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

Dick Bond

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

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

"To me every hour of the light and dark is a miracle. Every cubic inch of space is a miracle."

– Walt Whitman

IN EVERY teaspoon of air ~5 cubic cm

Ordinary Matter ~amu /nm^3 4.8% O_2 N ; H,He

THE DARK

Dark Matter

~amu /m^3 26.0 ± 1% compressed in MilkyWay ~0.1 amu /cm^3 ;
for LHC@CERN-type relics ~ 1 every 10 cm

Dark Energy

~vacuum potential ~ 3 amu /m^3 69.2 ± 1.0%

THE LIGHT

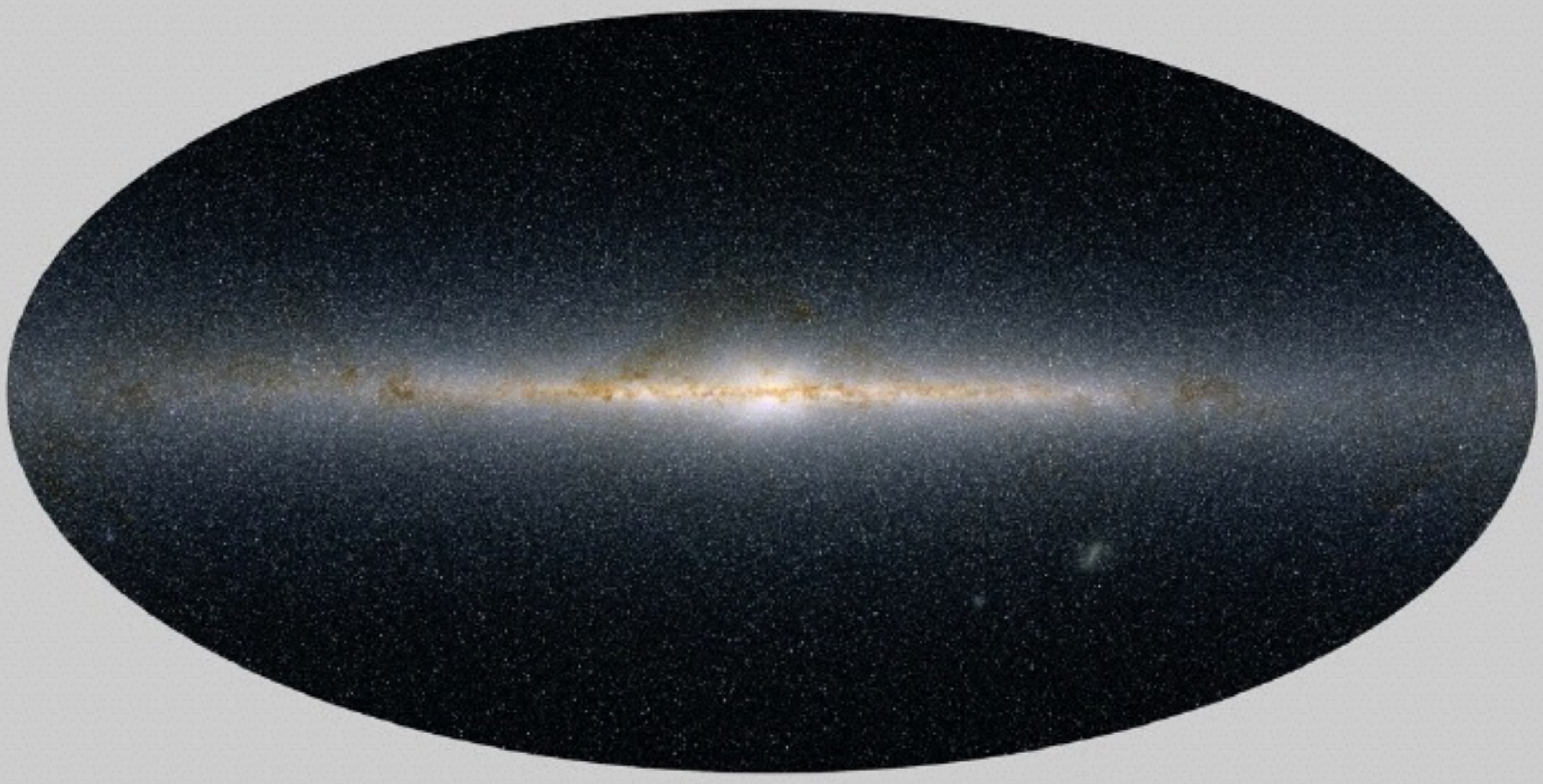
cosmic radiation

the 1st light of the universe 412 /cm^3 0.005%
cosmic neutrinos ~cosmic photons > 0.47%
cosmic gravity waves << cosmic photons

THE VACUUM

Higgs@CERN vacuum origin of mass
vacuum fluctuations origin of all the cosmic structure we see
the vacuum is under gravitational strain, differentially accelerating

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



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

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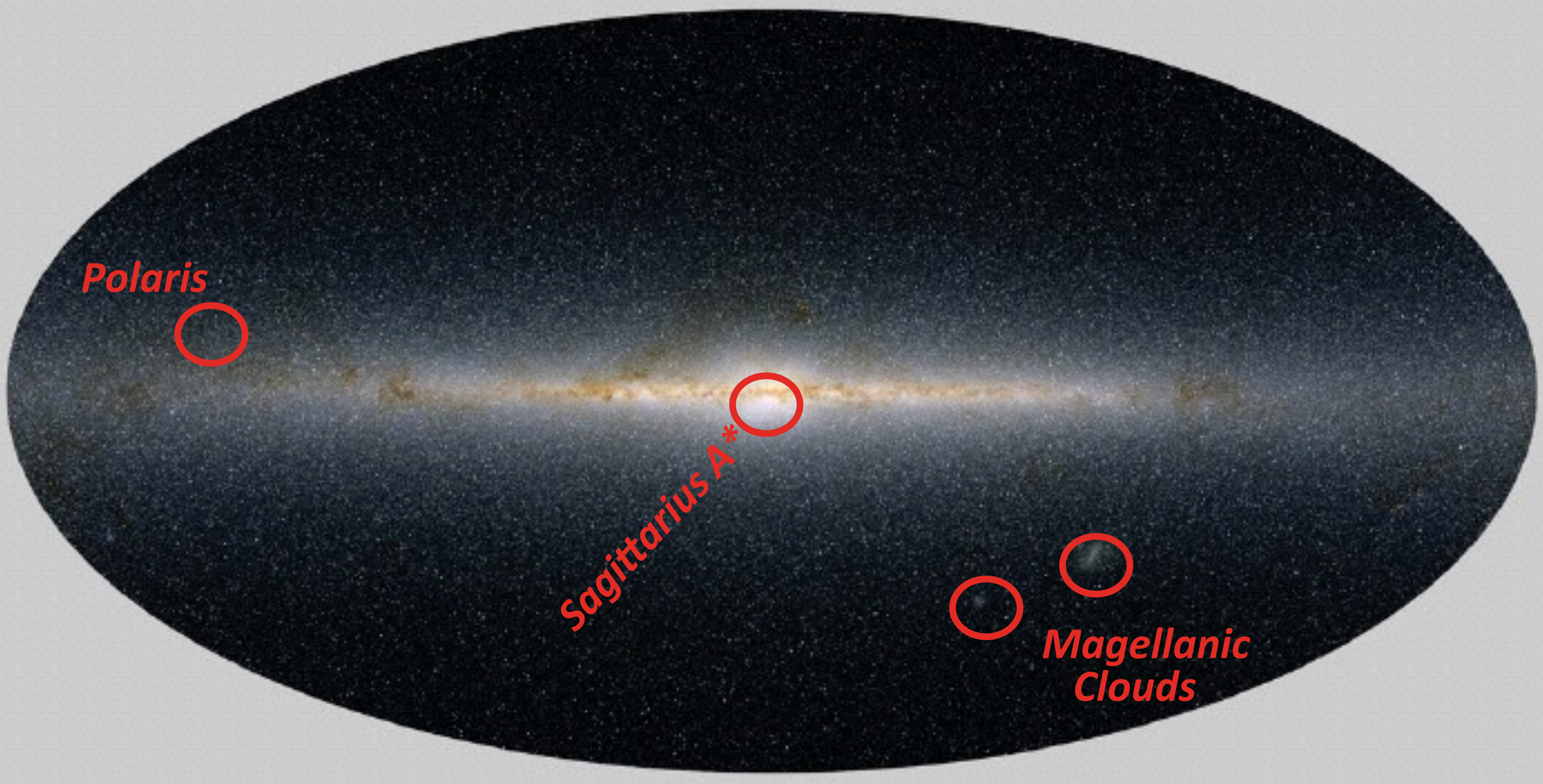
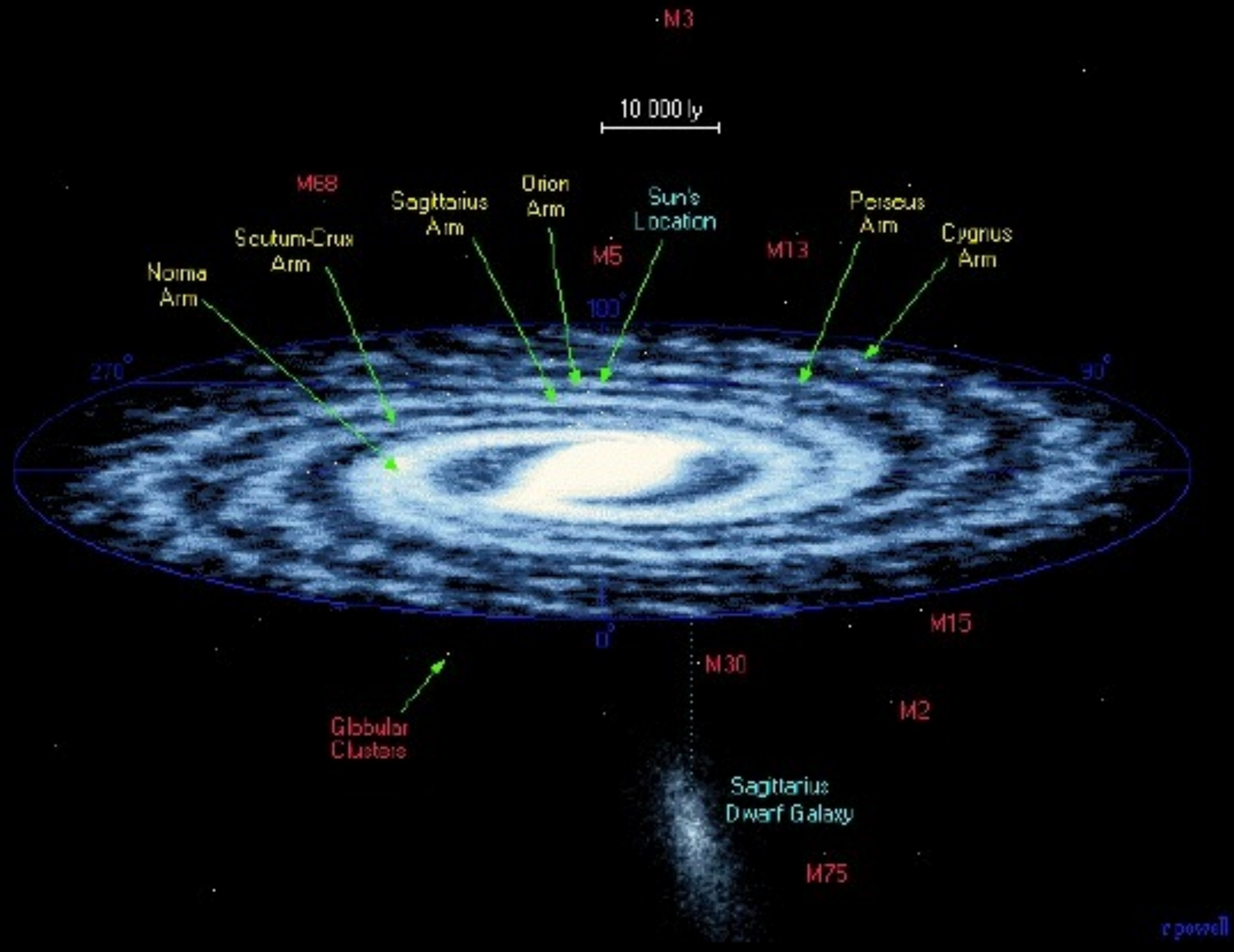


Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

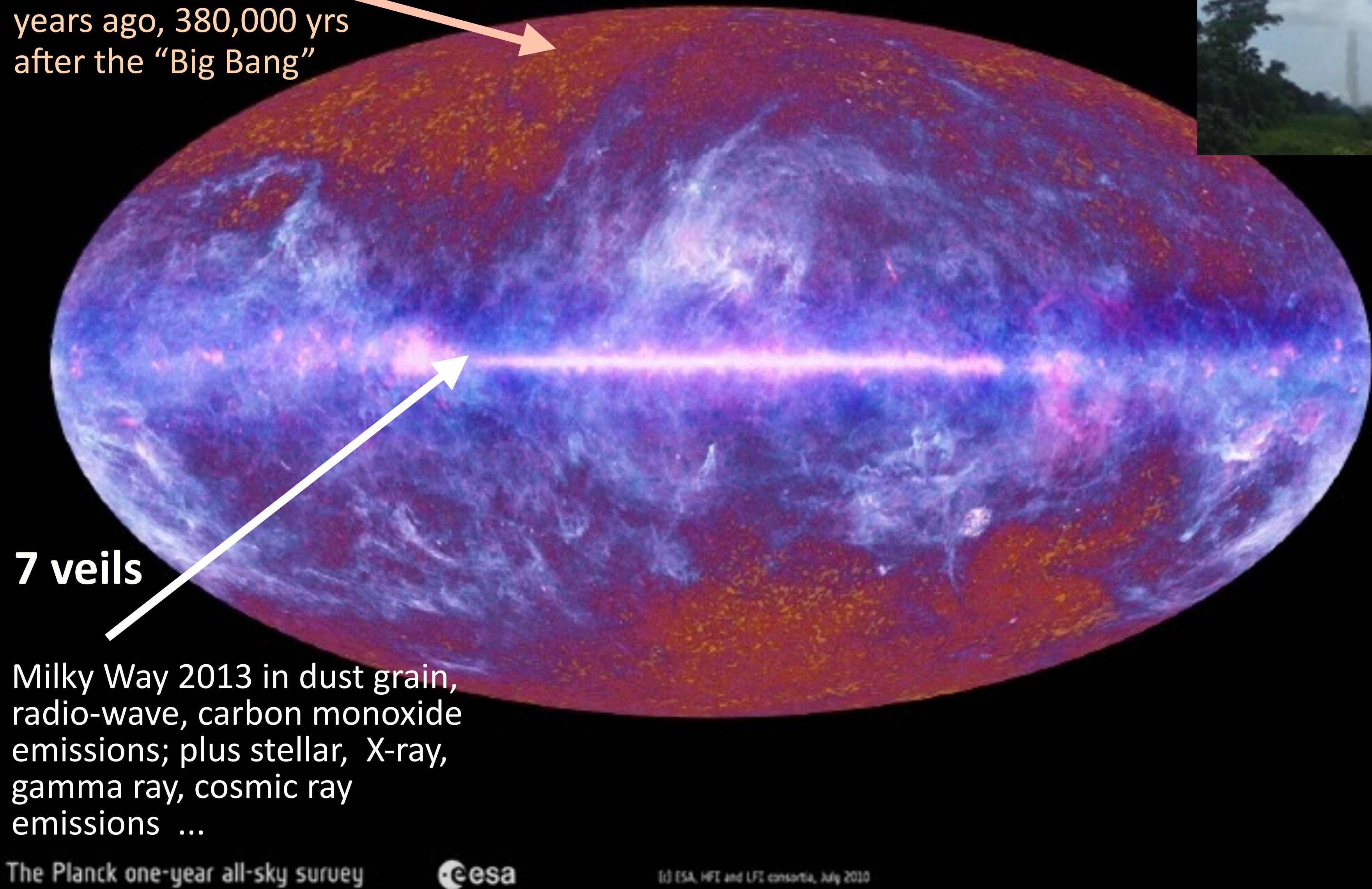
Milky Way in 3D:

a disk galaxy with a large dark matter halo



COMPLEXITY of here & now

the primordial light, released 13.8 billion years ago, 380,000 yrs after the "Big Bang"



7 veils

Milky Way 2013 in dust grain, radio-wave, carbon monoxide emissions; plus stellar, X-ray, gamma ray, cosmic ray emissions ...

Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-15

Planck+Herschel Launch
May14 09 French Guiana

1.5m telescope,

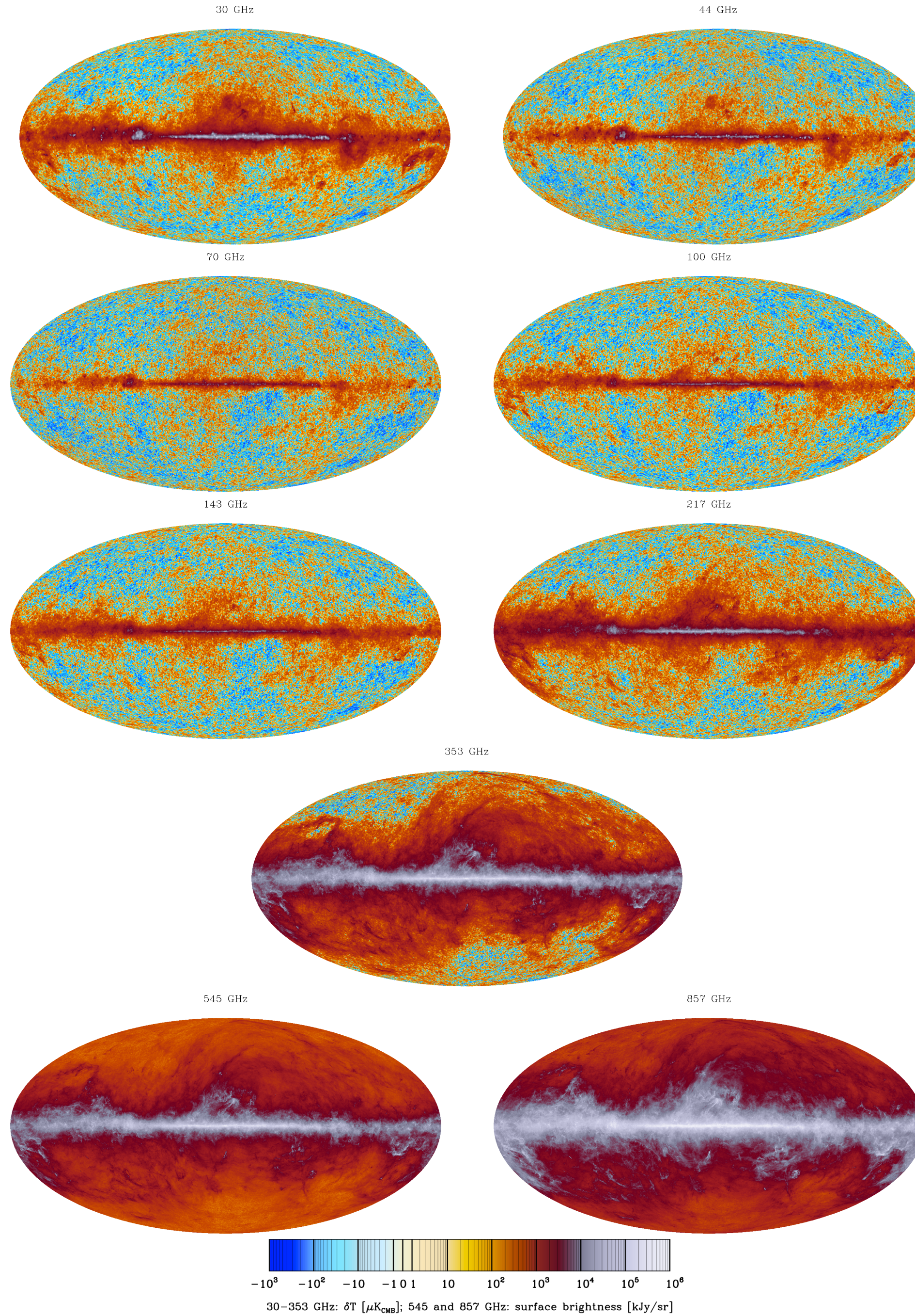
HFI bolometers @6freq
<100mK,

LFI HEMTs@3freq,

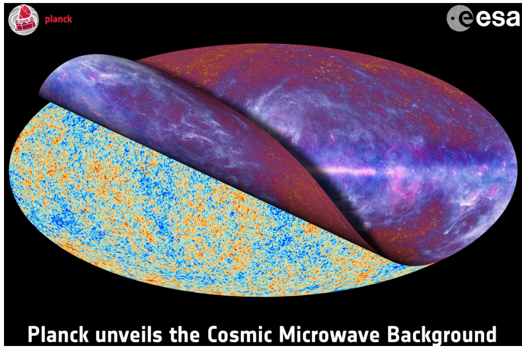
some bolometers & all HEMTS are polarization sensitive

- Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage). @L2 on July 2 09; Survey started on Aug 13 09
- spin@1 rpm, 40-50 minutes on the same circle, covered all-sky in ~6 month
- ~5 HFI all-sky surveys (to Jan 2012)
- ~8 LFI surveys
- kicked out of L2 Oct 2013

Planck 1.3yr Frequency Maps



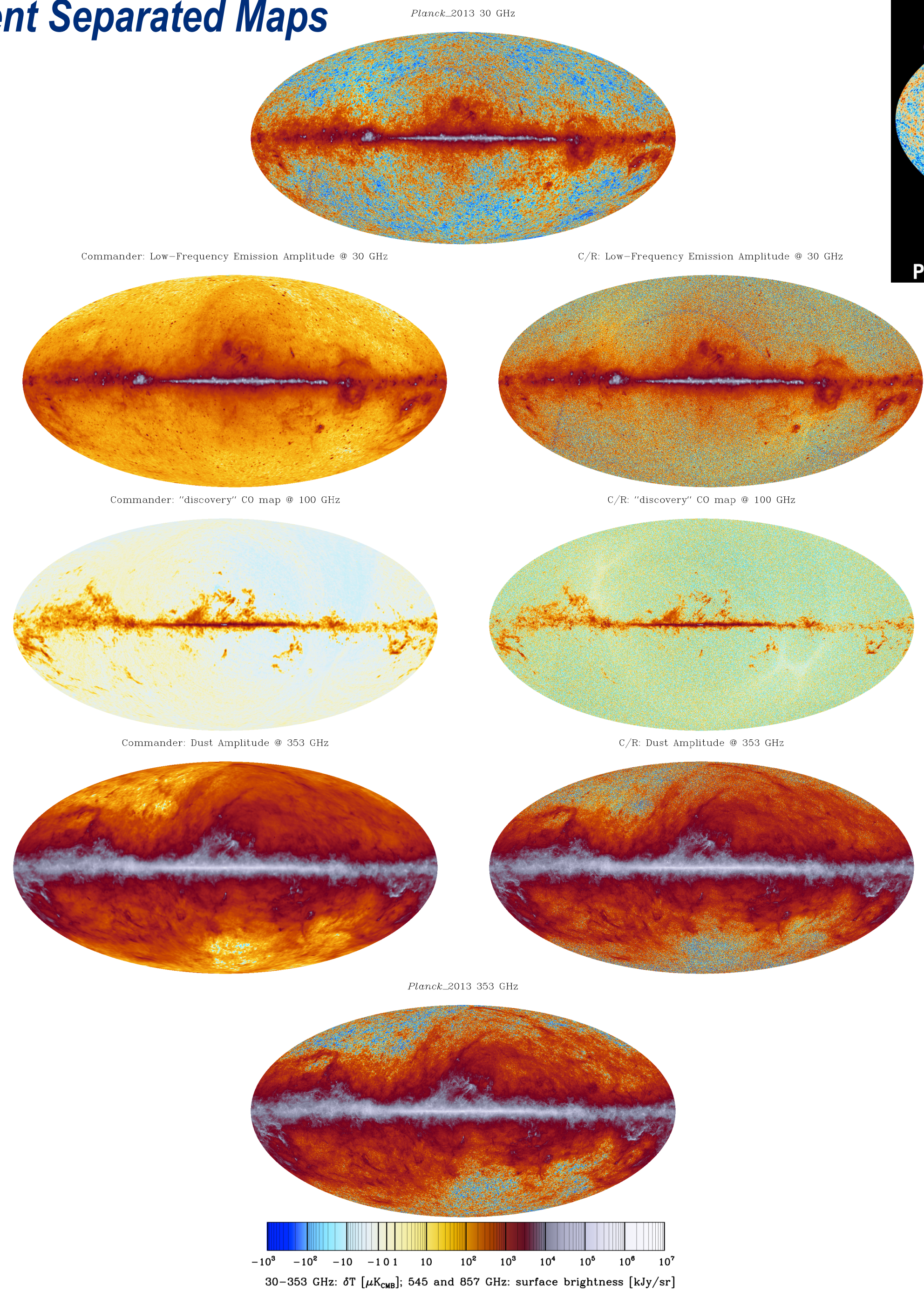
Some Planck Component Separated Maps



LF Synchrotron + bremsstrahlung

Galactic Carbon Monoxide

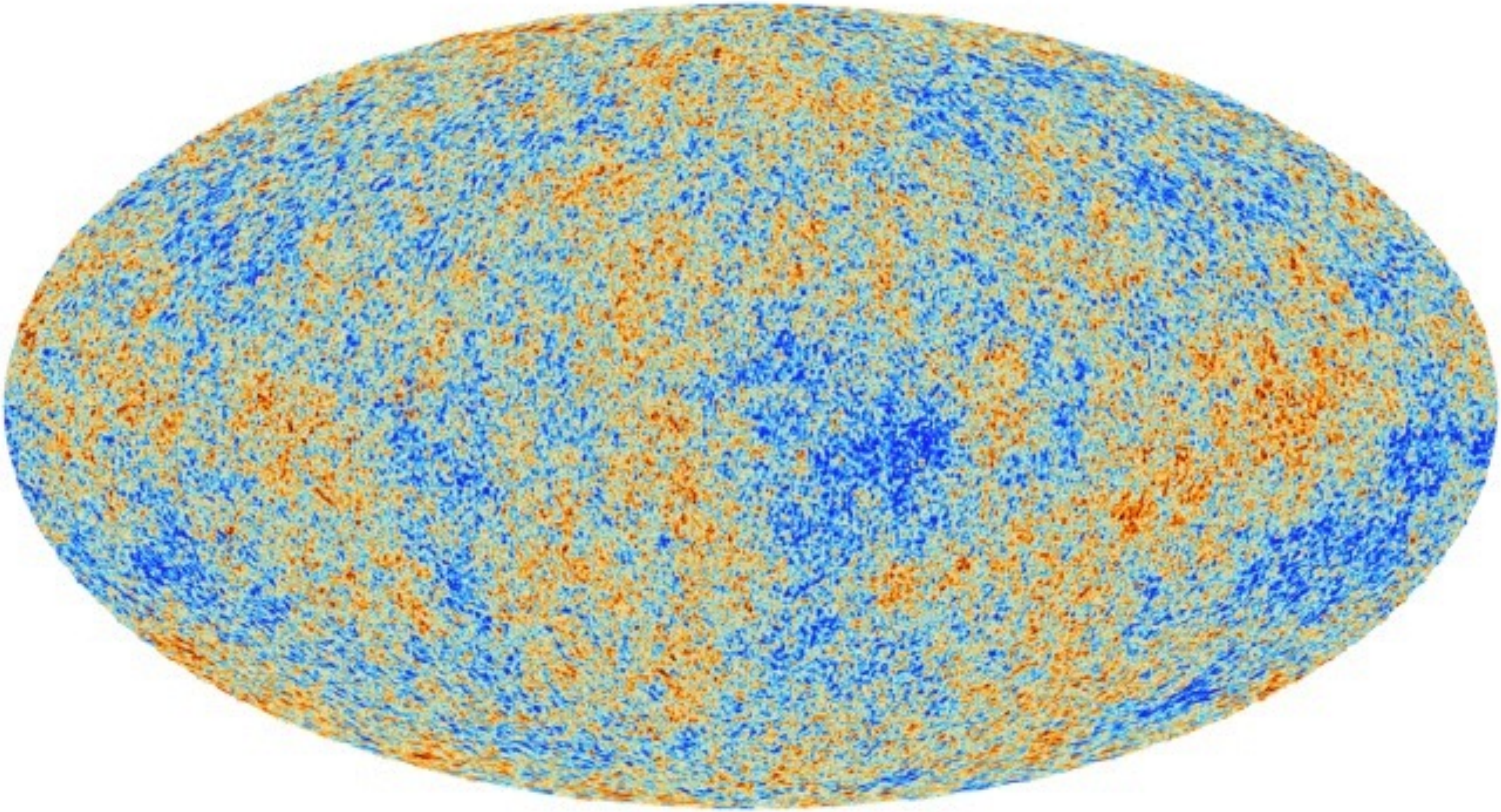
HF Thermal Dust Emission



Planck's primordial light unveiled, March 21, 2013

reveals the SIMPLICITY of primordial cosmic structure

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



Temperature changes
in micro-degrees

Google "Planck Satellite 2013 results" yields ~ 1 million links

Google "gravity waves from inflation 2014" yields ~ 0.3 million links"

THE GLOBE AND MAIL

SPACE

New glimpses of ancient light fuel cosmic debate

Government of Canada | Gouvernement du Canada | Canada

Canadian Space Agency

Home > Audiences > Media > News releases > 2013
> Canadian astronomers reveal surprising new portrait of the Early Universe

Canadian astronomers reveal surprising new portrait of the Early Universe

The New York Times — Space & Cosmos

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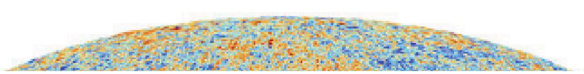
ENVIRONMENT SPACE & COSMOS

Universe as an Infant: Fatter Than Expected and Kind of Lumpy



L'enfance de l'Univers dévoilée

LE MONDE | 21.03.2013 à 11h27 • Mis à jour le 21.03.2013 à 13h44

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Plancking at U of T: space

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

CIFAR cosmologists contribute to new portrait of the Early Universe

CITA–ICAT

NEWS ARCHIVE

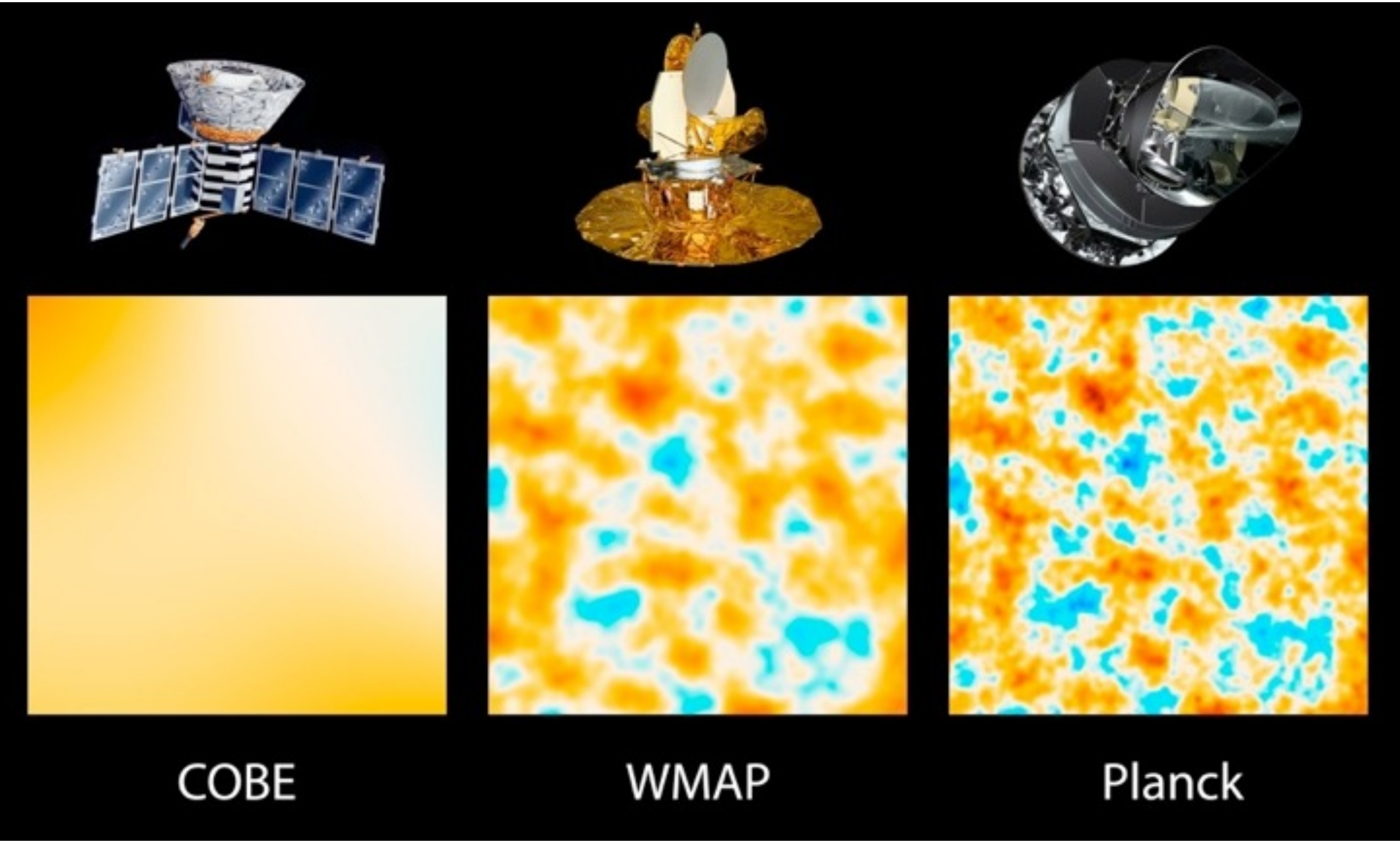
PLANCK Light

gravity waves from inflation

http://www.nytimes.com ***Space Ripples Reveal Big Bang's Smoking Gun*** *By DENNIS OVERBYE MARCH 17, 2014*

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

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



goal: high enough resolution to plumb all cosmic parameter information. but high L foregrounds, extragalactic sources => higher L expts ACT (1.4'), SPT (1') = PlanckEXT to nail the "nuisance"

SIMPLICITY

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

at $a \sim e^{-67+60} \sim 1/10^{30+25}$

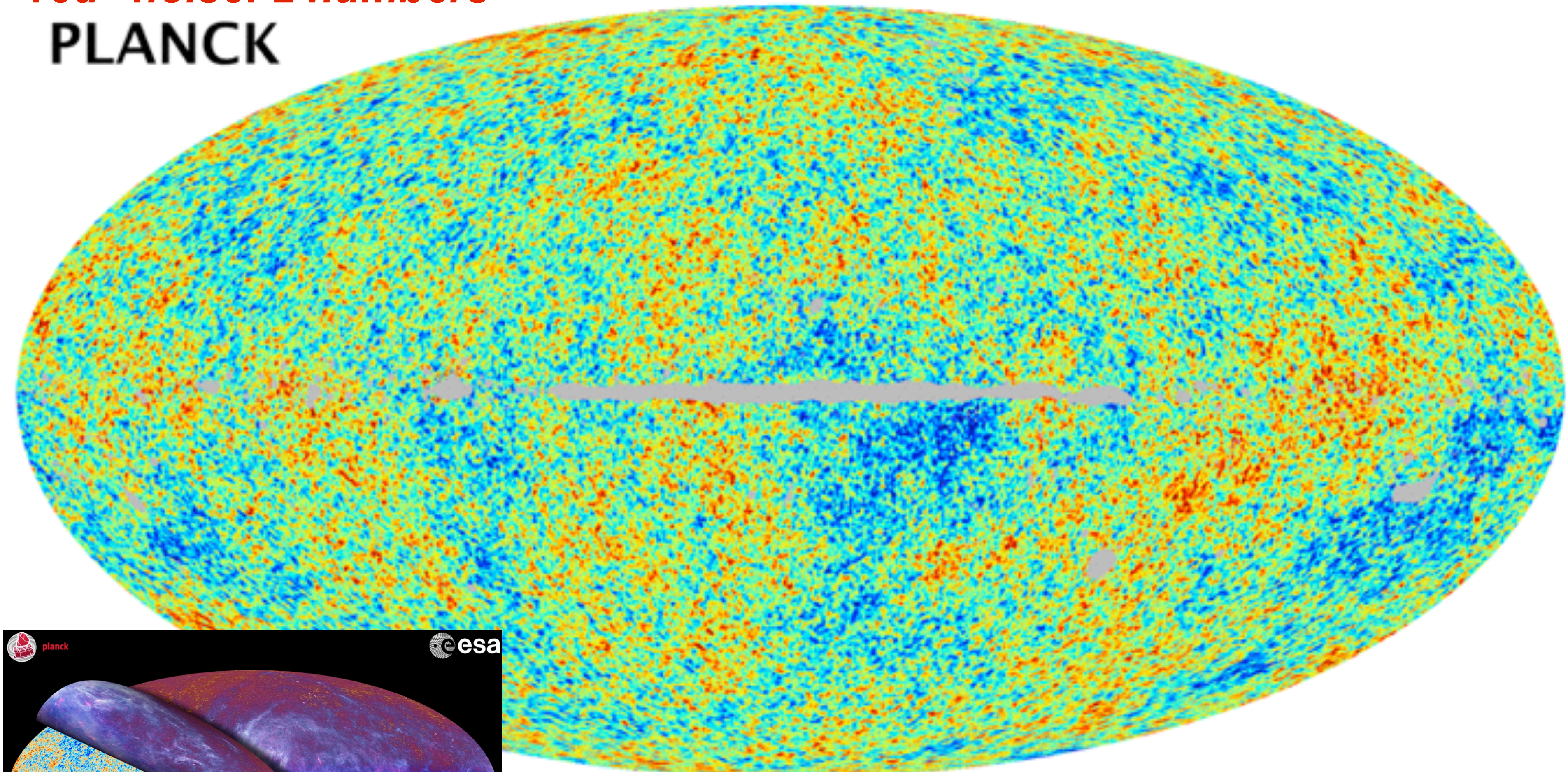
"red" noise: 2 numbers

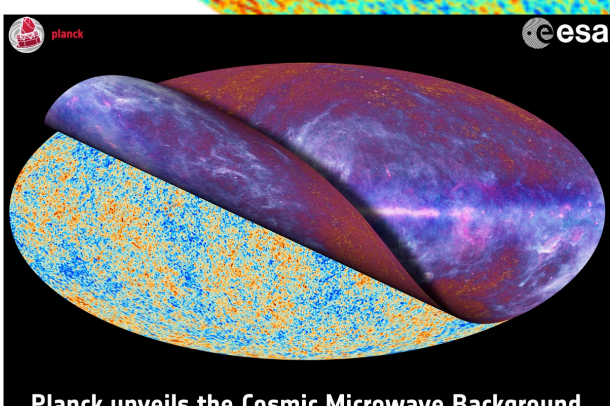
PLANCK

Planck 09 launch

Planck SMICA Map

CMB-data Concordance





Planck CMB / SMICA map, ~5′ resolution
+ NILC, SEVEM, C-R 3 independent component separated CMB maps show the same features

SIMPLICITY

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

at $a \sim e^{-67+60} \sim 1/10^{30+25}$

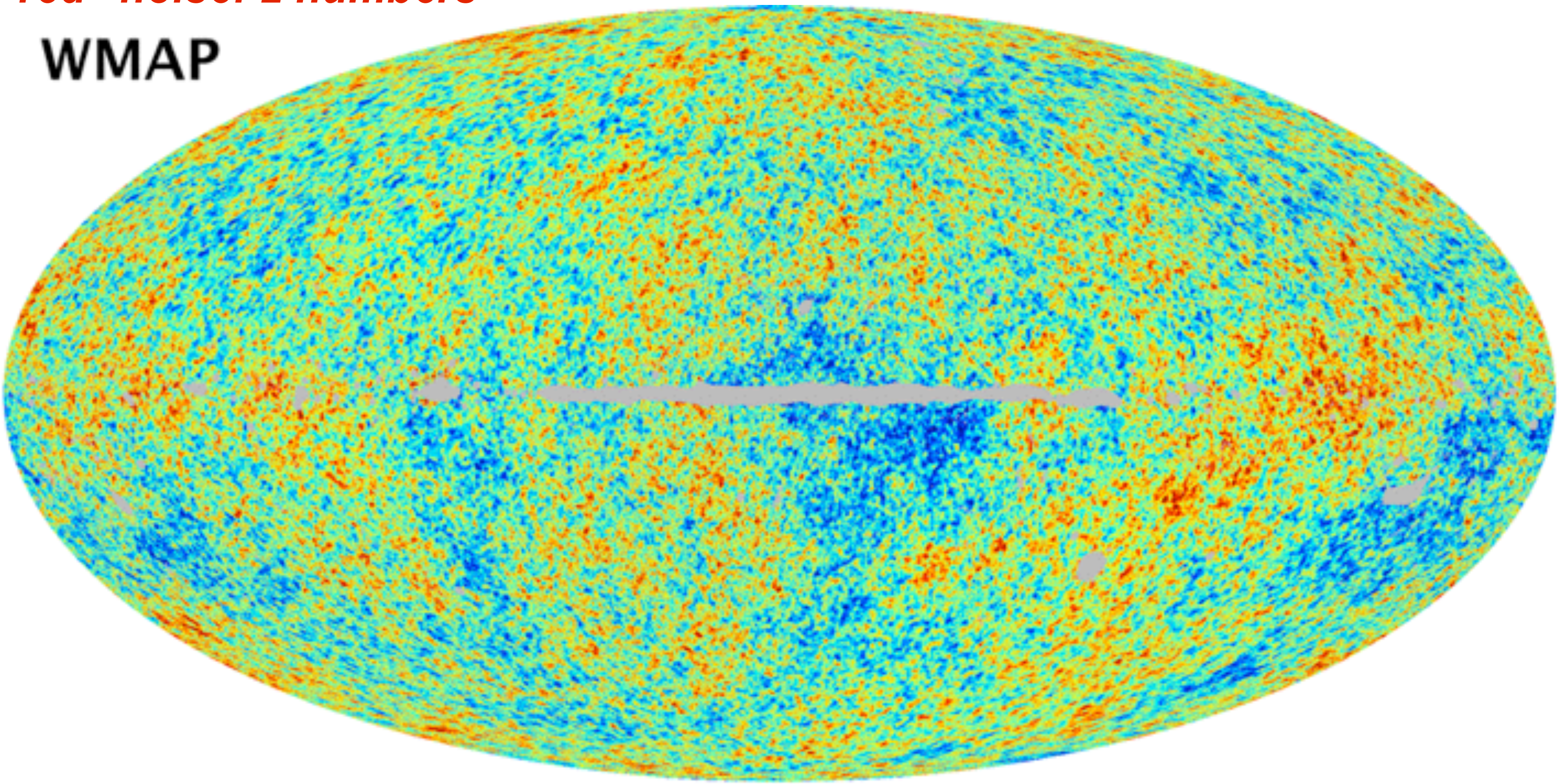
"red" noise: 2 numbers

WMAP

WMAP 01 launch

WMAP W–band, Template Cleaned

CMB-data Concordance



Cleaned with Planck 353 GHz dust map and low-frequency templates. 12′ resolution.

similar tremendous agreement with the much higher (5X) resolution ACT & SPT maps

total focus on the 1.2% difference in "calibration" between P13 (HFI &LFI) & WMAP9

Planck's information > 4X WMAP9 in multipoles

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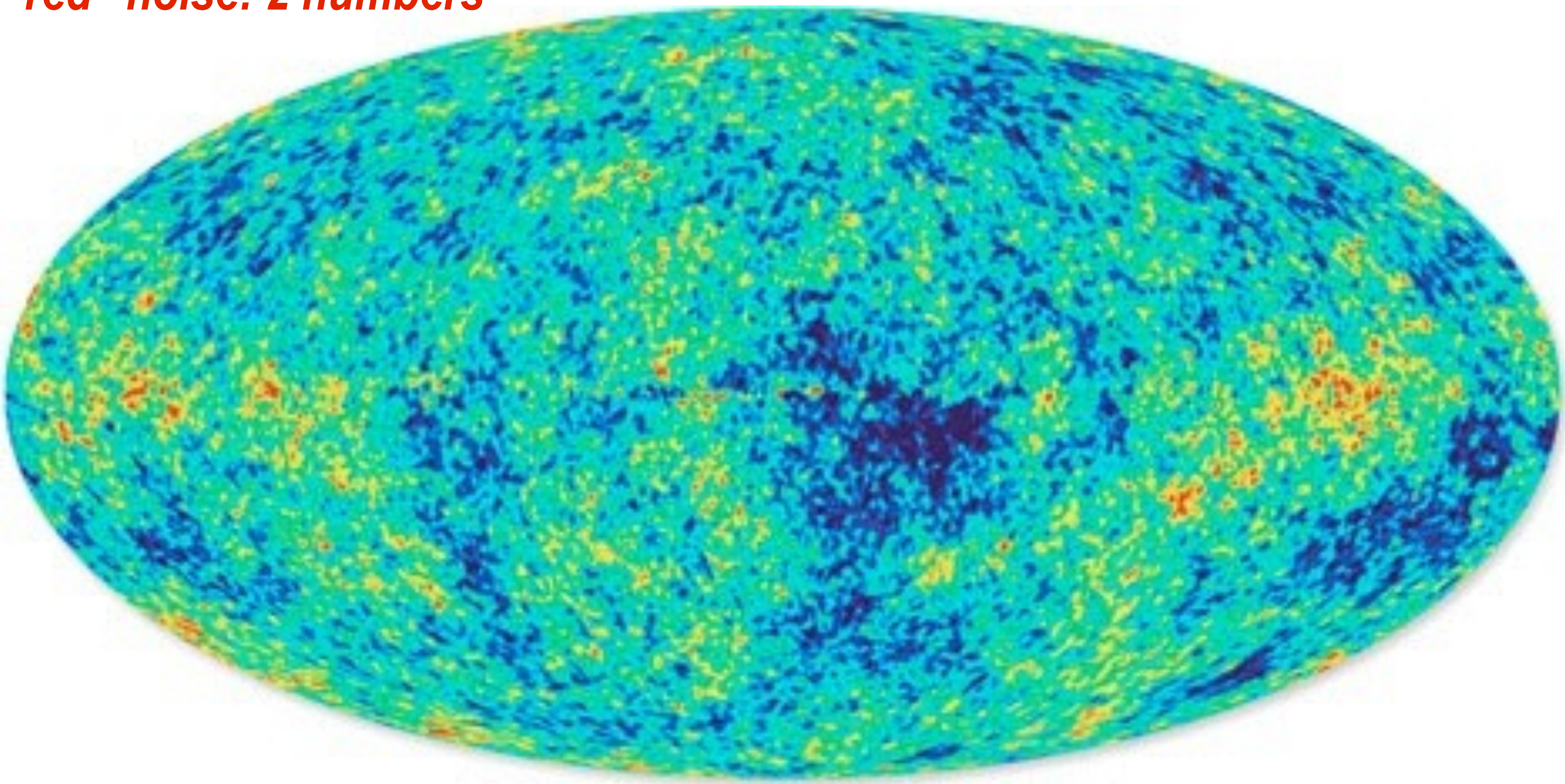

Cleaned with low-frequency templates only.

