Quantum Inflation in the 2015 Planck Era & Beyond

what are the degrees of freedom / parameters of the ultra early Universe? TBD

universe = system / signal parameters + noise / reservoir parameters
= coarse-grain (collective) parameters + fine-grain parameters
effective "field" eqns for coarse-grain system variables EFT
by marginalizing the fine-grain reservoir
=> coupling constant functions: potentials, modified kinetic energies, …
feedback: coarse <=> fine

70s phenomenology of gravitons = Transverse_Traceless_Strain quanta

~80 ***phonon*** δρ/ρ eos ***=> sb89, bb15*** $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ <= *dE+pdV*

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Inflation = phenomenology of phonons = energy-density quanta
Trace_Strain quanta of isotropic volume δVol / Vol

inflaton = "condensate" of phonon fluctuations, $<\rho|_{k<Ha}> + \delta\rho$ ***oscillations***
relativistic negative-pressure Equation of State (1+w)

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in linear perturbation theory, the phonon = linear combination of fundamental scalars

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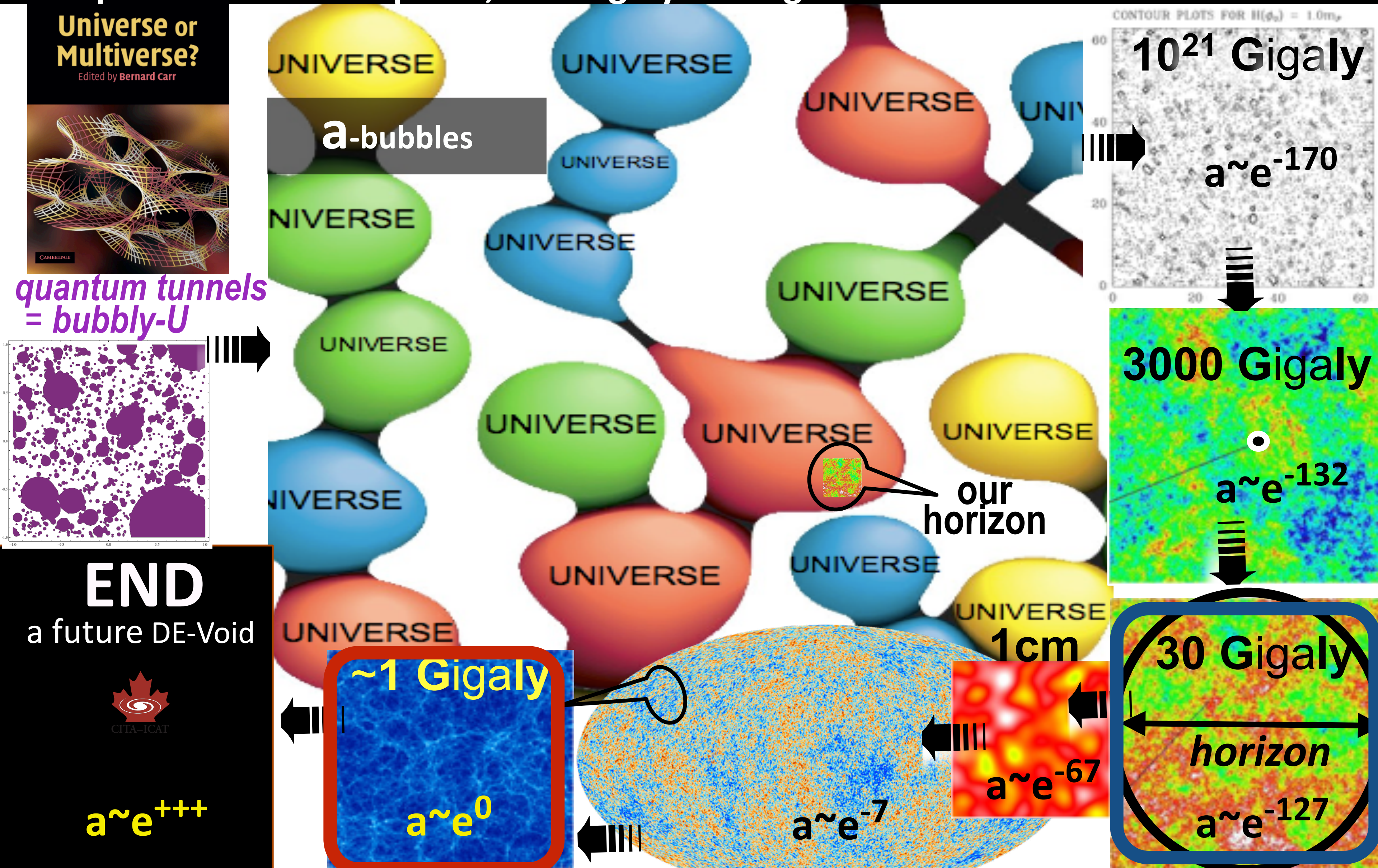
all that CMB+LSS can deliver is this phonon+ /strain+ Inflation Phenomenology
how does it fit into a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

SuperWeb of ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information

a highly strained & stressed state in the universe at large *(very, very)*, randomly simple in our Hubble patch, and highly entangled in the small to medium scale



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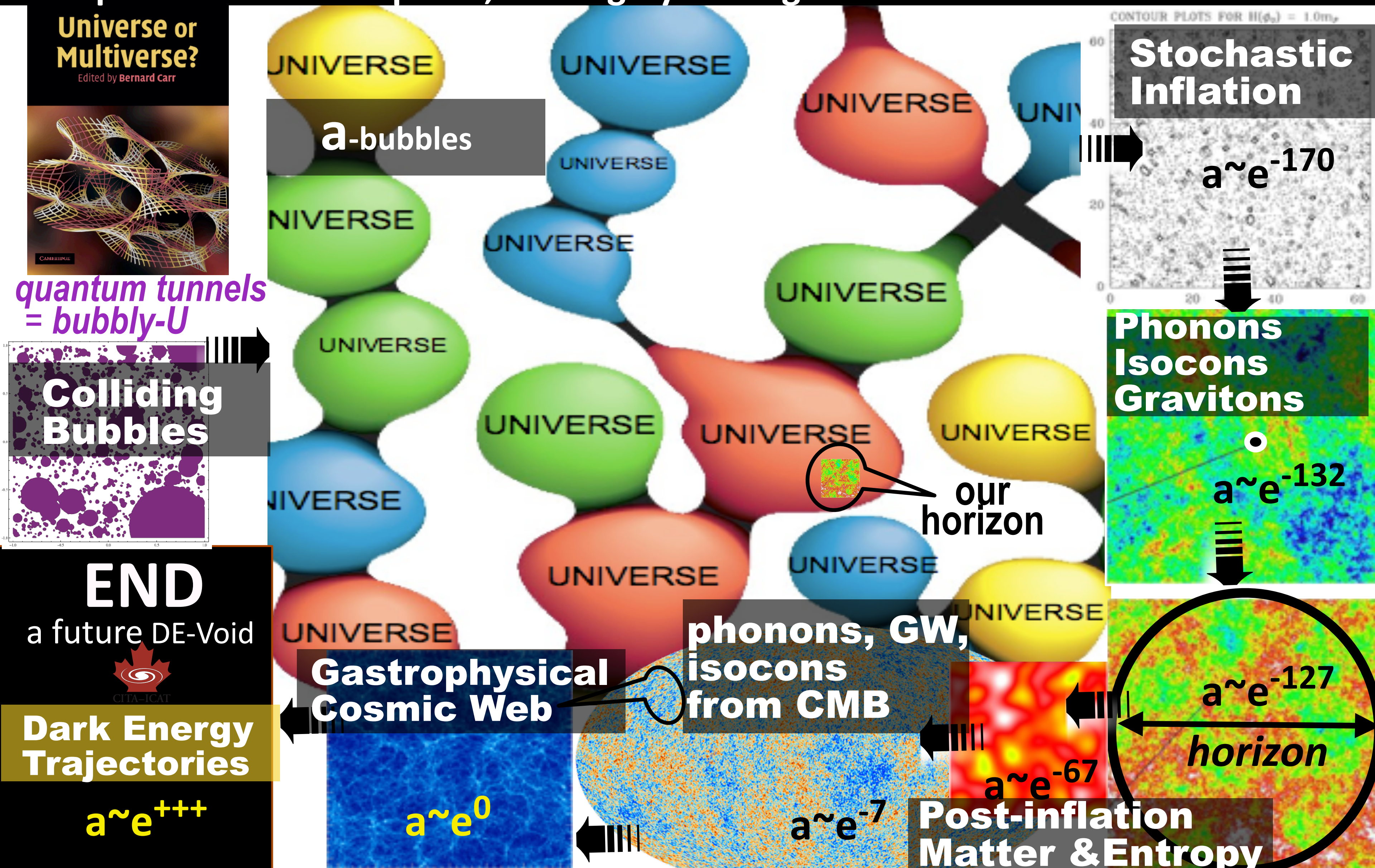
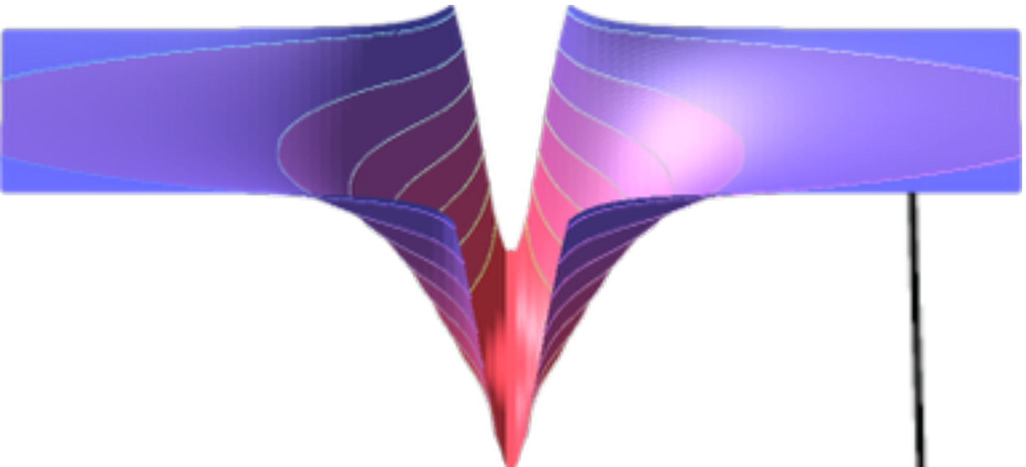
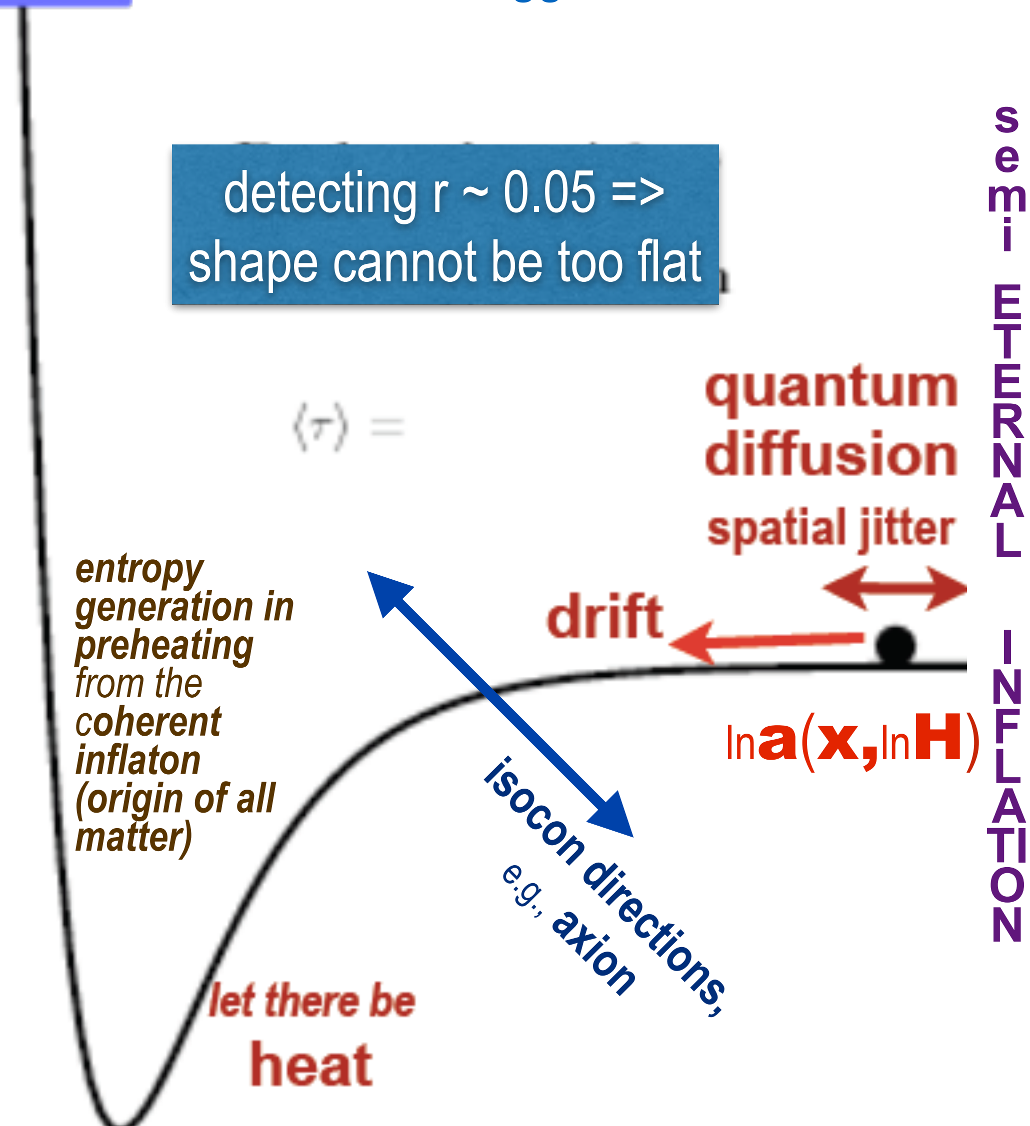


what is the **inflaton's potential**?

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

Relate it to the Higgs & standard model?



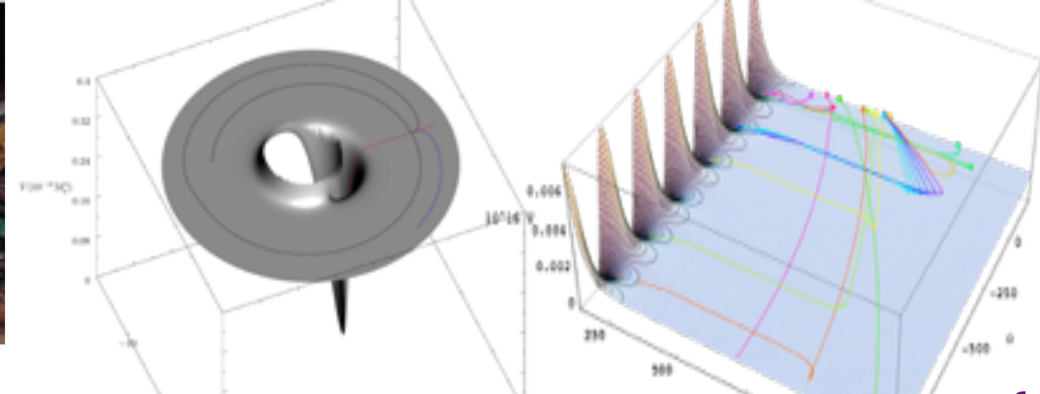


entropy generation in preheating** from the **coherent inflaton (origin of all matter & radiation)

nonG from post-inflation but pre-entropy generation (B²FH15) drift trajectories can lead to pre-shock-in-time caustics and other phase space convergences in the deformations

$\partial \ln a / \partial \chi_i(x)$, $\partial \ln a / \partial g(x)$ =>

$a = \quad 1$



Barnaby,Bond,Huang,Kofman09

NL,nonG curvature distribution($\chi_i(x)$, g(x),..)

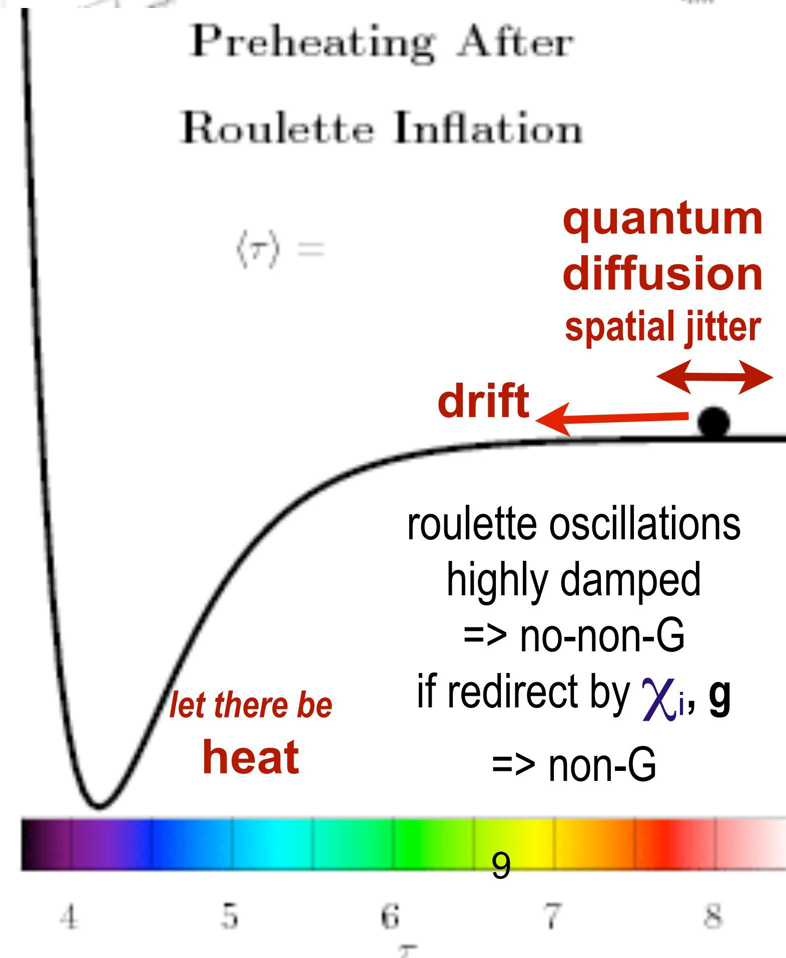
Preheating After

Roulette Inflation

$\langle\tau\rangle =$

A visualized 2D slice

in lattice simulation



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

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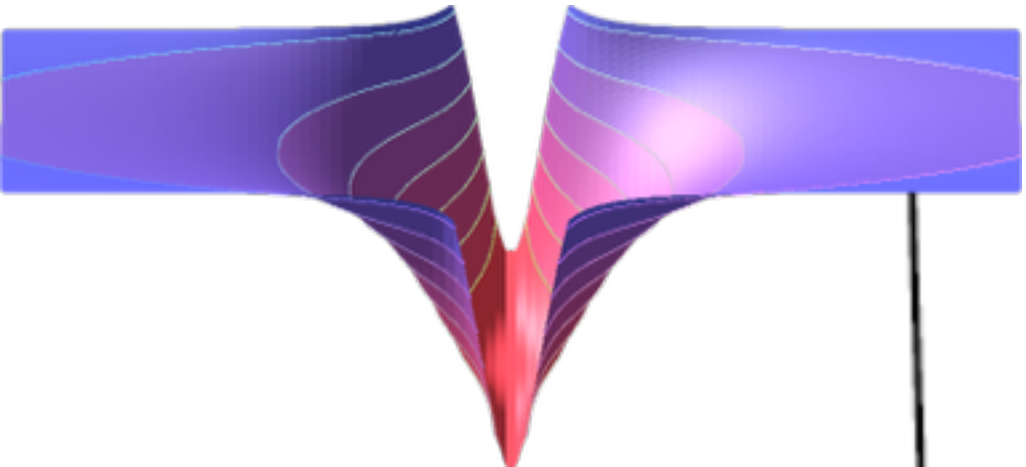

