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CANADIAN INSTITUTE FOR ADVANCED RESEARCH

Dick Bond @ CIFAR14
Mapping Inflation

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

Bond, Frolov, Huang, Braden 14a,b,c,…

a ***Map*** *is an* ***ensemble = mean-map + fluctuation-maps,*** *e.g.,*

linear: $\langle T\rangle(pixel)+C^{TT}(pix, pix')^{1/2}\ GRD_{pix'}$, ***quadratic:*** $\langle C^{TT}_L\rangle + \langle \Delta C^{TT}_L \Delta C^{TT}_{L'}\rangle\ GRD_{L'}$,

Primordial Curvature/phonon-maps $\zeta = ln\ a_{com}$ from the CMB

Linear: ***Wiener-filtered ζ_b all-sky maps & stacking maps on (oriented) Peaks***

Quadratic: ***$P_\zeta(k)$ Power Spectra maps, Acceleration History $\epsilon(ln\ a)$ maps & Inflaton Potential $V_{eff}(\phi)$ maps if r-measurements (BICEP2, Planck, Spider, AdvACT,..)***

Implications for **post-Inflation *heating* *given r-measurements?***

Implications for ***anomalies: caustic trajectories*** **& non-Gaussian Intermittency**

CMB Polarization Q,U,E,B & Temperature Stacking maps on (oriented) T-Peaks

Super-duper LSS & the Super-WEB aka the gravitational potential web Φ_N ~ primordial 3-curvature web

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

$= Trace(\alpha|_H)$ *sb90 aka* $Trace(\alpha|_{com})$

cf. the density web ~ strain web

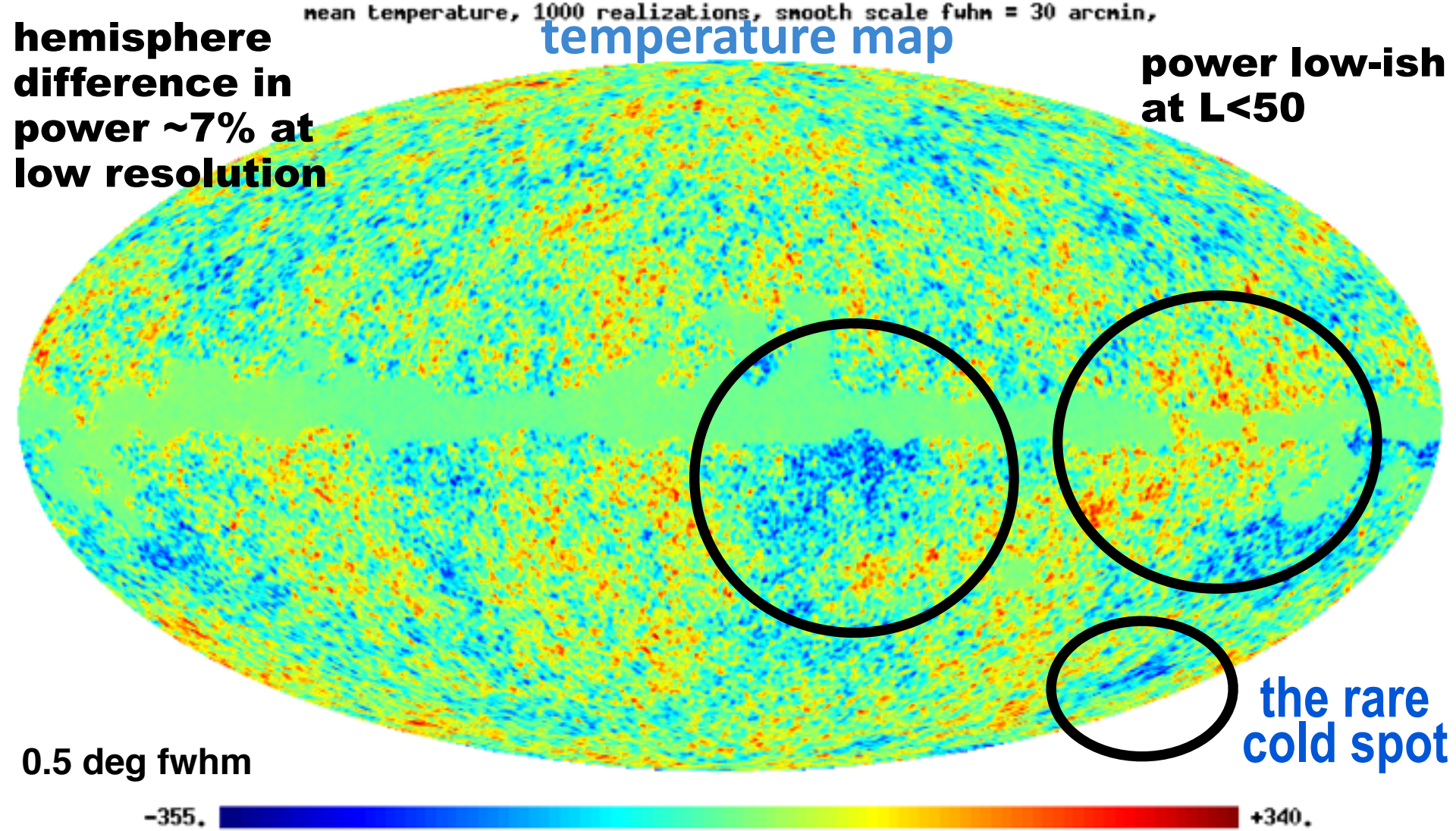
$$dX^i(r,t) = exp(\alpha)_J{}^j(r,t)\, dr_{eq}{}^J$$

Φ_N => $-Trace(\alpha|_{NL,longitudinal})$ *with no anisotropic stress*

Φ_N => $-3/5(D(t)/a(t))\, Tr\alpha$ if linear (low L ISW $2\int d\Phi_N/dt$)

Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

anomalies => inflation COMPLEXITY at $t \sim 10^{-36}$ seconds?



Grand Unified Theory of Anomalies? TBD

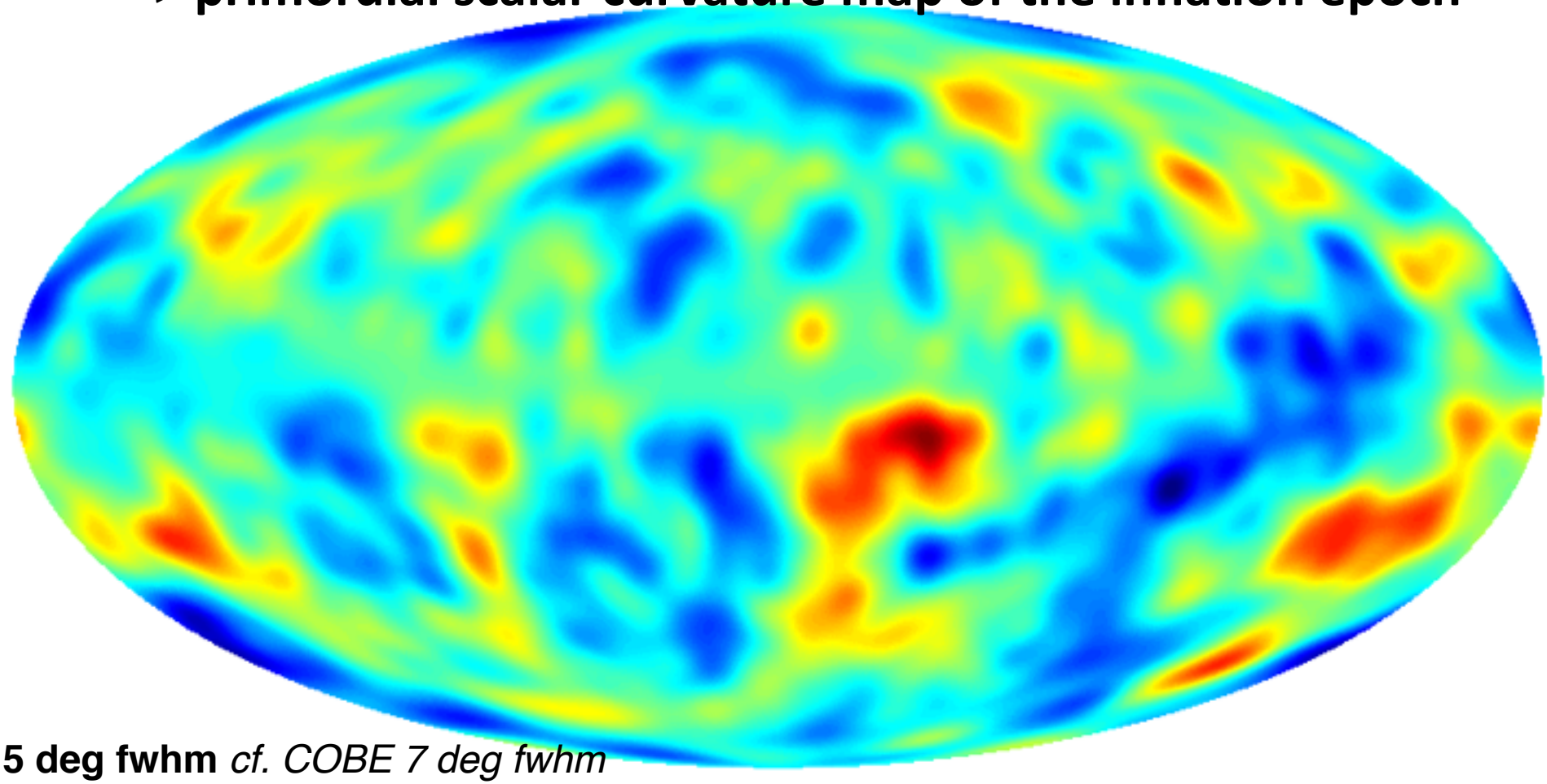
intermittent *strain-power bursts (in curvature)?*

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

$\int d$ ***visibility***$(distance)$ $\langle Trace(\alpha) | Temp \rangle$ $(angles, distance)$

