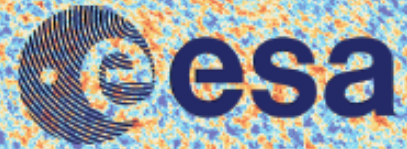




planck

Quantum Universe in the Planck Era & Beyond

Dick Bond @ PSU 19 02 02



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

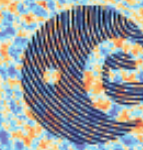
7+ numbers
3 densities,
2+1 early-
Universe
inflation

CMB+LSS future
SMc -> BSMc

Beyond the
Standard Model
of Cosmology



planck

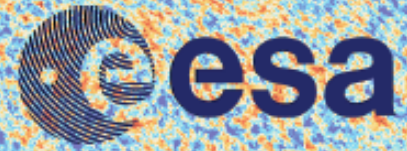




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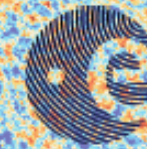
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planck



CIFAR
CANADIAN
INSTITUTE
FOR
ADVANCED
RESEARCH

goal today: CMB maps baby pics $\Rightarrow$ early Universe maps! embryo pics



CITA
ICAT

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



planck

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the Universe at Large

a tale of
Planck**4

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

CMB past =>
CMB present

7+ numbers
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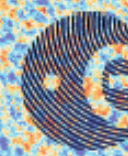
coarse-grained quantum diffusion (Fokker-Planck) $\sqrt{D_H} \sim \hbar H \sim T_H$ in

the emergence of our Universe from the Planck-era

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



planck



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

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

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



CMB prediction

Alpher, Gamow Herman 1950s Tcmb ~5K

CMB Discovery

Penzias & Wilson 65

@7cm

CMB dipole 70s DT /T~ V/c 360km/s

Delta T over Tea 87 @CITA theory+expt

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=> future

.. CMB Stage 3 (now) => SO Spider2

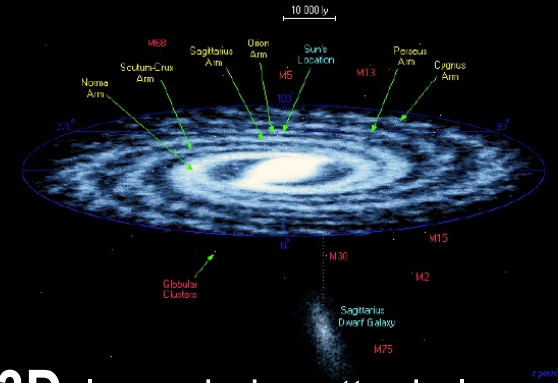
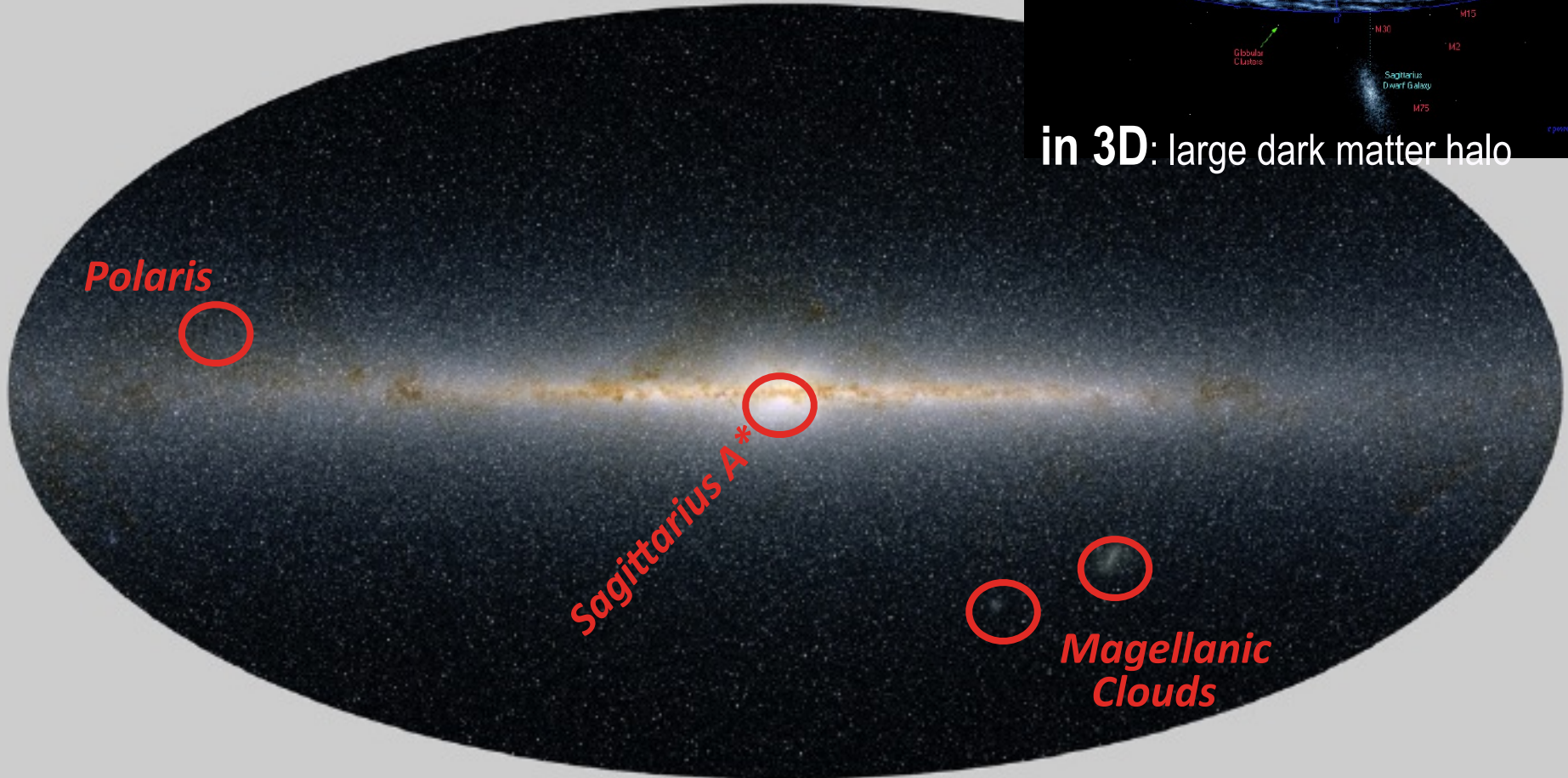
.. Stage 4 > 2025

.. LiteBird 2028, other satellites ??



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

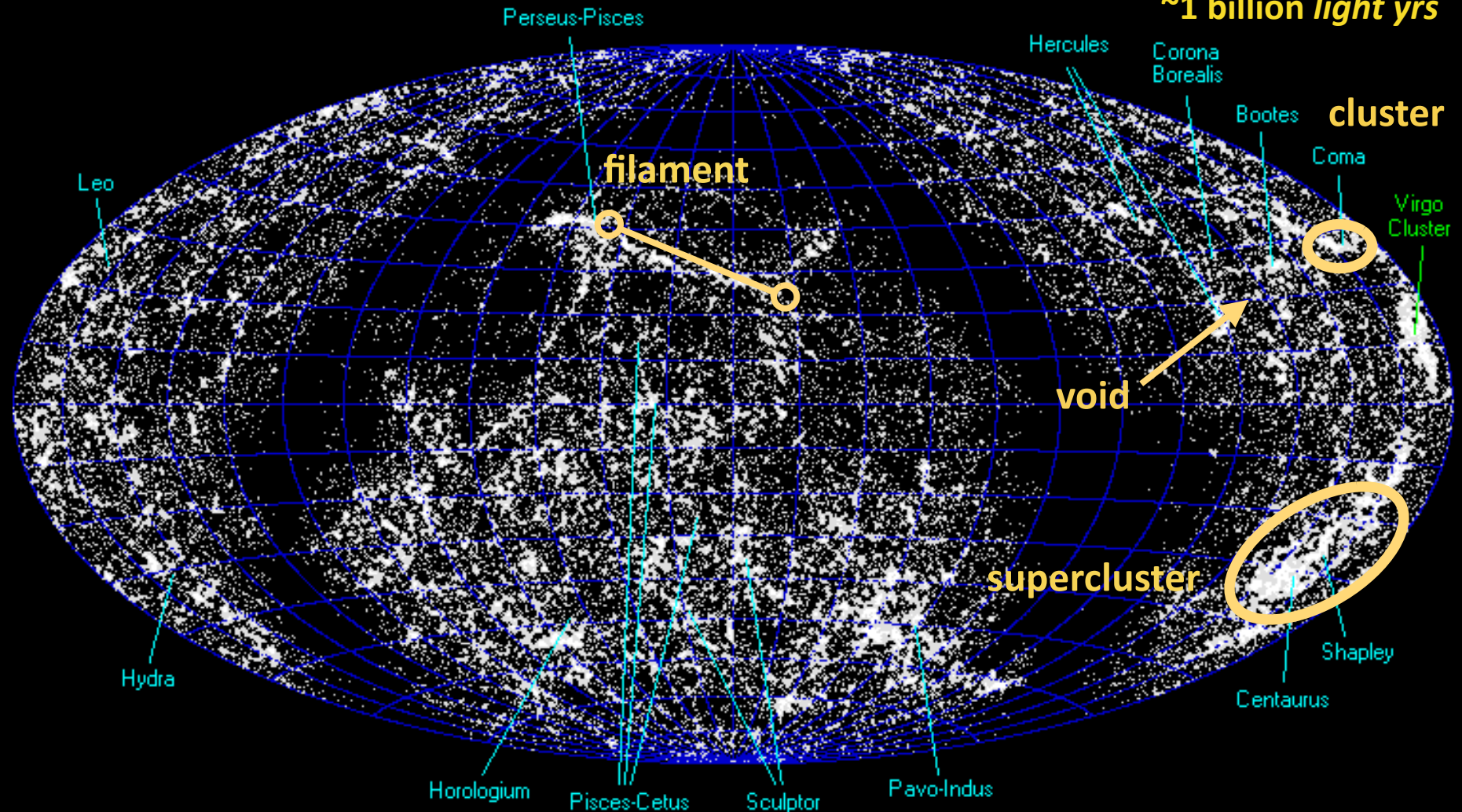
in 3D: large dark matter halo



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

$a \sim e^{-0.1} = 1/1.1$ 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 $\equiv \langle \ln a \rangle$

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 $\sim 1/4$ 1 $\Downarrow$ 2

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

light nuclei

Dark Matter

21 $\Downarrow$ 35

Heat: matter & radiation

67

quantum noise $\hbar$ 67 $\Downarrow$ 127

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

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galaxies forming ~ 1/4 1 ↓↓ 2