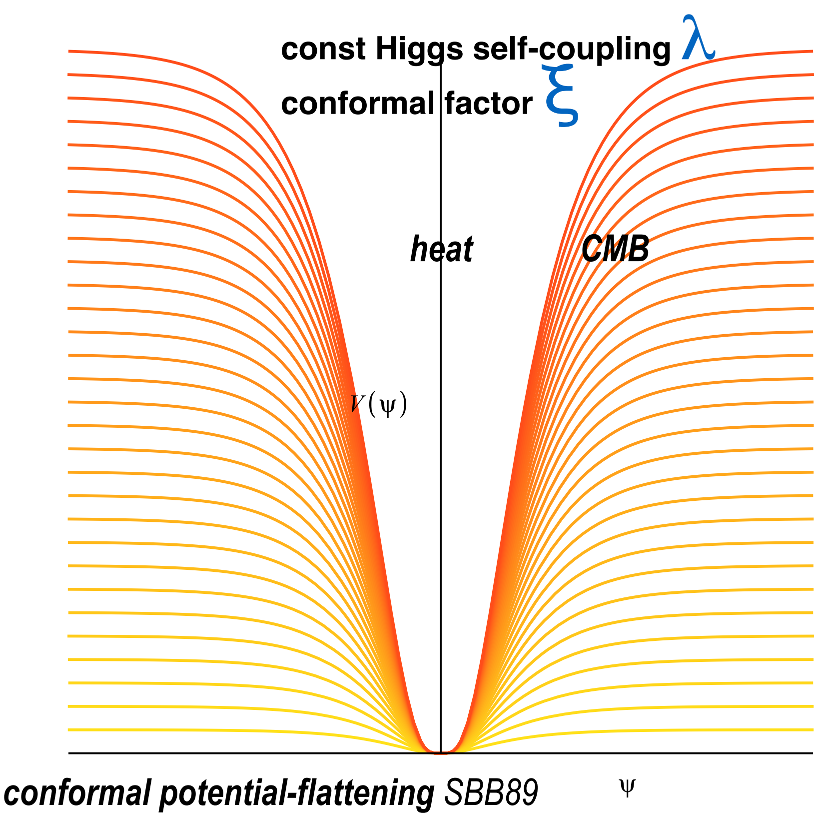

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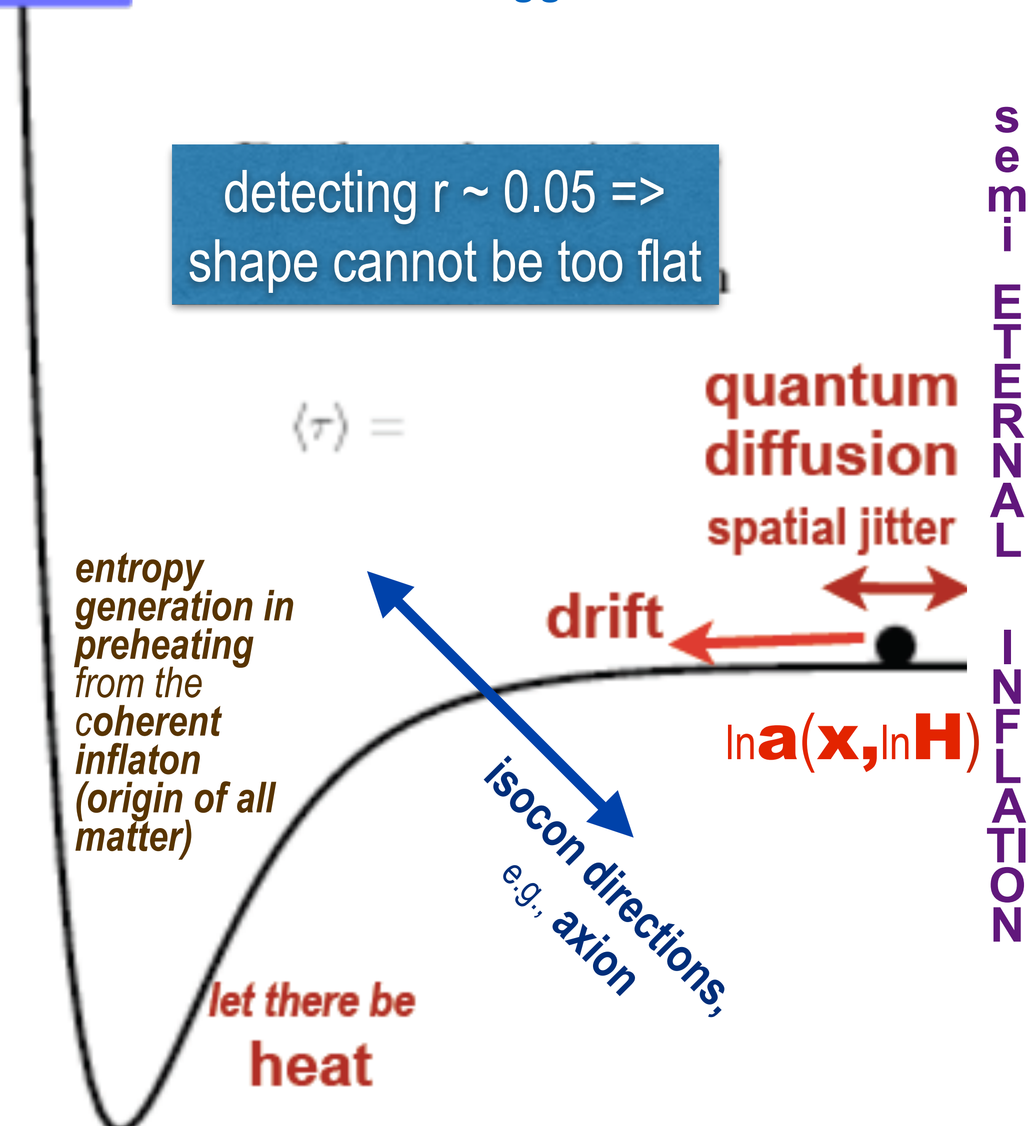

Planck 2015 inflation paper: allow number of e-folds to the end of inflation & preheating duration & number of degrees of freedom … to vary

check ***specific potentials => specified r, n_s*** *cf. LCDM standard.*

Comparison among different inflationary models

Model	$\Delta\chi^2$
$R + \frac{R^2}{6M^2}$	3.7
$n = 4$	46.9
$n = 3$	22.9
$n = 2$	9.7
$n = 4/3$	7.2
$n = 1$	6.2
$n = 2/3$	4.9
Natural	8.6
Hilltop ($p = 2$)	4.4
Hilltop ($p = 4$)	6.0
Double well	6.9
Exponential	4.0

$$V(\tilde{\phi}) = \frac{\Lambda^4}{4}\left(1 - e^{-2\tilde{\phi}/\sqrt{6}M_{\rm pl}}\right)^2$$

Preliminary

$$V(\phi) = \Lambda^4\left(1 - e^{-q\phi/M_{\rm pl}} + \ldots\right)$$

Planck TT + lowP + BAO

$w_{int} = 0$ for all the models

$\Delta\chi^2$ wrt LCDM

The shift to higher n_s sets tighter constraints on natural inflation, hilltop models, ...

R^2 (Starobinsky 1980) is still among the preferred models, although favouring $N^* > 54$, which is the value expected on theoretical grounds (a positive w_{int} helps in this respect). The quadratic model prefer large N^* to decrease r. These are just examples of how reheating uncertainties will combine with the inflationary predictions of the primordial power spectrum for a given model.

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phenomenology of gravitons = Transverse_Traceless_Strain quanta 70s

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relativistic negative-pressure Equation of State (1+w)

phonon = **collective mode composed of** fundamental **scalar+ fields (many** ϕ_b**?)**

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phenomenology of isocons = quanta $\perp$ *phonons (curvatons …)*

$\rho(\phi_b, \pi_b, \ln a)$ => *coarse-grained k<Ha Hamiltonian-density* **attractor** $\rho(\phi_b) = 3M_P^2H^2$

$d\phi_b / d\ln a = -M_P^2 \nabla_{\phi b} \ln\rho$, a gradient / Morse flow <= *Hamilton-Jacobi eq*^{n}

"adiabatic" fluctuations along the Morse flow river valleys (phonons)

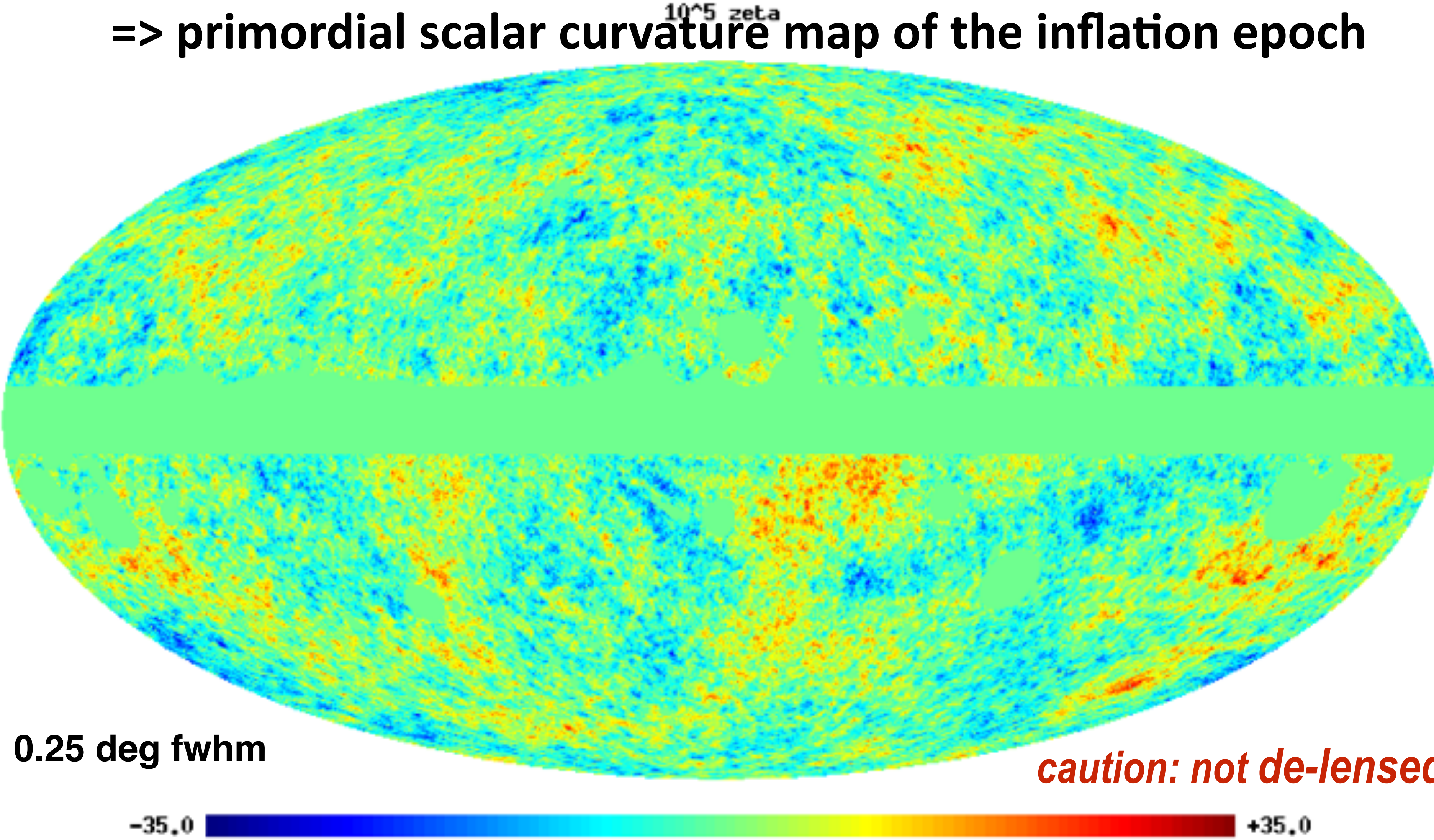
isocurvature directions $\perp$ *flow*

reduced action (Hamilton's Principal function) ~ $H \sim \rho^{1/2}$

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility***(*distance*) $\langle \zeta \,|\, \mathit{Temp},\, E\ \mathit{pol} \rangle$ (*angles, distance*)

=> primordial scalar curvature map of the inflation epoch



0.25 deg fwhm

caution: not de-lensed

visibility mask

Reconstructing the Early Universe

Dick Bond CITA on behalf of the Planck collaboration

Quantum Inflation in the 2015 Planck Era & Beyond

phonon ~ $\zeta = \ln\rho|_a /3(1+\langle w \rangle)$ = *energy-density quanta*

isotropic (volume) strain ~ $\zeta = \ln a|_\rho$ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ <= $dE+pdV$

Cosmic_Probes[$\zeta(\mathbf{x})$, q_{cosmic}, isoc, ..] or $\zeta(\mathbf{k})$,

or looking out: $\zeta_{LM}(\chi)$, $\chi = |\mathbf{x}|$ & $\zeta_{LM}(k)$, $k = |\mathbf{k}|$ maps

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or looking out $\zeta_{LM}(\chi)$, $\chi=|\mathbf{x}|$ & $\zeta_{LM}(k)$, $k=|\mathbf{k}|$ **maps**

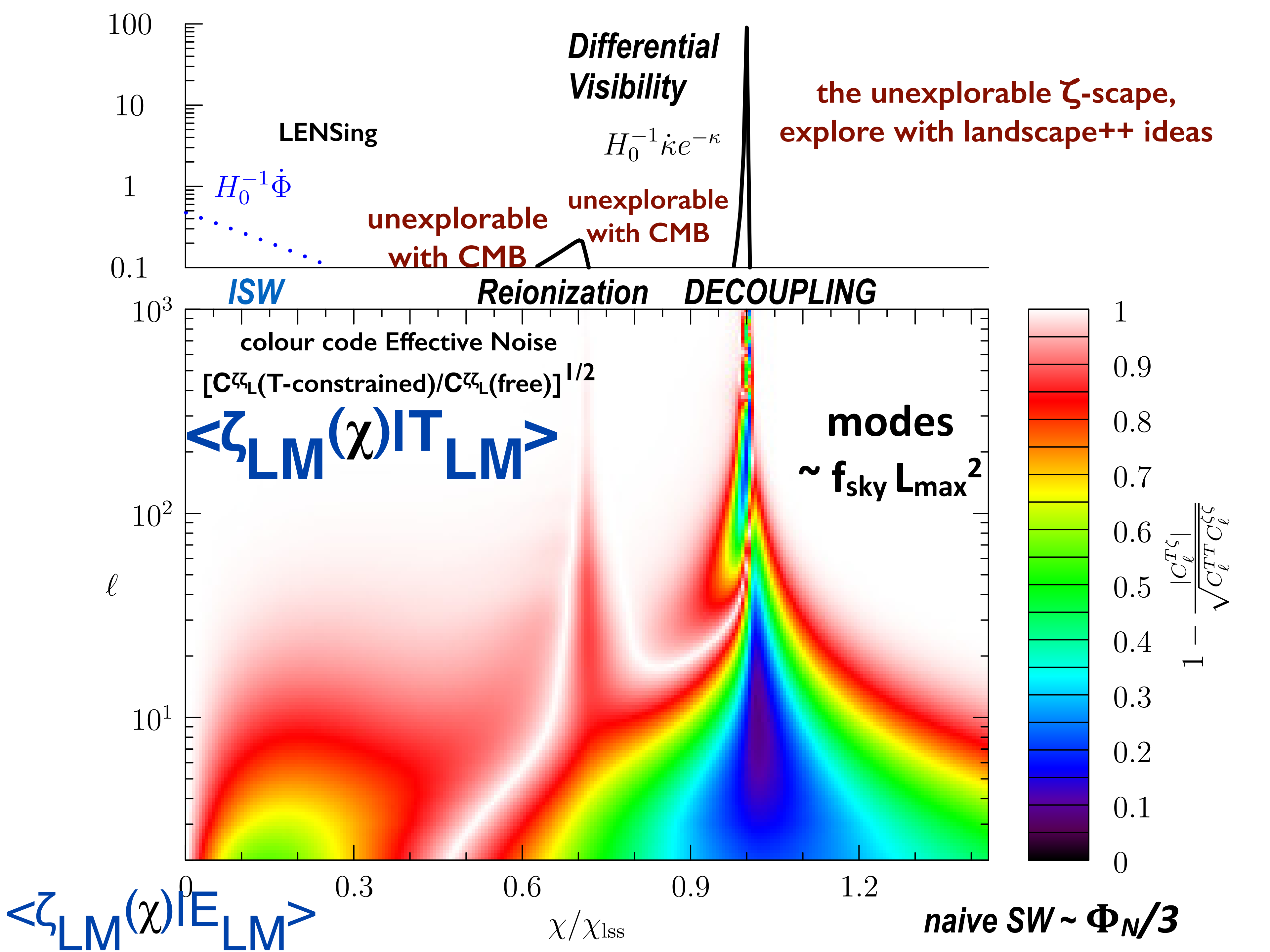
CMB_Probe no tomography:

projected-χ *few modes per LM* $\langle\zeta_{LM}(\chi) | T_{LM}\rangle$ $\langle\zeta_{LM}(\chi) | E_{LM}\rangle$

available modes: $f_{sky} L_{max}^2$ $-f_{sky} L_{min}^2$ $L_{max} \sim L_{damp}$