mean zeta, 1000 realizations, smooth scale fwhm = 300 arcmin,

=> primordial scalar curvature map of the inflation epoch



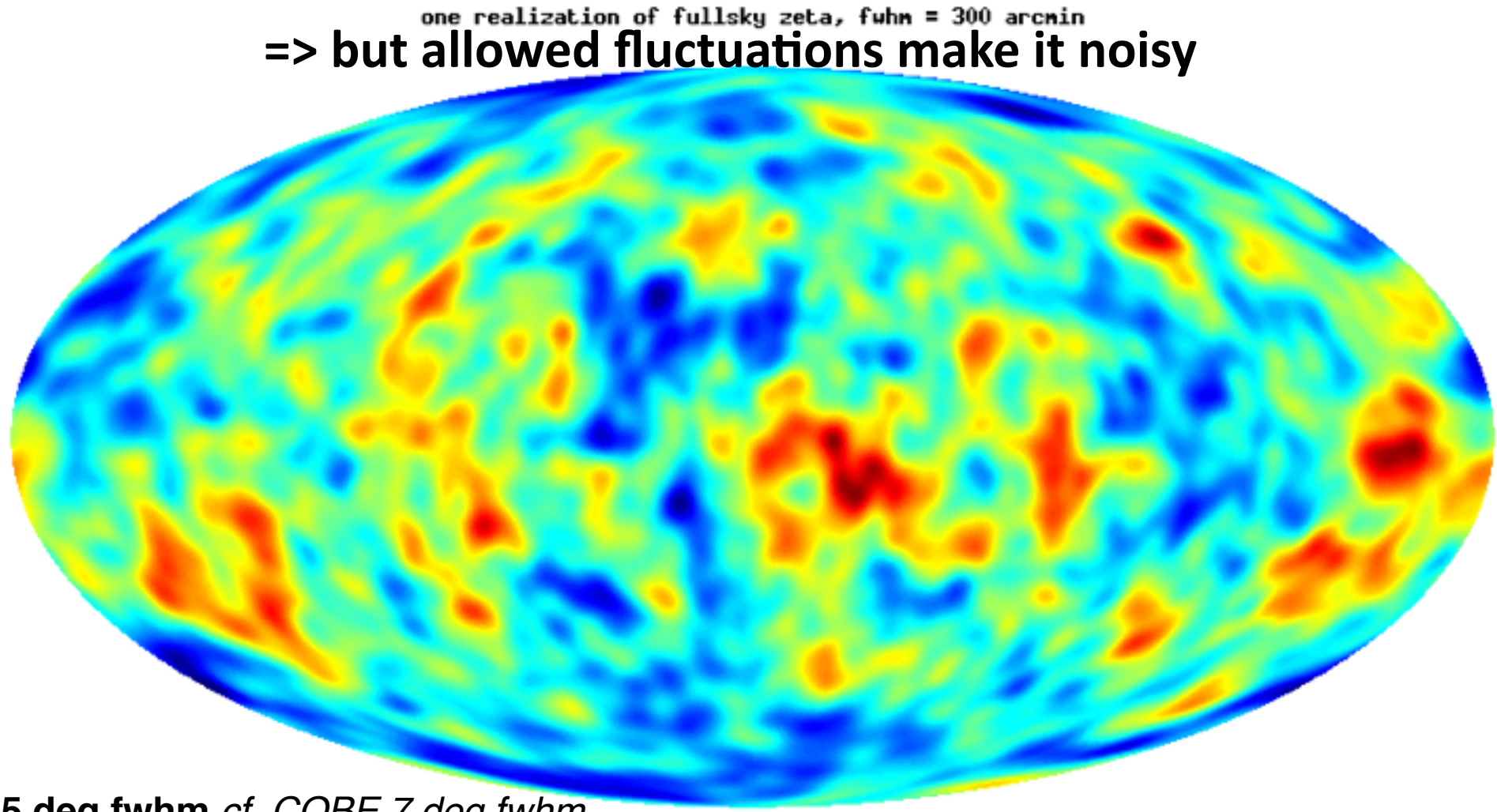
5 deg fwhm *cf. COBE 7 deg fwhm*

-2.94 +3.58

Reconstructing the Early Universe **visibility mask**

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

$\int d$ ***visibility***$(distance)$ $\langle Trace(\alpha)|Temp\rangle + \delta Trace(\alpha)$



=> but allowed fluctuations make it noisy

5 deg fwhm *cf. COBE 7 deg fwhm*

-3.59 +4.06

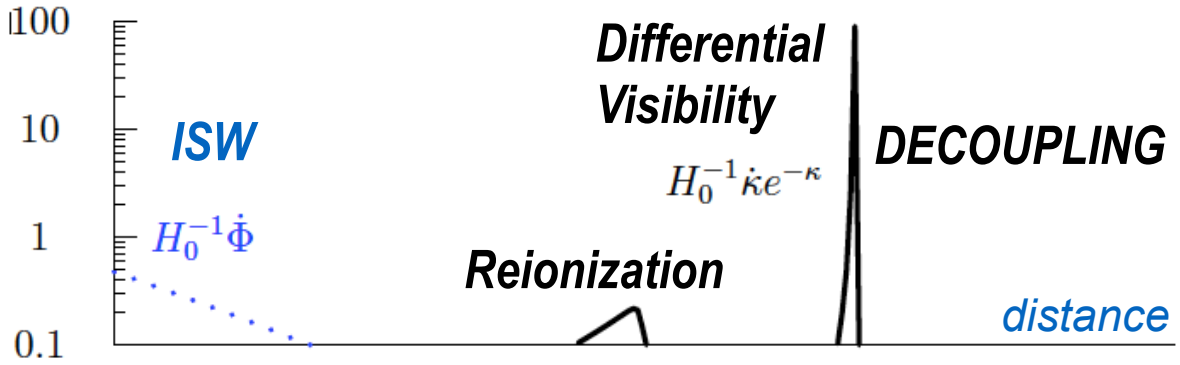
Reconstructing the Early Universe

visibility mask

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

$\int d$***visibility***$(distance)$ $\langle$***Trace***$(\boldsymbol{\alpha})|Temp\rangle + \delta$***Trace***$(\boldsymbol{\alpha})$

=> but allowed fluctuations make it noisy



CMB-*probe* no tomography (*radial distance (redshift)*):

CMB-*probe* ~ differential visibility

at decoupling/recombination (all L)

reionization/reheating (low L)

CMB-*probe* ~ changing gravitational potential

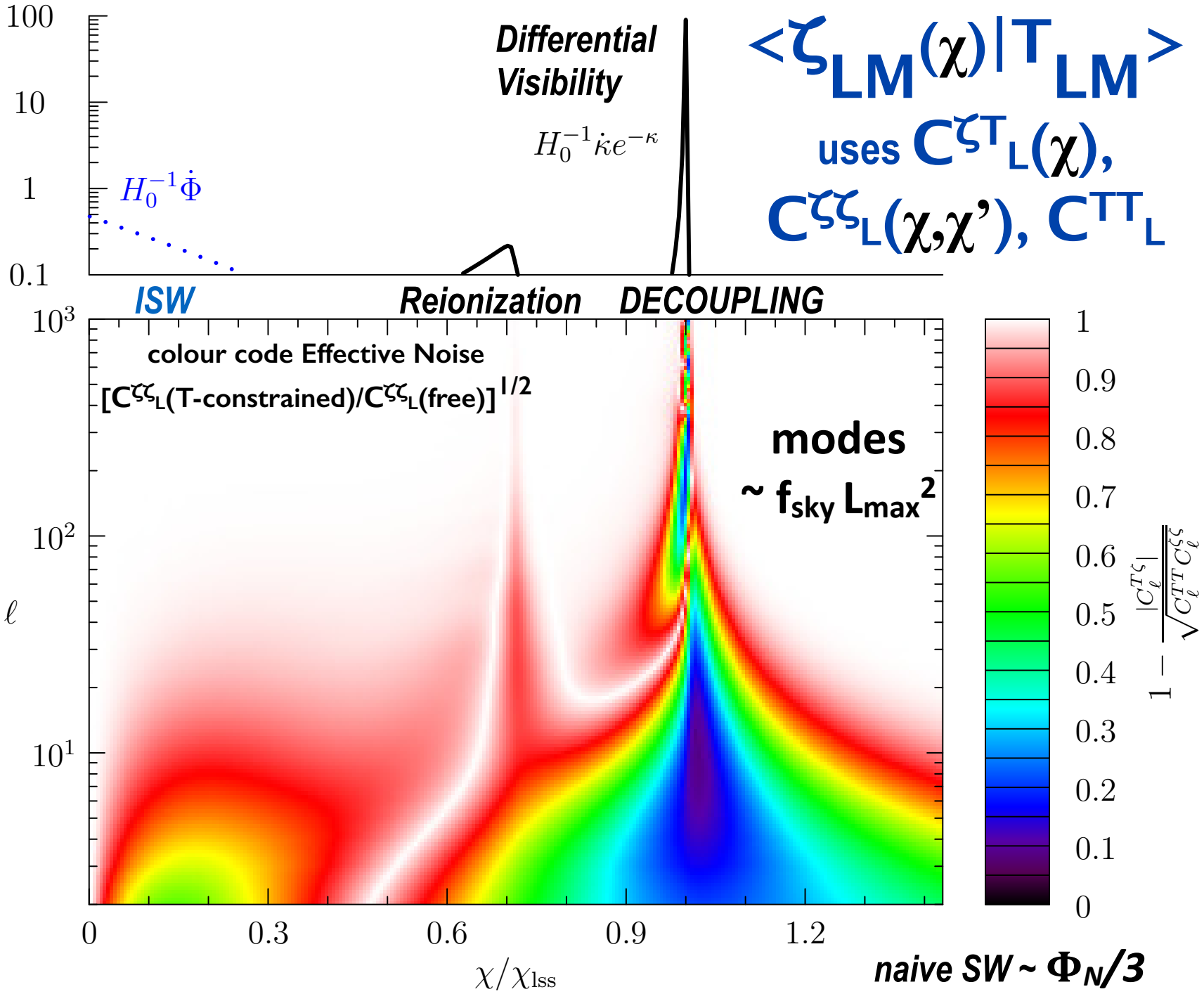
Integrated Sachs Wolfe effect **(low L), Rees-Sciama** effect **(hi L)**

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

Large Scale Structure Galaxy Surveys

available modes ~ $f_{sky} L_{max}^2 k_{max} d_{max}$

~ $f_{sky} (k_{max}^3 d_{max}^3)$, $k_{min} \sim 2\pi/d_{max}$ $V_{com} \sim d_{max}^3$


100
10
1
0.1
$H_0^{-1}\dot{\Phi}$
Differential Visibility
$H_0^{-1}\dot{\kappa}e^{-\kappa}$
ISW
Reionization
DECOUPLING
$<\zeta_{LM}(\chi)|T_{LM}>$
uses $C^{\zeta T}{}_L(\chi)$, $C^{\zeta\zeta}{}_L(\chi,\chi')$, $C^{TT}{}_L$
10^3
10^2
10^1
ℓ
colour code Effective Noise
$[C^{\zeta\zeta}{}_L(\text{T-constrained})/C^{\zeta\zeta}{}_L(\text{free})]^{1/2}$
modes
~ f_{sky} L_{max}^2
0
0.3
0.6
0.9
1.2
χ/χ_{lss}
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$1-\frac{|C_\ell^{T\zeta}|}{\sqrt{C_\ell^{TT}C_\ell^{\zeta\zeta}}}$
naive SW ~ $\Phi_N/3$

reconstructing ζ *aka* primordial ***scalar curvature*** *@uniform density*

Bond, Frolov, Huang, Braden, Nolta

Wiener-filtered ζ maps instead of $\zeta(\mathbf{x})$, $\zeta(\mathbf{k})$, make $\zeta_{LM}(\chi)$, $\chi=|\mathbf{x}|$ & $\zeta_{LM}(k)$, $k=|\mathbf{k}|$ maps

$$T_{LM\,c,s} \sim \int \zeta_{LM\,c,s}(k)\, U^{T}_{L\,c,s}(k)\, dk + res \sim \int \zeta_{LM\,c,s}(\chi)\, V^{T}_{L\,c,s}(\chi)\, d\chi + res$$

Gaussian stats => $C^{\zeta\zeta}{}_{L}(\chi_1,\chi_2)$, $C^{\zeta T}{}_{L}(\chi)$, $C^{TT}{}_{L}$

$$\langle \int \mu_b(\chi)\, \zeta_{LM\,c,s}(\chi)\, d\chi \,|\, a_{LM\,c,s}\rangle + \textit{inhomog}$$ **Gaussian fluctuations**

visibility masks $\mu_b(\chi)$ select bands $\Delta\chi_b$ about χ_b ~ decoupling, reionization (also ISW). ∃ only a single-mode $V^{T}_{L\,c,s}$ direction, fluctuations in orthogonal directions are huge. use the mask for shaped-weighting to control fluctuation-swamping.

full $\zeta_{LM}(k)$ *reconstruction* $\langle\zeta_{LM}(k) \,|\, a_{LM}\rangle$ *is fluctuation-swamped*

∃ E-pol vector $V^{E}_{L\,c,s}$ overlaps V^{T} but it differs enough so reconstruction improves with E-pol

