



planck

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 **BOUND**ed flow of information
the **BOUND**less thought of man

CMB past => CMB present

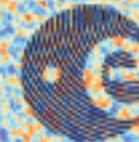
7⁺ numbers
3 densities,
2+1 early-
Universe
inflation

CMB+LSS future
SMc -> BSMc

Beyond the Standard Model of Cosmology



planck





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**a tale of
Planck**4**

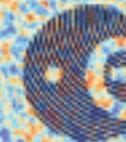
How the Planck satellite helped decode
the role of Planck's quantum \hbar &

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

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



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

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 ??



CITA
ICAT

CIFAR
CANADIAN
INSTITUTE
FOR
ADVANCED
RESEARCH

Dick Bond

CMB@53:

on cosmic **Photons** cosmic microwave background radiation 1st light $412 / \text{cm}^3$ 0.005%

on cosmic **Baryons** Ordinary Matter air $\sim \text{amu} / \text{nm}^3$ O₂ N ; U 4.9% H,He $\sim 0.055 \text{ amu} / \text{cm}^3$

on cosmic **Dark Matter** $\sim \text{amu} / \text{m}^3$ $26.6 \pm 0.7\%$ compressed in MilkyWay $\sim 0.3 \text{ amu} / \text{cm}^3$; 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** \sim vacuum potential density $\sim 3 \text{ amu} / \text{m}^3$ $68.5 \pm 0.7\%$ late-inflaton KE/PE?

on cosmic **Neutrinos** number density \sim cosmic photons Energy fraction $> 0.47\%$ \sim stars **CnuB**

on cosmic **Phonons** \sim isotropic **Strain** Deformations $h_{\text{Planck}} .. M_{\text{Planck}}$

on cosmic **Inflatons** - source the phonons $h_{\text{Planck}} .. M_{\text{Planck}}$

on cosmic **Gravitons** anisotropic **Strain** (*Transverse Traceless*) \ll 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

\Rightarrow **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

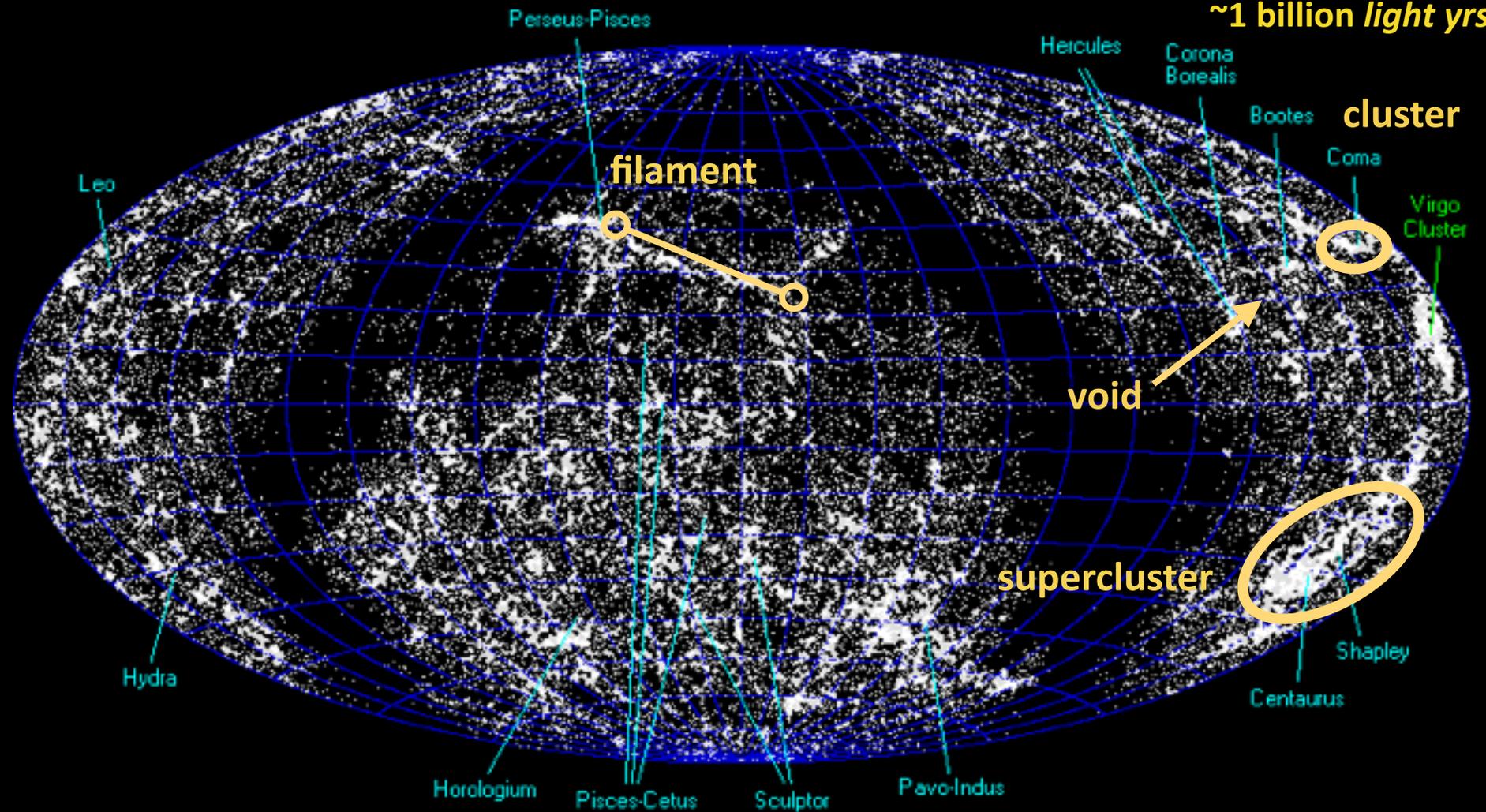
\Rightarrow **BSMc** = *Beyond the SMc* neutrino masses, dynamical coupled Dark Energy, modified Gravity ...



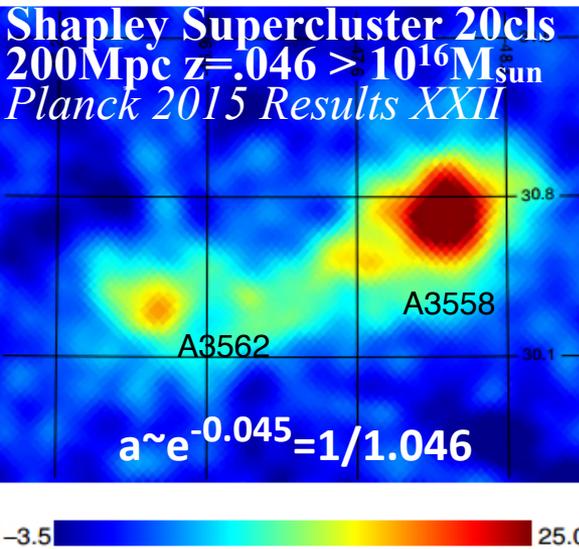
Cosmic Web of 60,000 nearby galaxies: exhibits “local” COMPLEXITY

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

~1 billion light yrs



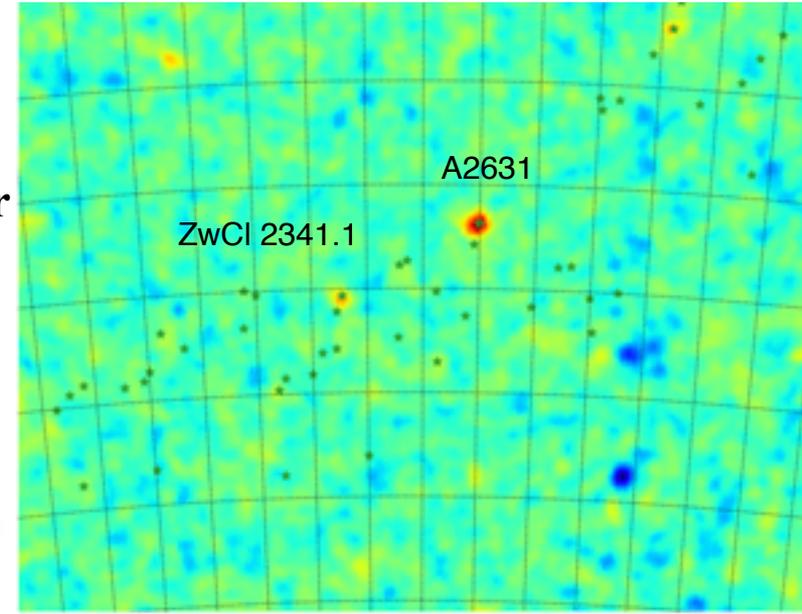
observational emergence of the web = ~80s tour de force, e.g., Coma supercluster ++. voids
interconnected structures from a Gaussian random adiabatic field under gravitational instability



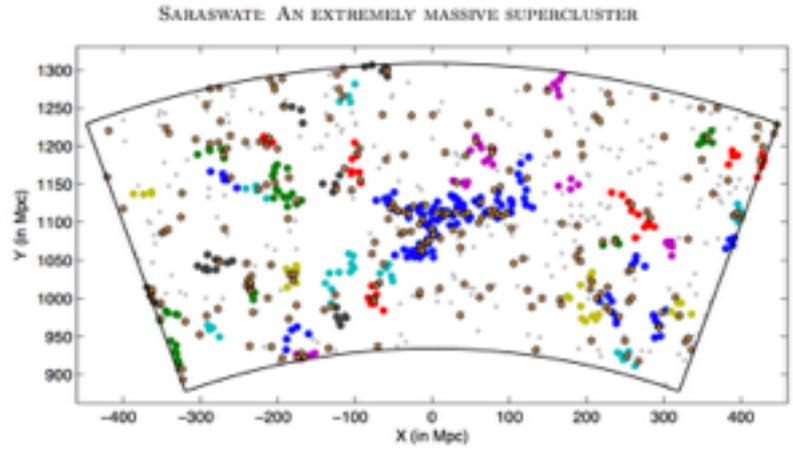
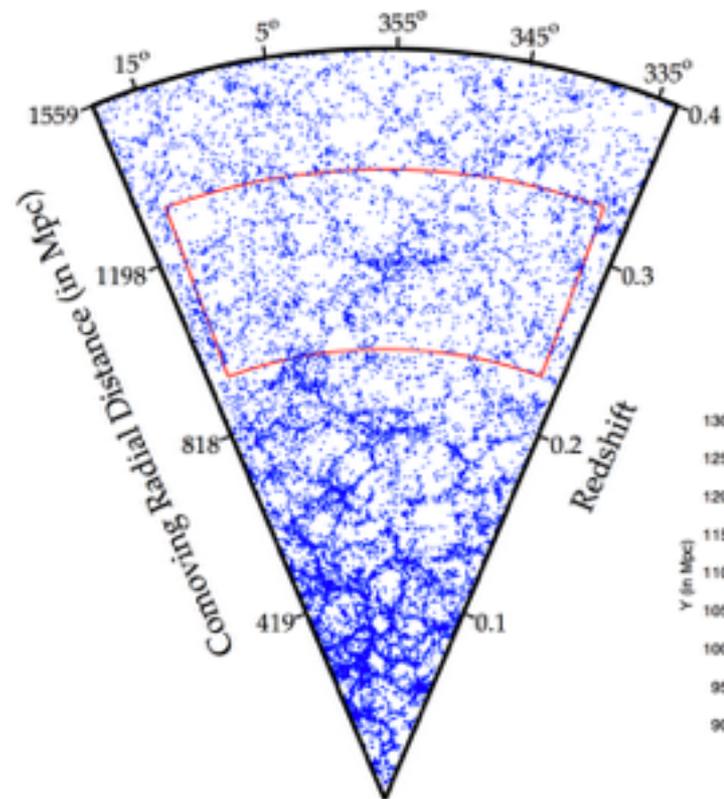
SARASWATI: AN EXTREMELY MASSIVE ~ 200 MEGAPARSEC SCALE SUPERCLUSTER
Saraswati supercluster $z \sim .28$, > Shapley?