Planck near limit of nonG exploration with CMB (ACT/SPT) $f_{NL} \pm 5$

***gravity waves ~Transverse_Traceless_Strain:** no tomography, limited L range* n_t

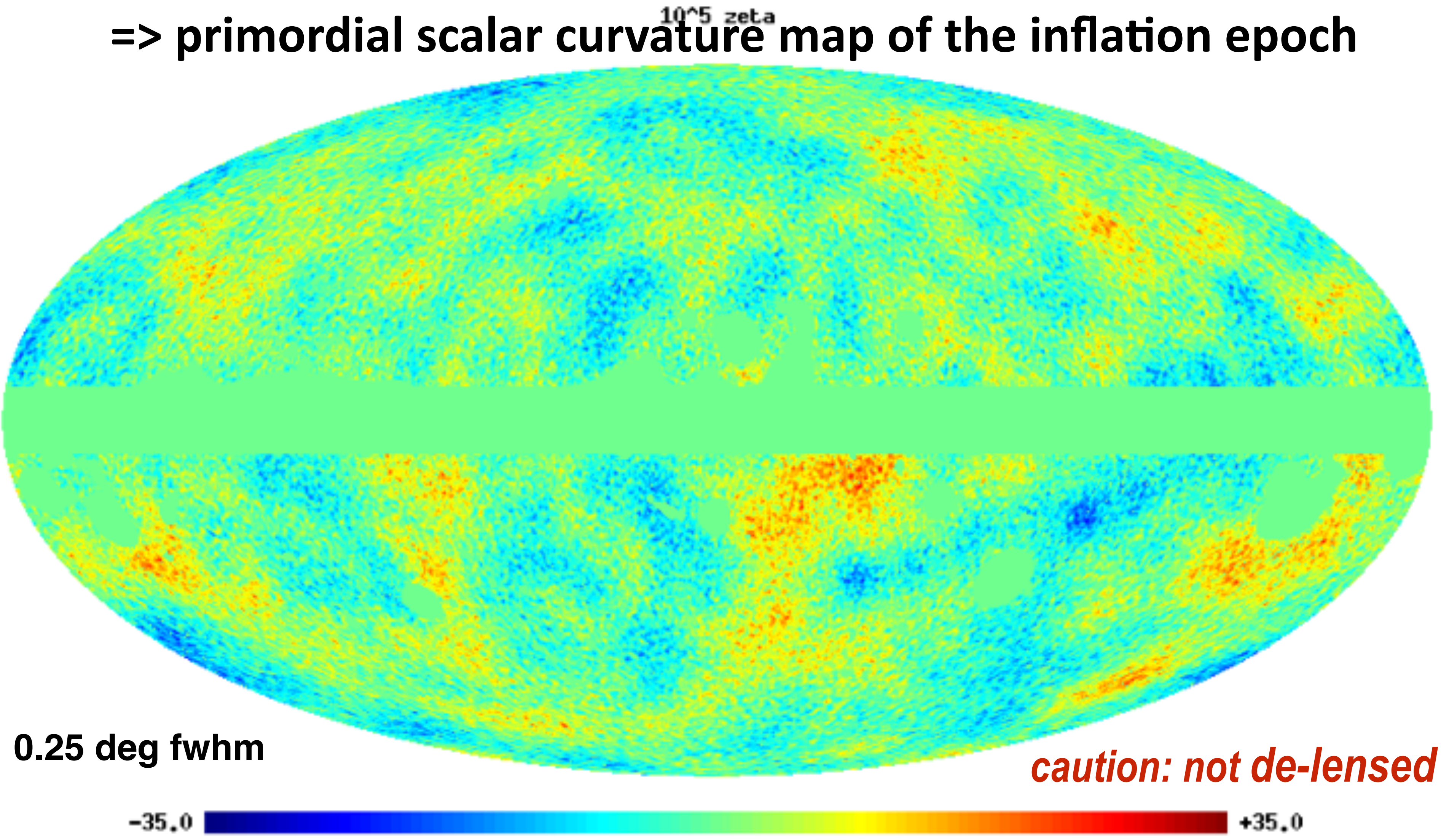


Differential
Visibility
$H_0^{-1}\dot{\kappa}e^{-\kappa}$
the unexplorable ζ-scape,
explore with landscape++ ideas
LENSing
$H_0^{-1}\dot{\Phi}$
unexplorable
with CMB
unexplorable
with CMB
ISW
Reionization
DECOUPLING
colour code Effective Noise
$[C^{\zeta\zeta}_L(\text{T-constrained})/C^{\zeta\zeta}_L(\text{free})]^{1/2}$
$<\zeta_{LM}(\chi)|T_{LM}>$
modes
$\sim f_{sky} L_{max}^2$
ℓ
$1 - \frac{|C_\ell^{T\zeta}|}{\sqrt{C_\ell^{TT} C_\ell^{\zeta\zeta}}}$
$\chi/\chi_{\rm lss}$
$<\zeta_{LM}(\chi)|E_{LM}>$
naive SW ~ $\Phi_N/3$

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* $<\zeta\,|Temp>$ *(angles, distance)*

=> primordial scalar curvature map of the inflation epoch

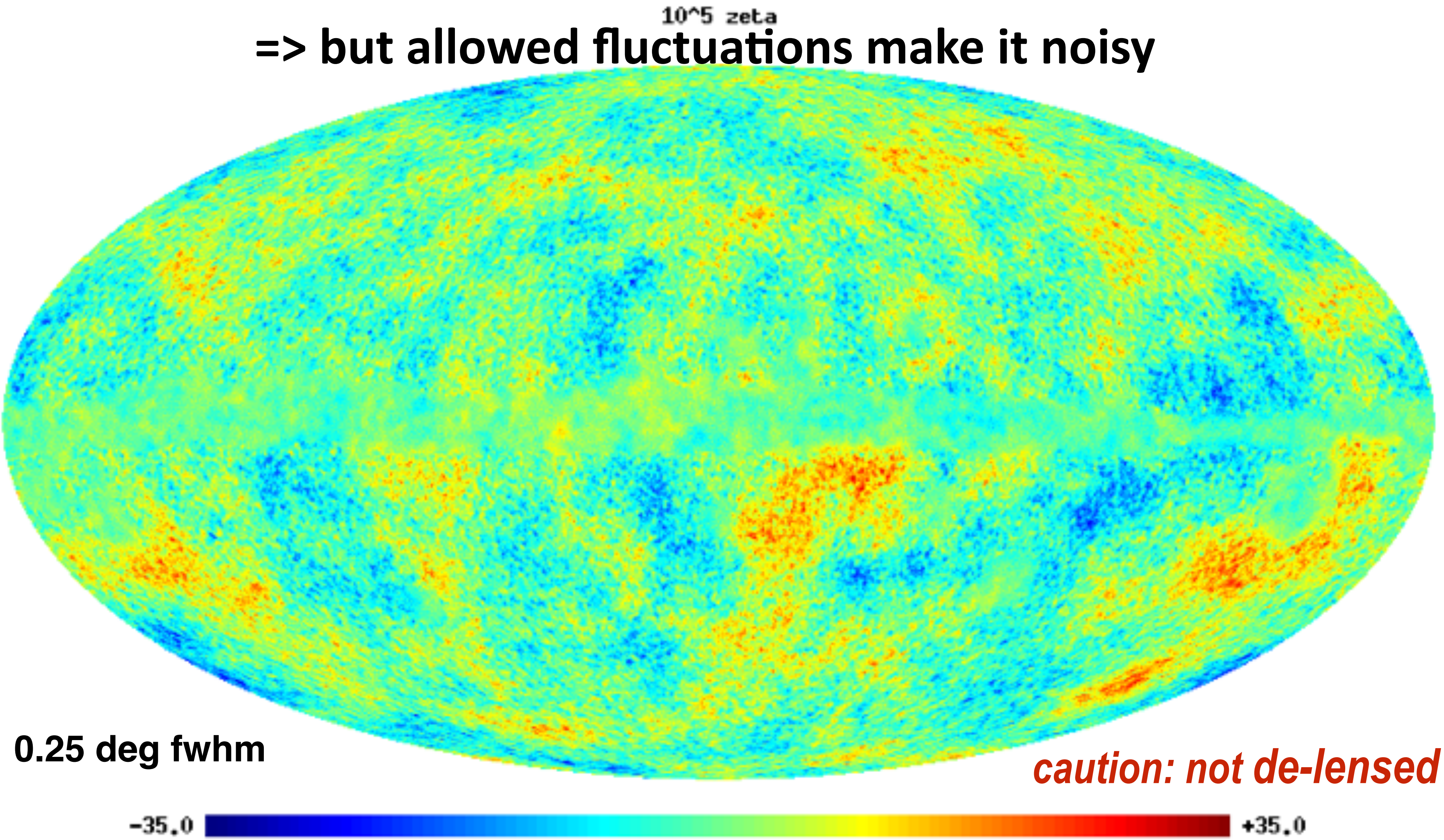


Reconstructing the Early Universe

reveals map of **primordial isotropic strain** /phonons

$\int d$ ***visibility***(*distance*) $<\zeta\,|\,Temp> + \delta\zeta$ (*angles, distance*)

=> but allowed fluctuations make it noisy



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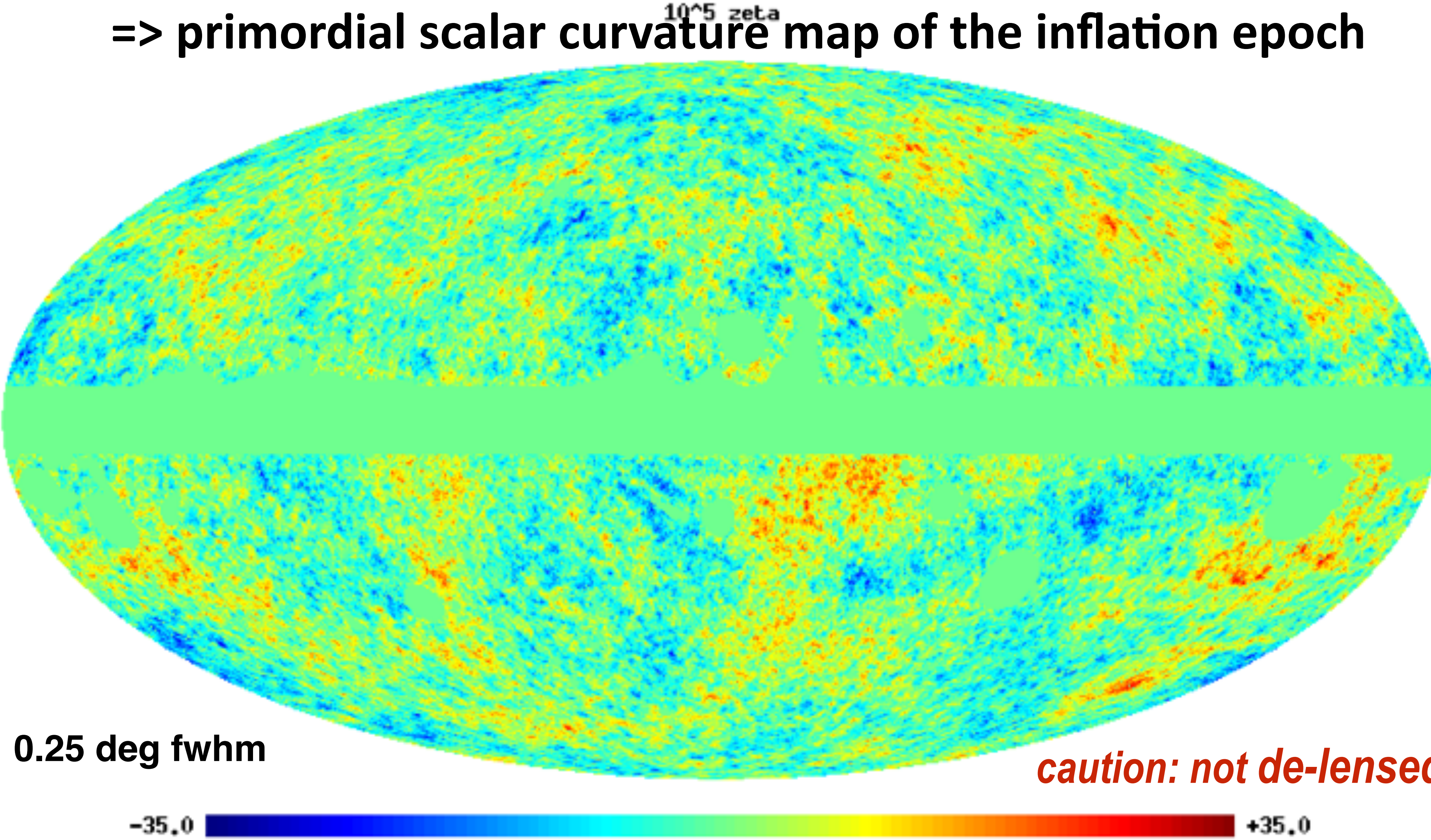
visibility mask

Reconstructing the Early Universe

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* $\langle \zeta \,|\, Temp,\, E\ pol \rangle$ *(angles, distance)*

=> primordial scalar curvature map of the inflation epoch



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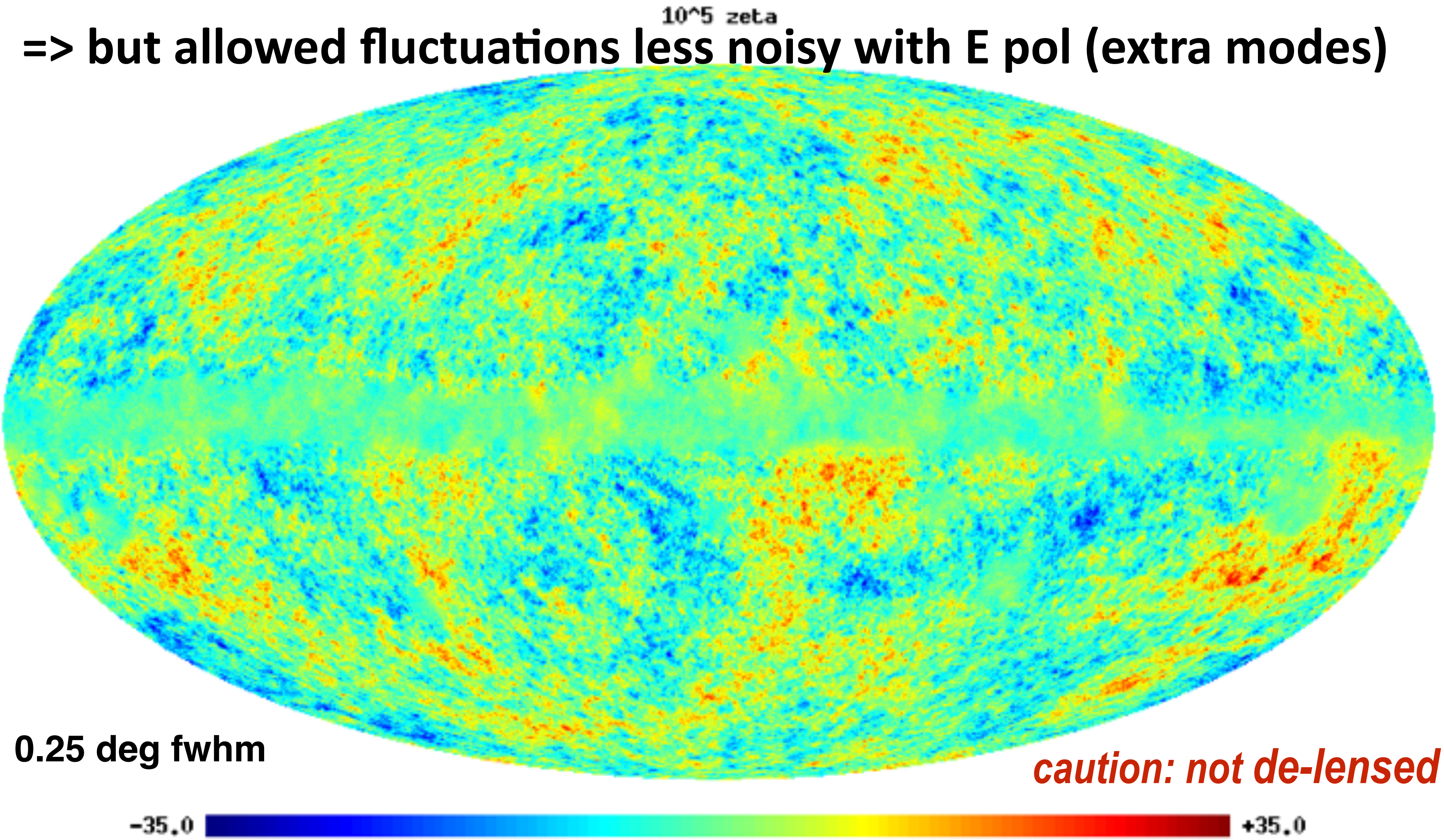
visibility mask

Reconstructing the Early Universe

reveals map of **primordial isotropic strain** /phonons

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

=> but allowed fluctuations less noisy with E pol (extra modes)



0.25 deg fwhm

caution: not de-lensed

visibility mask

Reconstructing the Early Universe

Stacked Wiener filtered ζ_{dv}

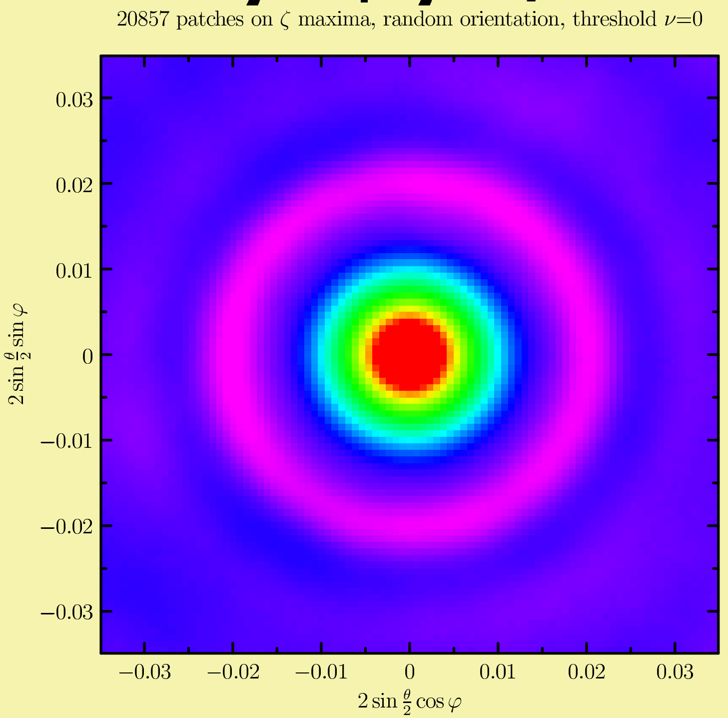
stacking=> $\delta\zeta_{dv}$ *destructive interference* => *reveals* <ζ_{dv} |T-peak>, <ζ_{dv} |ζ_{dv}-peak>

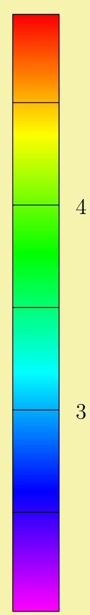
used in
Planck 2014

caution: not de-lensed

Isotropy and Statistics paper, extensive stacking of T,Q,U,E,ζ_{dv} on T,$P^2=Q^2+U^2$,E,ζ_{dv} peaks

stacked
<ζ_{dv} | ζ_{dv}-*pk*>



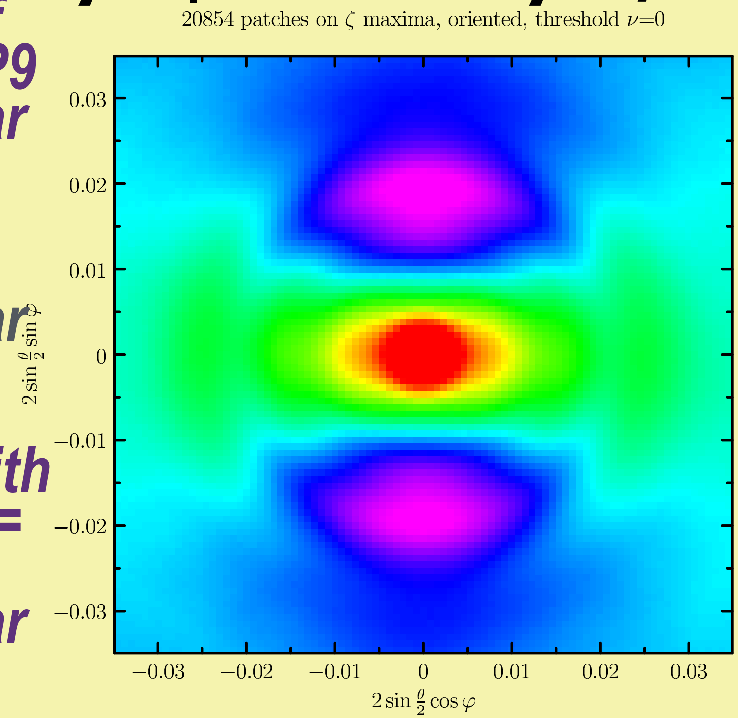


ζ stacks of P13 & WMAP9 look v. similar

FFP8 simulations look v. similar

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

stacked
<ζ_{dv} | oriented ζ_{dv}-*pk*>



we don't need all LM+k modes to reconstruct L-independent $\mathcal{P}_\zeta$**(k)** *in quadratic space*