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

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

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

light nuclei

Dark Matter

21 ↓↓ 35

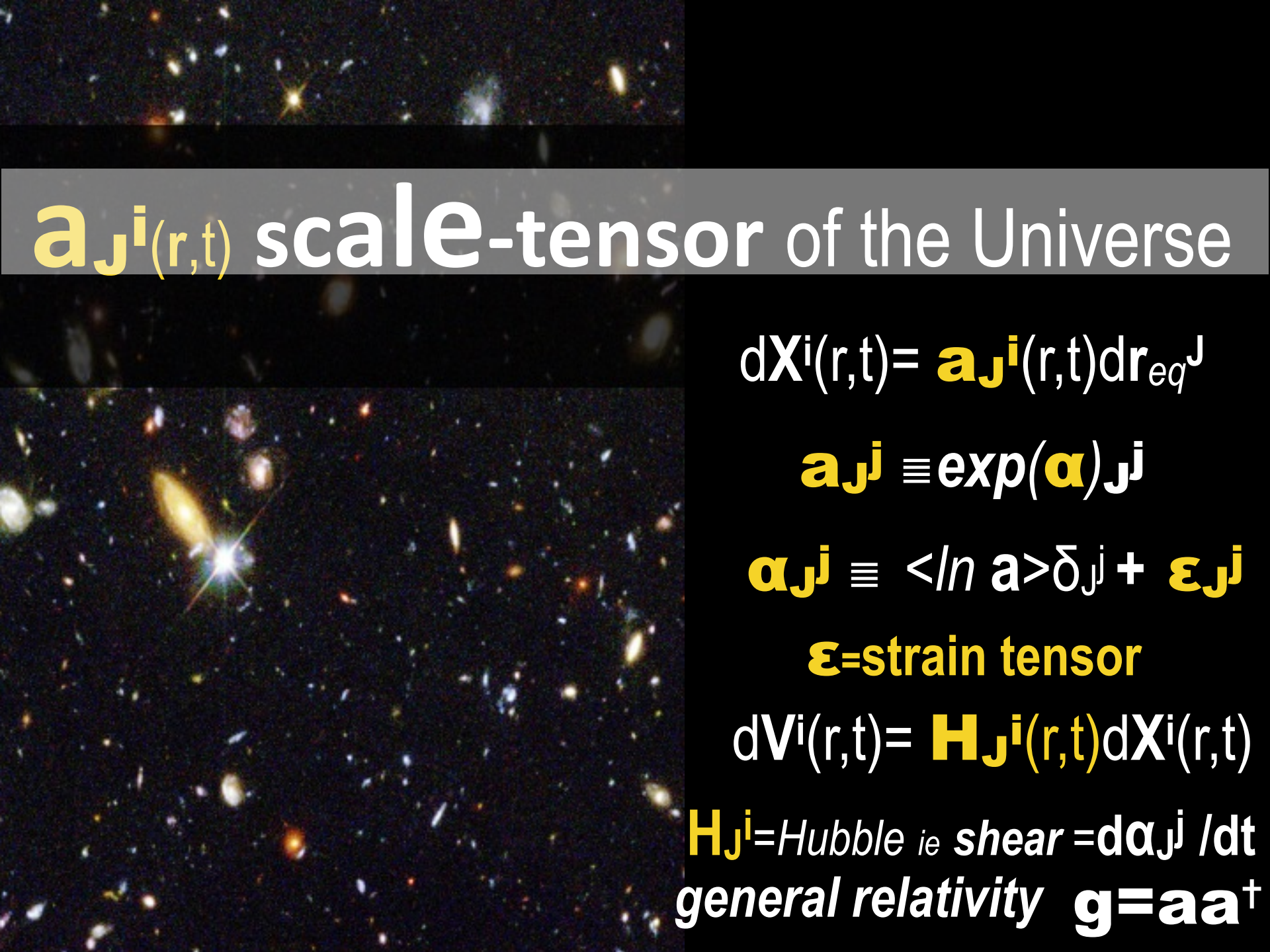
Dark Matter ~amu /m³ 26.6 ± 0.7%
compressed in MilkyWay X4e-folds ~0.3 amu /cm³

Heat: matter & radiation 67

Dark Energy ~ vacuum potential +++

~ 3 amu /m³ 68.5 ± 0.7% late-inflaton cannot compress

quantum noise $\hbar$ 67 ↓↓ 127

A deep-field astronomical image showing a vast number of galaxies at various distances and orientations, set against a dark cosmic background. The galaxies appear as bright, elongated or point-like sources of light.

$\mathbf{a}_J^i(r,t)$ scale-tensor of the Universe

$$d\mathbf{X}^i(r,t) = \mathbf{a}_J^i(r,t) dr_{eq}^J$$

$$\mathbf{a}_J^i \equiv \exp(\boldsymbol{\alpha})_J^i$$

$$\boldsymbol{\alpha}_J^i \equiv \langle \ln a \rangle \delta_J^i + \boldsymbol{\epsilon}_J^i$$

$\boldsymbol{\epsilon}$ =strain tensor

$$d\mathbf{V}^i(r,t) = \mathbf{H}_J^i(r,t) d\mathbf{X}^i(r,t)$$

$\mathbf{H}_J^i$ =Hubble ie shear = $d\boldsymbol{\alpha}_J^i / dt$
general relativity $\mathbf{g} = \mathbf{a}\mathbf{a}^\dagger$

Earth under Strain:
earthquakes, seismic waves

$\boldsymbol{\epsilon}$ =strain tensor

elastic deformation $d\mathbf{x}^i = \mathbf{e}_J^i d\mathbf{r}_{eq}^J$ $e_J^i = a_J^i / \langle a \rangle$
anisotropic strain, shear waves $\boldsymbol{\epsilon} - \text{Trace}(\boldsymbol{\epsilon})/3$
isotropic strain, sound $\text{Trace}(\boldsymbol{\epsilon})$

Universe under Strain:
space-quakes, gravity waves

scale-deformation a_J^i

anisotropic strain, gravity waves
isotropic strain, sound

linear: strain $\propto$ tide
cosmic web story



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

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

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

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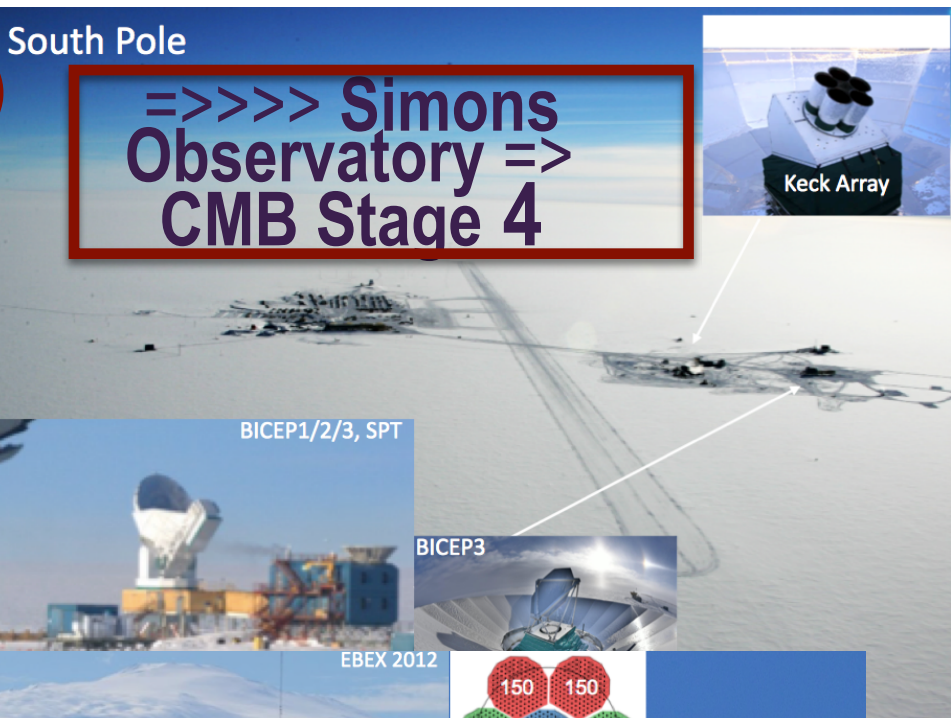
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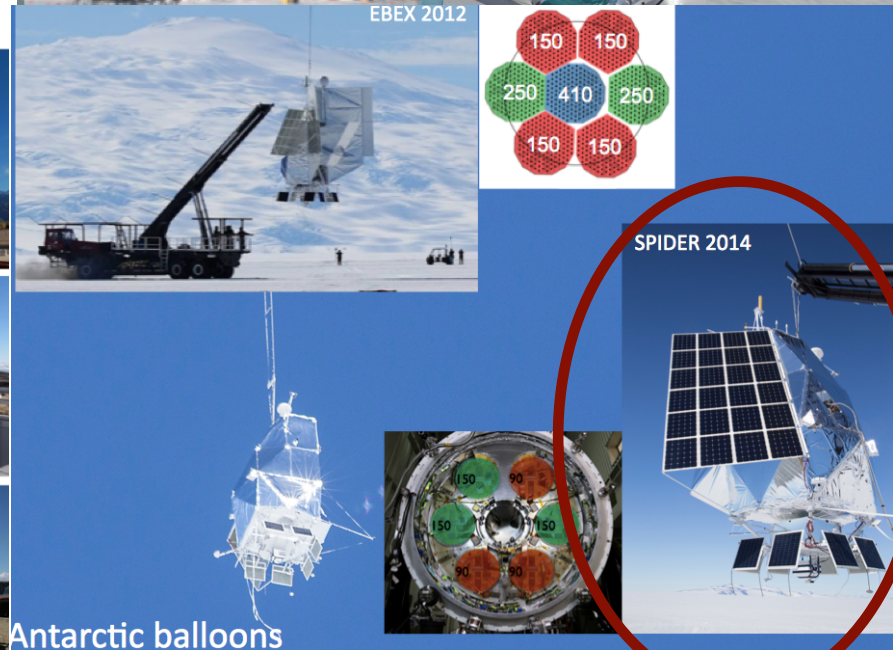
**California+
South Africa**
C-BASS 5 GHz



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

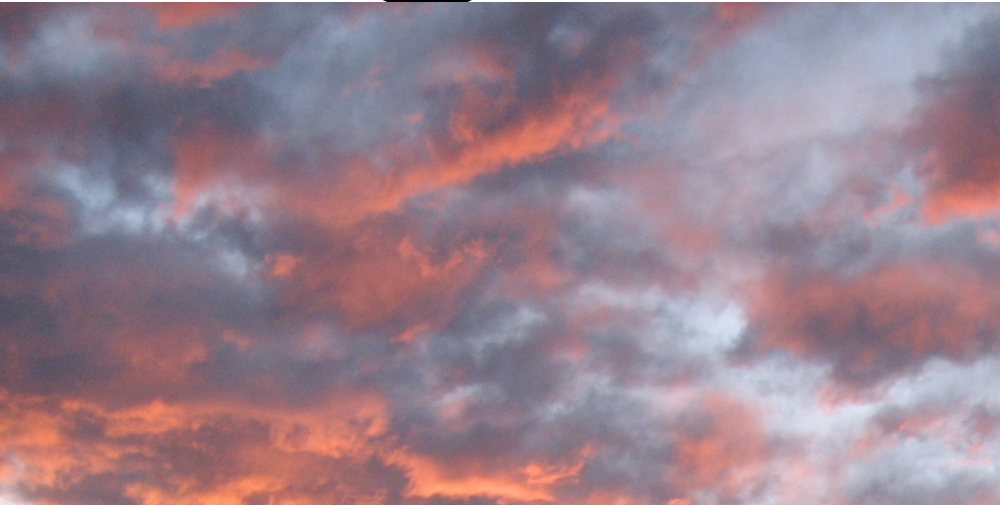


California
B-Machine 40 GHz



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

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

managing the CMB

on to SO -> CMB-S4
Advanced ACTPol



boomerang ~40/paper

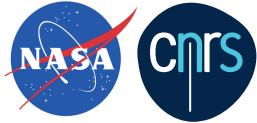


planck

Cobras/Samba @Capri93

~250/paper, ~100 institutions

Bond since 1993, Canada since 2001



DTU Space
National Space Institute

Science & Technology
Facilities Council



National Research Council of Italy



Deutsches Zentrum
für Luft- und Raumfahrt e.V.

UK SPACE
AGENCY



SPIDER

PRINCETON
UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

Imperial College
London

UNIVERSITY OF
TORONTO

CITA
ICAT
Canadian Institute for
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l'Institut canadien
d'astrophysique théorique

STANFORD
UNIVERSITY

CASE WESTERN RESERVE
UNIVERSITY

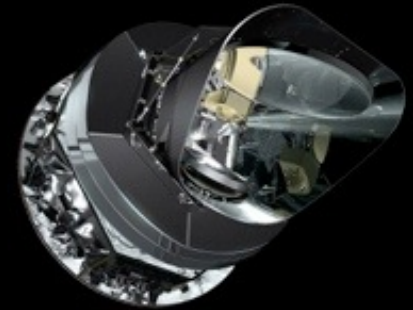


Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch

WMAP 01 launch

Planck 09 launch



420'

12.5'

~5-7'

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')

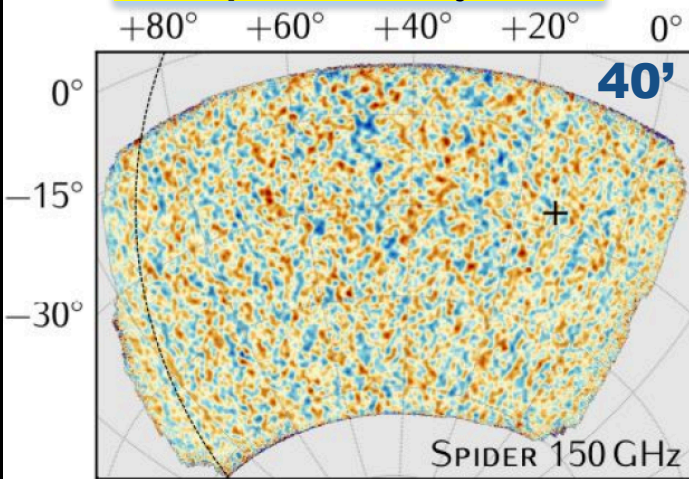
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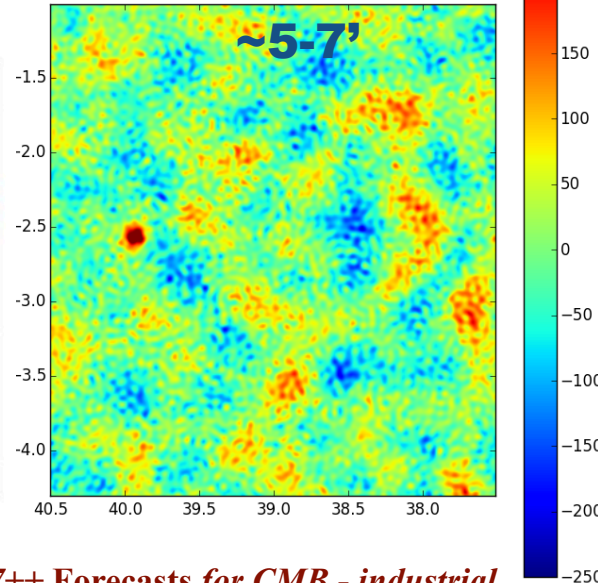
Planck 09 launch

