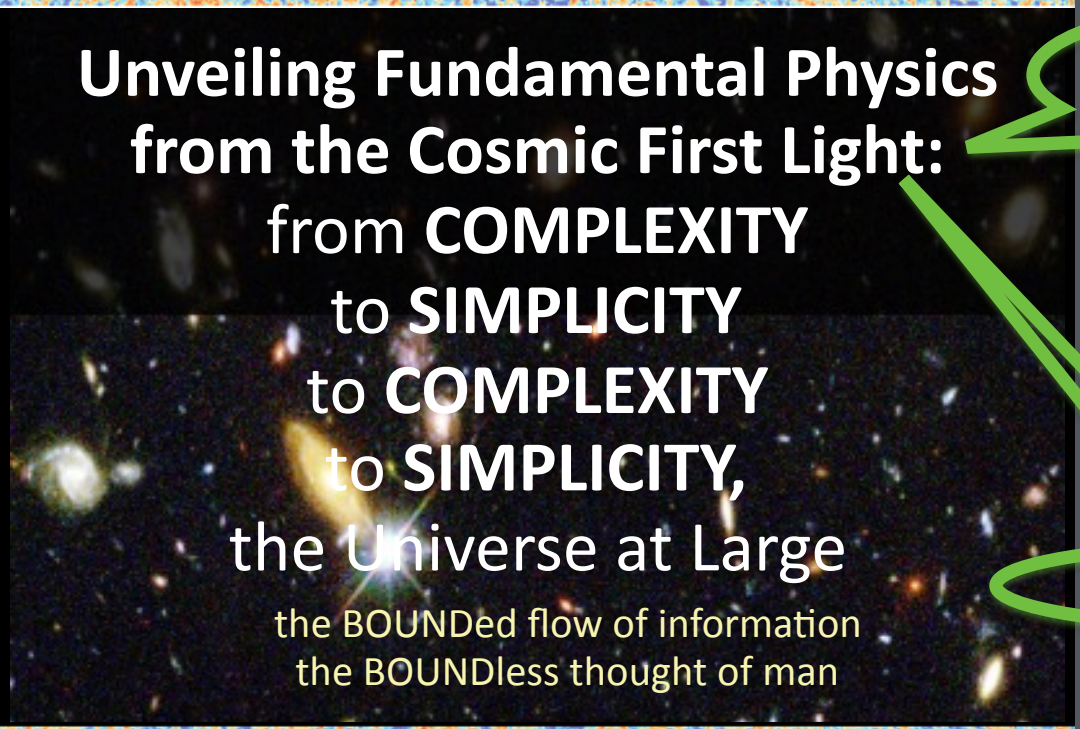
Quantum Universe in the Planck Era & Beyond

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
Canadian Institute for Theoretical Astrophysics
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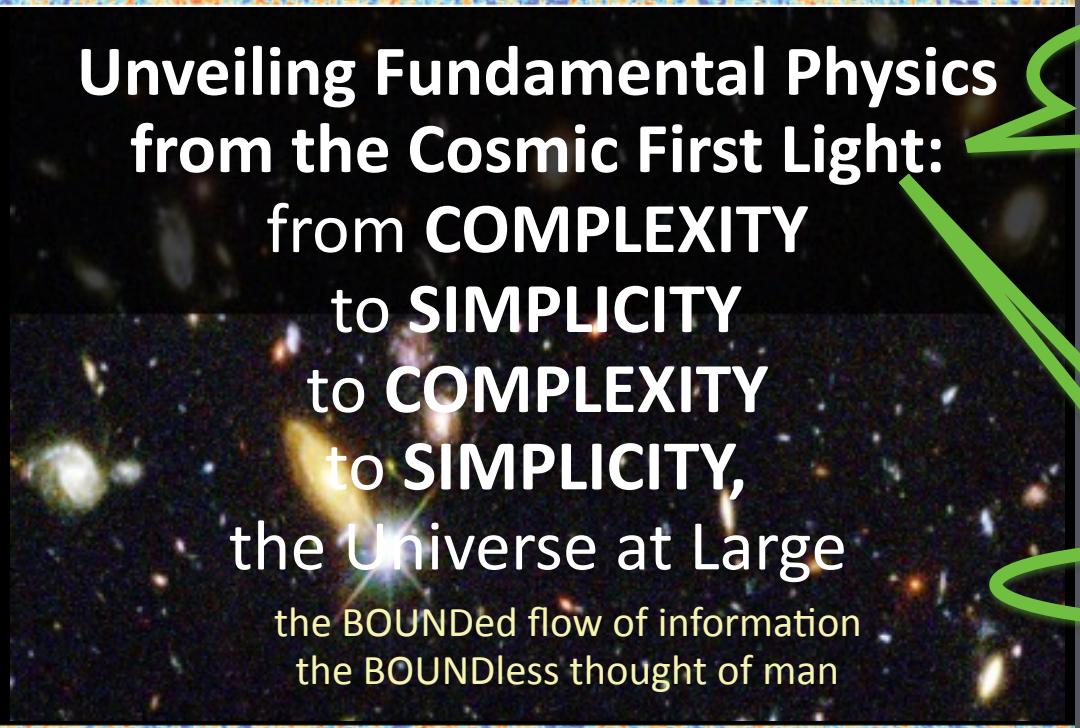

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goal today: *CMB maps baby pics ⇒ early Universe maps! embryo pics*
⇒ star of today's show is an entropy-like early Universe measure

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

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planck

esa

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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,
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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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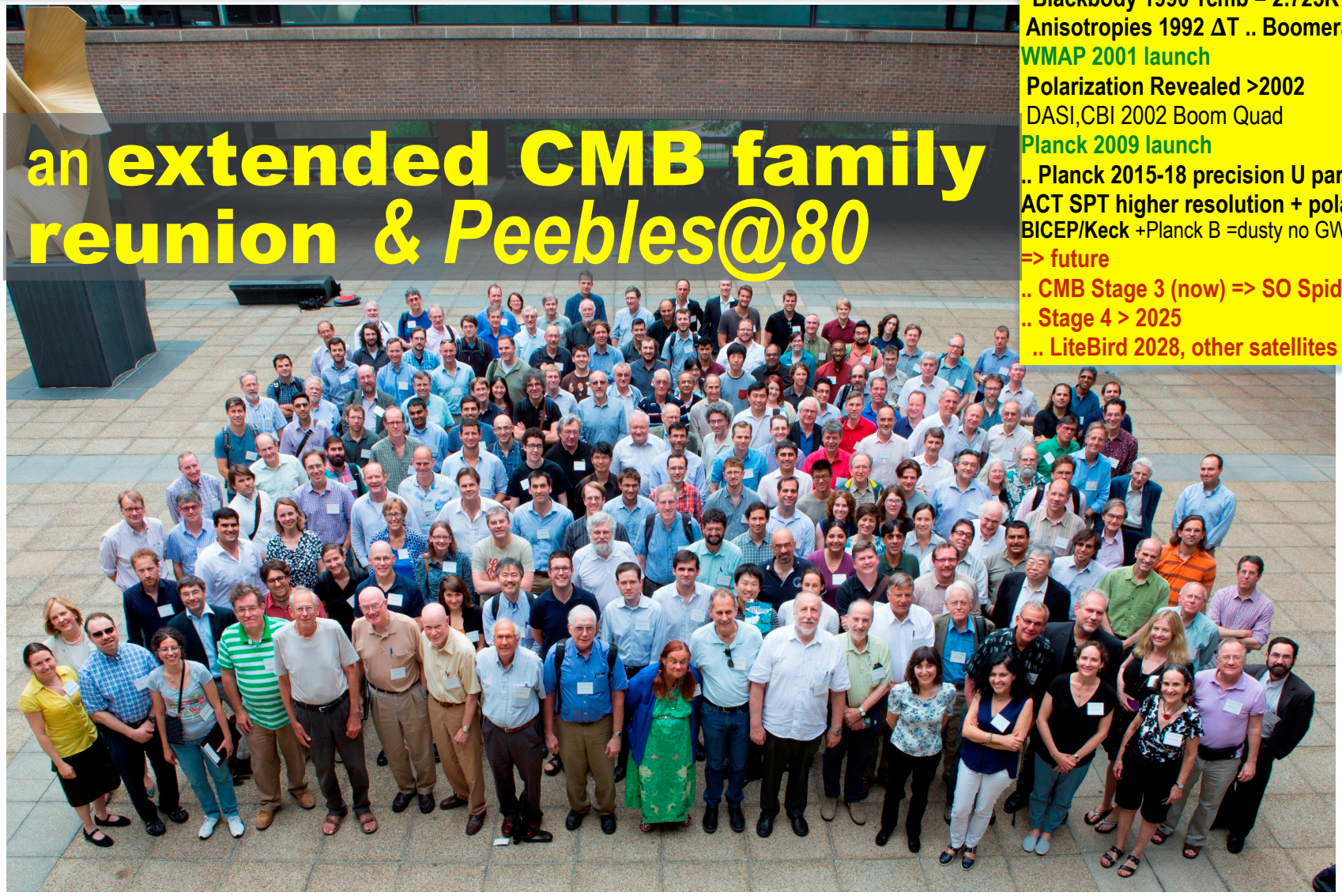
=> future
.. CMB Stage 3 (now) => SO Spider2
.. Stage 4 > 2025
.. LiteBird 2028, other satellites ??

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



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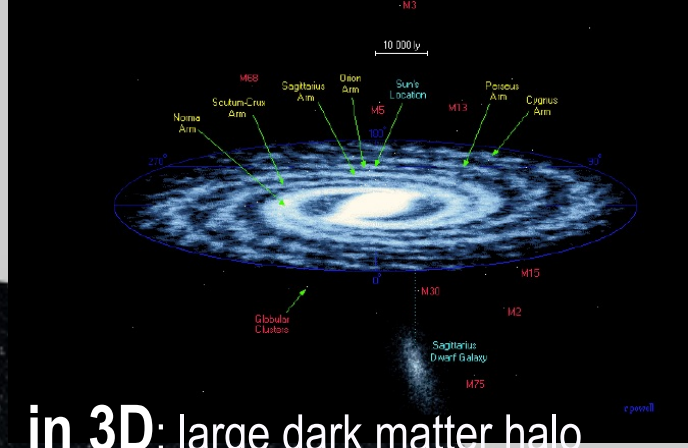
Milky Way in infra-red:

half a billion stars, a disk galaxy



in 3D: large dark matter halo

Polaris

*Sagittarius A**

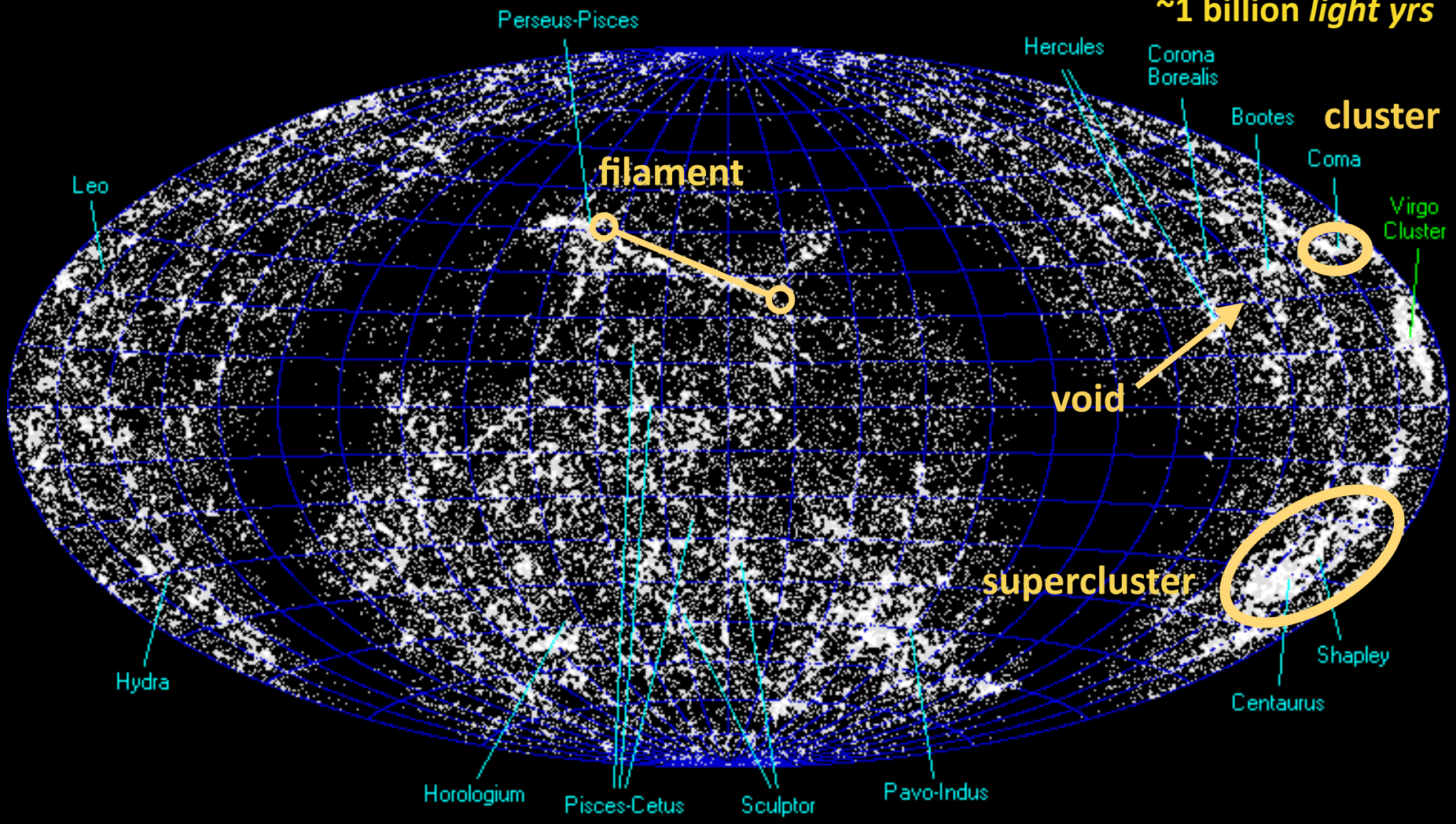
Magellanic Clouds

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

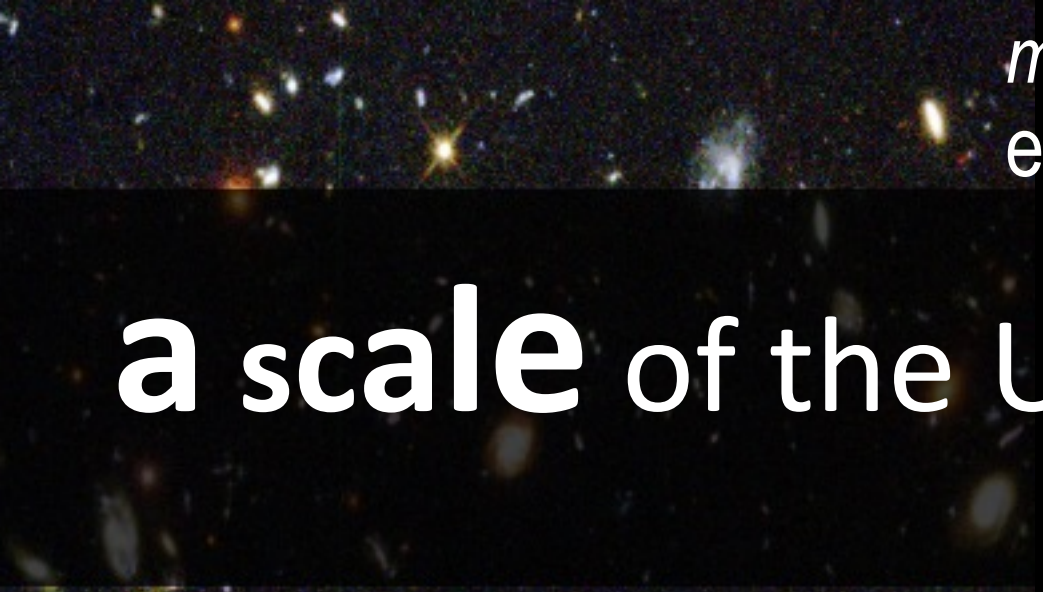
there were **no galaxies** when a < 1/20 — 3