$k^2 \sim L^2/d_{rec}^2 + k_{||}^2$

bonus: top-down ***de-lens***

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

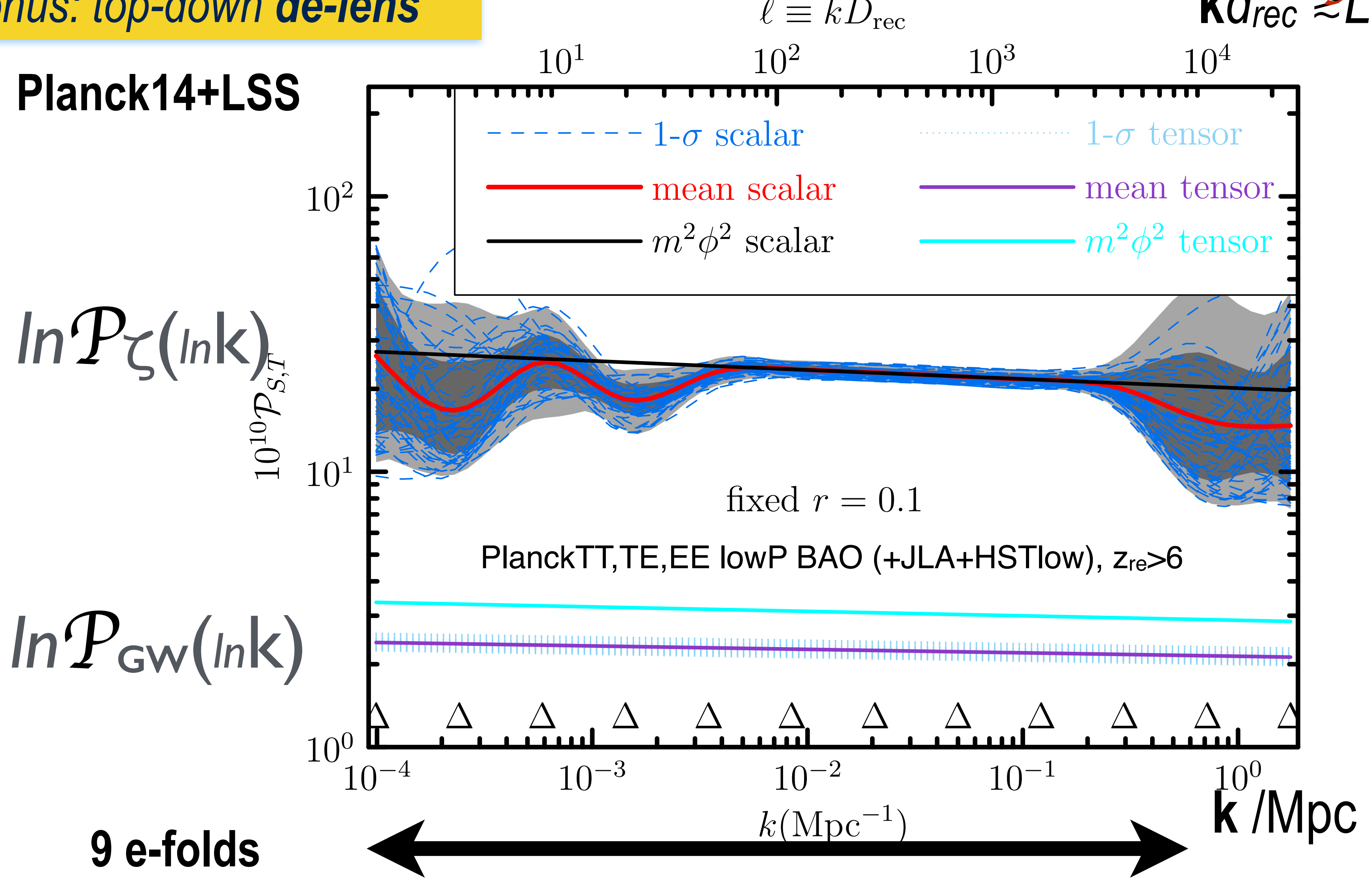
aka Radical Compressions

=> ultra-early Universe sound/phonon spectrum

12 knots, cubic spline

Preliminary

Planck14+LSS



9 e-folds

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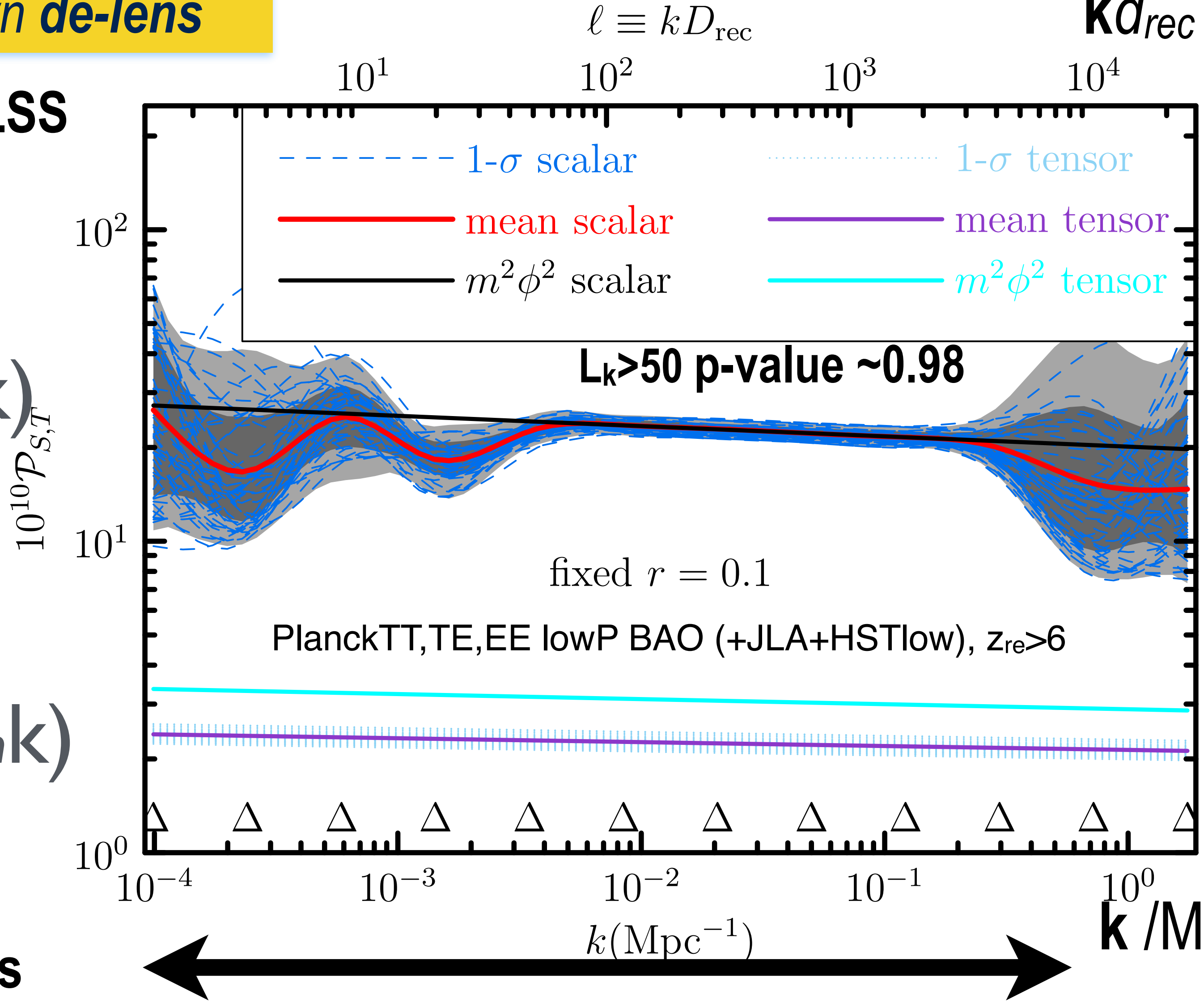
$ln\mathcal{P}_\zeta(ln k)$

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



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

k /Mpc

9 e-folds

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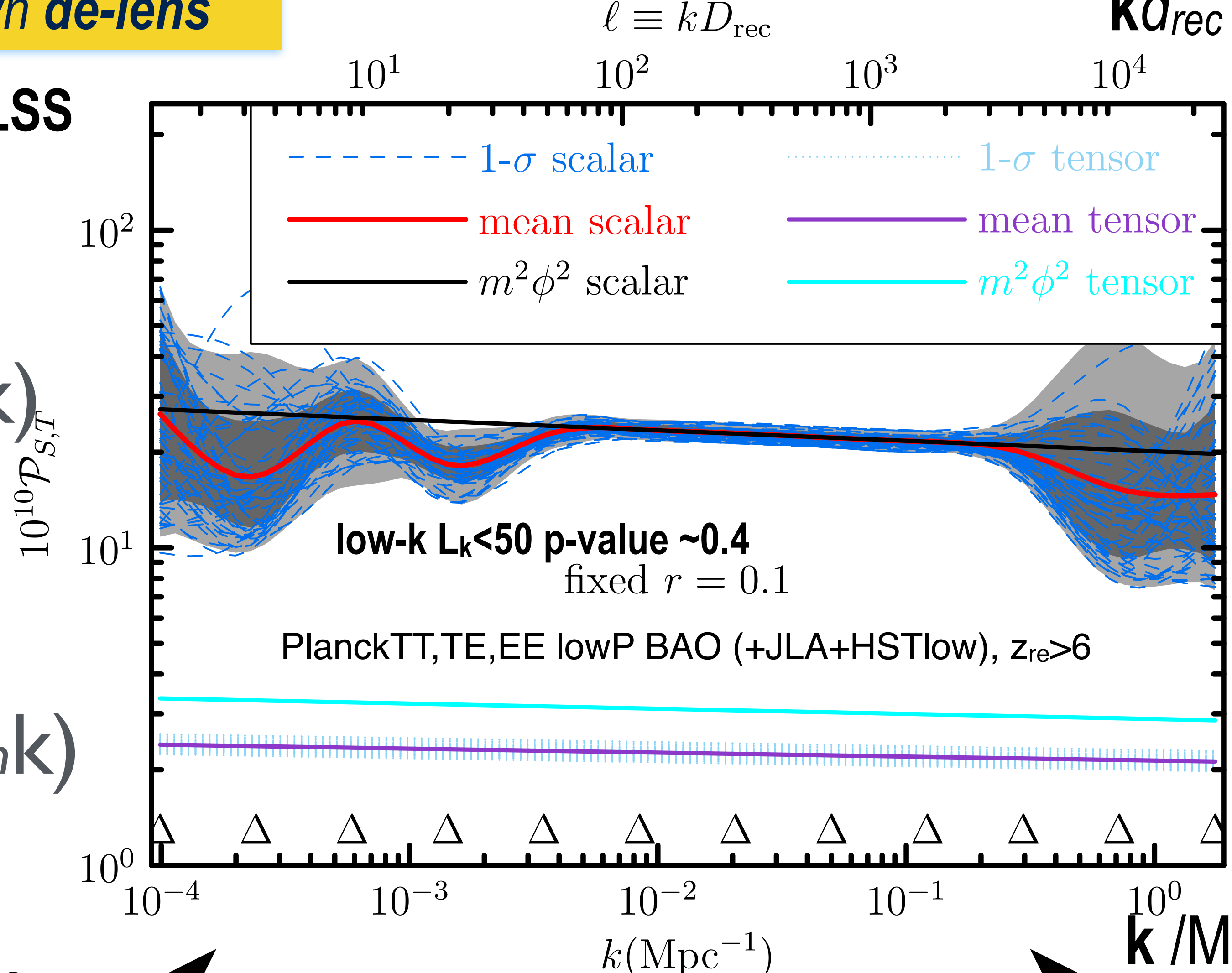
$kd_{rec} \gtrsim L$