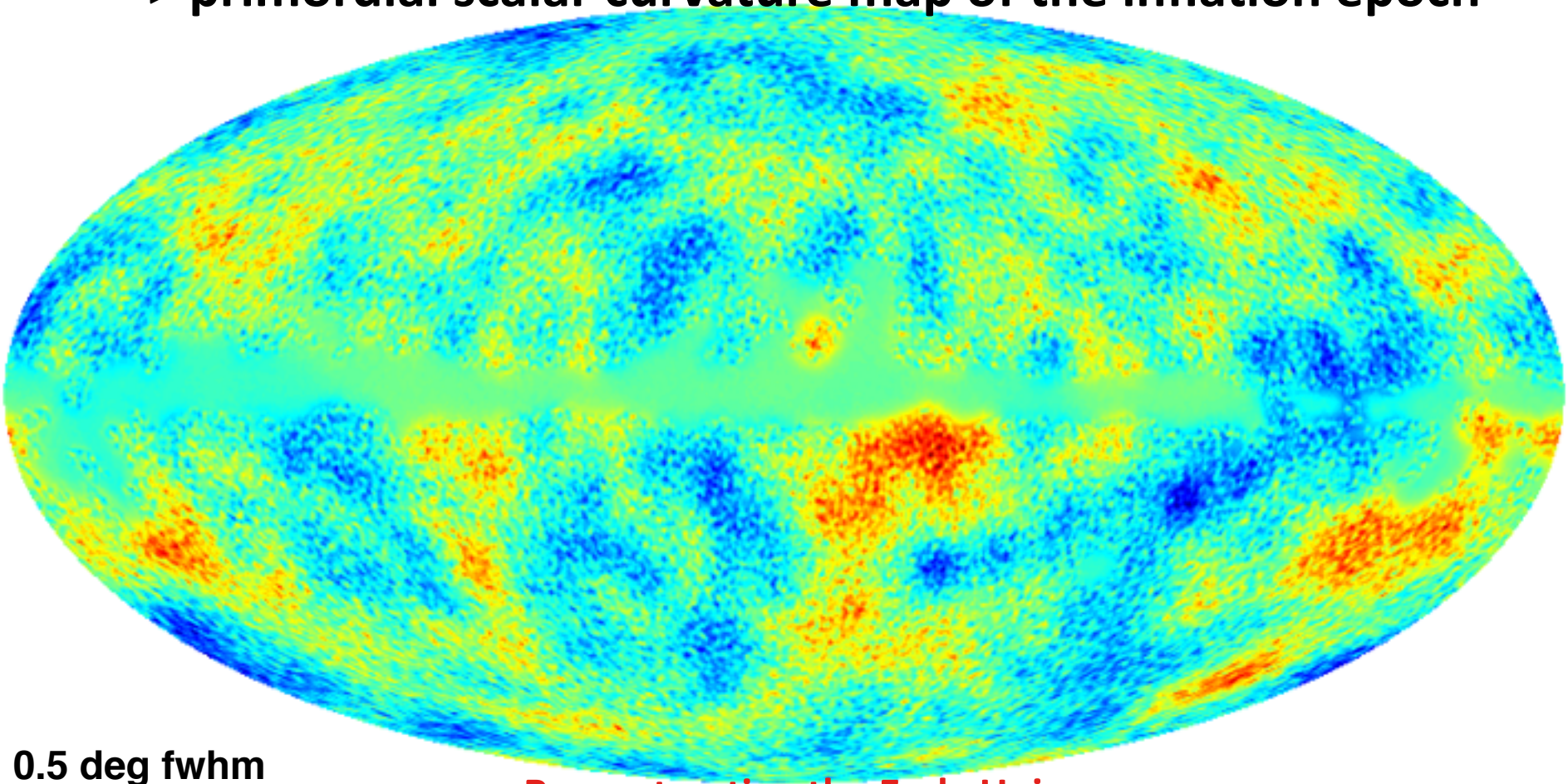
$C^{\zeta E}{}_{L}(\chi)$, $C^{EE}{}_{L}$, $C^{TE}{}_{L}$

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

$\int d$ ***visibility***$(distance)\ \langle Trace(\alpha) | Temp \rangle$ *(angles, distance)*

mean zeta, 1000 realizations, smooth scale fwhm = 30 arcmin,

=> primordial scalar curvature map of the inflation epoch



0.5 deg fwhm

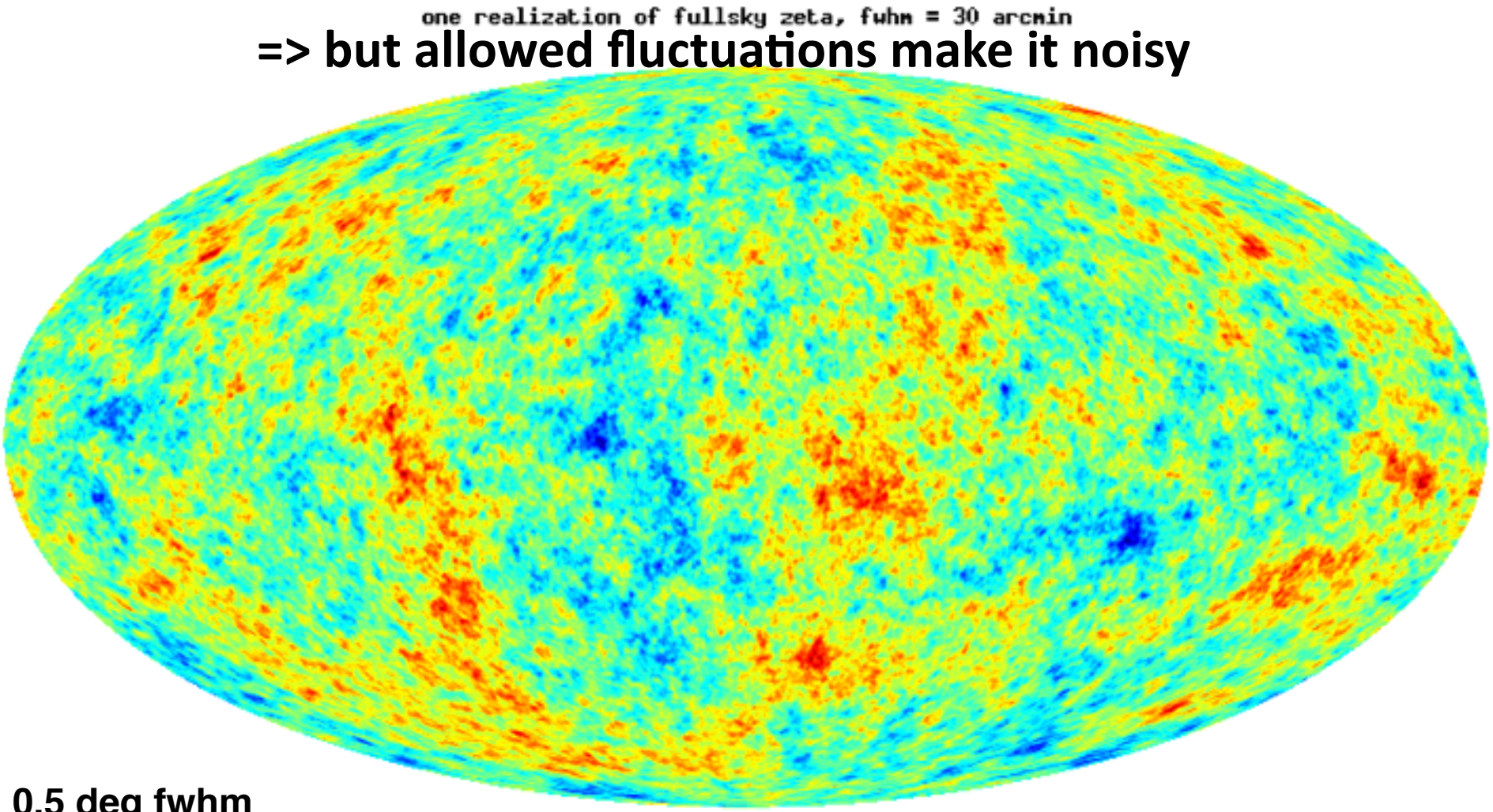
Reconstructing the Early Universe

-4.70 +5.18

visibility mask

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

$\int d$ ***visibility***$(distance)$ $\langle Trace(\alpha)|Temp\rangle + \delta Trace(\alpha)$



=> but allowed fluctuations make it noisy

0.5 deg fwhm

-8.61 +7.54

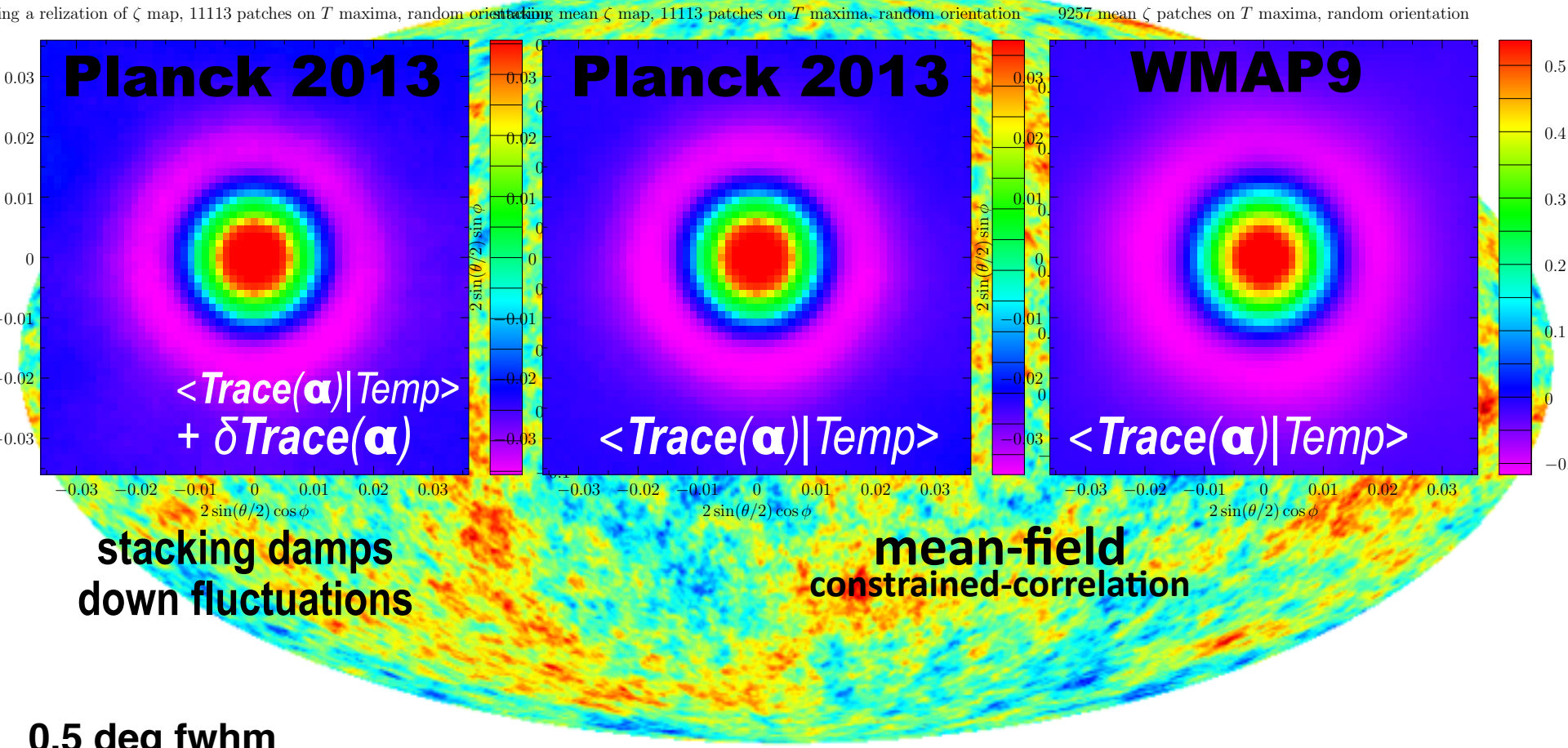
Reconstructing the Early Universe **visibility mask**