light nuclei

Dark Matter — 21 ⇓ 35

Heat: matter & **radiation** — 67

quantum **noise** $\hbar$ — 67 ⇓ 127



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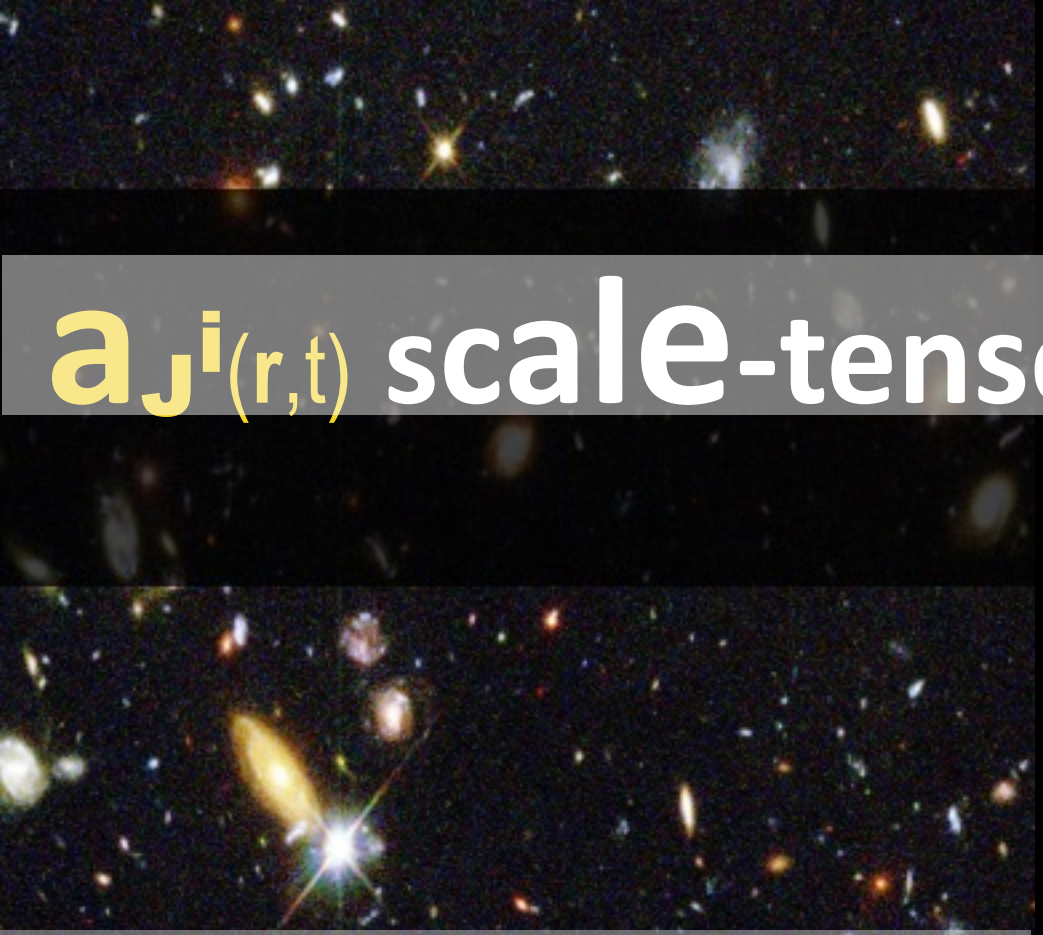
Baryons Ordinary Matter 4.9% H,He ~0.2 amu /m³

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*

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

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

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

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

scale-deformation a_J^i

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

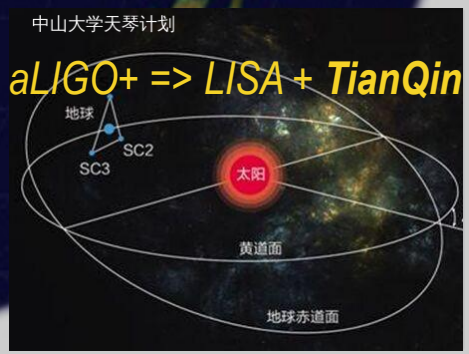
anisotropic strain, gravity waves

isotropic strain, sound Trace(ε)

isotropic strain, sound

linear: **strain** ∝ **tide**

cosmic web *story*

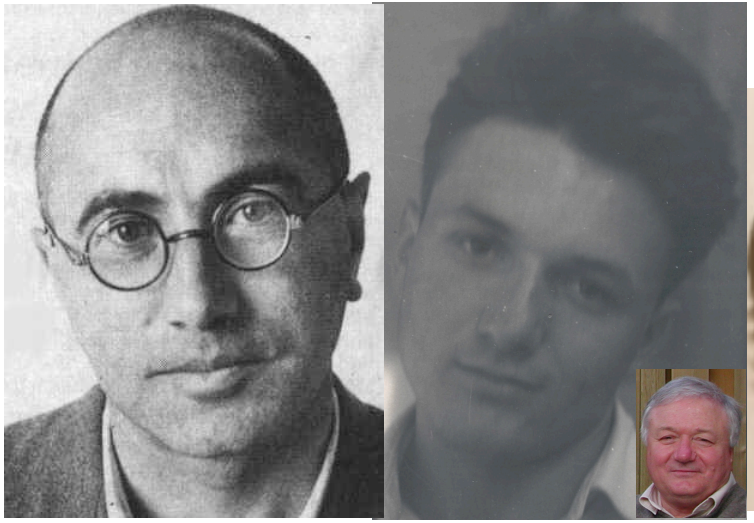


light and gravity are entangled: wavelength stretches under space-strain: ***redshift CMB***

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*

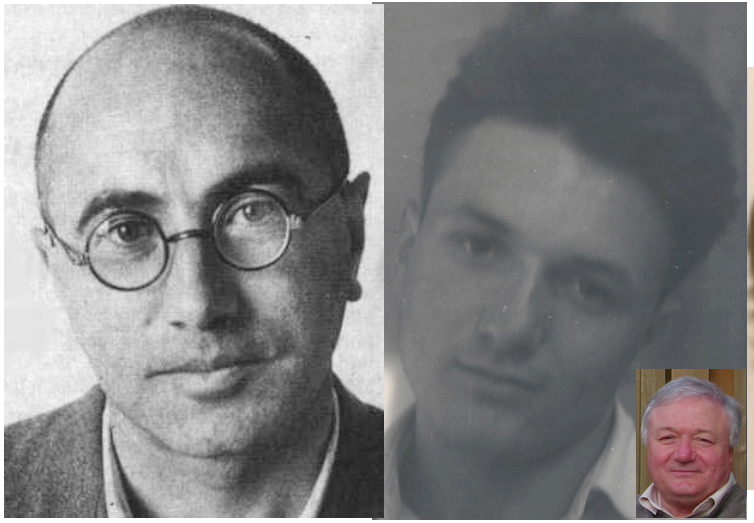
test with **CMB**+LSS

~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



test with CMB+LSS

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

Dick Bond CITA *the summary talk*

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a Who's Who of the CMB world

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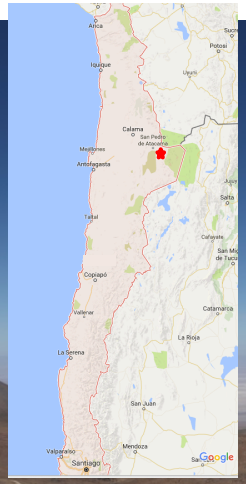
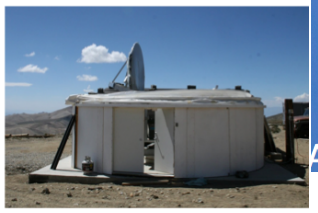
an extended CMB family reunion & *Peebles@80*

Atacama



California+
South Africa
C-BASS 5 GHz

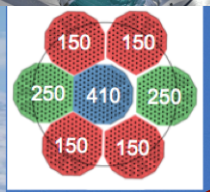
Tenerife (+South Africa?)
QUIJOTE 11, 13, 17, 19 GHz
(2015/16 - 30, 40 GHz)

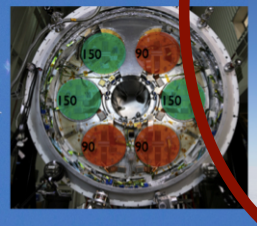


California
B-Machine 40 GHz

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

planck ~250/paper, ~100 institutions

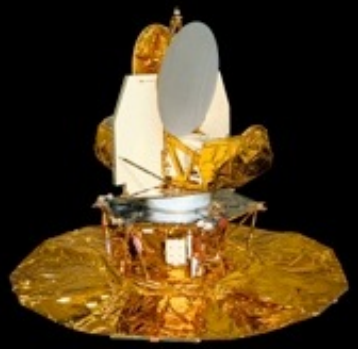
Cobras/Samba @Capri93

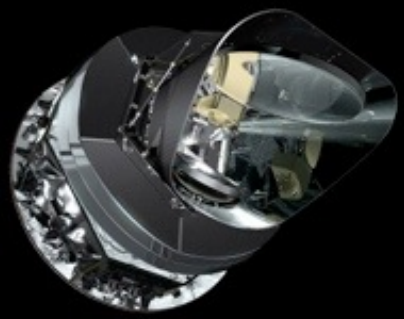
Bond since 1993, Canada since 2001

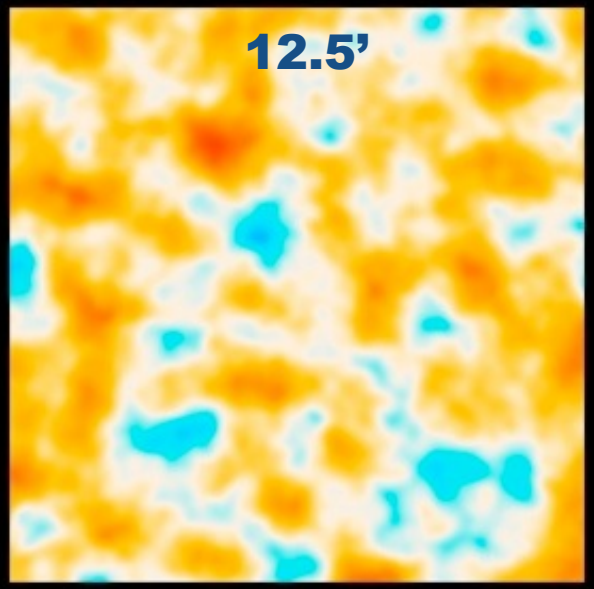
SPIDER

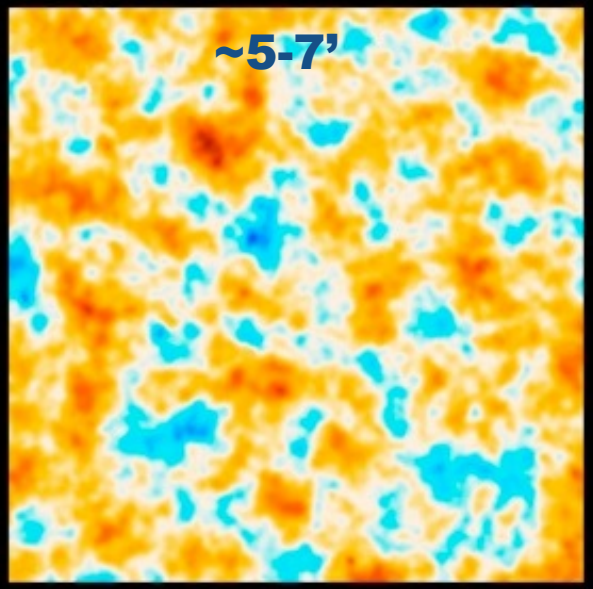
Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

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'

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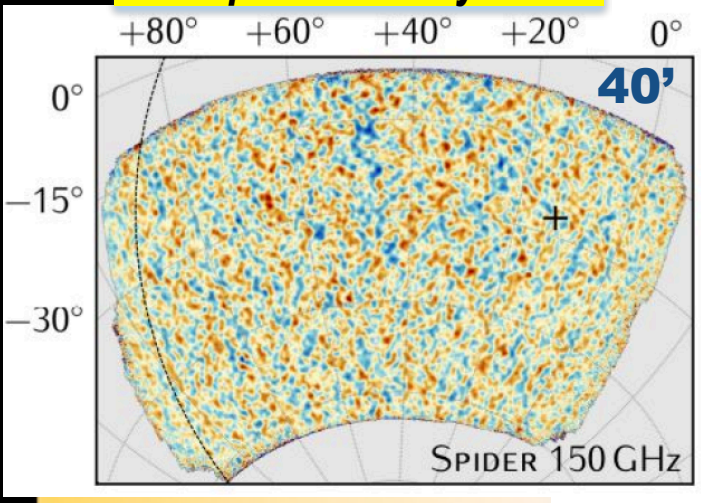
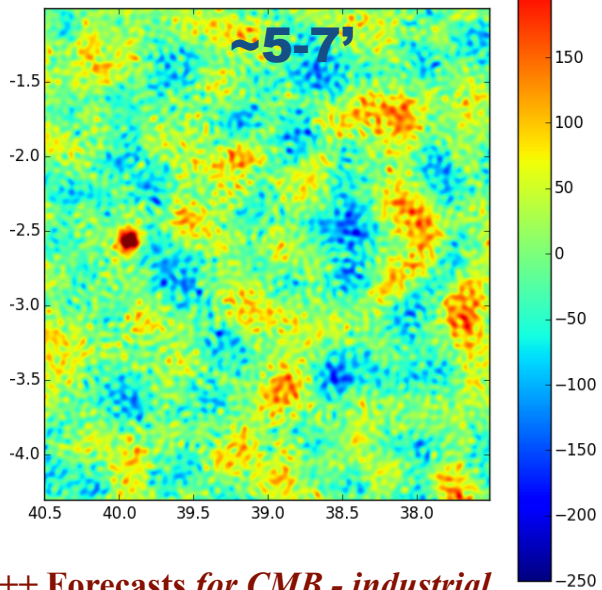
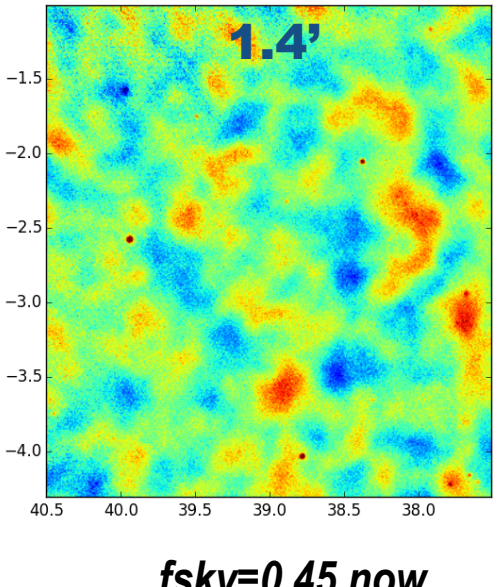
Spider 40' fsky~.08



