PLANCK 2014

THE MICROWAVE SKY IN TEMPERATURE AND POLARIZATION

Dick Bond CITA on behalf of the Planck collaboration

Mapping *the Planck 2014 Early Universe* Phonon Spectrum $\zeta = \ln a|_\rho = \ln \rho|_a / 3(1+\langle w \rangle)$

Acceleration Histories $\epsilon(Ha) = 3(1+w)/2 = -d\ln\rho/d\ln a / 2$ *& Inflaton Effective Potential* $V(\phi)$ *Reconstruction*

Maps = *(radical)* **compressions** *of the* ***time ordered information*** **ToI** ***onto a parameterized space:*** ***Linear maps, Quadratic maps (power), cosmic parameter maps***

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

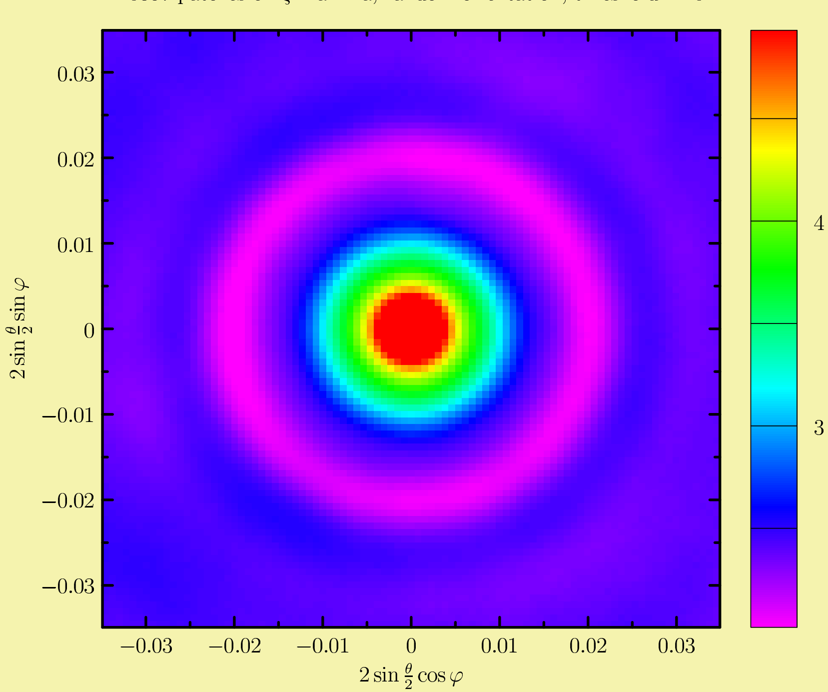
Mapping *the Planck 2014 Early Universe*
Phonon Spectrum $\zeta = \ln a|_\rho = \ln\rho|_a / 3(1+\langle w \rangle)$

Planck 2014 Isotropy and Statistics paper: extensive stacking of T,Q,U,E,ζ_{dv} on $T, P^2=Q^2+U^2, E, \zeta_{dv}$ peaks as in Martinez-Gonzalez, Huang/Frolov talks; & Wandelt

stacking=> $\delta\zeta_{dv}$ *destructive interference* => *reveals* $\langle\zeta_{dv}\,|\text{T-peak}\rangle$, $\langle\zeta_{dv}\,|\zeta_{dv}\text{-peak}\rangle$

stacked

$\langle\zeta_{dv}\,|\,\zeta_{dv}\text{-}pk\rangle$



ζ stacks of P13 & WMAP9 look v. similar

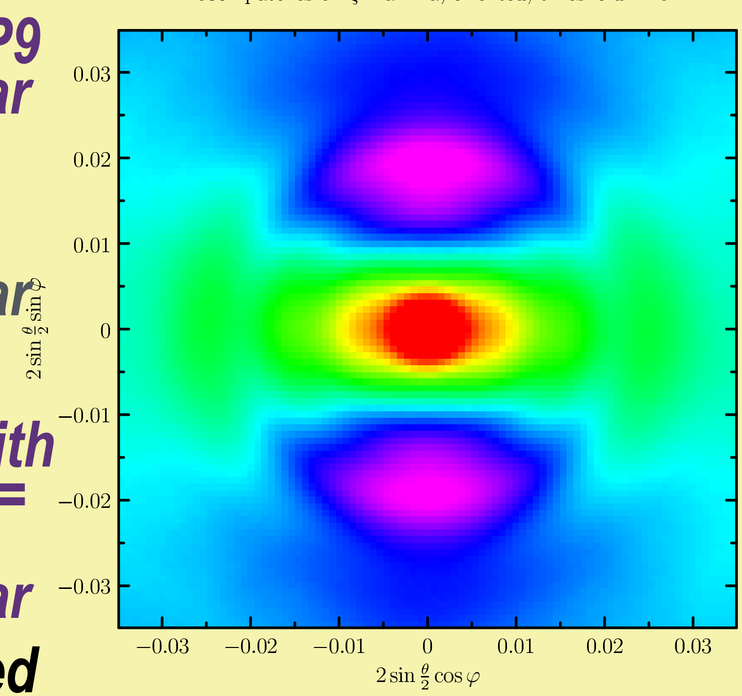
FFP8 simulations look v. similar

stack one FFP8 map with fluctuations = FFP8 mean look v. similar

not de-lensed

stacked

$\langle\zeta_{dv}\,|$ oriented $\zeta_{dv}\text{-}pk\rangle$



Mapping *the Planck 2014 Early Universe* Phonon Spectrum $\zeta = \ln a|_\rho = \ln\rho|_a / 3(1+\langle w\rangle)$

phonon ~ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ ~ ∇^{-2}***scalar curvature @ iso-density***

Inflation = phenomenology of phonons = energy-density quanta
inflaton = "condensate" of phonon fluctuations, $\langle\rho|_{k<Ha}\rangle + \delta\rho$ ***oscillations***
relativistic negative-pressure Equation of State (1+w)

phonon = ***collective mode composed of*** *fundamental* ***scalar fields (many*** ϕ_b***?)***
in linear perturbation theory, the phonon = linear combination of *fundamental scalars*

Geometrical view: *theory of* ***isotropic*** *(volume)* ***strain, Trace (Strain) ~phonons***
& gravity waves Transverse Traceless (Strain)

all that CMB+LSS can deliver is this phonon/strain wave Inflation Phenomenology
how does it fit into a UV-complete theory (ultra-high energy to the Planck scale) *strings, landscape, ..*
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

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$\rho(\phi_b, \pi_b, \ln a)$ =>*coarse-grained k<Ha* ***Hamiltonian-density attractor*** $\rho(\phi_b)^{\text{landscape}} = 3M_P^2H^2$
$d\phi_b/d\ln a = -M_P^2 \nabla_{\phi b} \ln\rho$, **a gradient / Morse flow =>** ***Hamilton-Jacobi eq***^{n},
"adiabatic" fluctuations along the Morse flow (phonons) isocurvature directions ⊥ the flow

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Quadratic ζ-Maps *aka* Radical $\mathcal{P}_\zeta$ Compressions via ***expansion in knot-centered modes***

compression onto primordial power spectrum bandpowers

<=> compression onto C_L bandpowers *e.g., the nuisance-marginalized Gibbs-sampled grand unified* ***CMB-only bandpowers****, bandcentres = knots, bandshapes =modes*

Parameters of the $\mathcal{P}_\zeta$ Quadratic Mode Expansion

which function to expand/scan $u = \ln \mathcal{P}_\zeta(k)/\mathcal{P}_{\zeta fid}(k) = \sum q_b\, e_b(\ln k)$

which modes $e_b(k)$ (***cubic spline****, **linear**, B-splines, Chebyshev, …)*

how many modes *aka* ***knots*** *(until feature convergence,* ***12 OK****, 16 ~same, 8 too few)*

what are the priors/measures on amplitudes q_b *(uniform, independent)*

since the C_L^{TT} anomalies of WMAP, we have tried $n_s(\ln k)$, $\varepsilon(\ln Ha)$, $\ln H(\ln Ha)$ as well, => priors change, but we get qualitatively similar features. ***Planck 2014 clarifies features & their story.***

fiducial choice $\ln \mathcal{P}_{\zeta fid}(k) = \ln A_s + (n_s - 1)\ln(k/k_{pivot})$, $n_s \equiv 0.967$ ($m^2\varphi^2$) (also $\mathcal{P}_{\zeta fid} = A_s$)

maxL solutions are (quadratic) Wiener-filtered maps! with Fisher/Hessian errors

here we use MCMC, show the mean $\langle \ln \mathcal{P}_\zeta(k)\ |TT,TE,EE,\ldots\rangle$ ***trajectory &***

$\langle \ln \mathcal{P}_\zeta \rangle + \delta \ln \mathcal{P}_\zeta$ ***±1σ trajectories to illustrate ensemble variance & coherence***

scan q_b, $\ln A_s$, $r(k_{pivot,t}=.05/\mathrm{Mpc})$ $(n_t = -r/8)$; *consistency => reconstruct* $\varepsilon(\ln Ha)$, $V(\phi)$

Quadratic $ln\mathcal{P}_\zeta(ln k)$ Maps *aka* Radical Compressions

=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline

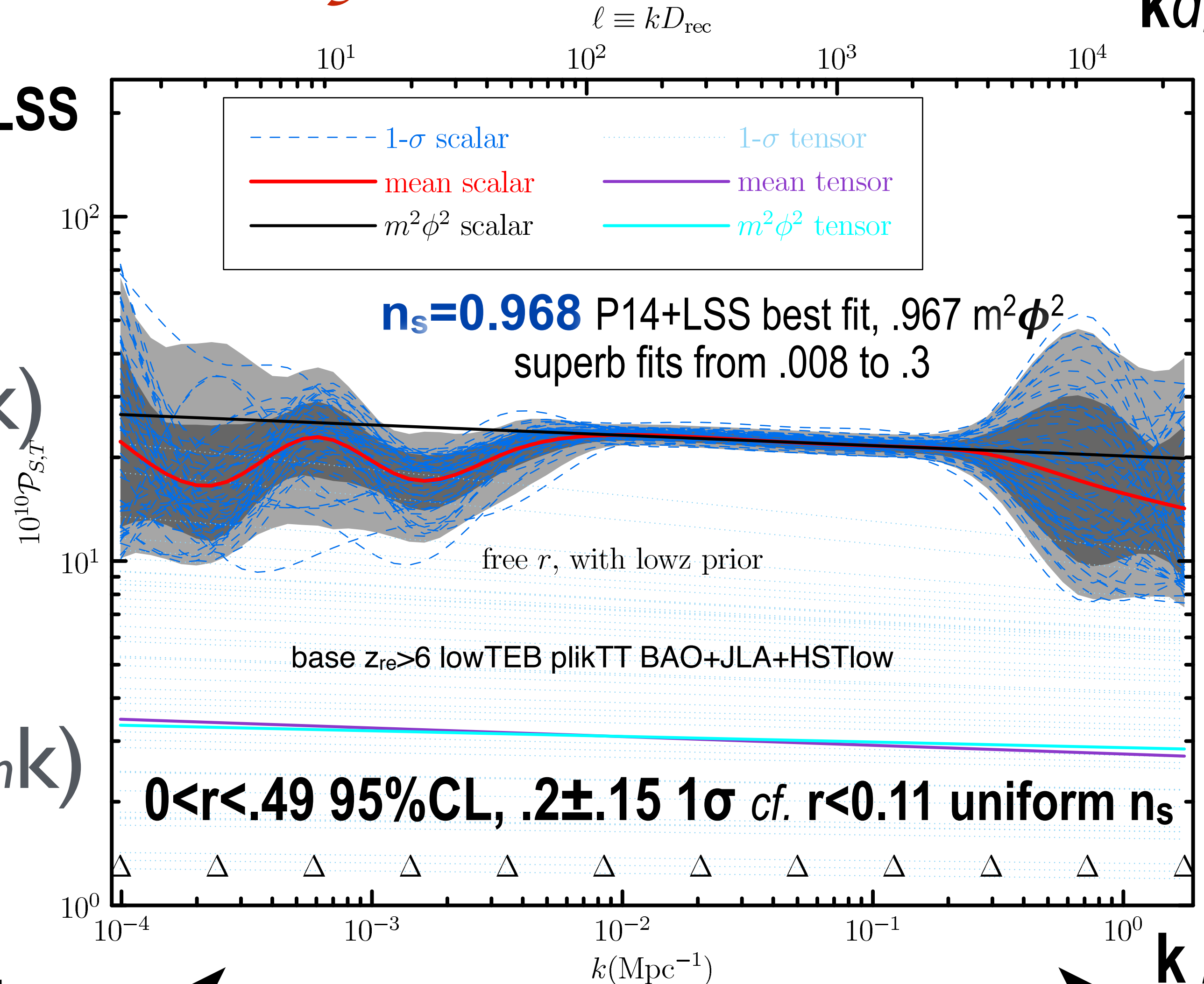
$kd_{rec} \gtrsim L$

Planck14+LSS

$ln\mathcal{P}_\zeta(ln k)$

r - $\mathcal{P}_\zeta$ partial degeneracy if r floats

$ln\mathcal{P}_{GW}(ln k)$



k /Mpc

9 e-folds

Quadratic $ln\mathcal{P}_\zeta(ln k)$ Maps *aka* Radical Compressions
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12 knots, cubic spline