Joydeep Bagchi,¹ Shishir Sankhyayan,² Prakash Sarkar,³ Somak Raychaudhury,¹ Joe Jacob,⁴ and Pratik Dabhadre¹

the Indian Supercluster
 $a \sim e^{-0.25} = 1/1.28$



on (88.179, -57.37)



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

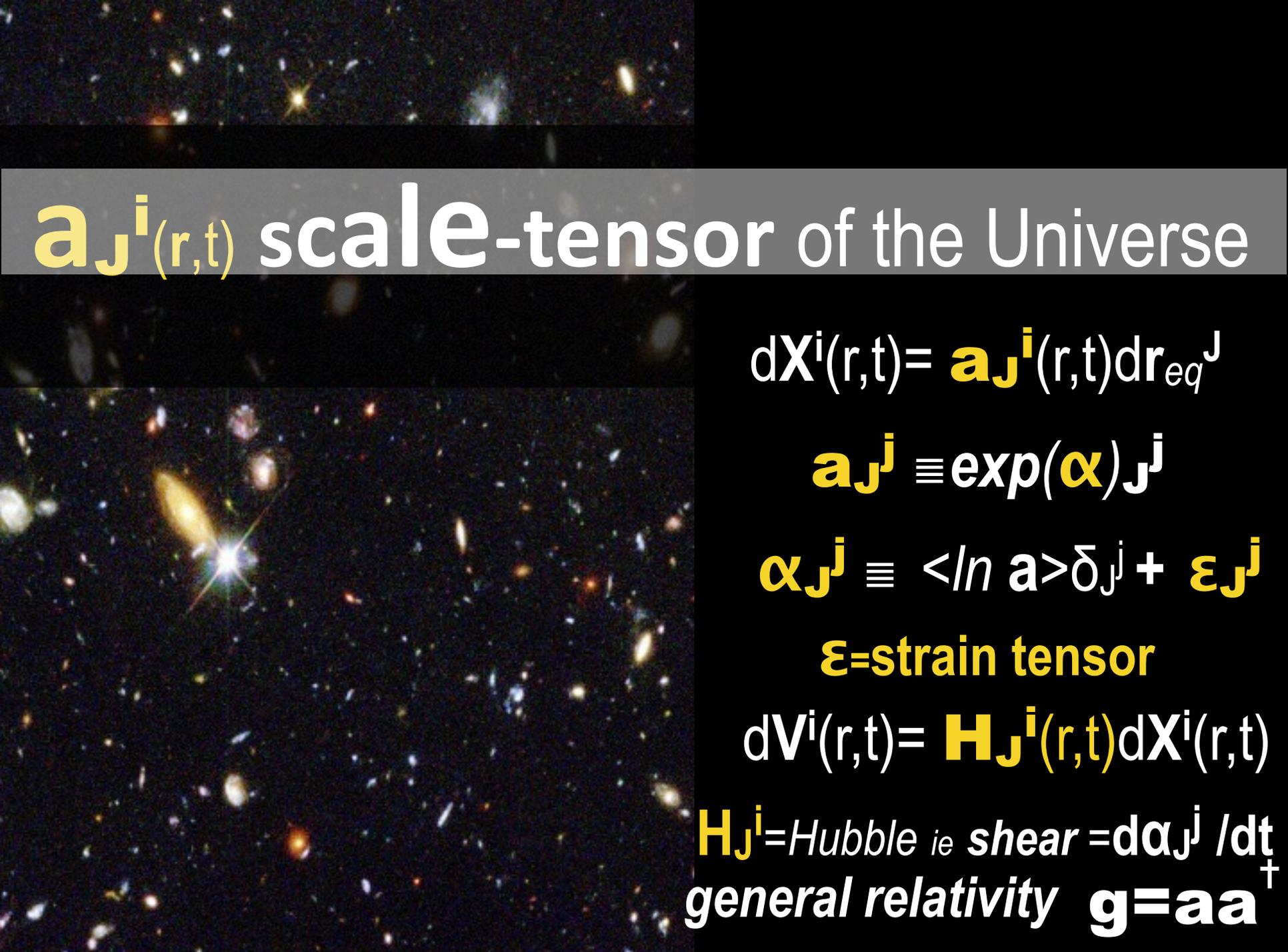
21 \Downarrow 35

Heat: matter & radiation

67

quantum noise

67 \Downarrow 127



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

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

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

$$\boldsymbol{\alpha}_J^j \equiv \langle \ln \mathbf{a} \rangle \delta_J^j + \boldsymbol{\varepsilon}_J^j$$

$\boldsymbol{\varepsilon}$ =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 = $d\boldsymbol{\alpha}_J^j / dt$
general relativity $\mathbf{g} = \mathbf{a}\mathbf{a}^+$

Earth under Strain:
earthquakes, seismic waves

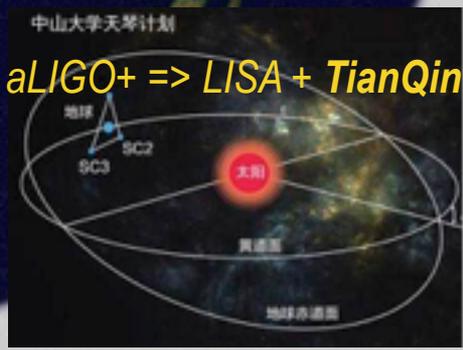
$\boldsymbol{\varepsilon}$ =strain tensor

Universe under Strain:
space-quakes, gravity waves

elastic deformation $d\mathbf{x}^i = \mathbf{e}_j^i dr_{eq}^j$ $e_j^i = a_j^i / \langle a \rangle$
anisotropic strain, shear waves $\boldsymbol{\varepsilon} = \text{Trace}(\boldsymbol{\varepsilon})/3$
isotropic strain, sound $\text{Trace}(\boldsymbol{\varepsilon})$

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

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

$\boldsymbol{\varepsilon}$ =strain tensor

Earth under Strain:
earthquakes, seismic waves

elastic deformation $\mathbf{dx}^i = \mathbf{e}_j^i \mathbf{dr}_{eq}^j$ $e_j^i = a_j^i / \langle a \rangle$

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Universe under Strain:
space-quakes = gravity waves

scale-deformation a_j^i

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

sound speed $c_s^2 = BEM/\rho$ anisotropic shear-wave speed² $\sim SEM/\rho$

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

Gravity: Stress = BAM * Strain-acceleration \sim BAM * Tide

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



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 = $Q_{qfluc}(H) - Q_{qfluc}(H=0)$ drives emergence

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

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

isotropic strain & phonons

$$3\zeta(x,t) = \int_{\text{field-path}} (dE + pdV) / (E + pV)$$
$$= \text{Trace } \alpha_j^i + \int_{\text{field-path}} d \ln \rho_{Ec} / (1 + w_c)$$



energy-density & gravity are entangled
combined **entropy-like measure** ζ = inflaton

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

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

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

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

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?

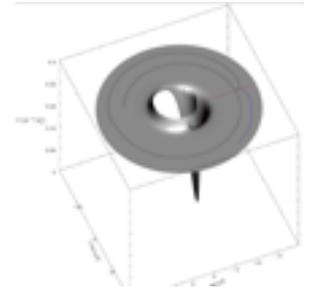
Relate to standard model? to Higgs?

conformal potential-flattening eg Higgs inflation SBB89 etc

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

$\varphi_C, \chi_C, \dots, \alpha_C, H_C$

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



Preheating After
 Roulette Inflation

$\langle \tau \rangle =$

$\hbar H_C$
 quantum
 diffusion
 spatial jitter

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

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

isocon directions,
 e.g., axion

let there be
 heat

SEMIFUNCTIONAL INFLATION-ONCE

B2FH, b+braden+frolov+huang

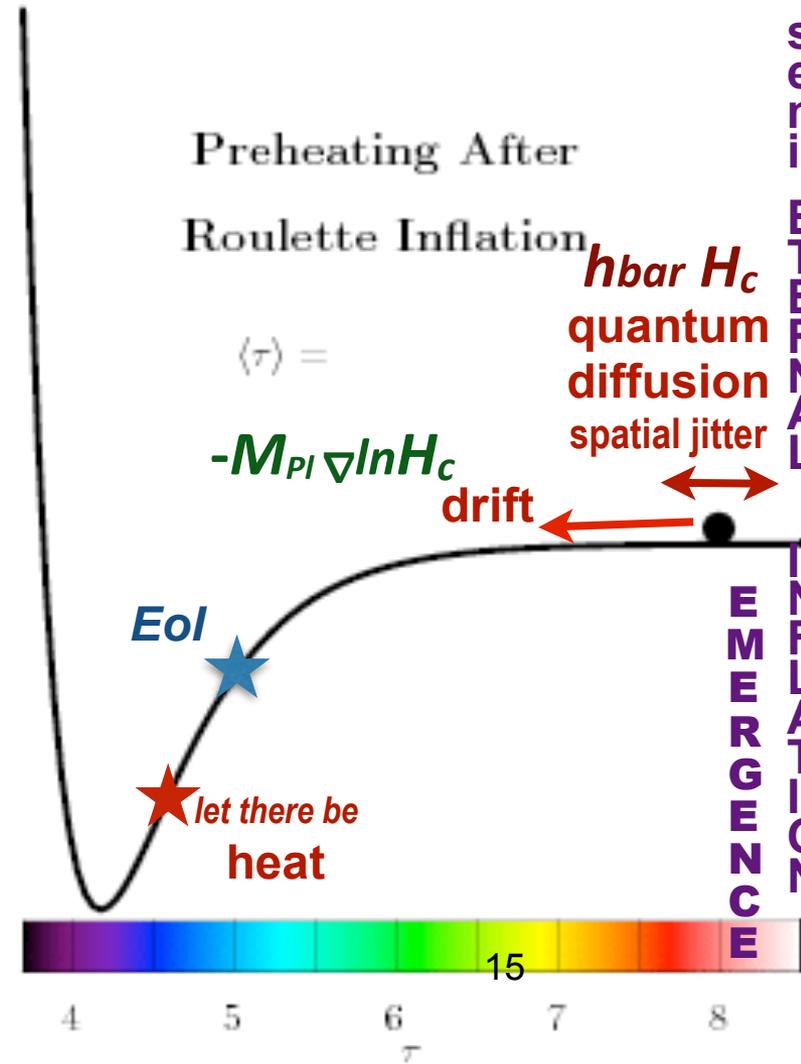
how was *matter & entropy* generated at the end of acceleration = inflation?

Relate to standard model? to Higgs?

$$a = 1$$

A visualized 2D slice
in lattice simulation

Eol horizon ~ 1cm comoving



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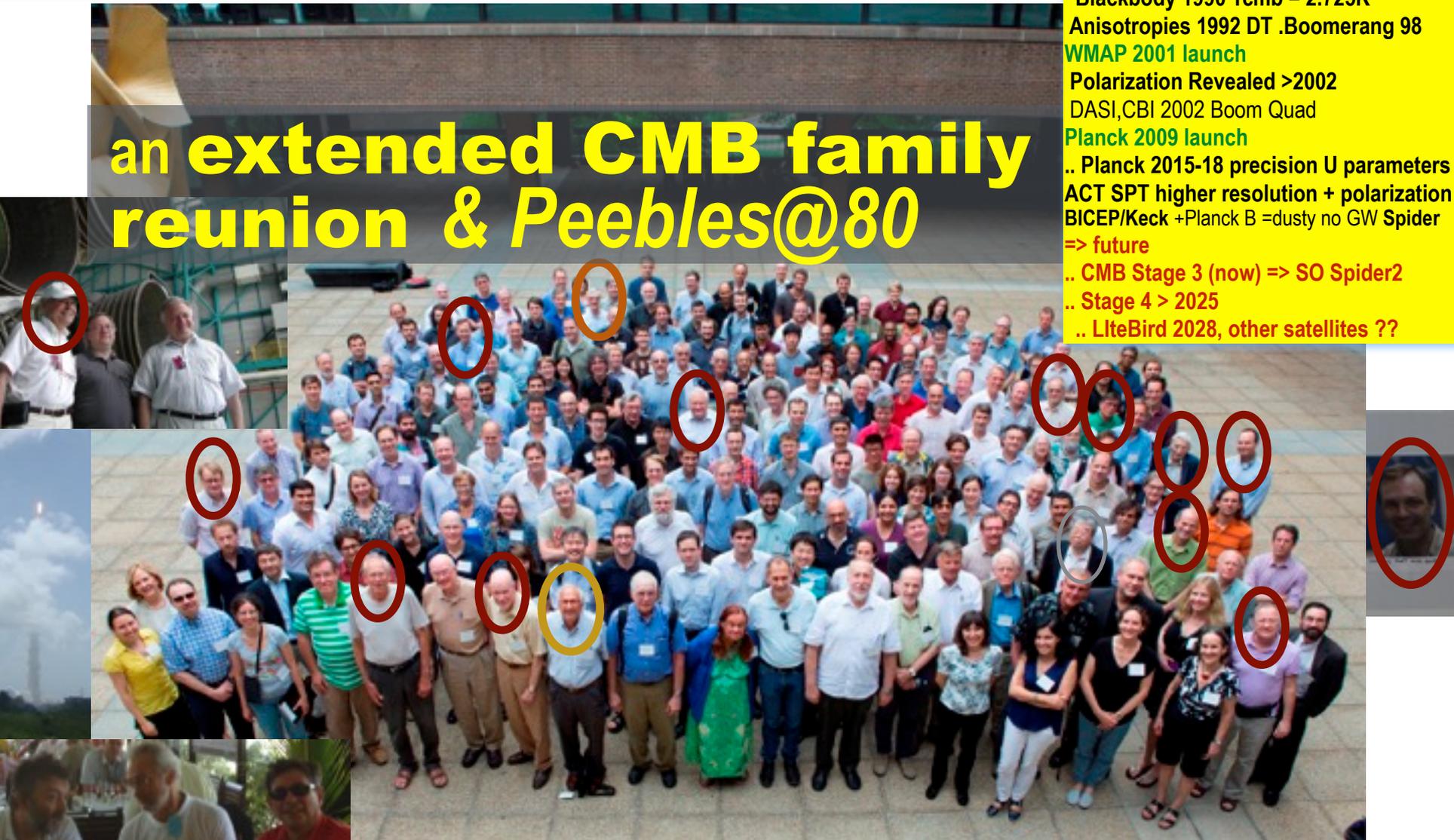
=> future

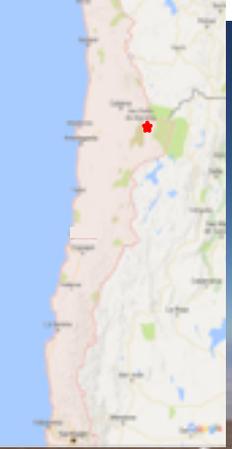
.. CMB Stage 3 (now) => SO Spider2

.. Stage 4 > 2025

.. LiteBird 2028, other satellites ??