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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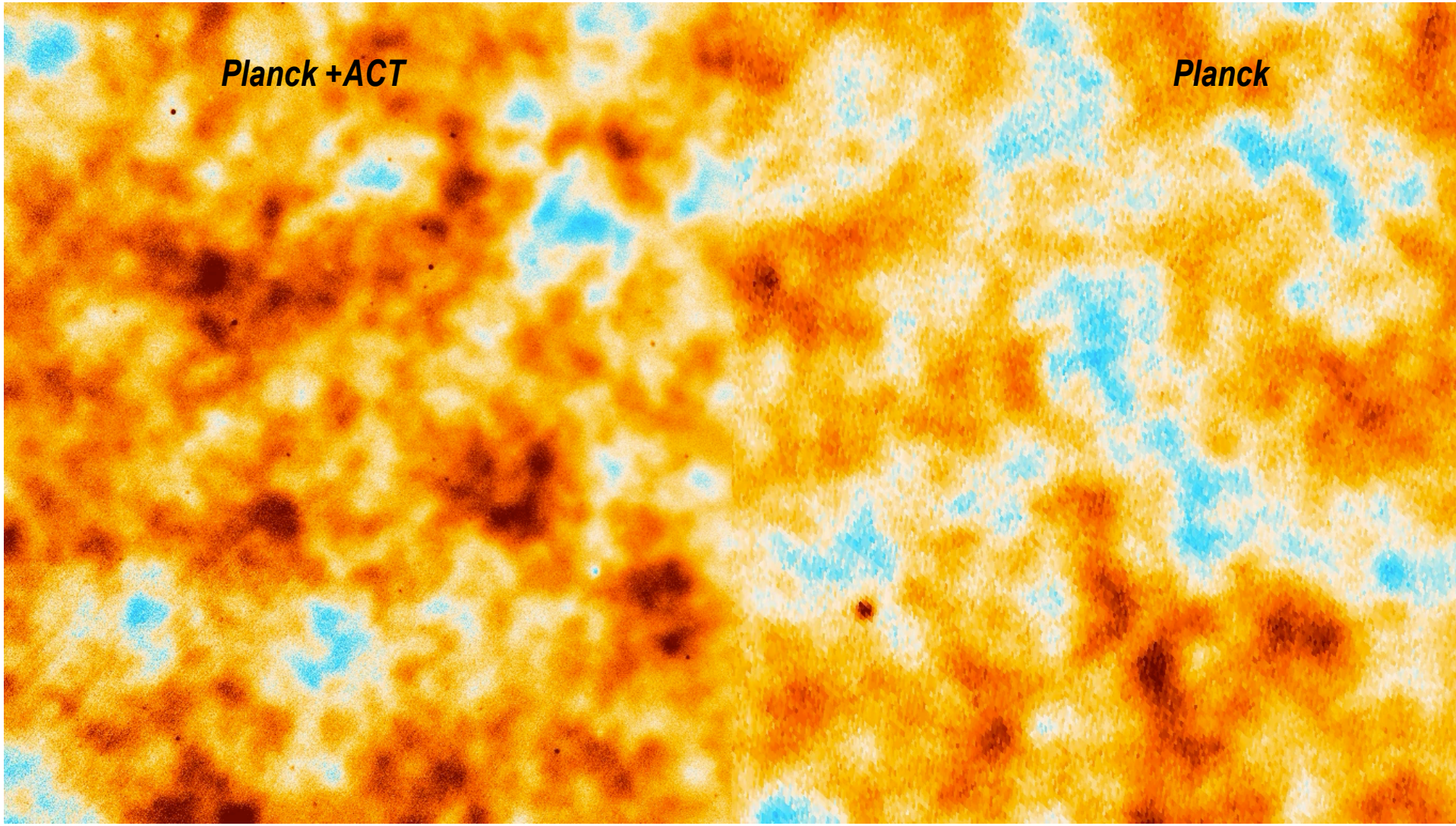

ACTer sigurd naess 2019

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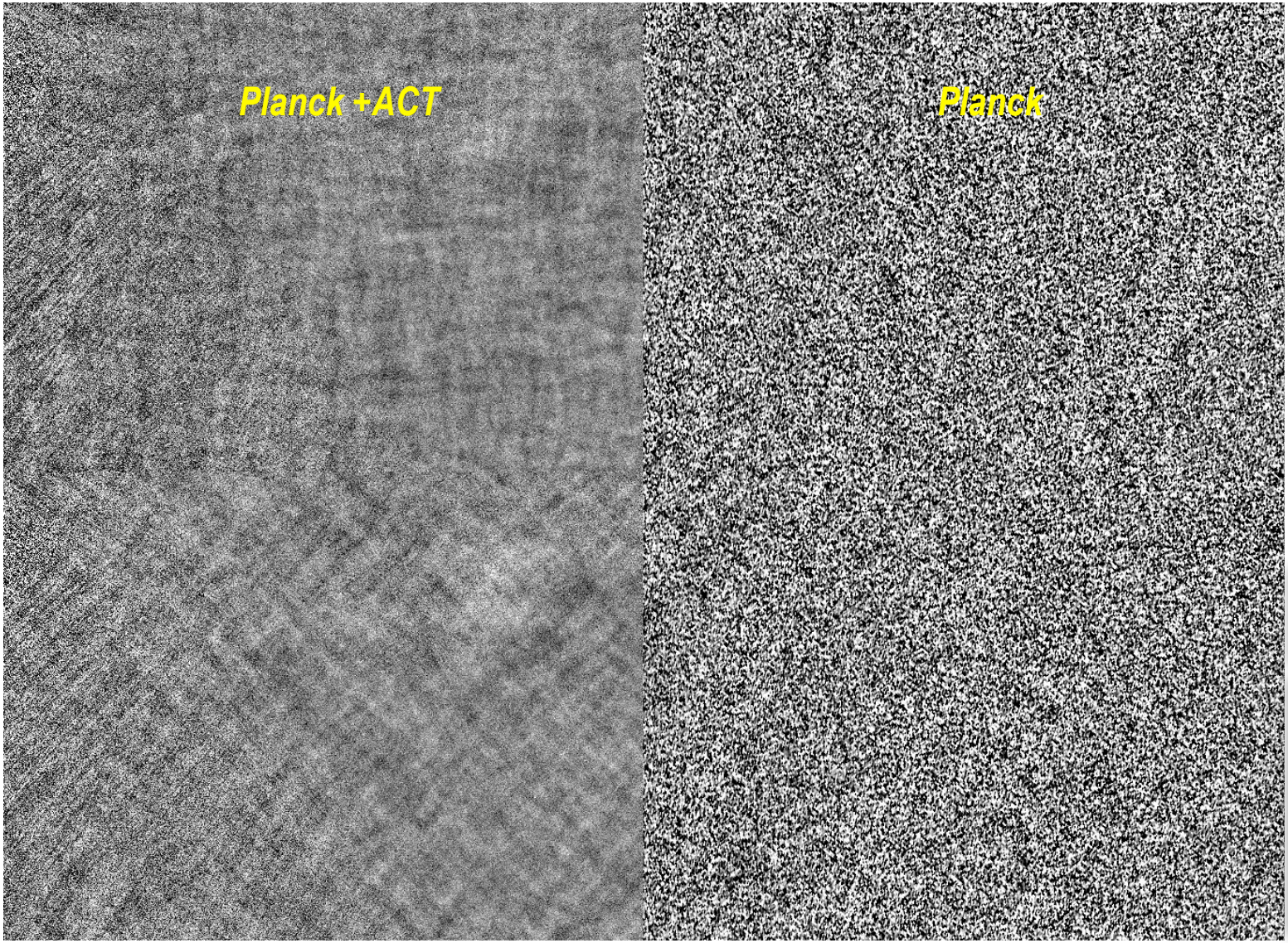

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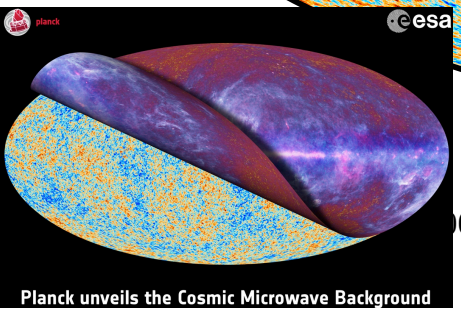
Planck's primordial light unveiled, *Mar 2013 =>* ***Feb 2015*** *=> pre-2016 =>* ***July 2018+*** *final*

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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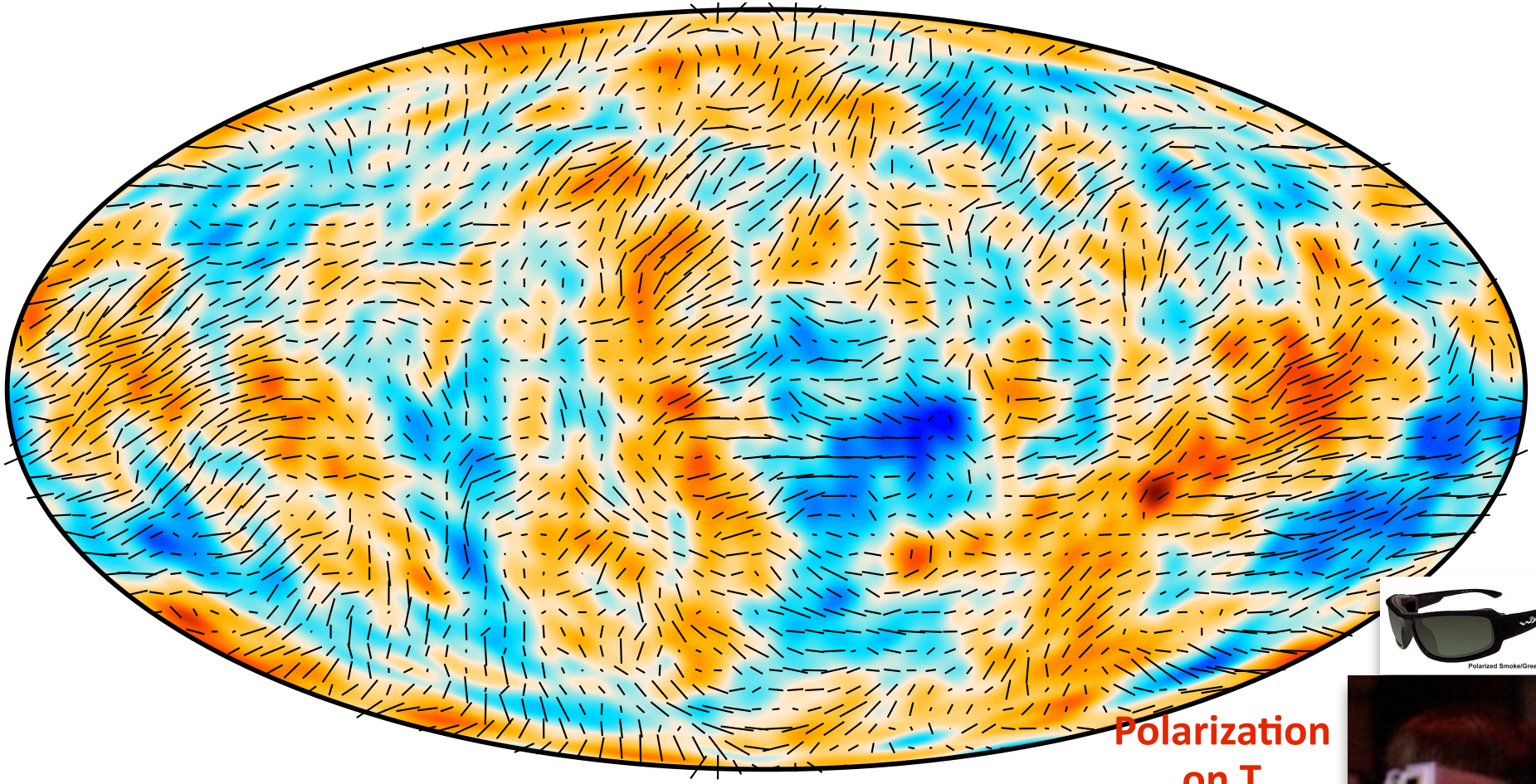

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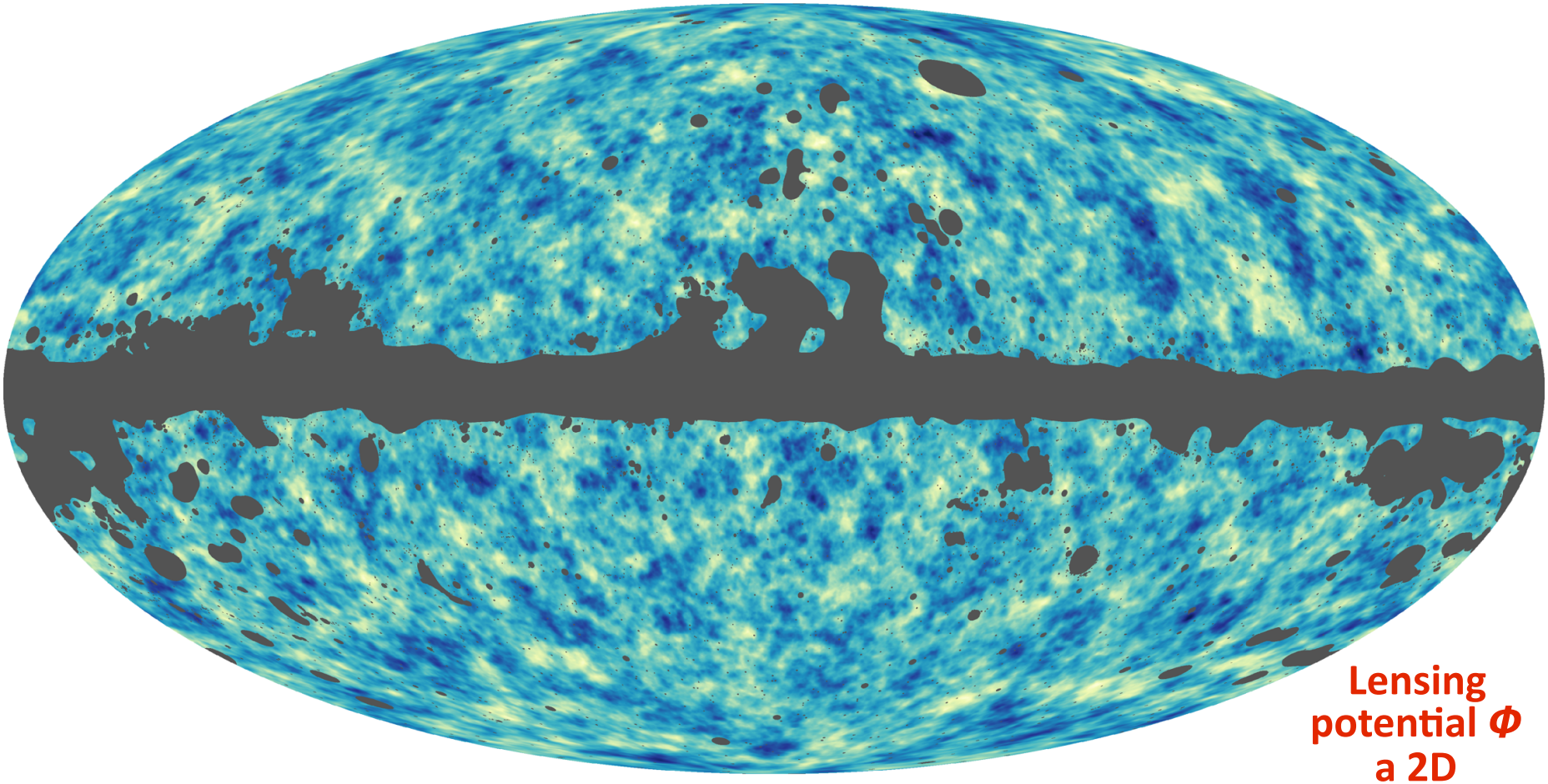