Planck14+LSS

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

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



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

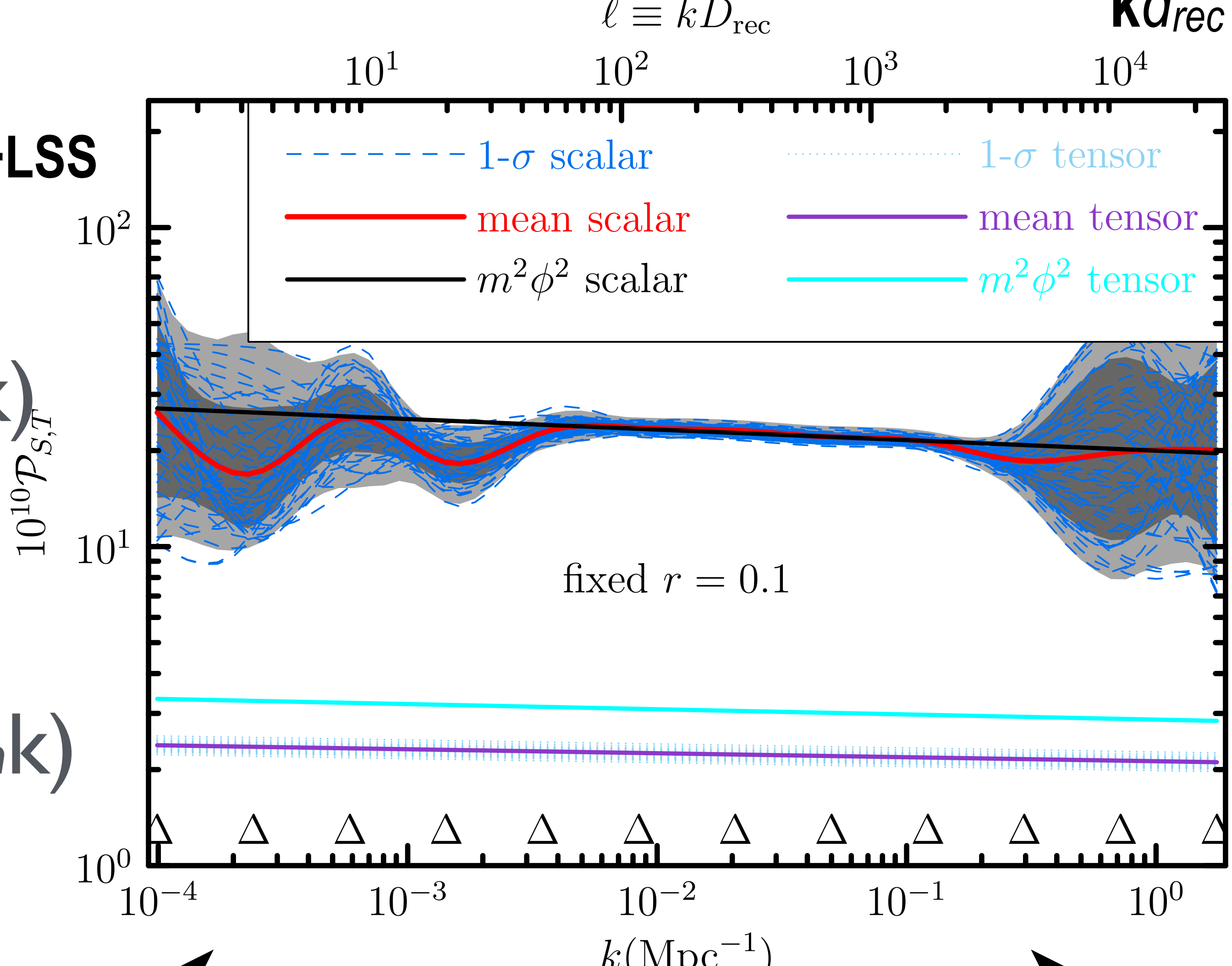
cf. Planck13+LSS

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

Planck13 & WMAP => stable features

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

$kd_{rec} \gtrsim L$

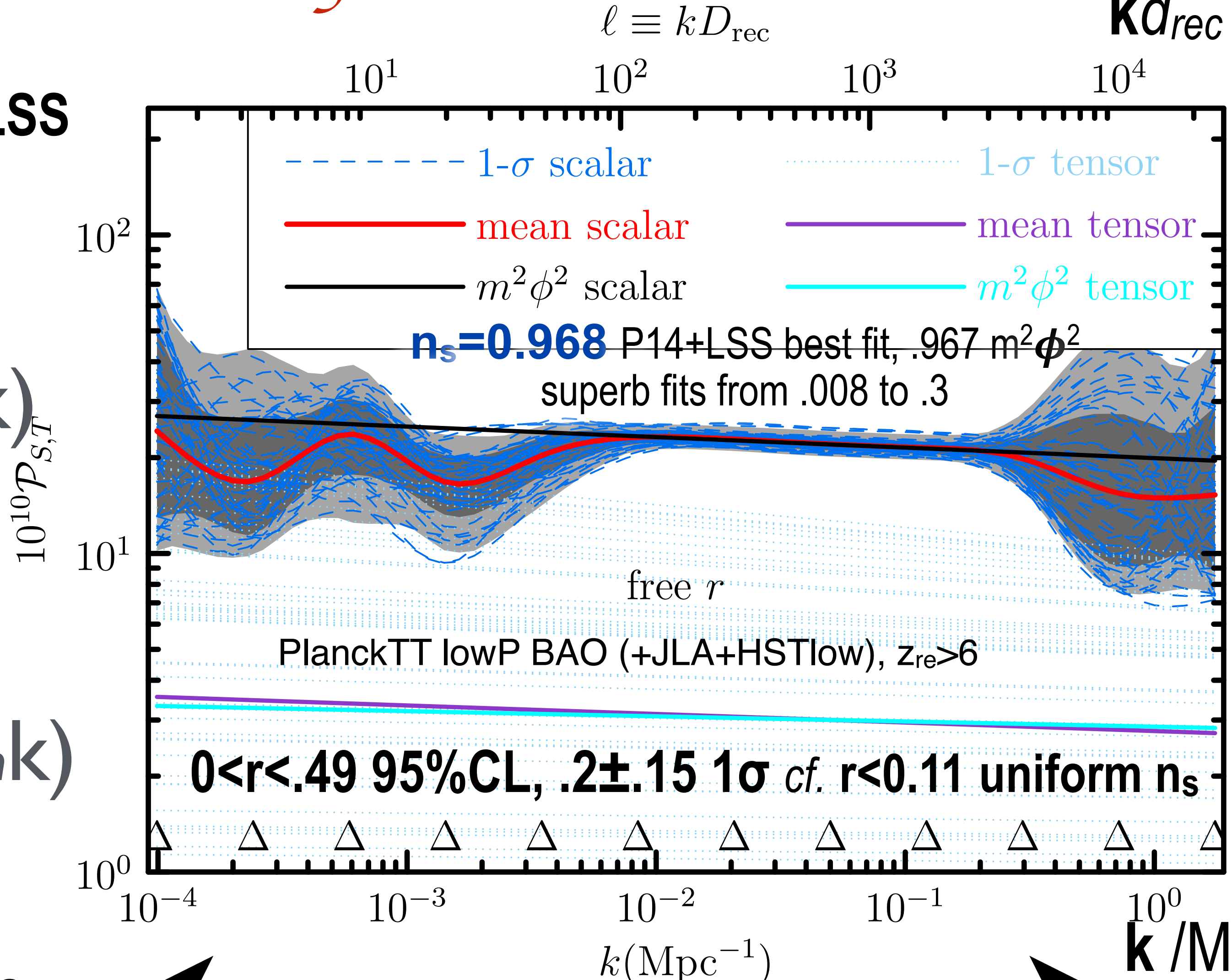


9 e-folds

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

Preliminary 12 knots, cubic spline

Planck14+LSS



kd_{rec} ≳L

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

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

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

k /Mpc

9 e-folds

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

Planck14+BKP+LSS

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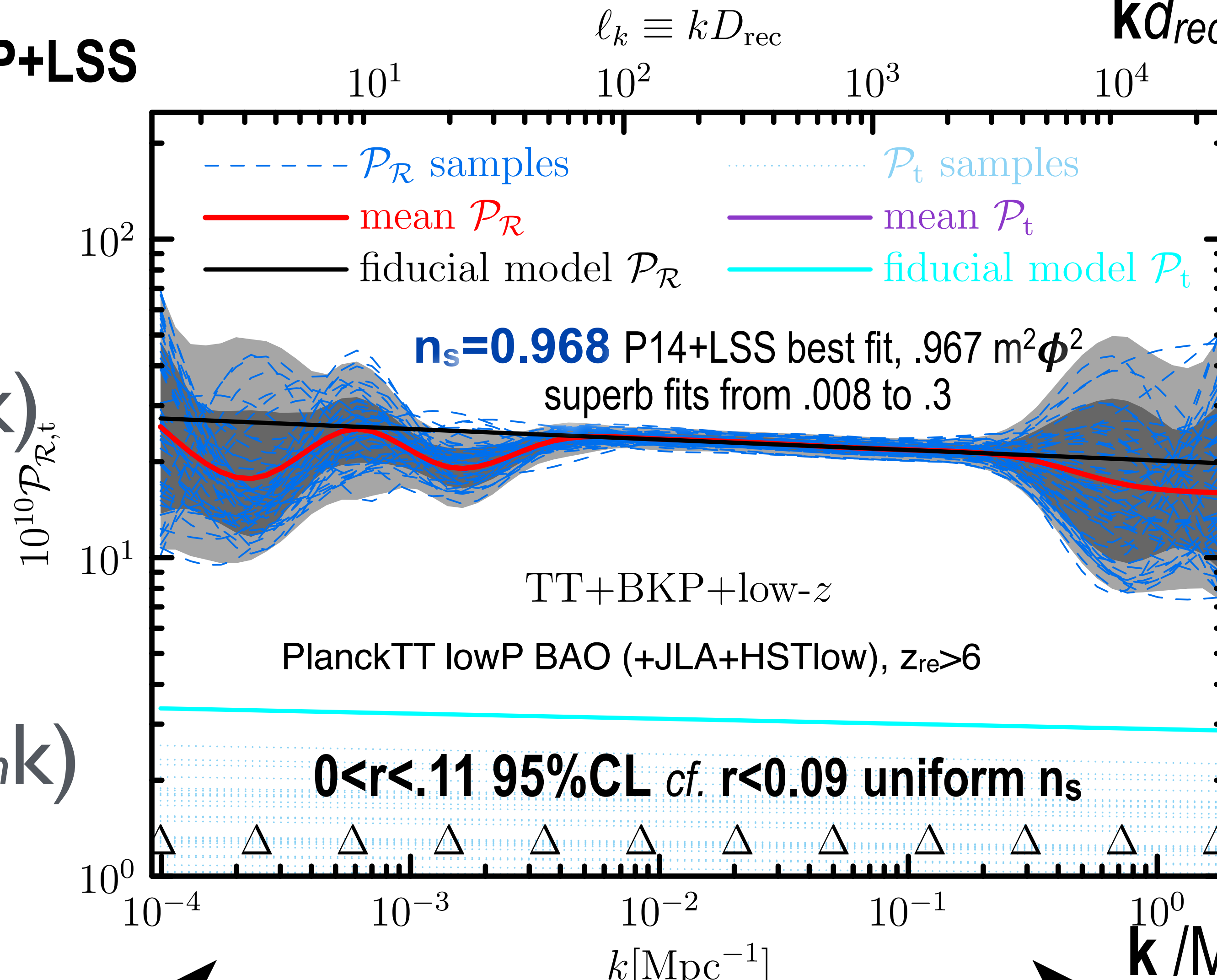
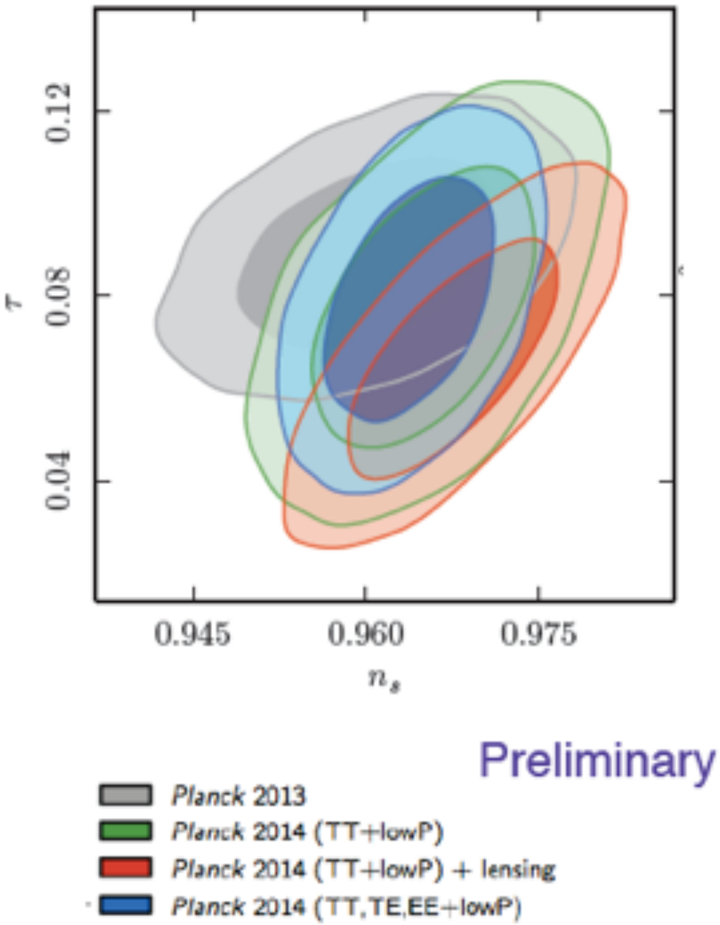


k /Mpc

9 e-folds

Planck 2014 n_s



$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$n_s = 0.9652 \pm 0.0062 \quad (68\,\%\mathrm{CL}\,,\, \textit{Planck}\,\mathrm{TT} + \mathrm{lowP})$$

$$\tau = 0.078 \pm 0.019 \quad (68\,\%\mathrm{CL}\,,\, \textit{Planck}\,\mathrm{TT} + \mathrm{lowP})$$

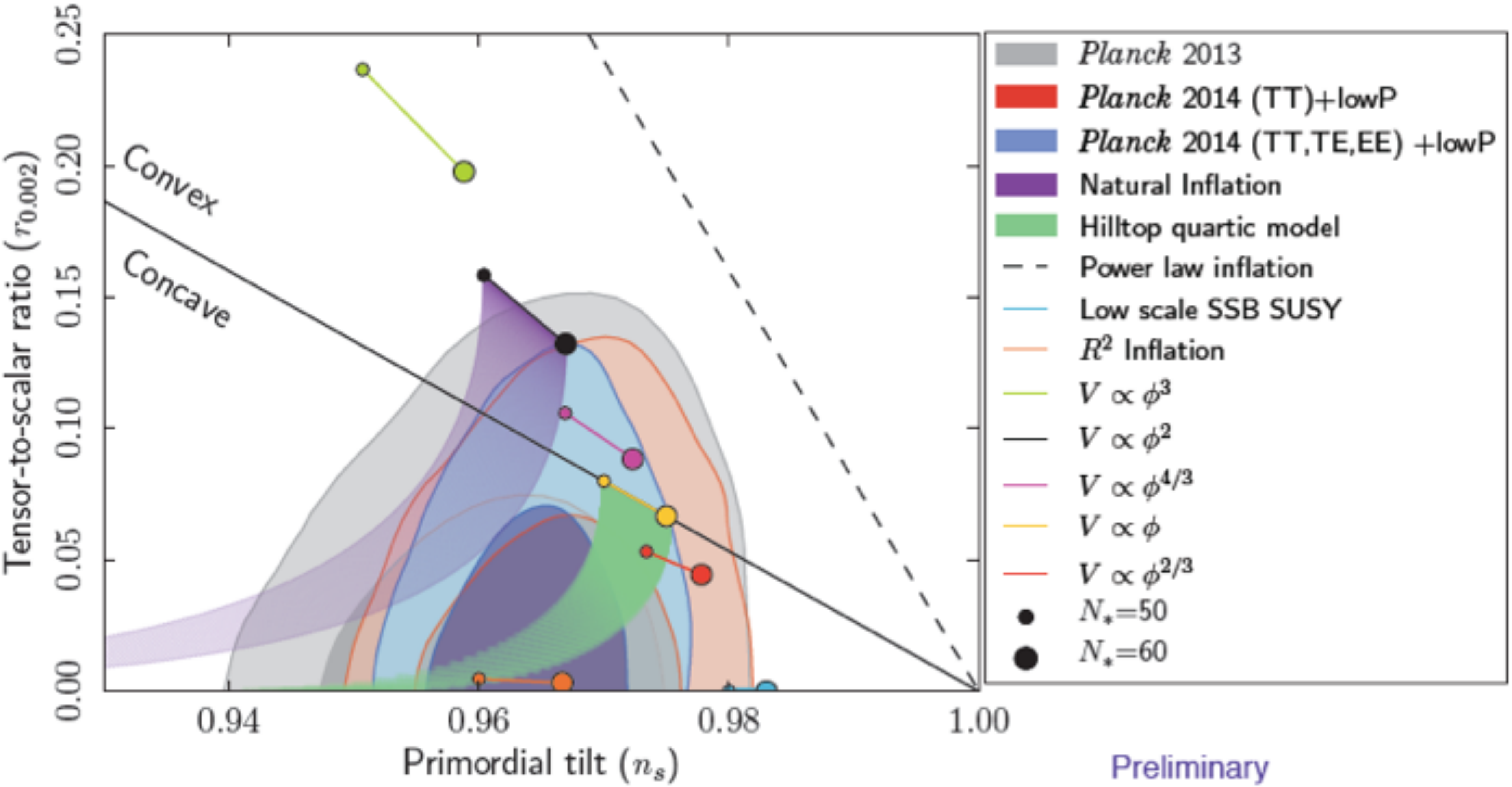
n_s=0.968 P14+LSS best fit superb fits from .008/Mpc to .3/Mpc

Compare with Planck 2013 results:

$$n_s = 0.9603 \pm 0.0073 \quad (68\,\%\mathrm{CL}\,,\, \textit{Planck}\,2013)$$

The polarization results reported here and in the folllowing slides are preliminary, because we do not yet have confidence that all systematic and foreground uncertainties have been properly characterized, and the results may therefore be subject to revision.

Inflationary models & Planck



Preliminary

$r_{0.002} < 0.10$ (95 %CL , *Planck* TT + lowP) Preliminary

$r_{0.002} < 0.11$ (95 %CL , *Planck* TT + lensing + lowP)

$r_{0.002} < 0.10$ (95 %CL , *Planck* TT, TE, EE + lowP)

$r_{0.002} < 0.09$ (95 %CL , *Planck* TT + lowP/wWMAP)

WMAP 9 low resolution polarization data dust cleaned with Planck 353 GHz

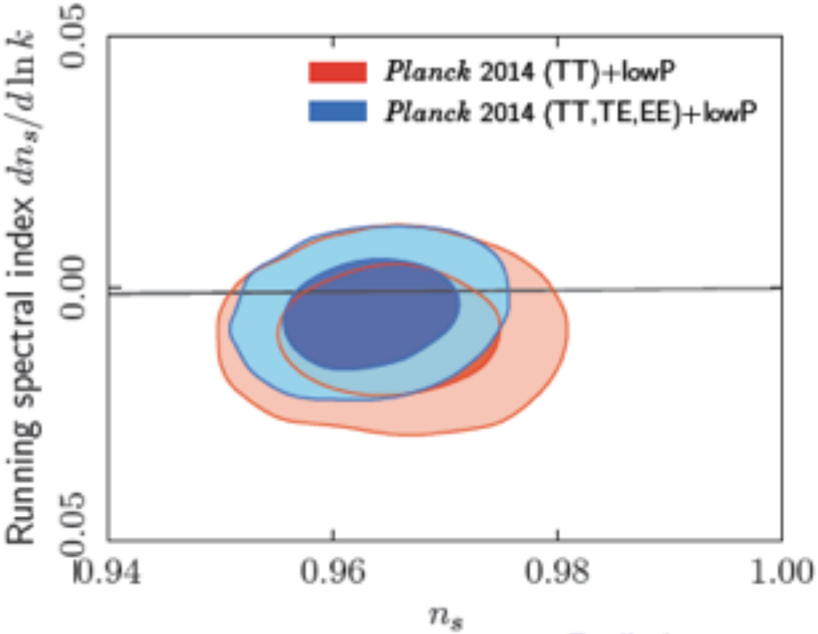
0<r<.49 95%CL, .2±.15 1σ

cf. **r<0.11 uniform n_s**

$\mathcal{P}_\zeta$ reconstruction demonstrates that running is not what the data wants. Running also connects low k to high k, a stiff expansion of $\mathcal{P}_\zeta$

Planck 2014 results on running

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{ns-1+\frac{1}{2}\frac{dn_s}{d\ln k}\ln(k/k_*)}$$



Preliminary

$$\frac{dn_s}{d\ln k} = -0.0087 \pm 0.0082 \quad (68\,\%\mathrm{CL}\,, \mathit{Planck}\,\mathrm{TT+lowP})$$

$$\frac{dn_s}{d\ln k} = -0.0031 \pm 0.0074 \quad (68\,\%\mathrm{CL}\,, \mathit{Planck}\,\mathrm{TT+lensing+lowP})$$

$$\frac{dn_s}{d\ln k} = -0.0049 \pm 0.0070 \quad (68\,\%\mathrm{CL}\,, \mathit{Planck}\,\mathrm{TT,TE,EE+lowP})$$

Compare with Planck 2013 results:

$$dn_s/d\ln k = -0.013 \pm 0.009 \quad 68\,\%\mathrm{CL}\,, \mathit{Planck}\,2013$$

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=> ultra-early Universe sound/phonon spectrum

