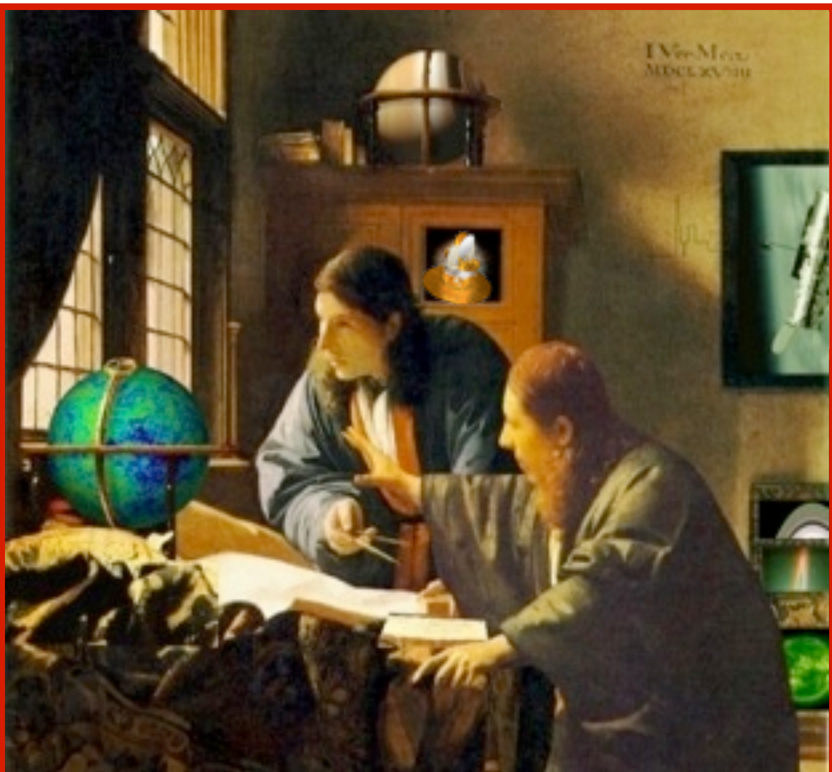
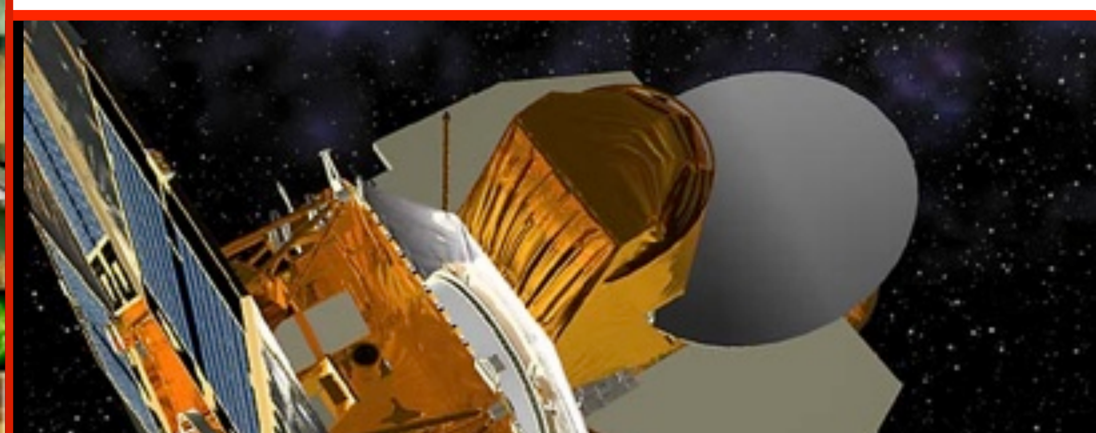
Observational Cosmology & Fundamental Physics



