

CMB@53

Unveiling Fundamental Physics from the Cosmic First Light: from COMPLEXITY to SIMPLICITY to COMPLEXITY to SIMPLICITY, the Universe at Large

the BOUNDed flow of information
the BOUNDless thought of man

How the Planck satellite helped decode
the role of Planck's quantum in the
emergence of our Universe from the Planck-mass era

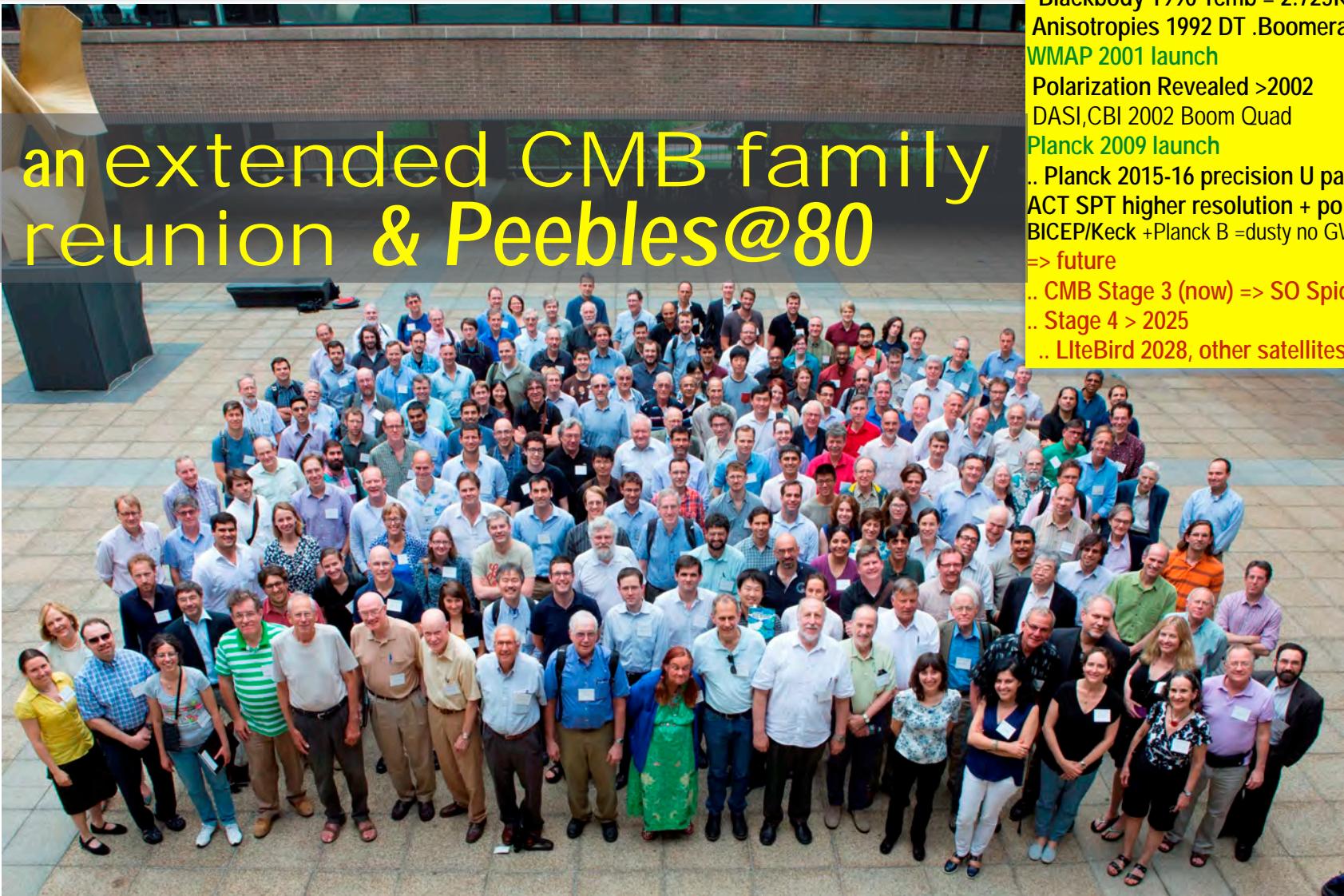
CMB past =>
CMB present
7+ numbers
3 densities,
2+1 early-
Universe
inflation

CMB+LSS future
S_Mc -> **B_SM_C**

*Beyond the
Standard Model
of Cosmology*

Dick Bond **CITA** the summary talk

CMB@50 THEN & NOW & THEN a celebration Princeton June 2015



CMB prediction
Alpher, Gamow Herman 1950s Tcmb ~5K
CMB Discovery
Penzias & Wilson 65
CMB dipole 70s DT /T~ V/c
Delta T over Tea 87 @CITA theory+expt
COBE 1989 launch
Blackbody 1990 Tcmb = 2.725K
Anisotropies 1992 DT .Boomerang 98
WMAP 2001 launch
Polarization Revealed >2002
DASI,CBI 2002 Boom Quad
Planck 2009 launch
.. Planck 2015-16 precision U parameters
ACT SPT higher resolution + polarization
BICEP/Keck +Planck B =dusty no GW Spider
=> future
.. CMB Stage 3 (now) => SO Spider2
.. Stage 4 > 2025
.. LiteBird 2028, other satellites ??

CMB@53:

on cosmic **Photons** cosmic microwave background radiation 1st light 412 /cm^3 0.005%

on cosmic **Baryons** Ordinary Matter air $\sim \text{amu /nm}^3$ O₂ N ; U 4.9% H,He $\sim 0.055 \text{ amu /cm}^3$

on cosmic **Dark Matter** $\sim \text{amu /m}^3$ $26.6 \pm 0.7\%$ compressed in MilkyWay $\sim 0.3 \text{ amu /cm}^3$; for LHC@CERN-type relics ~ 1 every 10 cm *or axions or ? e.g., ultra-low axions h_Planck/m quantum diffusion*

on cosmic **Dark Energy** \sim vacuum potential density $\sim 3 \text{ amu /m}^3$ $68.5 \pm 0.7\%$ late-inflaton KE/PE?

on cosmic **Neutrinos** number density \sim cosmic photons Energy fraction $> 0.47\%$ \sim stars

on cosmic **Phonons** \sim isotropic **Strain** Deformations *h_Planck .. M_Planck*

on cosmic **Inflatons** - source the phonons *h_Planck .. M_Planck*

on cosmic **Gravitons** anisotropic **Strain** (*Transverse Traceless*) \ll photons / neutrinos *h_Planck*

on cosmic **Isocons** degrees of freedom transverse to the inflaton on the potential surface *h_Planck*

SMpp = Standard Model of particle physics electroweak + strong interactions

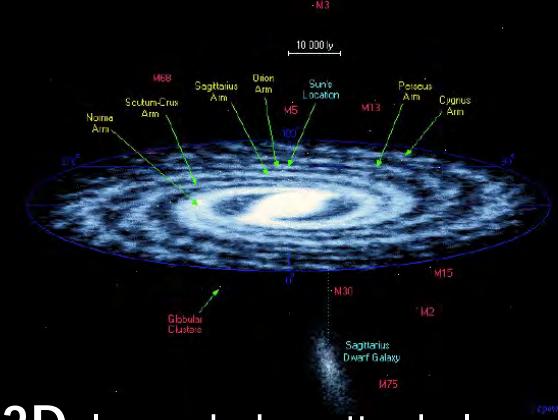
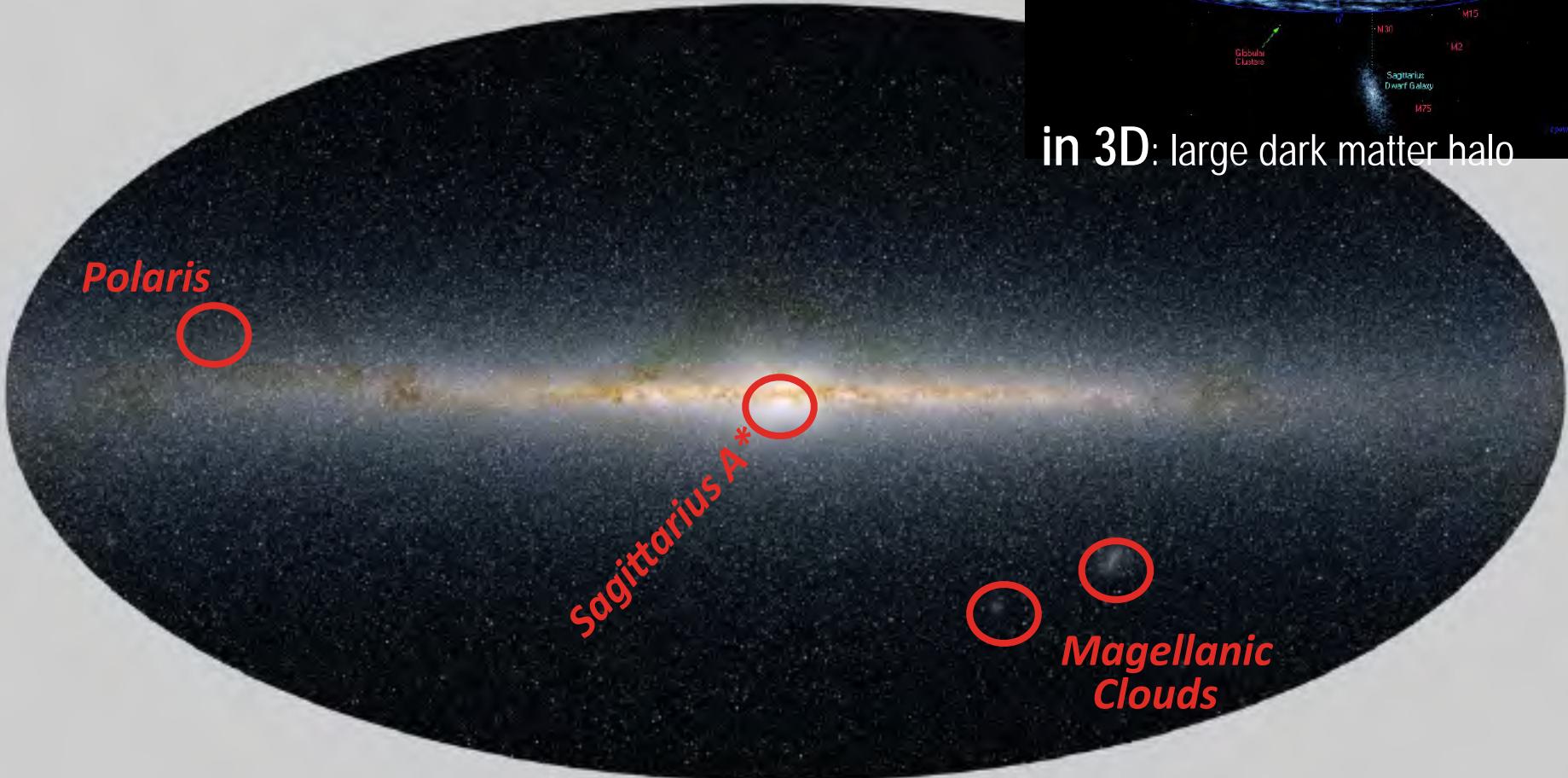
=> **BSMpp** = Beyond the **SMpp** neutrino masses, Dark Matter, Dark Energy, Gravity, SUSY ...

SMc = Standard Model of cosmology tilted Gaussian LCDM model, B+DM+DE+photons+neutrinos

=> **BSM**c = Beyond the **SMc** neutrino masses, dynamical coupled Dark Energy, modified Gravity ...



Milky Way in infra-red: half a billion stars, a disk galaxy

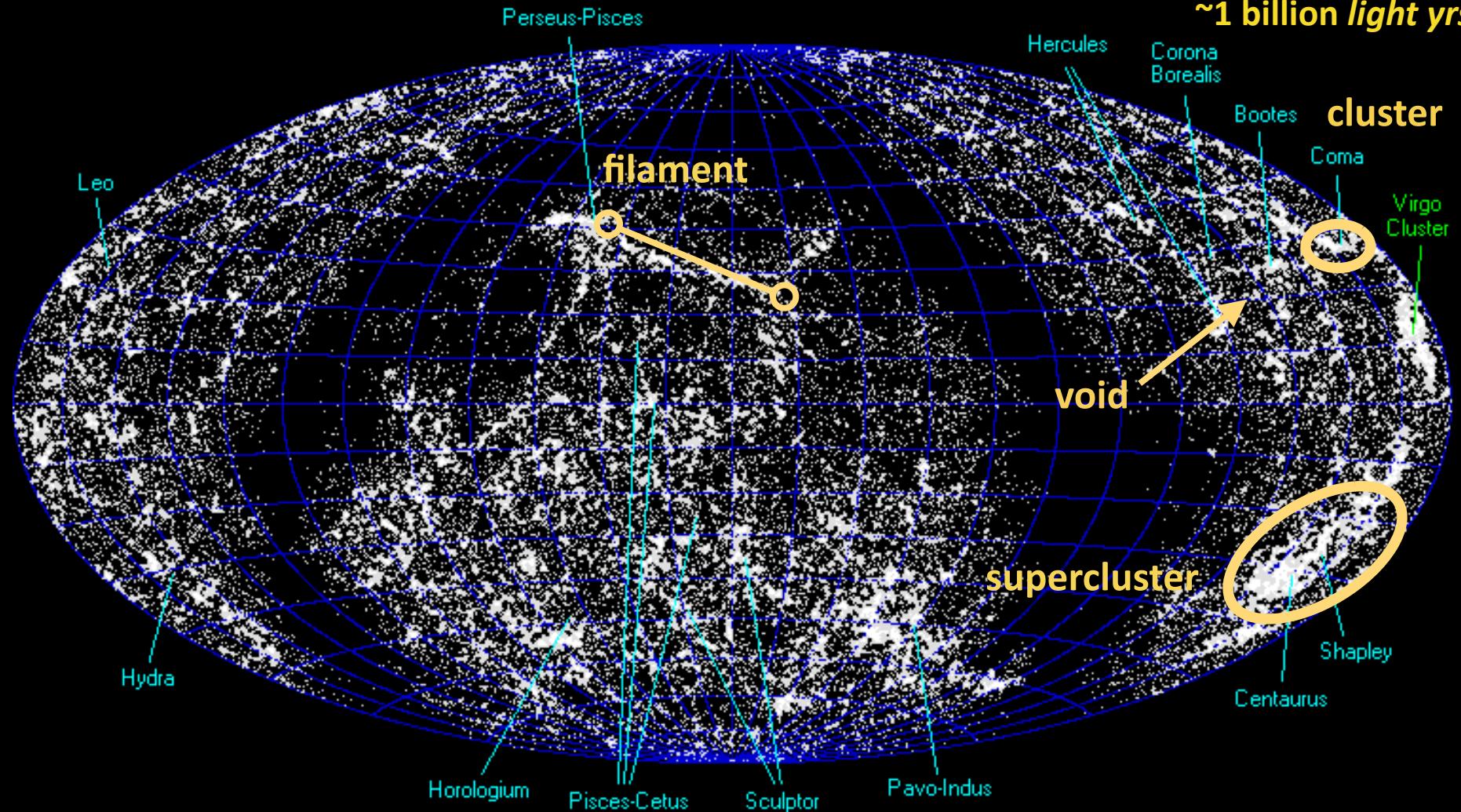


in 3D: large dark matter halo

Cosmic Web of 60,000 nearby galaxies: exhibits “local” COMPLEXITY

$$a \sim e^{-0.1} = 1/1.1$$

~1 billion *light yrs*



observational emergence of the web = ~80s tour de force, e.g., Coma + supercluster. voids
interconnected structures from a Gaussian random adiabatic field under gravitational instability



mean (isotropic) number of
e-foldings of scale $\equiv \langle \ln a \rangle$

a scale of the Universe

$\langle \ln a \rangle$	0
now = 1 when we observe the 1st light	7
then = 1/1100 when the 1st light was released from matter, billion X denser	1 ↓ 2
galaxies forming ~ 1/4	3
there were no galaxies when $a < 1/20$	21 ↓ 35
light nuclei	67
Dark Matter	67 ↓ 127
Heat: matter & radiation	quantum noise