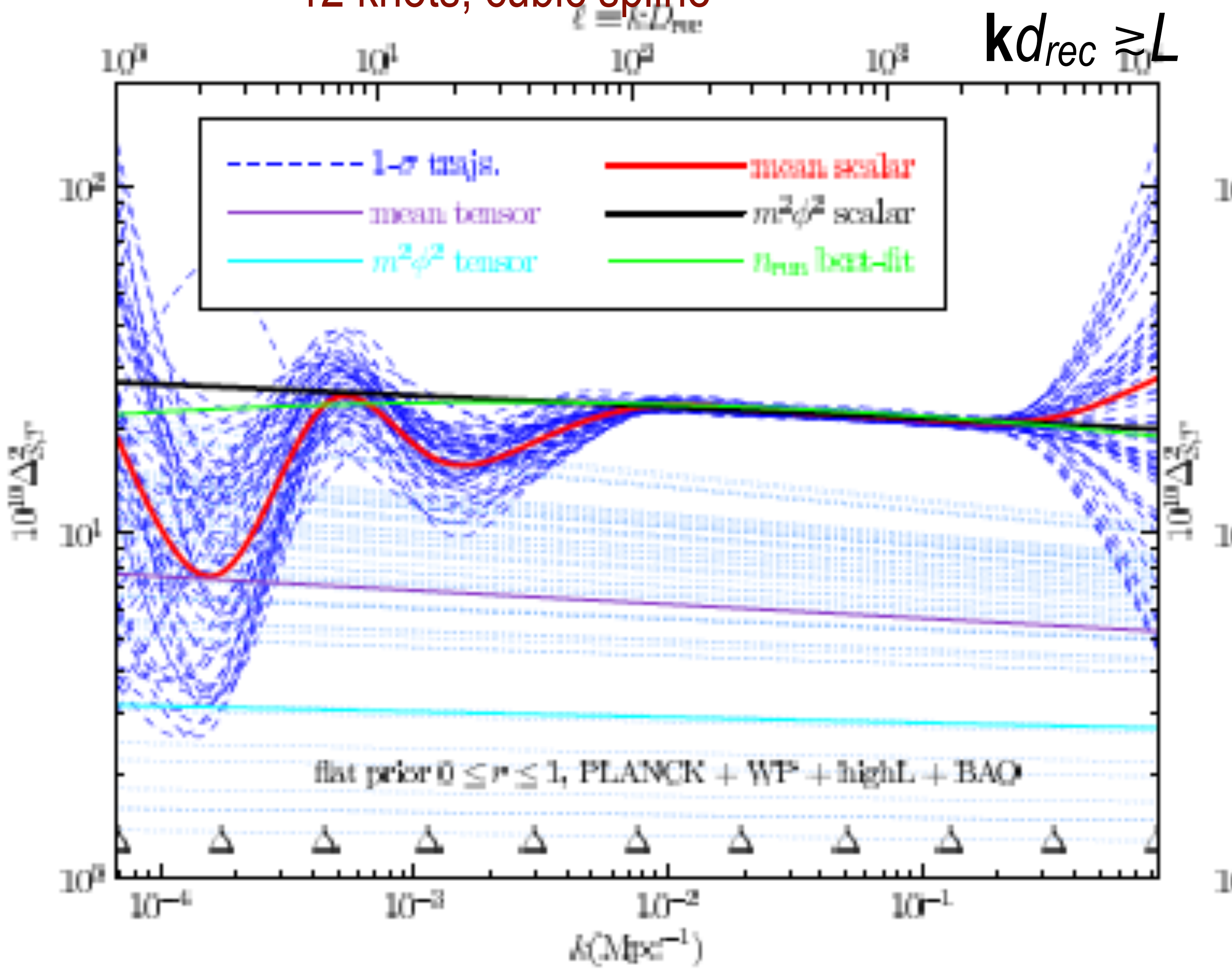
kd_{rec} ≳L

cf. **Planck13+LSS**

$ln\mathcal{P}_\zeta(ln k)$

Planck13 & WMAP => stable features

$ln\mathcal{P}_{GW}(ln k)$



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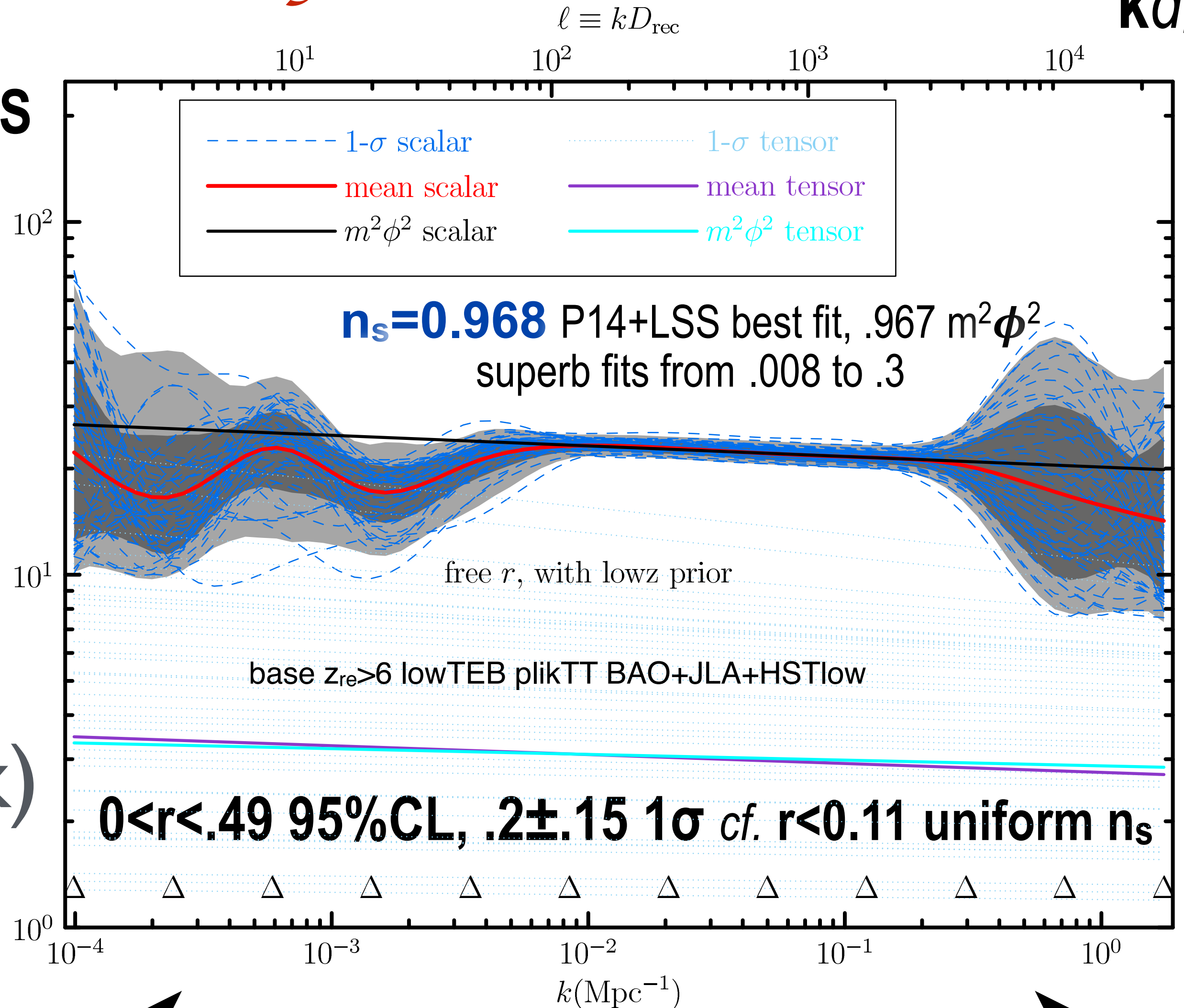

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constrain r ≡ 0.1

Planck14+LSS

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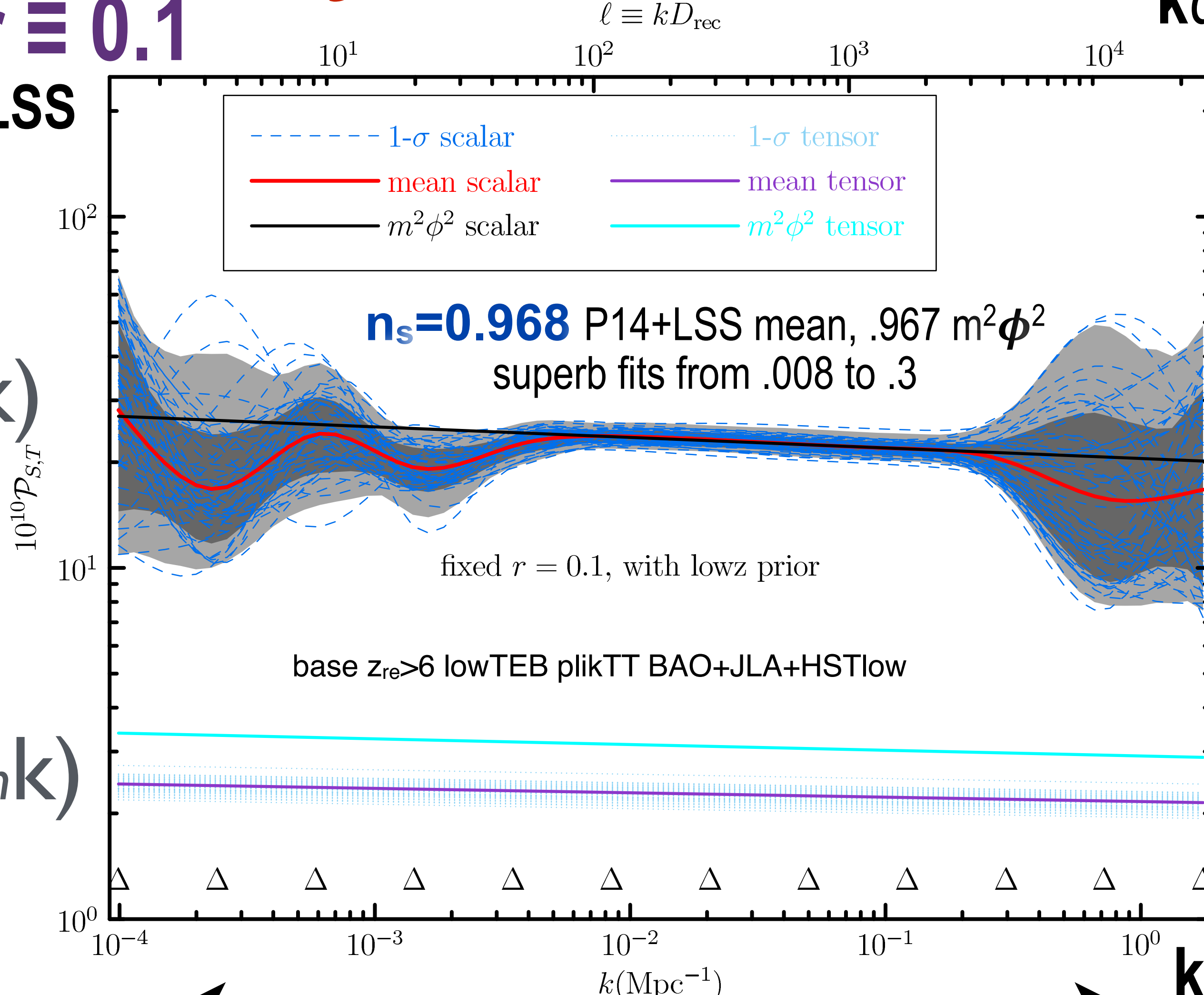
$ln\mathcal{P}_\zeta(lnk)$

