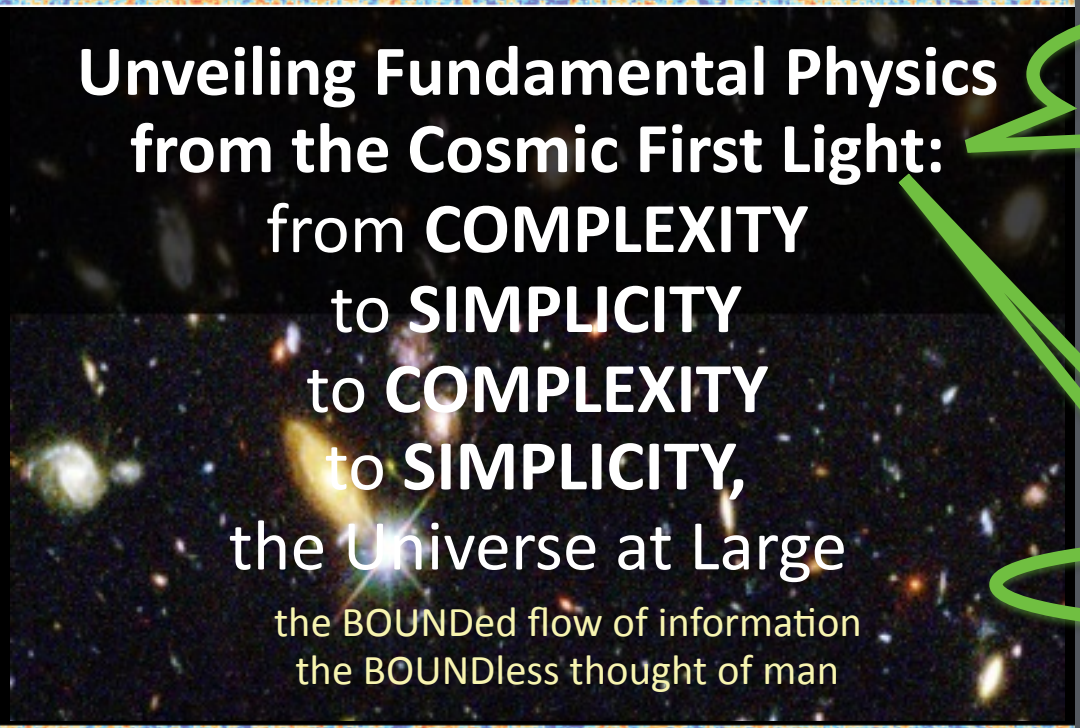
Quantum Universe in the Planck Era & Beyond

Dick Bond @ ENS19 03 19



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
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L'institut Canadien d'astrophysique théorique

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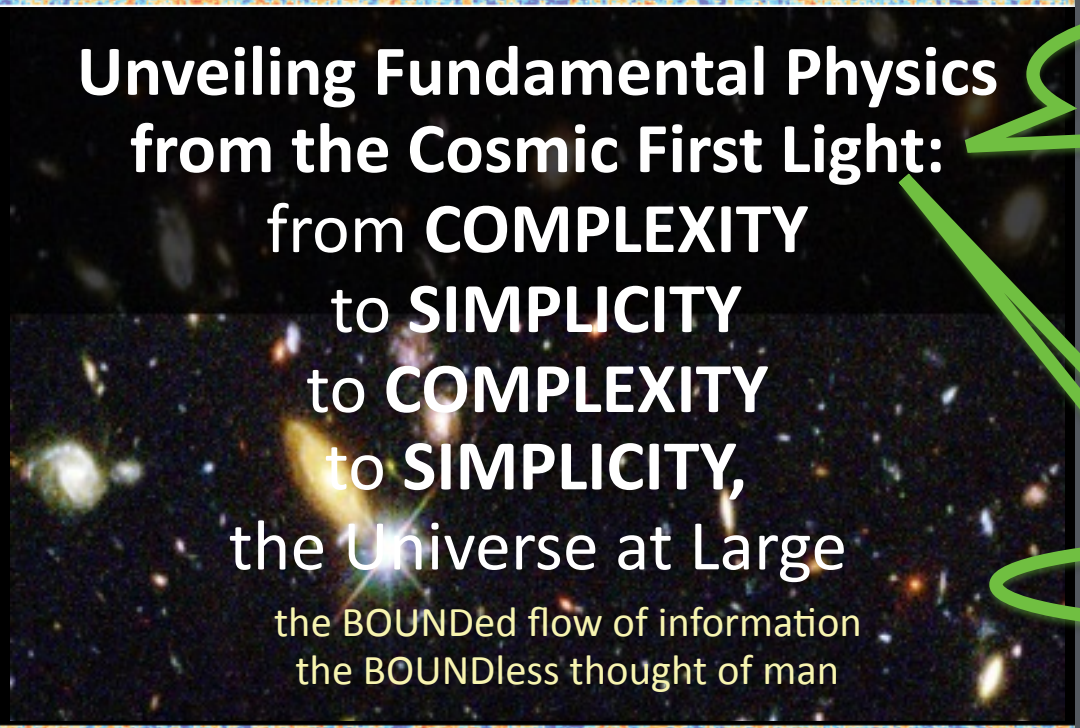

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goal today: *CMB maps baby pics ⇒ early Universe maps! embryo pics*
⇒ star of today's show is an entropy-like early Universe measure

$3\zeta(x,t) = \int_{path} (dE+pdV)/(E+pV) \sim dV/V|_{\rho}$

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a tale of Planck4**

How the Planck satellite helped decode the role of Planck's quantum $\hbar$ &

CMB past => CMB present

7⁺ numbers

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

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coarse-grained quantum diffusion (Fokker-Planck) $\sqrt{D_H} \sim \hbar\, H \sim T_H$ in the emergence of our Universe from the Planck-era

$$M_{Planck}\, c^2 = \hbar c \,/\sqrt{8\pi G_N}$$

Dick Bond CITA *the summary talk*

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

CMB prediction
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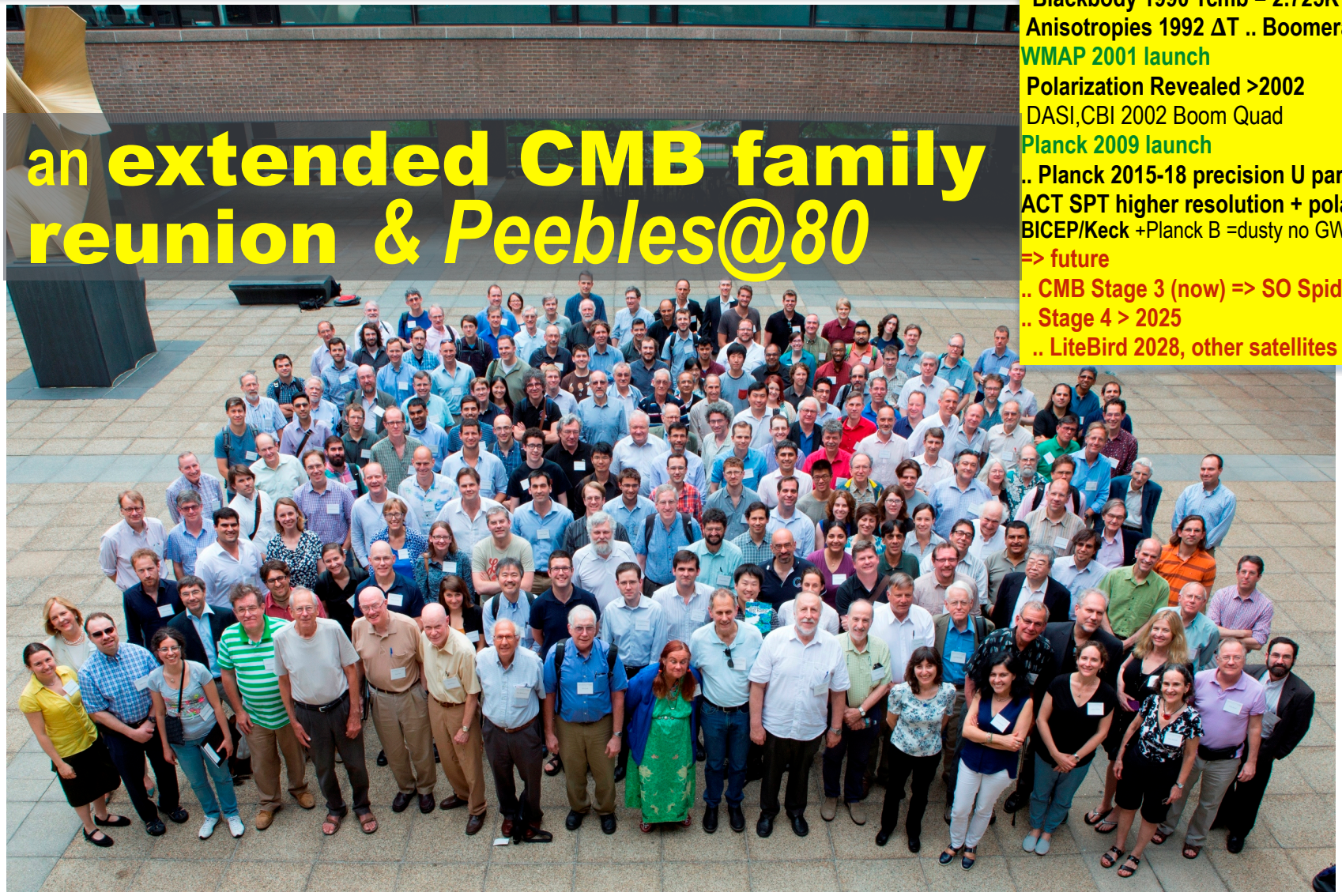
ACT SPT higher resolution + polarization
BICEP/Keck +Planck B =dusty no GW Spider
=> future
.. CMB Stage 3 (now) => SO Spider2
.. Stage 4 > 2025
.. LiteBird 2028, other satellites ??

an **extended CMB family reunion** *& Peebles@80*



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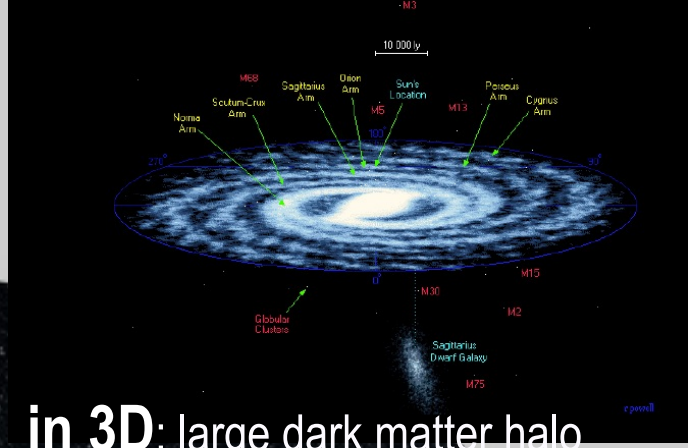
Milky Way in infra-red:

half a billion stars, a disk galaxy



in 3D: large dark matter halo

Polaris

*Sagittarius A**

Magellanic Clouds

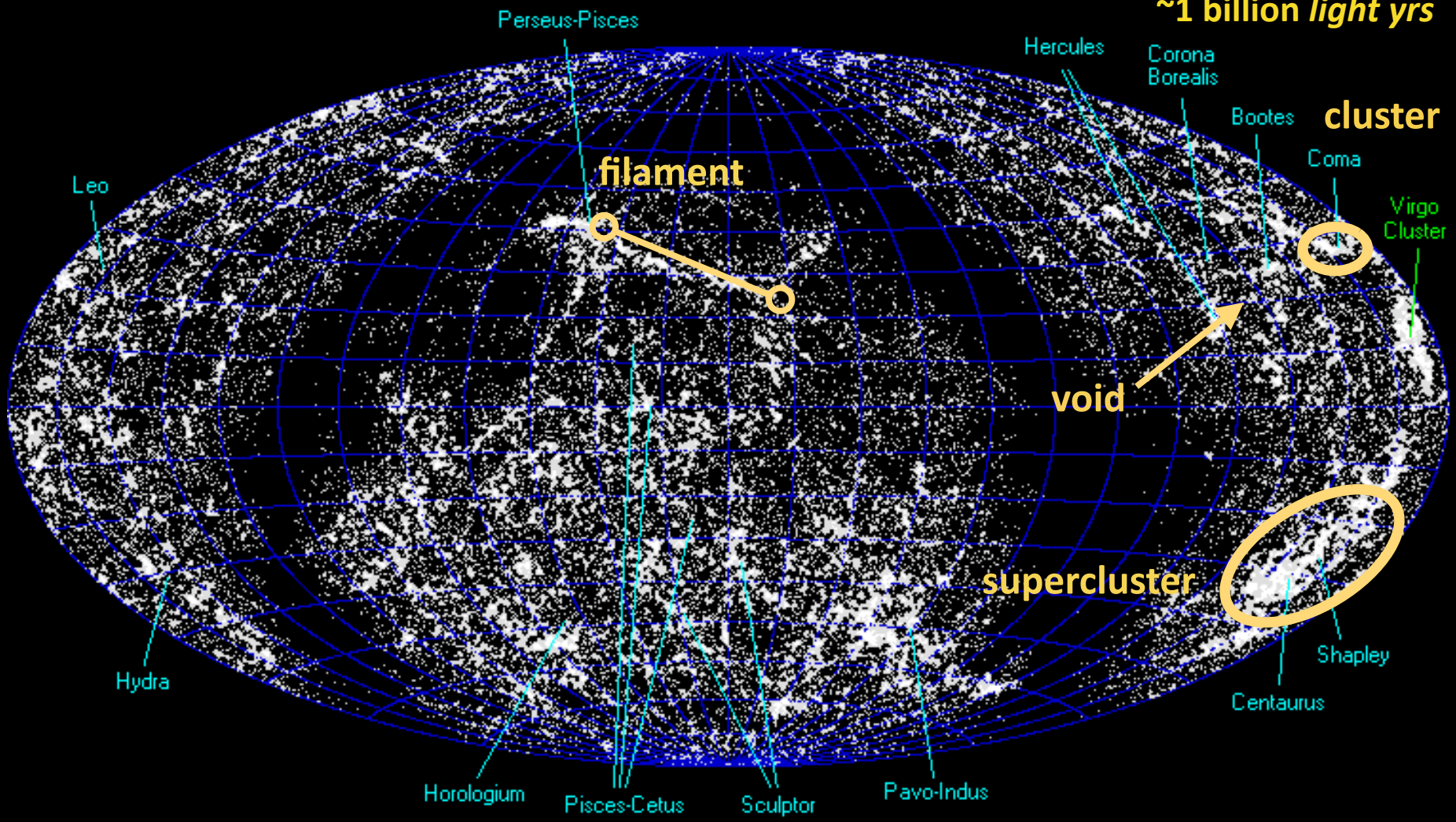
Two Micron All Sky Survey Image Mosaic Infrared Processing and Analysis Center/Caltech & University of Massachusetts

