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

Planck 2015 on Cosmic Photons, Phonons, Gravitons & Neutrinos

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

Dick Bond

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 ~0.3 amu /cm^3 ;
for LHC@CERN-type relics ~ 1 every 10 cm

Dark Energy
~ vacuum potential density ~ 3 amu /m^3 68.8 ± 0.9%
inflaton-phonon condensate

THE LIGHT

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

THE VACUUM

Higgs@CERN vacuum origin of mass
vacuum fluctuations in **phonons** origin of all cosmic structure we see
the vacuum is under **gravitational strain**, differentially accelerating
gravitons vacuum fluctuations a byproduct r=Tensor/Scalar =?
isocons vacuum fluctuations in light scalars, … axions

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inflaton-phonon condensate

THE LIGHT

$S_{U,\gamma+\nu} \sim 10^{88.6}$
cf. $S_{th,cl} \sim 10^{76}$ *cf.* $S_{G,DE} \sim 10^{121.9}$

cosmic radiation
the 1st light of the universe 412 **photons**/cm^3 0.005% 5.2 bits/γ
cosmic **neutrinos** ~ cosmic **photons** Energy fraction > 0.47% ~ stars
cosmic **gravity waves** << cosmic photons
5.0 bits/ν (N_{eff}/3.046)

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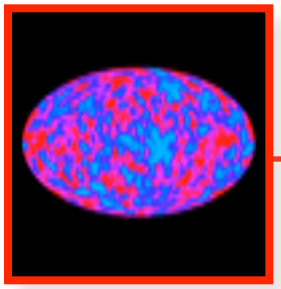
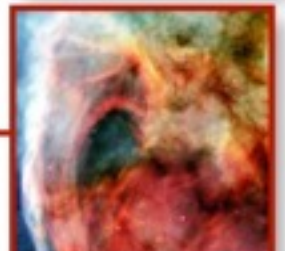


Radiation:
0.005%

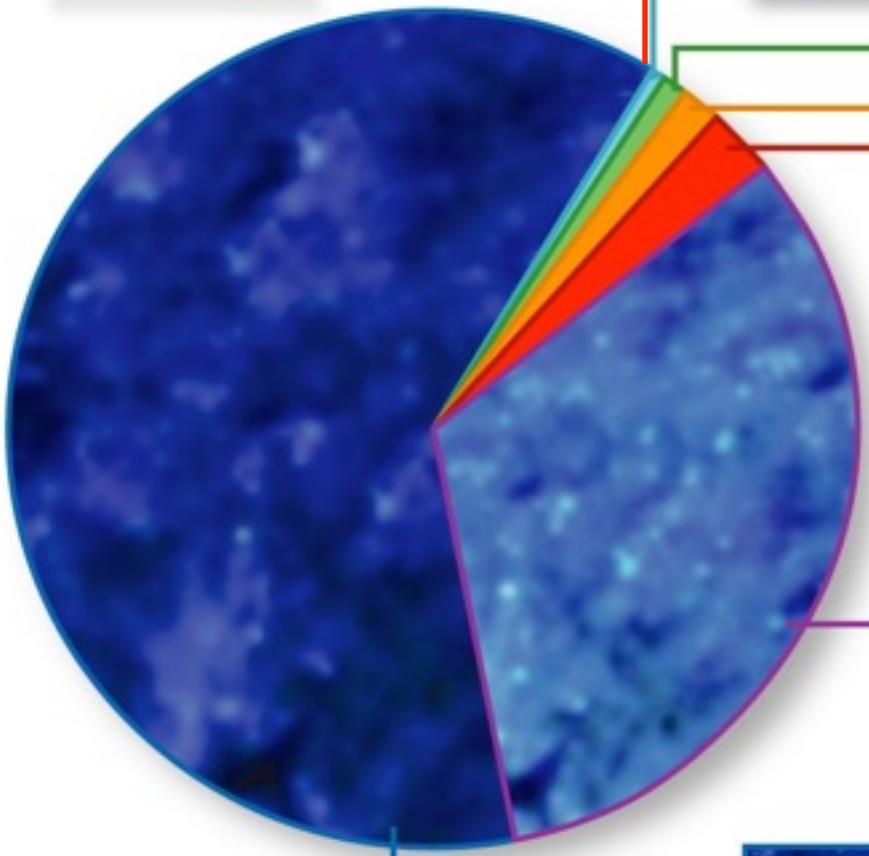
Chemical Elements:
(other than H & He) 0.025%

Neutrinos:
> 0.47%

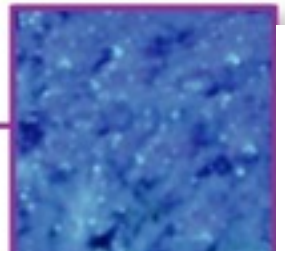
Stars:
0.5%



Free
H & He:
4.3%



$\Omega_{total} = 1$



Dark Matter:

$\Omega_{dm} = 26.8 \pm 0.9\%$

Dark Energy:

$\Omega_{de} = 68.8 \pm 0.9\%$

Gravity Waves

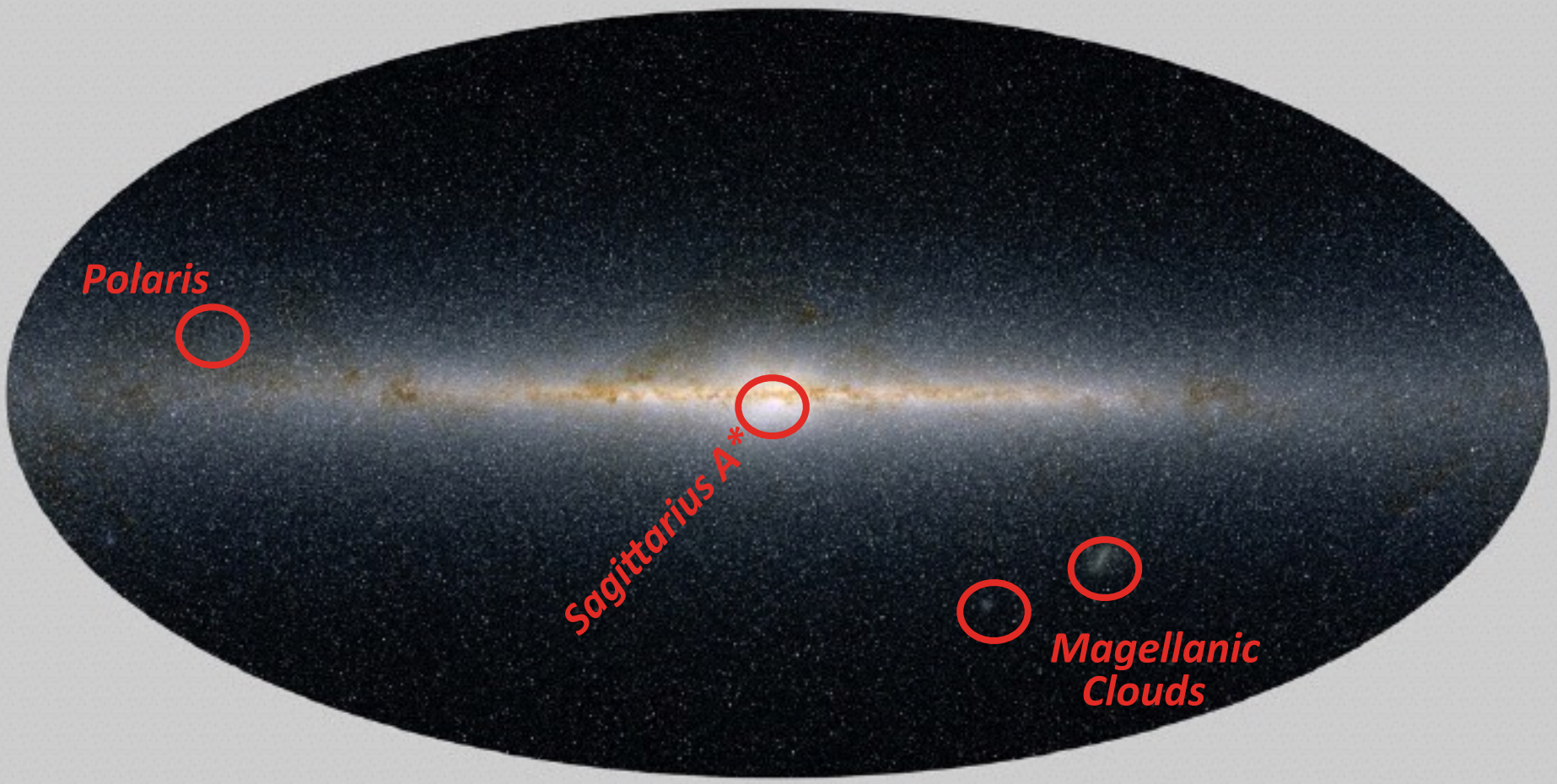
Ω_{GW} ~10^{-14} - 10^{-10} LIGO

$\Omega_{BlackHoles}$ ~10^{-7}

\

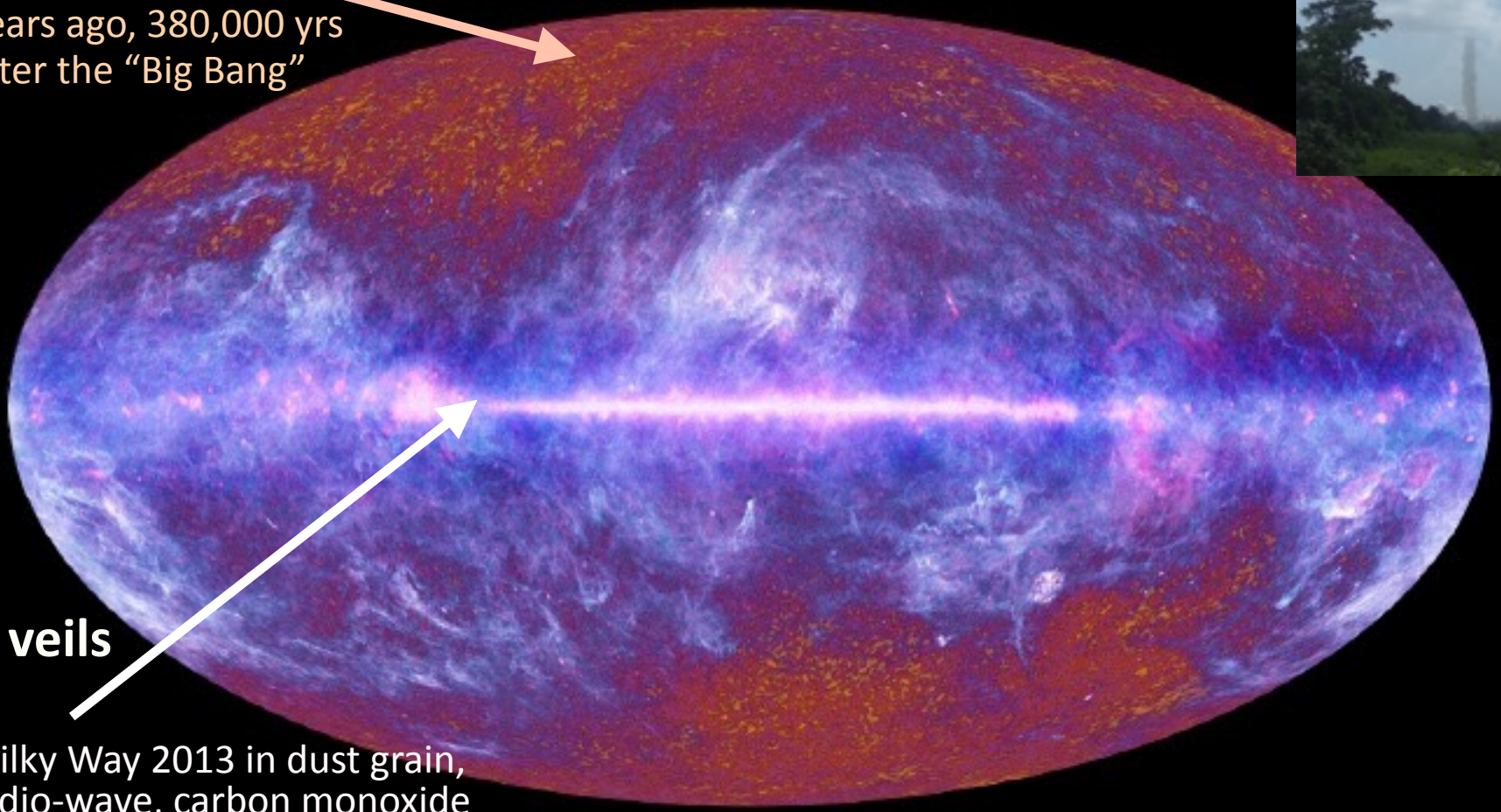
Milky Way in infra-red:

half a billion stars, a disk galaxy



COMPLEXITY of here & now

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



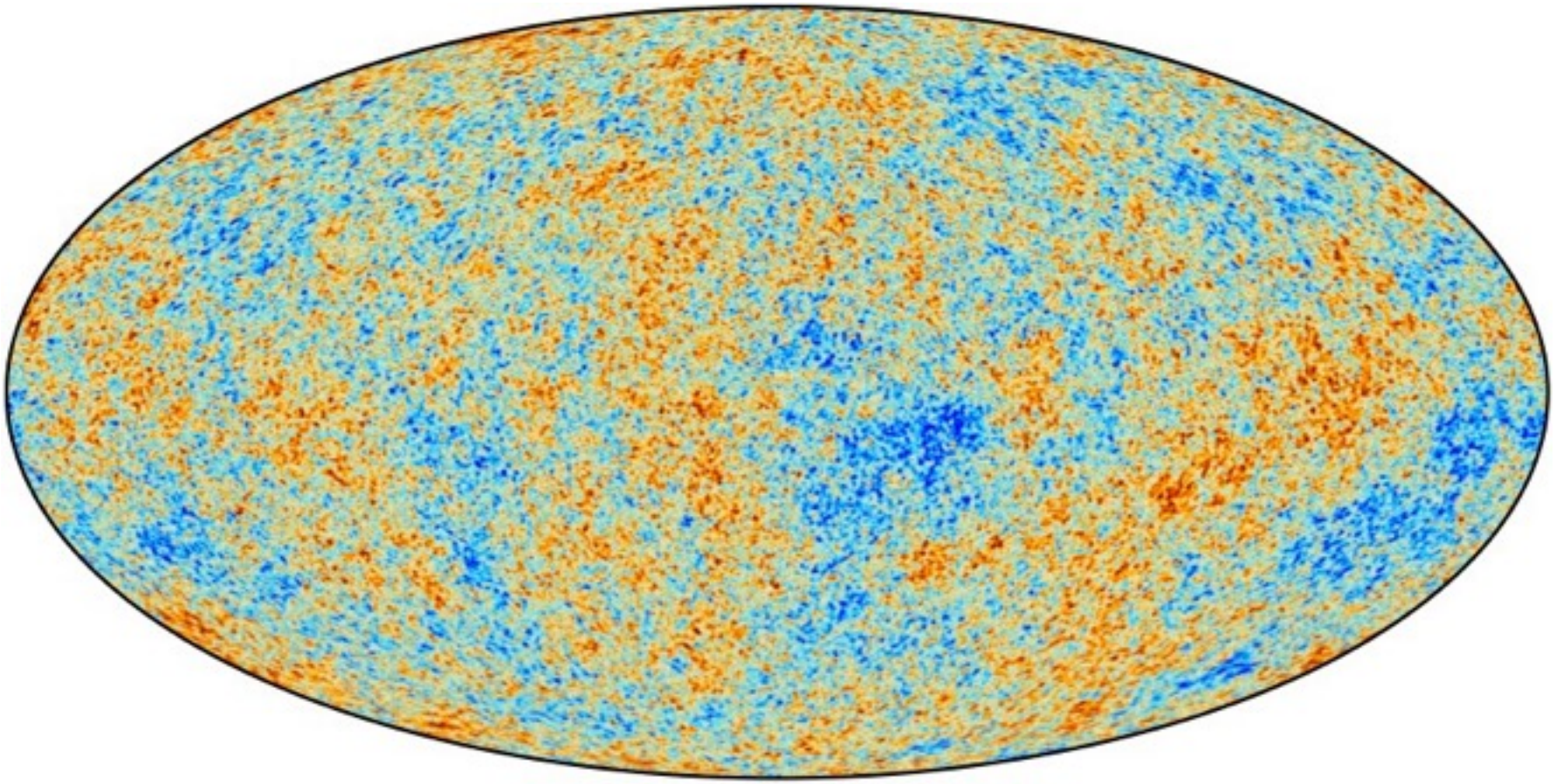
7 veils

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

Planck's primordial light unveiled, Feb 5, 2015

reveals the SIMPLICITY of primordial cosmic structure

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



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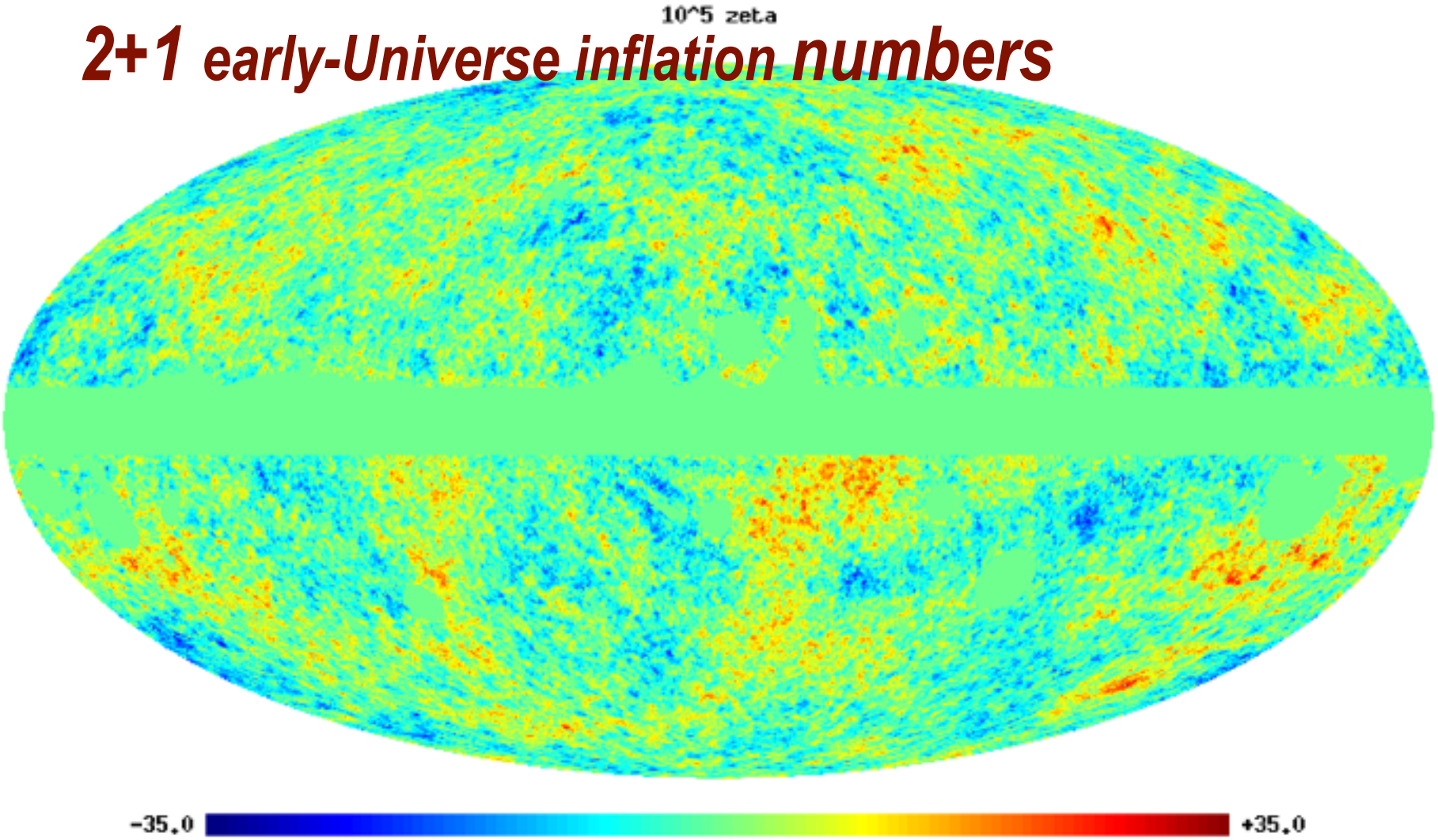
2+1 early-Universe inflation numbers



