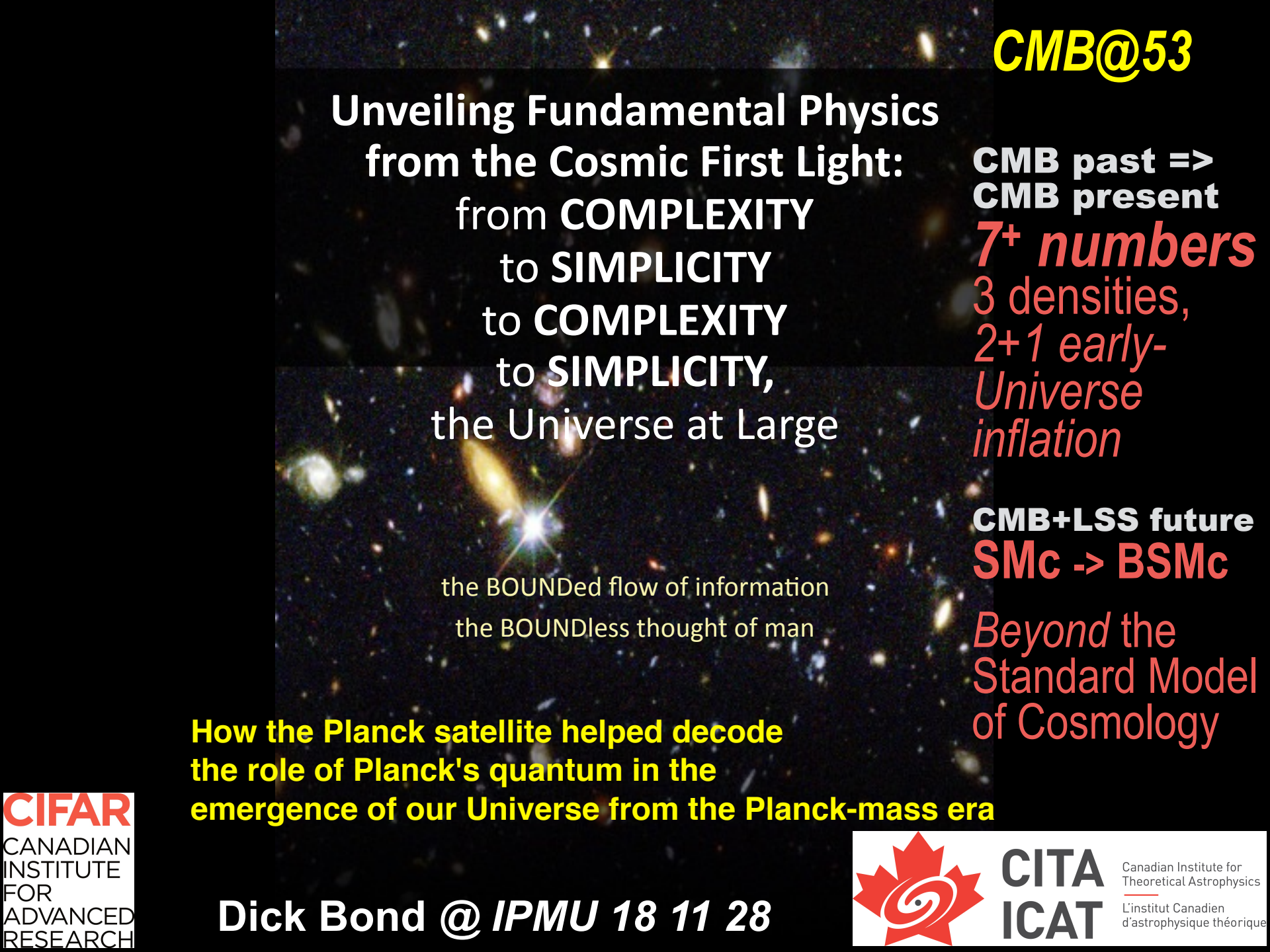

Unveiling Fundamental Physics from the Cosmic First Light:

from **COMPLEXITY**
to **SIMPLICITY**
to **COMPLEXITY**
to **SIMPLICITY,**
the Universe at Large

the BOUNDed flow of information
the BOUNDless thought of man

CMB@53

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

CMB+LSS future
SMc -> BSMc

Beyond the Standard Model of Cosmology

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

CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH

Dick Bond @ *IPMU 18 11 28*

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

Dick Bond **CITA** *the summary talk*

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

CMB prediction
Alpher, Gamow Herman 1950s Tcmb ~5K
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Delta T over Tea 87 @CITA theory+expt
COBE 1989 launch
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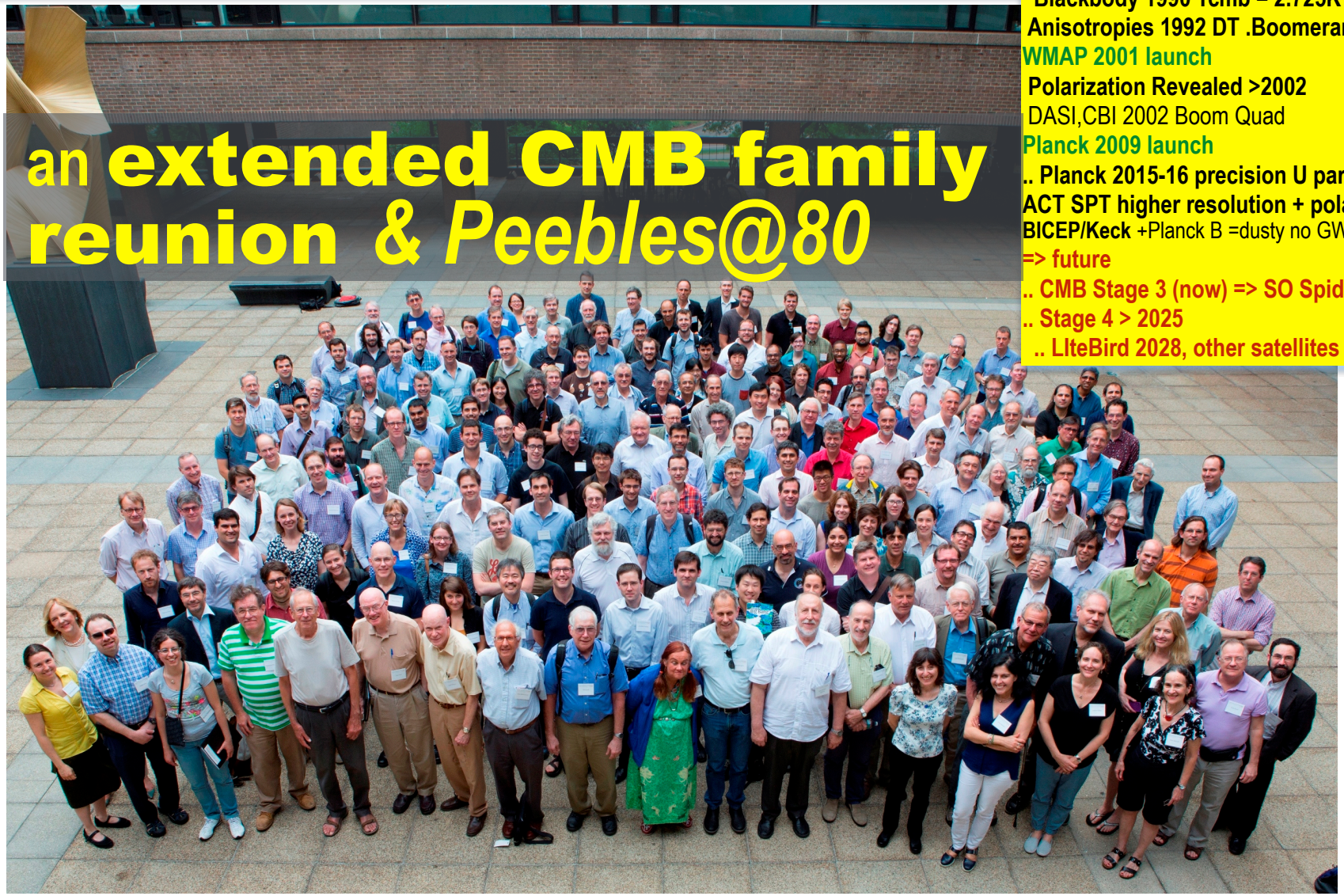
=> future
.. CMB Stage 3 (now) => SO Spider2
.. Stage 4 > 2025
.. LIteBird 2028, other satellites ??

an extended CMB family reunion & *Peebles@80*



CMB@53:

CITA ICAT
CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH
Dick Bond

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

on cosmic **Baryons** Ordinary Matter air ~amu /nm^3 O_2 N ; U 4.9% H,He ~0.055 amu /cm^3

on cosmic **Dark Matter** ~amu /m^3 26.6 ± 0.7% compressed in MilkyWay ~0.3 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 ~ vacuum potential density** ~ 3 amu /m^3 68.5 ± 0.7% late-inflaton KE/PE?

on cosmic **Neutrinos** number density ~ cosmic photons Energy fraction > 0.47% ~stars

THE LIGHT

on cosmic **Phonons ~ isotropic Strain Deformations** ***h_Planck .. M_Planck***

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

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

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

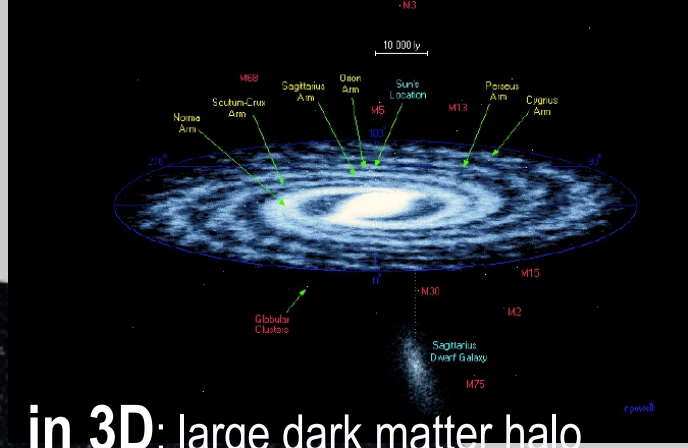
SMpp = Standard Model of particle physics electroweak + strong interactions
=> *BSMpp = Beyond the SMpp* neutrino masses, Dark Matter, Dark Energy, Gravity, SUSY …

SMc = Standard Model of cosmology tilted Gaussian LCDM model, B+DM+DE+photons+neutrinos
=> *BSMc = Beyond the SMc* neutrino masses, dynamical coupled Dark Energy, modified Gravity …

