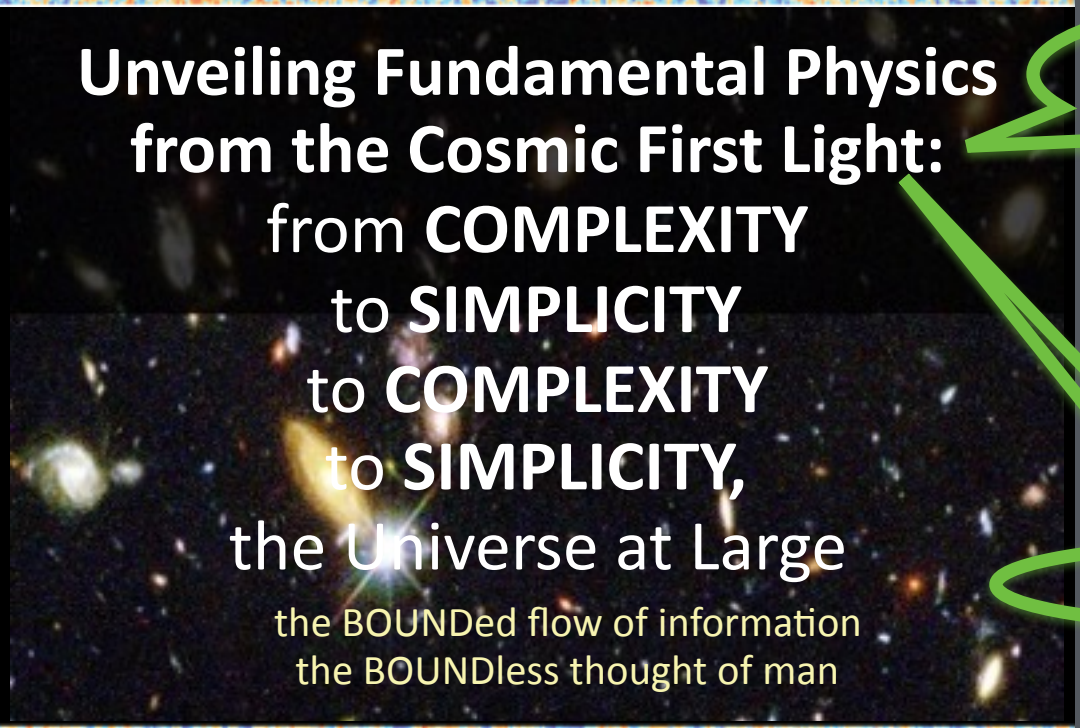
Quantum Inflation in the Planck Era & Beyond

Dick Bond @ ICTS 19 01 15



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 past => CMB present

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

CMB+LSS future

SMc -> BSMc

Beyond the Standard Model of Cosmology

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

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

Quantum Inflation in the Planck Era & Beyond

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

a tale of Planck4**

How the Planck satellite helped decode the role of Planck's quantum h_{bar} &

CMB past => CMB present

7+ numbers

3 densities, *2+1 early-Universe inflation*

CMB+LSS future

SMc -> BSMc

Beyond the Standard Model of Cosmology

coarse-grained quantum diffusion (Fokker-Planck) in the emergence of our Universe from the Planck-era

$\sqrt{D_H} \sim h_{bar} H \sim T_H$

$M_{Planck} c^2 = h_{bar} c / \sqrt{8\pi G_N}$

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 2015-18 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 ??

an extended CMB family reunion & *Peebles@80*

CMB@53:

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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 ***CnuB***

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 …

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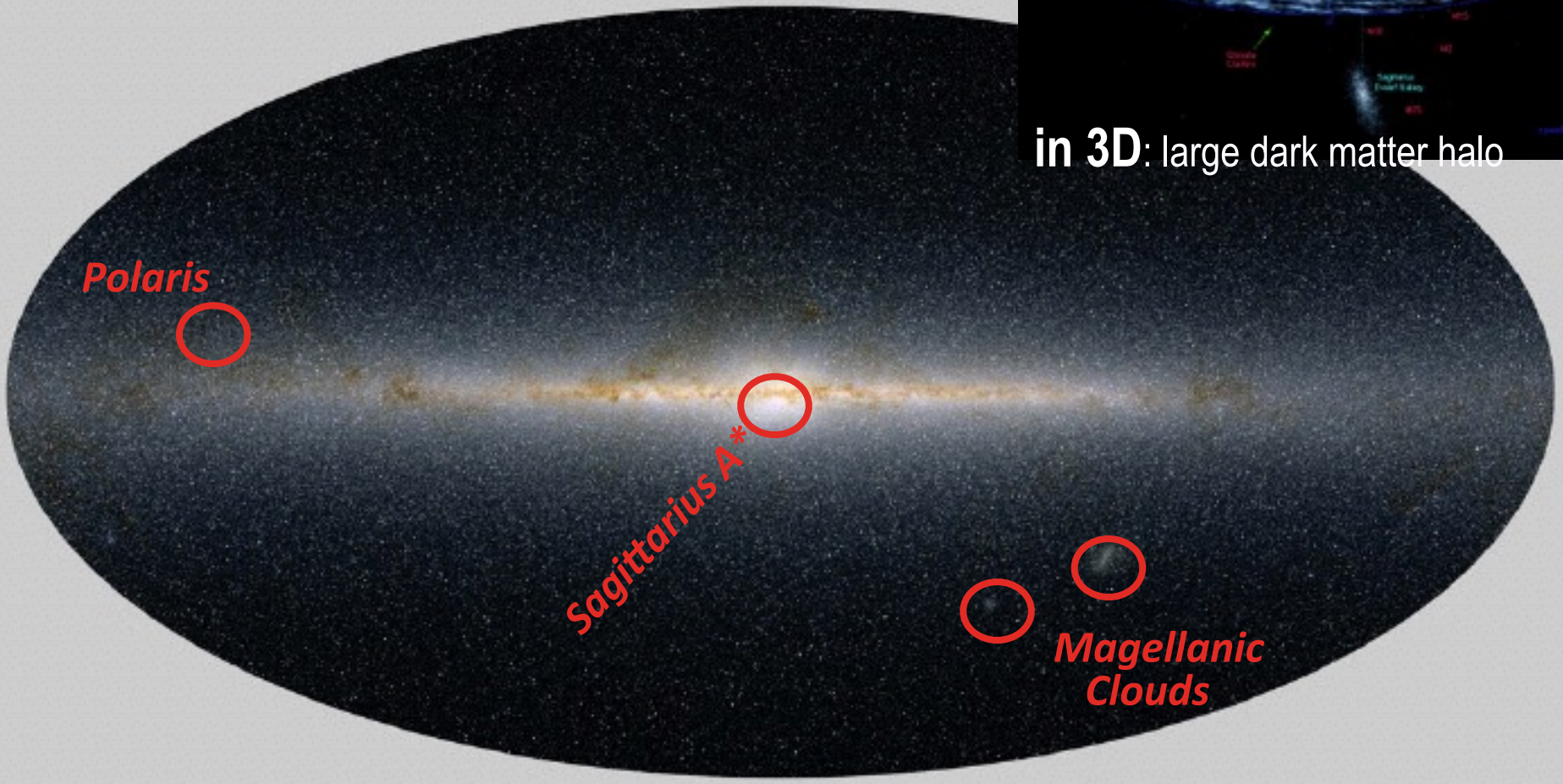
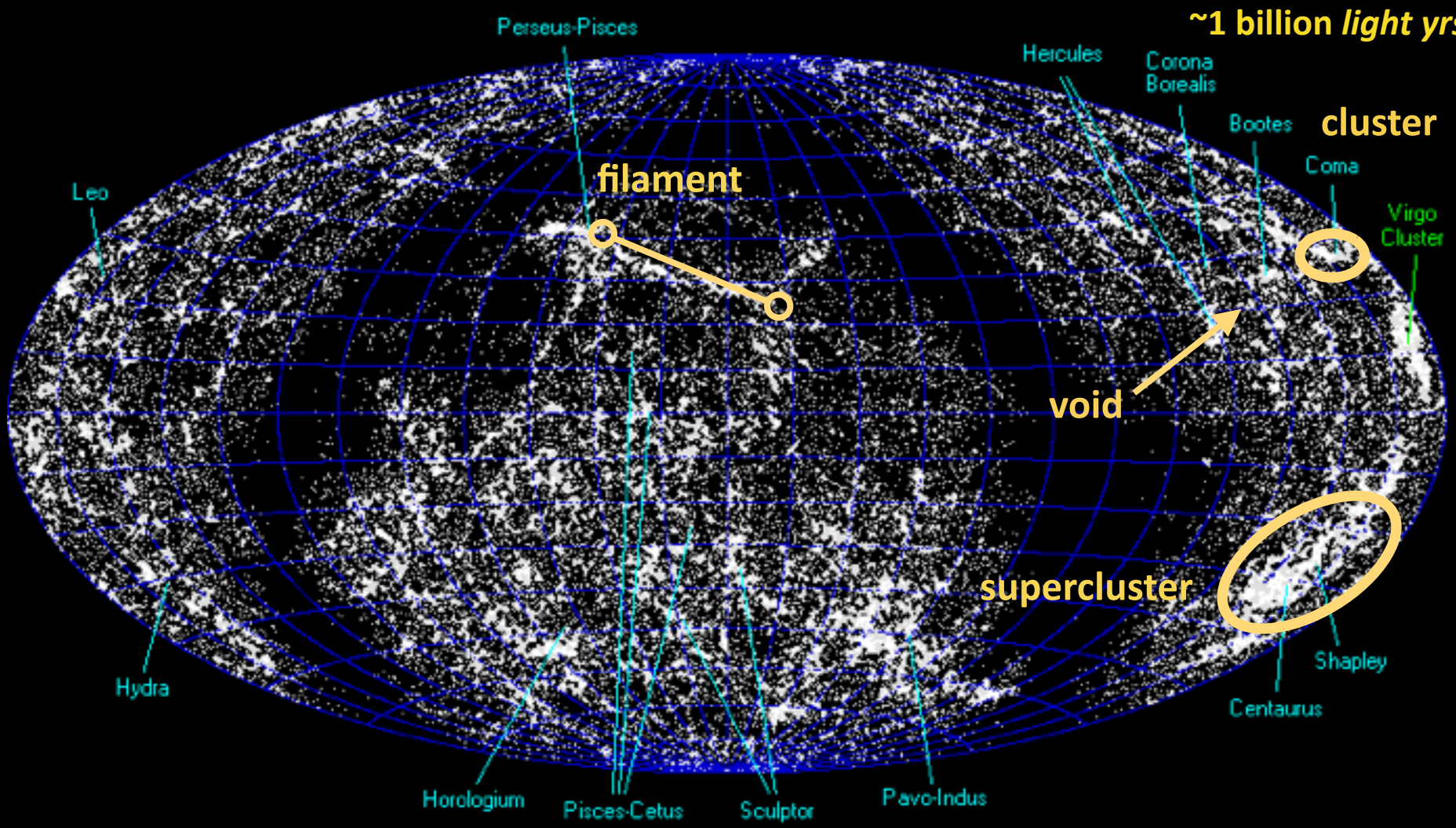
Milky Way in infra-red:

half a billion stars, a disk galaxy

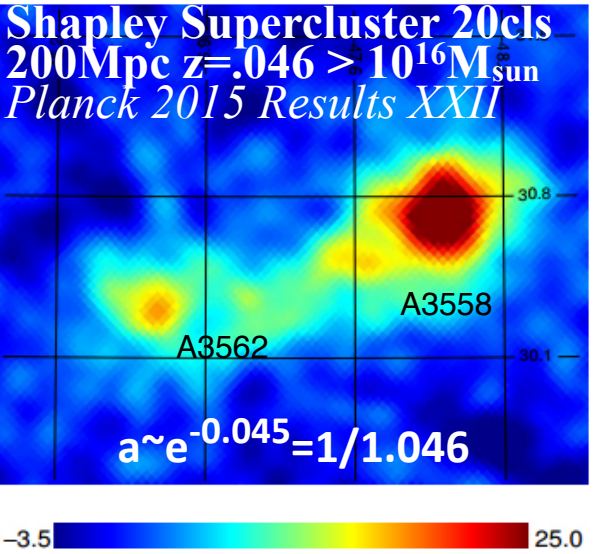
in 3D: large dark matter halo



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

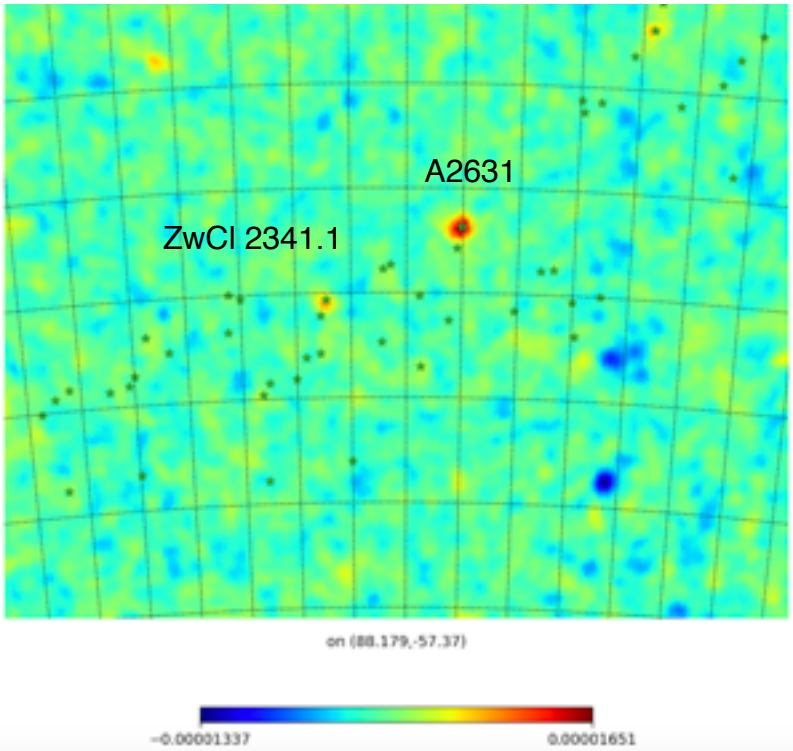


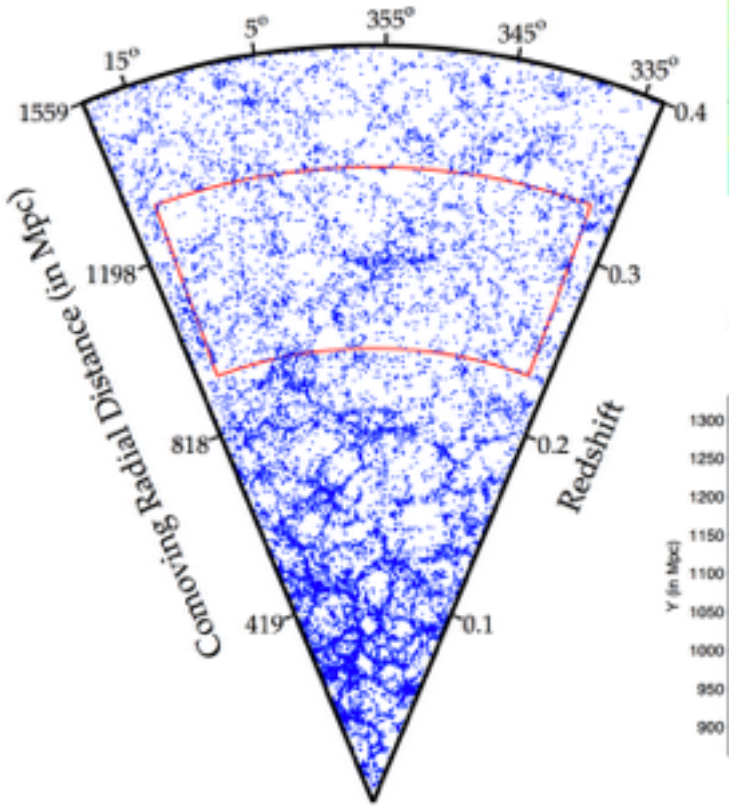
observational emergence of the web = ~80s tour de force, e.g., Coma supercluster ++. voids
interconnected structures from a Gaussian random adiabatic field under gravitational instability

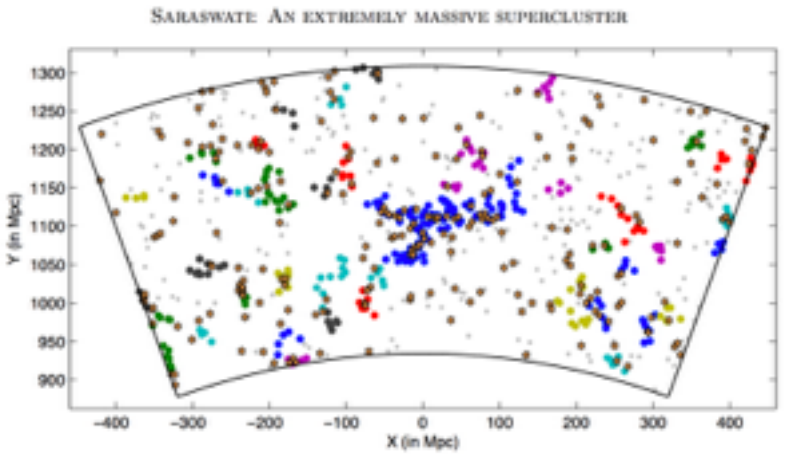


the **Indian Supercluster**

a~e$^{-0.25}$=1/1.28







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

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

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

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

ε=strain tensor

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

H_J^i=*Hubble ie* ***shear*** $=d\alpha_J^j/dt$

general relativity $g=aa^\dagger$

Earth under Strain: earthquakes, seismic waves

ε=strain tensor

Universe under Strain: space-quakes, gravity waves

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

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

isotropic strain, sound Trace(**ε**)

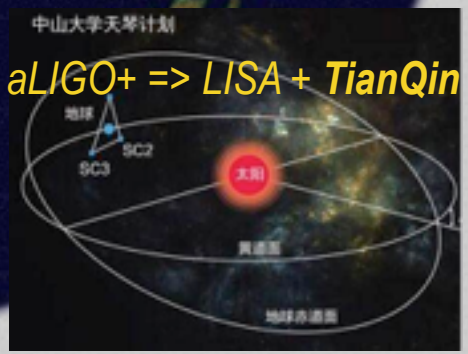
scale-deformation $\mathbf{a_J^i}$

anisotropic strain, gravity waves

isotropic strain, sound

linear: **strain** ∝ **tide**

cosmic web *story*



light and gravity are entangled: wavelength stretches under space-strain: **redshift**

inflation theory = vacuum deformation under strain, condensate(t) + quantum fluctuations

Earth under Strain: earthquakes, seismic waves

ε=strain tensor

Universe under Strain: space-quakes = gravity waves

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

scale-deformation a_J^i

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

anisotropic strain, gravity waves

isotropic strain, sound Trace(ε)

isotropic strain, sound

linear: **strain ∝ tide**

cosmic web *story*

Elastic: **Stress =** ***Bulk+Shear-elastic-moduli**** **Strain**

sound speed $c_s^2 = BEM/\varrho$ ***anistropic shear-wave speed***^{2} $\sim SEM/\varrho$

Viscous: **Stress =** ***Bulk+Shear-viscous-moduli**** **Strain-rate**

Gravity: **Stress =** ***BAM**** **Strain-acceleration ~** ***BAM**** **Tide**

$$BAM = 1 / 8\pi G_N = (M_{Planck}\, c/hbar)^2 \propto 1 / L_{Planck}^2$$

~

inflation theory = vacuum deformation under strain, condensate(t) + quantum fluctuations

stable quantum fluctuations $p = hbar\, k > hbar\, H/c$ oscillate,
become *Jeans-unstable* $p < hbar\, H/c$ fluctuations as $H(x,t)$ drops

generalized Fokker-Planck equation for coherent-condensate-probabilities *aka stochastic inflation*

coarse-grain system = ***coherent unstable modes,*** **fine-grain reservoir =** ***stable modes***

transport across the ***hbar H boundary:*** *the newly-unstable* ***quantum-entangles*** *with the* ***unstable-condensate***

H(x,t) cg-deSitter space sequence. Casimir energy = $\varrho_{qfluc}(H) - \varrho_{qfluc}(H=0)$ ***drives emergence***

this really is like the Jeans instability, and intimately related to cluster-halos as mass-density condensates

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

H_J^i=*Hubble ie* **shear** $= d\alpha_J^j/dt$

general relativity $g = aa^\dagger$

isotropic strain & phonons

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

$= \text{Trace}\ \alpha^i_j + \int_{field\text{-}path} d\ln \rho_{Ec}/(1+w_c)$

energy-density & gravity are entangled

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

stochastic inflation:
the battle of classical drift V_c &
diffusion of quantum fluctuations V_D
$V_c \sim \nabla S_R$ $V_D = D_H \nabla S_I$
eternal inflation $\Rightarrow V_D$ dominates

emergence $\Rightarrow V_C$ dominates

to be fit into a

☛ ***UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..***

☚ ***IR-complete theory***

non-equilibrium post-inflation heating relaxes to an equilibrium quark/gluon plasma ???

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

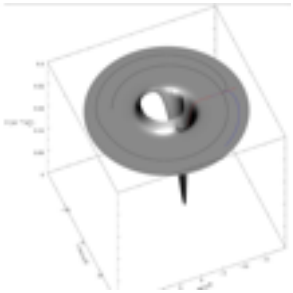
Relate to standard model? to Higgs?

conformal potential-flattening eg Higgs inflation SBB89 etc

inflaton+isocons potential $V(\varphi,\chi,..)$=?

$\varphi_c, \chi_c, .., \alpha_c, H_c$

$V(\varphi,\chi,..)$



Preheating After

Roulette Inflation

$\langle \tau \rangle =$

hbar H_c
quantum diffusion
spatial jitter

$-M_{Pl}\nabla \ln H_c$
drift

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

isocon directions, *e.g.,* ***axion***

let there be heat

semi ETERNAL INFLATION EMERGENCE

B2FH, b+braden+frolov+huang

BBKH09 + BBFH19 +

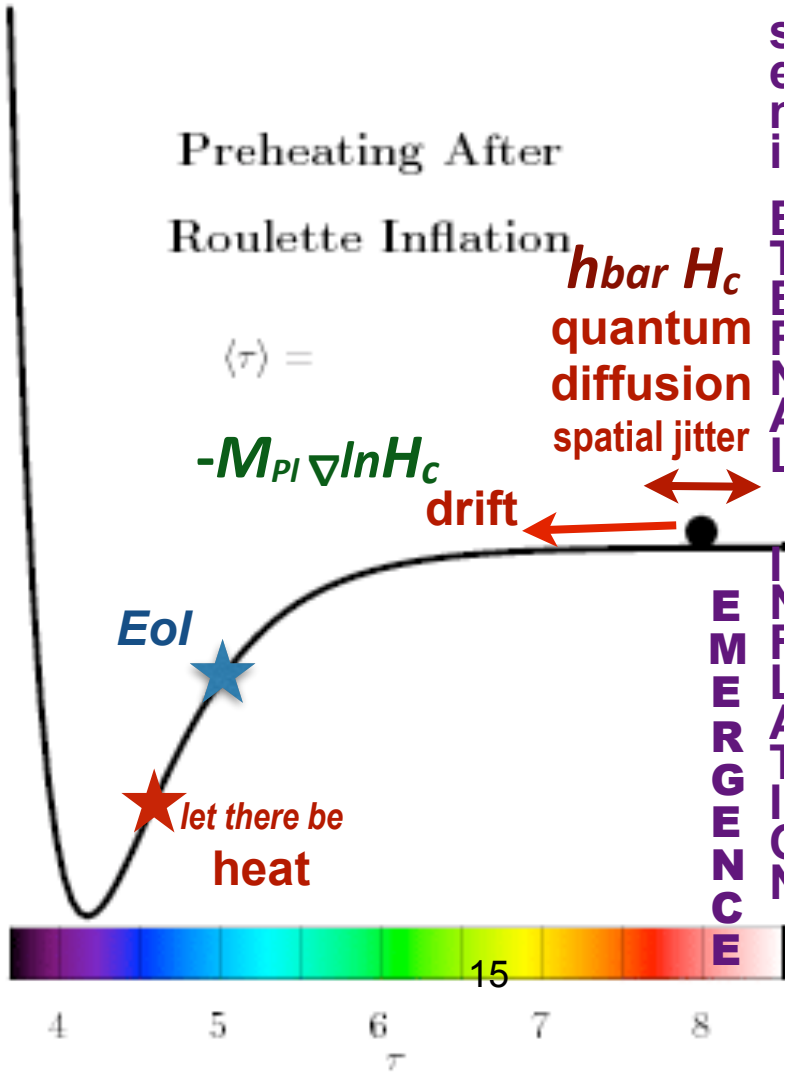
how was *matter & entropy generated at the end of acceleration = inflation*?