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

$\int d\,visibility(distance)\ \langle Trace(\alpha)|Temp\rangle + \delta Trace(\alpha)$

one realization of fullsky zeta, fwhm = 30 arcmin

=> but allowed fluctuations make it noisy



stacking damps down fluctuations

mean-field
constrained-correlation

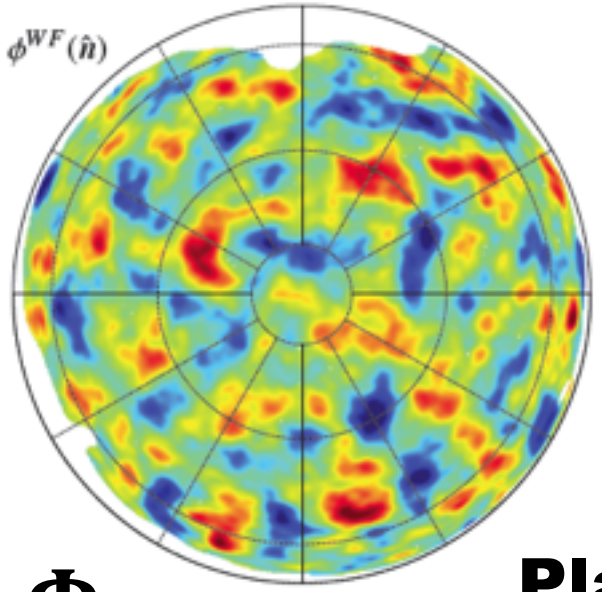
0.5 deg fwhm

Reconstructing the Early Universe

visibility mask

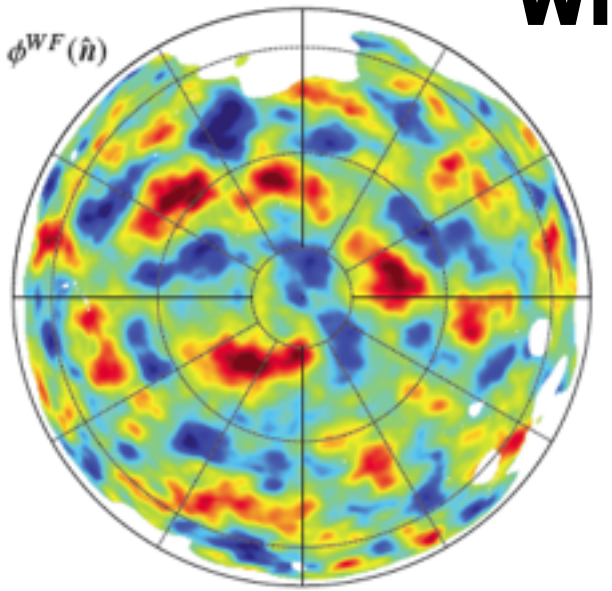
Planck13 CMB Lensing: reconstructed projected Φ_N =-3/5(D(t)/a(t)) Trα grav. potential

~ dark+baryonic matter map, mean-field map = Wiener filter (beware: fluctuations about mean-field)



Φ_N Galactic North

Planck 2013
Wiener-filtered



Galactic South

cf. **primordial isotropic strain maps Trα**

Power Deviation from fiducial $\langle\zeta|T\rangle\langle\zeta|T\rangle+\langle\delta\zeta\delta\zeta|T\rangle-\langle\zeta\zeta|\text{free}\rangle$

byproduct, cf. quadratic $P_{\zeta\zeta}$ reconstruction, extra C_s/C_{tot} & regularizer $P^{(i)}{}_{\zeta\zeta}$

complications: other cosmic parameters fixed at maxL value; inhomogeneous generalized noise enters Wiener filters; is error assessment with sims adequate?; de-lensing; …

Quadratic expansions in mode functions: which function to expand (ln $P_{\zeta\zeta}$), *which modes (cubic B-spline), number?, priors on amplitudes, etc.*

maxL solutions with Fisher/Hessian errors are Wiener-filtered maps

we use MCMC *Bond, Braden, Huang, Frolov, Vaudrevange 2014*

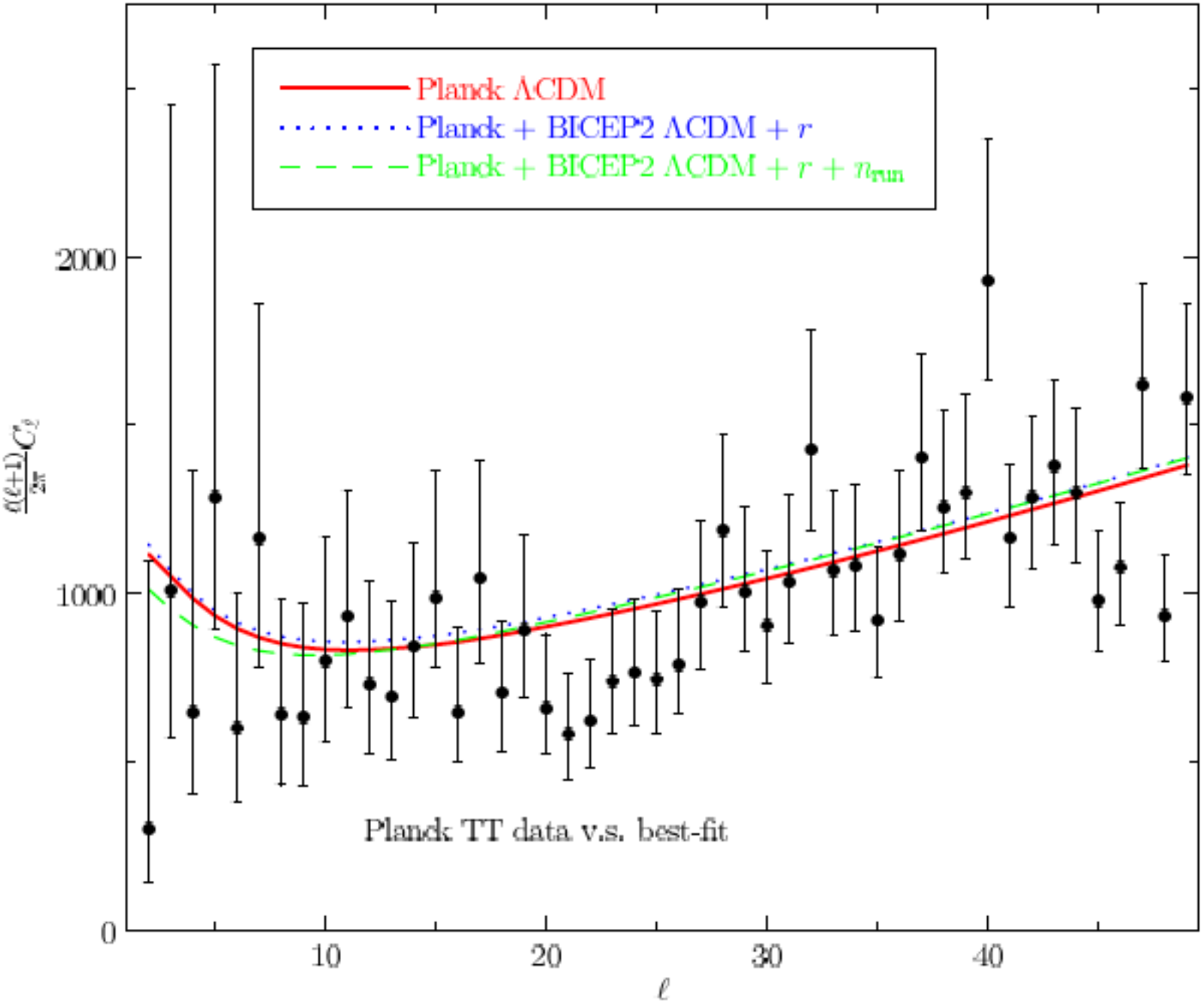
scan $ln\mathbf{P_s}(ln k)/A_s$, $ln\mathbf{A_s}=ln P_s(k_{pivot,s})$, $\boldsymbol{r}(k_{pivot,t})$; *consistency => reconstruct* $\boldsymbol{\varepsilon}(ln\mathbf{Ha})$, $\mathbf{V}(\psi)$

new parameters: **trajectory probabilities for early-inflatons**

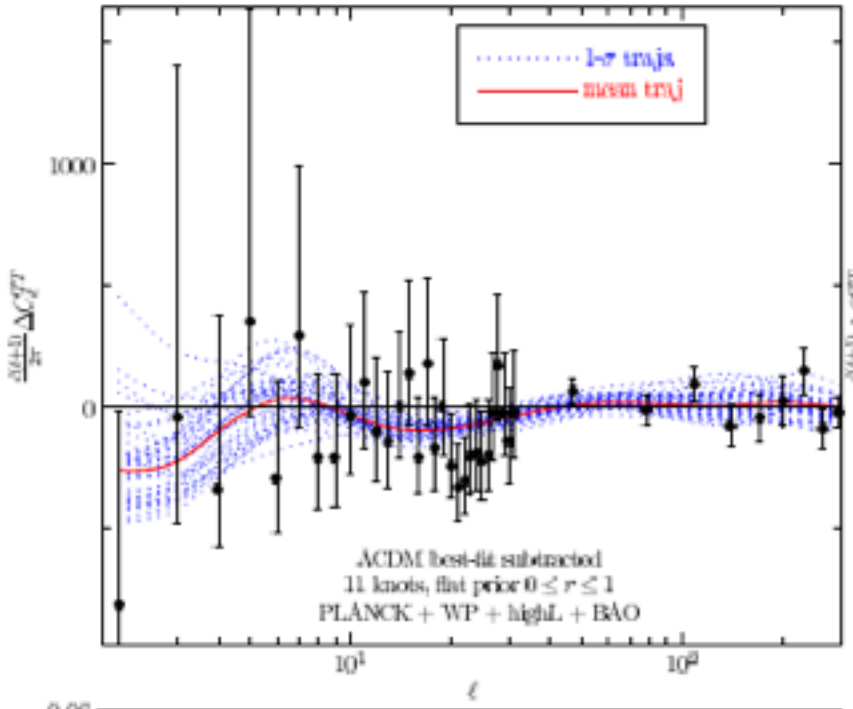
over the years, b2fhv have also scanned mode expansions of $ln\boldsymbol{P_s}(ln k)$, $\boldsymbol{n_s}(ln k)$, $\boldsymbol{\varepsilon}(ln Ha)$, $ln\boldsymbol{H}(ln Ha)$, *which change the prior measure, but give qualitatively similar results in terms of features if there is an r detection (which breaks degeneracies);* $ln\boldsymbol{P_s}(ln k)/A_s$ *relative stiffness properties, connecting the well-determined data-region about* $k_{pivot,s}$ *to the band in k being targeted, like a coarse-grained broad band* $\boldsymbol{n_s}$

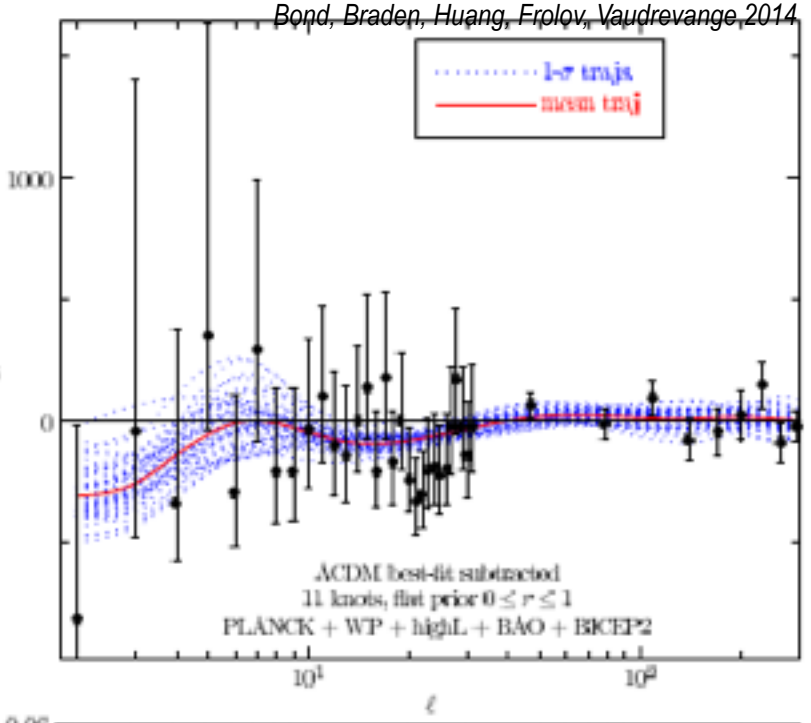
=> **ultra-early Universe sound spectrum**