\

Milky Way in infra-red:

half a billion stars, a disk galaxy



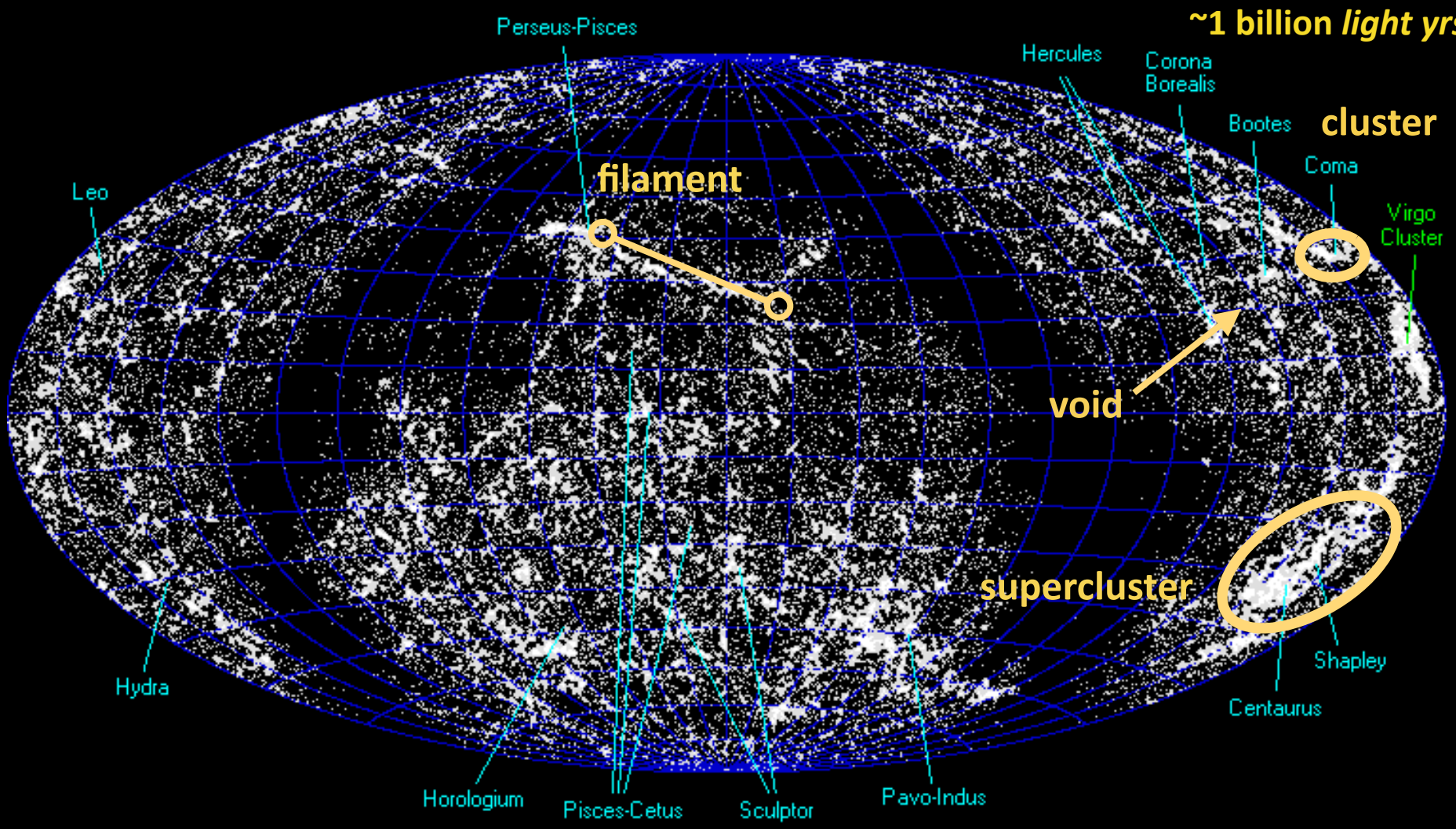
in 3D: large dark matter halo

Polaris

*Sagittarius A**

Magellanic Clouds

Cosmic Web of 60,000 nearby galaxies: exhibits "local" **COMPLEXITY**



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 ≡ $\langle \ln a \rangle$

a scale of the Universe

$\langle \alpha \rangle$

0

now = **1** when we **observe** the **1st light**

then = **1/1100** when the **1st light** was **released from matter**, billion X denser **7**

galaxies forming ~ 1/4 **1 ⇓ 2**

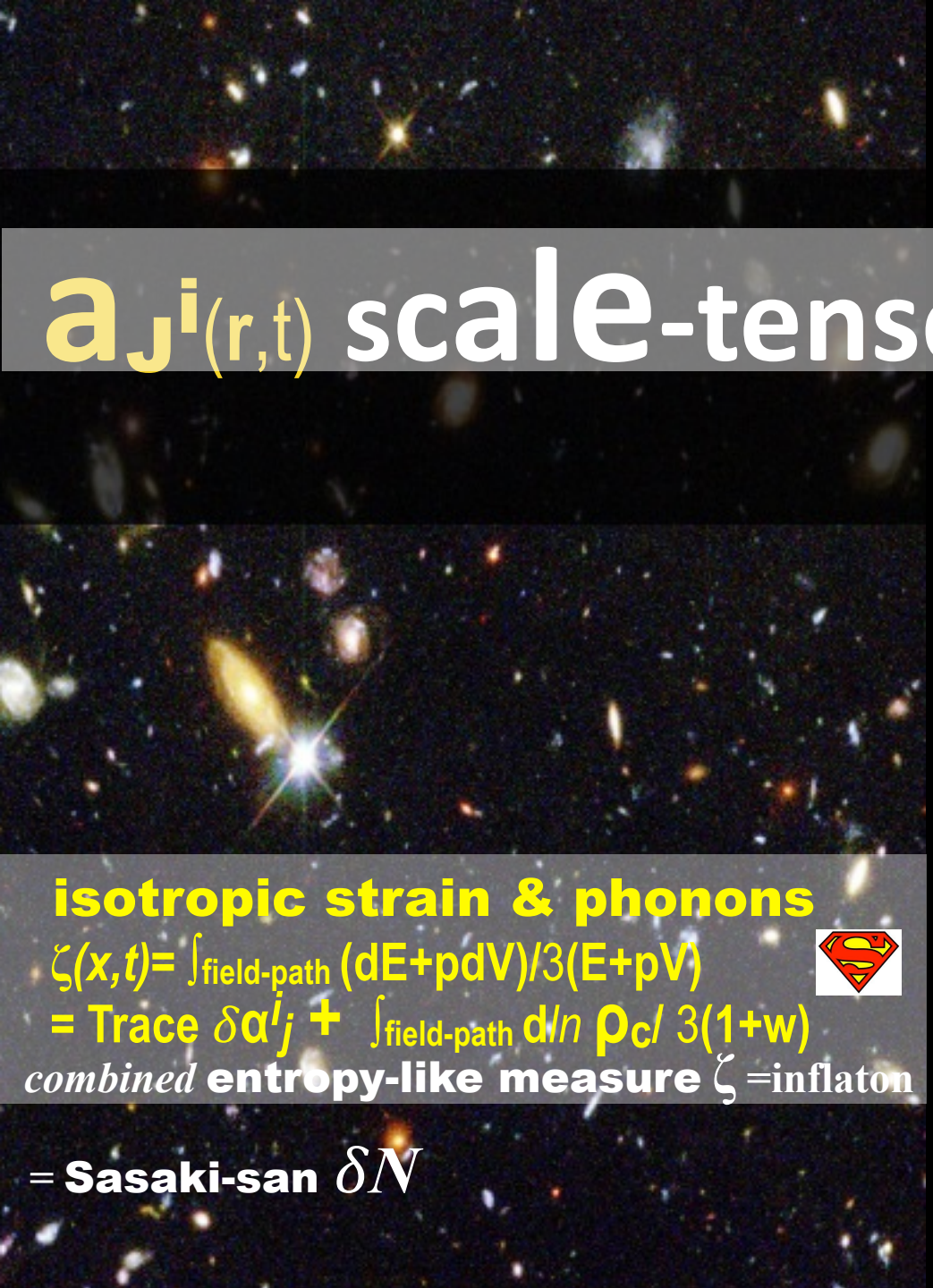
there were **no galaxies** when a < 1/20 **3**

light nuclei

Dark Matter **21 ⇓ 35**

Heat: matter & **radiation** **67**

quantum **noise** **67 ⇓ 127**



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

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

$$a_J^i \equiv exp(\alpha)_J^i$$

$$\alpha_J^i \equiv \langle ln\ a\rangle \delta_J^i + \varepsilon_J^i$$

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

$\zeta(x,t) = \int_{field\text{-}path} (dE+pdV)/3(E+pV)$

$=$ Trace $\delta\alpha^i{}_j + \int_{field\text{-}path} d\ln \rho_c / 3(1+w)$

combined **entropy-like measure** ζ **=inflaton**

= **Sasaki-san** δN

Earth under Strain: earthquakes, seismic waves

ε=strain tensor

Universe under Strain: space-quakes = gravity waves

elastic deformation $dx^i = e_J^i\, dr_{eq}^J$ $e_J^i = a_J^i / \langle a \rangle$

anisotropic strain, shear waves ε-Trace(ε)/3

isotropic strain, sound Trace(ε)

scale-deformation a_J^i

anisotropic strain, gravity waves

isotropic strain, sound

linear: **strain** ∝ **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 => **a**= *drei*bein, triad, Lagrangian-space metric $\mathbf{g}=\mathbf{a}\mathbf{a}^\dagger$

the flow of time => 4D *vier*bein *spacetime-strain* a_b^β $b,\beta=0,1,2,3$

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an extended CMB family reunion & *Peebles@80*



& futures S4, more ballooning, back into space

managing the CMB

on to SO -> CMB-S4
Advanced ACTPol

boomerang ~40/paper

planck ~250/paper, ~100 institutions

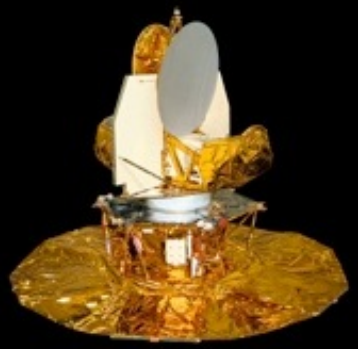
Cobras/Samba @Capri93

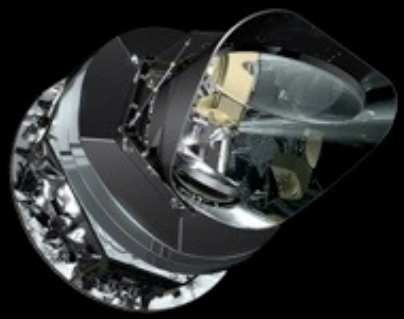
Bond since 1993, Canada since 2001

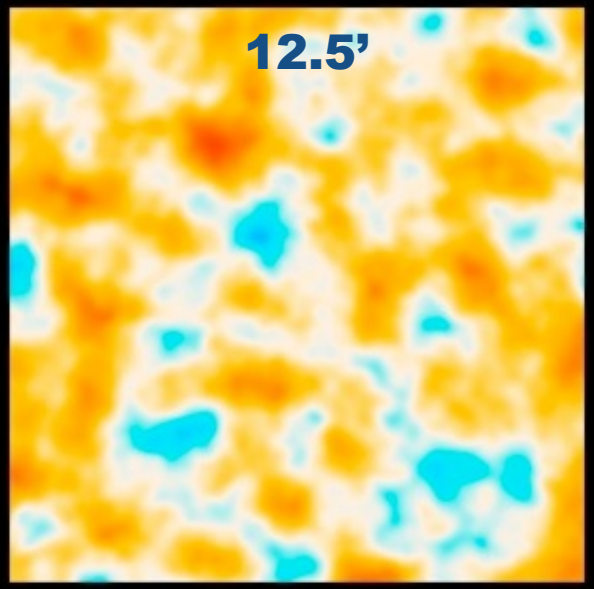
SPIDER

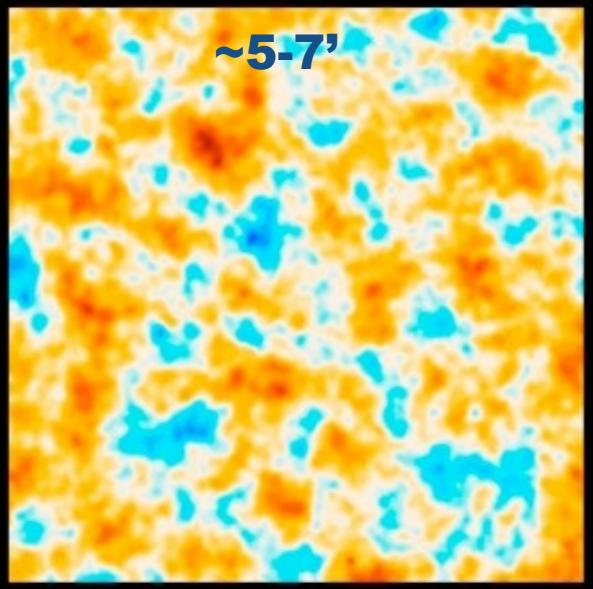
Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch *WMAP 01 launch* *Planck 09 launch*









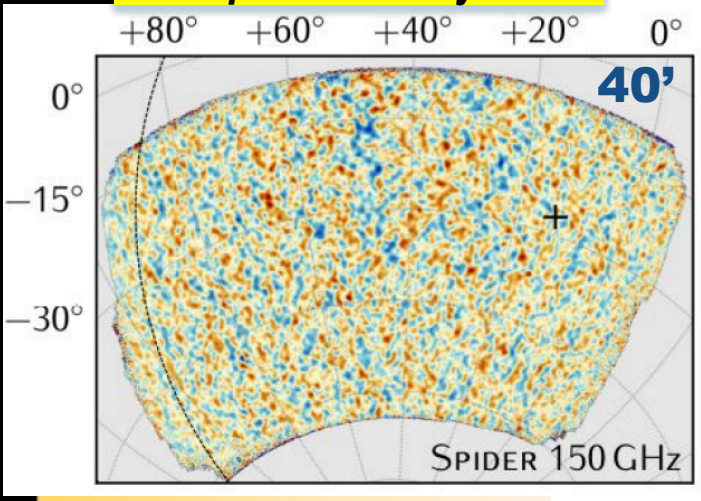
COBE WMAP Planck

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')