an extended CMB family reunion & Peebles@80





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



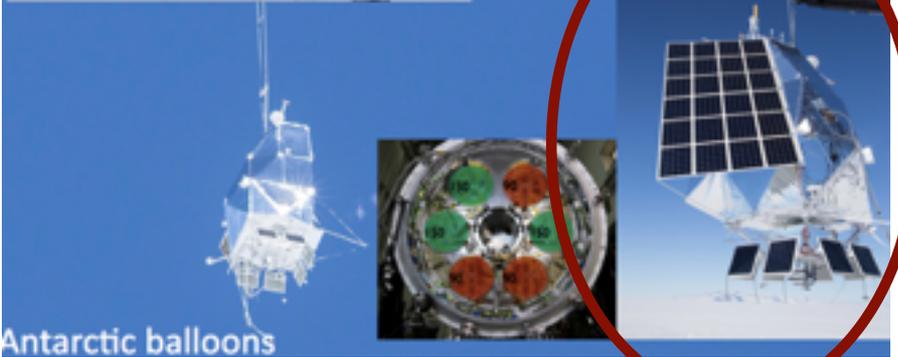
California+ South Africa
C-BASS 5 GHz



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



California
B-Machine 40 GHz



Antarctic balloons



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

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

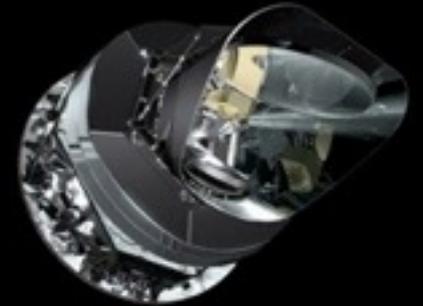
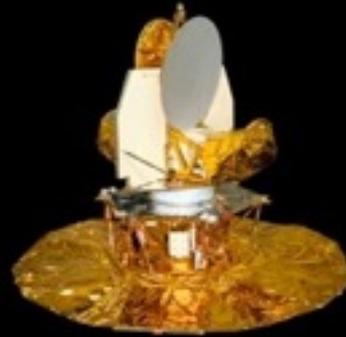


Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch

WMAP 01 launch

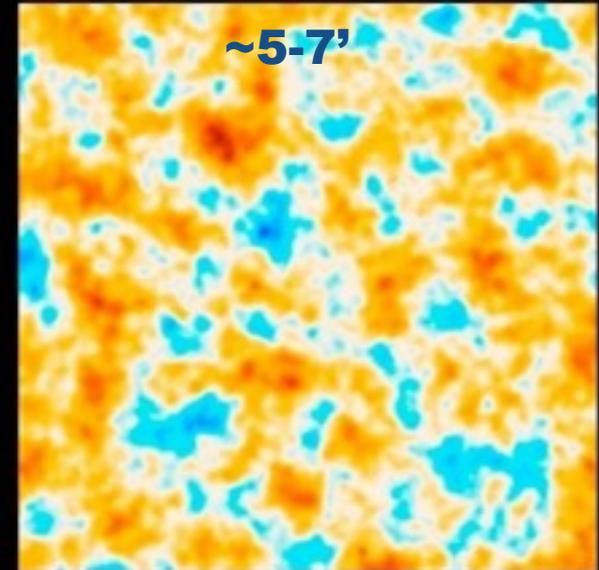
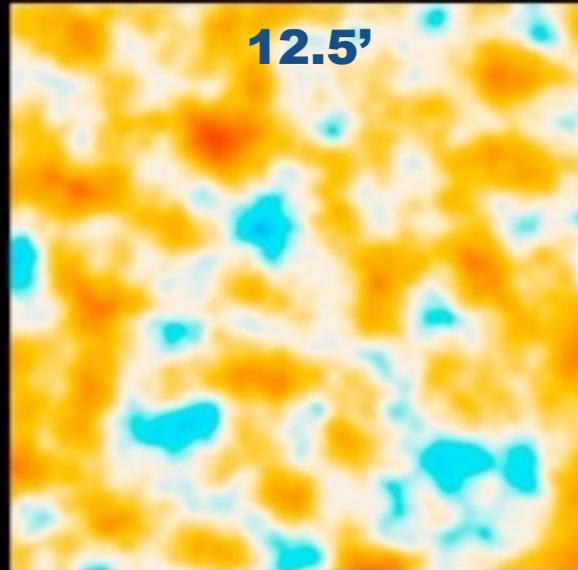
Planck 09 launch



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')

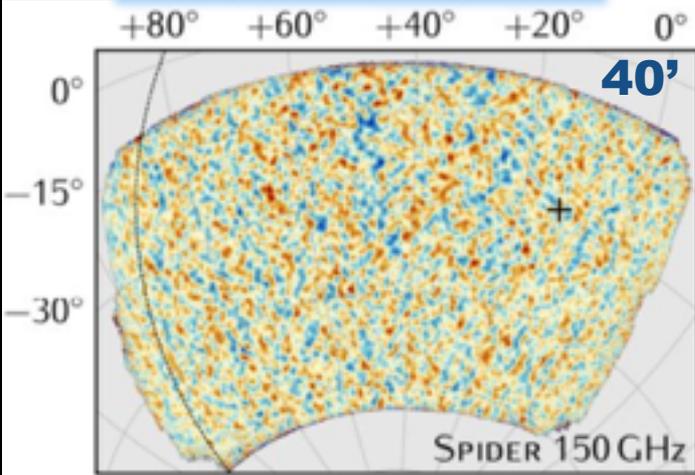
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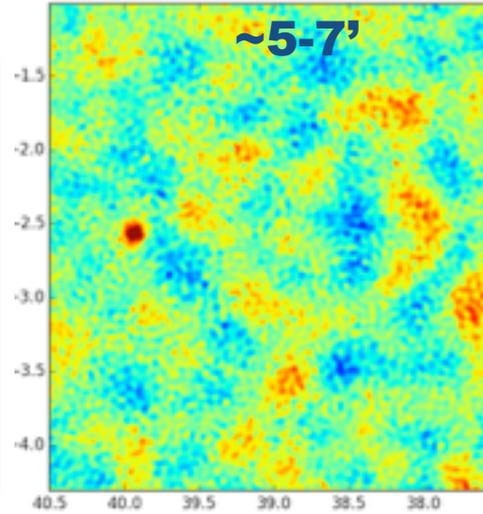
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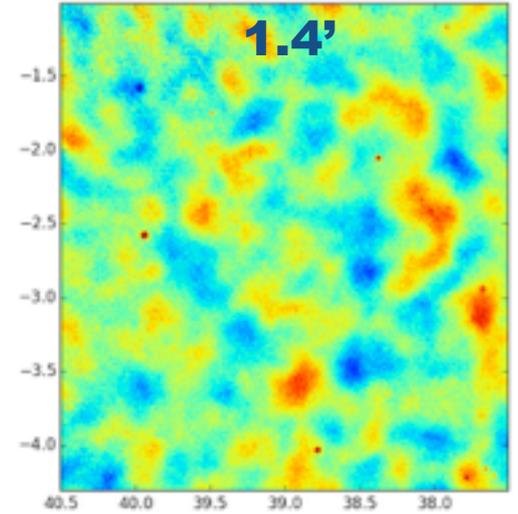
Spider 40' fsky~.08



**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



~500K detectors 10 X SO

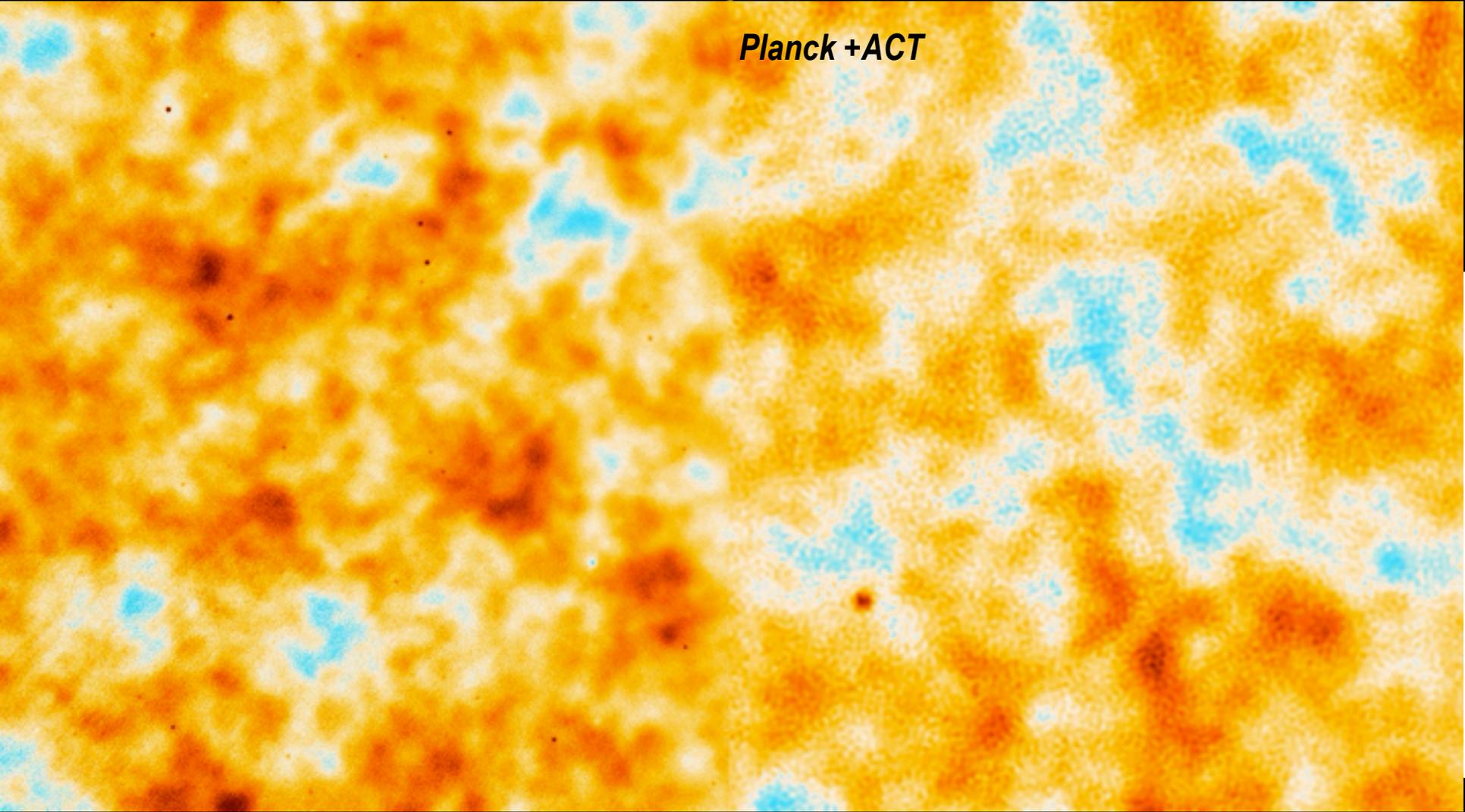
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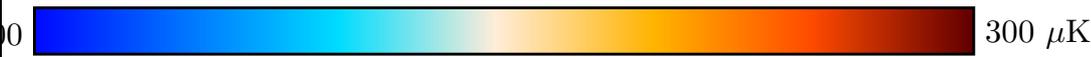
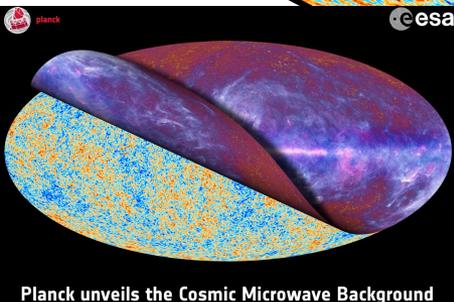
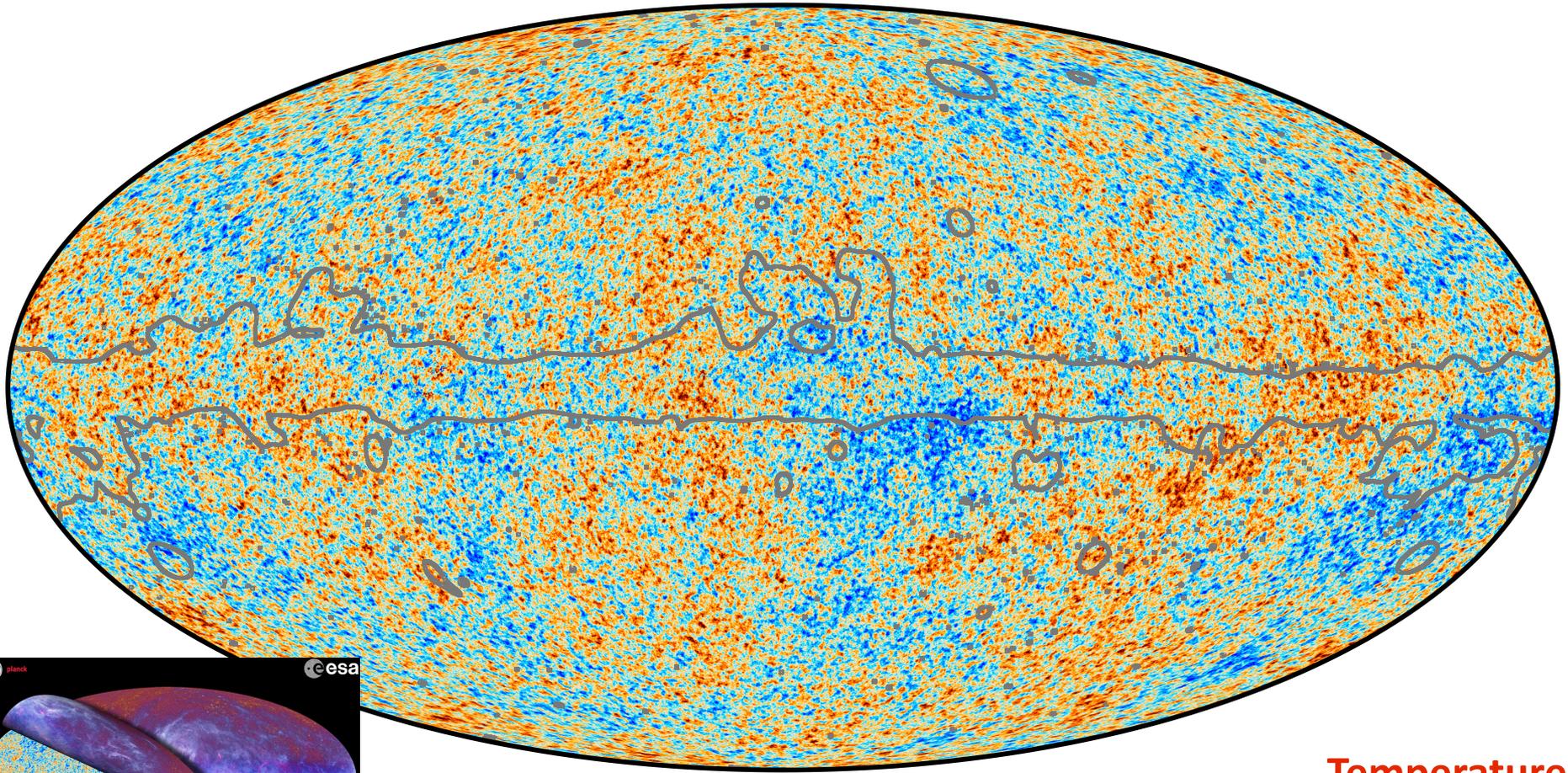