Spider 40' fsky~.08



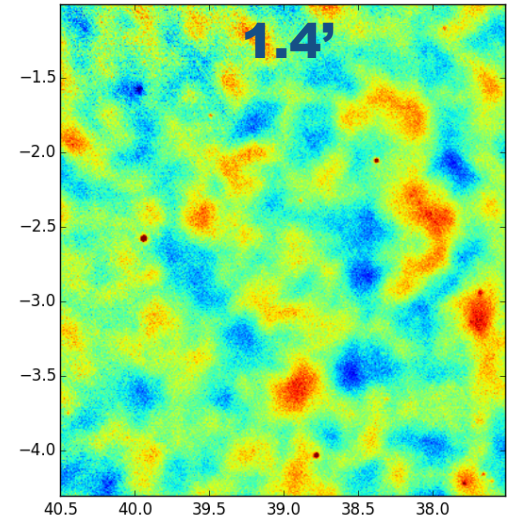
Planck

~5-7'



ACT

1.4'



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



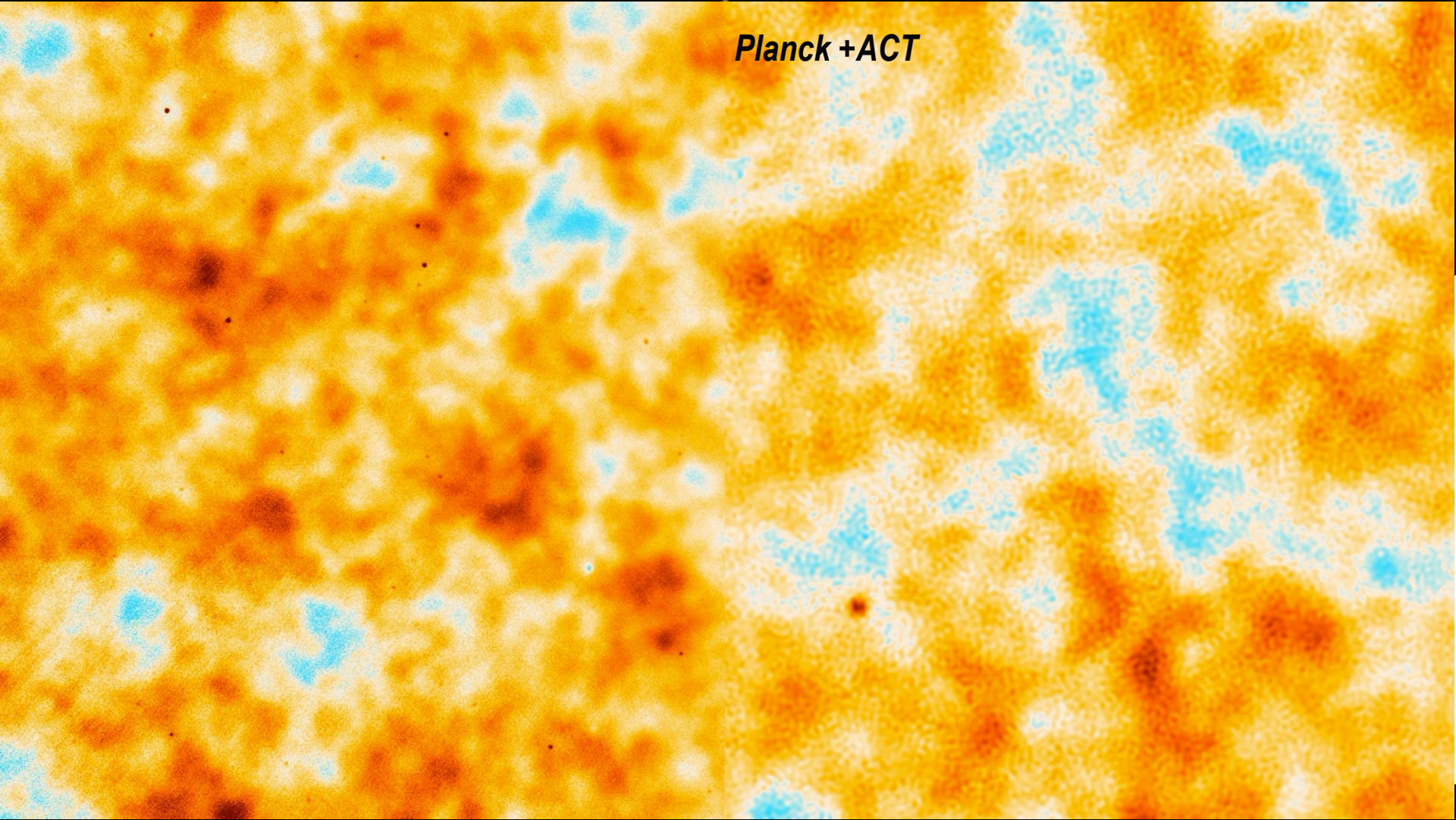
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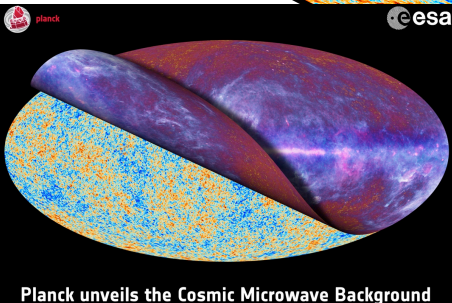
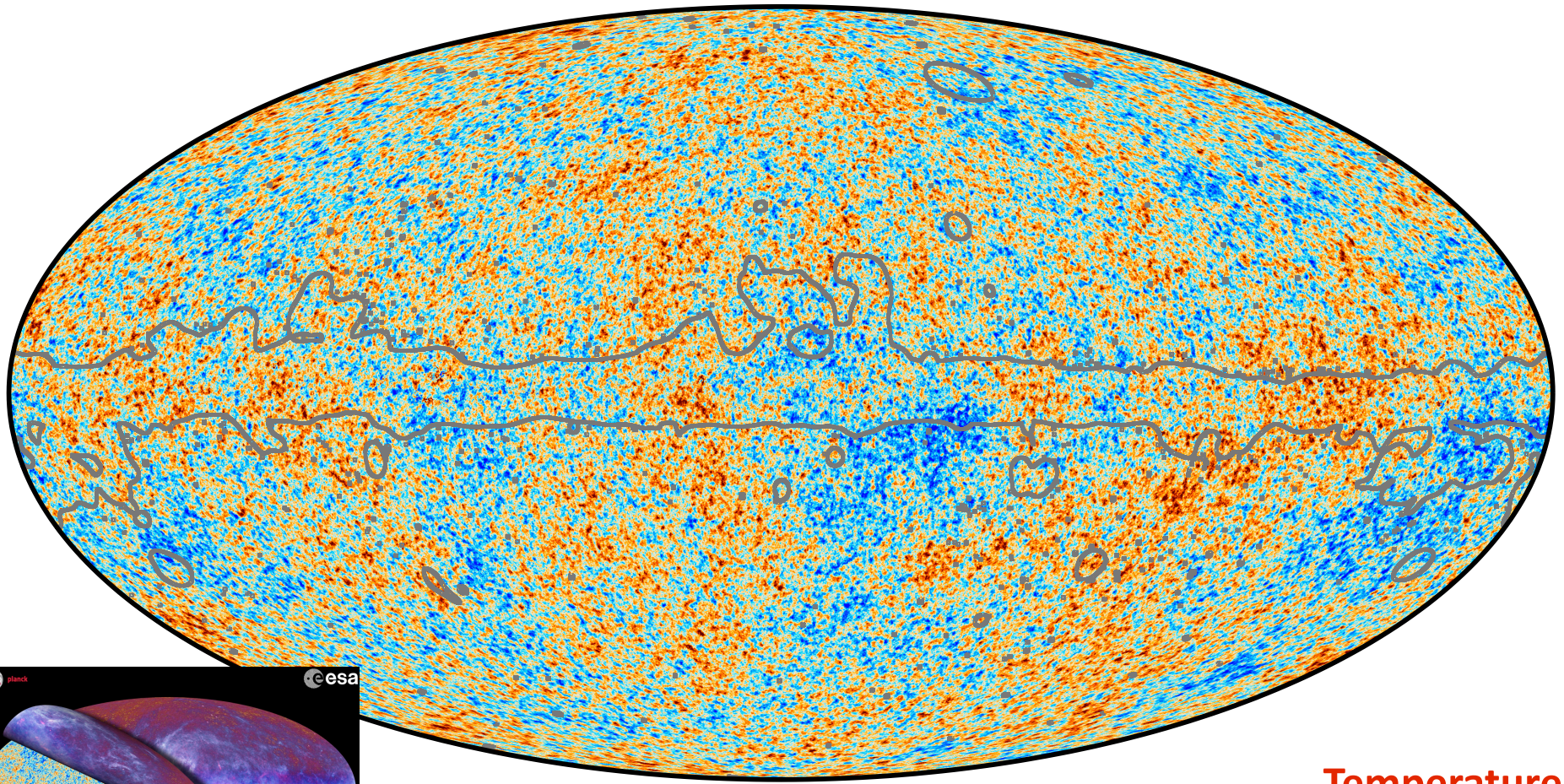
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Planck's primordial light unveiled, *Mar 2013 => Feb 2015 => pre-2016 => July 2018+ final*
reveals the **SIMPLICITY** of primordial cosmic structure

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

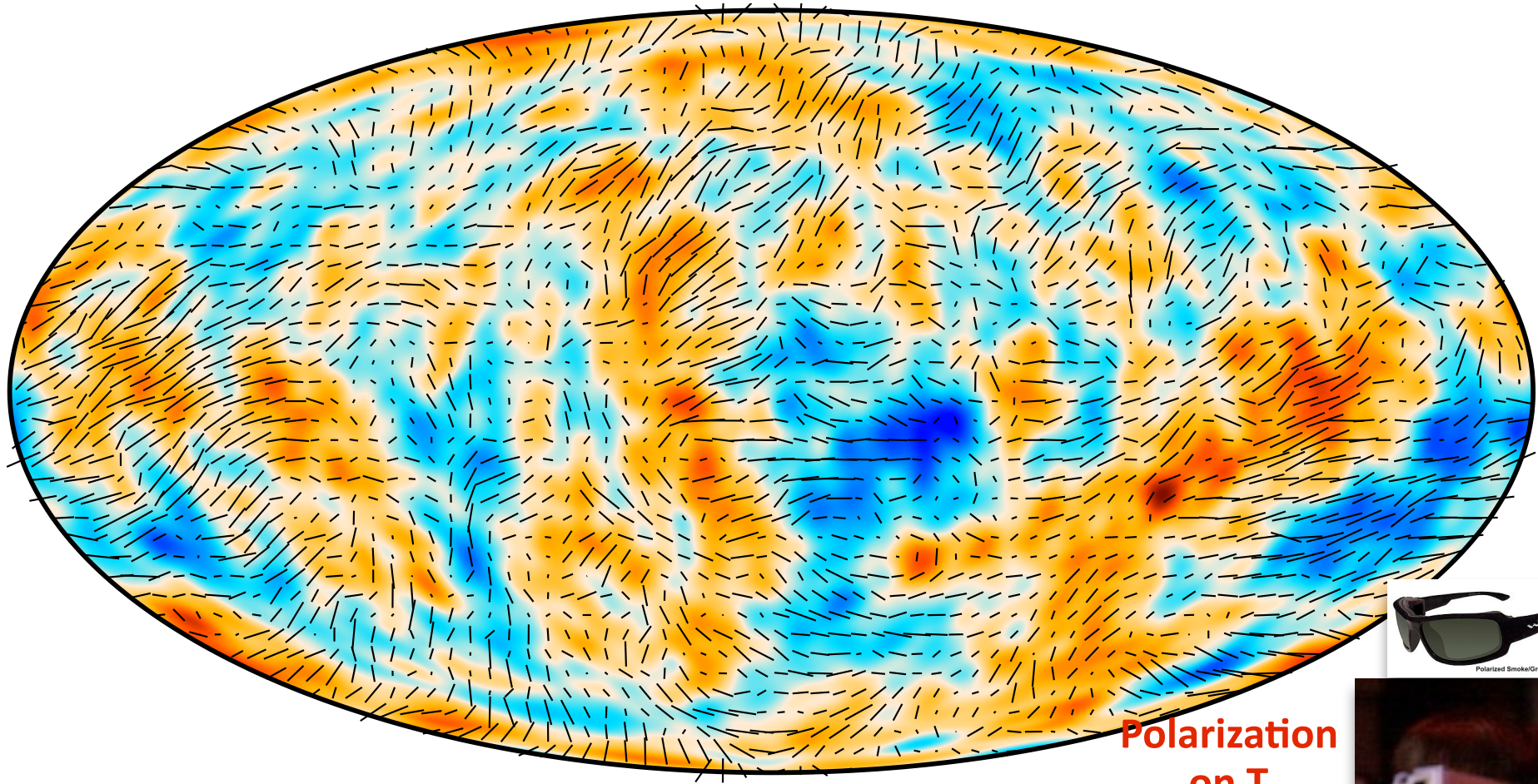


**Temperature
changes in
micro-degrees**

Planck unveils the Cosmic Microwave Background

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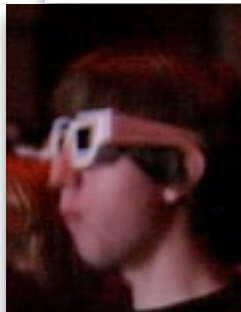