future r=0.1 constraint break degeneracy => stable features

$ln\mathcal{P}_{GW}(lnk)$



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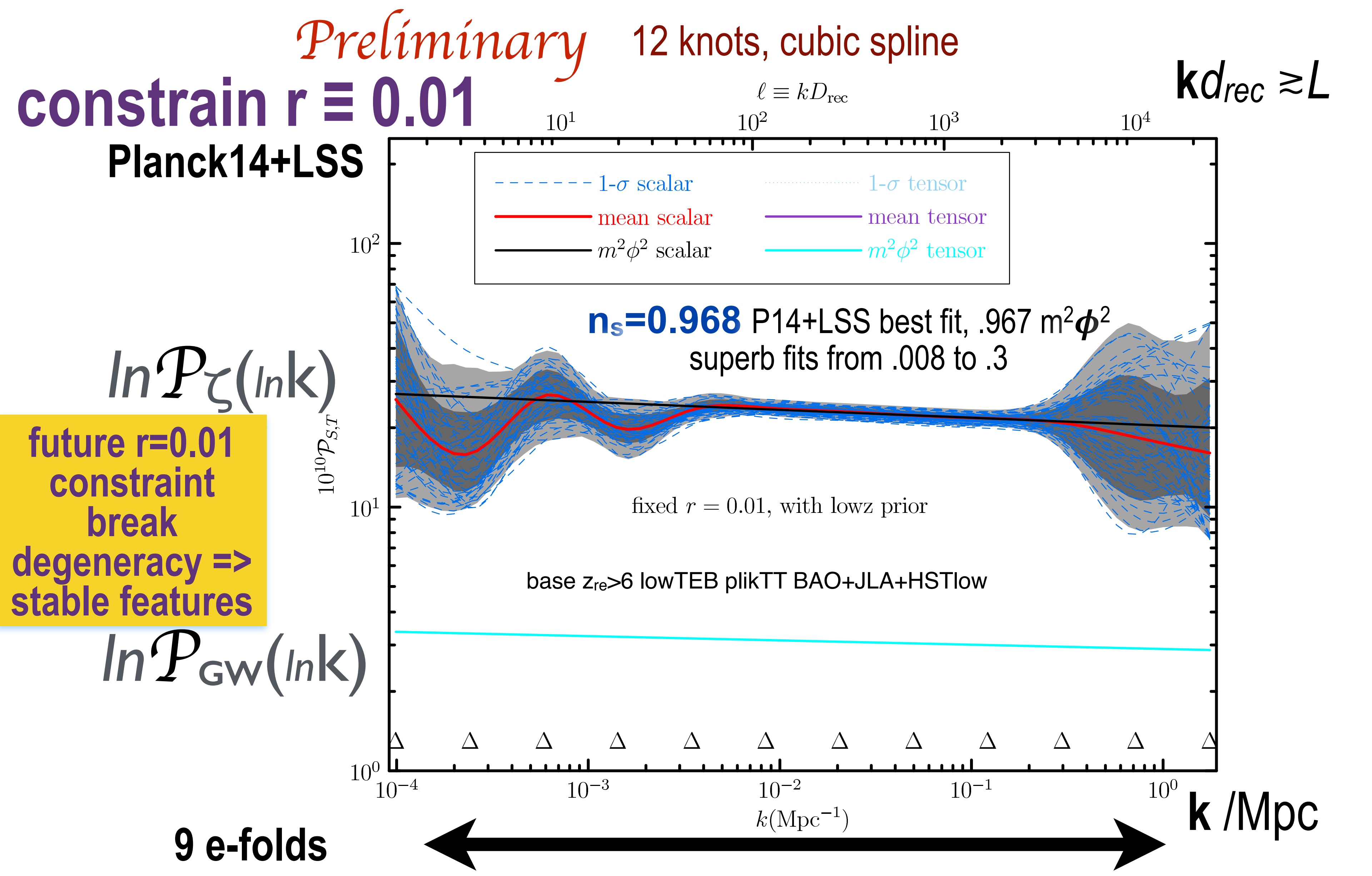

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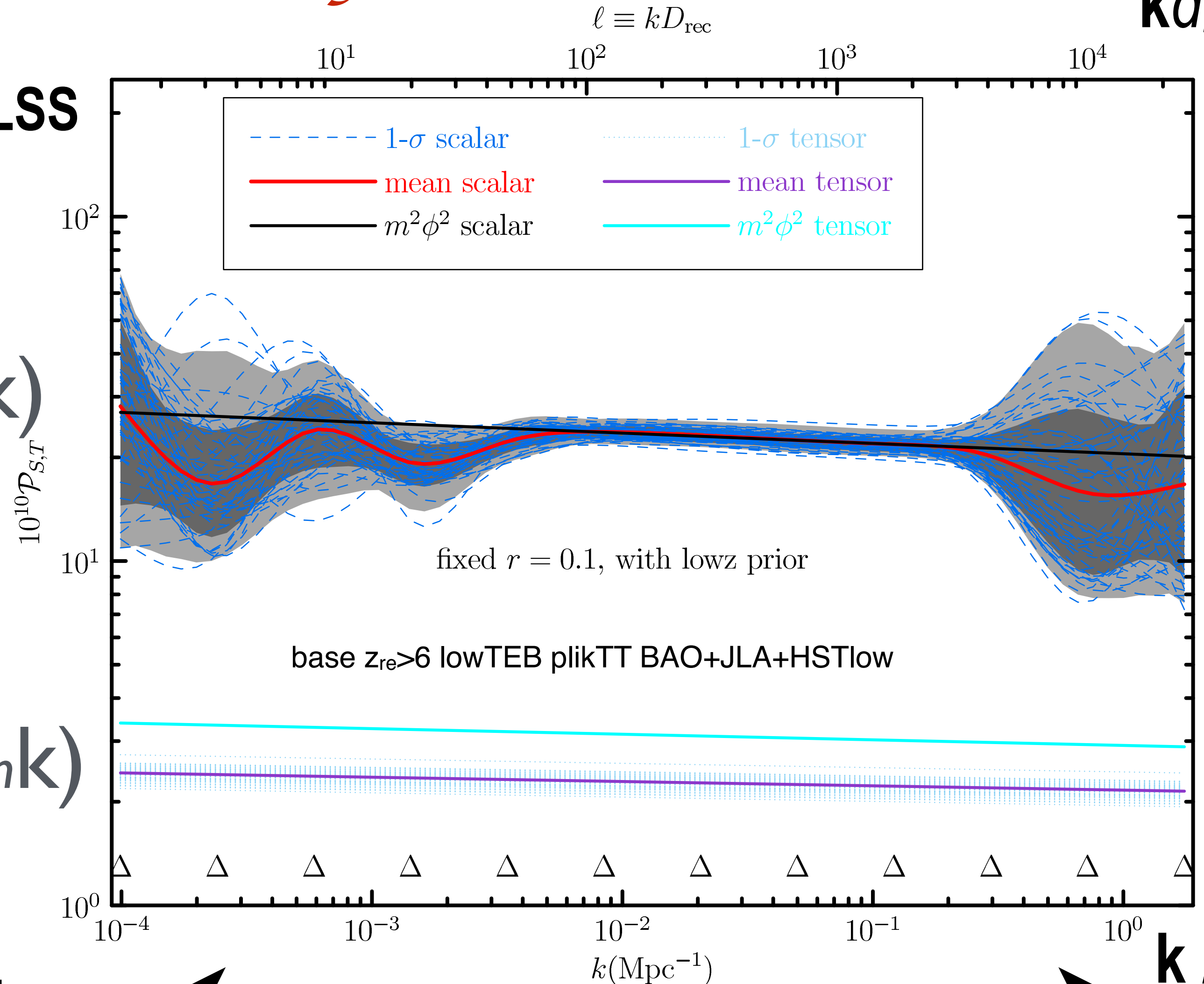
$ln\mathcal{P}_{GW}(lnk)$

$\mathbf{k}d_{rec} \gtrsim L$



k /Mpc

9 e-folds

Quadratic $ln\mathcal{P}_\zeta(ln k)$ Maps *aka* Radical Compressions
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Preliminary 12 knots, linear