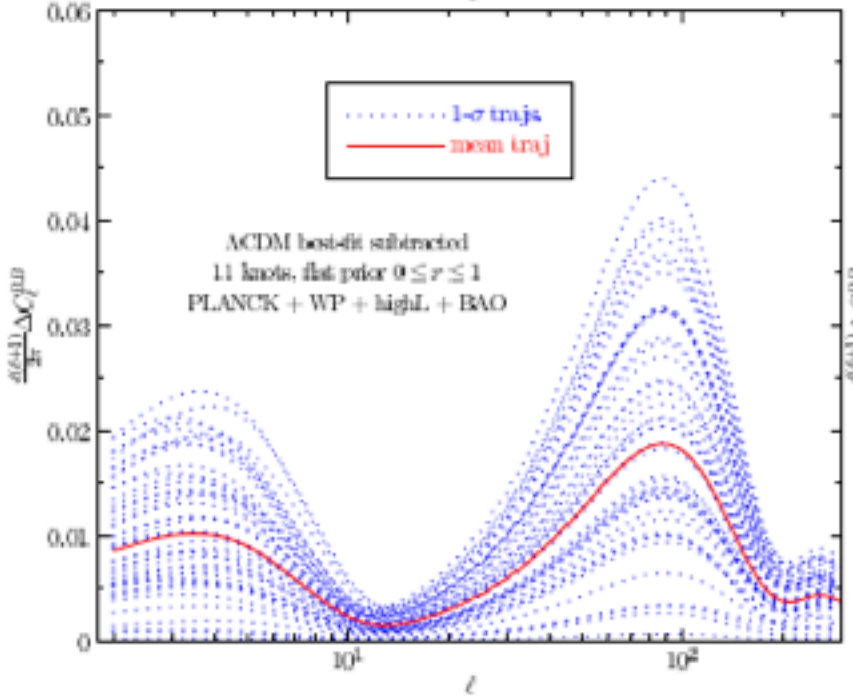
Bond, Braden, Huang, Frolov, Vaudrevange 2014

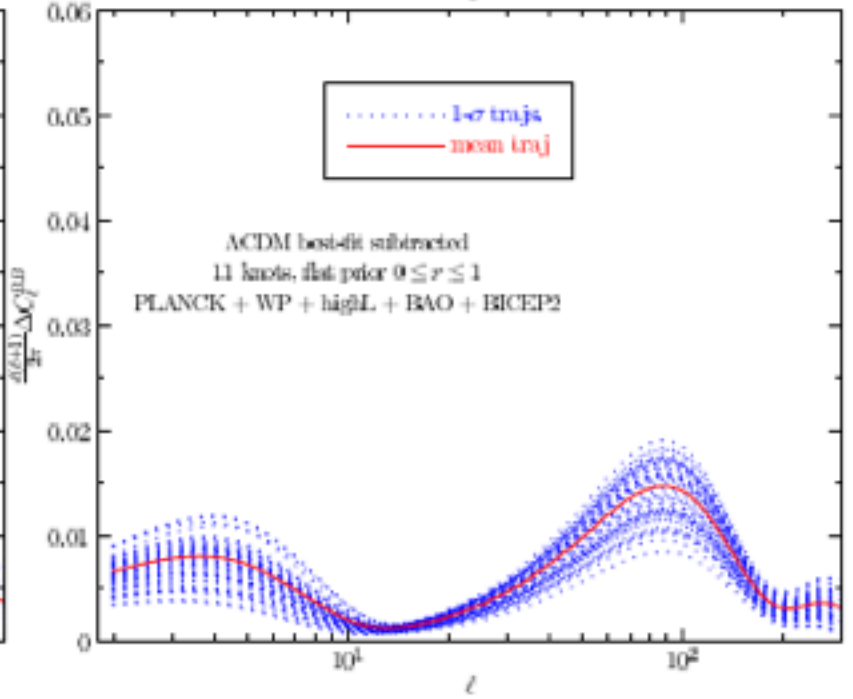


Bond, Braden, Huang, Frolov, Vaudrevange,2014









Power Deviation from fiducial $\langle\zeta|T\rangle\langle\zeta|T\rangle+\langle\delta\zeta\delta\zeta|T\rangle-\langle\zeta\zeta|free\rangle$

byproduct, cf. quadratic $P_{\zeta\zeta}$ reconstruction, extra C_s/C_{tot} & regularizer $P^{(i)}_{\zeta\zeta}$

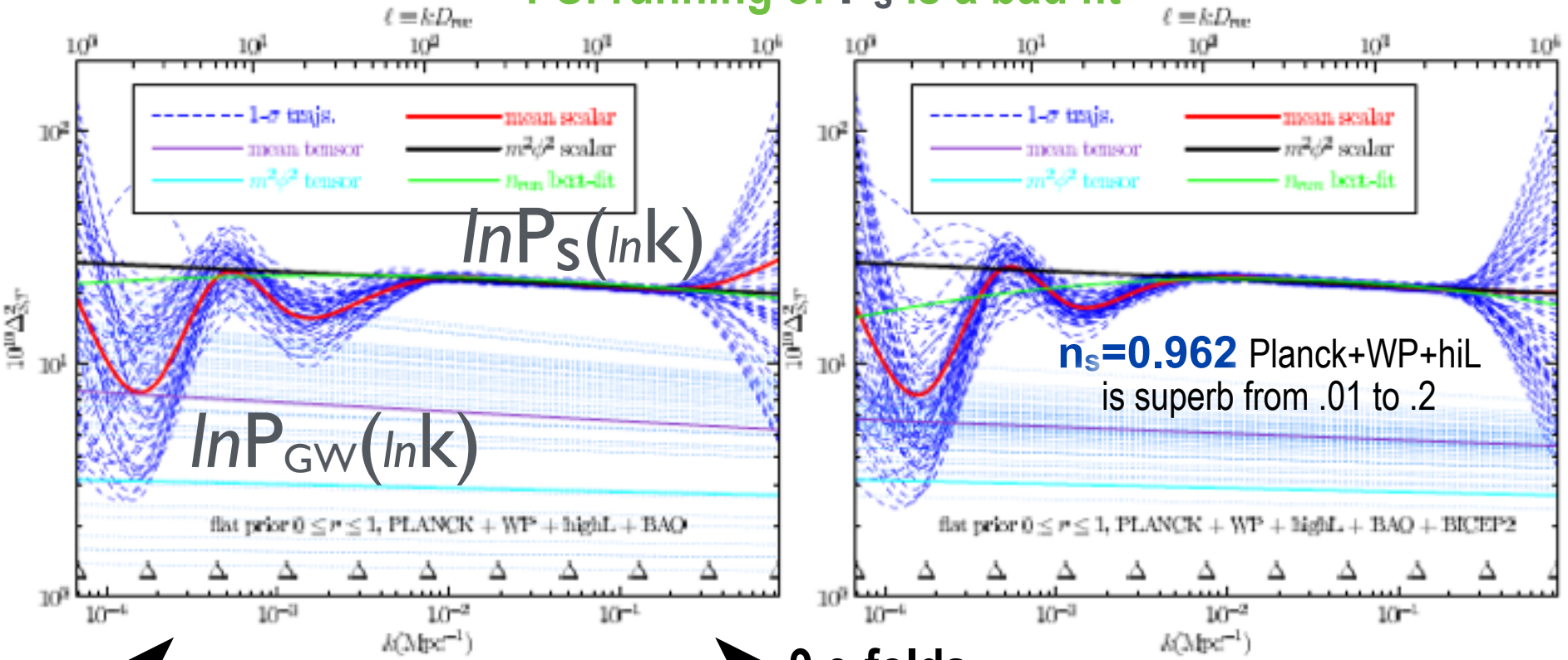
Quadratic expansions in mode functions: which function to expand (ln $P_{\zeta\zeta}$), *which modes (cubic B-spline), number?, priors on amplitudes, etc.*

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

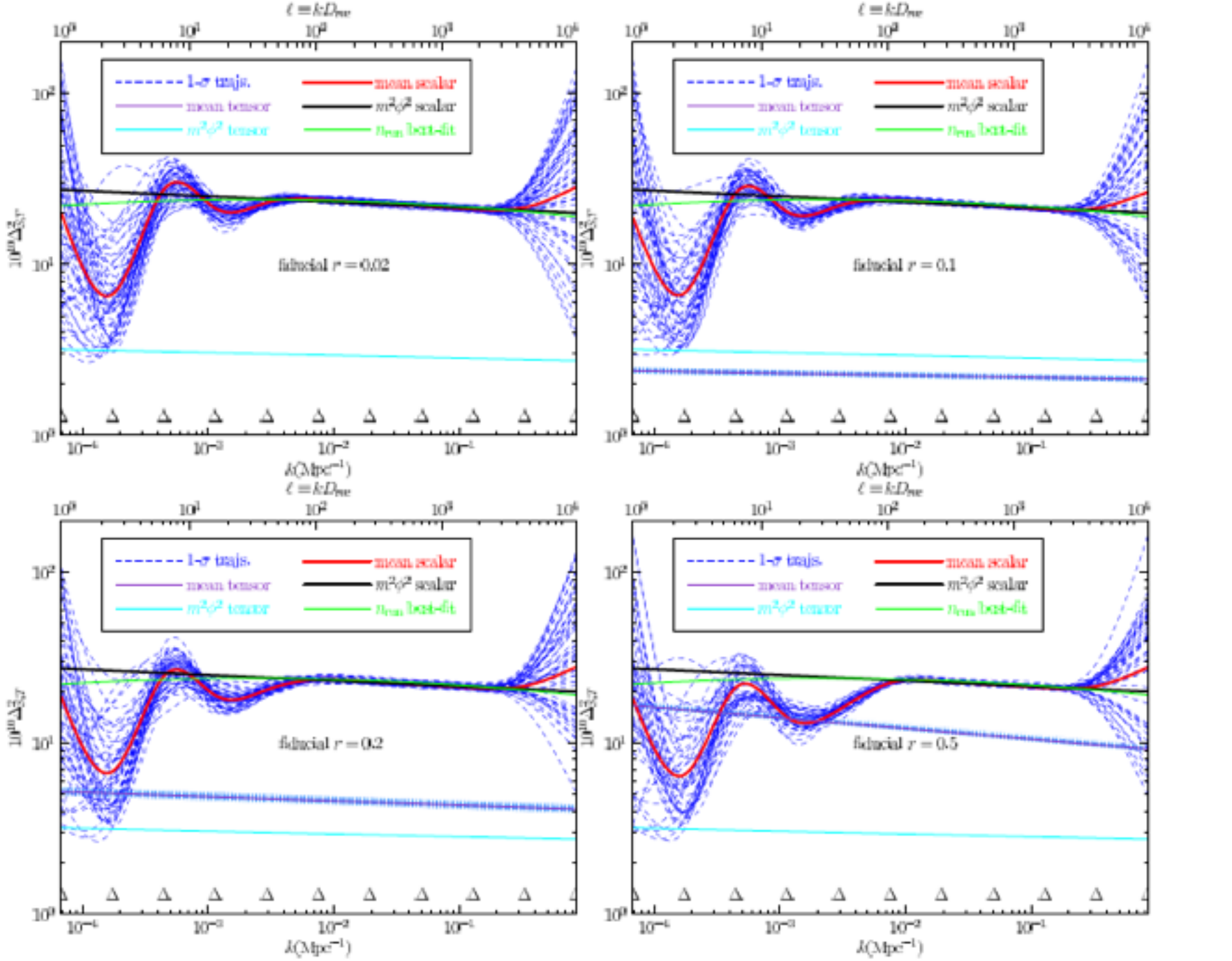
here MCMC <power> trajectory, 1 sigma mean+fluctuation trajectories

no strong evidence for oscillation patterns, cutoffs, local features; a change on large L<100 scales