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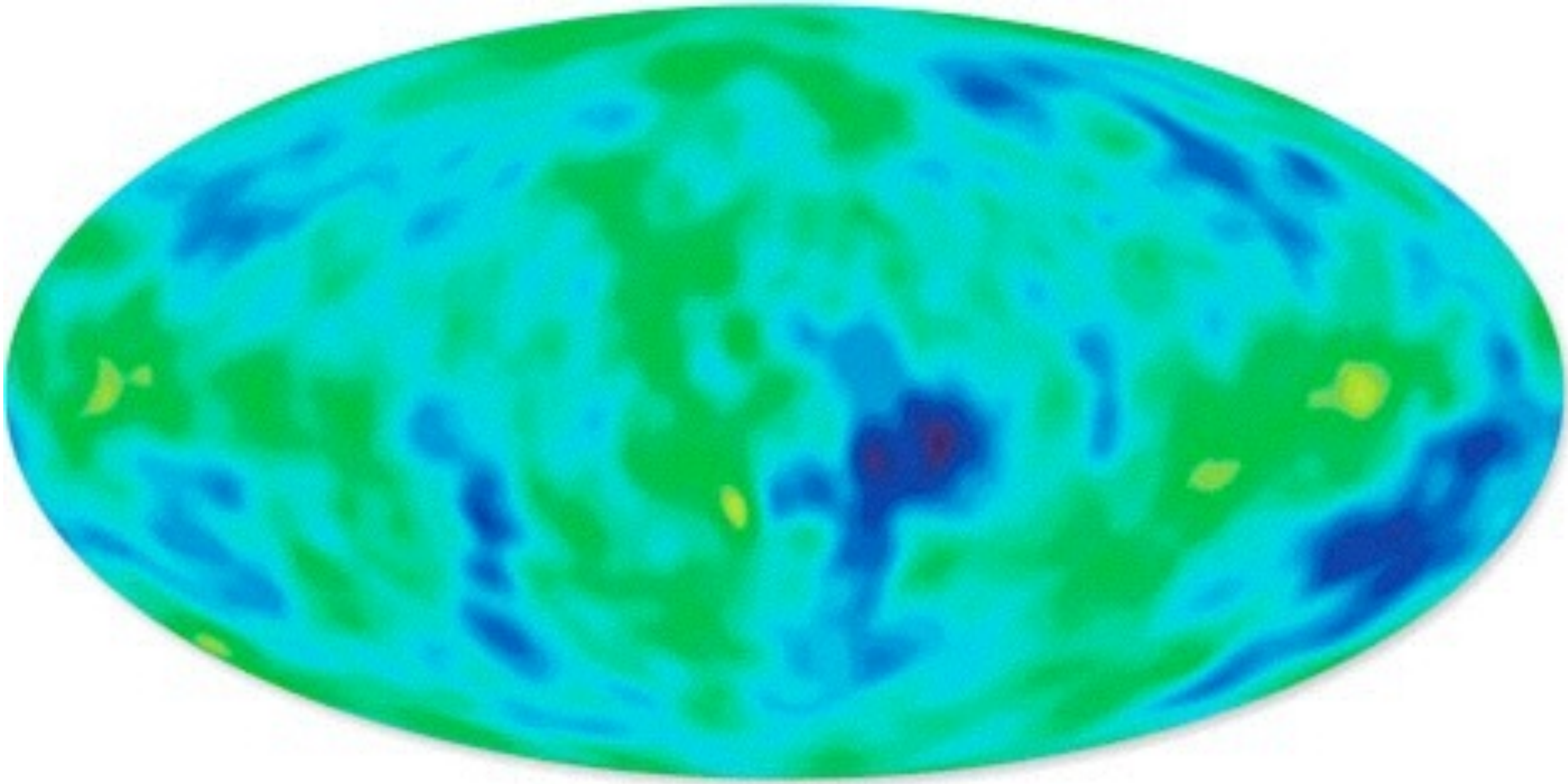
total focus on the 1.2% difference in "calibration" between P13 (HFI &LFI) & WMAP9

COBE 89 launch

COBE

CMB-data Concordance



ACT (1.4 arcmin res) vs Planck1.3 (~5.5 arcmin res @217) in limited sky region
=> excellent agreement; cross correlations also look great

ACT collaboration: Louis+14

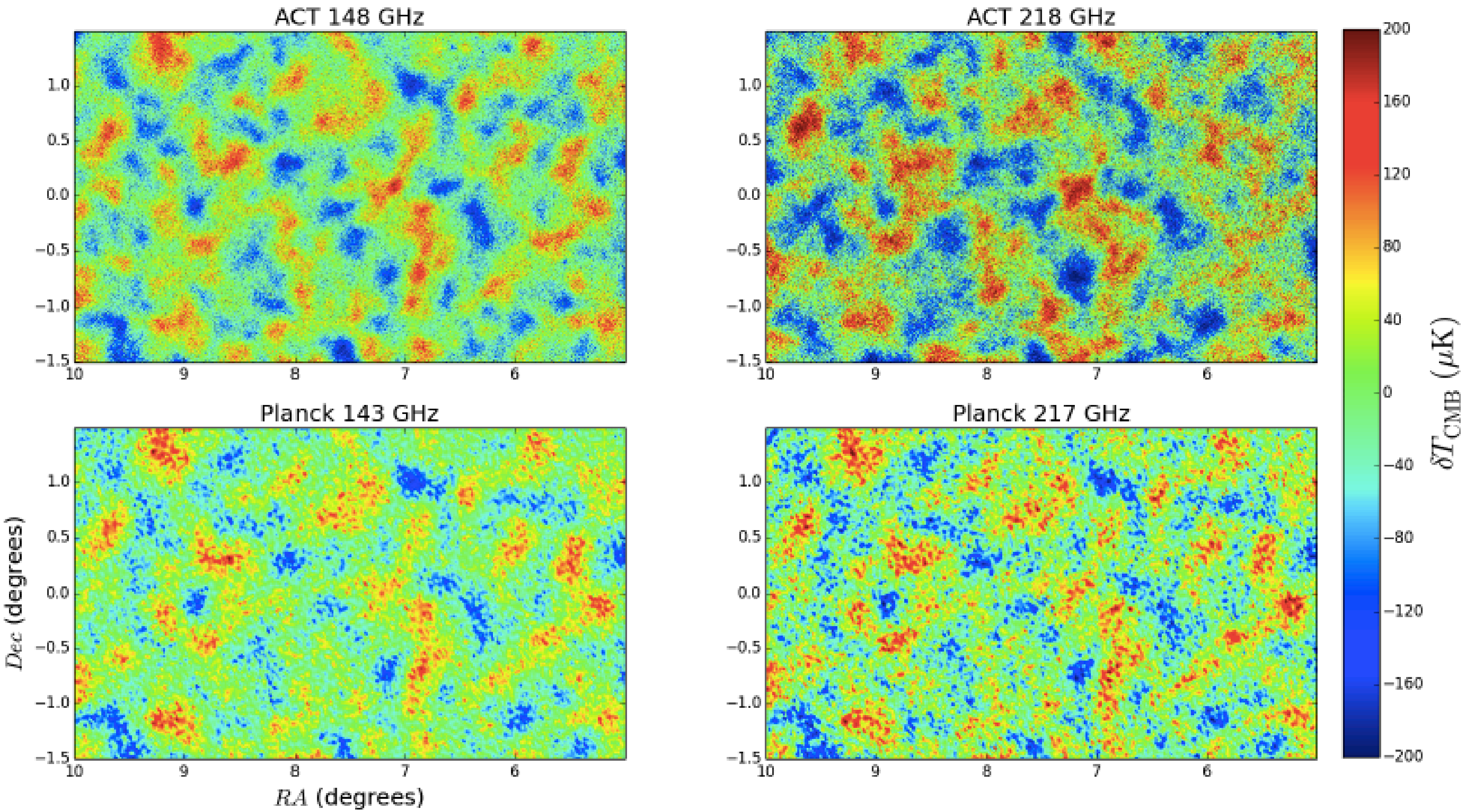
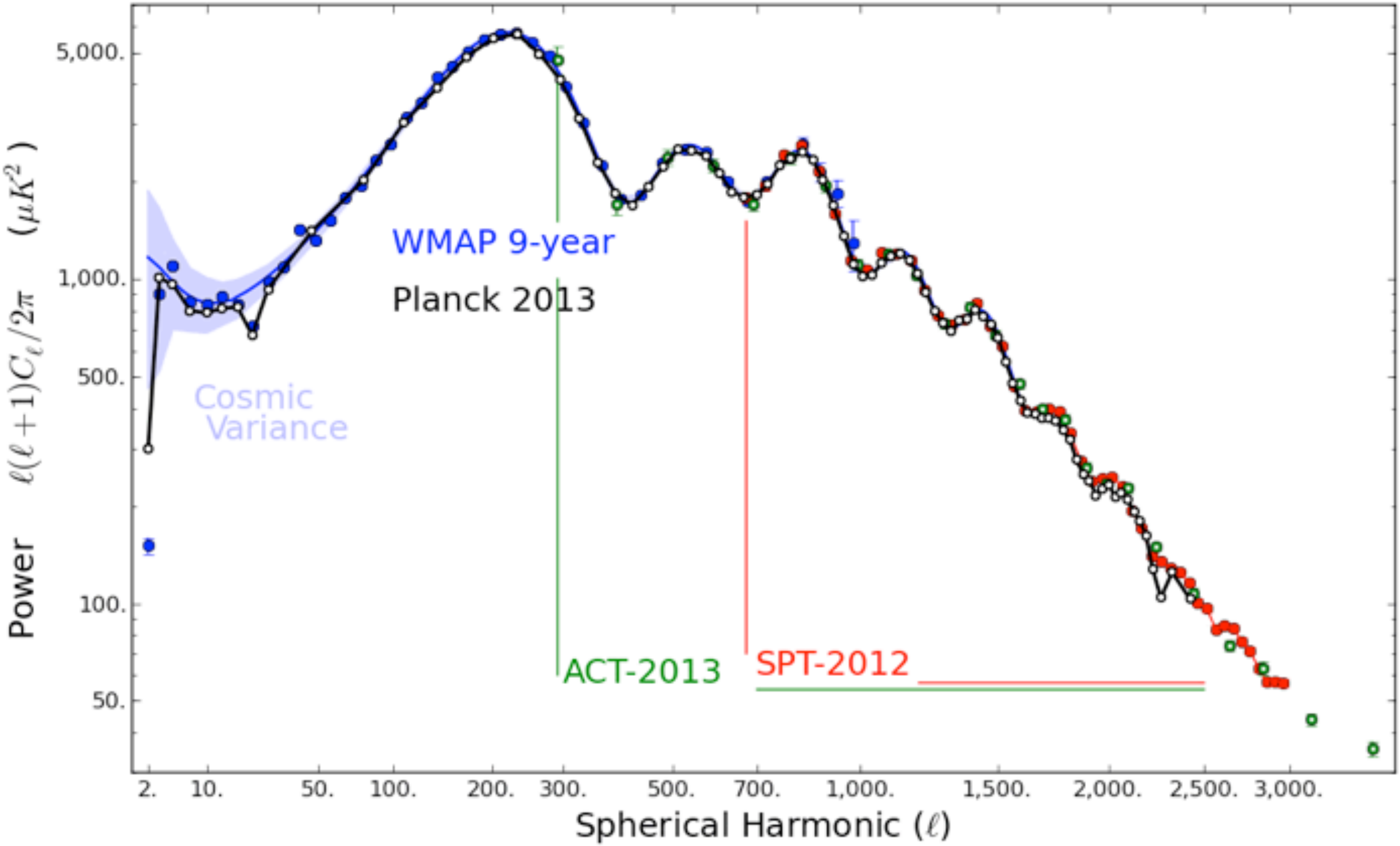


FIG. 1.— Comparison of ACT (*top*) and *Planck* (*bottom*) maps for a 15 deg^2 patch in the ACT Equatorial region. The maps are the inverse variance weighted combination of all ACT data at 148 GHz (*left*) and 218 GHz (*right*) and all *Planck* data at 143 GHz and 217 GHz. All maps have been filtered with a high pass filter (for modes on scales: $\ell < 500$). Artifacts of the HEALpix pixelization are seen in the *Planck* maps. The agreement is visually excellent.

Boomerang 2000, 2003 also agree, as does SPT in the overlap region

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



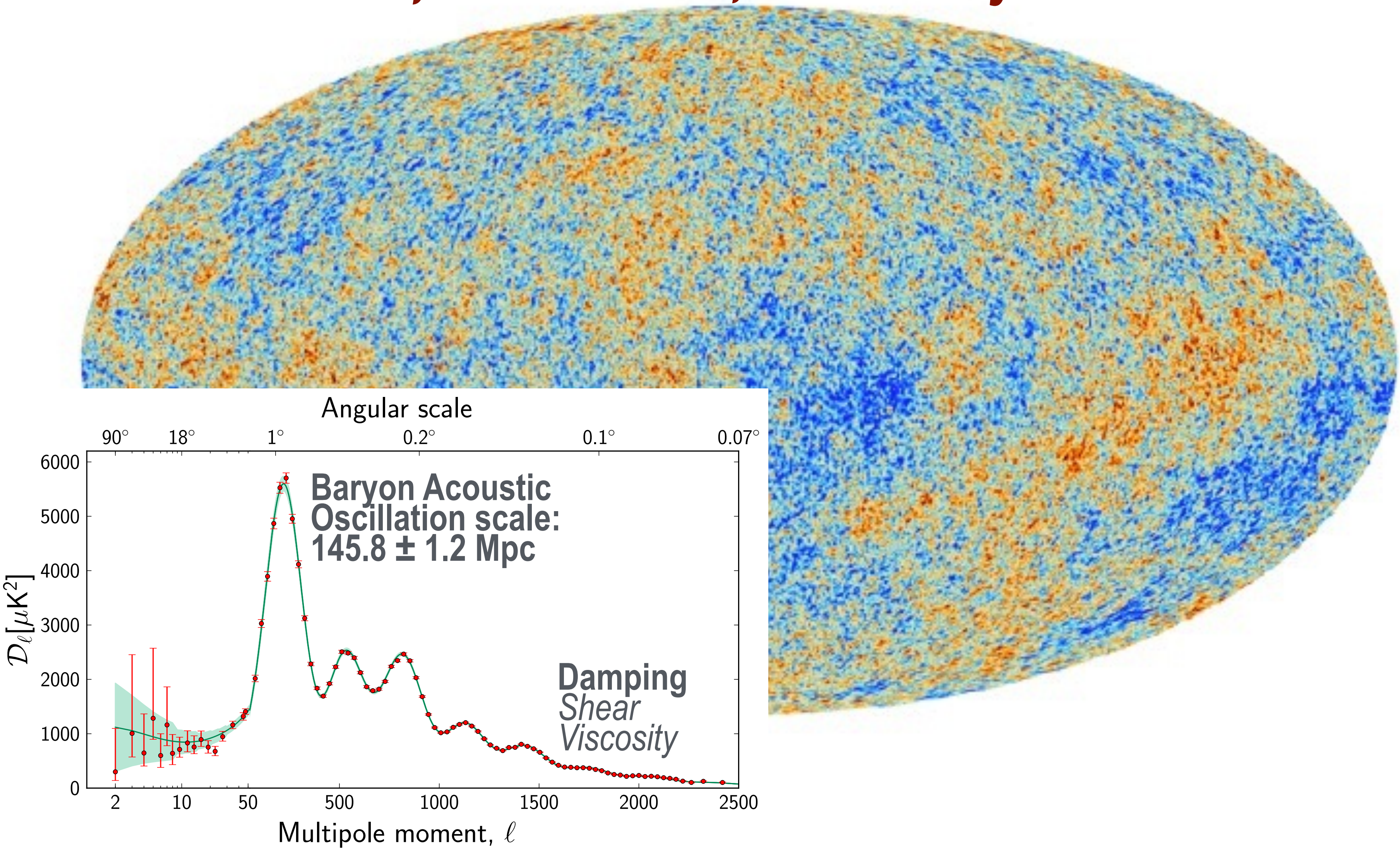
WMAP9 +ACT + SPT cf. Planck2013 = Planck1.3yr

Halpern13 gif

reveals **primordial sound waves**

=> the inharmonious *'music of the spheres'*

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



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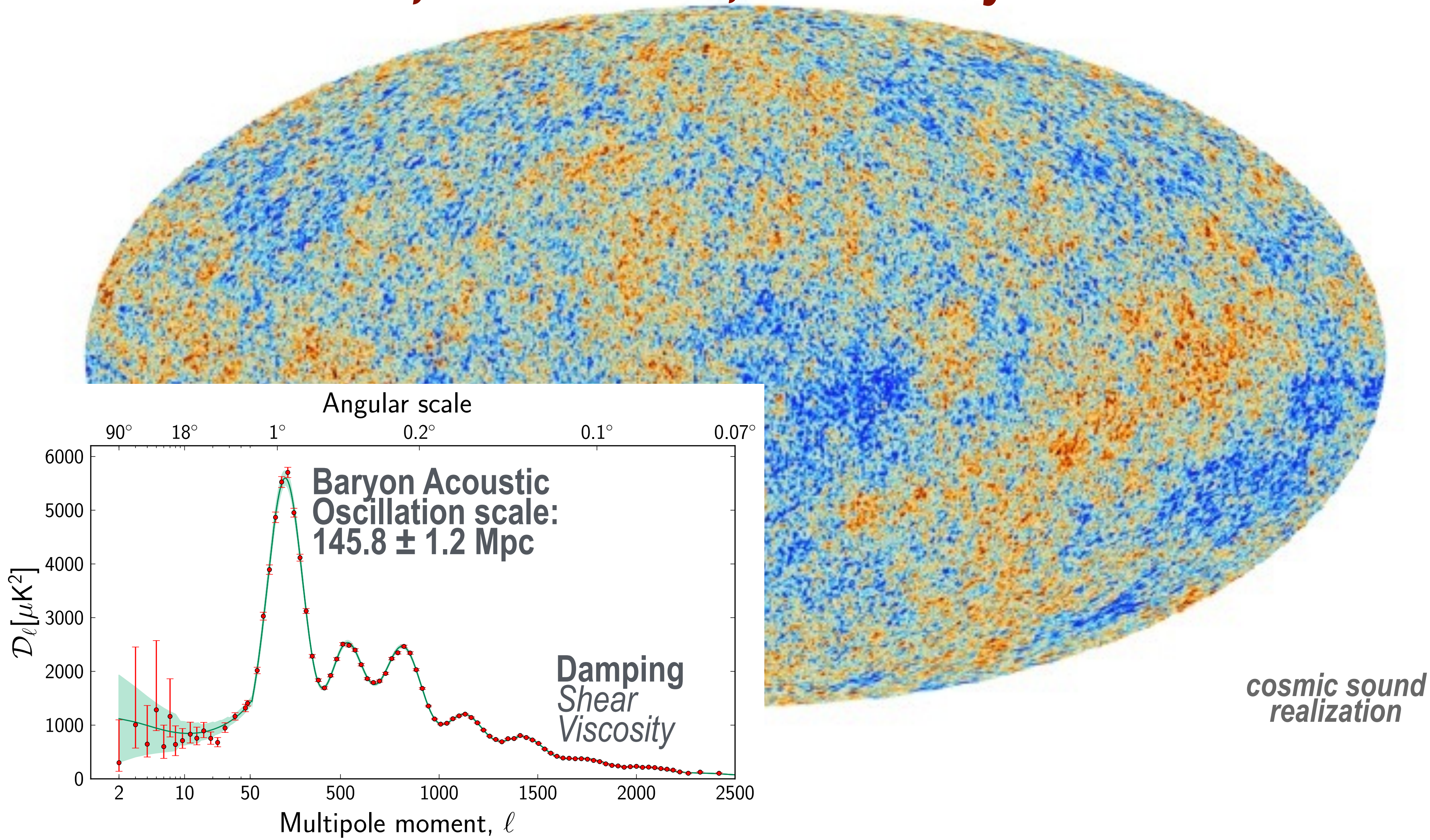


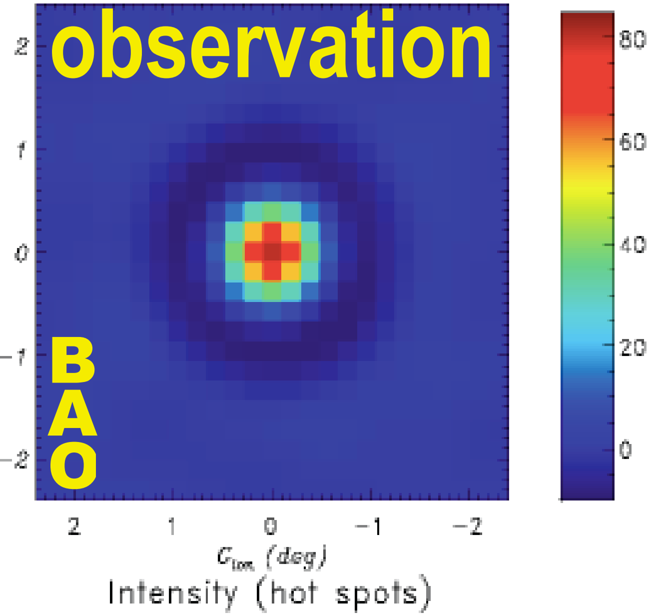
SIMPLICITY

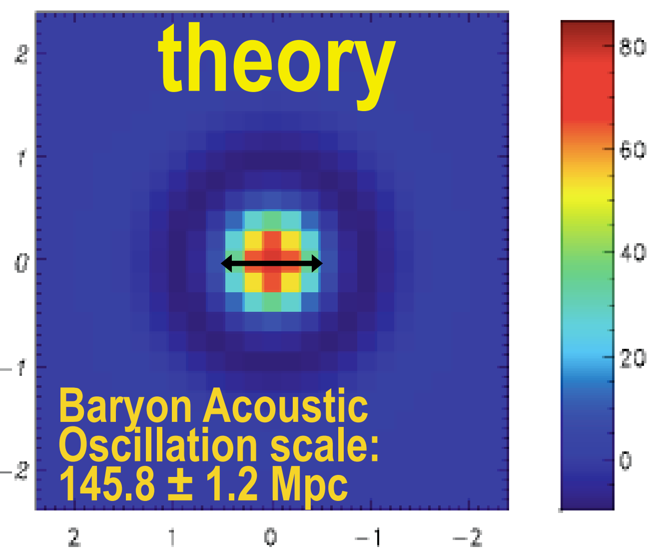
at $a\sim e^{-7}\sim 1/1100$ =>
at $a\sim e^{-67+60}\sim 1/10^{30+25}$

reveals **primordial sound waves** *in matter*

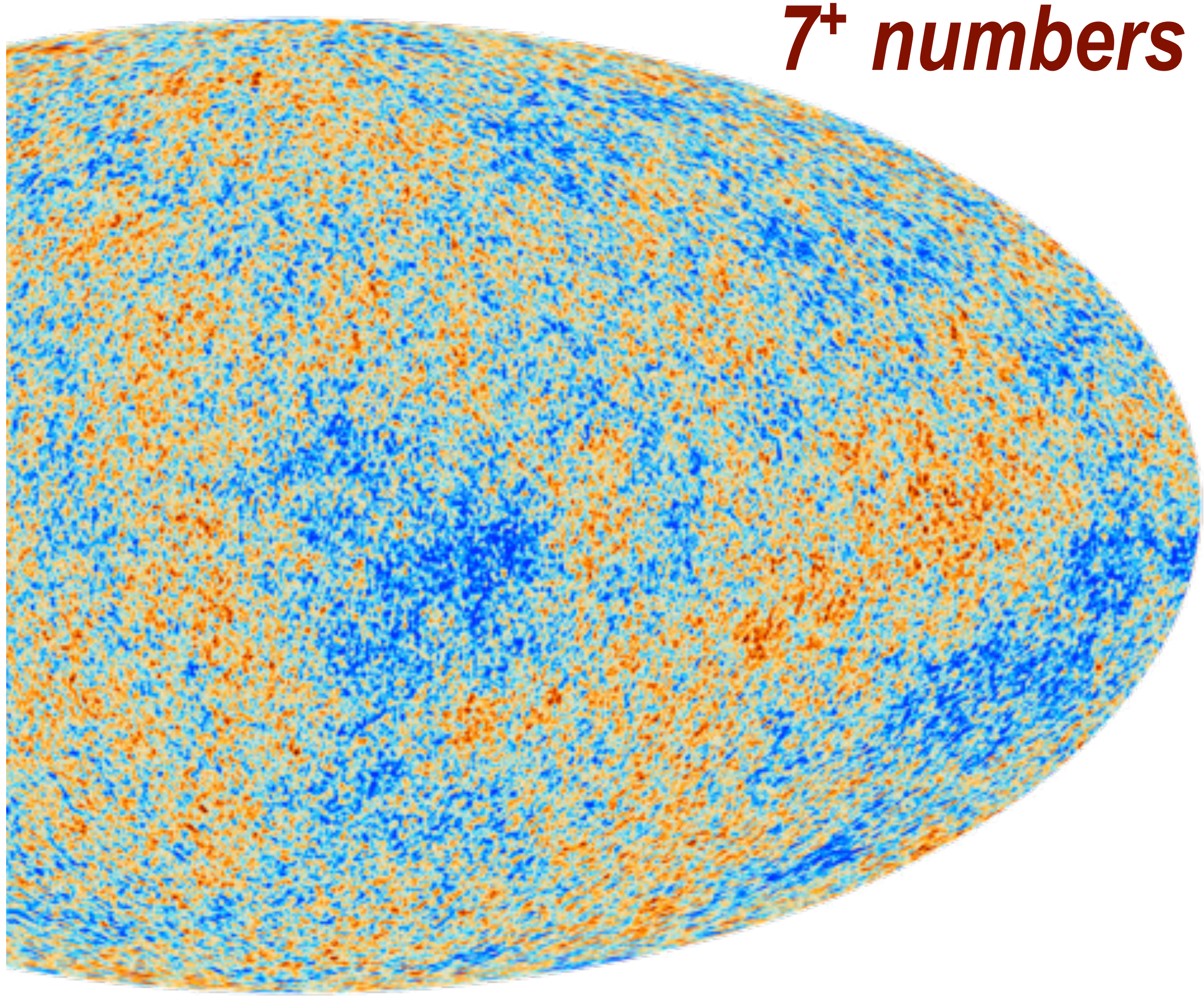
=> *learn* **contents & structure** *at 380000 yr,* $a\sim e^{-7}$

=> *infer the structure far far earlier* $a\sim e^{-67+60}$





7^+ numbers



SIMPLICITY *reveals primordial* **sound waves in matter**

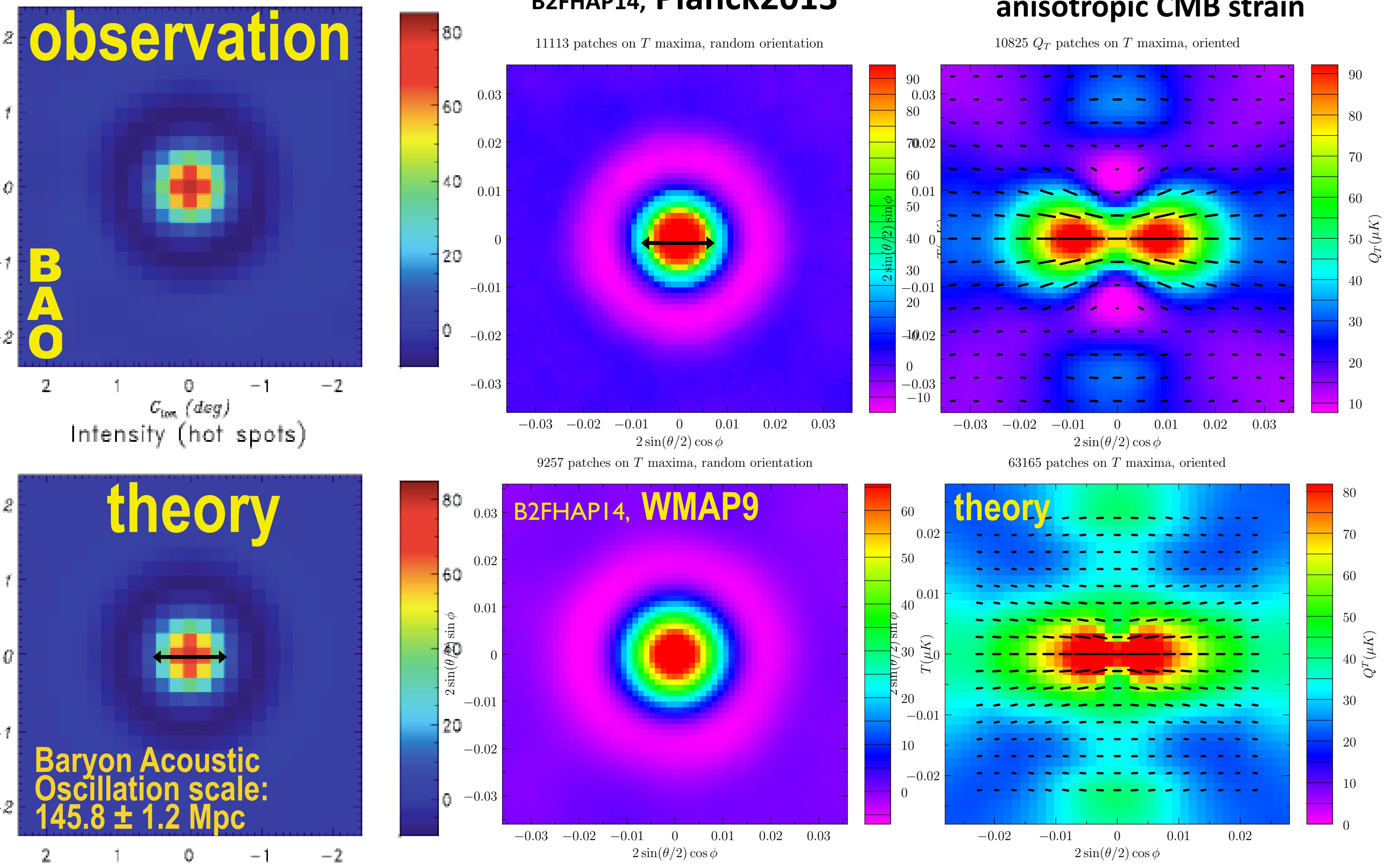
at $a \sim e^{-7} \sim 1/1100 \Rightarrow$

at $a \sim e^{-67+60} \sim 1/10^{30+25}$

B2FHAP14, Planck2013

Planck2013

oriented peaks, anisotropic CMB strain



strained photons redshift

a scale of the Universe =1/ (1+redshift)

now = **1** when we **observe** the **1st light**

then = **1/1100** when the **1st light** was **released from matter**, billion X denser

galaxies forming ~ 1/4

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

mean (isotropic) number of e-foldings of scale ≡ $\langle \ln \mathbf{a} \rangle$

a scale of the Universe

	$\langle \alpha \rangle$
now = 1 when we **observe** the **1st light**	0
then = 1/1100 when the **1st light** was **released from matter**, billion X denser	7
galaxies forming ~ 1/4	1 ⇓ 2
there were **no galaxies** when a < 1/20	3
light nuclei **Dark Matter**	21 ⇓ 35
Heat: matter & **radiation**	67
quantum **noise**	67 ⇓ 127

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

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

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

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

ε=strain tensor

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

$H_J{}^i$=*Hubble* aka ***shear*** $= d\alpha_J{}^j/dt$

general relativity

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** $\propto$ **tide**

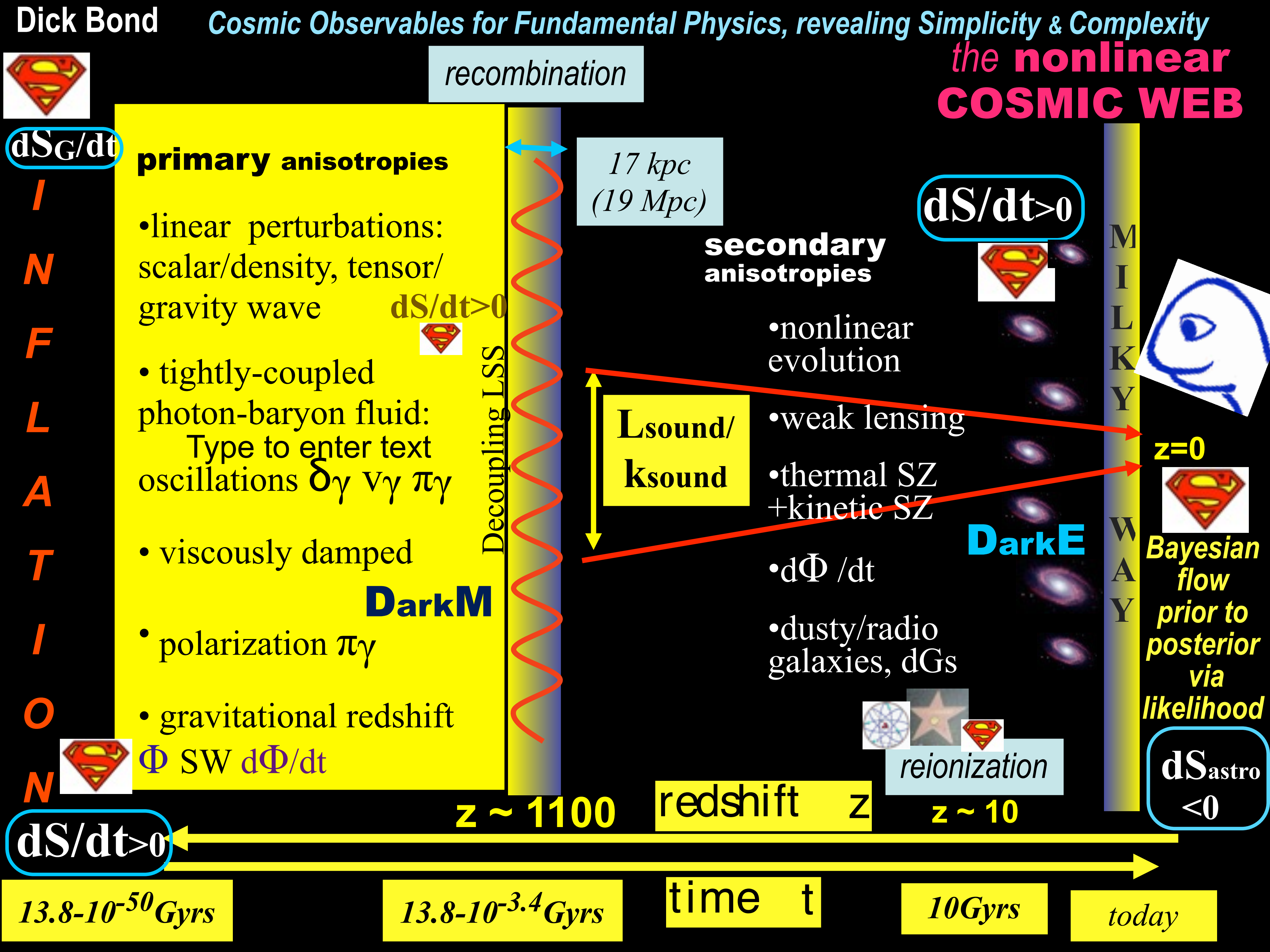
cosmic web *story*

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

the vacuum is modified under space-strain: inflation theory

general relativity => $\mathbf{a}$= *drei*bein, triad, Lagrangian-space metric $\mathbf{g=aa^\dagger}$

the flow of time => 4D *vier*bein *spacetime-strain* $\mathbf{a_b{}^\beta}$ *b,β=0,1,2,3*



Dick Bond
Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity
the nonlinear COSMIC WEB
recombination
dSG/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid:
Type to enter text
oscillations δγ vγ πγ
• viscously damped
DarkM
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
Decoupling LSS
17 kpc (19 Mpc)
dS/dt>0
secondary anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
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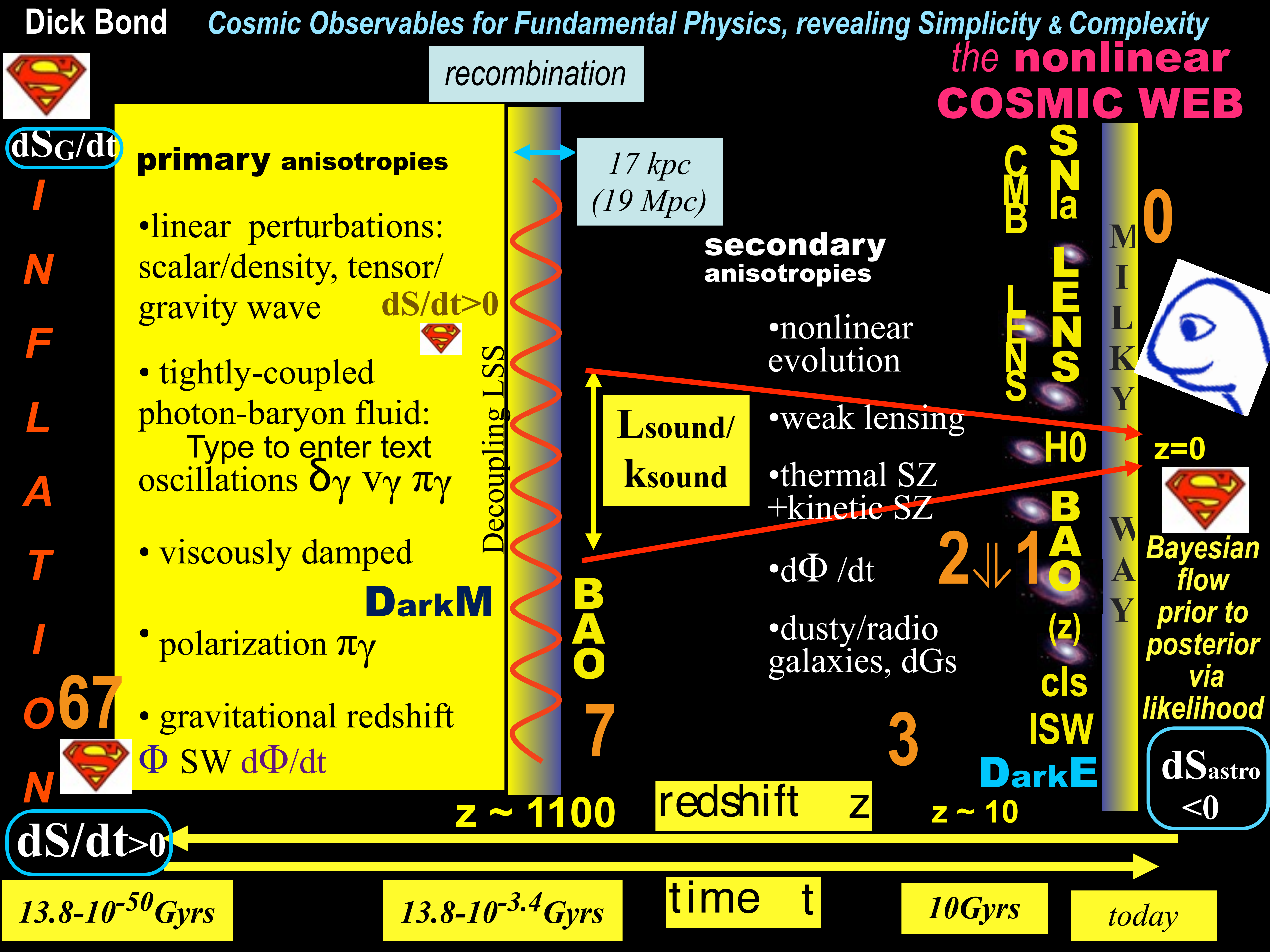
Lsound/ ksound
DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
dSastro <0
reionization
z ~ 1100
redshift z
z ~ 10
dS/dt>0
13.8-10-50Gyrs
13.8-10-3.4Gyrs
time t
10Gyrs
today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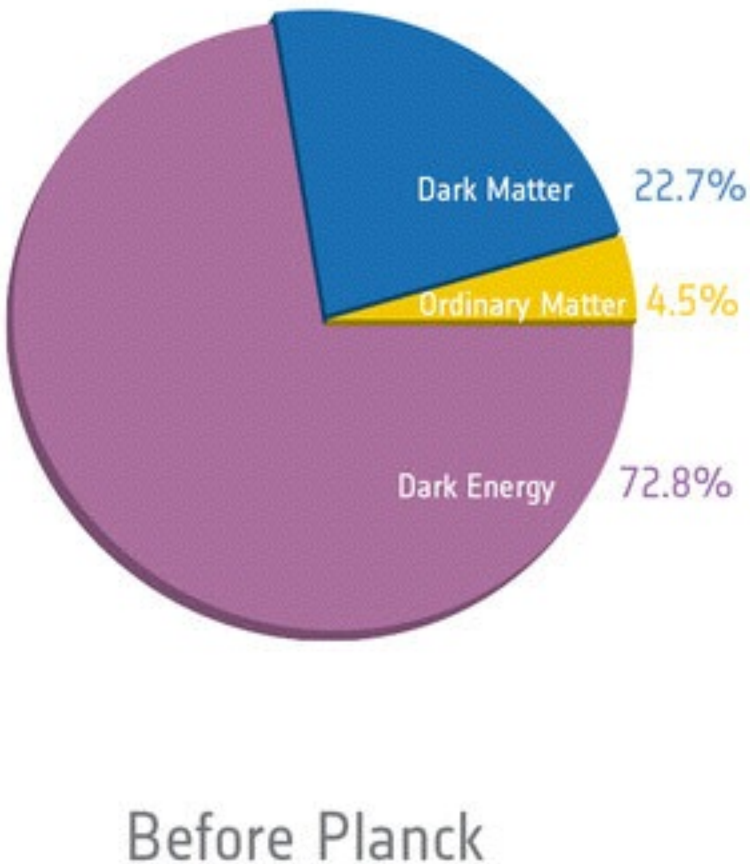
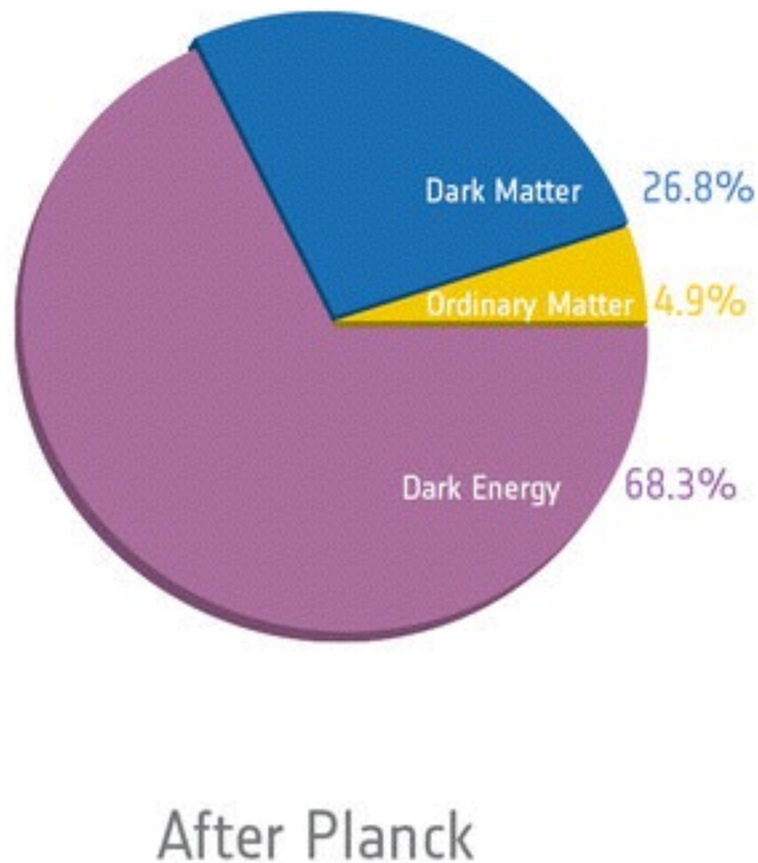
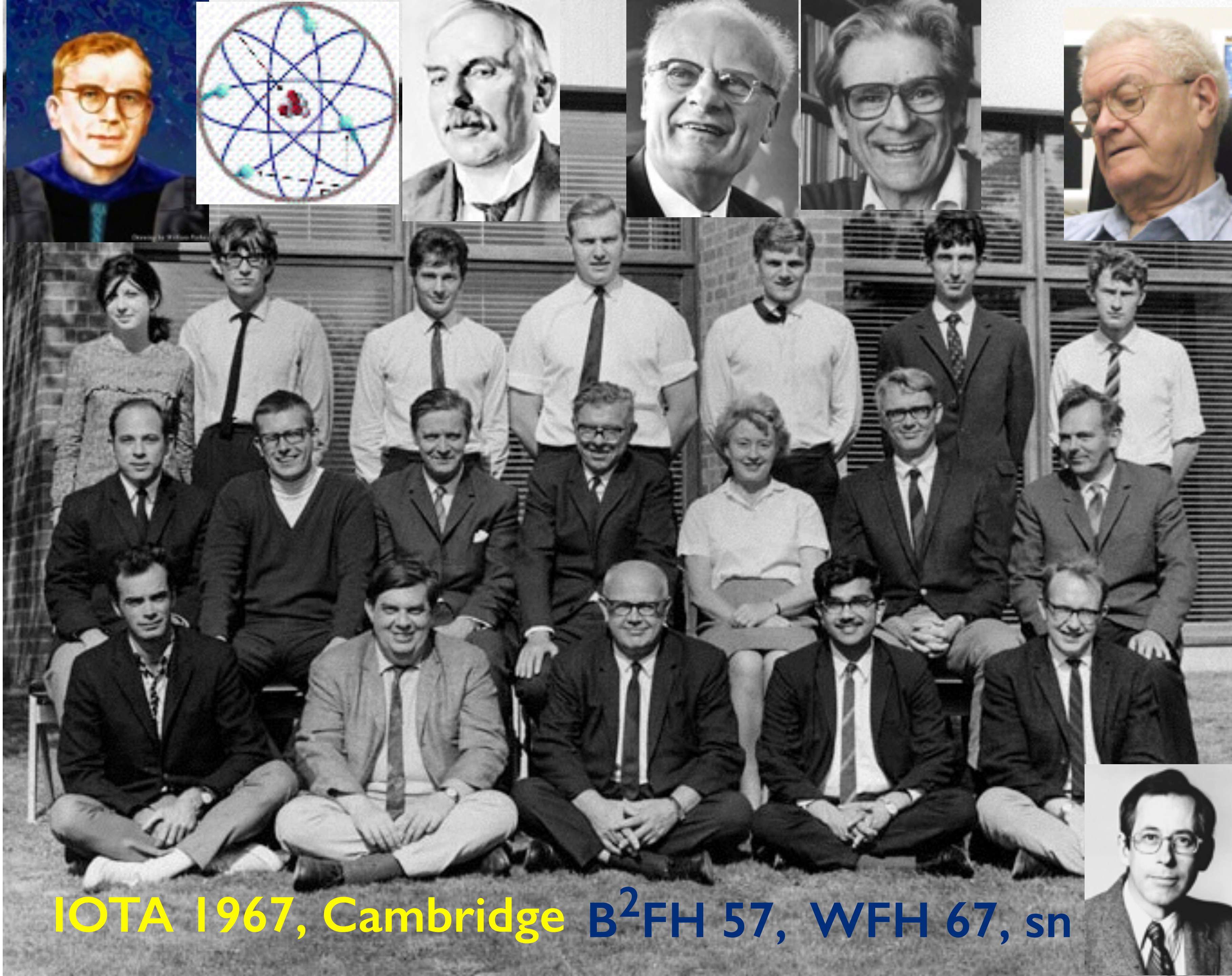
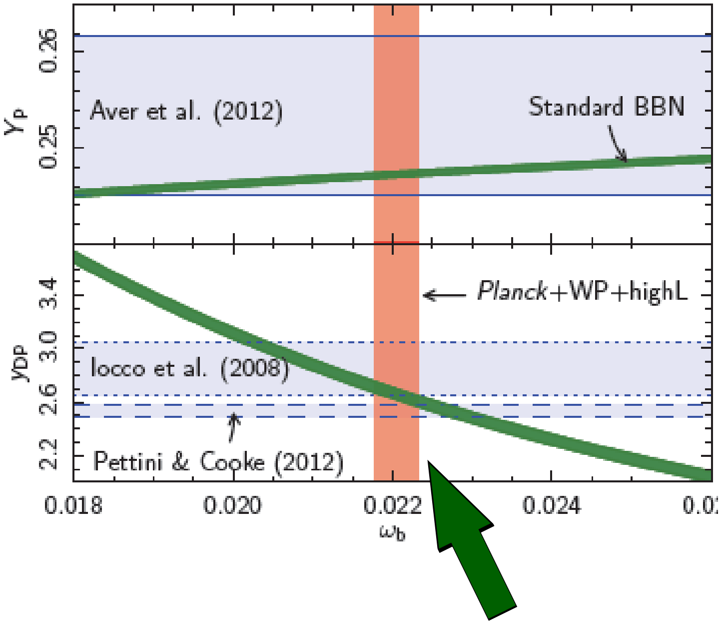
small shift in the pie chart make-up of the Universe