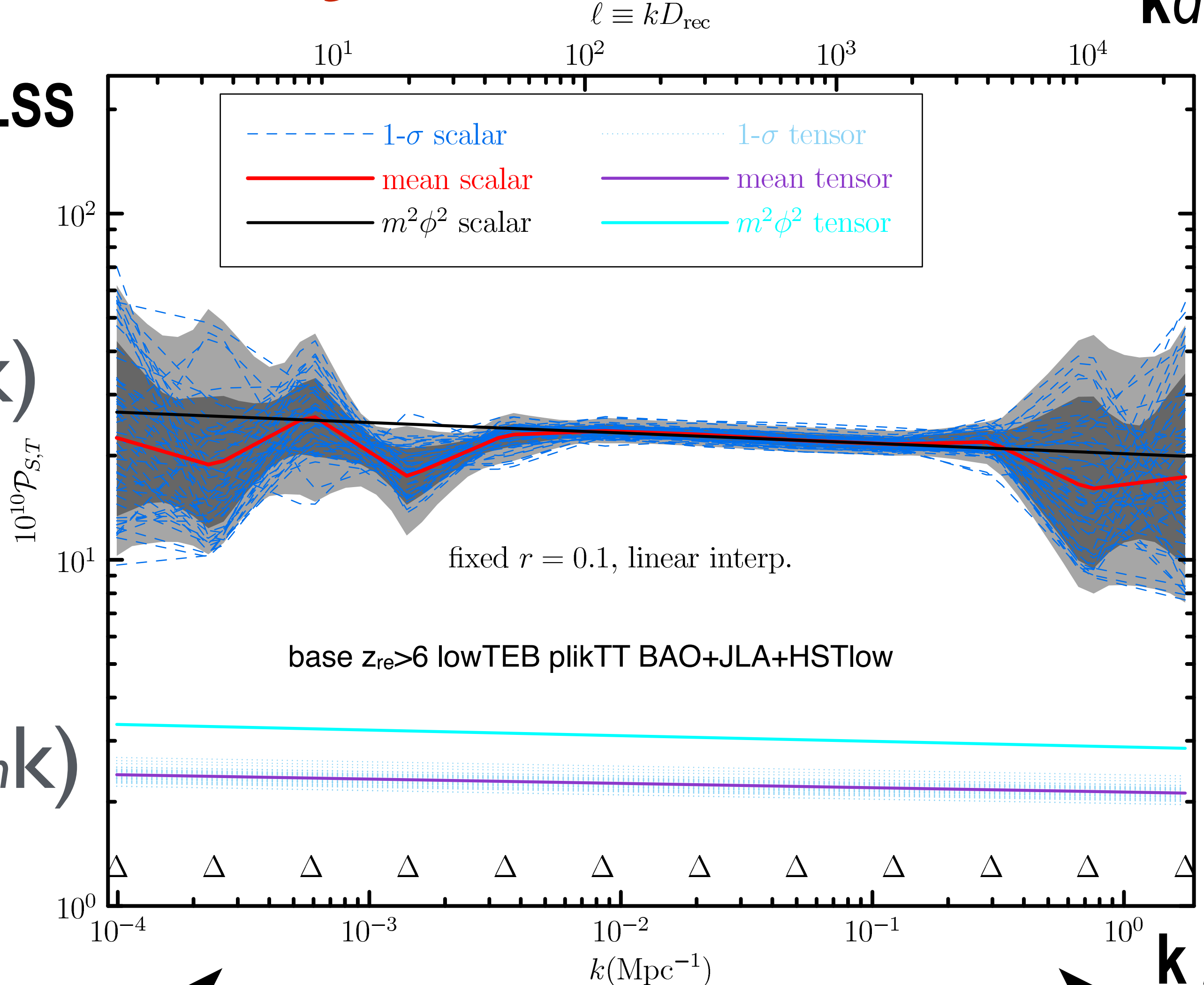
k$d_{rec} \gtrsim L$

Planck14+LSS

$ln\mathcal{P}_\zeta(ln k)$

mode function change to linear => stable features

$ln\mathcal{P}_{GW}(ln k)$



k /Mpc

9 e-folds

Quadratic $\ln \mathcal{P}_\zeta(\ln k)$ Maps *aka* Radical Compressions
=> ultra-early Universe sound/phonon spectrum

Preliminary 8 knots, cubic spline

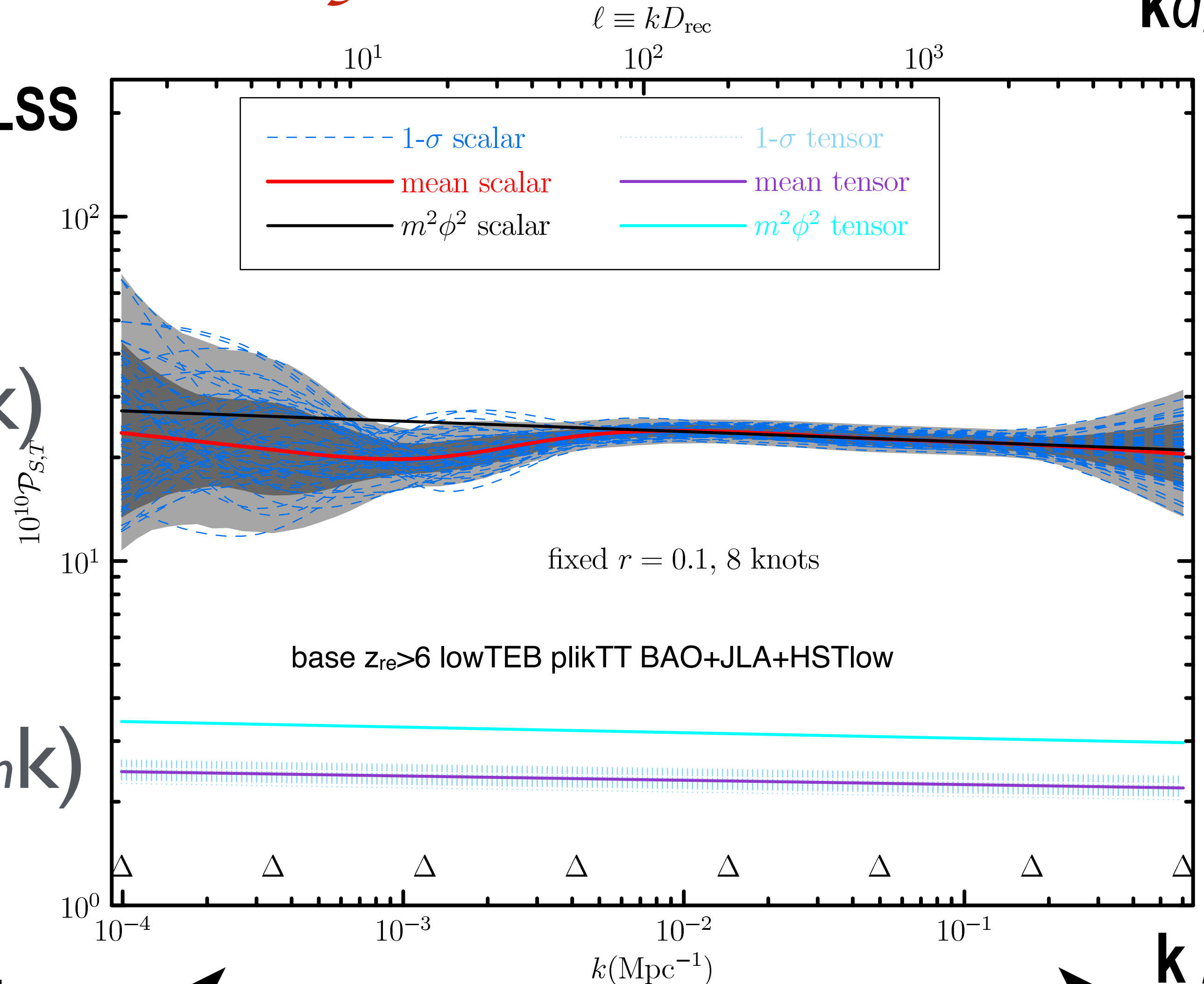
k$d_{rec} \gtrsim L$

Planck14+LSS

$\ln \mathcal{P}_\zeta(\ln k)$

$\ln \mathcal{P}_{GW}(\ln k)$

8 knots too few for stable features



k /Mpc

9 e-folds

Quadratic $ln\mathcal{P}_\zeta(ln k)$ Maps *aka* Radical Compressions

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Preliminary 12 knots, cubic spline