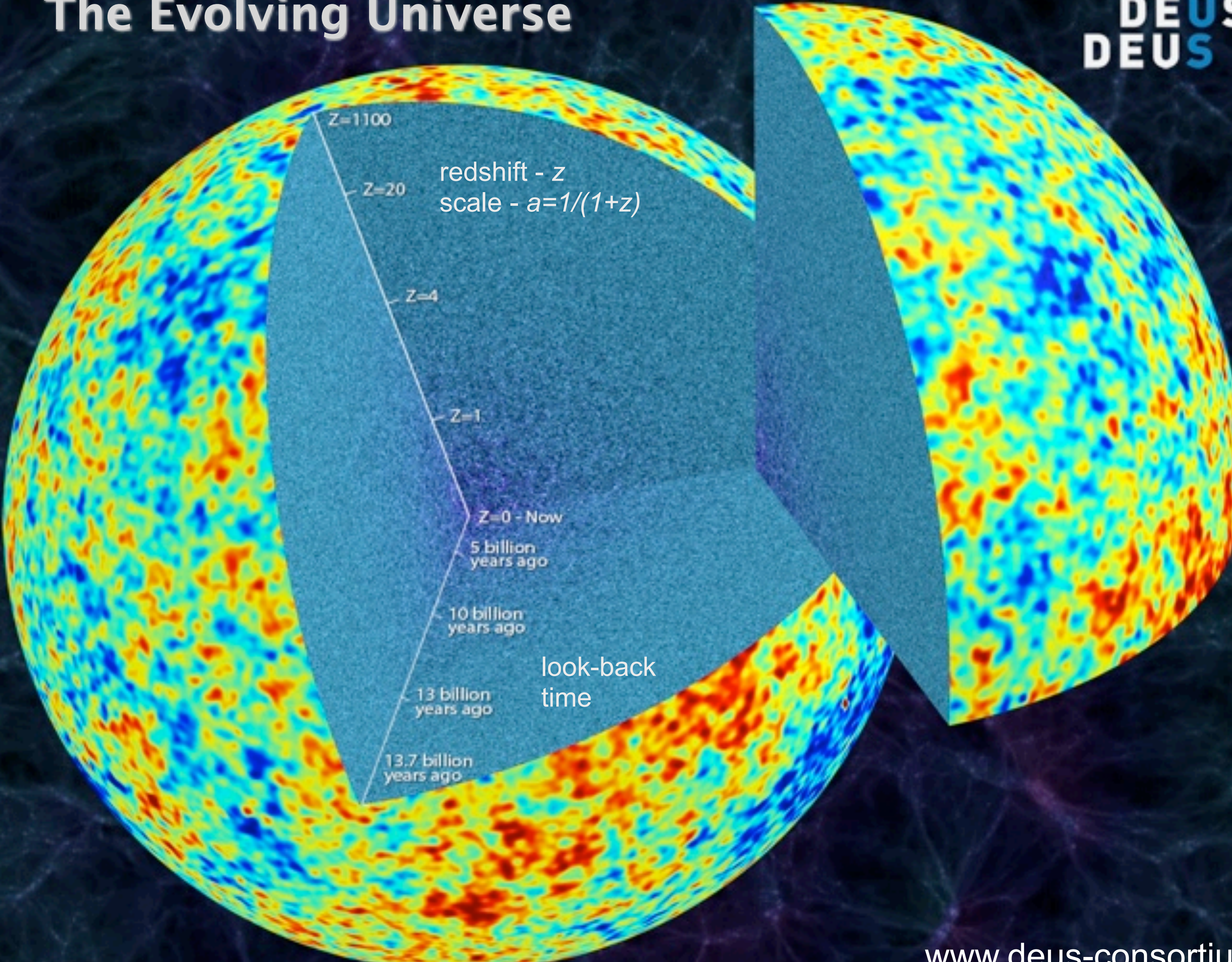


Gary Hinshaw

15 May 2015 **Seven Pines Symposium XIX**

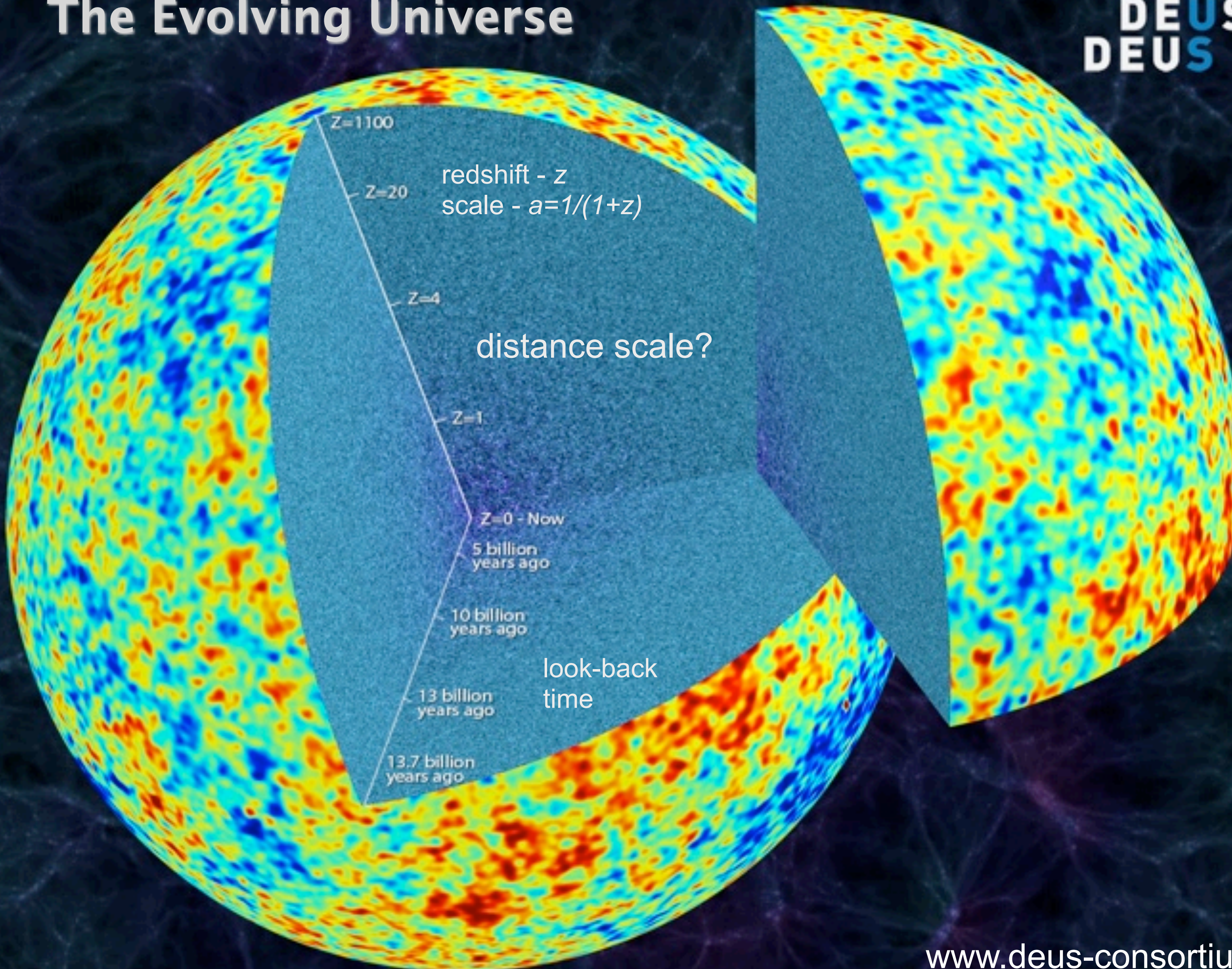
The Evolving Universe

DEUS
DEUS
DEUS



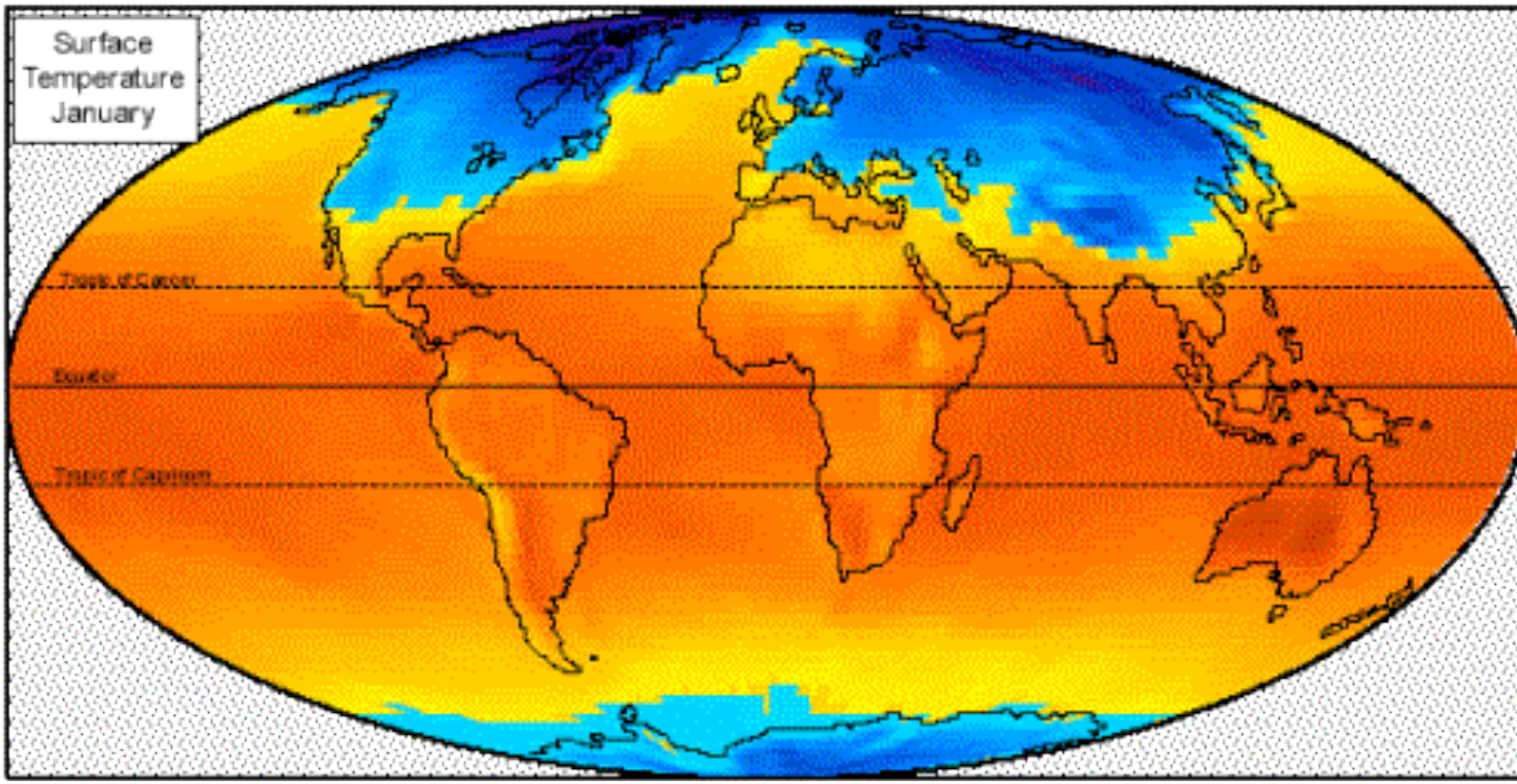
www.deus-consortium.org

The Evolving Universe



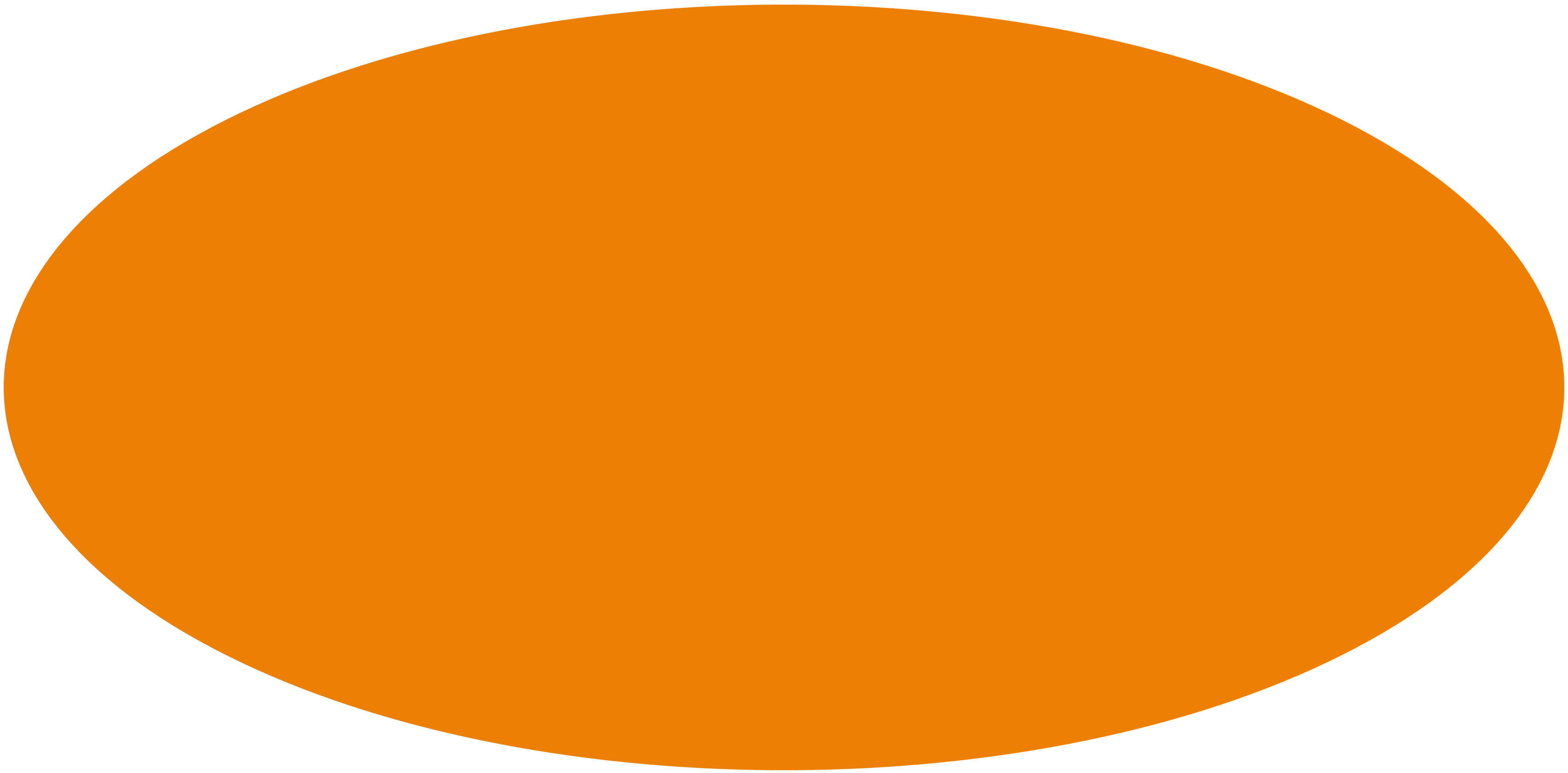
www.deus-consortium.org

Mapping the CMB Temperature



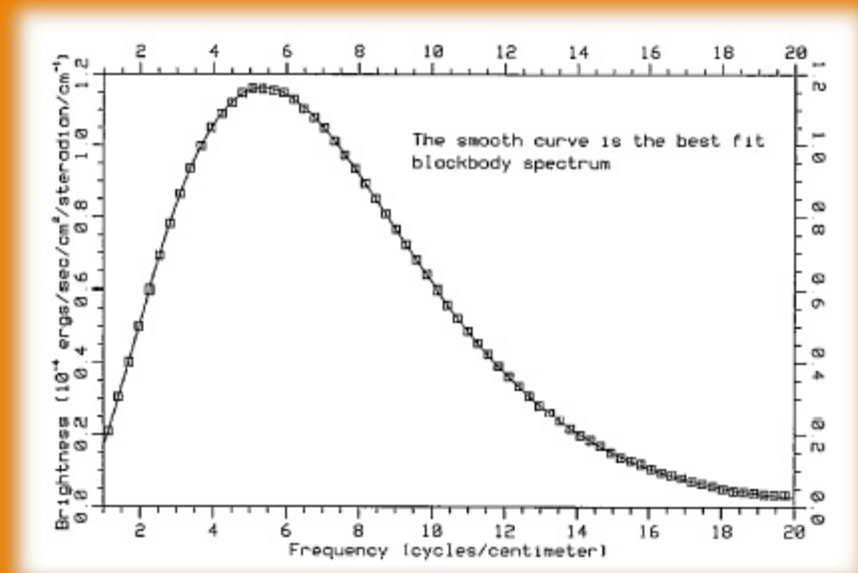
COBE-DMR was designed to measure brightness variations (anisotropy) across the sky - analogous to temperature variations across the surface of the Earth.

1990: COBE Limits on CMB Anisotropy



Preliminary results from COBE-DMR showed there was no significant variation in the CMB brightness across the sky (aside from the dipole anisotropy, due to our motion relative to the CMB rest frame).

The Universe as Seen by COBE

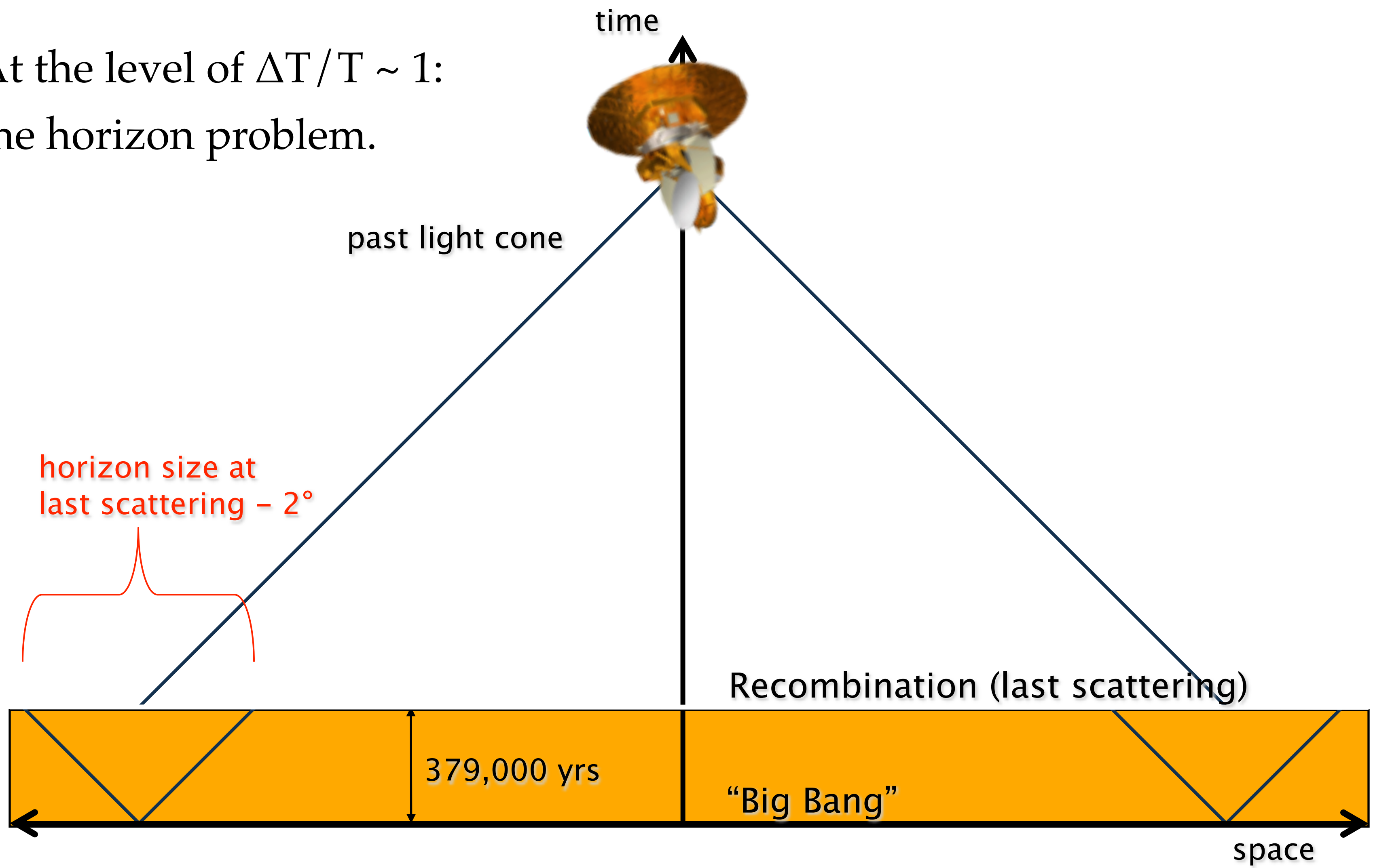


At the time of recombination (t=379,000 yr) the universe is filled with warm gas (T~3000 K) in thermal equilibrium. There is no discernible structure.