| 0.41 μK

-160

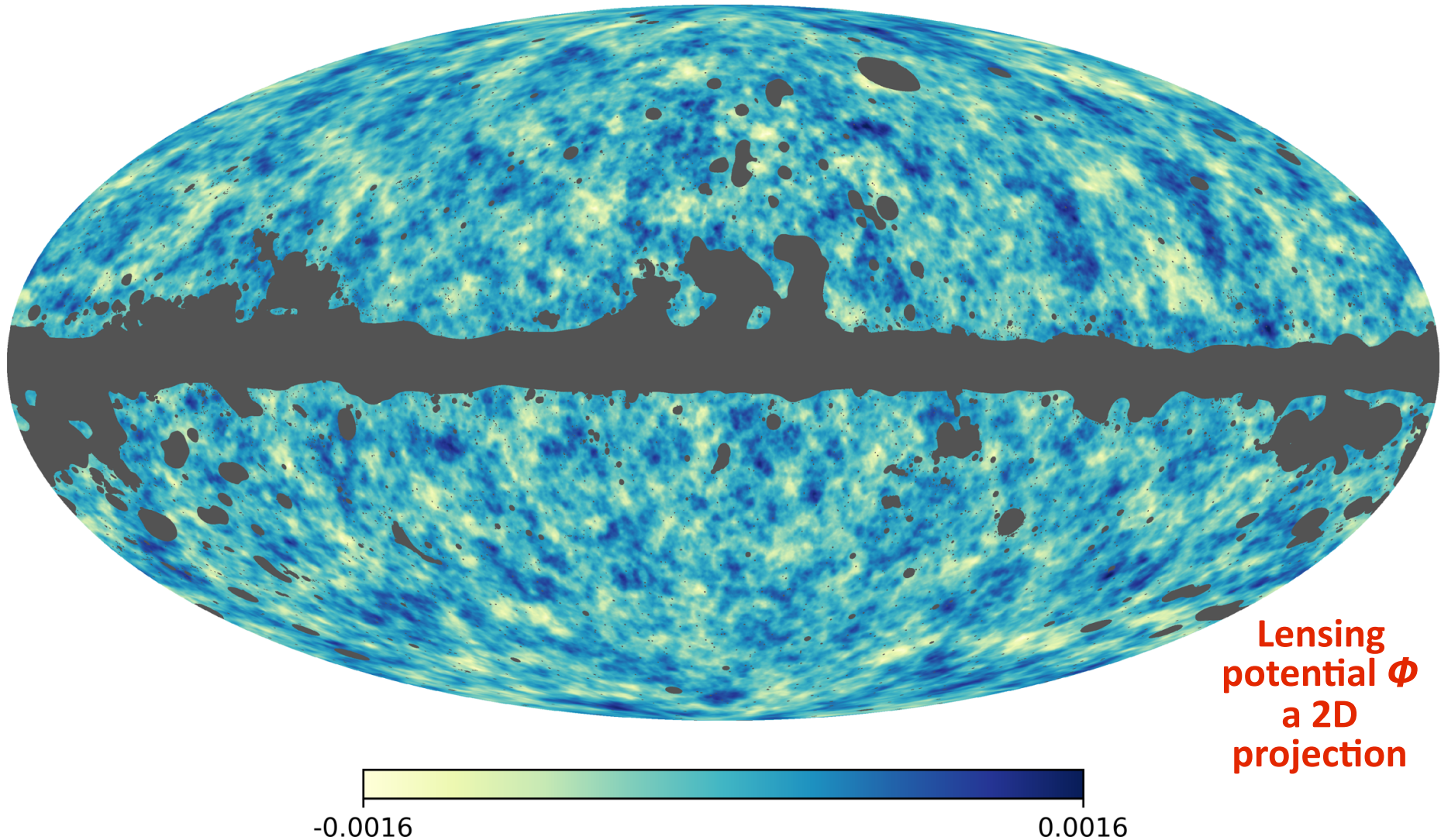


160 μK



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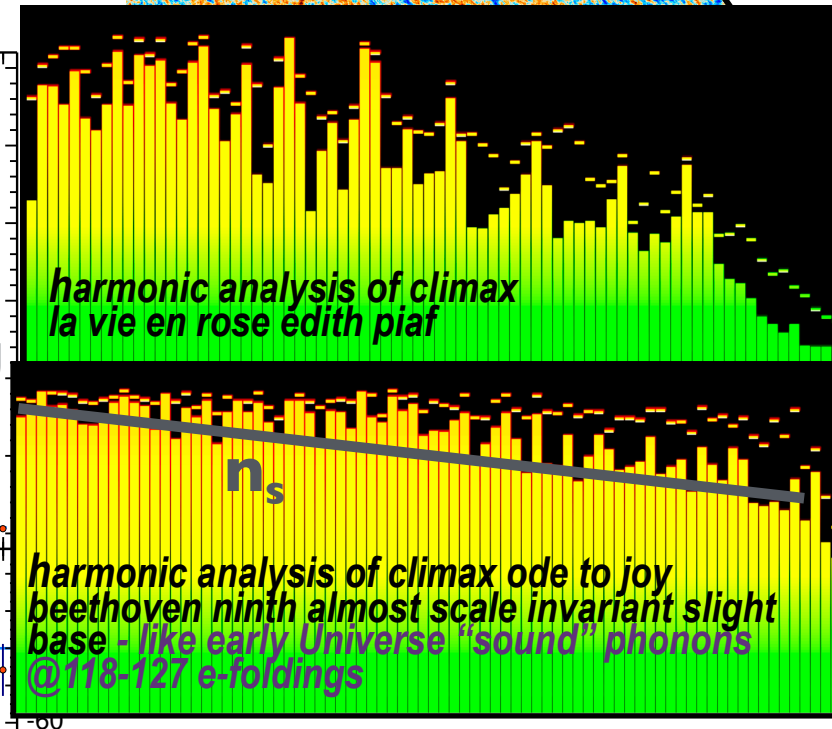
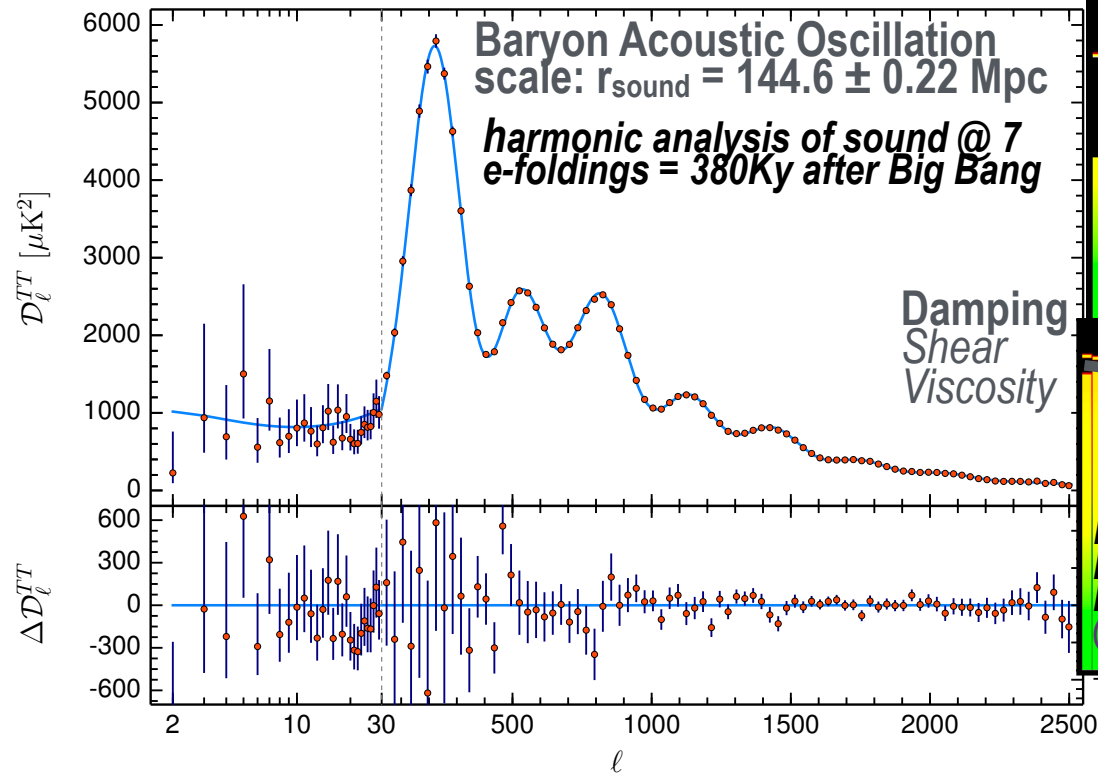
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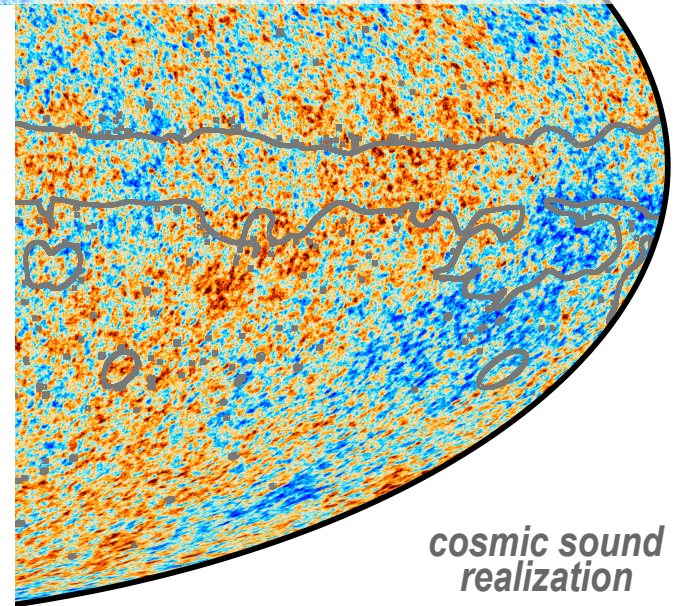
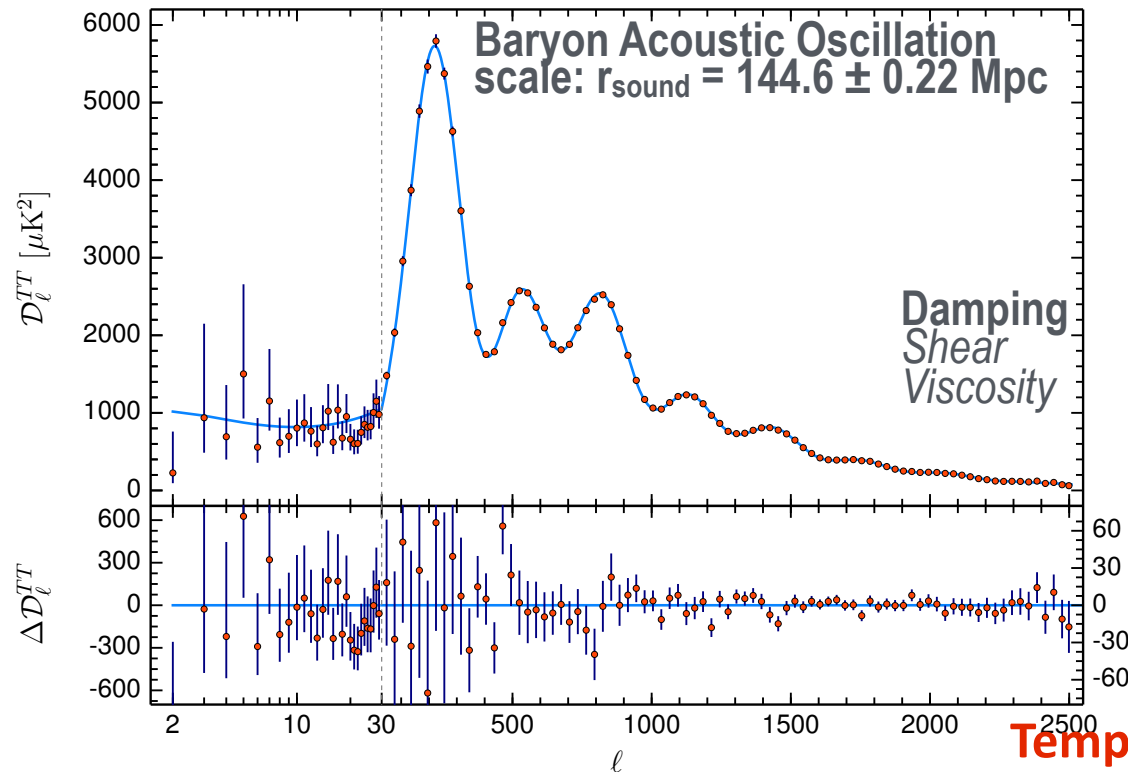
harmonic analysis of the 'music of the spheres'
 => *inharmonious, coloured noise in the CMB*