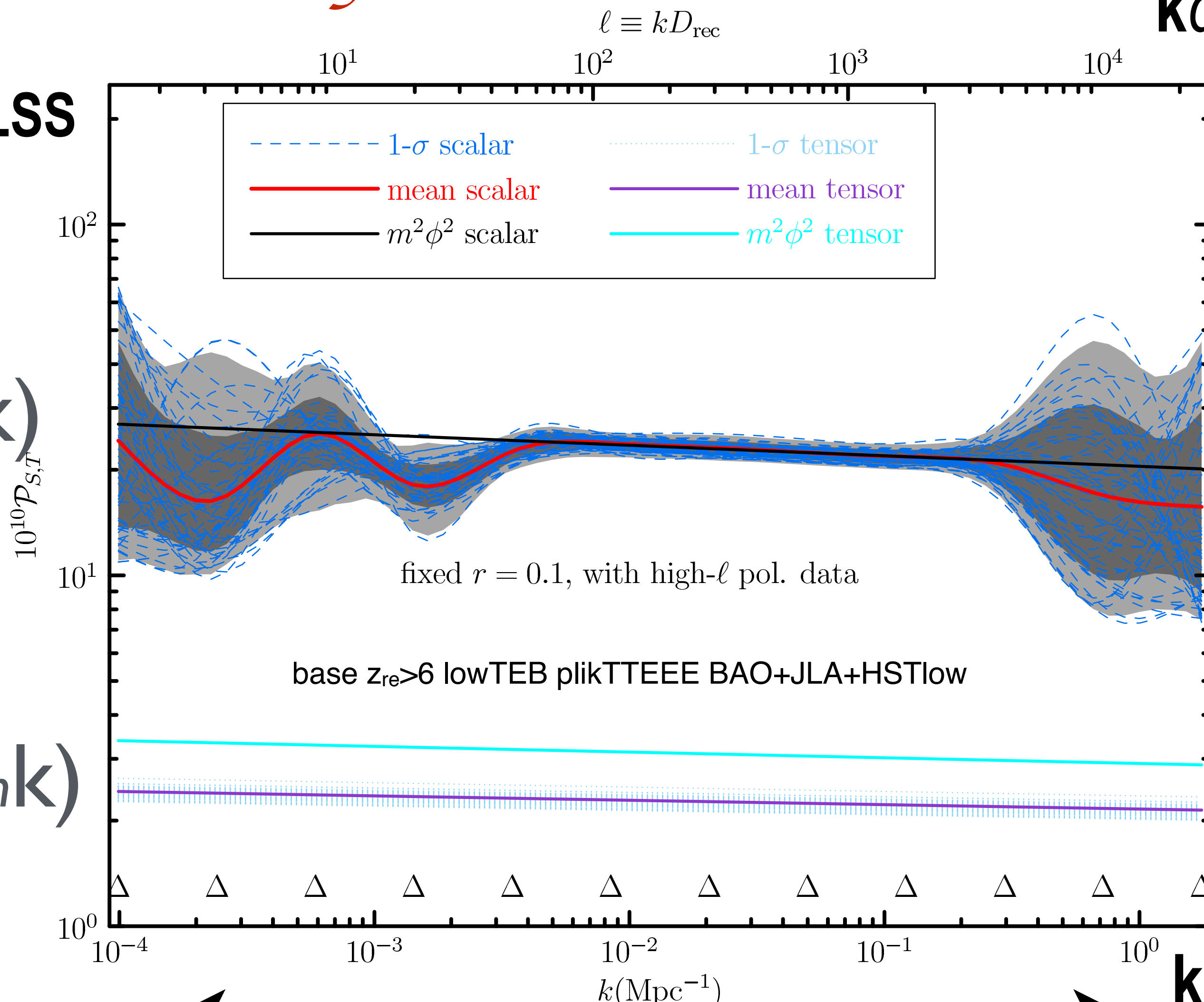
k$d_{rec} \gtrsim L$

Planck14+LSS

$ln\mathcal{P}_\zeta(ln k)$

adding high L polarization => stable features

$ln\mathcal{P}_{GW}(ln k)$

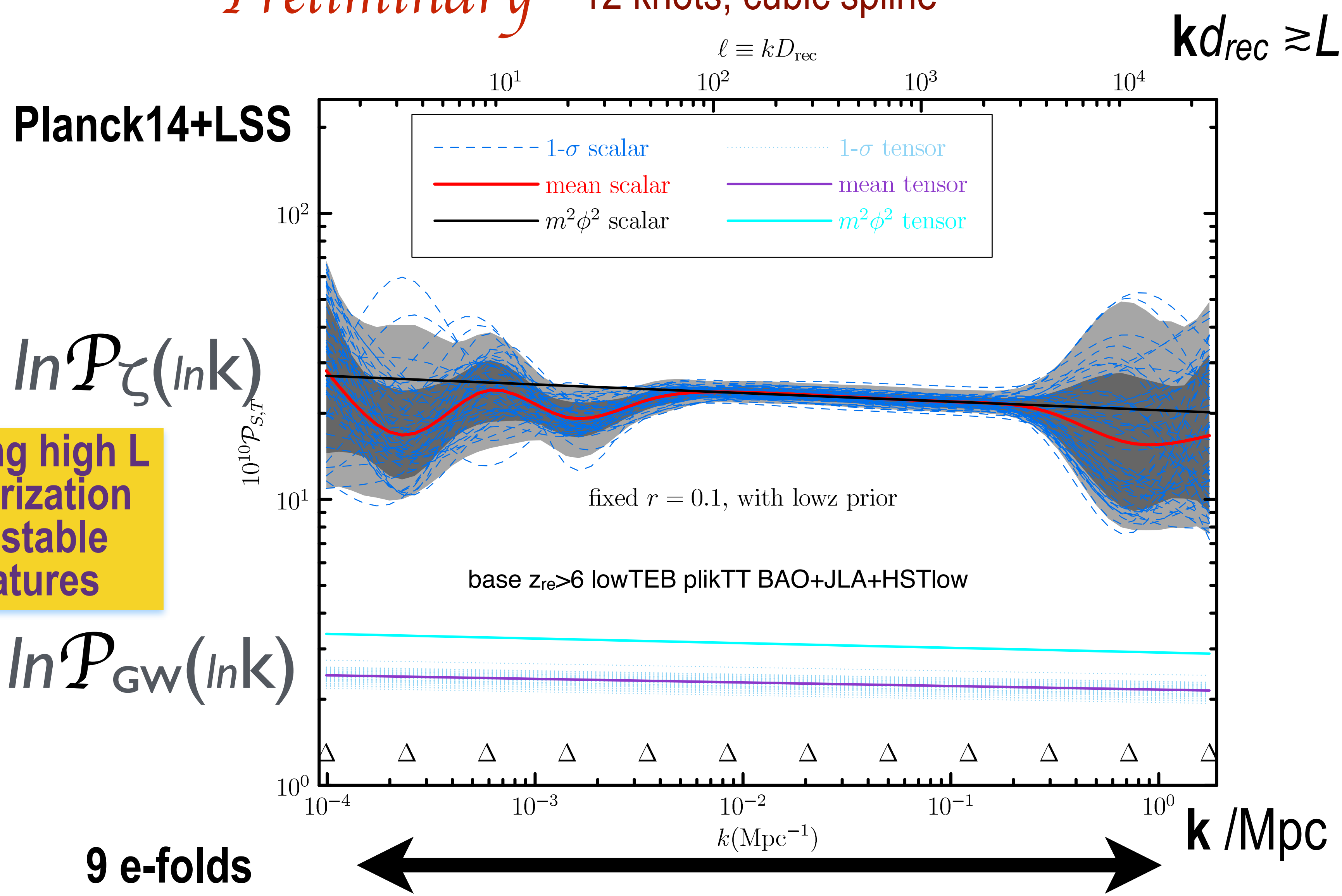


k /Mpc

9 e-folds

Quadratic $ln\mathcal{P}_\zeta(lnk)$ Maps *aka* Radical Compressions
=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline



adding high L polarization => stable features

Quadratic $ln\mathcal{P}_\zeta(lnk)$ Maps *aka* Radical Compressions
=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline

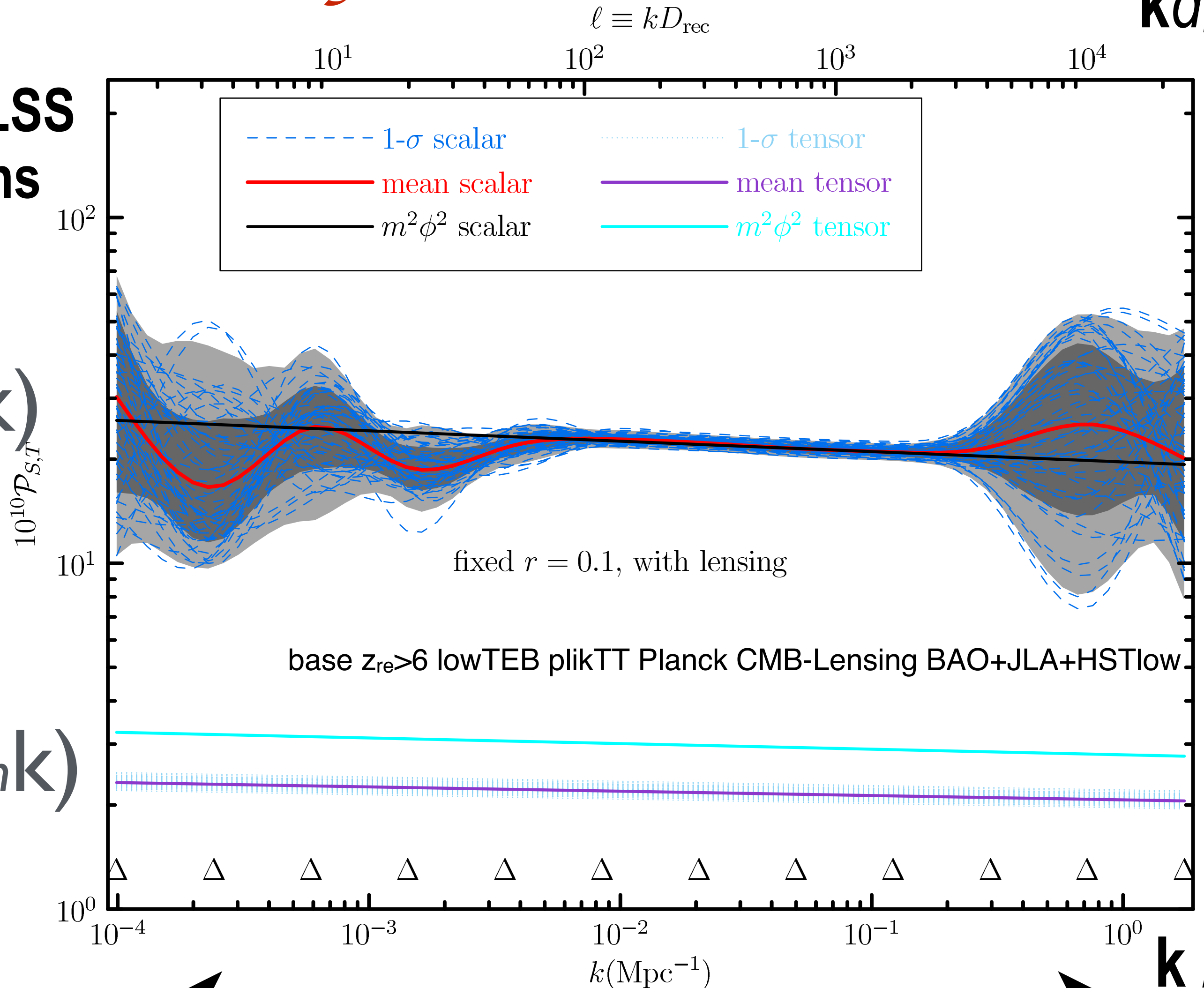
$kd_{rec} \gtrsim L$

Planck14+LSS +CMB Lens

$ln\mathcal{P}_\zeta(lnk)$

adding CMB lensing => stable features

$ln\mathcal{P}_{GW}(lnk)$



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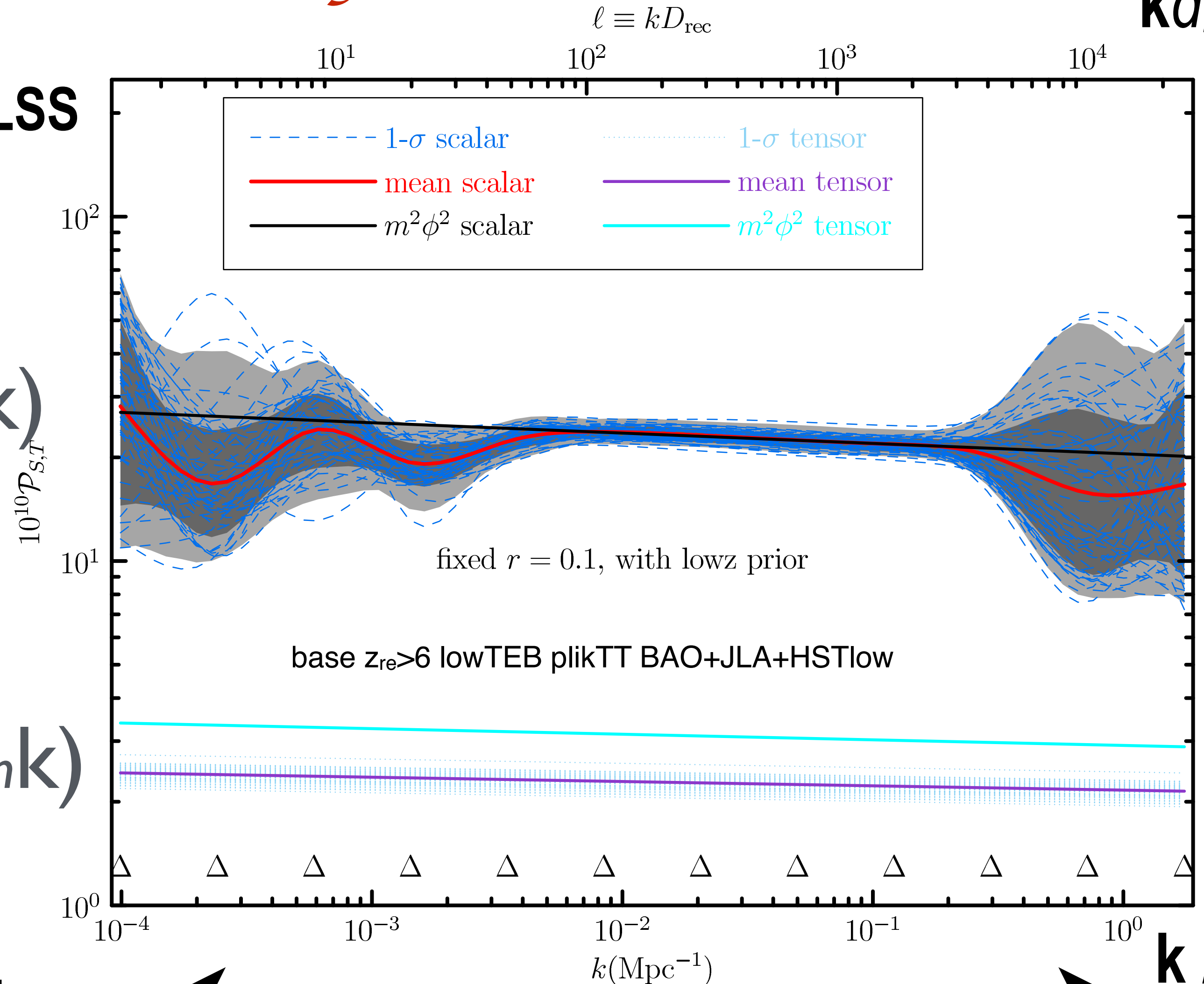
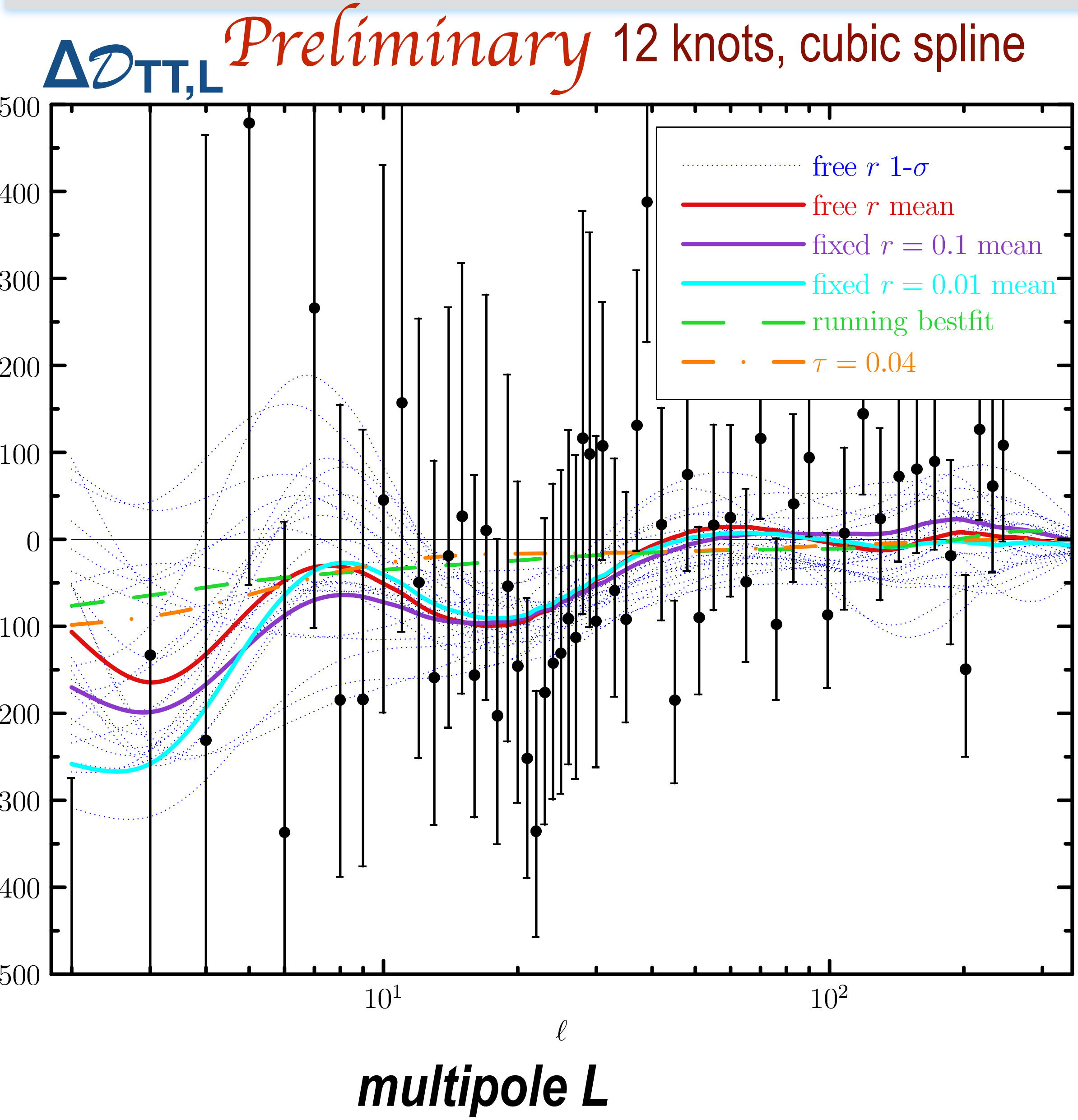