Lensing potential Φ a 2D projection

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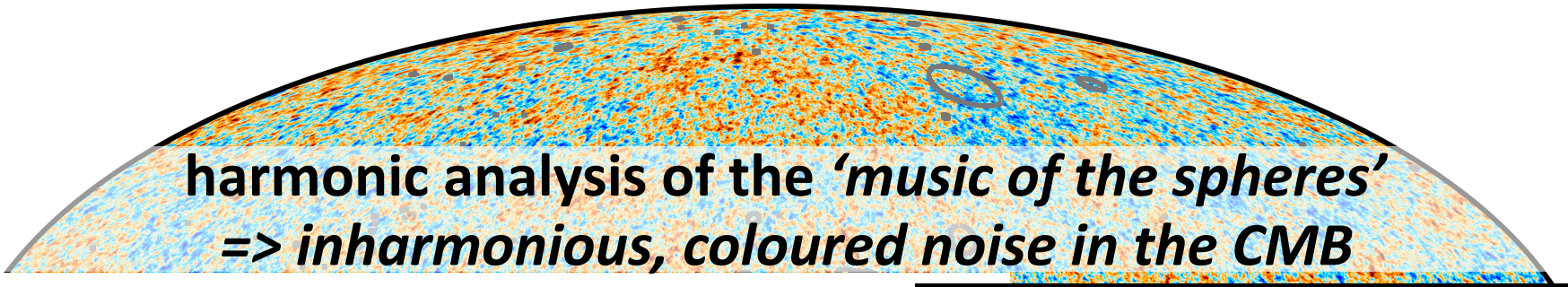
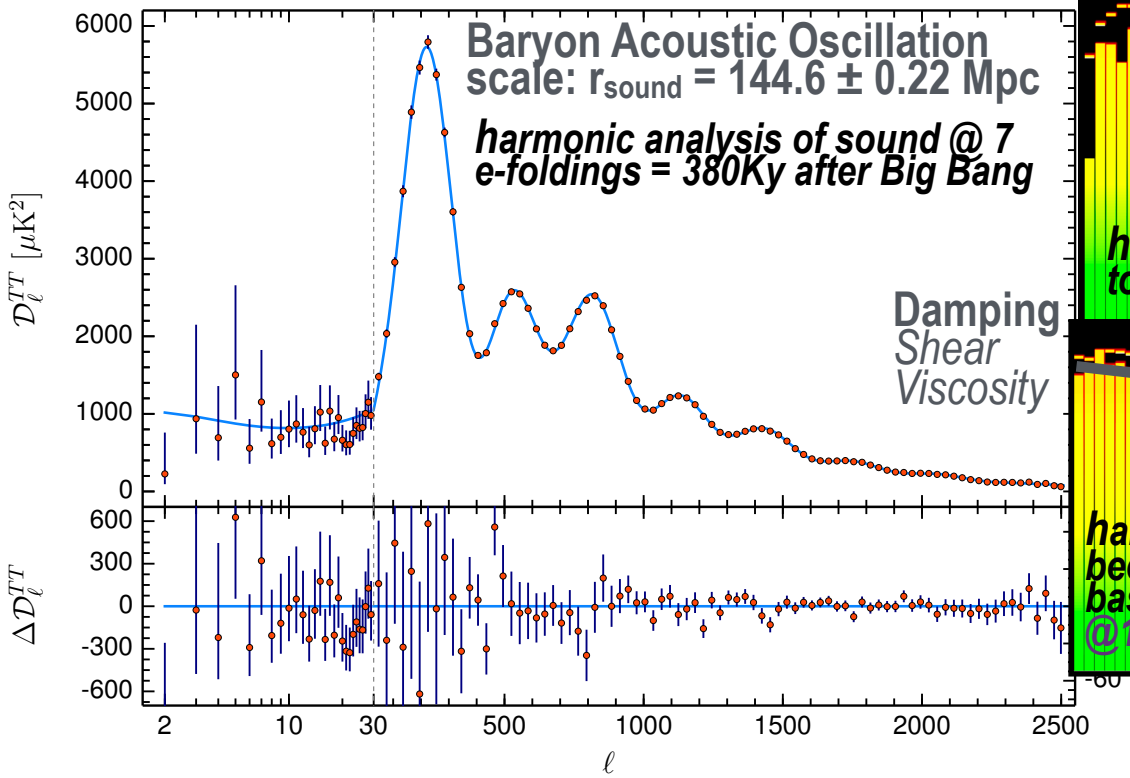
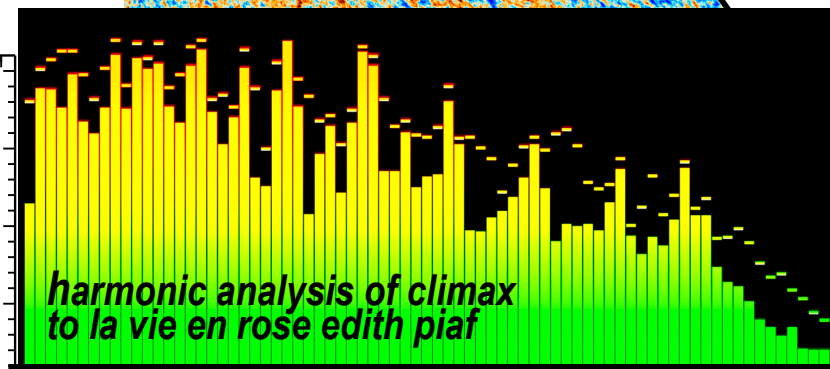
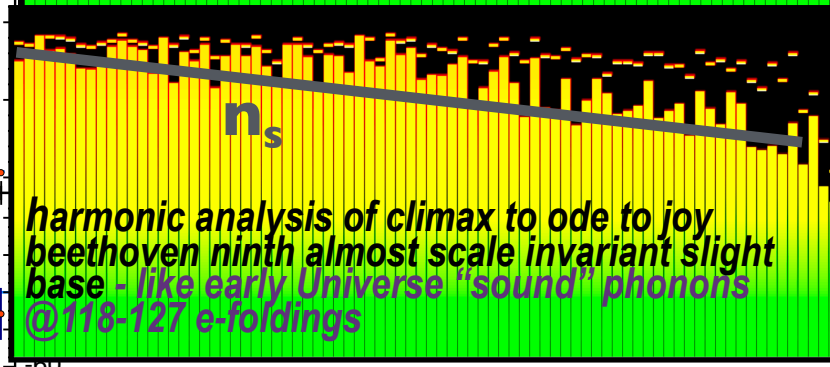


harmonic analysis of the *'music of the spheres'*
=> inharmonious, coloured noise in the CMB







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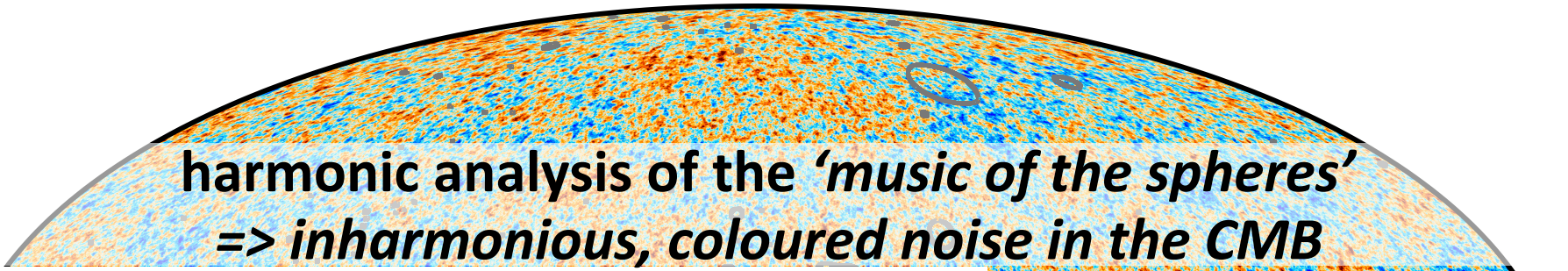

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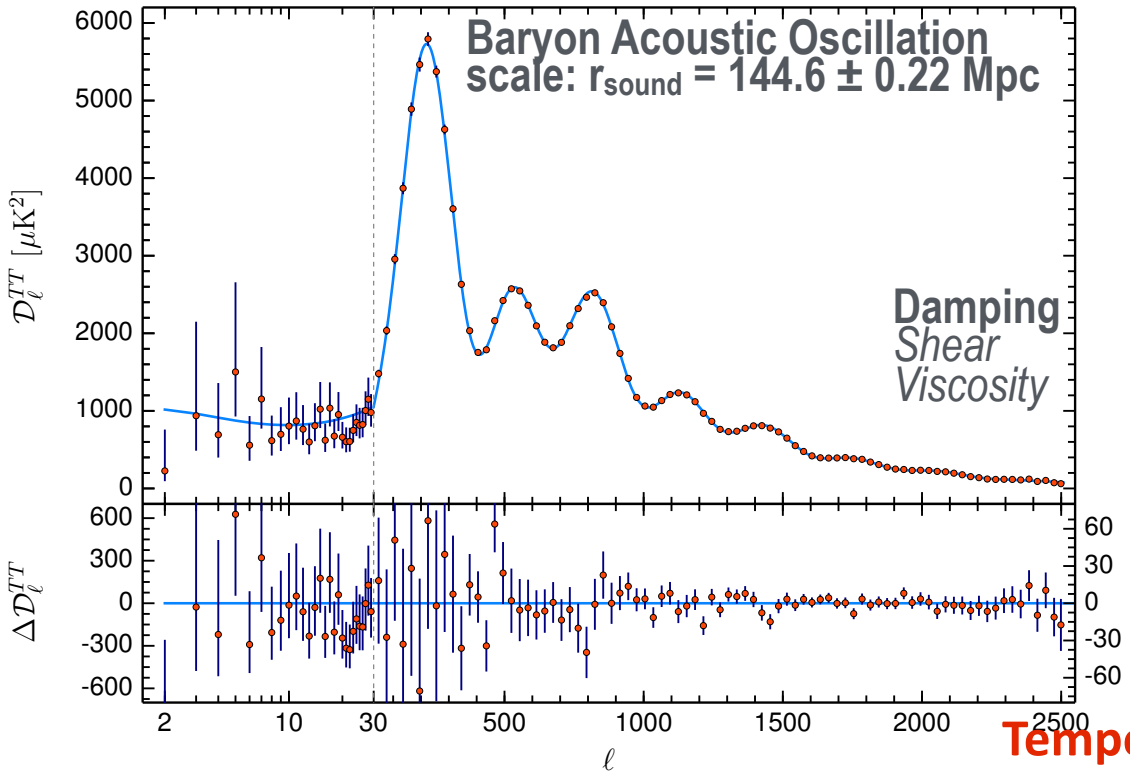
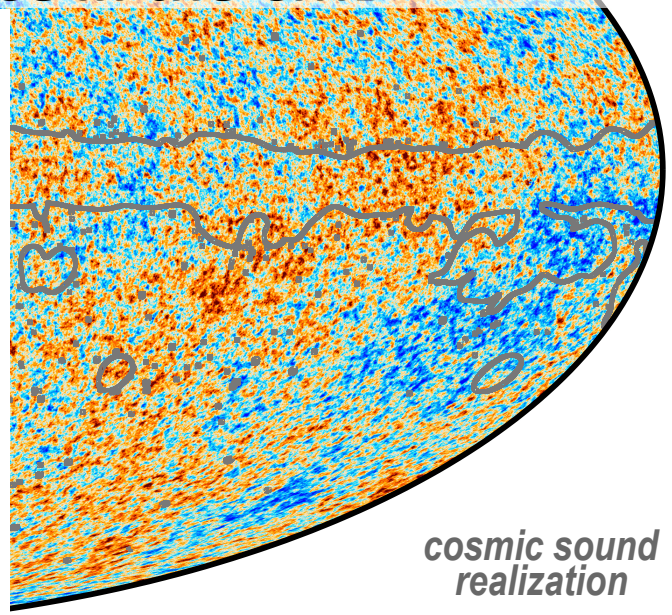




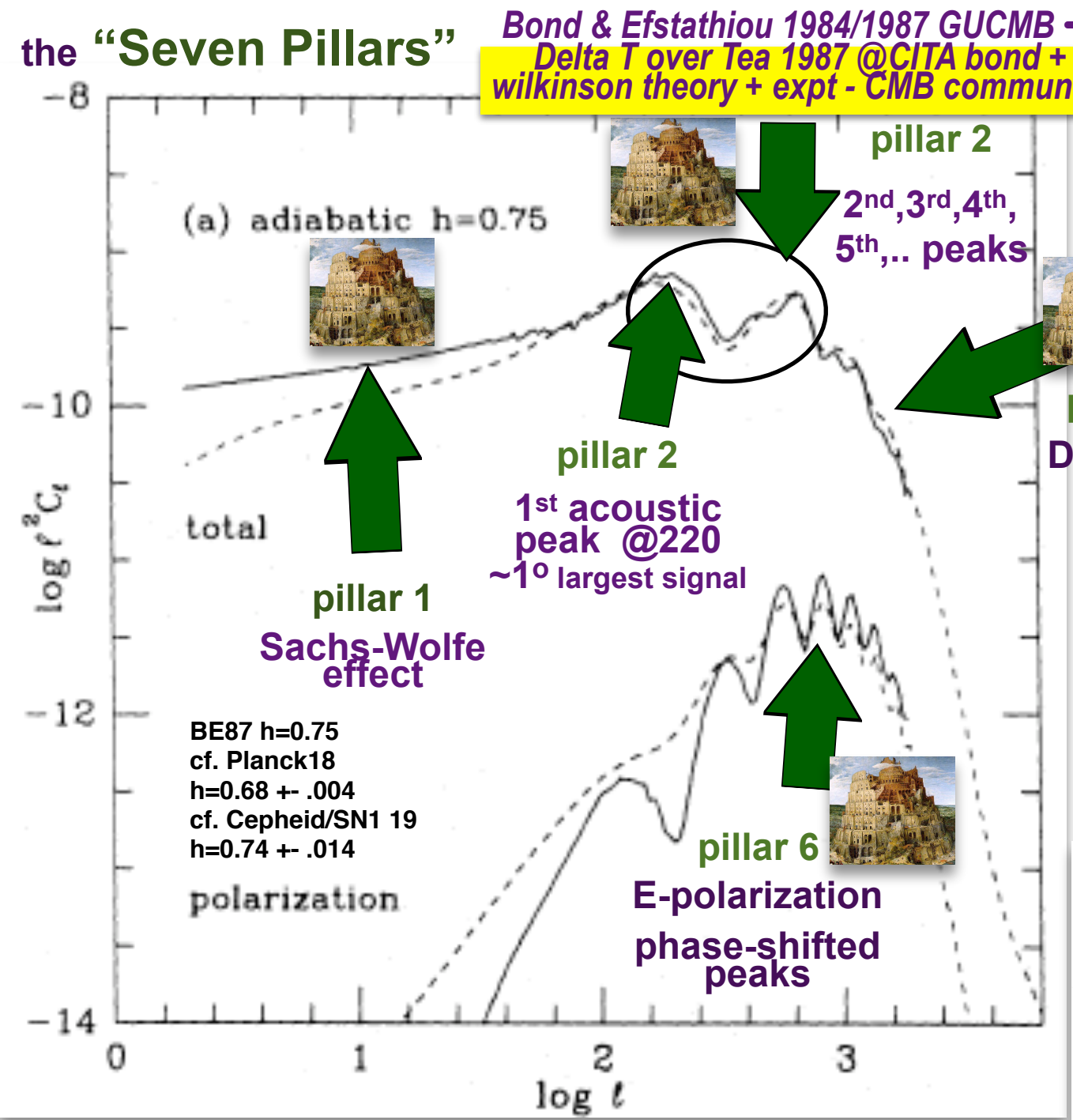
cosmic sound realization

300 μK

Temperature changes in micro-degrees

the "Seven Pillars"