Preliminary 12 knots, cubic spline

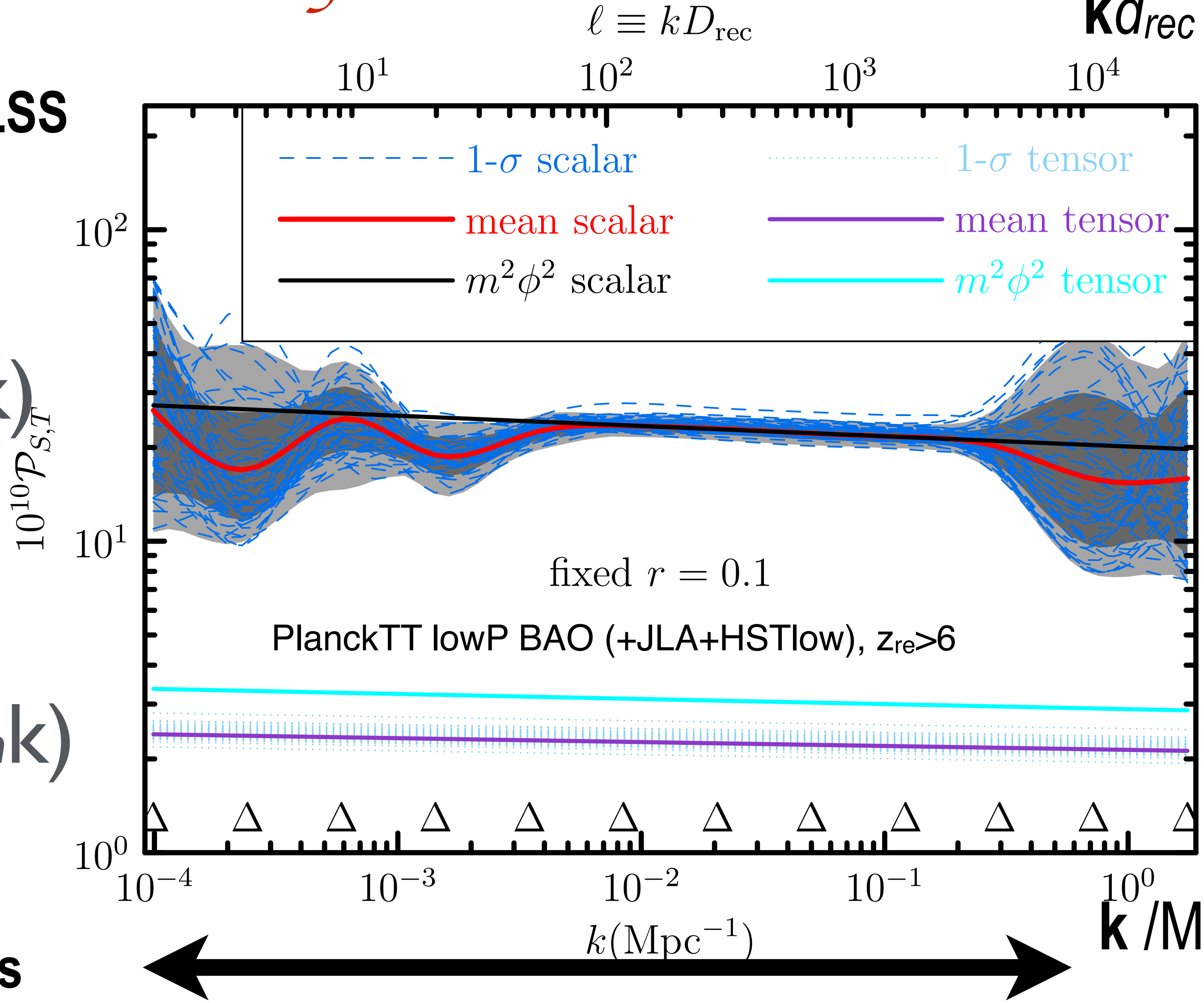
$\mathrm{k}d_{rec} \gtrsim L$

Planck14+LSS

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

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

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



k /Mpc

9 e-folds

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

Preliminary 12 knots, cubic spline

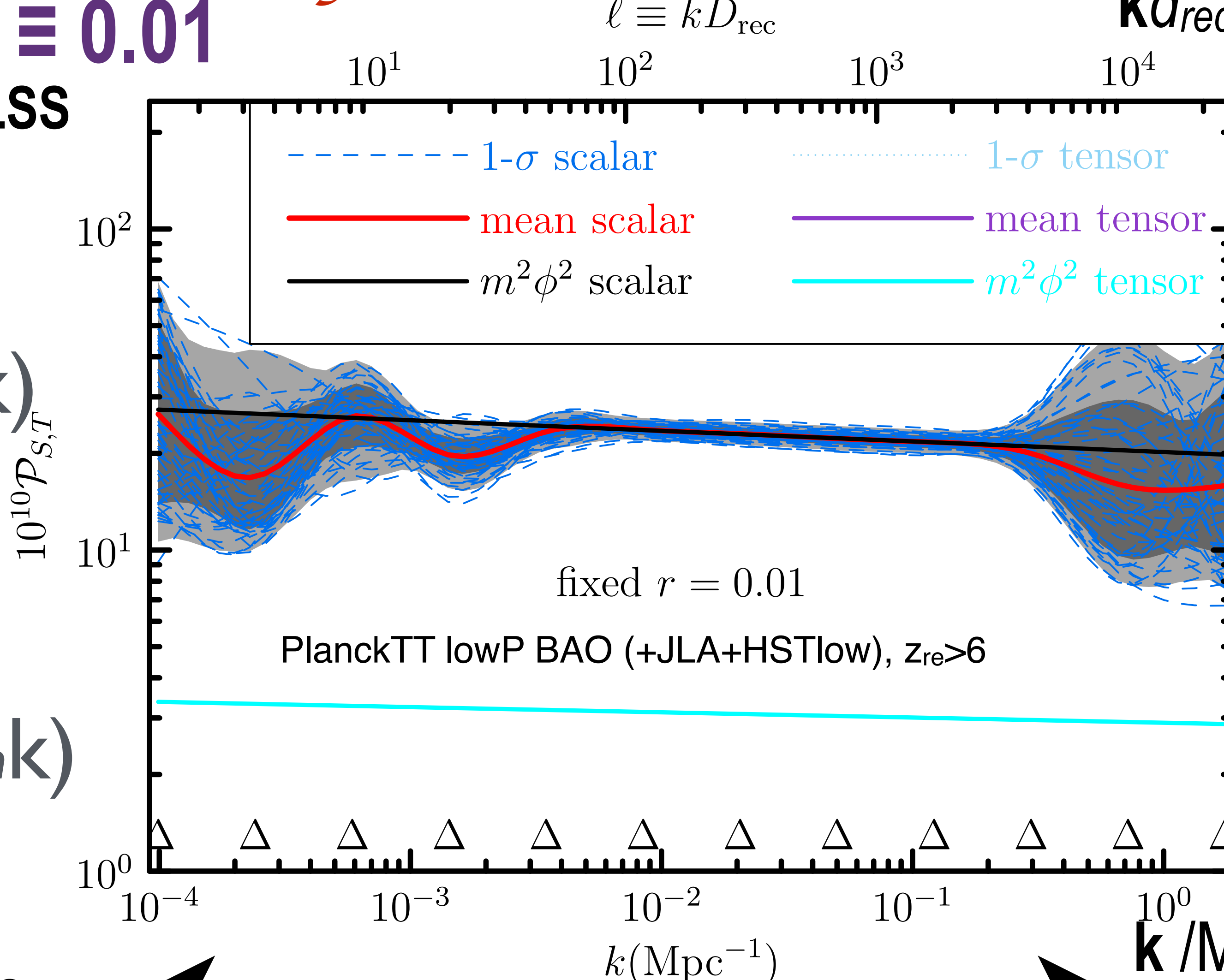
constrain r ≡ 0.01

Planck14+LSS

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

future r=0.01 constraint break degeneracy => stable features

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



$kd_{rec} \gtrsim L$

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

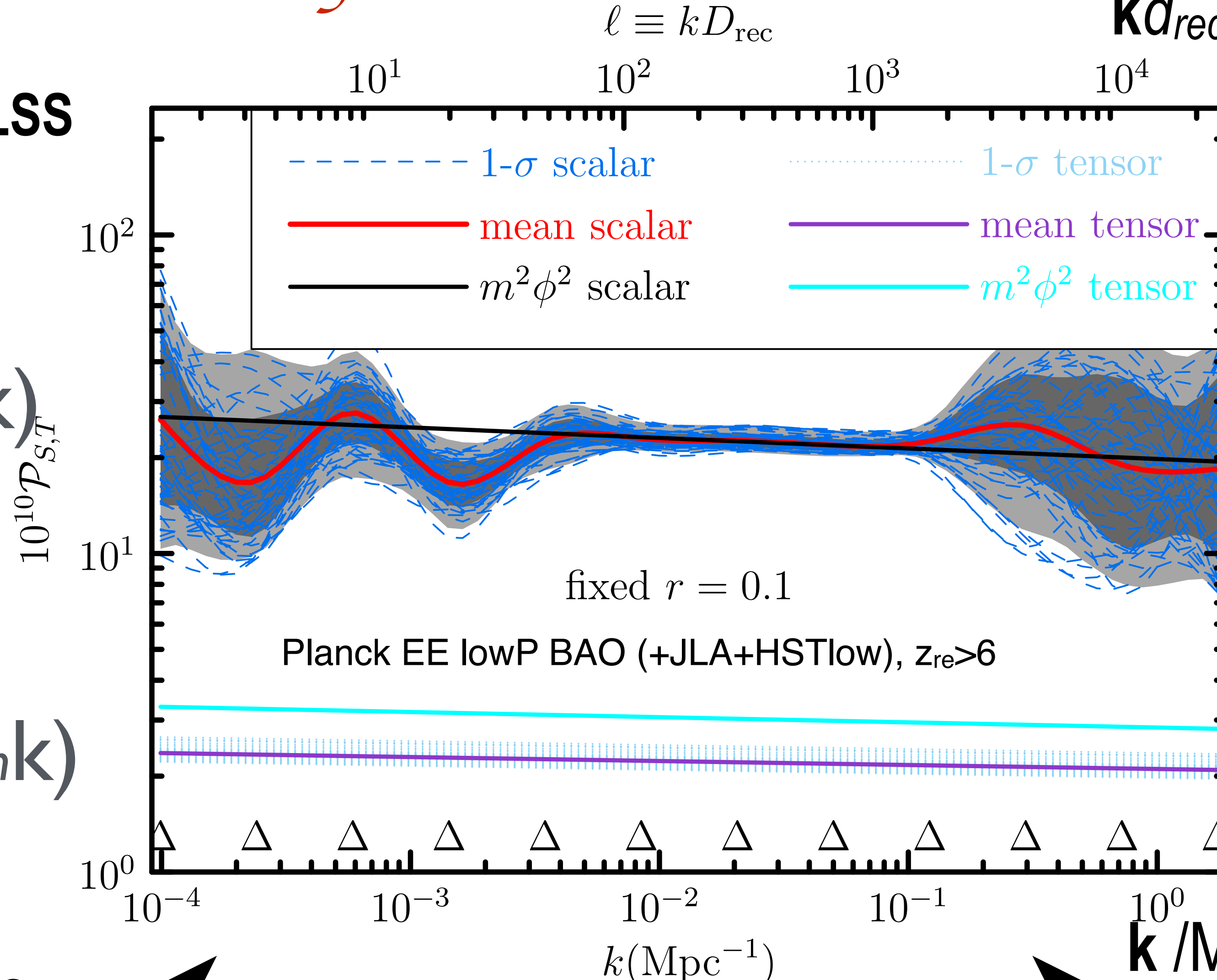
$kd_{rec} \gtrsim L$

Planck14+LSS

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

adding high L polarization => stable features

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



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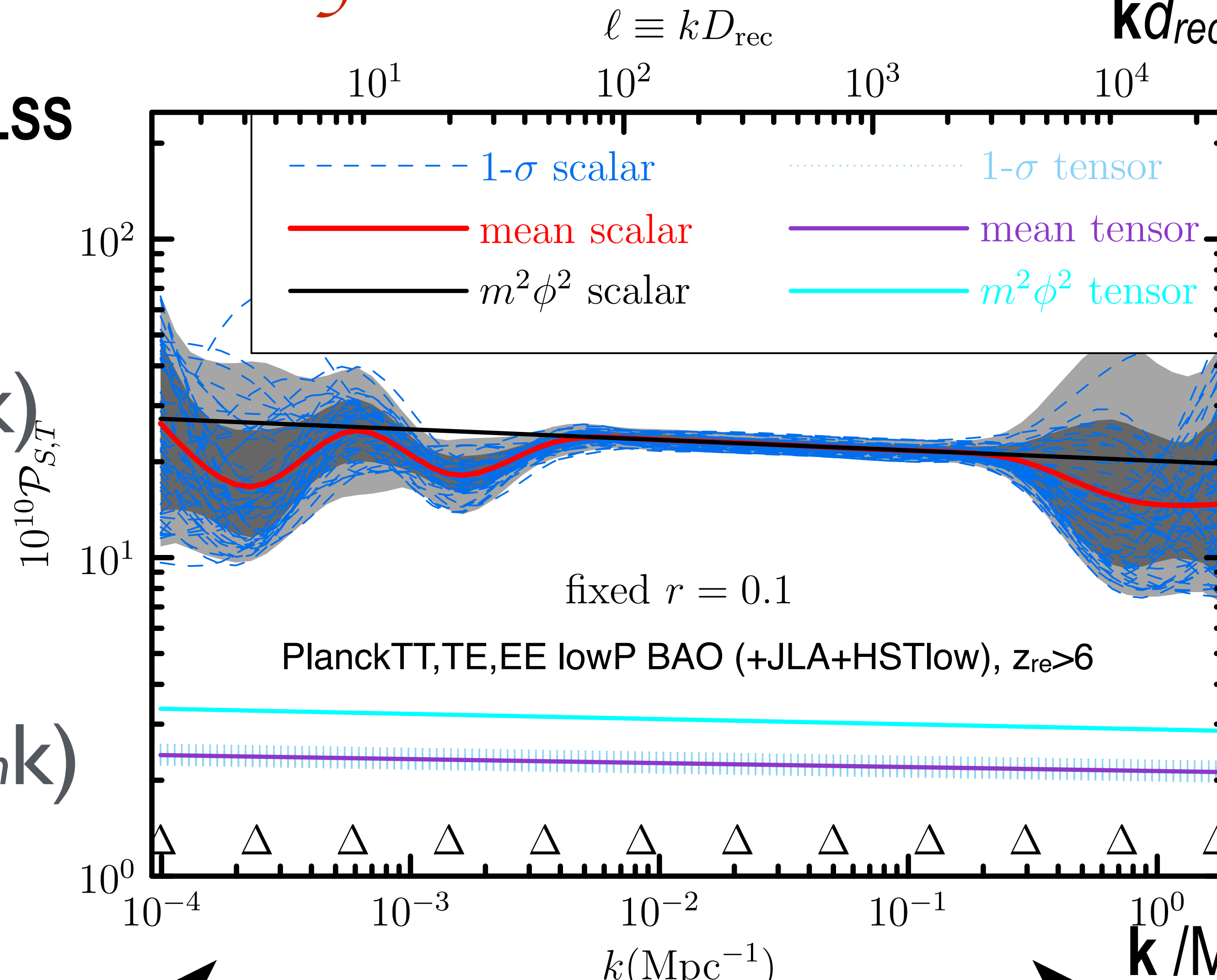


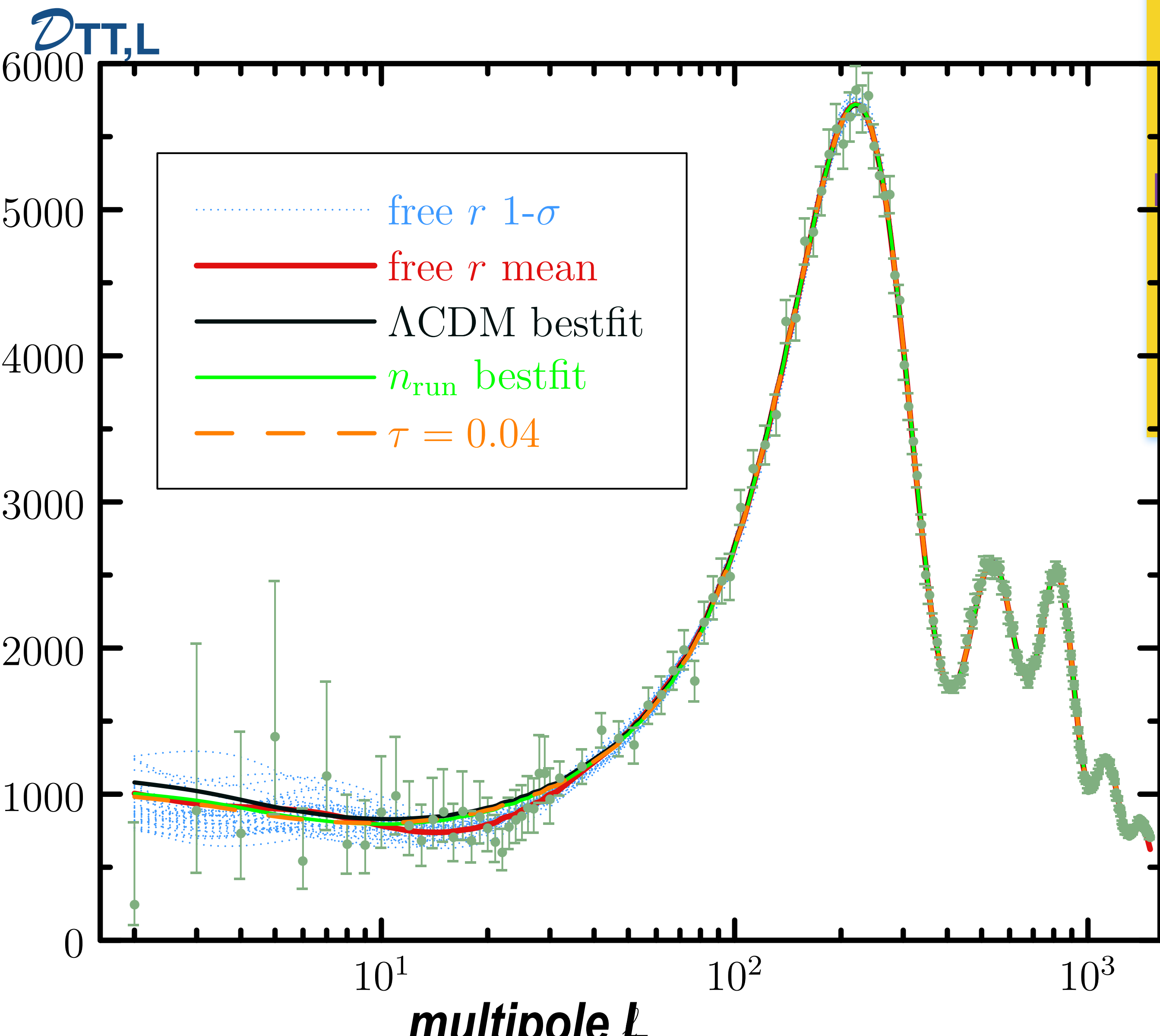
k /Mpc

9 e-folds

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

cf. Planck 2014 Commander Low L spectrum + Likelihood high L $\mathcal{D}_{TT,L}$

Preliminary 12 knots, cubic spline



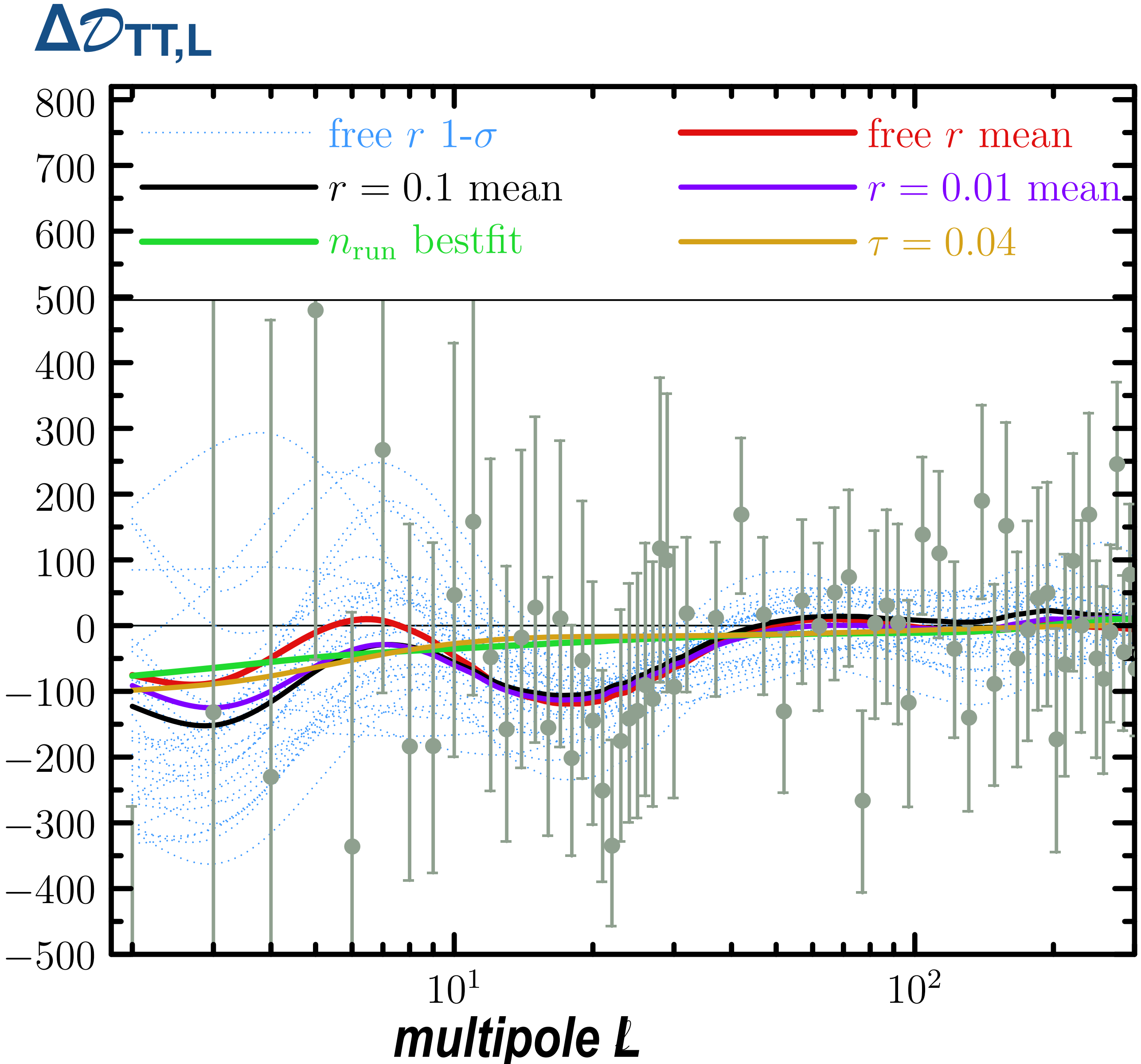
running of $\mathcal{P}_\zeta$
≡ 3 Chebyshev modes
=> very stiff
=> not what the data wants