Planck 2015 Feb Papers

Planck_BICEP2_Keck.pdf BKP marginalize over dust polarization => primordial gravity wave constraint no detection

Planck_2015_Results_I_Overview_Products_Results.pdf

Planck_2015_Results_II_LFI_Data_Processing.pdf
Planck_2015_Results_IV_LFI_Beams.pdf
Planck_2015_Results_VI_LFI_Maps.pdf

Planck_2015_Results_VII_HFI_Data_Proc_TOI_Beams.pdf
Planck_2015_Results_VIII_HFI_Data_Proc_Calibration_Maps.pdf

Planck_2015_Results_X_Diffuse_Comp_Sep_Foreground_maps.pdf

Planck_2015_Results_XIII_Cosmological_Parameters.pdf cf. PCP13 shifts <0.7σ except τ =0.066±.016, z_{re}=8.8+1.7-1.4 is down;
Planck_2015_Results_XIV_Dark_Energy_Mod_Gravity.pdf cosmological constant still works well
Planck_2015_Results_XV_Gravitational_Lensing.pdf 40sigma detection
Planck_2015_Results_XVII_Primordial_Non-Gaussianity.pdf limits similar to P13, polarization adds a bit
Planck_2015_Results_XVIII_Background_Geometry_Topology.pdf size/(2 distance to last scattering) >1
Planck_2015_Results_XIX_Constraints_Primordial_Magnetic_Fields.pdf
Planck_2015_Results_XX_Inflation.pdf m2phi2 ruled out, conformally flattened potentials OK
Planck_2015_Results_XXI_Integrated_Sachs-Wolfe_Effect.pdf

Planck_2015_Results_XXII_Map_Thermal_SZ_Effect.pdf public now, agrees with cluster count cosmology
Planck_2015_Results_XXIV_Cosmology_SZ_Clusters_Counts.pdf tension remains with primary CMB; nu mass?
Planck_2015_Results_XXVII_Second_Planck_Catalogue_SZ_Sources.pdf PSZ2 1652,1203 confirmed

Planck_2015_Results_XXVIII_Planck_Catalogue_Galactic_Cold_Clumps.pdf

Planck+Herschel Launch May14 09 French Guiana

1.5m telescope,

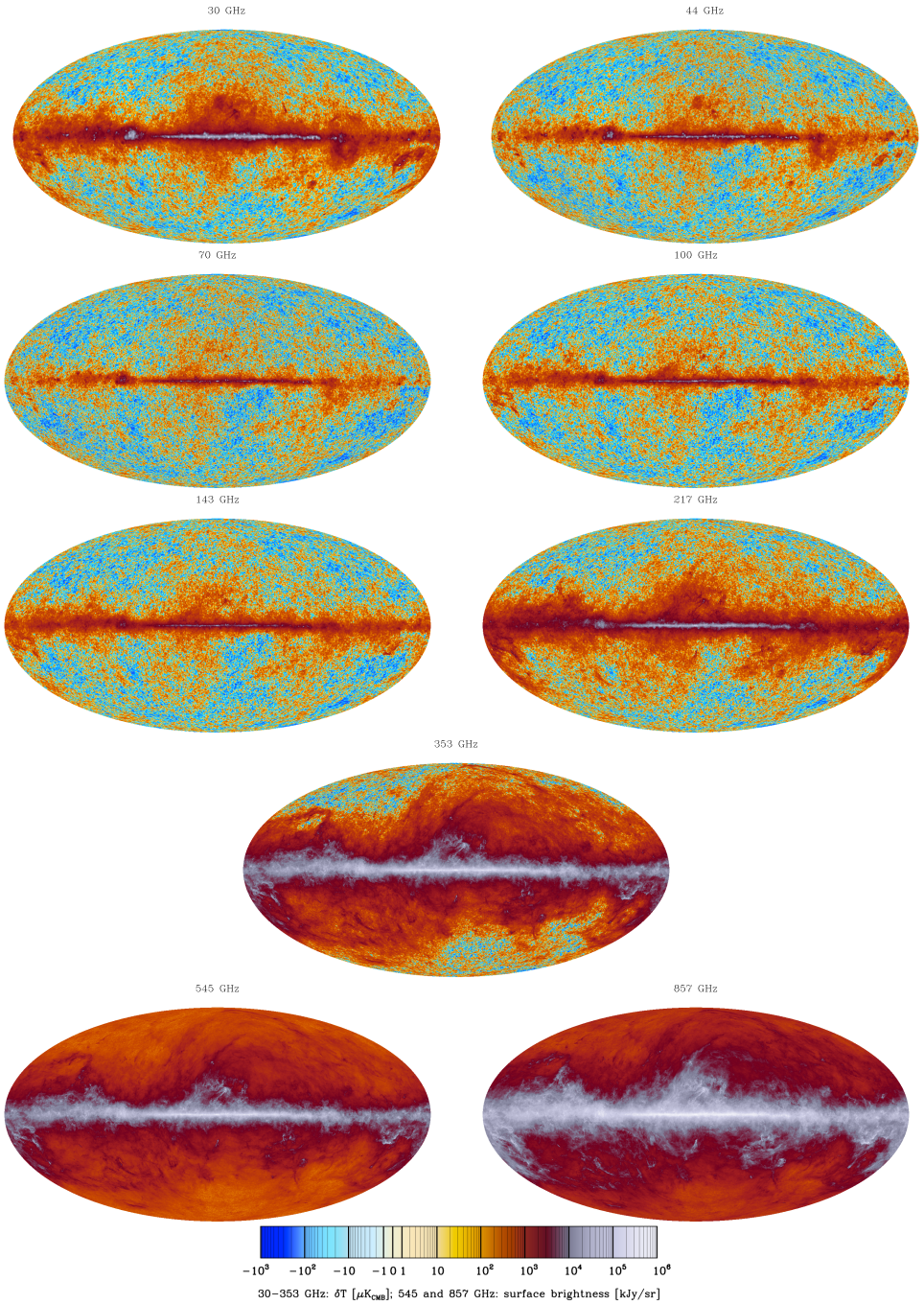
HFI bolometers @6freq <100mK,

LFI HEMTs@3freq,

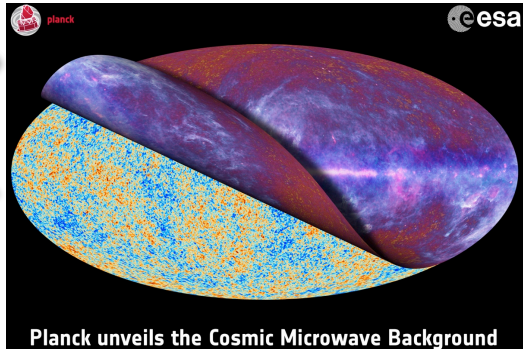
some bolometers & all HEMTS are polarization sensitive

- 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
- spun@1 rpm, 40-50 minutes on the same circle, covered all-sky in ~6 month
- kicked out of L2 Oct13
- 5 HFI all-sky surveys (to Jan 2012) 29 months
- 8 LFI surveys 48 months
- Feb15 T some Q,U all-data, more Mar15, Q/U Jun15 refined final set Mar 2016

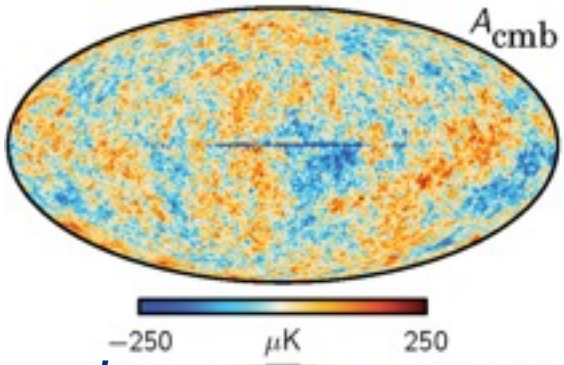
Planck 2013 Frequency Maps Mar13

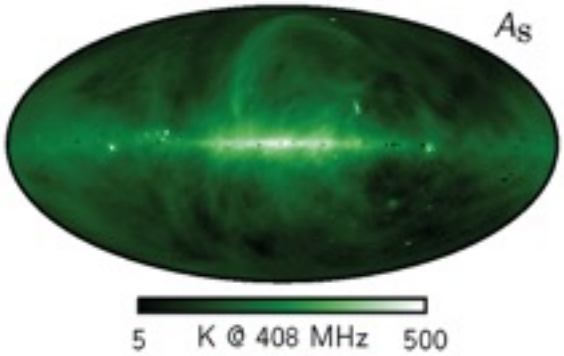


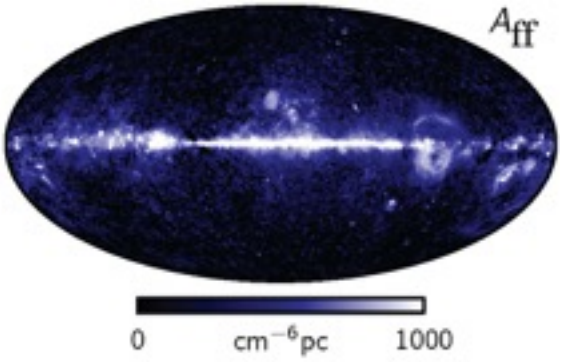
Feb 2015 Planck Component Separated Temperature Maps