k /Mpc

9 e-folds

trajectories of $\mathcal{D}_{TT,L}$

cf. Planck 2014 Commander Low L spectrum with Blackwell-Rao errors



running of $\mathcal{P}_\zeta$
≡ 3 Chebyshev modes
=> very stiff
=> not what the data wants

Lower τ => shape similar to running at low L

similar response on $\mathcal{D}_{TT,L}$ for constrained & free r

modified by τ freedom

Quadratic $ln\mathcal{P}_\zeta(ln k)$ Maps *aka* Radical Compressions
=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline

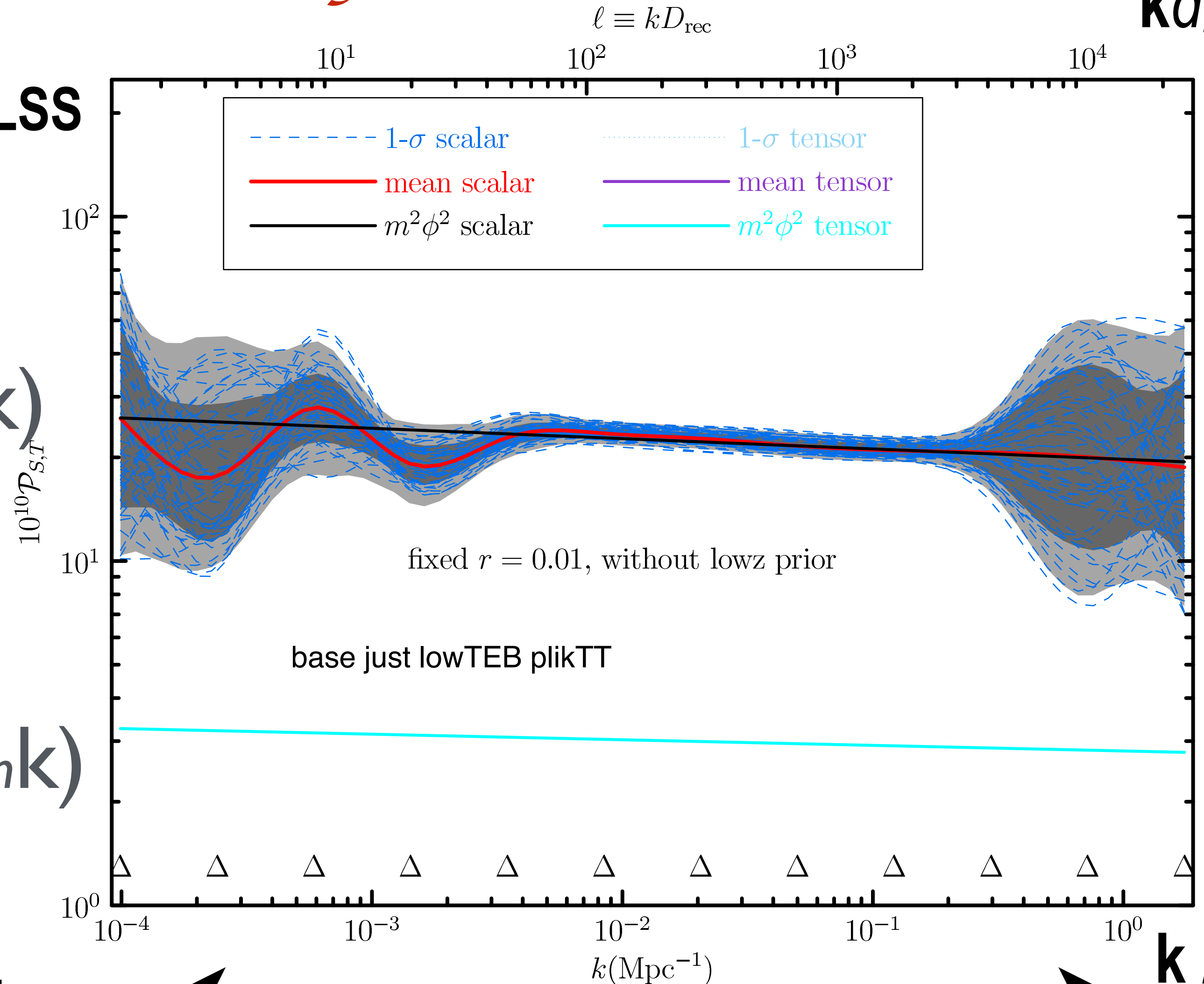
$kd_{rec} \gtrsim L$

Planck14 no LSS

$ln\mathcal{P}_\zeta(ln k)$

drop z_{re} > 6 & LSS, stable features

$ln\mathcal{P}_{GW}(ln k)$



k /Mpc

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=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline

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Planck14+LSS

$\ln\mathcal{P}_\zeta(\ln k)$

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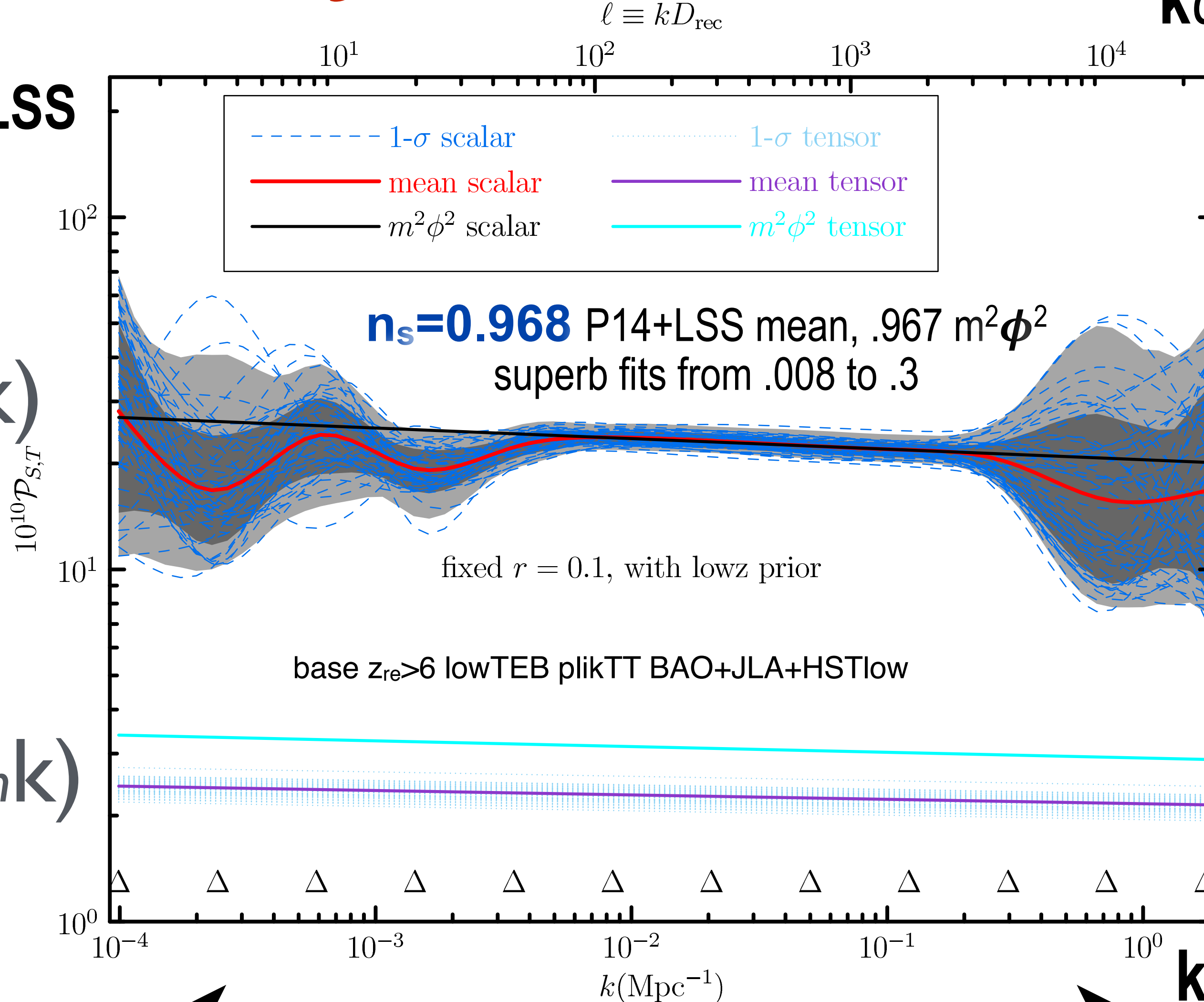
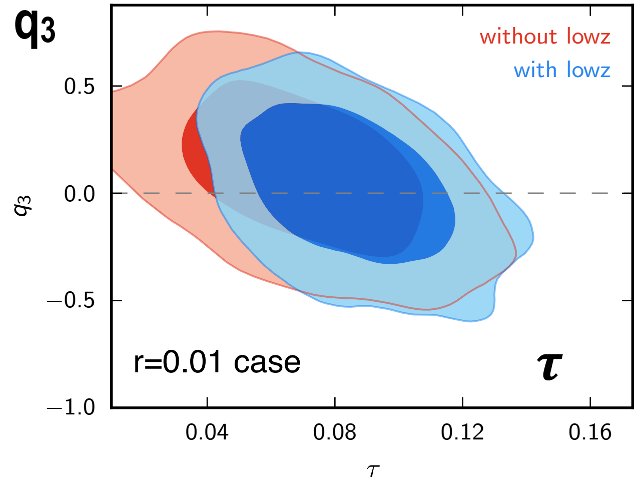


k /Mpc

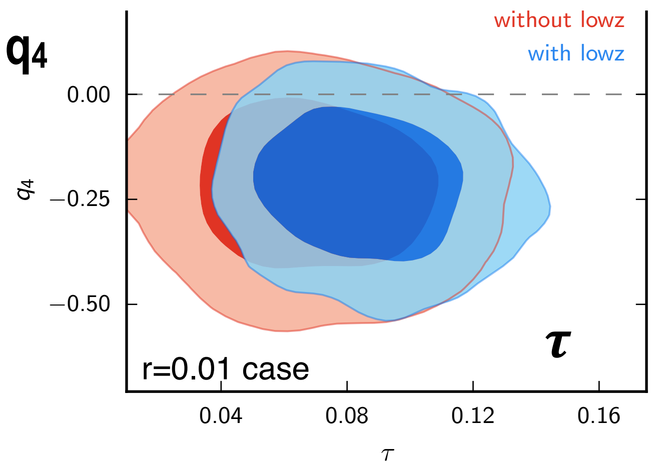
9 e-folds

$q_b = \ln[\, \mathcal{P}_\zeta(k_b) \,/\, A_s\, (k/k_p)^{(ns-1)}\,]$ at knot k_b