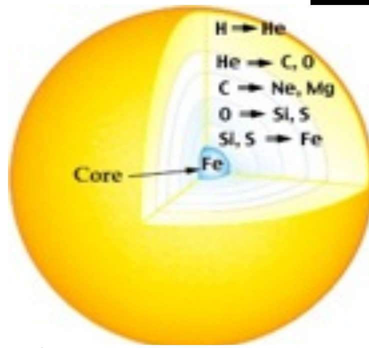


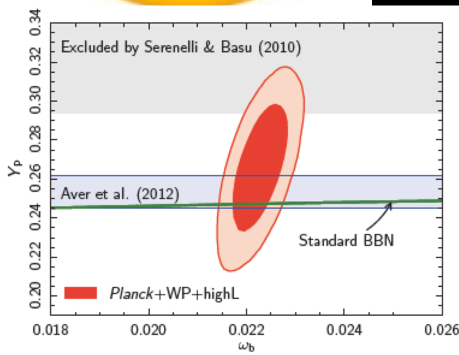



IOTA 1967, Cambridge B^2FH 57, WFH 67, sn

Baryometers







Nobel Prize 84 Willy Fowler + Chandra -sekhar

	pre-boom	boom+	boom+cbi	boom+cbi+acbar	wmap1+
	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_b h^2$	$0.0339^{+0.0443}_{-0.0246}$	$0.0222^{+0.0025}_{-0.0021}$	$0.0221^{+0.0024}_{-0.0020}$	$0.0221^{+0.0023}_{-0.0018}$	$0.0233^{+0.0013}_{-0.0013}$

0.0226 +- 0.0006 wmap3+acbar+cbi+... LSS

0.0233 +- 0.0005 wmap5+acbar+cbi+b03+.+WL+LSS+SN1+Lya

0.02217 +- 0.00033 Planck13+CMBLensing

0.02214 +- 0.00024 Planck13+WP+hiL+BAO

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the **nonlinear COSMIC WEB**

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dS_G/dt

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z ~ 1100 — redshift z — z ~ 10

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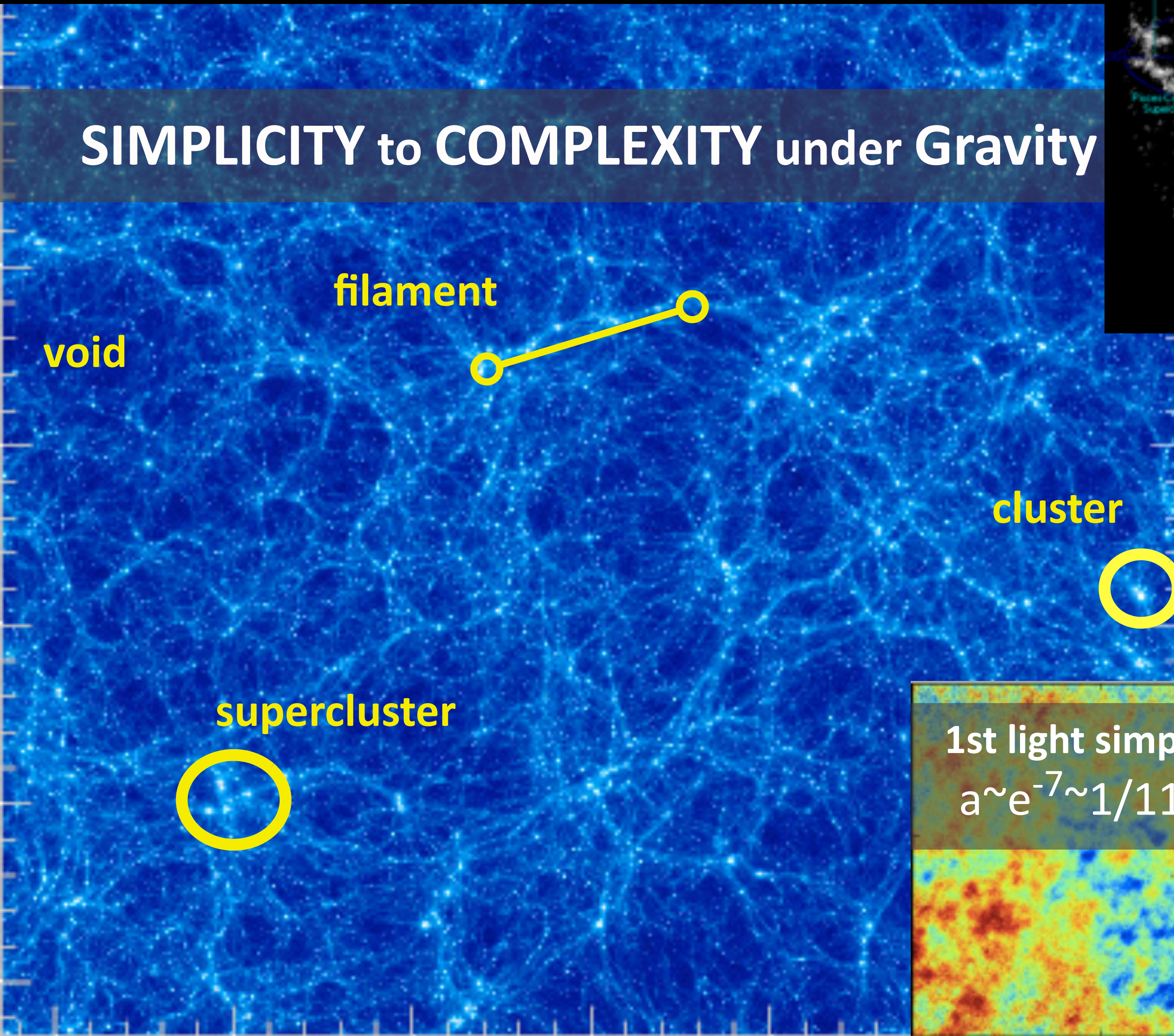
time t

13.8-10^{-50}Gyrs	*13.8-$10^{-3.4}$Gyrs*	*10Gyrs*	*today*

Simulation of the 7^+ numbers begets the Cosmic Web of clusters now a~1 & galaxies then a~1/4

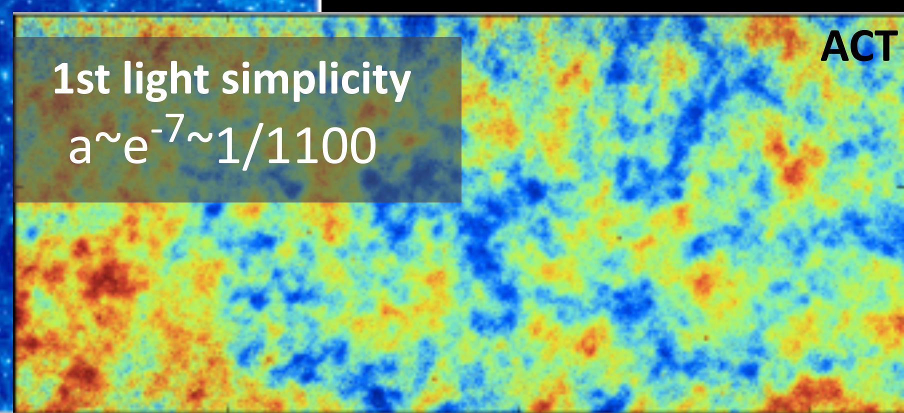
SIMPLICITY to COMPLEXITY under Gravity



~ billion light years

state of the art simulations
a~1 to 1/1.1

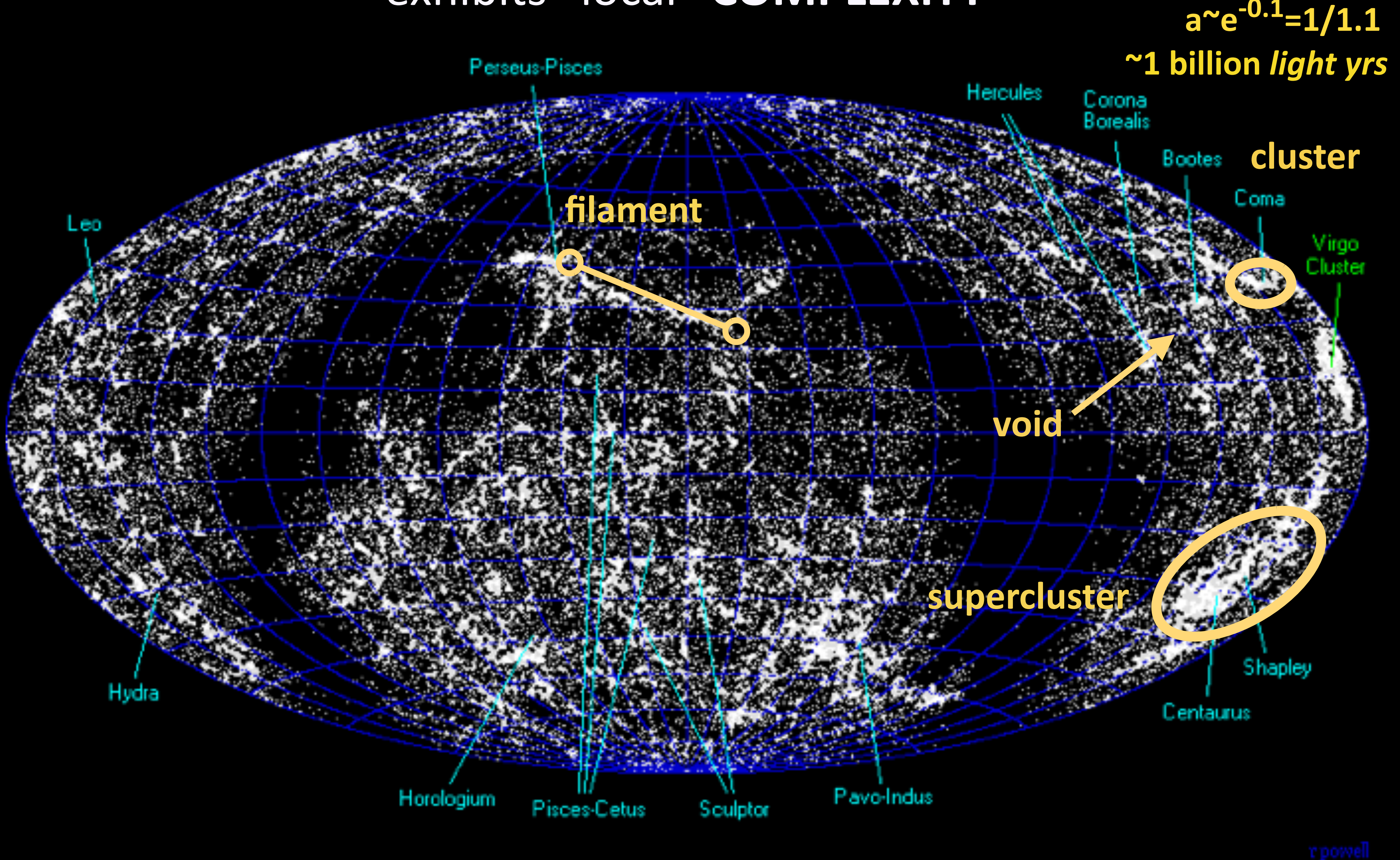
ordinary matter
dark matter
dark energy



1st light simplicity

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

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



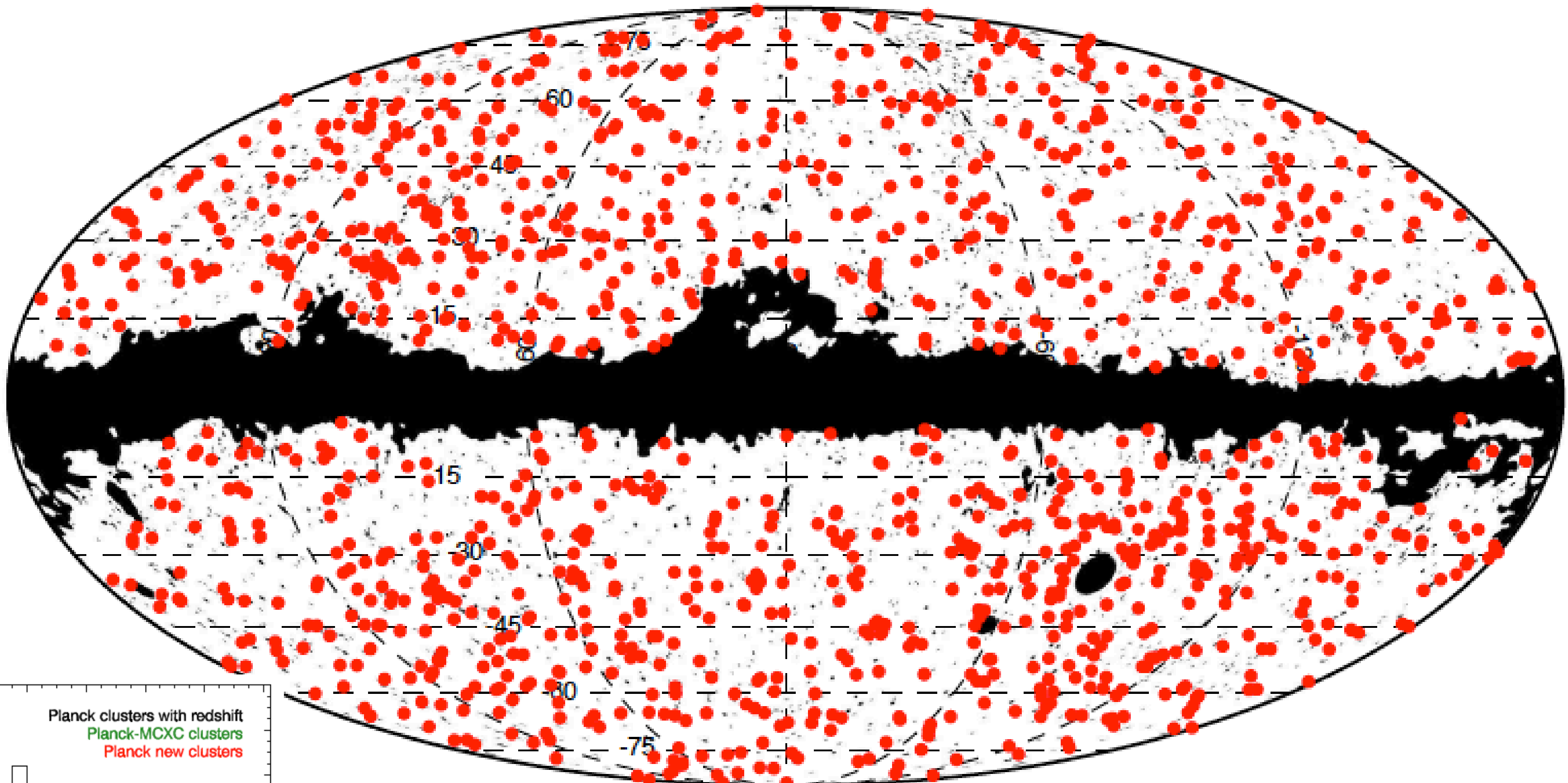
Compton cooling of high pressure / entropy electrons by the CMB

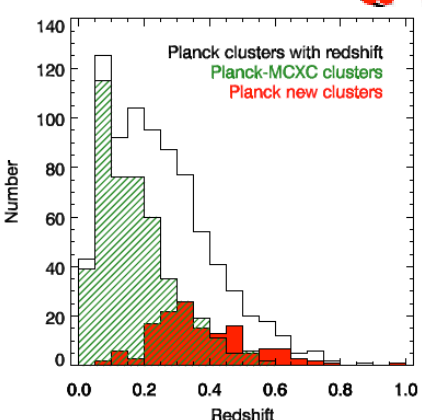
thermal SZ effect **Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls**

PSZ: 1227 clusters, 861 confirmed, 178 by Planck + 683 known, rest in class 1, 2, 3

cf. X-ray sample from ROSAT+ All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*

REFLEX, BCS, SGP, NEP, MACS, CIZA, 400SD, 160SD, SHARC, WARPS, EMSS





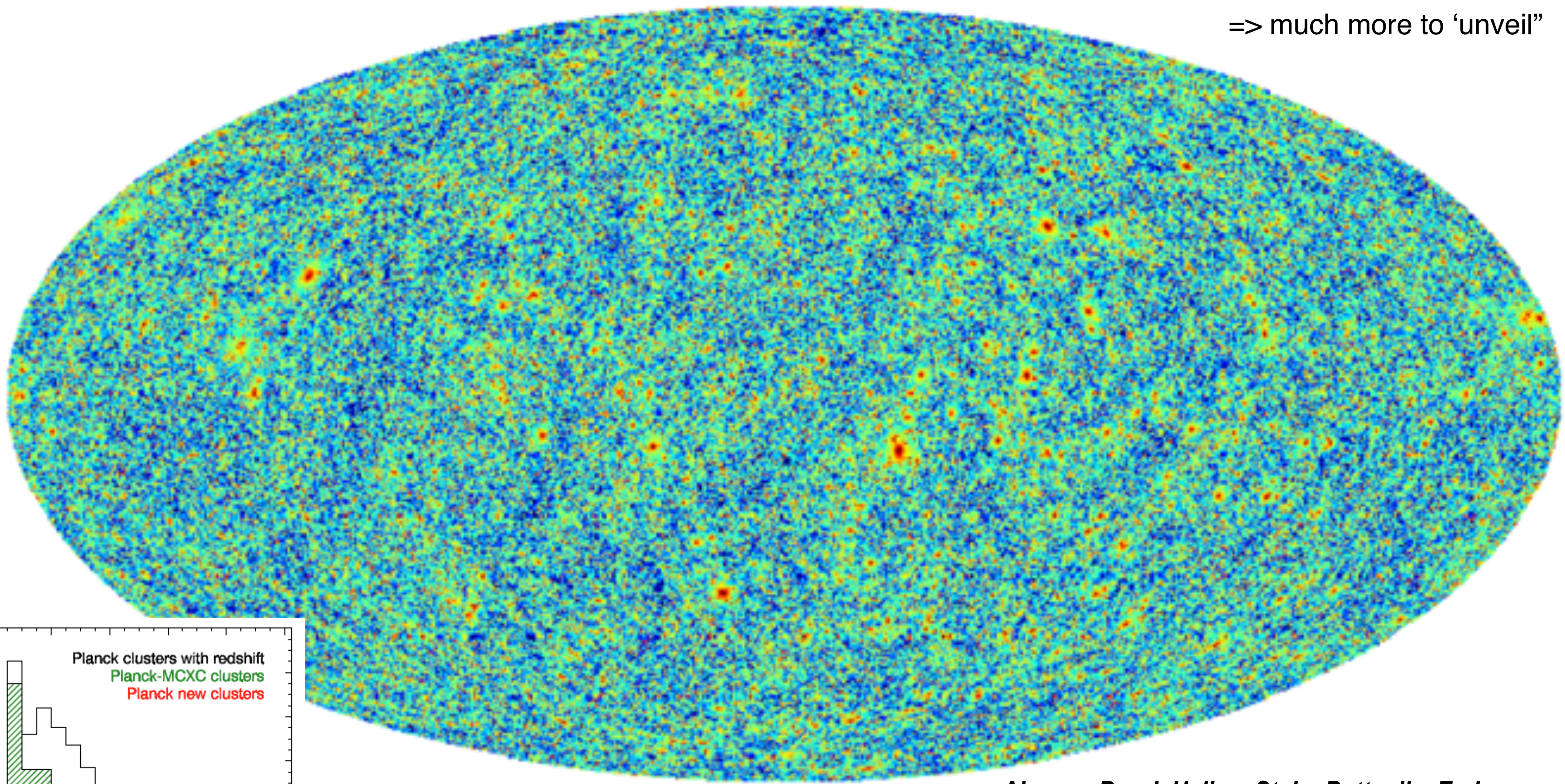
the **Cosmic Web of Clusters**, seen thru Compton cooling of high pressure electrons by the CMB

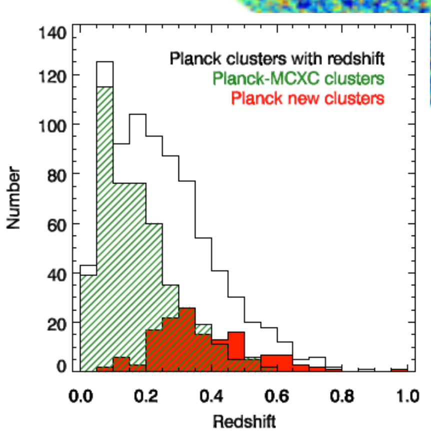
tSZ effect

Lightcone Simulation of 35000 Clusters > 2×10^{13} M_{sun} to z=0.5 in projected pressure

Planck all-sky, ~5', ACT ~ 1000 sq deg 1.4', SPT ~ 2500 sq deg 1'

=> much more to 'unveil"





Alvarez, Bond, Hajian, Stein, Battaglia, Emberson,..2014

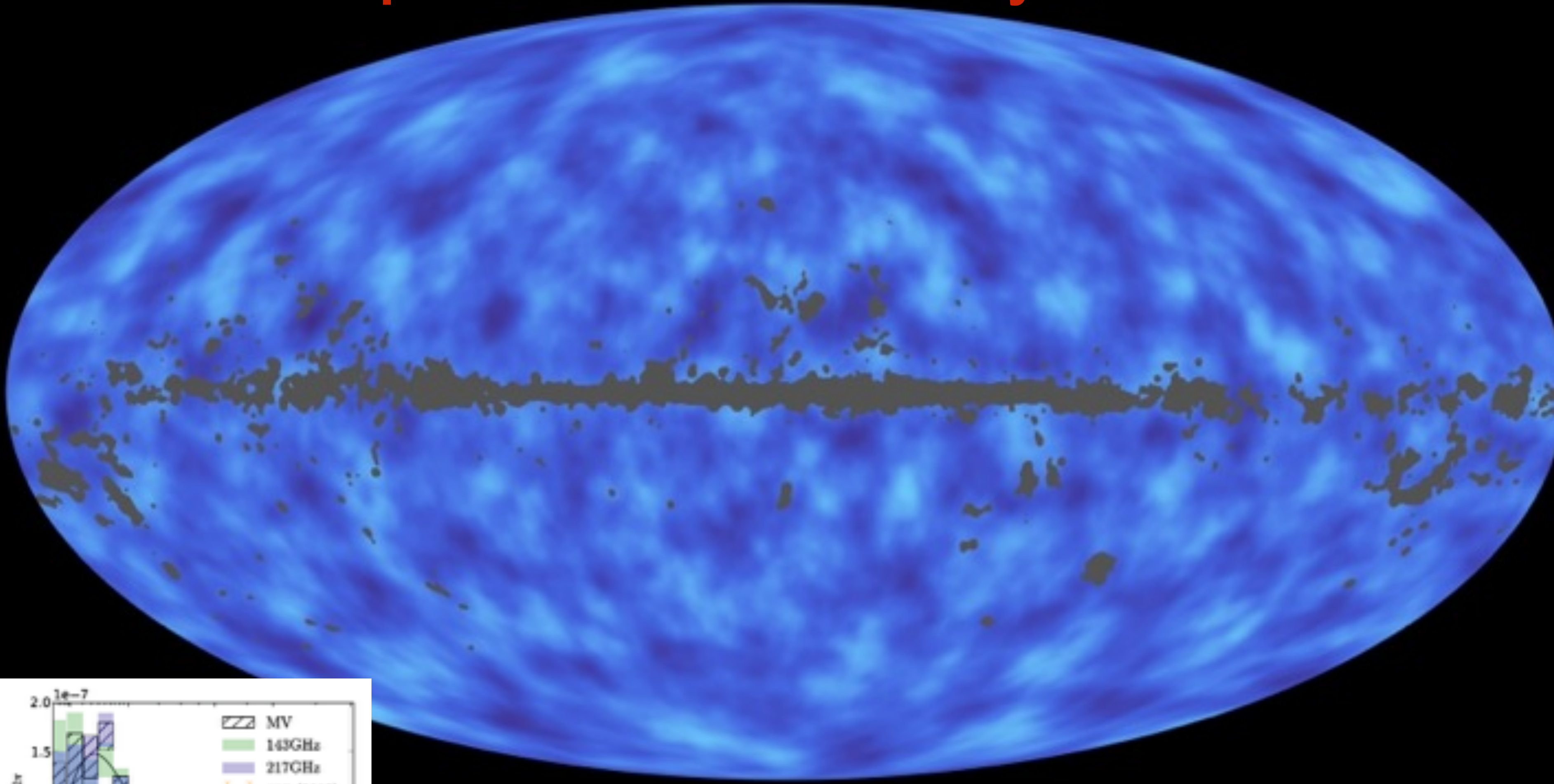
wall clock ~ 1.5 hrs on 256 cores of SciNet@UofT,

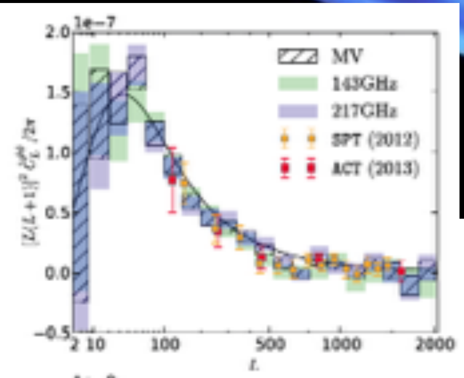
painted-on BBPS mean-fields from hydro sims with AGN feedback

Planck1.3 CMB Lensing: reconstructed projected gravitational potential map *(!)*

*~ dark+baryonic matter map, mean-field map = **Wiener filter** (beware: fluctuations about mean-field)*

photons under strain by tides

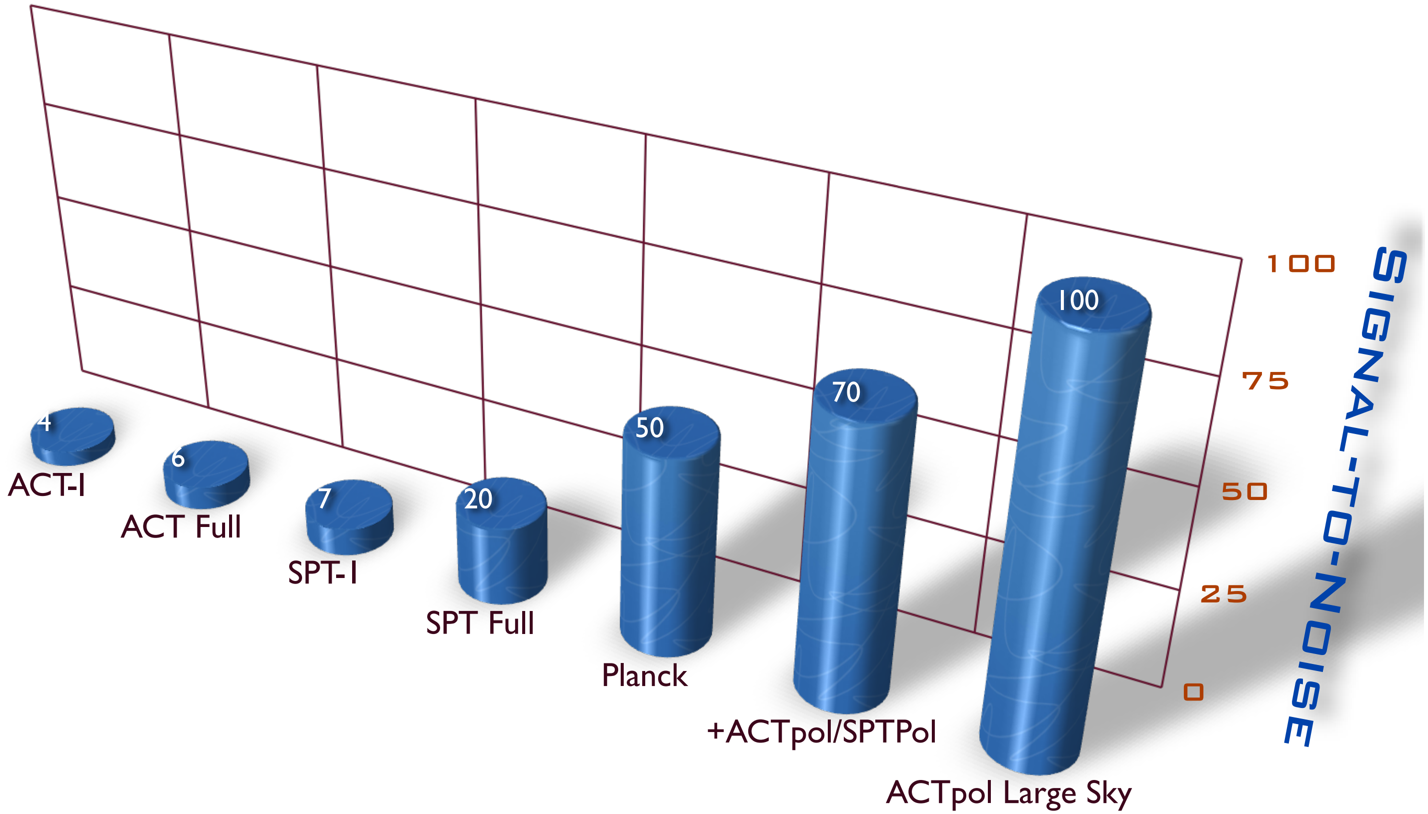




related to primordial scalar curvature map

photons under strain by tides

CMB Lensing is going to explode as a field in the next few years



Das, pre-Planck

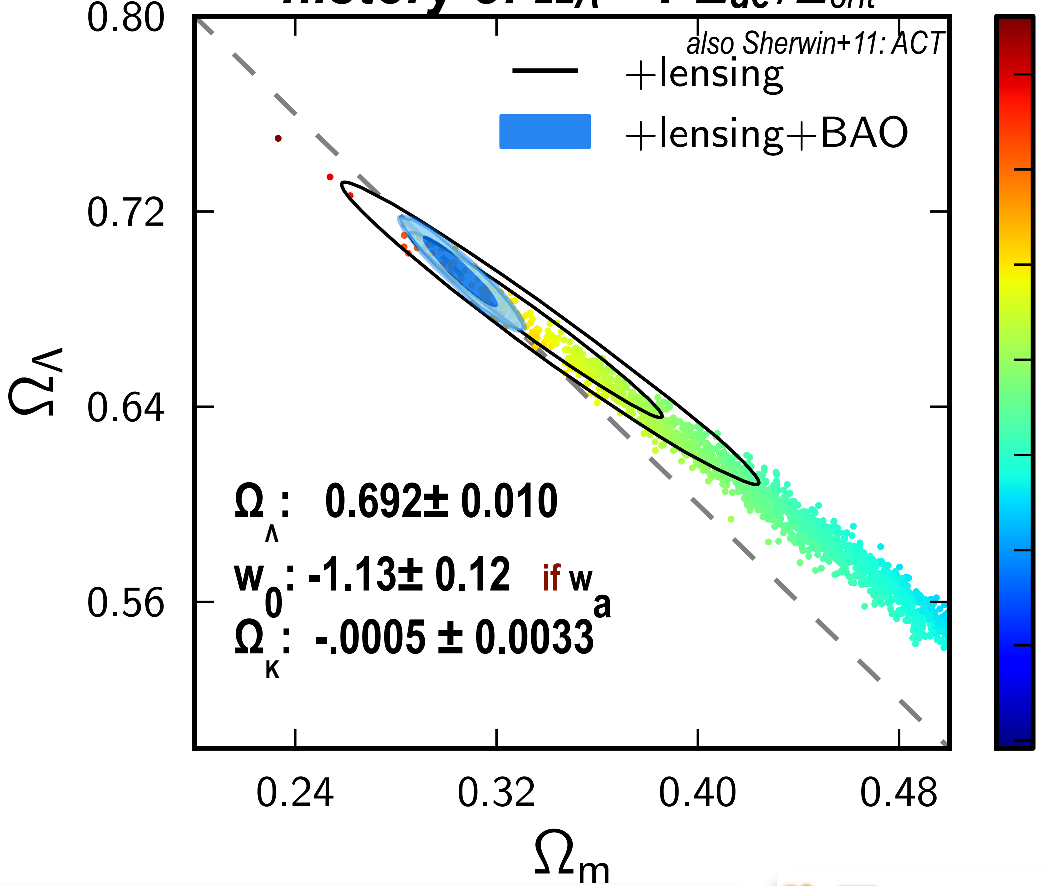
Dark Energy => inflation now

*CMB **lensing breaks "geometrical degeneracy":***

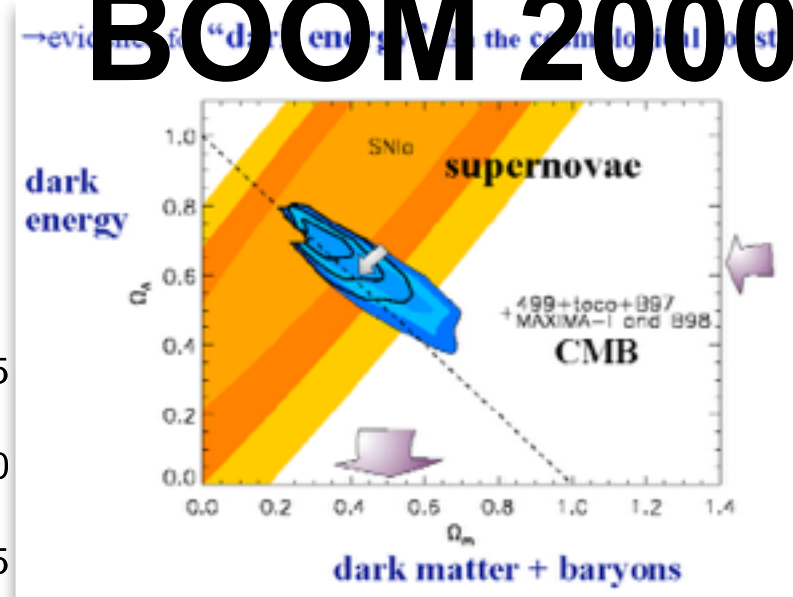
Planck alone cf. Planck+BAO

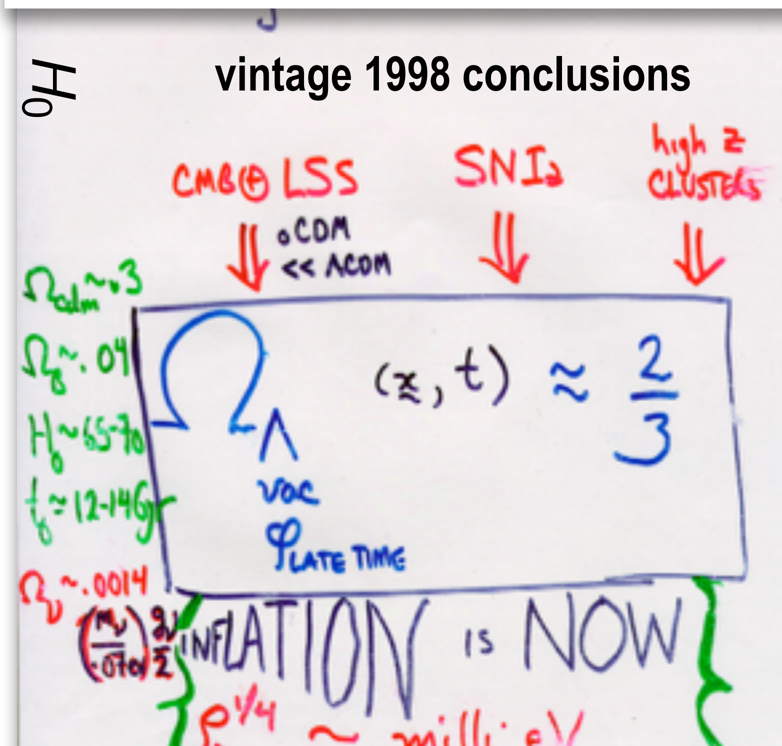
Planck1.3 cf. CMB+LSS

history of $\Omega_\Lambda = PE_{de}/E_{crit}$



BOOM 2000

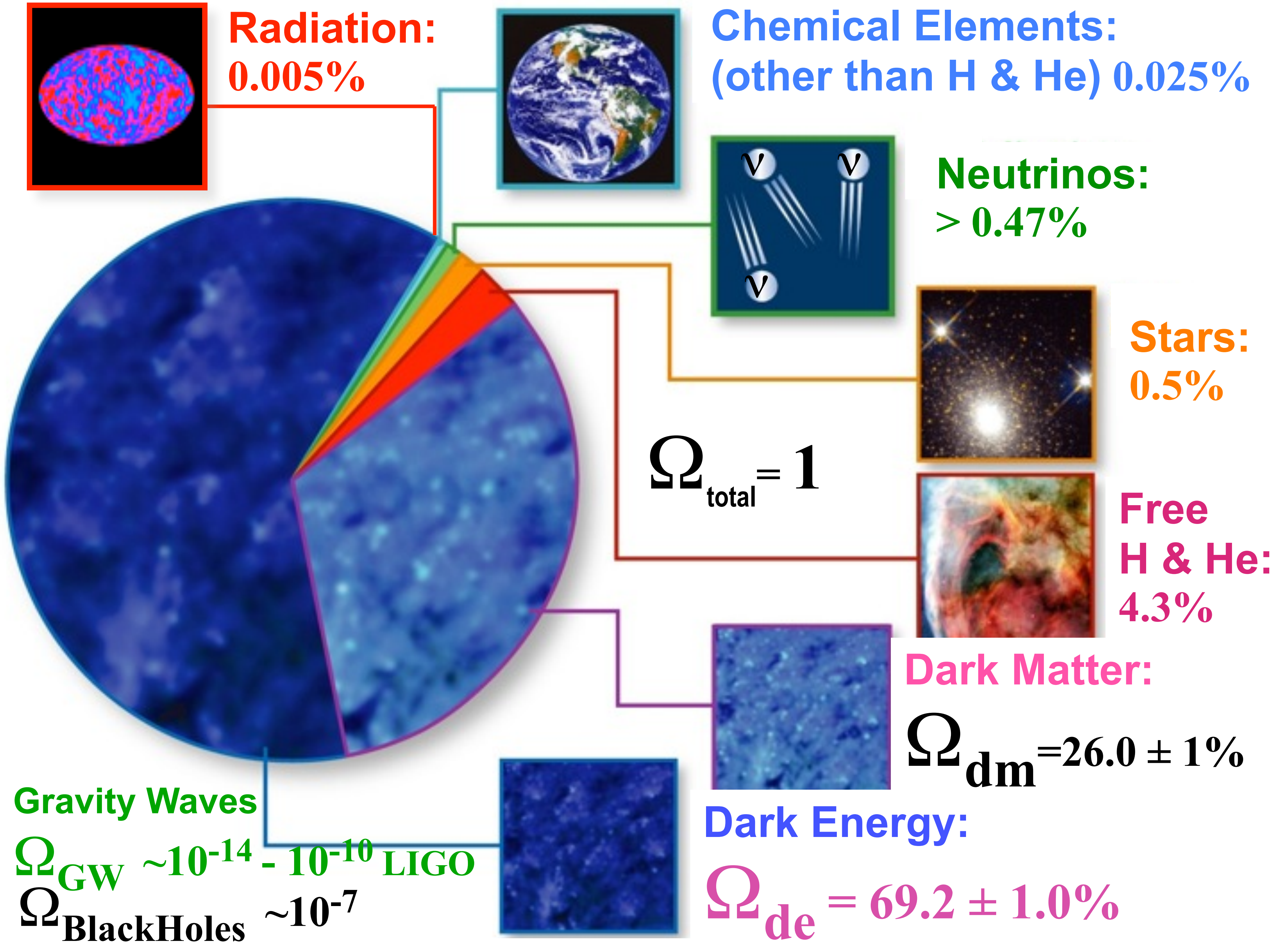




B+Jaffe'96,'98

$\Omega_\Lambda \approx 2/3 \pm .07$ +LSS

$n_s=$
$.98 \pm .07$
$.96 \pm .06$



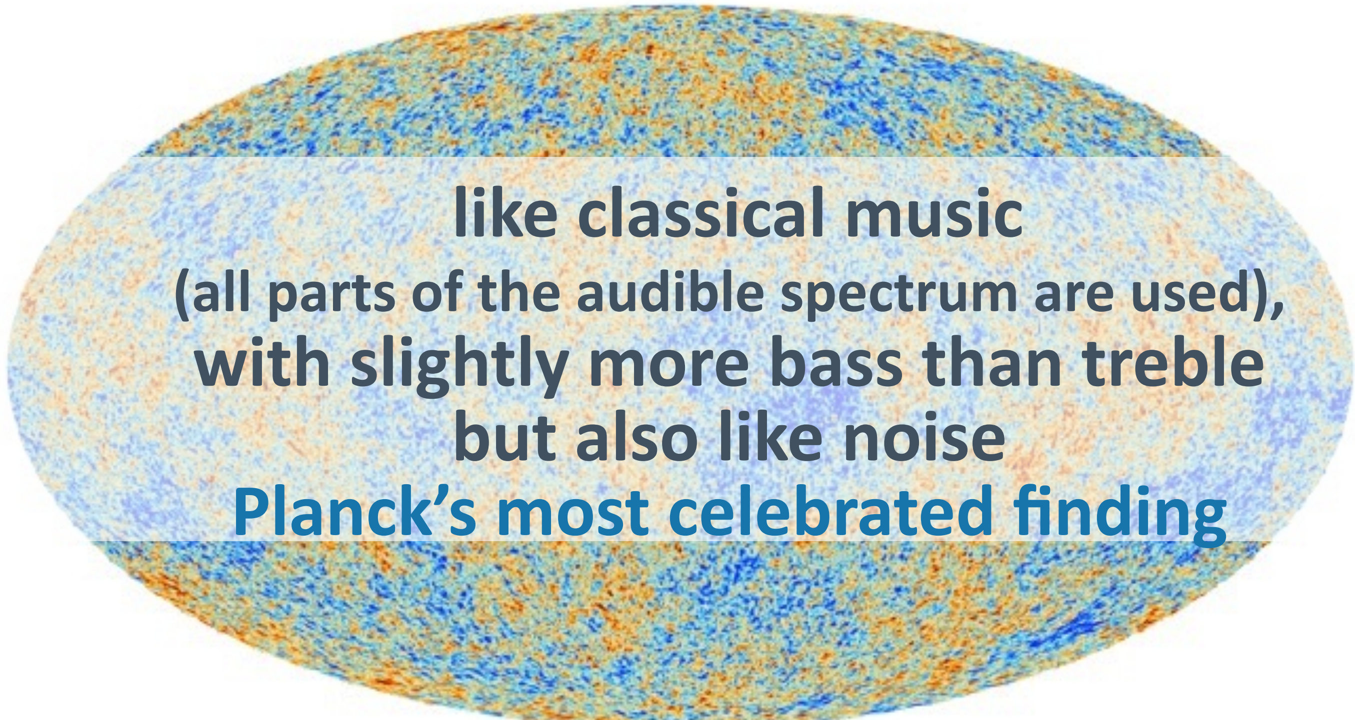
Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
> 0.47%
Stars:
0.5%
$\Omega_{total} = 1$
Free
H & He:
4.3%
Dark Matter:
$\Omega_{dm}=26.0 \pm 1\%$
Dark Energy:
$\Omega_{de} = 69.2 \pm 1.0\%$
Gravity Waves
Ω_{GW} ~10^{-14} - 10^{-10} LIGO
$\Omega_{BlackHoles}$ ~10^{-7}

CMB reveals ultra-early Universe sound waves

=> the inharmonious *'music of the spheres'* **in 7$^+$ numbers**

=> learn **matter & energy content & structure** at a~e^{-7} 380000 yr

=> infer structure **far far earlier** a~e^{-127} ~1/10^{55} **in 2 numbers**



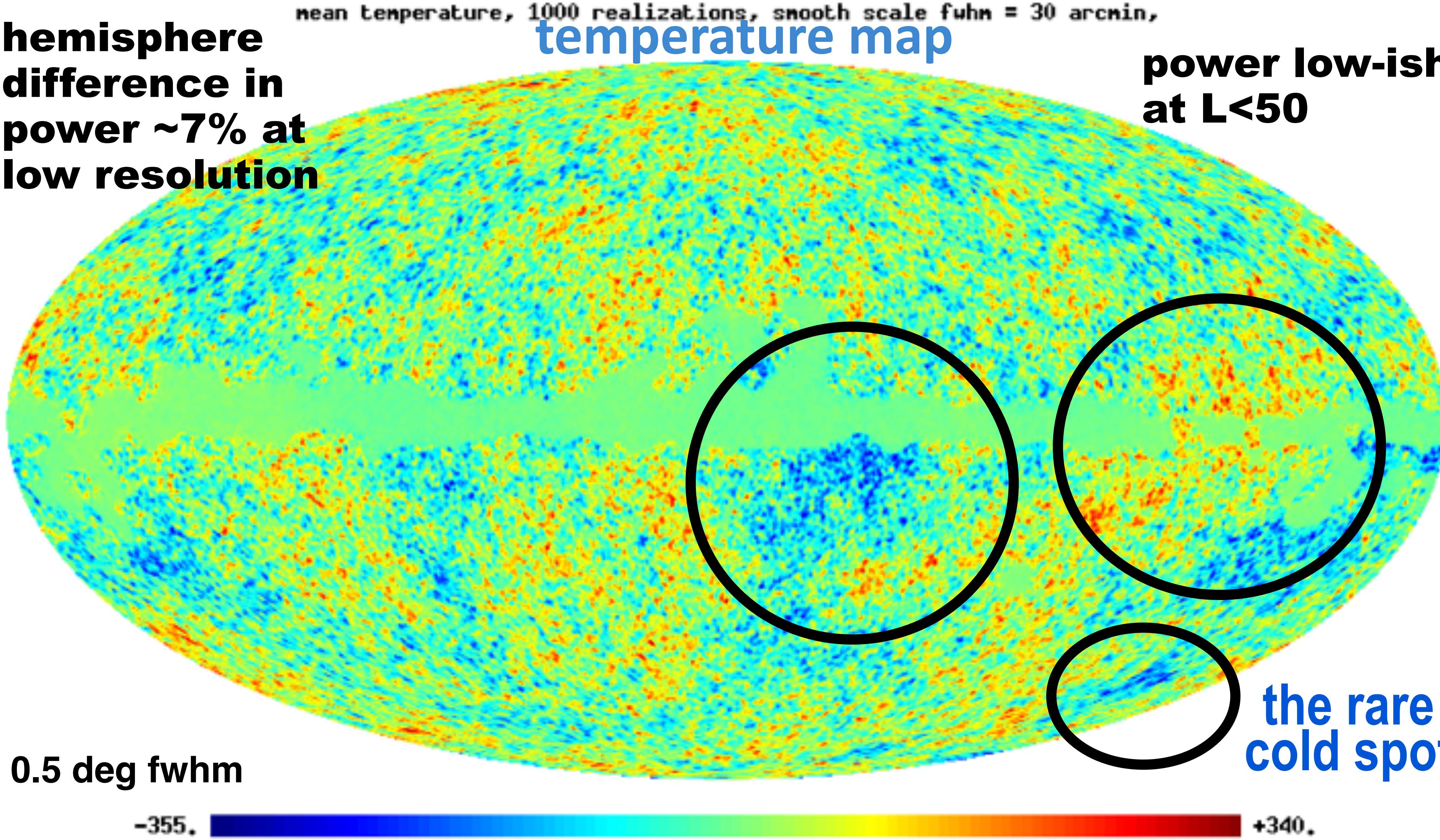
standard inflation space: P_s n_s $dn_s/d\ln k$ r =T/S @k-pivots

5σ from 1 **n_s =0.9608±0.0054** -0.014±0.009 **r <0.12** *cf.* **BICEP2**

*ln*Power$_s$~*ln*22.0x10^{-10} ±0.025 **r=0.20+.07-.05**

Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

anomalies => inflation COMPLEXITY at $t \sim 10^{-36}$ seconds?