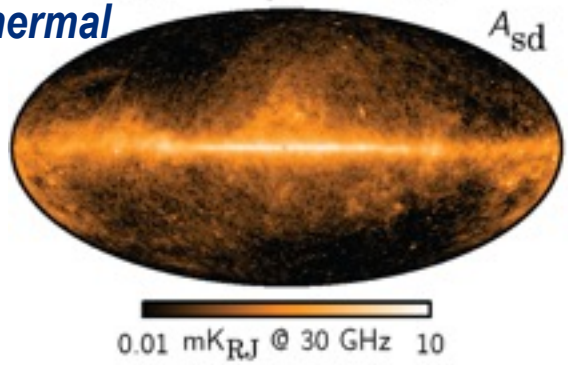
LF Synchrotron + bremsstrahlung

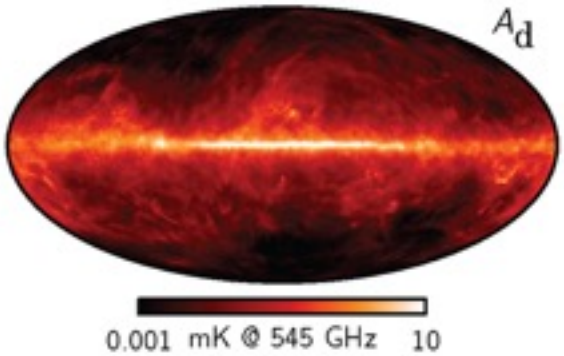


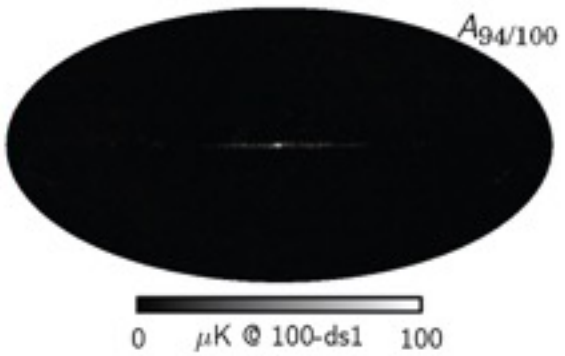




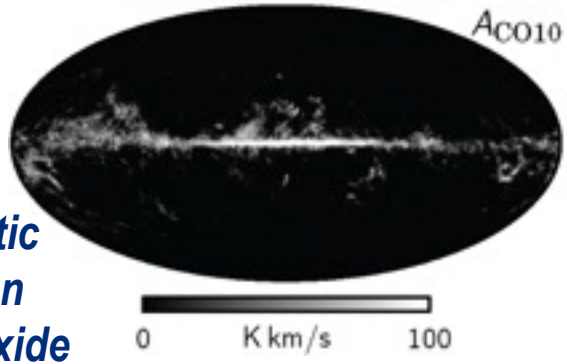
HF Thermal Dust

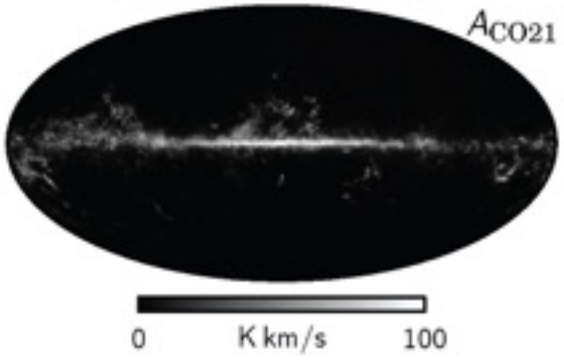


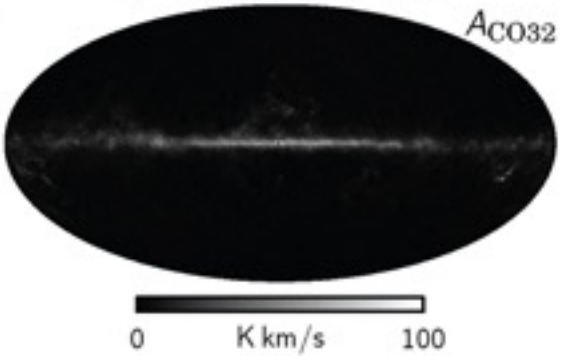




Galactic Carbon Monoxide

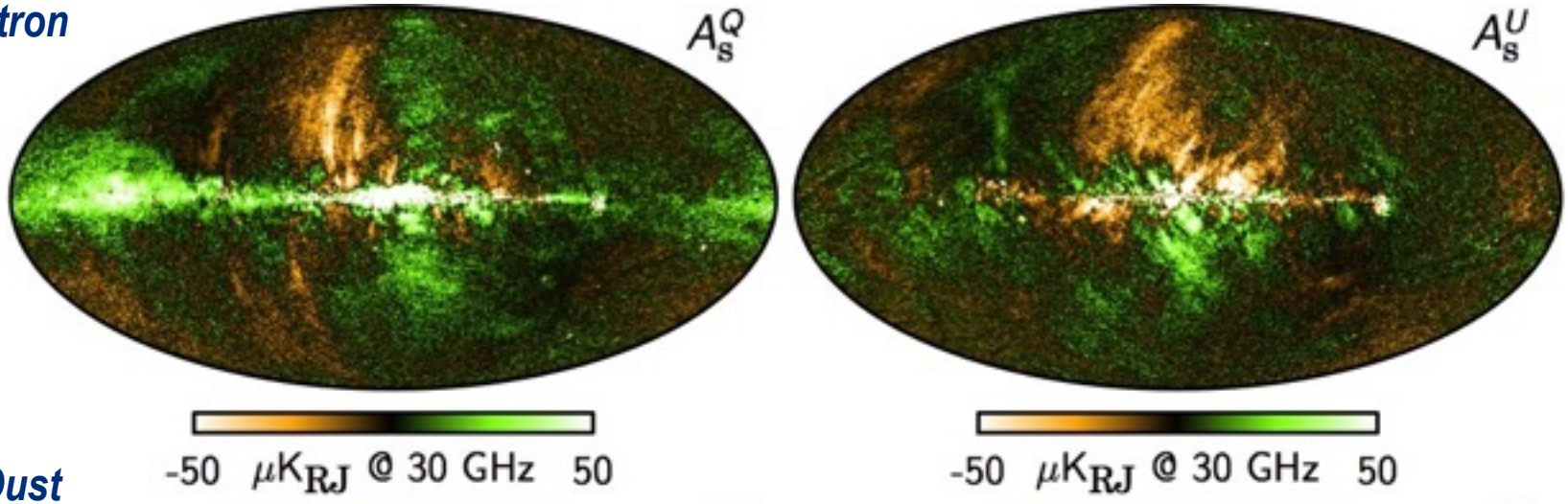






Feb 2015 Planck Component Separated Polarization Maps

LF Synchrotron



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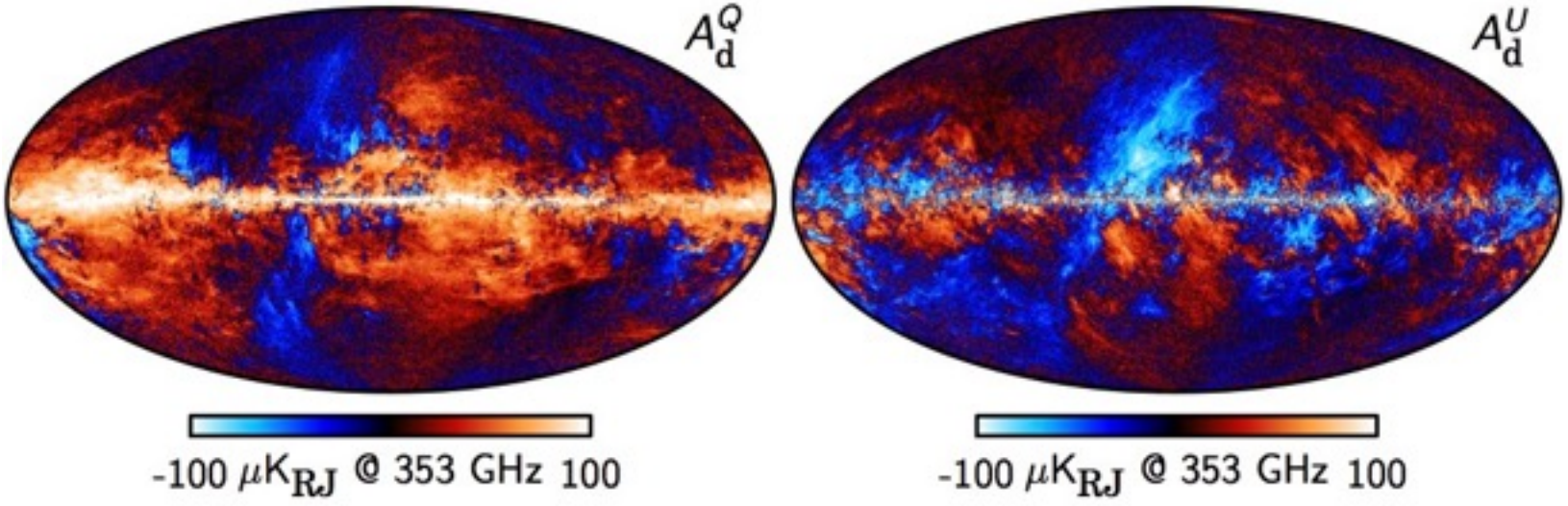
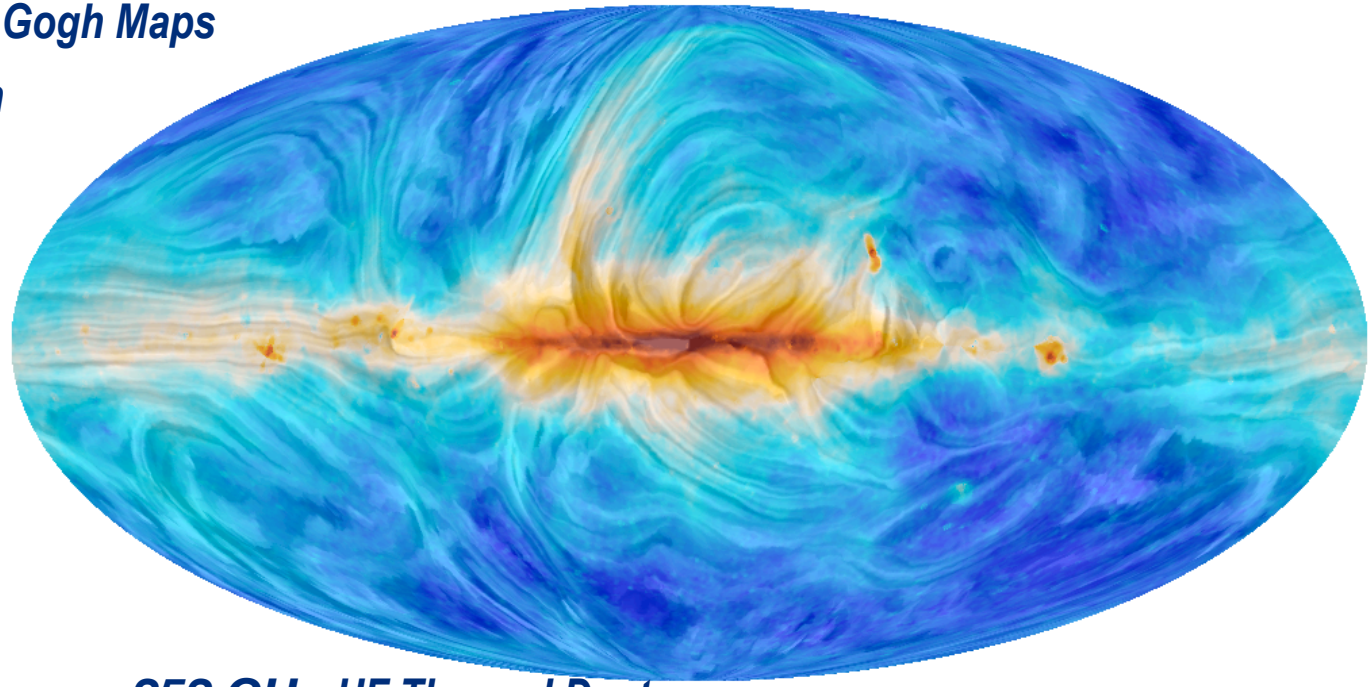


Galactic Dust Polarization Papers
4 in May 2014 on dust polarization, 1 in Sept 2014 power spectra, at high Galactic Latitude r_{dust} vs. BICEP2 claim of r=0.2 -> .16 T/S detection; Feb 15 BKP no r detection < 0.13, P15 XX r < .09

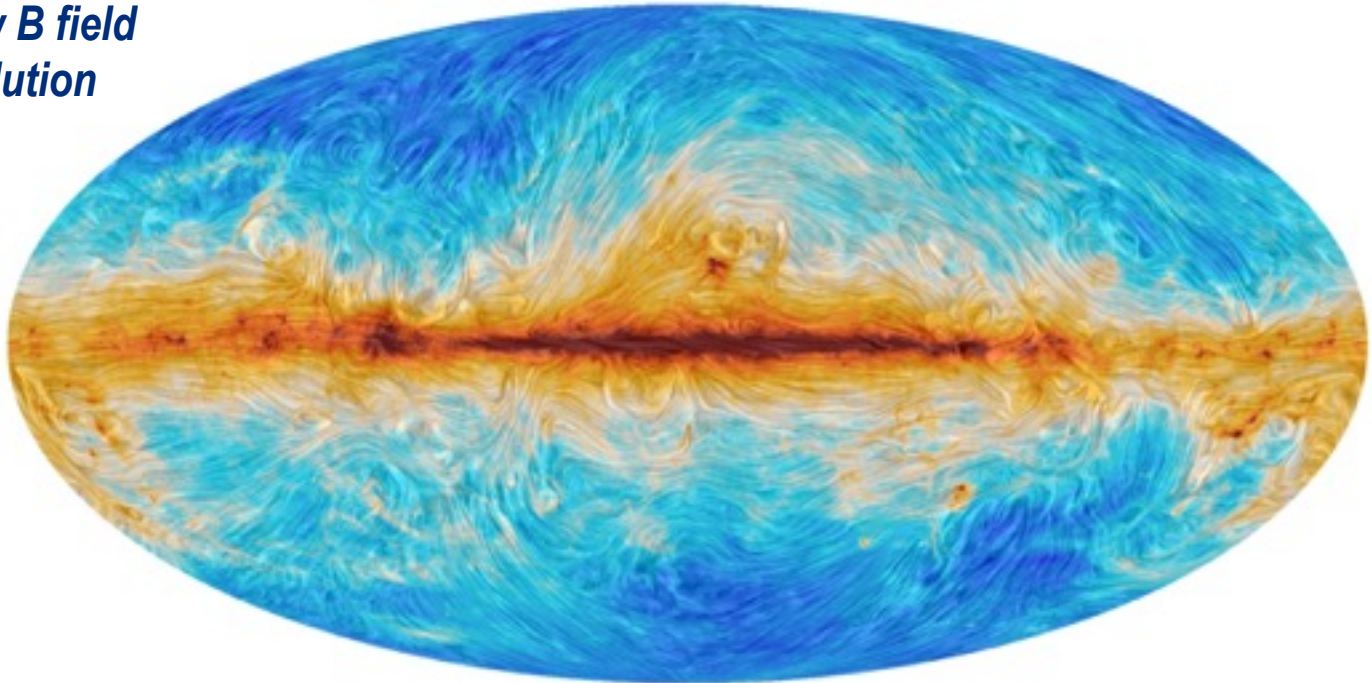
Planck T/P Combined van Gogh Maps

30 GHz LF Synchrotron



353 GHz HF Thermal Dust

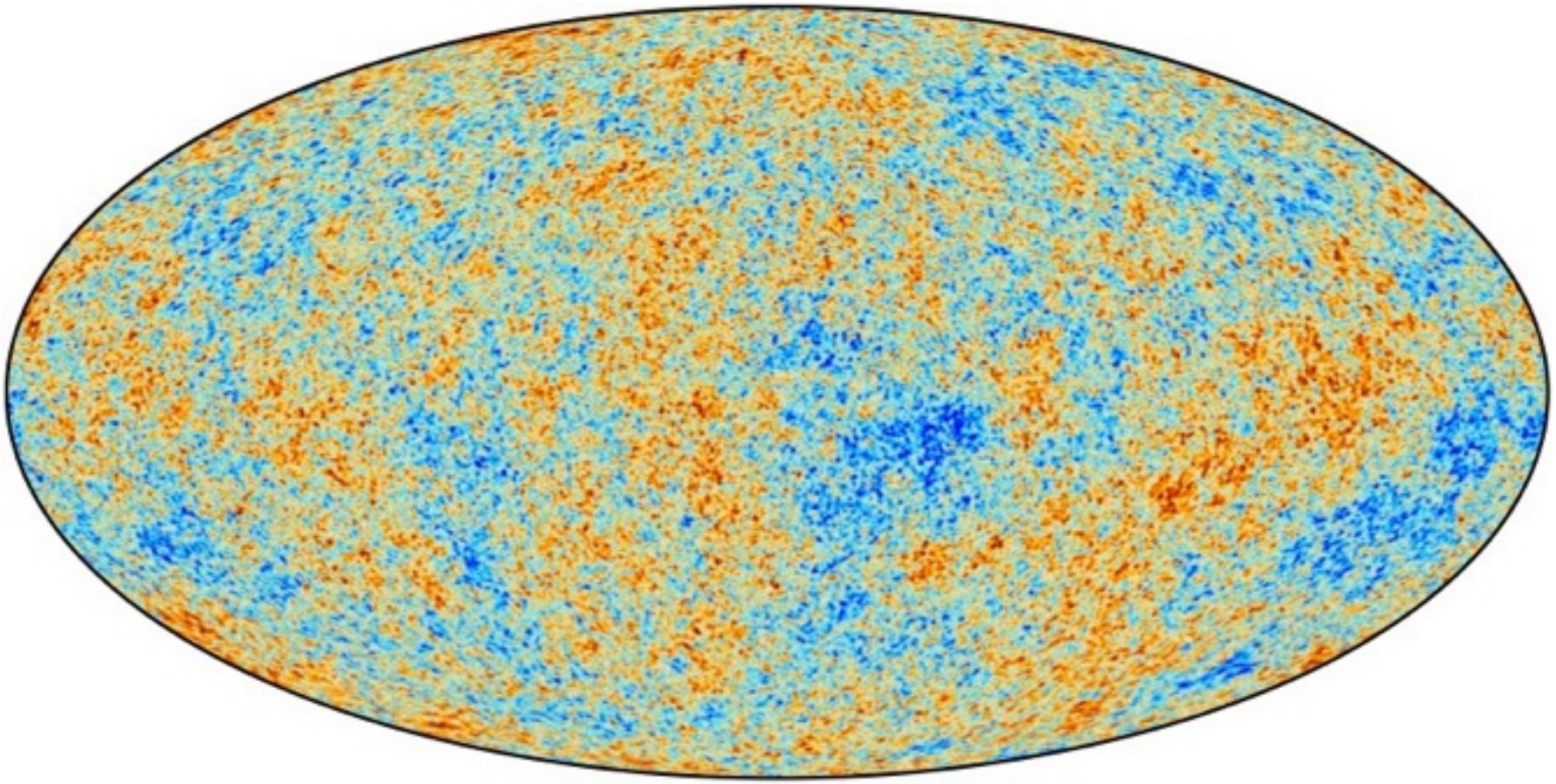
Polarization used to follow B field
using Line Integral Convolution
a directional "flow" mamd



Planck's primordial light unveiled, Feb 5, 2015

reveals the SIMPLICITY of primordial cosmic structure

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



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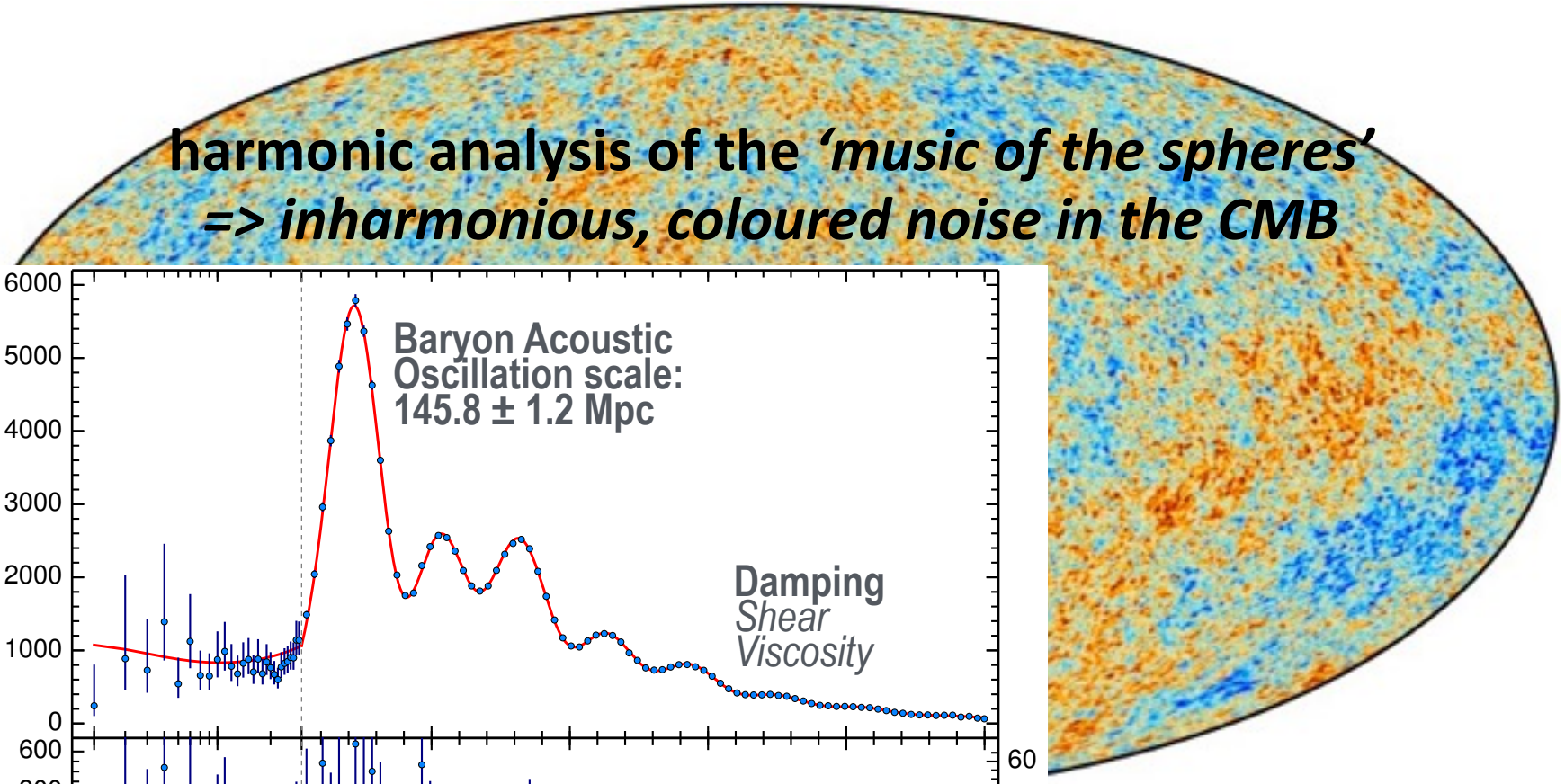
harmonic analysis of the *'music of the spheres'*