$a_J^i(r,t)$ scale-tensor of the Universe

$$dX^i(r,t) = a_J^i(r,t) dr_{eq^J}$$

$$a_J^j \equiv \exp(\alpha)^{jj}$$

$$\alpha_{J^j} \equiv \langle \ln a \rangle \delta_{J^j} + \epsilon_{J^j}$$

ϵ =strain tensor

$$dV^i(r,t) = H_J^i(r,t) dX^i(r,t)$$

H_J^i =Hubble ie shear = $d\alpha_J^i / dt$
general relativity

isotropic strain & phonons

$$\zeta(x,t) = \int_{\text{field-path}} (dE + pdV)/3(E + pV) \\ = \text{Trace } \delta\alpha_j^i + \int_{\text{field-path}} d\ln \rho_c / 3(1+w)$$



combined entropy-like measure ζ =inflaton

= Sasaki-san δN

Earth under Strain:
earthquakes, seismic waves

$\boldsymbol{\epsilon}$ =Strain tensor

elastic deformation $dx^i = e_j^i dr_{eq}^j$ $e_j^i = a_j^i / \langle a \rangle$

anisotropic strain, shear waves $\boldsymbol{\epsilon}$ -Trace($\boldsymbol{\epsilon}$)/3
isotropic strain, sound Trace($\boldsymbol{\epsilon}$)

Universe under Strain:
space-quakes = gravity waves
scale-deformation a_j^i

anisotropic strain, gravity waves
isotropic strain, sound

linear: strain \propto tide
cosmic web story



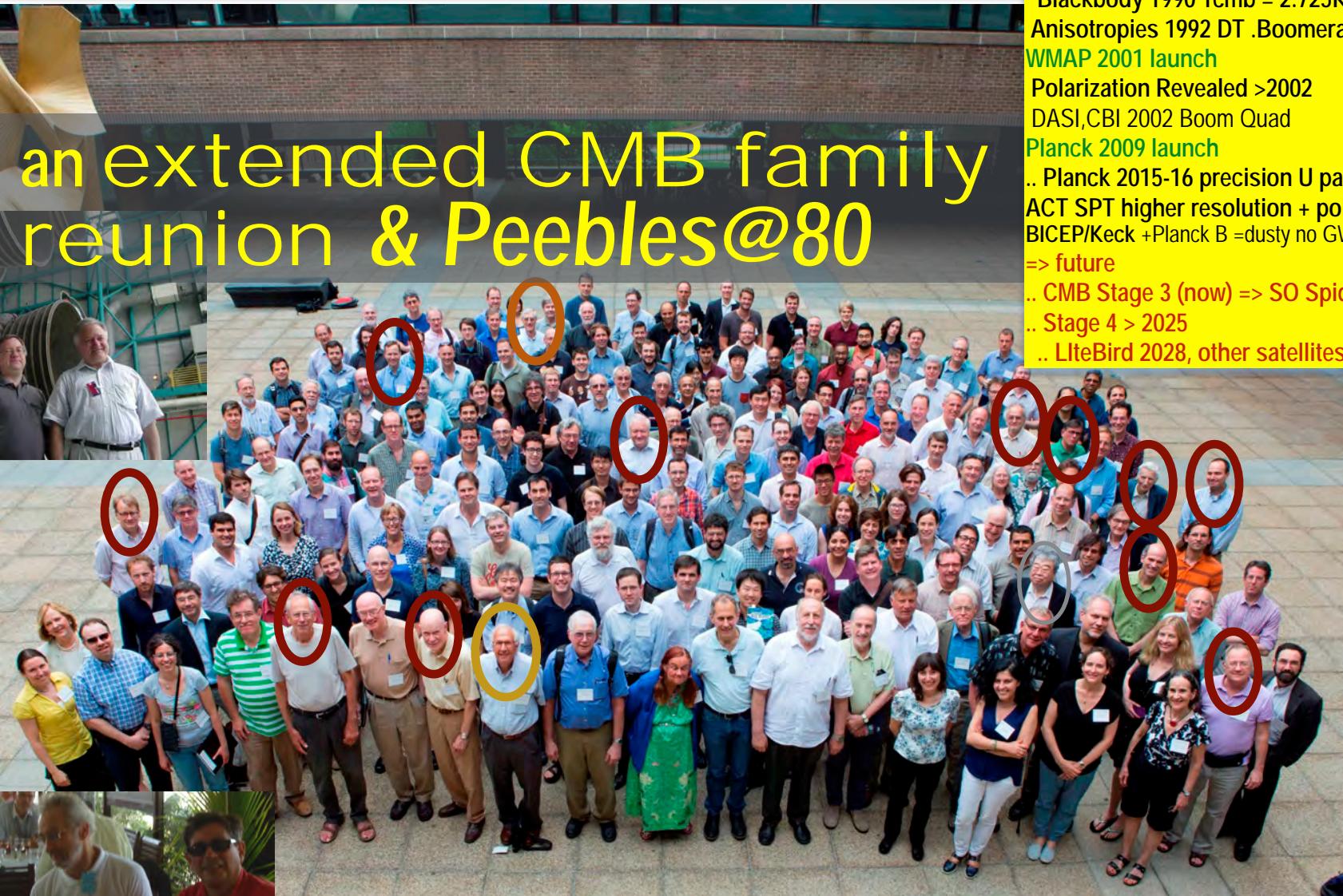
*light and gravity are entangled: wavelength stretches under space-strain: redshift
vacuum deformation under strain, condensate(t) + quantum fluctuations = inflation theory*

general relativity => \mathbf{a} = dreibein, triad, Lagrangian-space metric $\mathbf{g}=aa^\dagger$

the flow of time => 4D vierbein spacetime-strain $a_b{}^\beta$ $b,\beta=0,1,2,3$

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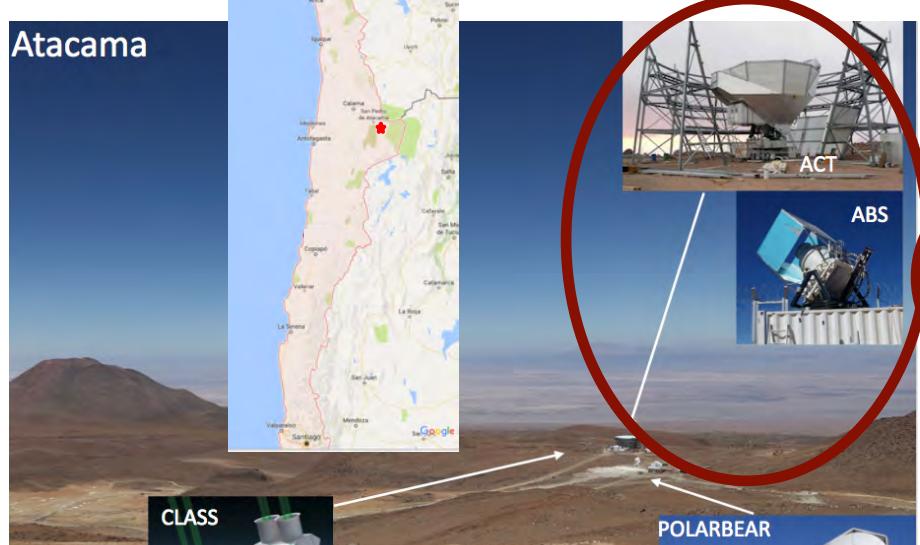
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.. LiteBird 2028, other satellites ??



Atacama



California+
South Africa
C-BASS 5 GHz

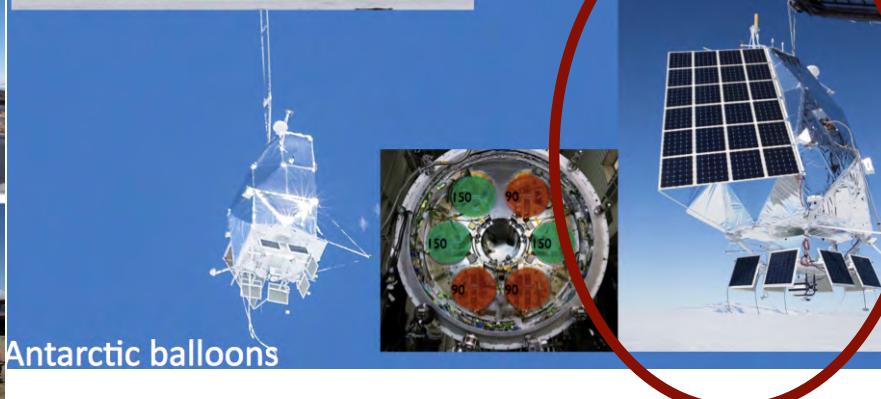
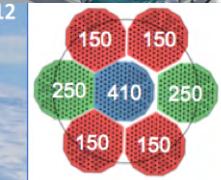


Tenerife (+South Africa?)
QUIJOTE 11, 13, 17, 19 GHz
(2015/16 - 30, 40 GHz)



California
B-Machine 40 GHz

South Pole



& futures S4, more ballooning, back into space



managing the CMB

on to SO -> CMB-S4 Advanced ACTPol

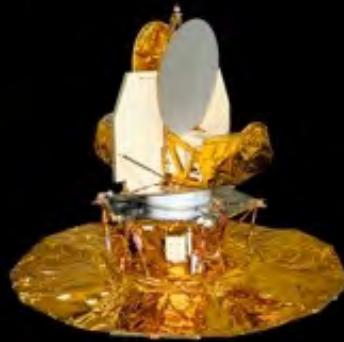


Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

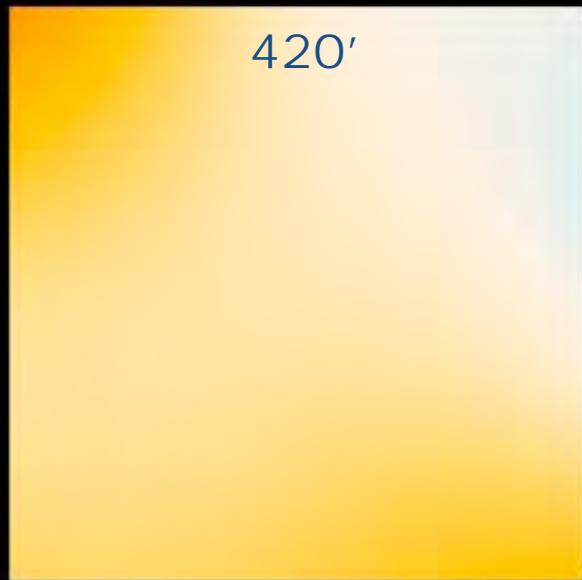
COBE 89 launch

WMAP 01 launch

Planck 09 launch

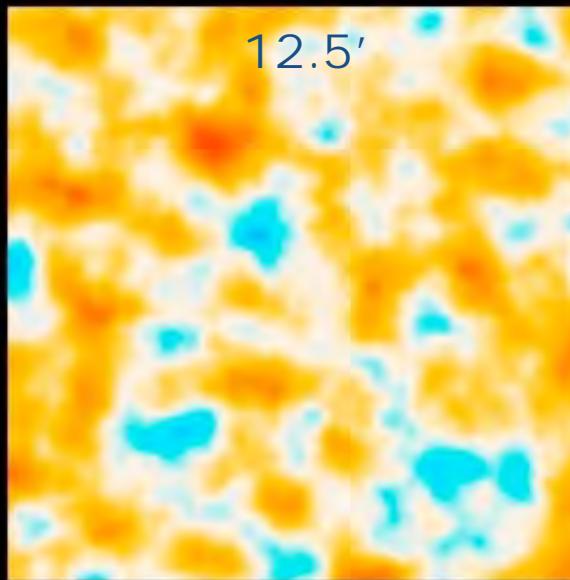


420'



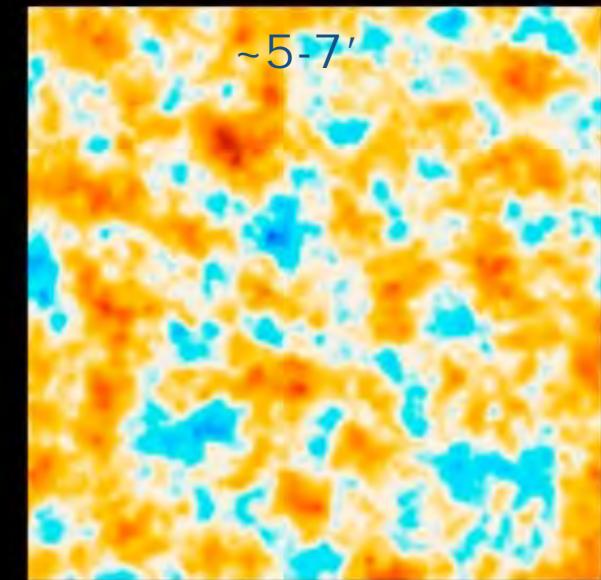
COBE

12.5'



WMAP

~5-7'



Planck

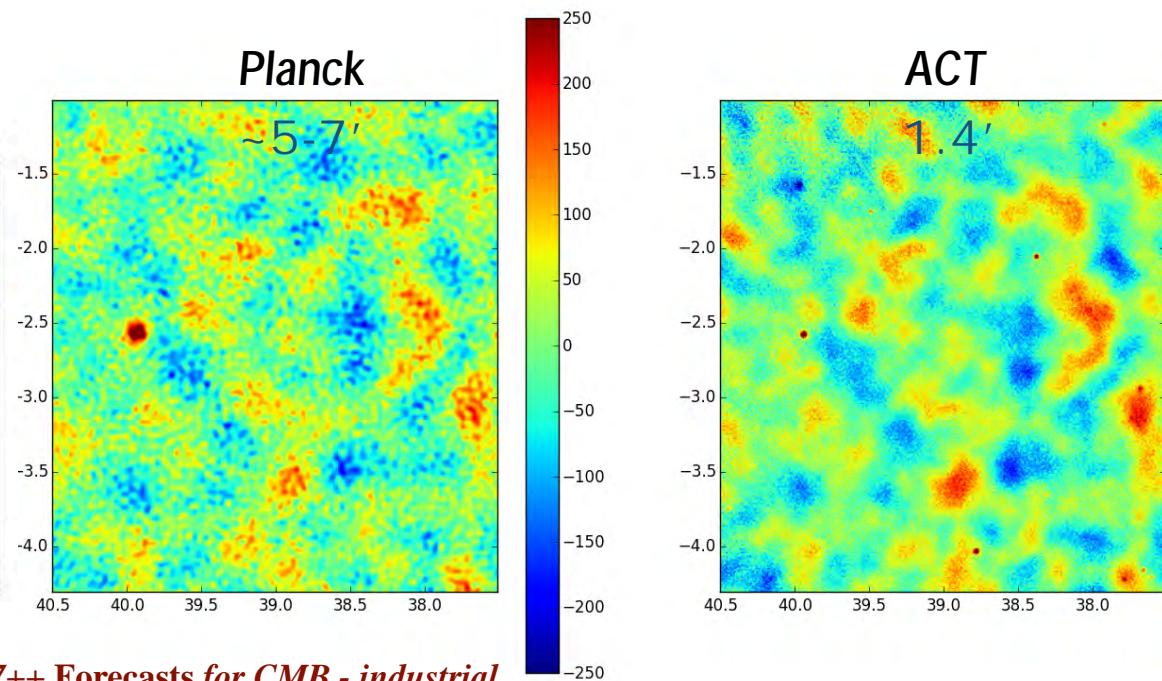
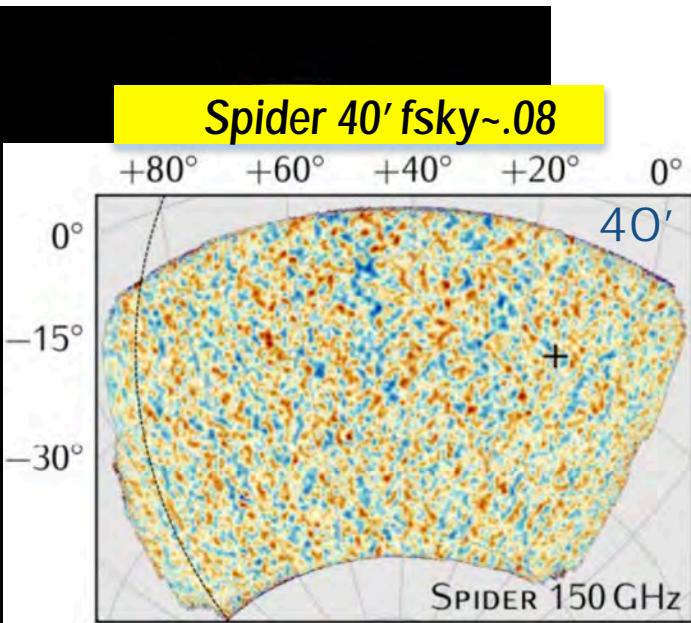
goal: high enough resolution to plumb all cosmic parameter information, but high L foregrounds, extragalactic sources => higher L expts ACT (1.4'), SPT (1') => SO/S4 (1')

Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch

WMAP 01 launch

Planck 09 launch



cf. Litebird res ~ 30'
fsky=1 & 12bands

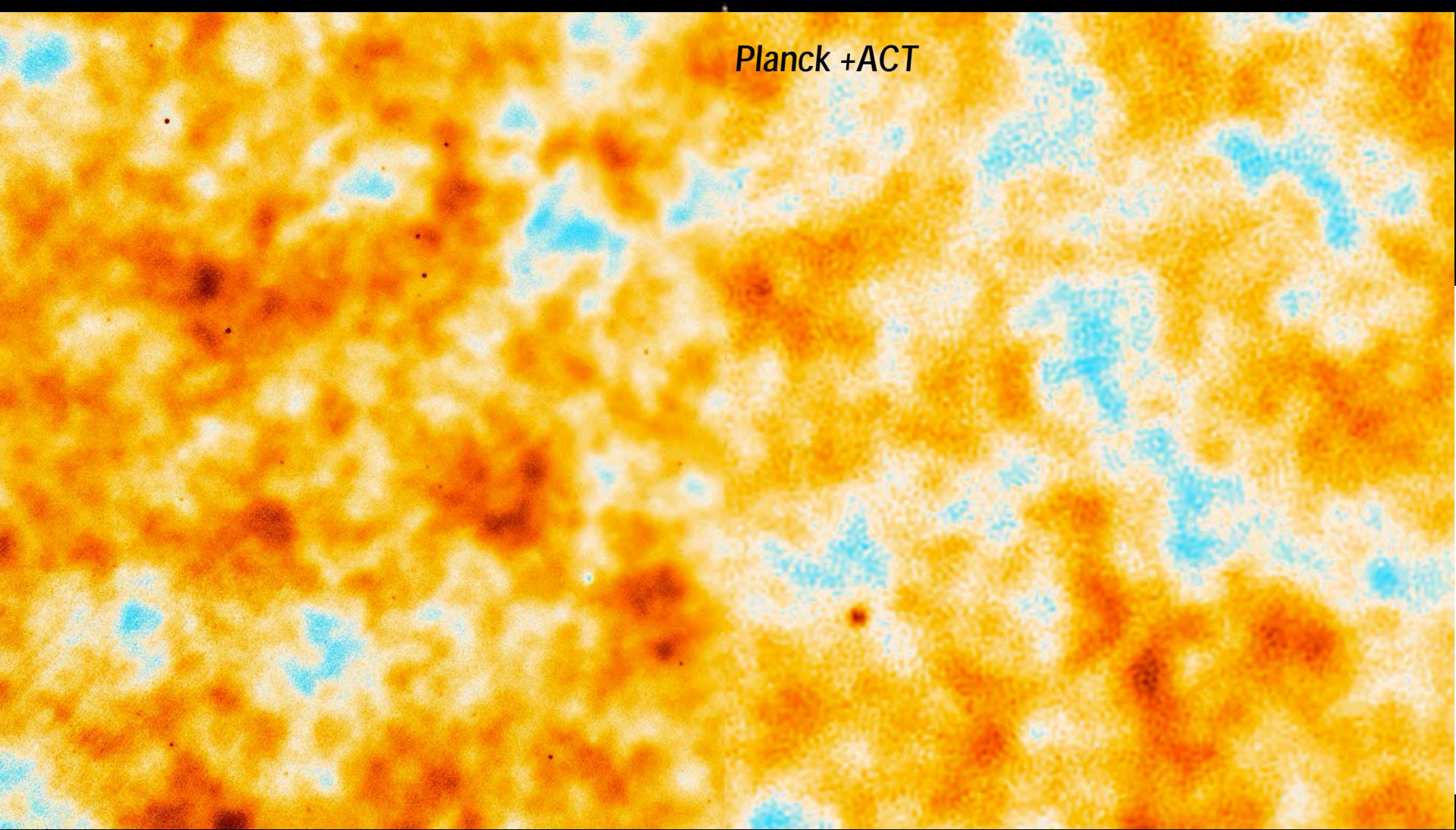
BET97++ Forecasts for CMB - industrial
2018 Simons Observatory Science Goals and Forecasts

2016 CMB Stage 4 Science Book: forecasts for S4+Planck => S4+Litebird



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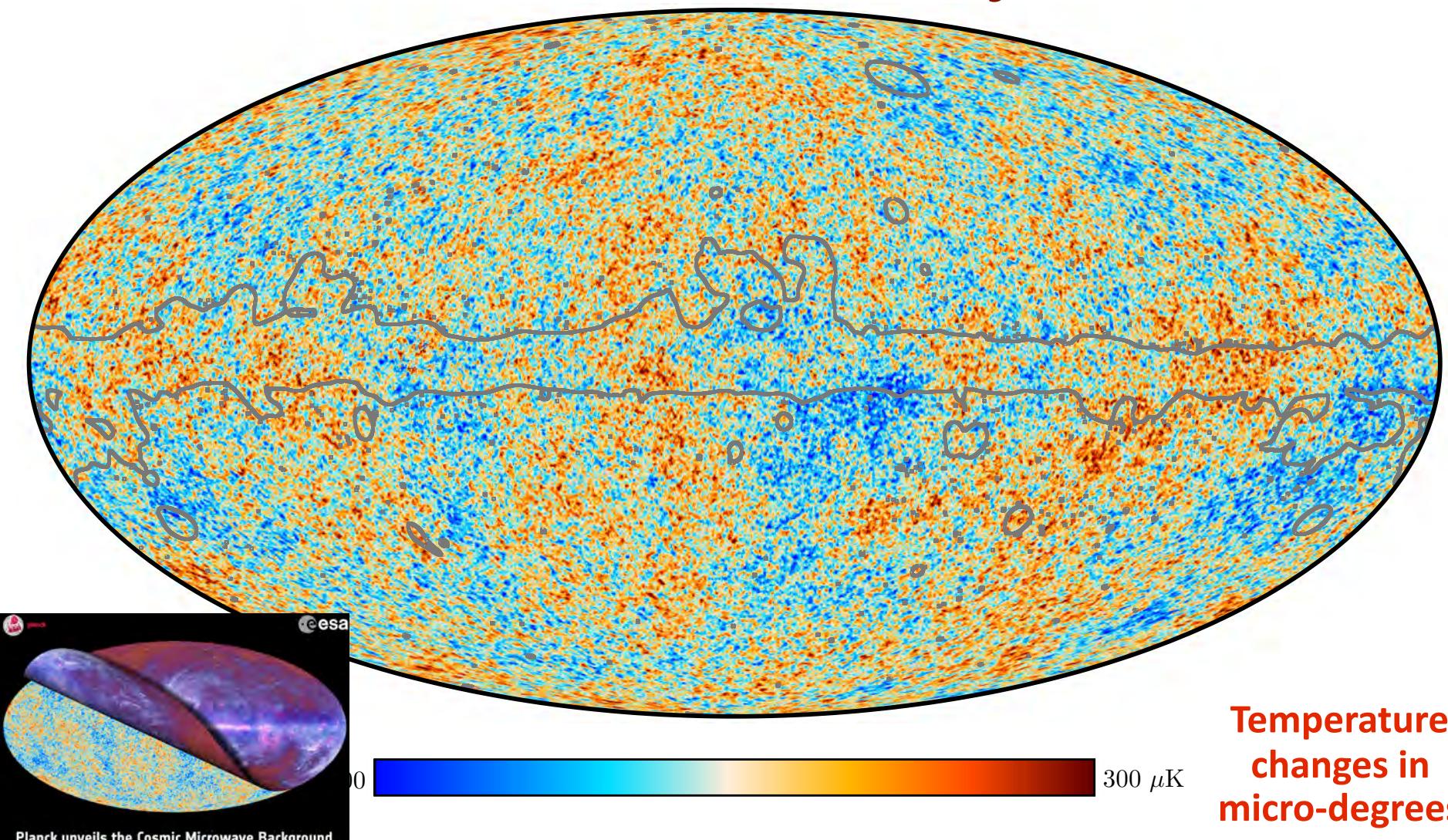


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Planck's primordial light unveiled, Mar 2013 => Feb 2015 => pre-2016 => july 2018+ final

reveals the **SIMPLICITY** of primordial cosmic structure

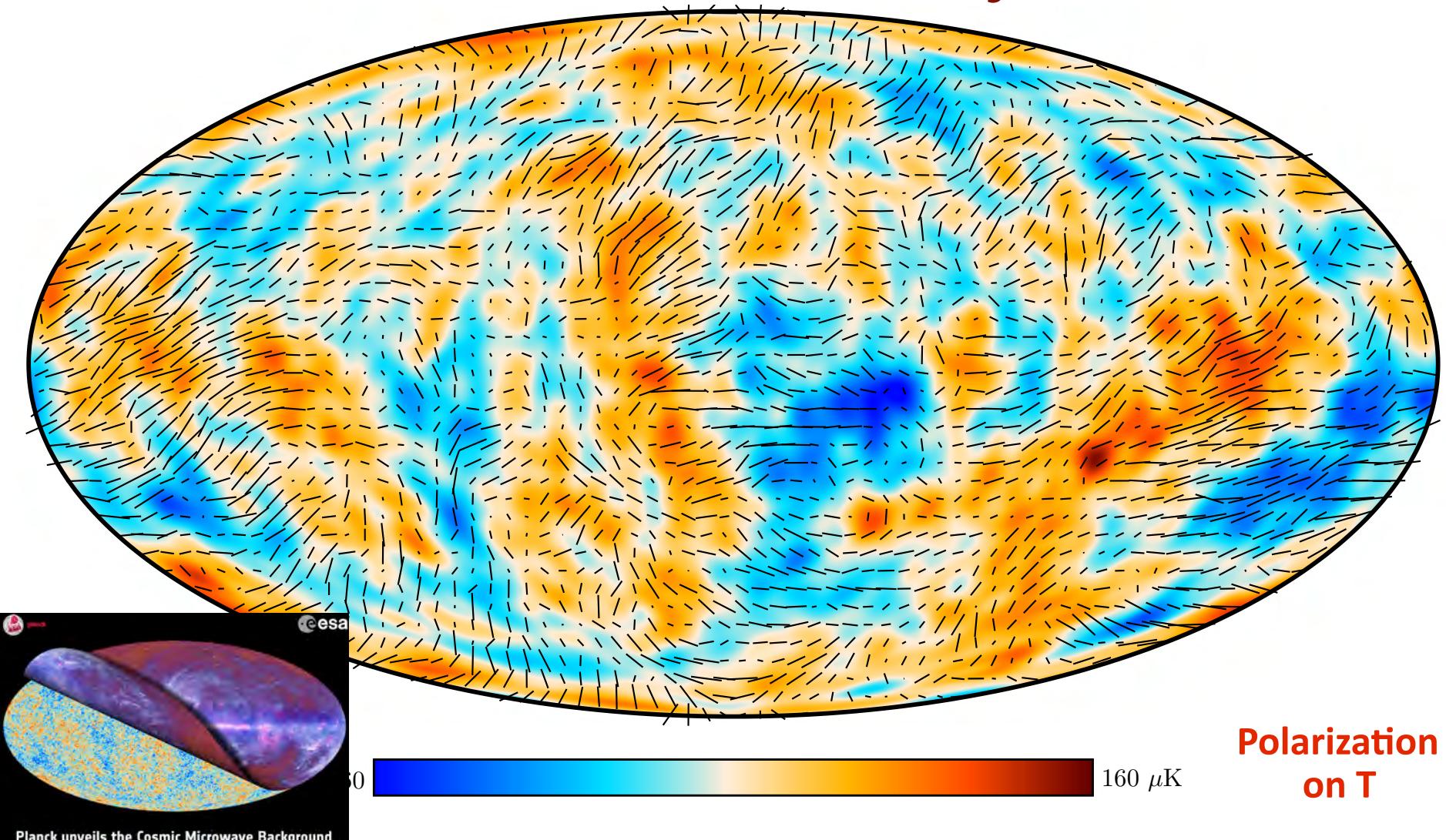
7+ numbers, 3 densities, 2+1 early-Universe inflation