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



pillar 2

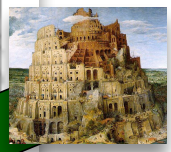
2nd,3rd,4th, 5th,.. peaks

pillar 1

Sachs-Wolfe effect

pillar 2

1st acoustic peak @220
~1° largest signal



pillar 3

Damping tail

pillar 4

Gaussianity *maximal randomness for given C_L*

pillar 5

secondary nonlinear *Compton SZ weak lensing..*

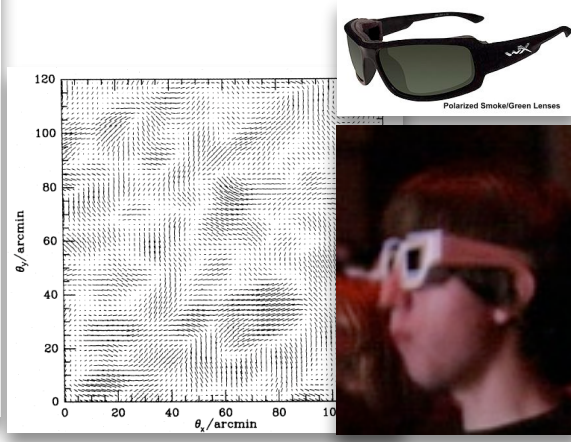
pillar 7

B-polarization Gravity Waves

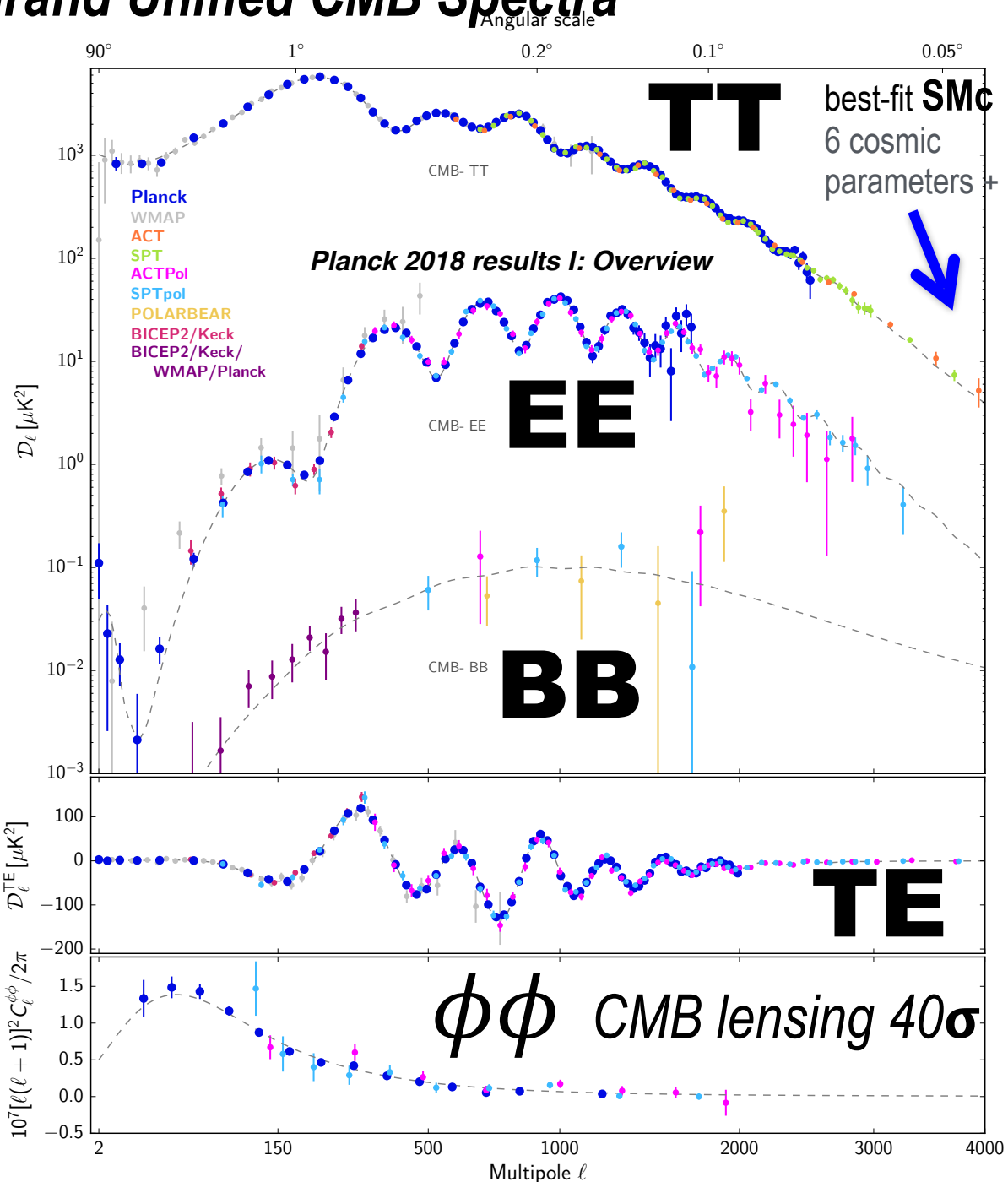
pillar 6

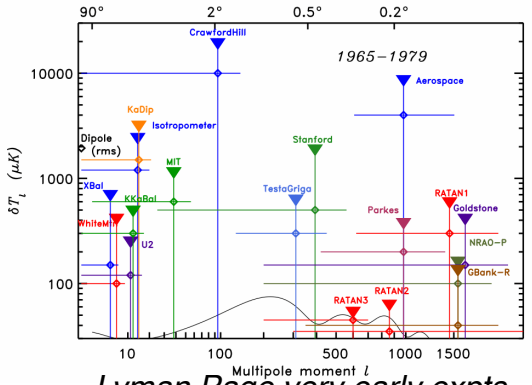
E-polarization

phase-shifted peaks



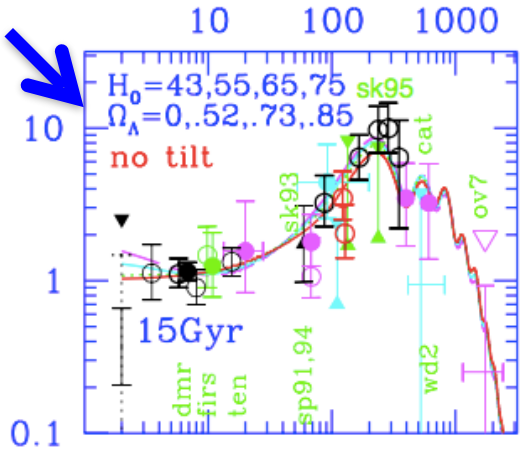
Grand Unified CMB Spectra



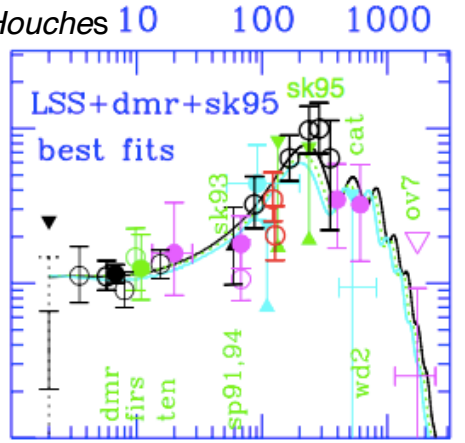


Lyman Page very early expts

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*

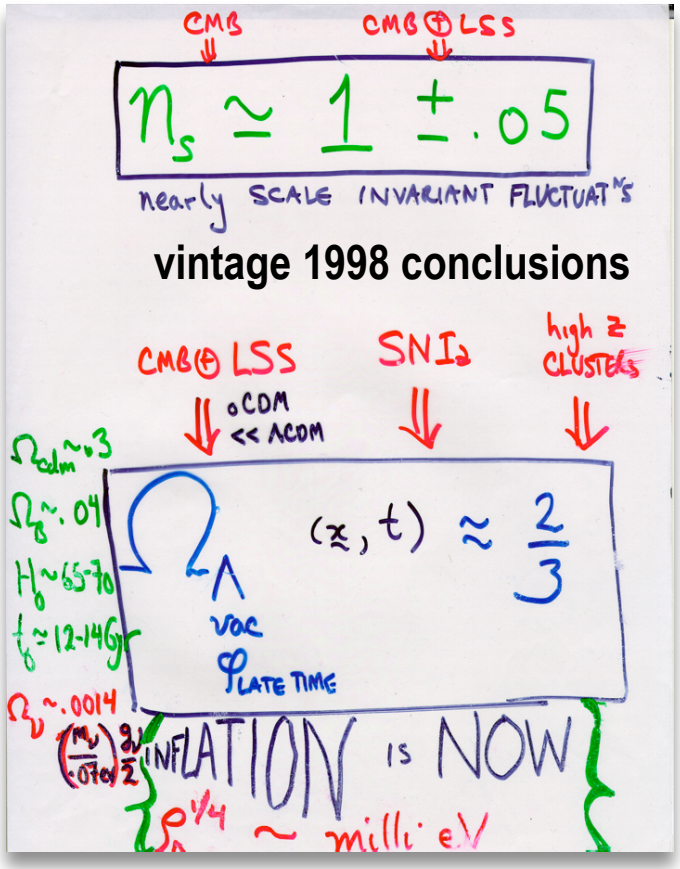
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

- 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.

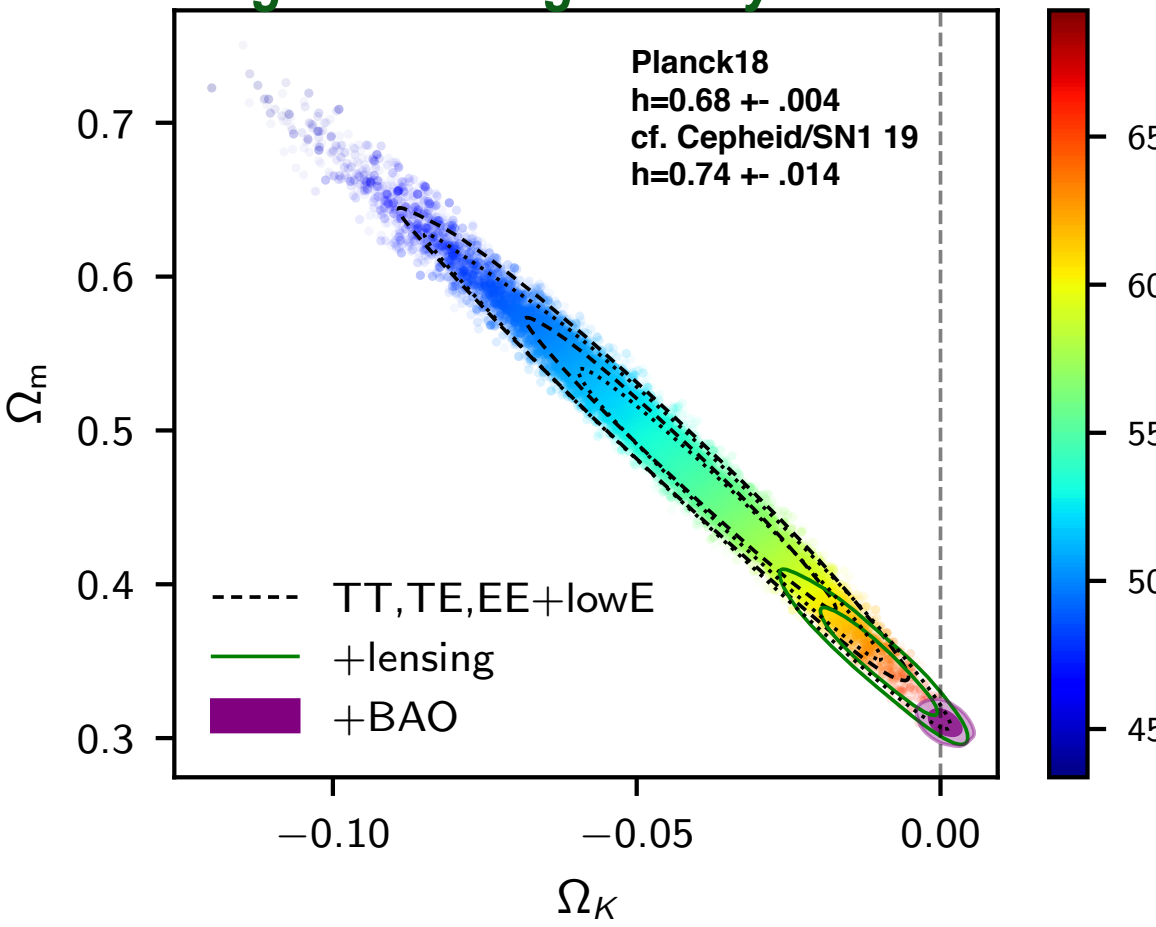
CMB@22, *Who's Who in North America*

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

anisotropic strain, gravity waves

isotropic strain, sound Trace(ε)

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**

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

~

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

$p=\hbar k$ $E=\hbar\omega$ *are other main ingredients*

these are the mysteries

not $\Delta k\Delta x \gtrsim 1$ *&* $\Delta\omega\Delta t \gtrsim 1$

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

Earth under Strain: earthquakes, seismic waves

ε=strain tensor

Universe under Strain: space-quakes = gravity waves

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

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** $\propto$ **tide**

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

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

~

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

$\alpha_{\jmath}^{j}(r,t)$ 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

$\zeta(x)$

energy-density & gravity are entangled

isotropic strain & energy-phonons

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

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

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

ζ- TOPOGRAPHY & CARTOGRAPHY

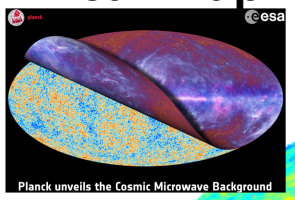
=> @a ~1/10^{55} only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