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

$\langle \alpha \rangle = -0.1$

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

~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 ≡ $\langle \ln a \rangle$

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

Photons cosmic microwave background
412 /cm³ 0.005% from red to far-infrared- stretched

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** $\hbar$ — 67 ⇓ 127

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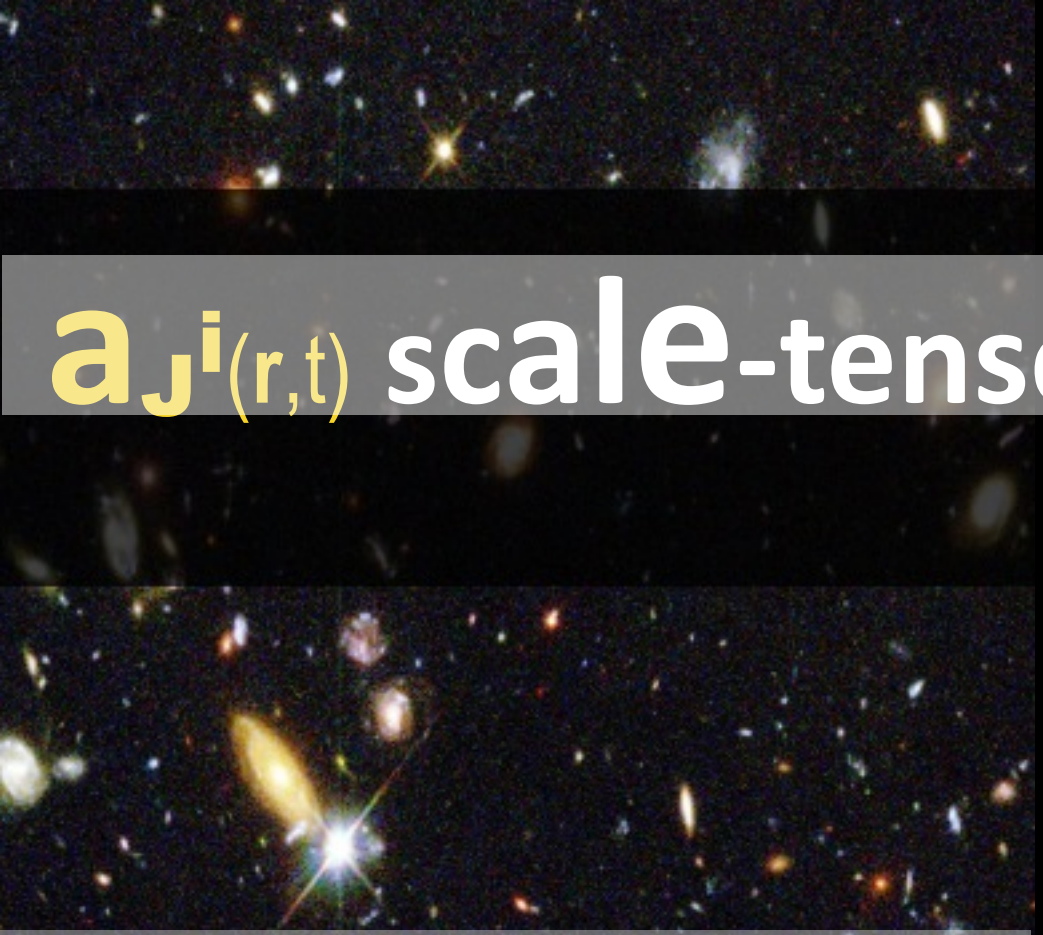
Photons cosmic microwave background
412 /cm³ 0.005% from red to far-infrared- stretched

Baryons Ordinary Matter 4.9% H,He ~0.2 amu /m³

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

Dark Matter ~amu /m³ 26.6 ± 0.7%
compressed in MilkyWay X4e-folds ~0.3 amu /cm³

Dark Energy ~ vacuum potential +++
~ 3 amu /m³ 68.5 ± 0.7% late-inflaton cannot compress



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

Phonons = isotropic Strain Deformations $\hbar$, M_{Planck}

Inflatons - source the phonons $\hbar$, M_{Planck}

Gravitons anisotropic Strain (*Transverse Traceless*) $\hbar$

Isocons transverse to inflaton *on* $V(\Phi_A)$ $\hbar$

+ *+ Standard Model of particle physics particles*
+ *+ Beyond BSMpp particles*

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

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

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

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 $g=aa^\dagger$

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 $\mathbf{a_J^i}$

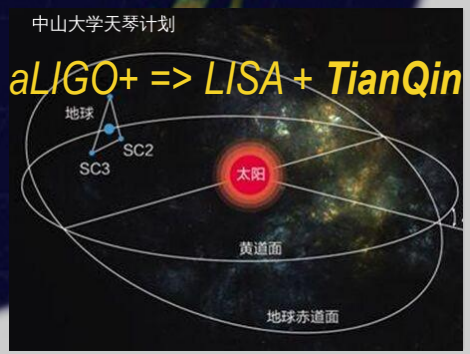
anisotropic strain, gravity waves

isotropic strain, sound

linear: **strain ∝ tide**

cosmic web *story*

strain-acceleration ~ gravity

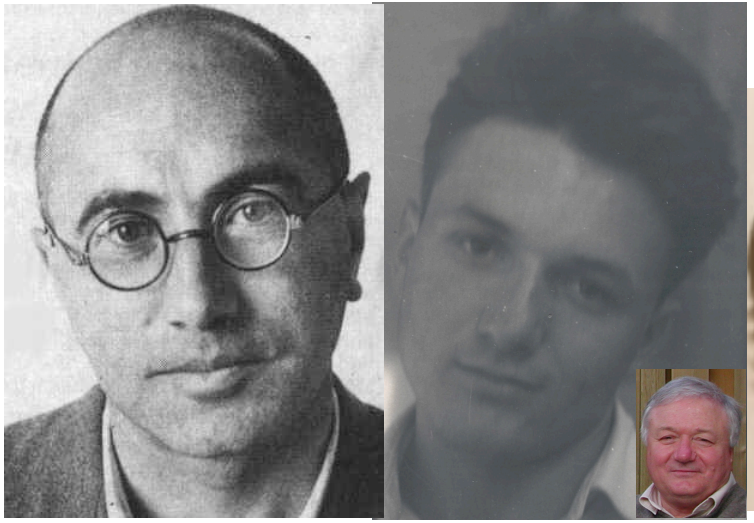


light and gravity are entangled: wavelength stretches under space-strain: ***redshift CMB***

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

Hawking BH evaporation = vacuum deformation under strain, condensate(t) + quantum fluctuations

& dark energy is a condensate



*some **CMB** theorists*

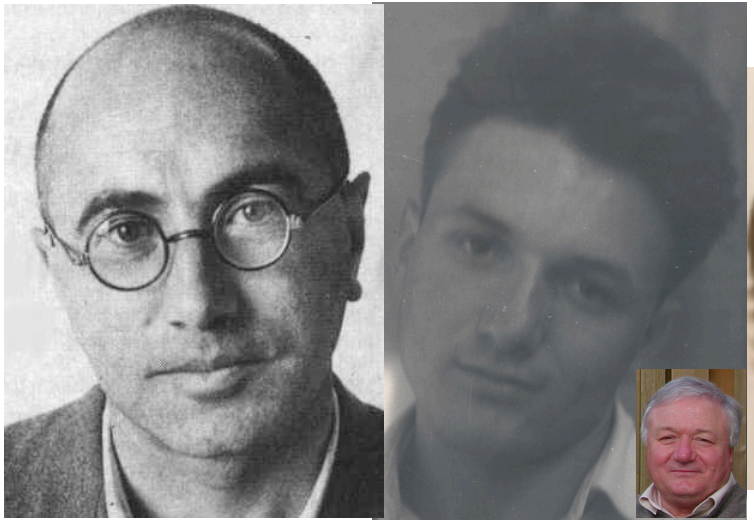
test with **CMB**+LSS

~85-87 reconsider Λ, quintessence
"what you see is what you get"

~80-84: Hot (light ν), Warm, Cold DM
hot Big Bang collisionless relics
or
black holes from Very Massive Stars,
Jupiters, primordial black holes

anthropic matters with BJ Carr

vary ***x*** in ***x*CDM:** find x by the tests **x**=*tiltedHBΛ*



test with CMB+LSS

theory of polarization of the CMB 60s 80s - 90s for GW

Dick Bond CITA *the summary talk*

CMB@50 THEN & NOW & THEN

a celebration *Princeton June 2015*

a Who's Who of the CMB world

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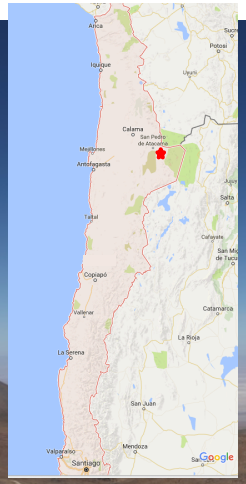
.. LIteBird 2028, other satellites ??

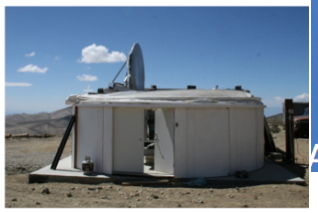
an **extended CMB family reunion** *& Peebles@80*

Atacama



California+
South Africa
C-BASS 5 GHz

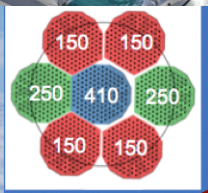
Tenerife (+South Africa?)
QUIJOTE 11, 13, 17, 19 GHz
(2015/16 - 30, 40 GHz)

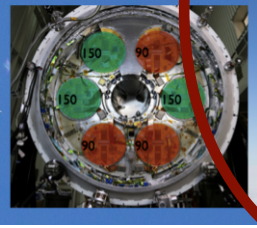


California
B-Machine 40 GHz

South Pole

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





Antarctic balloons

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

ACT@5170m

why Atacama? driest desert in the world. thus: cbi, toco, apex, asti, act, alma, quiet, polarbear, CLASS, CCATp@5600m, Simons Observatory, CMB Stage 4 also @South Pole - water vapour sublimates out

ACT ⇒ ACTPol ⇒ AdvancedACTPol fsky=0.45 now ⇒ Simons Observatory

managing the CMB

on to SO -> CMB-S4
Advanced ACTPol

boomerang ~40/paper

esa

planck

~250/paper, ~100 institutions

Cobras/Samba @Capri93

Bond since 1993, Canada since 2001

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

CSIC

National Research Council of Italy

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

SPIDER

PRINCETON UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

Imperial College London

UNIVERSITY OF TORONTO

CITA ICAT

STANFORD UNIVERSITY

CASE WESTERN RESERVE UNIVERSITY

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

CESR

CITA–ICAT

IASF

INSU Observer & comprendre

IN2P3 Les deux infinis

ipac

HELSINKI INSTITUTE OF PHYSICS

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

IPAG

ISDC

JPL

LPSC Grenoble

MilliLab

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

SAPIENZA

Rutherford Appleton Laboratory

UBC

UC UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

US University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

asdc

NASA

NSF

NIST

NSERC CRSNG

JPL

the David & Lucile Packard FOUNDATION

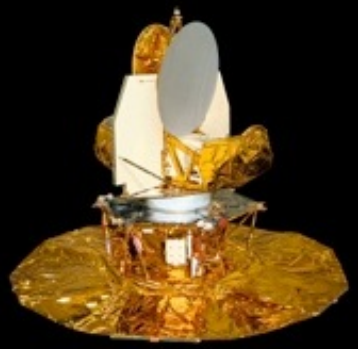
UNIVERSITY OF KWAZULU-NATAL

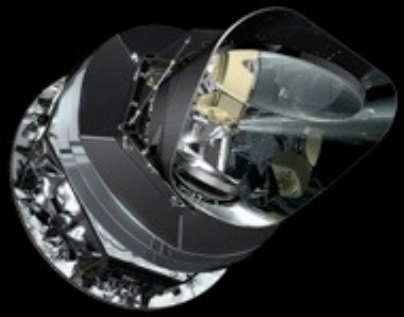
UBC

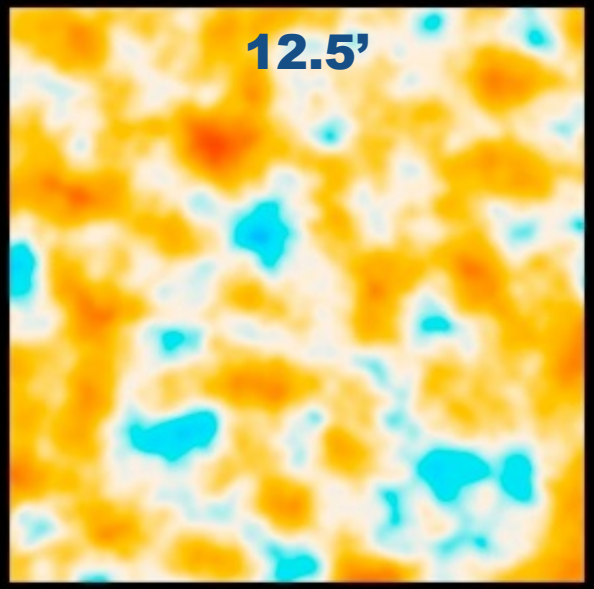
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

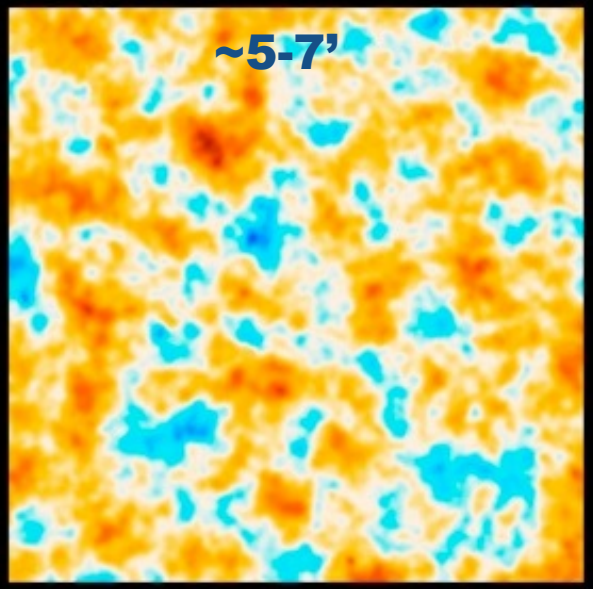
Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