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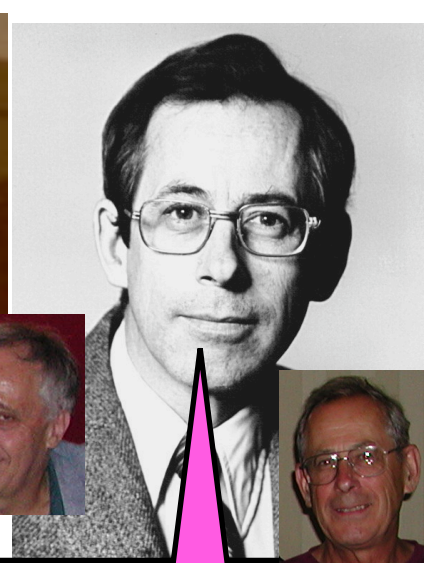
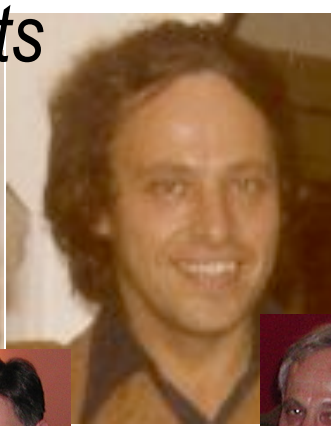
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Temperature changes in micro-degrees

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

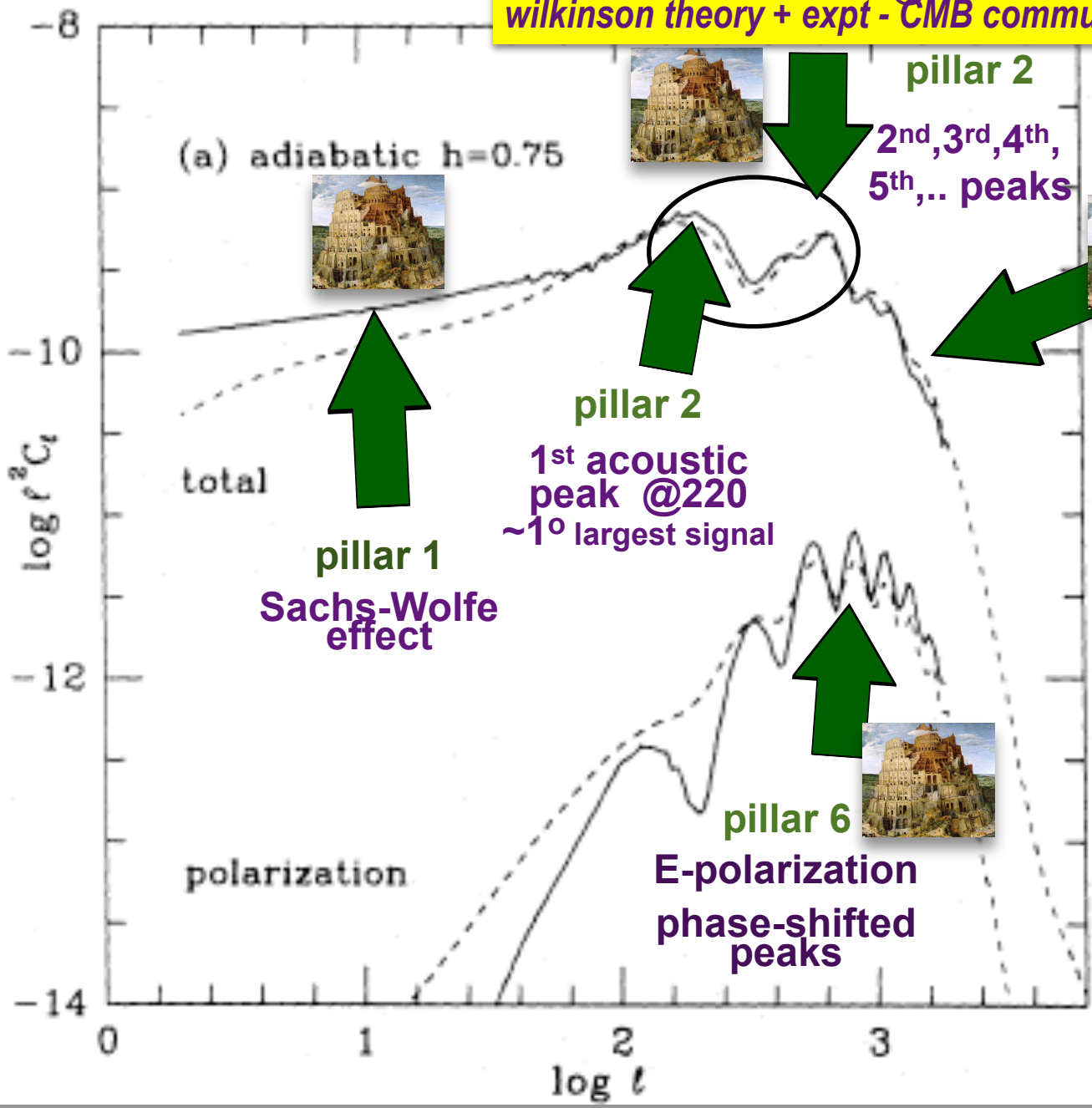


anthropic matters with Bj Carr

vary x in x CDM: find x by the tests

the "Seven Pillars"

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



pillar 4

Gaussianity
maximal
randomness
for given C_L



pillar 5

secondary
nonlinear
Compton SZ
weak lensing..



pillar 7

B-polarization
Gravity Waves



pillar 3

Damping
tail

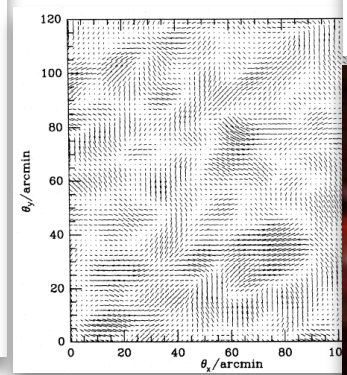


pillar 6

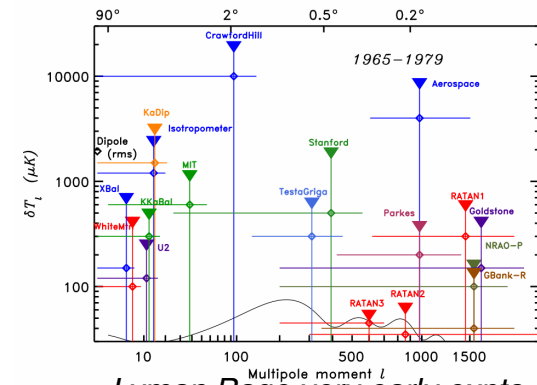
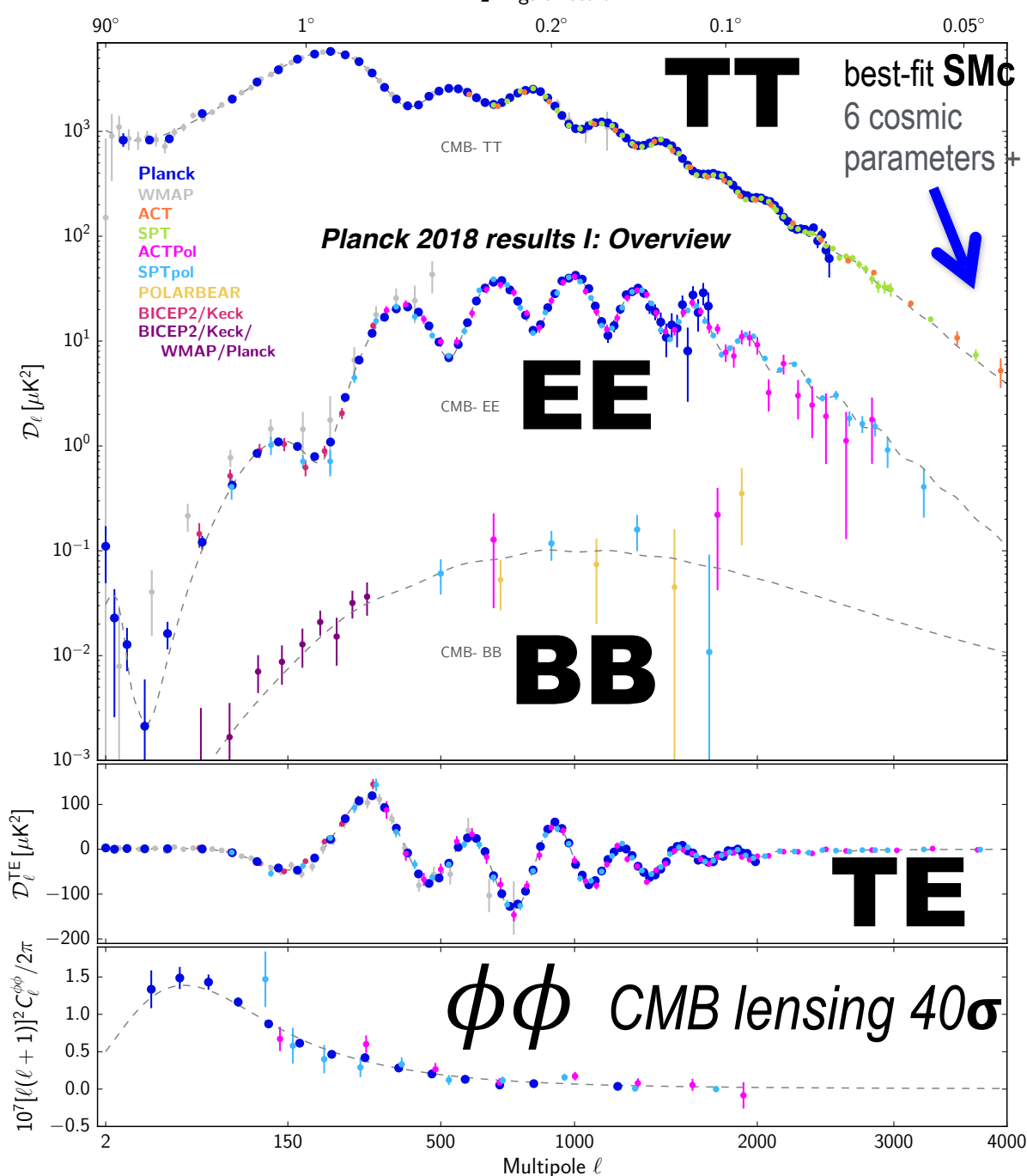
E-polarization
phase-shifted
peaks