goal: high enough resolution to plumb all cosmic parameter information. but high L foregrounds, extragalactic sources => higher L expts ACT (1.4'), SPT (1') => SO/S4 (1')

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



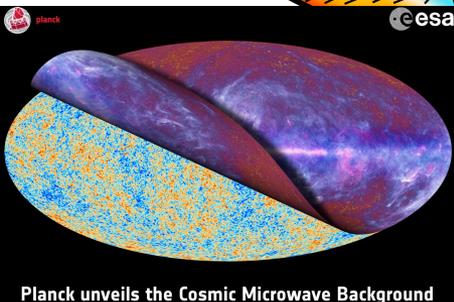
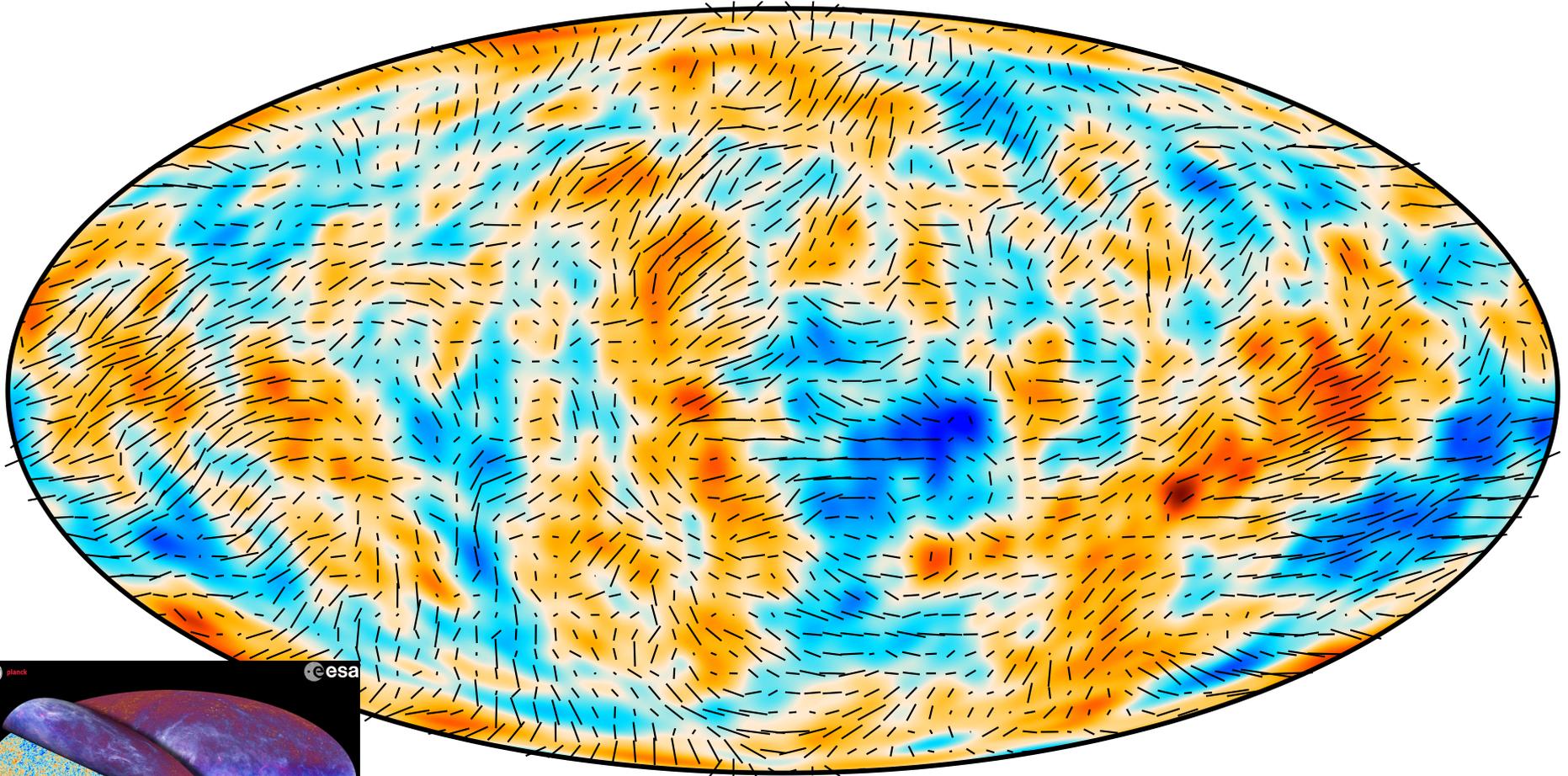
**Temperature
changes in
micro-degrees**

Planck unveils the Cosmic Microwave Background

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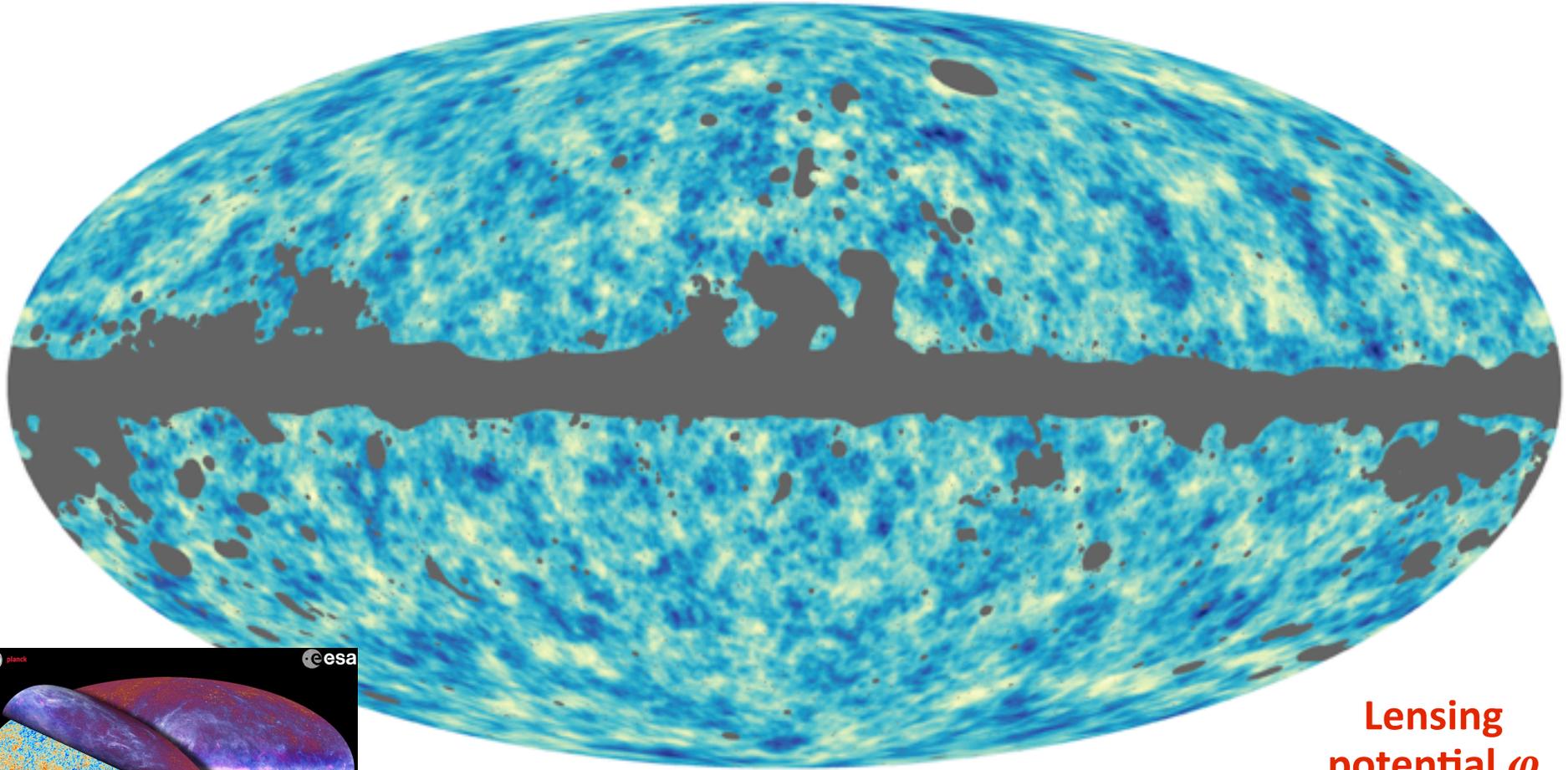


**Polarization
on T**

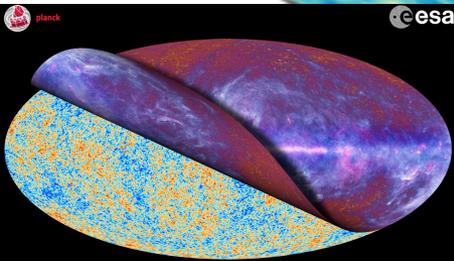
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Lensing potential ϕ



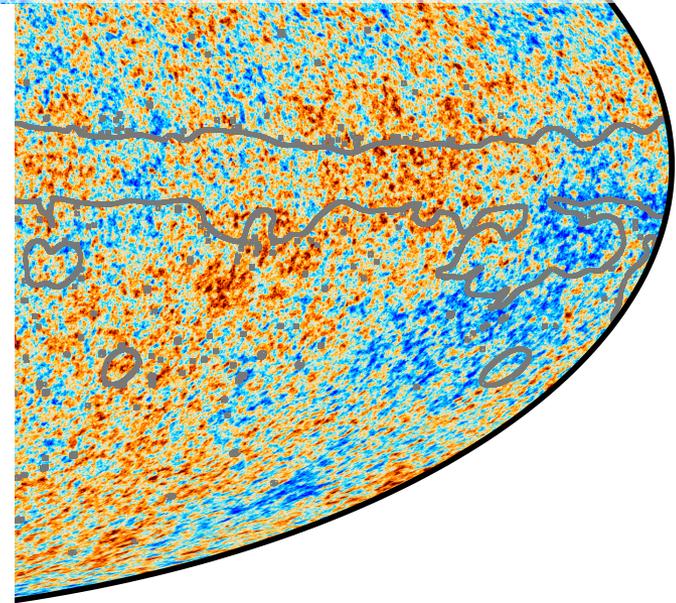
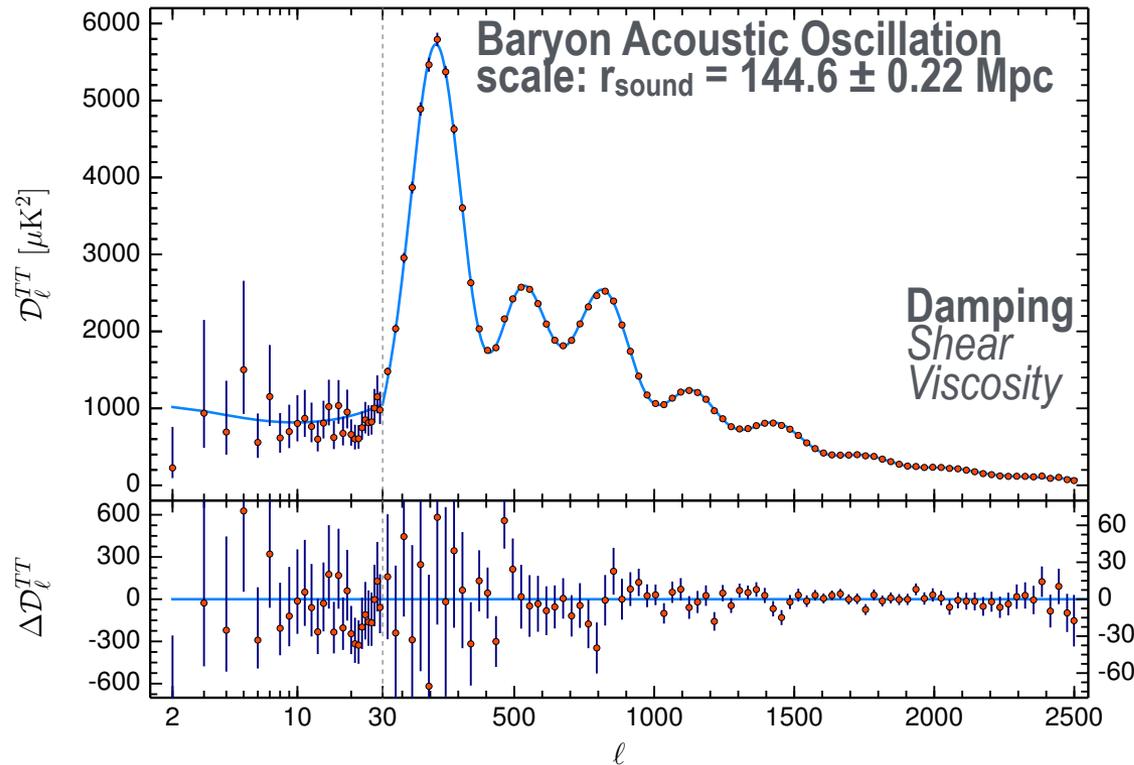
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harmonic analysis of the 'music of the spheres'
=> *inharmonious, coloured noise in the CMB*