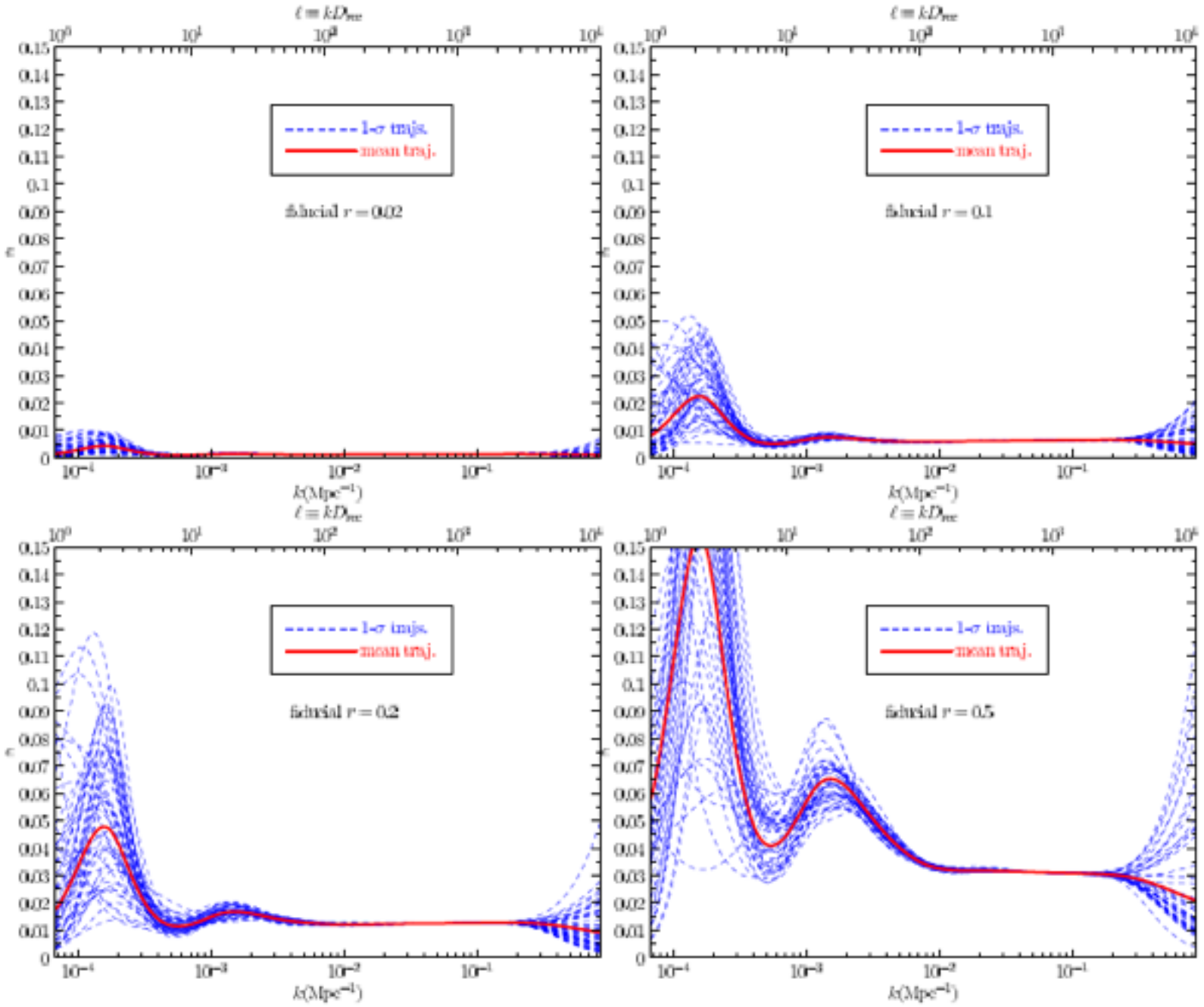
PS: running of P_s is a bad fit



Bond, Braden, Huang, Frolov, Vaudrevange 2014



cf. r=0.2+-0.02 Spider forecast no fgnd, better if r lower cf. r=0.01+-0.003 AdvACTpol forecast w/ fgnds

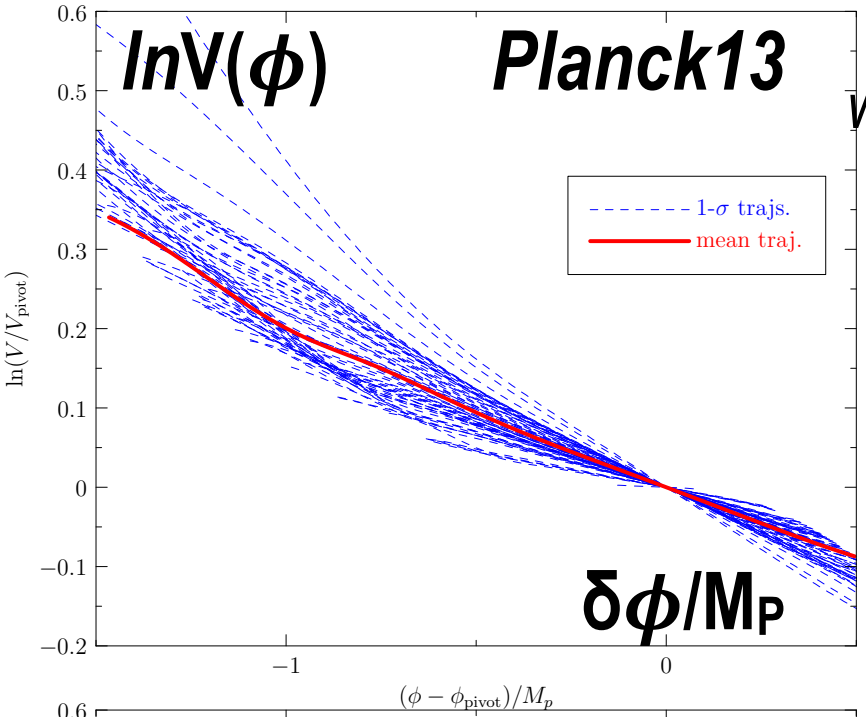


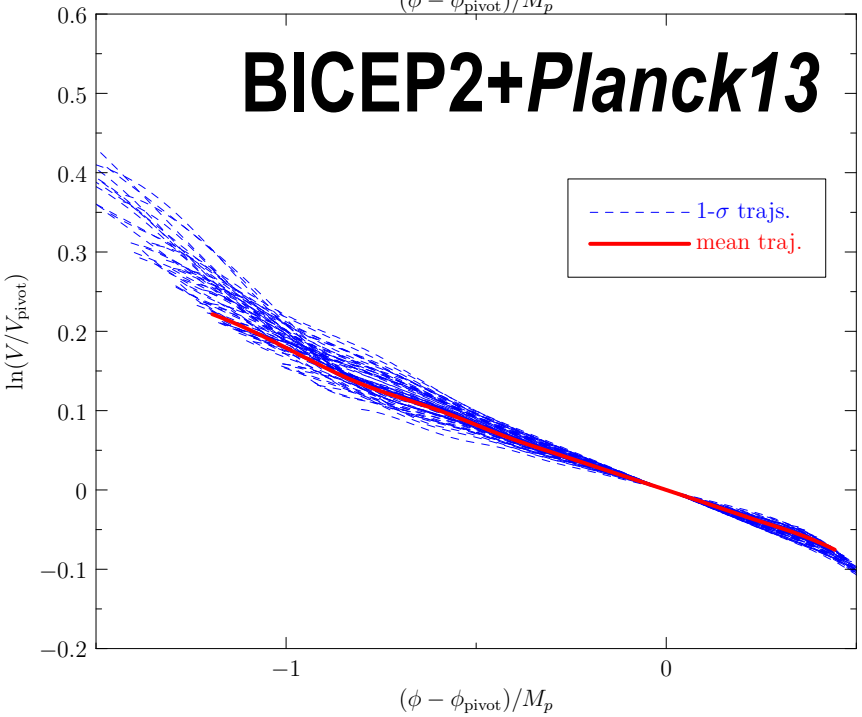
cf. r=0.2+-0.02 Spider forecast no fgnd, better if r lower cf. r=0.01+-0.003 AdvACTpol forecast w/ fgnds

what is the inflaton's V(ϕ)?

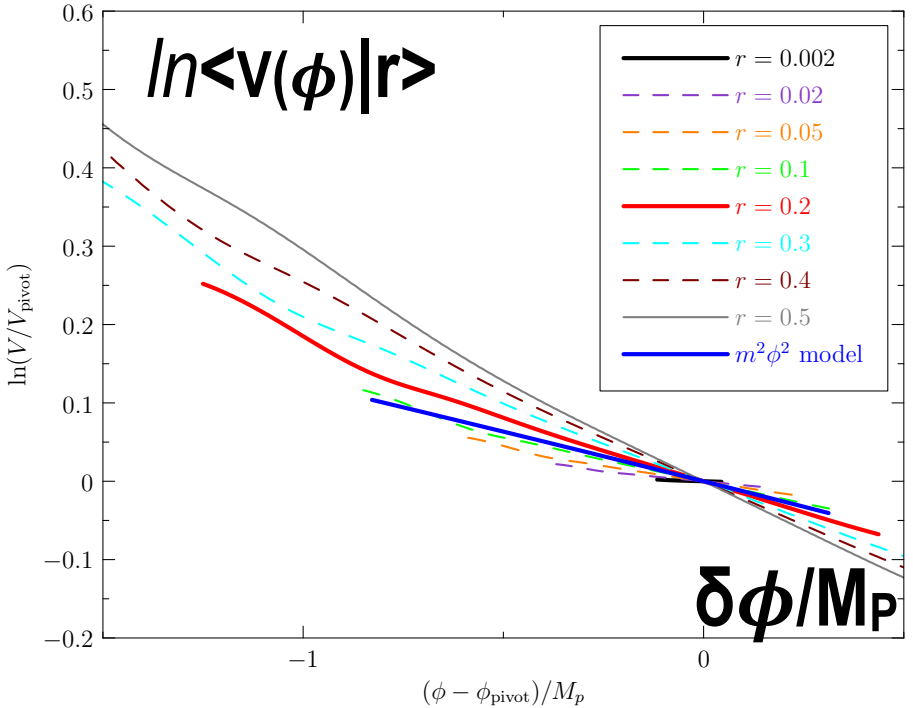
we **reconstruct** *the* ***scalar curvature power*** *(isotropic strain) & the early universe* ***acceleration histories*** *as well*