=> inharmonious, coloured noise in the CMB



0 300

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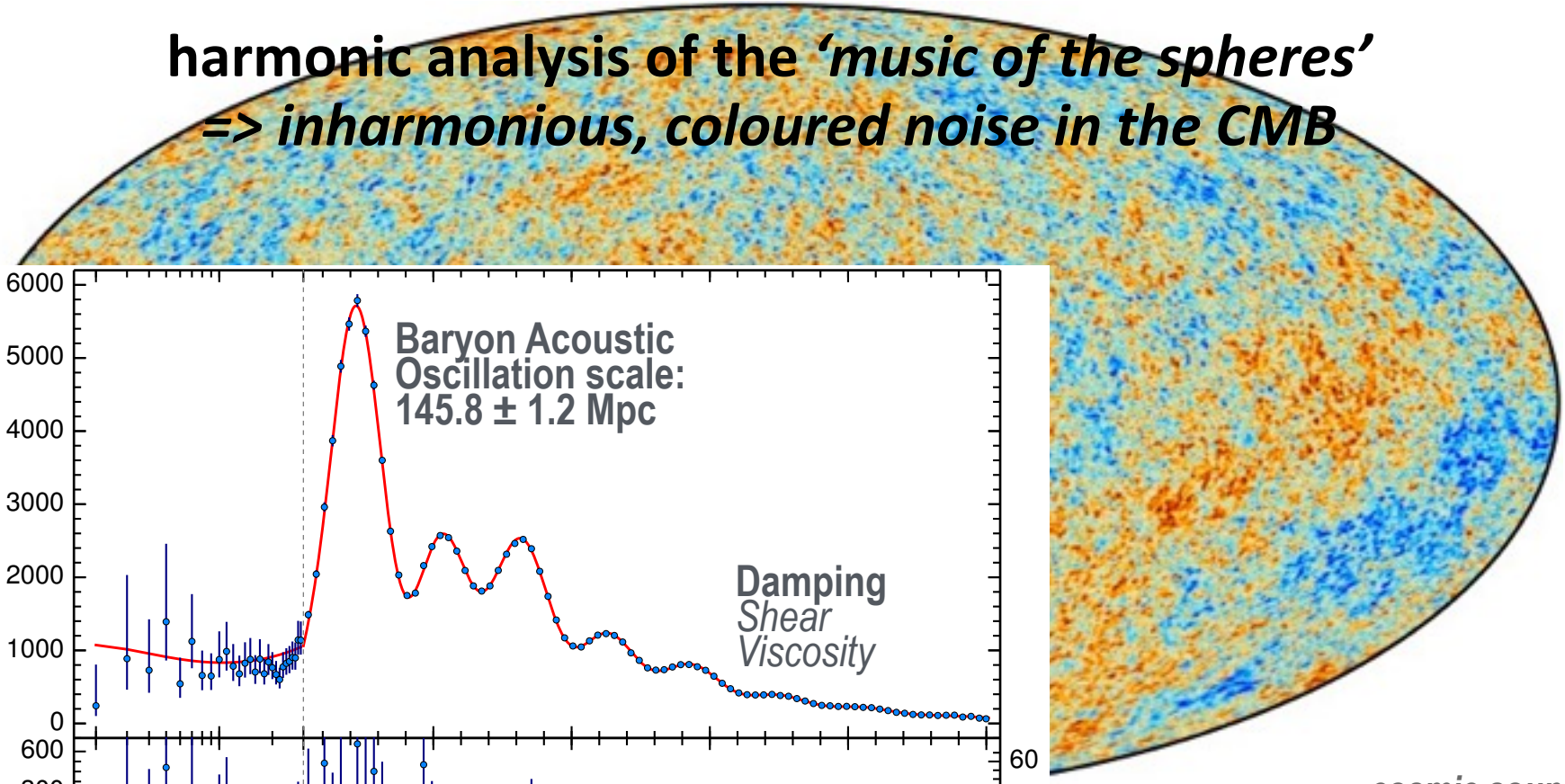
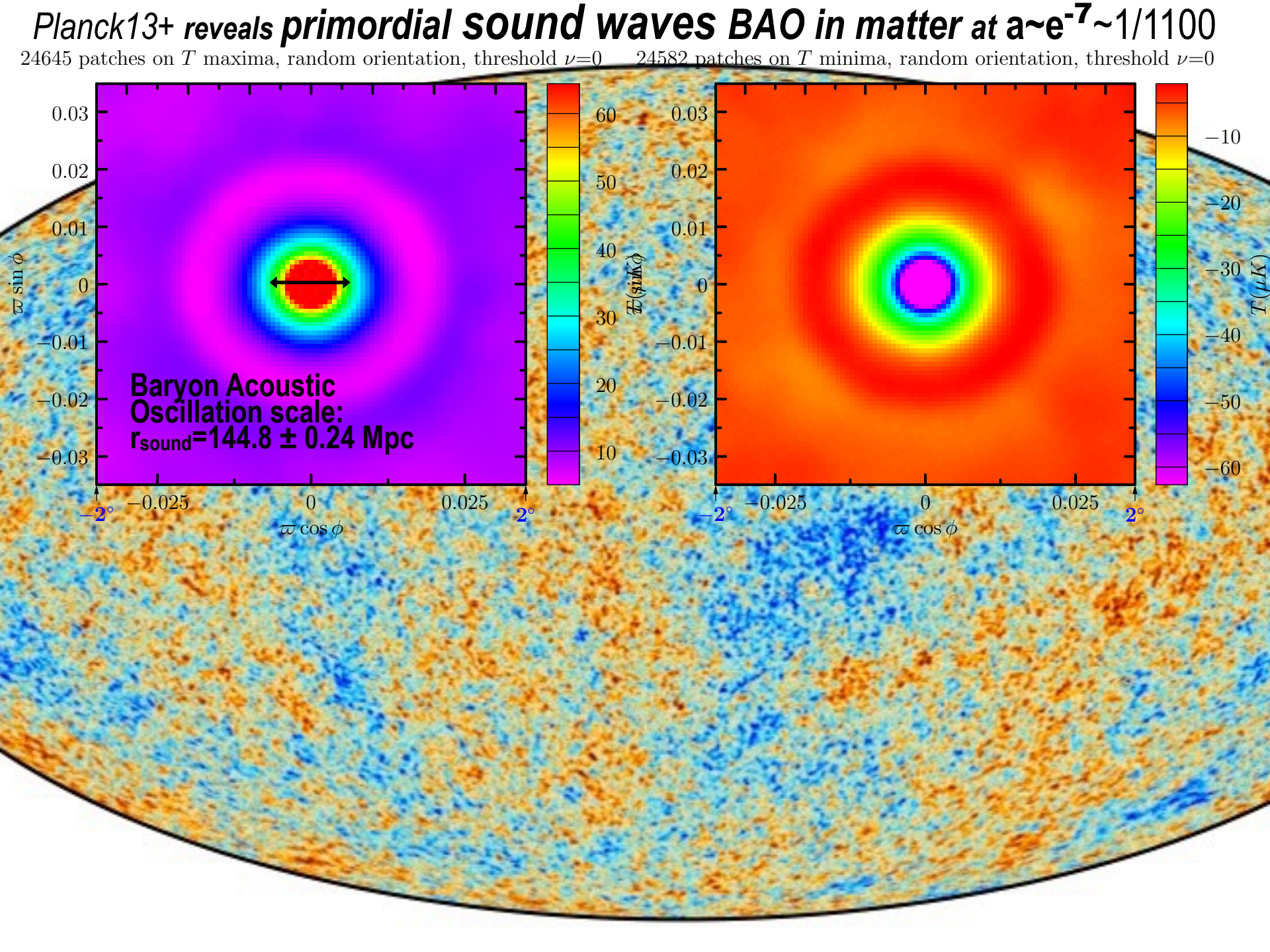


Planck13+ reveals ***primordial sound waves BAO in matter at*** $a \sim e^{-7} \sim 1/1100$



Dick Bond

Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity

the nonlinear COSMIC WEB

ν decoupling ~ms

recombination

dS_G/dt

INFLATION

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave $dS/dt>0$
- tightly-coupled photon-baryon fluid: oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$
- viscously damped

DarkM

- polarization $\pi\gamma$
- gravitational redshift Φ SW $d\Phi/dt$

Decoupling LSS

17 kpc (19 Mpc)

$dS/dt>0$

secondary anisotropies

- nonlinear evolution
- weak lensing
- thermal SZ +kinetic SZ
- $d\Phi/dt$
- dusty/radio galaxies, dGs

L_{sound}/k_{sound}

DarkE

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

$dS_{astro}<0$

reionization

z ~ 1100

redshift z

z ~ 10

$dS/dt>0$

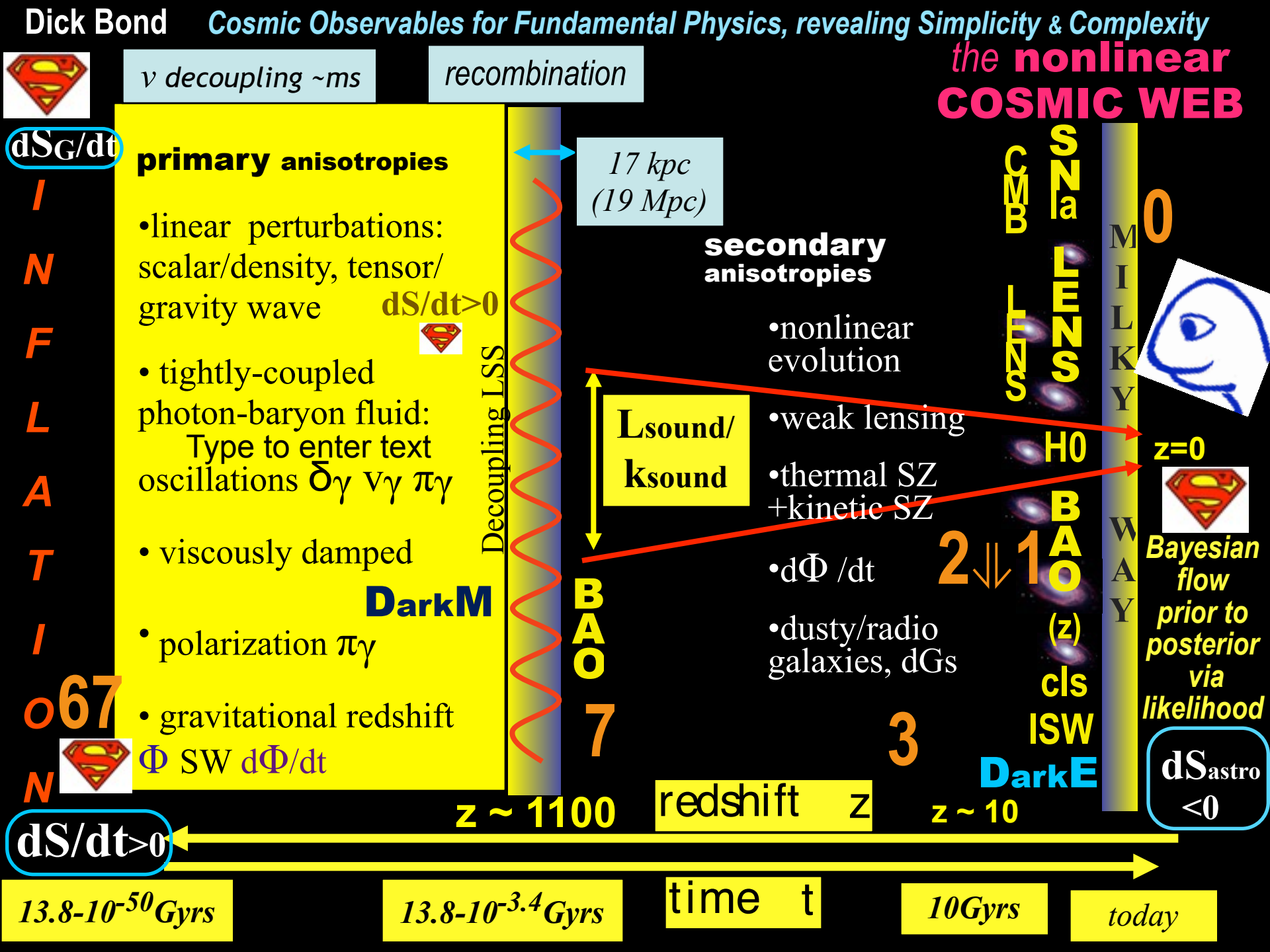
time t

13.8-10^{-50}Gyrs

13.8-10$^{-3.4}$Gyrs

10Gyrs

today


Dick Bond
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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
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67
17 kpc (19 Mpc)
Decoupling LSS
BAO
7
secondary anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
Lsound/ ksound
CMB LENS
SNa LENS
H0
BAO (z)
cls
ISW
3
2⇓1
DarkE
MILKY WAY
0
z=0
Bayesian flow prior to posterior via likelihood
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
13.8-10-50Gyrs
13.8-10-3.4Gyrs
time t
10Gyrs
today

SIMPLICITY

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

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

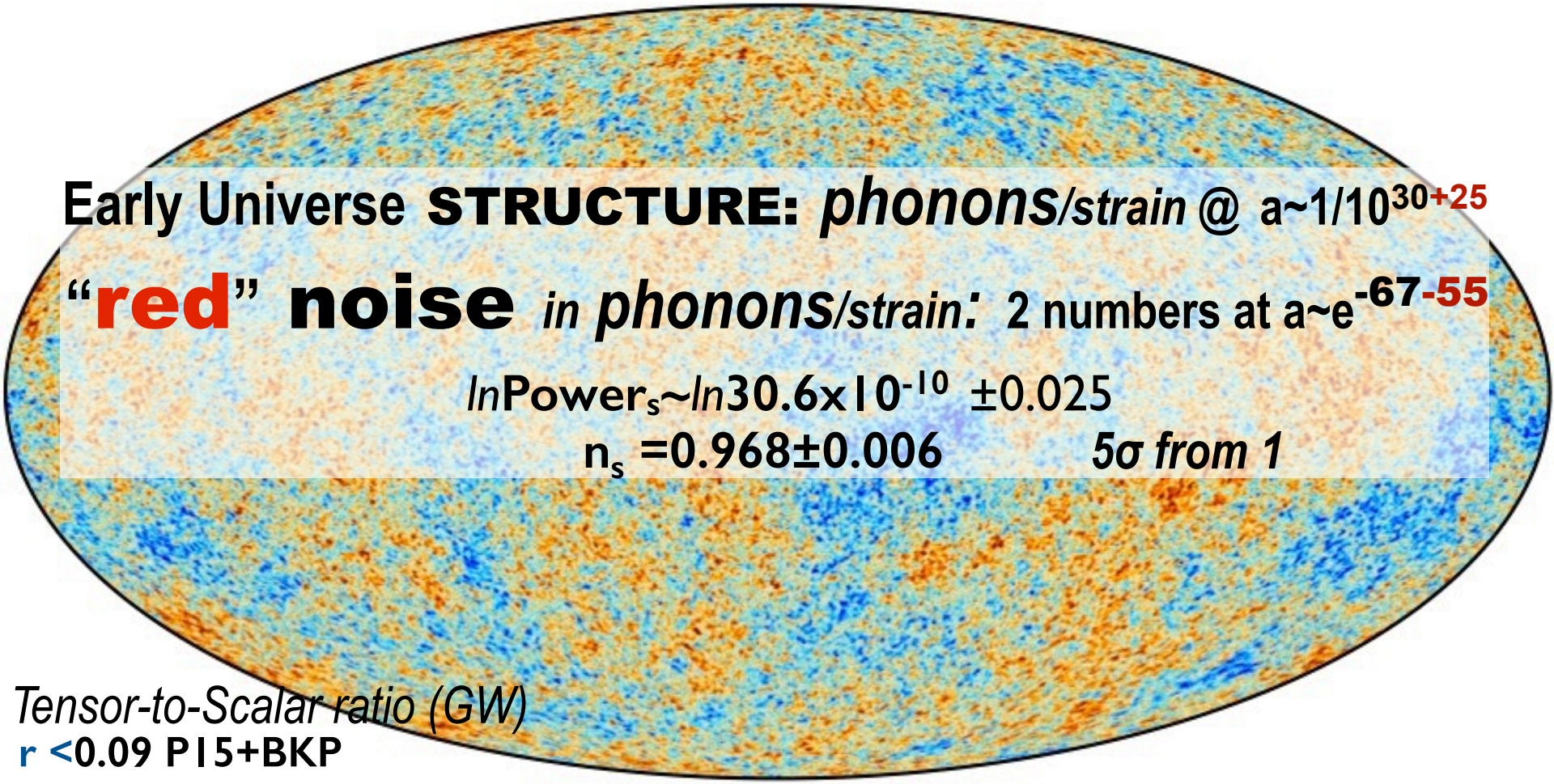
Planck2015 CMB map

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:** ***phonons****/strain @* $a \sim 1/10^{30+25}$

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

$\ln \text{Power}_s \sim \ln 30.6 \times 10^{-10} \pm 0.025$

$n_s = 0.968 \pm 0.006$ *5σ from 1*

Tensor-to-Scalar ratio (GW)

$r < 0.09$ P15+BKP

SIMPLICITY

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

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

Planck2015 early U structure map

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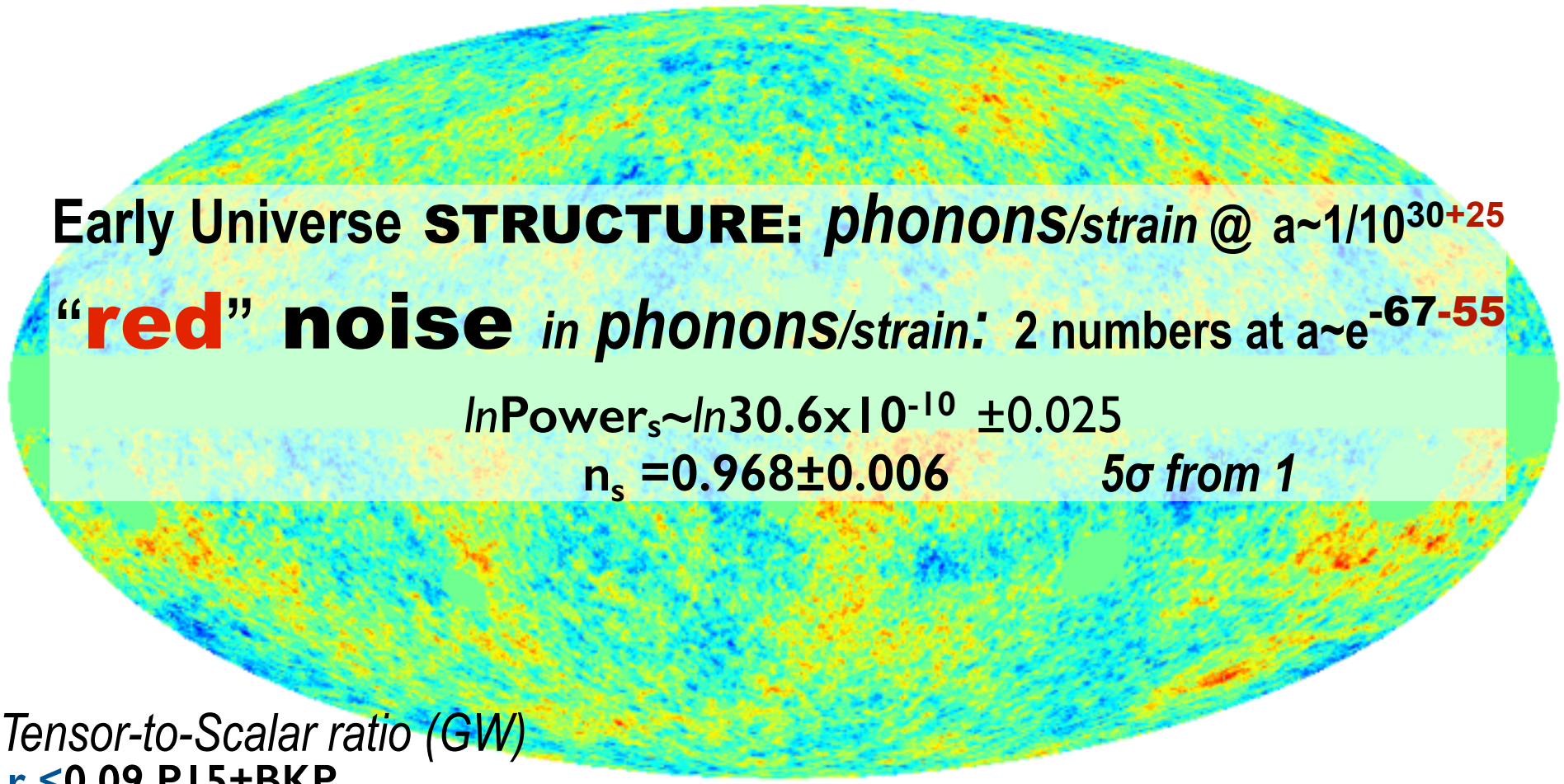
2^+ ***numbers***