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')

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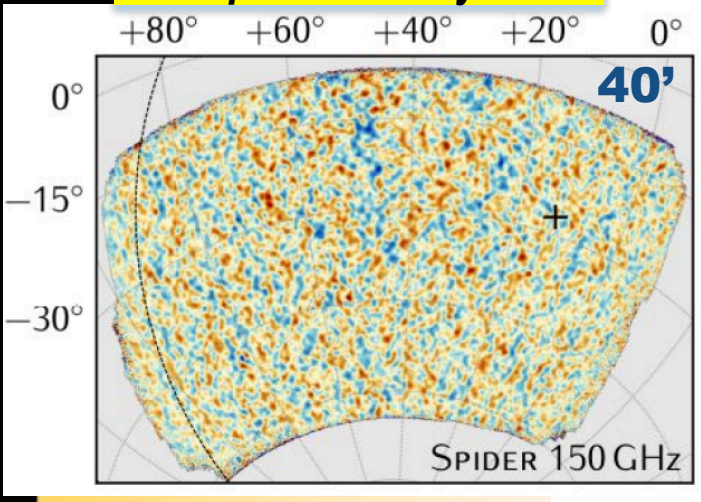
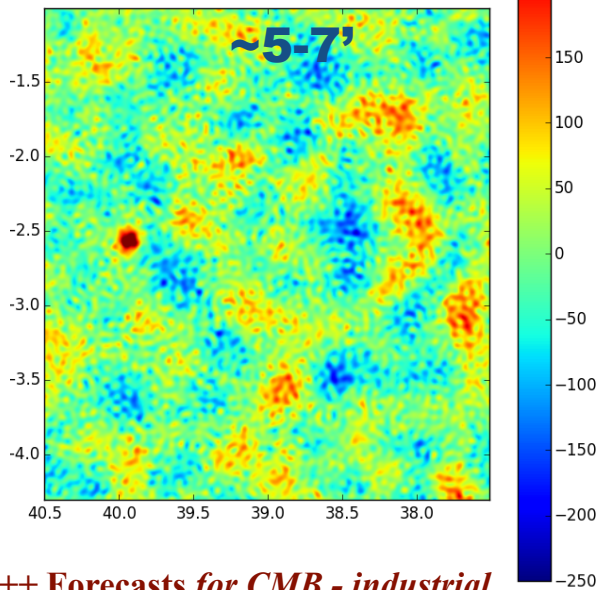
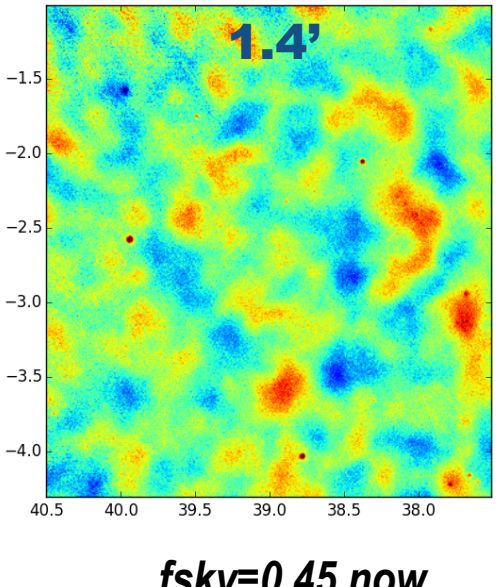
Spider 40' fsky~.08



Planck



ACT



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

BET97++* Forecasts *for CMB - industrial

fsky=0.45 now

2018 Simons Observatory Science Goals and Forecasts

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

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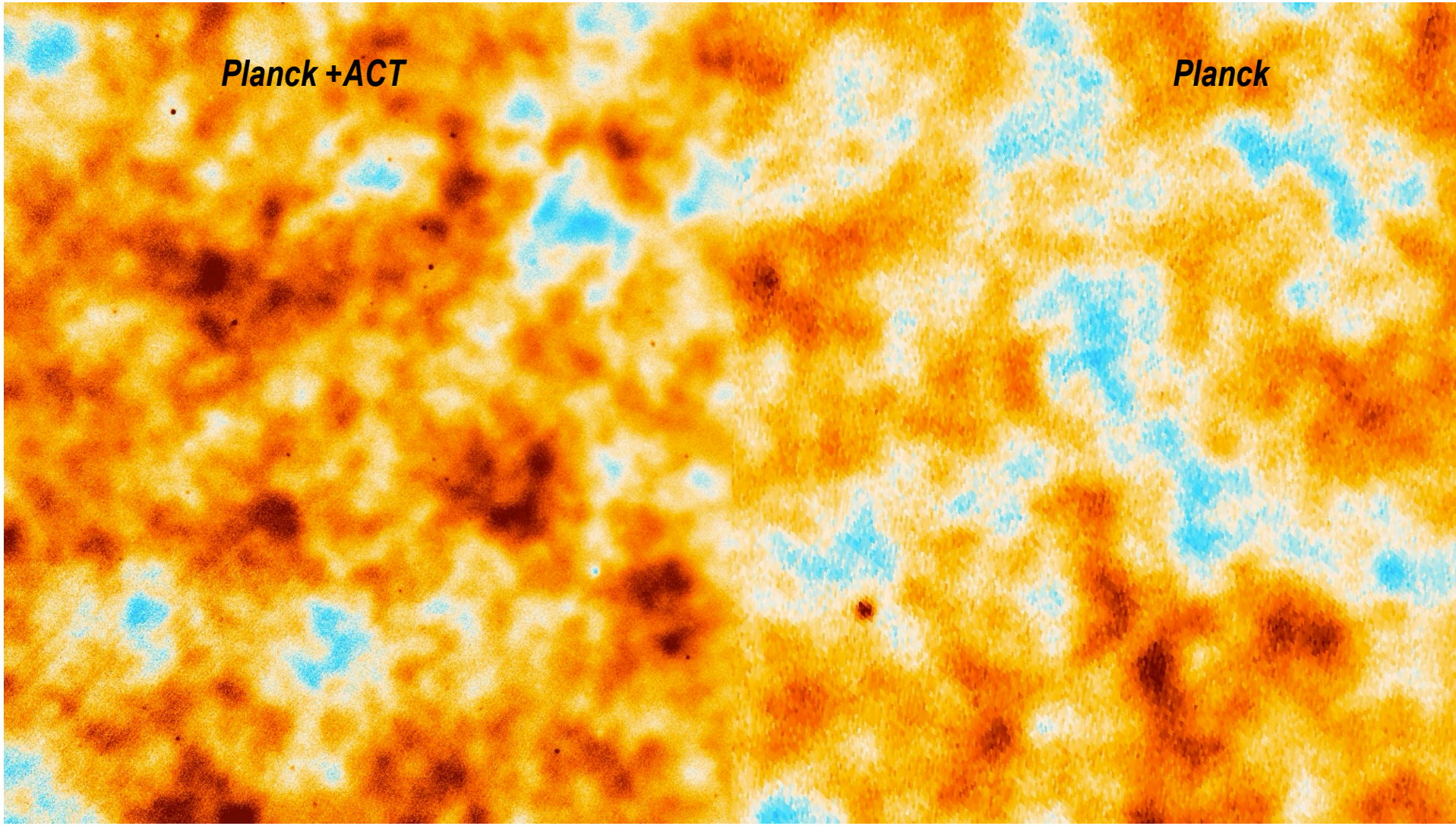

ACTer sigurd naess 2019

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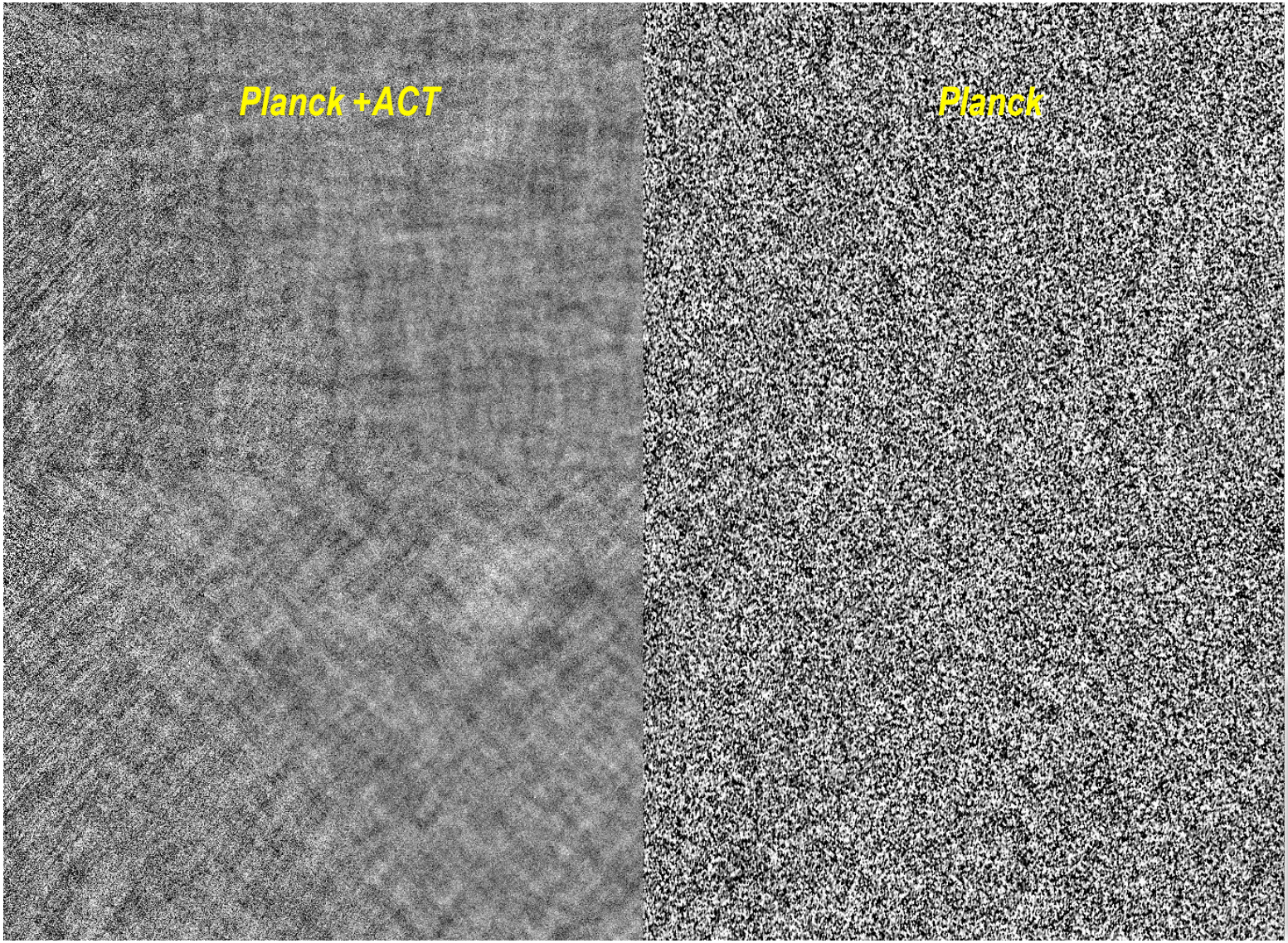

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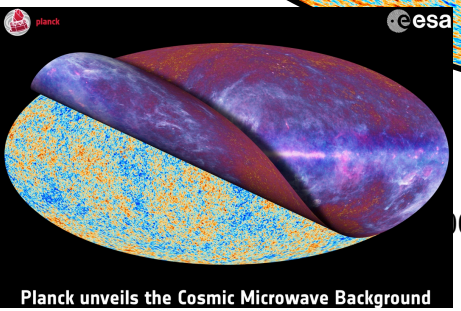
Planck's primordial light unveiled, *Mar 2013 =>* ***Feb 2015*** *=> pre-2016 =>* ***July 2018+*** *final*

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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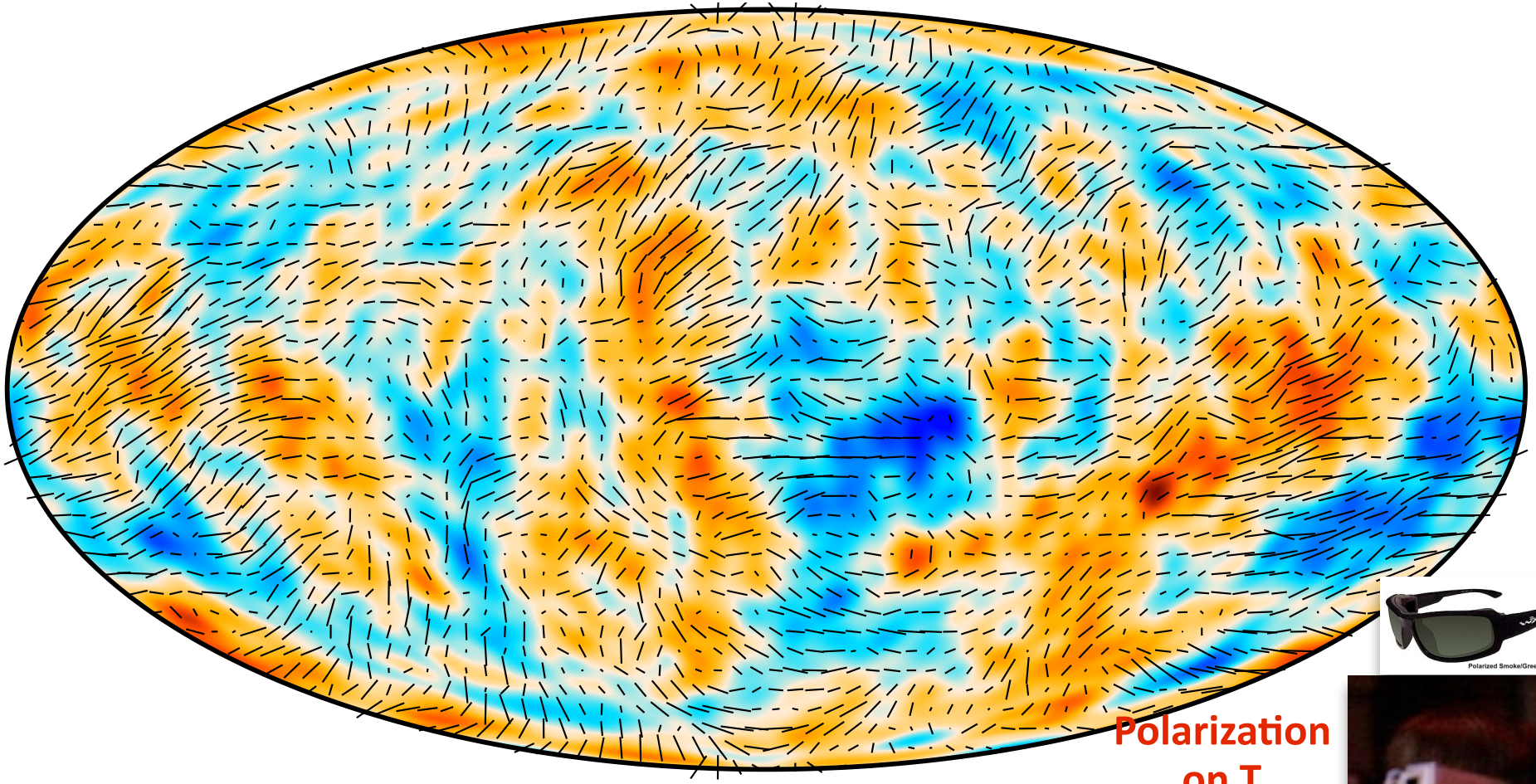