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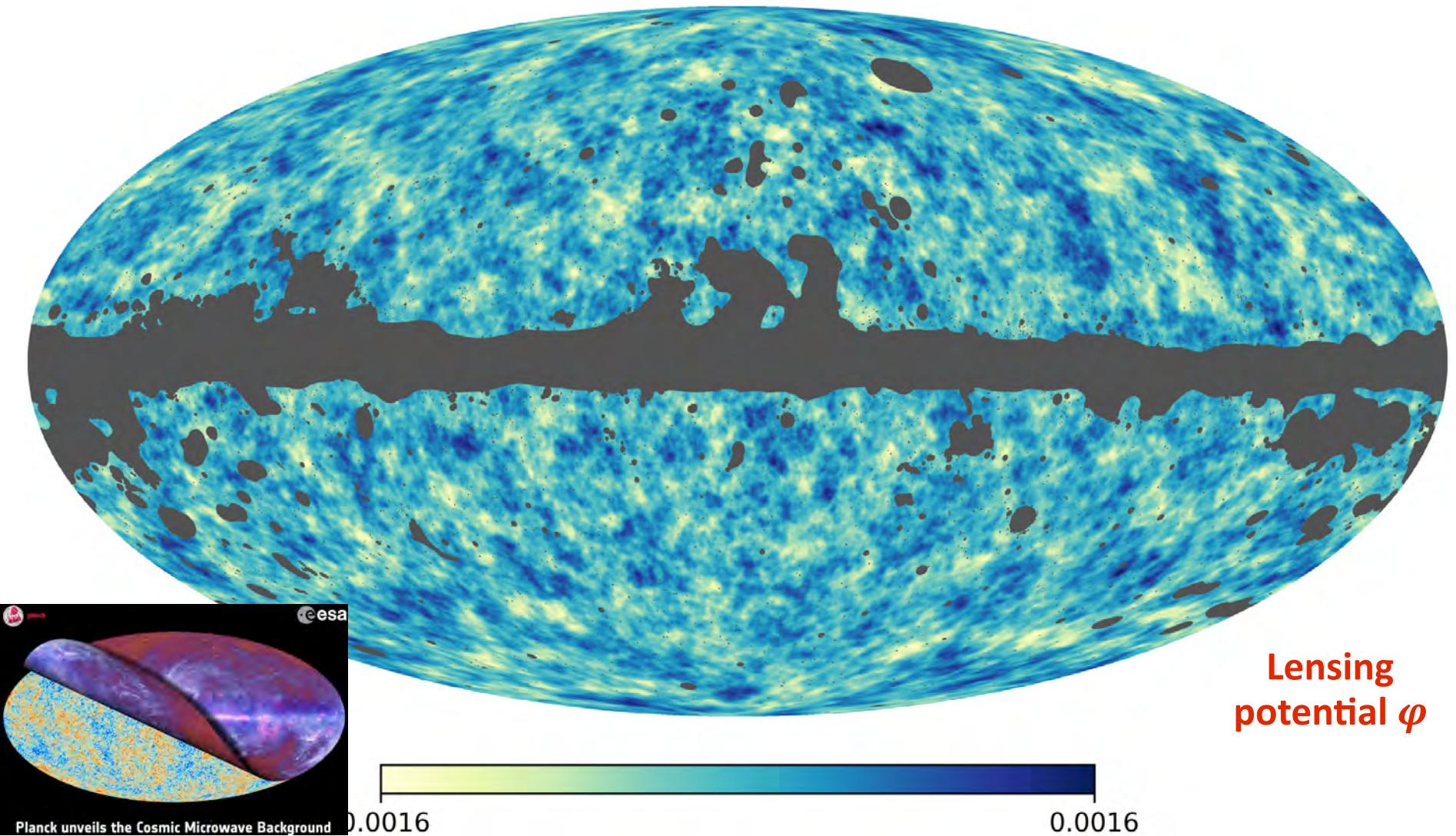
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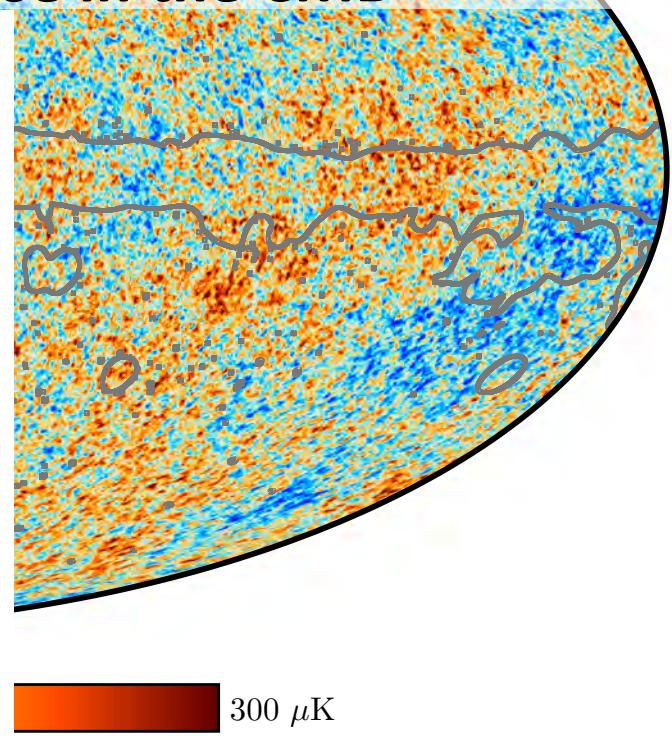
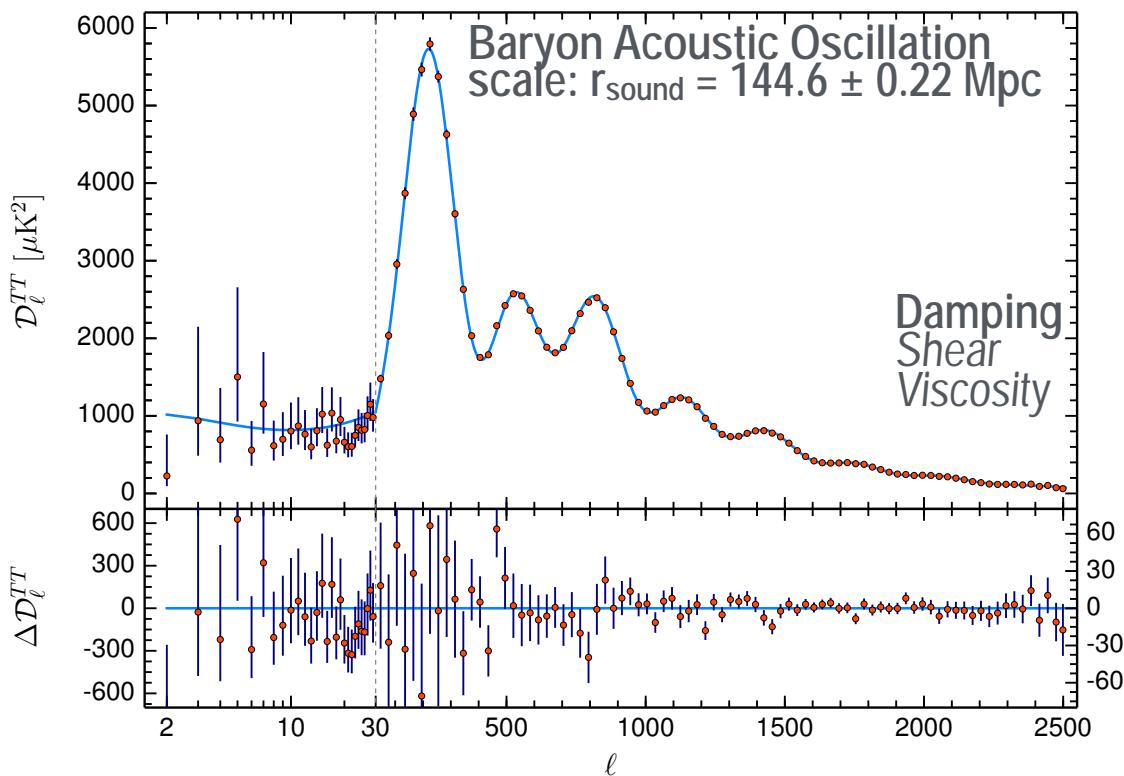
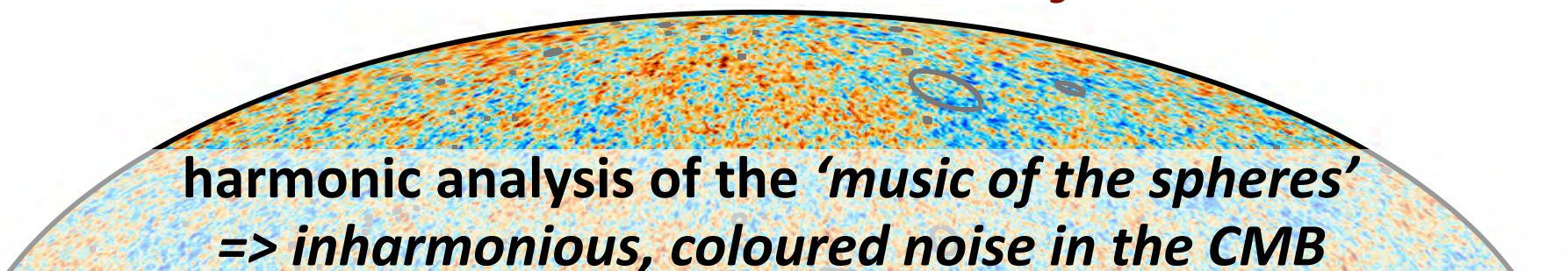
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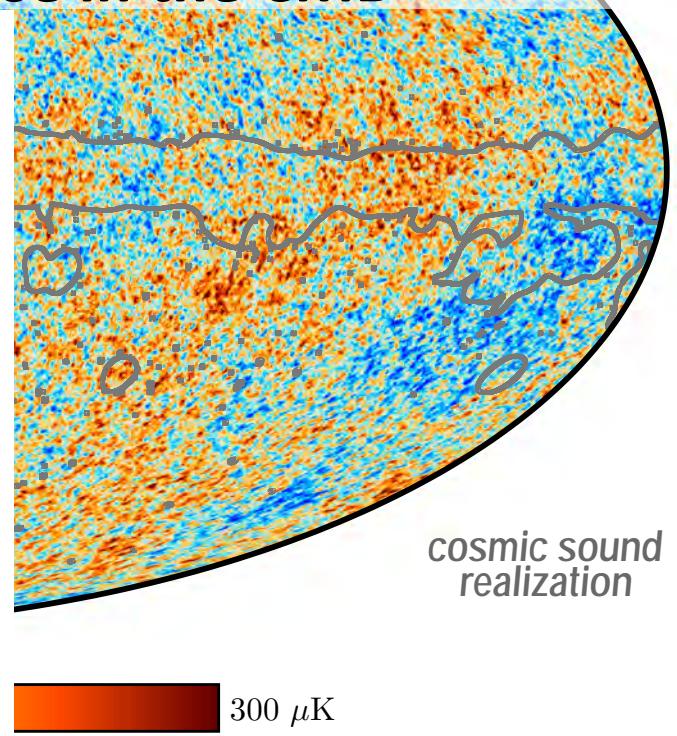
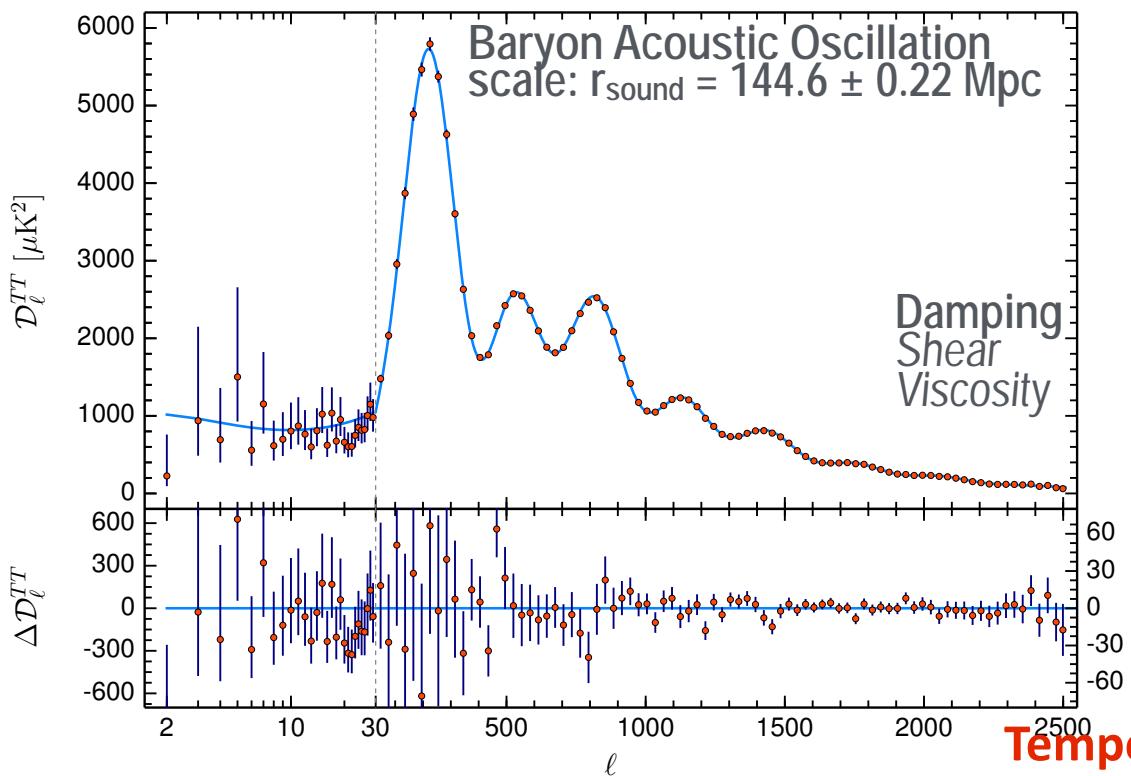
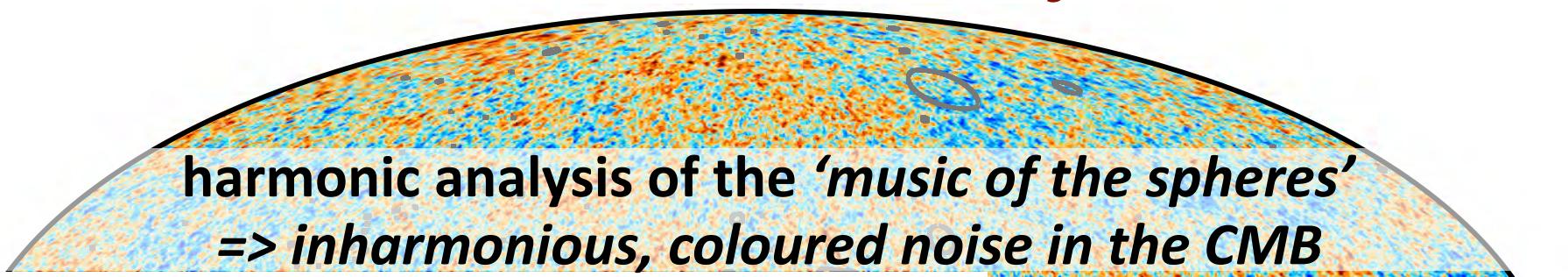
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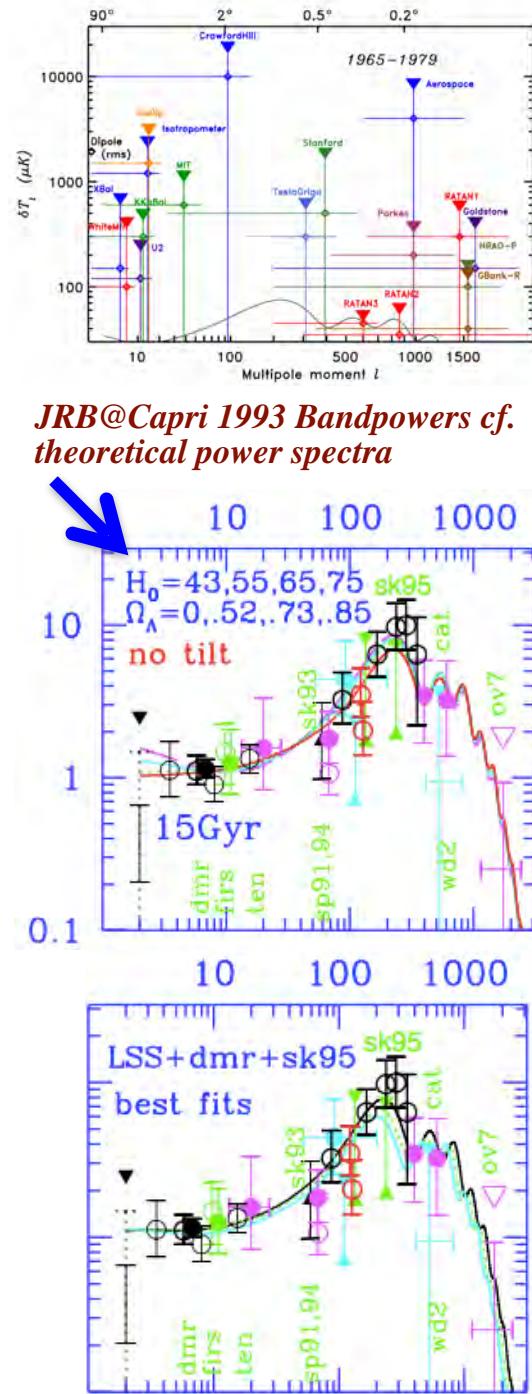
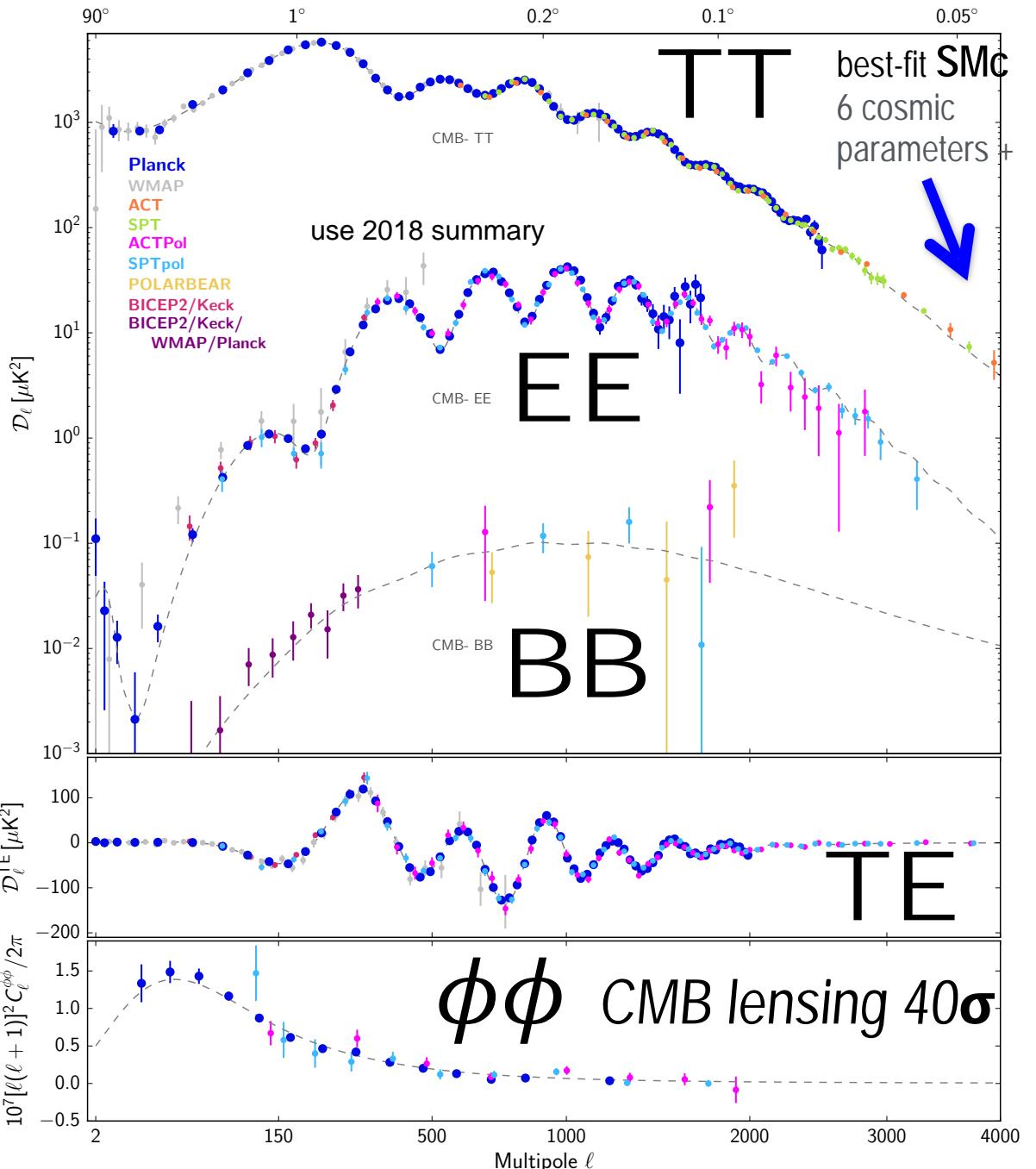
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Grand Unified CMB Spectra