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

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Planck2015 early U structure map

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

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

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

2^+ *numbers*

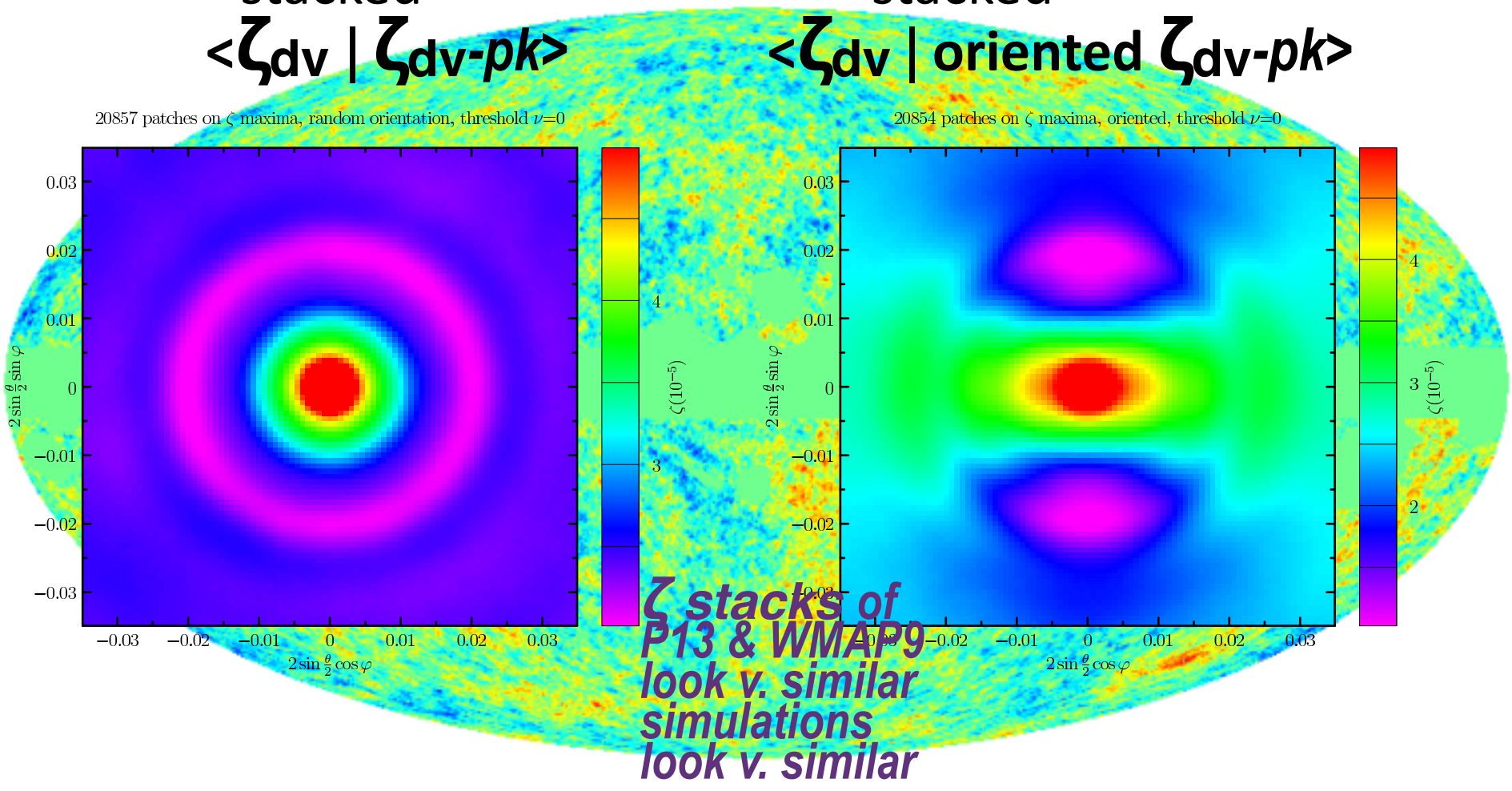
10^5 zeta

stacked

$\langle \zeta_{dv} \mid \zeta_{dv\text{-}pk} \rangle$

stacked

$\langle \zeta_{dv} \mid$ oriented $\zeta_{dv\text{-}pk} \rangle$



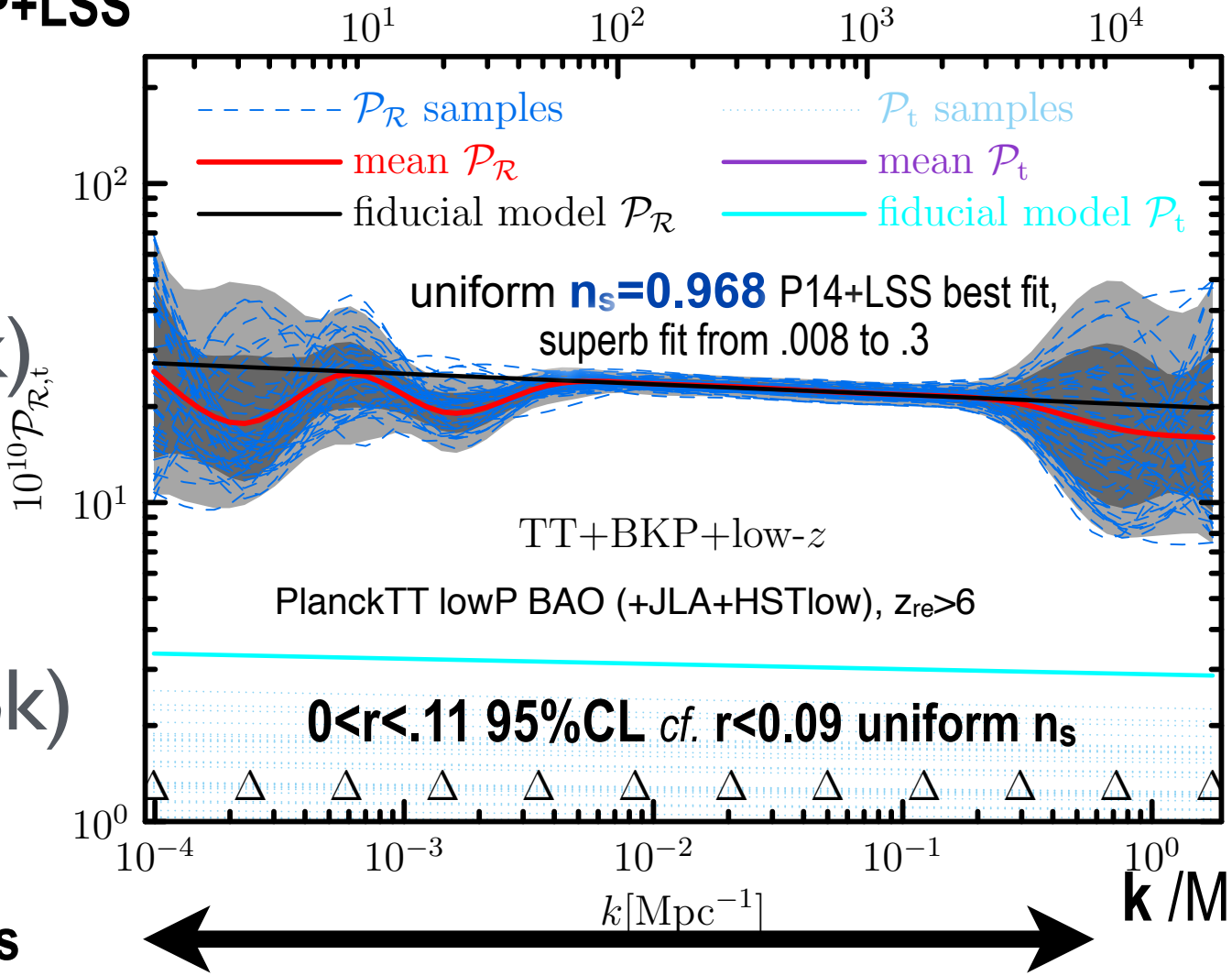
ζ stacks of P13 & WMAP9 look v. similar simulations look v. similar

Quadratic $ln\mathcal{P}_\zeta(lnk)$ Maps *aka* Radical Compressions => ultra-early Universe sound/phonon spectrum

12 knots, cubic spline

Planck15+BKP+LSS

kd_{rec} ≳L



$ln\mathcal{P}_\zeta(lnk)$

r -$\mathcal{P}_\zeta$ partial degeneracy if r floats

$ln\mathcal{P}_{GW}(lnk)$

9 e-folds

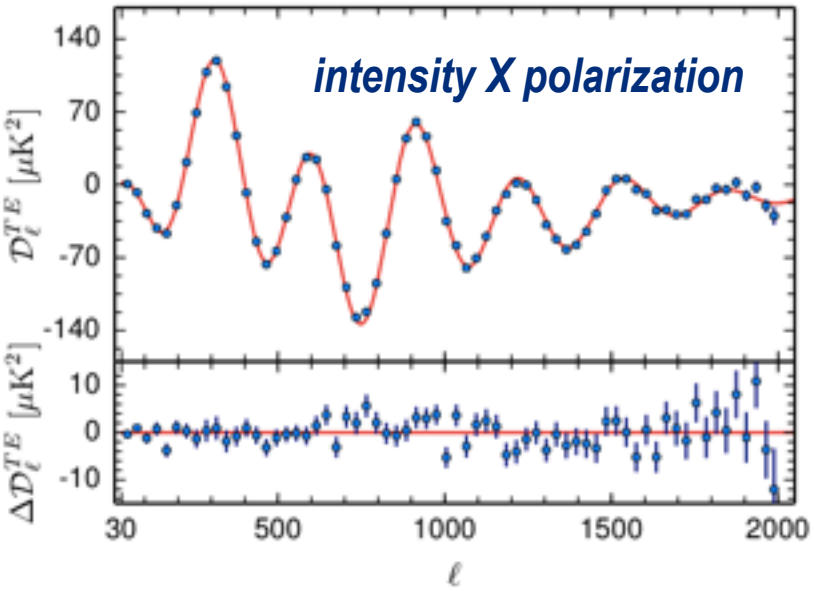
k /Mpc

Mar 2014: bicep2 GW detection r~0.2 =>BKP Feb 2015 Planck: thou shalt not ignore dust polarization r<0.13 P15+BKP r<.09 95%CL

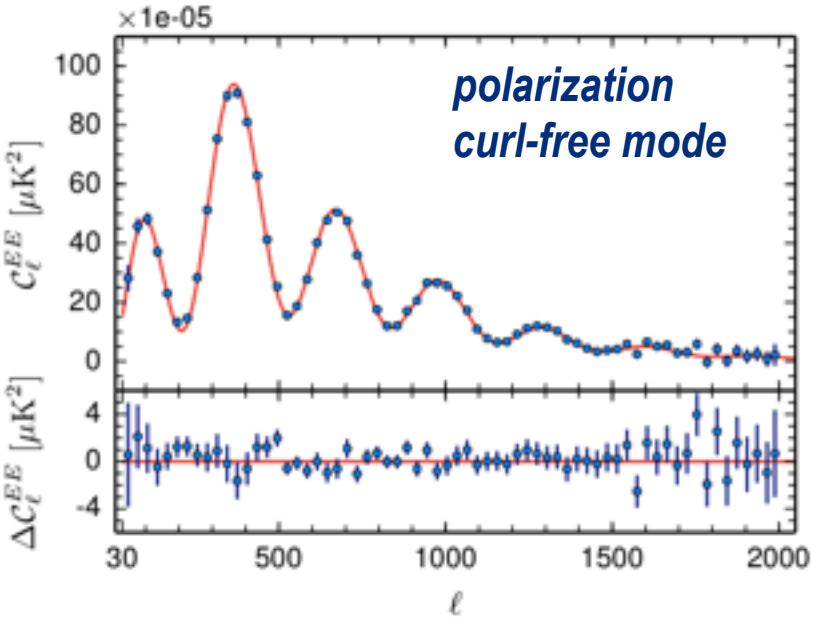
harmonic analysis of polarization

Planck 2015 TE/EE cf. TT => constrains subdominant primordial power contributions not phase-locked with the acoustic-peaks of the pure adiabatic case => constrain isocon spectra /parameters