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*>

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

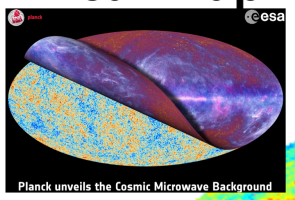
only partial de-lens

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

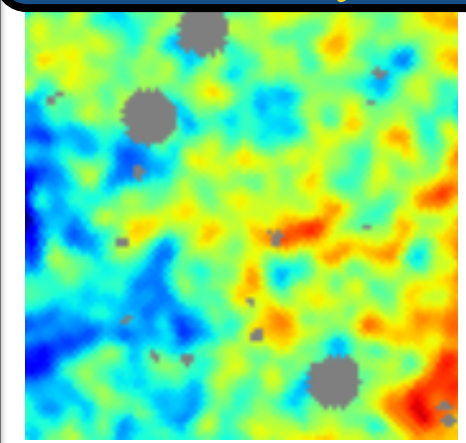
∫d ***visibility***(*distance*) <ζ|*Temp, E pol*>

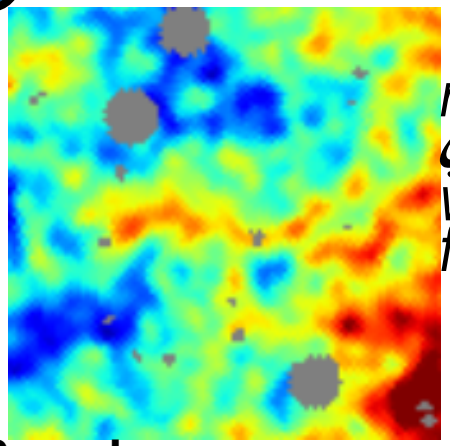
bond + huang

-40.0 +40.0

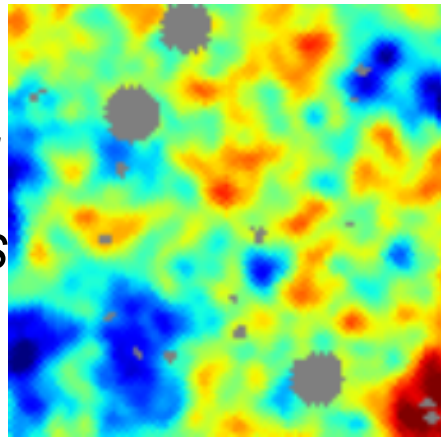
real ζ -WebSky mean field

visibility mask





real ζ-WebSkys with fluctuations

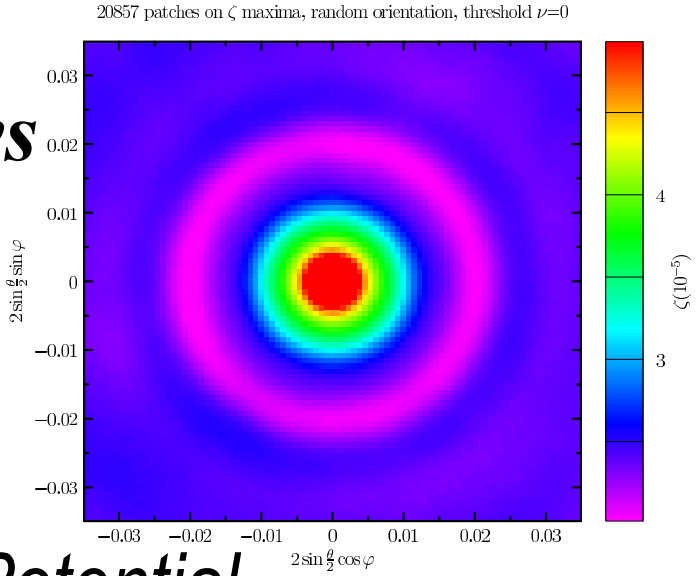


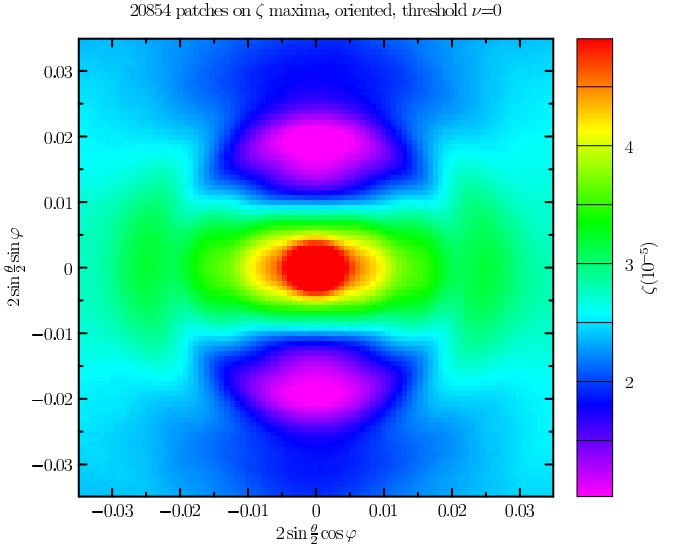
20x20 sq deg

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.

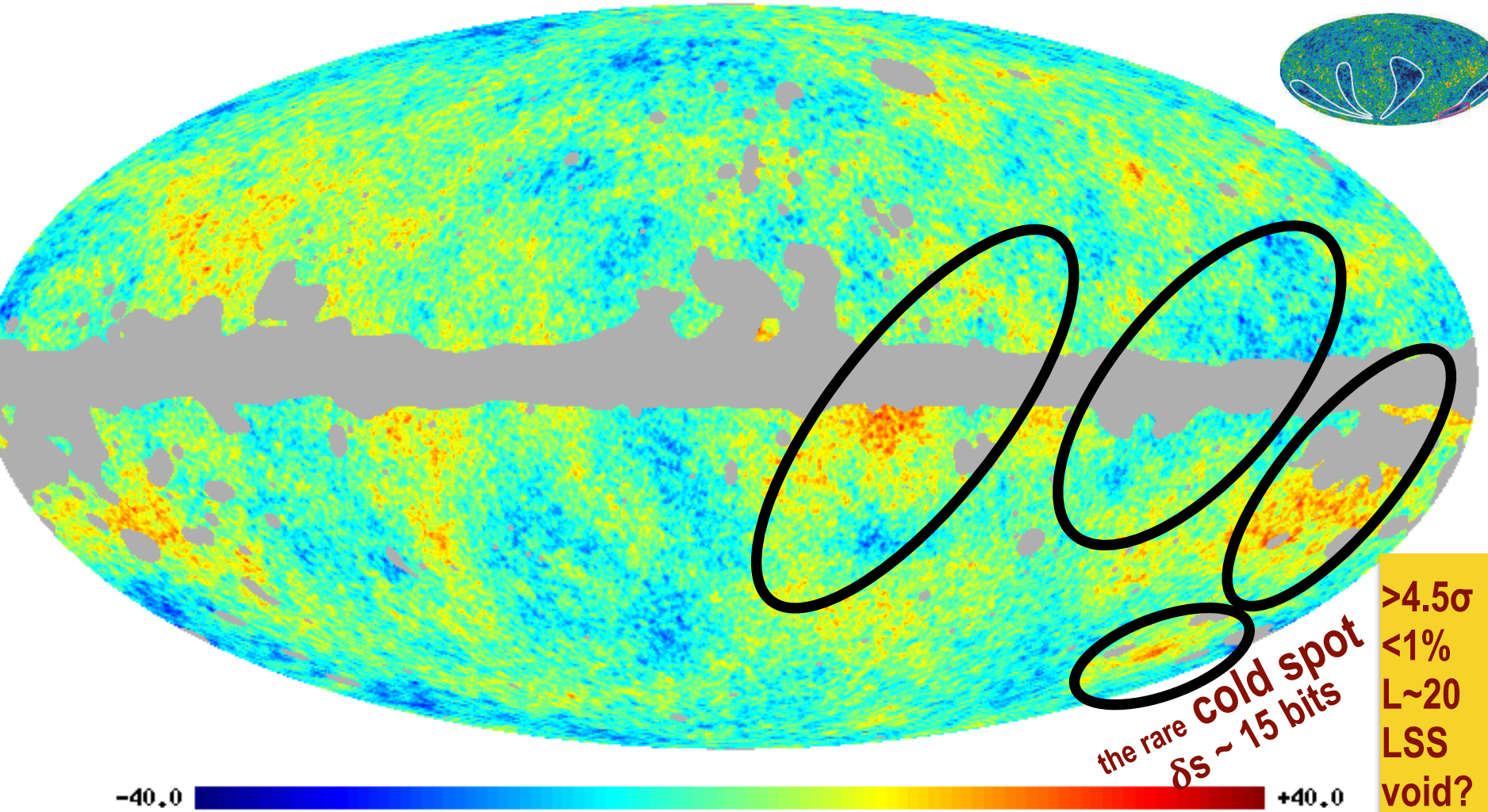
Beyond the Standard Model of cosmology? SMc = *tilted*ΛCDM +r aka (ζ,h_{+x})

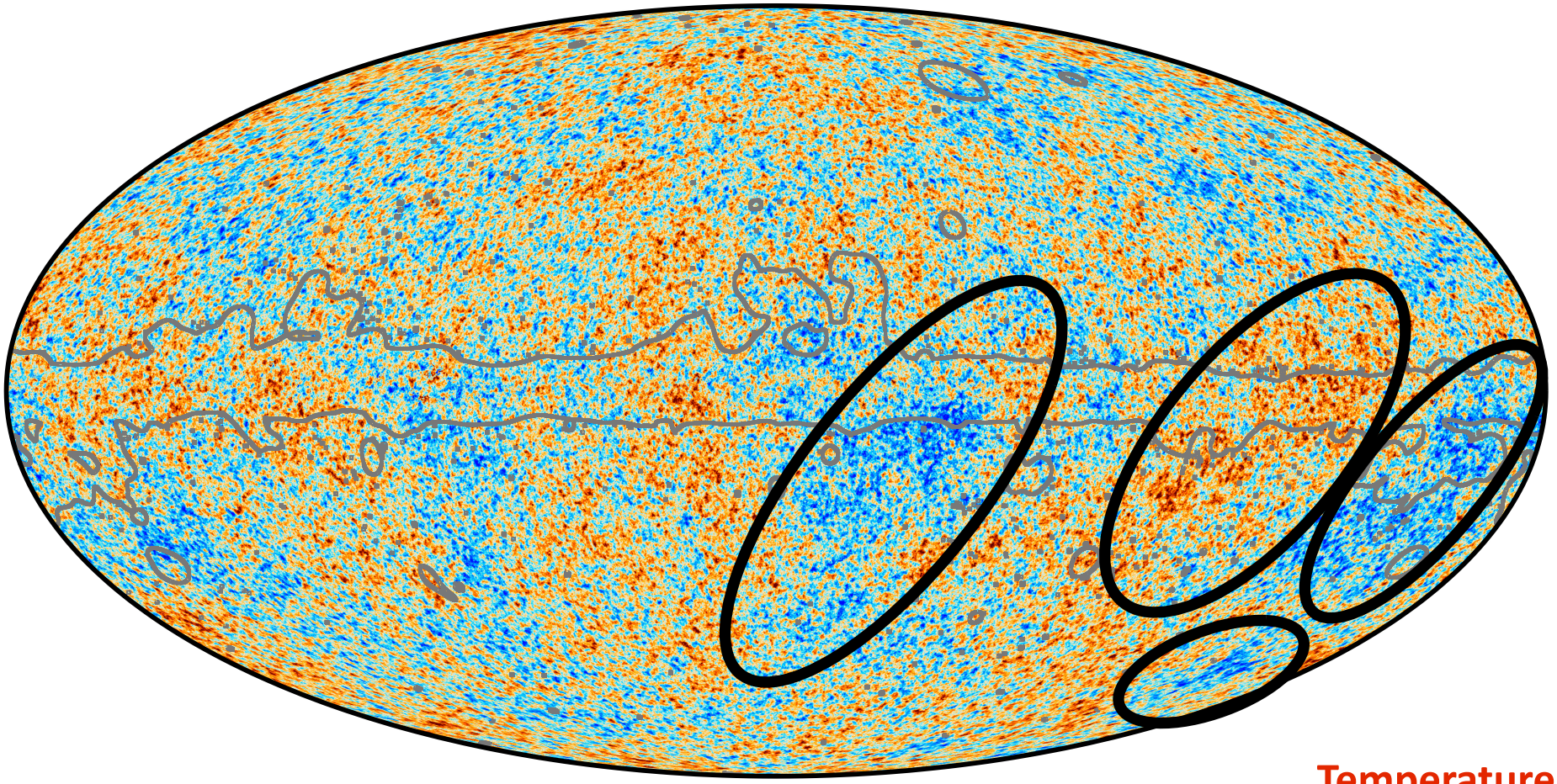
BSMc = SMc + primordial anomalies in the true ζ -WebSky

<ζ|*T,E-pol*>

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

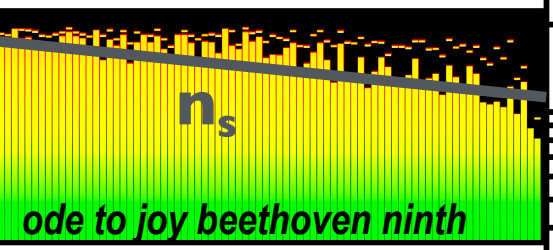
P18+BK15

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

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

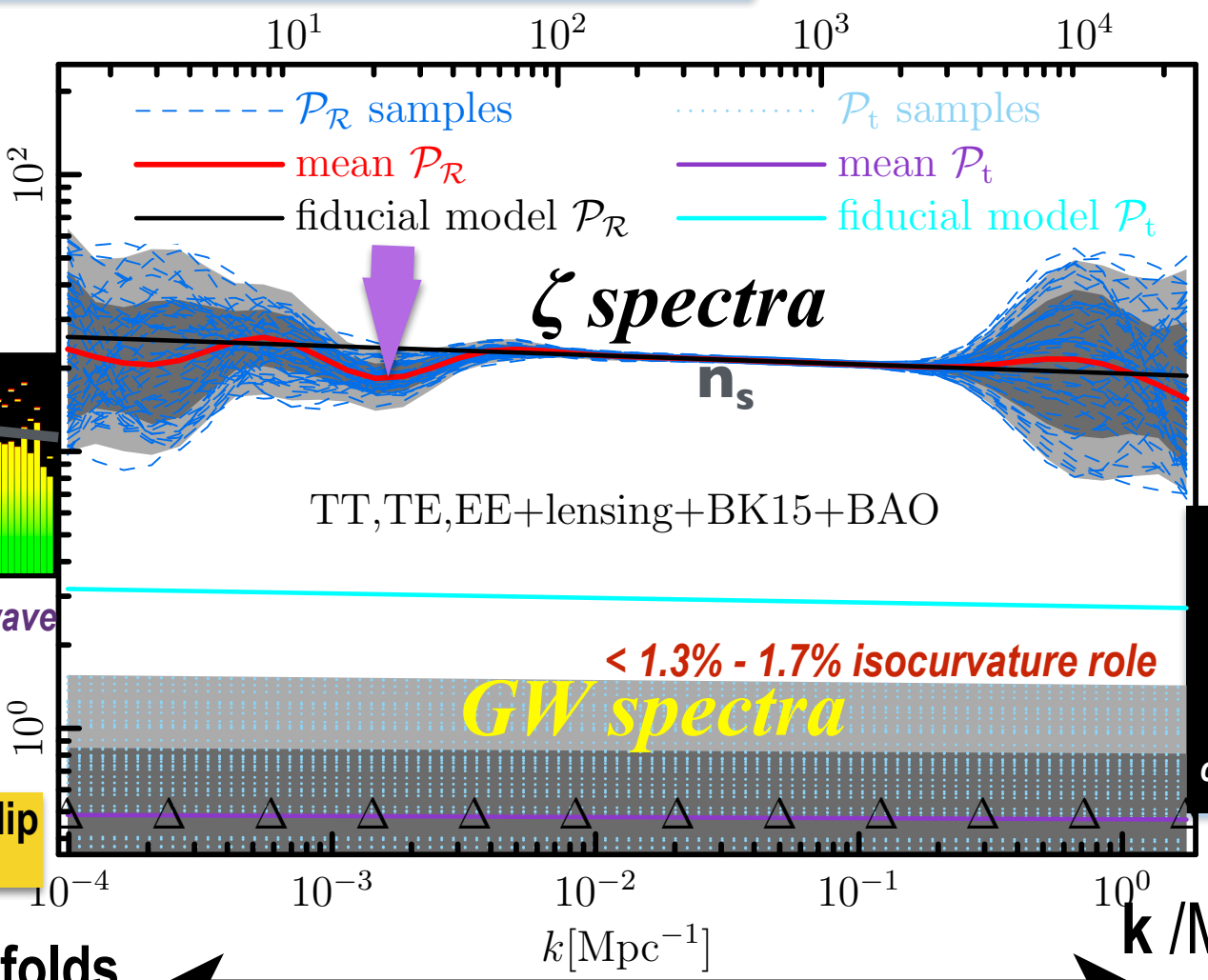
12-knot fit from k~ .008 to .3
uniform n_s is perfect