Lower τ => shape similar to running at low L

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

trajectories of $\mathcal{D}_{TT,L}$
cf. Planck 2014 Commander Low L spectrum with Blackwell-Rao errors

Preliminary 12 knots, cubic spline



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

Lower τ => shape similar to running at low L

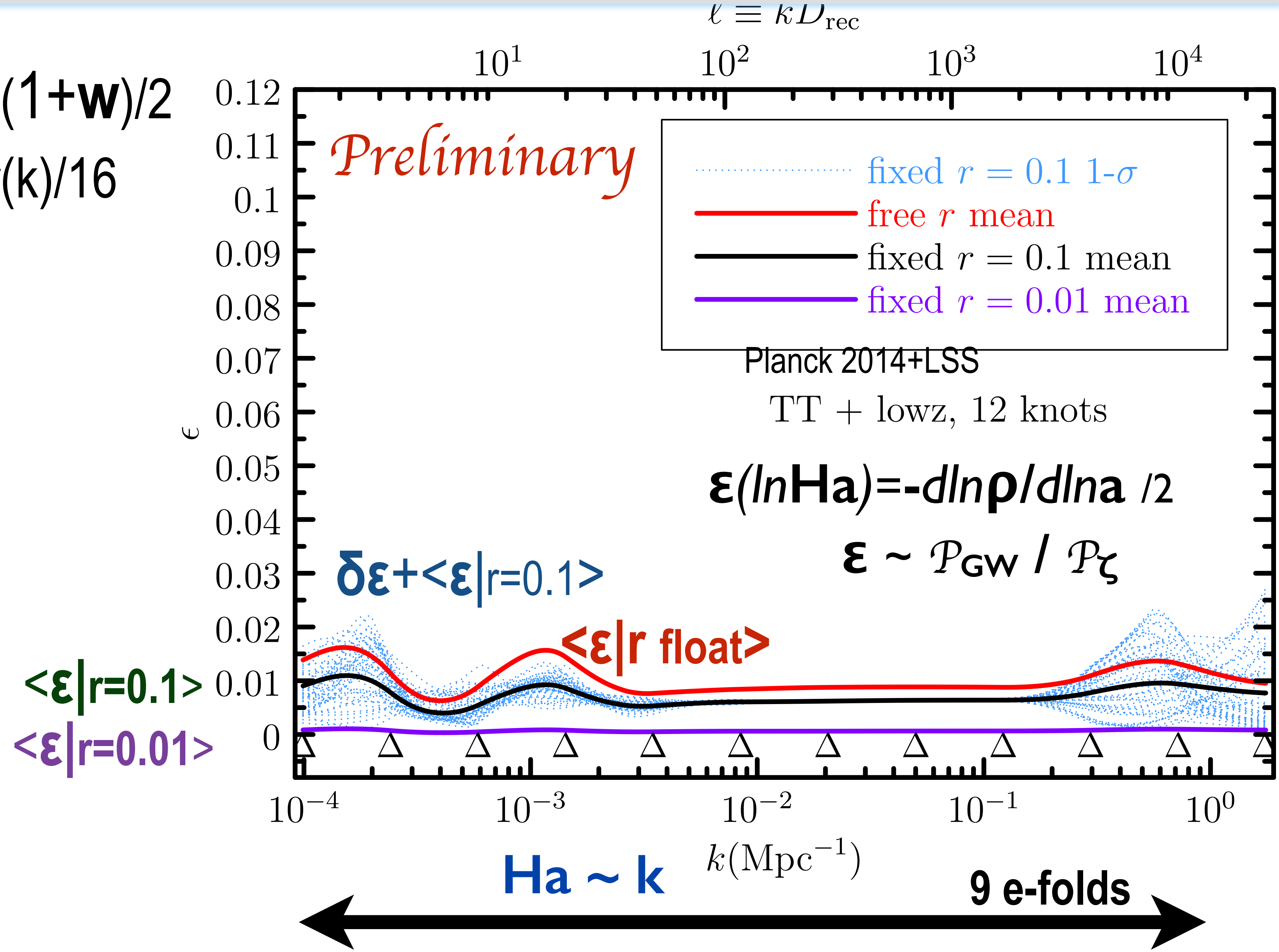
similar response on $\mathcal{D}_{TT,L}$ for constrained & free r
modified by τ freedom

running of $\mathcal{P}_\zeta$
NOT wanted

the down-up-down tendency
is here to stay,
2014-2022-…

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

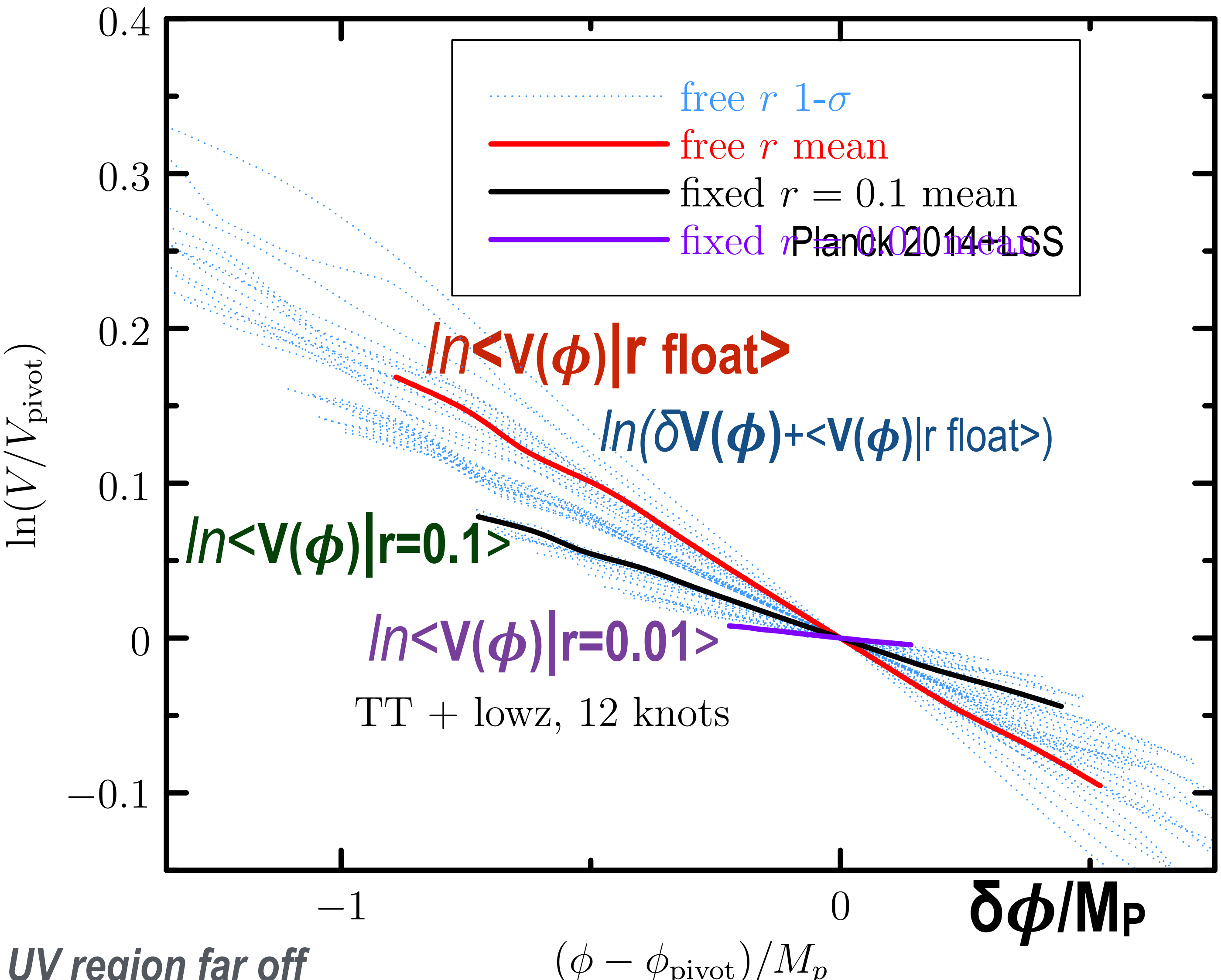
ε=3(1+**w**)/2 ≈ **r**(k)/16



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

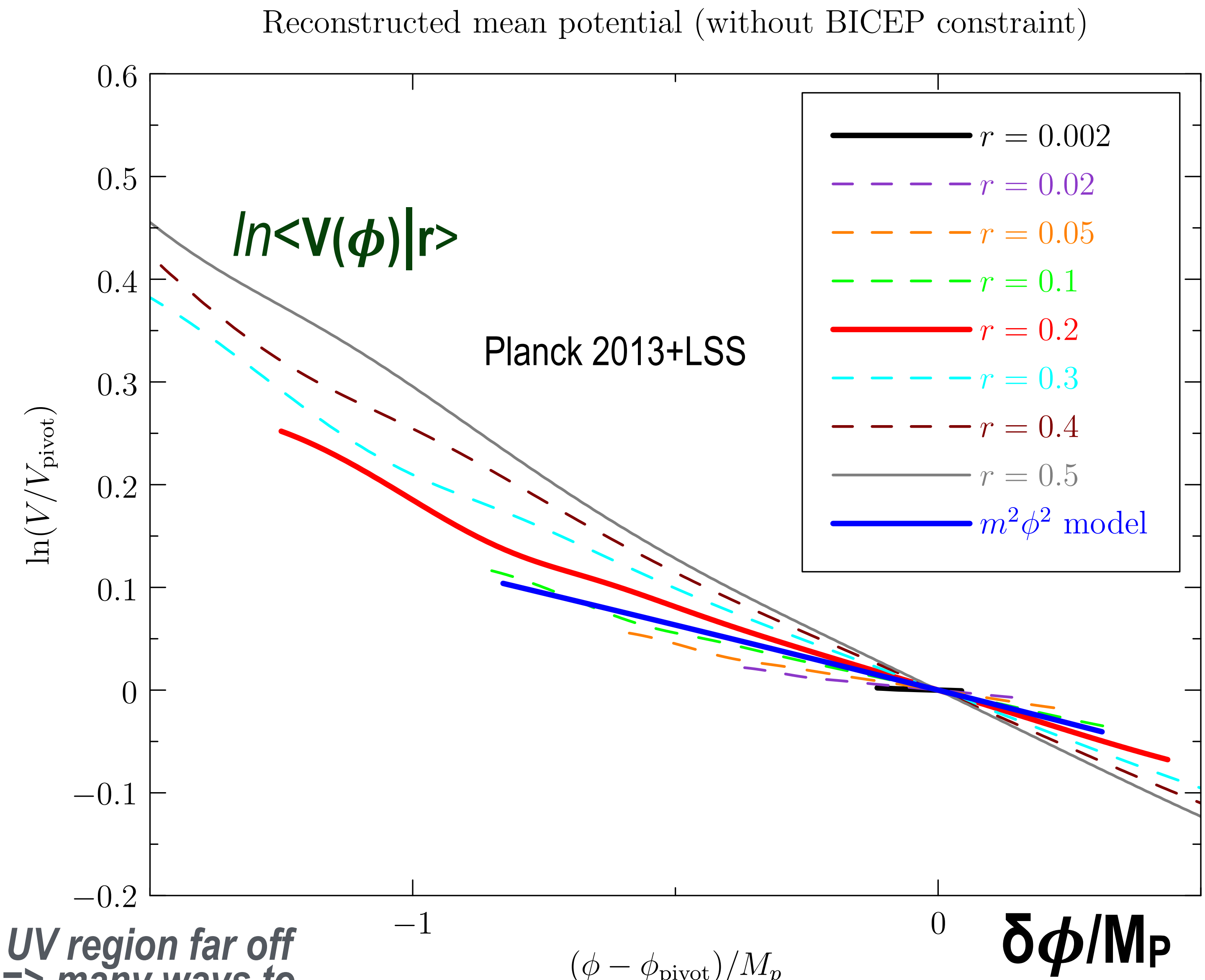
UV region far off => many ways to extrapolate

r to **+-0.02 Spider** forecast

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

inflaton V(ϕ)-maps $=3M_P^2$ H^2 (1-ε/3) *HJ eqn,* dϕ/M$_P$ /dl*n*a=±sqrt(2ε)

along the gradient / Morse flow



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

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Planck 2015 zeta-reconstruction 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 2015 Inflation paper. e.g., using moving linear knots: the stable features & conclusions agree. Planck 2015 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 P15 cf. P13), no matter r

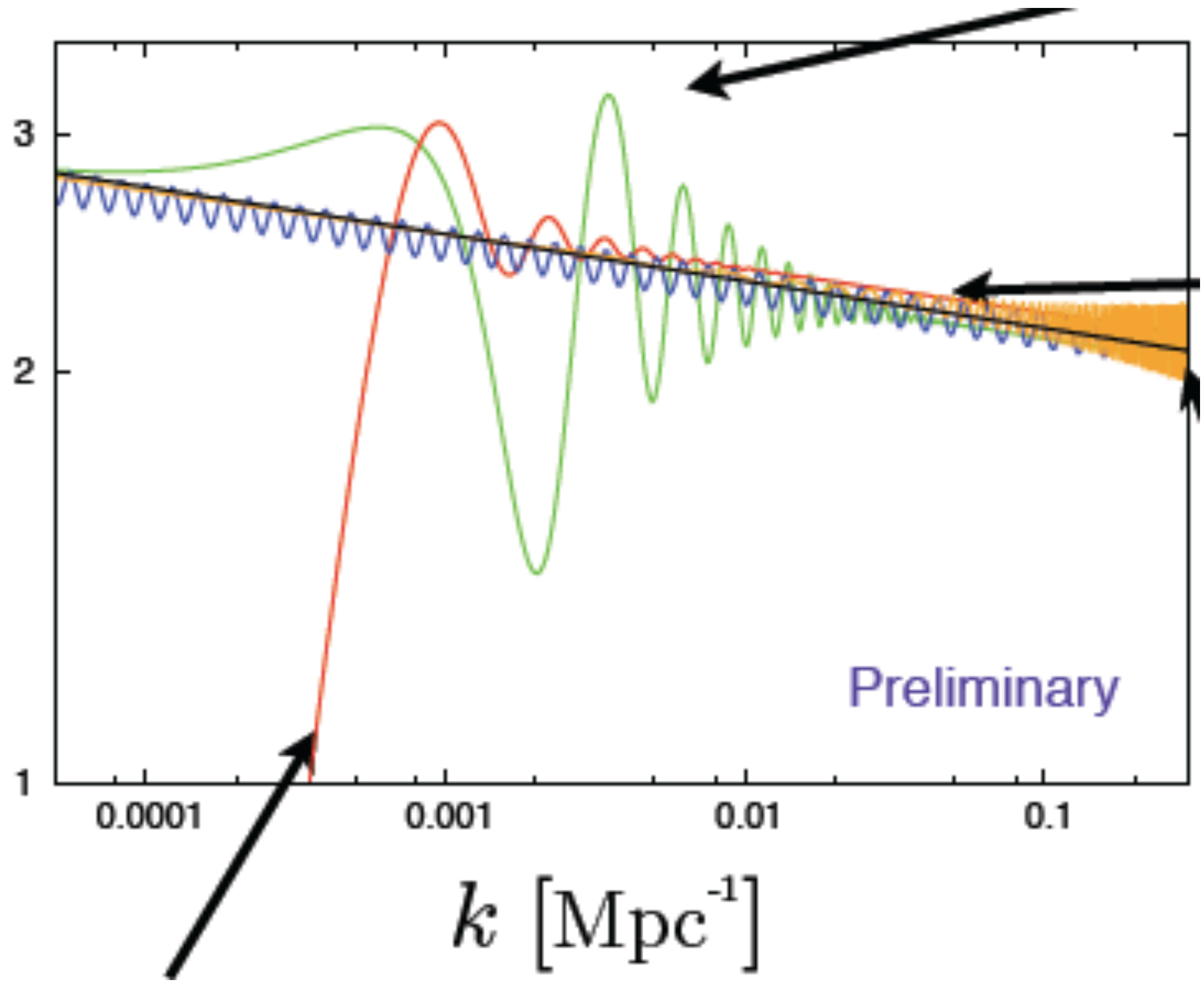
fit into a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

Planck 2015 inflation paper:

check **features in** $\mathcal{P}_\zeta$

monodromy => oscillations, no detection
other models don't really explain the dip/rise unless shaped to do it, no evidence in favour

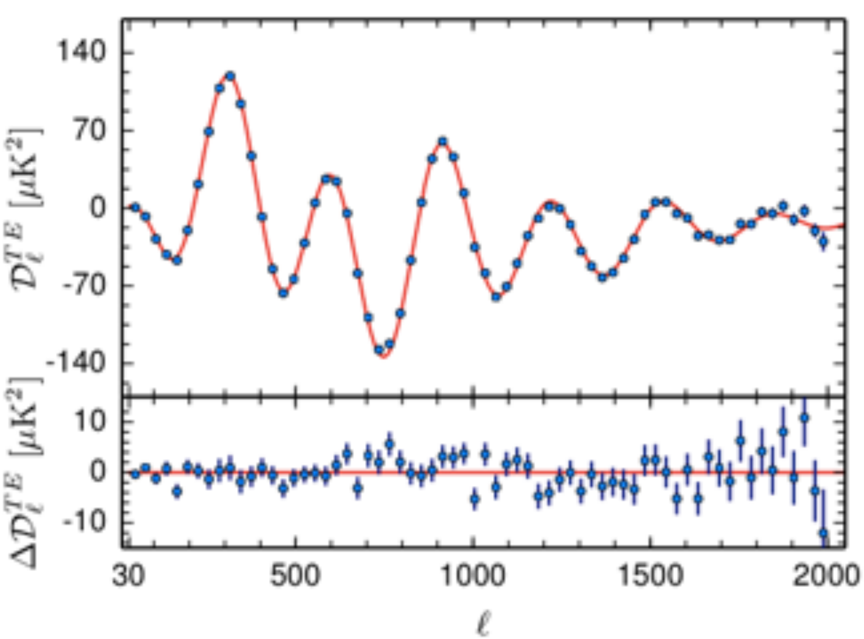
$\mathcal{P}_\zeta(\ln k)$



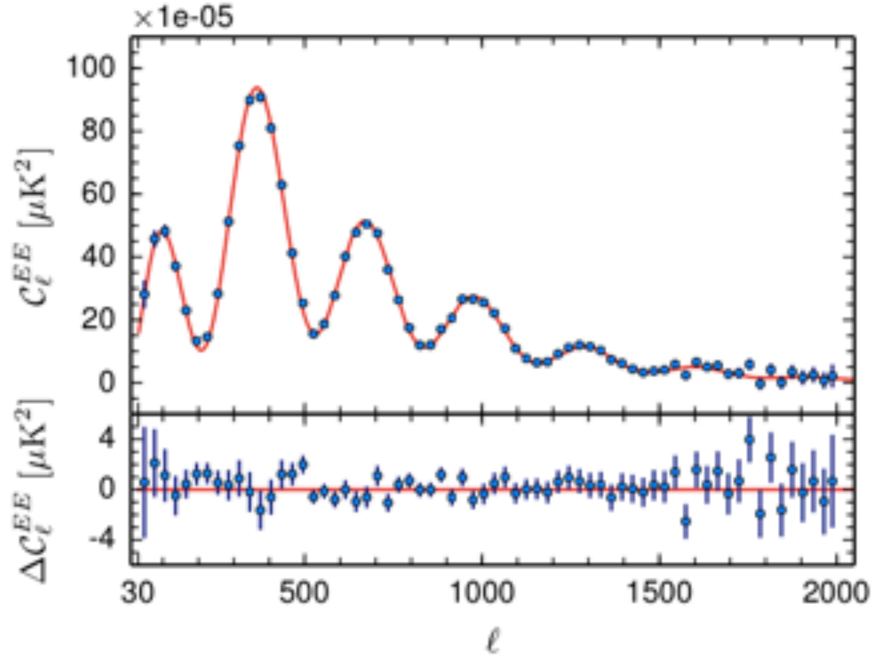
Beyond Planck 2014 +LSS: Inflation futures from CMB & LSS