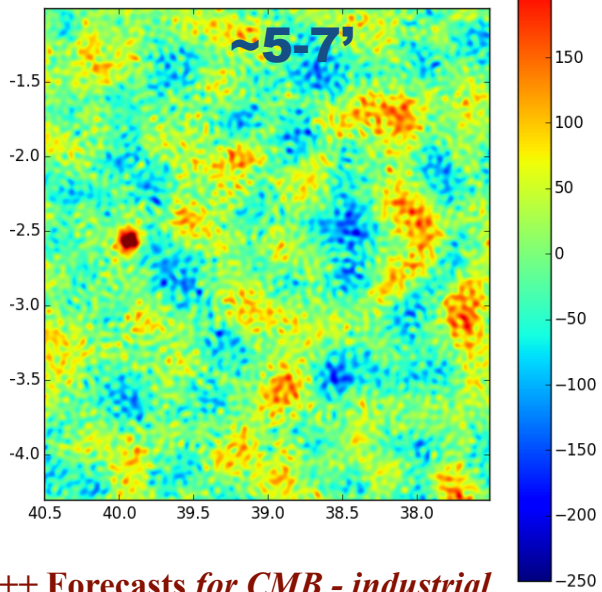
Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch *WMAP 01 launch* *Planck 09 launch*

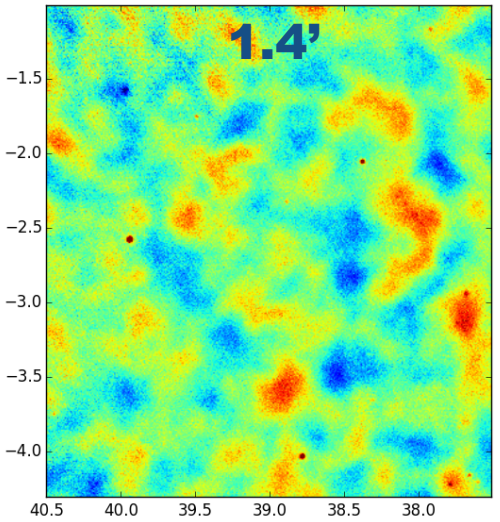
Spider 40' fsky~.08



Planck



ACT



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

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')

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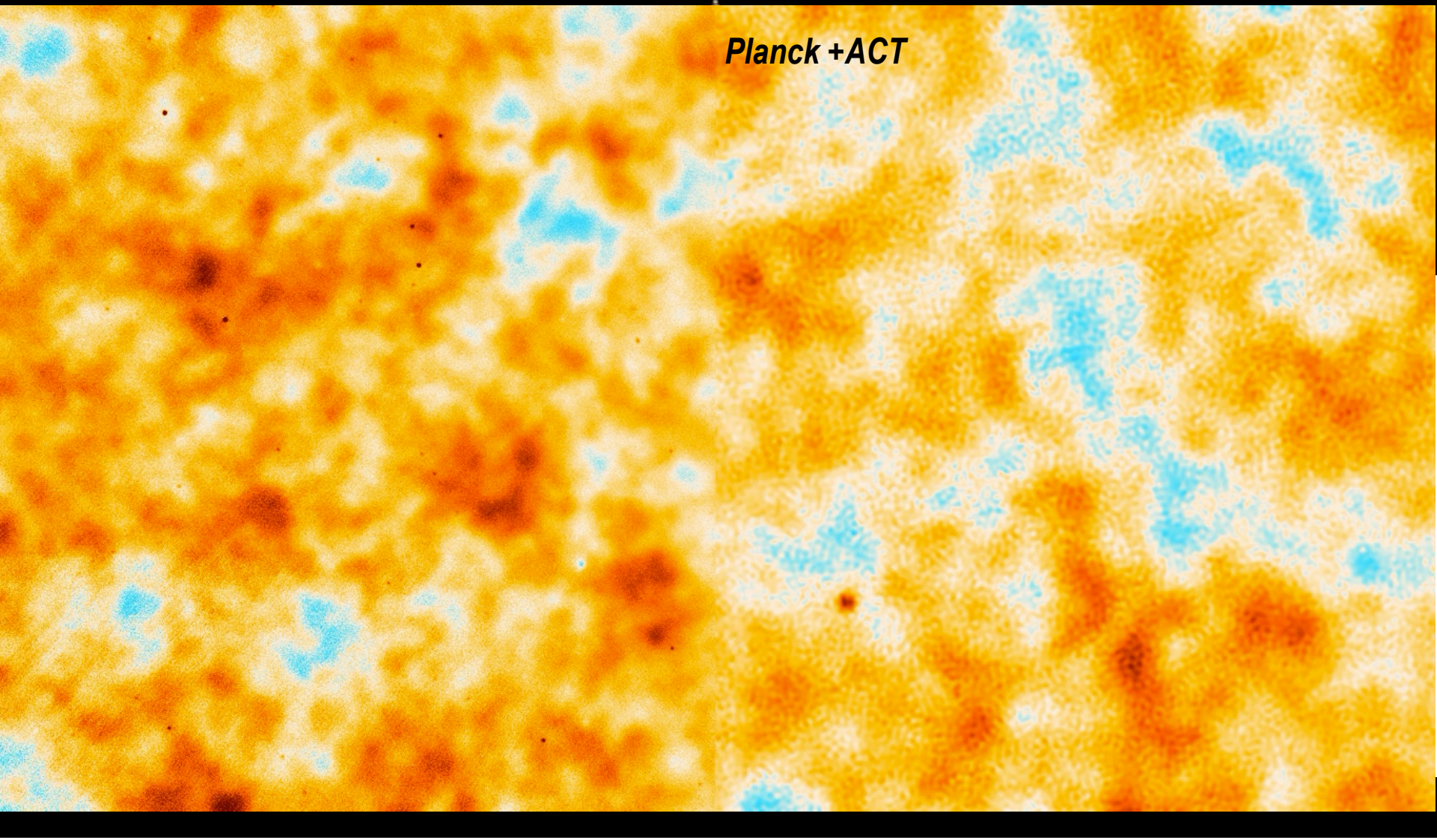

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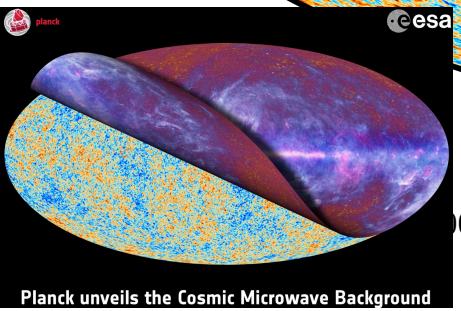
Planck's primordial light unveiled, *Mar 2013 =>* **Feb 2015** *=> pre-2016 =>* ***july 2018+*** *final*

reveals the SIMPLICITY of primordial cosmic structure

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



300 μK

Temperature changes in micro-degrees

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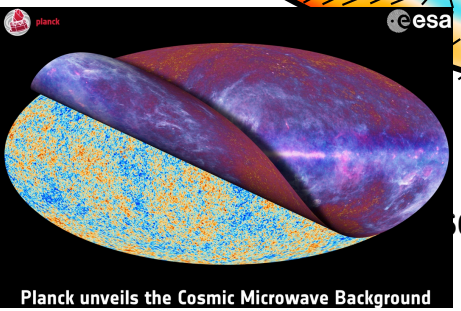

160 μK

Polarization on T

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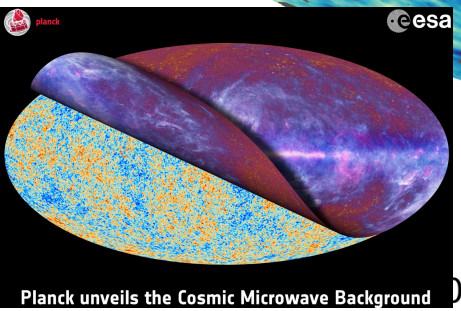

Lensing potential φ

0.0016

0.0016

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

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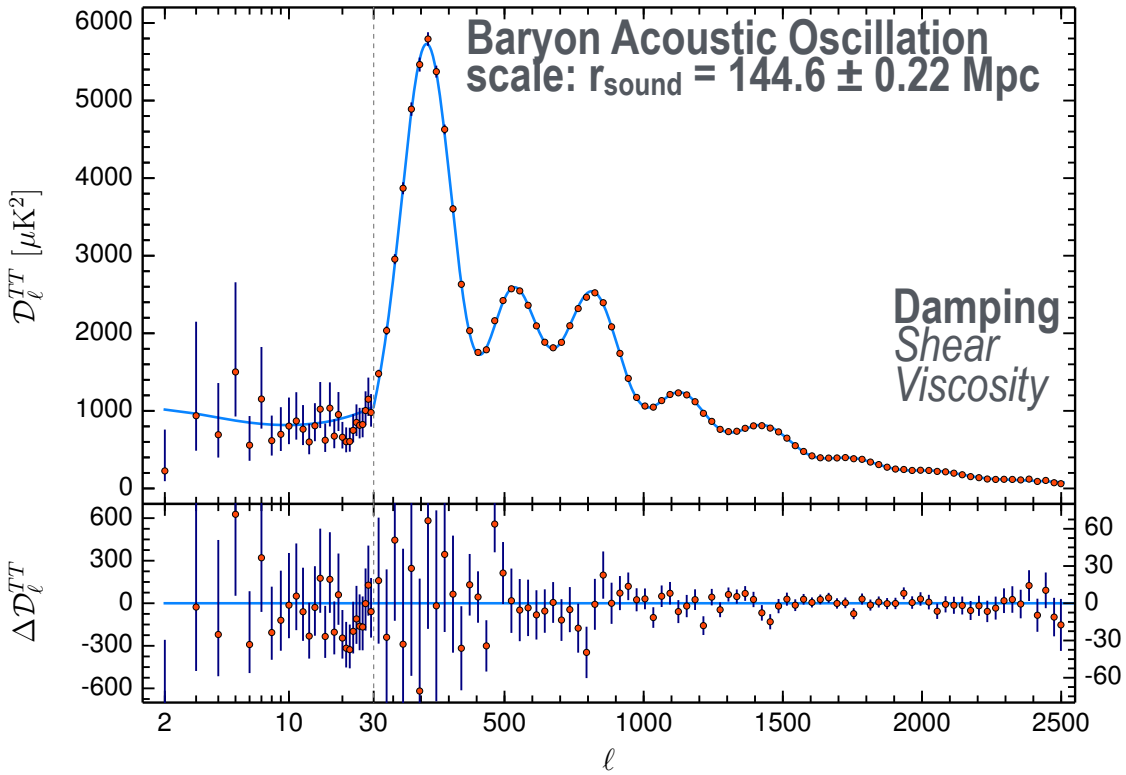
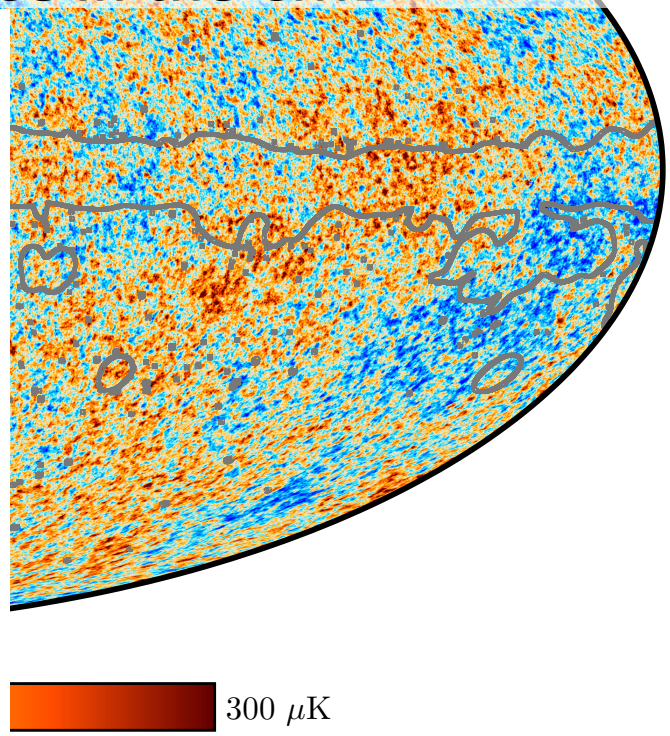
harmonic analysis of the *'music of the spheres'*
=> inharmonious, coloured noise in the CMB