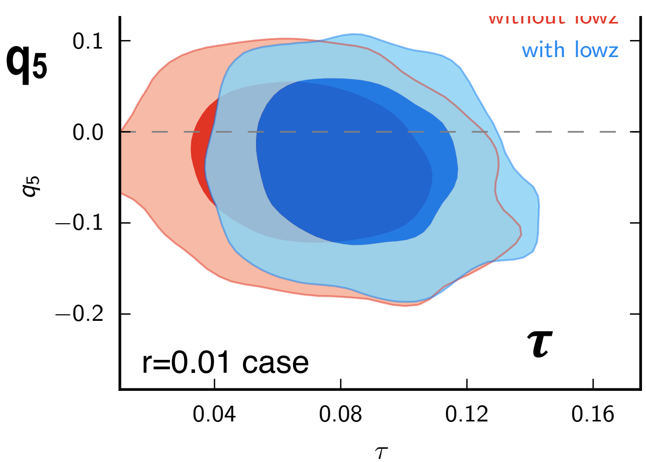


τ-dependence creates the slight low L bump

Preliminary

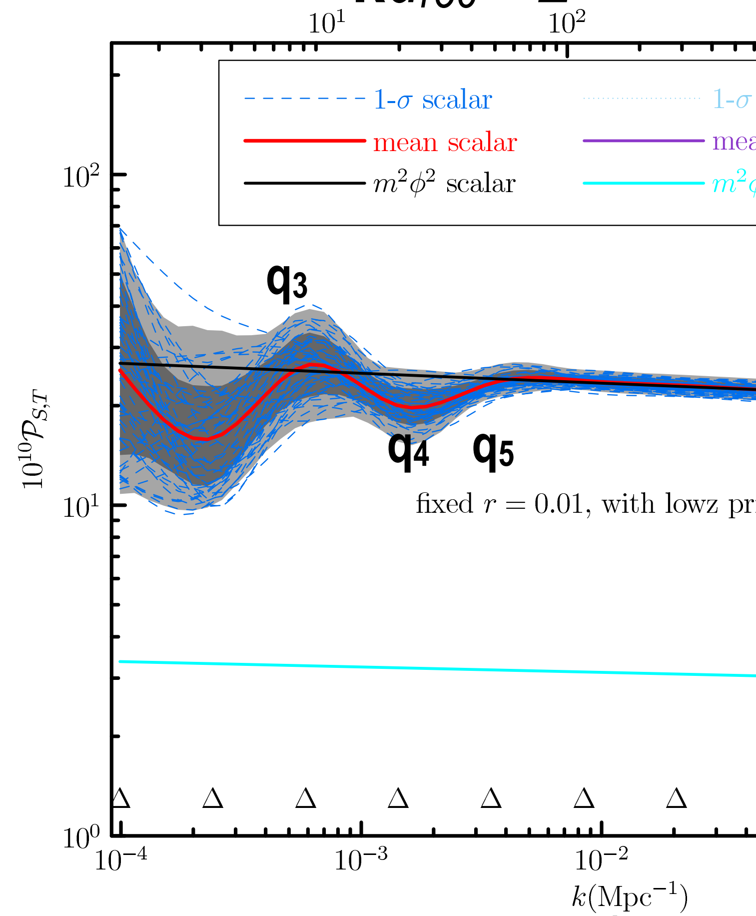


L~20-30 downturn creates the q_4 dip no τ-dependence beyond since before / beyond reionization



deviation from *tΛCDM* mended by q_5

$kd_{rec} \gtrsim L$ $\quad \ell \equiv kD_{\rm rec}$



k /Mpc

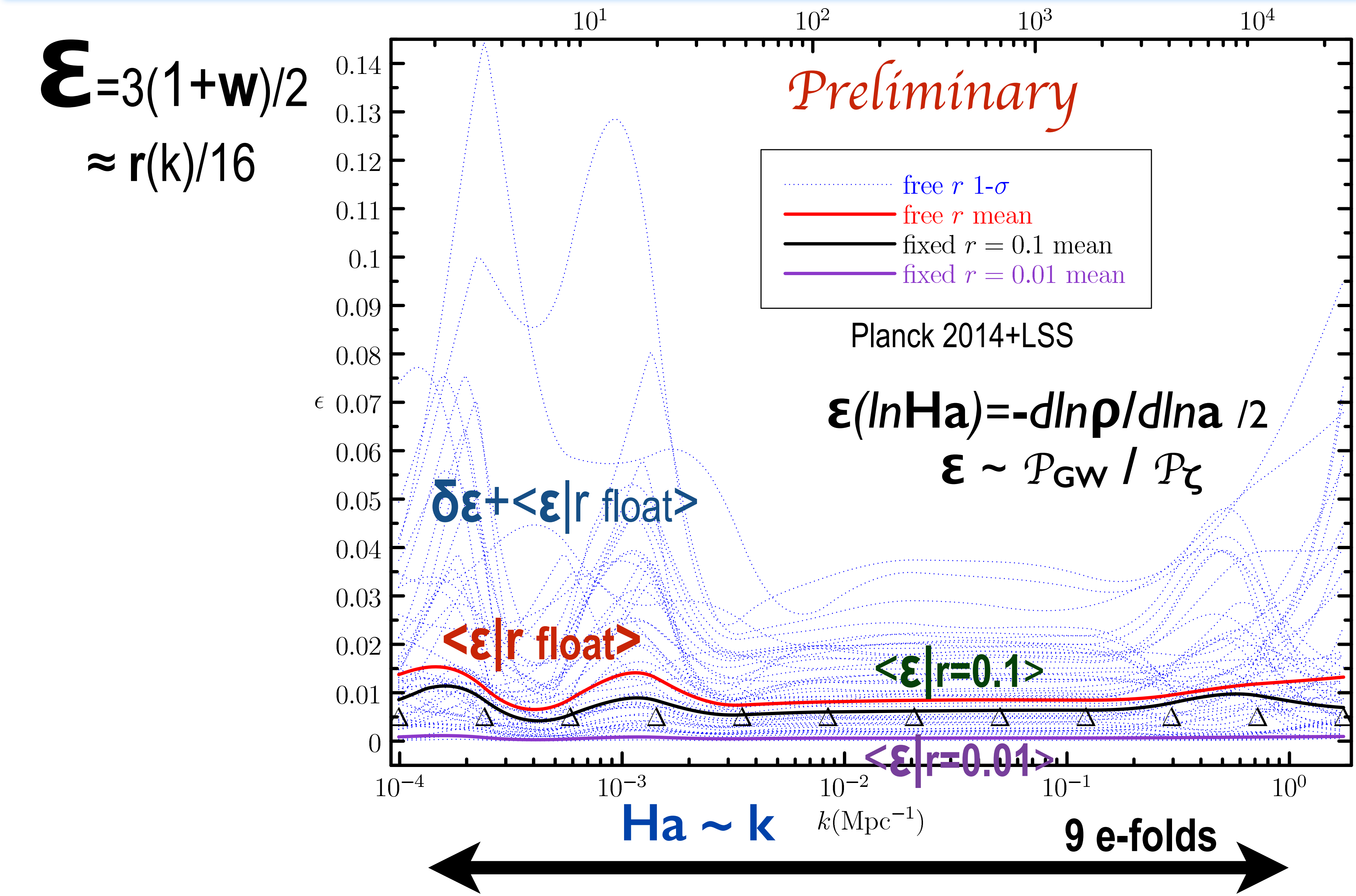
p-values from chi-squared in P_ζ space

q_1 to q_5 L<50 p-value = 0.42 uniform ns χ^2/dof =1.00

q_6 to q_{12} L> 50 P-value = 0.99 uniform ns χ^2/dof =0.11

trajectory coherence => correlated errors

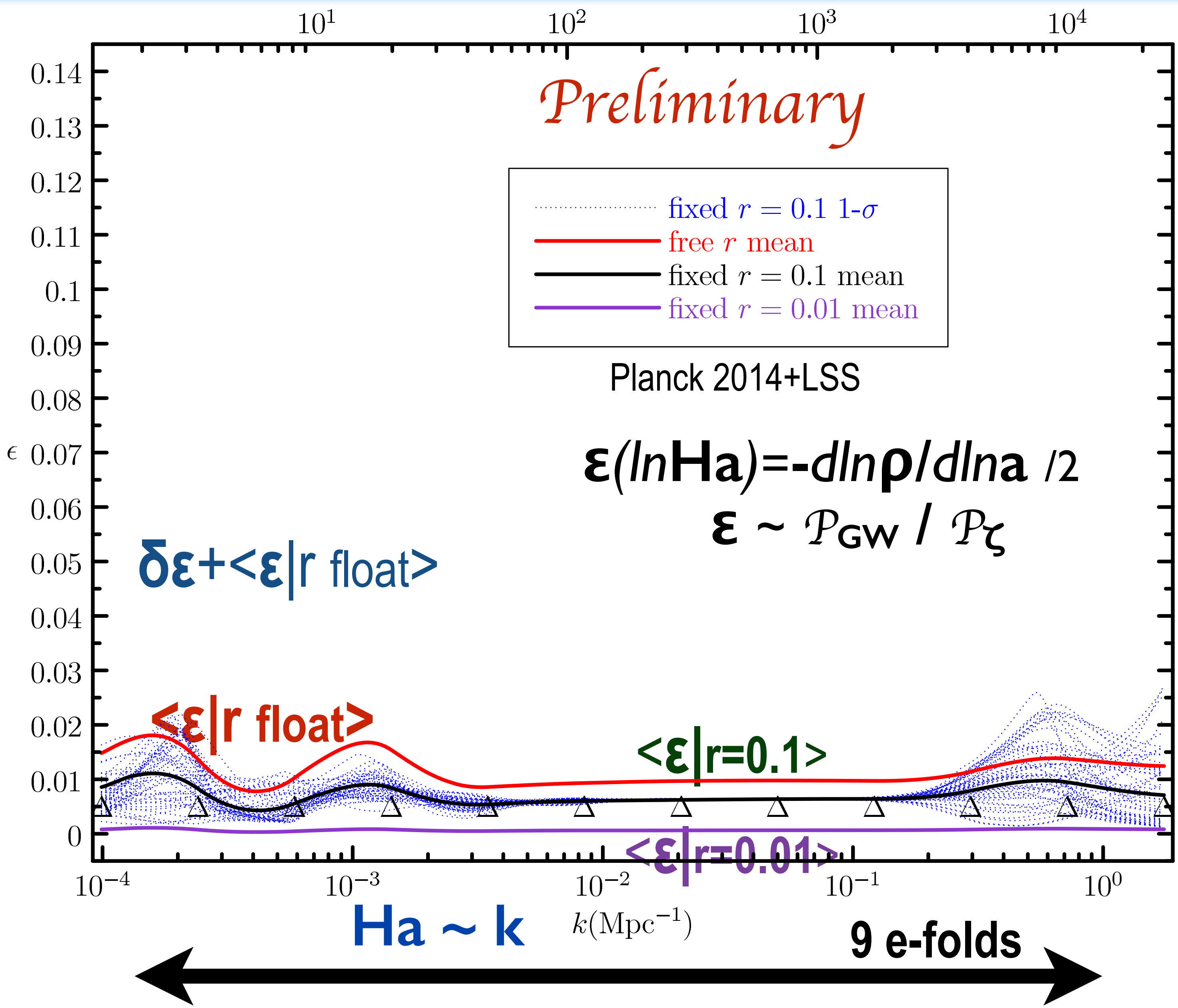
early universe **acceleration histories = EOS histories** 3(1+w)/2