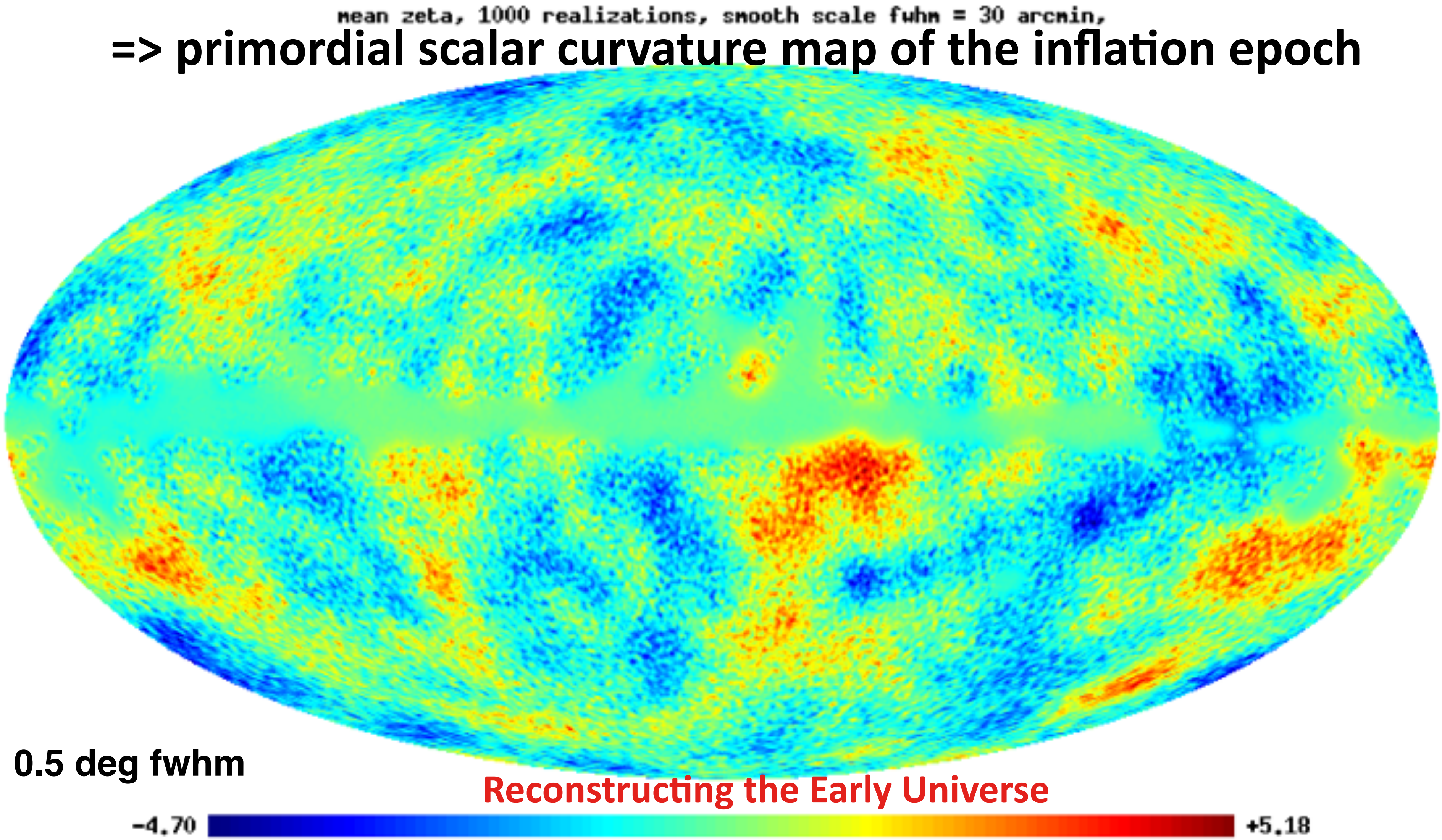


Grand Unified Theory of Anomalies? TBD

intermittent *strain-power bursts (in curvature)?*

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* $<$ ***Trace*****(α)**$|$*Temp*$>$ *(angles, distance)*



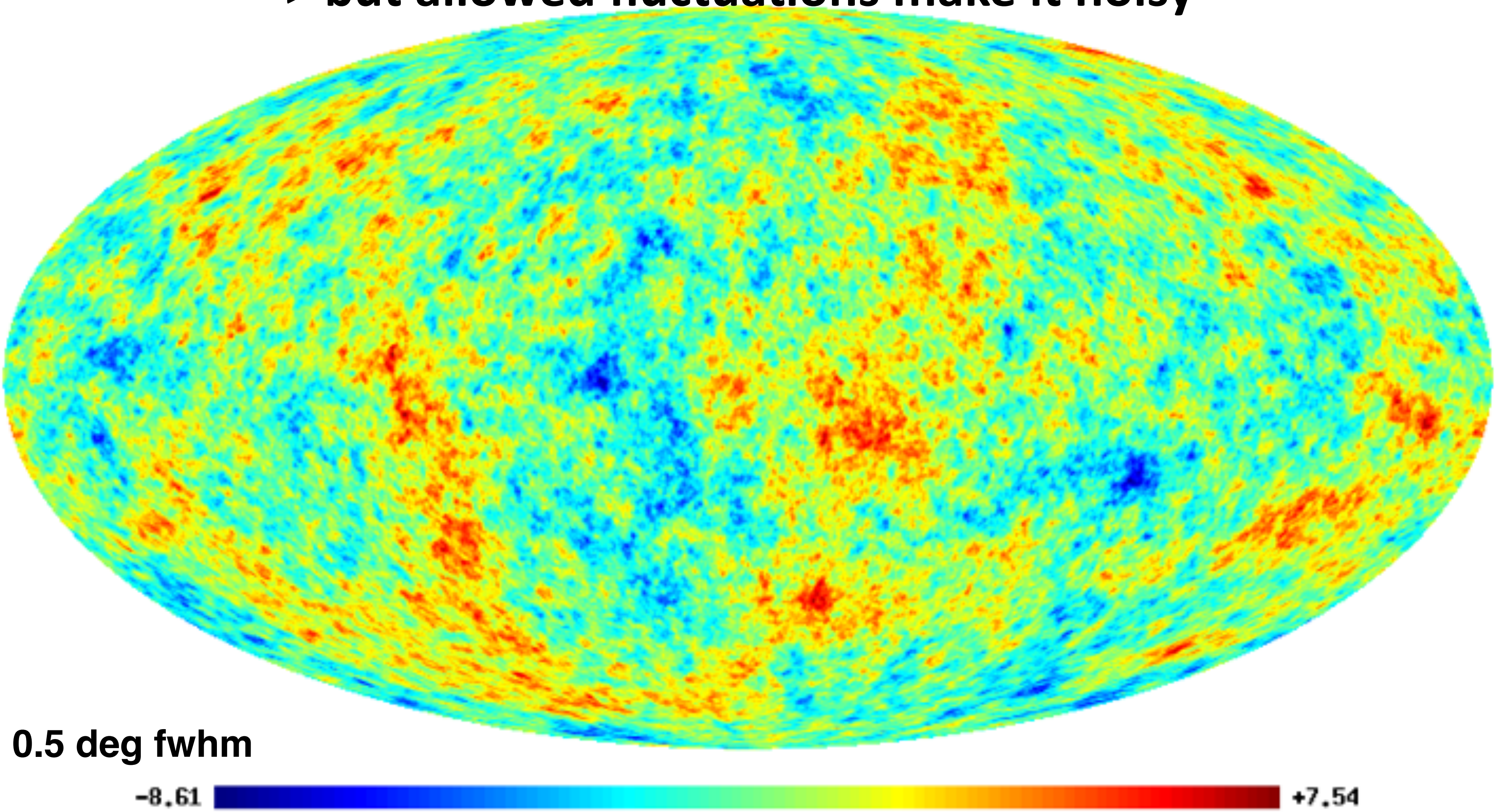
visibility mask

reveals map of **primordial isotropic strain /phonons**

$\int d\, \textit{visibility}(\textit{distance}) \;\; <\textbf{\textit{Trace}}(\boldsymbol{\alpha})|\textit{Temp}> + \delta \textbf{\textit{Trace}}(\boldsymbol{\alpha})$

one realization of fullsky zeta, fwhm = 30 arcmin

=> but allowed fluctuations make it noisy



Reconstructing the Early Universe **visibility mask**

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility*** *(distance)* $<\mathit{Trace}(\boldsymbol{\alpha})|\mathit{Temp}> + \delta \mathit{Trace}(\boldsymbol{\alpha})$

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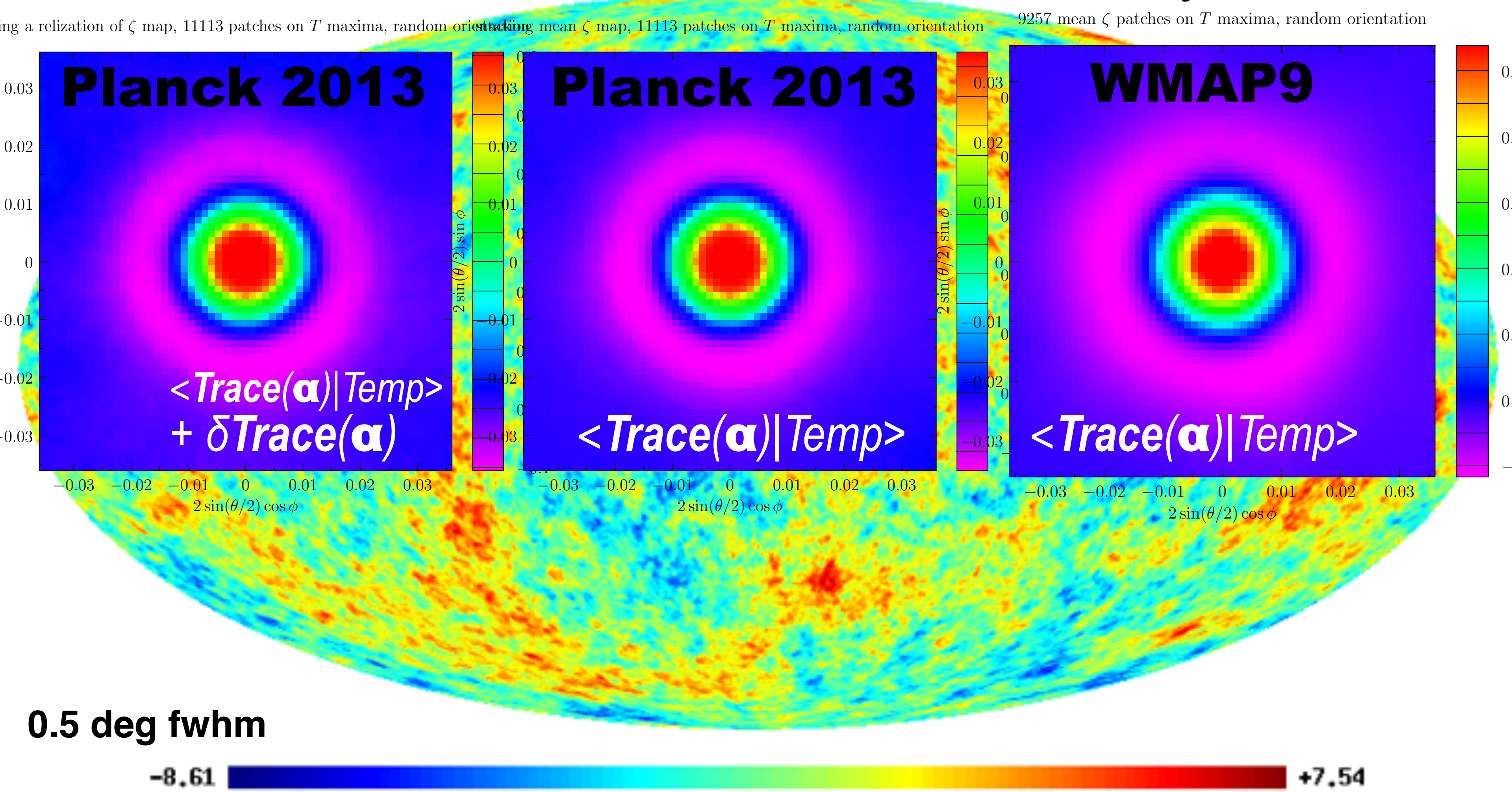

Reconstructing the Early Universe **visibility mask**

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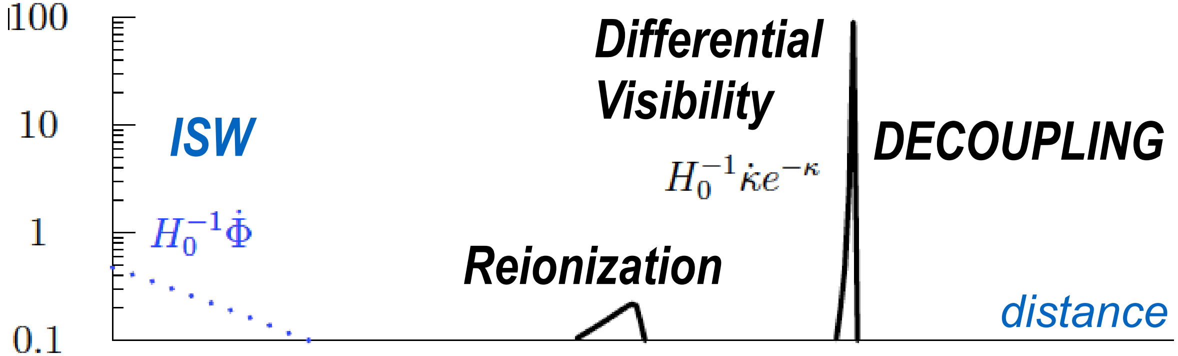


CMB-*probe* no tomography (***radial distance (redshift)***):

CMB-*probe* ~ differential visibility

at decoupling/recombination (all L)

reionization/reheating (low L)

CMB-*probe* ~ changing gravitational potential

Integrated Sachs Wolfe effect **(low L), Rees-Sciama** effect **(hi L)**

available modes: $f_{sky} L_{max}^2$ $-f_{sky} L_{min}^2$ $L_{max} \sim L_{damp}$

Large Scale Structure Galaxy Surveys

available modes ~ $f_{sky} L_{max}^2\ k_{max}\, d_{max}$

~ $f_{sky} (k_{max}^3\, d_{max}^3)$, $k_{min} \sim 2\pi/d_{max}$ $V_{com} \sim d_{max}^{\ 3}$

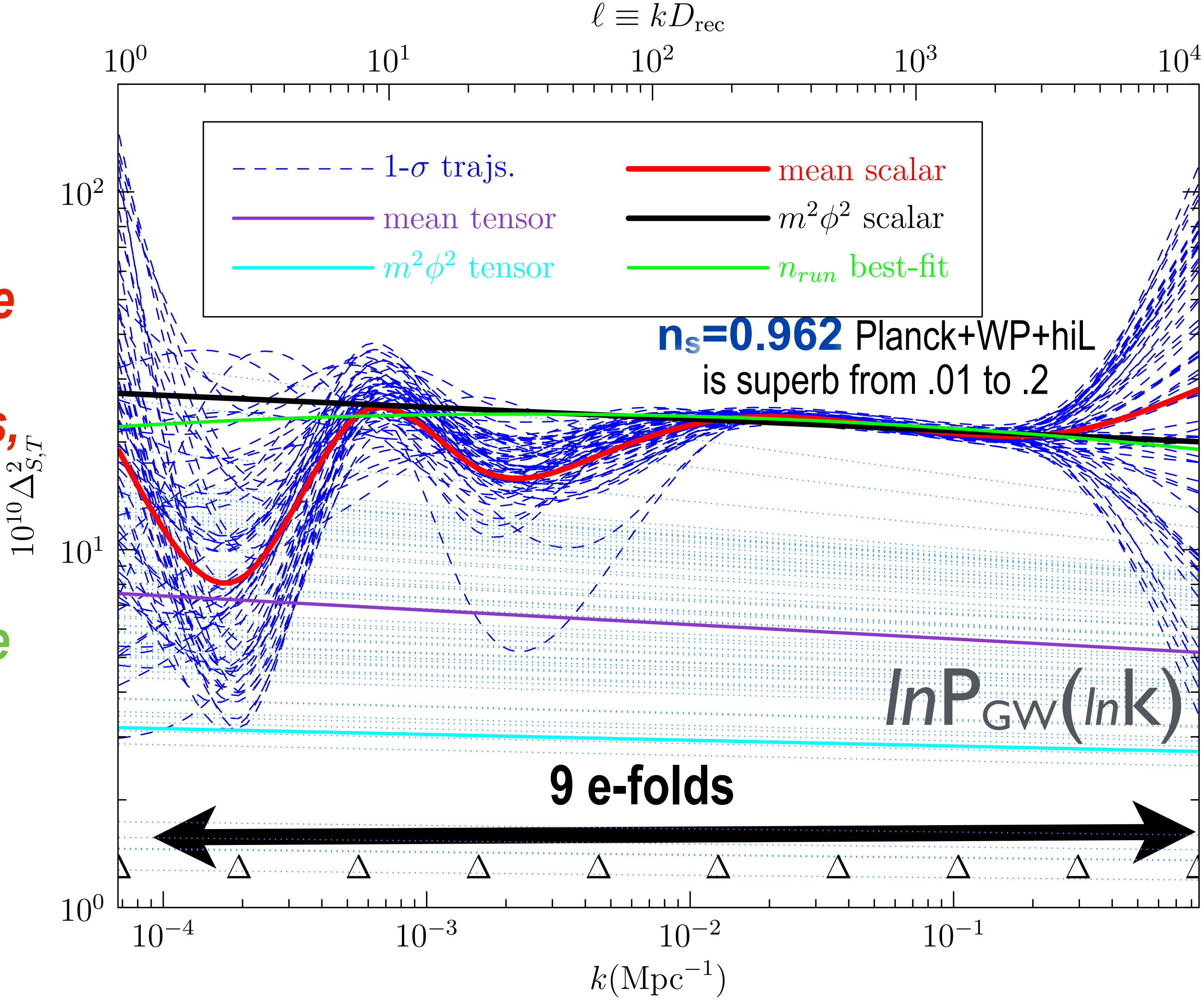
ultra-early Universe sound spectrum $ln P_s(ln k)$

new parameters:
trajectory probabilities for early-inflatons

no strong evidence for oscillation patterns, cutoffs, local features

but hints of change on large L<100 scales

PS: running of P_s is a bad fit



Bond, Braden, Huang, Frolov, Vaudrevange 2014

scan $ln\mathbf{P_s}(ln k)/A_s$, $ln\mathbf{A_s}=lnP_s(k_{pivot,s})$, $\boldsymbol{r}(k_{pivot,t})$; *consistency => reconstruct* **ε(lnHa), V(ψ)**

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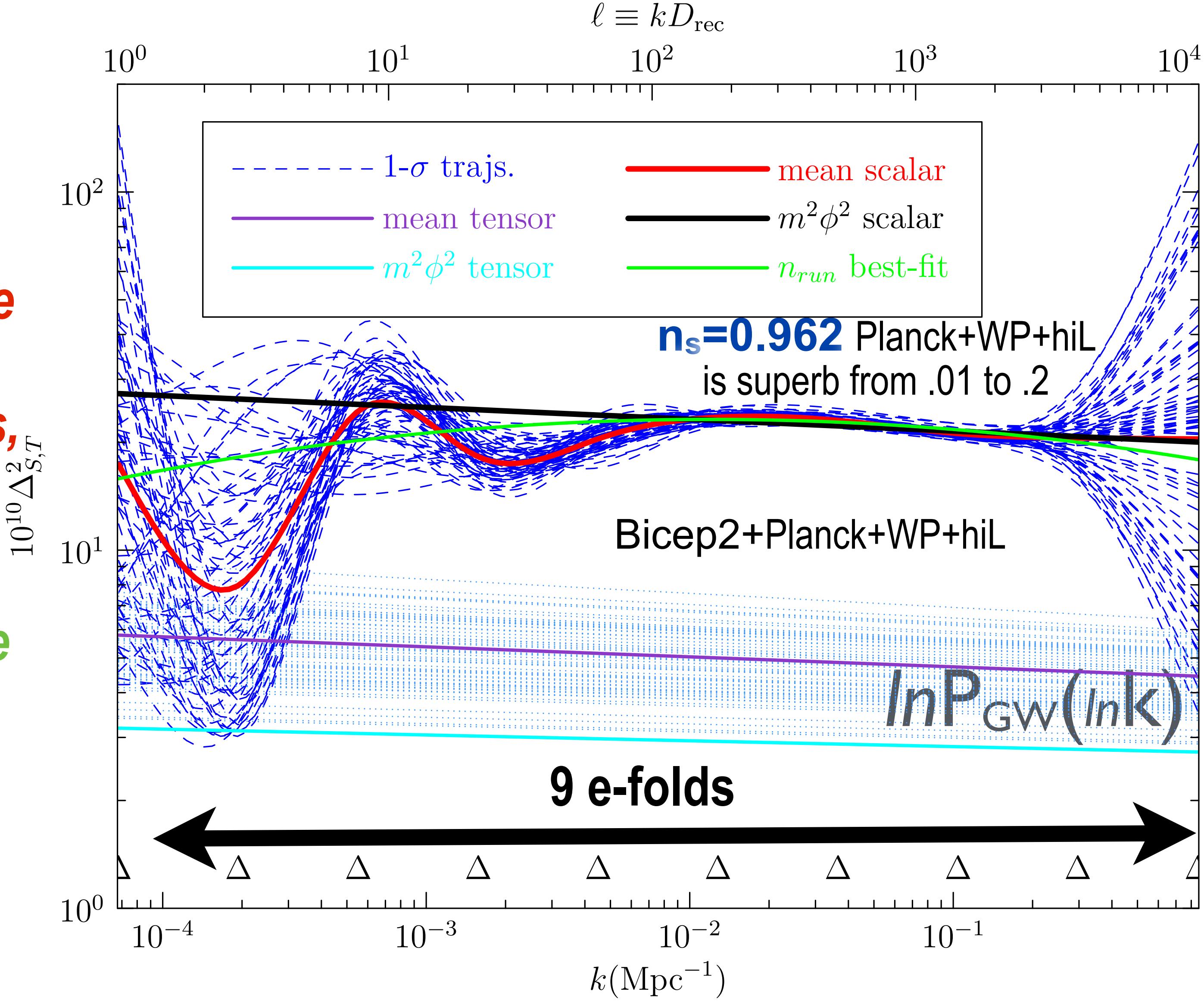


Bond, Braden, Huang, Frolov, Vaudrevange 2014

scan $\ln \mathbf{P_s}(\ln k)/A_s$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\boldsymbol{r}(k_{pivot,t})$; *consistency => reconstruct* $\boldsymbol{\varepsilon}(\ln Ha)$, $\mathbf{V}(\psi)$

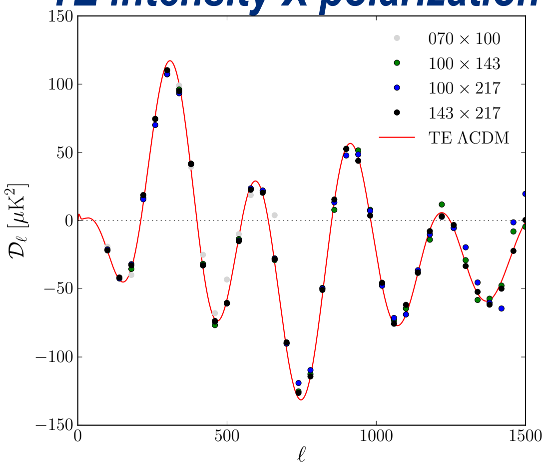
CMB Peak Statistics

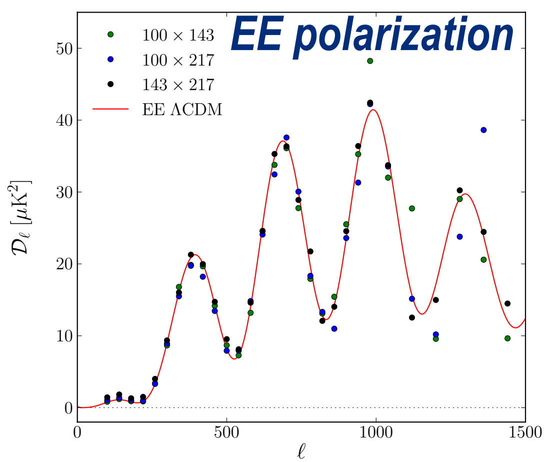
temperature stacked on temperature Peaks

polarization rotated & stacked on temperature Peaks

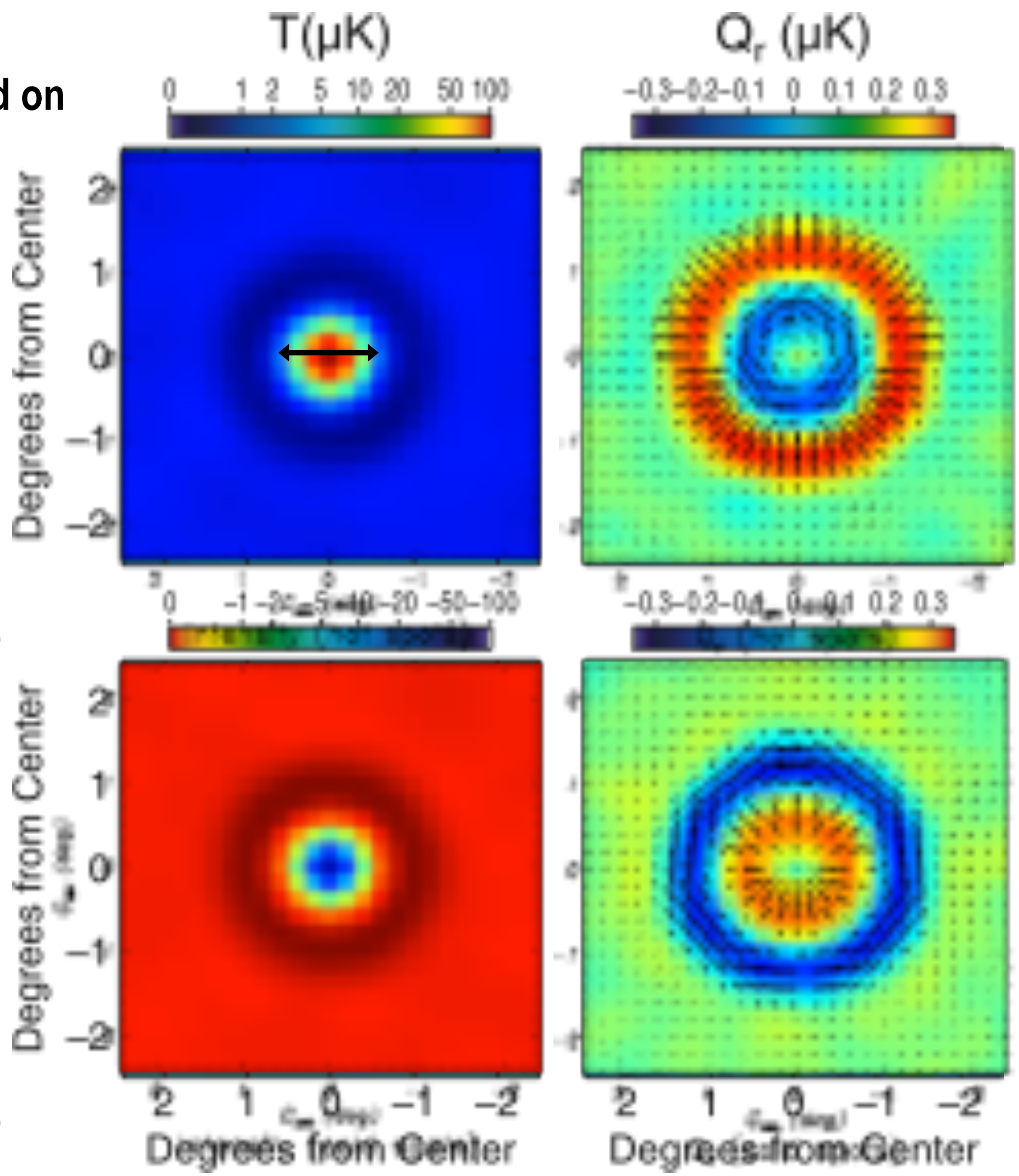
CMB Polarization
BAO in the CMB – Planck2013

TE intensity X polarization





EE polarization



Planck2013 teaser for Planck2014 polarization release

E mode patterns

no B here

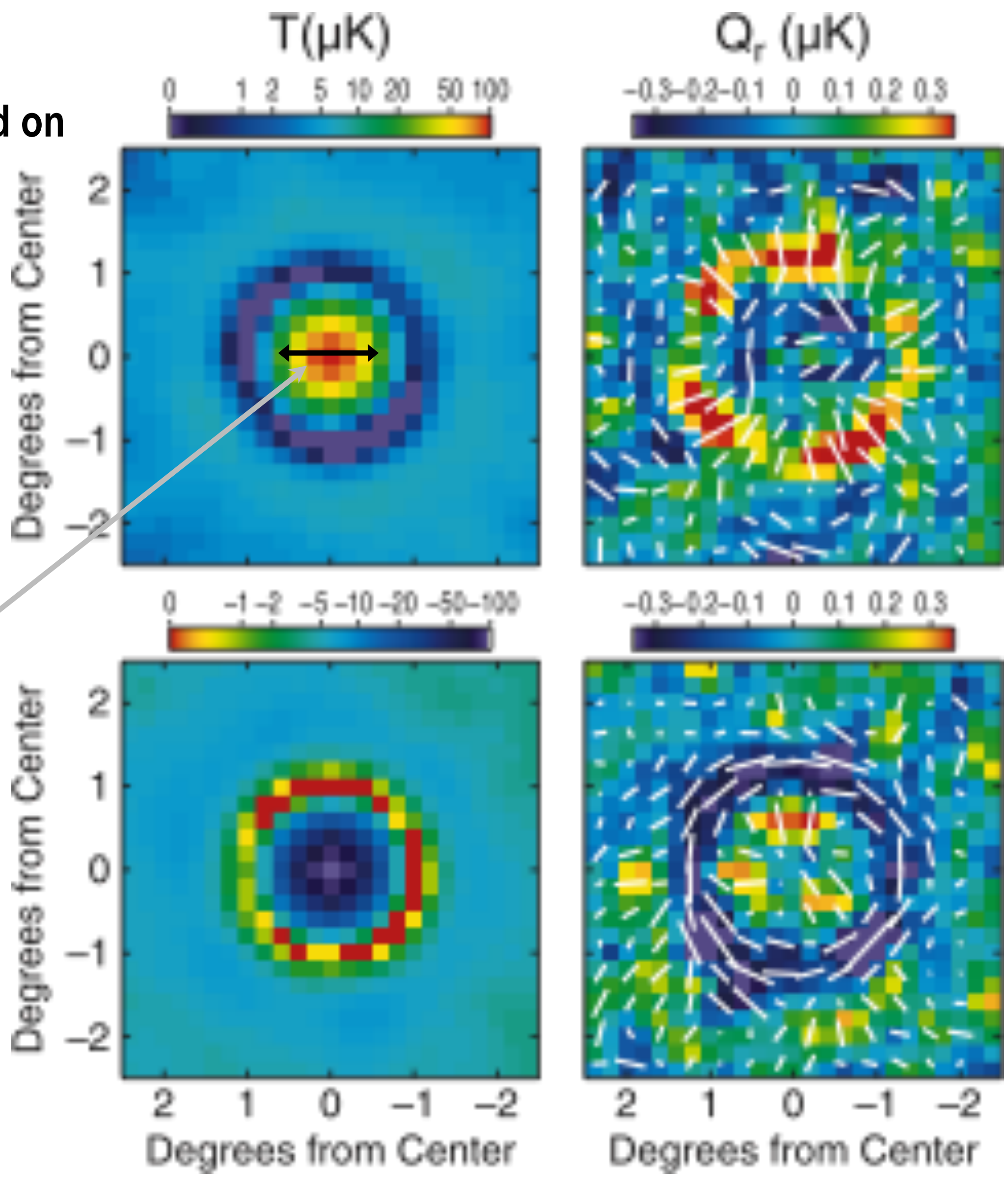
Planck2014, 2015 ACTpol, ABS, Spider, AdvACT, *GLP, ..*

CMB Peak Statistics

CMB Polarization
BAO in the CMB – WMAP9

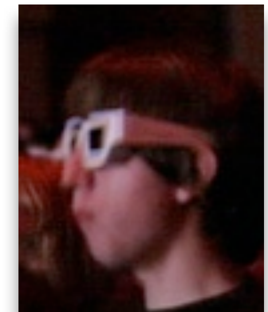
temperature stacked on temperature Peaks

polarization rotated & stacked on temperature Peaks



BAO scale:

145.8 ± 1.2 Mpc



CMB Peak Statistics

CMB Polarization
BAO in the CMB – WMAP9

temperature stacked on temperature Peaks

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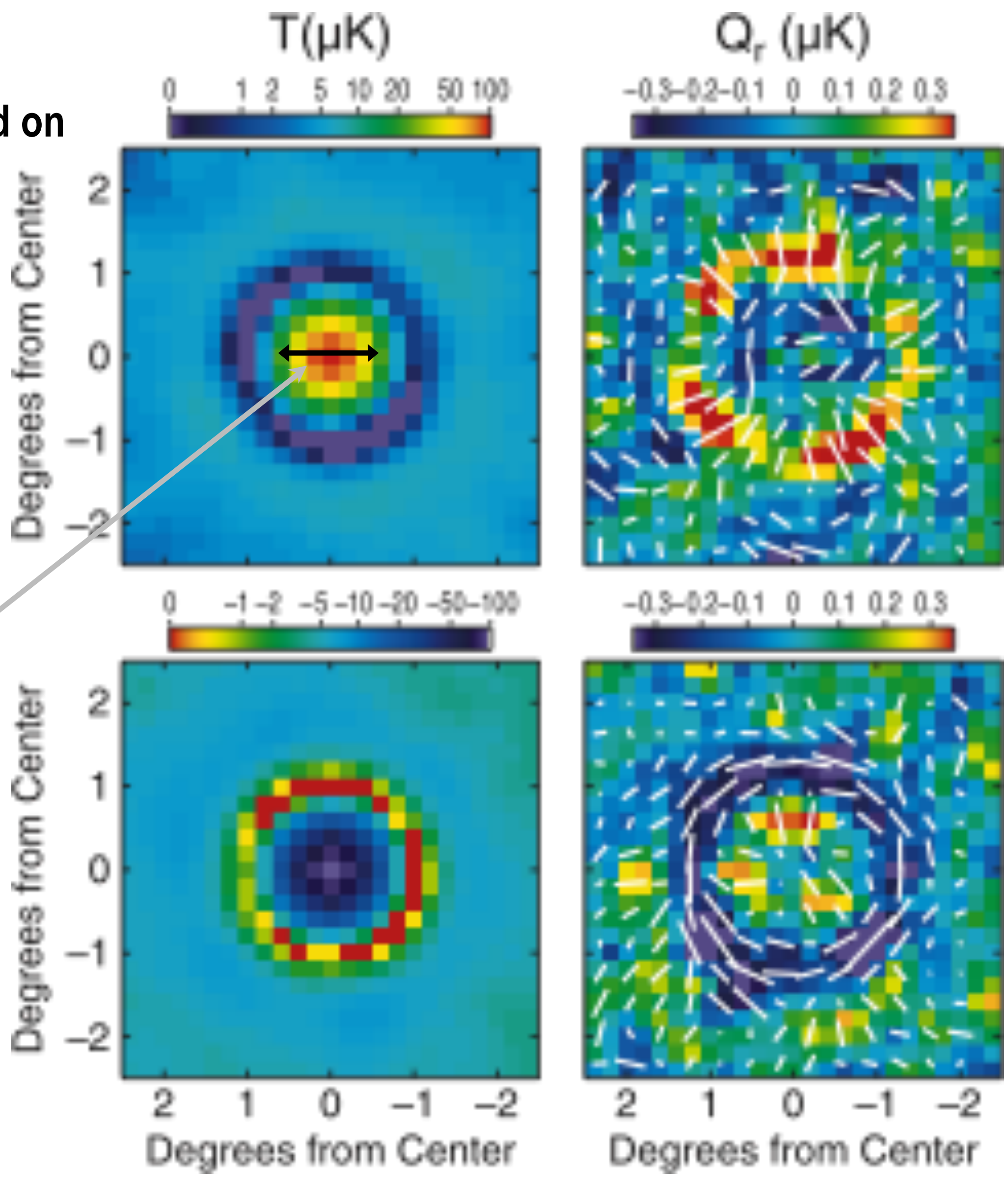
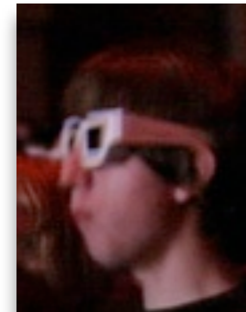


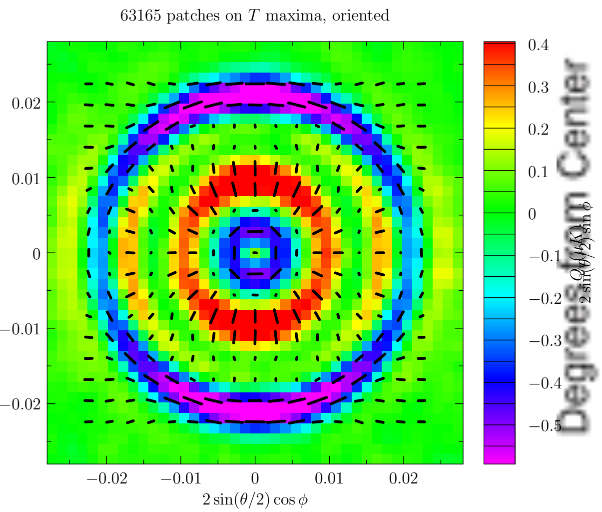


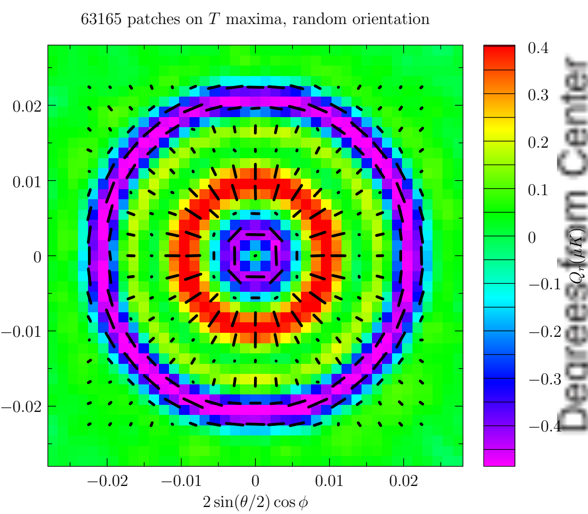
CMB Peak Statistics

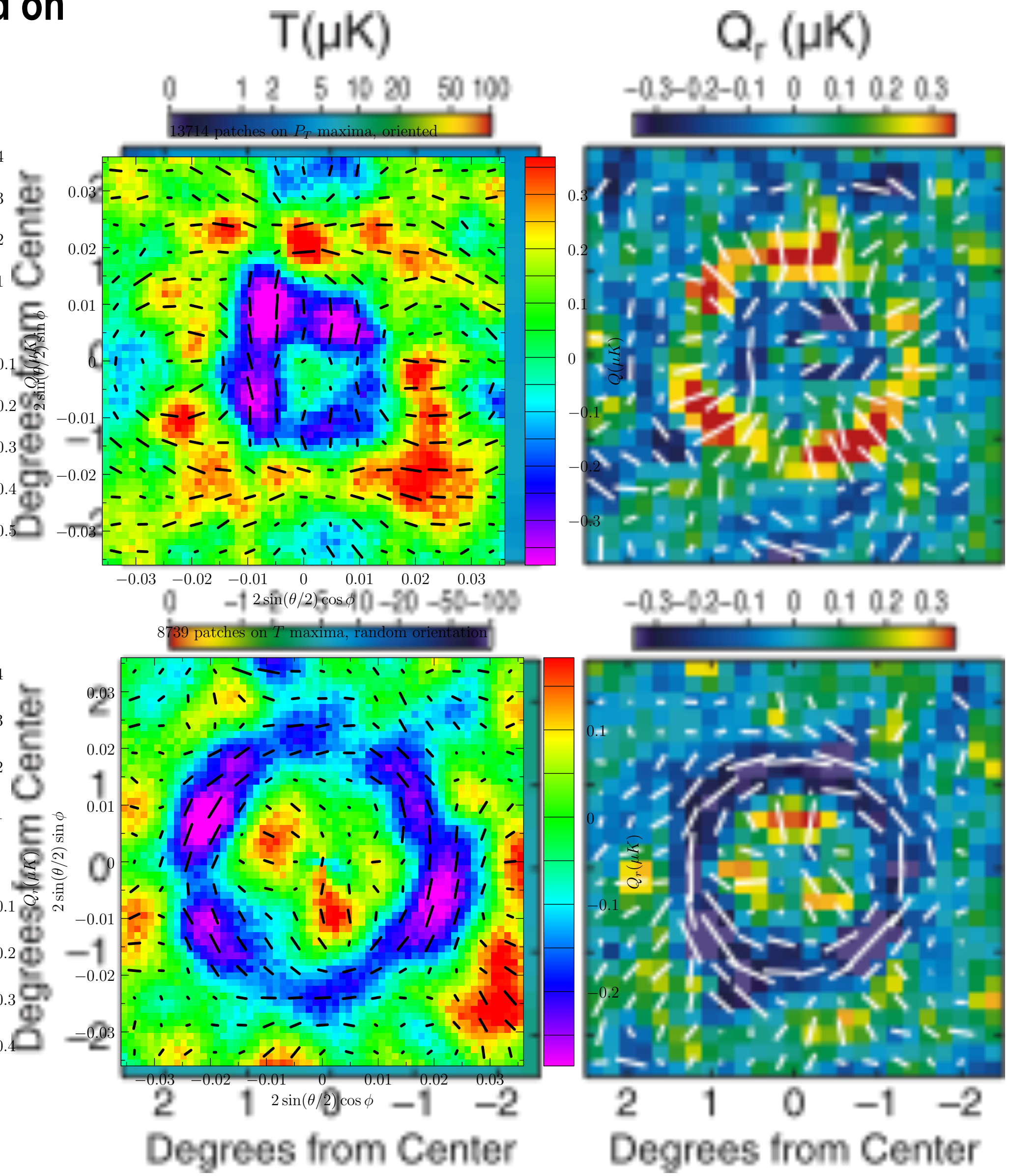
CMB Polarization

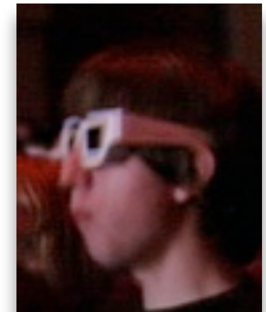
BAO in the CMB – WMAP9

polarization rotated & stacked on temperature Peaks









B mode of polarization *cf.* E mode

linear scalar fluctuations create only E patterns

strain from CMB lensing tides distorts E pattern into a bit of B *SPT*

anisotropic strain from **gravity waves => E & B**

photons under strain

BICEP2 collaboration 2014

380 sq deg

f_{sky}=0.009

512 antenna coupled TES bolometers
150 GHz for 3 seasons
cross-correlate with BICEP1, 100 GHz,
preliminary cross-correlate with KECK

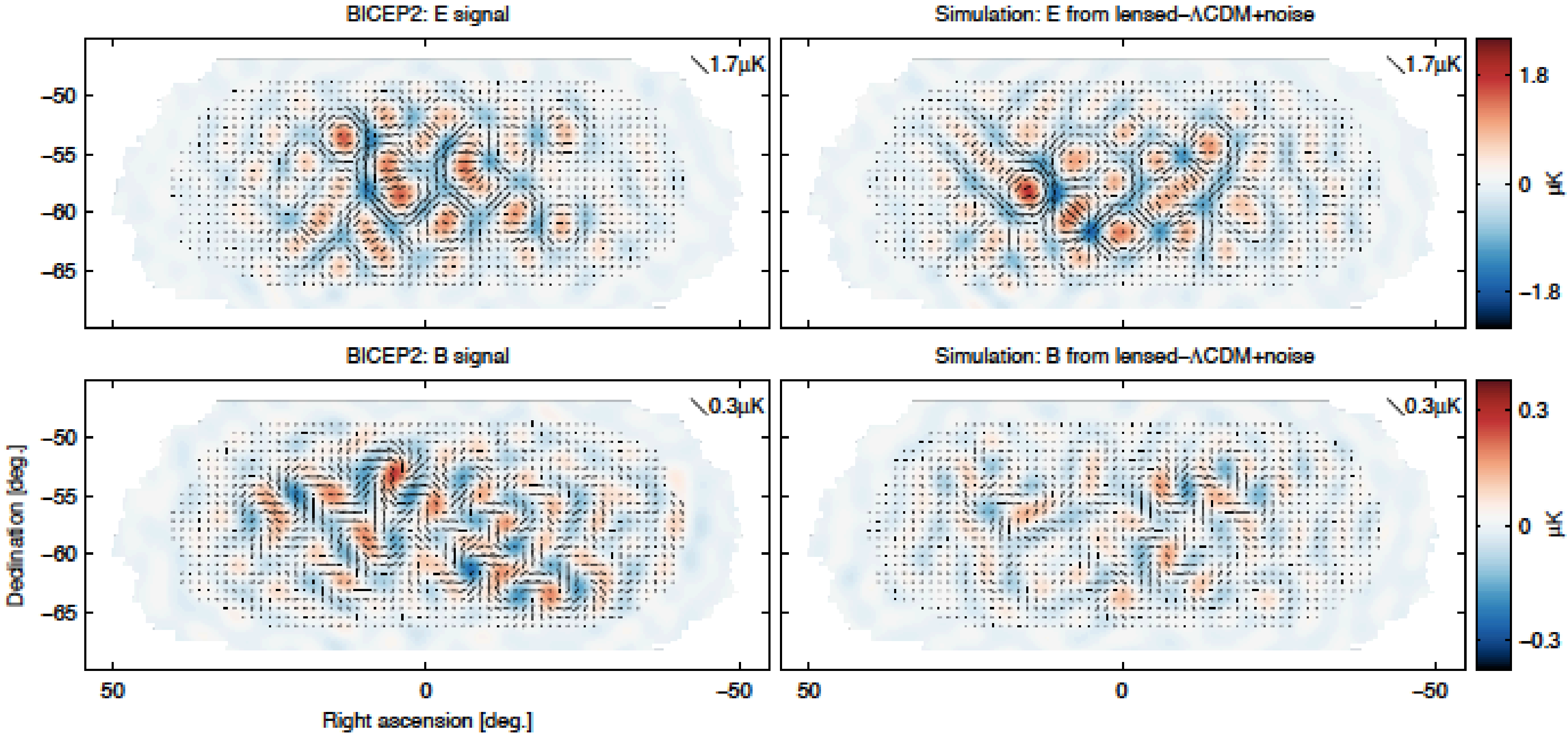
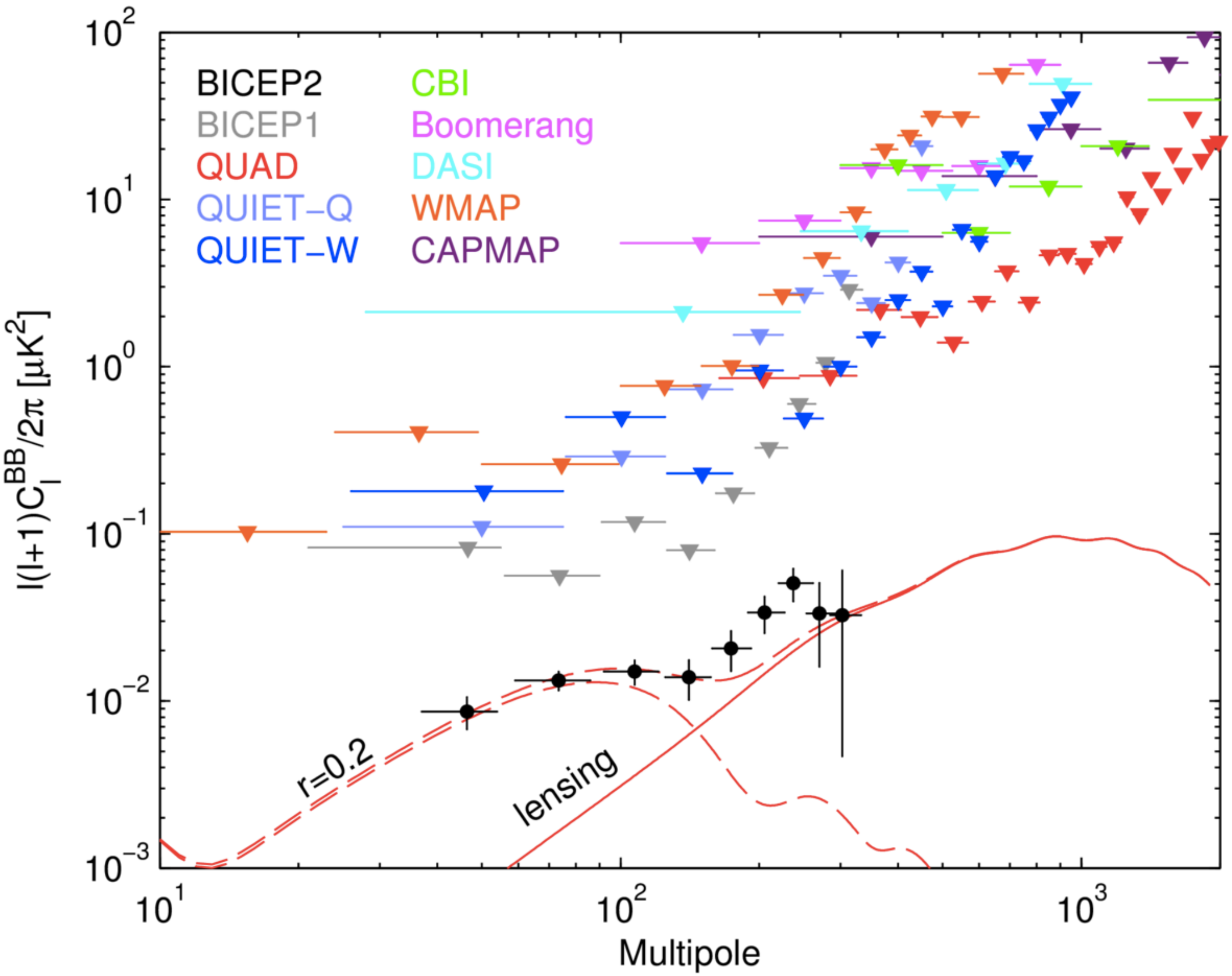


FIG. 3.— *Left:* BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-ΛCDM+noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess B-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the E-mode and B-mode maps use different color/length scales.)

