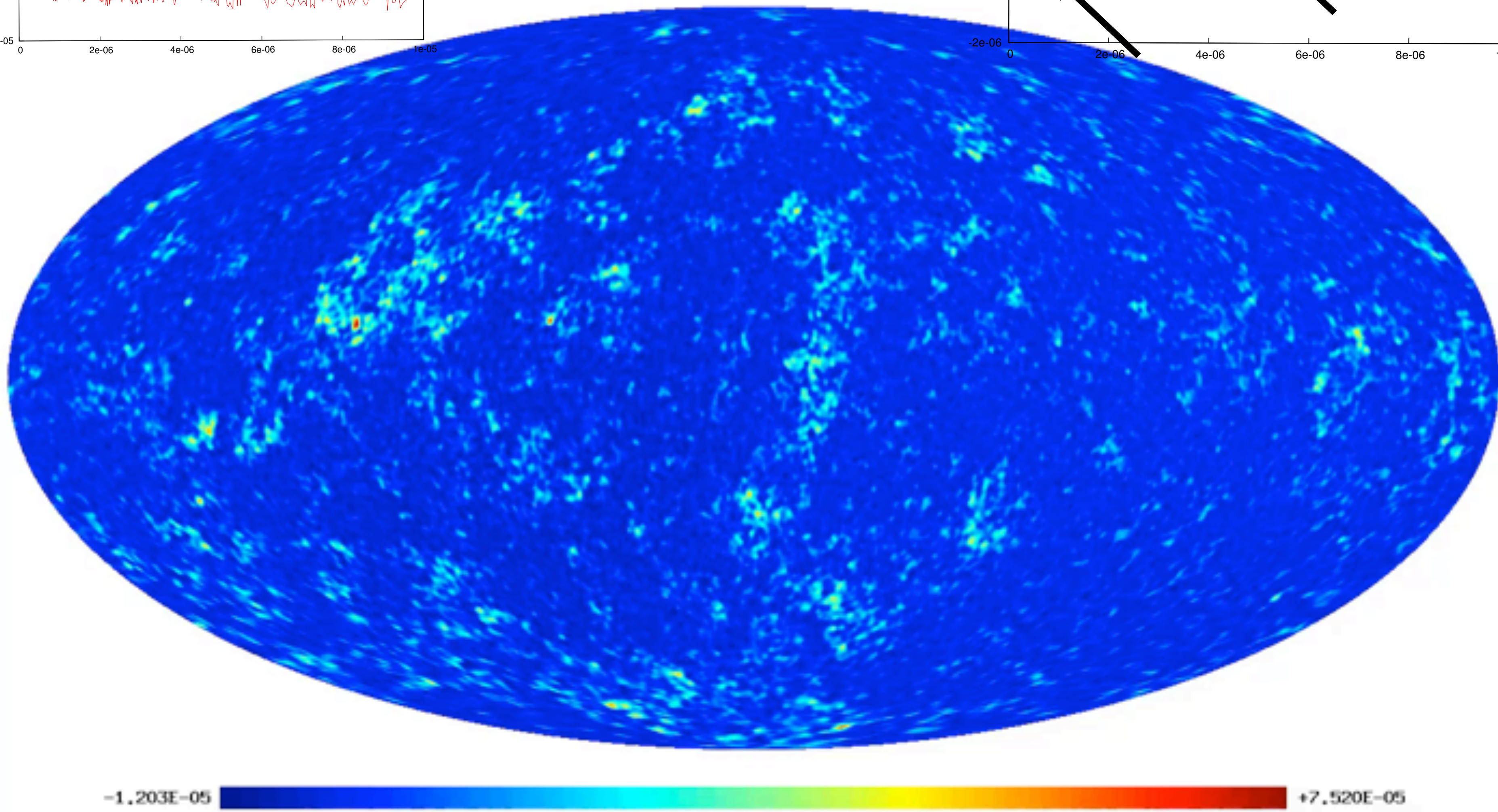


subdominant structure change as we scan $\chi > h$



Bond,Braden,Frolov,Huang13





conclusions:

nothing definitive

yet for anomalies,

may just lead to

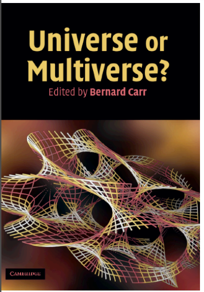
potential & >horizon

constraints

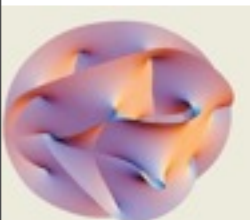
but amusing patterns do arise

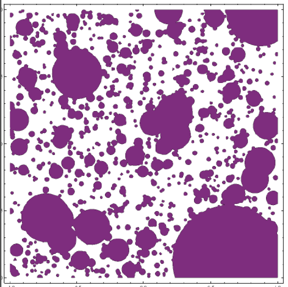
UltraUltraUltraLargeScaleStructure beyond our Horizon via *early* dark energy+quantum+gravity