Questions Raised by Isotropy – I

At the level of $\Delta T/T \sim 1$:

the horizon problem.

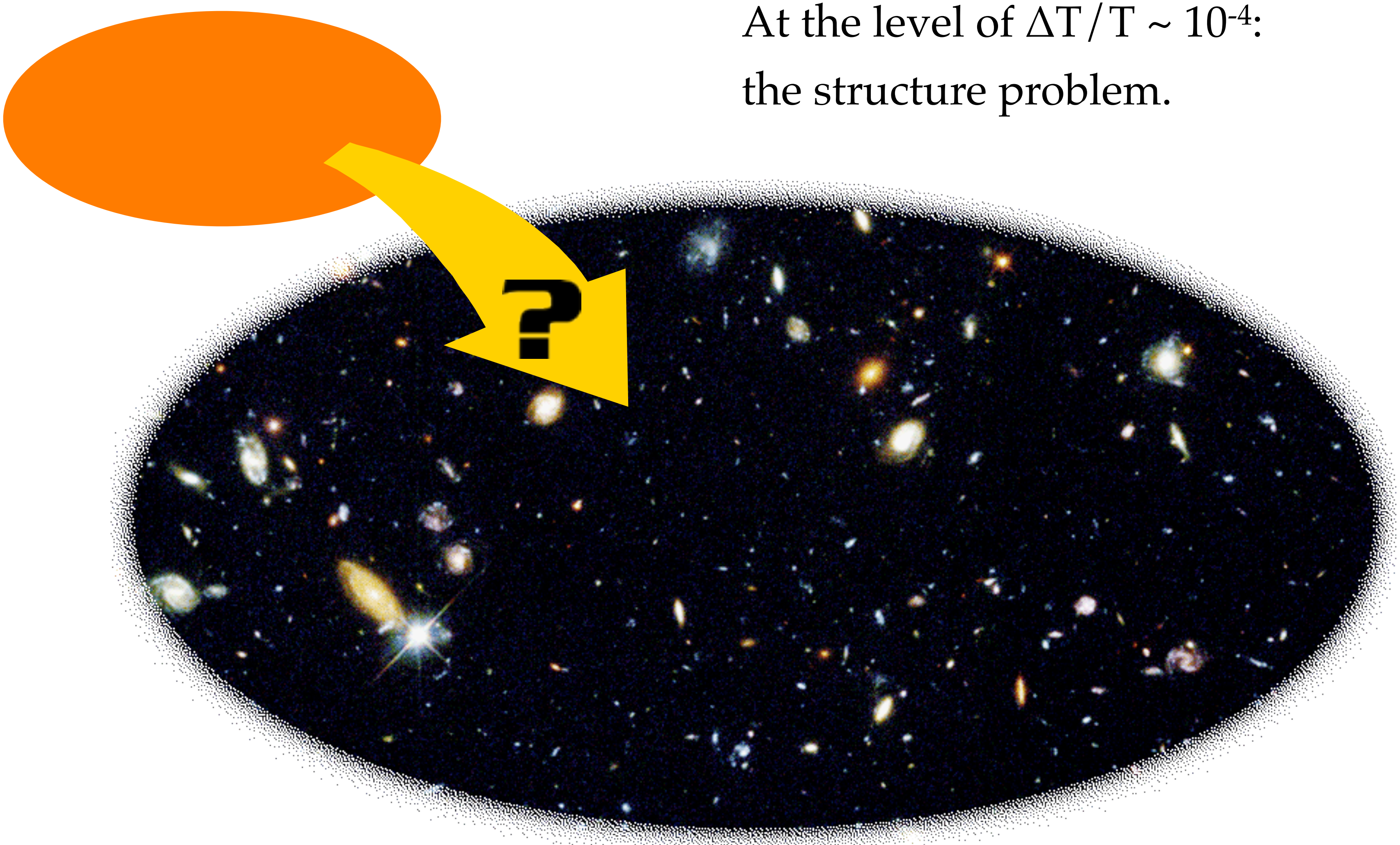


Why is the last scattering surface so isotropic?

Questions Raised by Isotropy – II

At the level of $\Delta T/T \sim 10^{-4}$:

the structure problem.



Where is the precursor to observed cosmic structure?

1992: CMB Anisotropy Detected

STRUCTURE IN THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER FIRST-YEAR MAPS

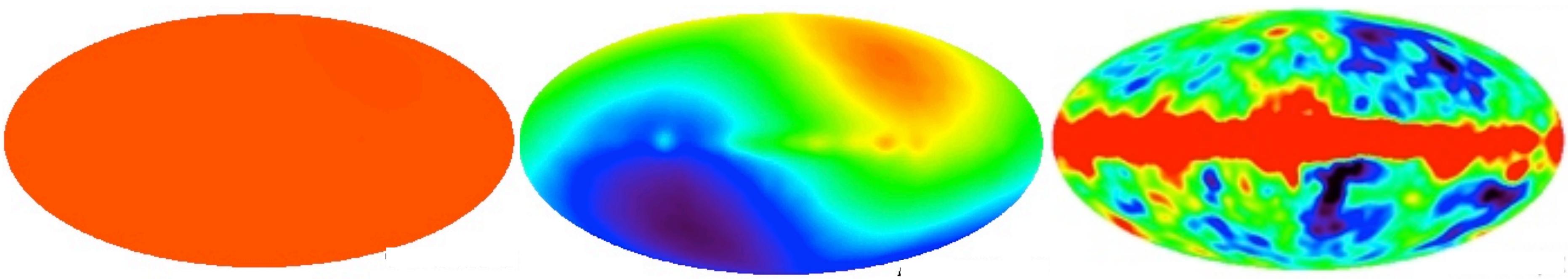
G. F. SMOOT,[2] C. L. BENNETT,[3] A. KOGUT,[4] E. L. WRIGHT,[5] J. AYMON,[2] N. W. BOGGESS,[3] E. S. CHENG,[3] G. DE AMICI,[2] S. GULKIS,[6] M. G. HAUSER,[3] G. HINSHAW,[4] P. D. JACKSON,[7] M. JANSSEN,[6] E. KAITA,[7] T. KELSALL,[3] P. KEEGSTRA,[7] C. LINEWEAVER,[2] K. LOEWENSTEIN,[7] P. LUBIN,[8] J. MATHER,[3] S. S. MEYER,[9] S. H. MOSELEY,[3] T. MURDOCK,[10] L. ROKKE,[7] R. F. SILVERBERG,[3] L. TENORIO,[2] R. WEISS,[9] AND D. T. WILKINSON[11]

THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

"PRELIMINARY SEPARATION OF GALACTIC AND COSMIC MICROWAVE EMISSION…"
BENNETT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

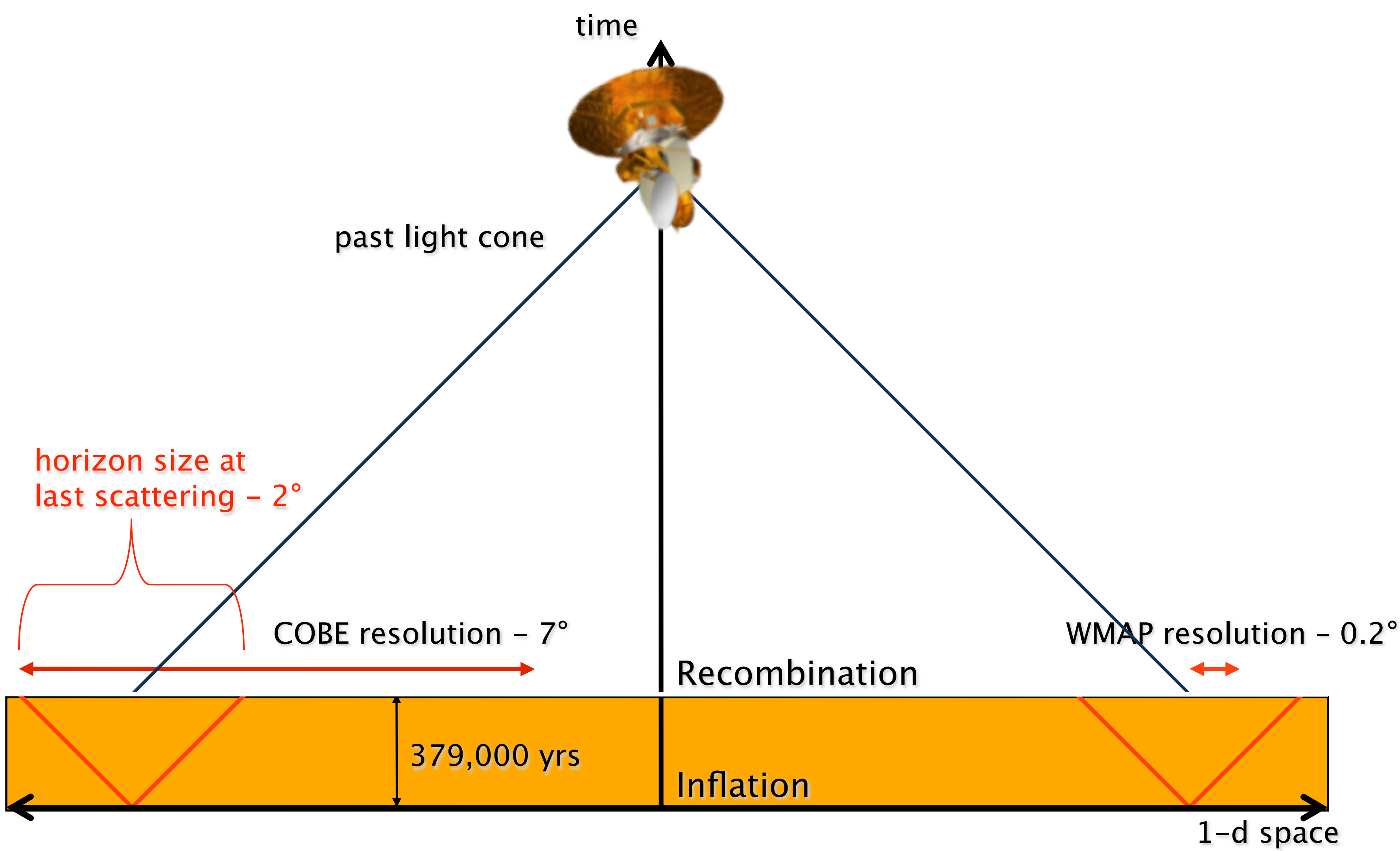
"INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY…"
WRIGHT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

"COBE DIFFERENTIAL MICROWAVE RADIOMETERS – PRELIMINARY SYSTEMATIC ERROR…"
KOGUT ET AL, THE ASTROPHYSICAL JOURNAL, 401, 1-18, 1992