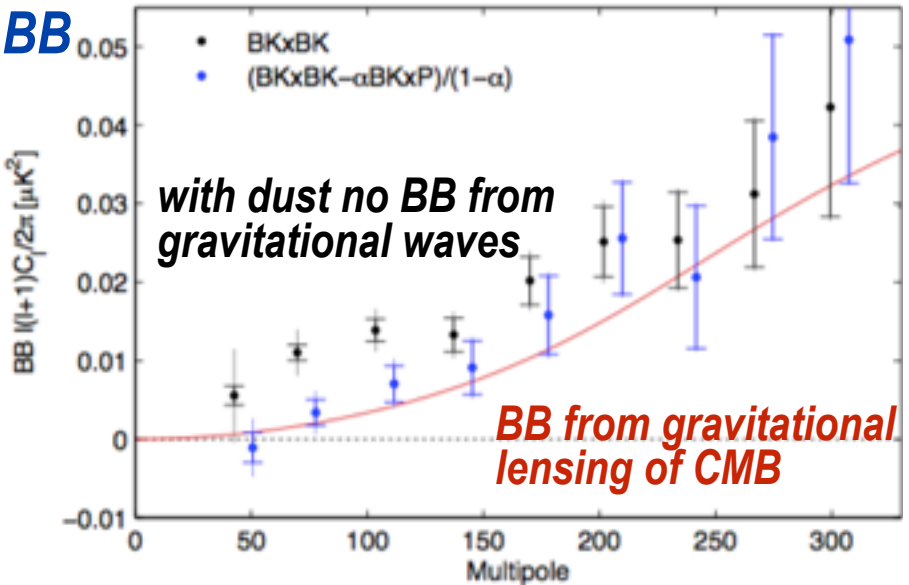
TE

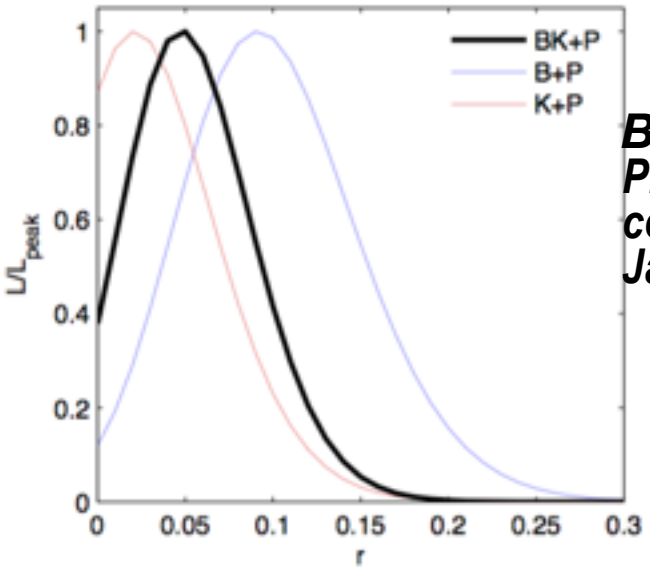


EE

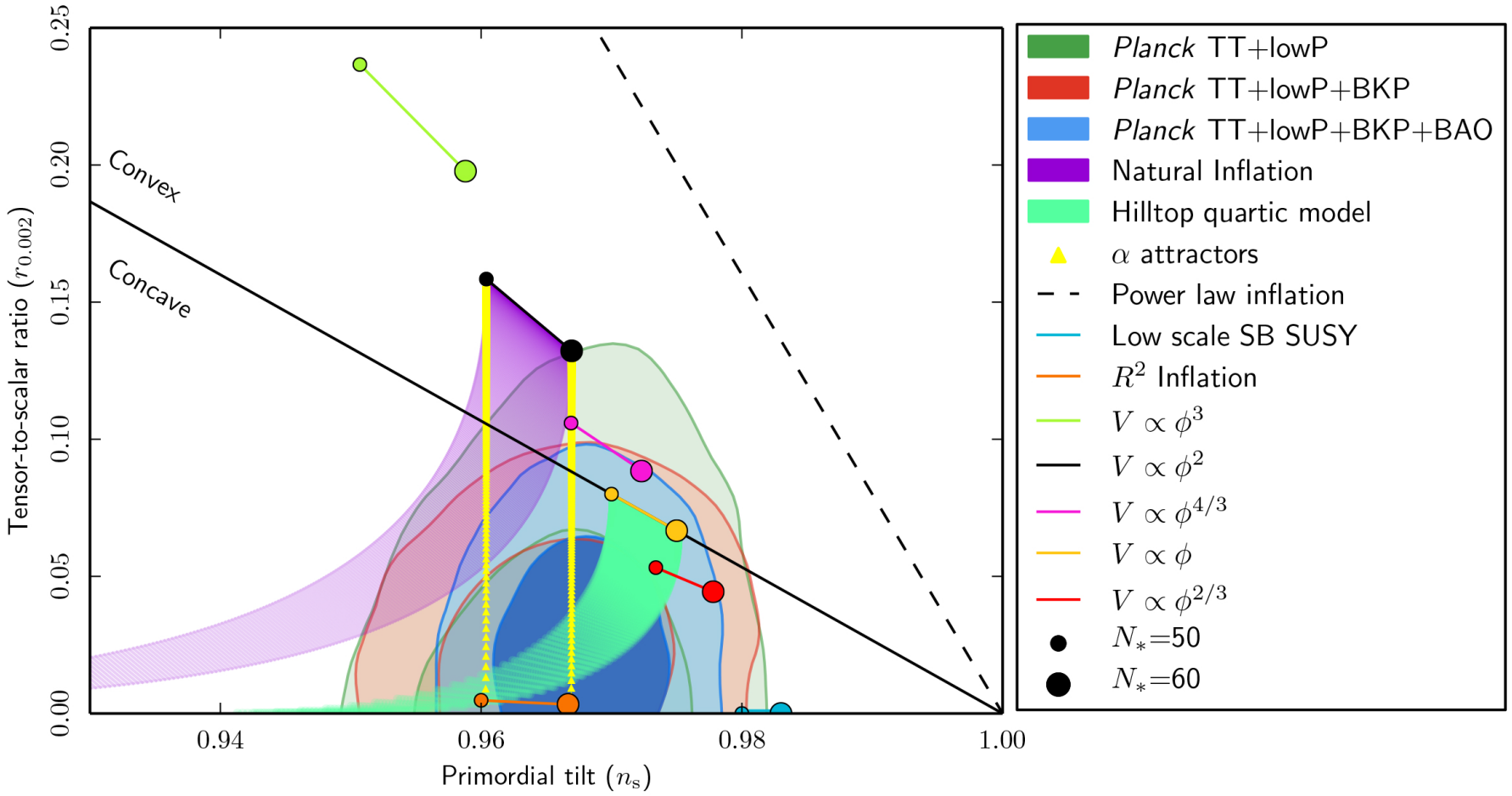


BB





***BKP** Bicep2, Keck, Planck cross correlation analysis Jan 30, 2015*

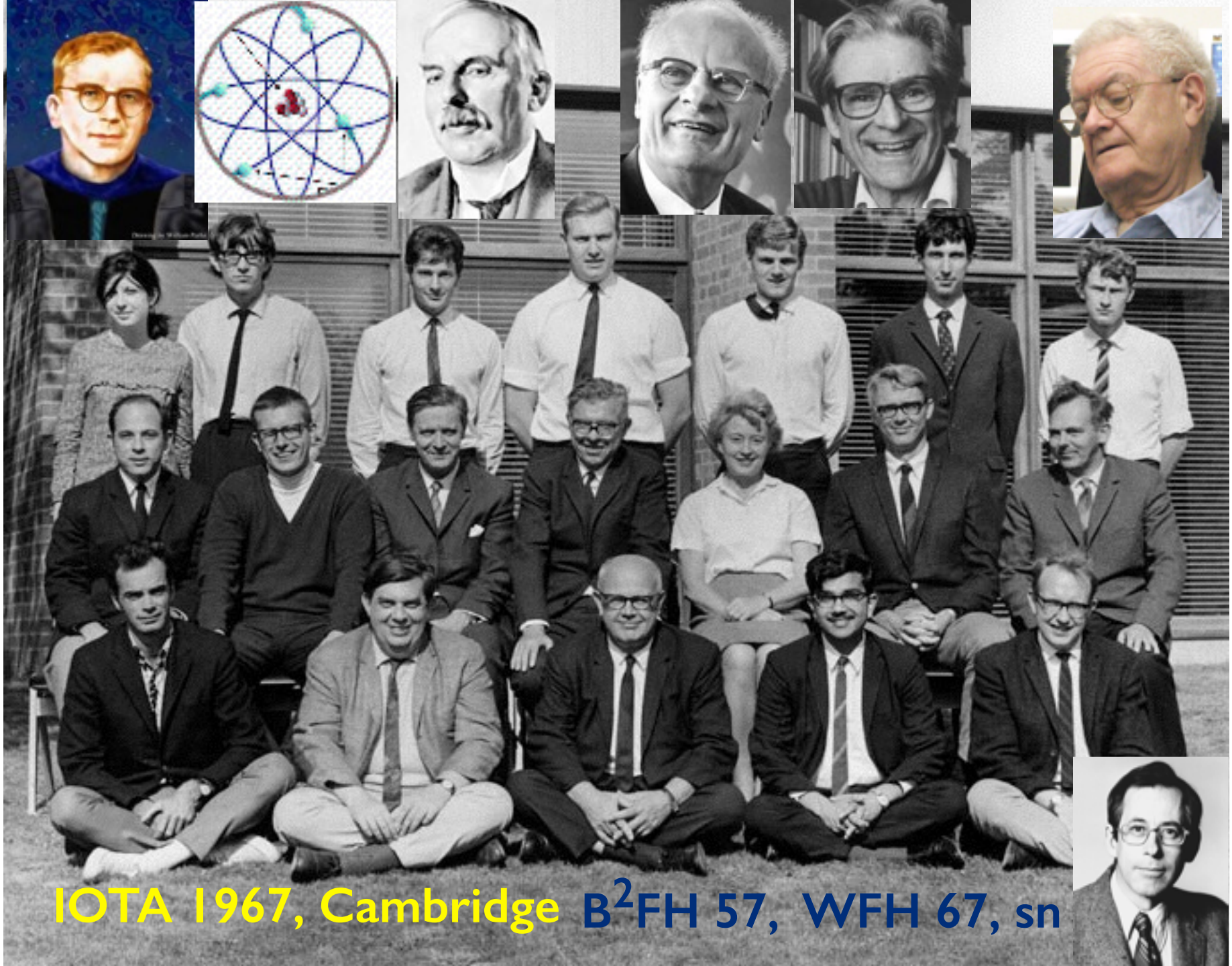


0<r<.11 95%CL P15+BKP 12 knots

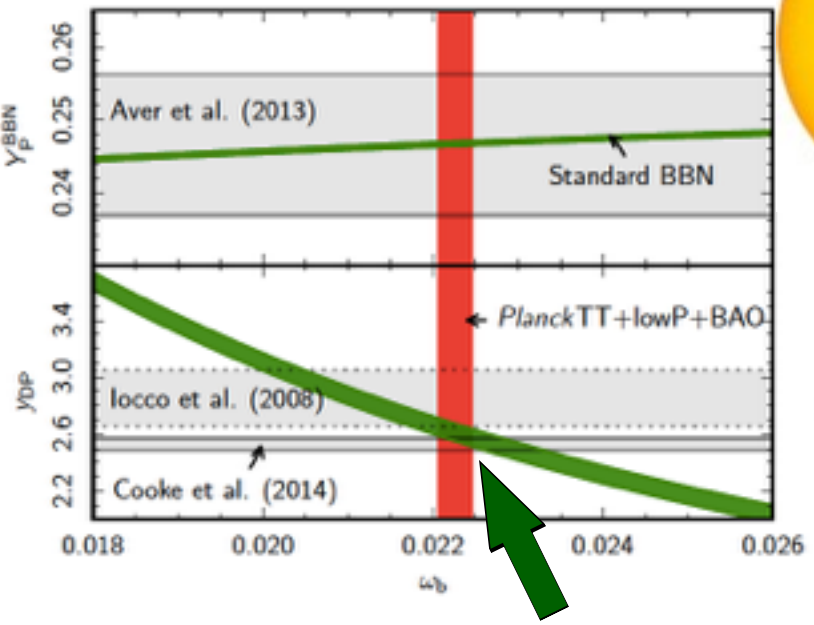
***cf.* P15+BKP r<0.09 uniform n_s**

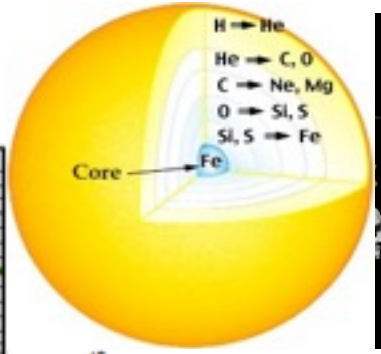
cf.* P15+TE,EE loP r<0.10 uniform n_s *cf.

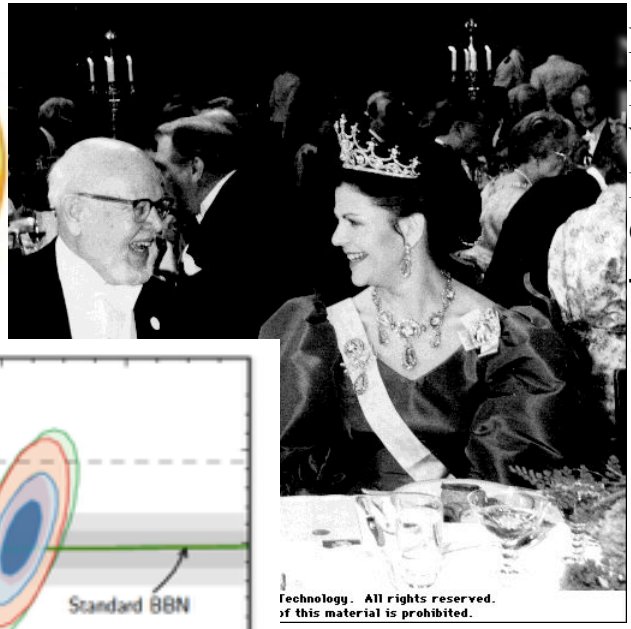
P15+loP+WMAP r<0.09 uniform n_s


IOTA 1967, Cambridge B²FH 57, WFH 67, sn

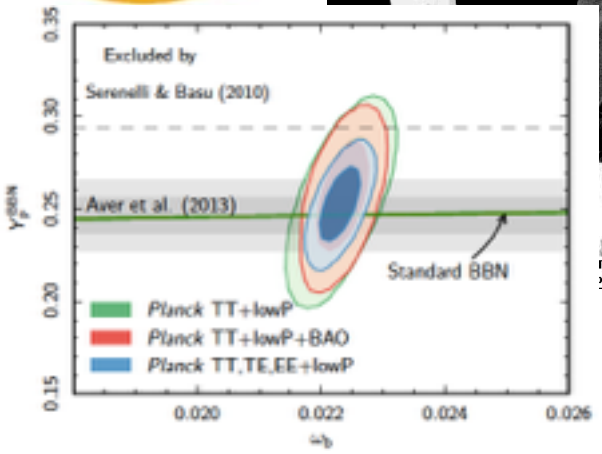
Baryometers







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

0.02214 +- 0.00024 Planck13+WP+hiL+BAO

0.02229 +- 0.00033 Planck15 TT,TE,EE +loP+BAO

Dark Energy => inflation now

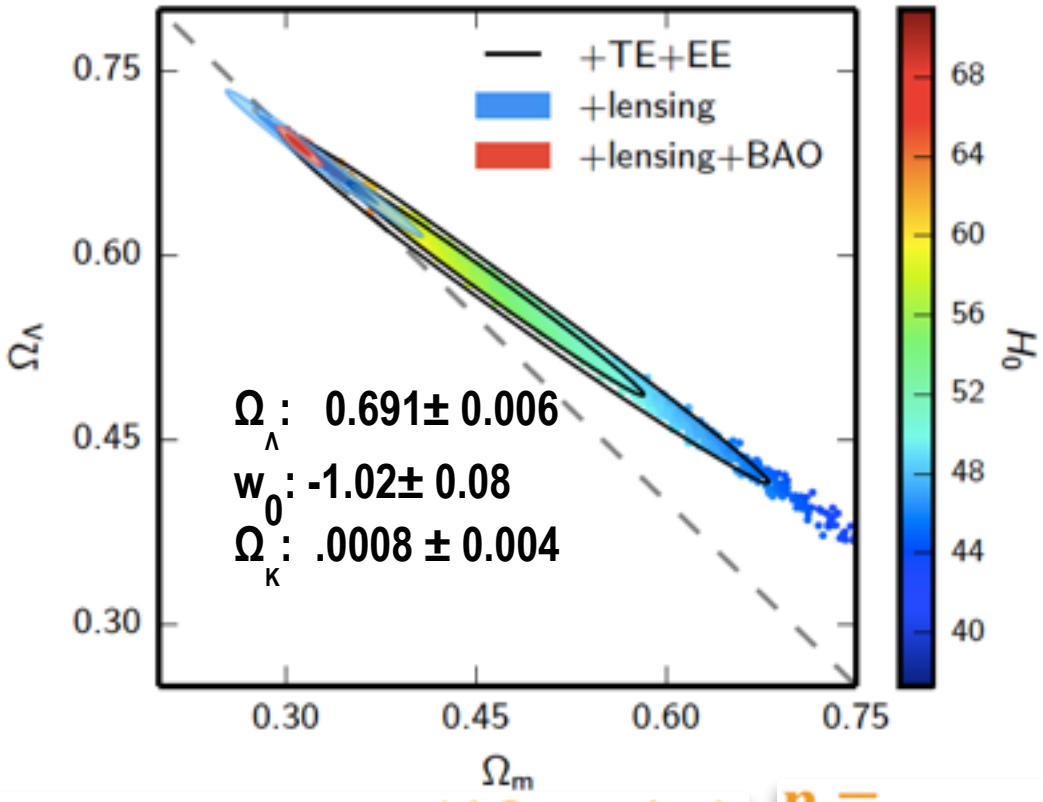
CMB lensing breaks "geometrical degeneracy":

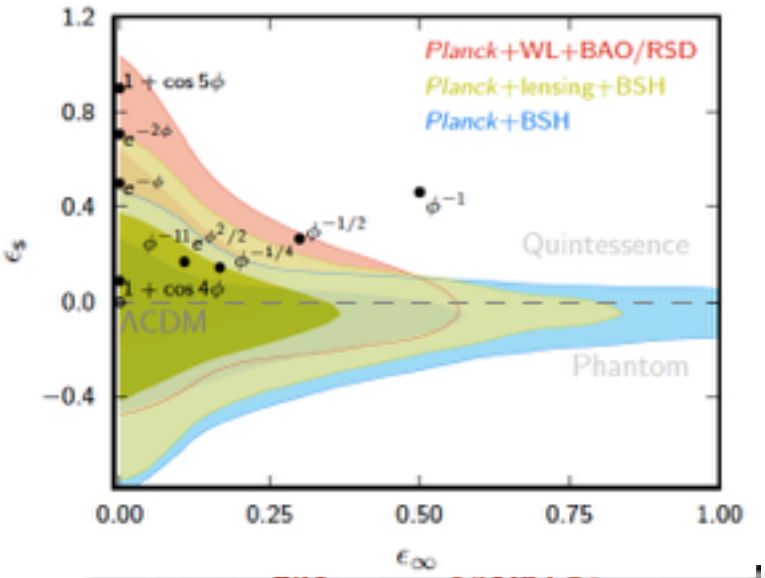
Planck alone cf. Planck+BAO

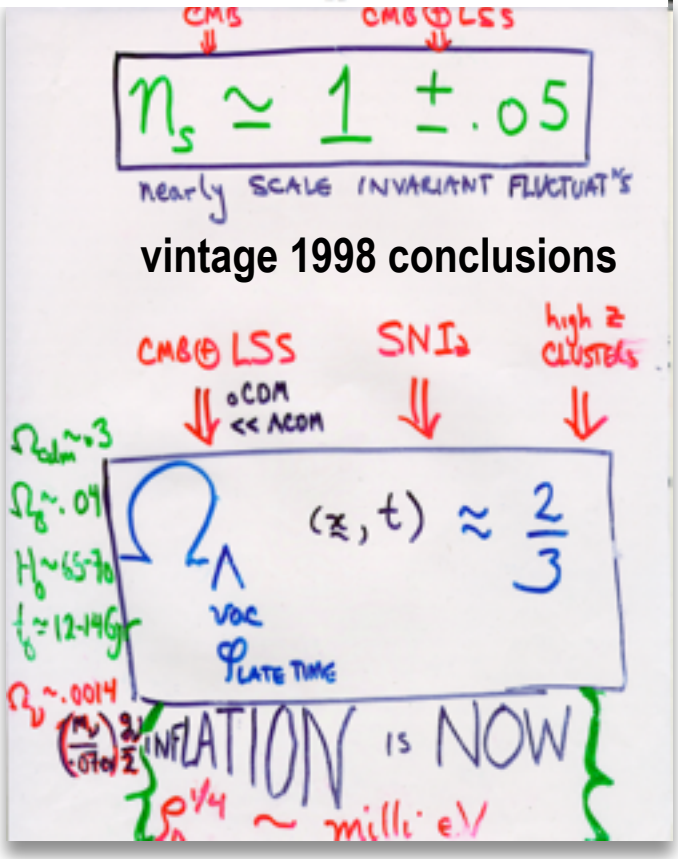
Planck15 cf. CMB+LSS history

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

also Sherwin+11: ACT







B+Jaffe'96,'98

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

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

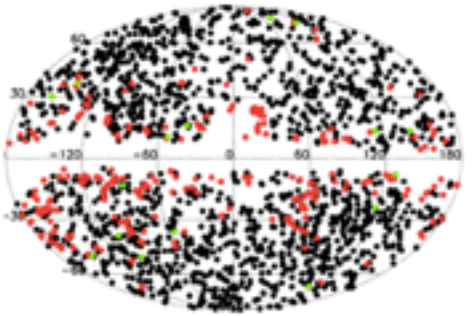
NEUTRINOS: number of species, sum of masses

thermal SZ effect **Compton cooling of high pressure / entropy electrons by the CMB**

Planck2015 PSZ2: 1652 clusters, 1203 confirmed, SPT 224 =>747cls, ACT 91 cls

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



mild **Tension: primary *vs.* clusters**

σ_{8SZ} **~ 0.78**

cf.