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)

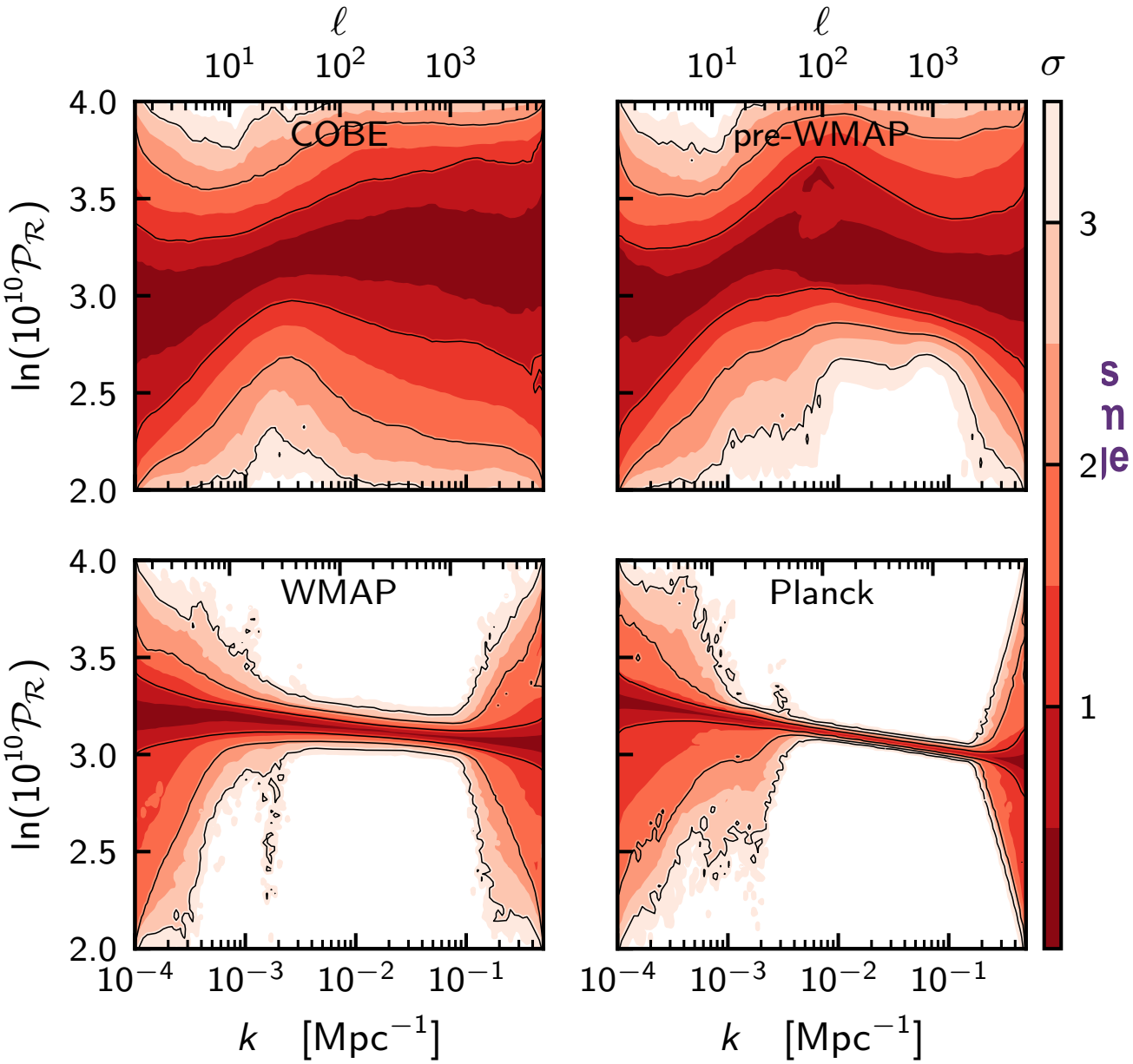
⇒ 50 e-folds to EoI
poorly constrained

9 e-folds

the true quadratic ζ-Websky of the ζ-scape

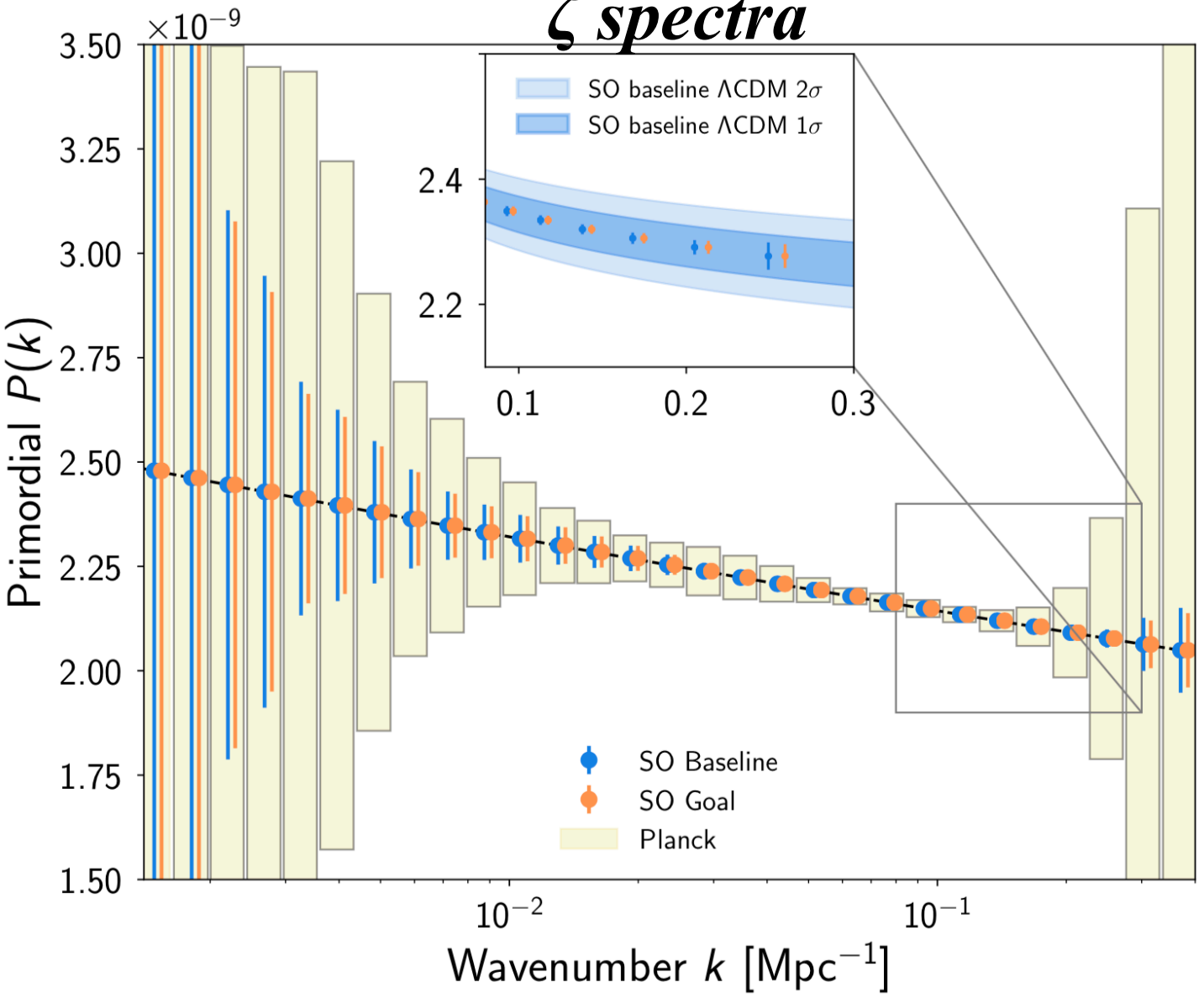
Planck 2018 I: TTTEEE lowL Epol + CMBlens + BK14 BB *+ BAO*

Evolution of ζ power over time



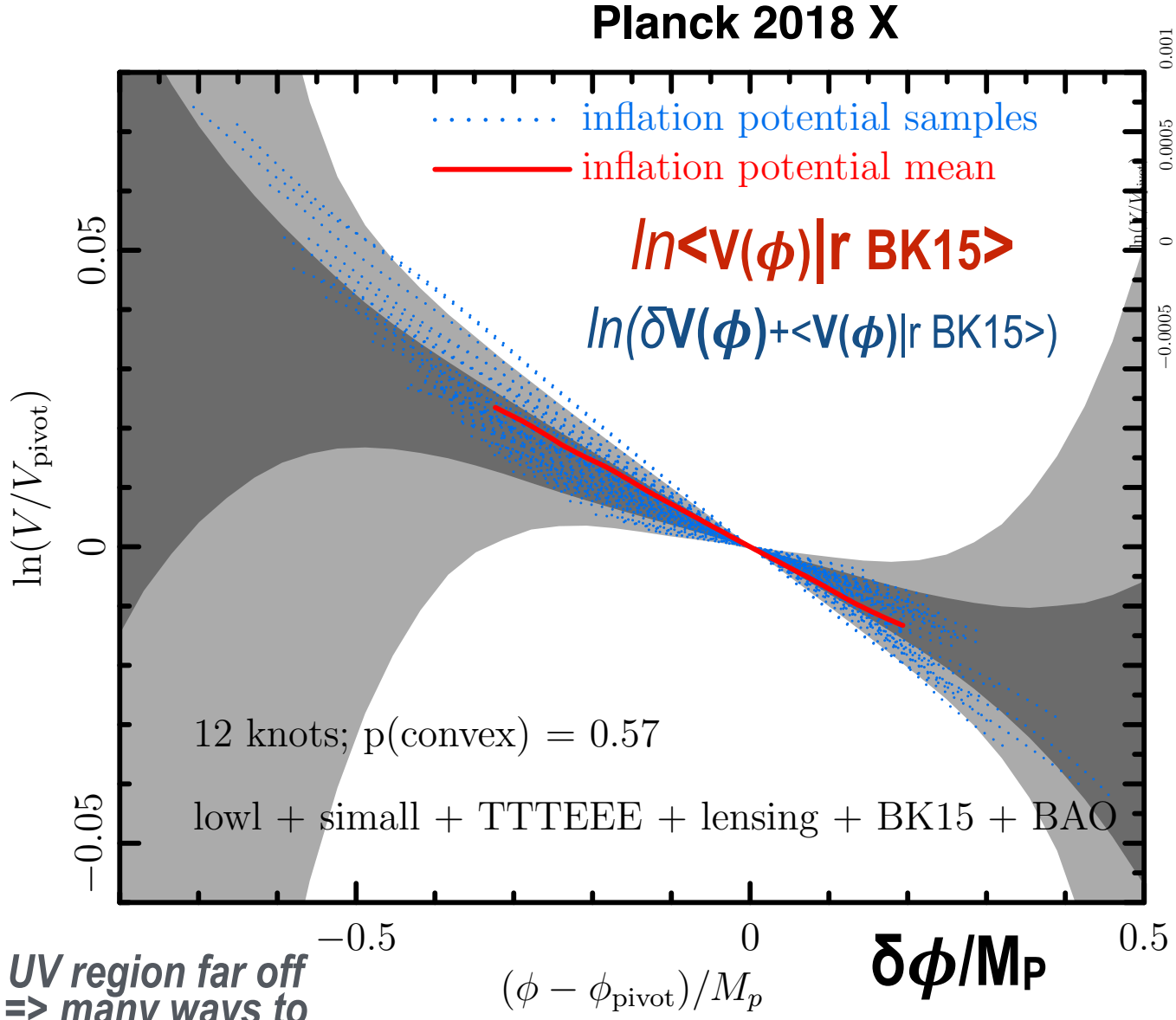
the **true quadratic ζ-Websky** of the **ζ-scape**

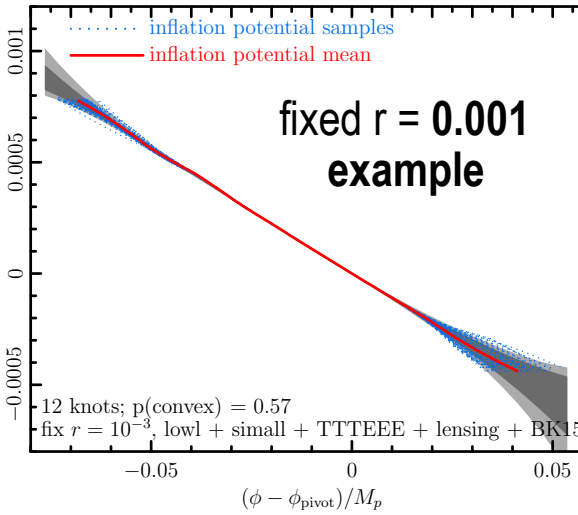
Sample Cosmological Forecast: Simons Observatory 2021+



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)???