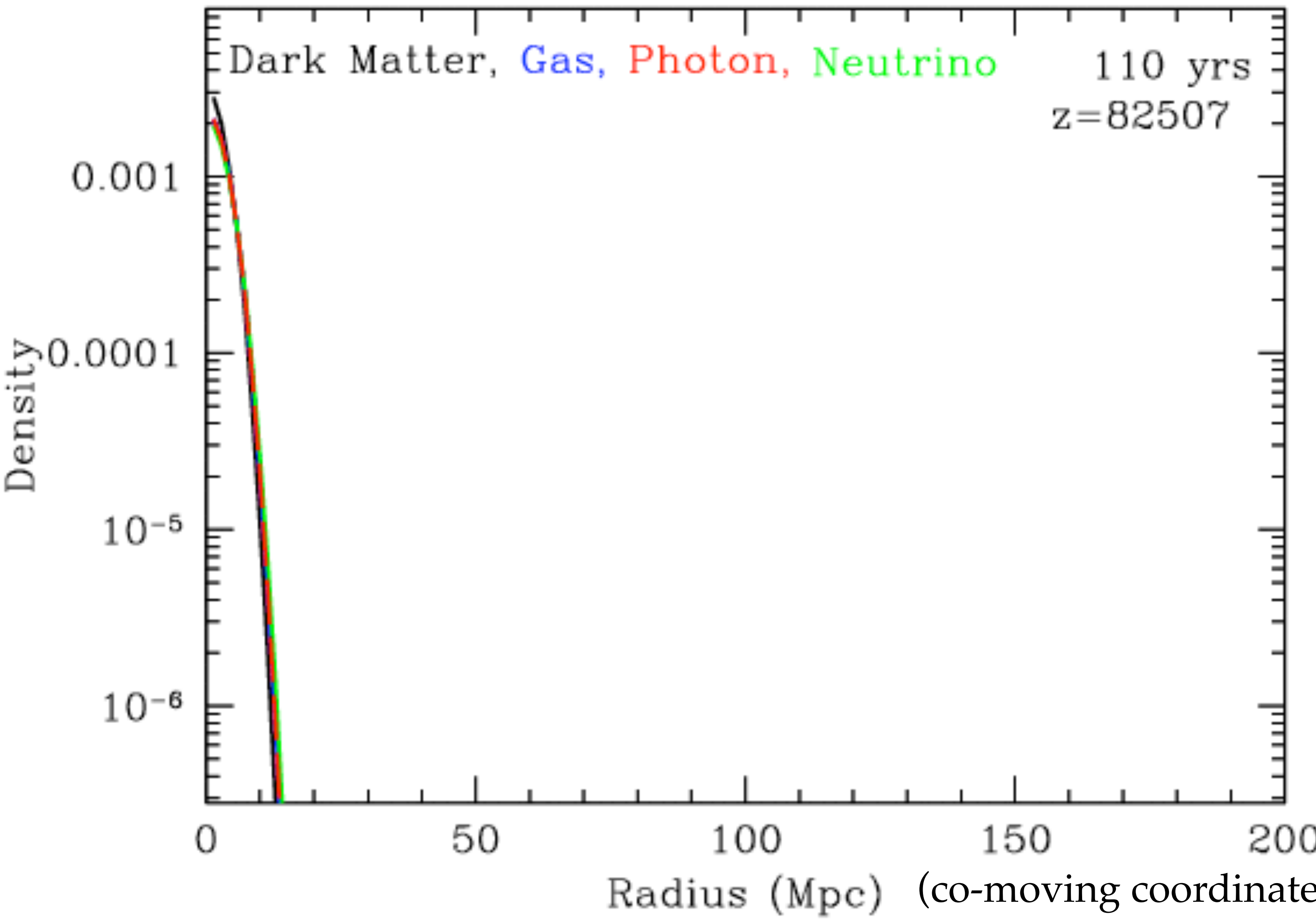
First detection of temperature fluctuations (anisotropy): sets the scale of the signal – brighter than the Galactic foreground!

Post-COBE: Push for Higher Resolution



COBE does not probe causal (e.g. acoustic) effects that occur during the plasma epoch.

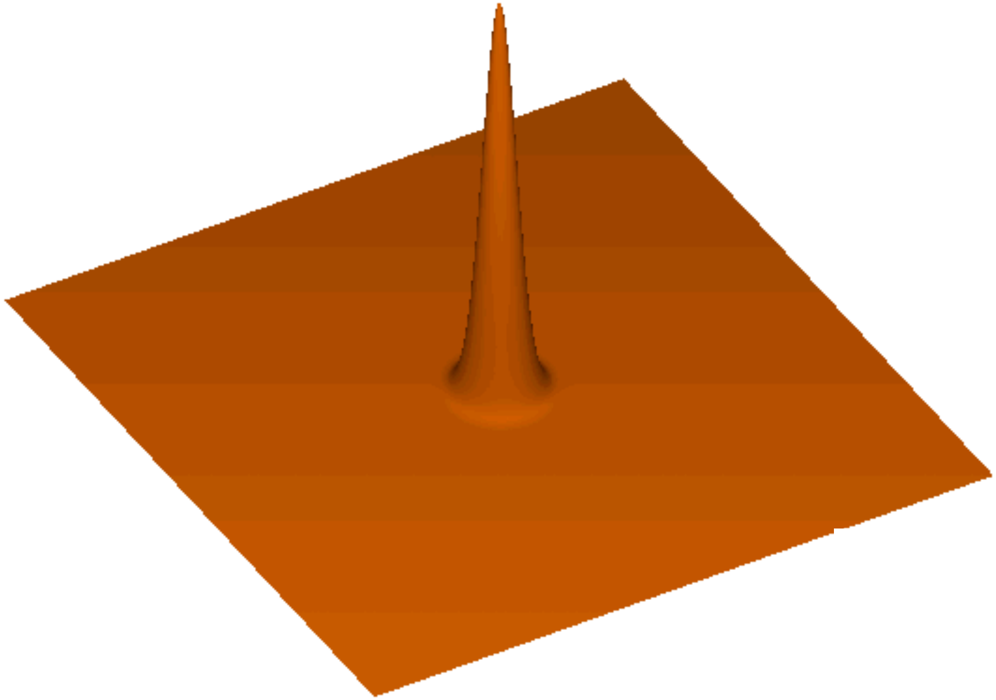
BAO the Movie: evolution of a density peak

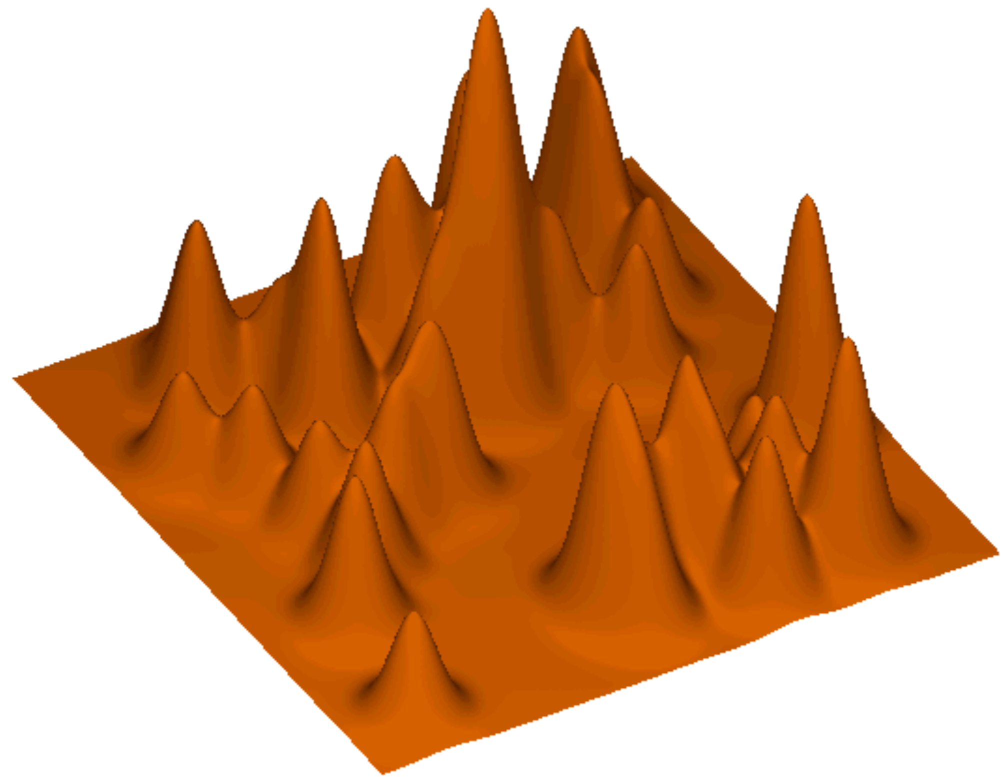


(co-moving coordinates)