Relate to standard model? to Higgs?

$a =$ 1

A visualized 2D slice

in lattice simulation



EoI horizon ~ 1cm comoving

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

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ACT SPT higher resolution + polarization
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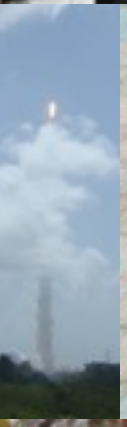
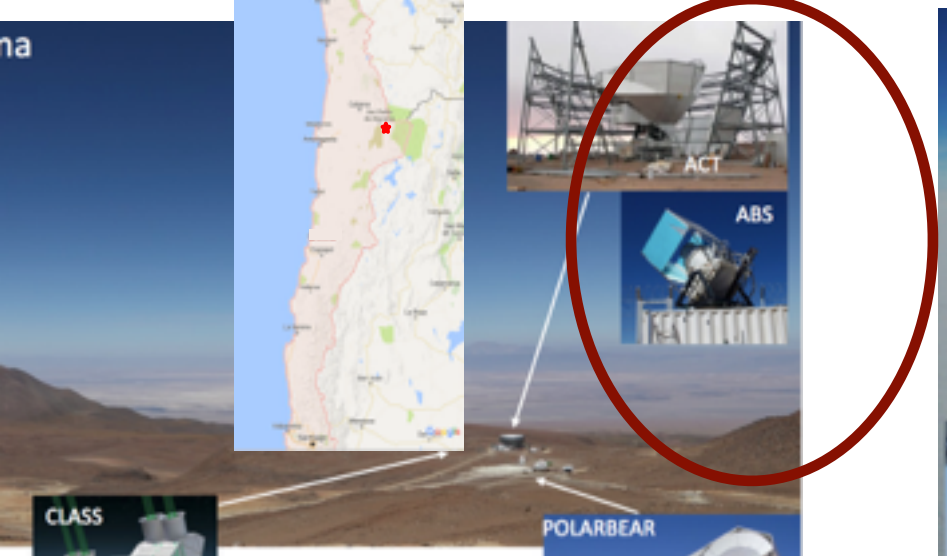
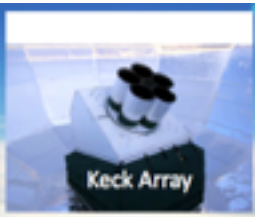
=> future
.. CMB Stage 3 (now) => SO Spider2
.. Stage 4 > 2025
.. LIteBird 2028, other satellites ??

an extended CMB family reunion & *Peebles@80*

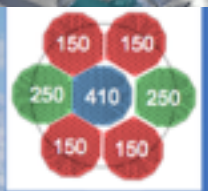





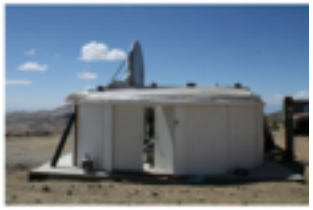
=>>>> Simons Observatory => CMB Stage 4



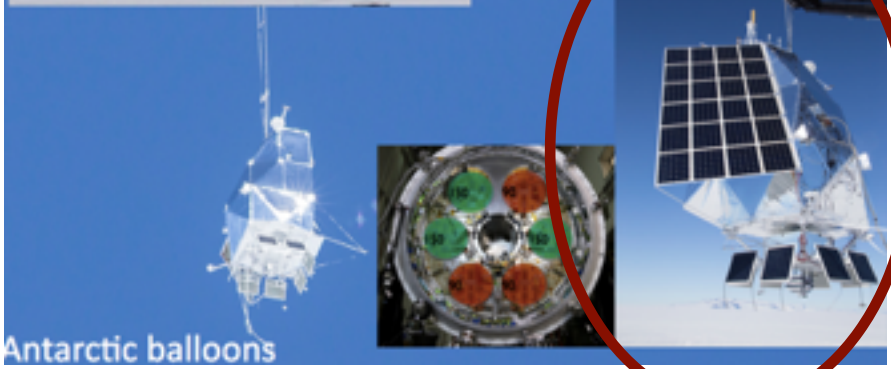
California+
South Africa
C-BASS 5 GHz



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



California
B-Machine 40 GHz



& futures CMB-S4, more ballooning, back into space

managing the CMB

on to SO -> CMB-S4
Advanced ACTPol

boomerang ~40/paper

planck ~250/paper, ~100 institutions

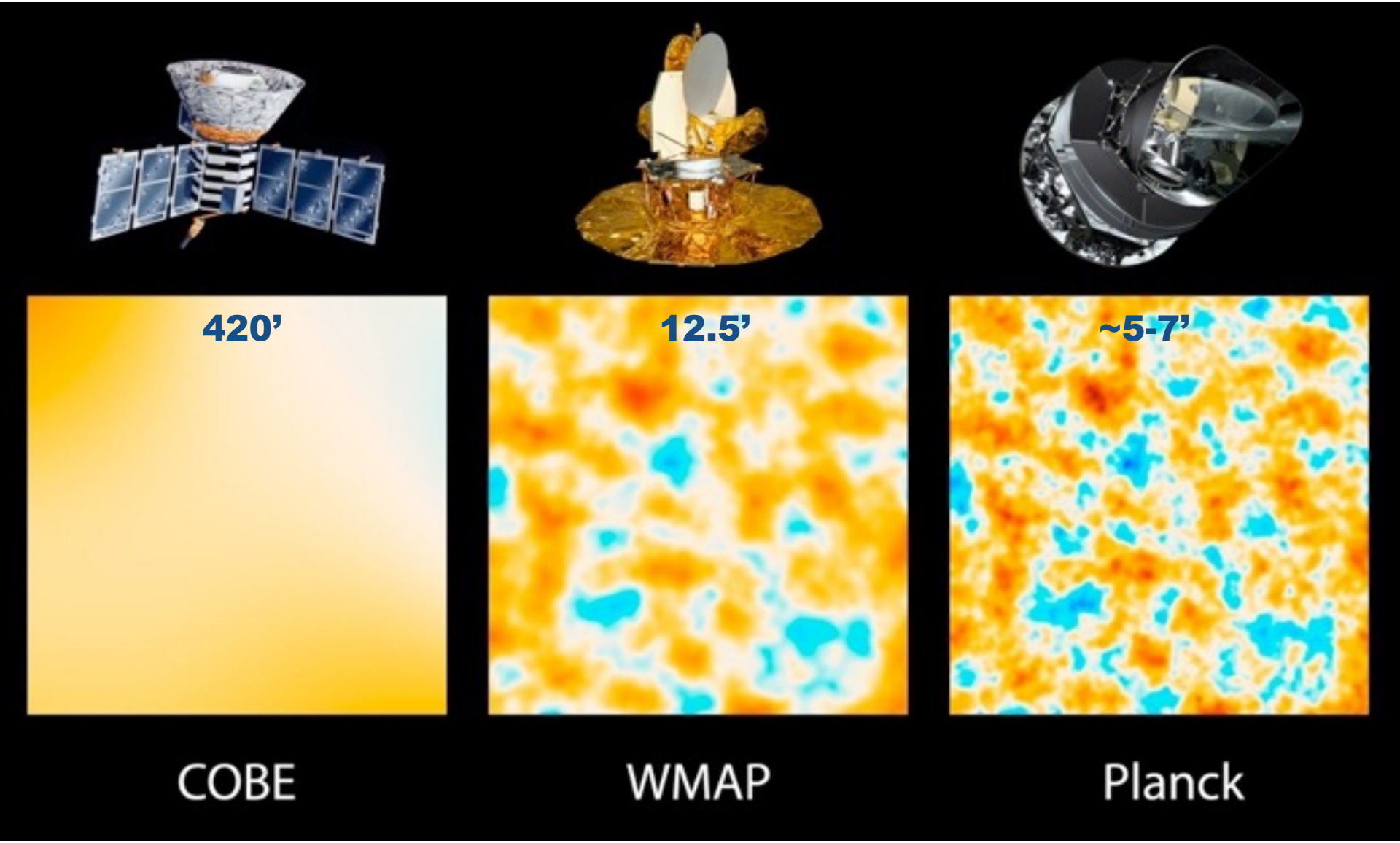
Cobras/Samba @Capri93

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*

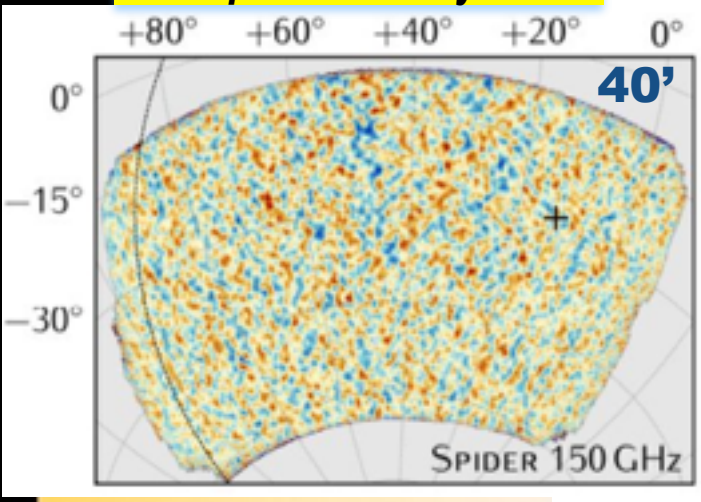


goal: high enough resolution to plumb all cosmic parameter information. but high L foregrounds, extragalactic sources => higher L expts ACT (1.4'), SPT (1') => SO/S4 (1')

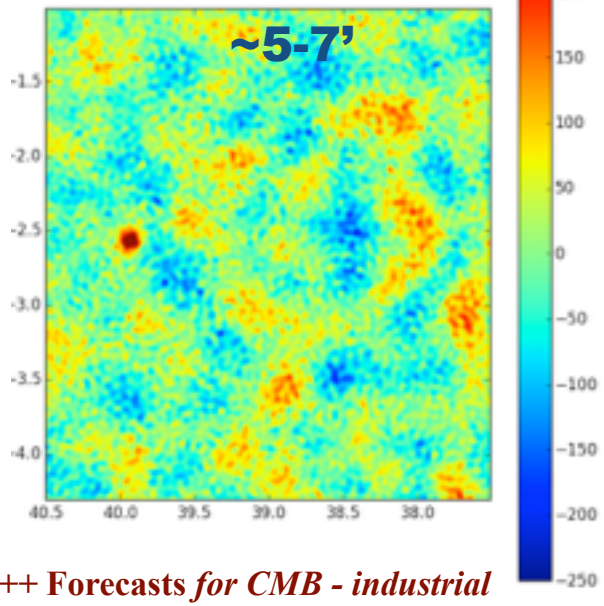
Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