BICEP2 collaboration 2014 non-lensing B mode => **r=0.20 +.07-.05**

cf. P13: r from TT < 0.12 95% CL



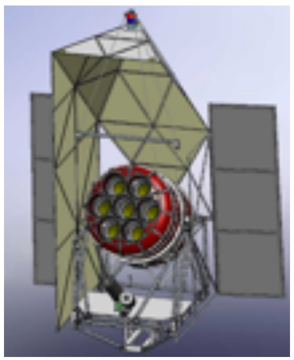
r=GW power/scalar-curvature power ≈0.13V/(2x10^{16}Gev)^4

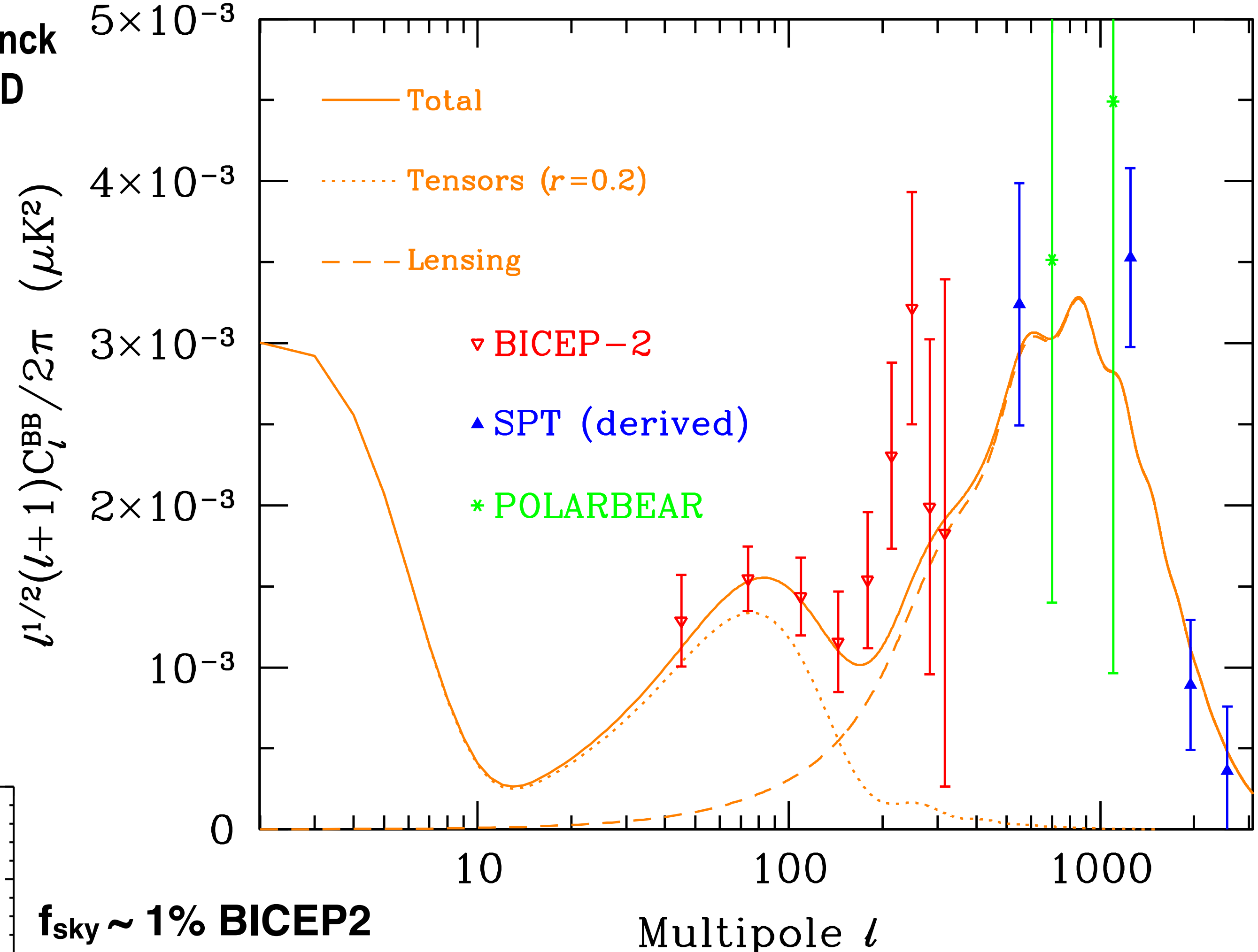
Potential Energy scale is the GUT level!

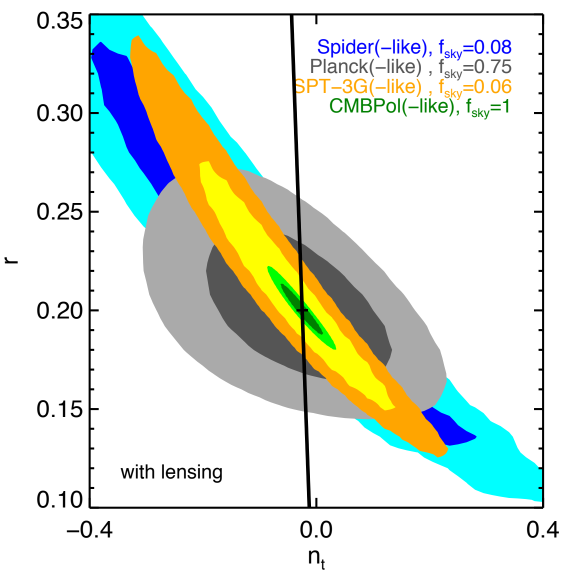
We are working heavily on Planck polarization, E Nov 2014, B TBD

Spider collaboration, LDB flight Fall 2014 +-.02

supposed to fly Fall 13, but US sequester stopped it







f_{sky} ~ 1% BICEP2
= 6% SPT3G
= 8% SPIDER
~ 70% + PLANCK

~ 50% AdvACT

Spider24days+Planck2.5yr:
r-n_t *matrix*-forecast
for r=0.2 input
($2\sigma_r$ ~0.04 including fgnds)

*similar r-forecasts for **ABS+, Keck, AdvACT,..***

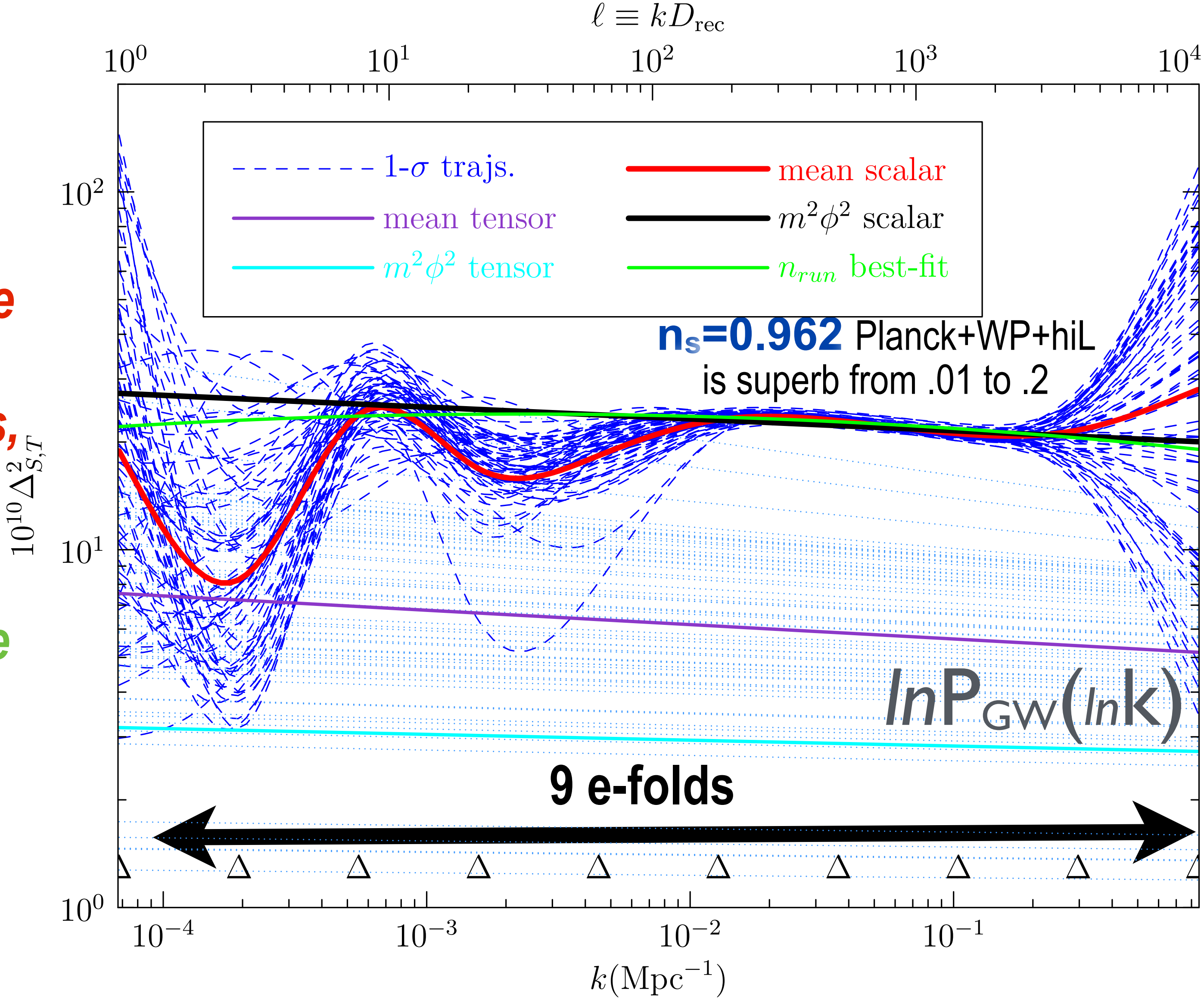
ultra-early Universe sound spectrum $lnP_s(lnk)$

new parameters:
trajectory probabilities for early-inflatons

no** strong **evidence for oscillation patterns, cutoffs, local features

but hints of change on large L<100 scales

PS: running of P_s is a bad fit



Bond, Braden, Huang, Frolov, Vaudrevange 2014

scan $ln\mathbf{P_s}(lnk)/A_s$, $ln\mathbf{A_s}=lnP_s(k_{pivot,s})$, $\boldsymbol{r}(k_{pivot,t})$; *consistency => reconstruct* **$\varepsilon(lnHa)$, $V(\psi)$**

ultra-early Universe **sound** spectrum *ln*P_s(*ln*k)

new parameters:
trajectory probabilities for early-inflatons

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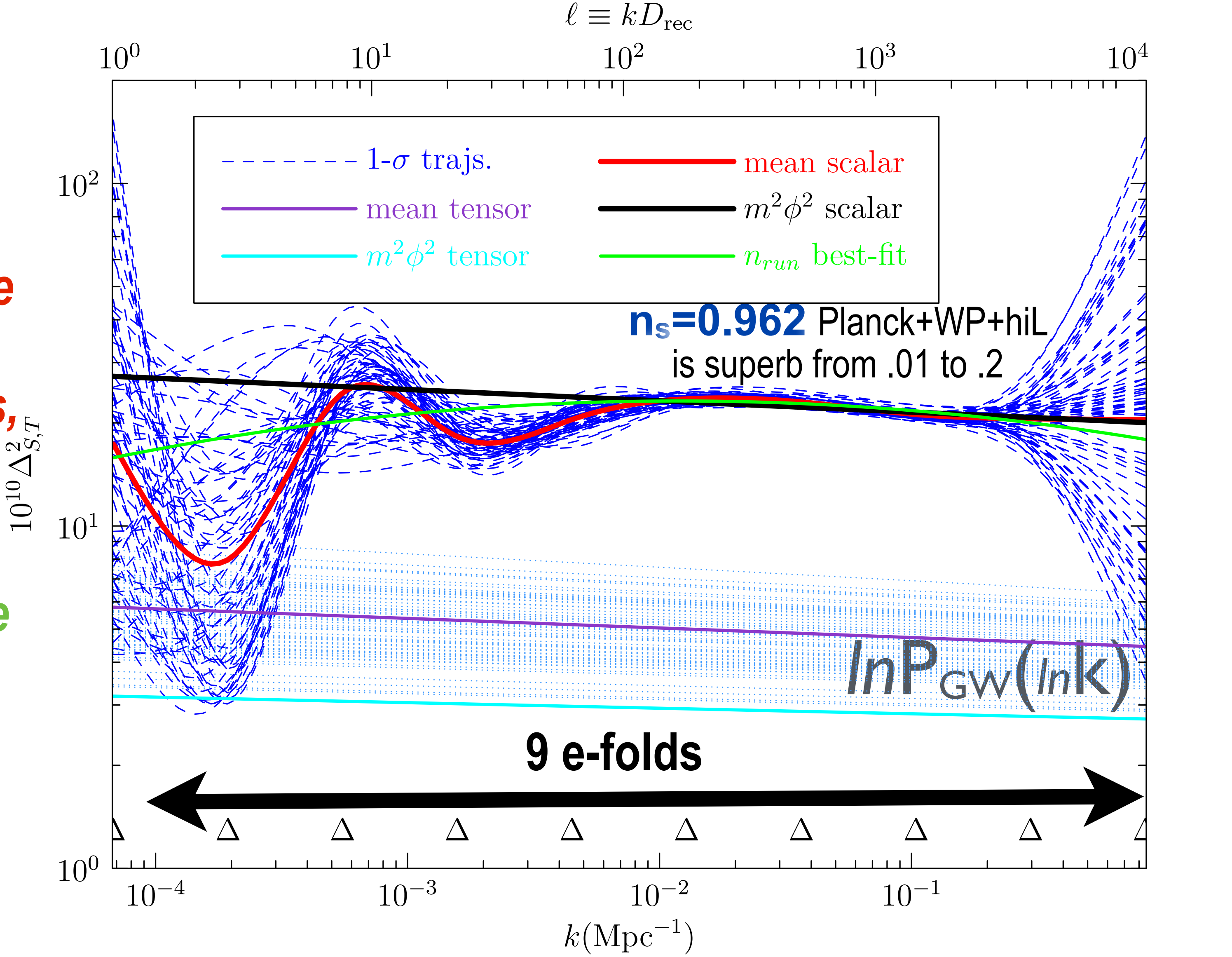
PS: running of **P**$_s$ is a bad fit



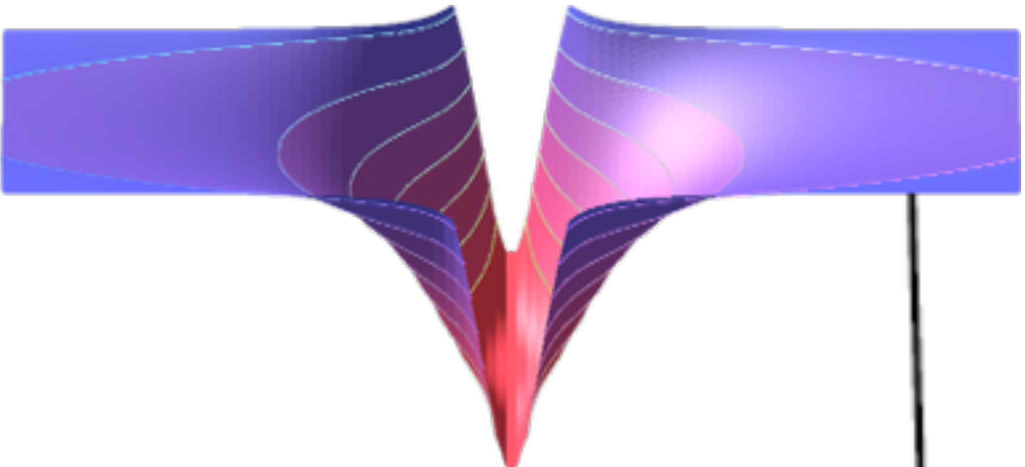
Bond, Braden, Huang, Frolov, Vaudrevange 2014

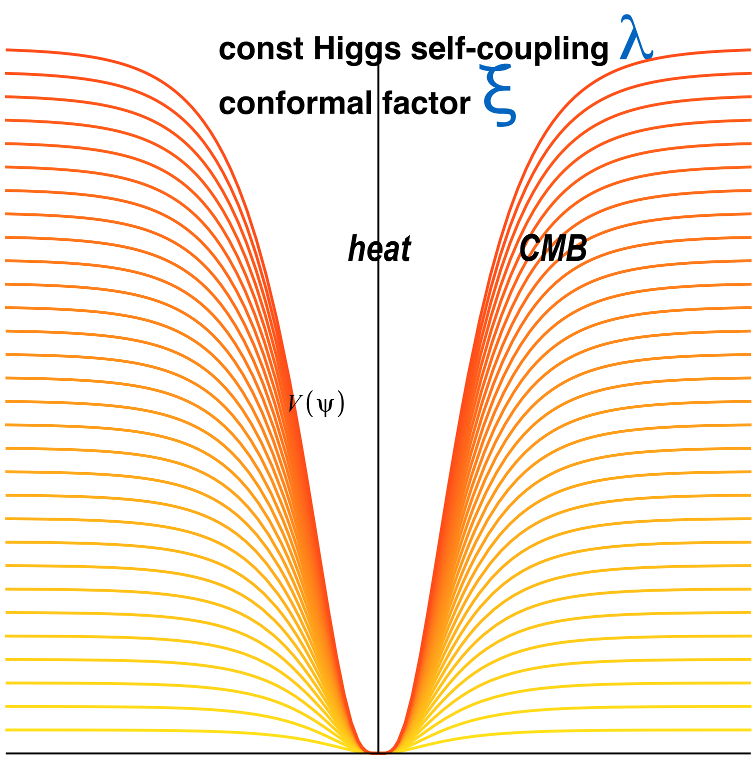
*scan ln***P**$_s$(*ln*k)/A$_s$, *ln***A**$_s$=*ln*P$_s$($k_{pivot,s}$), ***r***($k_{pivot,t}$); *consistency => reconstruct* **ε(*ln*Ha), V(ψ)**

what is the **inflaton's potential**?

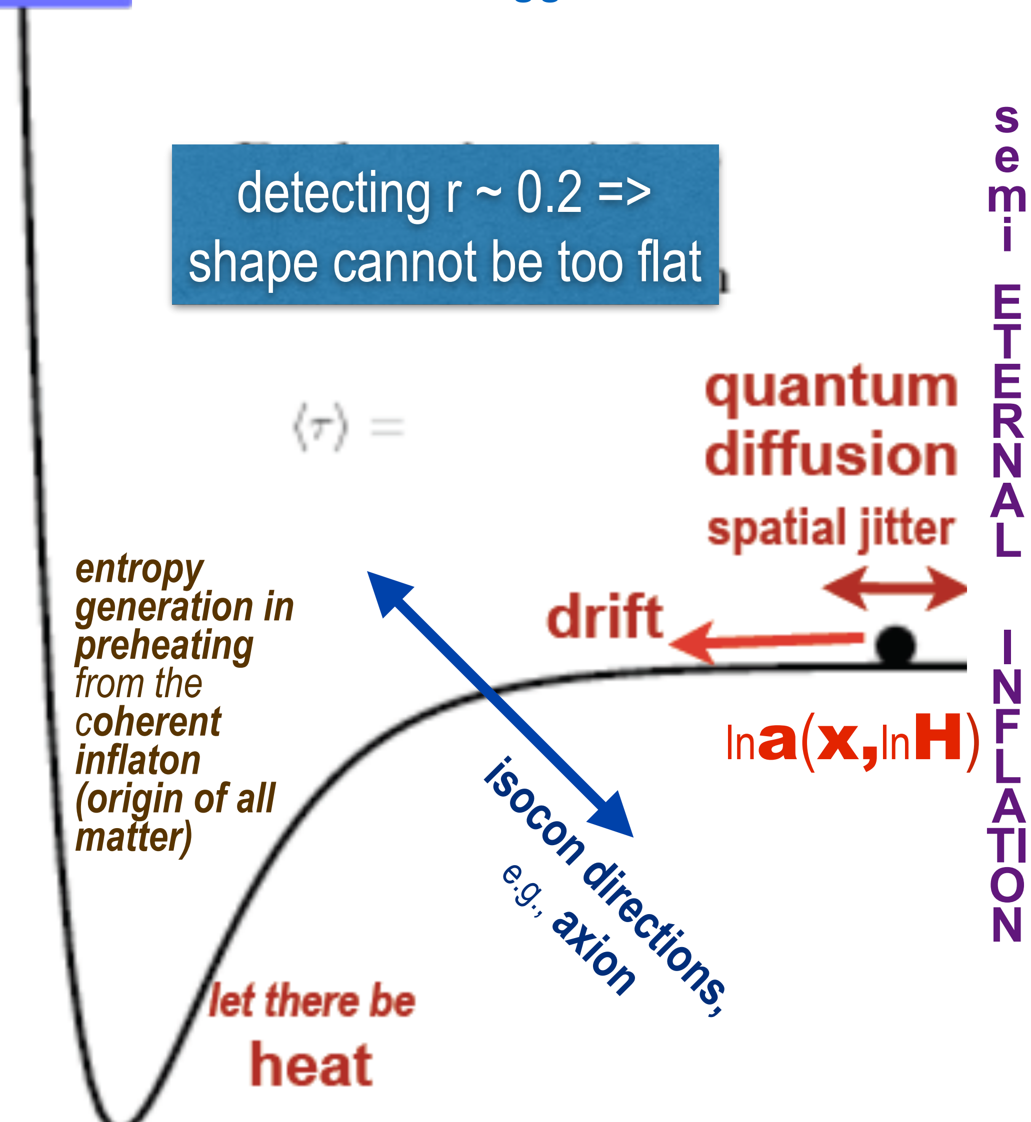
how was ***matter & entropy generated at the end of acceleration = inflation***?

Relate it to the Higgs & standard model?





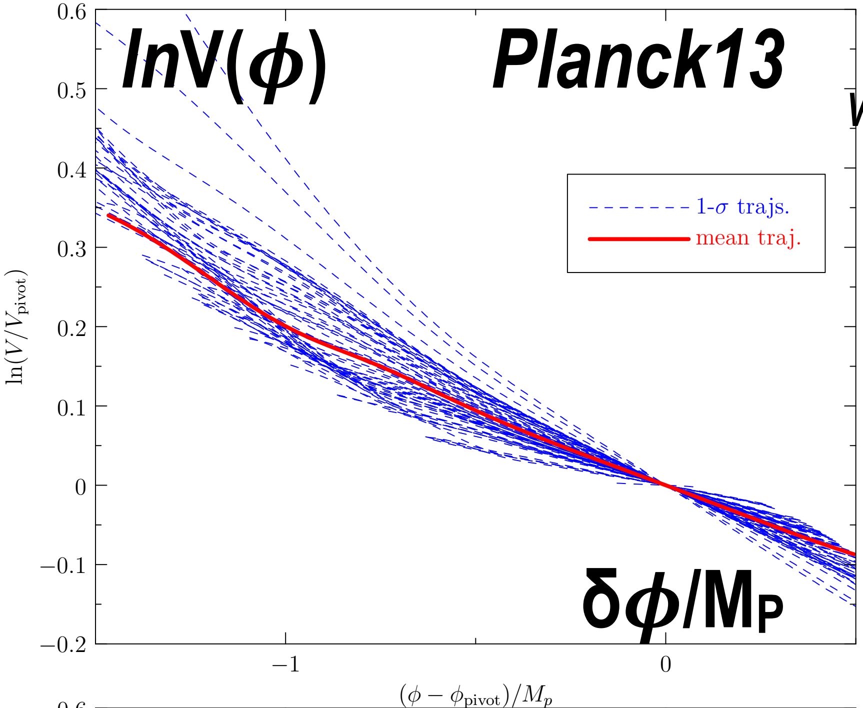
conformal potential-flattening *SBB89*

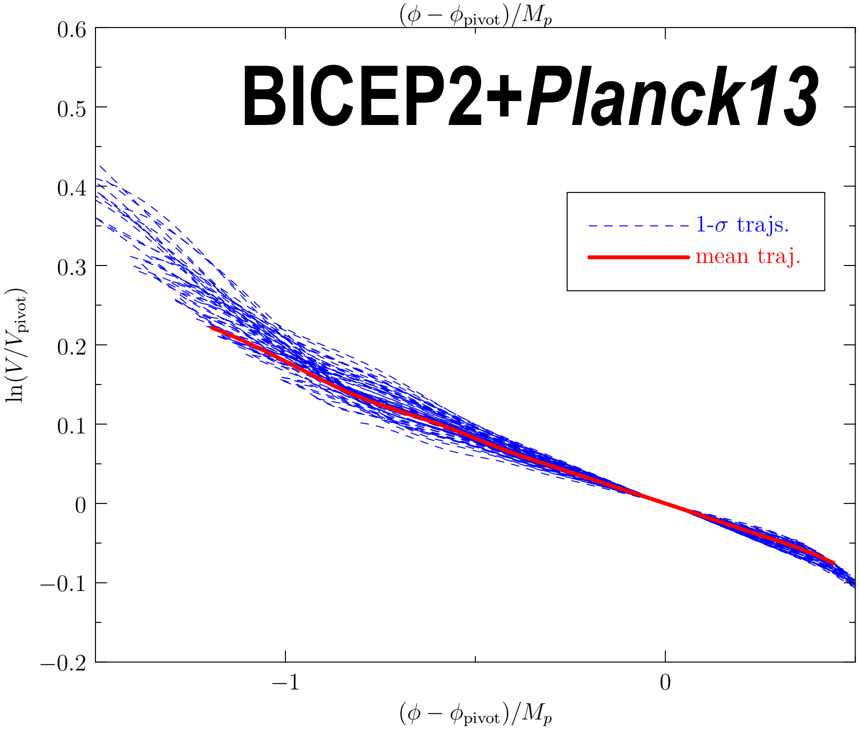


what is the **inflaton's V(ϕ)**?

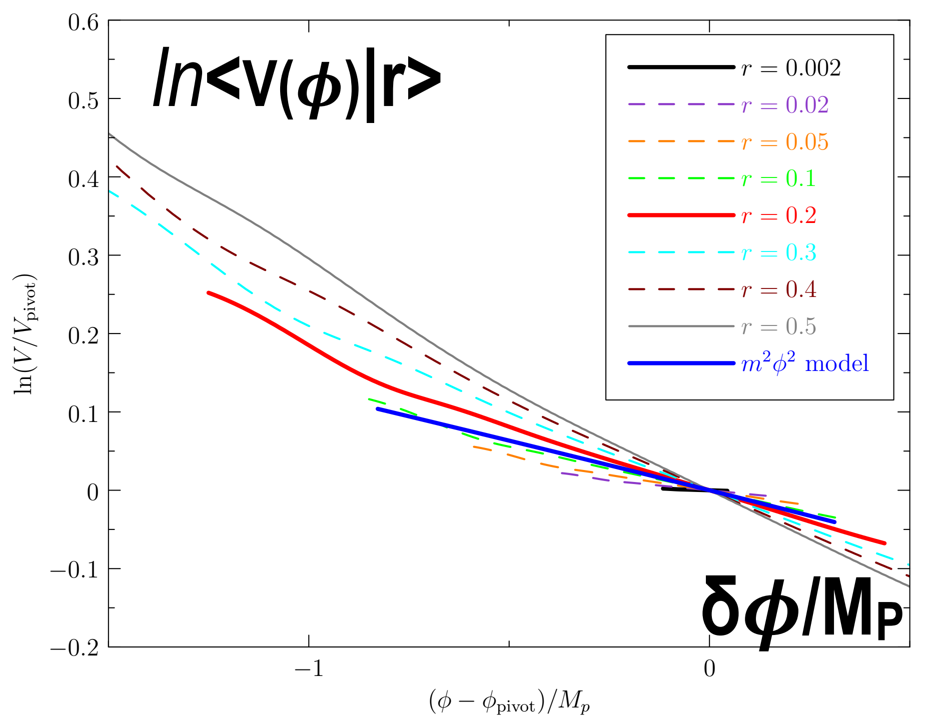
we **reconstruct** *the* ***scalar curvature power*** *(isotropic strain) & the early universe* ***acceleration histories*** *as well*

detecting r ~ 0.2 => V(ϕ) shape cannot be too flat over the observable range

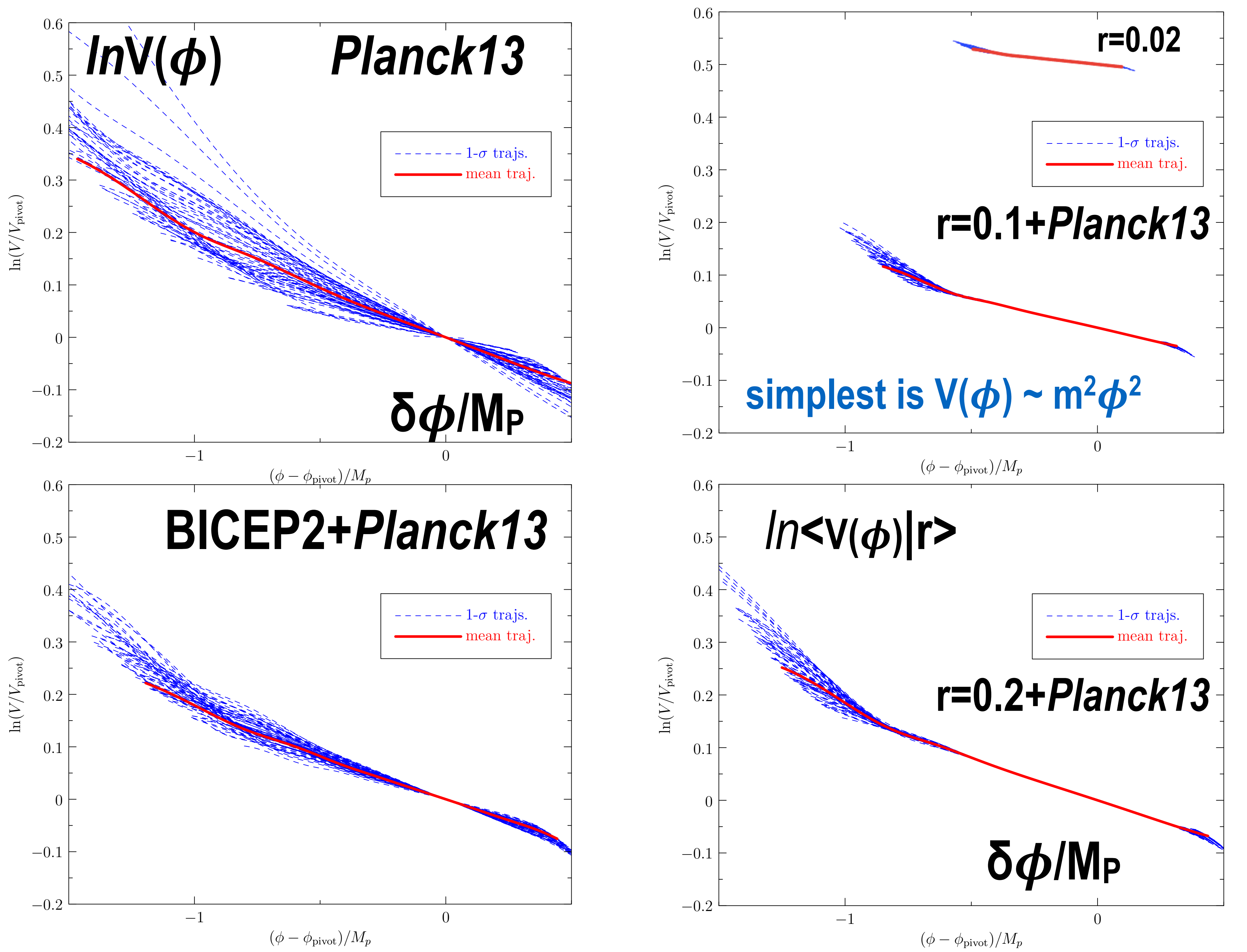




Reconstructed mean potential (without BICEP constraint)



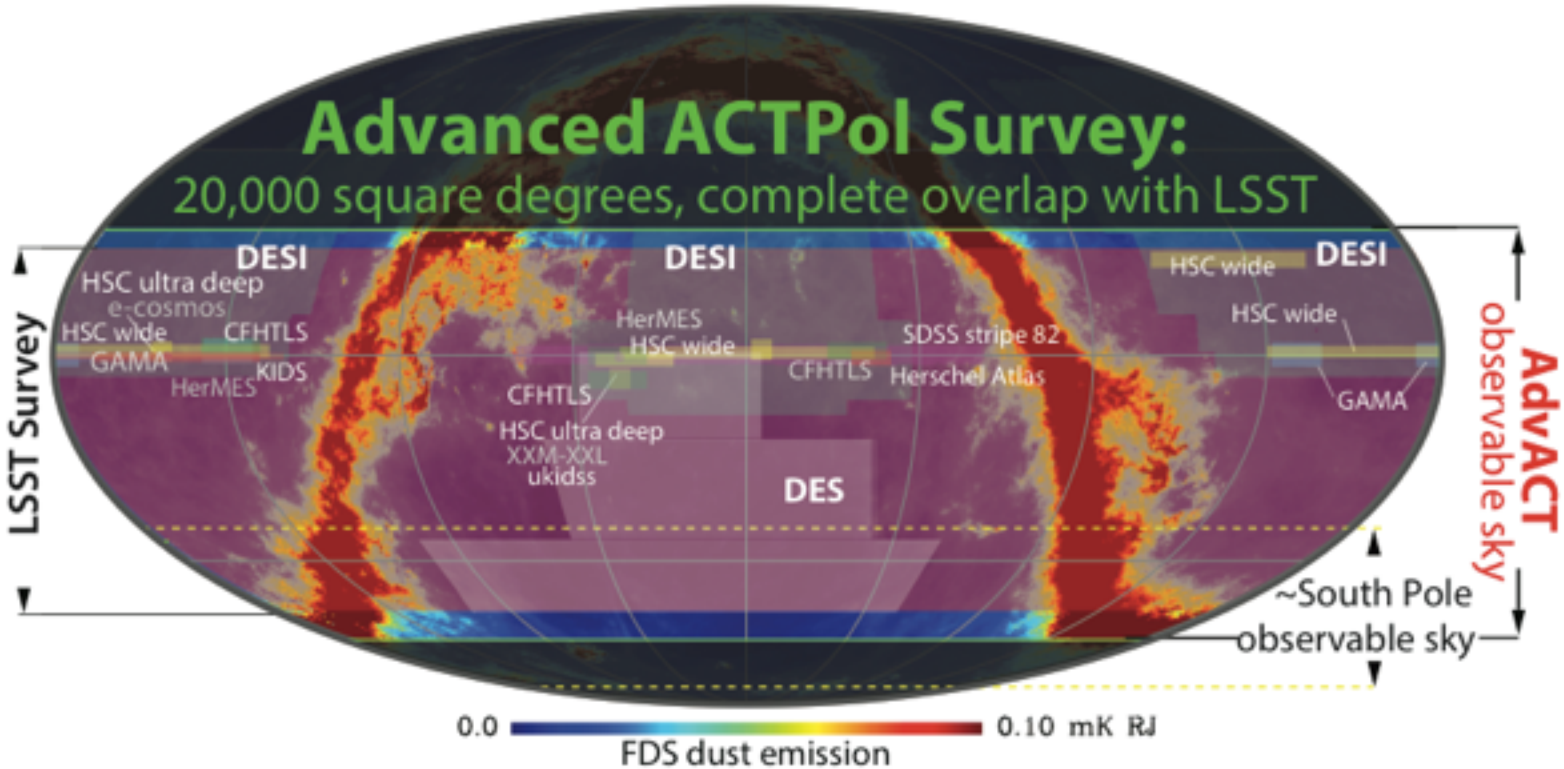
simplest is V(ϕ) ~ $m^2\phi^2$


lnV(ϕ)
Planck13
1-σ trajs.
mean traj.
δϕ/MP
ln(V/Vpivot)
(ϕ − ϕpivot)/Mp
r=0.02
r=0.1+Planck13
simplest is V(ϕ) ~ m2ϕ2
BICEP2+Planck13
ln<V(ϕ)|r>
r=0.2+Planck13

The ACT Collaboration

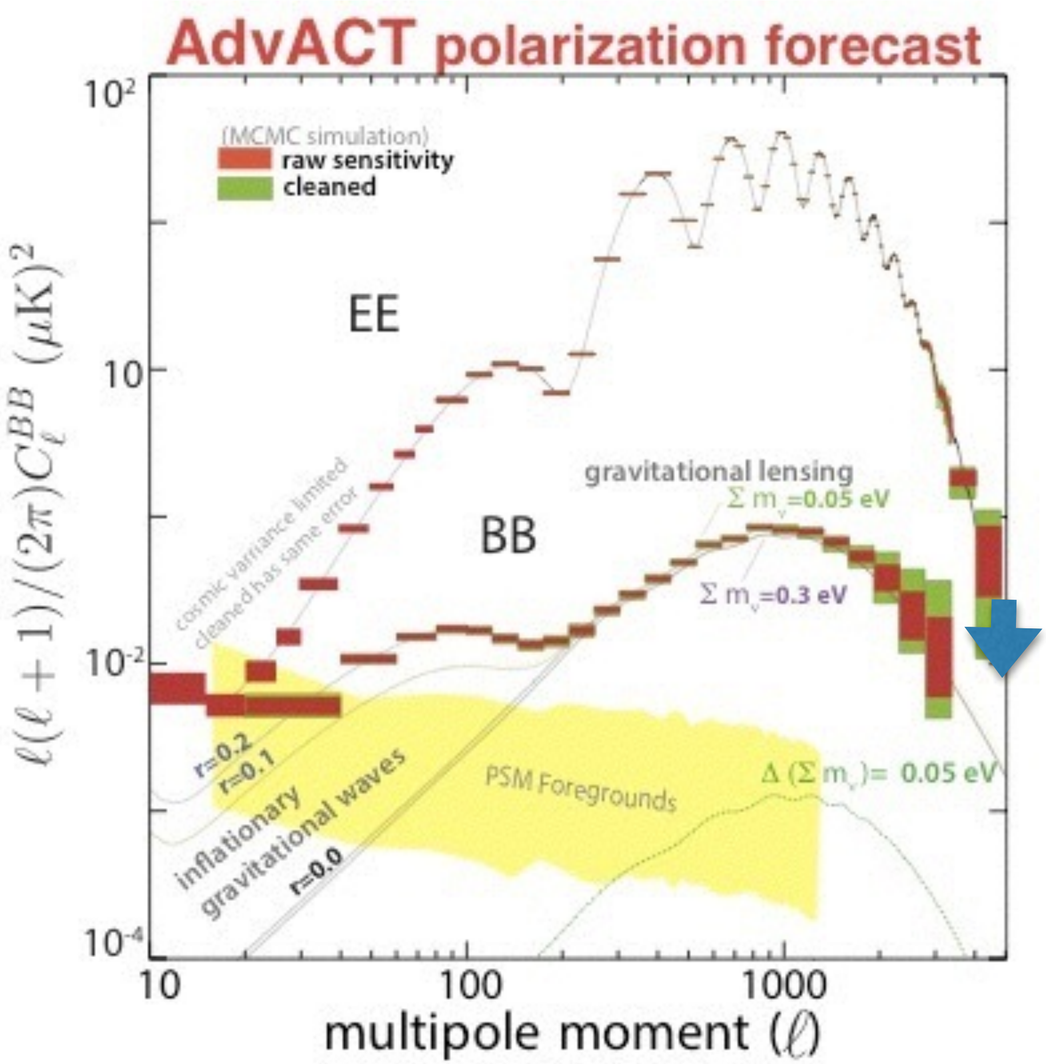
ACT, now ACTpol, => Advanced ACTpol

Advanced ACTPol (AdvACT) Observations



- ~20,000 deg^2 survey (f_{sky}~0.5) with complete LSST overlap as well as DES, ALMA, and other observatories located in Chile
- Substantial overlap with spectroscopic surveys (SDSS, PFS, DESI)

AdvACT: Power Spectra



Error bars above shown for r = 0.2

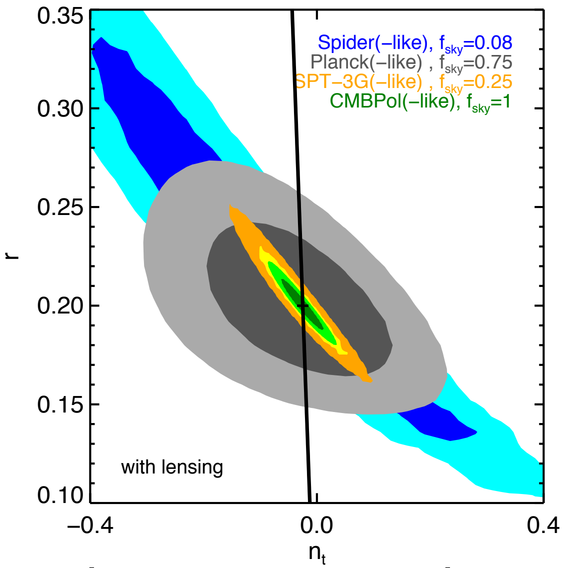
High S/N B-mode detections for r > 0.01 are measured in independent frequency bands (90 & 150 GHz) and on many patches across the sky.