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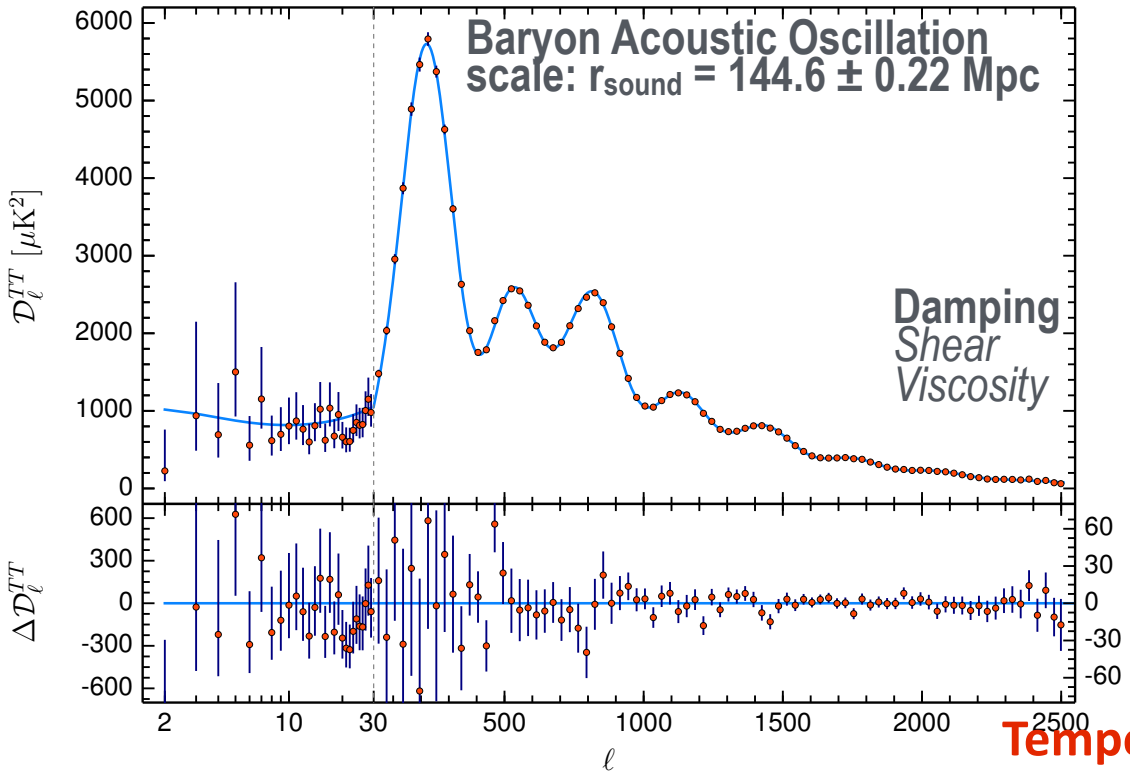
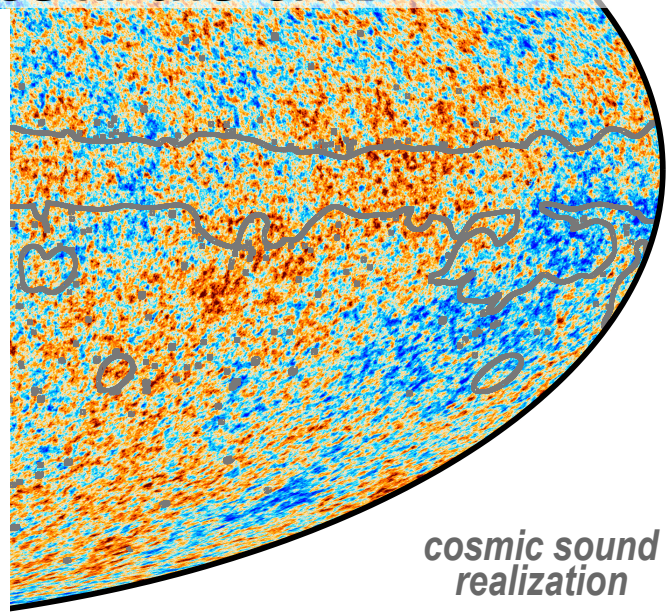
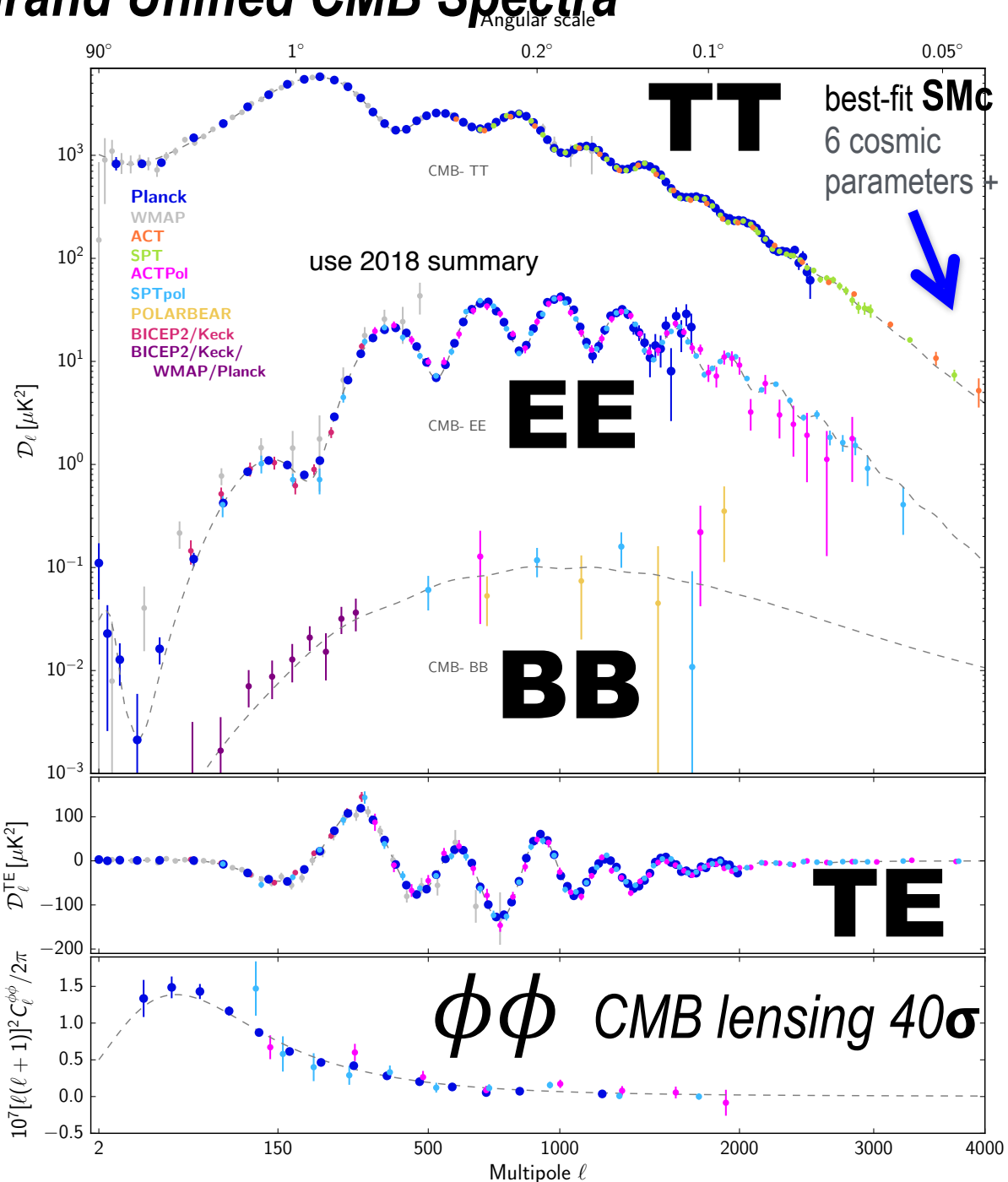


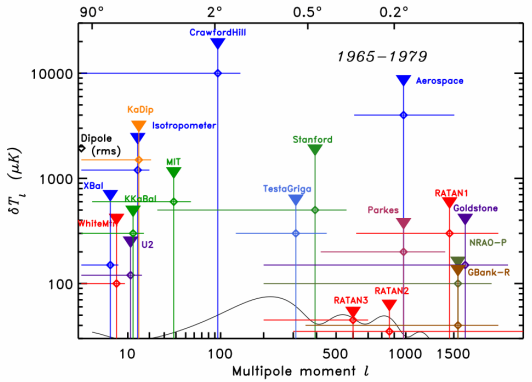


300 μK

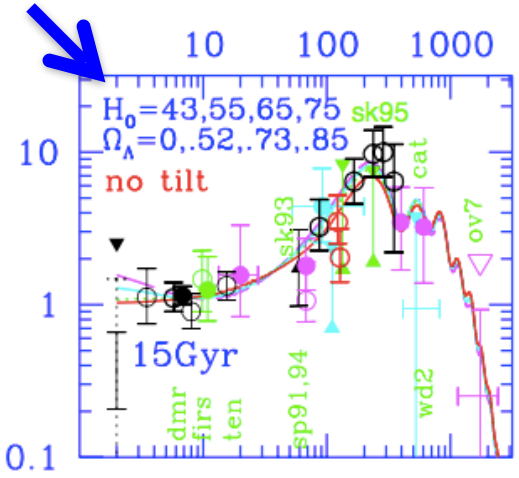
Temperature changes in micro-degrees

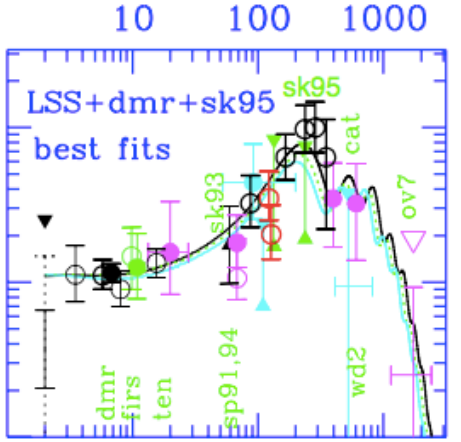
Grand Unified CMB Spectra





JRB@Capri 1993 Bandpowers cf. theoretical power spectra





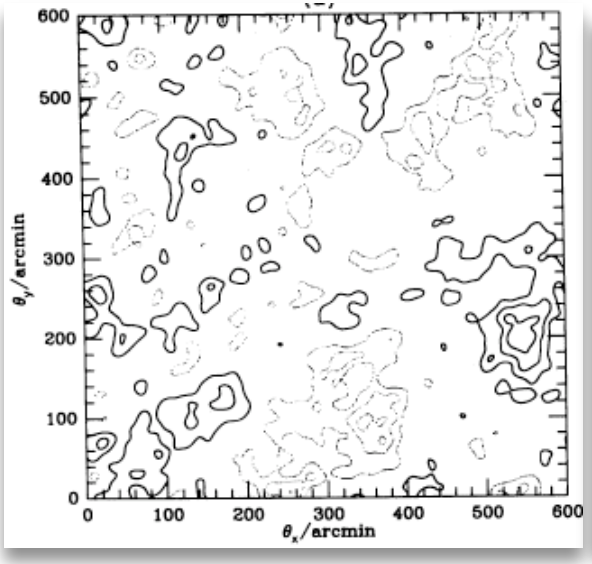
Delta T over Tea Toronto May 1987: first dedicated CMB conference, expts+theorists, primary+secondary ΔT/T