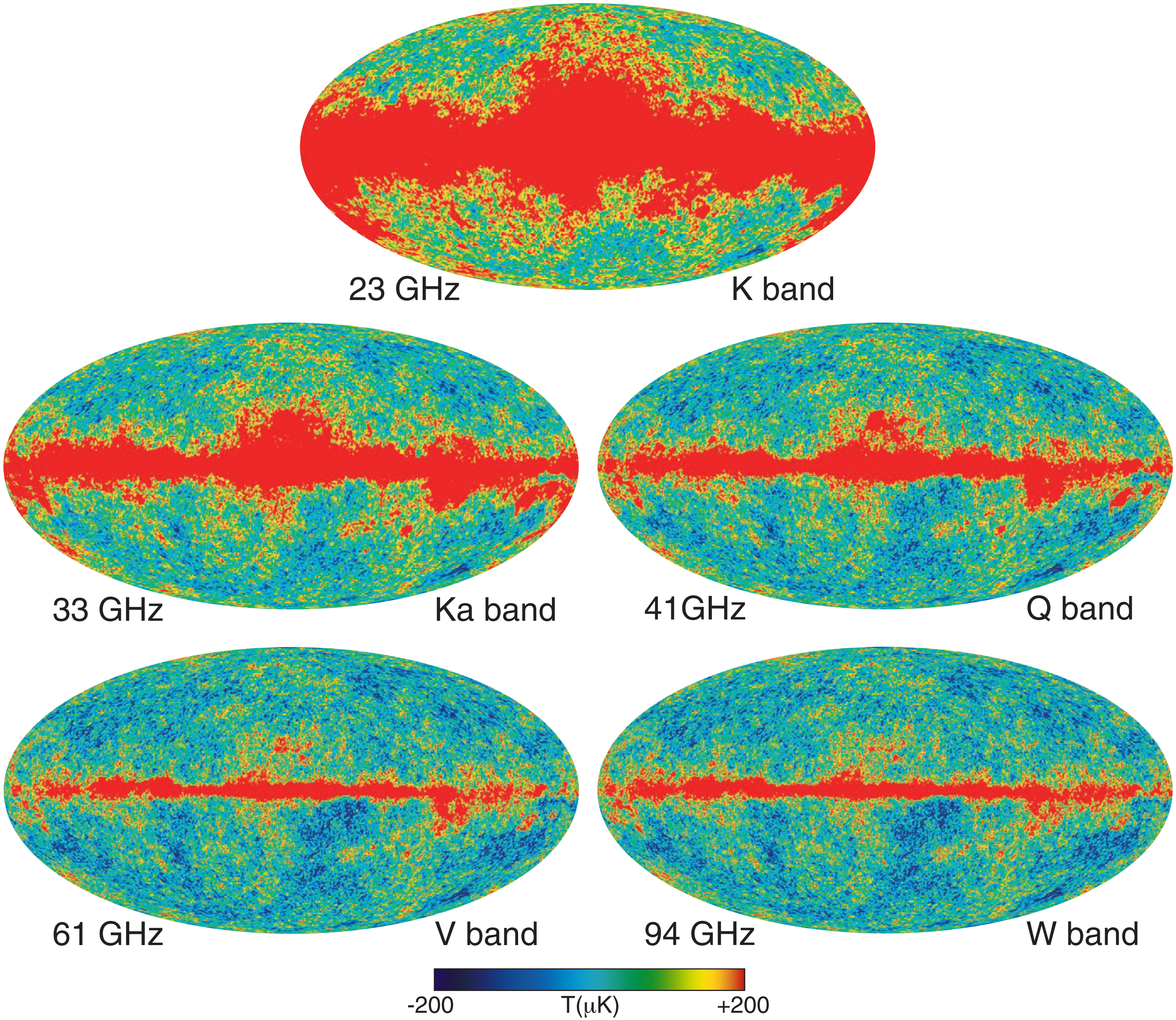
Credit: SDSS Collaboration

Animation: SDSS Collaboration

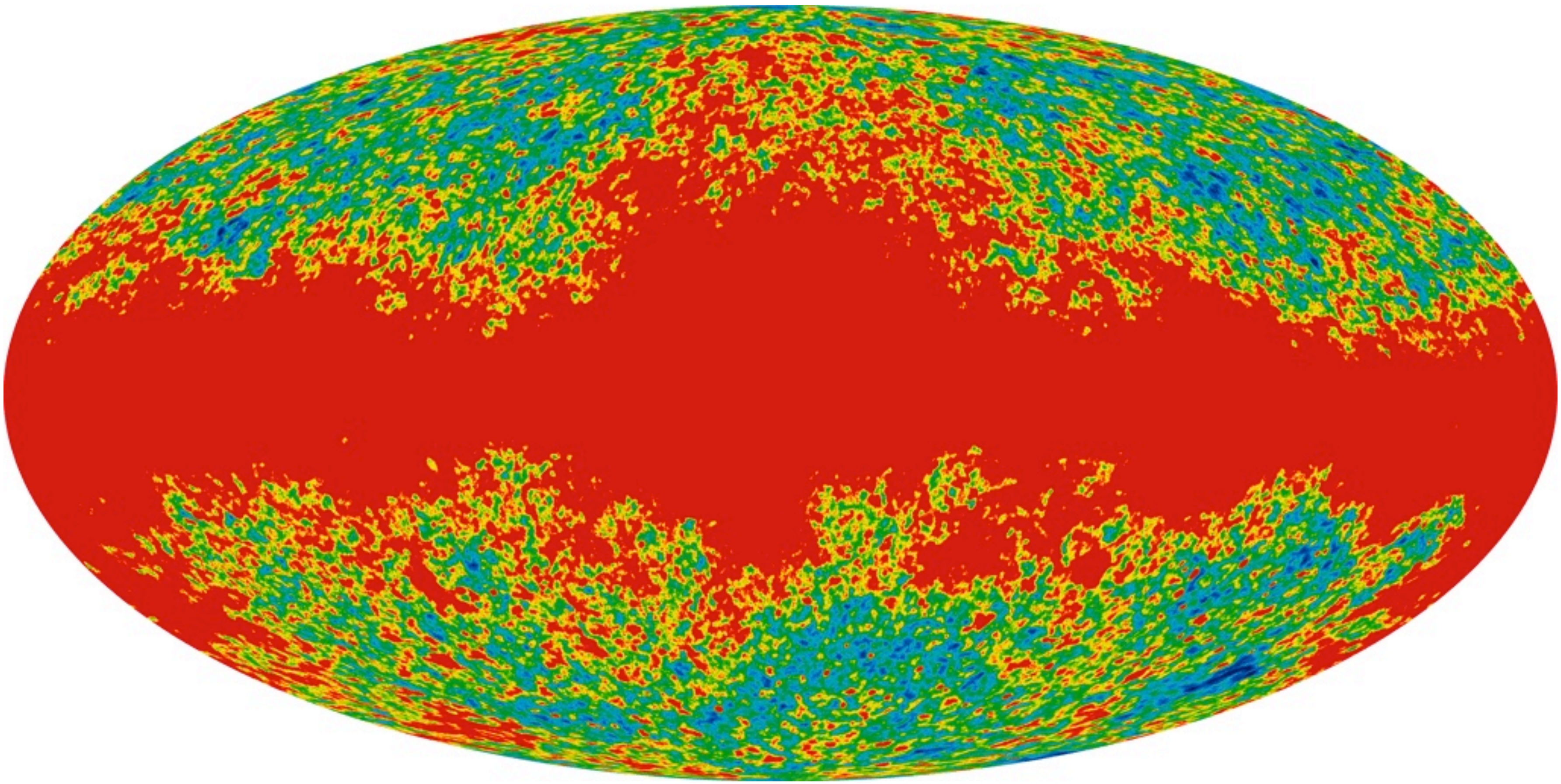




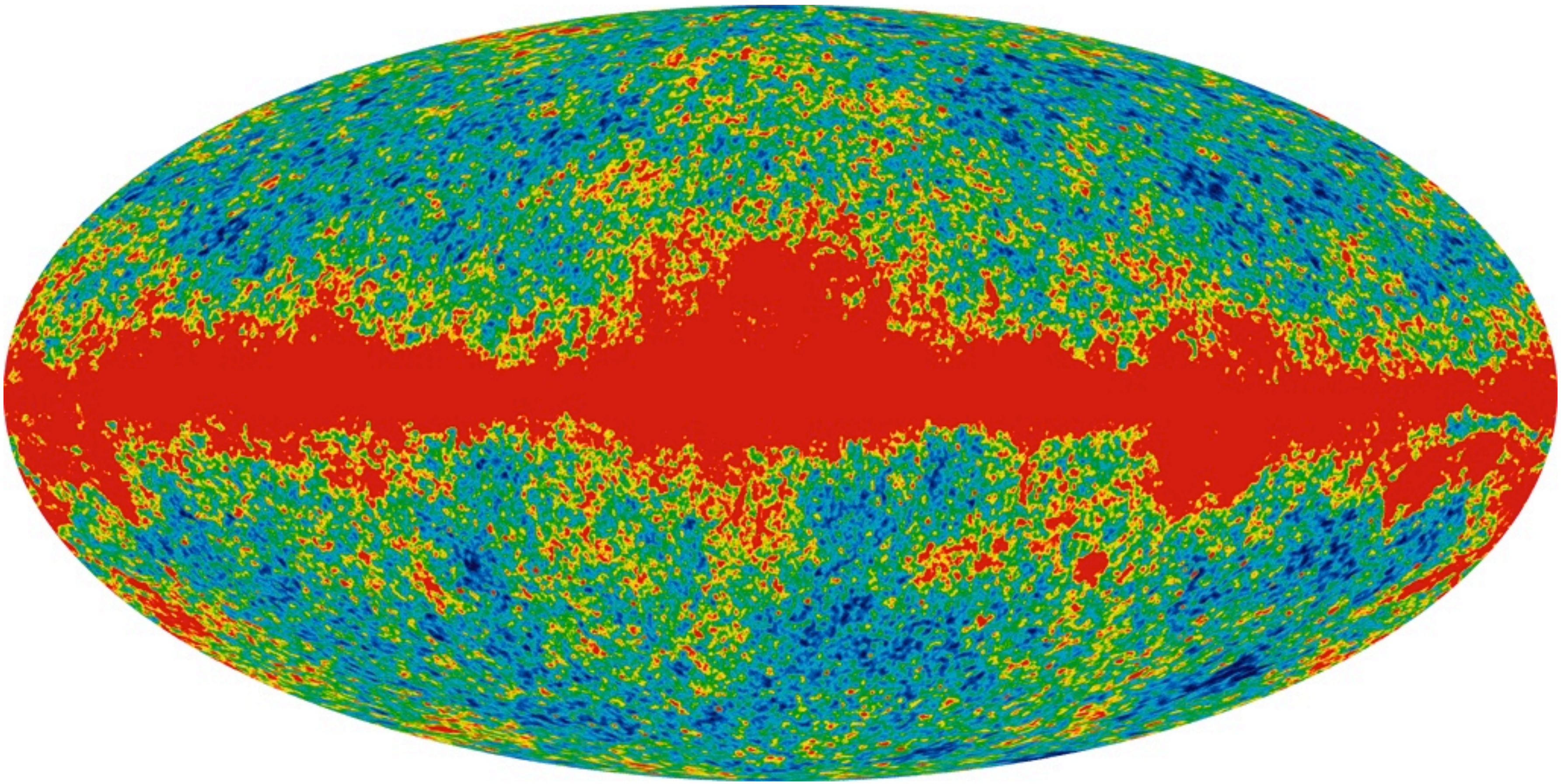
9-year Temperature Maps



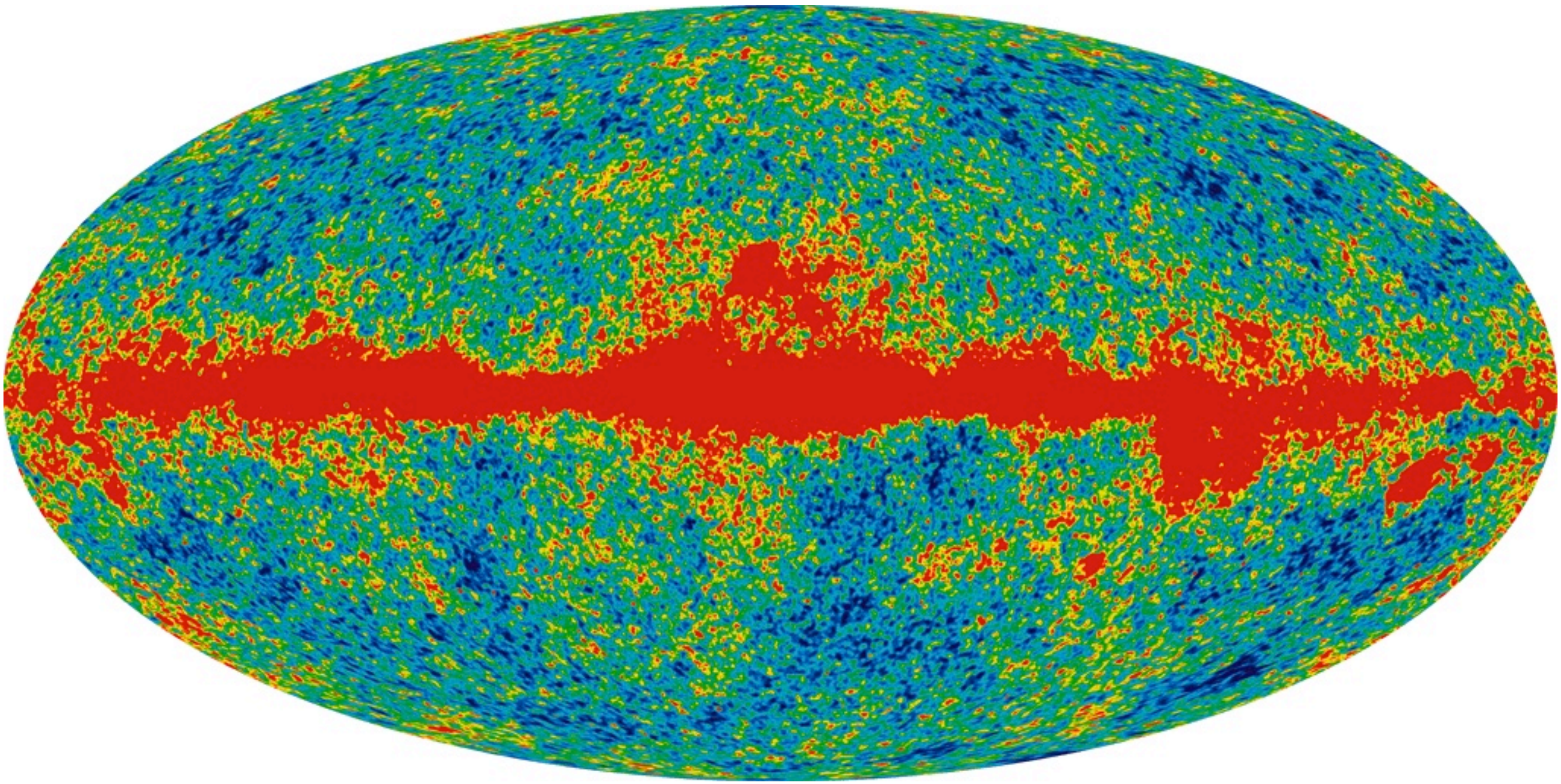
K Band Temperature, 23 GHz



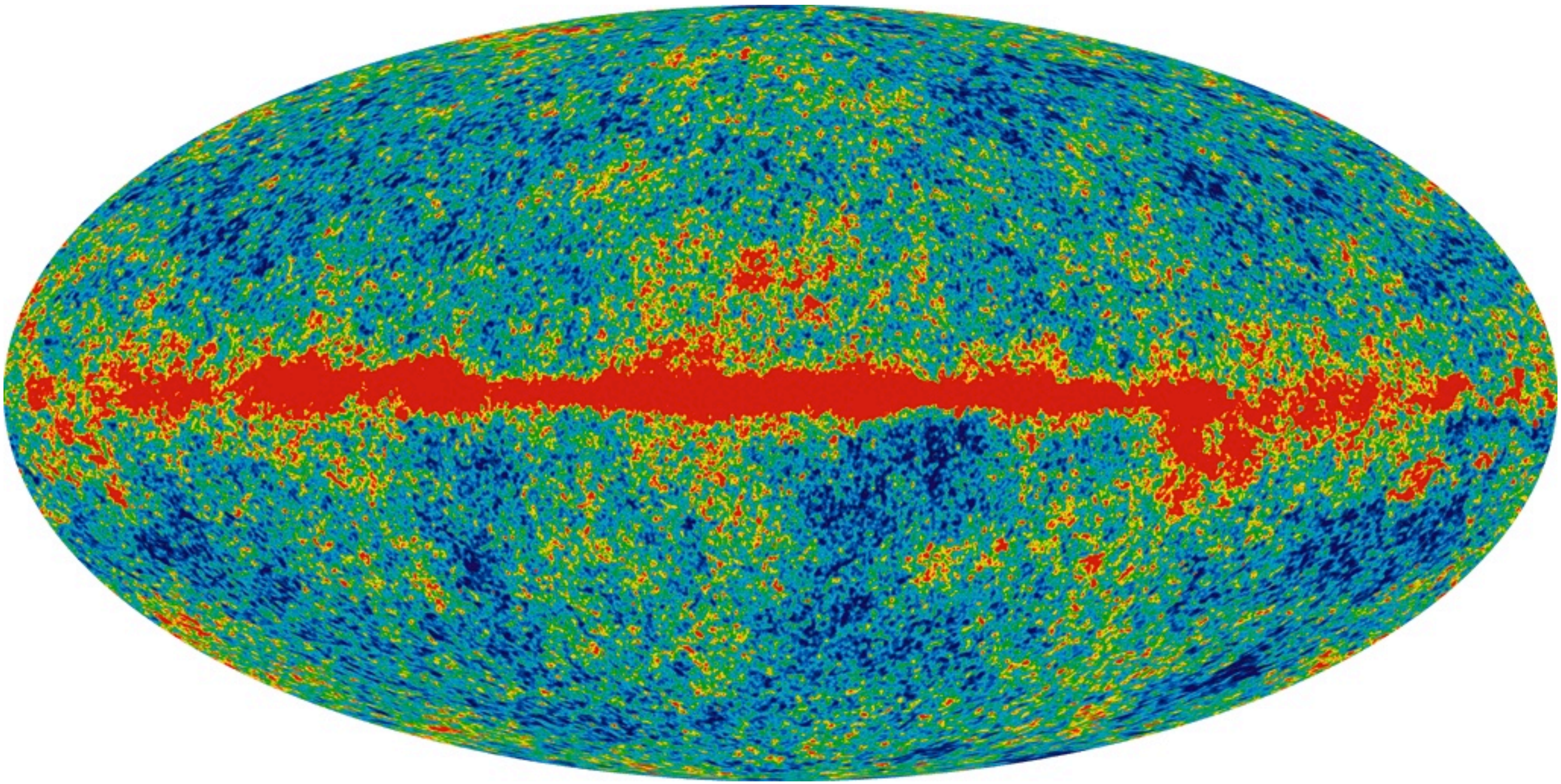
Ka Band Temperature, 33 GHz



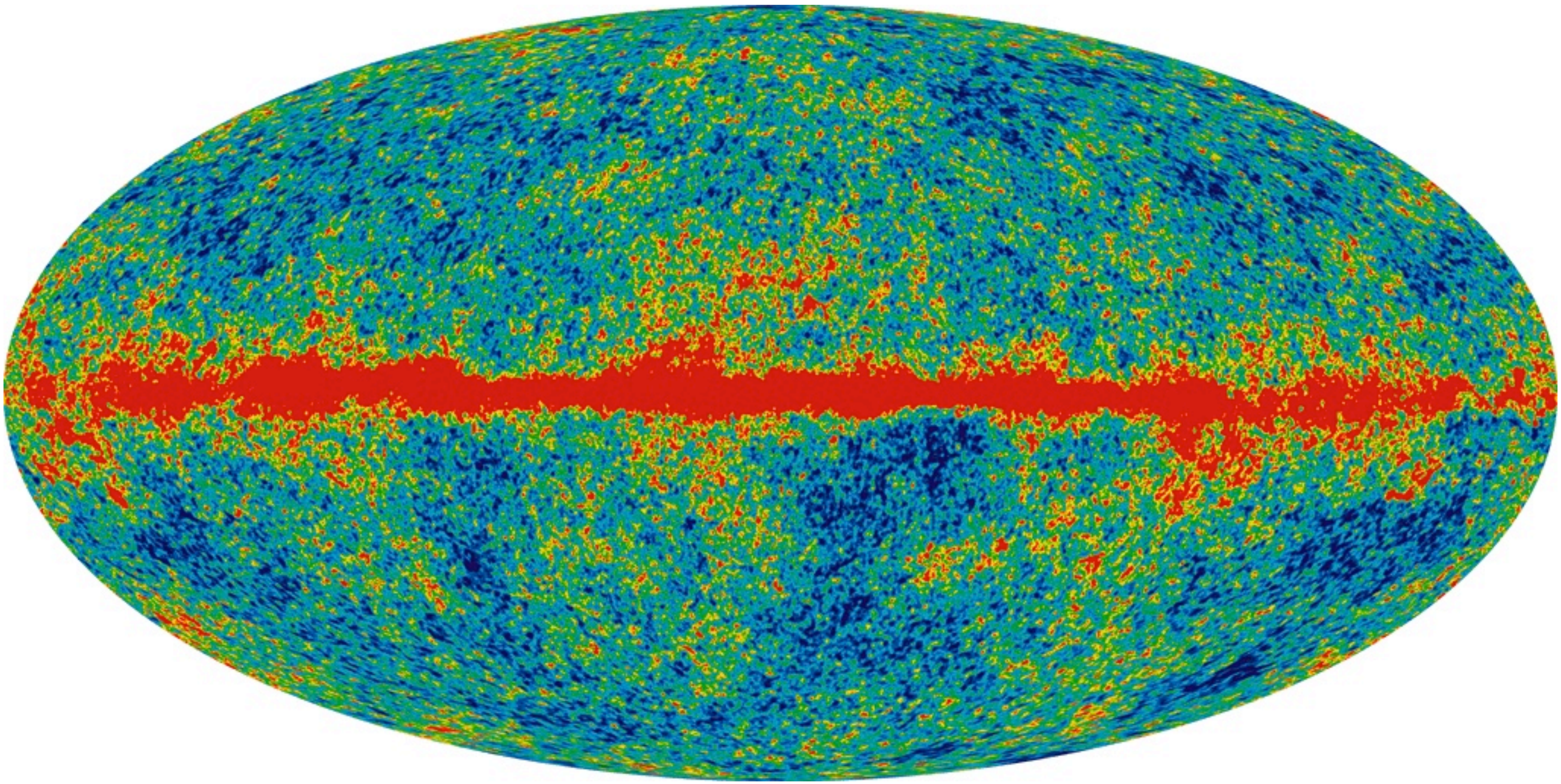