300 μK

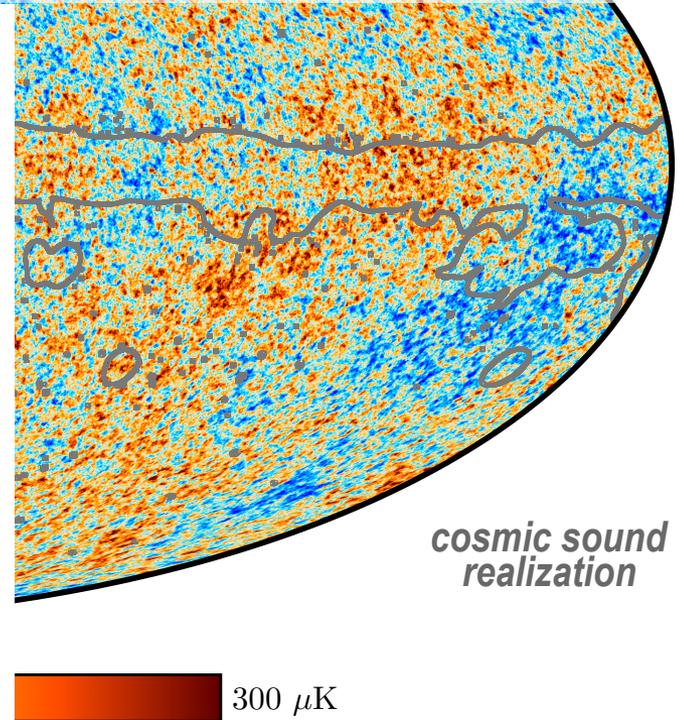
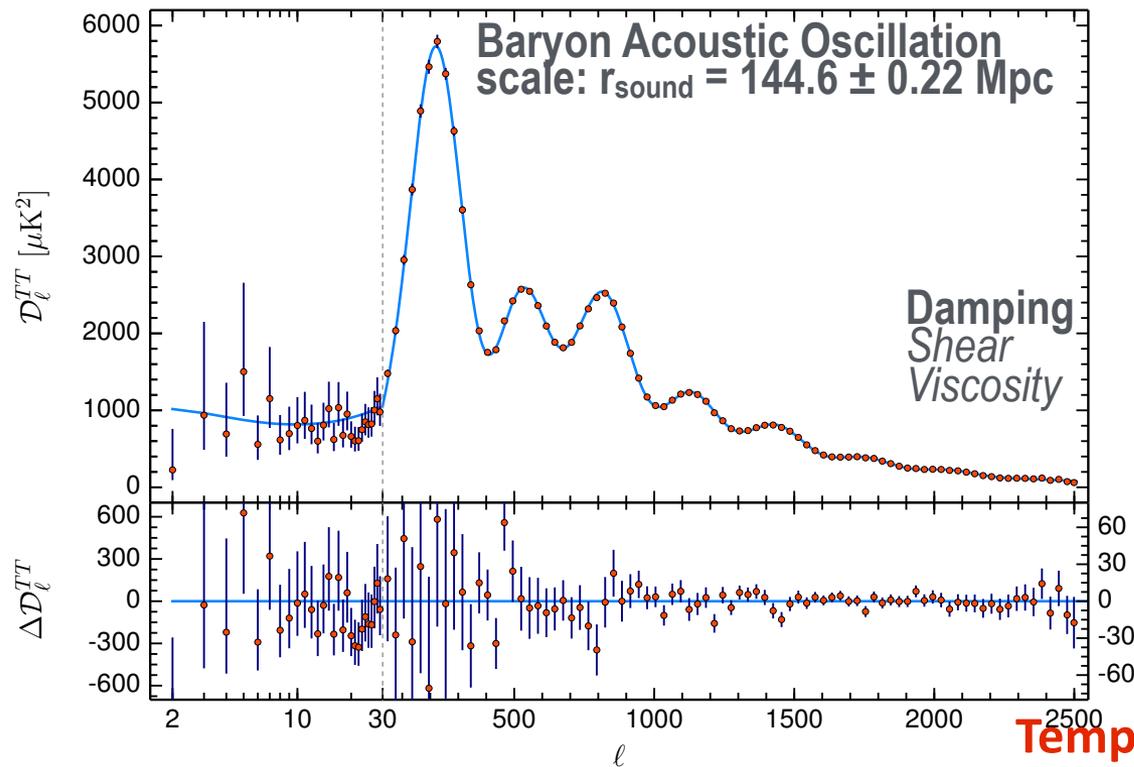
structure changes in micro-degrees

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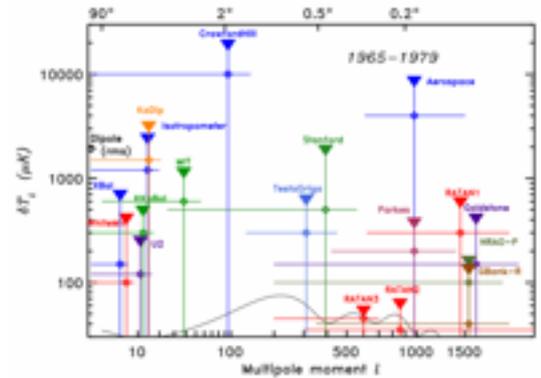
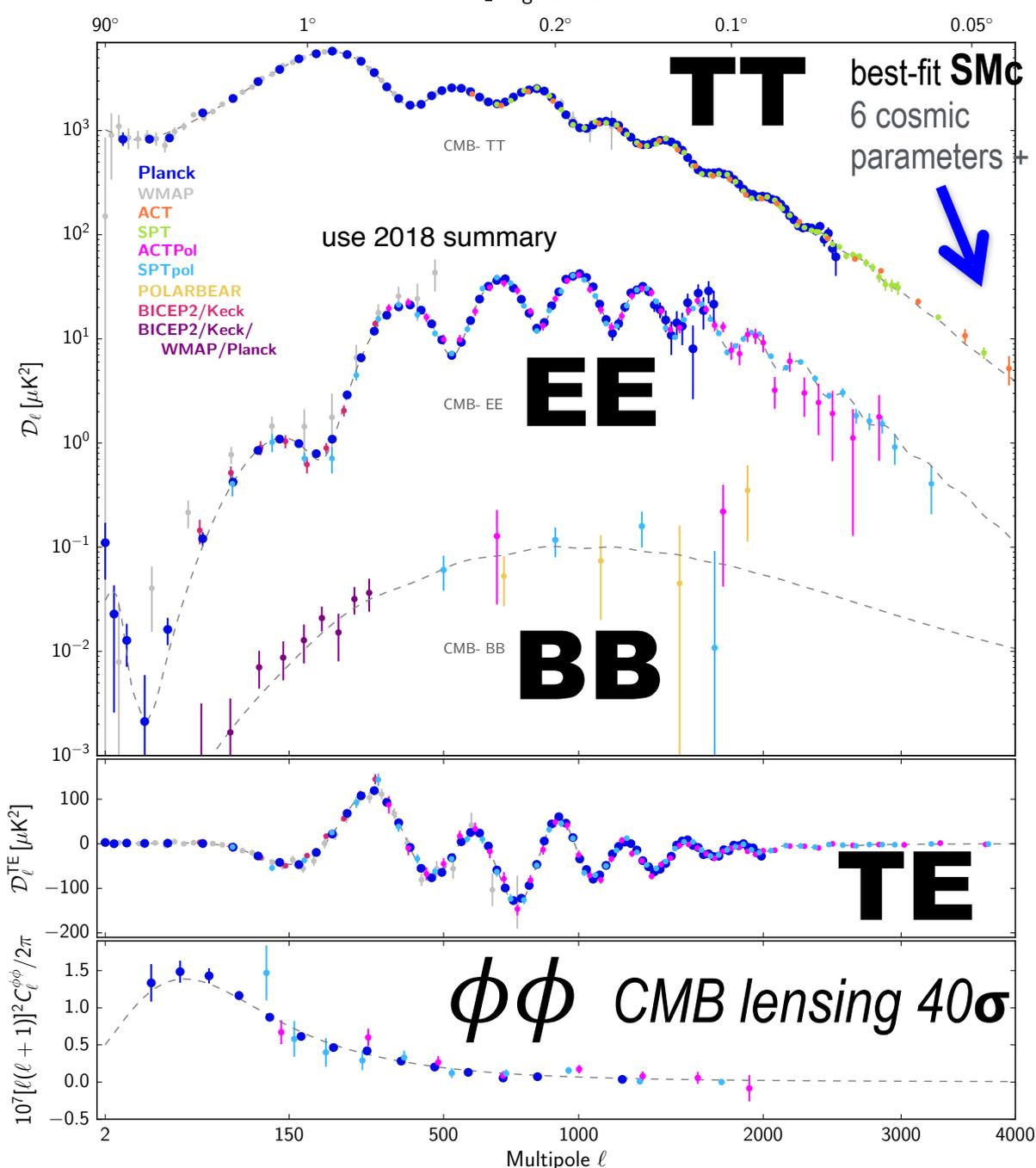
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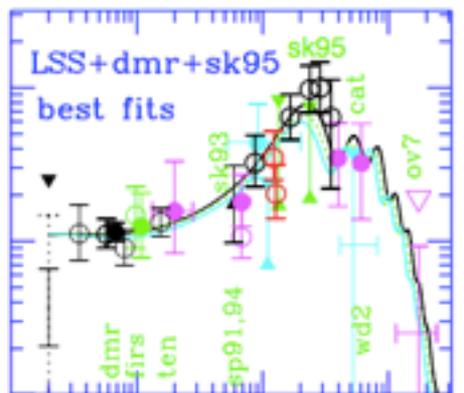
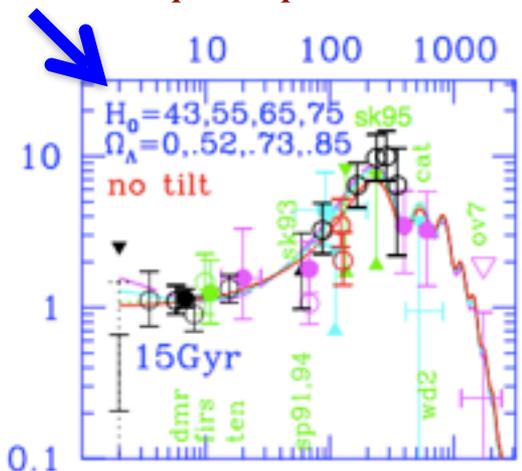