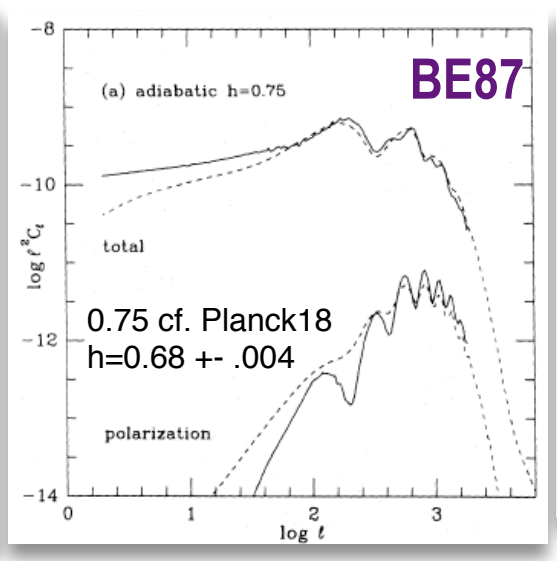
organizers: Bond *theory* + Wilkinson *experiment*

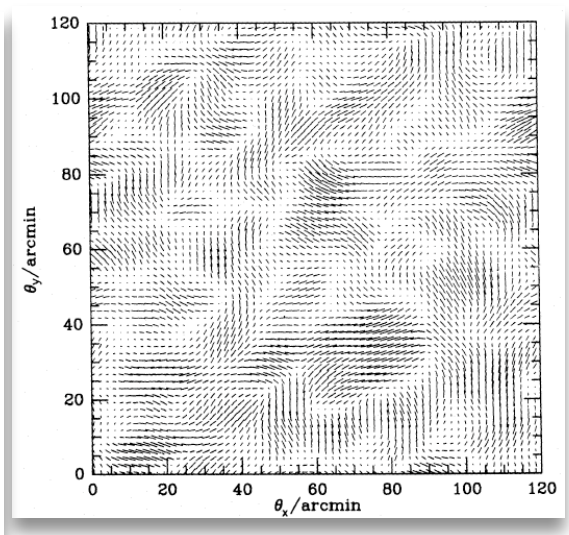
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle |\Delta T(LM)|^2 \rangle$ *with target* C_L *shapes*

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 - $5^o - 10^o$ results, future experiments at $\sim 1^o$, 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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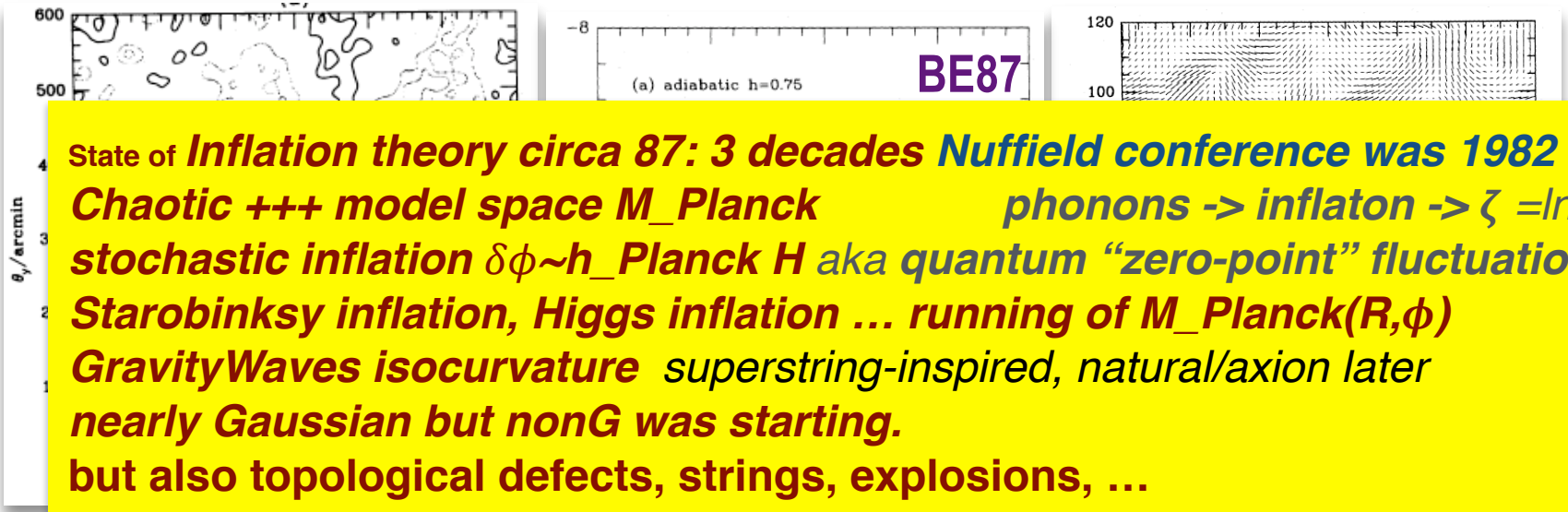
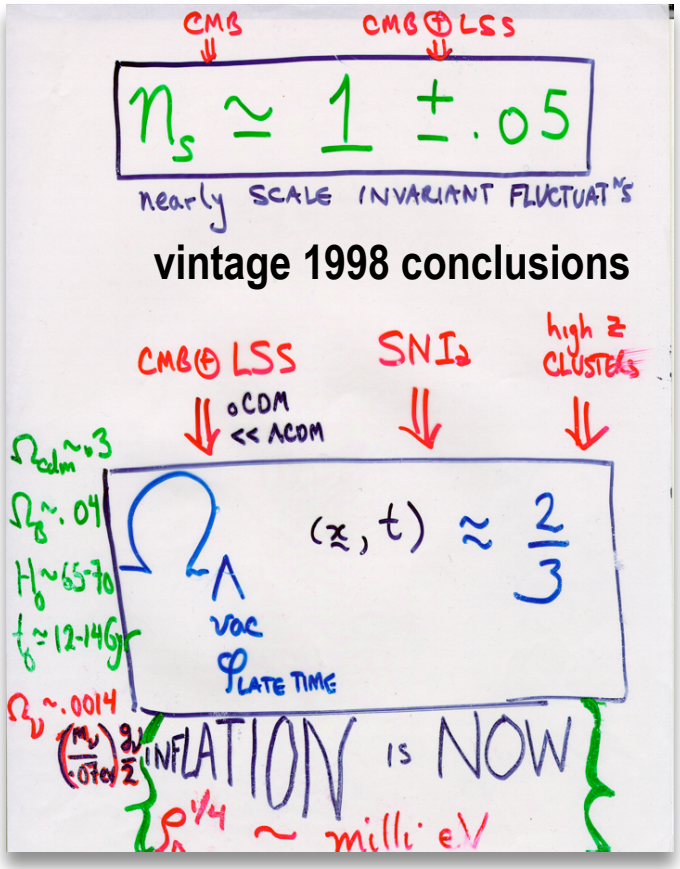


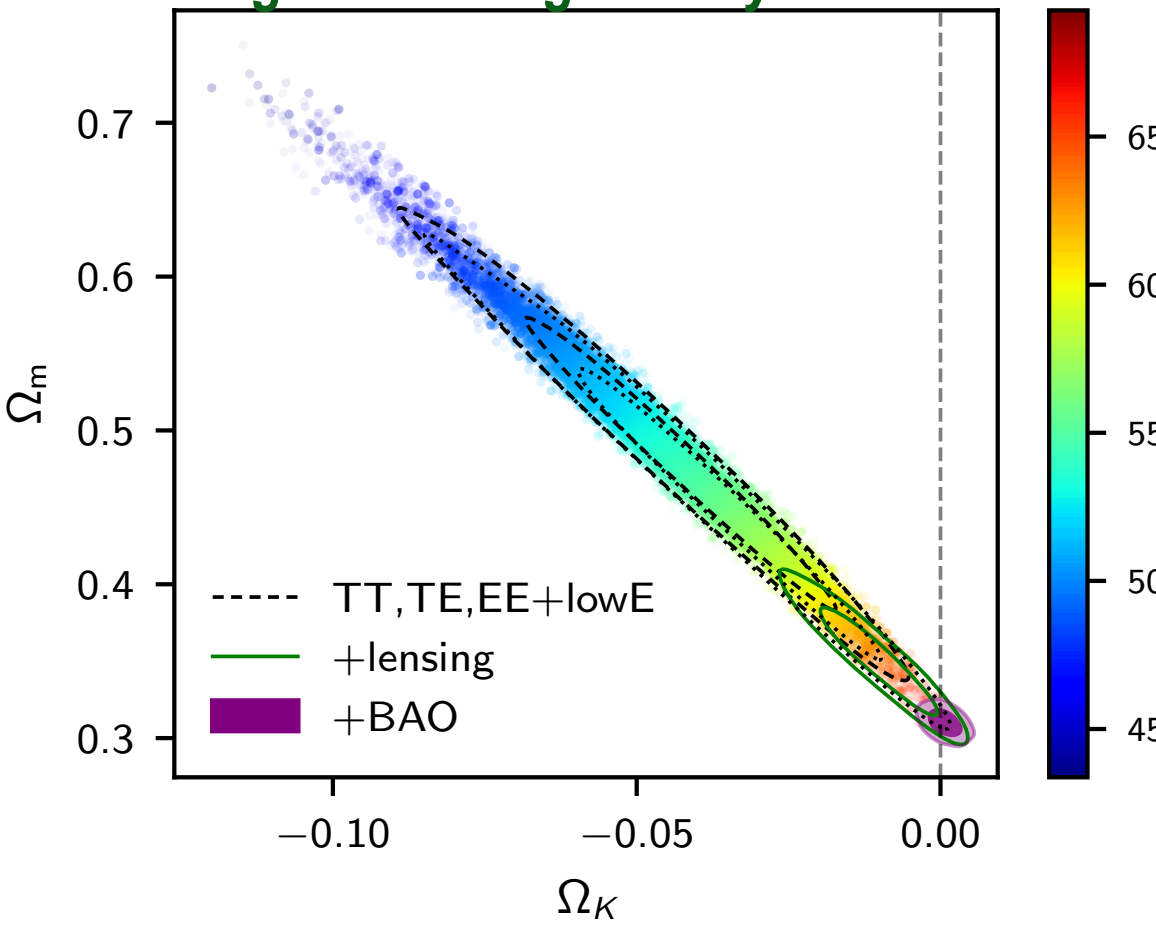
State of ***Inflation theory circa 87: 3 decades Nuffield conference was 1982***
Chaotic +++ model space M_Planck ***phonons -> inflaton -> ζ =ln a***
stochastic inflation δφ~h_Planck H *aka* ***quantum "zero-point" fluctuations***
Starobinksy inflation, Higgs inflation … running of M_Planck(R,φ)
GravityWaves 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 I*



n_s =0.9665±0.004 *P18VI*
8.8σ *from 1*

B+Jaffe'96,'98

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

$n_s =$
$.98 \pm .07$
$.96 \pm .06$

Ω_Λ =0.6889±0.0034 *P18VI*
w_0: -1.04± 0.1
Ω_κ: .0007 ± 0.004

<ζ|Temp, E pol>-*WebSky* reveals *early universe phonons*

ζ- TOPOGRAPHY & CARTOGRAPHY

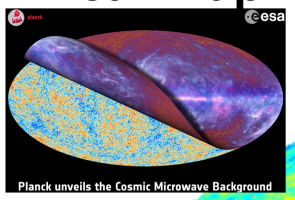
=> @a ~1/10^{55} only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

only partial de-lens

Planck 2018

15 arcmin fwhm

linear map



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

visibility mask

∫d ***visibility***(*distance*) <ζ|*Temp, E pol*>

-40.0 +40.0

<ζ|Temp, E pol>-*WebSky* reveals *early universe phonons*

ζ- TOPOGRAPHY & CARTOGRAPHY

=> @a ~1/10^{55} only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

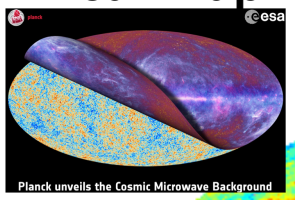
only partial de-lens

cmin

Planck 2018

15 arcmin fwhm

linear map



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

visibility mask

∫d ***visibility***(*distance*) <ζ|*Temp, E pol*>

-40.0 +40.0

Beyond the Standard Model of cosmology? SMc = *tilted*ΛCDM +r aka (ζ, h_{+x})

BSMc = SMc + primordial anomalies in the true ζ -WebSky

f_{NL^*} =-0.52 ± 3.0 for ζ

std **nonG** $\zeta = \zeta_G + \mathbf{f_{NL^*}}\ (\zeta_G^2 - \langle\zeta_G^2\rangle)$ local & equilateral pattern & orthogonal

non-std nonG $\zeta = \zeta_{inflaton}$ + ***uncorrelated*** $\zeta_{[GRF}\}$ modulated heating intermittent?