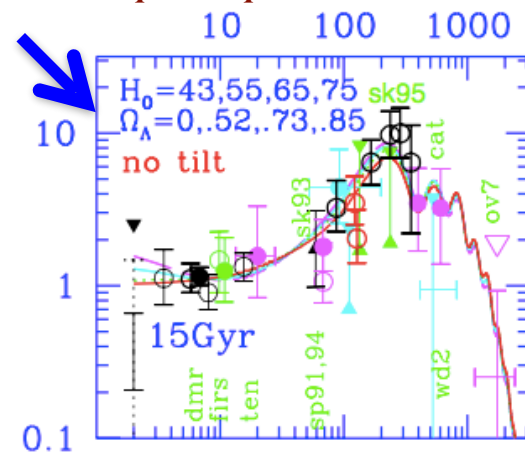
Polarized Smoke/Green Lenses



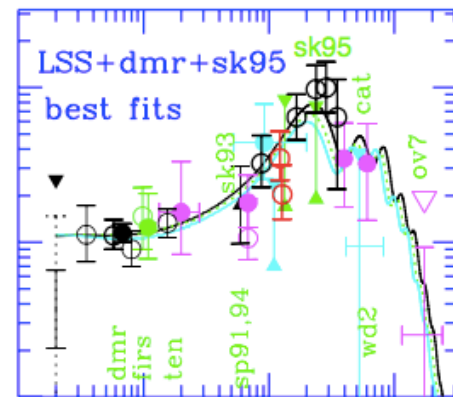
Grand Unified CMB Spectra



JRB@Capri 1993 Bandpowers cf. theoretical power spectra



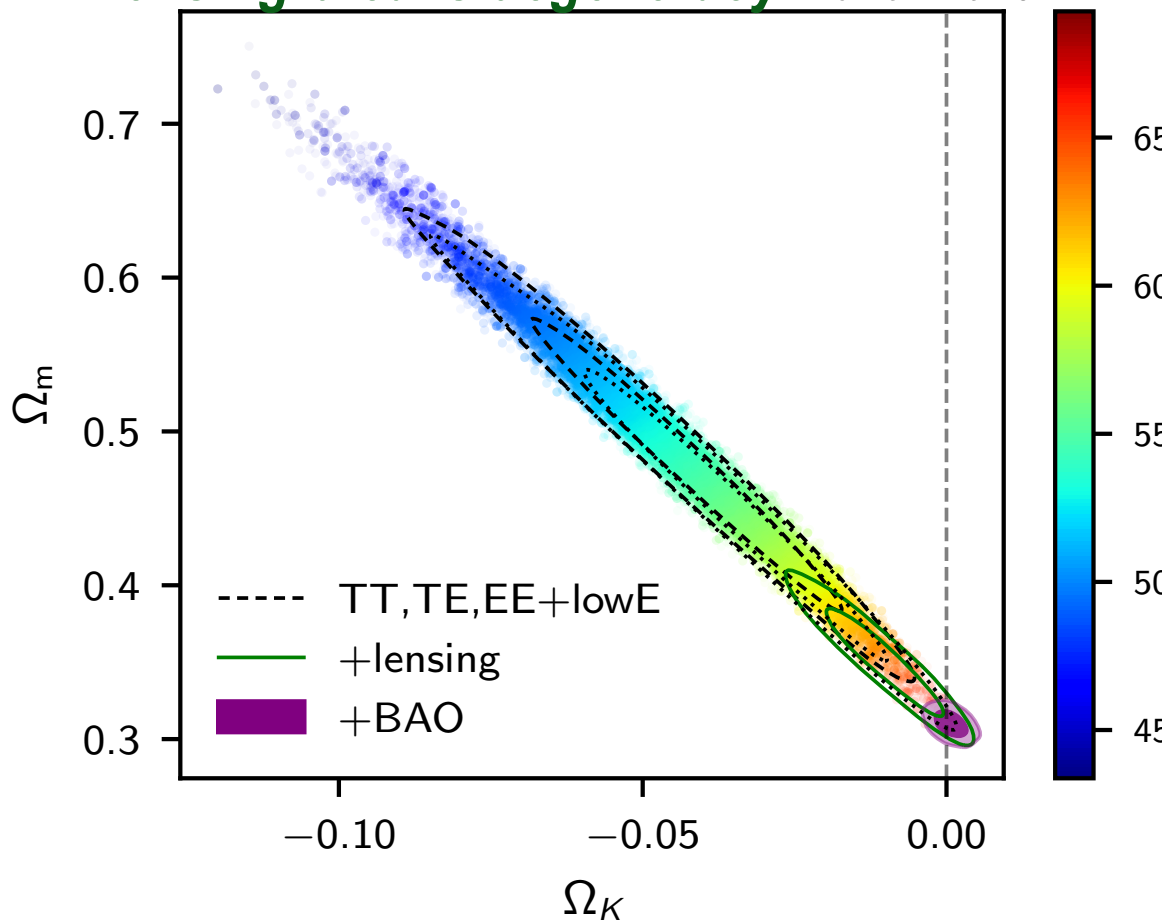
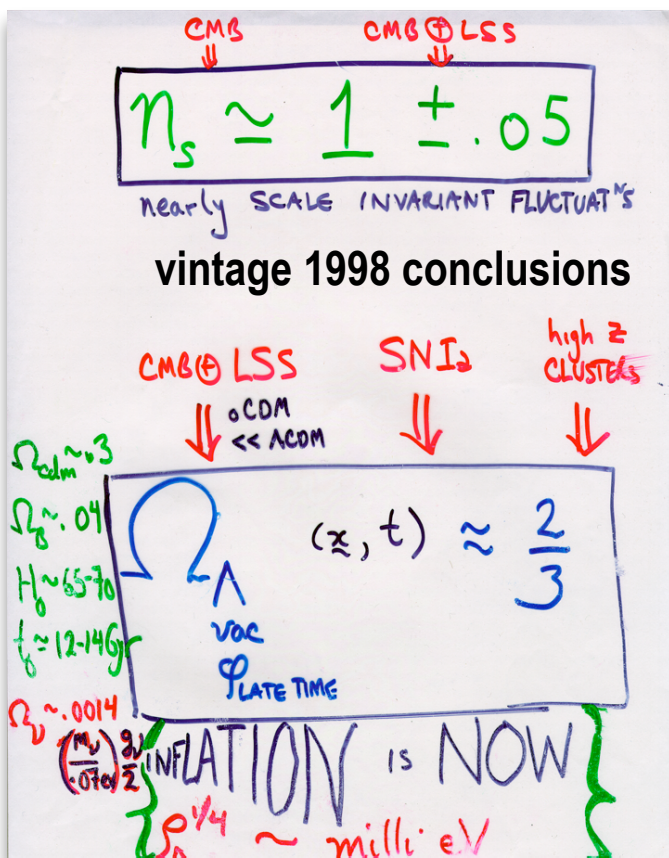
b95 Les Houches



inflation 1997/98

cf. inflation 2018

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



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

$$8.8\sigma \text{ from } 1$$

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

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

$$.96 \pm .06$$

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

$$w_0: -1.04 \pm 0.1$$

$$\Omega_K: .0007 \pm 0.004$$

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

$$\alpha_{ji} \equiv \langle \alpha \rangle \delta_{ji} + \epsilon_{ji}$$

ϵ =strain tensor

the star of our show

$\zeta(x)$



energy-density & gravity are entangled
isotropic strain & energy-phonons
Trace ϵ_{ji} @uniform density

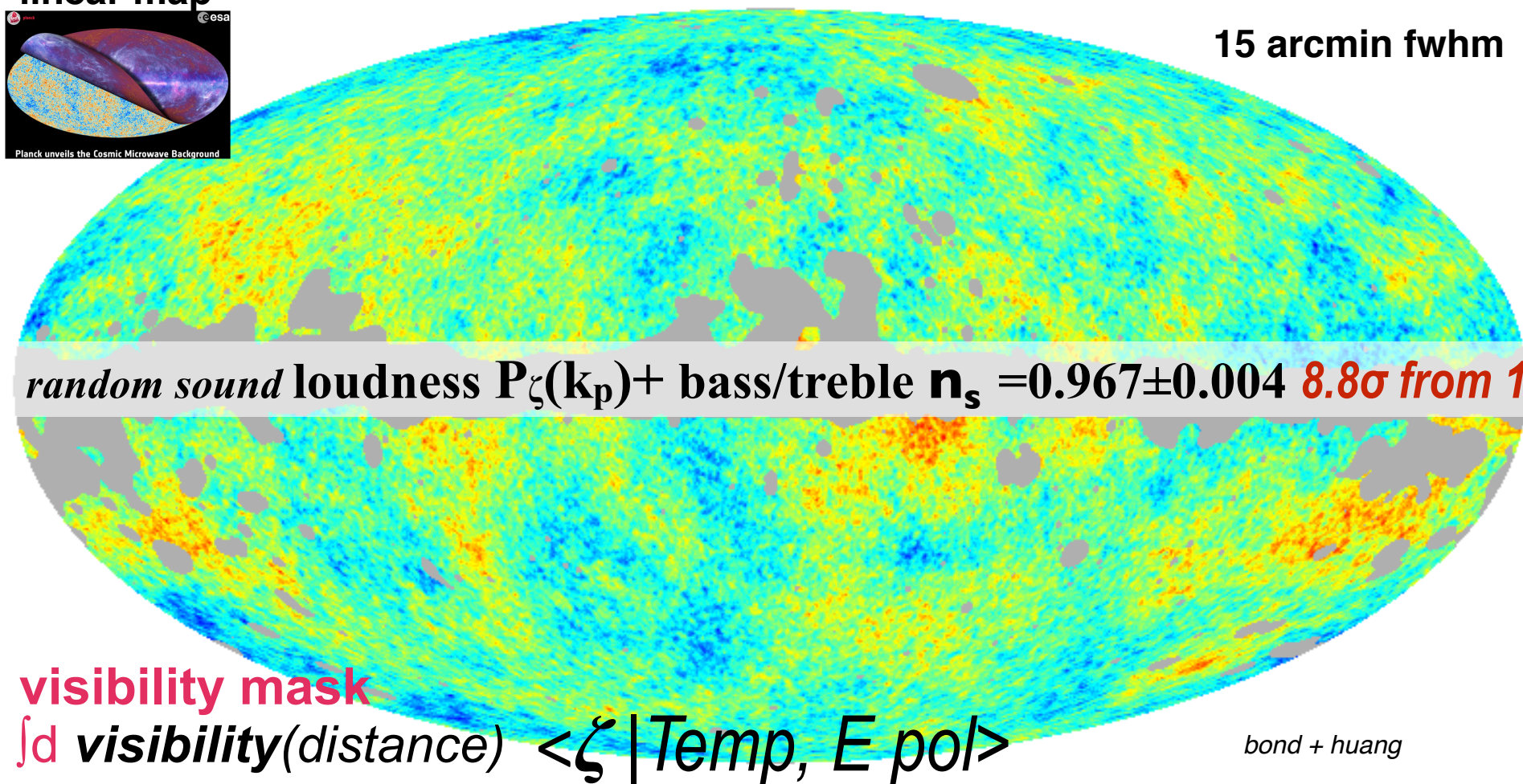
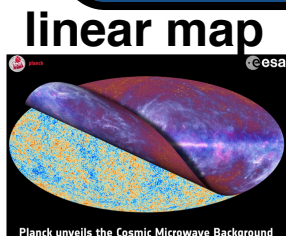
$\langle \zeta | \text{Temp}, E \text{ pol} \rangle$ -WebSky reveals *early universe phonons* ζ - TOPOGRAPHY & CARTOGRAPHY