Temperature changes in micro-degrees

Grand Unified CMB Spectra



JRB@Capri 1993 Bandpowers cf. theoretical power spectra



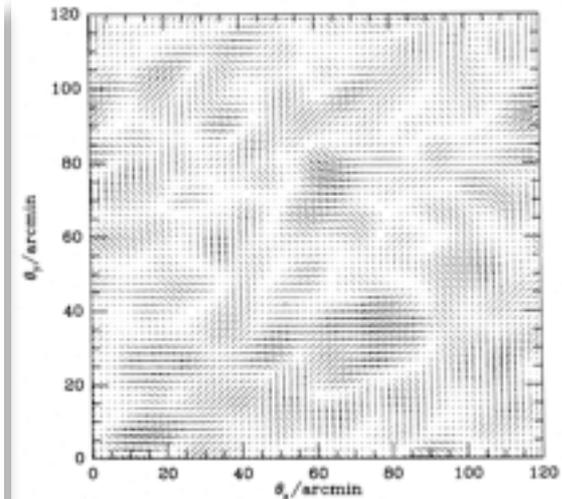
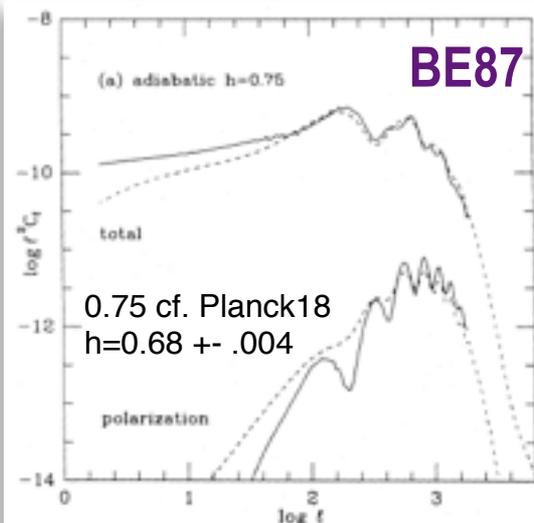
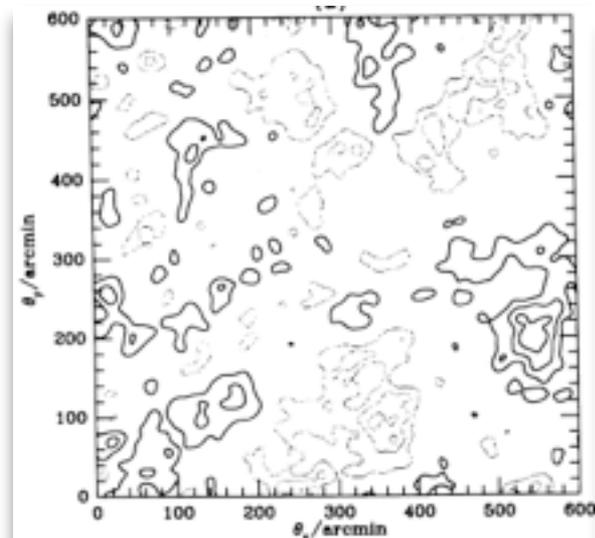
Delta T over Tea Toronto May 1987: first dedicated CMB conference. exptalists+theorists. primary+secondary $\Delta T/T$

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



Delta T over Tea Toronto May 1987: first dedicated CMB conference. exptalists+theorists. primary+secondary $\Delta T/T$

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

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

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

Starobinsky 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

CMB CMB ⊕ LSS

$$n_s \approx 1 \pm .05$$

nearly SCALE INVARIANT FLUCTUATIONS

vintage 1998 conclusions

CMB ⊕ LSS SNIa high z CLUSTERS

↓ $\omega_{CDM} \ll \Lambda_{CDM}$ ↓ ↓

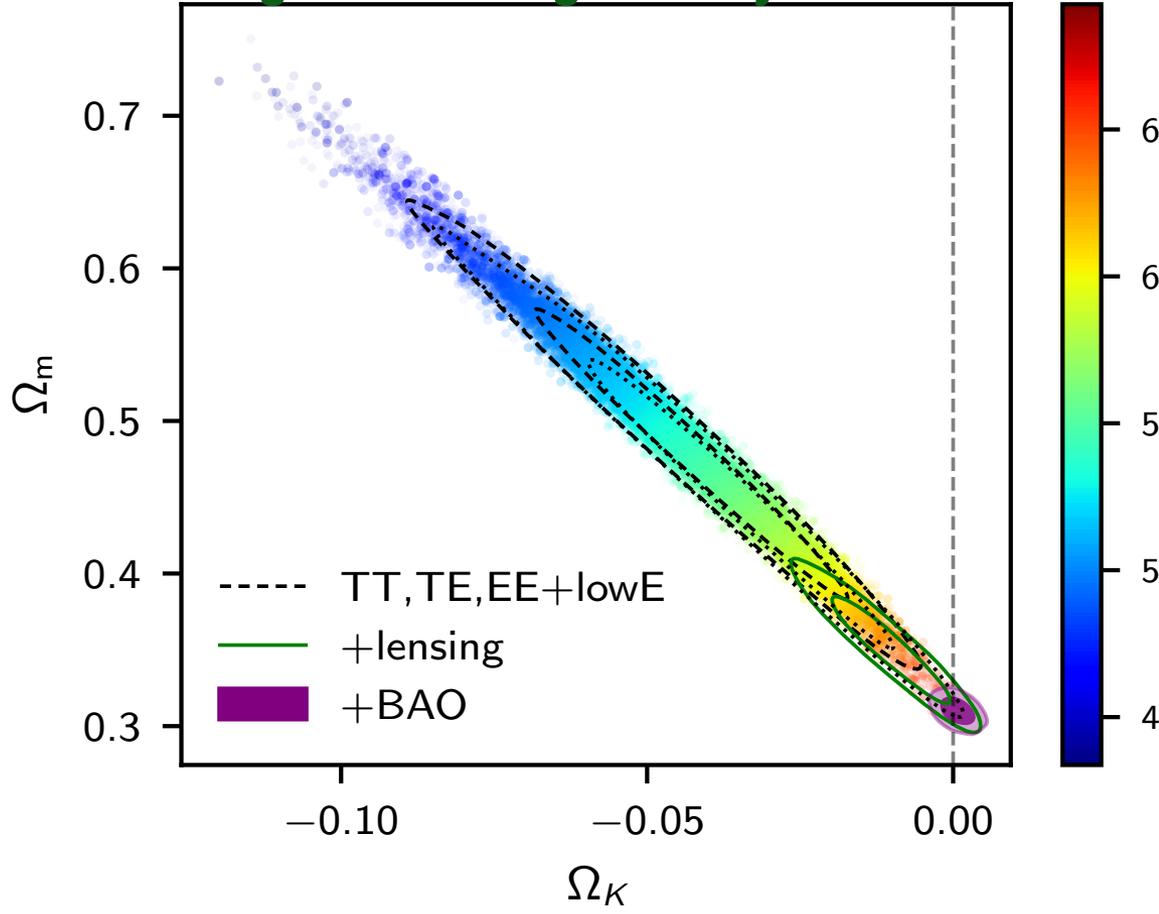
$$\Omega(z, t) \approx \frac{2}{3}$$

Λ
vac
PLATE TIME

INFLATION IS NOW

$\rho^{1/4} \sim \text{milli-eV}$

Handwritten notes:
 $\Omega_{dm} \sim 0.3$
 $\Omega_b \sim 0.04$
 $H_0 \sim 65-70$
 $t_0 \sim 12-14 \text{ Gyr}$
 $\Omega_{\nu} \sim 0.0014$
 $(\frac{M_{pl}}{10^2 \text{ GeV}})^2$



$n_s = 0.9665 \pm 0.004$ P18 VI
8.8σ from 1

$\Omega_{\Lambda} = 0.6889 \pm 0.0034$ P18 VI
 $w_0: -1.04 \pm 0.1$
 $\Omega_K: .0007 \pm 0.004$

B+Jaffe '96, '98
 $\Omega_{\Lambda} \approx 2/3 \pm .07$ +LSS
 $n_s = .98 \pm .07$
 $.96 \pm .06$

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

ζ - TOPOGRAPHY & CARTOGRAPHY

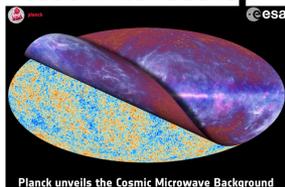
=> @a $\sim 1/10^{55}$ only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