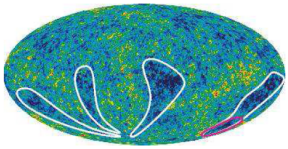
CMB TT correlation C(θ) ~0 @ >60°
hemisphere difference ~7% at low resolution

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

CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip

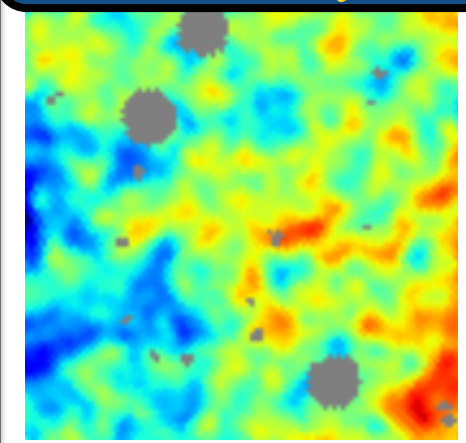
octupole/quadrupole alignment

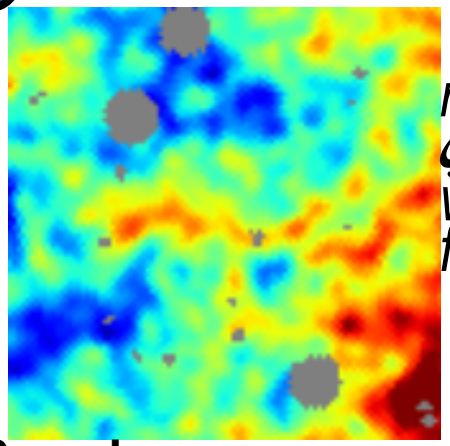
dipole modulation/ asymmetry direction



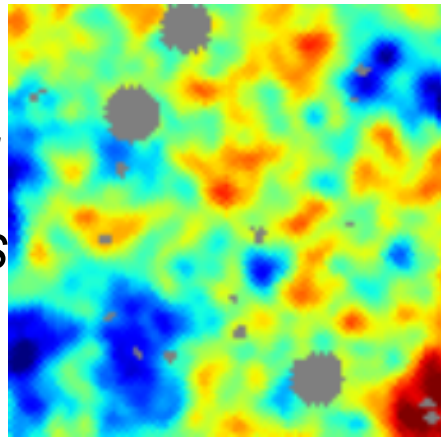
real ζ -WebSky mean field

visibility mask





real ζ-WebSkys with fluctuations

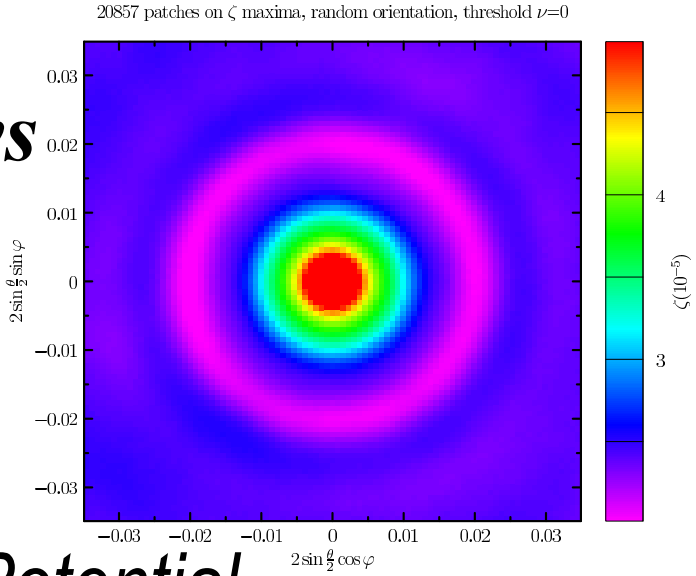


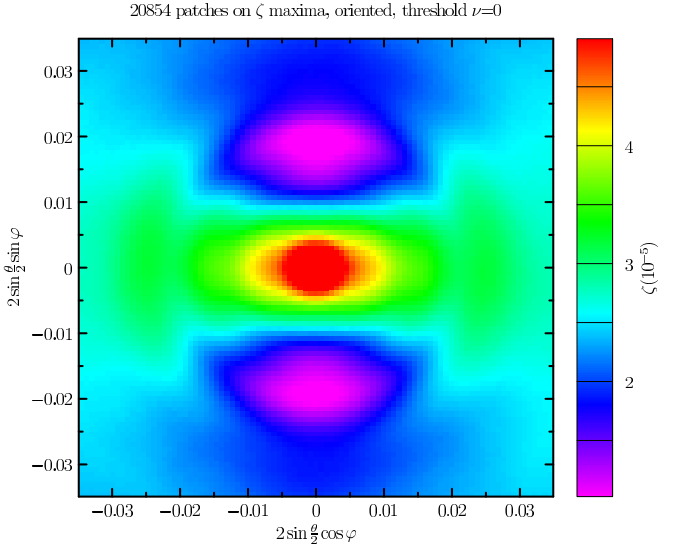
20x20 sq deg

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*

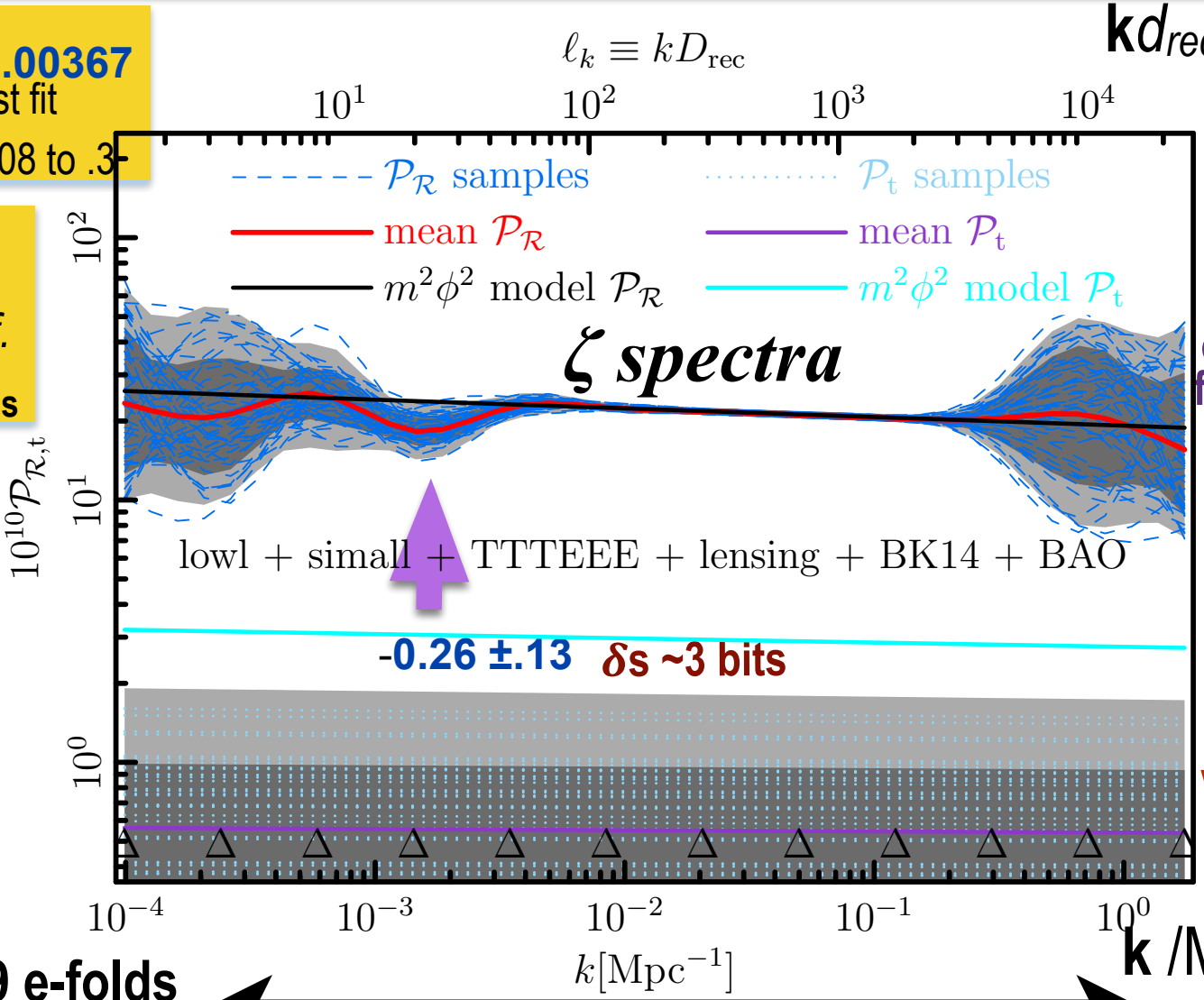
CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip; *includes CMB lensing, parameter marginalization*

uniform n_s=0.9669±.00367
P18+BK14 LSS best fit
superb 12-knot fit k~ .008 to .3

P18+BK14

r<.084 95%CL *cf.*
r<0.068 uniform n_s

kd_{rec} ≳L



=> lots of room for large ζ =>

=> V(ϕ)