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

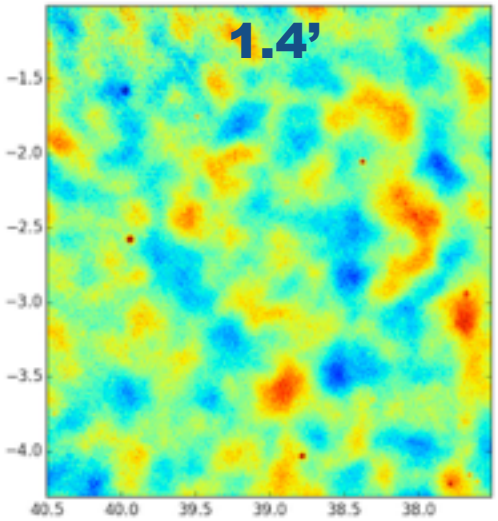
Spider 40' fsky~.08



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

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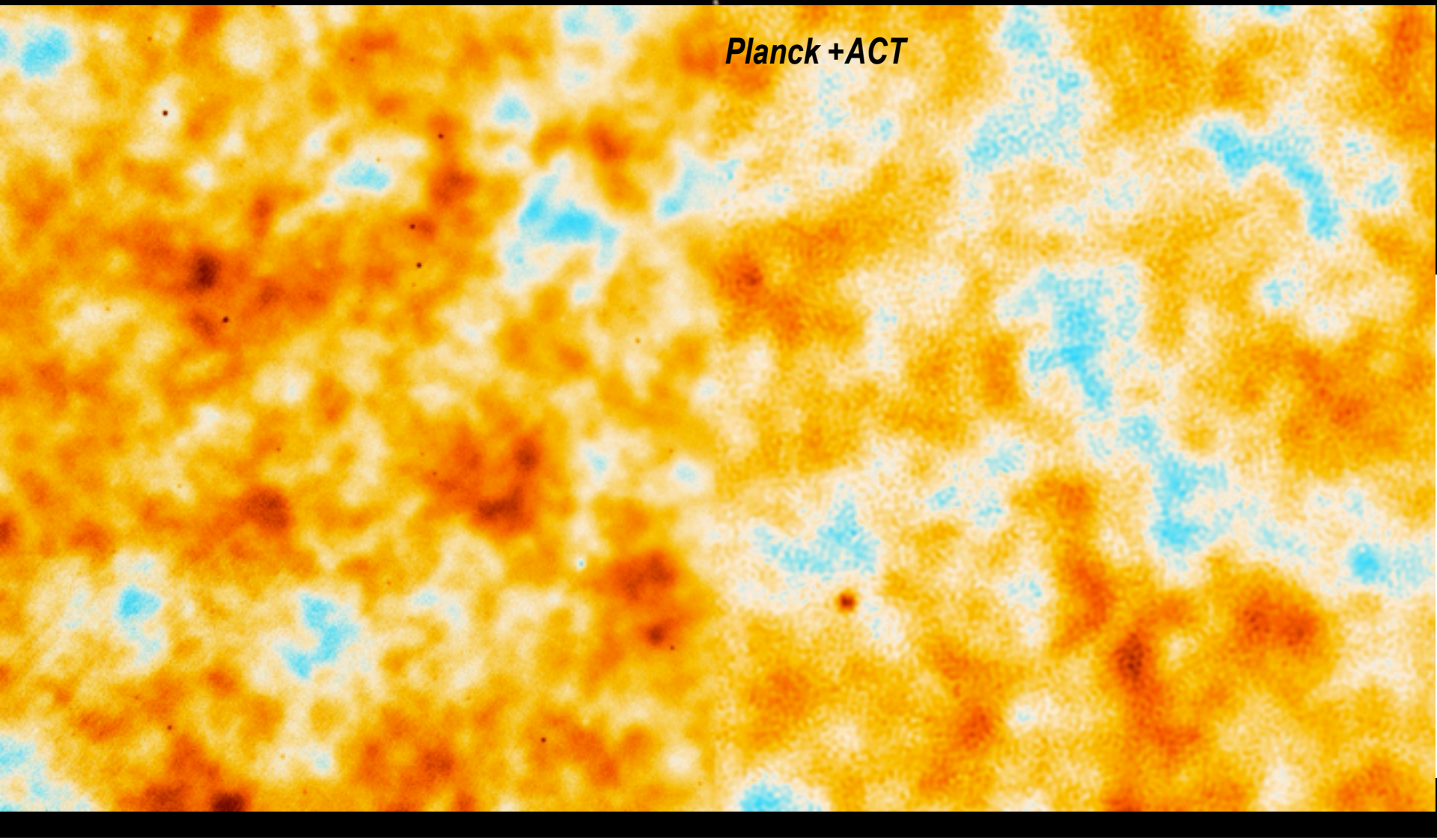

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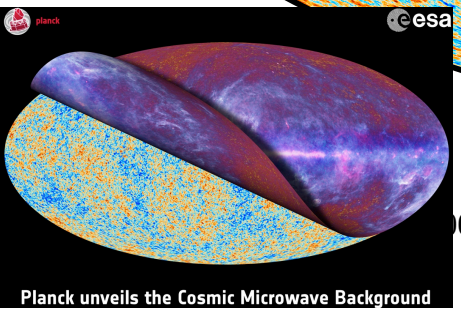
Planck's primordial light unveiled, *Mar 2013 =>* ***Feb 2015*** *=> pre-2016 =>* ***July 2018+*** *final*

reveals the SIMPLICITY of primordial cosmic structure

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



0 300 μK

Temperature changes in micro-degrees

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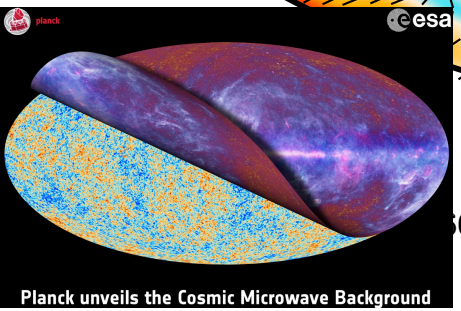

160 μK

Polarization on T

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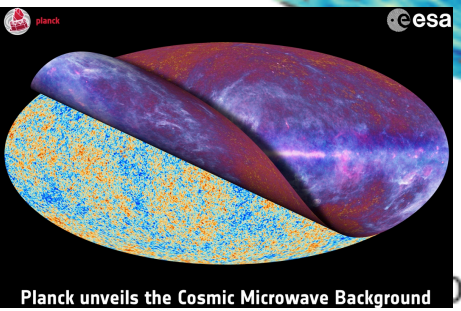

Lensing potential φ

-0.0016 0.0016

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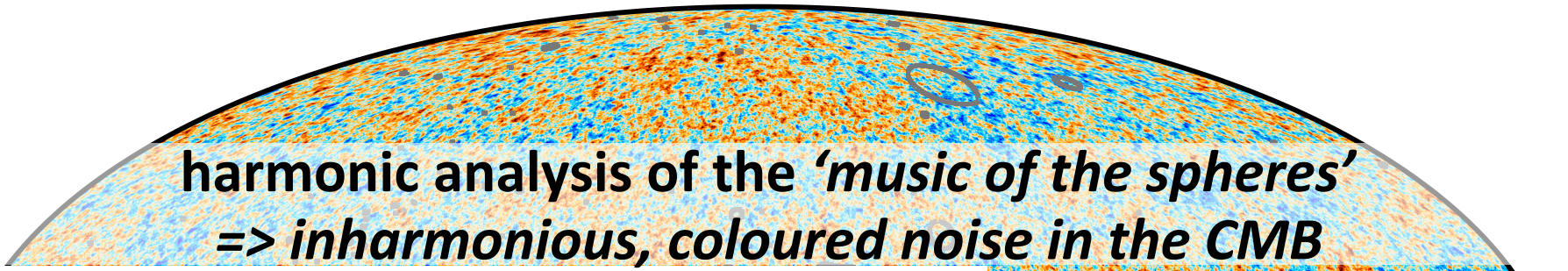
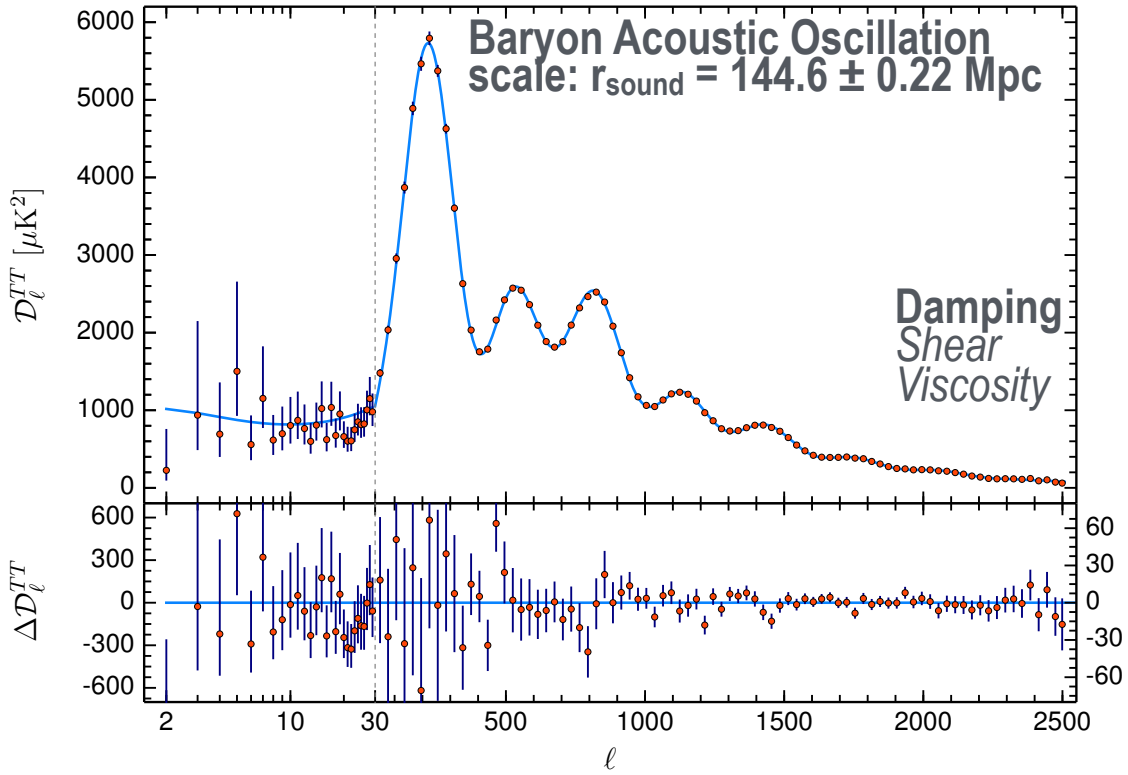
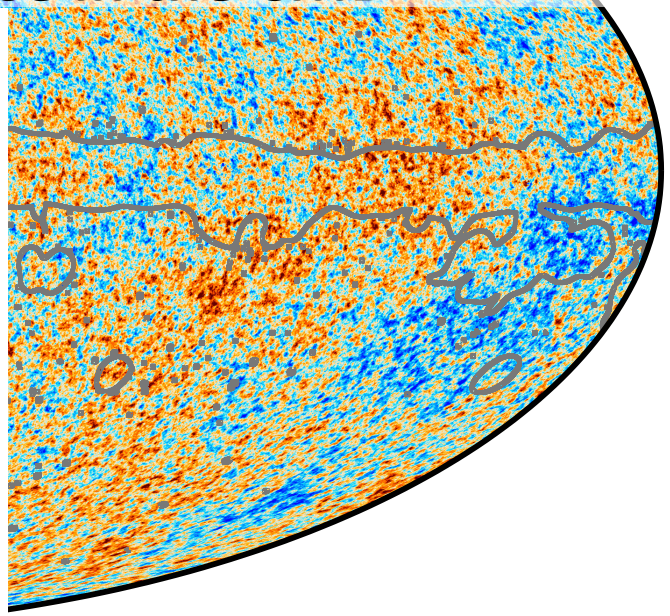


harmonic analysis of the *'music of the spheres'*
=> inharmonious, coloured noise in the CMB





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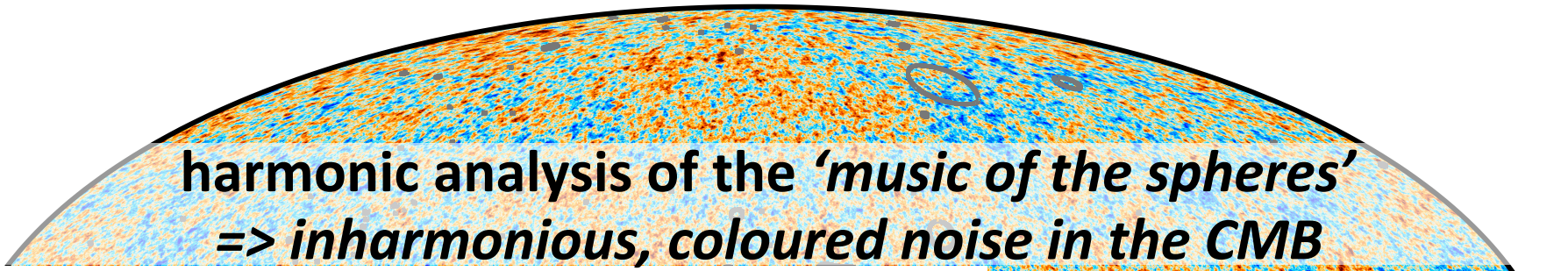