Planck 2015 TE/EE cf. TT => constrains subdominant primordial power contributions not phase-locked with the acoustic-peaks *of the* pure adiabatic case. see Planck 2015 inflation paper

TE



EE



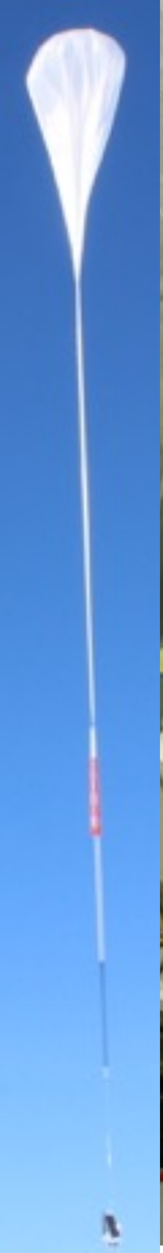
Preliminary

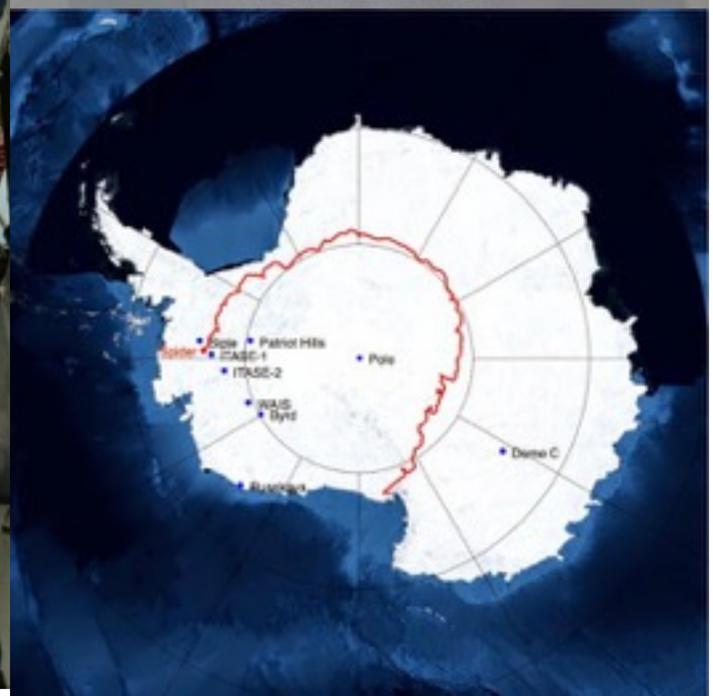
constraints on isocon spectra /parameters: Planck 2013 => Planck 2015 inflation paper

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.

SPIDER





PRINCETON UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

Imperial College London

UNIVERSITY OF TORONTO

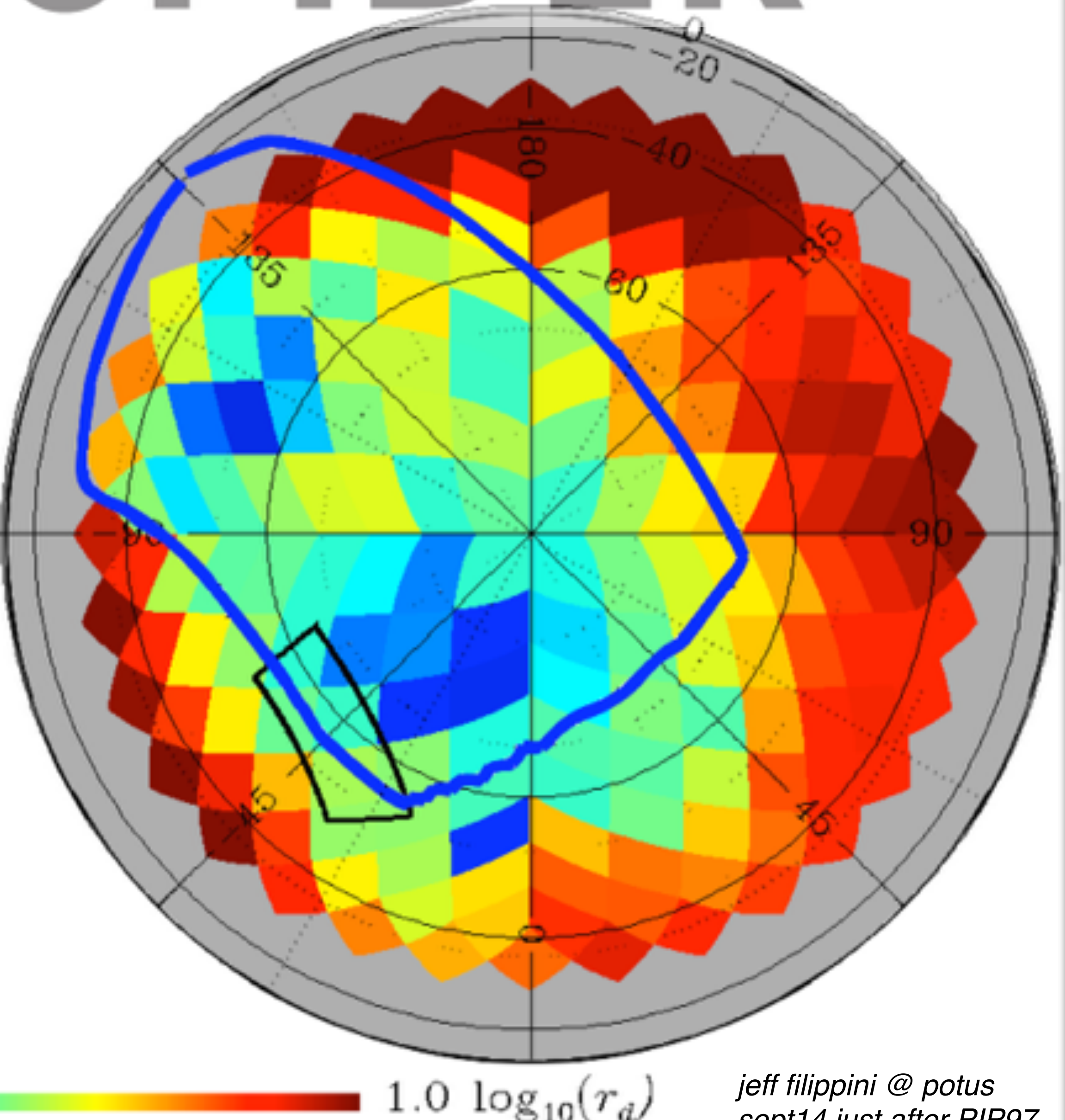
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

STANFORD UNIVERSITY

CASE WESTERN RESERVE UNIVERSITY EST. 1826

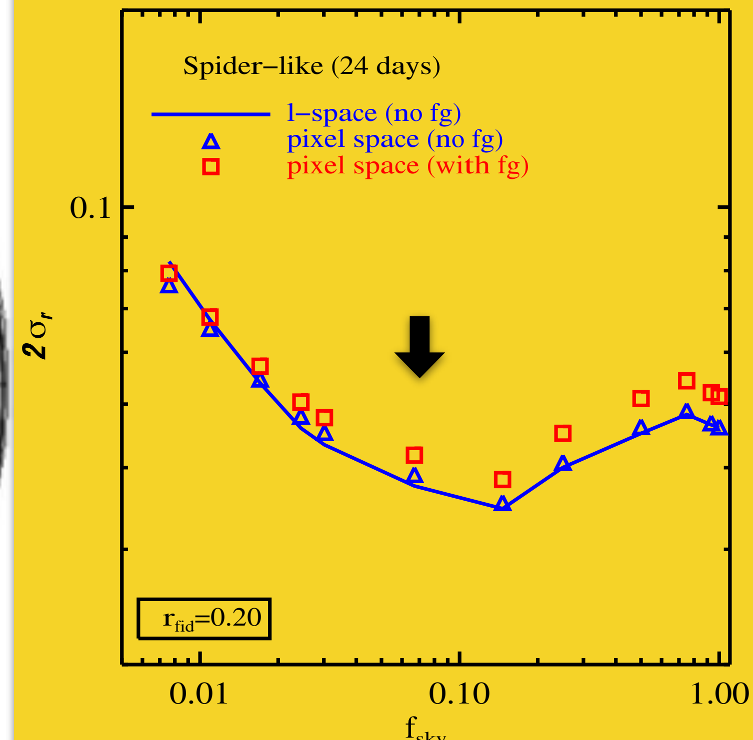
NASA NSF NIST NSERC CRSNG CSA ASC JPL the David & Lucile Packard FOUNDATION UNIVERSITY OF KWAZULU-NATAL UBC CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

SPIDER



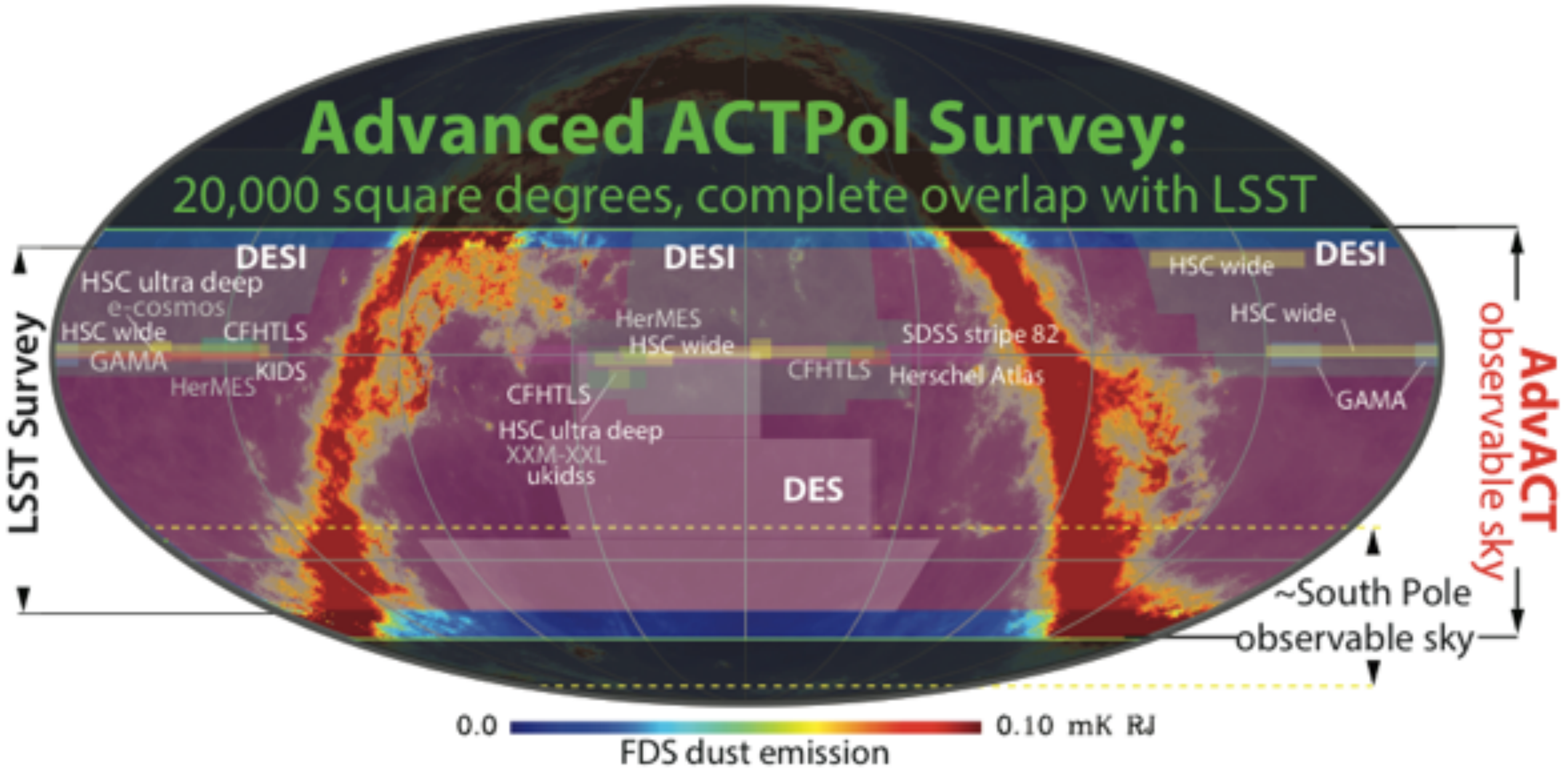
jeff filippini @ potus
sept14 just after PIP97

Jan 2015 flight ~ 16d
fsky,eff=0.65
3/3 @ 90/150 GHz
~2K detectors incl yield
L ~ 10-300
2016+ flight
2/2/2 @ 90/150/280 GHz



forecasts
0.03 2 sigma 1st flight no fgnd
0.02 2 sigma 2nd flight
0.03 2 sigma 2nd flight fgnd cleaned

Advanced ACTPol (AdvACT) Observations

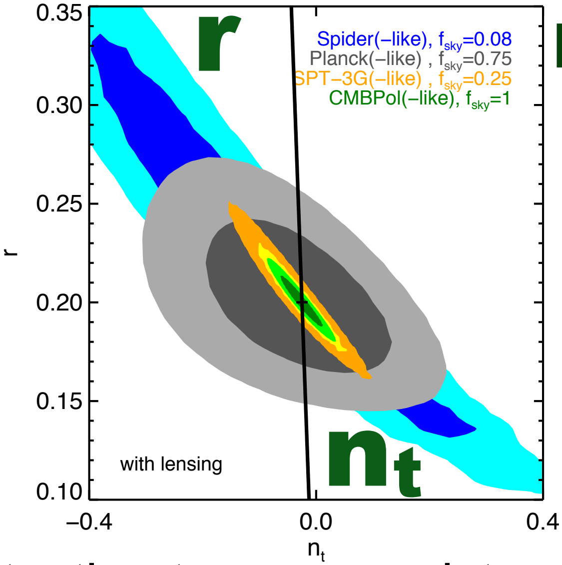


- ~20,000 deg^2 survey (f_{sky}~0.5) with complete LSST overlap as well as DES, ALMA, and other observatories located in Chile
- Substantial overlap with spectroscopic surveys (SDSS, PFS, DESI)

future

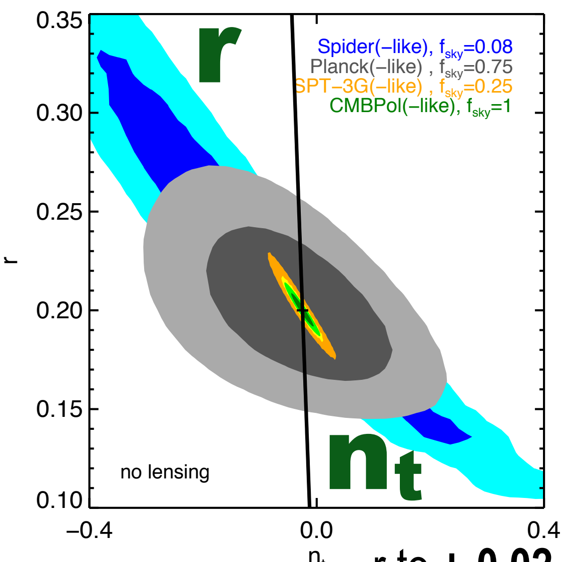
AdvACTpol (f_{sky}~50%): *Cosmological Forecasts*

Planck_f, Spider, SPT3g, .. CMBpol (CoRE+,Pixie,.)



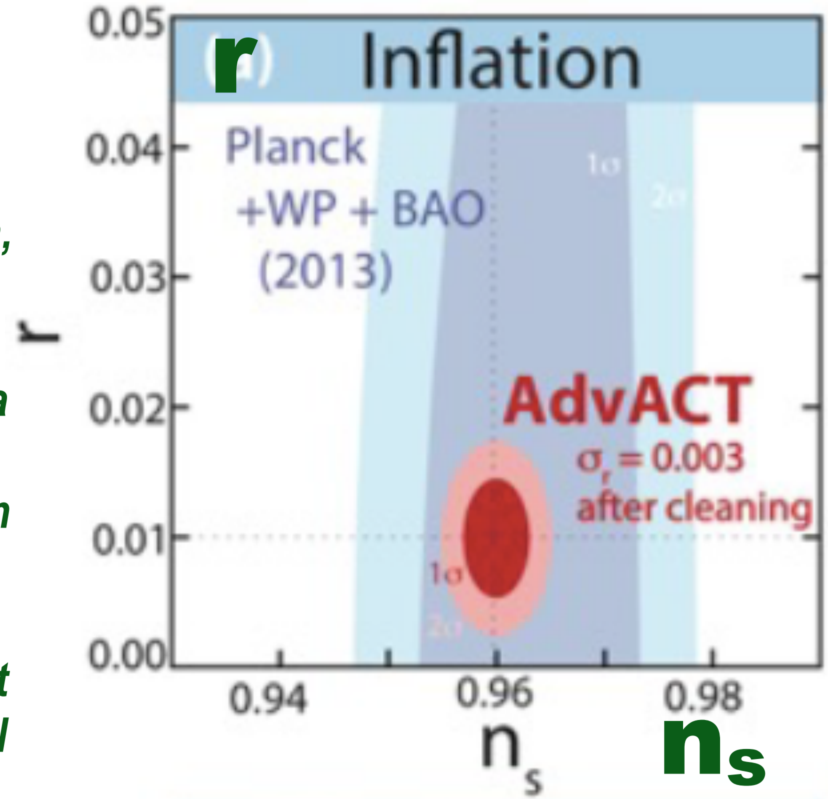
testing tensor consistency?

better f_{sky}=25% for spt3g/AdvACT-like than current 6% goal for spt3g



$n_t \approx -r/8$

nice BB spectra, hence a slope, but tensor consistency is a steep relation. how well we can do will depend upon the ability to de-lens to get to the high L tail



Planck_f uses pre-launch blue book forecast sensitivities

r to **+-0.02 Spider** forecast

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