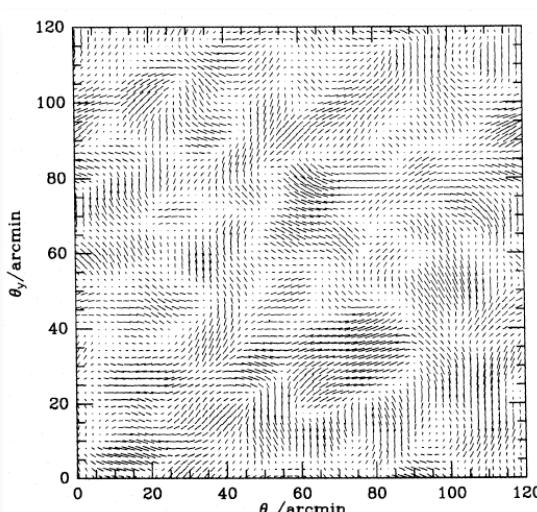
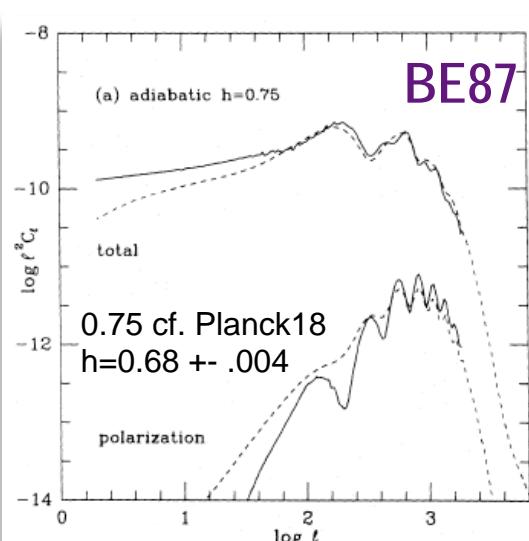
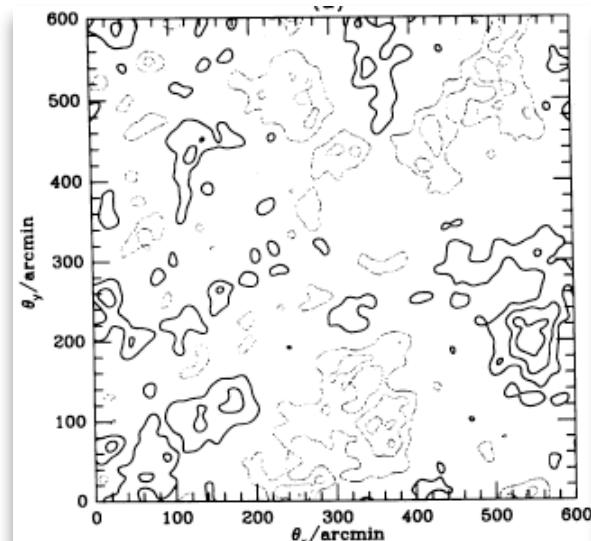
Delta T over Tea Toronto May 1987: first dedicated CMB conference. exptalists+theorists. primary+secondary $\Delta T/T$

organizers: Bond theory + Wilkinson experiment

Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle |\Delta T(LM)|^2 \rangle$ with target C_L shapes

A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^\circ - 10^\circ$ results, future experiments at $\sim 1^\circ$, COBE and other large angle analyses, theoretical $C(\theta)$'s and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



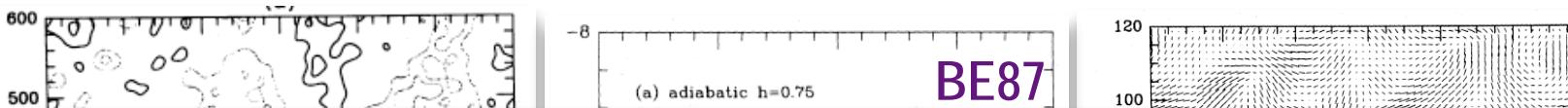
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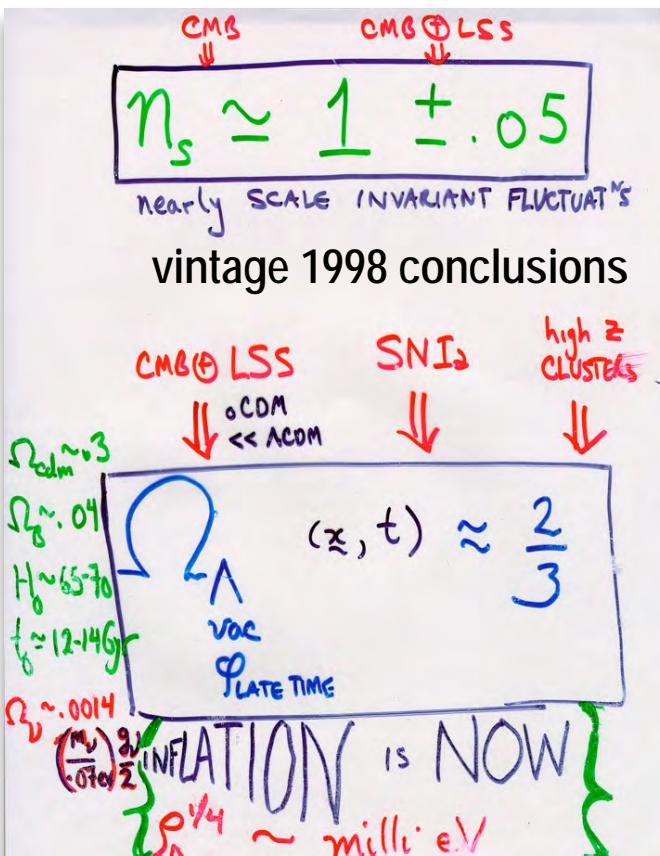
State of Inflation theory circa 87: 3 decades Nuffield conference was 1982

Chaotic +++ model space M_{Planck} phonons \rightarrow inflaton $\rightarrow \zeta = \ln a$
stochastic inflation $\delta\phi \sim h_{\text{Planck}} H$ aka quantum “zero-point” fluctuations
Starobinsky inflation, Higgs inflation ... running of $M_{\text{Planck}}(R, \phi)$

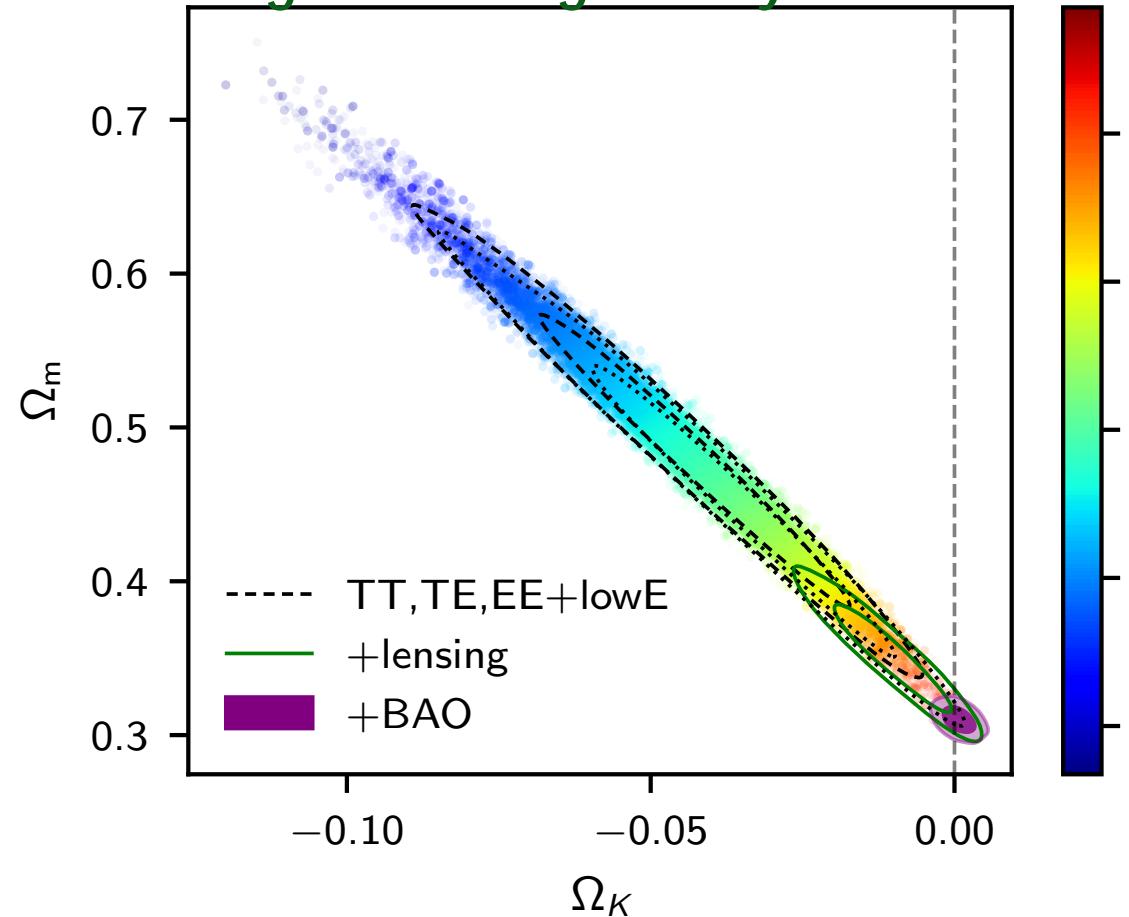
Gravity Waves isocurvature superstring-inspired, natural/axion later
nearly Gaussian but nonG was starting.
but also topological defects, strings, explosions, ...

inflation 1997/98

cf. inflation 2018



dark energy from Planck alone! CMB lensing breaks degeneracy Planck 2018 |



$$n_s = 0.9665 \pm 0.004 \text{ P18 VI}$$

8.8 σ from 1

B+Jaffe'96,'98

$$\Omega_\Lambda \approx 2/3 \pm .07 + \text{LSS}$$

$$n_s =$$

$.98 \pm .07$

$.96 \pm .06$

$$\Omega_\Lambda = 0.6889 \pm 0.0034 \text{ P18 VI}$$

$w_0: -1.04 \pm 0.1$

$\Omega_K: .0007 \pm 0.004$

$\langle \zeta | \text{Temp, E pol} \rangle$ -WebSky reveals *early universe phonons*

ζ -TOPOGRAPHY & CARTOGRAPHY

=> @ $a \sim 1/10^{55}$ only 2 numbers

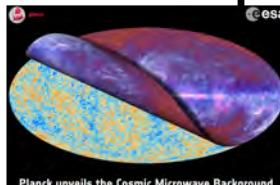
more: $r?$ $n_s(k)?$ nonGaussian; isocons

only partial de-lens

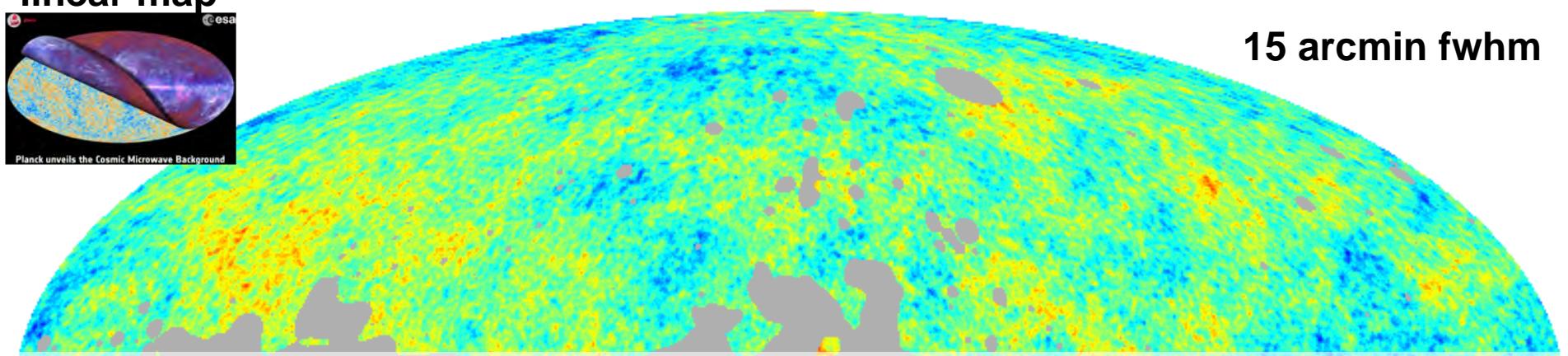
Planck 2018

15 arcmin fwhm

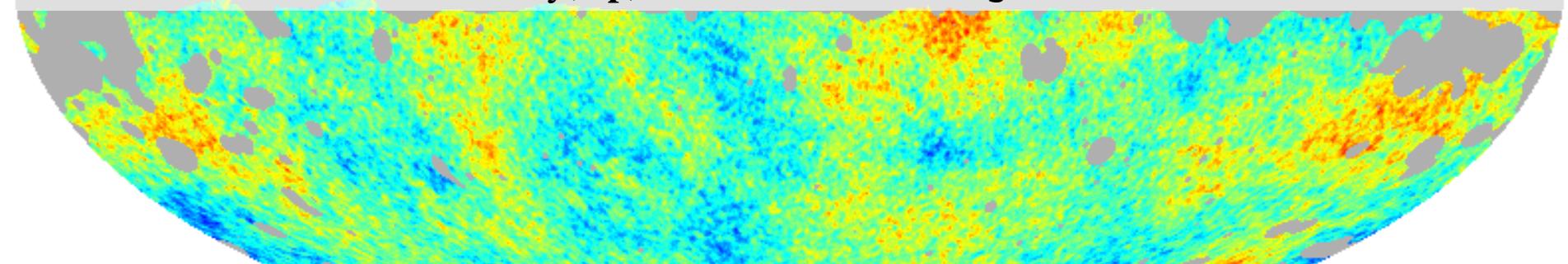
linear map



Planck unveils the Cosmic Microwave Background



random sound loudness $P_\zeta(k_p) +$ bass/treble $n_s = 0.967 \pm 0.004$ 8.8σ from 1