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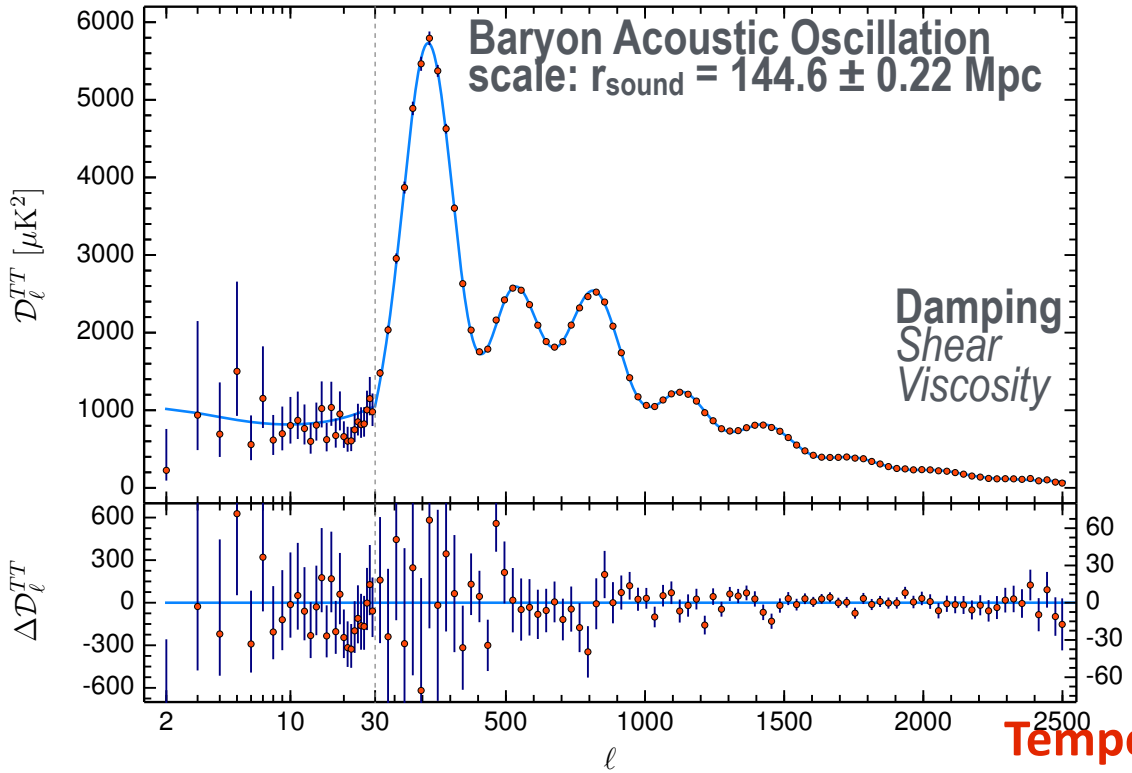
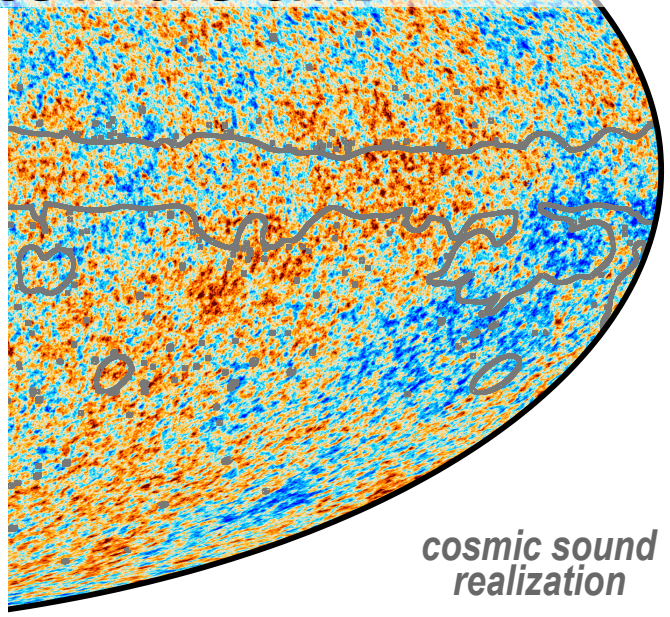


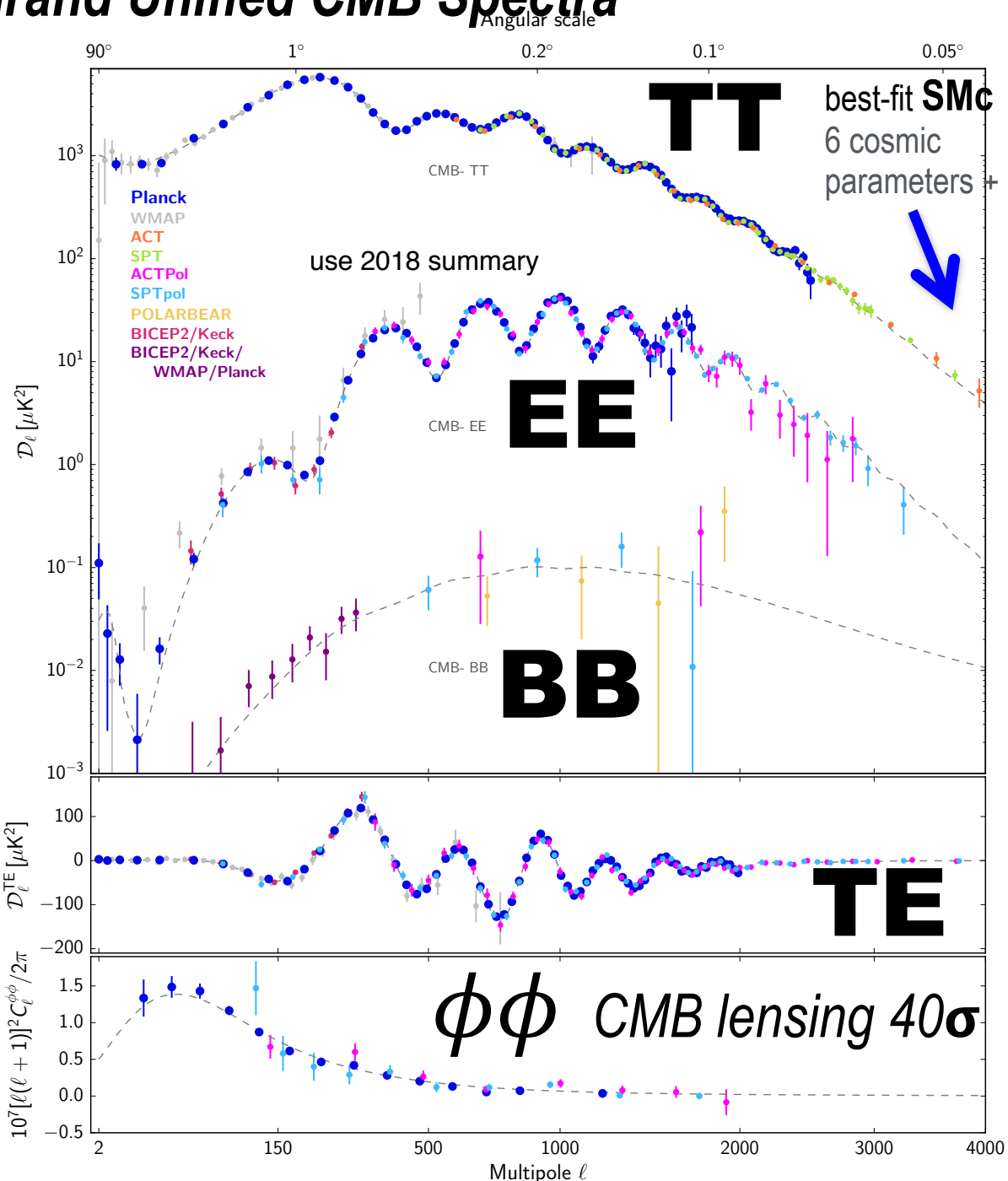


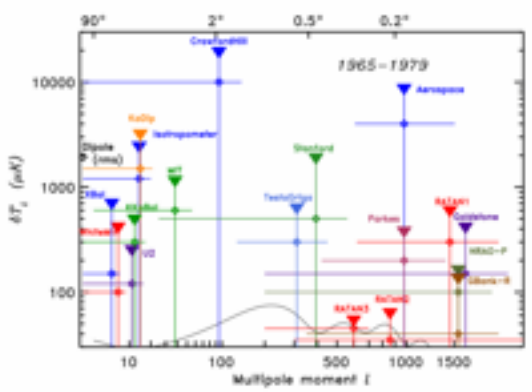
cosmic sound realization

300 μK

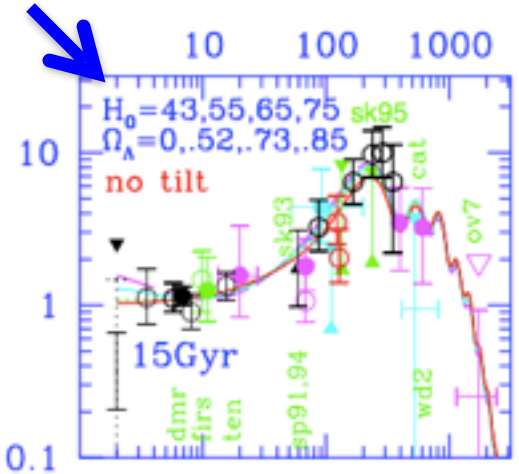
Temperature changes in micro-degrees

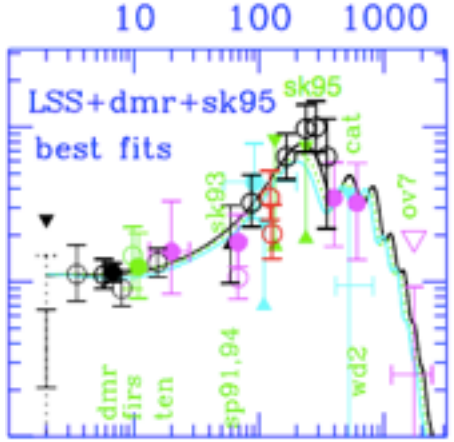
Grand Unified CMB Spectra





JRB@Capri 1993 Bandpowers cf. theoretical power spectra





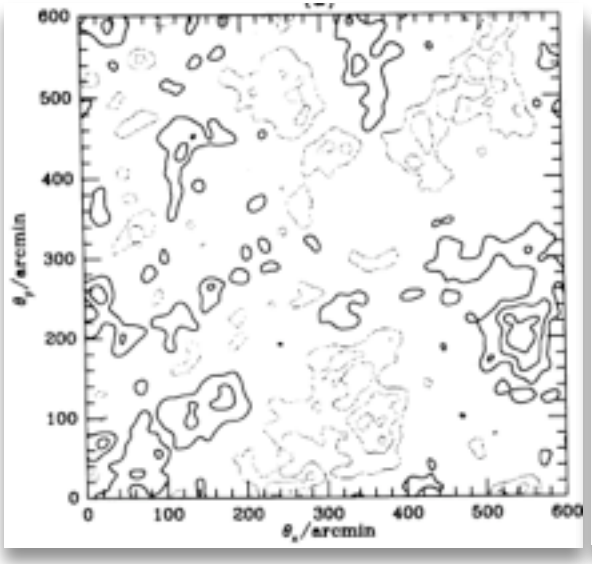
Delta T over Tea Toronto May 1987: first dedicated CMB conference, expts+theorists, primary+secondary ΔT/T

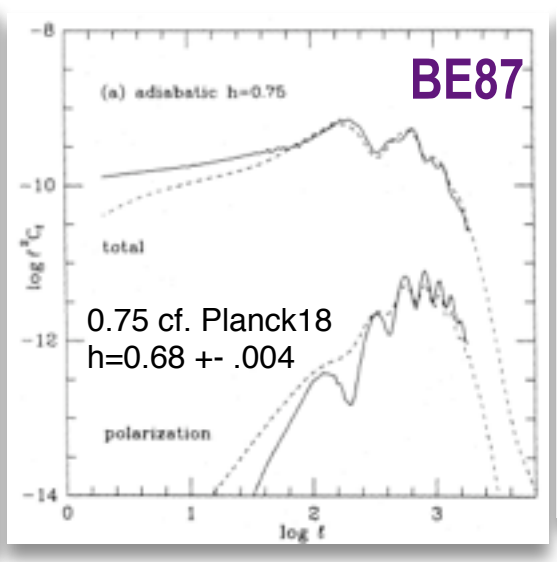
organizers: Bond *theory* + Wilkinson *experiment*