k /Mpc

=> σ(r)
SO 0.003 =>
S4 0.0005
Litebird 0.001

9 e-folds

the **true quadratic ζ-Websky** of the **ζ-scape**

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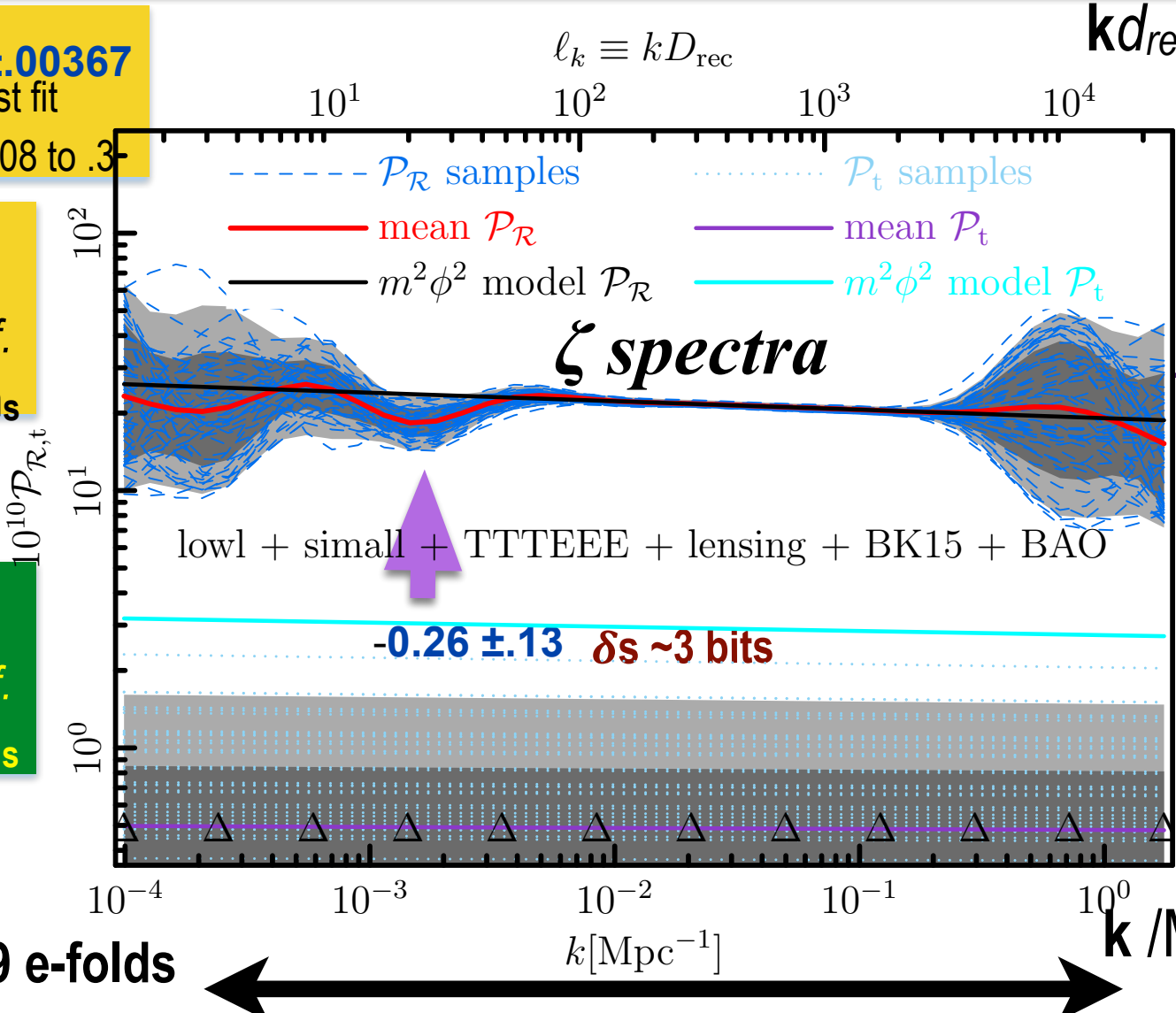
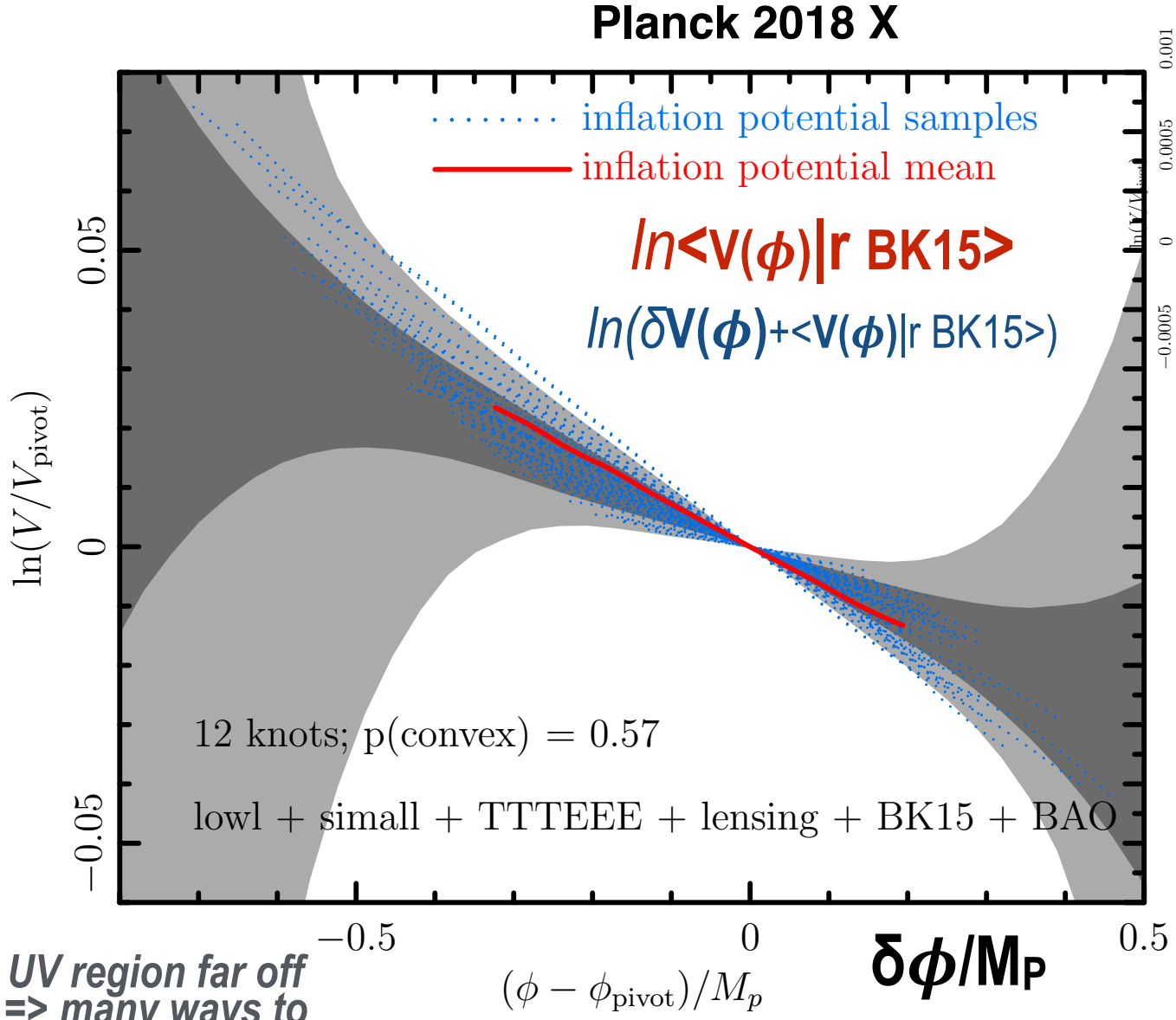
r<.069 95%CL *cf.*
r<0.061 uniform n_s

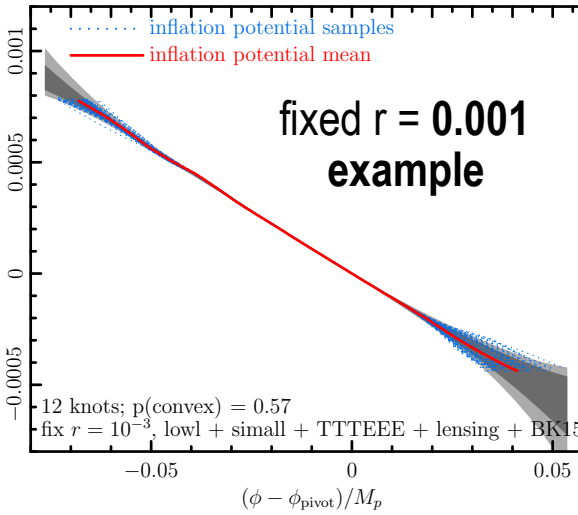
=> $\sigma(r)$
SO 0.003 =>
S4 0.0005
Litebird 0.001



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

along the gradient / Morse flow





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

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

UV region far off => many ways to extrapolate

r to **+-0.003 Simons Observatory** forecast w/ fgnds; 0.0005 S4; 0.001 Litebird

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±.00367
P18+BK14 LSS best fit
superb 12-knot fit k~ .008 to .3

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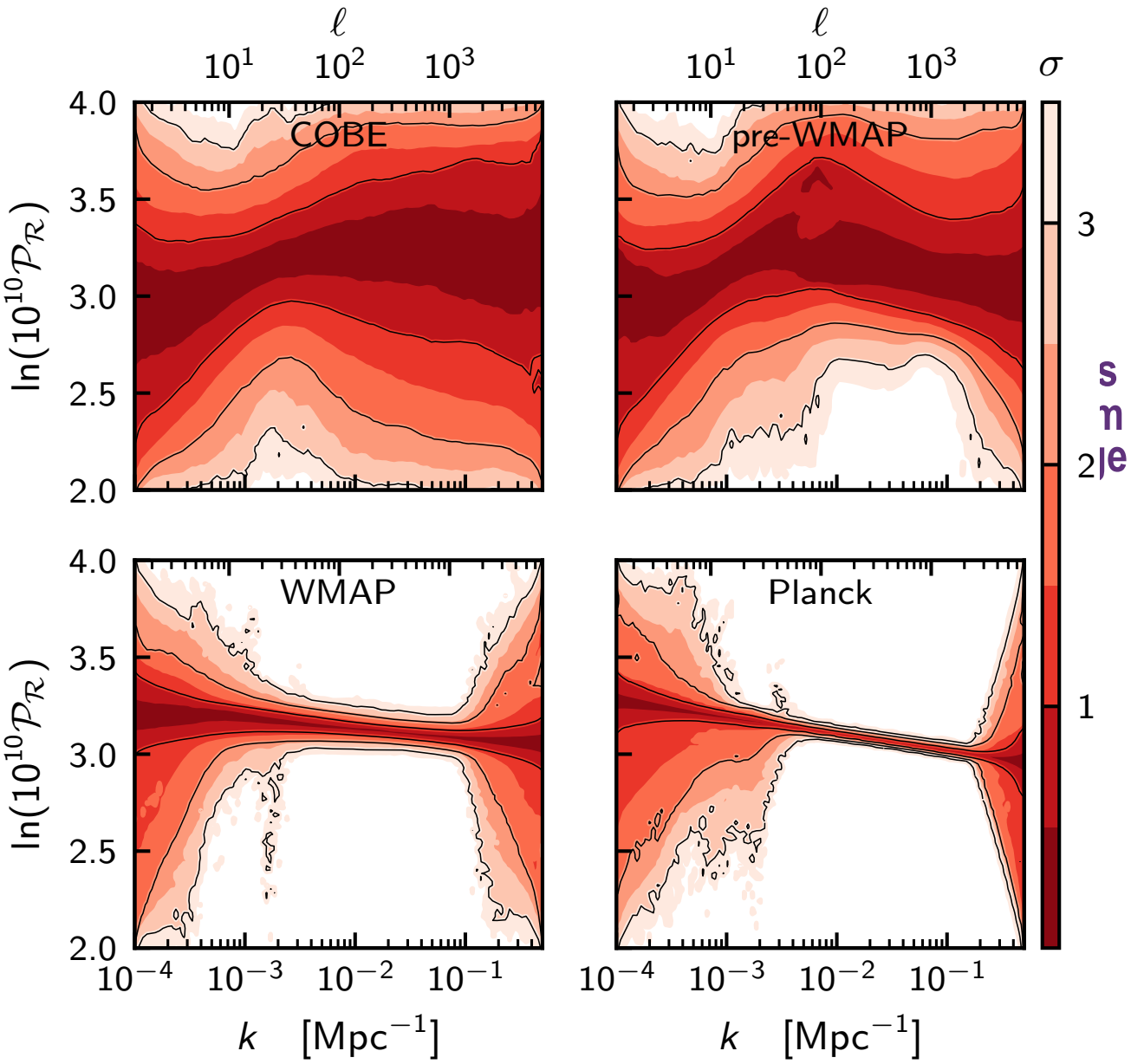
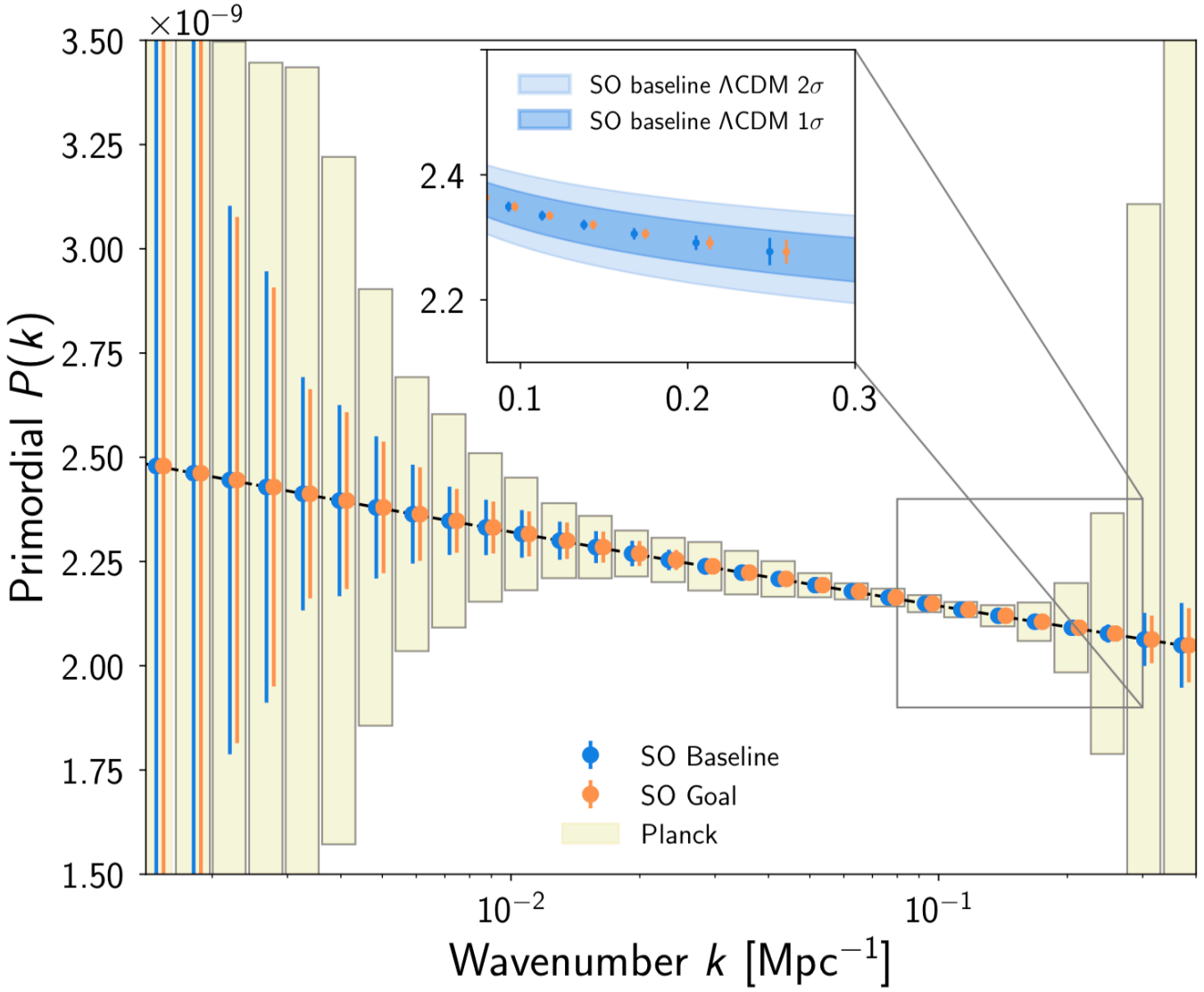