This provides important cross-checks on any detected signal

Also shown:

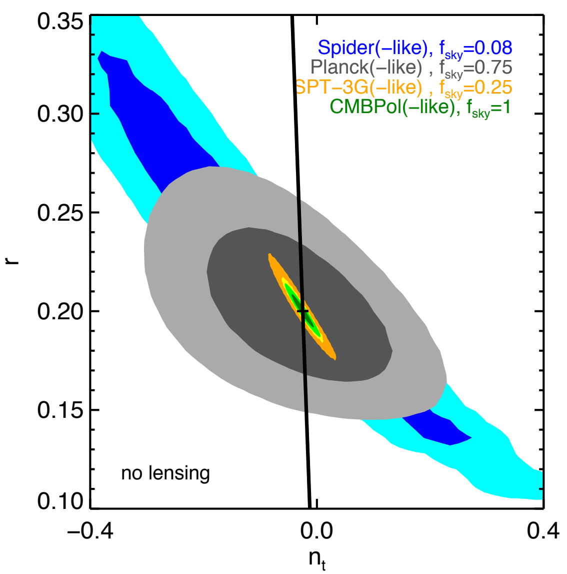
- Error bars before and after foreground cleaning
- Varying amplitudes of the gravitational lensing signal for different values of the sum of the neutrino masses
- Planck forecasts

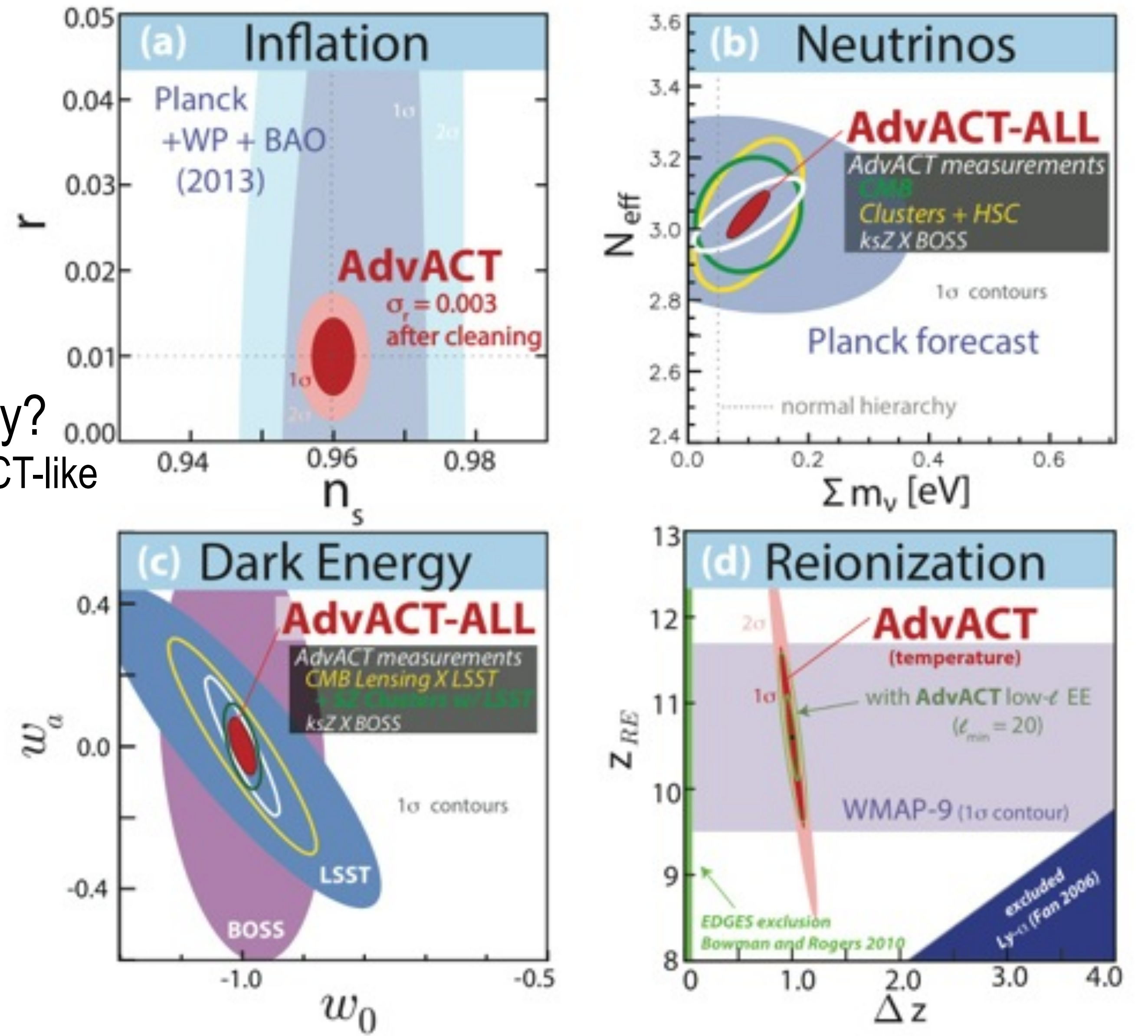
AdvACT: Cosmological Forecasts & Planck2.5, Spider, future SPT3g, CMBpol



testing tensor consistency?

better f_{sky}=25% for spt3g/AdvACT-like than current 6% goal for spt3g





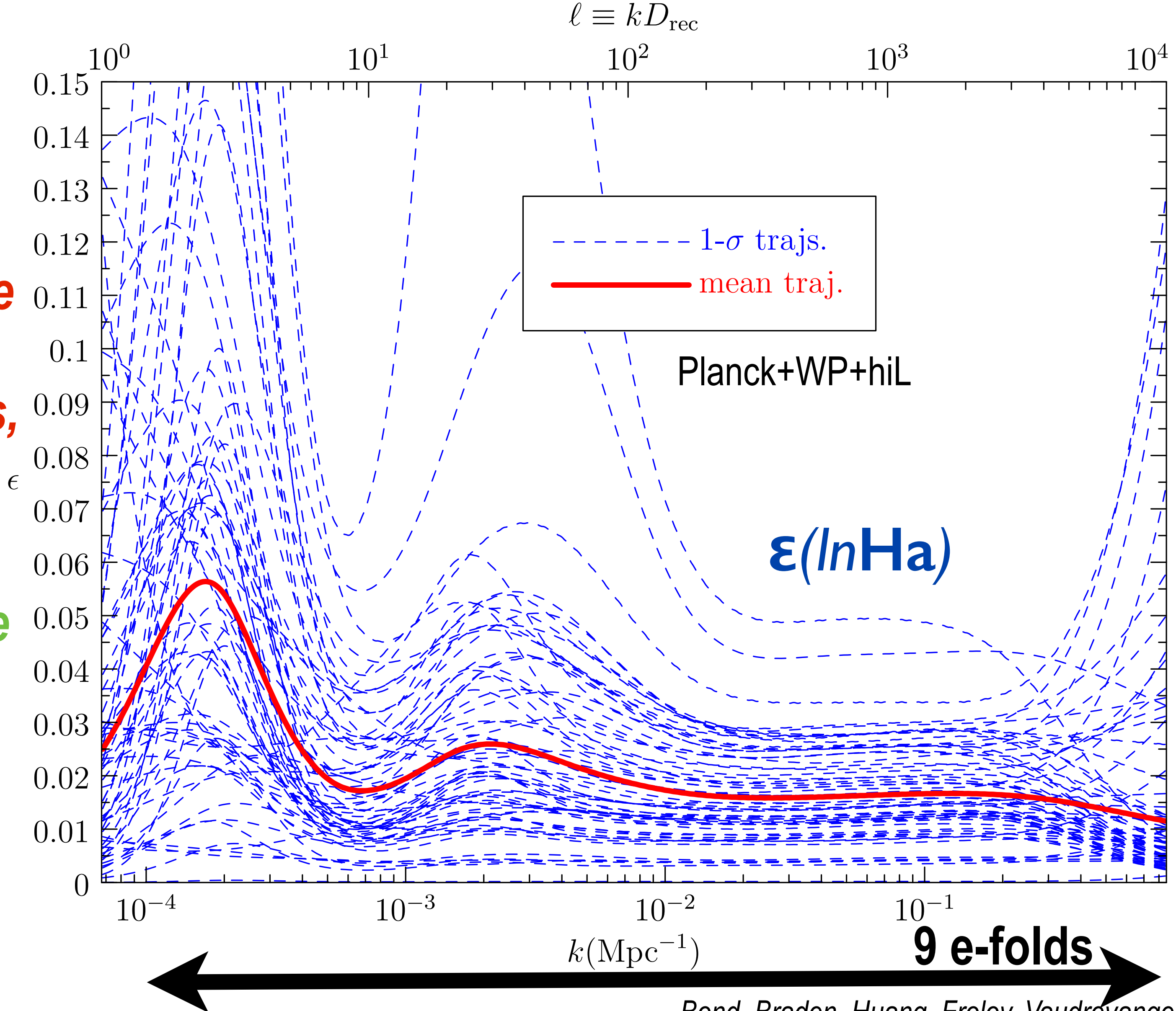
ultra-early Universe sound spectrum ε=-dlnH/dlna

new parameters:
trajectory probabilities for early-inflatons

no strong evidence for oscillation patterns, cutoffs, local features

but hints of change on large L<100 scales

PS: running of P_s is a bad fit



Bond, Braden, Huang, Frolov, Vaudrevange 2014

scan $\ln \mathbf{P_s}(\ln k)/A_s$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$; *consistency => reconstruct* **ε(lnHa), V(ψ)**

ultra-early Universe sound spectrum $\epsilon = -d\ln H/d\ln a$

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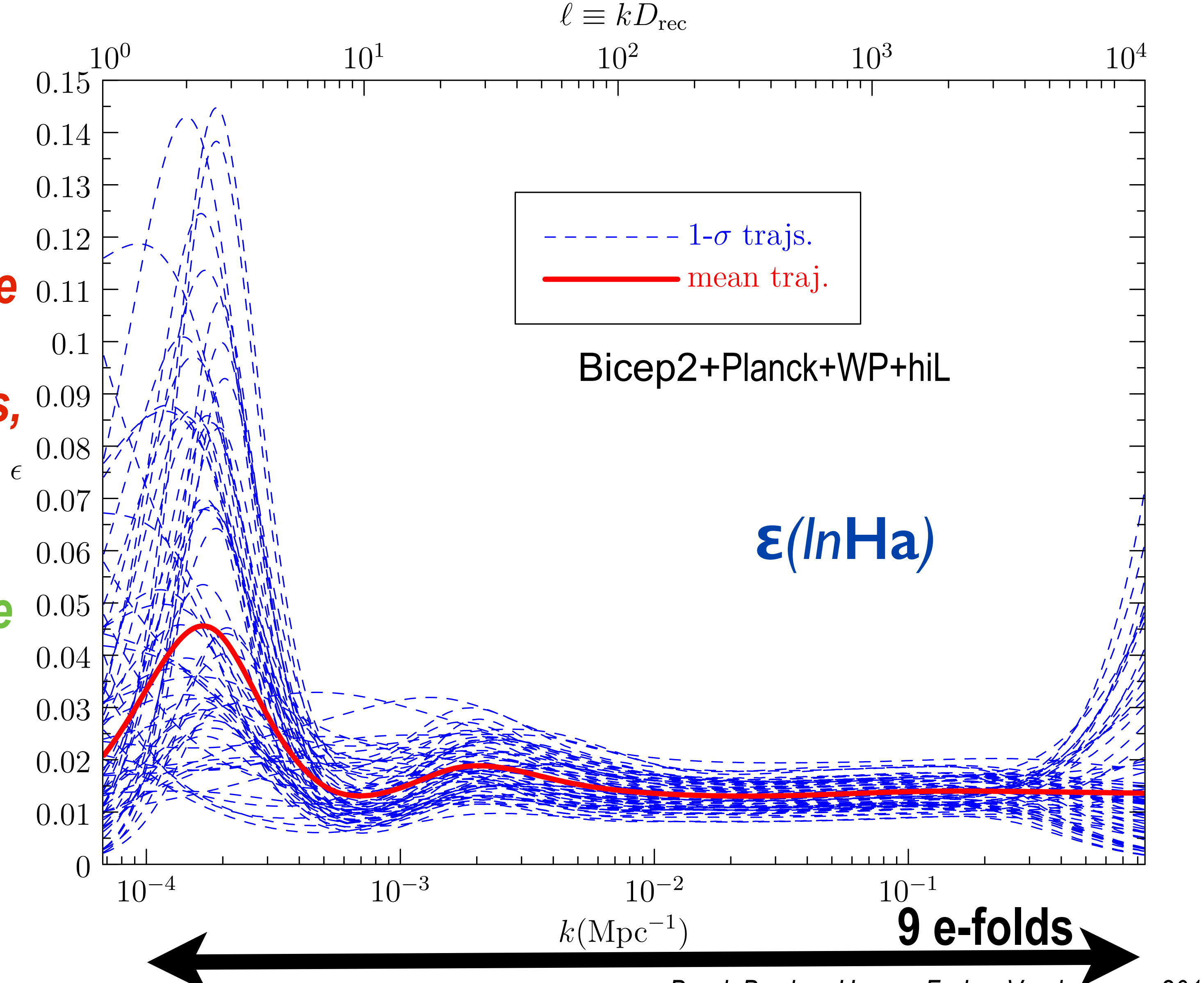

Bond, Braden, Huang, Frolov, Vaudrevange 2014

scan $\ln \mathbf{P_s}(\ln k)/A_s$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$; *consistency => reconstruct* $\epsilon(\ln Ha)$, $V(\psi)$

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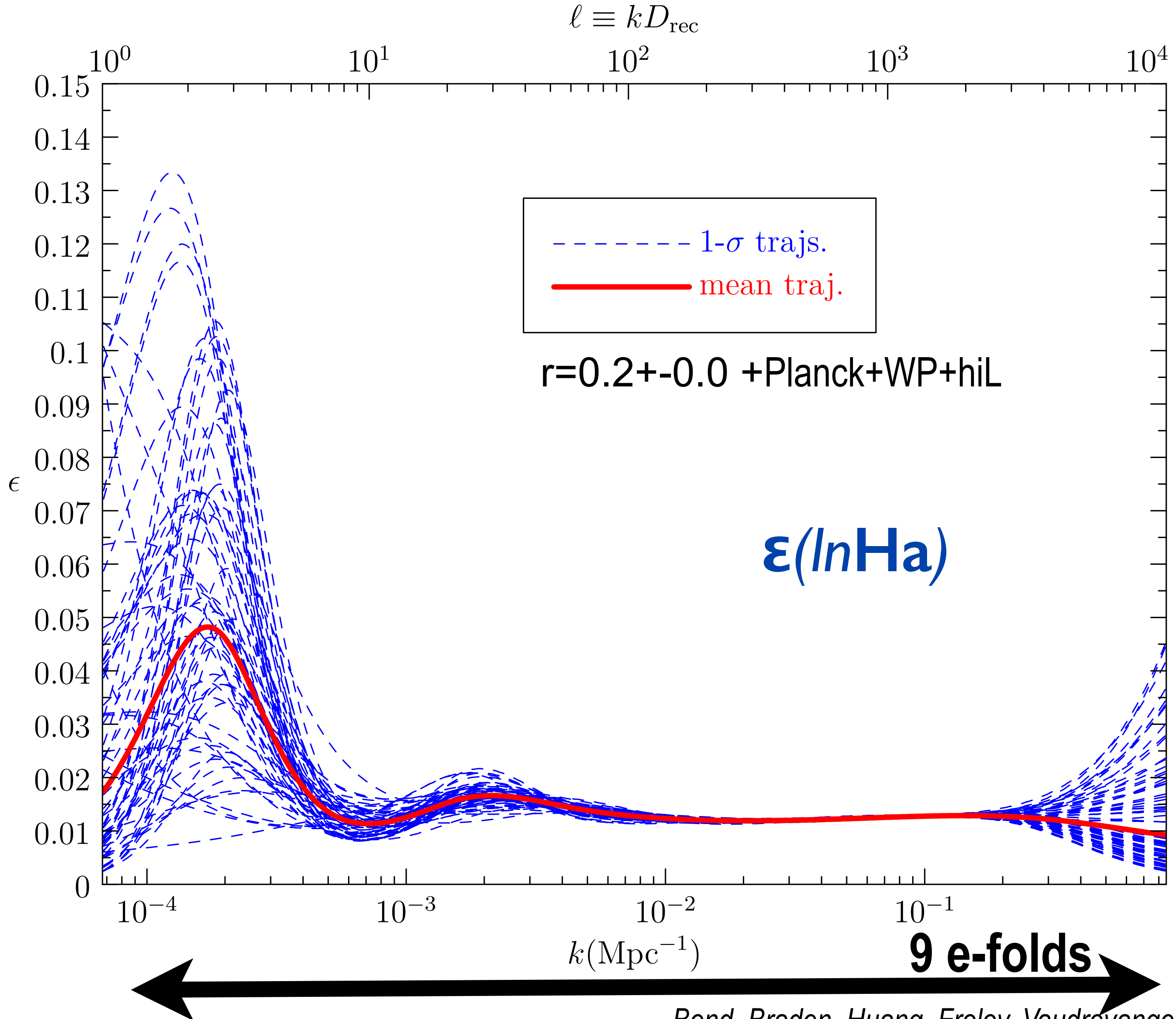

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ultra-early Universe sound spectrum   ε=-$d\ln H/d\ln a$

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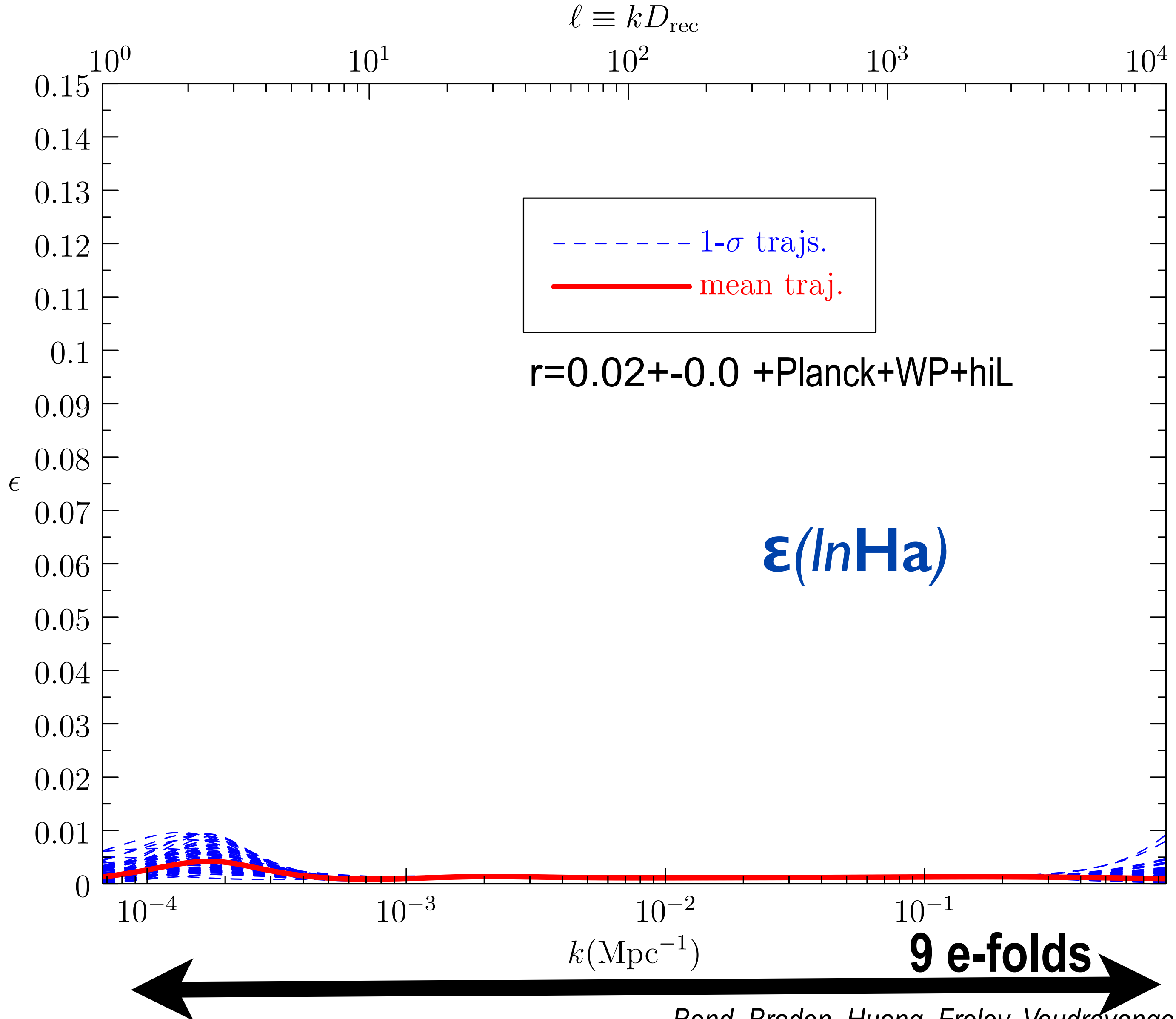

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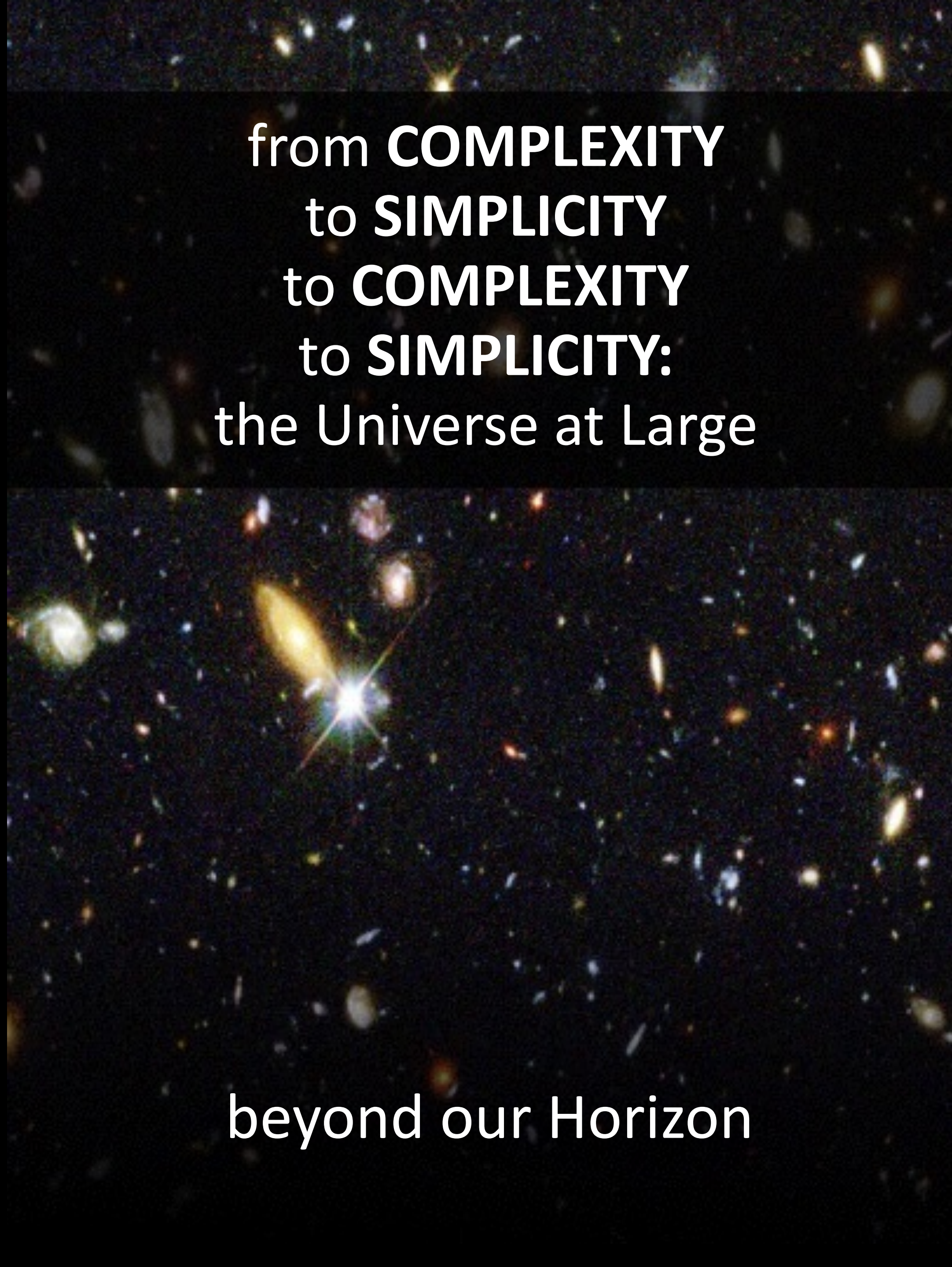
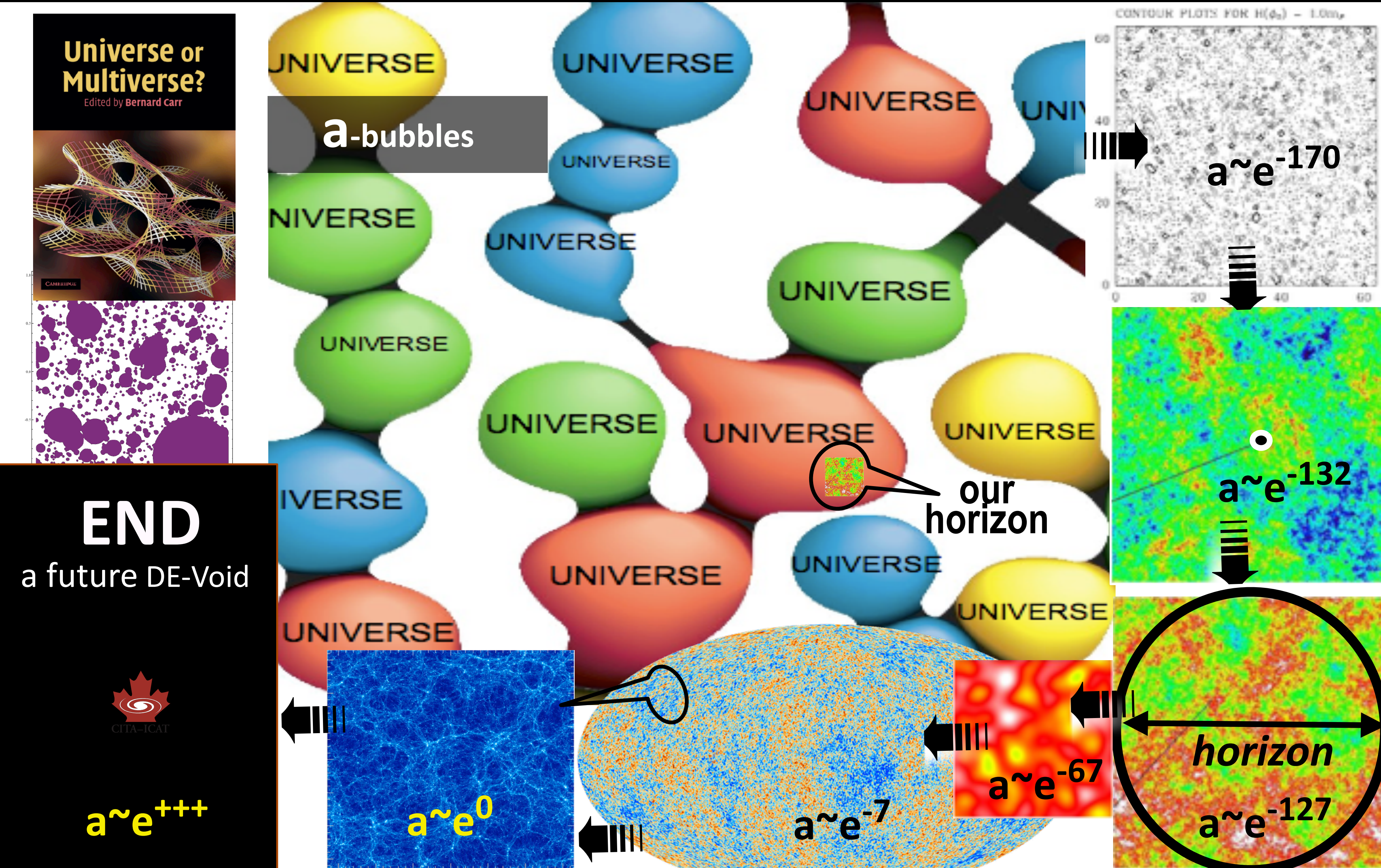

from **COMPLEXITY**
to **SIMPLICITY**
to **COMPLEXITY**
to **SIMPLICITY:**
the Universe at Large
beyond our Horizon

ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information



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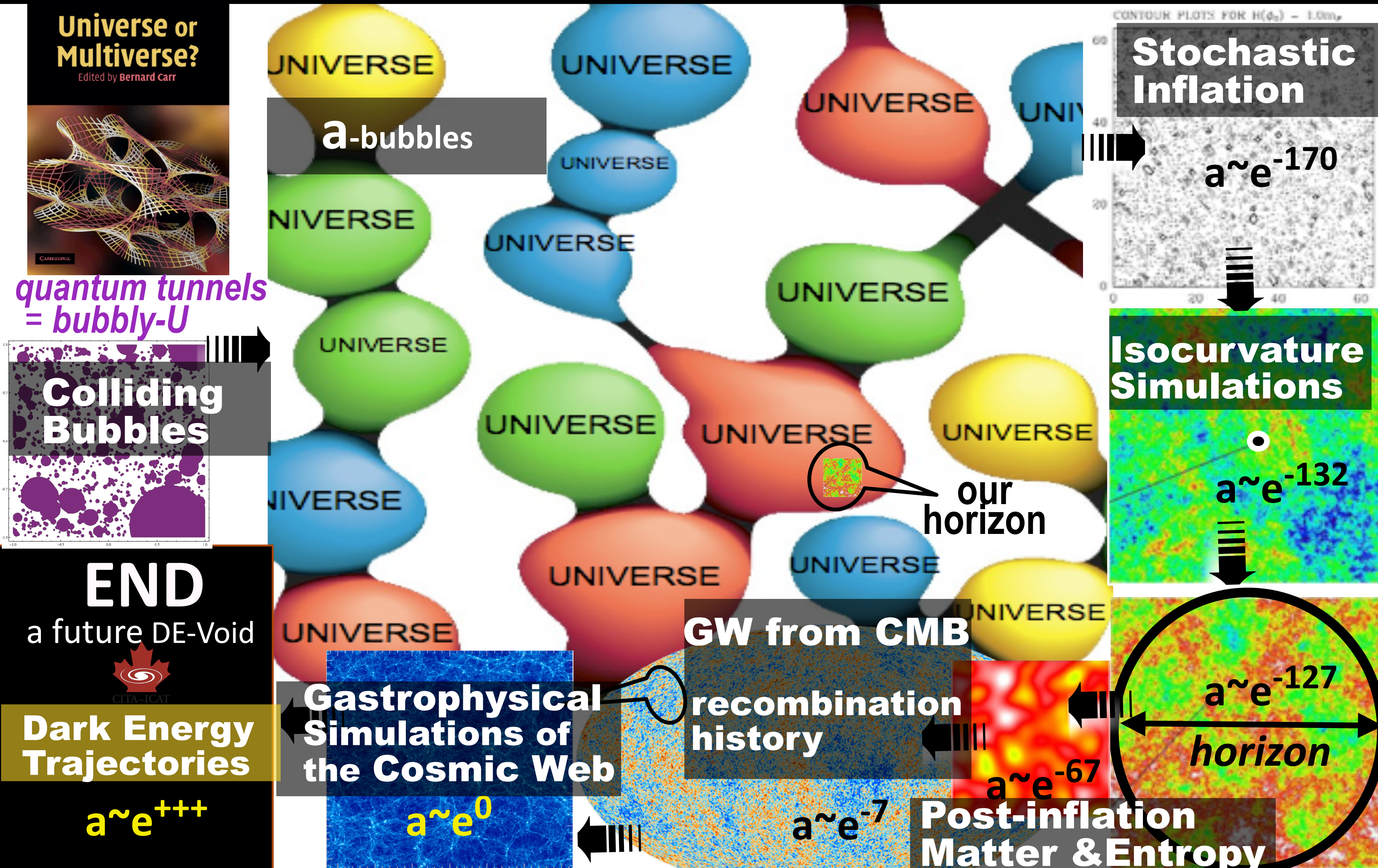


END

Let there be.....

Early **Dark Energy** from $e^{-170?}$ to e^{-67}

2+1 numbers quantum **noise** e^{-127} to e^{-67} in phonons (inflaton) & GW

Heat: matter & **radiation** $a \sim e^{-67}$

Dark Matter, light nuclei $a \sim e^{-21}$ to e^{-35}

Cosmic **Light**: 1st light released, 1st atoms $a \sim e^{-7}$

1st stars $a \sim e^{-3}$, 1st heavy nuclei (O, C, Fe,..)

Galaxies $> e^{-2.2}$

Earth $a \sim e^{-0.34}$

1st human writing $a \sim e^{-0.0000004}$

Late **Dark Energy** to e^{+++}

Let there be.....

semi **ETERNAL** Universe
most of it never Banged

Early **Dark Energy** from $e^{-170?}$ to e^{-67}

2+1 numbers quantum **noise** e^{-127} to e^{-67} in phonons (inflaton) & GW

Heat: matter & **radiation** $a \sim e^{-67}$ Our little **Big Bang**

Dark Matter, light nuclei $a \sim e^{-21}$ to e^{-35}

Cosmic **Light**: 1st light released, 1st atoms $a \sim e^{-7}$

1st stars $a \sim e^{-3}$, 1st heavy nuclei (O, C, Fe,..)

Galaxies $> e^{-2.2}$

Earth $a \sim e^{-0.34}$

1st human writing $a \sim e^{-0.0000004}$

Late **Dark Energy** to e^{+++}

Will our bit of the Universe re-Bang?
NO... maybe

SIMPLICITY

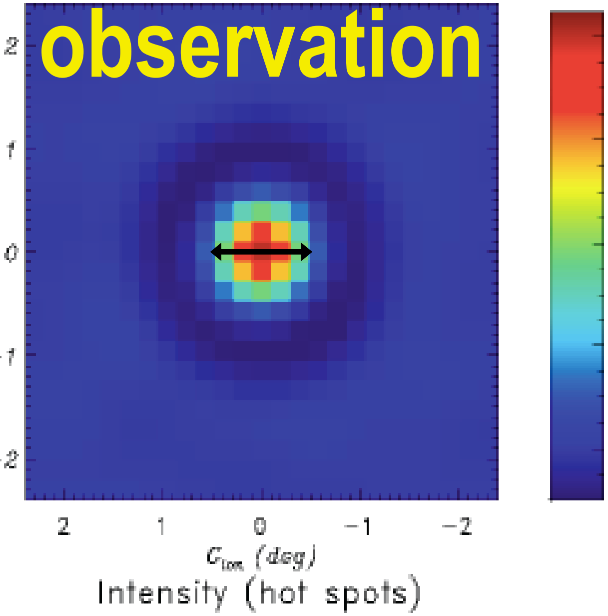
at $a \sim e^{-7} \sim 1/1100$ =>

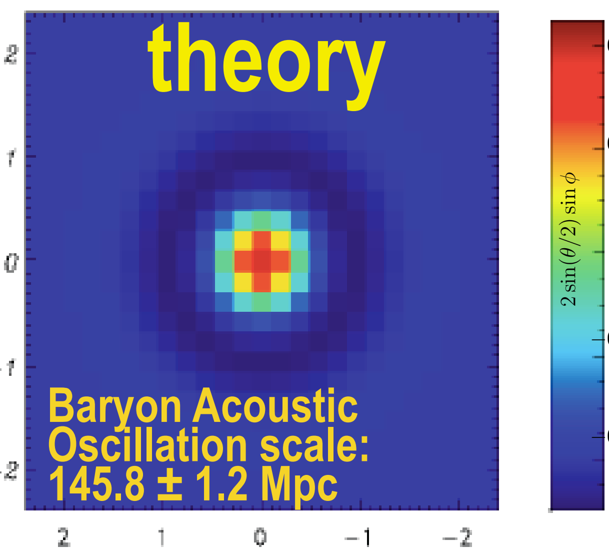
at $a \sim e^{-67+60} \sim 1/10^{30+25}$

reveals primordial **sound waves** *in matter*

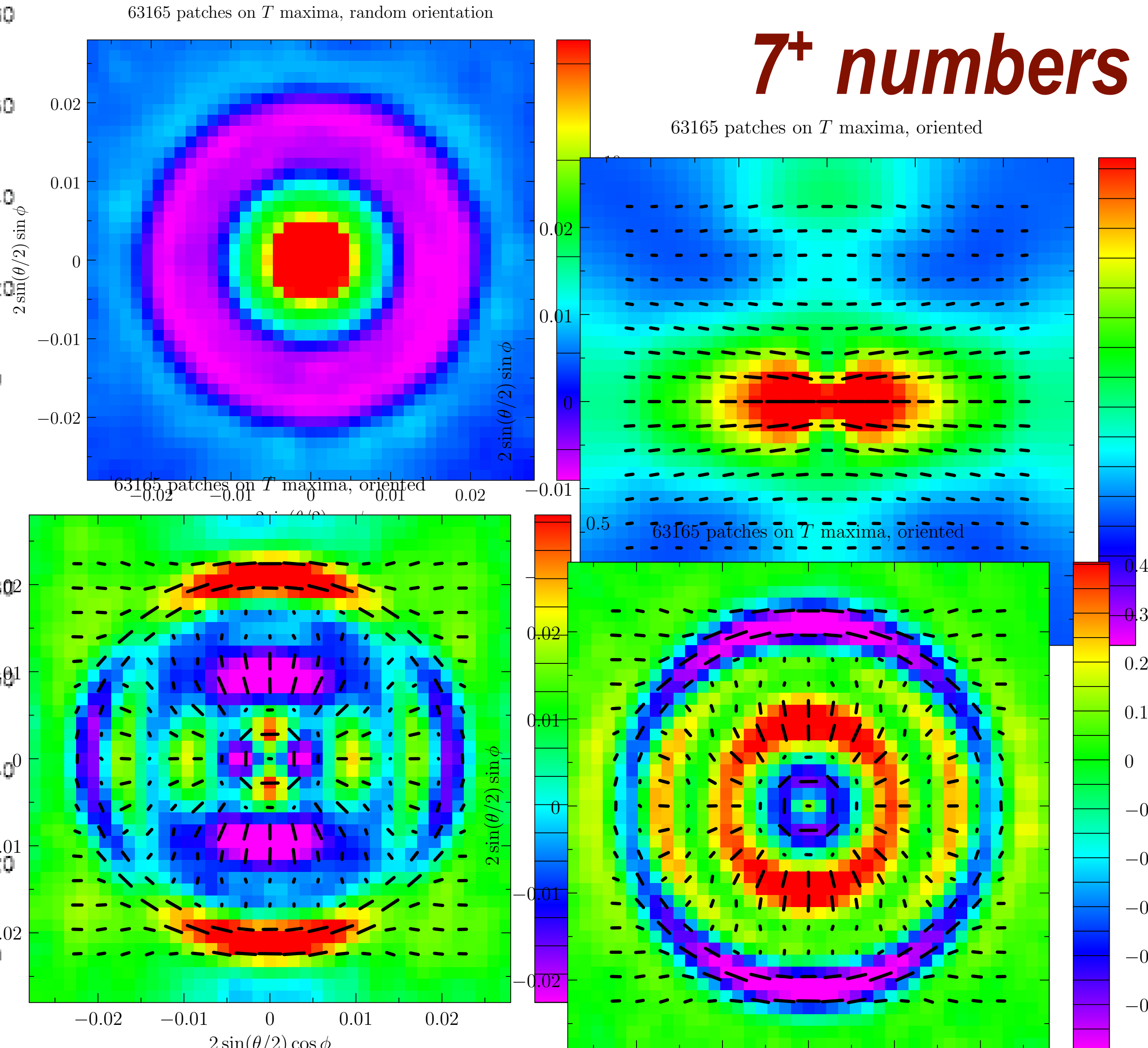
=> *learn* **contents** & **structure** *at 380000 yr,* $a \sim e^{-7}$

=> *infer the structure far far earlier* $a \sim e^{-67+60}$





7⁺ numbers

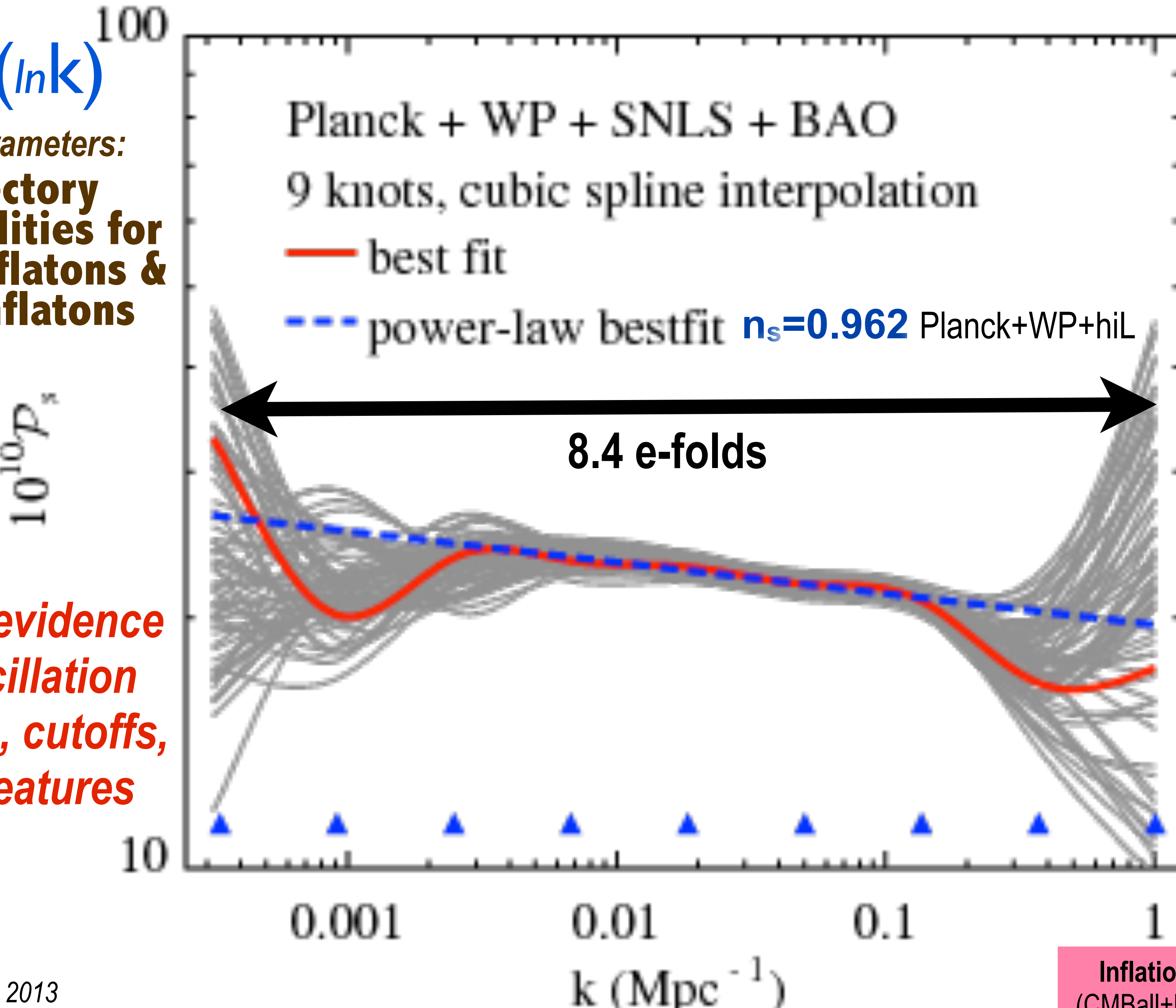


scan $\ln \mathbf{P_s}(\ln k)/A_s$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$; *consistency => reconstruct* $\boldsymbol{\varepsilon}(\ln \mathbf{Ha})$, $\mathbf{V}(\boldsymbol{\psi})$

$\ln P_s(\ln k)$

new parameters:
trajectory probabilities for early-inflatons & late-inflatons

no strong evidence for oscillation patterns, cutoffs, local features



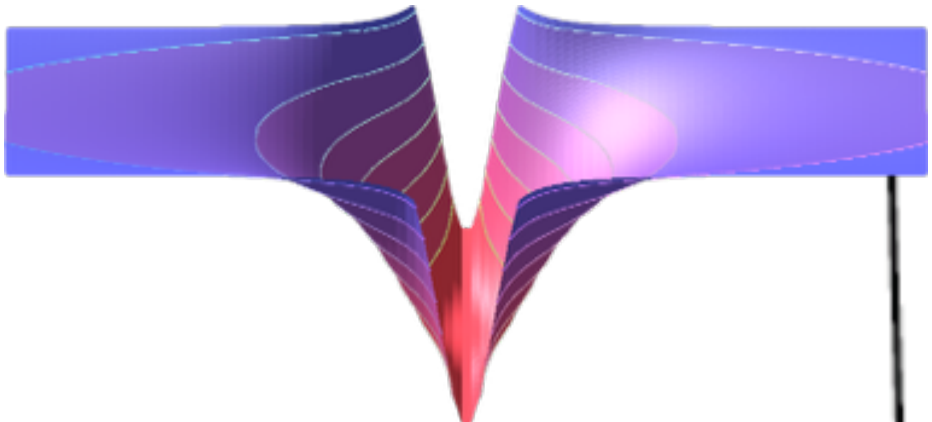
Bond, Huang 2013

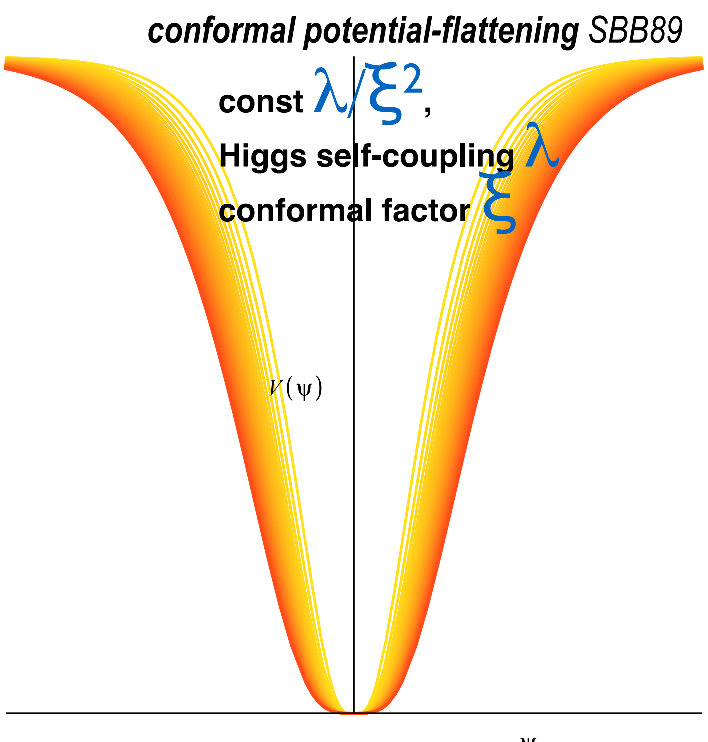
Inflation Histories
(CMBall+LSS+SN+WL)

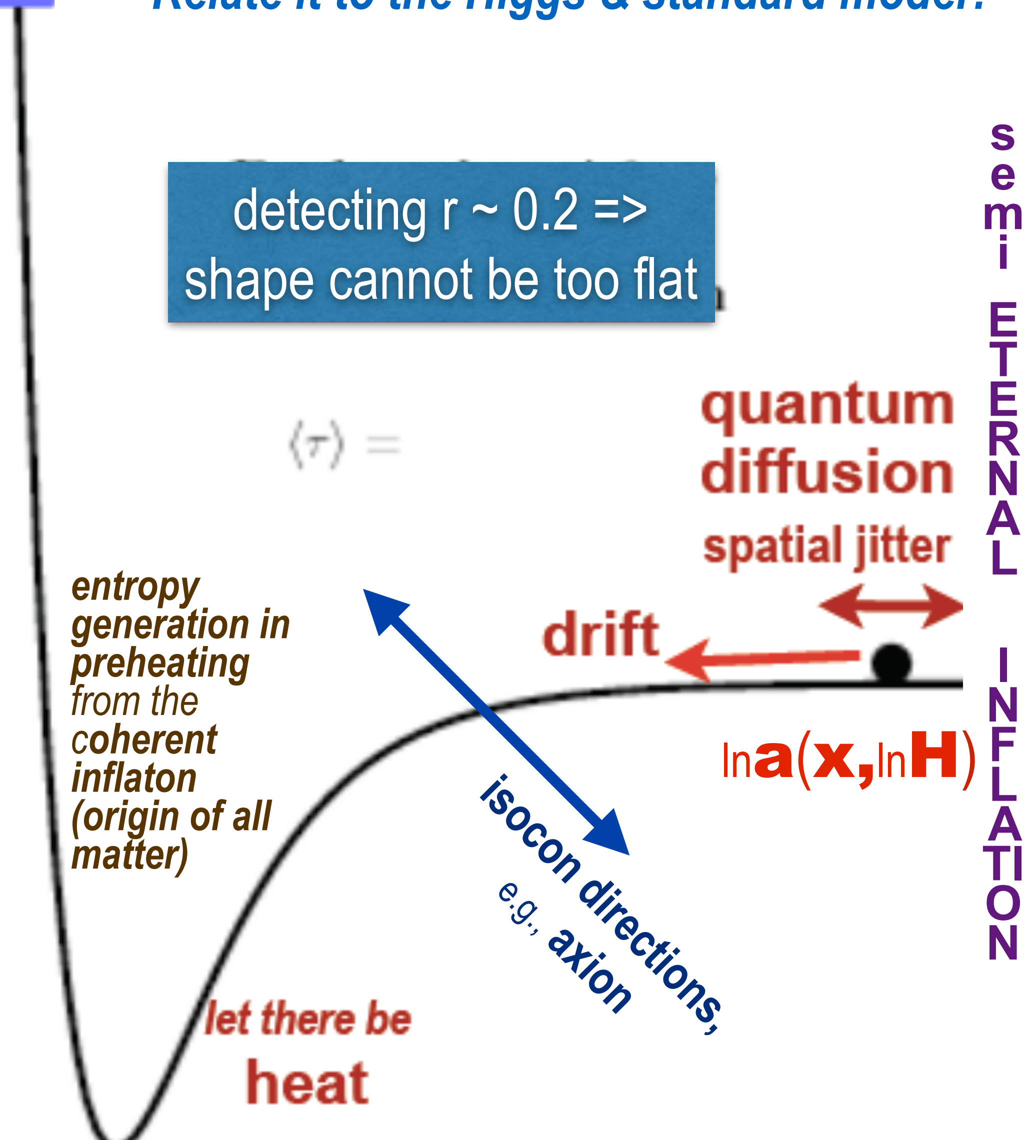
what is the **inflaton's potential**?