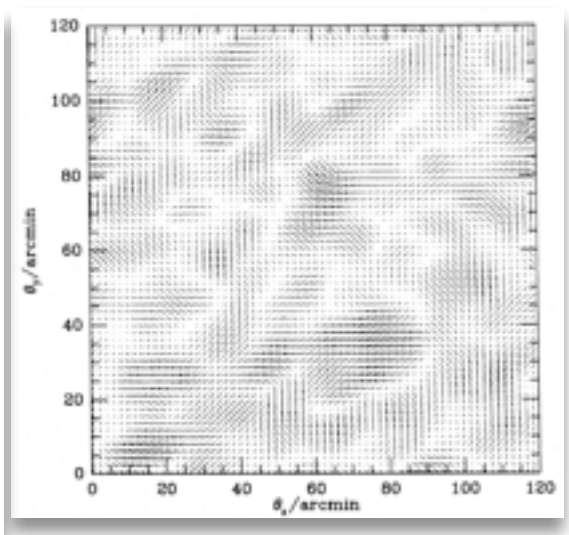
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle |\Delta T(LM)|^2 \rangle$ *with target* C_L *shapes*

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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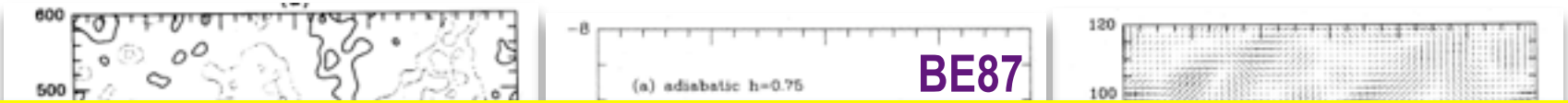


BE87

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

Chaotic +++ model space M_{Planck} ***phonons -> inflaton ->*** $\zeta = \ln a$

stochastic inflation $\delta\phi \sim h_{Planck}$ ***H*** *aka* ***quantum "zero-point" fluctuations***

Starobinksy inflation, Higgs inflation … running of $M_{Planck}(R,\phi)$

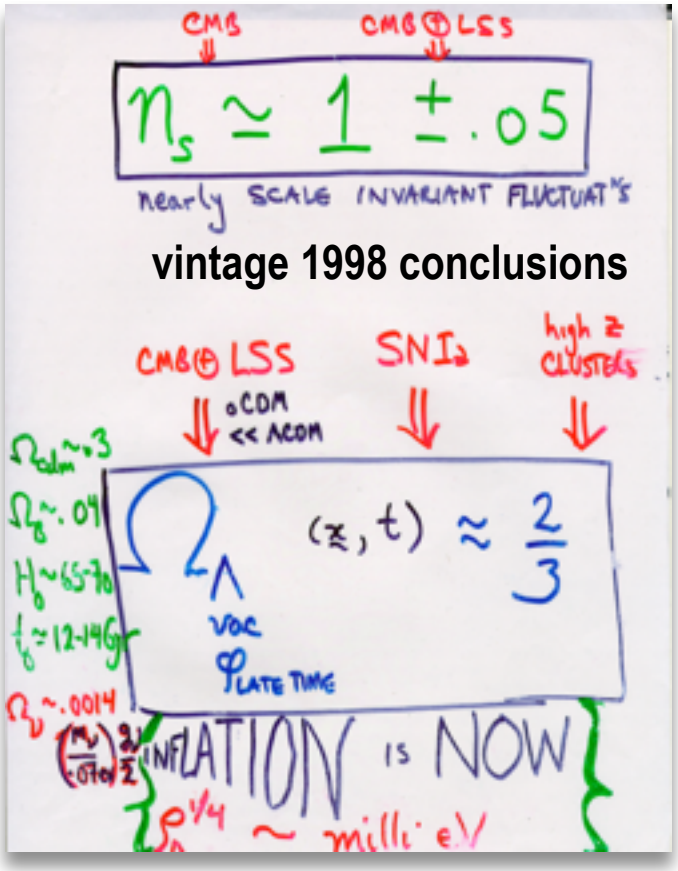
GravityWaves & isocurvature *superstring-inspired, natural/axion-inflation later*

nearly Gaussian ζ ***was expected but nonG*** ζ ***was starting.***

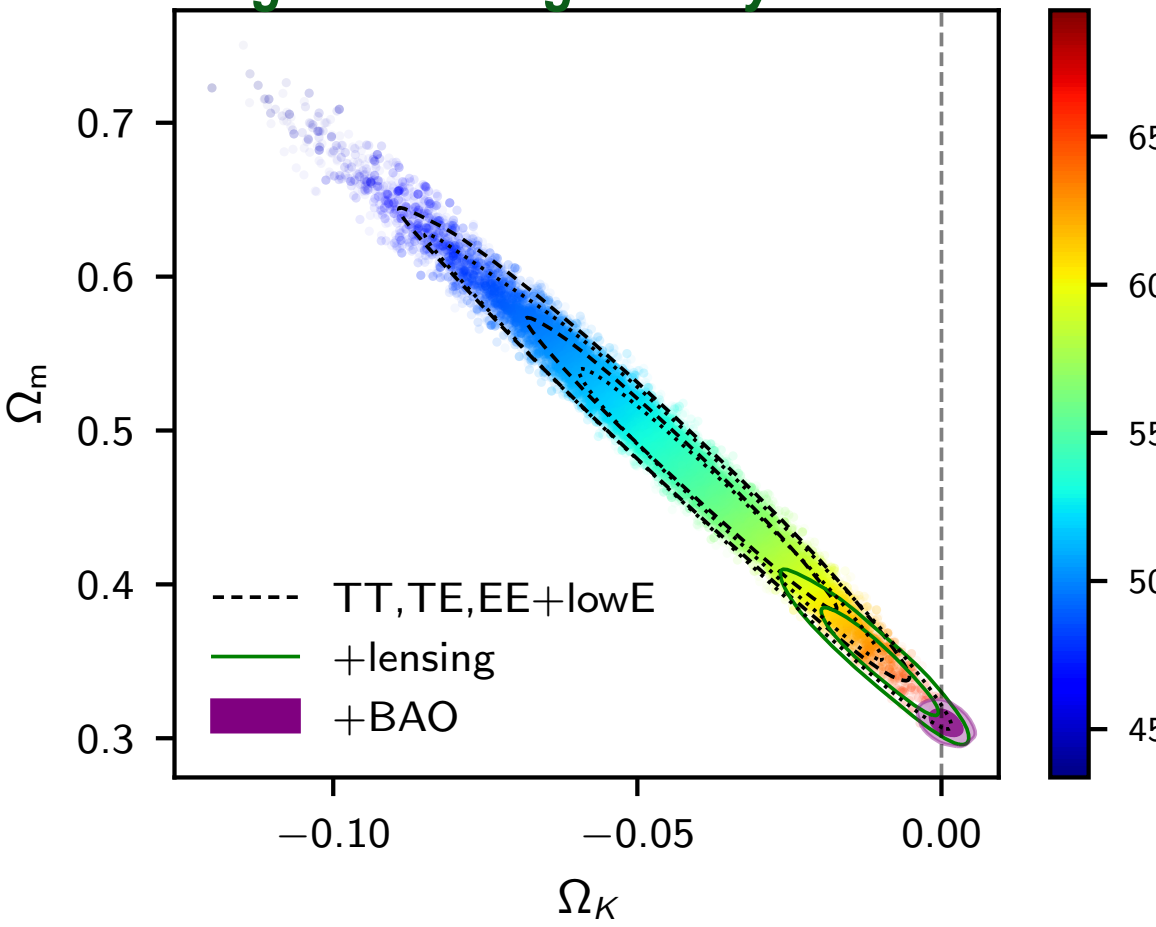
but also topological defects, strings, explosions, … were possible then, but now very subdominant

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

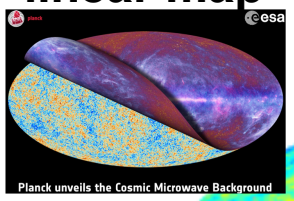
=> @a ~1/10^{55} only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

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

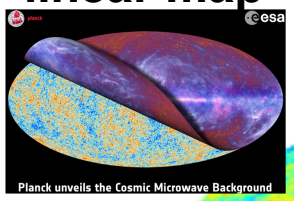
only partial de-lens

cmin

Planck 2018

15 arcmin fwhm

linear map



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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})

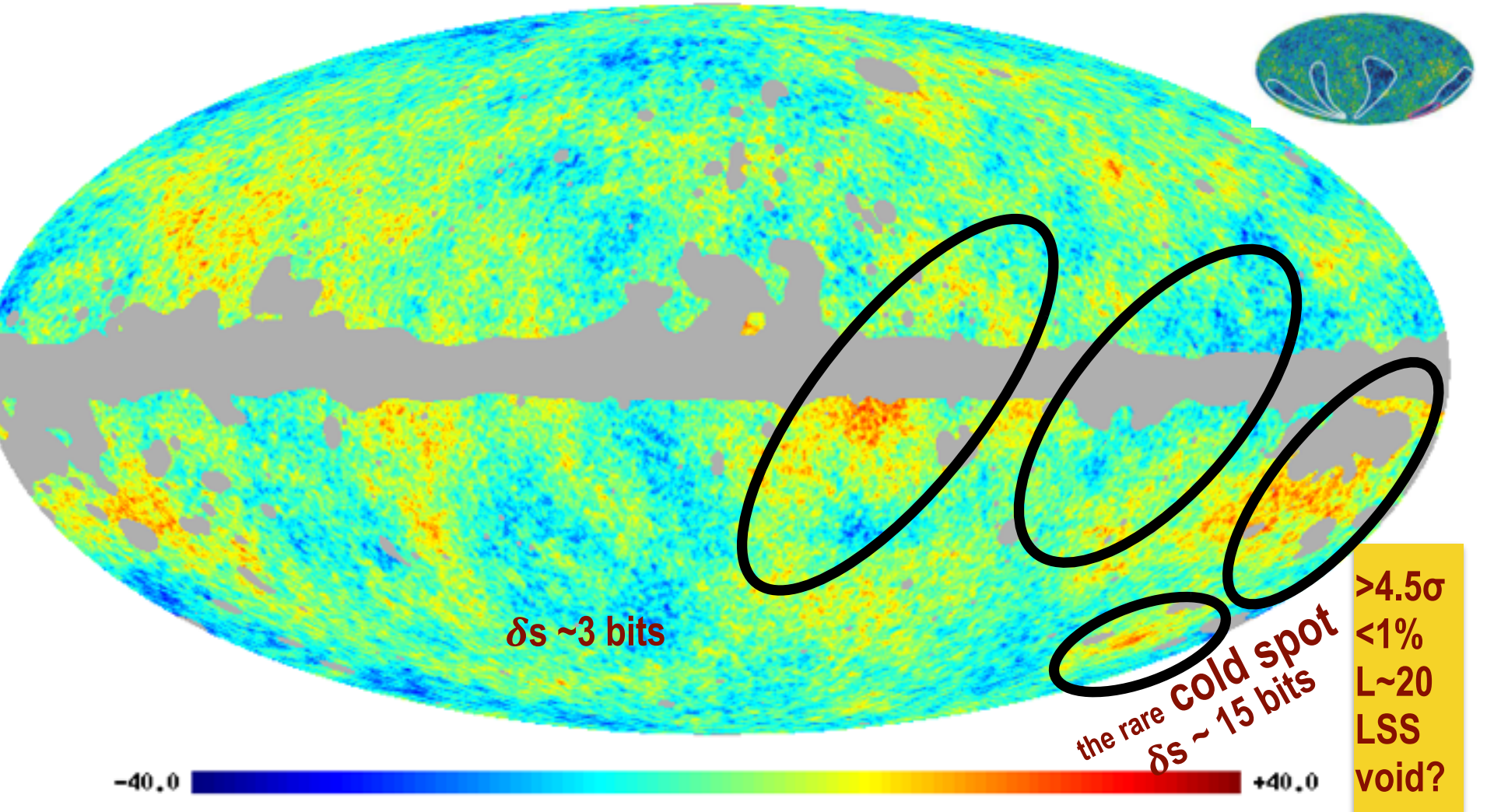
BSMc = SMc + primordial anomalies in the true ζ -WebSky