visibility mask

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

-40.0

+40.0

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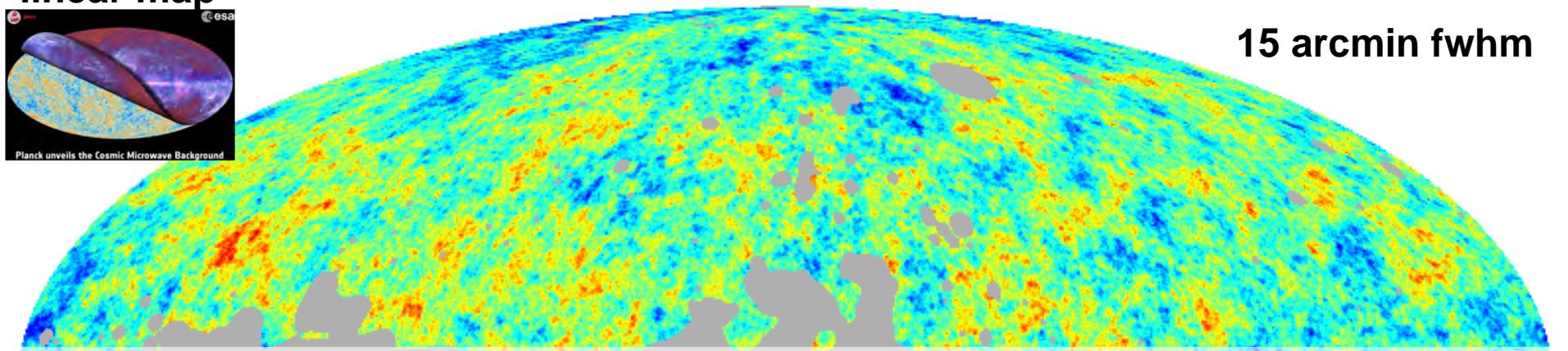
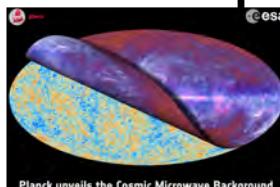
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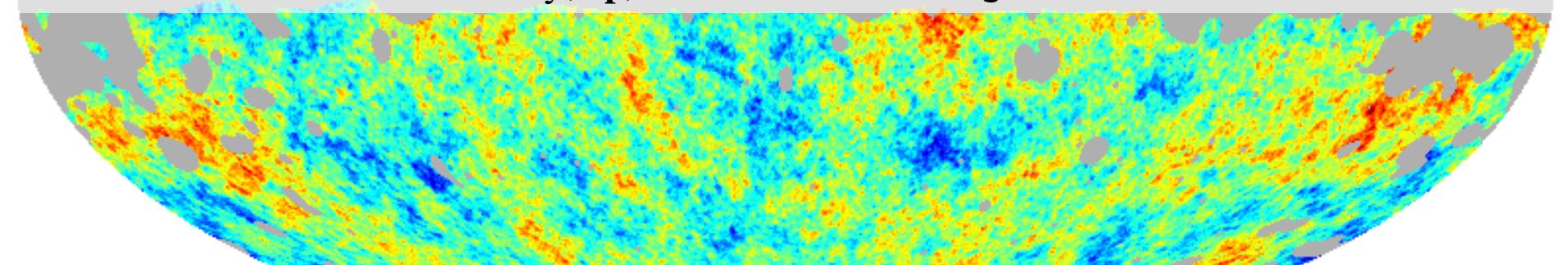
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Beyond the Standard Model of cosmology? SMC = tilted Λ CDM + r aka (ζ, h_{+x})

BSMC = SMC + primordial anomalies in the true ζ -WebSky

std nonG $\zeta = \zeta_G + f_{NL}^* (\zeta_G^2 - \langle \zeta_G^2 \rangle)$ local & equilateral pattern & orthogonal
non-std nonG $\zeta = \zeta_{inflaton} + uncorrelated \zeta_{[GRF]}$ modulated heating intermittent

$$f_{NL}^* = -0.52 \pm 3.0 \text{ for } \zeta$$

CMB TT correlation $C(\theta) \sim 0 @ >60^\circ$
hemisphere difference ~7% at low resolution

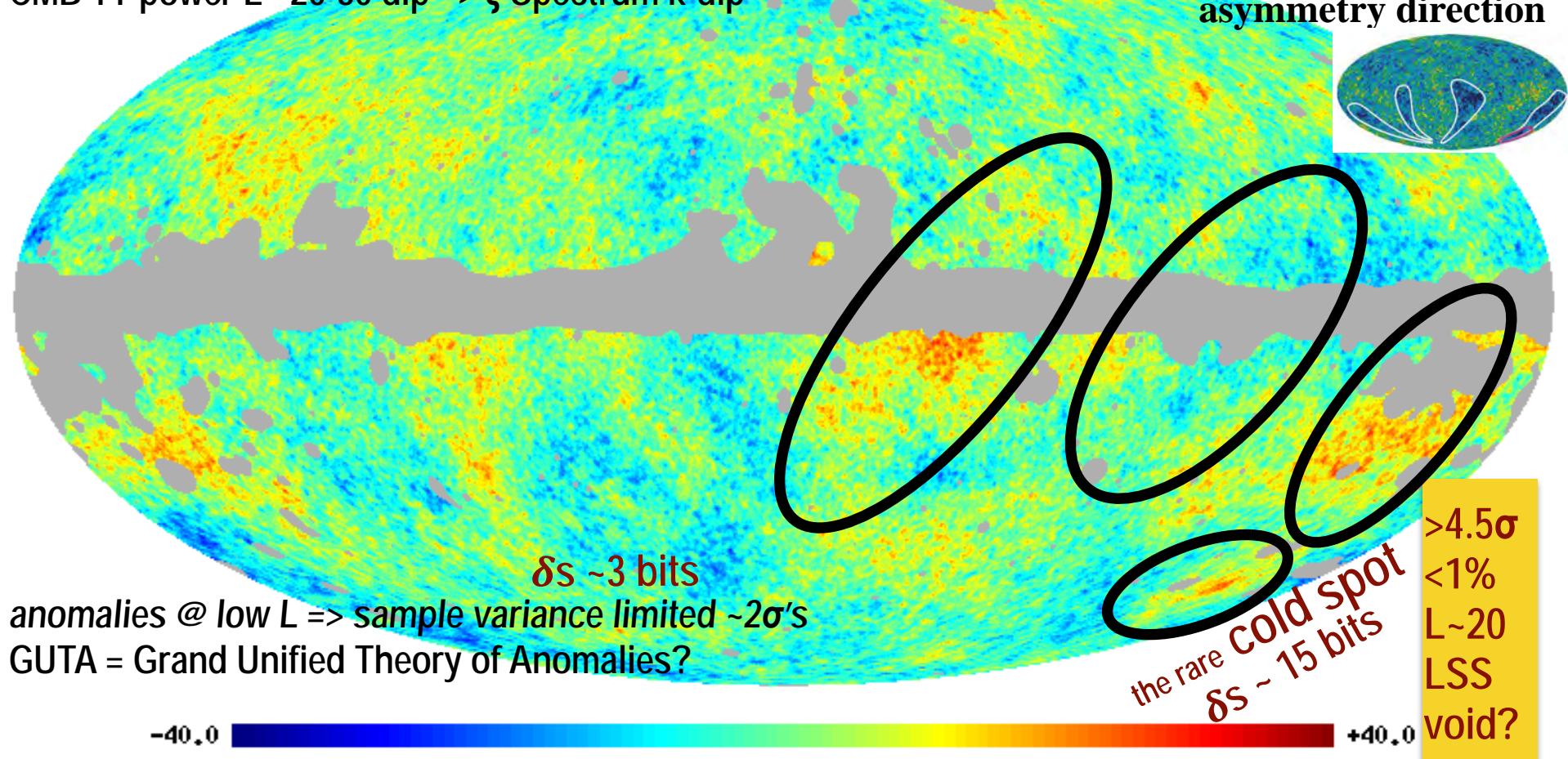
CMB TT power $L \sim 20-30$ dip $\Rightarrow \zeta$ -Spectrum k-dip

$\langle \zeta | T, E\text{-pol} \rangle$

ζ_{min}

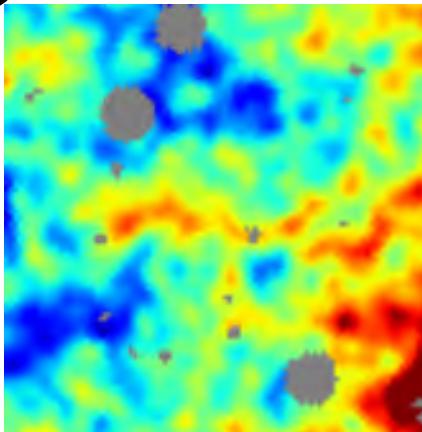
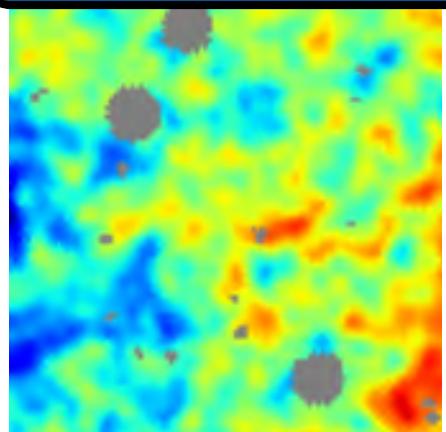
octupole/quadrupole alignment

dipole modulation/asymmetry direction

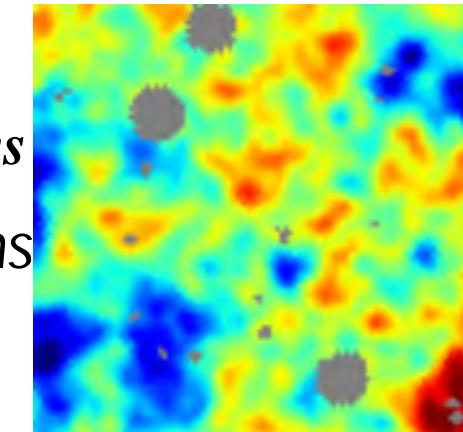


real ζ -WebSky mean field

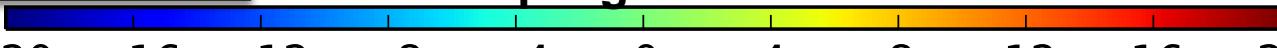
visibility mask



real
 ζ -WebSkys
with
fluctuations

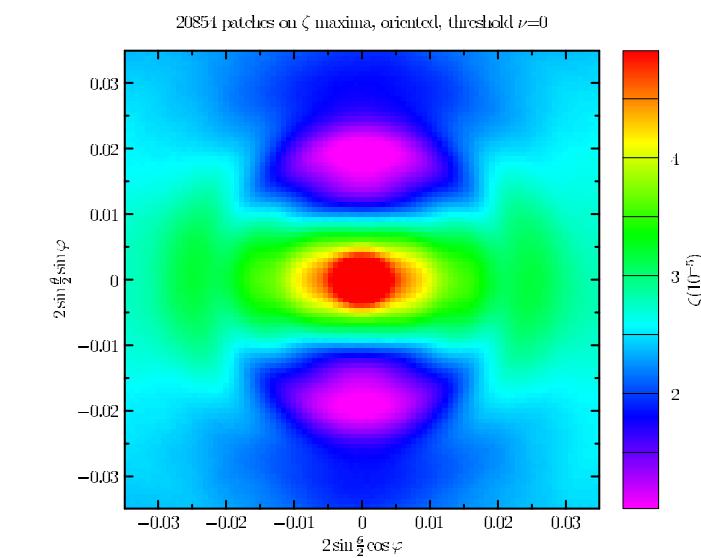
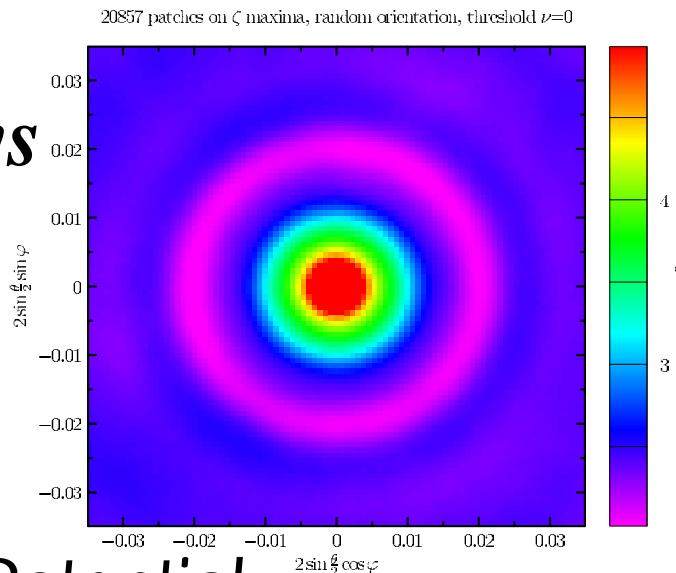


20x20 sq deg



zoom in, higher res: 20 arcmin fwhm

real ζ -WebSkys
stacked to damp
fluctuations
 $\langle \zeta/\zeta_{pk} \rangle|_{dv}$