Q Band Temperature, 41 GHz



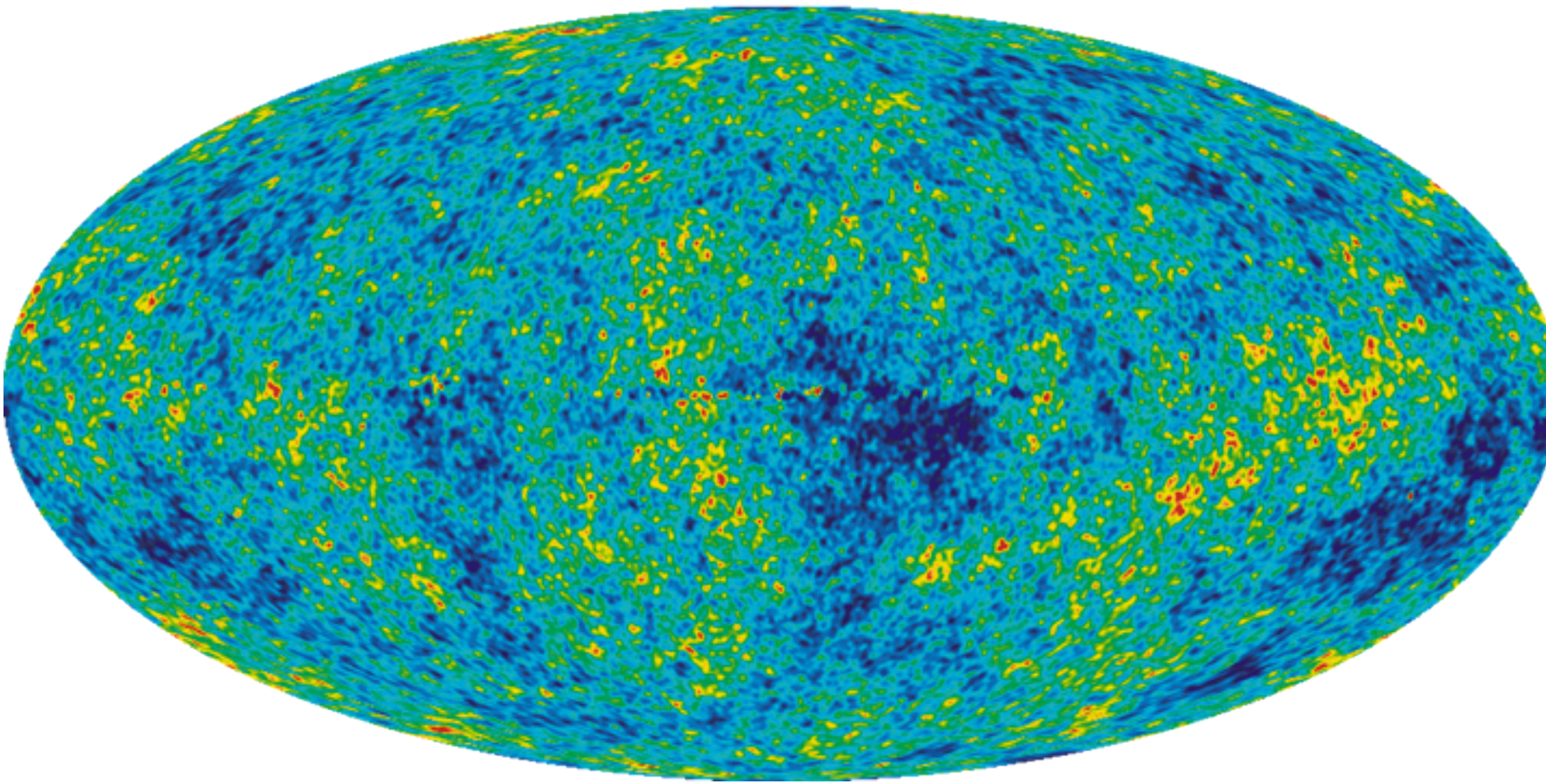
V Band Temperature, 61 GHz



W Band Temperature, 94 GHz



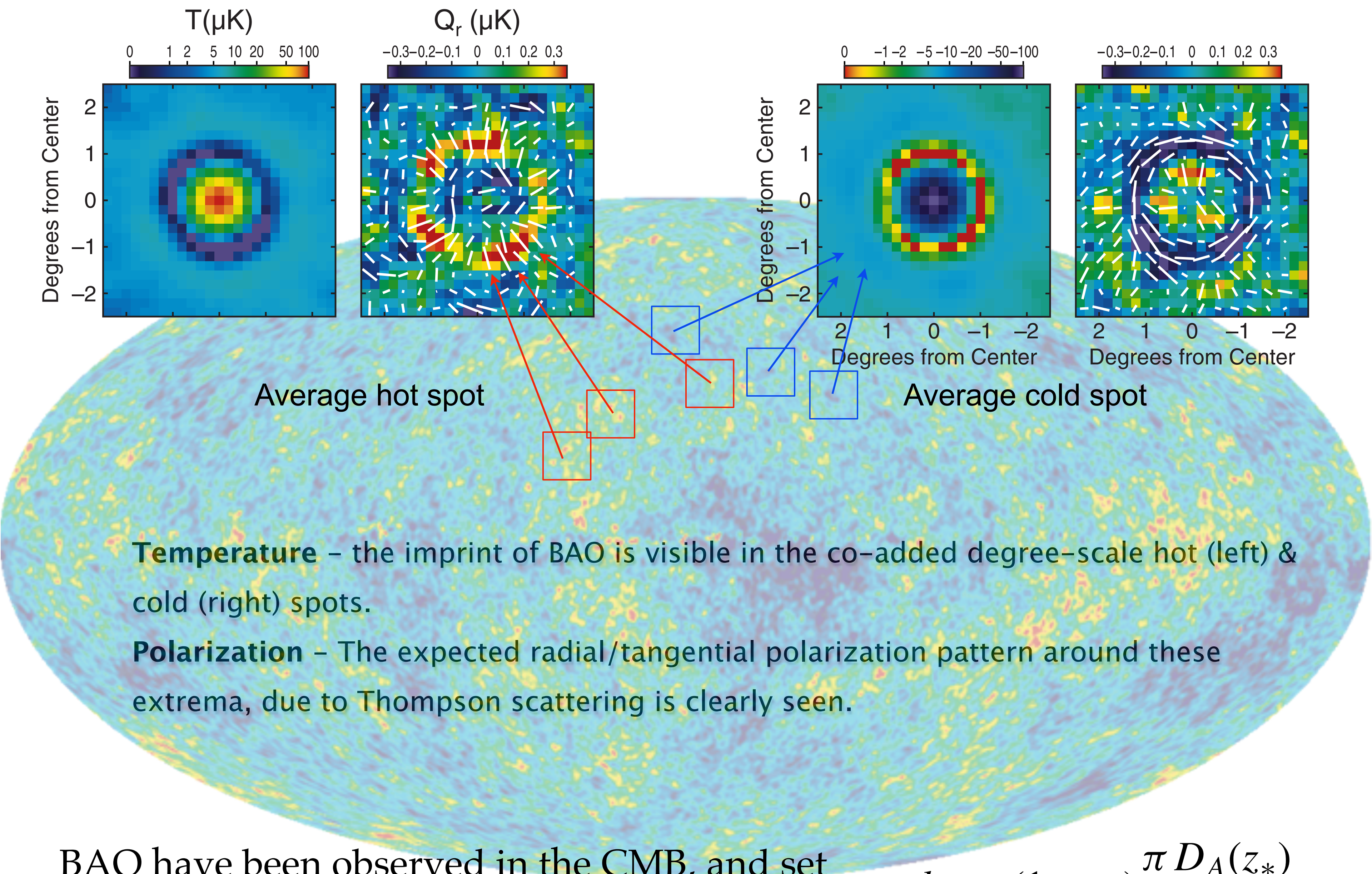
Foreground-Cleaned Primordial CMB



Minimum variance ILC: the internal linear combination (ILC) of frequency bands that minimizes the variance of the final map: $T = \sum_i w_i T_i$ with $\sum_i w_i = 1$.