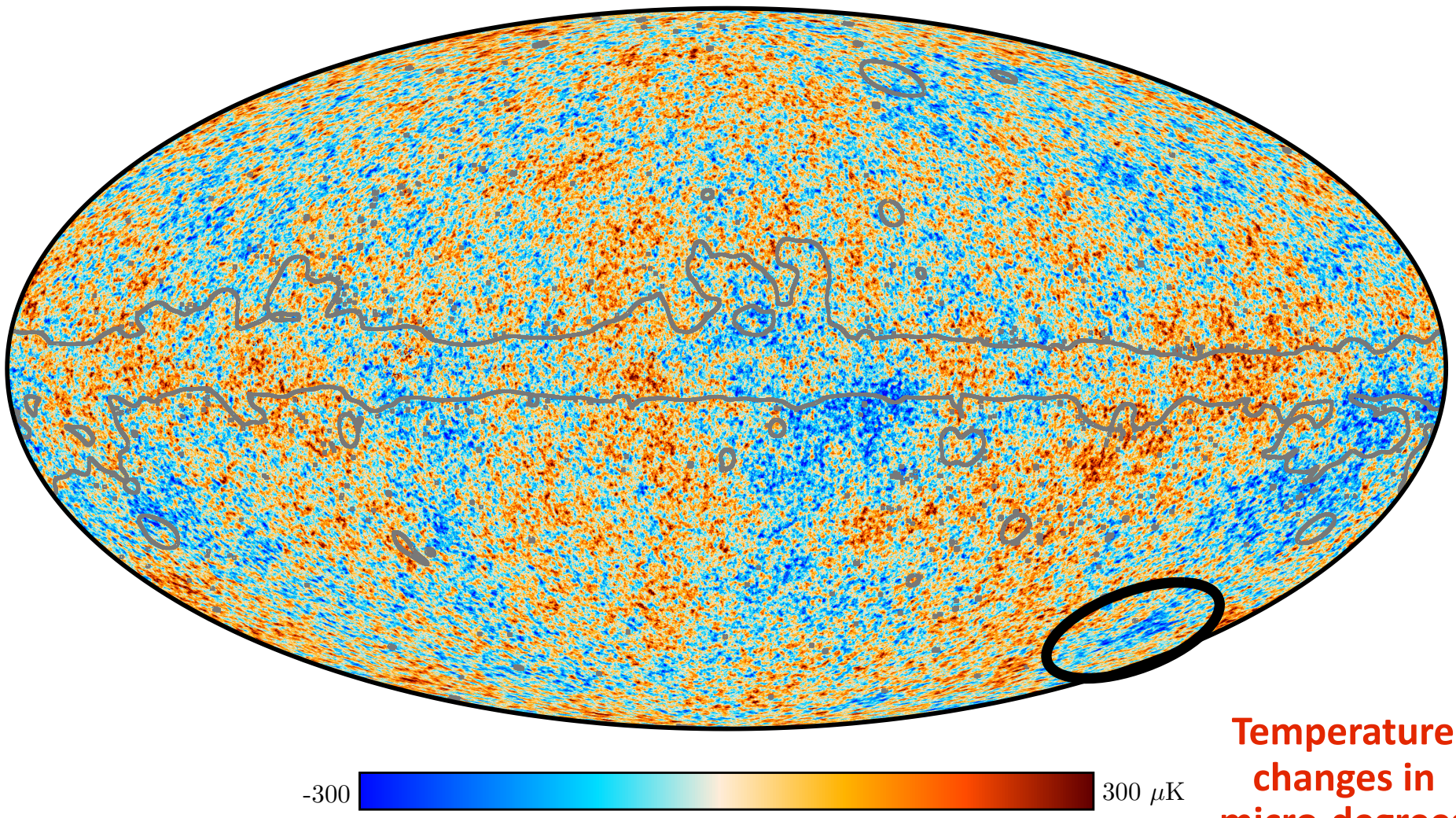
$<\zeta|T,E\text{-}pol>$

GUTA = Grand Unified Theory of Anomalies?

anomalies @ low L => sample variance limited ~2σ's

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





Temperature changes in micro-degrees

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 => ζ-Spectrum k-dip; *includes CMB lensing, parameter marginalization*

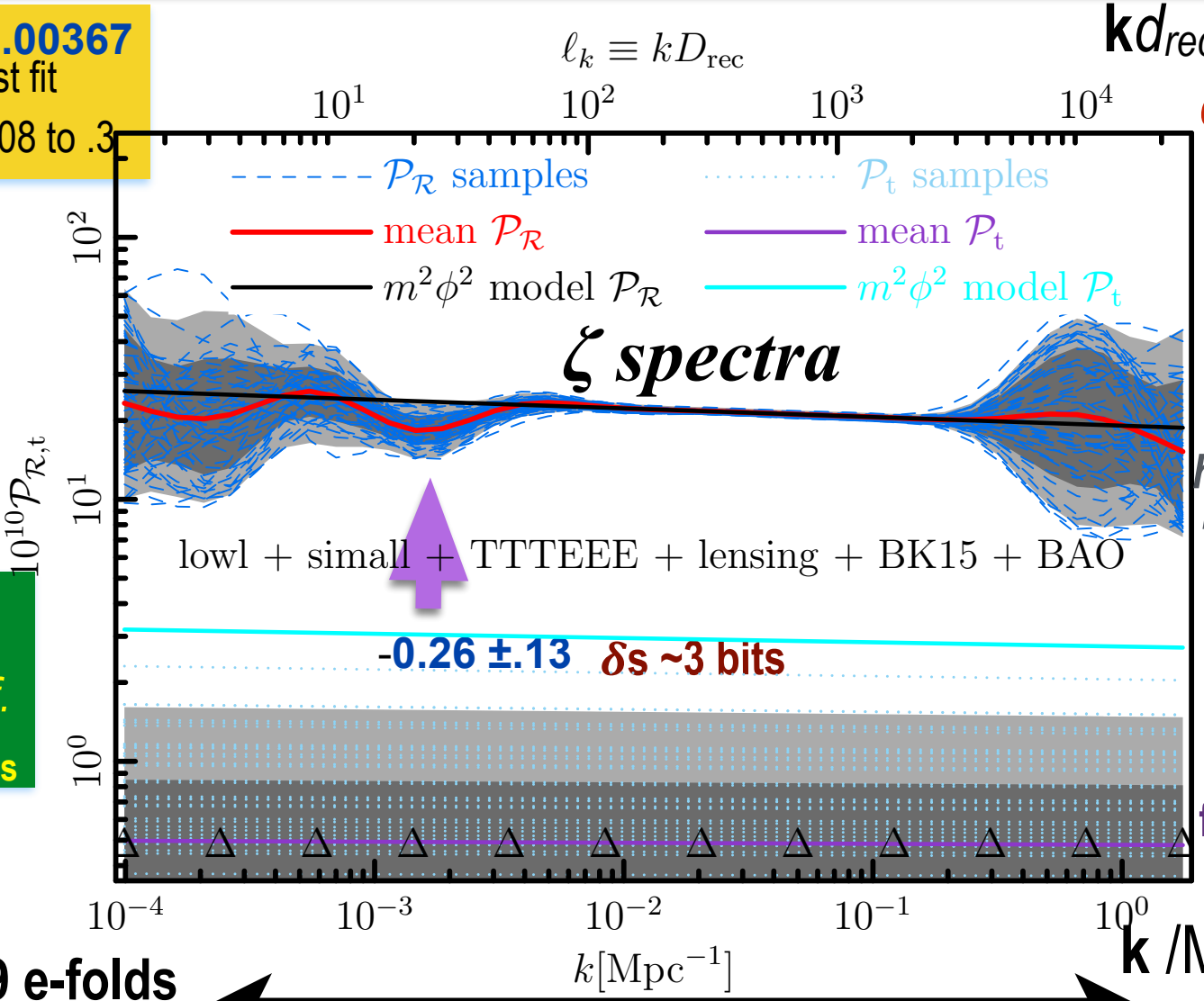
uniform n_s=0.9669±.00367
P18+BK15 LSS best fit
superb 12-knot fit k~ .008 to .3

UV ⇐

M_{Planck} region far off
many ways to extrapolate

P18+BK15
r<.069 95%CL *cf.*
r<0.061 uniform n_s

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



9 e-folds

k /Mpc

kd_{rec} ≳L

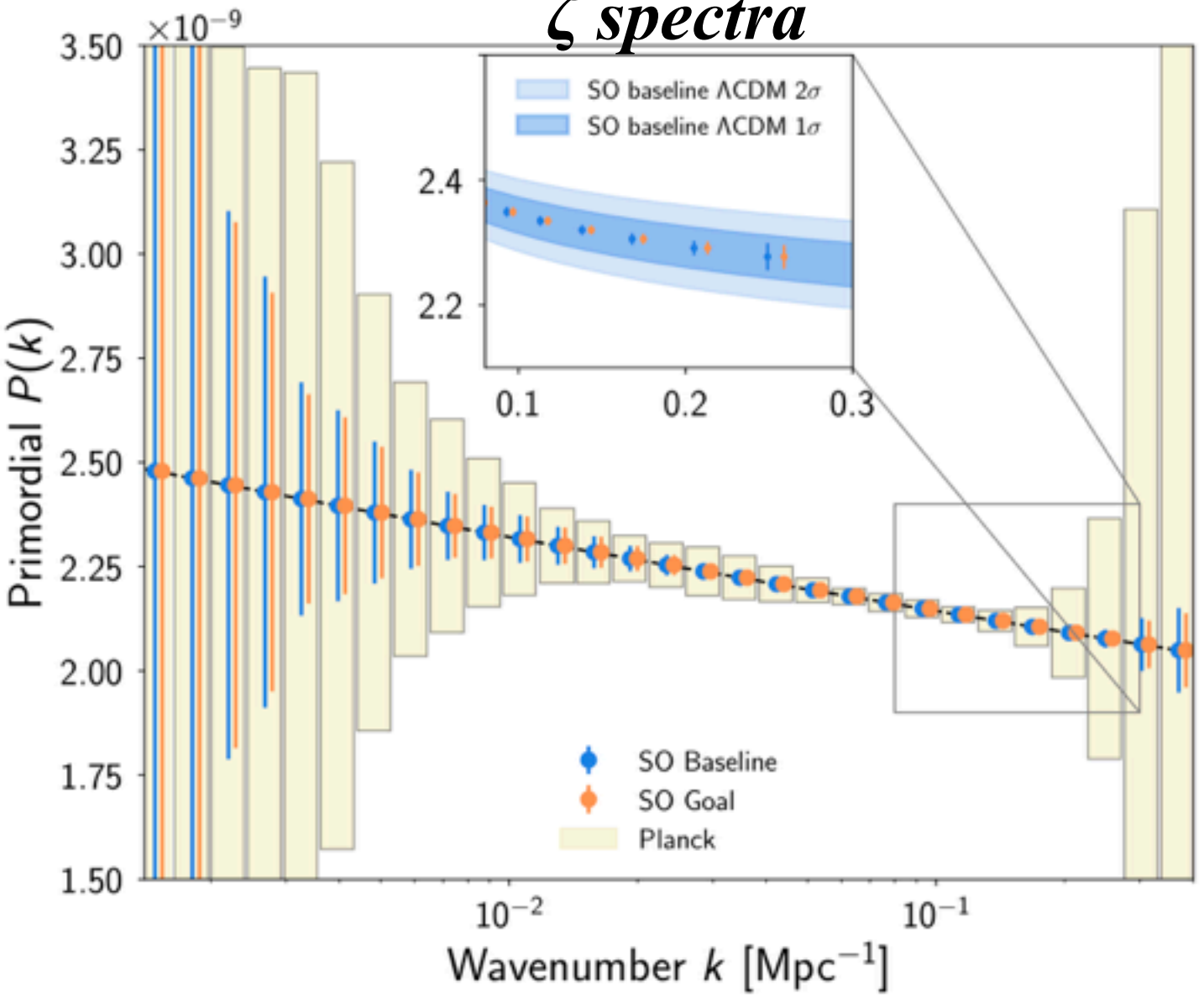
derive
V(ϕ)
H(α)
ε(α)