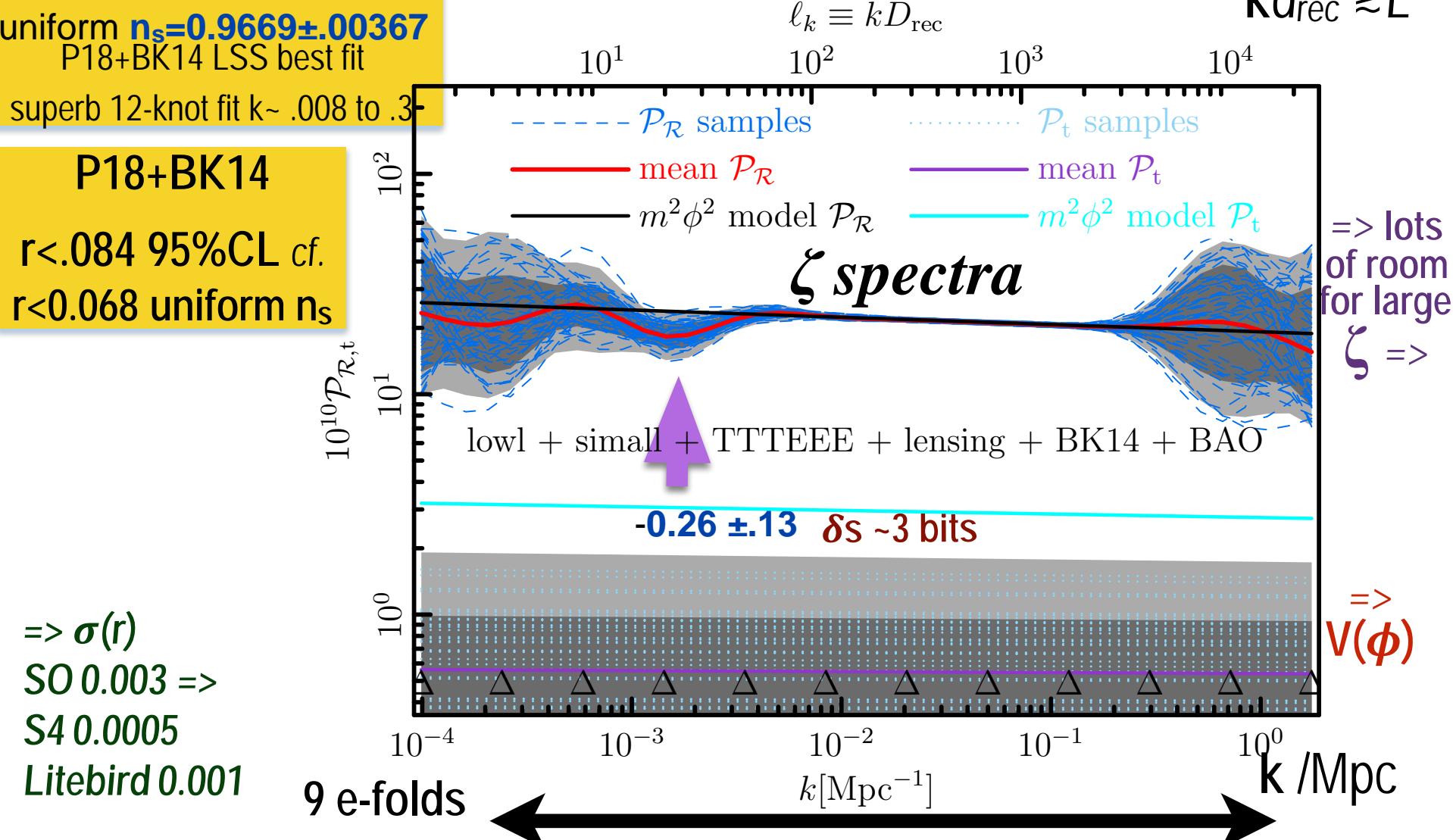
similar to
-Gravitational Potential
WebSkys

oriented stacks, etc.

the true quadratic ζ -Websky of the ζ -scape

Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK14 BB + BAO

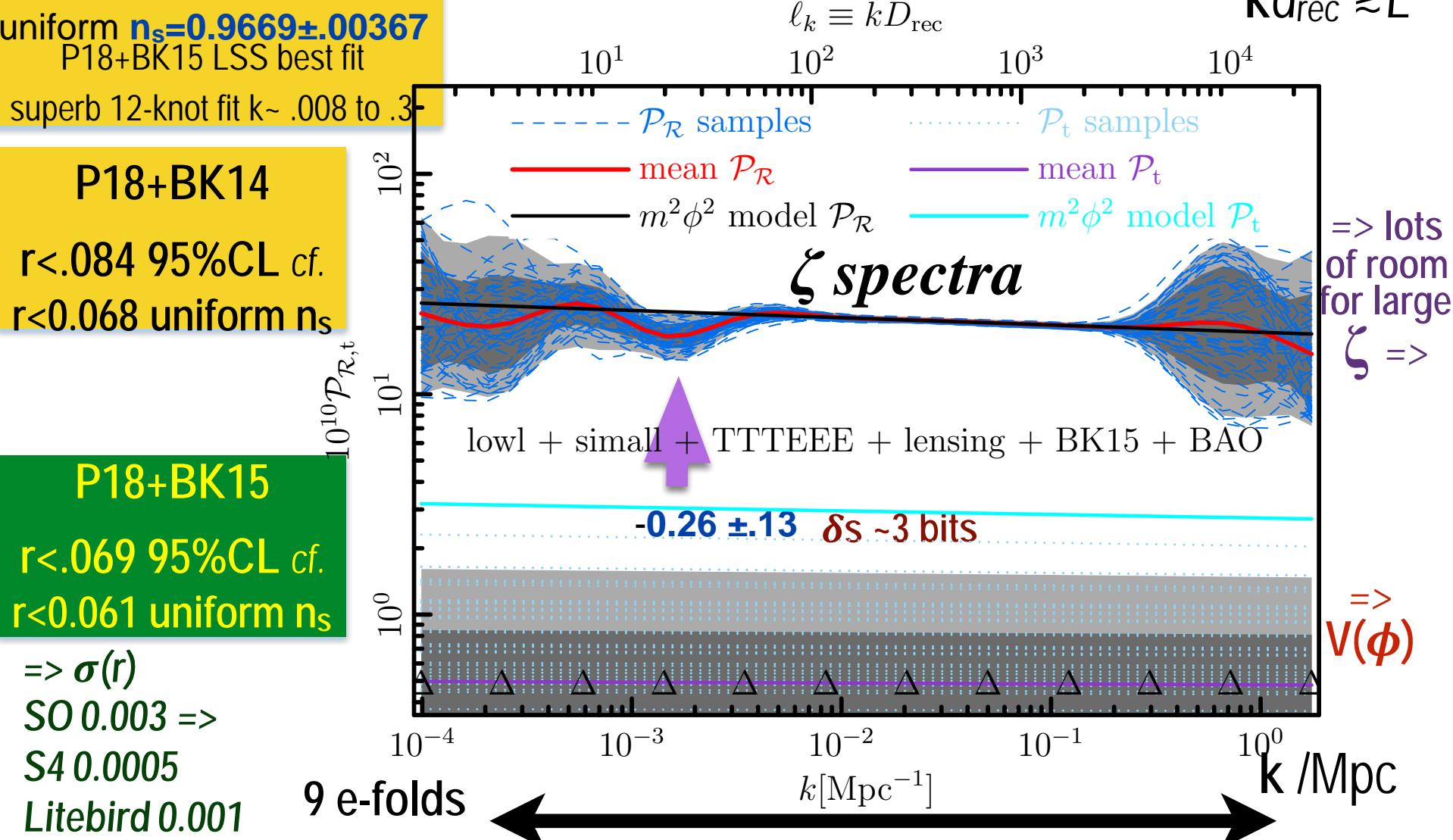
CMB TT power L~ 20-30 dip $\Rightarrow \zeta$ -Spectrum k-dip; includes CMB lensing, parameter marginalization



the true quadratic ζ -Websky of the ζ -scape

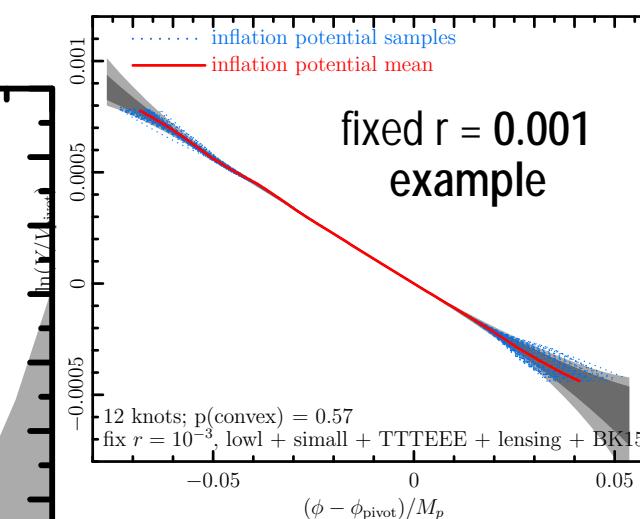
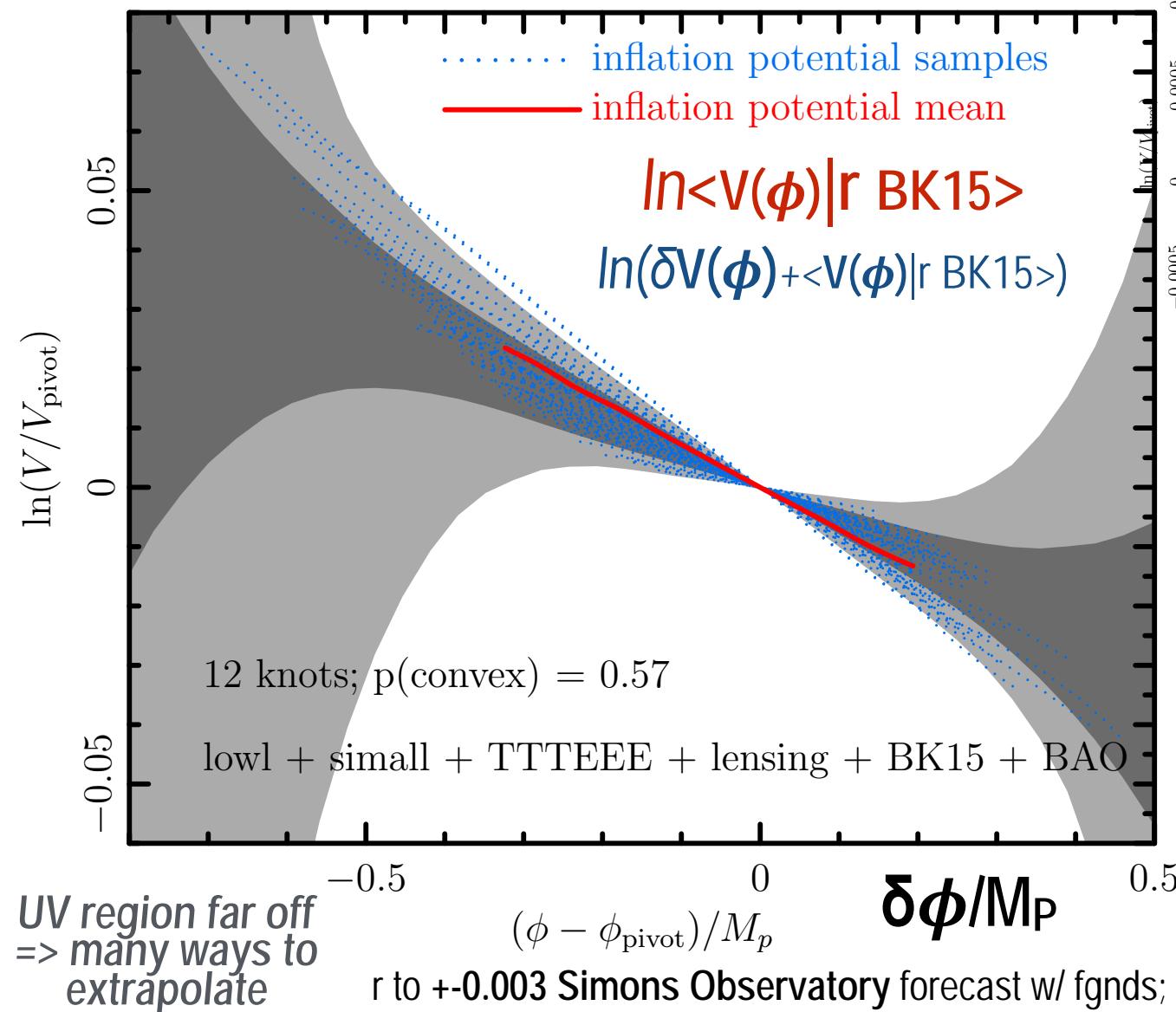
Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + BAO

CMB TT power L~ 20-30 dip $\Rightarrow \zeta$ -Spectrum k-dip; includes CMB lensing, parameter marginalization



inflaton $V(\phi)$ -maps = $3M_P^2 H^2 (1-\epsilon/3)$ HJ eqn, $d\phi/M_P/d\ln a = \pm \sqrt{2\epsilon}$
 along the gradient / Morse flow