Cosmological Analysis –
Baryon Acoustic Oscillations (BAO) in the CMB

WMAP Team 2012



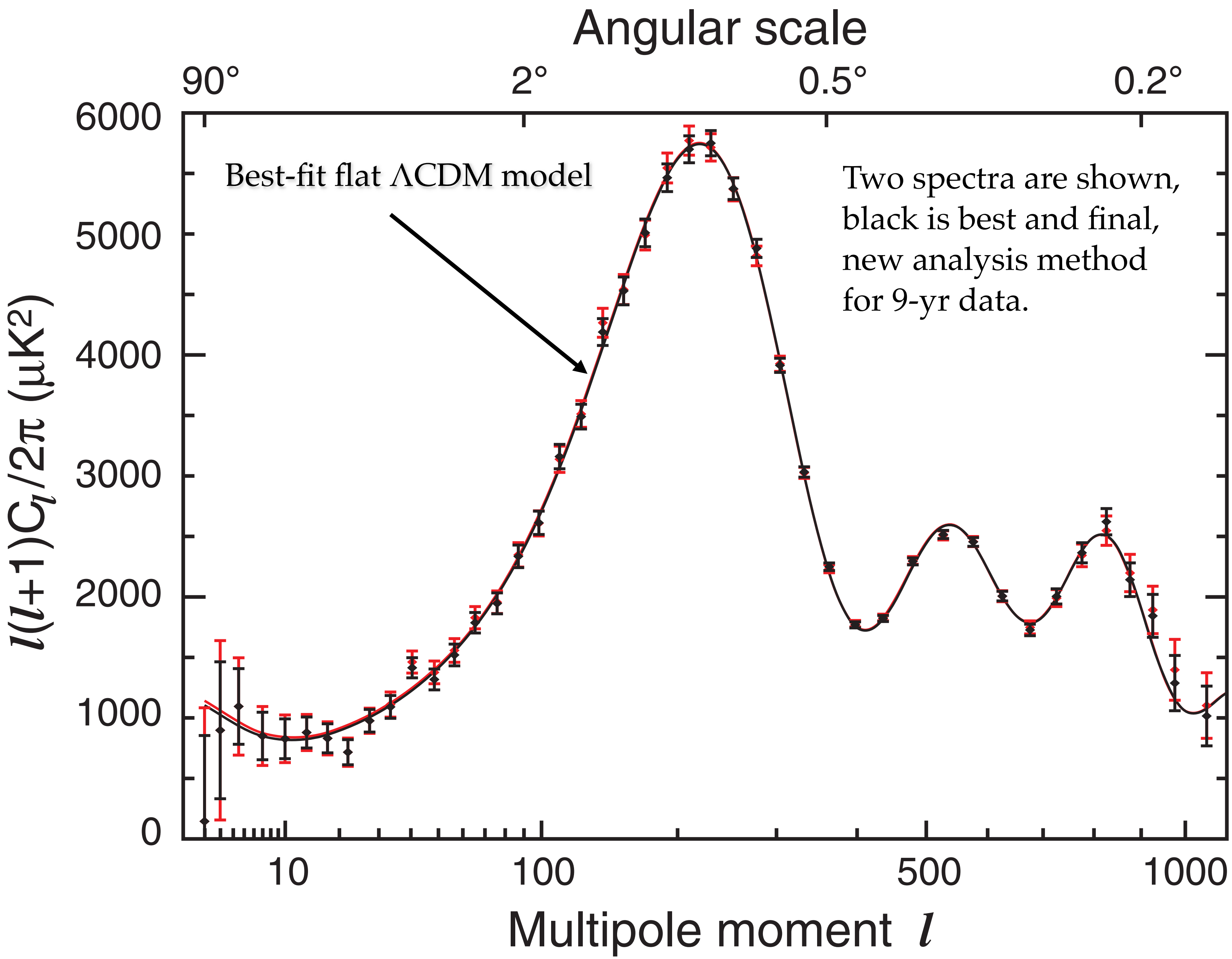
Temperature – the imprint of BAO is visible in the co-added degree-scale hot (left) & cold (right) spots.

Polarization – The expected radial/tangential polarization pattern around these extrema, due to Thompson scattering is clearly seen.

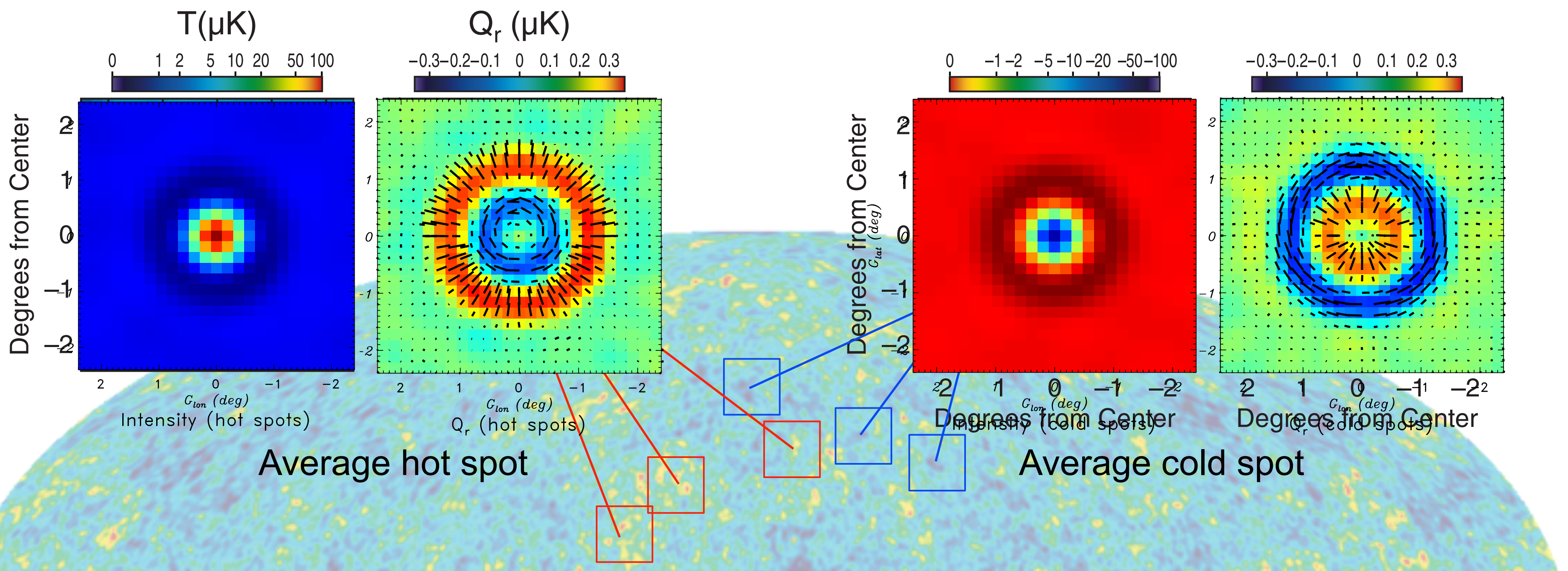
BAO have been observed in the CMB, and set the acoustic scale: $l_A = 302.35 \pm 0.65$ @ z_*=1091.

$$l_A = (1 + z_*) \frac{\pi D_A(z_*)}{r_s(z_*)},$$

The Final WMAP Power Spectrum



Planck Collaboration 2013



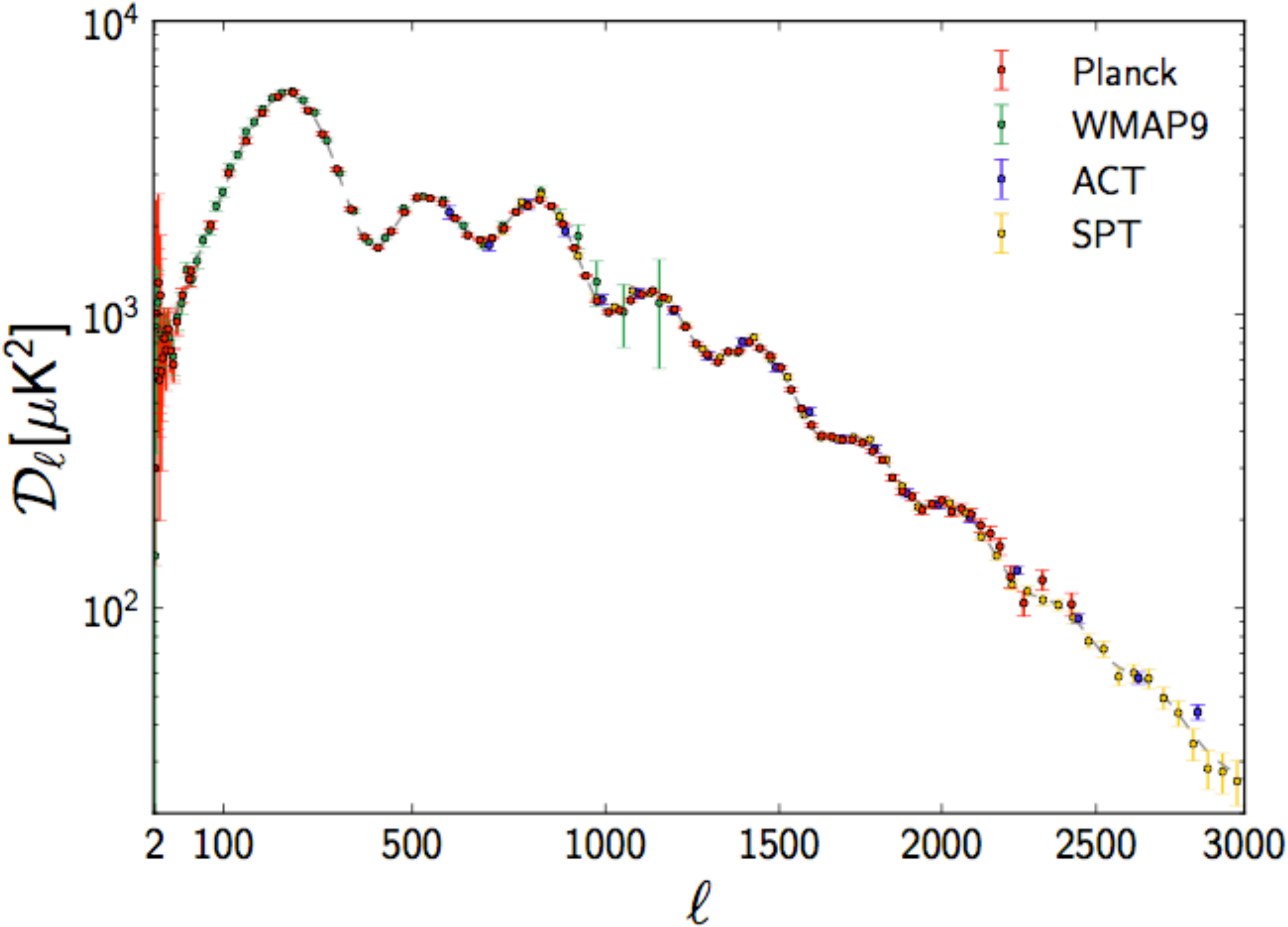
Temperature – the imprint of BAO is visible in the co-added degree-scale hot (left) & cold (right) spots.