Polarization on T

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

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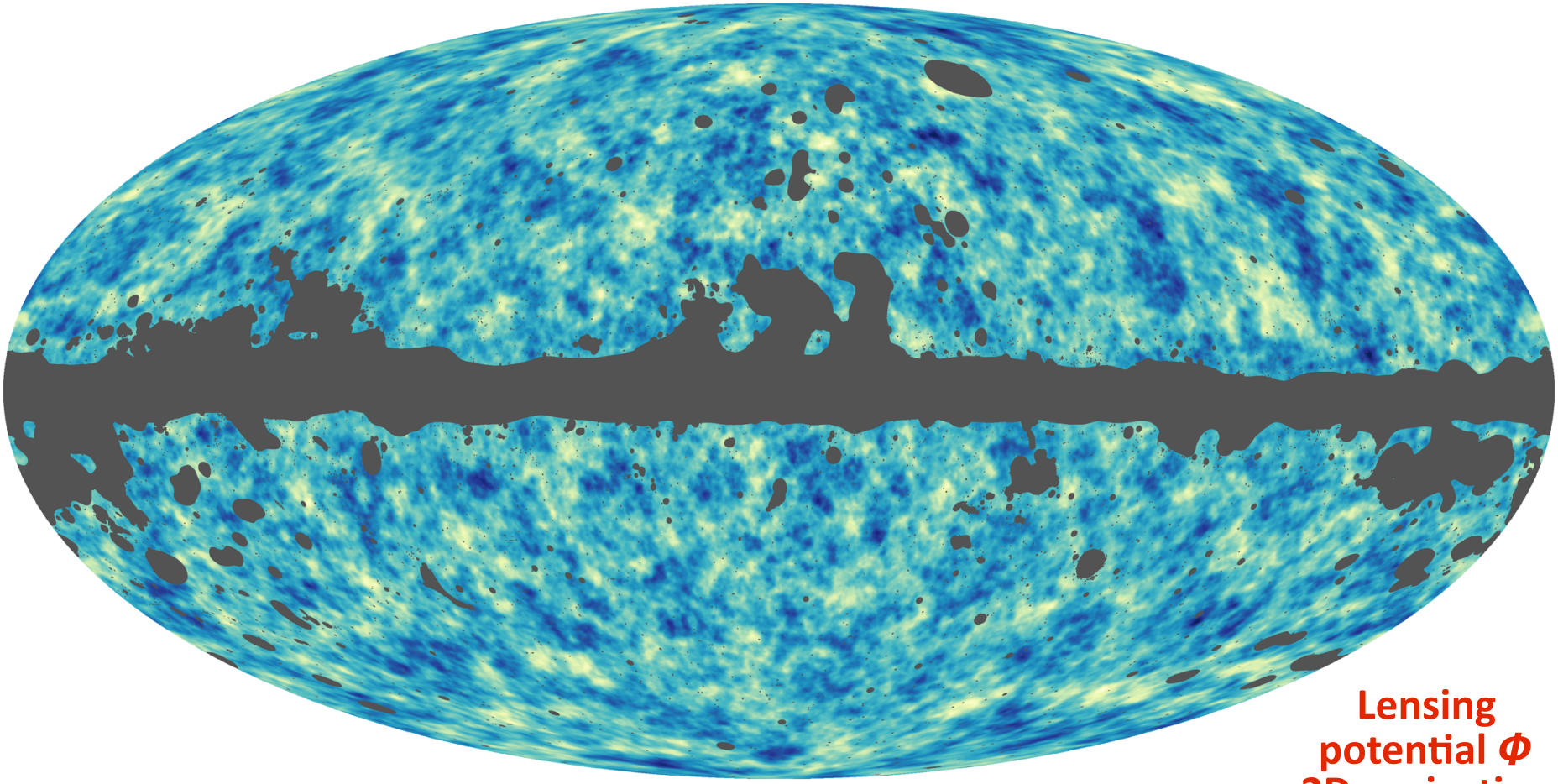

Lensing potential Φ 2D projection

similar to ζ

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

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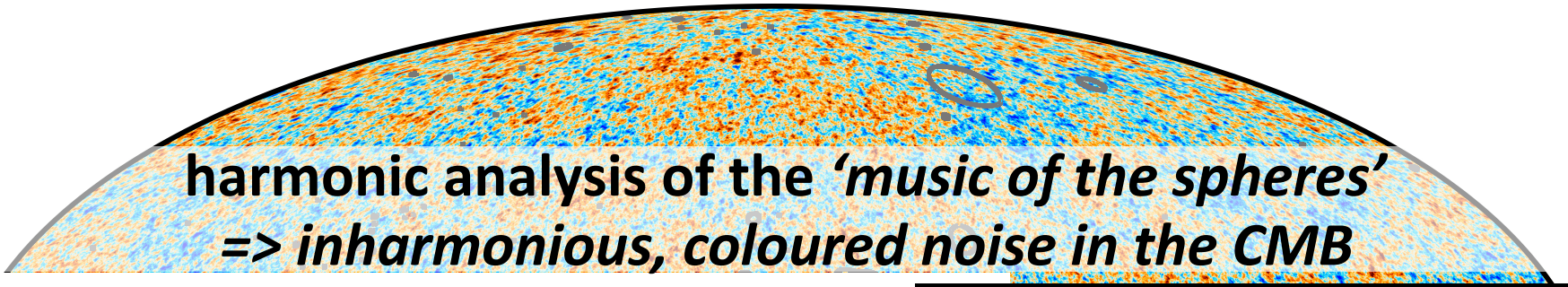
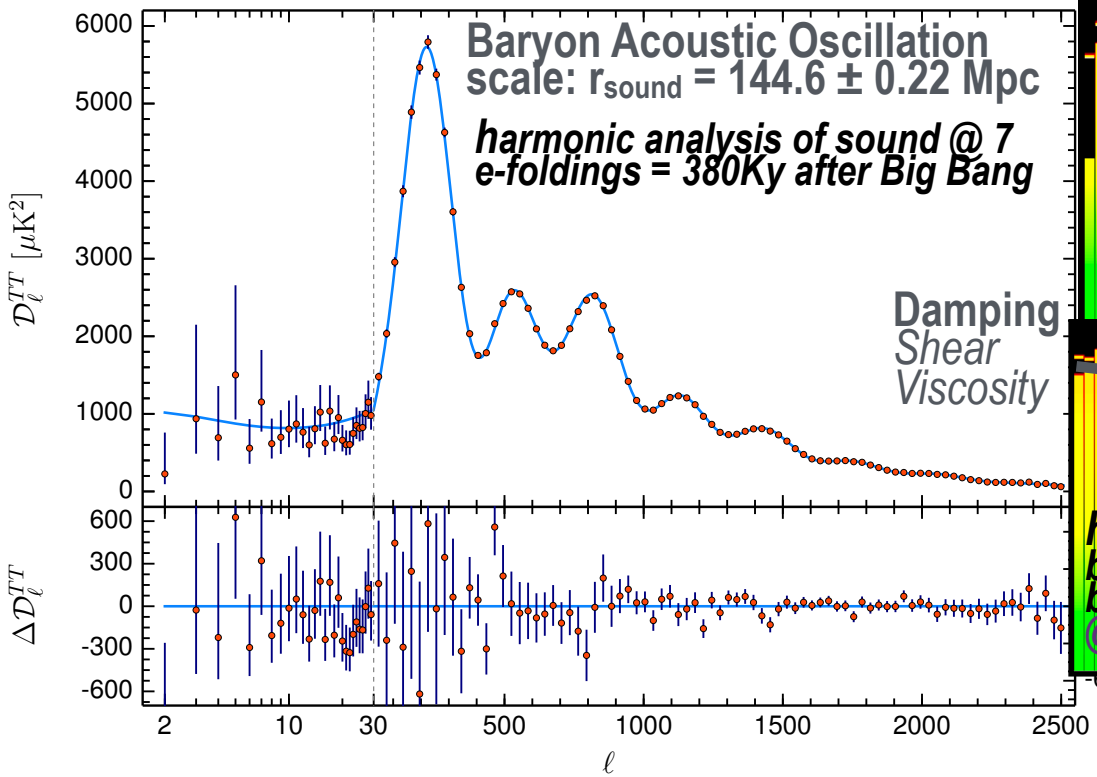
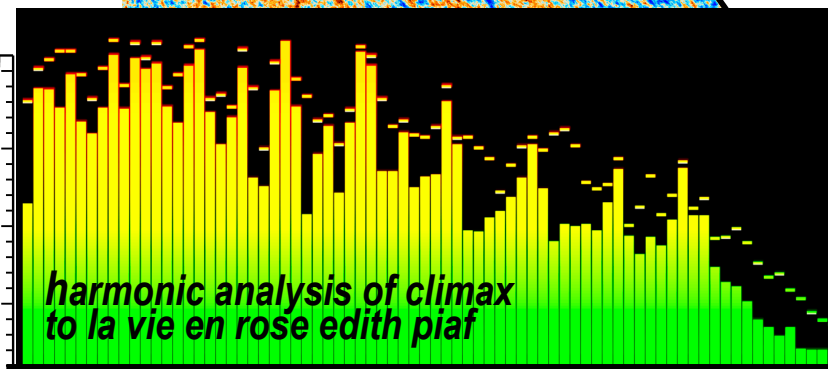
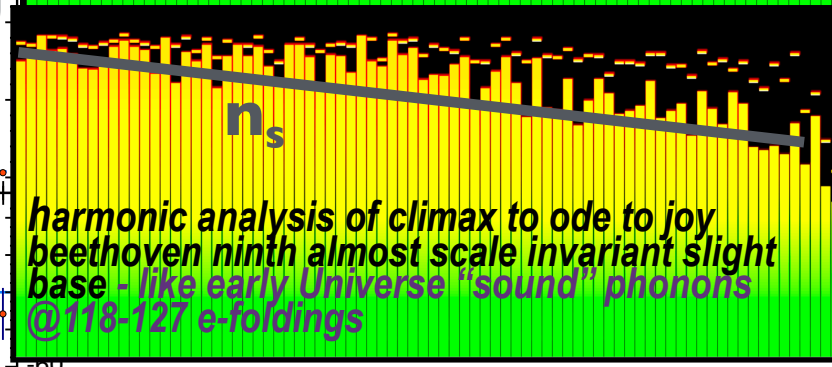


harmonic analysis of the *'music of the spheres'*
=> inharmonious, coloured noise in the CMB





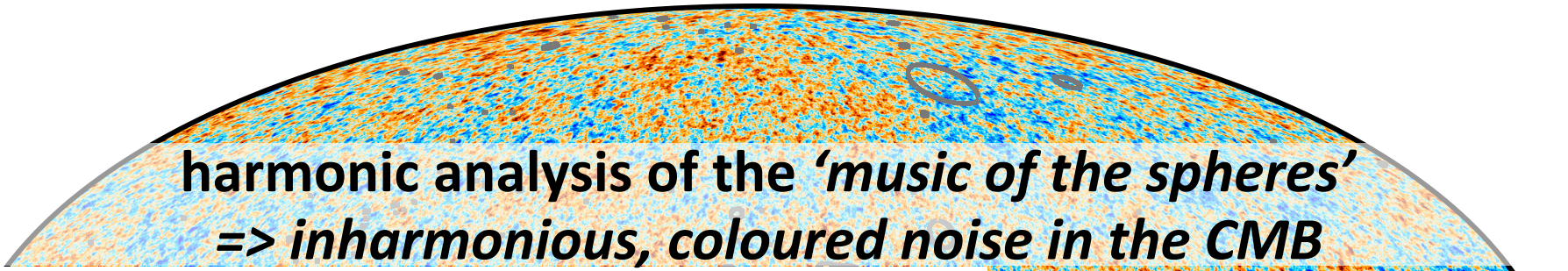


scale invariant - power all octaves equally 1D=1/f

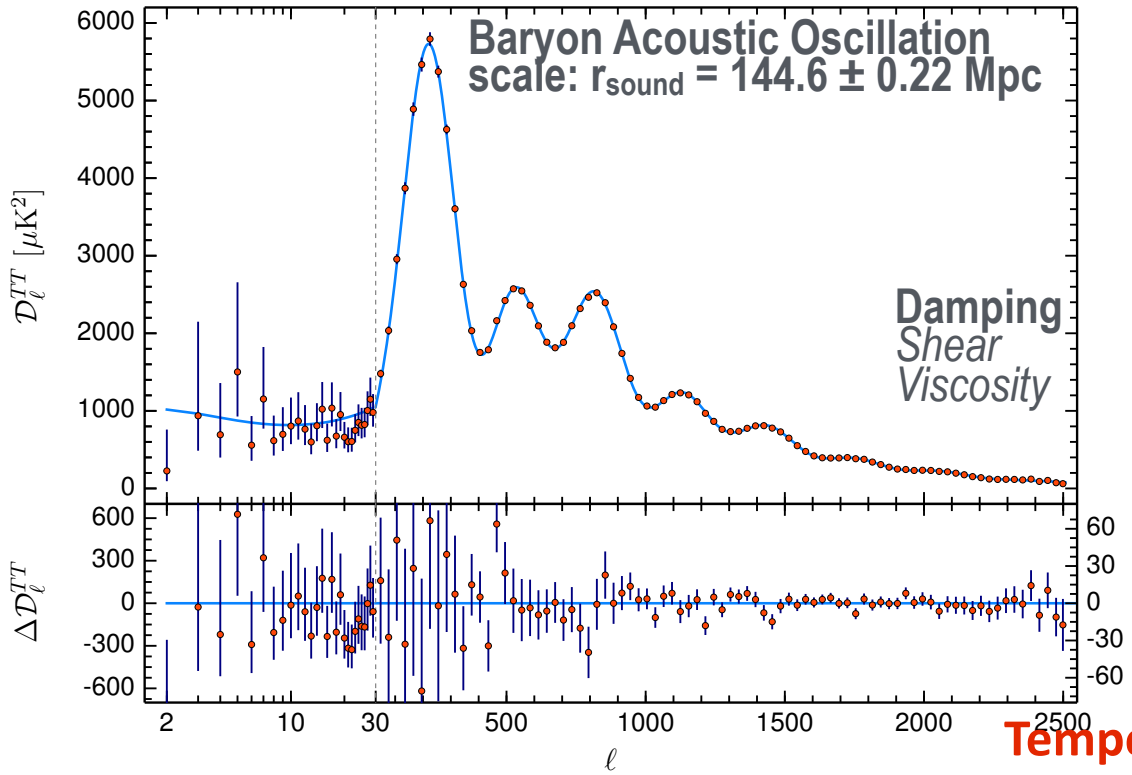
Planck's primordial light unveiled, *Mar 2013 =>* ***Feb 2015*** *=> pre-2016 =>* ***July 2018+*** *final*