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

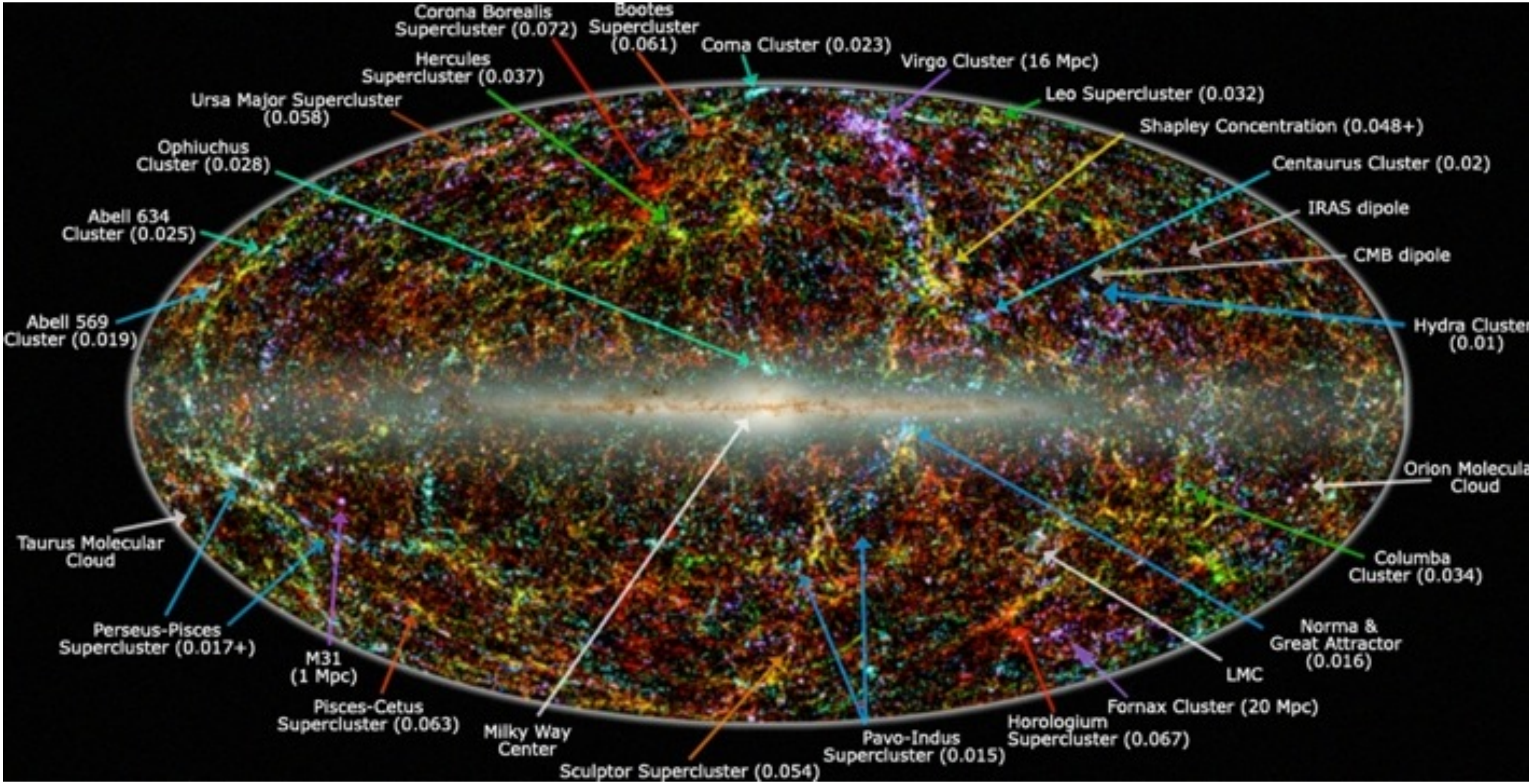
Relate it to the Higgs & standard model?





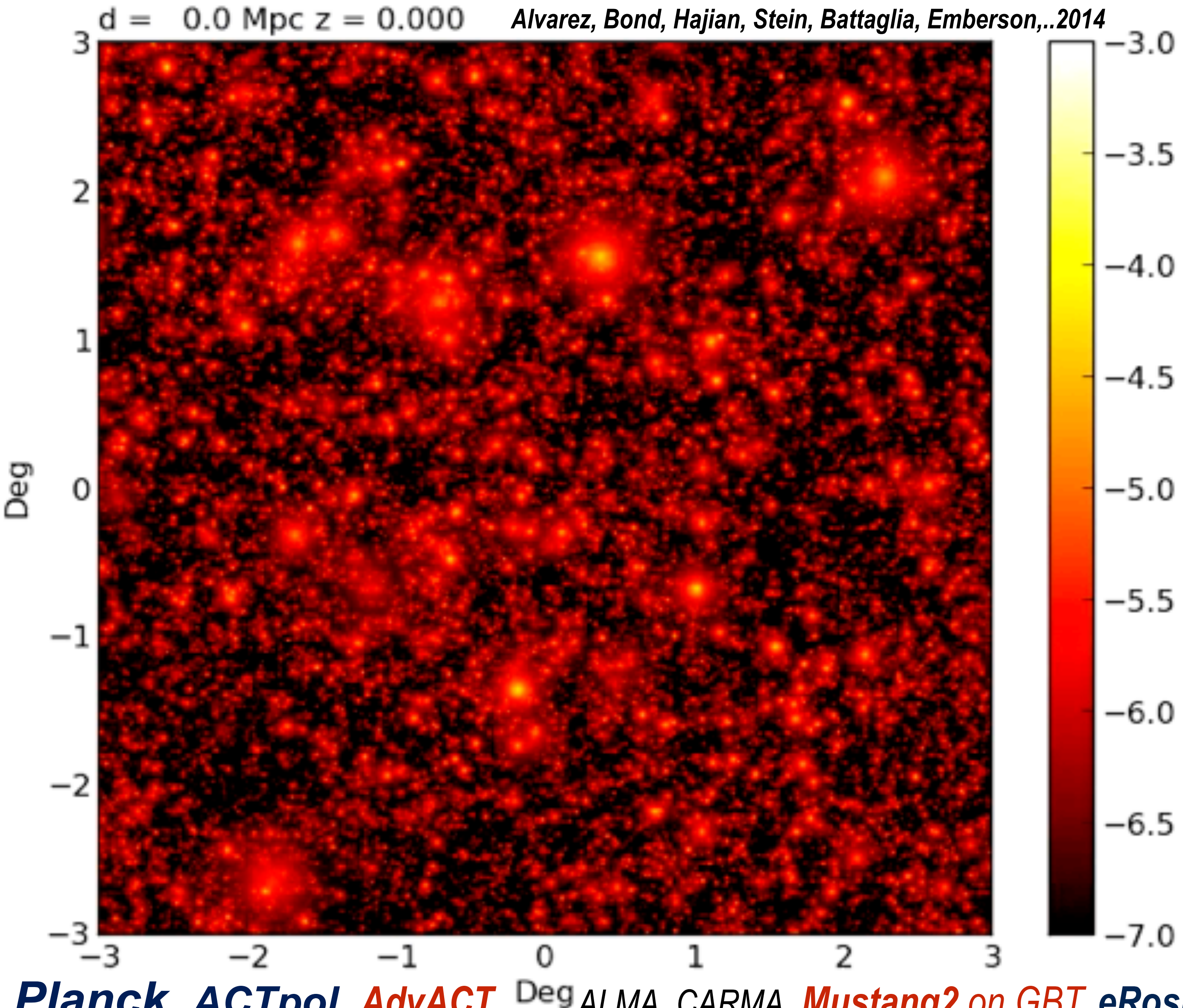


cosmic web of **nearby superclusters** from ***2mass+***

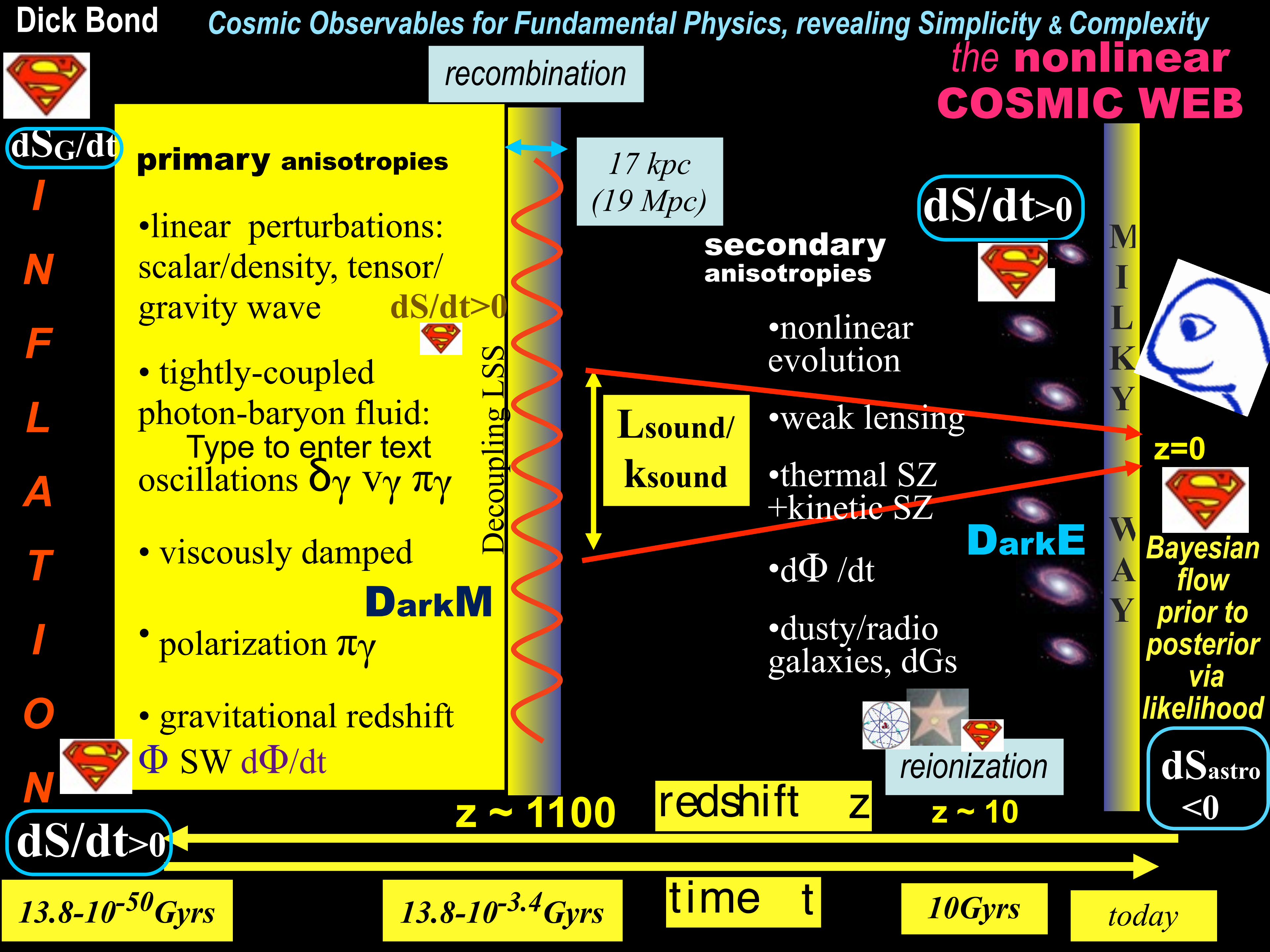


Mocking Heaven: lightcone sim for tLCDM. 36 sq deg to z=2

Planck all-sky tSZ mock 1.5 hours on 256 cores on SciNet, 30000 core IBM GPC

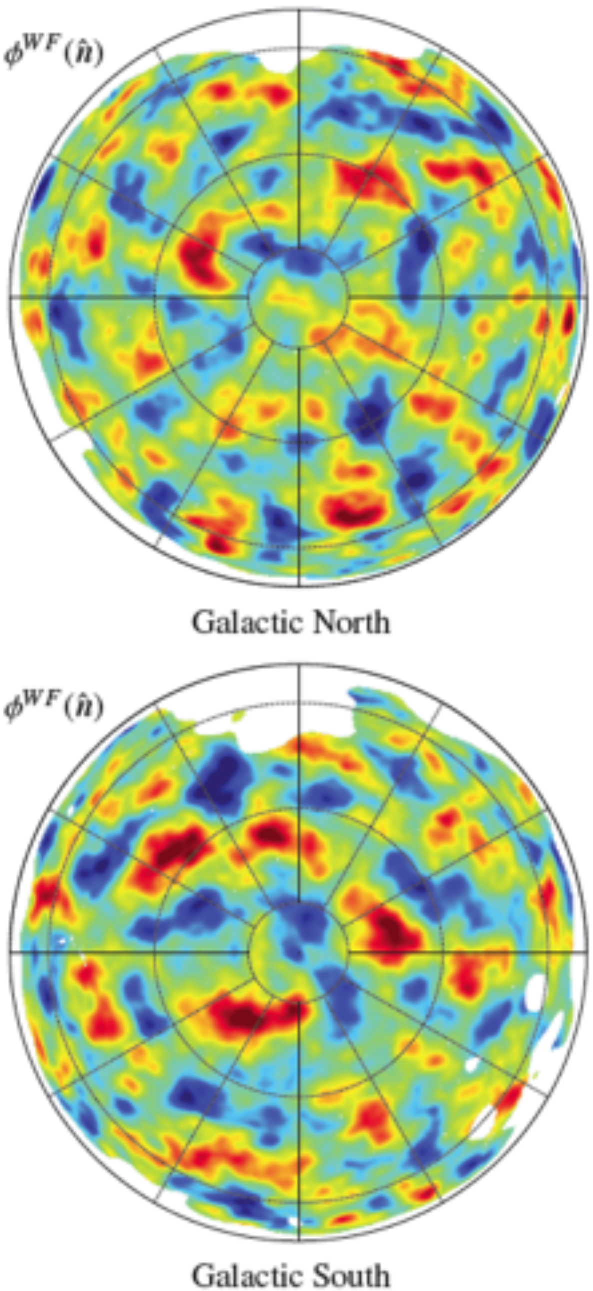


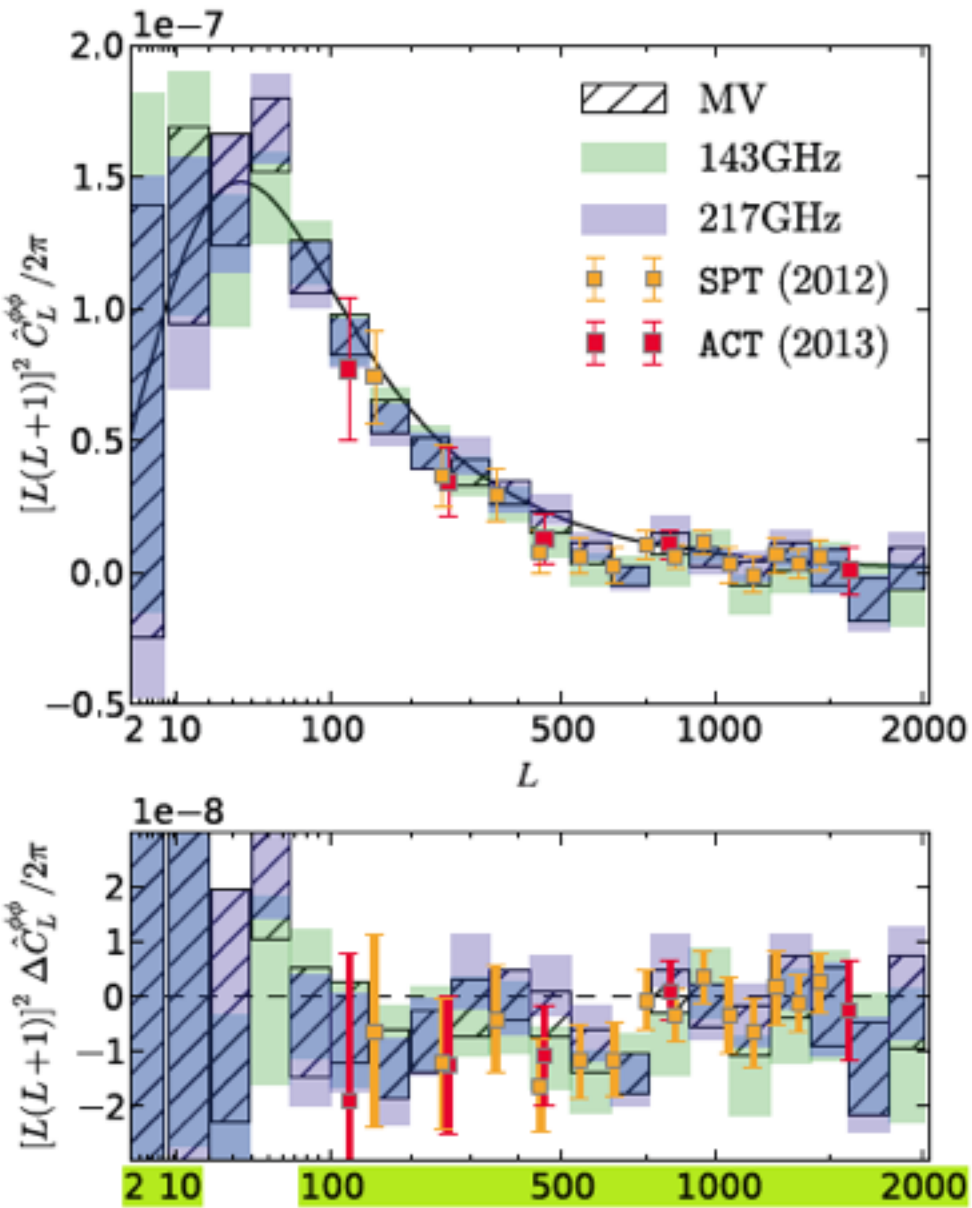
Planck, ACTpol, AdvACT, *ALMA, CARMA,* ***Mustang2*** *on GBT,* ***eRosita**..* ***COMA, CCAT**..* ***CHIME***



Dick Bond
Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity
the nonlinear COSMIC WEB
recombination
dS_G/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid:
Type to enter text
oscillations δγ vγ πγ
• viscously damped
DarkM
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
Decoupling LSS
17 kpc (19 Mpc)
Lsound/ ksound
dS/dt>0
secondary anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
DarkE
•dΦ /dt
•dusty/radio galaxies, dGs
reionization
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
dS_astro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.8-10^-50 Gyrs
13.8-10^-3.4 Gyrs
10Gyrs
today

CMB Lensing: Planck13 cf. ACT12 and SPT12, good agreement





SIMPLICITY

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

at $a \sim e^{-67-60} \sim 1/10^{30+25}$

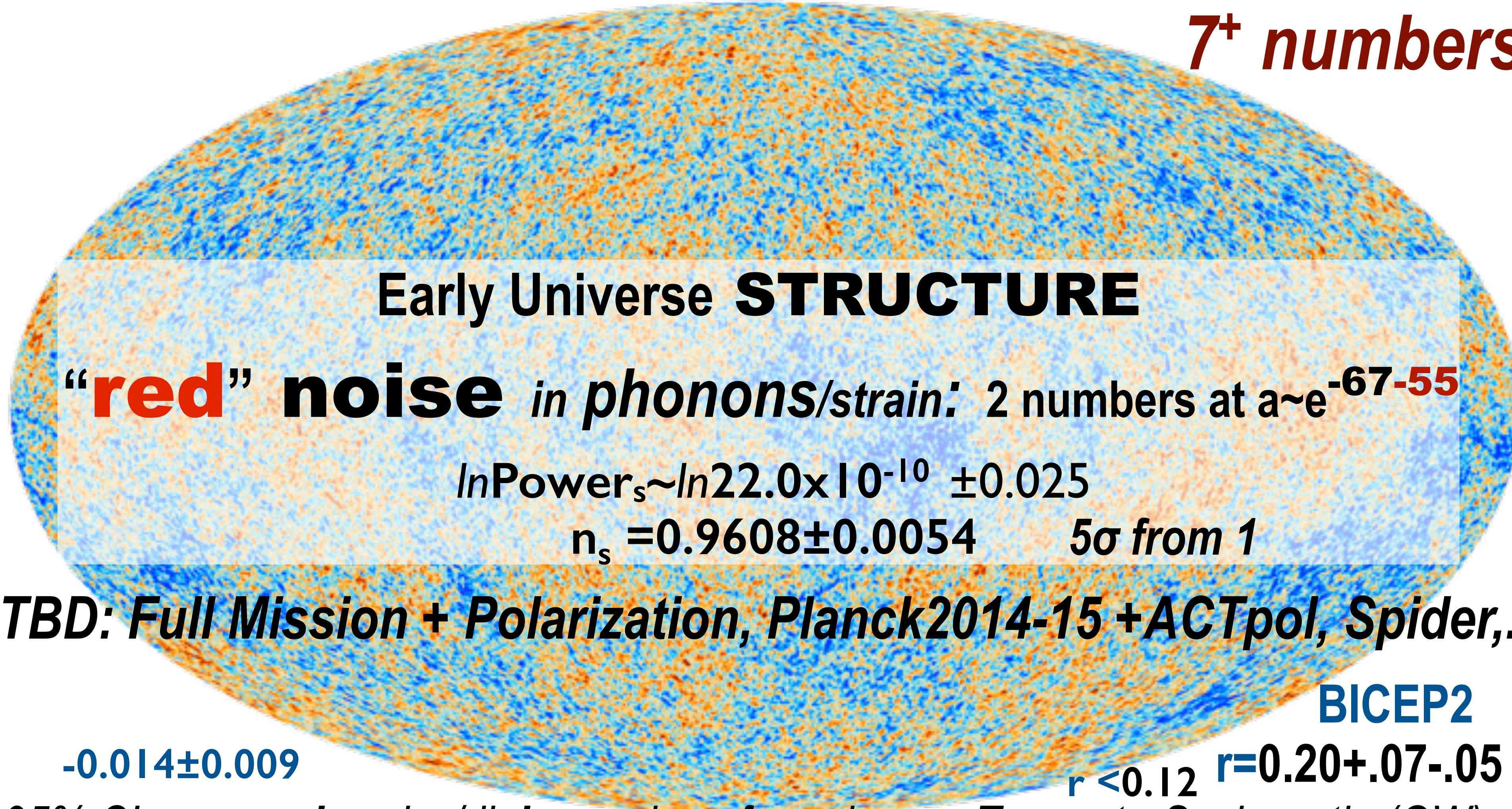
Planck2013 CMB map

reveals ***primordial*** **sound waves** ***in matter***

=> *learn* ***contents*** *&* ***structure*** *at 380000 yr,* $a \sim e^{-7}$

=> *infer the structure far far earlier* $a \sim e^{-67-60}$

7⁺ numbers



Early Universe STRUCTURE

"**red**" **noise** *in* ***phonons****/strain:* 2 numbers at $a \sim e^{-67-55}$

$\ln \mathrm{Power}_s \sim \ln 22.0 \times 10^{-10} \pm 0.025$

$n_s = 0.9608 \pm 0.0054$ *5σ from 1*

TBD: Full Mission + Polarization, Planck2014-15 +ACTpol, Spider,..

BICEP2

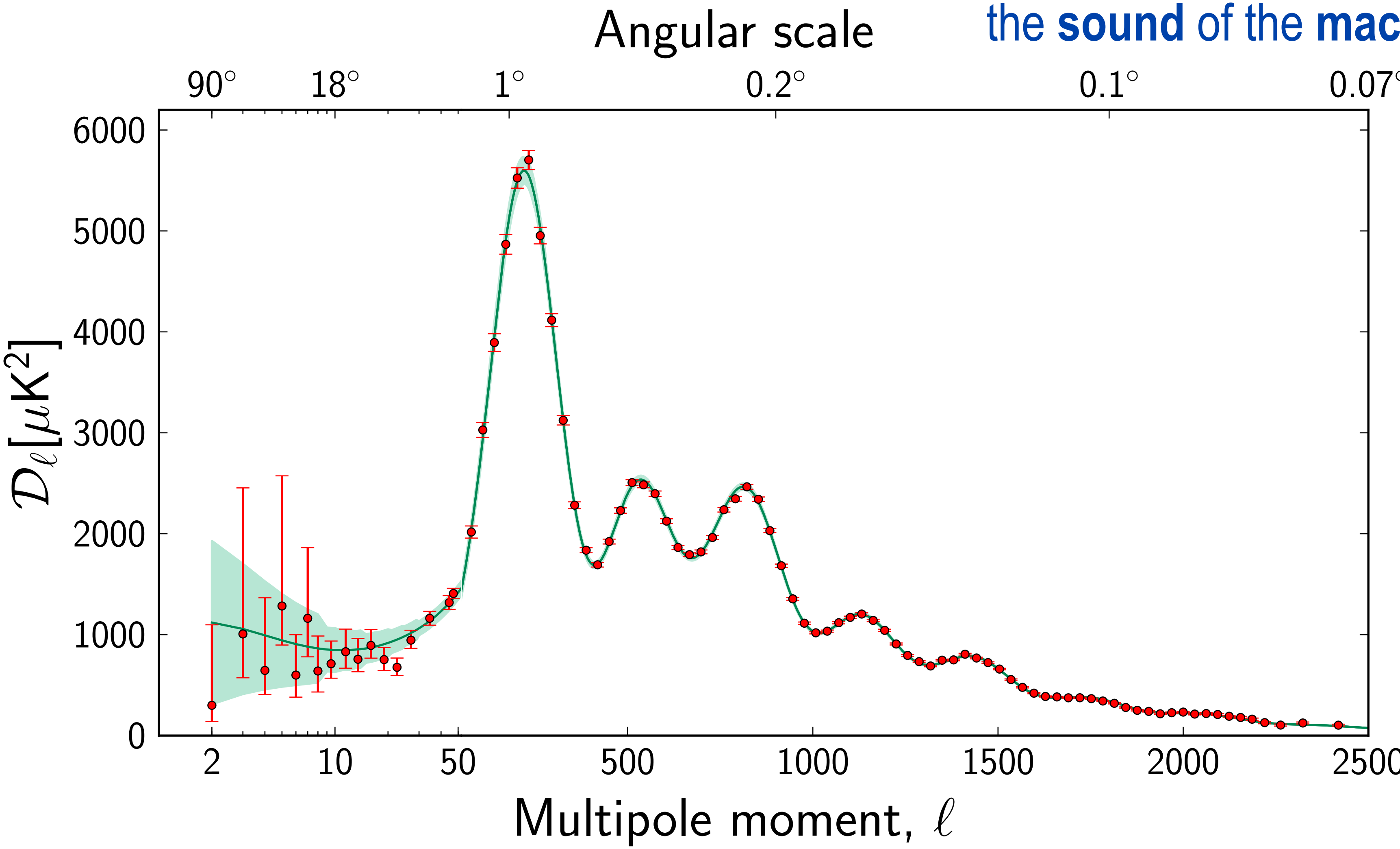
-0.014±0.009

$r < 0.12$ $r = 0.20 +.07 -.05$

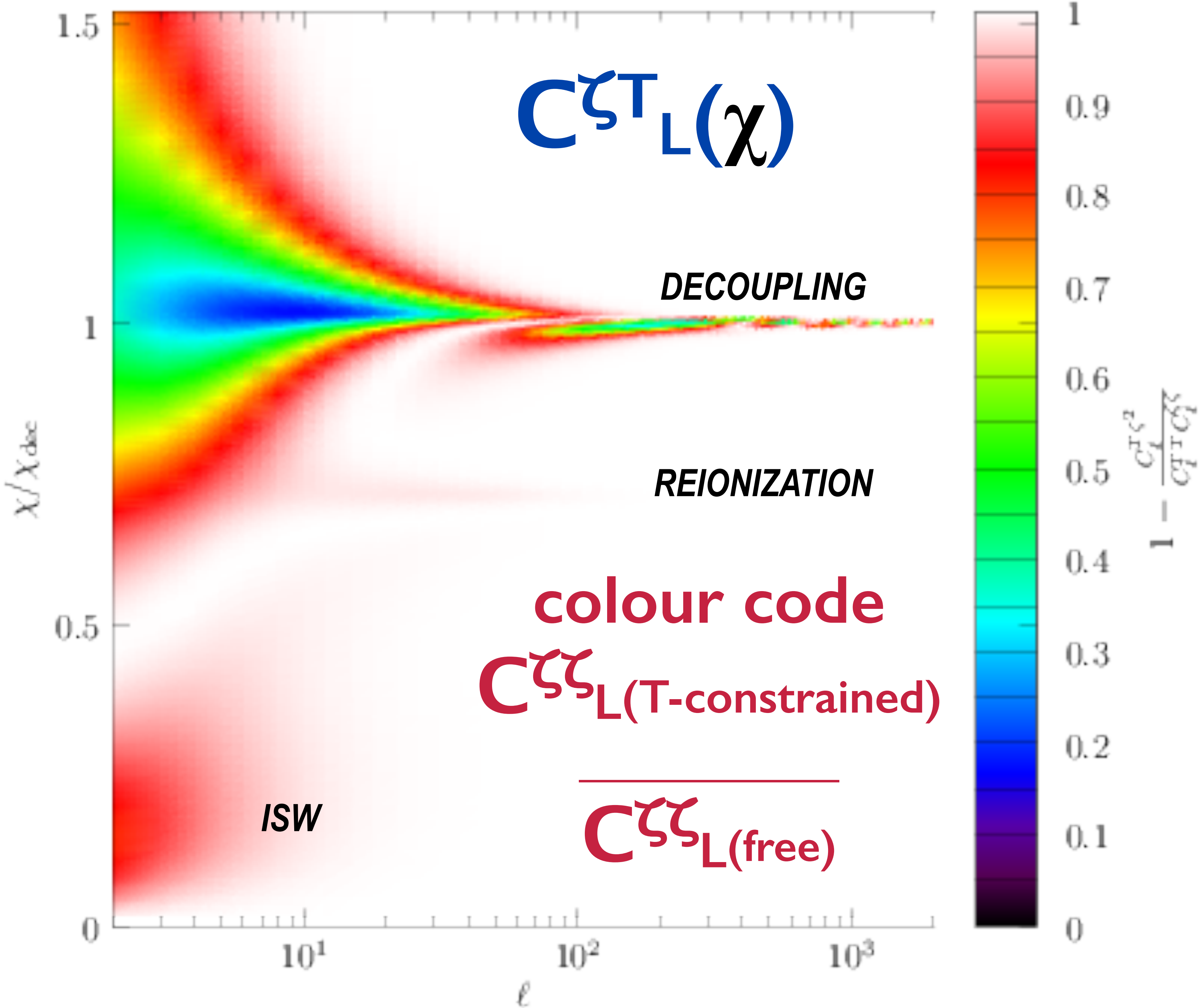
95% CL on ***running*** *d*$\mathbf{n}_s$*/dln****k****, running of running,* ***r*** *=Tensor-to-Scalar ratio (GW),*

isocurvature modes *for axions (<3.9%), baryons, neutrinos, curvatons (<0.25%)*

the **sound** of the **machine**



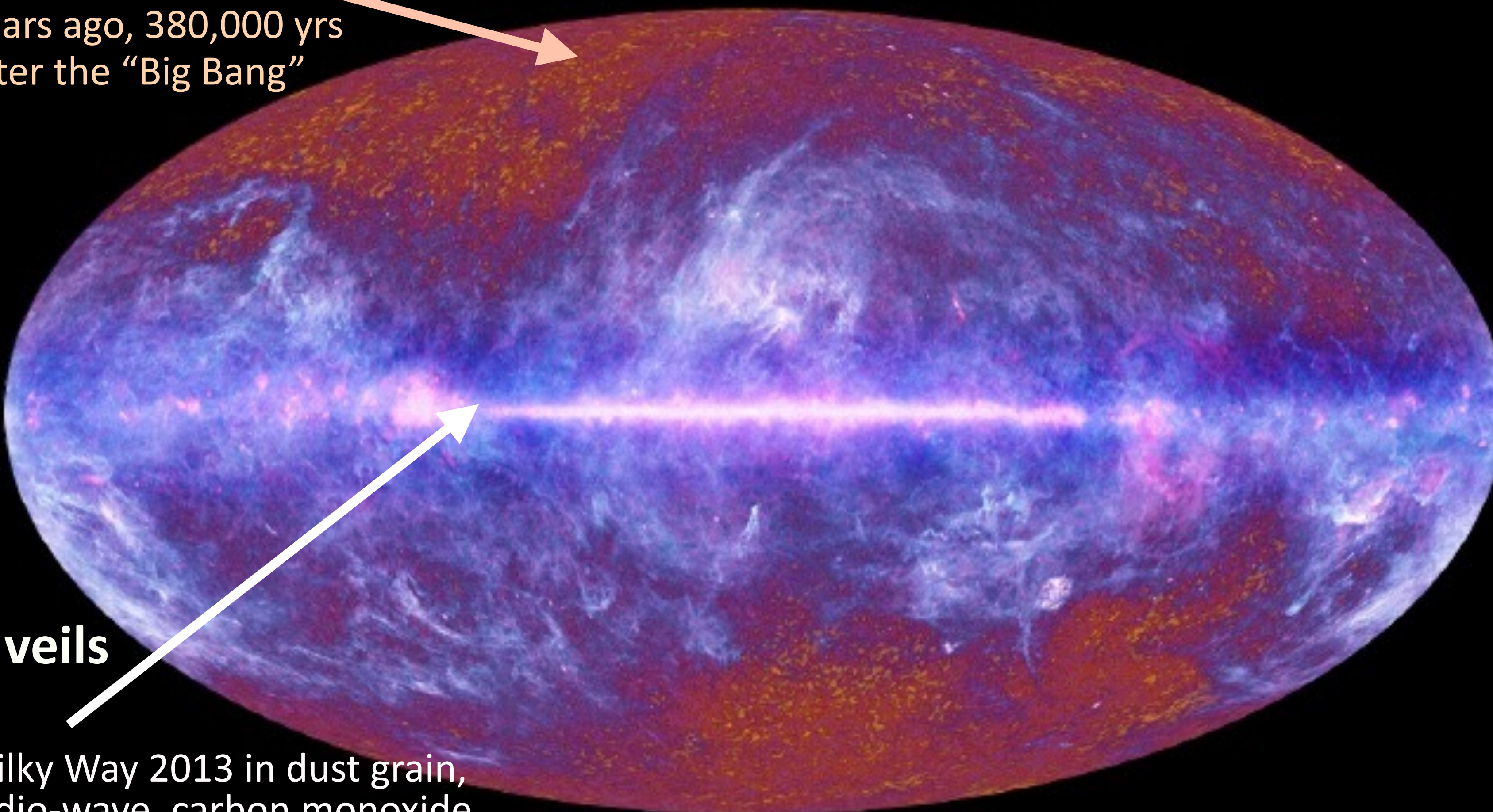
Excellent agreement between the Planck temperature spectrum at high L and the predictions of the tilted ΛCDM model.
Checks with polarization data provide full support to this conclusion.
extensive grid of cosmic models strongly constrain the x in tilted ΛCDM +x, x = subdominant deviations
Planck basic parameters (Ω_b, H_o ...), agree with BBN, BAO measure of acoustic scale. but H_o lower than HST, small age change
No evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model.
The first 30 multipoles are low for the standard ΛCDM, with no obvious explanation. *primordial fluctuation modification?*
Exact scale invariance ruled out, $n_s < 1$, at >4σ Planck alone, >5.4σ Planck + WMAP polarization
No substantial evidence for beyond basic single field slow roll, Bunch-Davis vacuum, standard kinetic term inflation. no f_{NL}



$C^{\zeta T}{}_L(\chi)$
DECOUPLING
REIONIZATION
ISW
colour code
$\frac{C^{\zeta\zeta}{}_{L(\text{T-constrained})}}{C^{\zeta\zeta}{}_{L(\text{free})}}$
$\chi/\chi_{\rm dec}$
ℓ
$1 - \frac{C_\ell^{T\zeta^2}}{C_\ell^{TT} C_\ell^{\zeta\zeta}}$

COMPLEXITY of here & now

the primordial light,
released 13.8 billion
years ago, 380,000 yrs
after the "Big Bang"



7 veils

Milky Way 2013 in dust grain, radio-wave, carbon monoxide emissions; plus stellar, X-ray, gamma ray, cosmic ray emissions ...

The Planck one-year all-sky survey

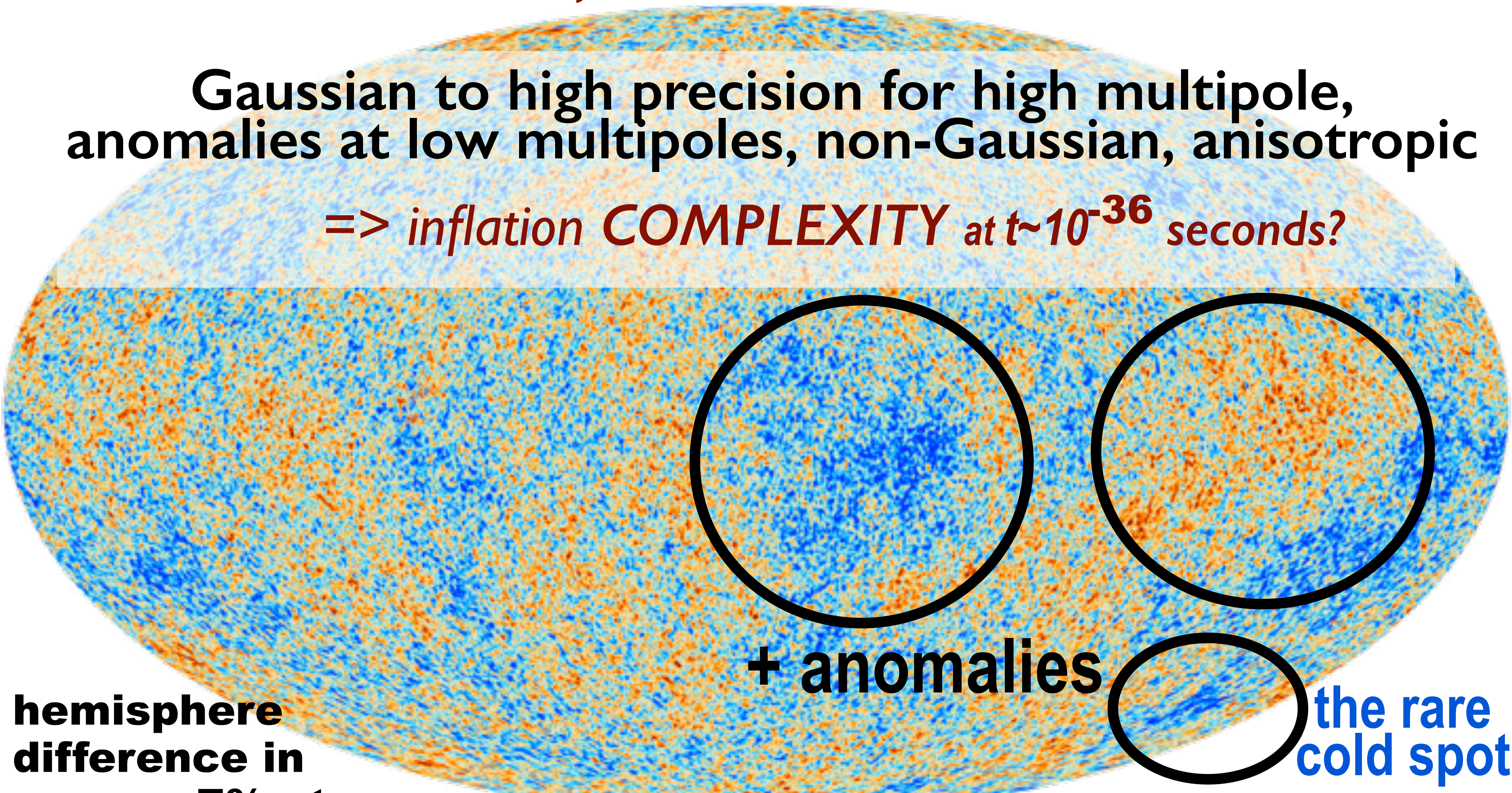
esa

(c) ESA, HFI and LFI consortia, July 2010

Planck's primordial light unveiled, March 21, 2013

reveals the SIMPLICITY of primordial cosmic structure

7⁺ numbers, 2+1 are inflation numbers



Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

=> inflation COMPLEXITY at $t\sim10^{-36}$ seconds?