only partial de-lens

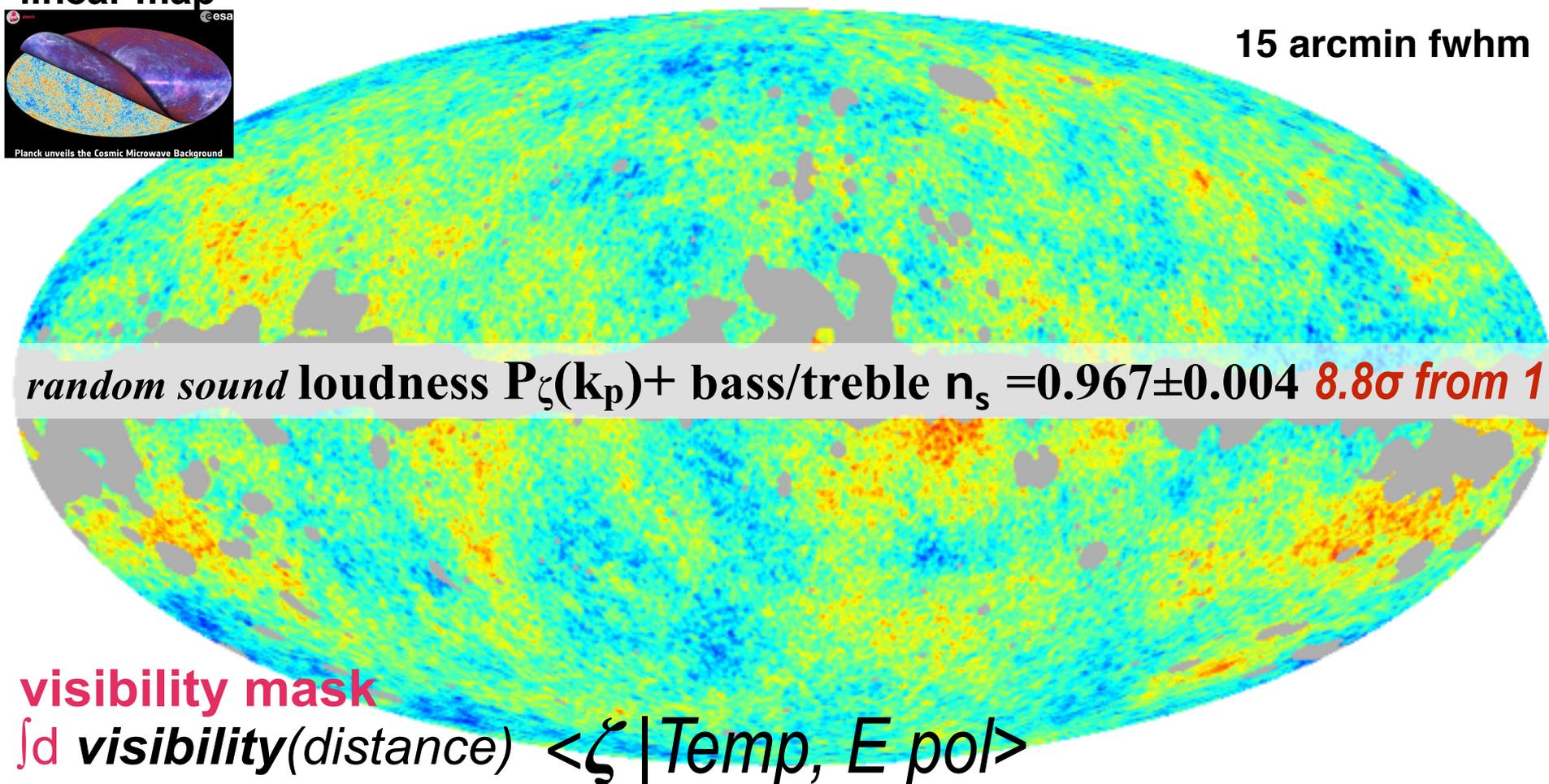
Planck 2018

15 arcmin fwhm

linear map



Planck unveils the Cosmic Microwave Background



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

visibility mask

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

-40.0

+40.0

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

ζ - TOPOGRAPHY & CARTOGRAPHY

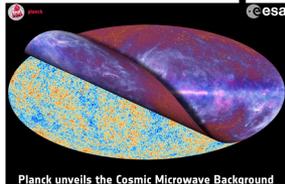
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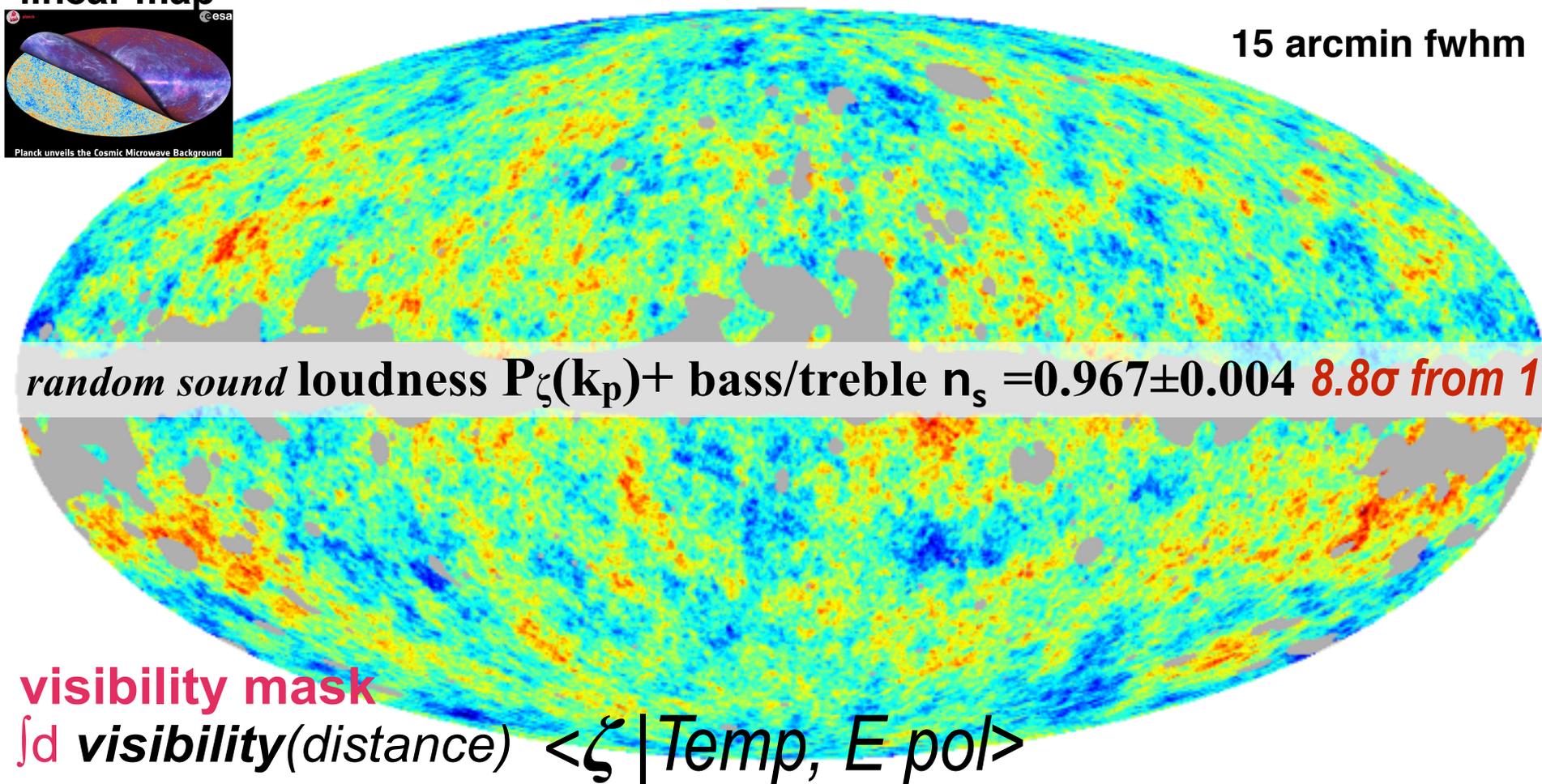
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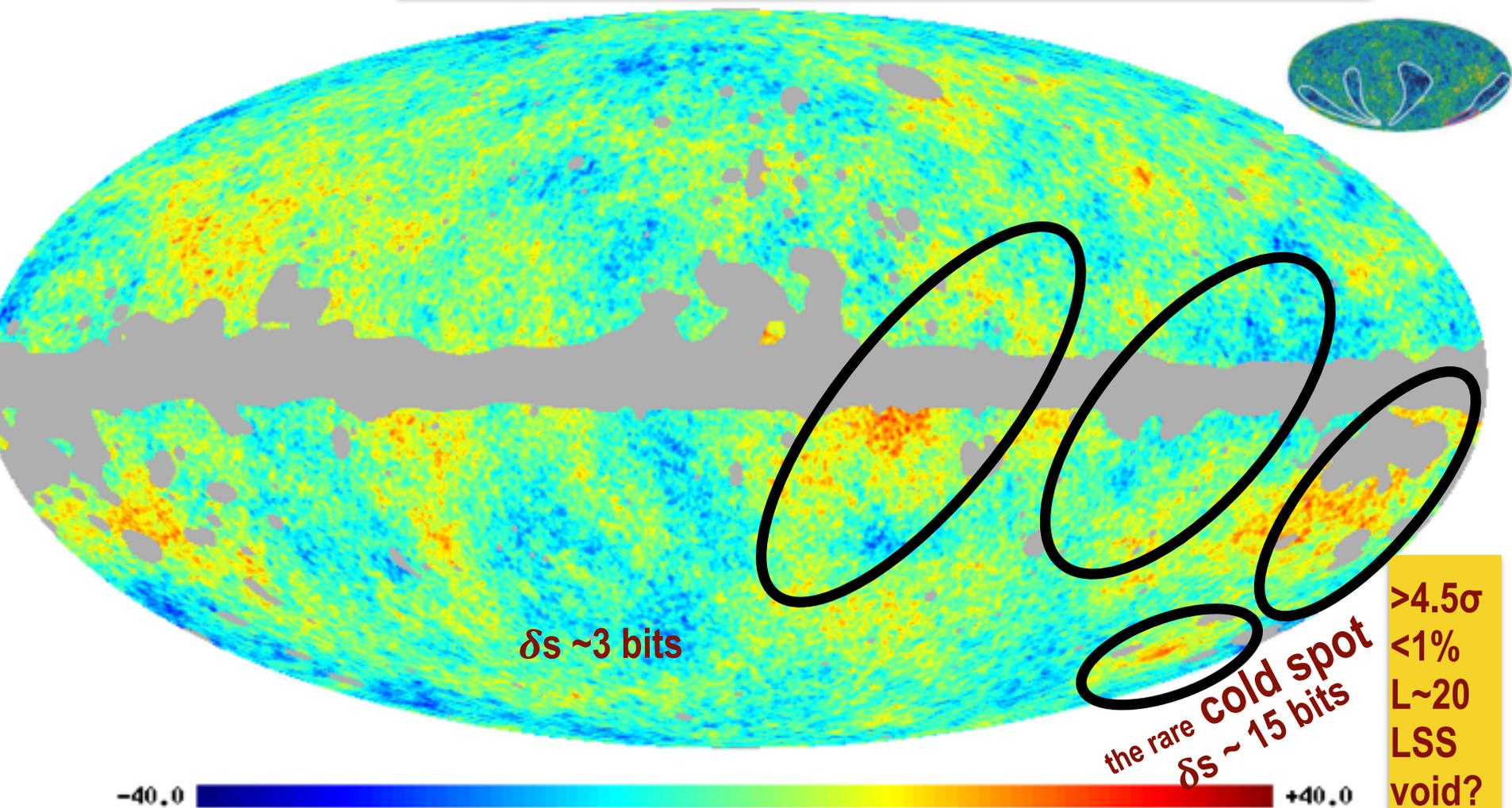


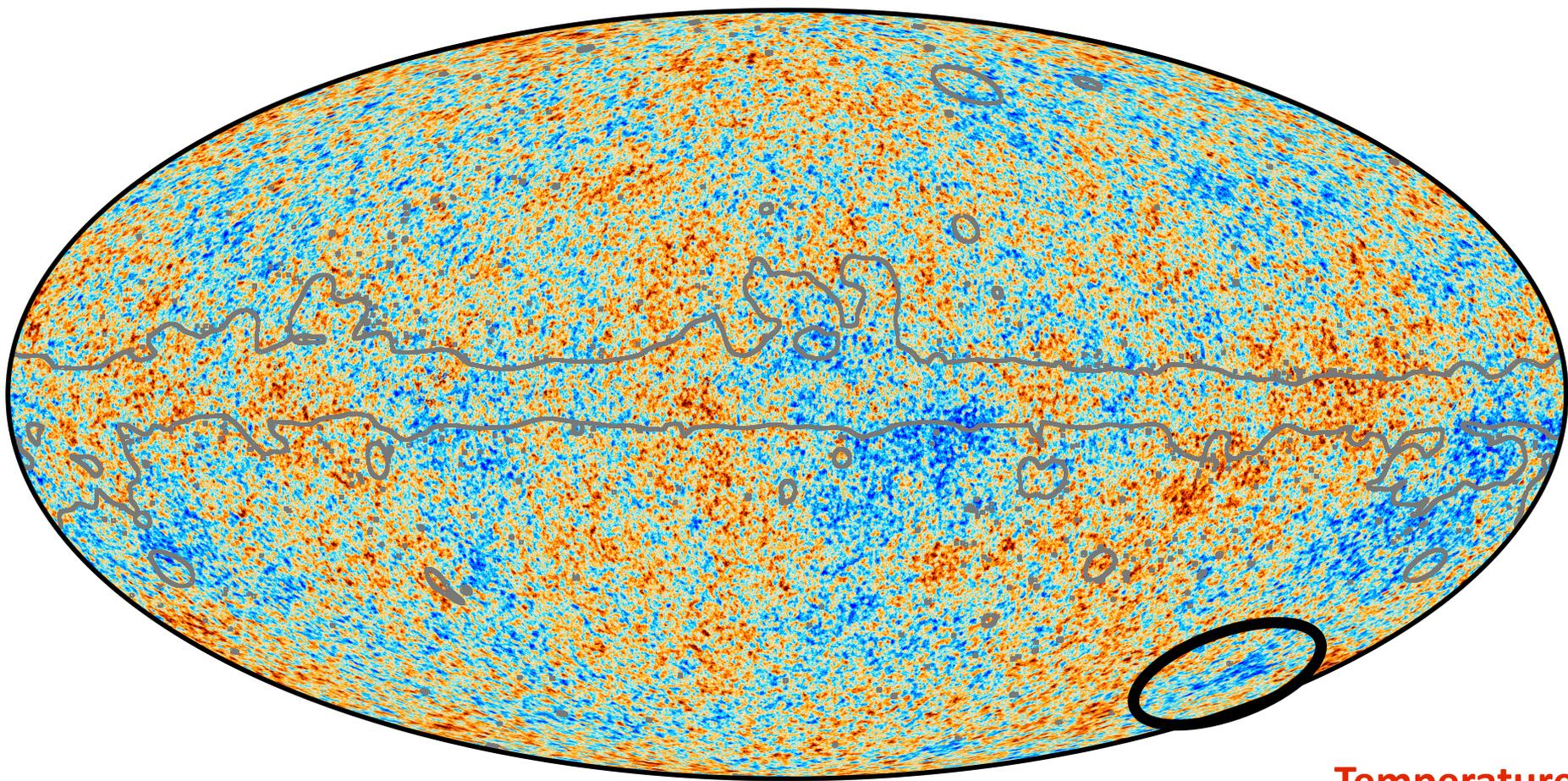
Beyond the Standard Model of cosmology? $\text{SMc} = \text{tilted } \Lambda\text{CDM} + r$ aka (ζ, h_{+x})

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

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

GUTA = Grand Unified Theory of Anomalies?
anomalies @ low L => sample variance limited $\sim 2\sigma$'s
CMB TT power $L \sim 20\text{-}30$ 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 + CMB lens + BK15 BB + BAO