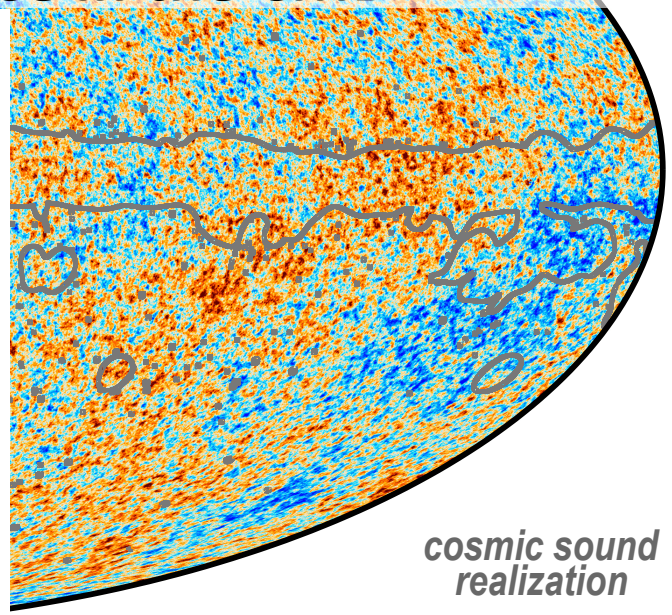
reveals the SIMPLICITY of primordial cosmic structure

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



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



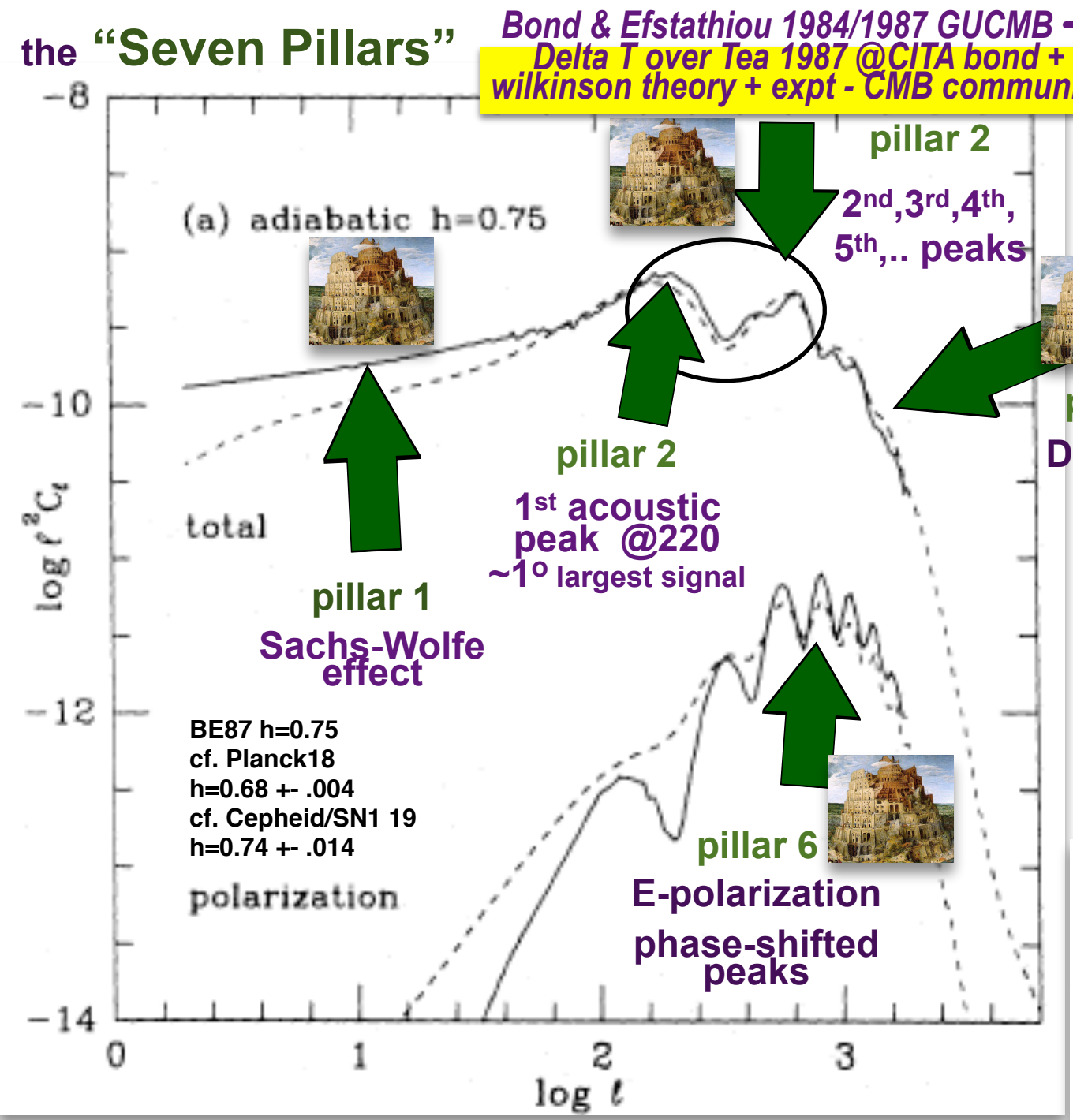


cosmic sound realization

Temperature changes in micro-degrees

the "Seven Pillars"

Bond & Efstathiou 1984/1987 GUCMB →
Delta T over Tea 1987 @CITA bond + wilkinson theory + expt - CMB community



pillar 1
Sachs-Wolfe effect

pillar 2
1st acoustic peak @220
~1° largest signal

pillar 2
2nd,3rd,4th, 5th,.. peaks

pillar 3
Damping tail

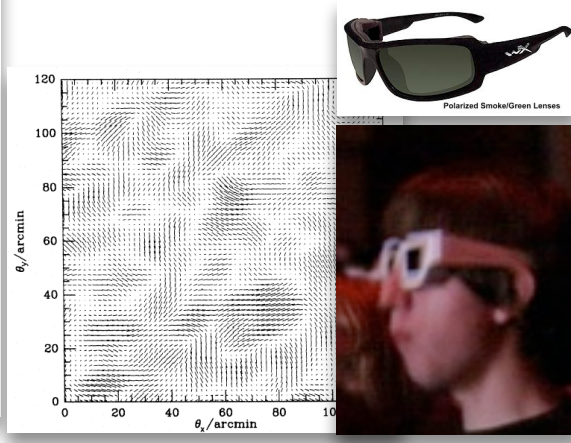
pillar 4
Gaussianity
maximal randomness for given C_L

pillar 5
secondary nonlinear
Compton SZ weak lensing..

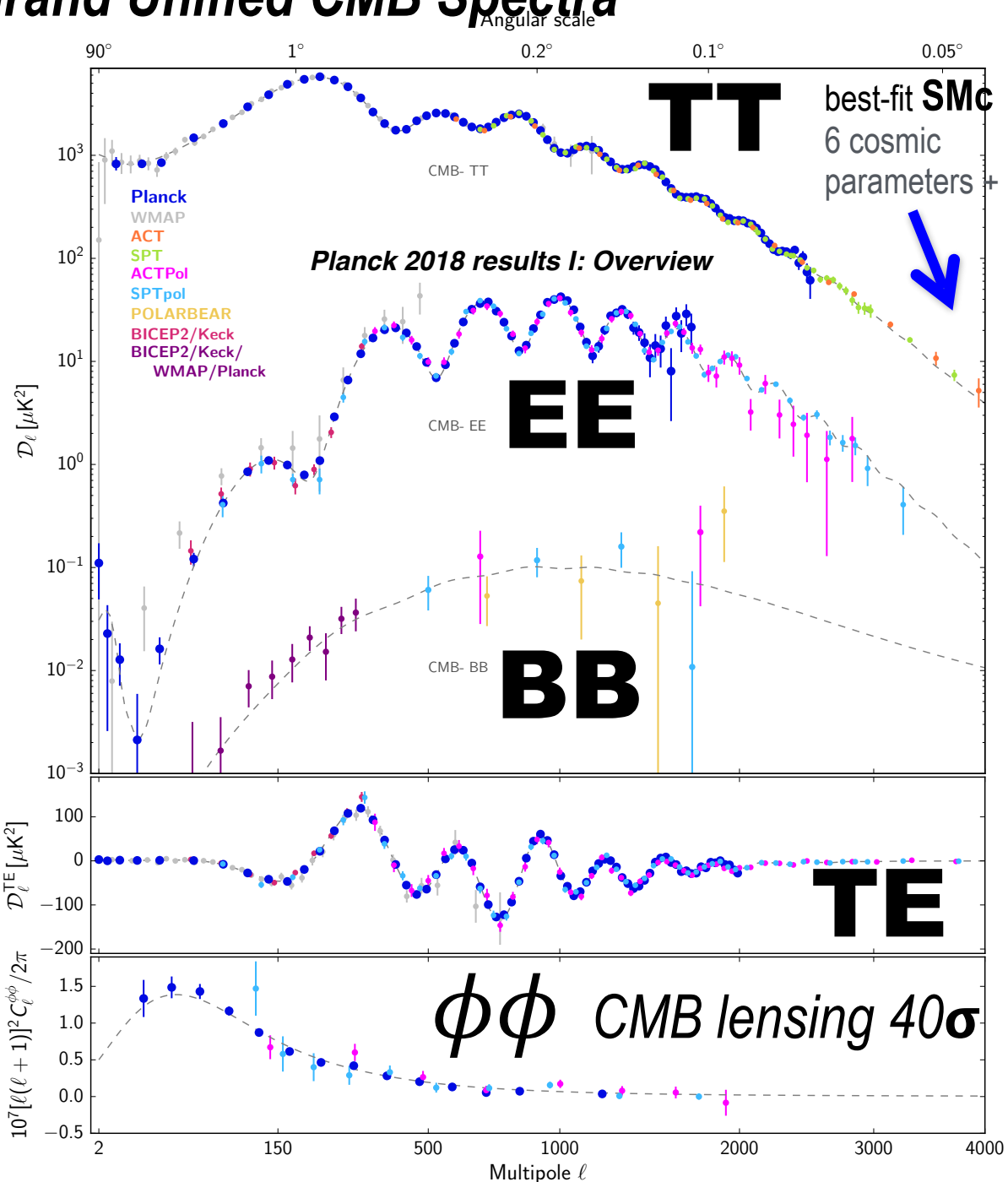
pillar 6
E-polarization
phase-shifted peaks