+ anomalies

the rare cold spot

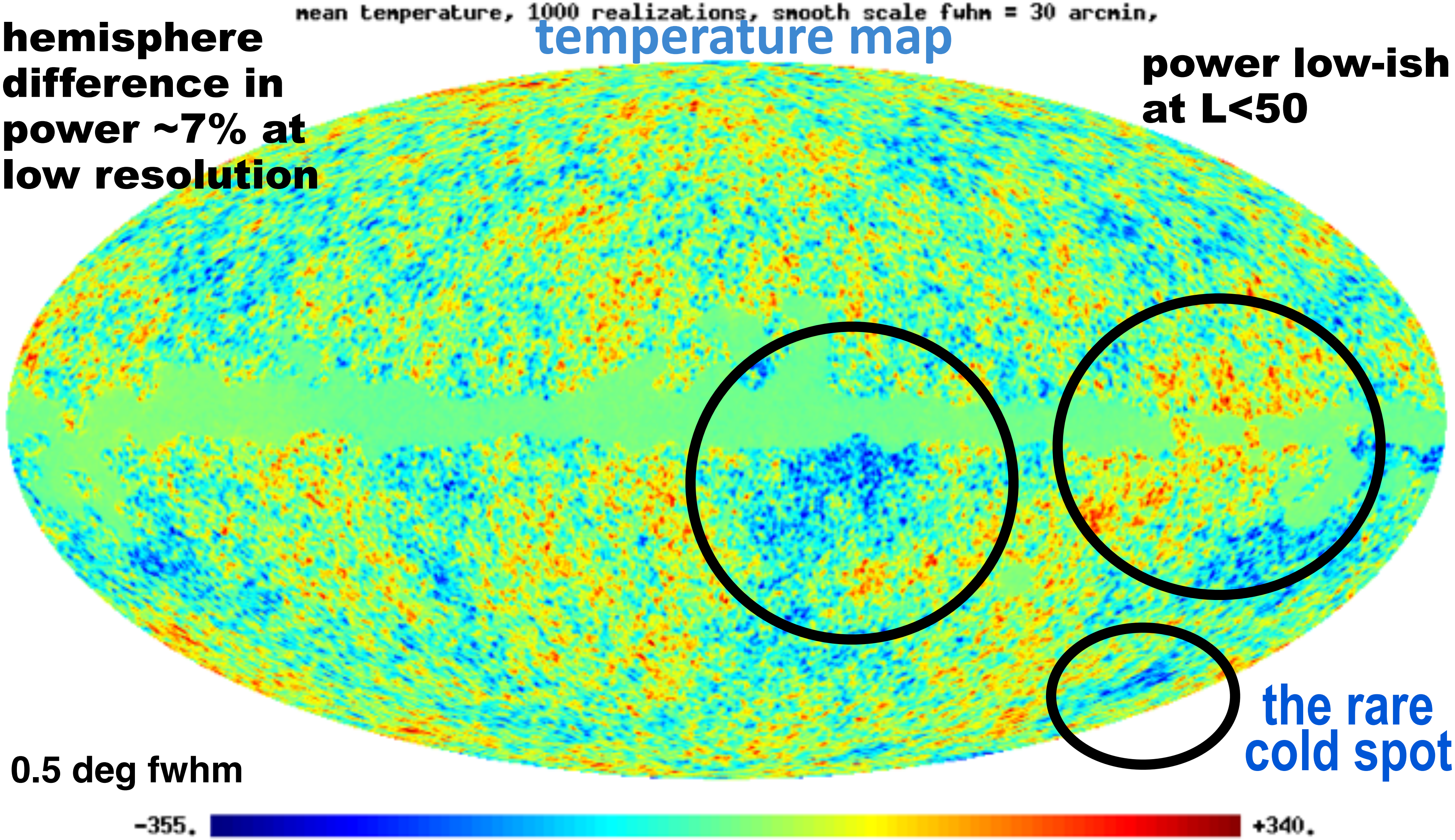
hemisphere difference in power ~7% at low resolution

Grand Unified Theory of Anomalies? TBD

intermittent *strain-power bursts (in curvature)?*

Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

anomalies => inflation ***COMPLEXITY*** *at $t \sim 10^{-36}$ seconds?*



Grand Unified Theory of Anomalies? TBD

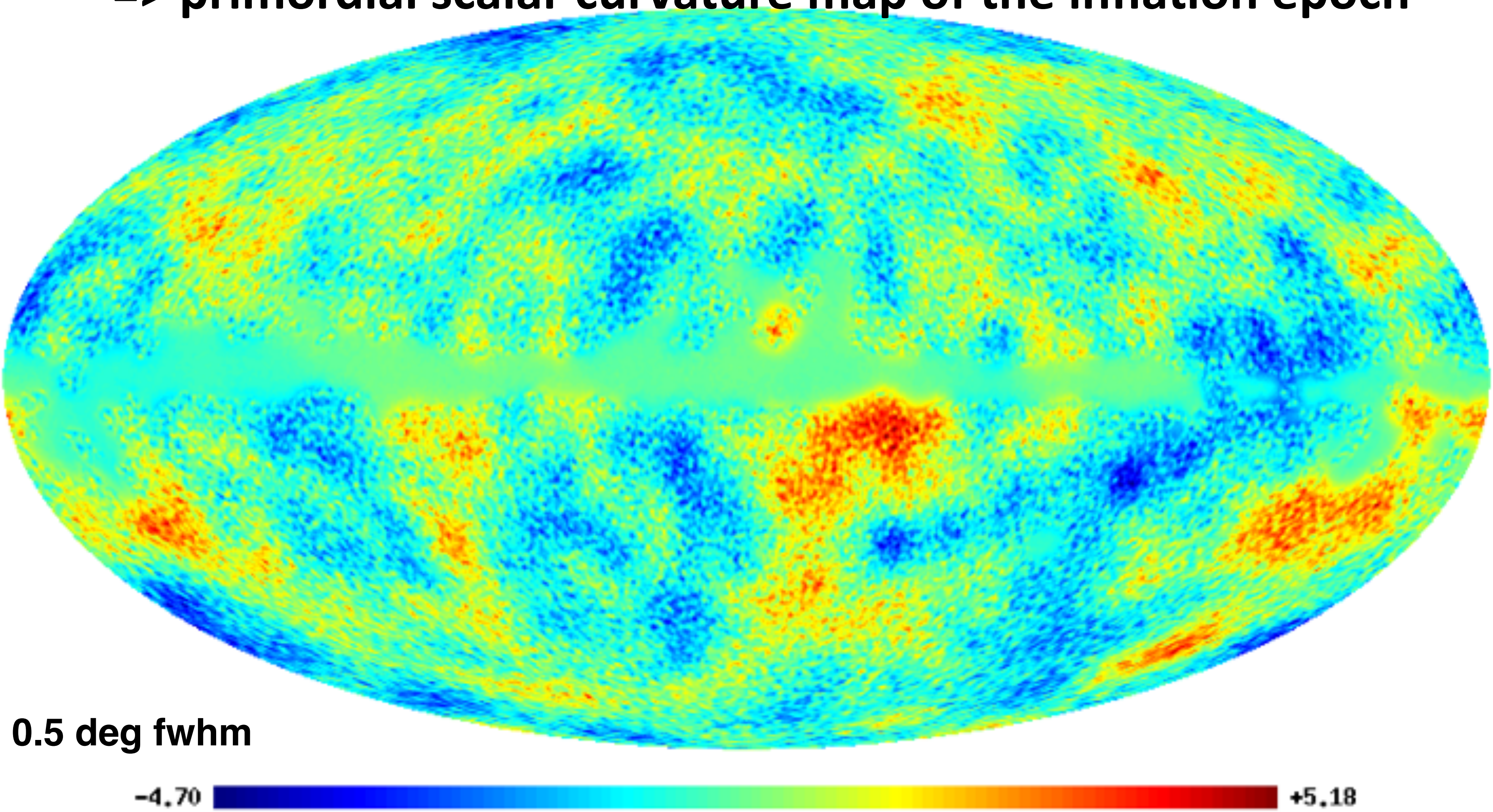
intermittent *strain-power bursts (in curvature)?*

reveals map of **primordial isotropic strain** /phonons

$\int d$ ***visibility***(*distance*) $<$***Trace*(α)**|*Temp*$>$ (*angles, distance*)

mean zeta, 1000 realizations, smooth scale fwhm = 30 arcmin,

=> primordial scalar curvature map of the inflation epoch



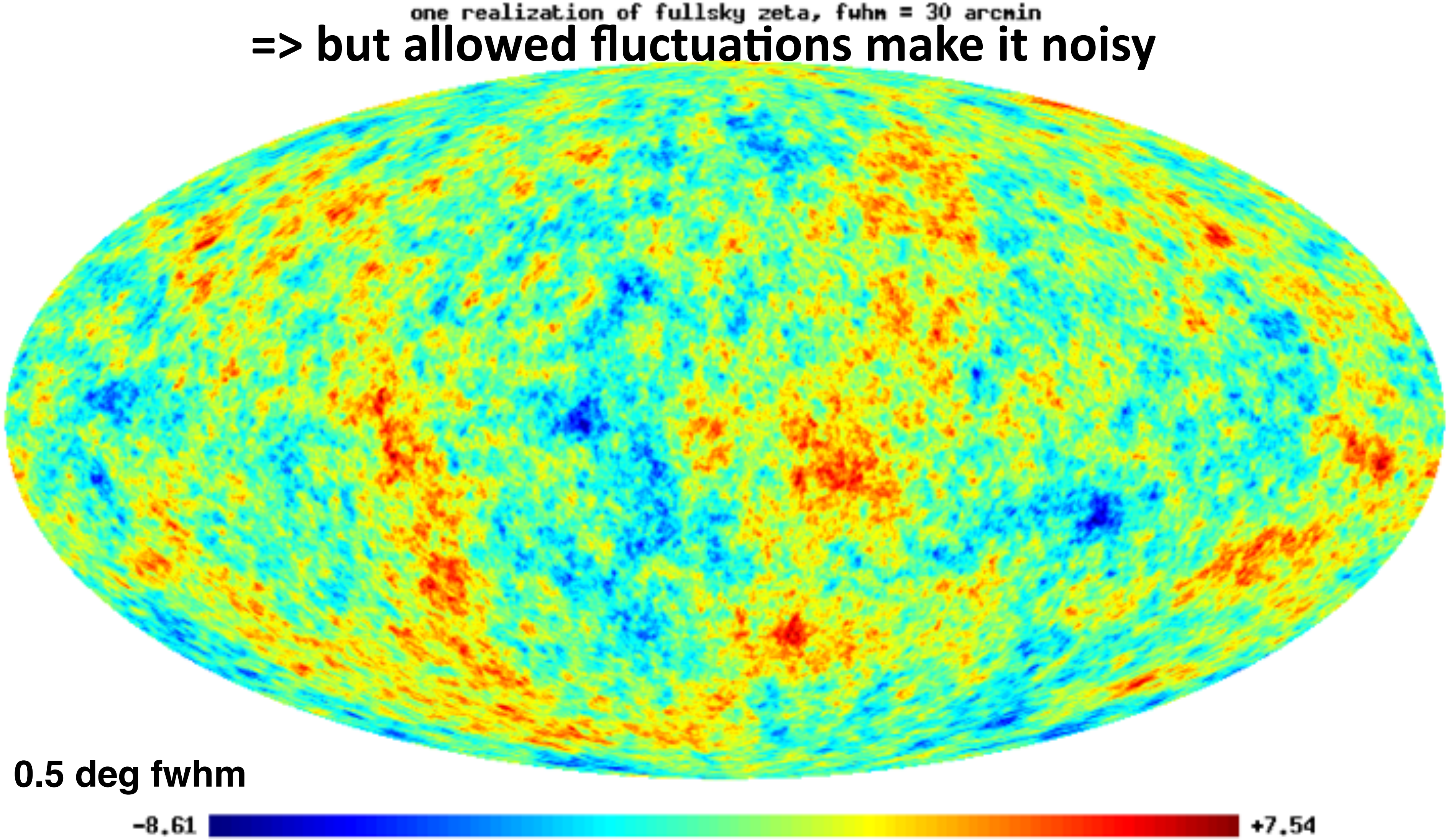
Reconstructing the Early Universe

visibility mask

reveals map of **primordial isotropic strain /phonons**

$\int d\,\textit{visibility}(distance)\ \ <\textbf{\textit{Trace}}(\boldsymbol{\alpha})|\textit{Temp}> + \delta\textbf{\textit{Trace}}(\boldsymbol{\alpha})$

=> but allowed fluctuations make it noisy

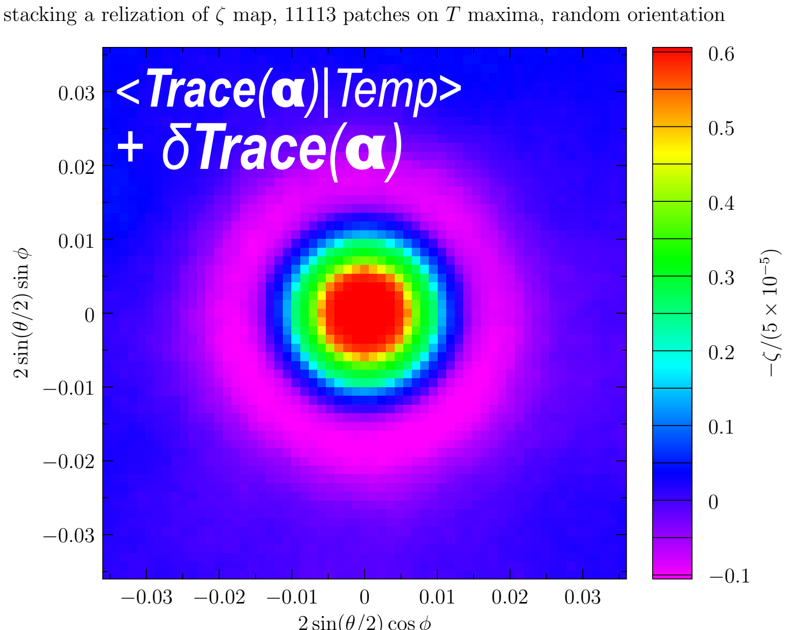


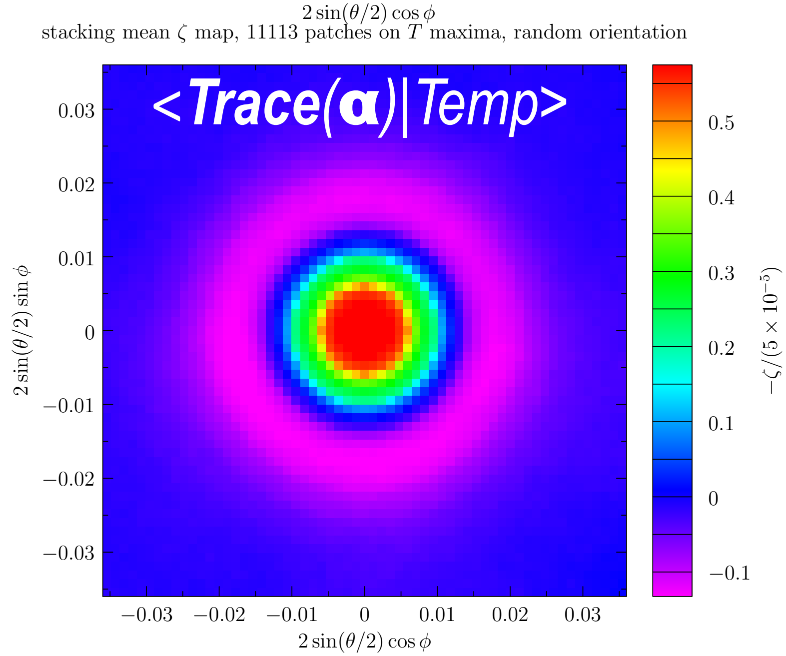
Reconstructing the Early Universe **visibility mask**

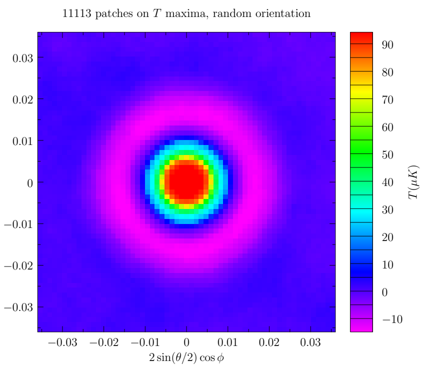
CMB Peak Statistics

curvature stacked on temperature Peaks

Primordial curvature stacked Planck 2013



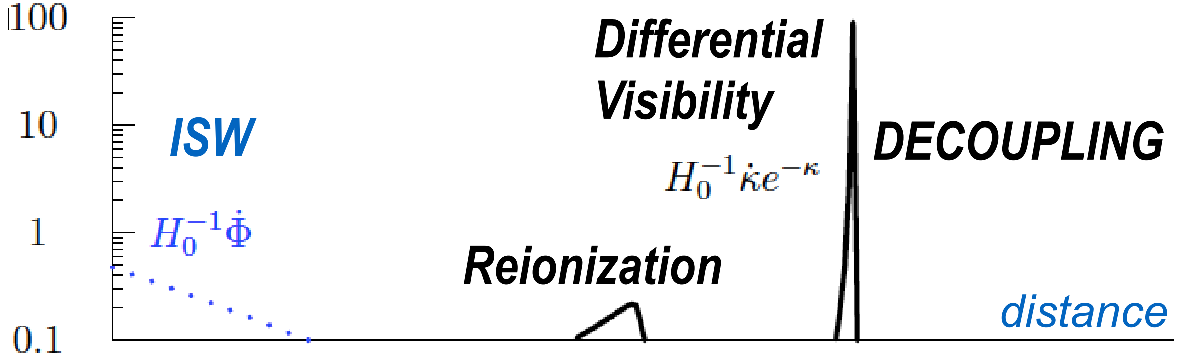




reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* $<\mathit{Trace}(\boldsymbol{\alpha})|\mathit{Temp}> + \delta \mathit{Trace}(\boldsymbol{\alpha})$

=> but allowed fluctuations make it noisy



CMB-*probe* no tomography (***radial distance (redshift)***):

CMB-*probe* ~ differential visibility

at decoupling/recombination (all L)

reionization/reheating (low L)

CMB-*probe* ~ changing gravitational potential

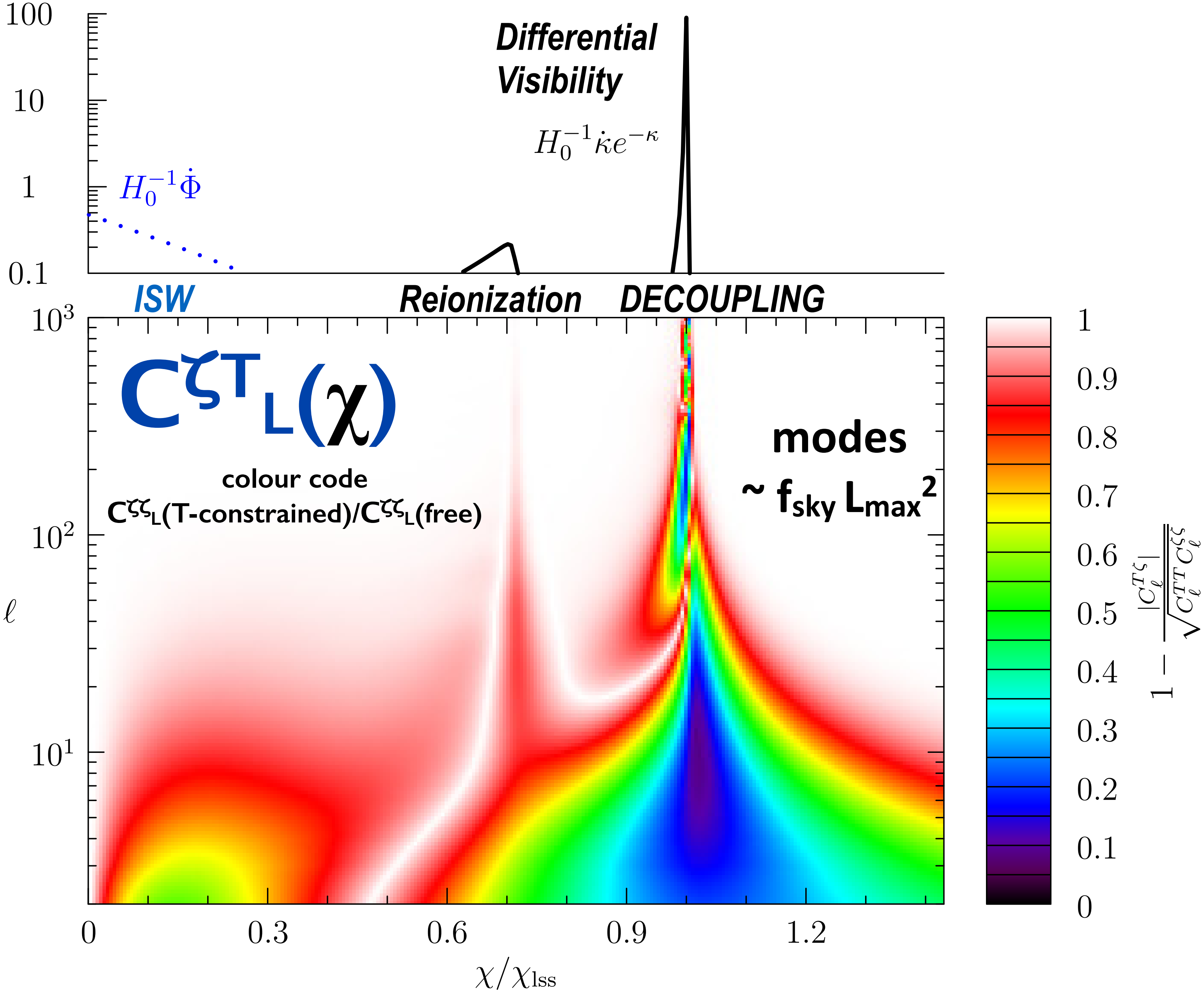
Integrated Sachs Wolfe effect **(low L), Rees-Sciama** effect **(hi L)**

available modes: $f_{sky} L_{max}^2$ $-f_{sky} L_{min}^2$ $L_{max} \sim L_{damp}$

Large Scale Structure Galaxy Surveys

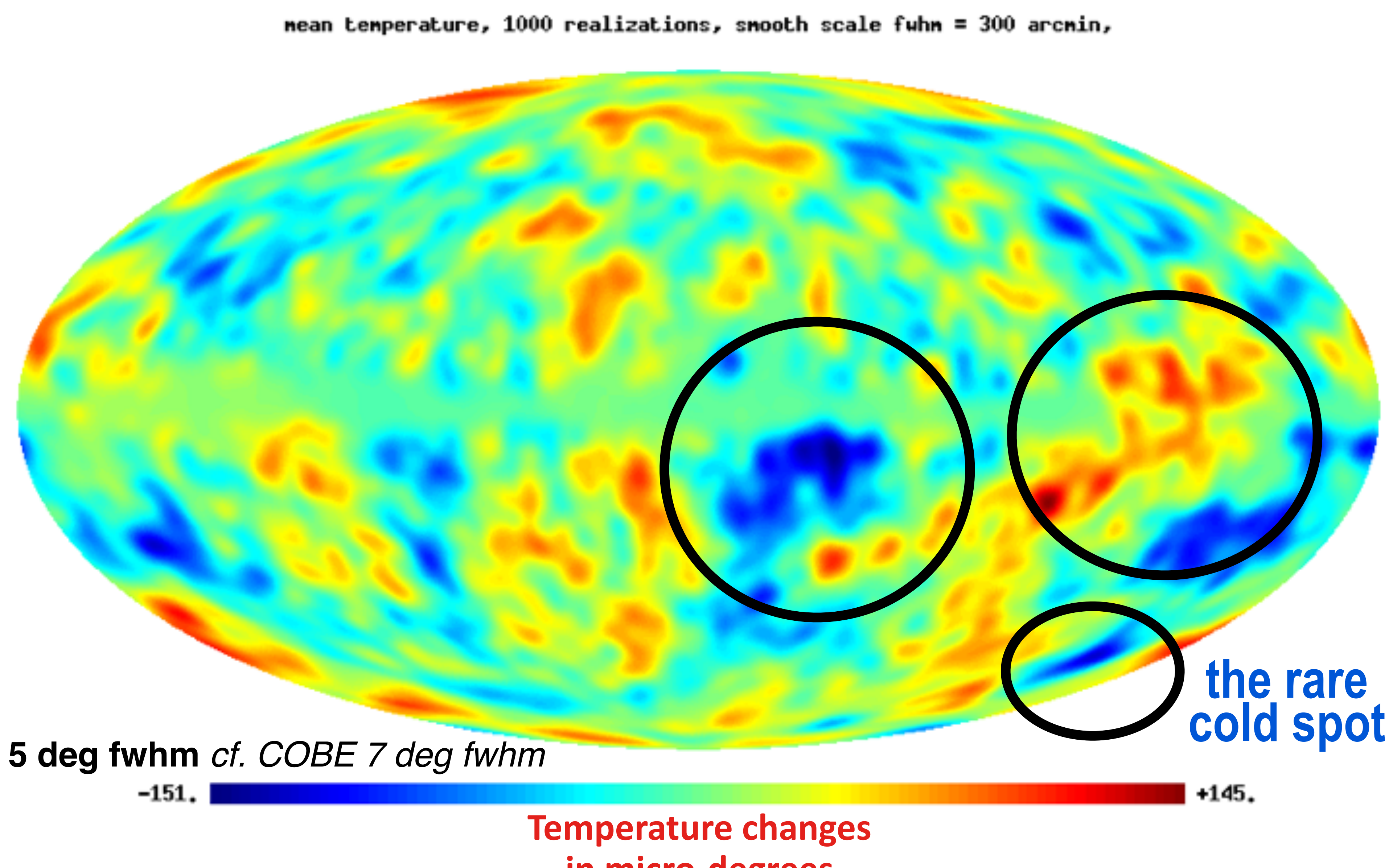
available modes ~ $f_{sky} L_{max}^2 \; k_{max} d_{max}$

$\sim f_{sky} (k_{max}^3 d_{max}^3)$, $k_{min} \sim 2\pi/d_{max}$ $V_{com} \sim d_{max}^3$



Differential Visibility
$H_0^{-1}\dot{\kappa}e^{-\kappa}$
$H_0^{-1}\dot{\Phi}$
100
10
1
0.1
ISW
Reionization
DECOUPLING
$C^{\zeta T}{}_{L}(\chi)$
colour code
$C^{\zeta\zeta}{}_{L}$(T-constrained)/$C^{\zeta\zeta}{}_{L}$(free)
modes
~ $f_{sky}\,L_{max}^2$
10^3
10^2
10^1
ℓ
0
0.3
0.6
0.9
1.2
$\chi/\chi_{\rm lss}$
$1-\frac{|C_\ell^{T\zeta}|}{\sqrt{C_\ell^{TT}C_\ell^{\zeta\zeta}}}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

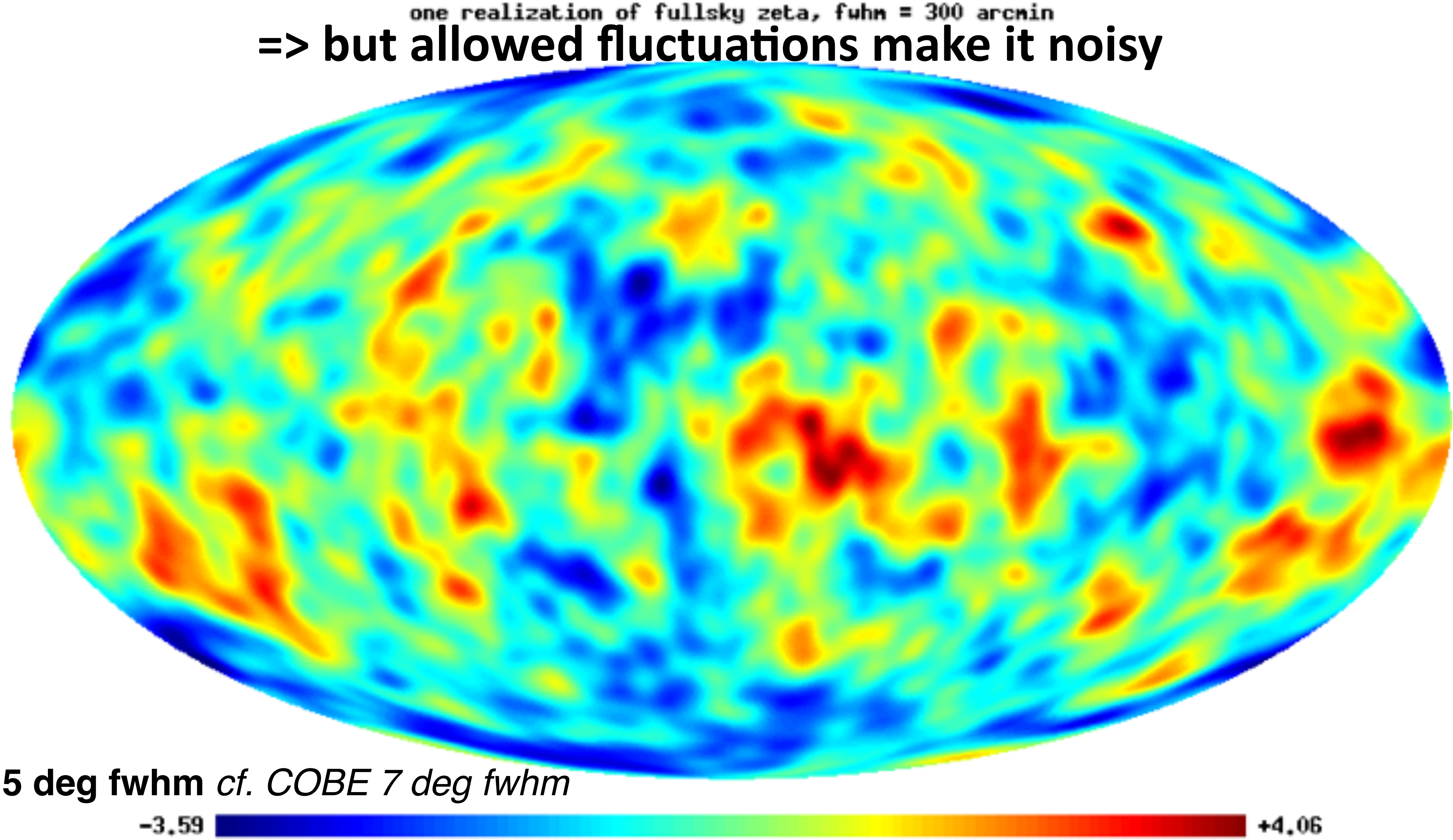
temperature map



reveals map of **primordial isotropic strain** /phonons

$\int d$ ***visibility****(distance)* $<\mathbf{Trace}(\boldsymbol{\alpha})|Temp> + \delta \mathbf{Trace}(\boldsymbol{\alpha})$

=> but allowed fluctuations make it noisy



5 deg fwhm *cf. COBE 7 deg fwhm*

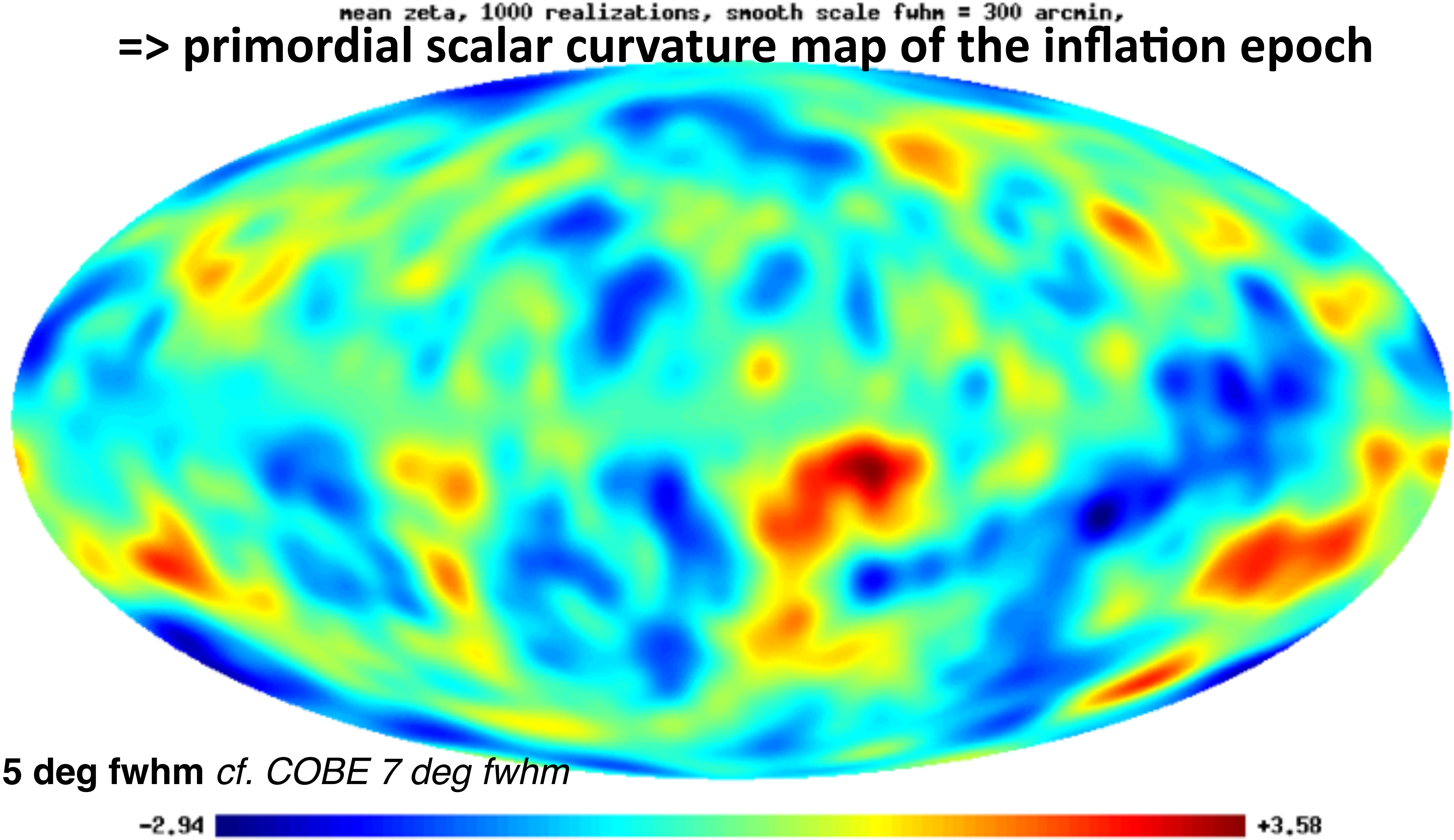
Reconstructing the Early Universe

visibility mask

reveals map of **primordial isotropic strain /phonons**

∫d***visibility***_(distance)_ <***Trace*(α)**|*Temp*> _(angles, distance)_

=> **primordial scalar curvature map of the inflation epoch**



5 deg fwhm *cf. COBE 7 deg fwhm*

Reconstructing the Early Universe

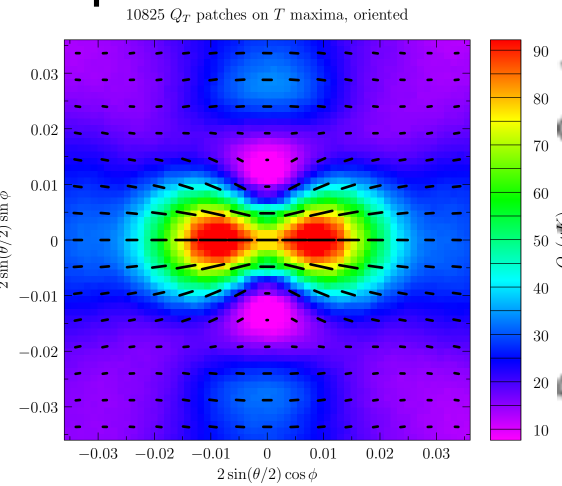
visibility mask

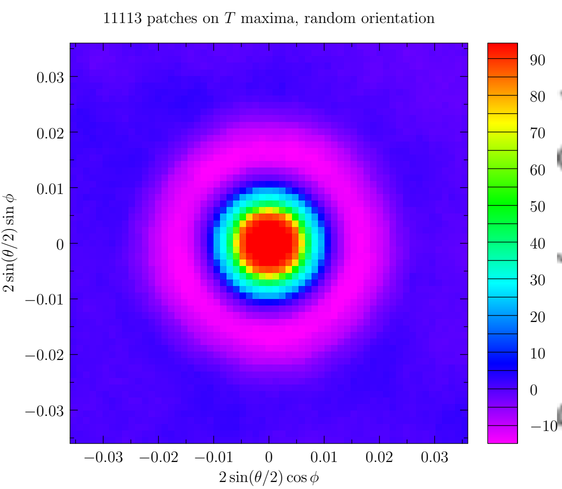
CMB Peak Statistics

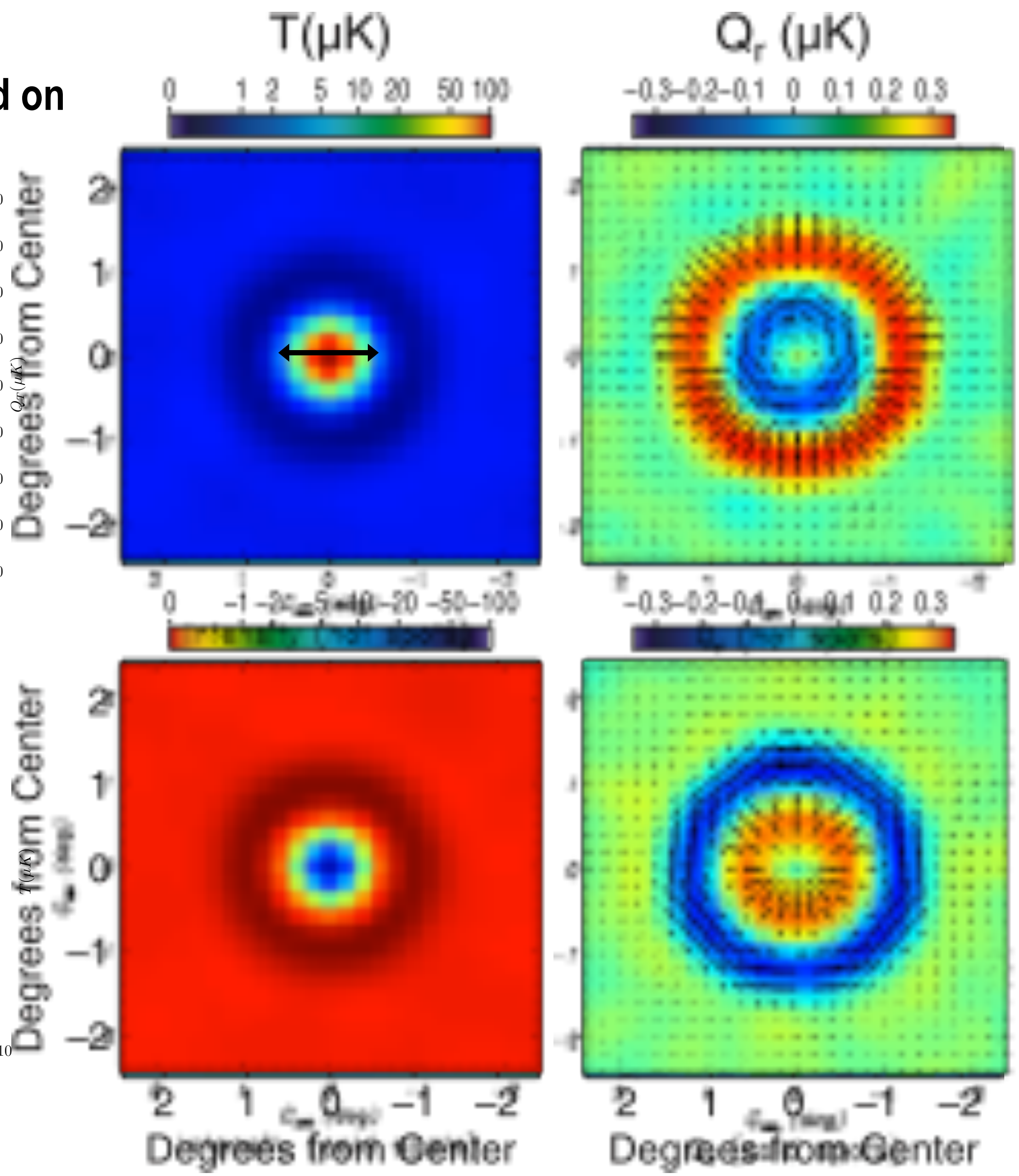
CMB Polarization
BAO in the CMB – Planck2013

temperature stacked on temperature Peaks

polarization rotated & stacked on temperature Peaks







Planck2013 teaser for Planck2014 polarization release

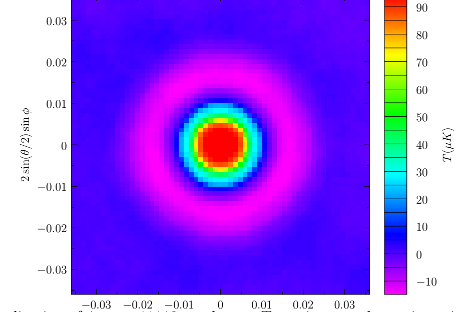
E mode patterns

no B here

Planck2014, 2015 ACTpol, ABS, Spider, AdvACT, GLP, ..

CMB Peak Statistics

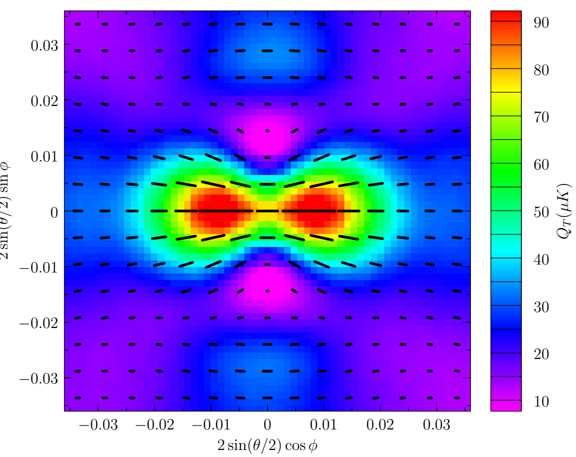
CMB Polarization Planck 2013



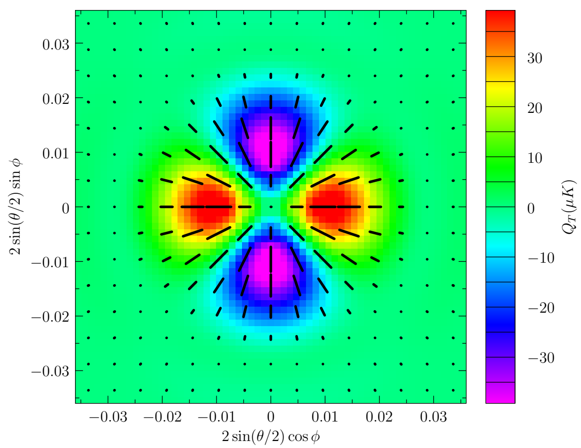
temperature stacked on temperature Peaks

polarization rotated & stacked on temperature Peaks

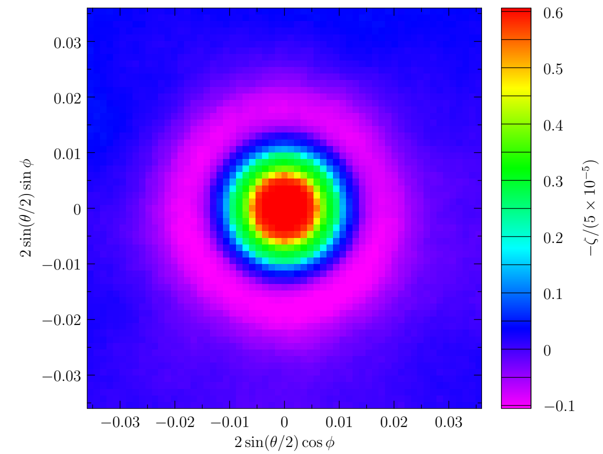
10825 Q_T patches on T maxima, oriented



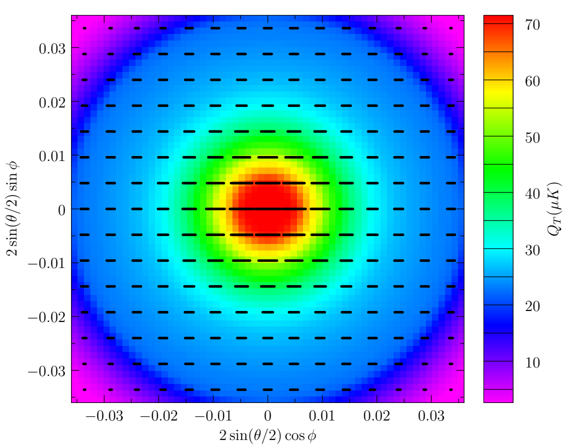
10825 Q_T patches on T maxima, oriented, $m=2$ component



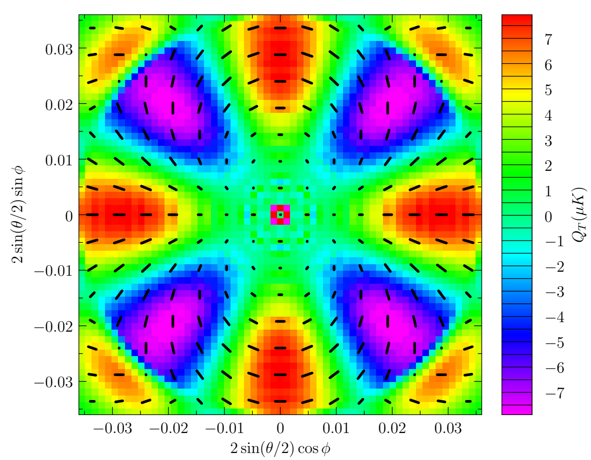
stacking a relization of ζ map, 11113 patches on T maxima, random orientation



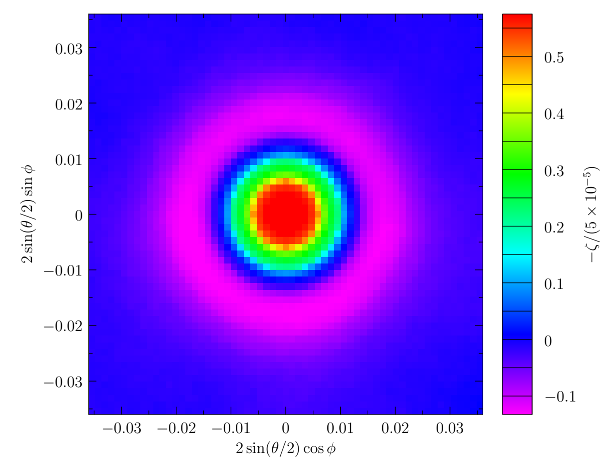
10825 Q_T patches on T maxima, oriented, $m=0$ component



10825 Q_T patches on T maxima, oriented, $m=4$ component



stacking mean ζ map, 11113 patches on T maxima, random orientation

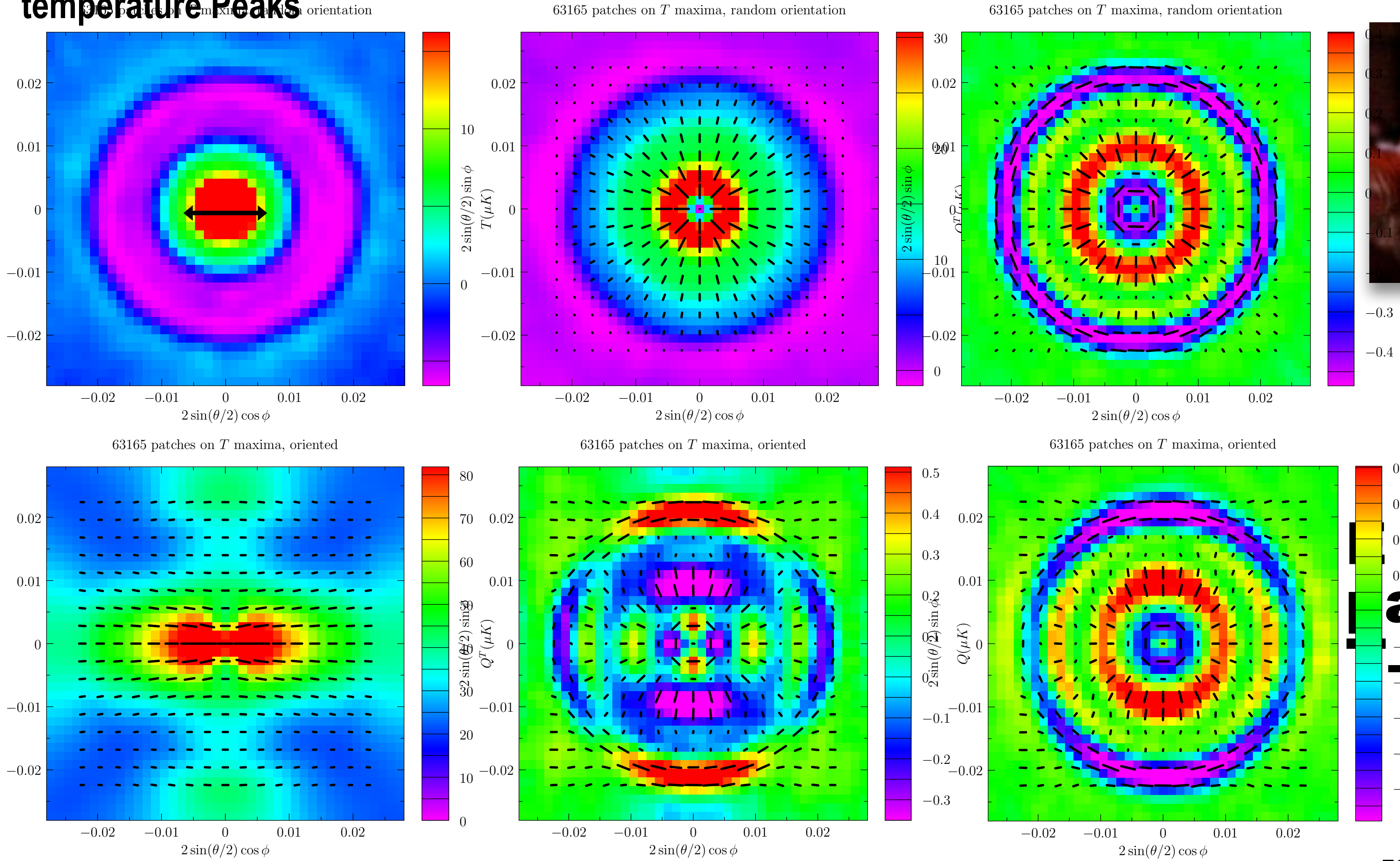


CMB Peak Statistics

temperature stacked on temperature Peaks
polarization rotated & stacked on temperature Peaks

CMB Polarization

sample temperature and polarization patterns for Planck2014: oriented peaks



E mode patterns -oriented

no B here

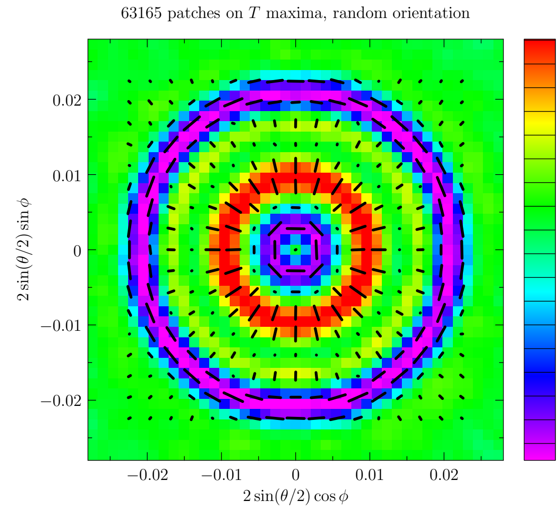
Planck2014, **2015** *ACTpol, ABS, Spider, AdvACT, GLP, ..*

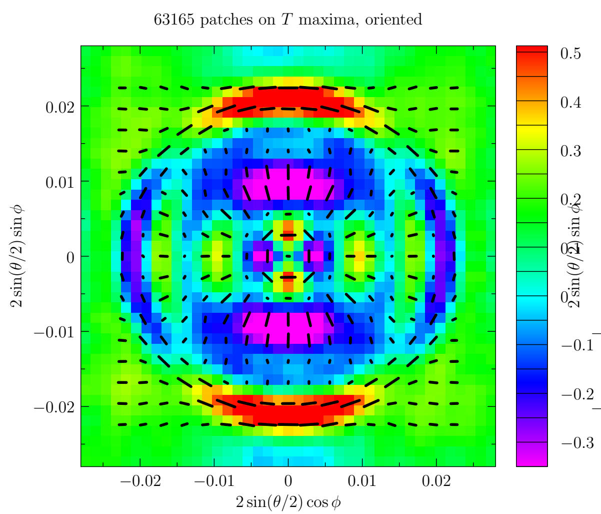
CMB Peak Statistics

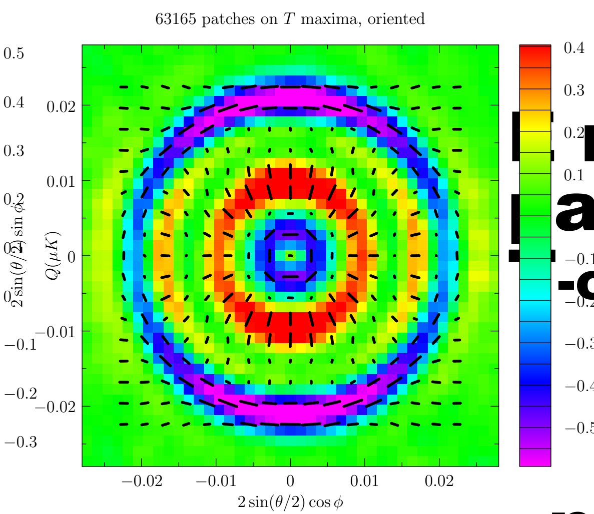
temperature stacked on temperature Peaks
polarization rotated & stacked on temperature Peaks

CMB Polarization

sample temperature and polarization patterns for Planck2014: oriented peaks







mode
atterns
-oriented

no B here

Planck2014, 2015 ACTpol, ABS, Spider, AdvACT, GLP, ..

SIMPLICITY *reveals primordial* **sound waves** *in matter*

at **a~e^{-7}~1/1100 =>**

at **a~e^{-67+60}~1/10^{30+25}**

B2FHAP14, Planck2013

oriented peaks, anisotropic CMB strain