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

uniform $n_s = 0.9669 \pm 0.00367$

P18+BK15 LSS best fit

superb 12-knot fit $k \sim .008$ to $.3$

$$\ell_k \equiv k D_{\text{rec}}$$

$$k D_{\text{rec}} \gtrsim L$$

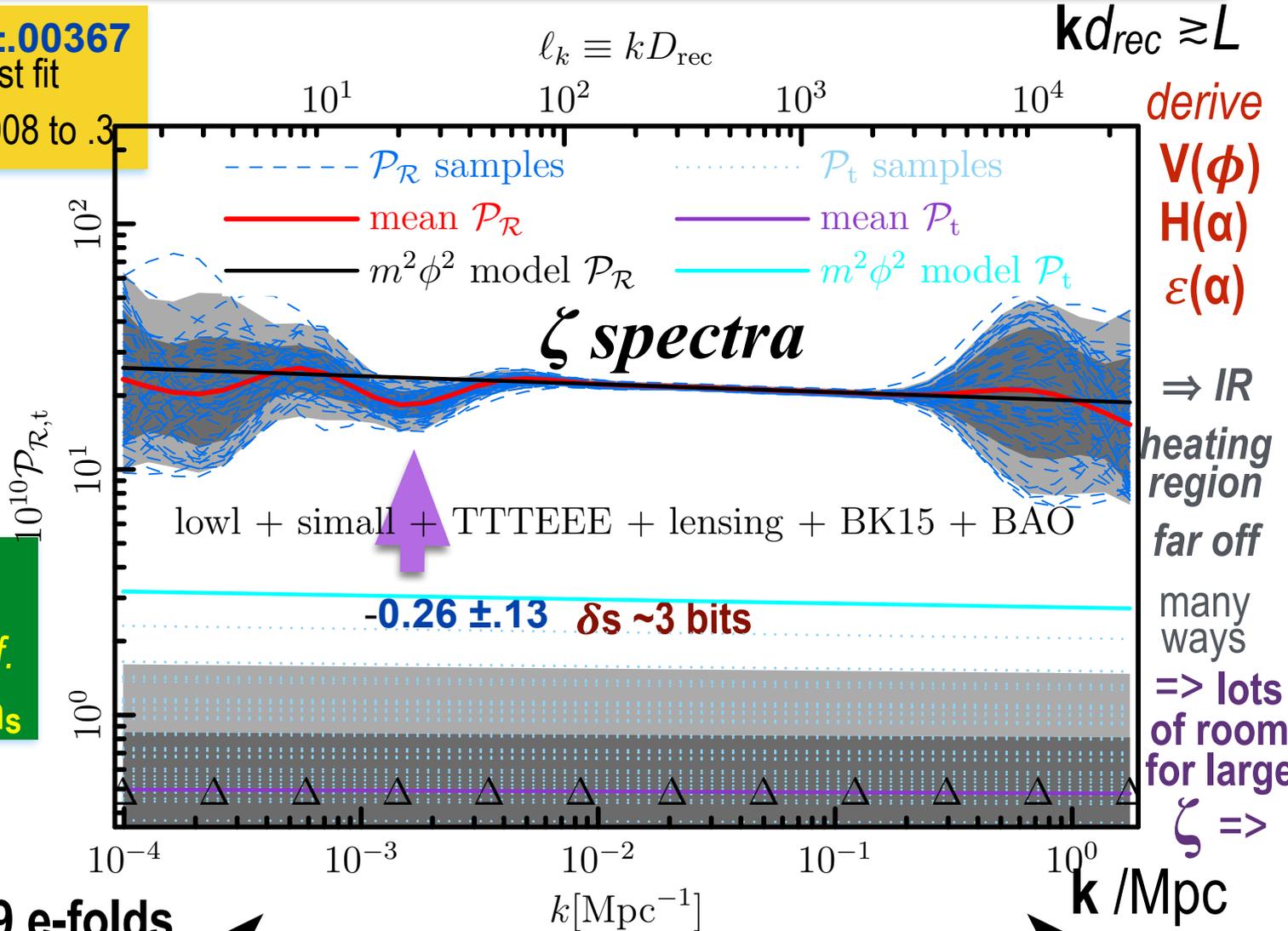
UV \Leftarrow

M_{Planck} region
far off
many ways to
extrapolate

P18+BK15

$r < 0.069$ 95%CL cf.
 $r < 0.061$ uniform n_s

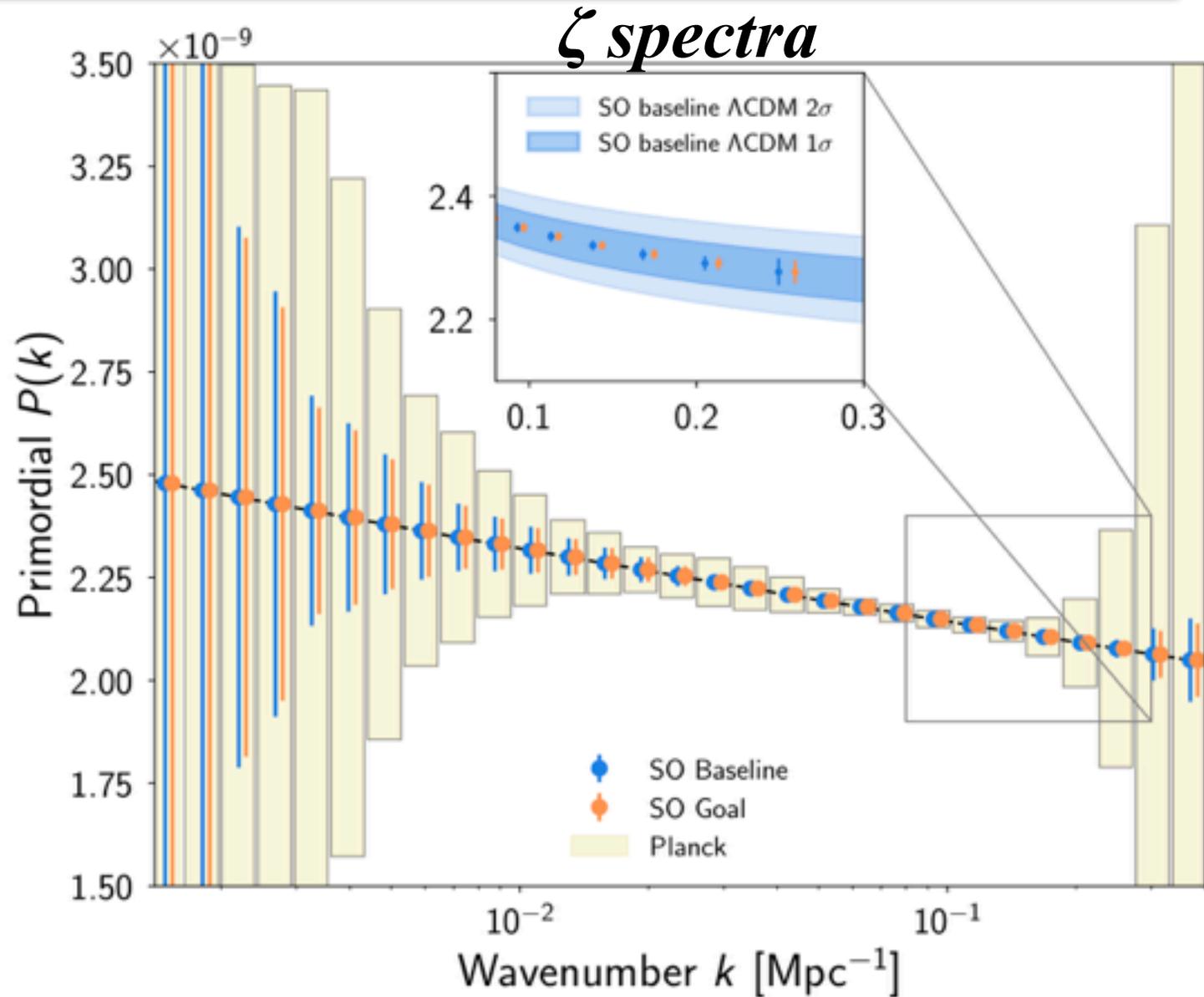
=> $\sigma(r)$
SO 0.003 =>
S4 0.0005
Litebird 0.001



9 e-folds

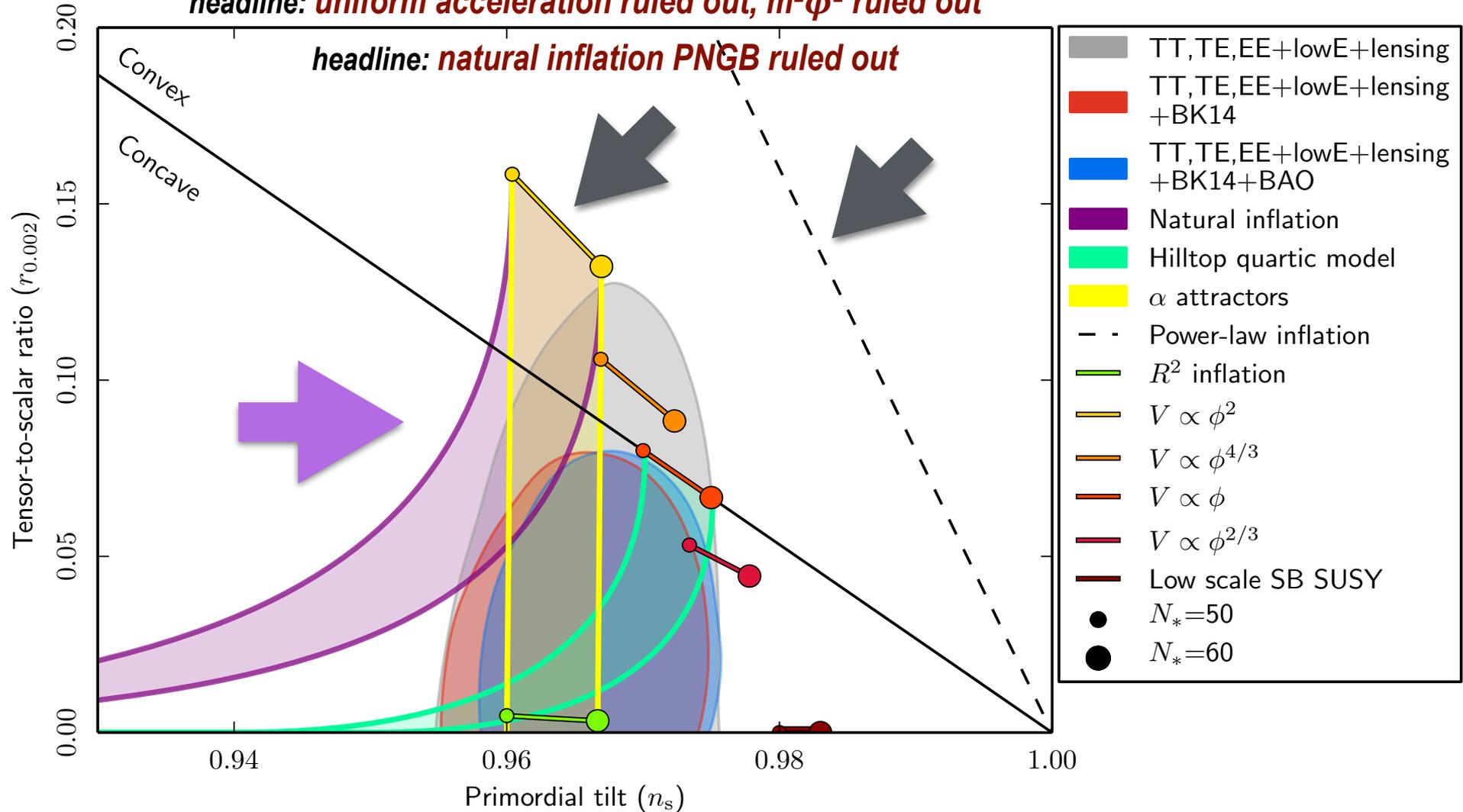
the true quadratic ζ -Websky of the ζ -scape

Sample Cosmological Forecast: Simons Observatory 2021+

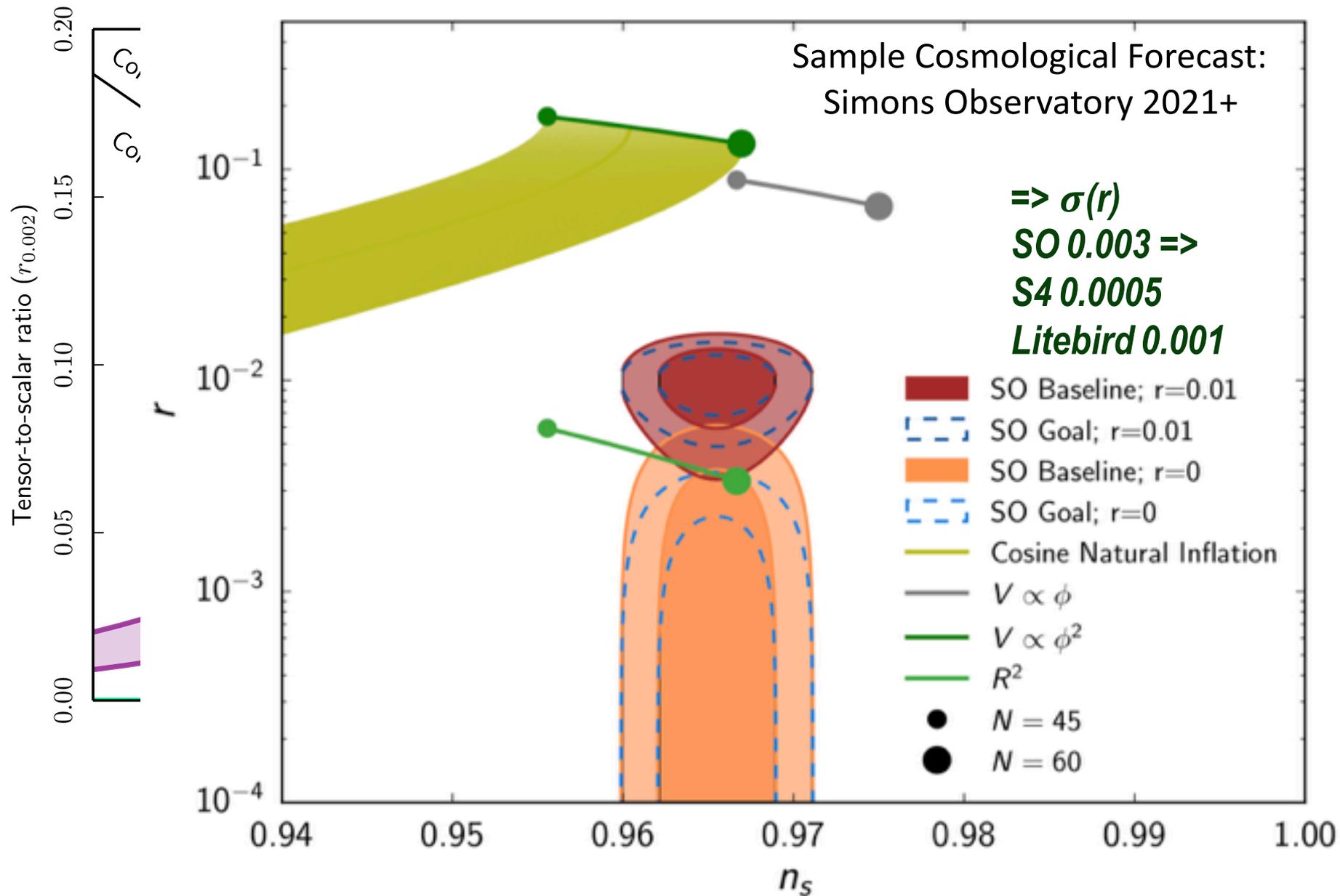


headline: uniform acceleration ruled out, $m^2\phi^2$ ruled out

headline: natural inflation PNBG ruled out



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 $S_{tot} = S_{CMB} + S_{CnuB}$
 $10^{88.6}$*

*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,..
 $26.6 \pm 0.7\%$*

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)
 $68.5 \pm 0.7\%$*



planck

Quantum Inflation in the Planck Era & Beyond



Dick Bond

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

T+E constrained mean of $10^5 \zeta$; $f_{\text{NL}} = 15$ 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

$$\ln 10^{l_0} \text{Power}_s = 3.05 \pm 0.014$$

$$n_s = 0.967 \pm 0.004$$

8.8 σ from 1 most celebrated Planck result

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

$\Rightarrow \sigma(r)$ SimonsO 0.003 CMB S4 0.0005? Litebird 0.001?

CMB+LSS as a fundamental physics laboratory YES

-40.0

+40.0

END