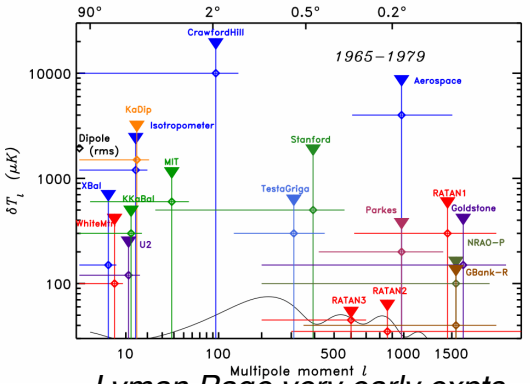
pillar 7
B-polarization
Gravity Waves

BE87 h=0.75
cf. Planck18
h=0.68 +- .004
cf. Cepheid/SN1 19
h=0.74 +- .014



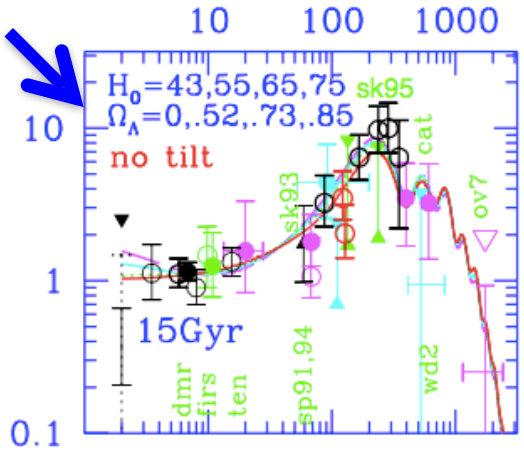
Grand Unified CMB Spectra



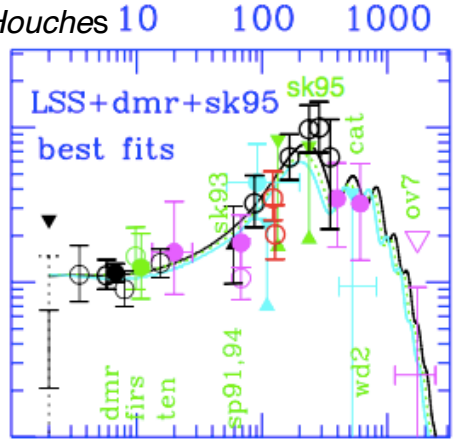


Lyman Page very early expts

JRB@Capri 1993 Bandpowers cf. theoretical power spectra



b95 Les Houches



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*

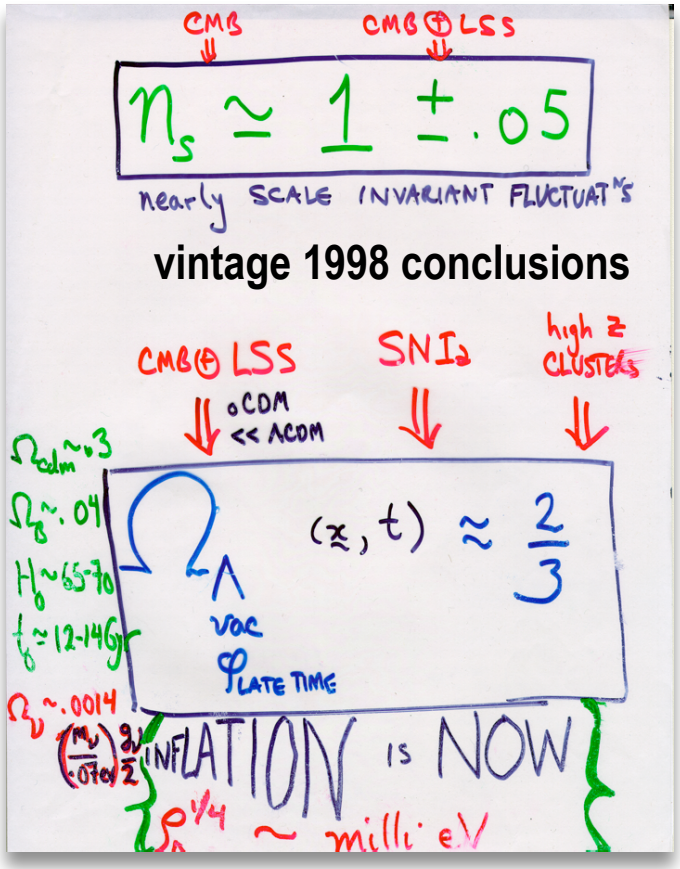
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

- 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.

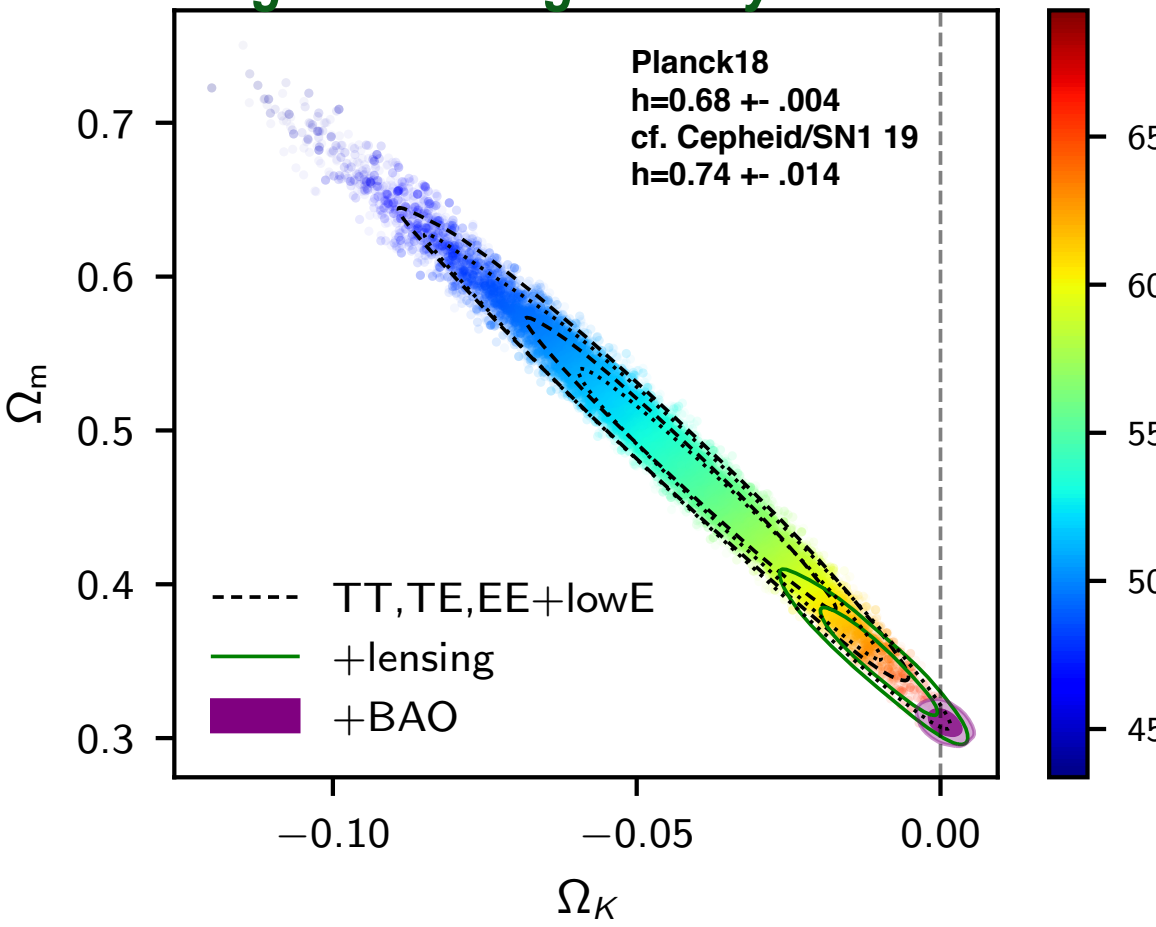
CMB@22, *Who's Who in North America*

inflation 1997/98

cf. inflation 2018



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



n_s =0.9665±0.004 *PI8VI*
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 *PI8VI*
w_0: -1.04± 0.1
Ω_κ: .0007 ± 0.004

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

isotropic strain, sound Trace(ε)

anisotropic strain, gravity waves

isotropic strain, sound

linear: **strain** $\propto$ **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**

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

$p=\hbar k$ $E=\hbar\omega$ ***other main ingredient - the mysteries not*** $\Delta k\Delta x\gtrsim 1$ ***&*** $\Delta\omega\Delta t\gtrsim 1$

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

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

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

H is inverse-time $T_{Hawking}=\hbar H$ ***is the Hawking temperature of inflation***

$\alpha_{\jmath}^{j}(r,t)$ scale-tensor of the Universe

$\alpha_{\jmath}^{j} \equiv \langle\alpha\rangle\delta_{\jmath}^{j} + \varepsilon_{\jmath}^{j}$

ε=strain tensor

the star of our show

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

isotropic strain & phonons

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

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

energy-density & gravity are entangled

ζ is an (the) adiabatic invariant
fluctuations in all fields are in response to ζ
photons, neutrinos dark matter baryons
...quarks gluons etal

$\zeta(x)$

energy-density & gravity are entangled

isotropic strain & energy-phonons

Trace $\varepsilon_{\jmath}^{j}$ @uniform density

$<\zeta|Temp, E\ pol>$-*WebSky* reveals *early universe phonons*

ζ- TOPOGRAPHY & CARTOGRAPHY

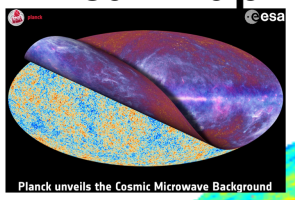
=> @a ~1/10^{55} only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

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

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

bond + huang

-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

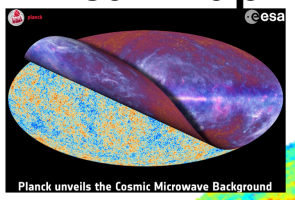
only partial de-lens

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

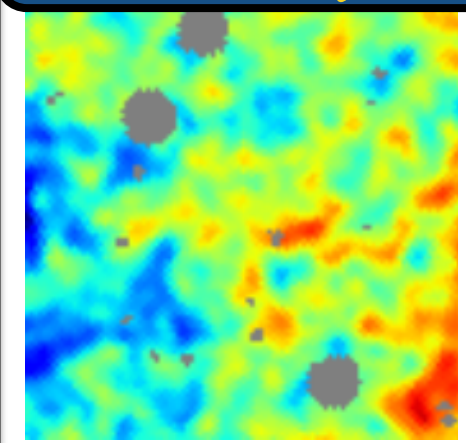
∫d ***visibility***(*distance*) <ζ|Temp, E pol>

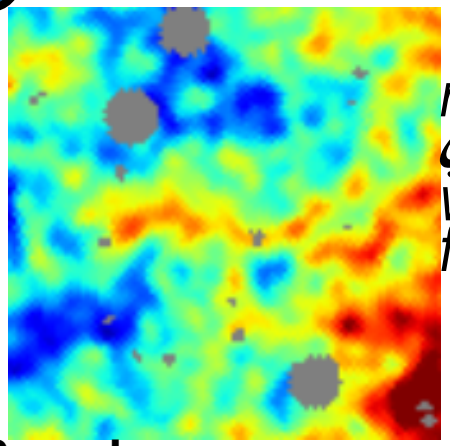
bond + huang

-40.0 +40.0

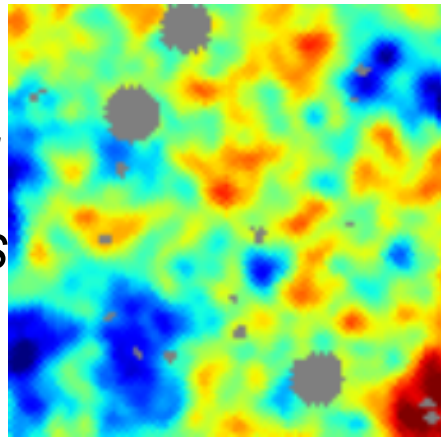
real ζ -WebSky mean field

visibility mask





real ζ-WebSkys with fluctuations

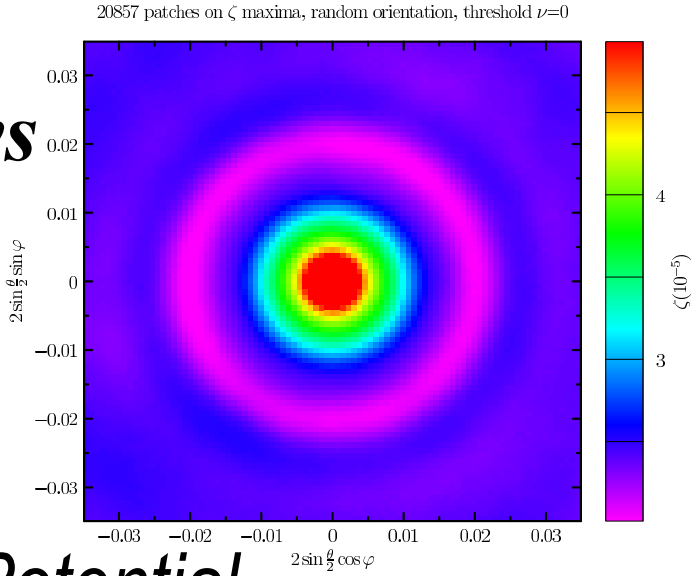


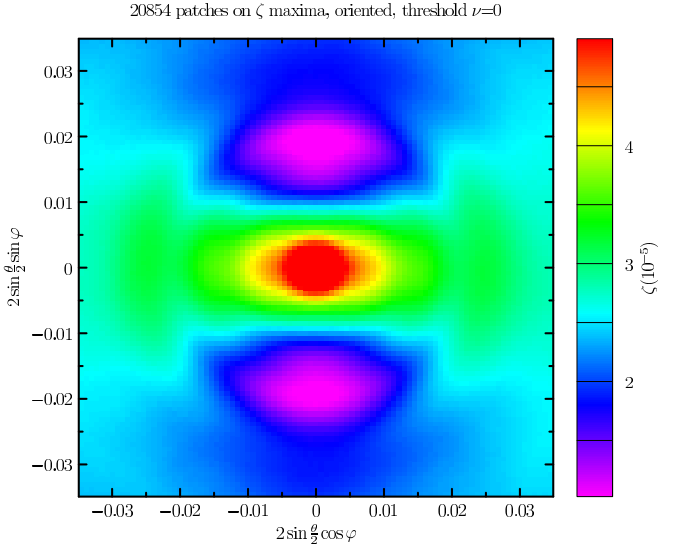
20x20 sq deg

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.