detecting r ~ 0.2 => V(ϕ) shape cannot be too flat over the observable range

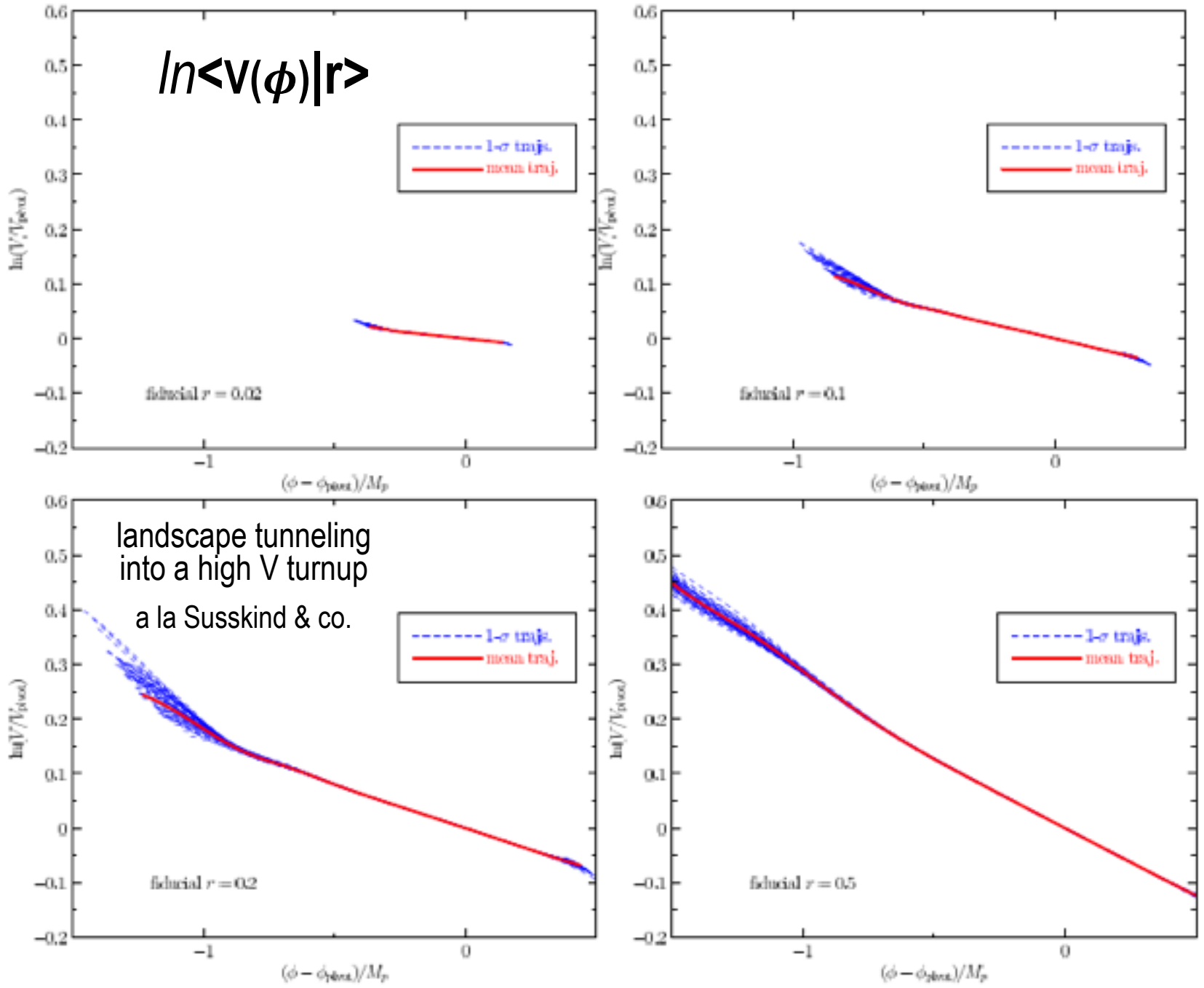




Reconstructed mean potential (without BICEP constraint)



simplest is V(ϕ) ~ $m^2\phi^2$



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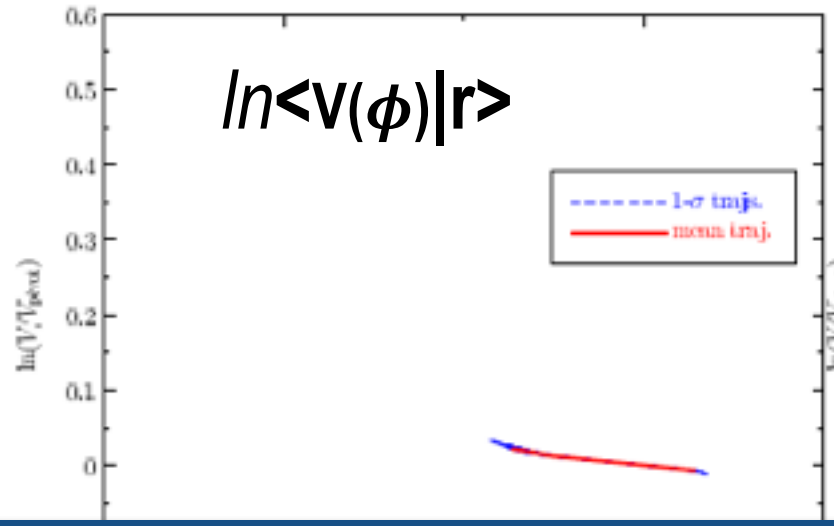
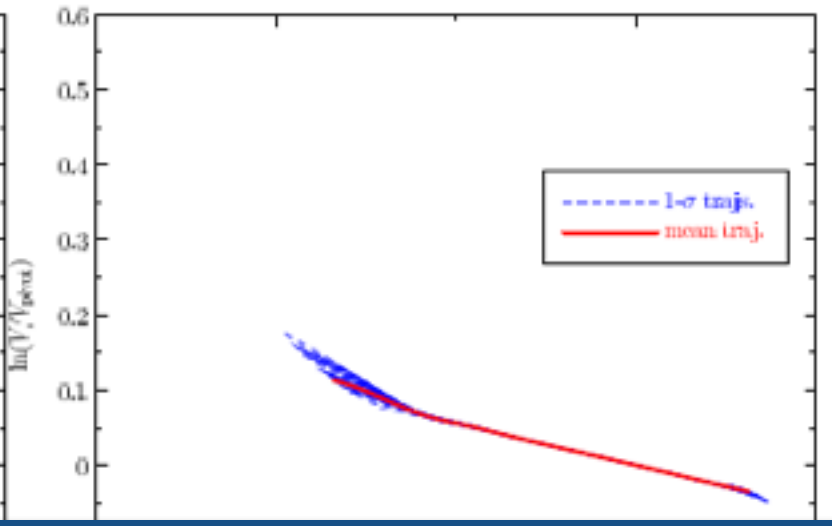
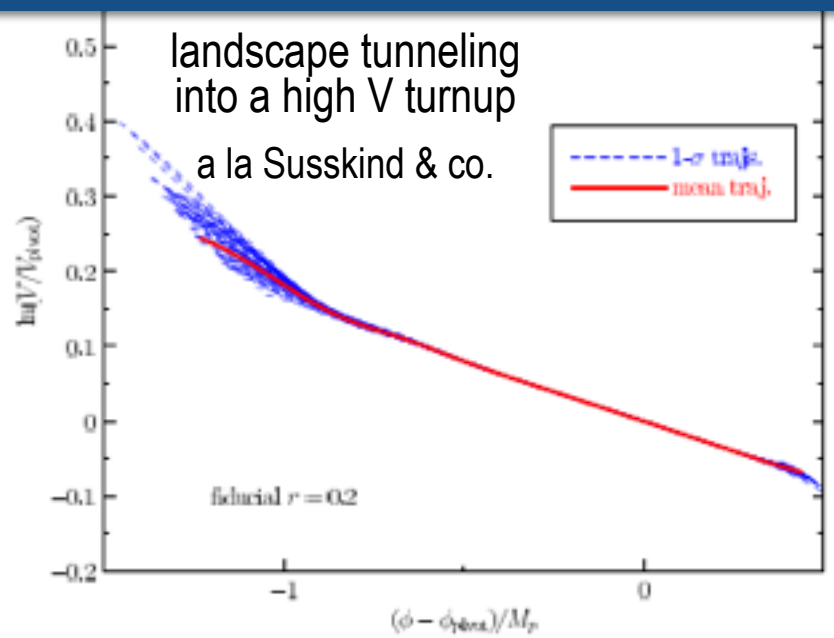
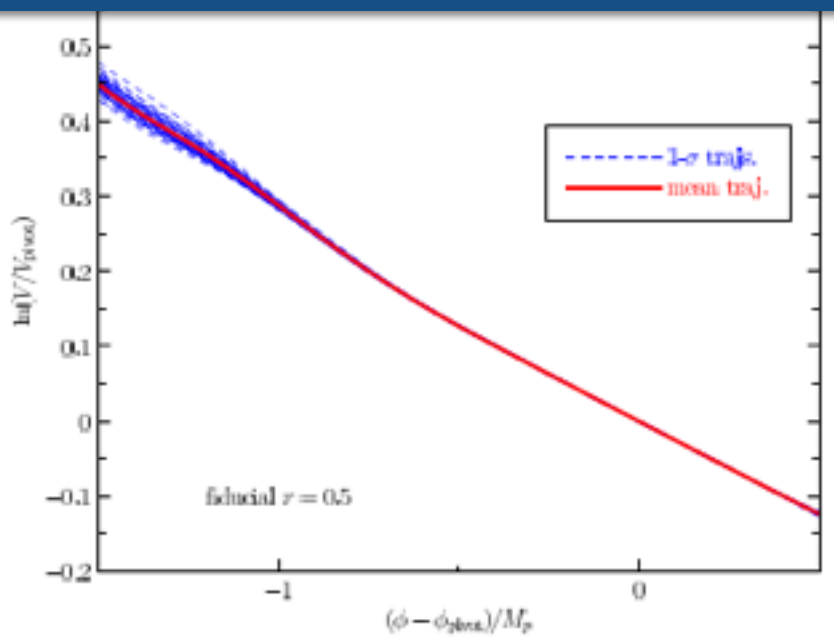




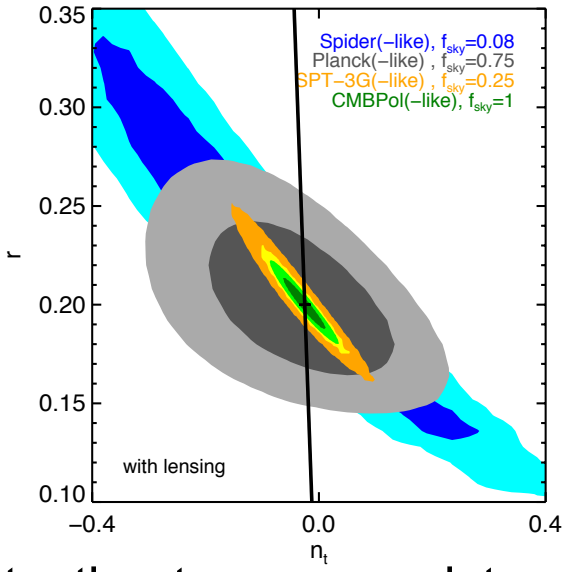
heating region is far off => many ways to extrapolate => ???
B2FH14: preheat with Einstein + canonical kinetic + V(ϕ) +G(ϕ)Vint(χ,…) sims
e.g., Higgs inflation with M_P^2 (ϕ) R/2 or K(ϕ) dϕ^2 /2 difficult with high r, but sims





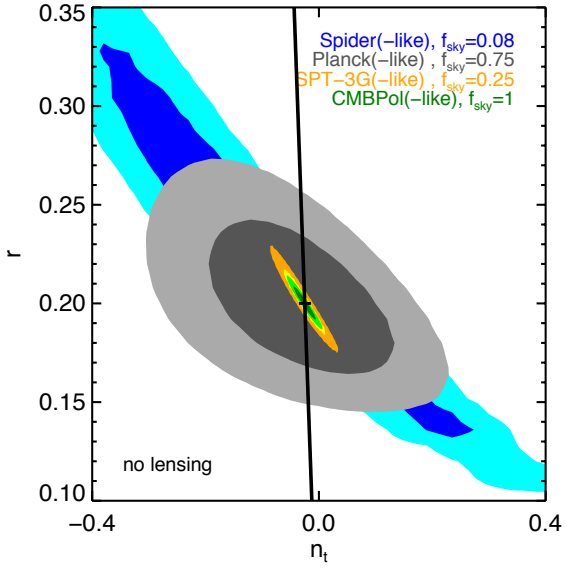
cf. r=0.2+-0.02 Spider forecast no fgnd, better if r lower cf. r=0.01+-0.003 AdvACTpol forecast w/ fgnds