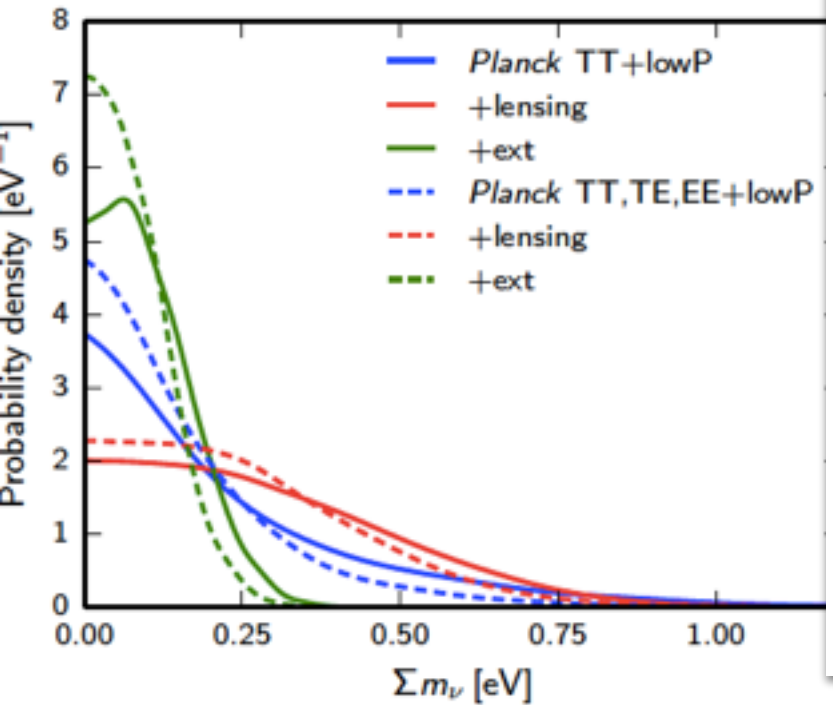
primary σ_8=0.816±0.009
gastrophysical problem with cls?
or higher ν mass relief of tension?

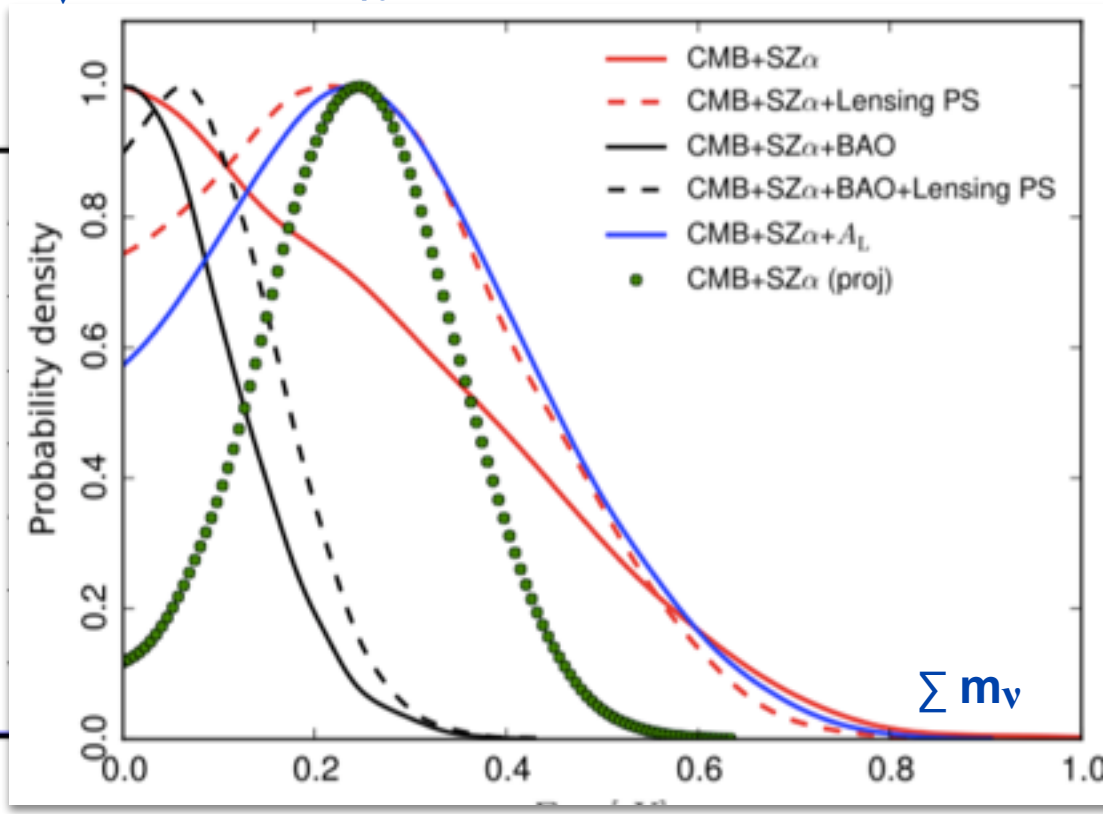
N_{veff} = 3.15 ± 0.23 relativistic dof

$\sum m_\nu$ > 60 meV

$\sum m_\nu$ < 220 meV 95%
P15+Planck(cls)+BAO

$\sum m_\nu$ < 170 meV 95% P15+BAO





Compton cooling of high pressure / entropy electrons by the CMB

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PSZ2: 1652 clusters, 1203 confirmed

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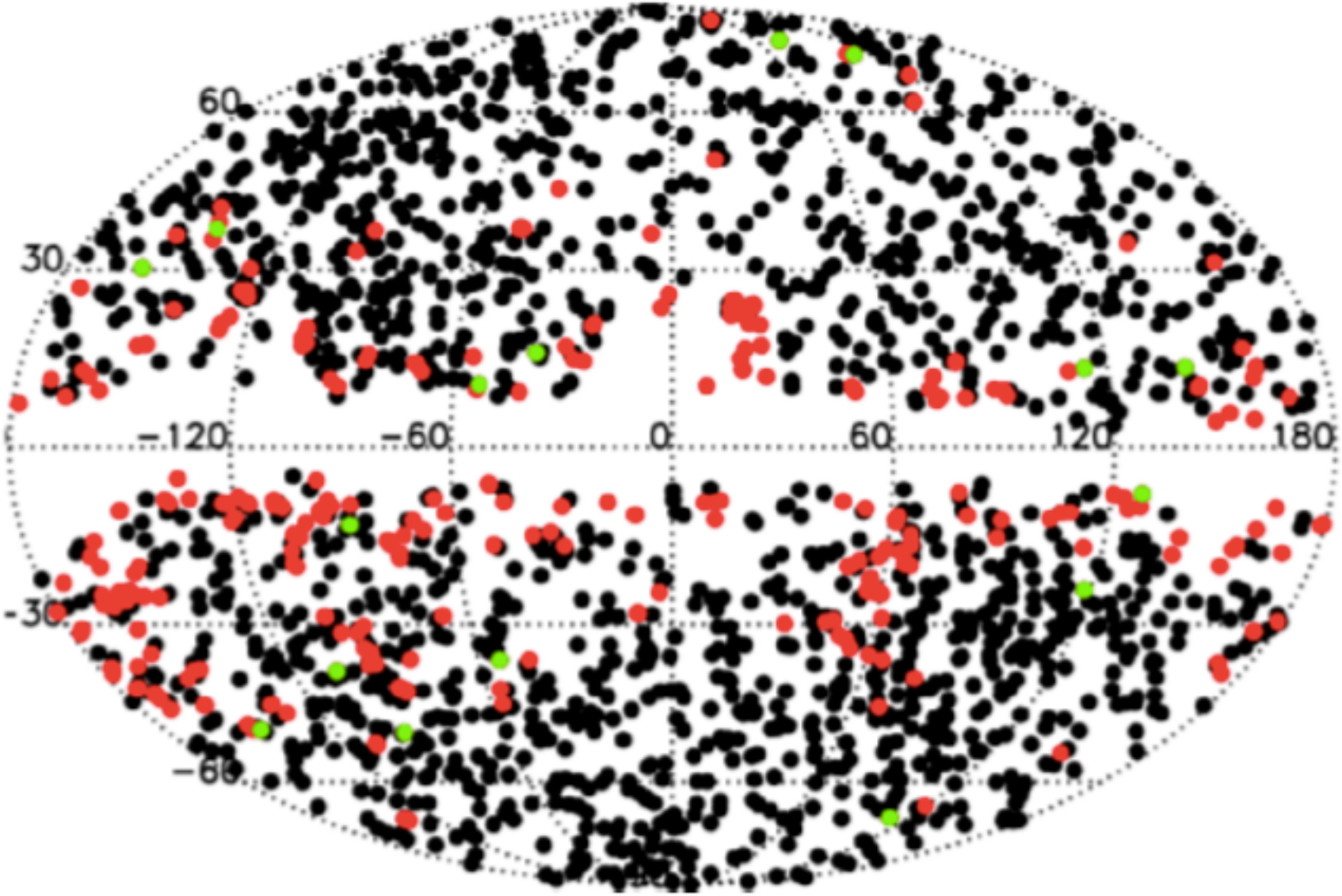

Compton cooling of high pressure / entropy electrons by the CMB

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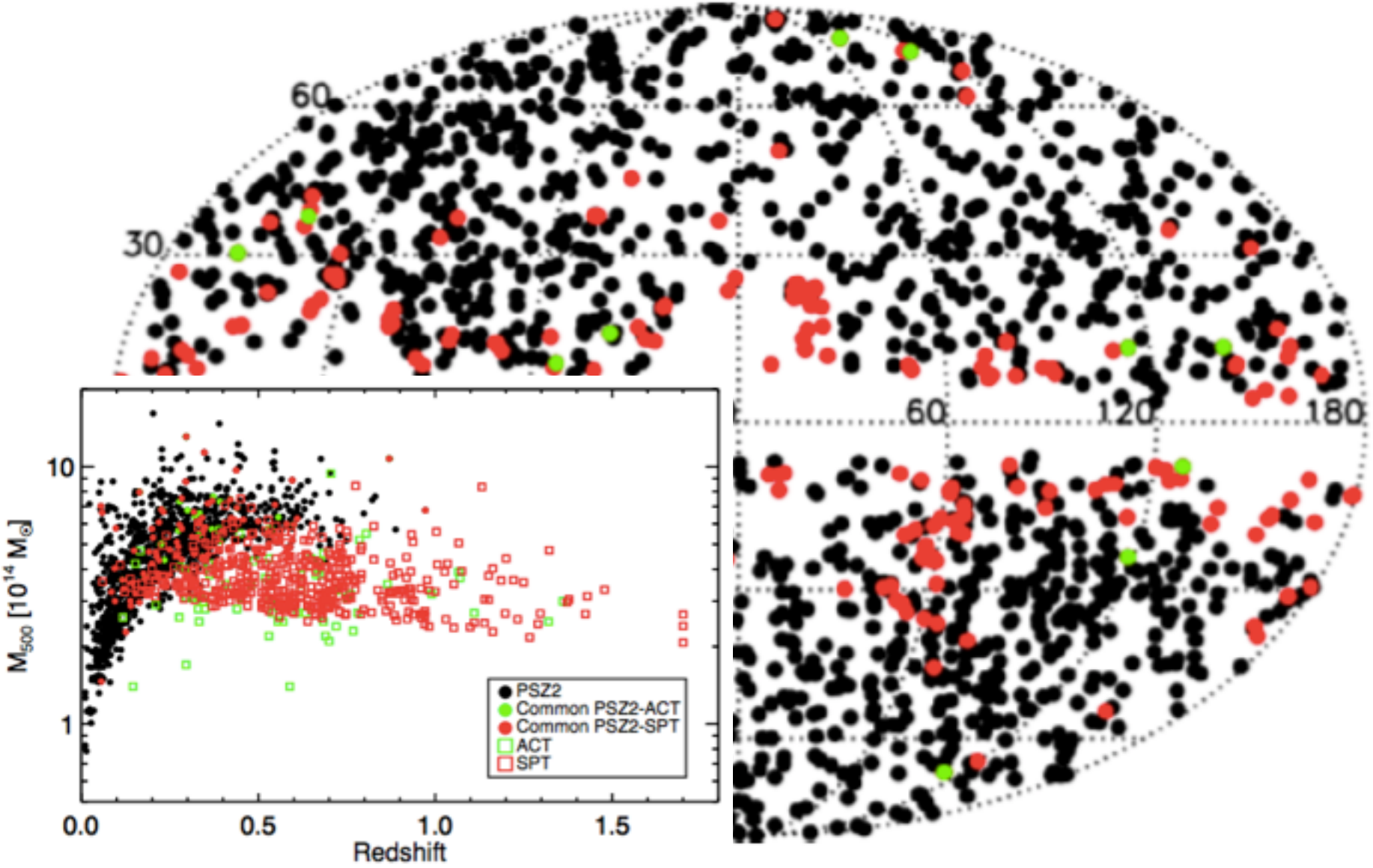
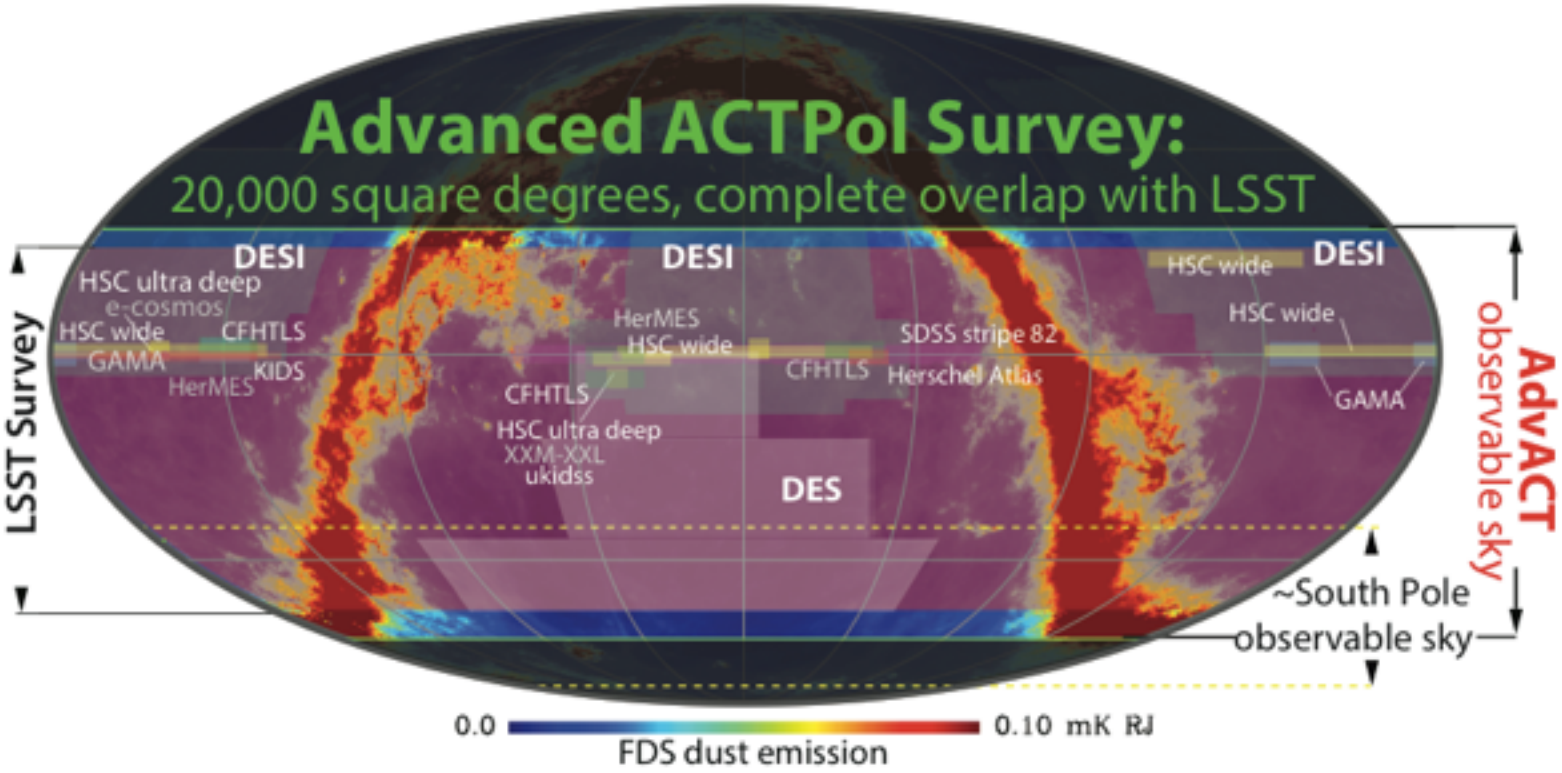


Advanced ACTPol (AdvACT) Observations



- ~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)

Planck 2015 Feb Papers

Planck_BICEP2_Keck.pdf BKP marginalize over dust polarization => primordial gravity wave constraint no detection

Planck_2015_Results_I_Overview_Products_Results.pdf

Planck_2015_Results_II_LFI_Data_Processing.pdf
Planck_2015_Results_IV_LFI_Beams.pdf
Planck_2015_Results_VI_LFI_Maps.pdf

Planck_2015_Results_VII_HFI_Data_Proc_TOI_Beams.pdf
Planck_2015_Results_VIII_HFI_Data_Proc_Calibration_Maps.pdf