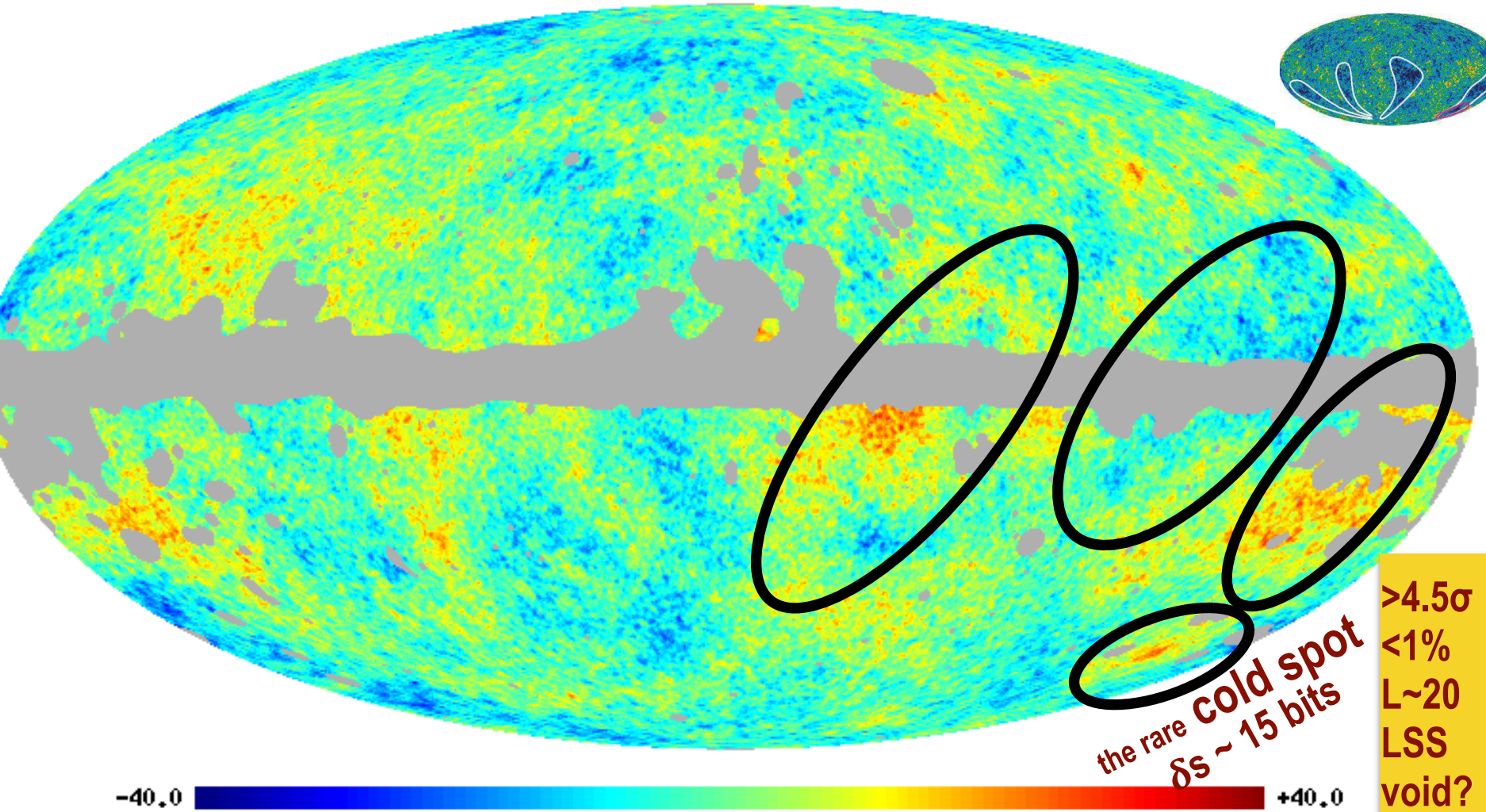
Beyond the Standard Model of cosmology? SMc = *tilted*ΛCDM +r aka (ζ, h_{+x})

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

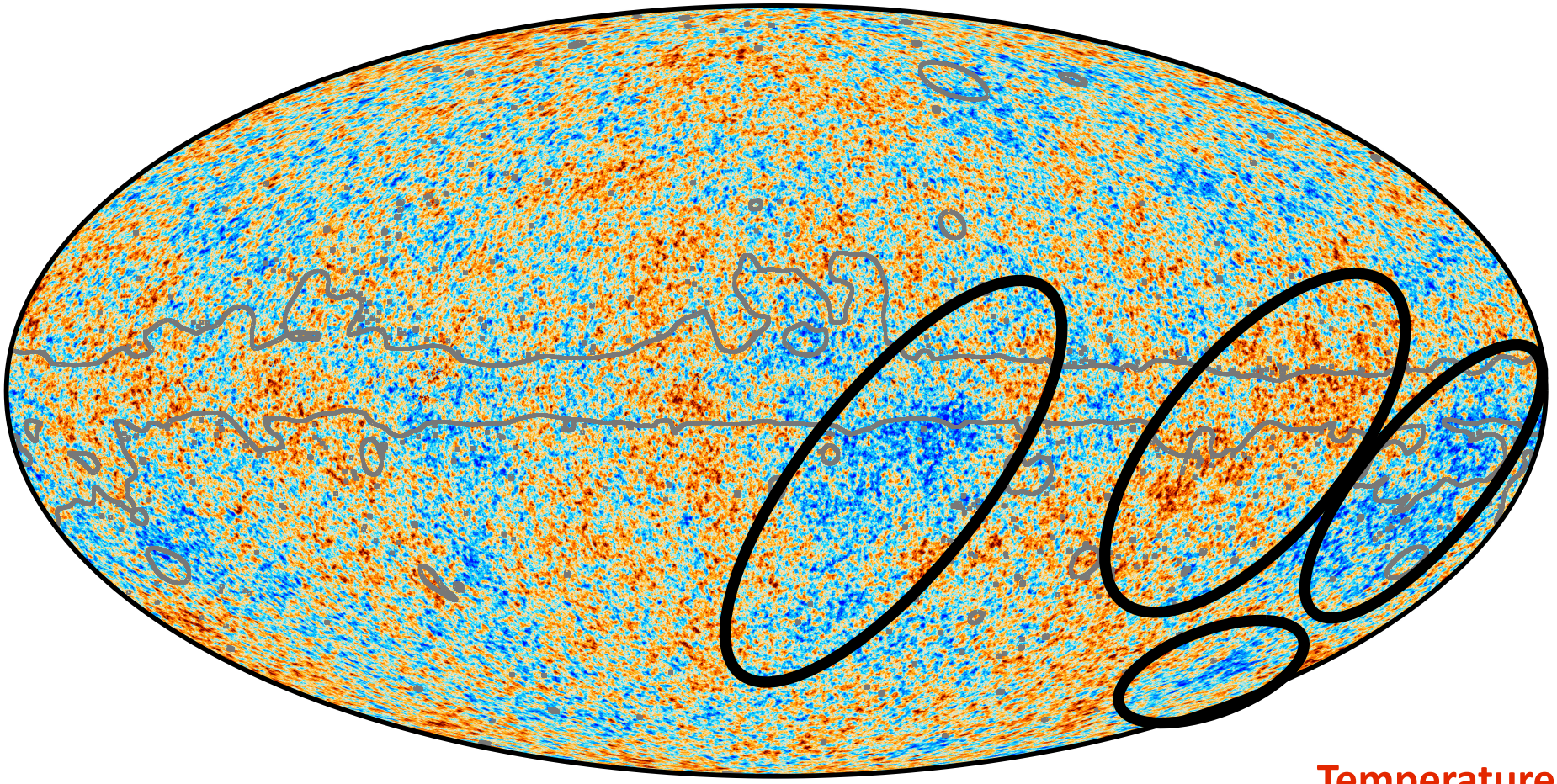
$<\zeta|T,E\text{-}pol>$

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

Grand Unified Theory of Anomalies?



>4.5σ
<1%
L~20
LSS
void?



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*

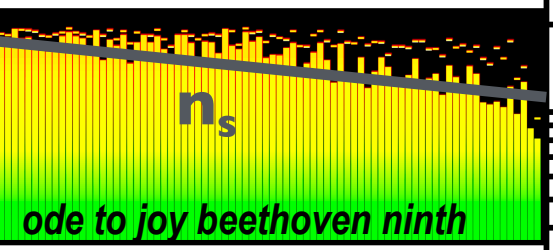
P18+BK15

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

uniform n_s=0.9669±.00367
future ±.002 SO

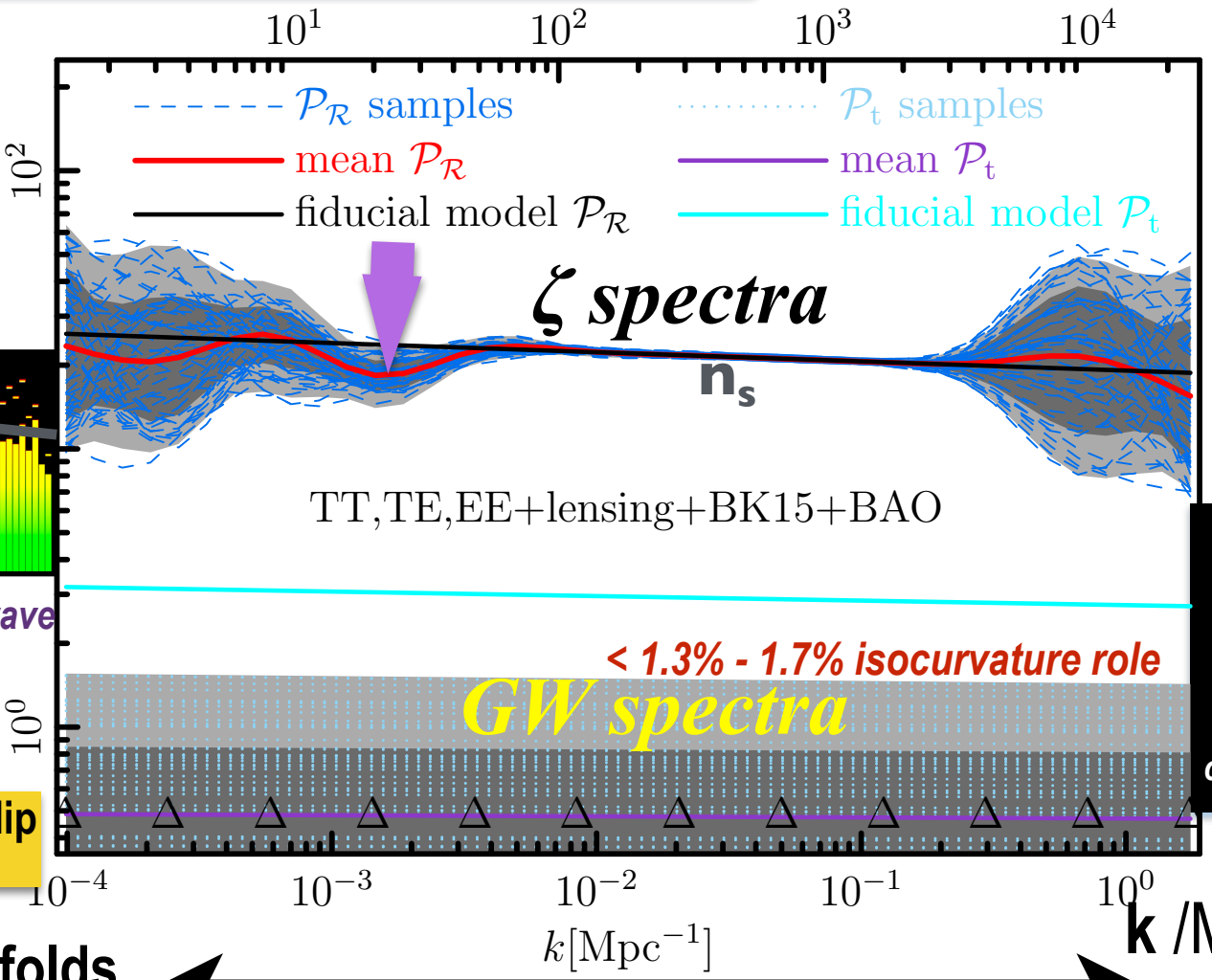
12-knot fit from k~ .008 to .3
uniform n_s is perfect

future 2σ(r)
SO 0.006
S4 0.001
Litebird 0.002



like early Universe elastic-wave sound@118-127 e-foldings

CMB TT power L~ 20-30 dip
=> ζ-Spectrum k-dip @2σ



derive
V(ϕ)
H(α)
ε(α)

⇒ 50 e-folds to EoI
poorly constrained

9 e-folds

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

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

P18+BK15

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

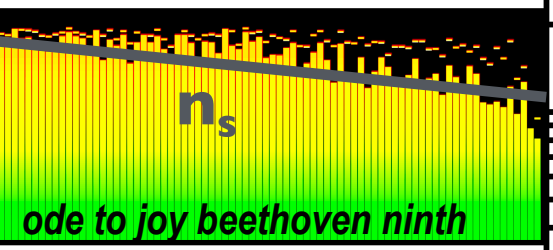
uniform n_s=0.9669±.00367
future ±.002 SO

12-knot fit from k~ .008 to .3
uniform n_s is perfect

we did ζ with WMAP+ACT +BOOM+ACBAR+... Planck much better, TDB SO+Planck

$L \sim k d_{rec}$

future 2σ(r)
SO 0.006
S4 0.001
Litebird 0.002



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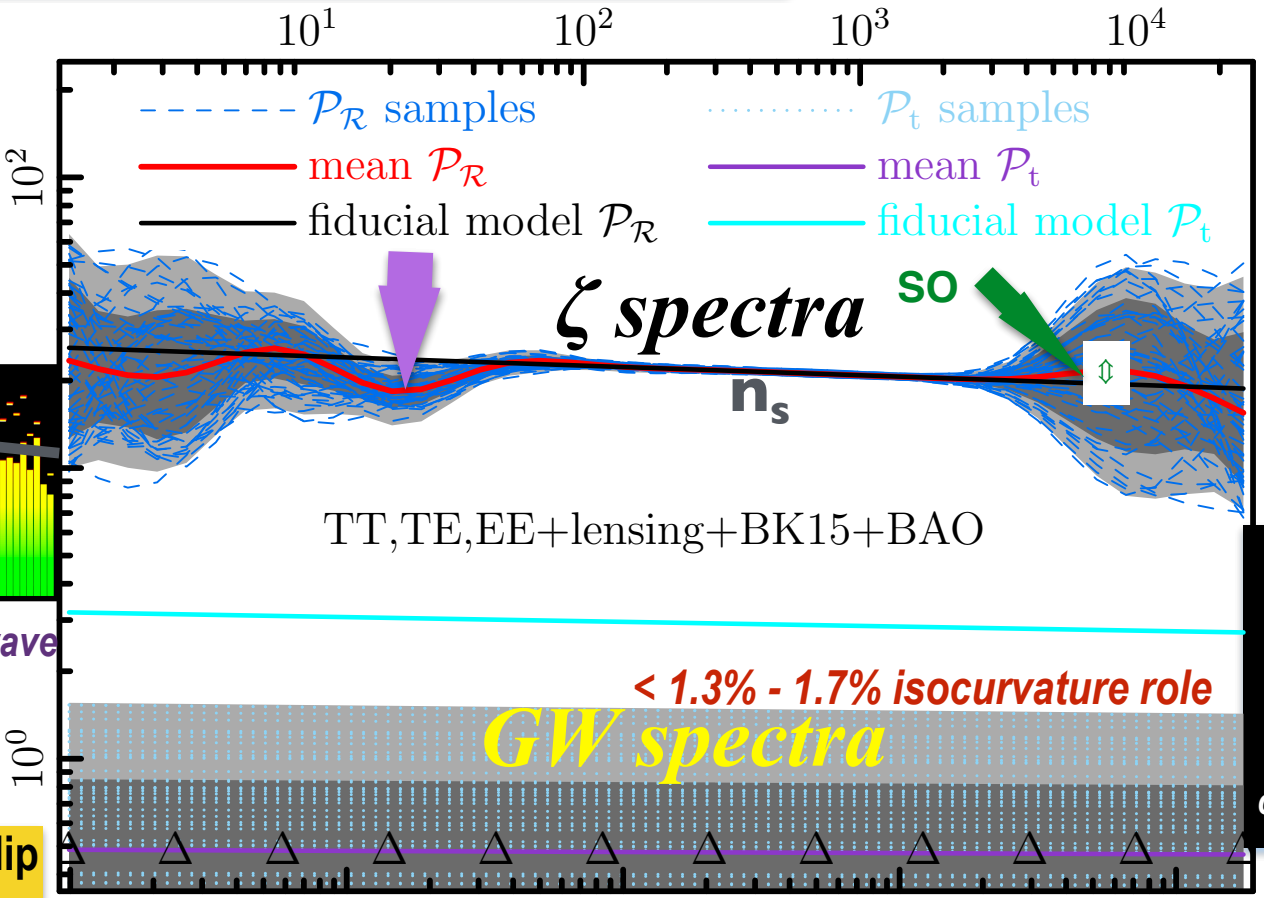