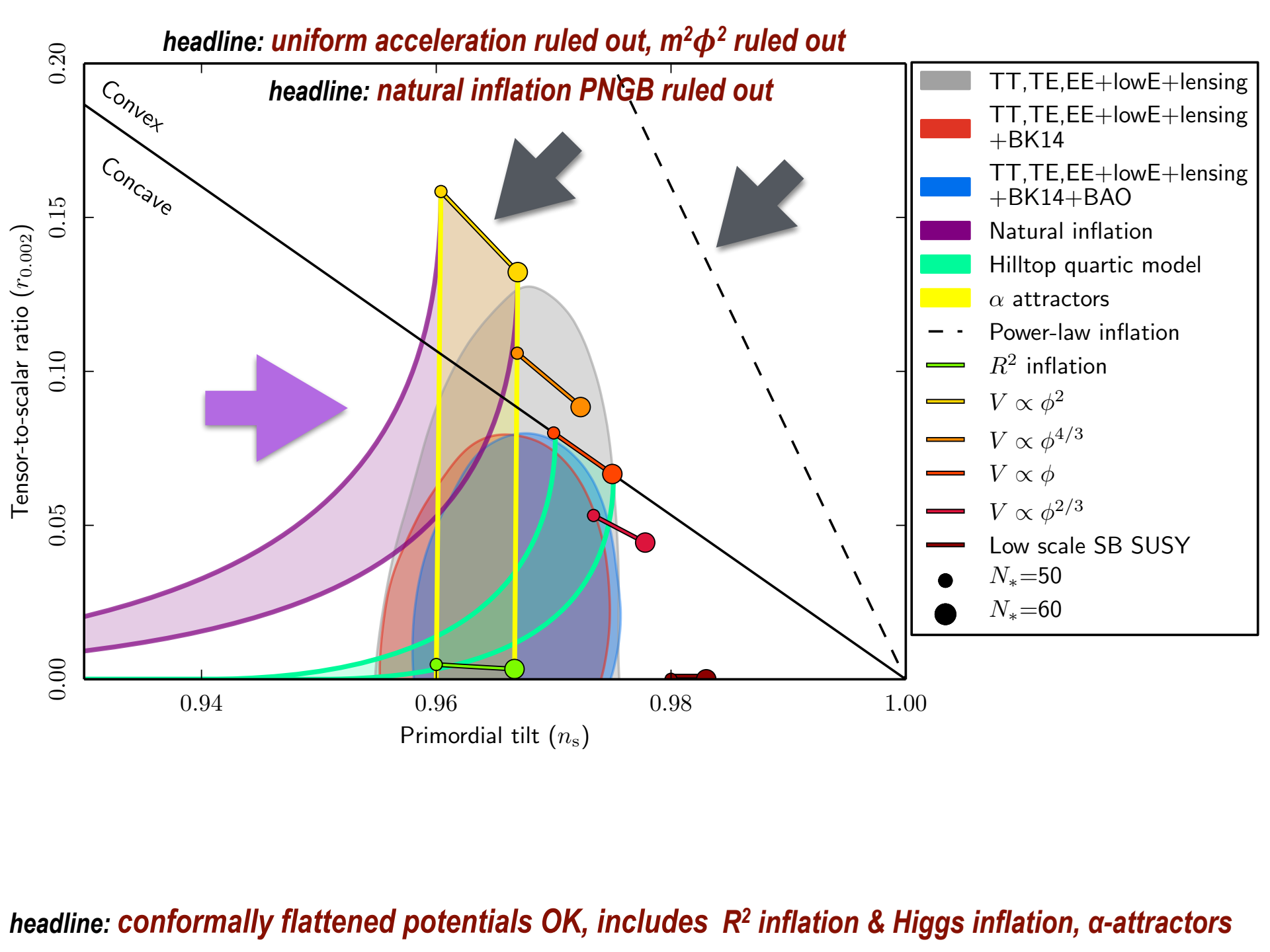
⇒ *IR heating region far off*

many ways
=> lots of room for large ζ =>

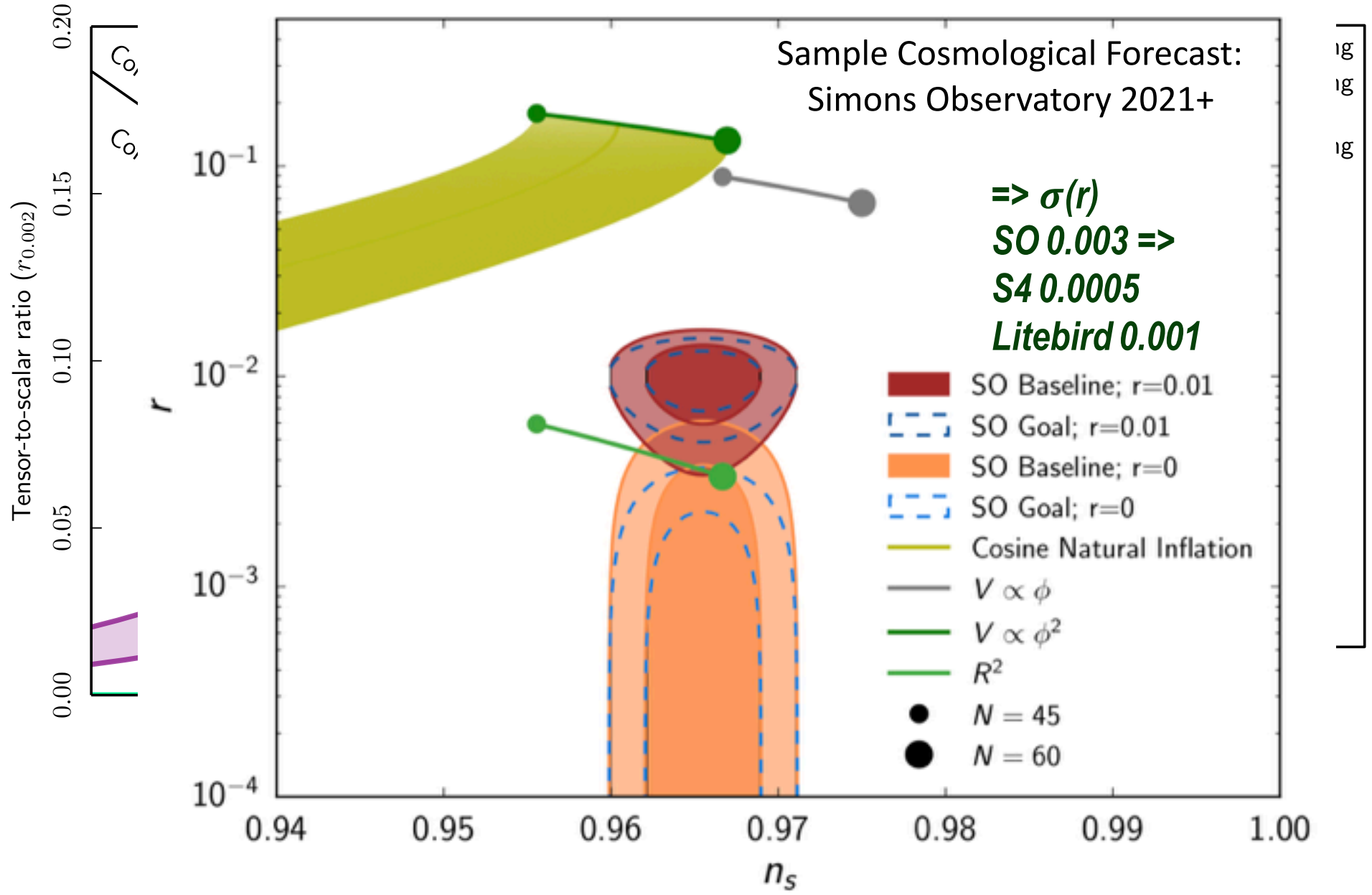
the **true quadratic ζ-Websky** of the **ζ-scape**

Sample Cosmological Forecast: Simons Observatory 2021+





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


Sample Cosmological Forecast:
Simons Observatory 2021+
=> σ(r)
SO 0.003 =>
S4 0.0005
Litebird 0.001
SO Baseline; r=0.01
SO Goal; r=0.01
SO Baseline; r=0
SO Goal; r=0
Cosine Natural Inflation
$V \propto \phi$
$V \propto \phi^2$
R^2
$N = 45$
$N = 60$
r
n_s
Tensor-to-scalar ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.94
0.95
0.96
0.97
0.98
0.99
1.00

Dick Bond

Quantum Inflation in the Planck Era & Beyond

relic1: ζ *from* **inflaton** *- observable = all cosmic structure CMB&LSS & stars/humans & .. 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 - weak physics)*

relic 6: **CMB** *with all its fluctuations & polarization*

relic 7: galaxies & large scale clustering, flows, gravitational lensing - tomography with redshift

relic 8: **dark energy** *- let it be dynamical (few params) & coupled (more params)*

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**
  - **large nonG from instabilities localized in k - open at high k. primordial black holes?**
- **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**
  < 2% isocurvature role

bubble remnants of tunneling during inflation
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 .. primordial black holes?**
- **rare WIMPzillas as dark matter**

from later quark gluon plasma

- **late phase transitions - whence first order?**

anomalies in CMB & LSS

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

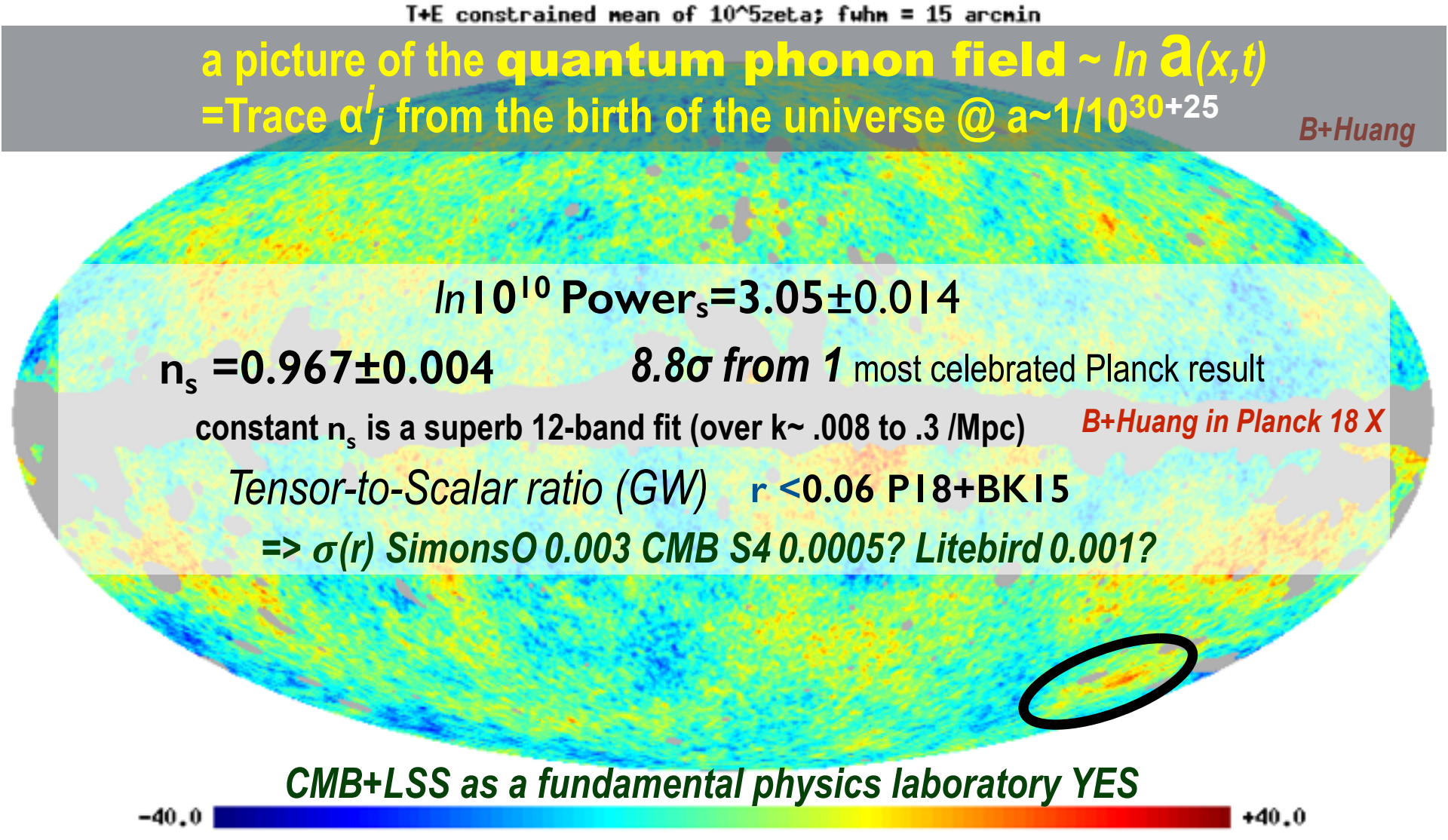
SIMPLICITY

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

at $a \sim e^{-67-55} \sim 1/10^{30+25}$

Planck2018 early U structure map

2^+ *numbers* - **red** strain-noise



a picture of the **quantum phonon field** ~ *ln* $a(x,t)$

=Trace α^i_j from the birth of the universe @ $a \sim 1/10^{30+25}$

B+Huang

ln10^{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) SimonsO 0.003 CMB S4 0.0005? Litebird 0.001?

CMB+LSS as a fundamental physics laboratory YES

END