Planck_2015_Results_X_Diffuse_Comp_Sep_Foreground_maps.pdf

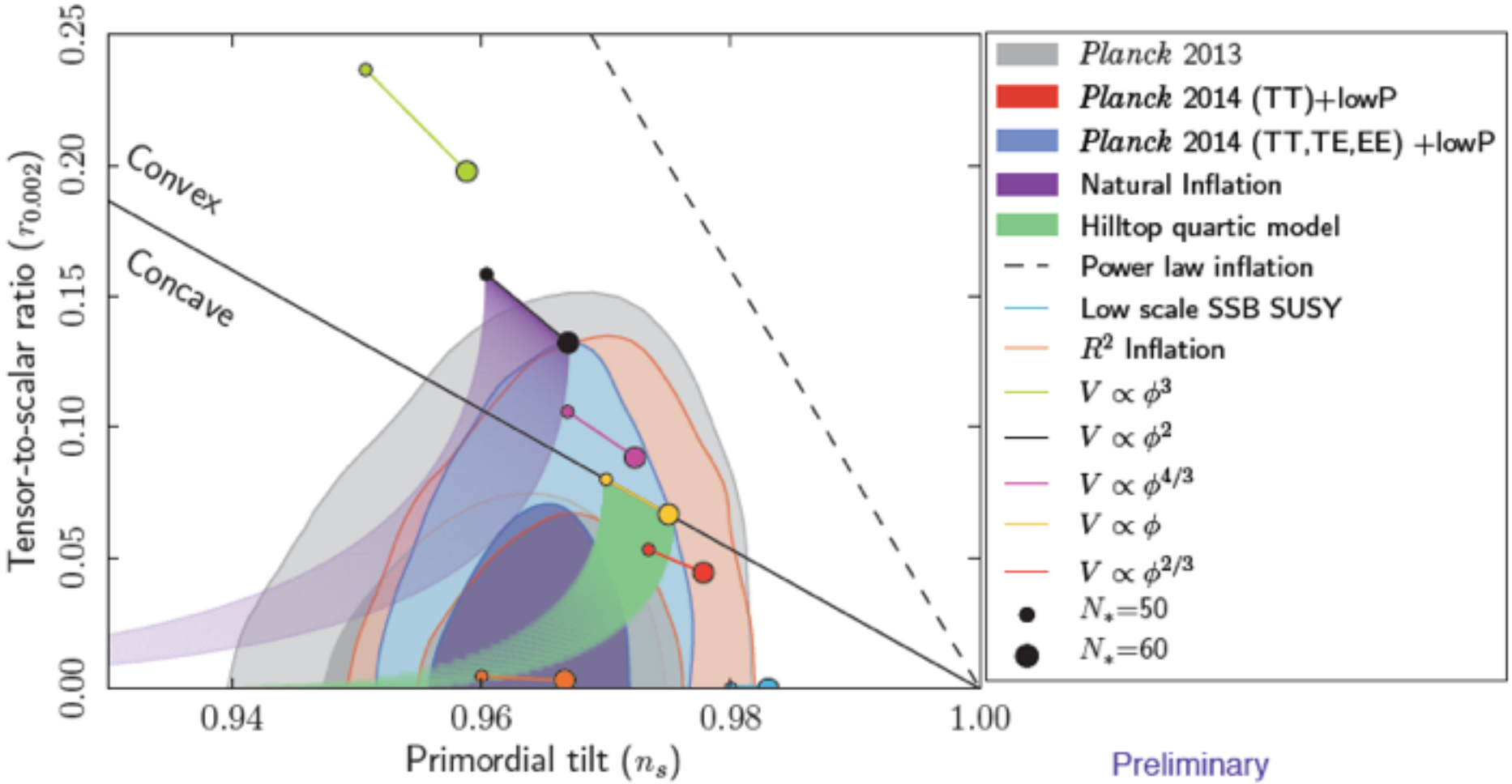
Planck_2015_Results_XIII_Cosmological_Parameters.pdf cf. PCP13 shifts <0.7σ except τ =0.066±.016, z_{re}=8.8+1.7-1.4 is down;
Planck_2015_Results_XIV_Dark_Energy_Mod_Gravity.pdf cosmological constant still works well
Planck_2015_Results_XV_Gravitational_Lensing.pdf 40sigma detection
Planck_2015_Results_XVII_Primordial_Non-Gaussianity.pdf limits similar to P13, polarization adds a bit
Planck_2015_Results_XVIII_Background_Geometry_Topology.pdf size/(2 distance to last scattering) >1
Planck_2015_Results_XIX_Constraints_Primordial_Magnetic_Fields.pdf
Planck_2015_Results_XX_Inflation.pdf m2phi2 ruled out, conformally flattened potentials OK
Planck_2015_Results_XXI_Integrated_Sachs-Wolfe_Effect.pdf

Planck_2015_Results_XXII_Map_Thermal_SZ_Effect.pdf public now, agrees with cluster count cosmology
Planck_2015_Results_XXIV_Cosmology_SZ_Clusters_Counts.pdf tension remains with primary CMB; nu mass?
Planck_2015_Results_XXVII_Second_Planck_Catalogue_SZ_Sources.pdf PSZ2 1652,1203 confirmed

Planck_2015_Results_XXVIII_Planck_Catalogue_Galactic_Cold_Clumps.pdf

END

Inflationary models & Planck



$r_{0.002} < 0.10$ (95 %CL, *Planck* TT + lowP) Preliminary

$r_{0.002} < 0.11$ (95 %CL, *Planck* TT + lensing + lowP)

$r_{0.002} < 0.10$ (95 %CL, *Planck* TT, TE, EE + lowP)

$r_{0.002} < 0.09$ (95 %CL, *Planck* TT + lowP/wWMAP)

WMAP 9 low resolution polarization data dust cleaned with Planck 353 GHz

0<r<.49 95%CL, .2±.15 1σ

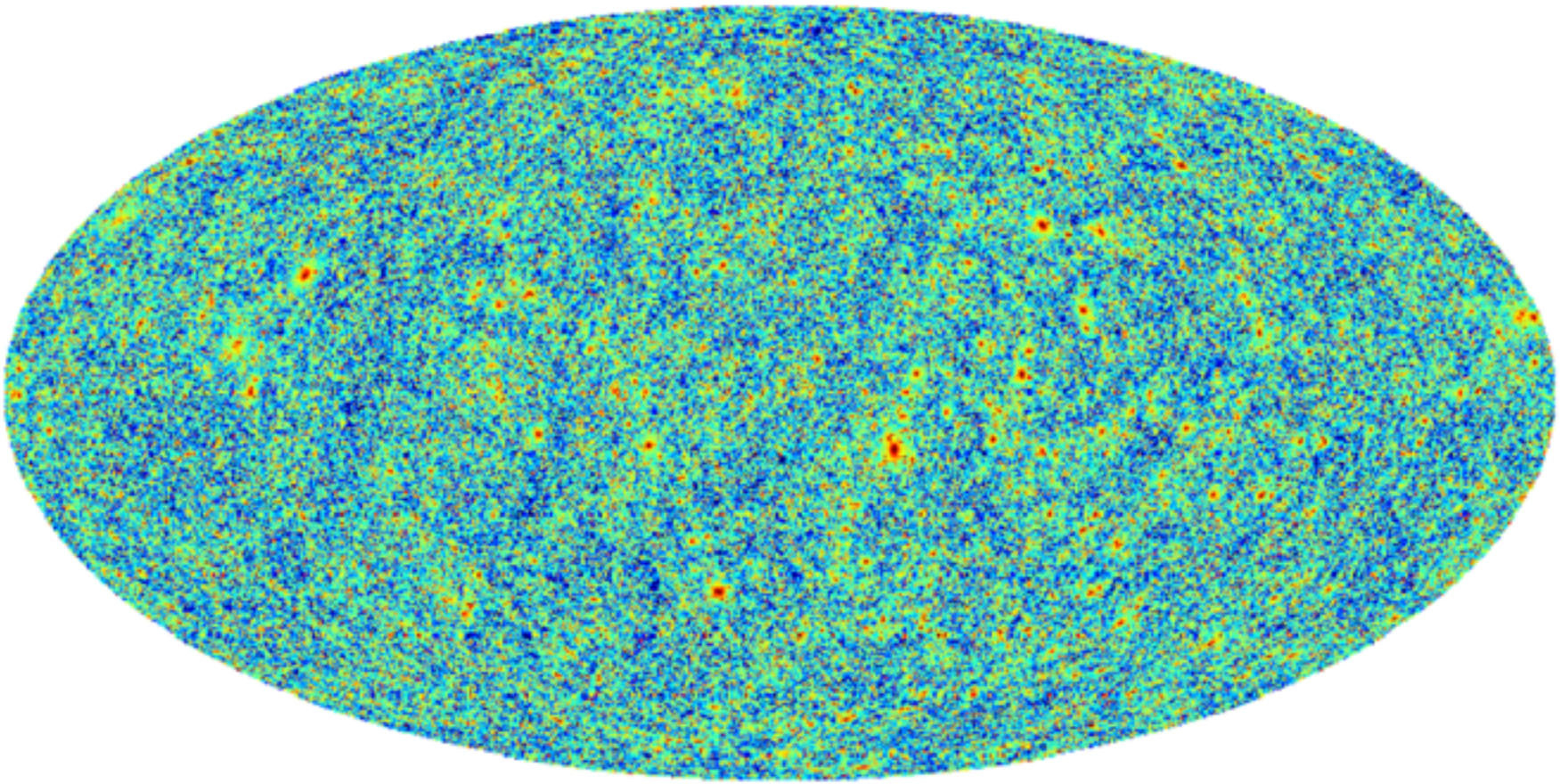
cf. **r<0.11 uniform n_s**

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

tSZ effect

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

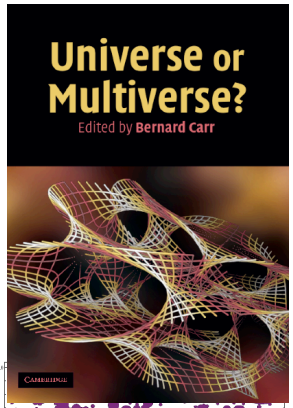
Alvarez, Bond, Hajian, Stein, Battaglia, Emberson,..2015

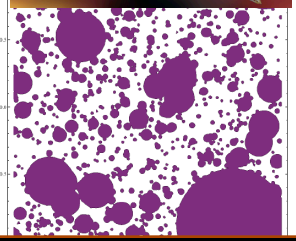


how to characterize map errors? by SIMs
inhomogeneous, CIB contamination, ..

ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information

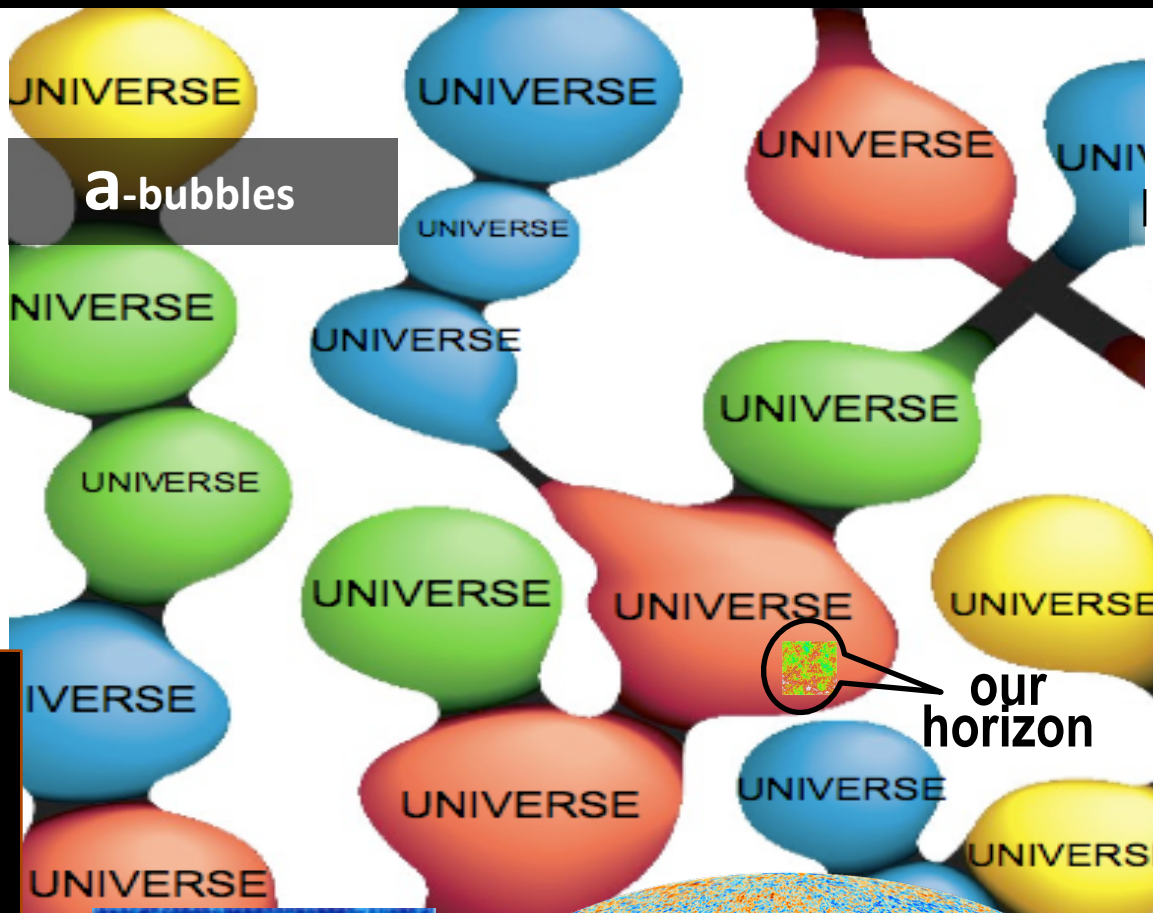


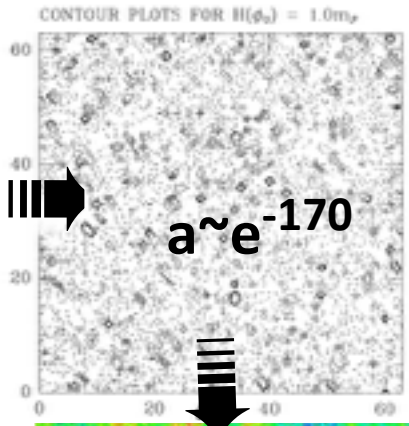


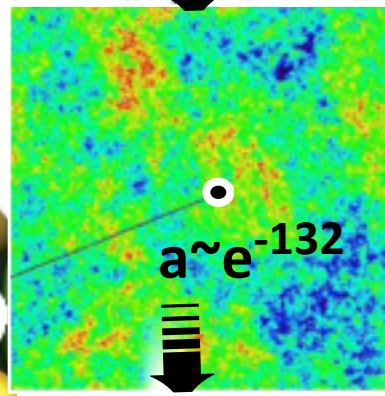
END

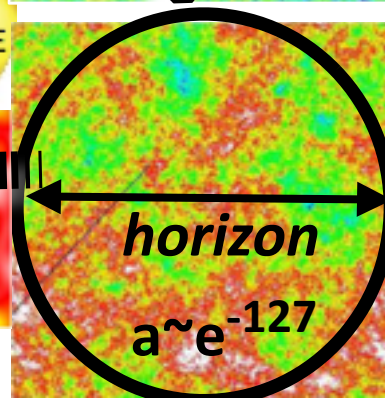
a future DE-Void

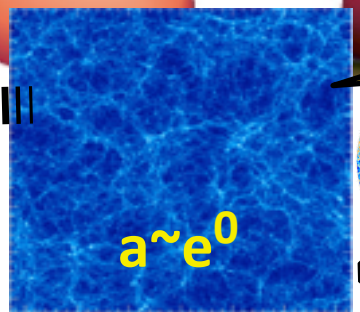
$a \sim e^{+++}$

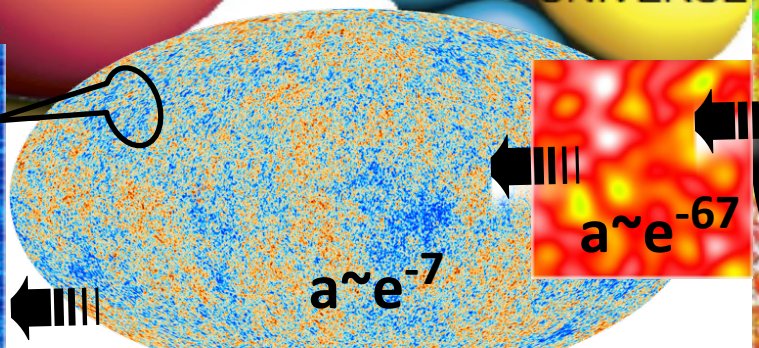












CBI pol to Apr'05 @Chile

53+35 cls **(>=40)**

CBI2

thermal SZ clusters

QUaD @SP

1652 cls

Planck09.4

52+ bolometers
+ HEMTs @L2

9 frequencies

WMAP @L2 to 2010

2004 2006 2008 LHC 2011

Bpol @L2

2005 2007 2009

Acbar@SP

~1 blind

AMIBA

6 cls

SZA@Cal

3 cls (z>1), x?

224 (=> **747**)

SPT

1000 bolos

@SPole

ACT **23+68~91 cls**

3000 bolos

3 freqs @Chile

>96

OVRO /BIMA

array

38 cls

AMI

7+1 cls >=50+25

APEX

~400 bolos@Chile

~25 cls

GBT Mustang

4 cls (~25 CLASH)

SCUBA2

12000 bolos

JCMT @Hawaii

SPTpol

ACTpol

ALMA

CCAT@Chile

LMT@Mexico

80s-90s

Ryle

OVRO

CBI pol to Apr'05 @Chile

53+35 cls (>=40)

CBI2

thermal SZ clusters

QUaD @SP

1652 cls

Planck09.4

52+ bolometers
+ HEMTs @L2

9 frequencies

Planck PSZ, cnts, ymap

1203 confirmed,

many ~ $10^{15}M_{sun}$ *0.<z<0.8*

WMAP @L2 to 2010

Reichardt+12, Benson@ESLAB13

100 cl cosmology, 400 with S/N > 5
now, 747 summer 2013 *2500 deg²*

Menanteau+12, Hasselfield+12

ACT Celestial Equator cls, 68 (49+19
in SDSS, half z>.5, 1 z~1.1 $10^{15}M_{sun}$
502 sq deg =>*91 in* 952 deg², 0.1<z<1.3

100% purity for S/N>5. 60% > 4.5

No significant evidence of SZ/BCG offset
M_{SZ}-N_{200} weak correlation, large scatter

2004 2006 2005 2007

224 (=> 747)

Acbar@SP

~1 blind

AMIBA

6 cls

SPT

1000 bolos
@SPole

SZA@Cal

3 cls (z>1), x?

ACT 23+68~91 cls

3000 bolos
3 freqs @Chile

>96

OVRO /BIMA

array

38 cls

AMI

7+1 cls >=50+25

APEX

~400 bolos@Chile

~25 cls

80s-90s

Ryle

OVRO

GBT Mustang

4 cls (~25 CLASH)

SCUBA2

12000 bolos

JCMT @Hawaii

SPTpol

ACTpol

ALMA

CCAT@Chile

LMT@Mexico