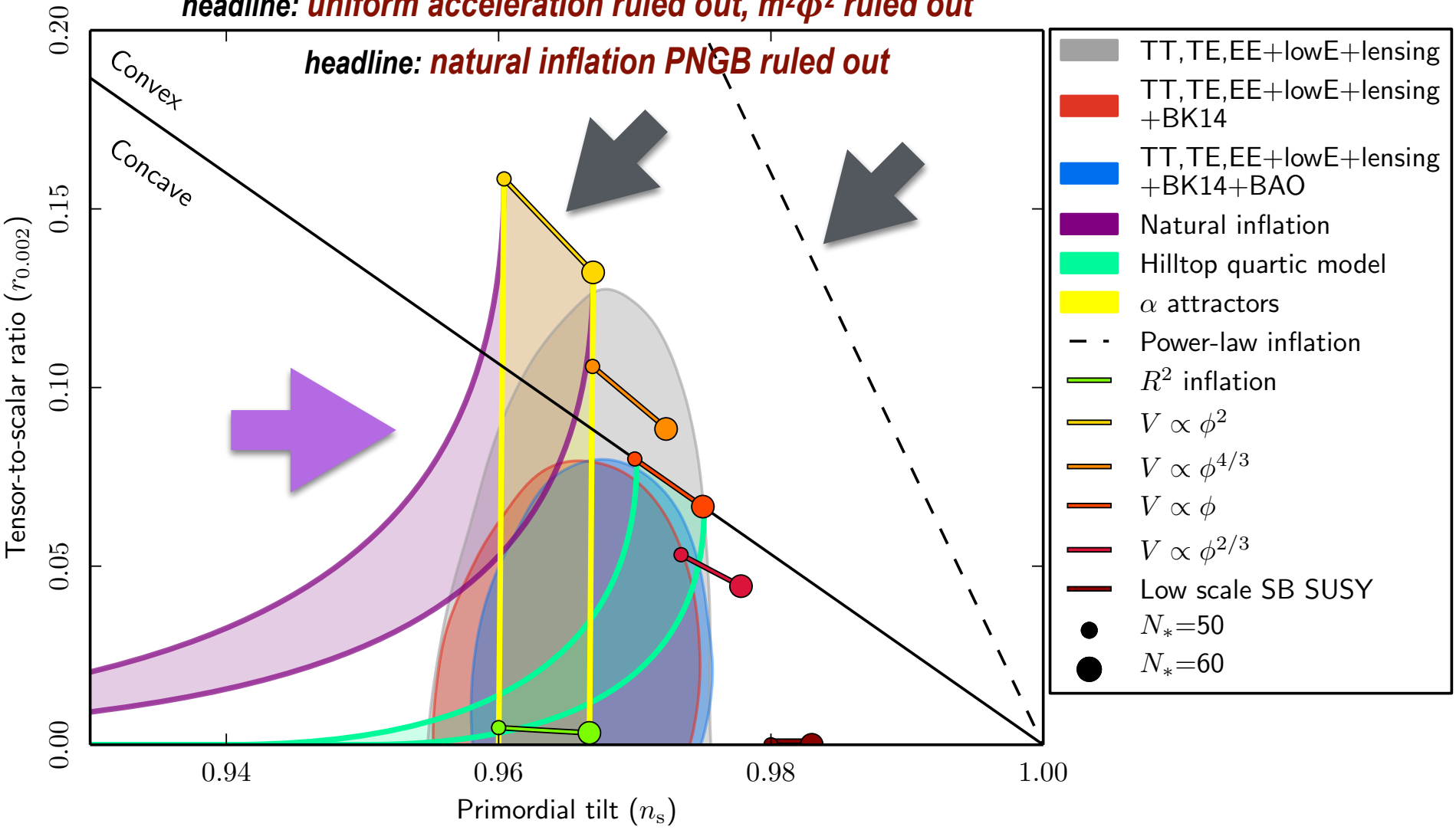
the **true quadratic ζ-Websky** of the **ζ-scape**

Sample Cosmological Forecast: Simons Observatory

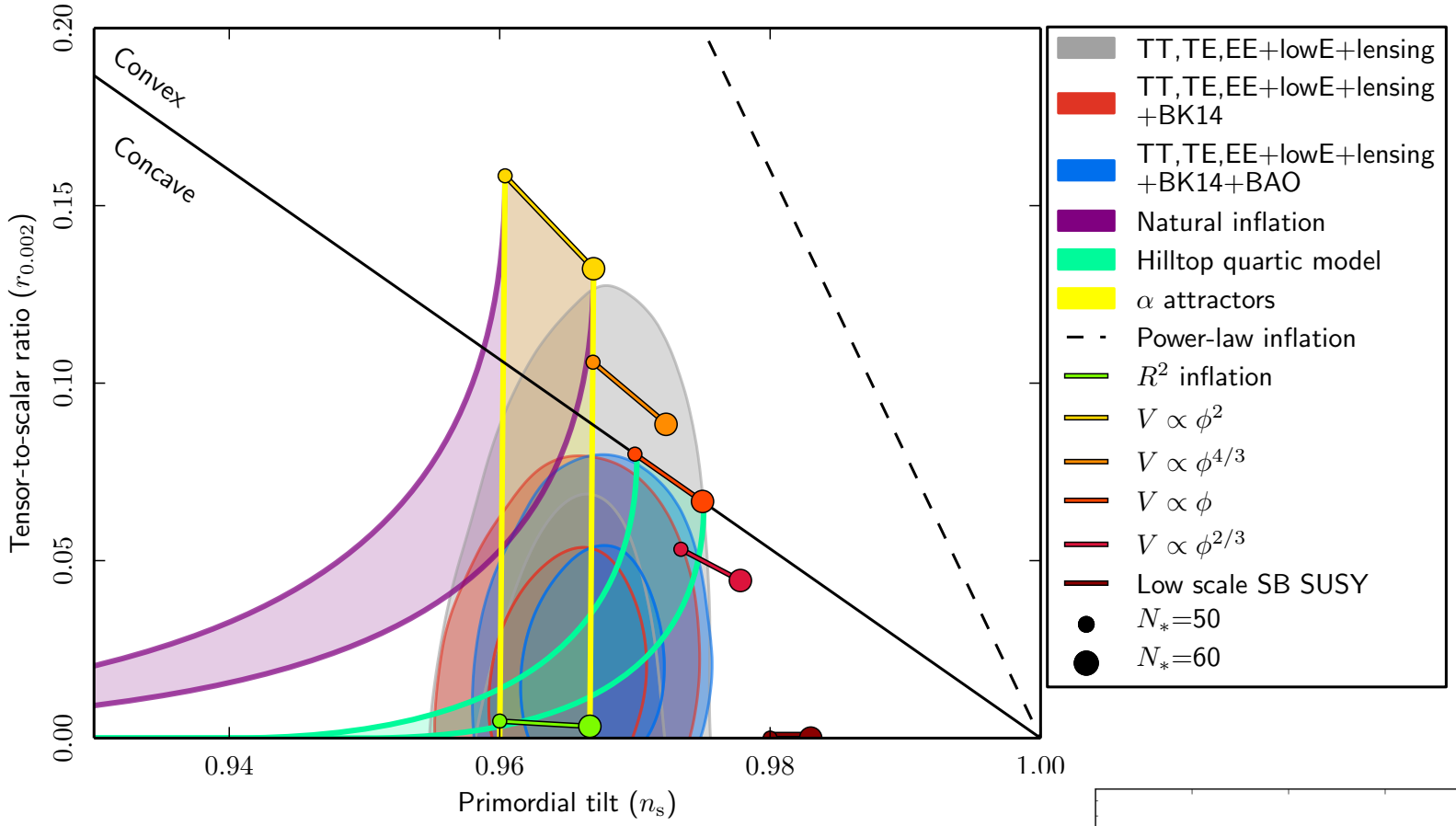


headline: ***uniform acceleration ruled out, $m^2\phi^2$ ruled out***

headline: ***natural inflation PNGB ruled out***

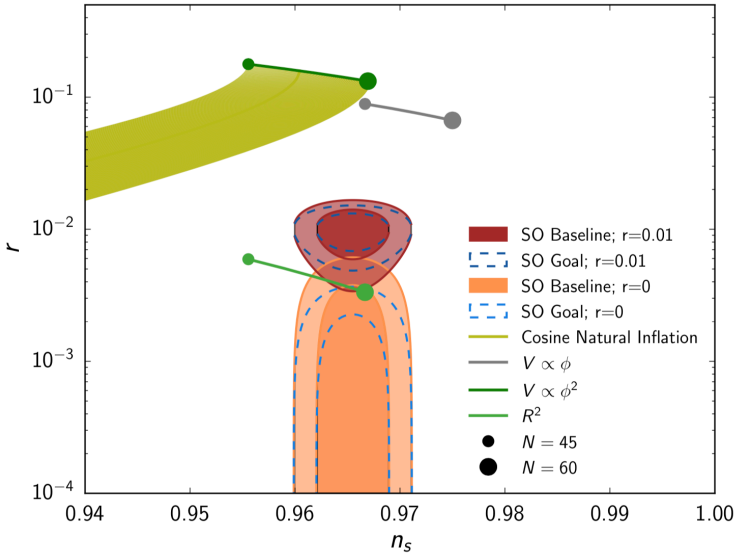


headline: ***conformally flattened potentials OK, includes R^2 inflation & Higgs inflation, α-attractors***



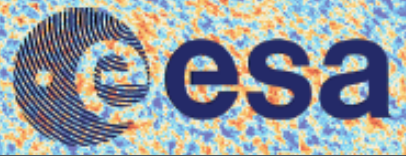
Sample Cosmological Forecast:
Simons Observatory

=> σ(r)
SO 0.003 =>
S4 0.0005
Litebird 0.001



Dick Bond

Quantum Inflation in the Planck Era & Beyond



relic1: ζ *from* ***inflaton*** *- observable = all cosmic structure CMB&LSS & stars/humans etal amplitude & slope <-> acceleration history & Veff 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 ± 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 ± 0.7%

Dick Bond

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 *cf.* 0<r<.,07 95% CL P15+BK15 12 knots
- isocon relic (not so far) - Planck on CDM isocurvature, neutrino, correlated

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

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

Planck2018 early U structure map

reveals primordial ***sound waves*** *in matter*

=> *learn* ***contents*** *&* ***structure*** *at 380000 yr,* $a\sim e^{-7}$

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

T+E constrained mean of 10^5zeta; fwhm = 15 arcmin

2⁺ numbers

a picture of the **quantum phonon field**

= *ln* $a(x,t)$ 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} **Power$_s$=3.05**±0.014

n_s =0.967±0.004 *8.8σ from 1* most celebrated Planck result

constant n_s is a superb 12-band fit (over k~ .008 to .3 /Mpc) B+Huang in Planck 18 X

Tensor-to-Scalar ratio (GW)

r <0.06 P18+BK15

=> σ(r) S4 0.0005?

Litebird 0.001?

CMB+LSS as a fundamental physics laboratory YES

-40.0 +40.0

END