Planck 2018 X



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

the true quadratic ζ -Websky of the ζ -scape

Planck 2018 I: TTTEEE lowL Epol + CMBlens + BK14 BB + BAO

CMB TT power L~ 20-30 dip

uniform $n_s = 0.9669 \pm .00367$

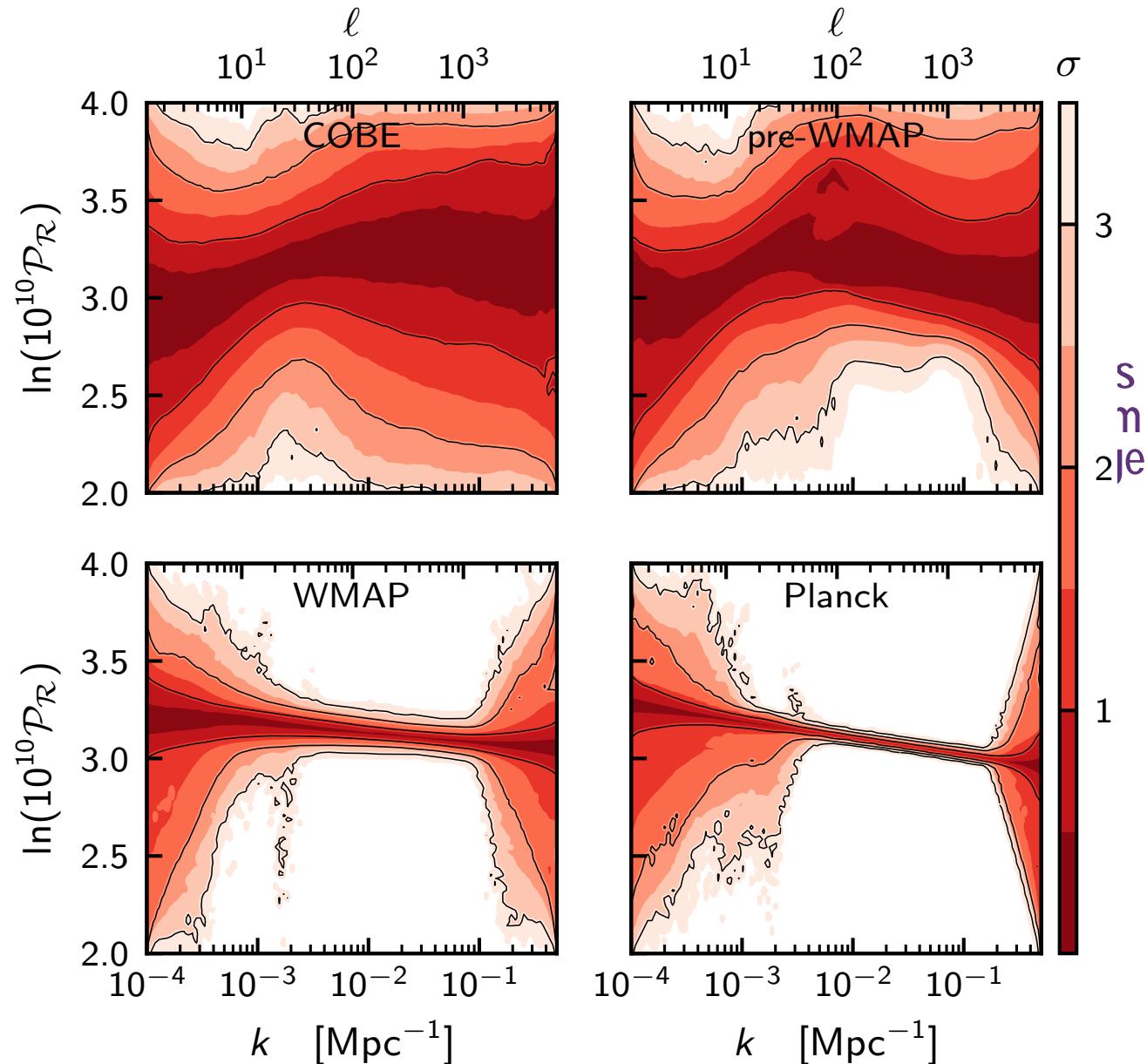
P18+BK14 LSS best fit

superb 12-knot fit k~ .008 to .3

P18+BK15

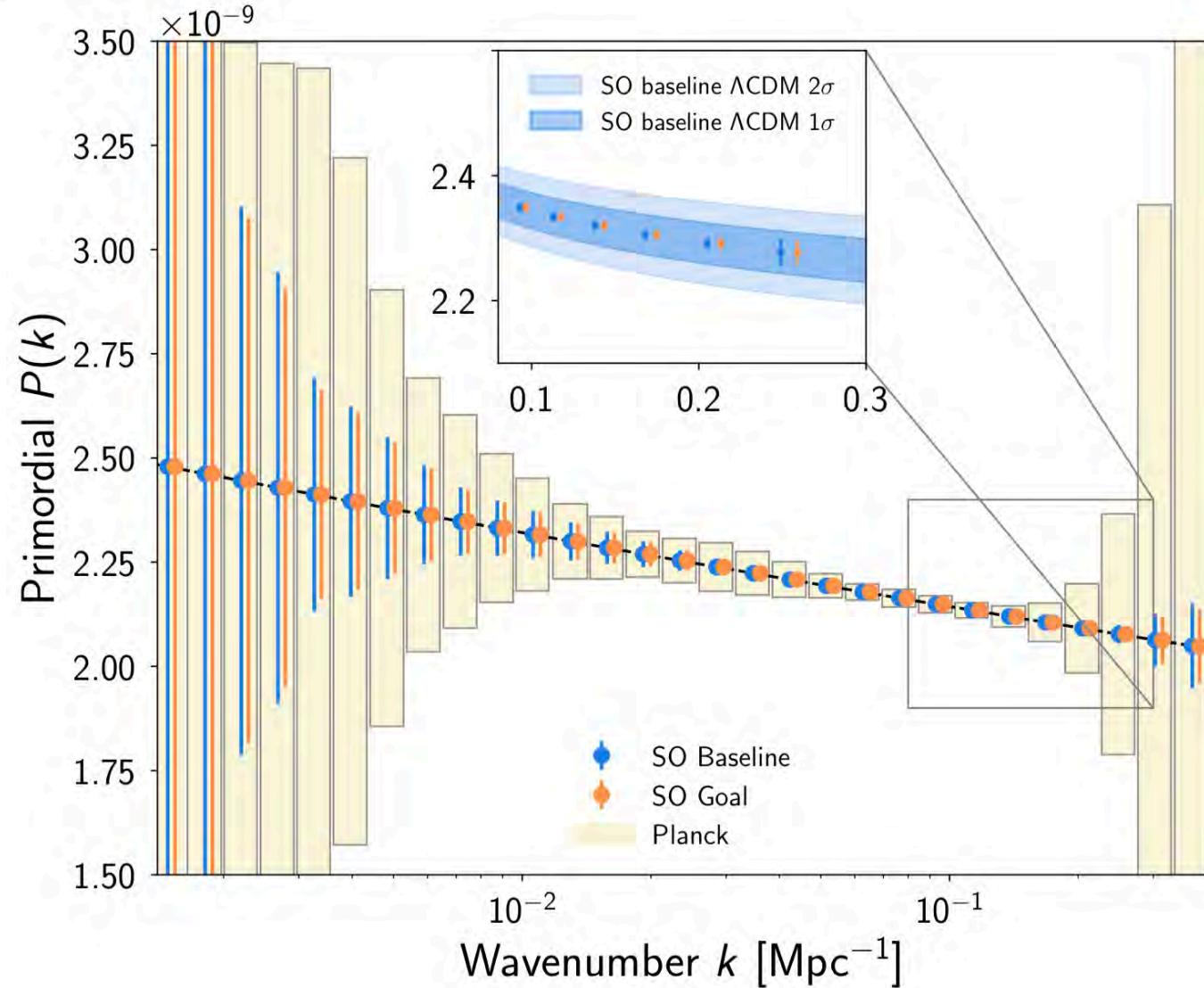
$r < .069$ 95%CL cf.

$r < 0.061$ uniform n_s

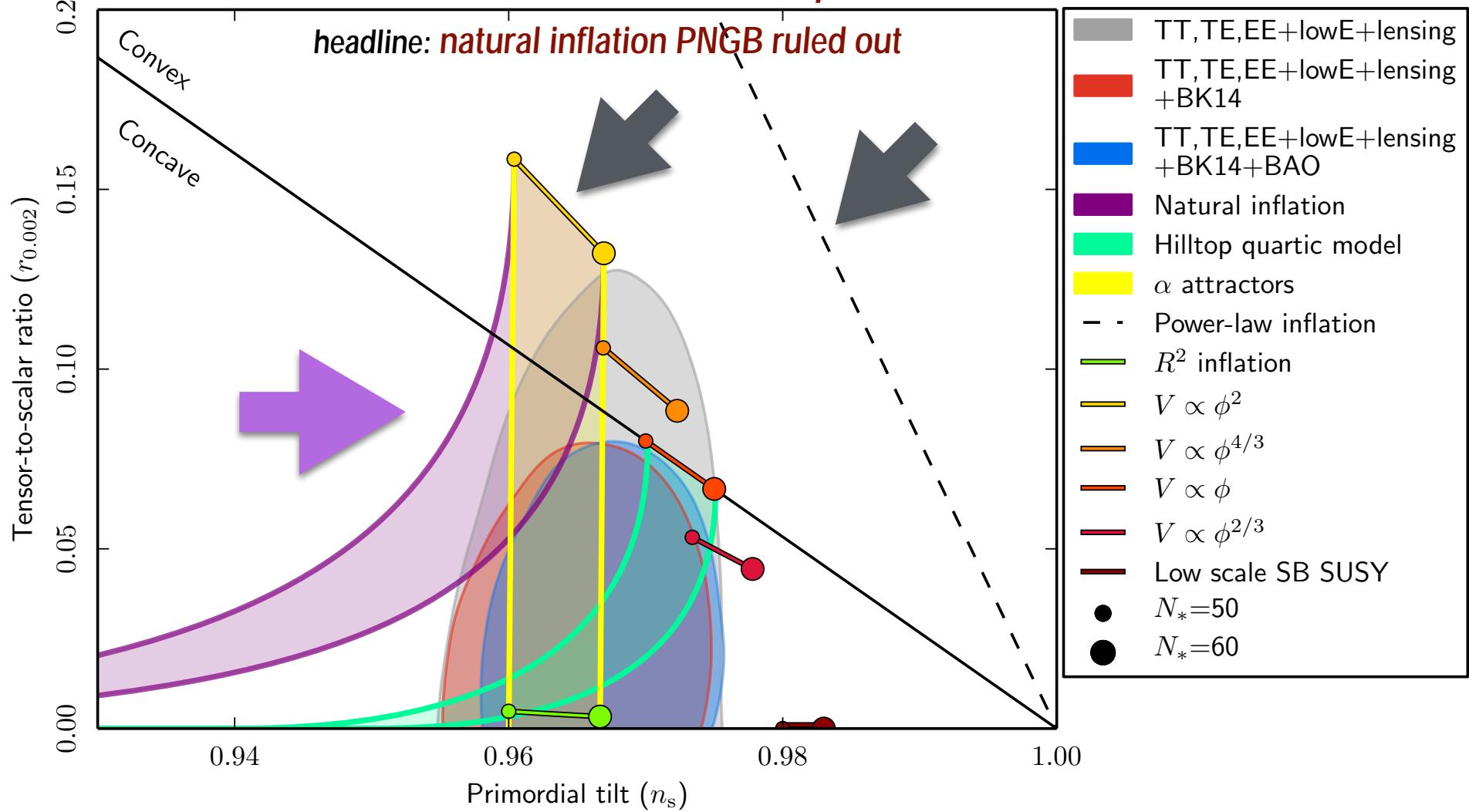


the true quadratic ζ -Websky of the ζ -scape

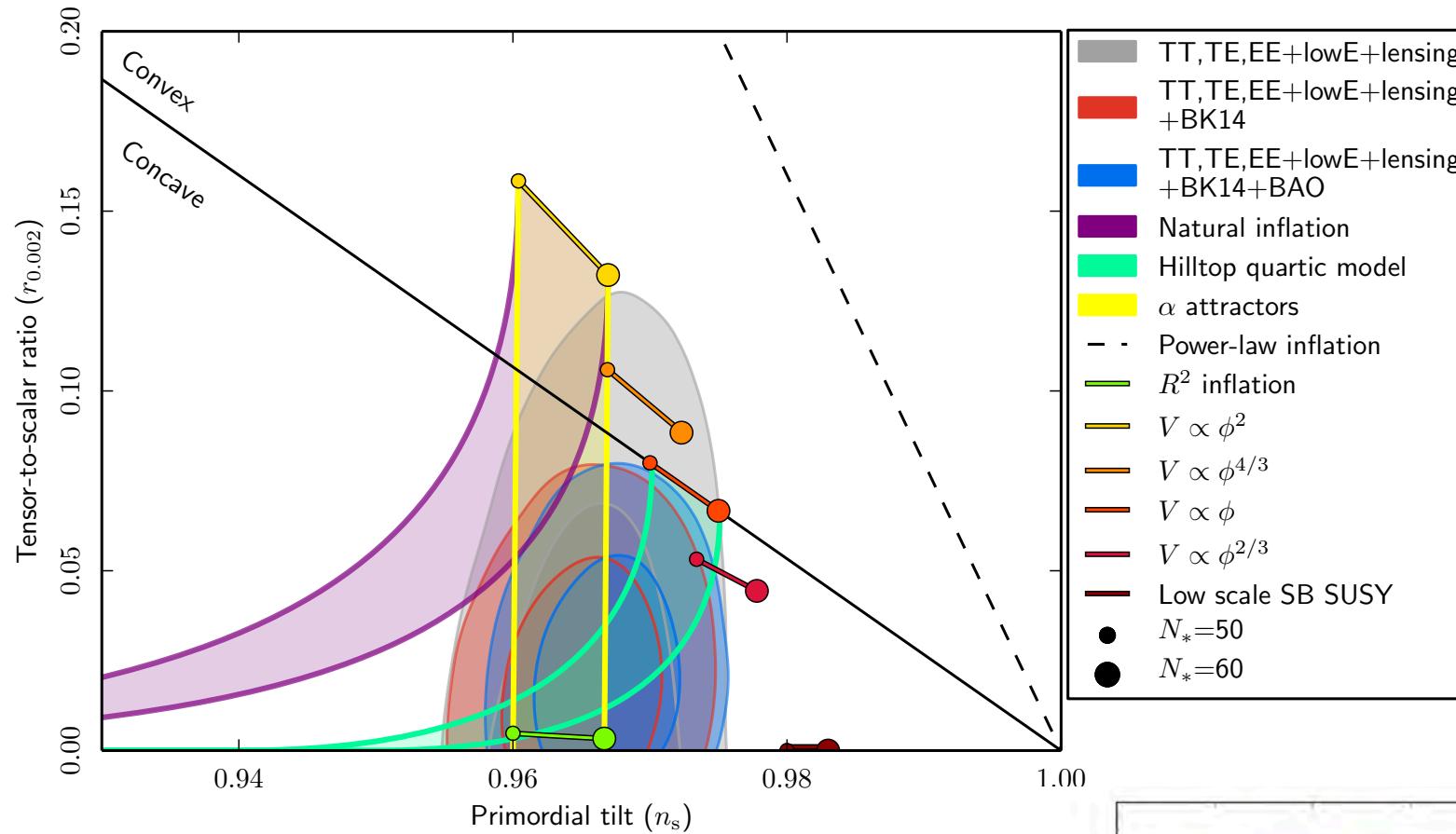
Sample Cosmological Forecast: Simons Observatory



headline: uniform acceleration ruled out, $m^2\phi^2$ ruled out

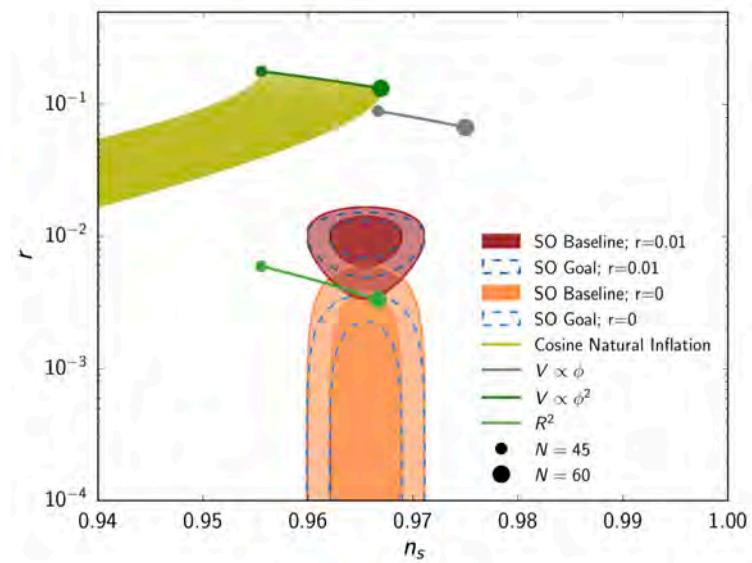


headline: conformally flattened potentials OK, includes R^2 inflation & Higgs inflation, α -attractors



Sample Cosmological Forecast:
Simons Observatory

$\Rightarrow \sigma(r)$
SO 0.003 \Rightarrow
S4 0.0005
Litebird 0.001





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Quantum Inflation in the Planck Era & Beyond



*relic1: ζ from inflaton - observable = all cosmic structure CMB&LSS & stars/humans etc
amplitude & slope \leftrightarrow acceleration history & V_{eff} simple over observable range*



relic2: entropy cooled remnant of particle/field plasma post-inflation $S_{tot} = S_{CMB} + S_{Cnub}$
 $10^{88.6}$

relic3: baryon asymmetry of matter over antimatter N_{baryon}/S_{tot}
 $10^{-10.06}$

relic4: dark matter from quark/gluon plasma - only seen gravitationally WIMPS, axions,..
 $26.6 \pm 0.7\%$

relic5: big bang nucleosynthesis products H, He, D, Li (influenced by Cnub)

relic 6: CMB with all its fluctuations & polarization

relic 7: galaxies & large scale clustering, flows, gravitational lensing

relic 8: dark energy
 $68.5 \pm 0.7\%$



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Quantum Inflation in the Planck Era & Beyond



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

relics not yet seen: in quest of what lies Beyond *the Standard Model of cosmology SMC*

from inflation

local nonG for $\Phi_N = G + f_{nl} G^2$ $f_{nl} = 0.8 \pm 5.0$ soon P18

non-Gaussian features in ζ from weak nonlinearities (*very nearly*) Gaussian random field
gravity waves (not so far - obscured by dust) $P18+BK15 r < 0.06$ uniform n_s
isocon relic (not so far) - Planck on CDM isocurvature, neutrino, correlated
 $cf. 0 < r < .07$ 95% CL $P15+BK15$ 12 knots

bubble remnants of tunneling during inflation

< 2% isocurvature role

from heating

isocon memories (not so far)

strong subdominant but intermittent nonlinearities in ζ (spikes via chaotic billiards)

curvatons oscillons strings domain walls - short lived

rare WIMPzillas as dark matter

from later quark gluon plasma

late phase transitions

anomalies in CMB & LSS

could be *primordial, large-scale, intermittent? statistics of just a few (modes, spatial rare events?)*

SIMPLICITY

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

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

Planck2018 early U structure map
reveals primordial sound waves in matter
 \Rightarrow learn **contents & structure** at 380000 yr, $a \sim e^{-7}$

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

T+E constrained mean of $10^5 \zeta$; $f_{\text{whm}} = 15 \text{ arcmin}$

2⁺ numbers

a picture of the quantum phonon field
 $= \ln \bar{a}(x,t)$ from the birth of the universe

B+Huang

Early Universe STRUCTURE: **phonons/strain** @ $a \sim 1/10^{30+25}$

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

$\ln 10^{10} \text{ Power}_s = 3.05 \pm 0.014$

$n_s = 0.967 \pm 0.004$ 8.8σ from 1 most celebrated Planck result

constant n_s is a superb 12-band fit (over $k \sim .008$ to $.3 / \text{Mpc}$) B+Huang in Planck 18 X

$\Rightarrow \sigma(r) S4 0.0005?$

Litebird 0.001?

CMB+LSS as a fundamental physics laboratory YES

Tensor-to-Scalar ratio (GW)
 $r < 0.06$ PI8+BK15

-40.0

+40.0

END