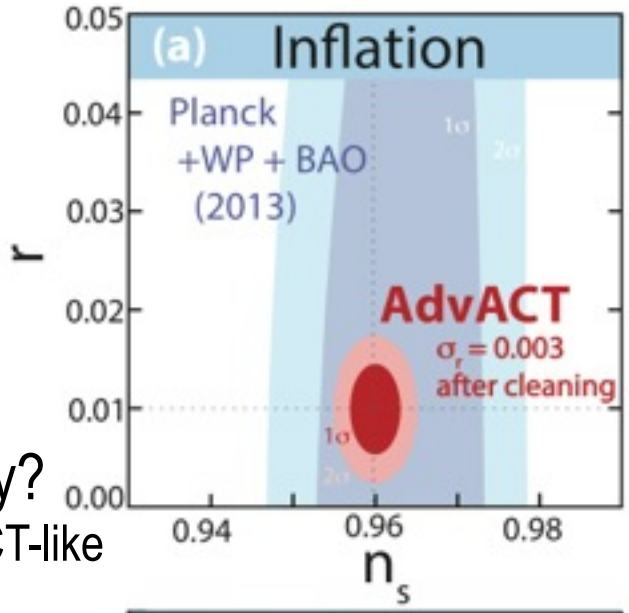
AdvACT: Cosmological Forecasts & Planck2.5, Spider, future SPT3g, CMBpol

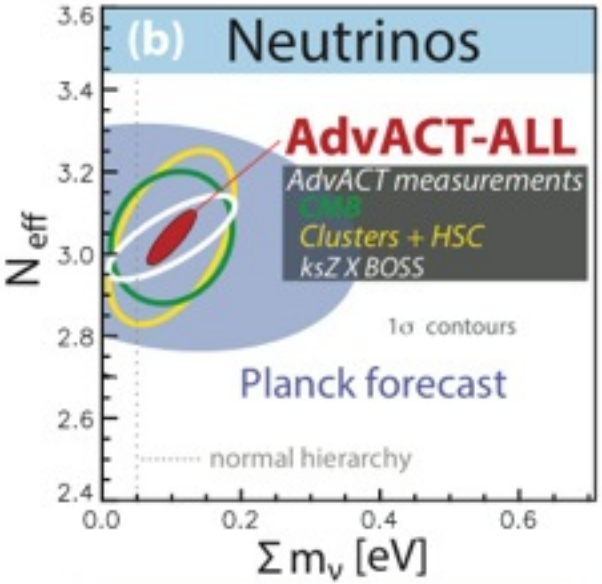


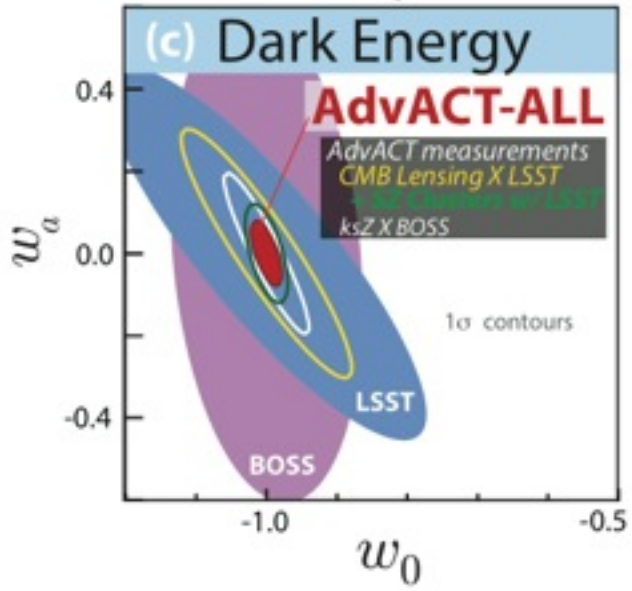
testing tensor consistency?

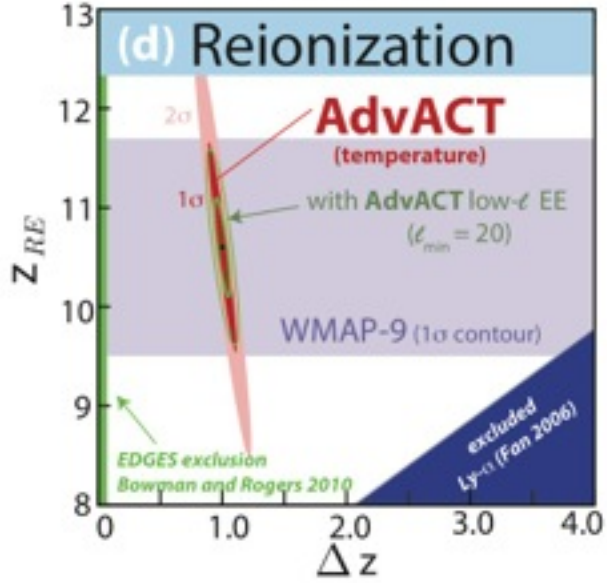
better f_{sky}=25% for spt3g/AdvACT-like than current 6% goal for spt3g











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

Bond, Frolov, Huang, Braden 14a,b,c,…

a ***Map*** *is an* ***ensemble = mean-map + fluctuation-maps,*** *e.g.,*

linear: $\langle T\rangle(\text{pixel}) + C^{TT}(\text{pix, pix}')^{1/2}\ GRD_{\text{pix}'}$, ***quadratic:*** $\langle C^{TT}_L\rangle + \langle \Delta C^{TT}_L\, \Delta C^{TT}_{L'}\rangle\ GRD_{L'}$,

Primordial Curvature/phonon-maps $\zeta = ln\ a_{com}$ from the CMB

Linear: ***Wiener-filtered ζ_b all-sky maps & stacking maps on (oriented) Peaks***

Quadratic: ***$P_\zeta(k)$ Power Spectra maps, Acceleration History $\epsilon(ln\ a)$ maps & Inflaton Potential $V_{eff}(\phi)$ maps if r-measurements (BICEP2, Planck, Spider, AdvACT,..)***

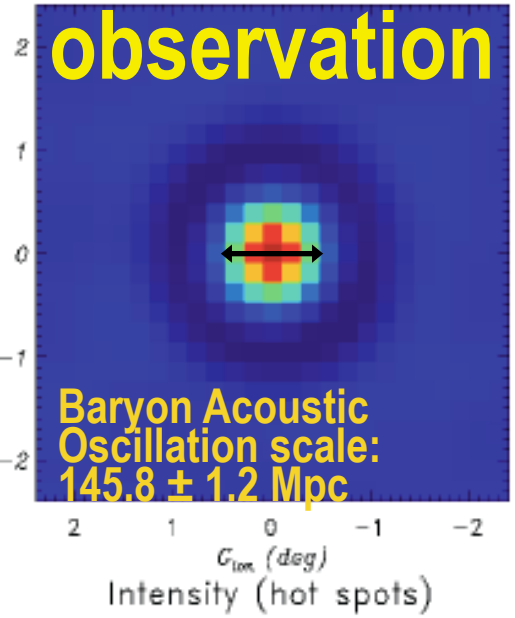
Implications for **post-Inflation *heating* *given r-measurements?***

Implications for ***anomalies: caustic trajectories*** **& *non-Gaussian Intermittency***

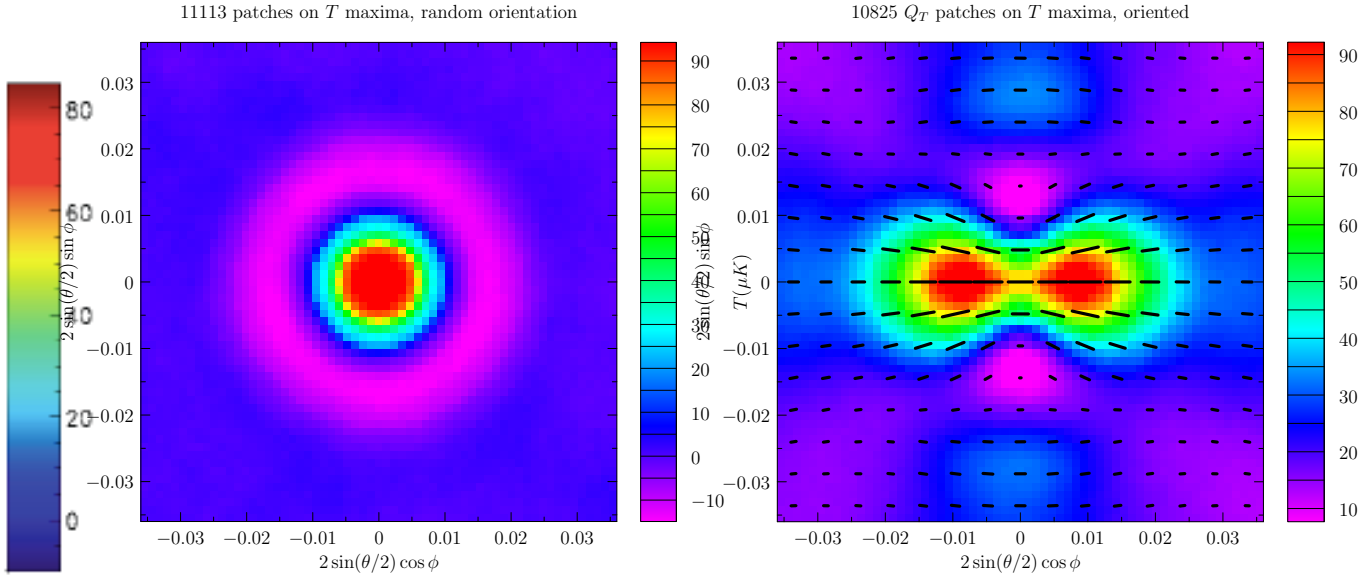
decompose T into Q_T U_T E_T E_T P_T ψ_T akin to Q U E P ψ, with enhanced peak-stacking correlations, oriented stacks

CMB Polarization Q,U,E,B & Temperature Stacking maps on (oriented) T-Peaks

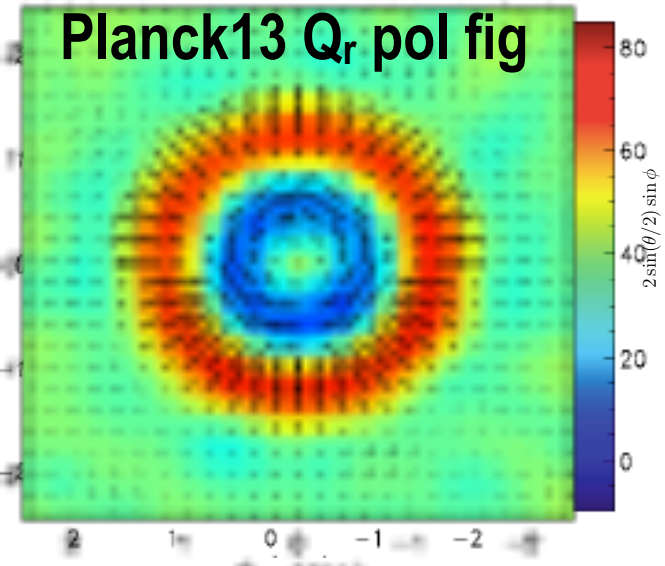
Planck13 T fig



Planck2013 data T Q_T stacked on oriented temperature Peaks



Planck13 Q_r pol fig



sims of polarization rotated & stacked on oriented temperature Peaks