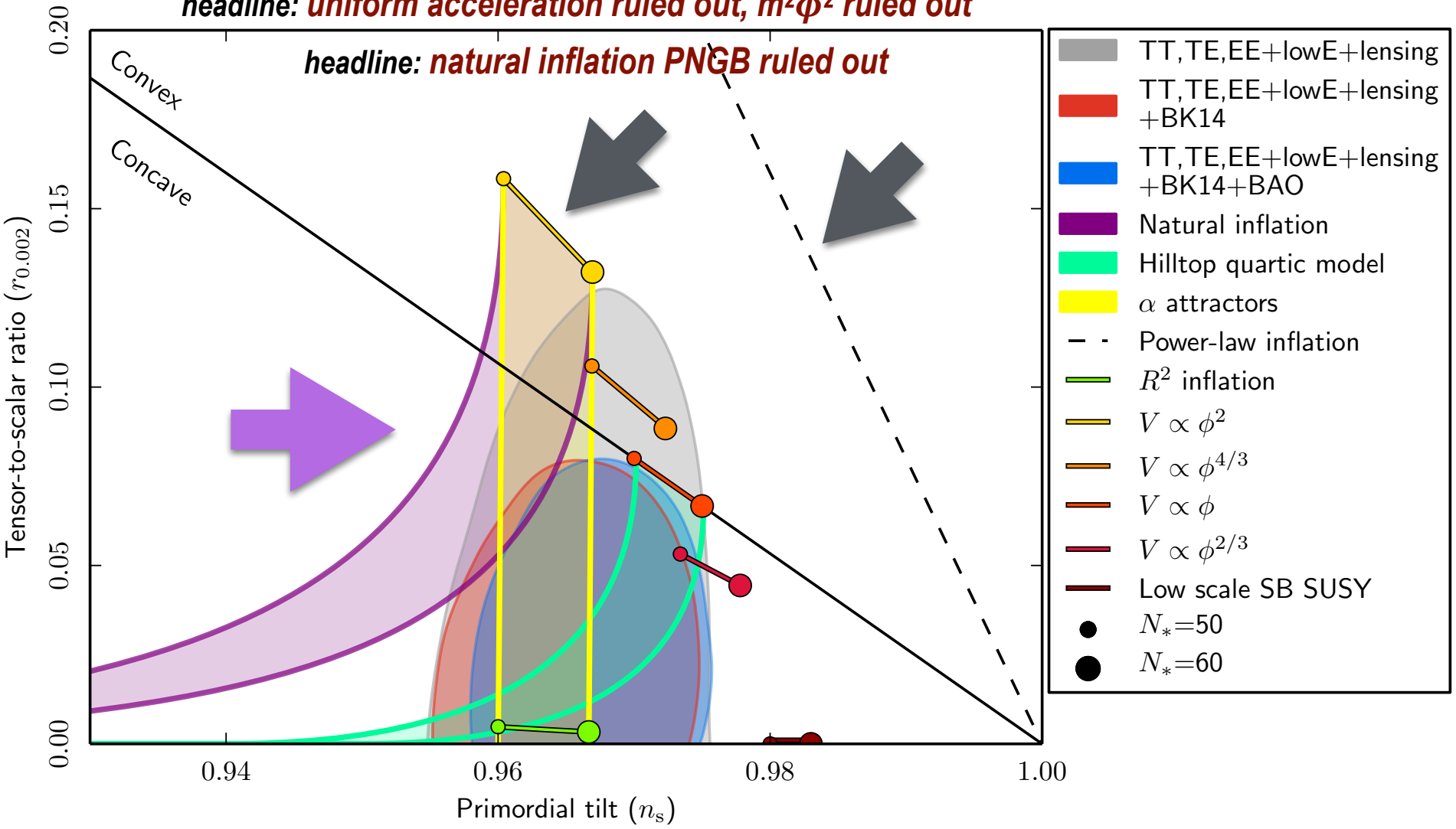
IR heating region is far off => many ways to extrapolate

UV region far off => many ways to extrapolate

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

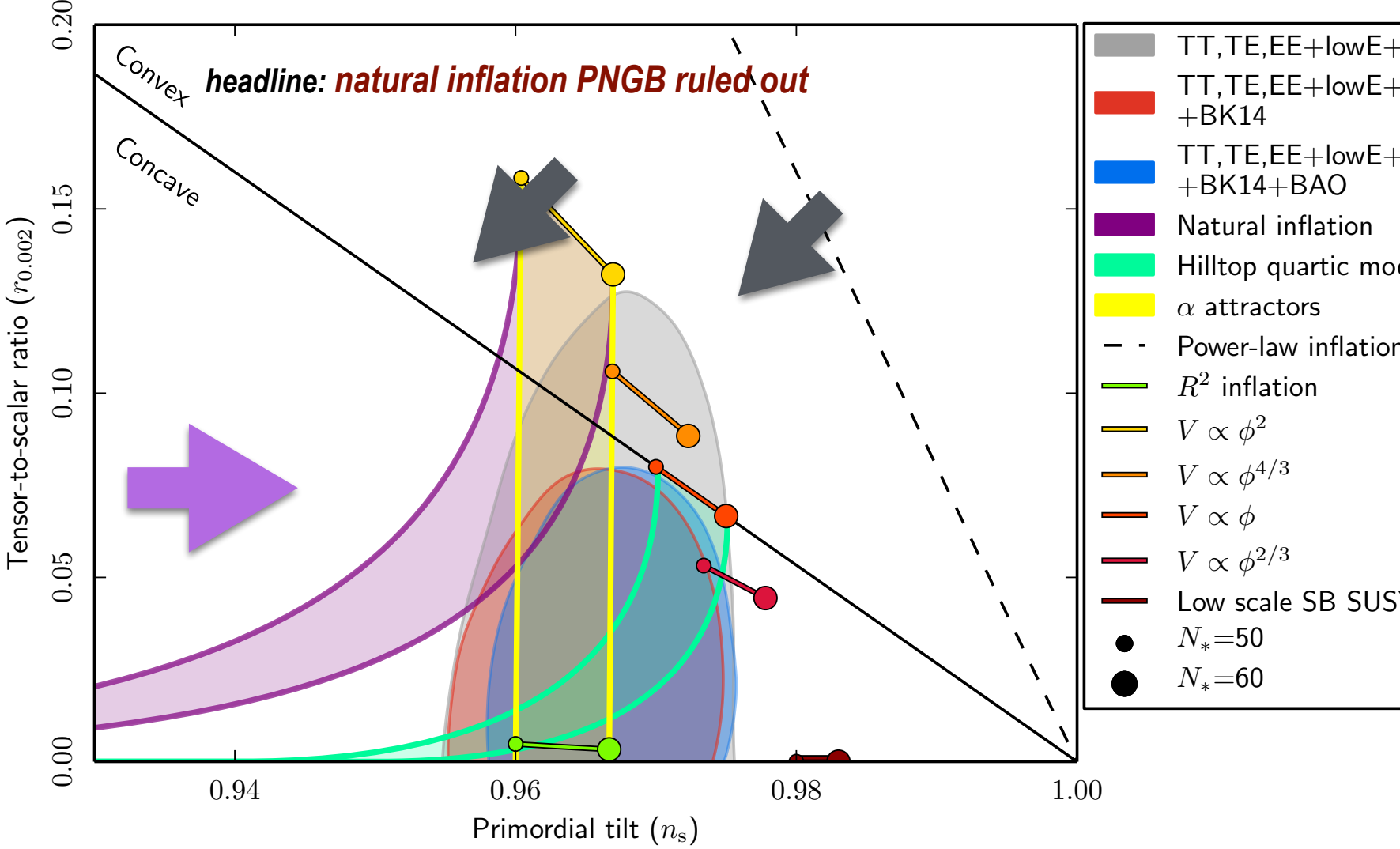
headline: ***uniform acceleration ruled out, $m^2\phi^2$ ruled out***

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***

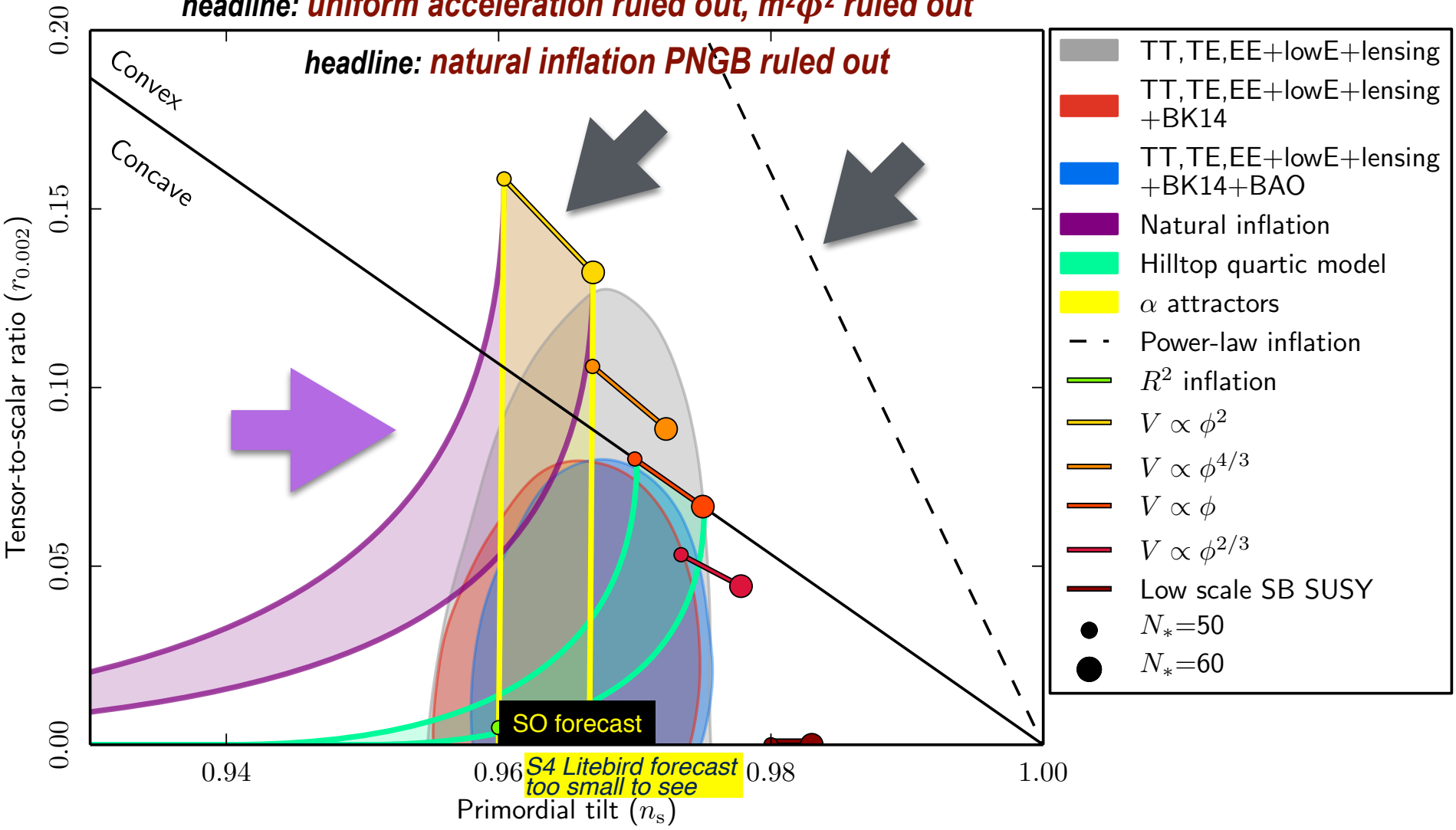


State of ***Inflation theory circa 87: 3 decades*** ***Nuffield conference was 1982***
Chaotic +++ model space M_{Planck} ***phonons -> inflaton -> ζ =ln a***
stochastic inflation $\delta\phi \sim \hbar H$ *aka* ***quantum "zero-point" fluctuations***

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

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

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



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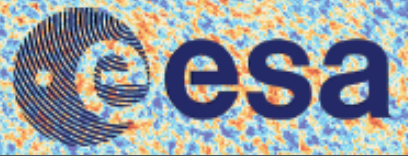
planck

Dick Bond
Quantum Inflation in the Planck Era & Beyond



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)?*

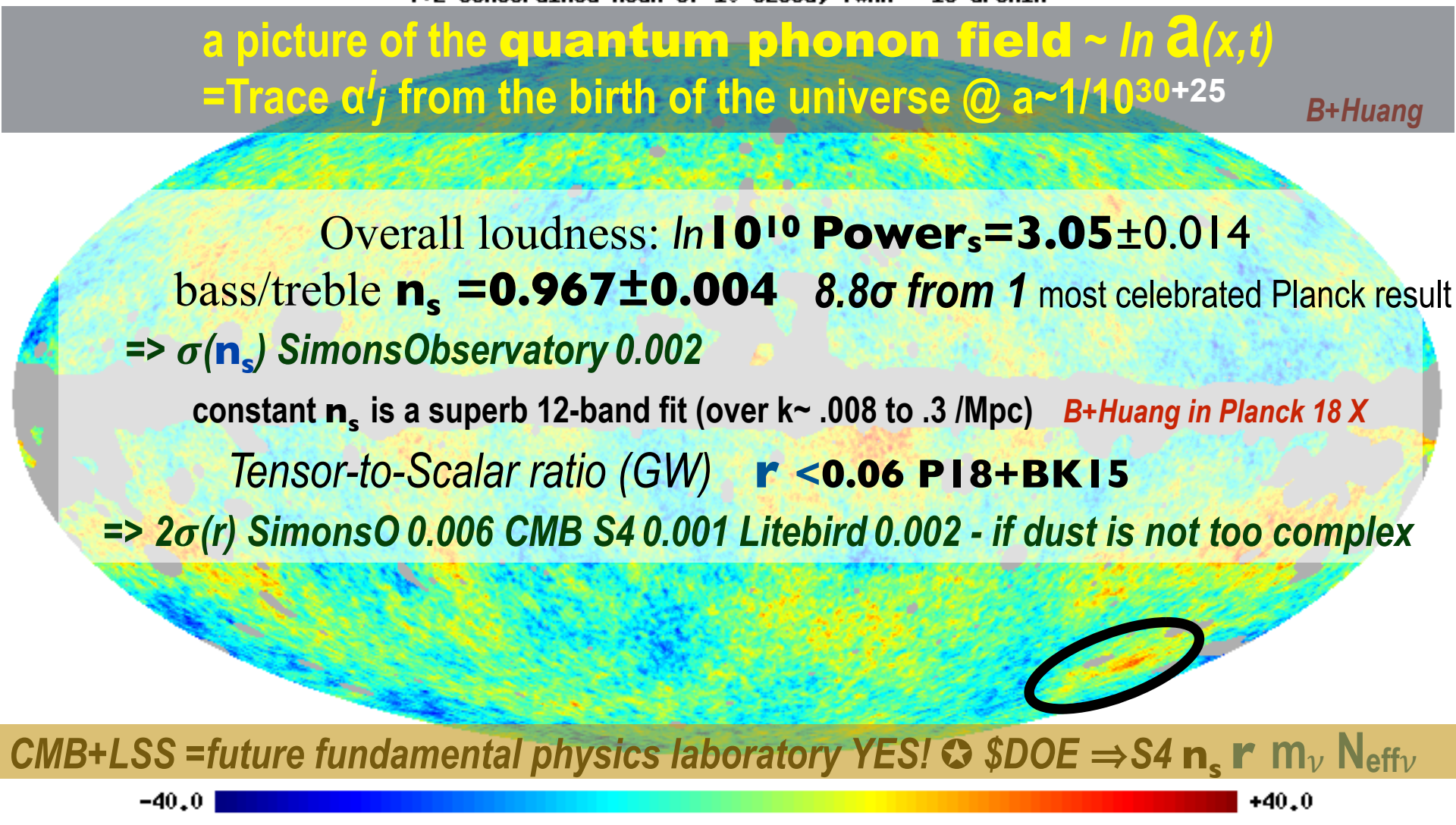
SIMPLICITY

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