early universe **acceleration histories = EOS histories** *3(1+w)/2*

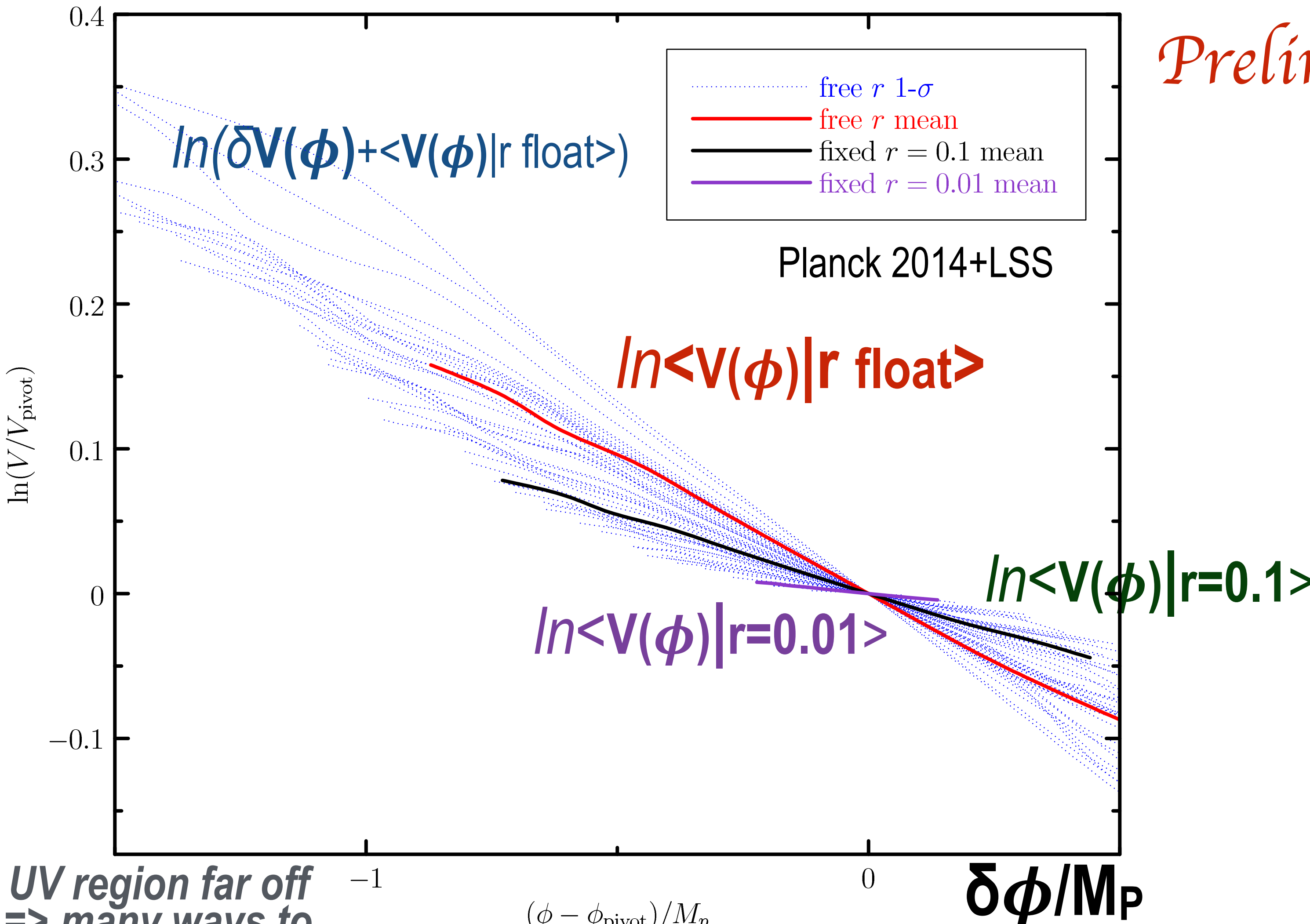
ε=3(1+**w**)/2

≈ **r**(k)/16



inflaton $V(\phi)$-maps $=3M_P^2 H^2 (1-\varepsilon/3)$ *HJ eqn,* $d\phi/M_P / d\ln a = \pm\mathrm{sqrt}(2\varepsilon)$

along the gradient / Morse flow



Preliminary

IR heating region is far off => many ways to extrapolate

UV region far off => many ways to extrapolate

r to **+-0.02 Spider** forecast

r to **+-0.003 AdvACTpol** forecast w/ fgnds

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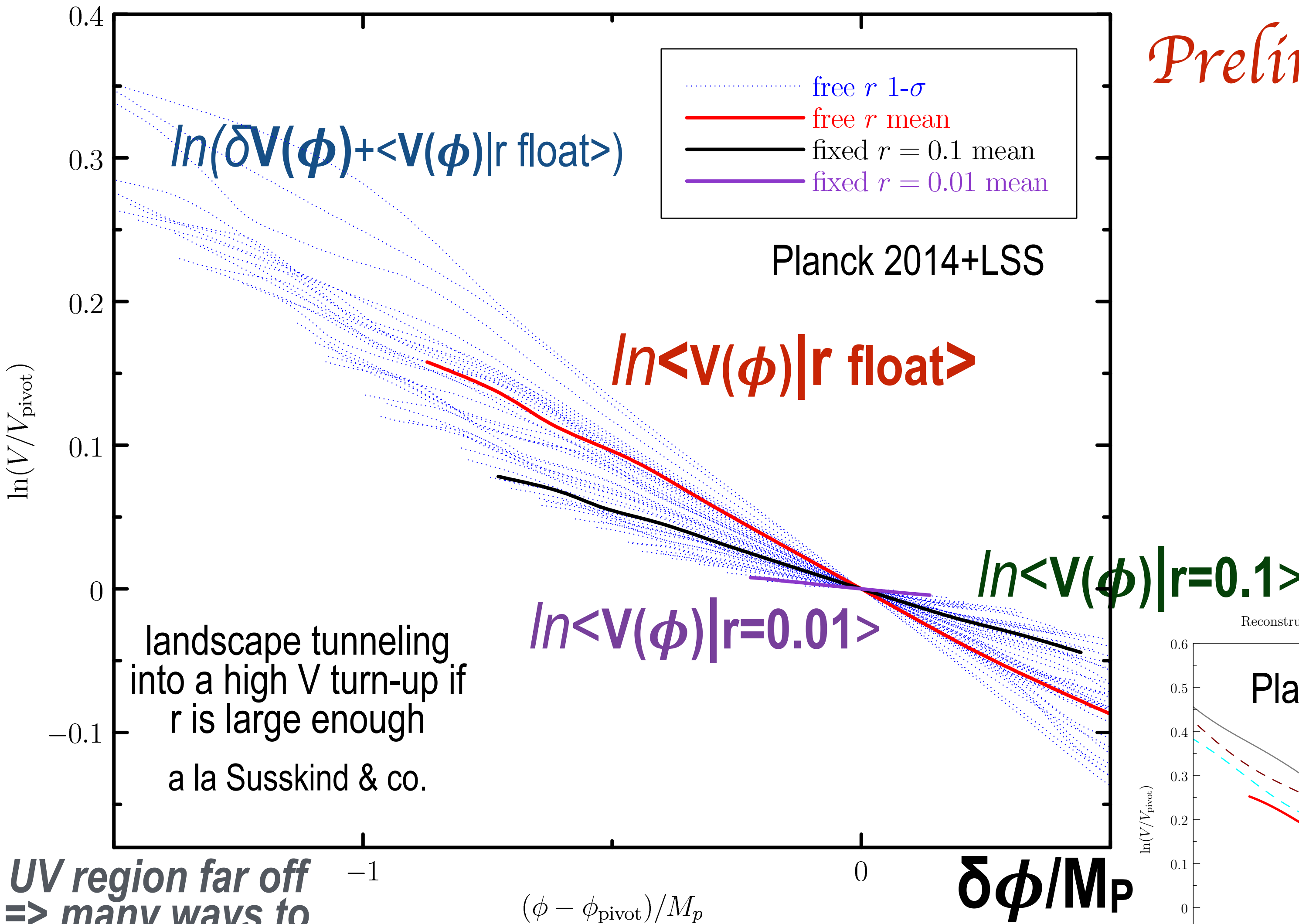

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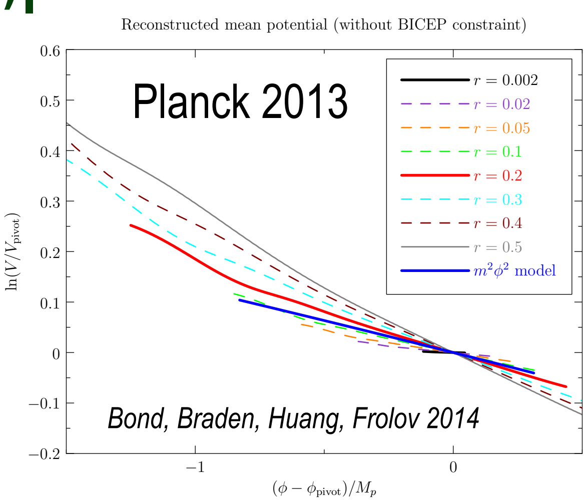

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conclusions

convergence testing *by increasing the number of knots, changing the knot mode functions, changing the fiducial to scale invariant => stable features & statistics*

12 knots is Good for low L features; *too few knots (8) => too stiff to respond to the CL data*

degeneracies in $\mathcal{P}_\zeta$ cf. $\mathcal{P}_{GW}$ unless r is constrained/measured => r=0.01,0.1 examples => same stable features. mild degeneracy with τ for lowest k-bands explain details of L<10 features

2 other $\mathcal{P}_\zeta$ reconstructions in Planck 2014 Inflation paper. e.g., Will Handley poster uses moving linear knots: the stable features & conclusions agree. Planck 2014 Inflation also reconstructs V directly 2 ways

simple uniform n_s triumphs at high k from 0.3 to 0.008/Mpc, OK (r) at low k

~10,000,000 T/E modes = tΛCDM L_k>50 p-value .98 (r free), .99 (r=0.01), .99 (r=0.1)

≲ 1000 T/E modes hint of uniform-n_s deviation, ≲ 100 T/E probe reionization history

no statistical evidence of oscillation patterns, cutoffs, at this level of coarseness/stiffness;

∃ a *mean-power change on large L<50 scales exists which is not well-fit by running*

the mean is statistically beaten by coherent power fluctuations: NO ANOMALY beyond 2 sigma

statistically insignificant deviation: low-k L_k<50 p-value .40 (r free), .42 (r=0.01), .14 (r=0.1)

all our anomaly hints are at low L, quadratic & linear: we are victims of cosmic variance

inflaton EOS aka ε trajectories => V trajectories: higher r, bigger $\delta\phi/M_P$ & steeper V, upturn?

the L_k=20-30 TT-driven mean downturn was/is a phenomenology (less in P14 cf. P13), no matter r

fit into a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, .. & IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

The scientific results that we present today are a product of 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.