derive
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⇒ 50 e-folds to EoI
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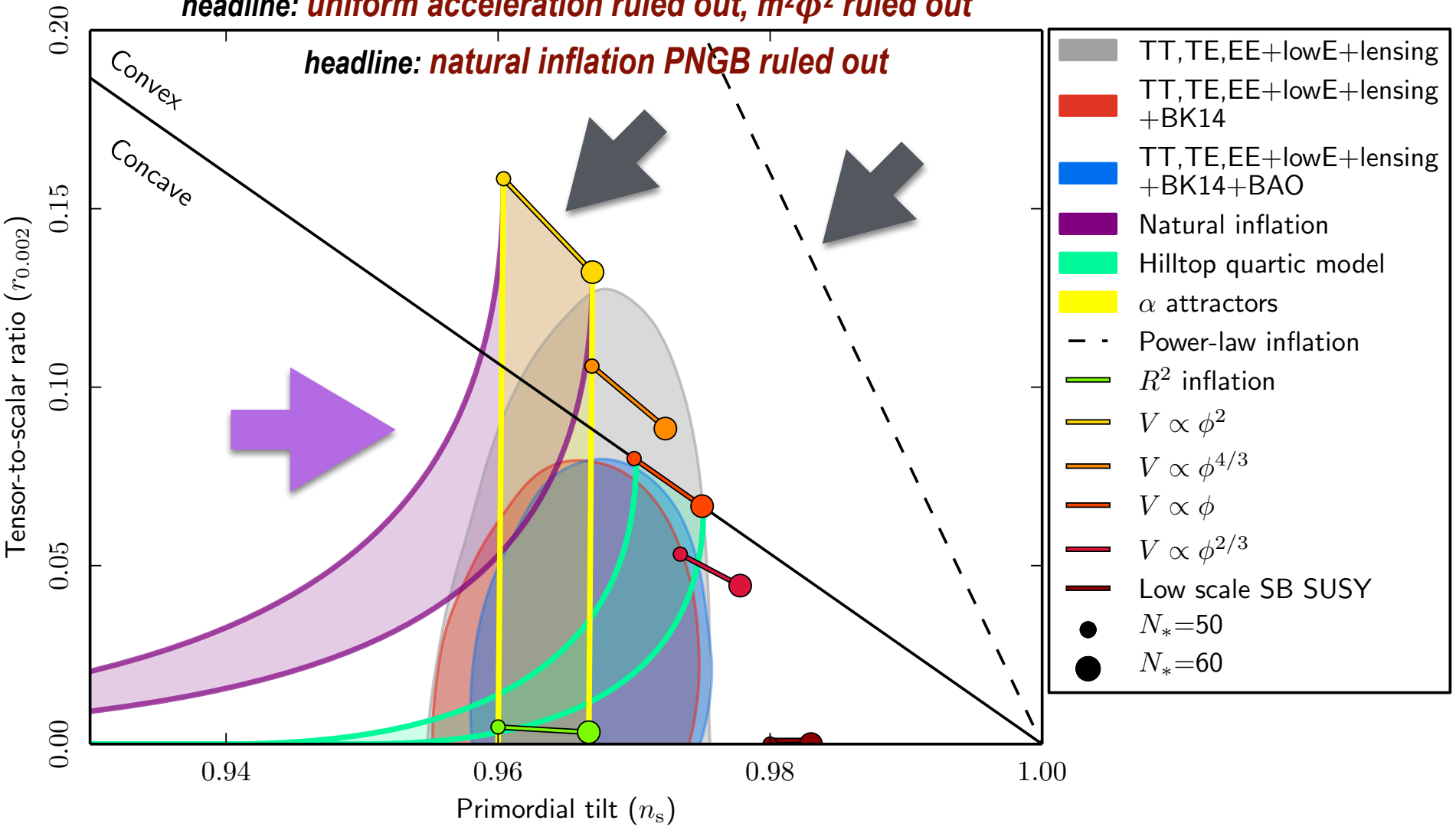
CMB TT power L~ 20-30 dip
=> ζ-Spectrum k-dip @2σ

9 e-folds

k /Mpc

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

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

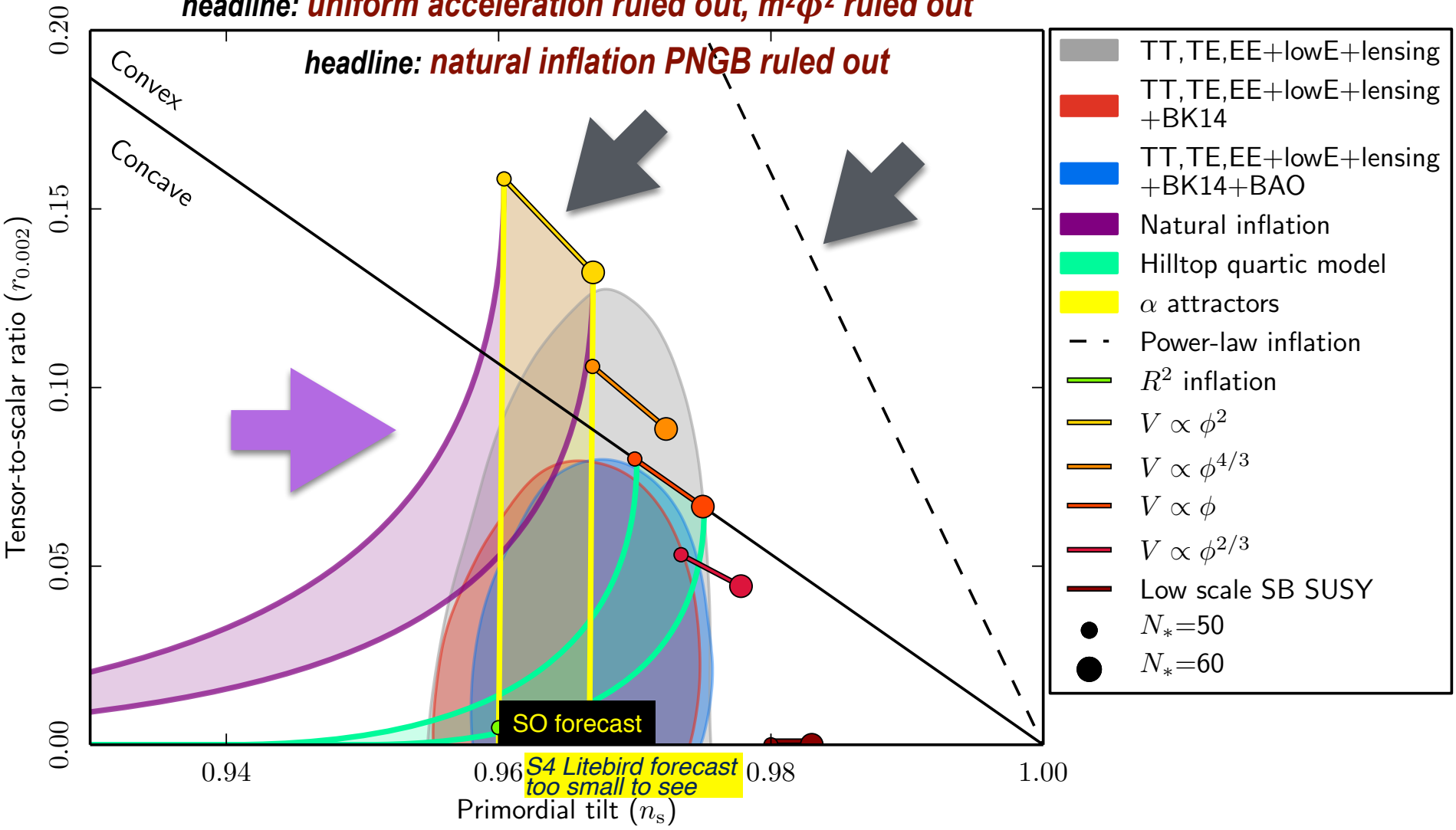


headline: ***Gravity Waves vs ζ: apart from the CMB T map, this r-n_s map most shown Planck figure***

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

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

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



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planck

Dick Bond
Quantum Inflation in the Planck Era & Beyond

esa

relic1: ζ *from* ***inflaton*** *- observable = all cosmic structure CMB&LSS & stars/humans & .. amplitude & slope <-> acceleration history & Veff simple over observable range*

relic2: ***entropy*** $S_{tot} = S_{CMB} + S_{CnuB}$ *cooled remnant of particle/field plasma post-inflation*

$10^{88.6}$ *cf.* $S_G \sim 10^{121.9}$ *asymptotic DE*

relic3: ***baryon asymmetry*** N_{baryon}/S_{tot} *of matter over antimatter*

$10^{-10.06}$

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 2D*** *with all its fluctuations & polarization ✔✔✔ -α=7 some 2-2.5*

$\sim f_{sky} L_{max}^2$ *cf.* ***LSS*** $X\ k_{max}\ d_{max}$

relic 7: ***LSS 3D*** *galaxies & large scale clustering, flows, lensing - tomography with redshift*

grav instability $S_{th,cl} \sim 10^{76}$ < stars S_{CIB} *-α<3 some CMB overlap*

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

68.5 ± 0.7%

Dick Bond

Quantum Inflation in the Planck Era & Beyond

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

< 1.3% - 1.7% 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)?*

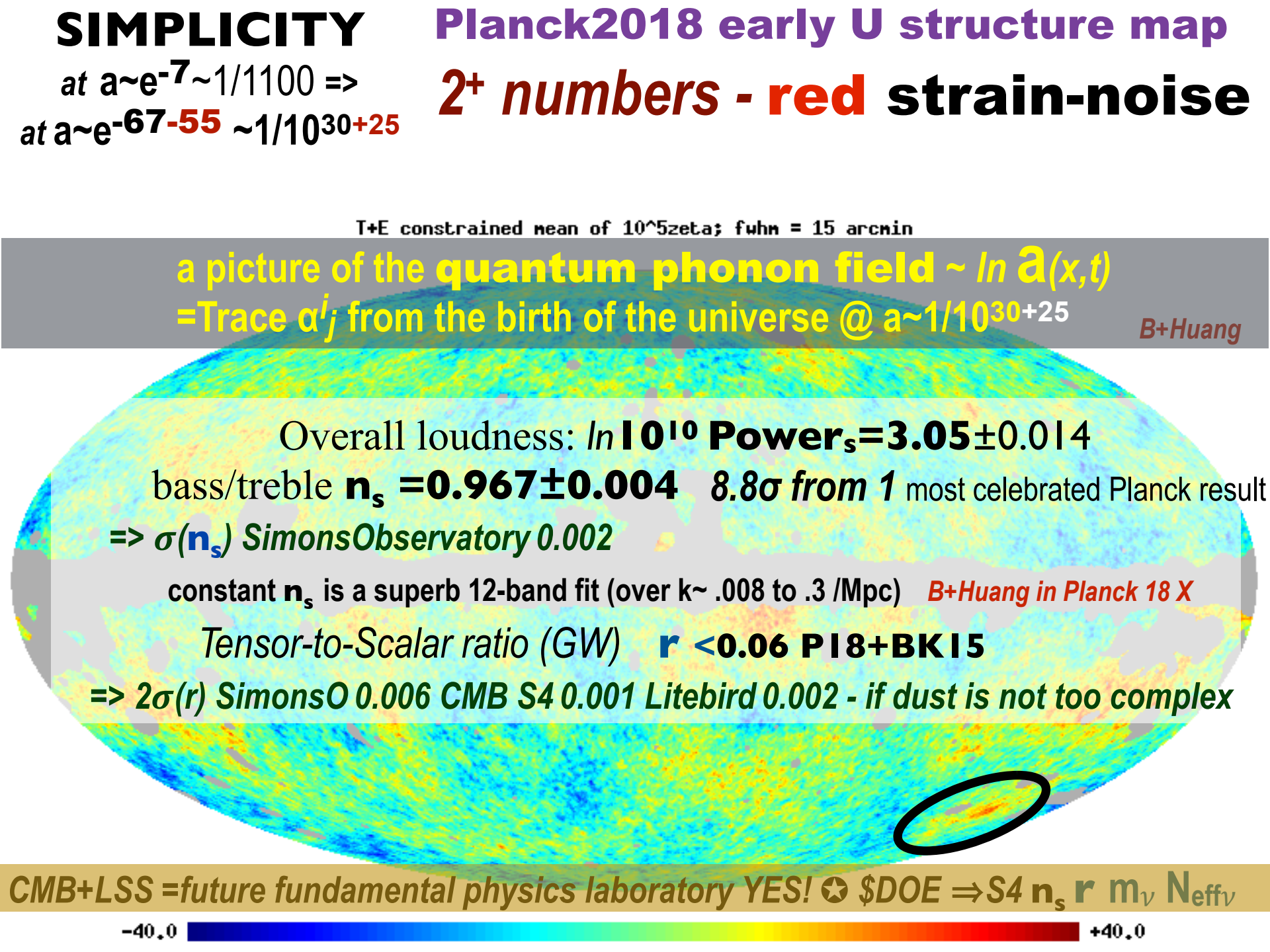
SIMPLICITY

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 $\alpha^i{}_j$ from the birth of the universe @ $a \sim 1/10^{30+25}$

B+Huang

Overall loudness: *ln* 10^{10} **Power$_s$=3.05**±0.014

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

=> *σ(n_s) SimonsObservatory 0.002*

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**

=> *2σ(r) SimonsO 0.006 CMB S4 0.001 Litebird 0.002 - if dust is not too complex*

CMB+LSS =future fundamental physics laboratory YES! ✪ $DOE ⇒S4 **$n_s$ r** m_ν $N_{eff\nu}$

end of Bond's TIME