Horizons: the ultimate-speed constraint on light & information

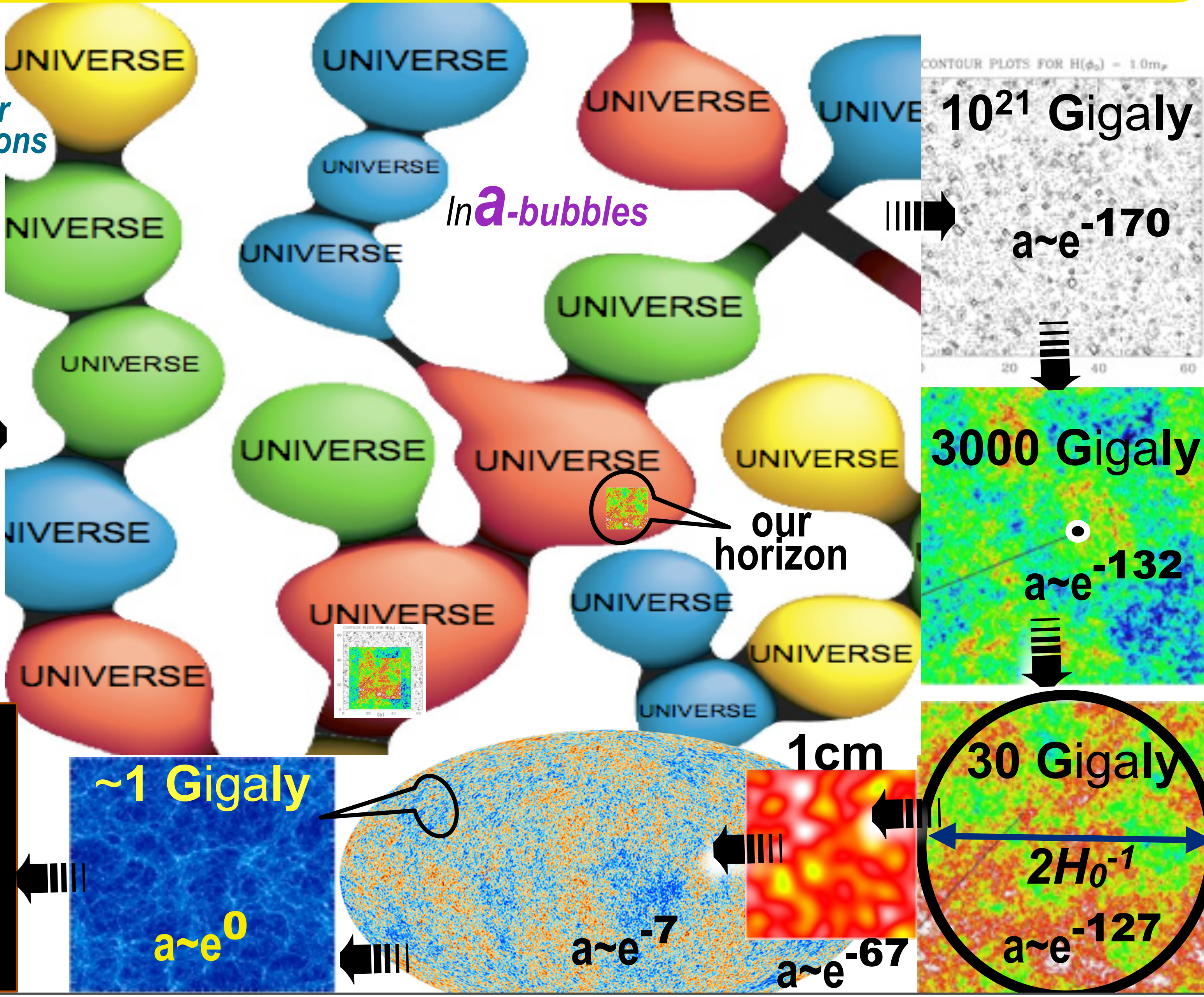


higher dimensions 6?





quantum tunnels = bubbly-U



a future DeVoid

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

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

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

END

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