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

only partial de-lens

Planck 2018

15 arcmin fwhm



visibility mask

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

bond + huang

-40.0

+40.0

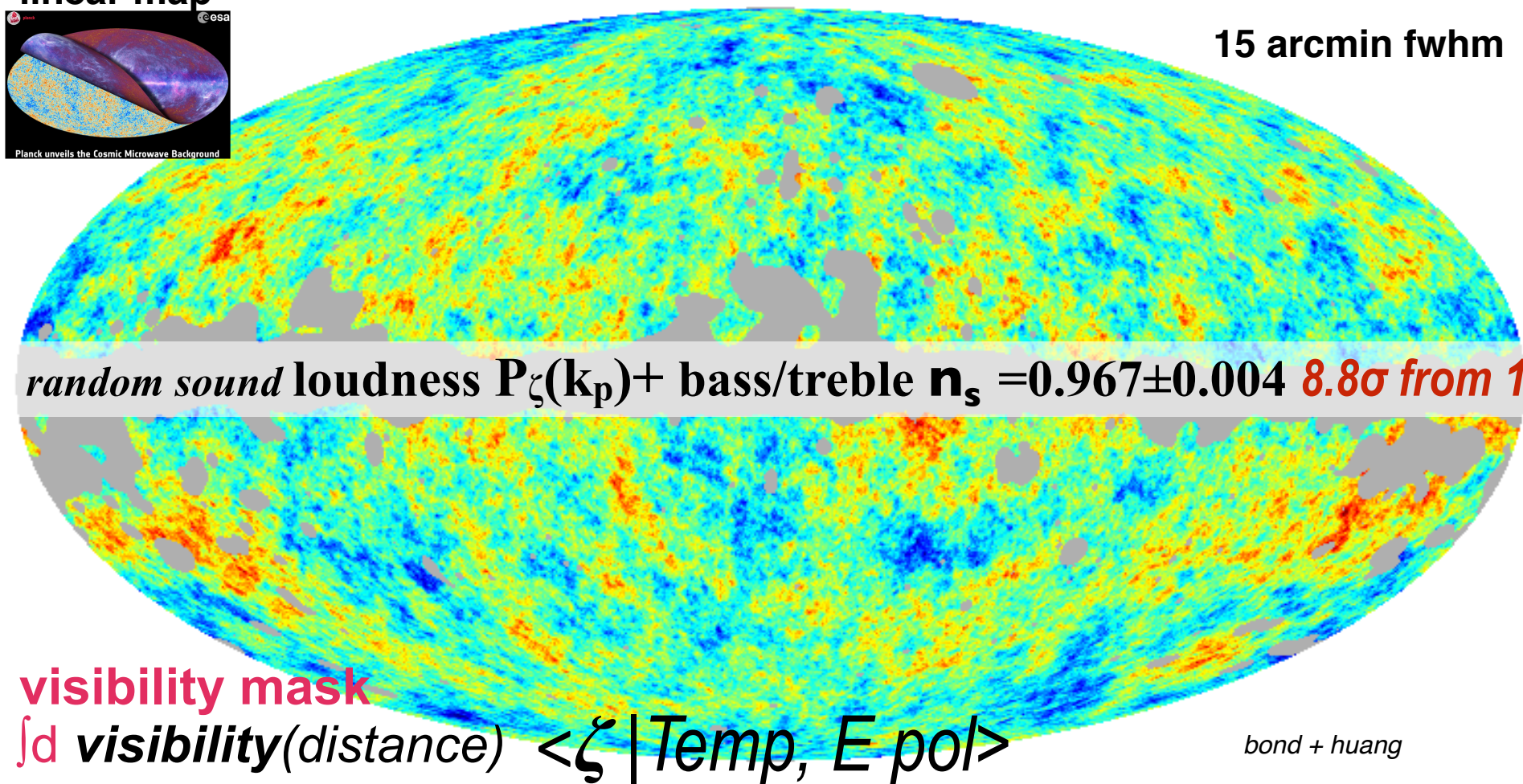
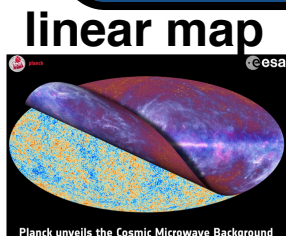
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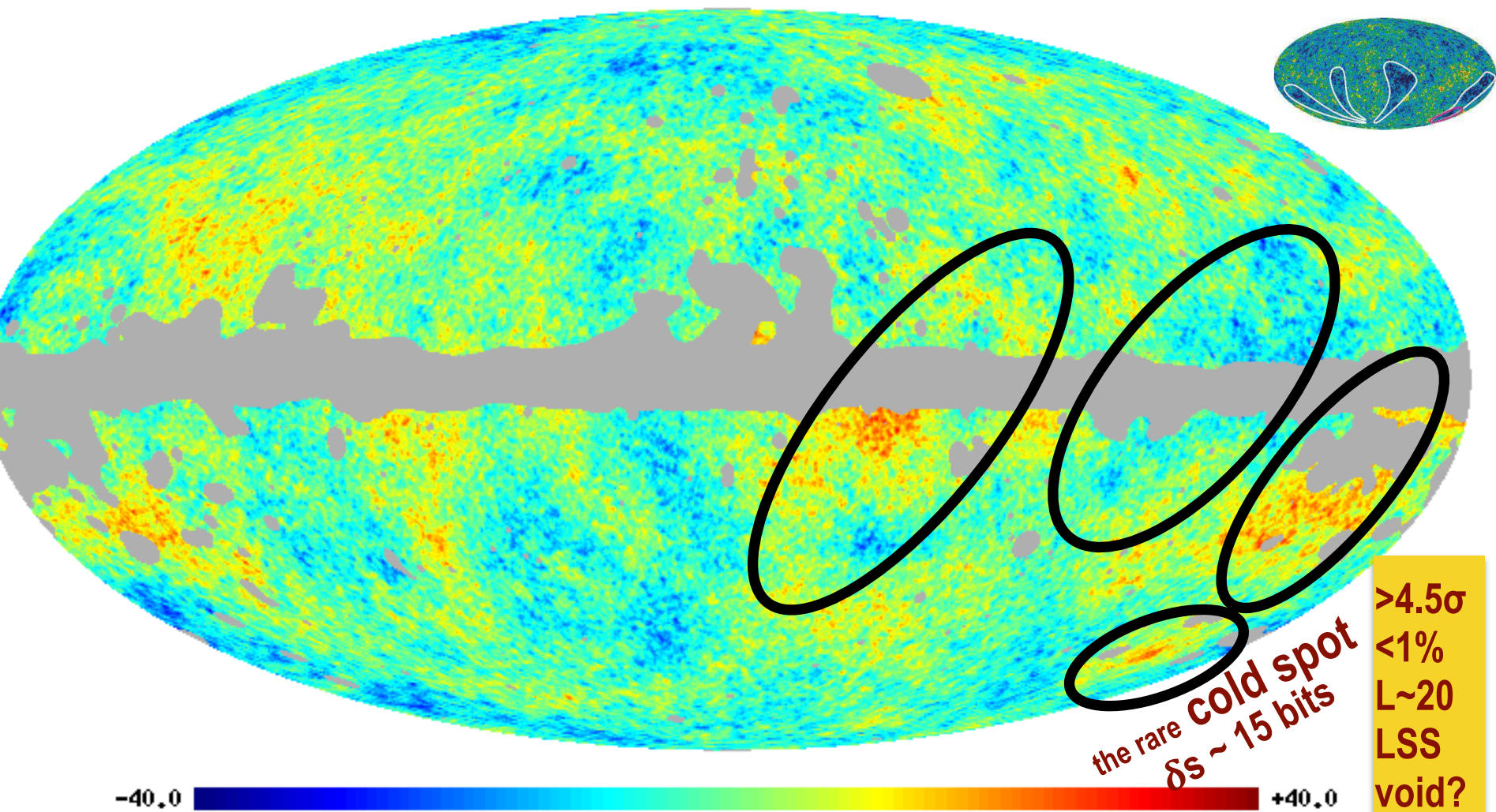
Beyond the Standard Model of cosmology? **SMc = tilted Λ CDM + r aka (ζ, h_{+x})**

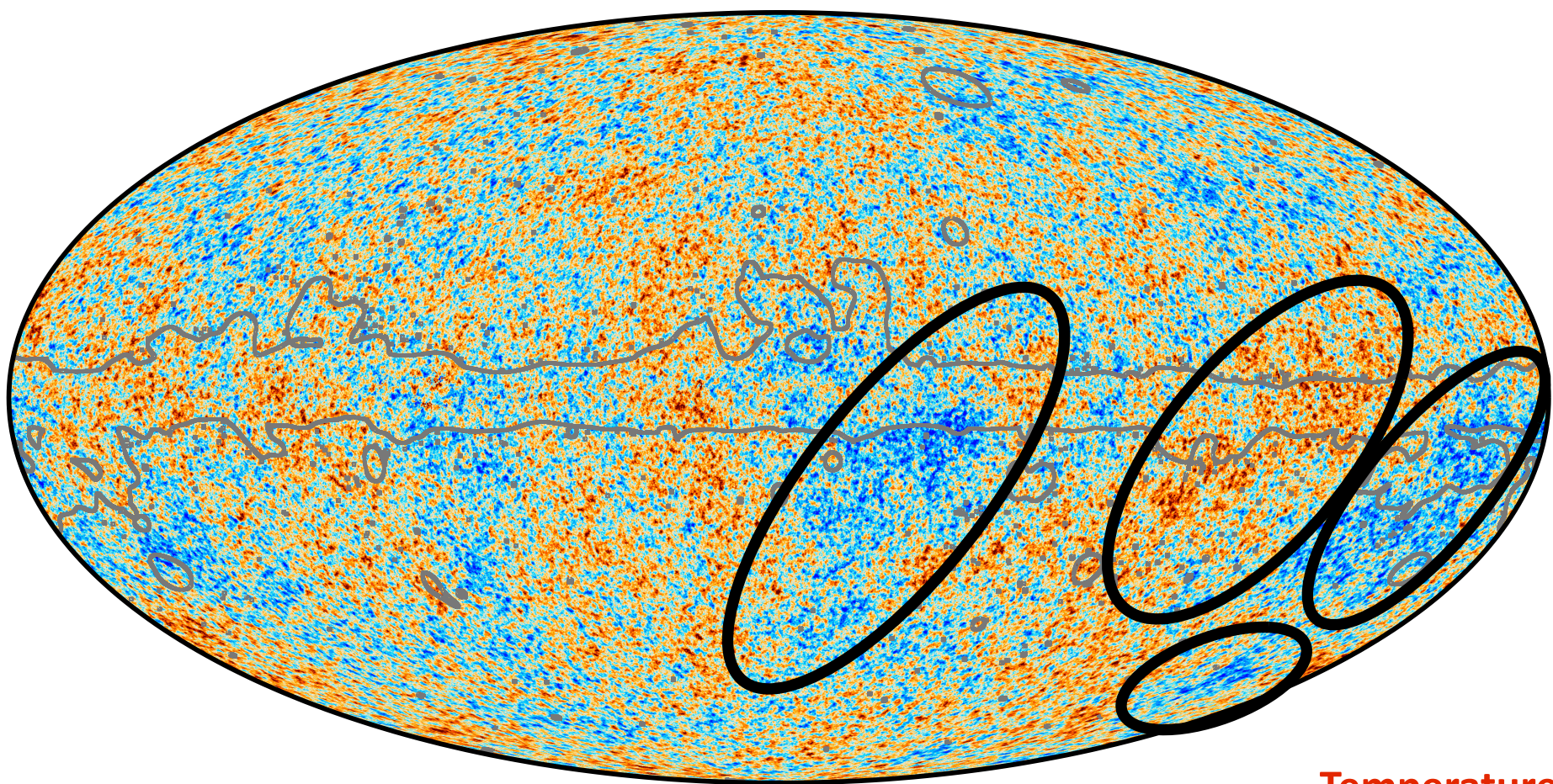
BSMc = SMc + primordial anomalies in the true ζ -WebSky

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

anomalies @ low L => sample variance limited $\sim 2\sigma$'s

Grand Unified Theory of Anomalies?





-300  300 μK

**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

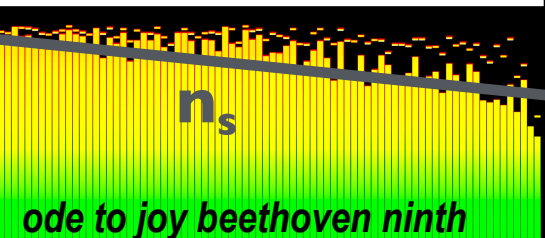
$r < .069$ 95%CL cf.
 $r < 0.061$ uniform n_s

uniform $n_s = 0.9669 \pm .00367$
 future $\pm .002$ SO

12-knot fit from $k \sim .008$ to $.3$
 uniform n_s is perfect

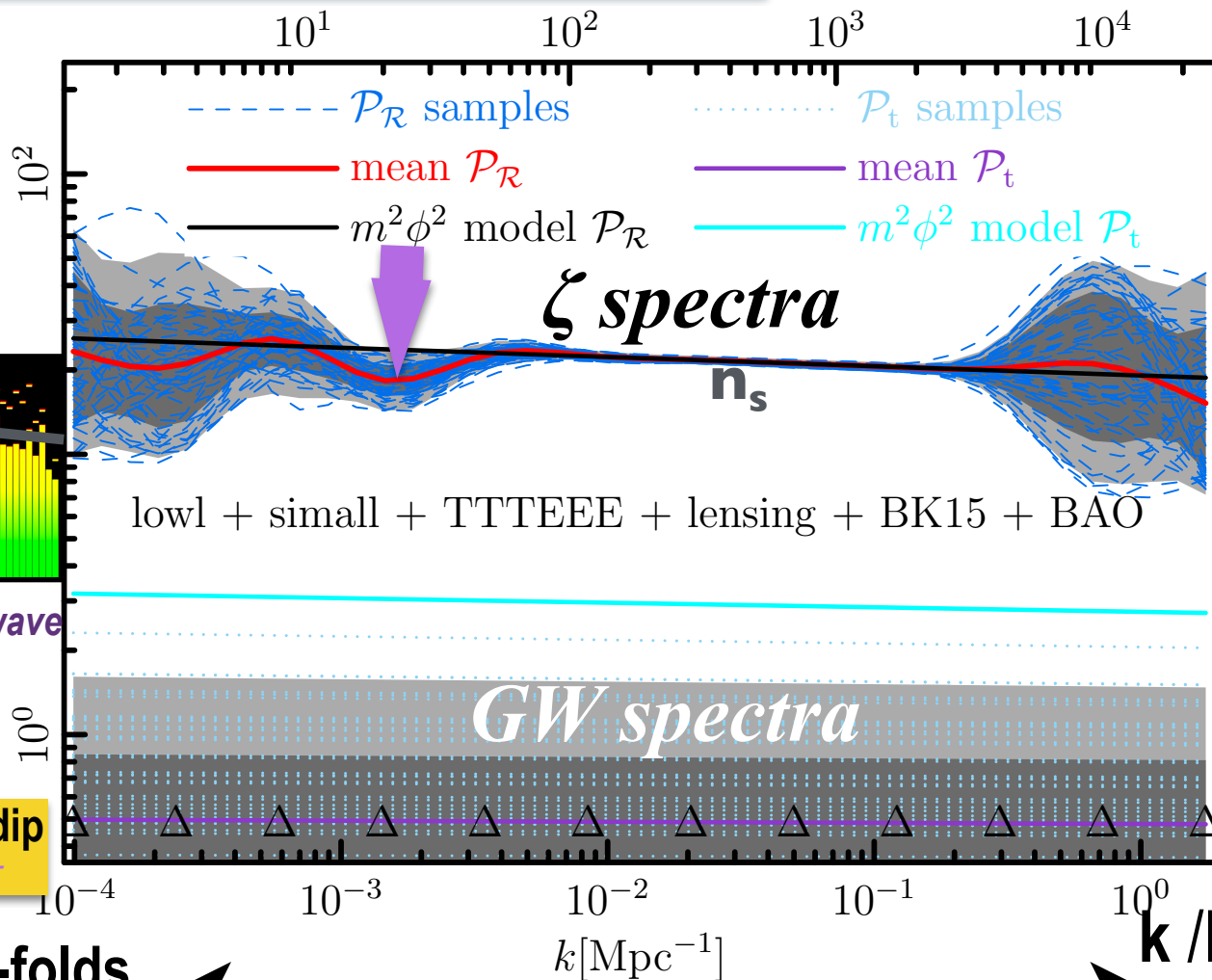
$L \sim k d_{\text{rec}}$

future $2\sigma(r)$
 SO 0.006
 S4 0.001
 Litebird 0.002



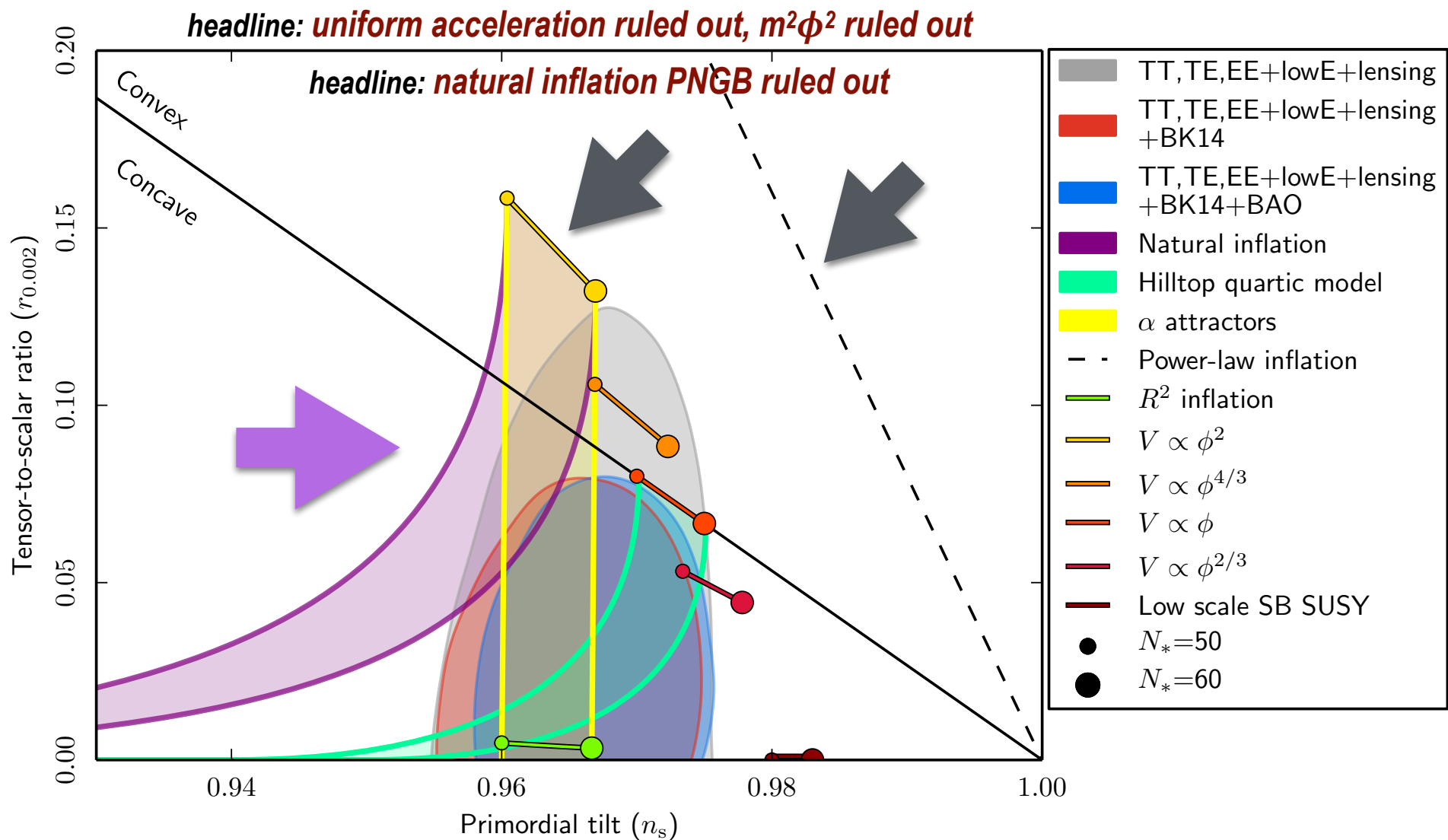
like early Universe elastic-wave
 sound @ 118-127 e-foldings

CMB TT power $L \sim 20-30$ dip
 $\Rightarrow \zeta$ -Spectrum k -dip @ 2σ



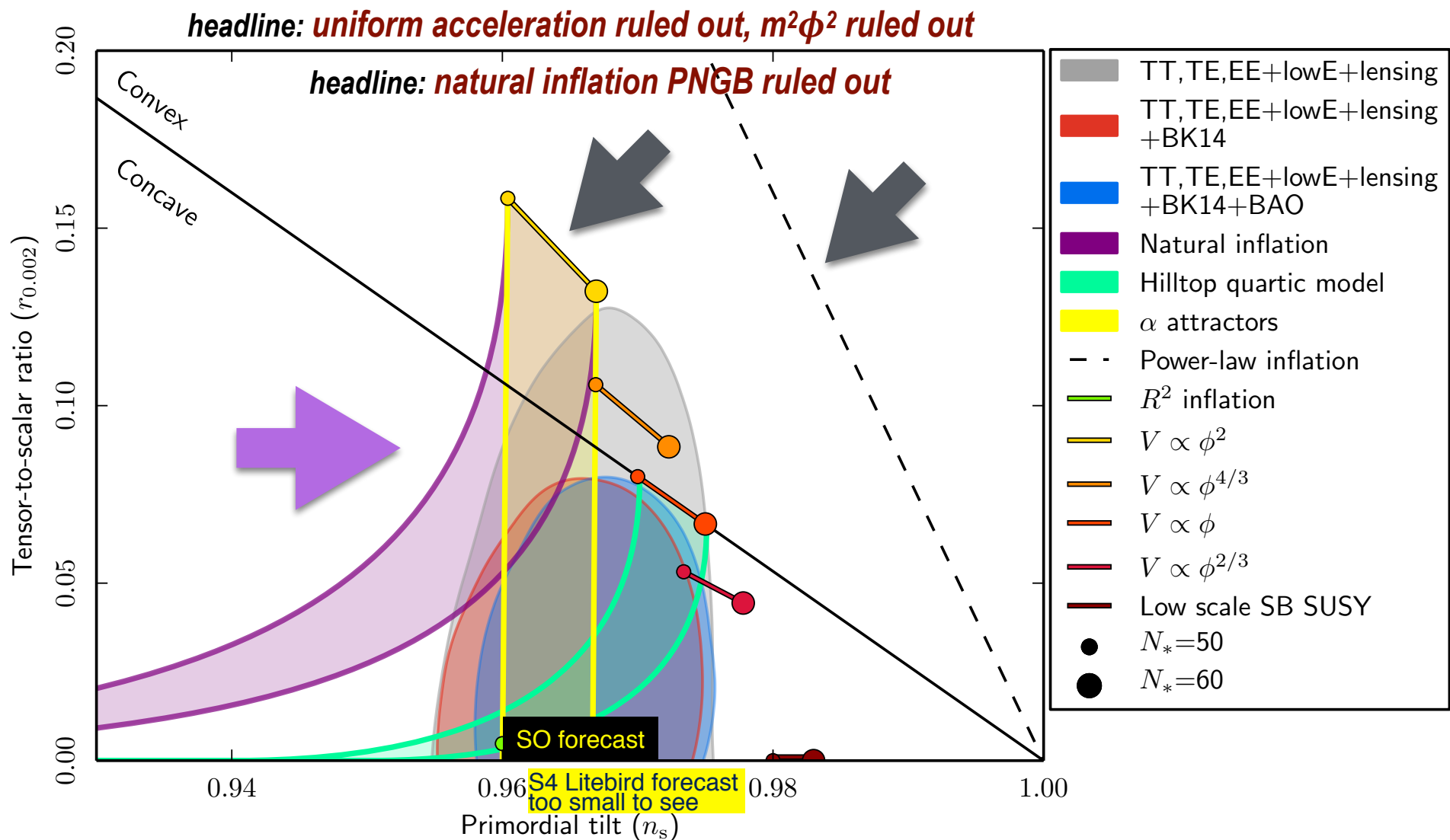
derive
 $V(\phi)$
 $H(\alpha)$
 $\varepsilon(\alpha)$

9 e-folds



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



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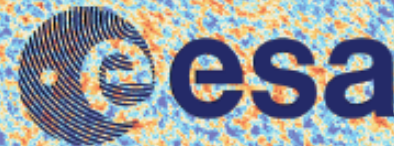
headline: conformally flattened potentials OK, includes R^2 inflation & Higgs inflation, α -attractors



planck

Dick Bond

Quantum Inflation in the Planck Era & Beyond



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



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

$10^{88.6}$



relic3: baryon asymmetry of matter over antimatter $N_{\text{baryon}}/S_{\text{tot}}$

$10^{-10.06}$



relic4: dark matter from quark/gluon plasma - only seen gravitationally WIMPS, axions,..

$26.6 \pm 0.7\%$

relic5: big bang nucleosynthesis products H, He, D, Li (influenced by C_{nuB} - 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)

$68.5 \pm 0.7\%$

SIMPLICITY

Planck2018 early U structure map

at $a \sim e^{-7} \sim 1/1100 \Rightarrow$
at $a \sim e^{-67-55} \sim 1/10^{30+25}$

2+ numbers - red strain-noise

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

a picture of the **quantum phonon field** $\sim \ln \mathcal{A}(x,t)$
= Trace α^i_j from the birth of the universe @ $a \sim 1/10^{30+25}$

B+Huang

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

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

$\Rightarrow \sigma(n_s)$ SimonsObservatory 0.002

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

Tensor-to-Scalar ratio (GW) $r < 0.06$ P18+BK15

$\Rightarrow 2\sigma(r)$ SimonsO 0.006 CMB S4 0.001 Litebird 0.002 - if dust is not too complex

CMB+LSS = future fundamental physics laboratory $\odot$ \$DOE $\Rightarrow$ S4 n_s r m_ν $N_{\text{eff}\nu}$

-40.0

+40.0

end of Bond's TIME