Polarization – The expected radial/tangential polarization pattern around these extrema, due to Thompson scattering is clearly seen.

BAO have been observed in the CMB, and set the acoustic scale: $l_A = 303.05 \pm 0.19$ @ z_*=1091.

$$l_A = (1 + z_*)\frac{\pi D_A(z_*)}{r_s(z_*)},$$

Extended CMB Data Used in WMAP9



Cosmological Parameters

Hinshaw et al., arXiv/1212.5226

TABLE 2
Maximum Likelihood ΛCDM Parameters[a]

Parameter	Symbol	*WMAP* data	Combined data[b]
Fit ΛCDM parameters			
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
Derived parameters			
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100h$ km/s/Mpc	H_0	69.7	69.7
Density fluctuations @ $8h^{-1}$ Mpc	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	z_{eq}	3273	3280
Redshift of reionization	z_{reion}	10.36	9.97

[a] The maximum-likelihood ΛCDM parameters for use in simulations. Mean parameter values, with marginalized uncertainties, are reported in Table 4.
[b] "Combined data" refers to *WMAP*+eCMB+BAO+H_0.

This gives most-likely model parameters for "vanilla" 6-parameter ΛCDM model. Stay tuned for errors and goodness of fit.

Cosmological Parameters

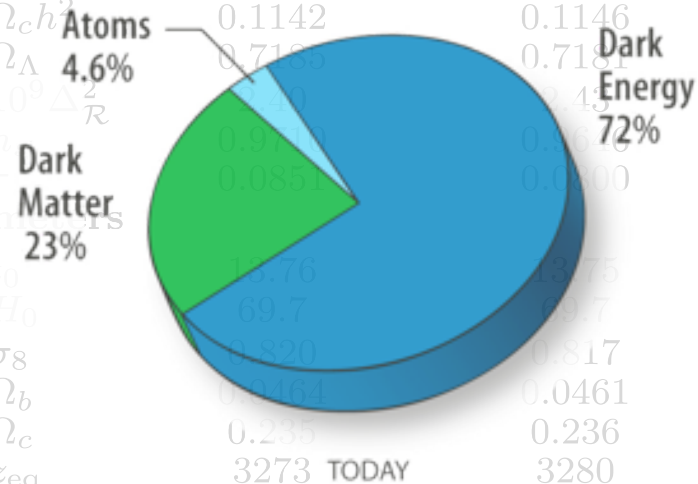
Hinshaw et al., arXiv/1212.5226

TABLE 2
MAXIMUM LIKELIHOOD ΛCDM PARAMETERS[a]

Parameter	Symbol	*WMAP* data	Combined data[b]
Fit ΛCDM parameters			
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
Derived parameters			
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100h$ km/s/Mpc	H_0	69.7	69.7
Density fluctuations @ $8h^{-1}$ Mpc	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	z_{eq}	3273	3280
Redshift of reionization	z_{reion}	10.36	9.97

[a] The maximum-likelihood ΛCDM parameters for use in simulations. Mean parameter values, with marginalized uncertainties, are reported in Table 4.
[b] "Combined data" refers to *WMAP*+eCMB+BAO+H_0.

ΛCDM: the model everyone loves to hate…



This gives most-likely model parameters for "vanilla" 6-parameter ΛCDM model. Stay tuned for errors and goodness of fit.

Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

? Flatness

? Adiabaticity

? Gaussianity

? Tilt of primordial spectrum

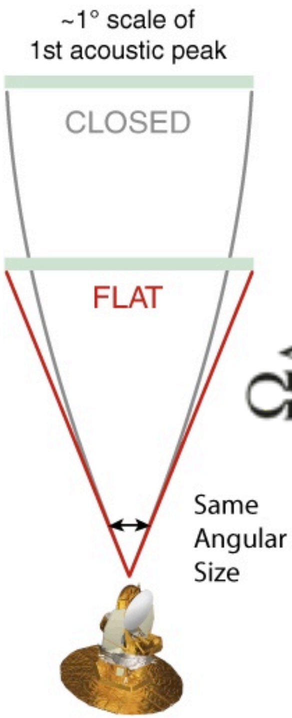
? Gravitational waves

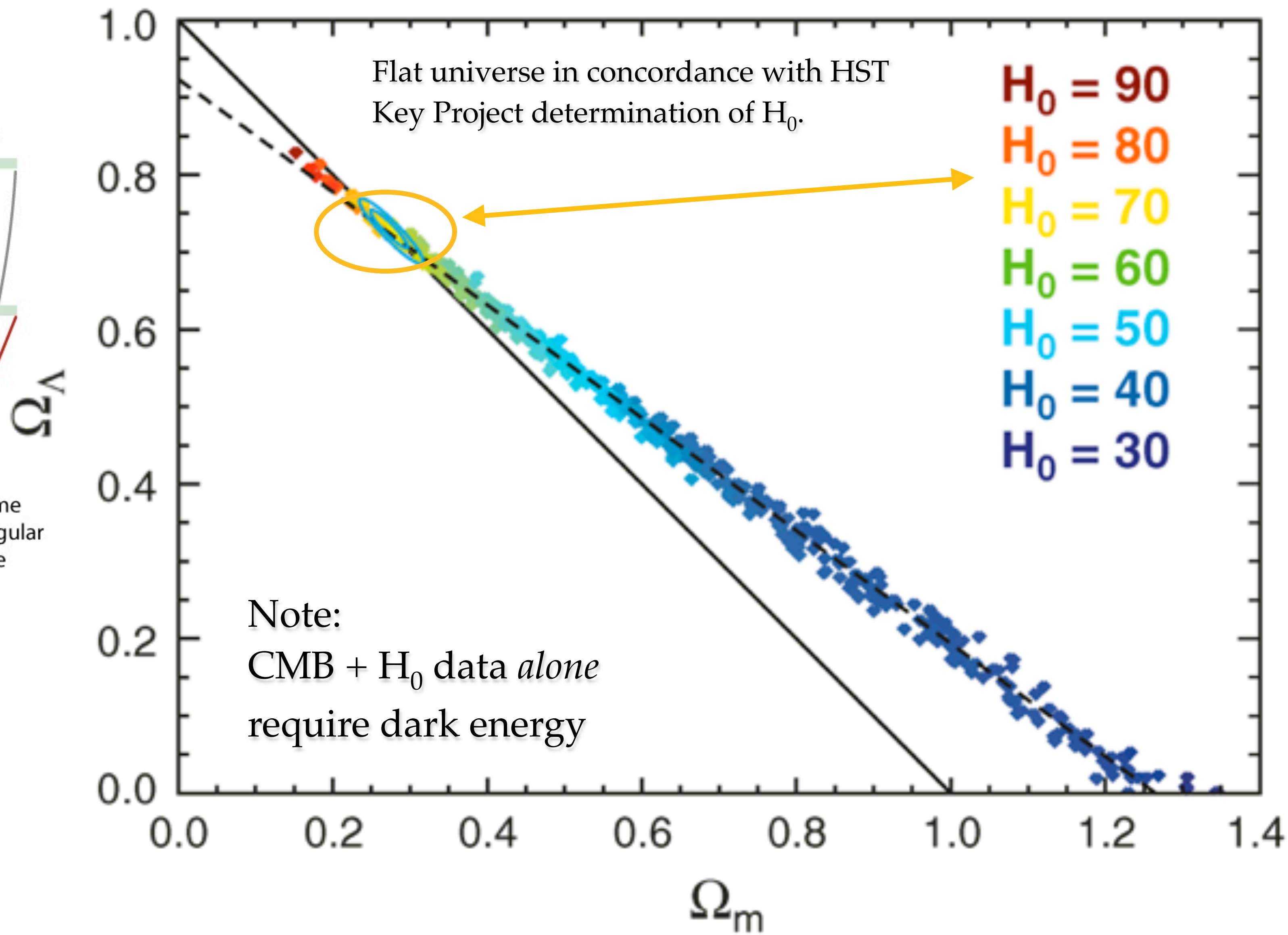
Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

?	Flatness
?	Adiabaticity
?	Gaussianity
?	Tilt of primordial spectrum
?	Gravitational waves

Testing Assumptions: Flatness





Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

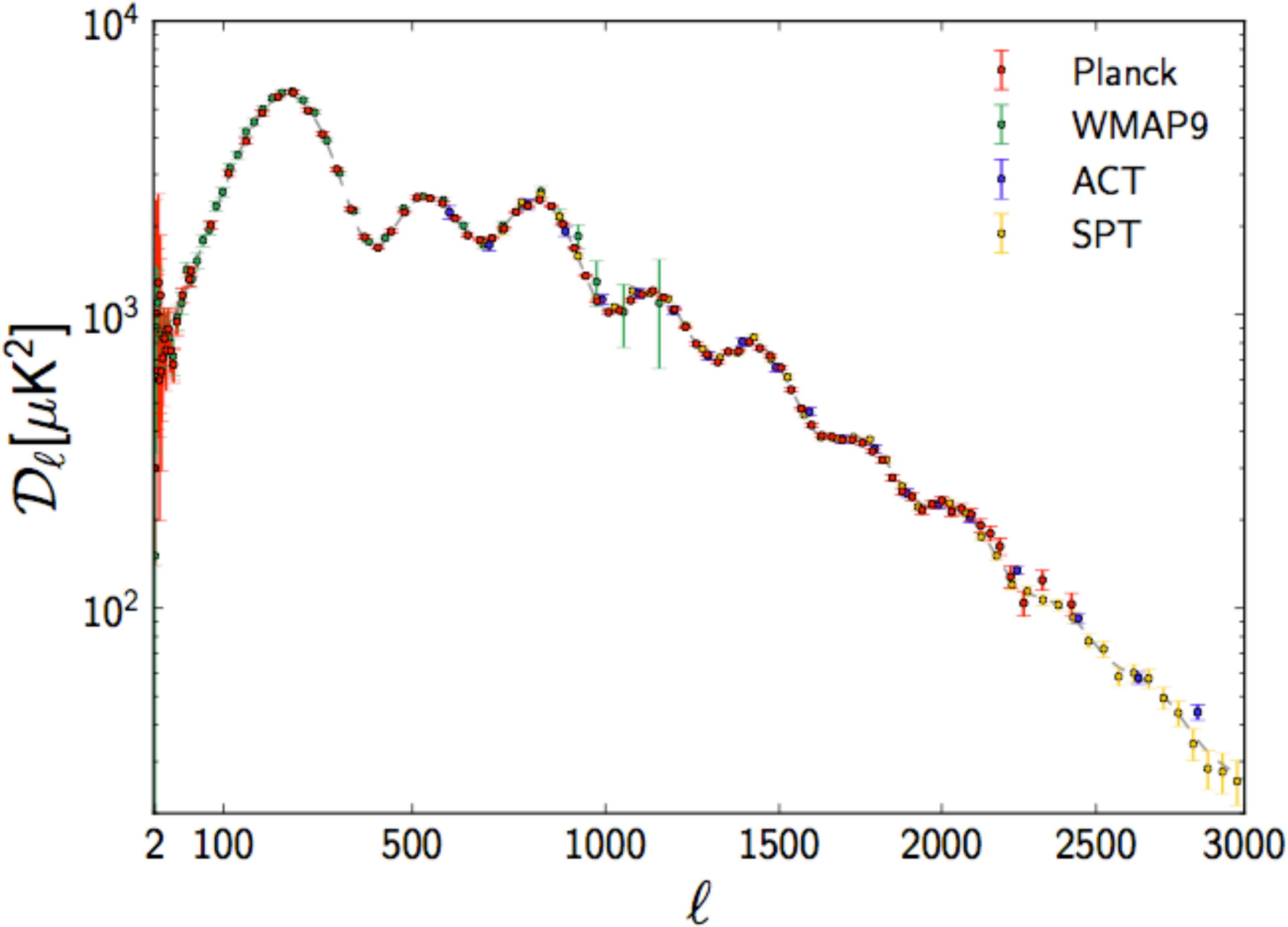
- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- ? Adiabaticity
- ? Gaussianity
- ? Tilt of primordial spectrum
- ? Gravitational waves

Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- ? Adiabaticity
- ? Gaussianity
- ? Tilt of primordial spectrum
- ? Gravitational waves

Extended CMB Data Used in WMAP9



Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

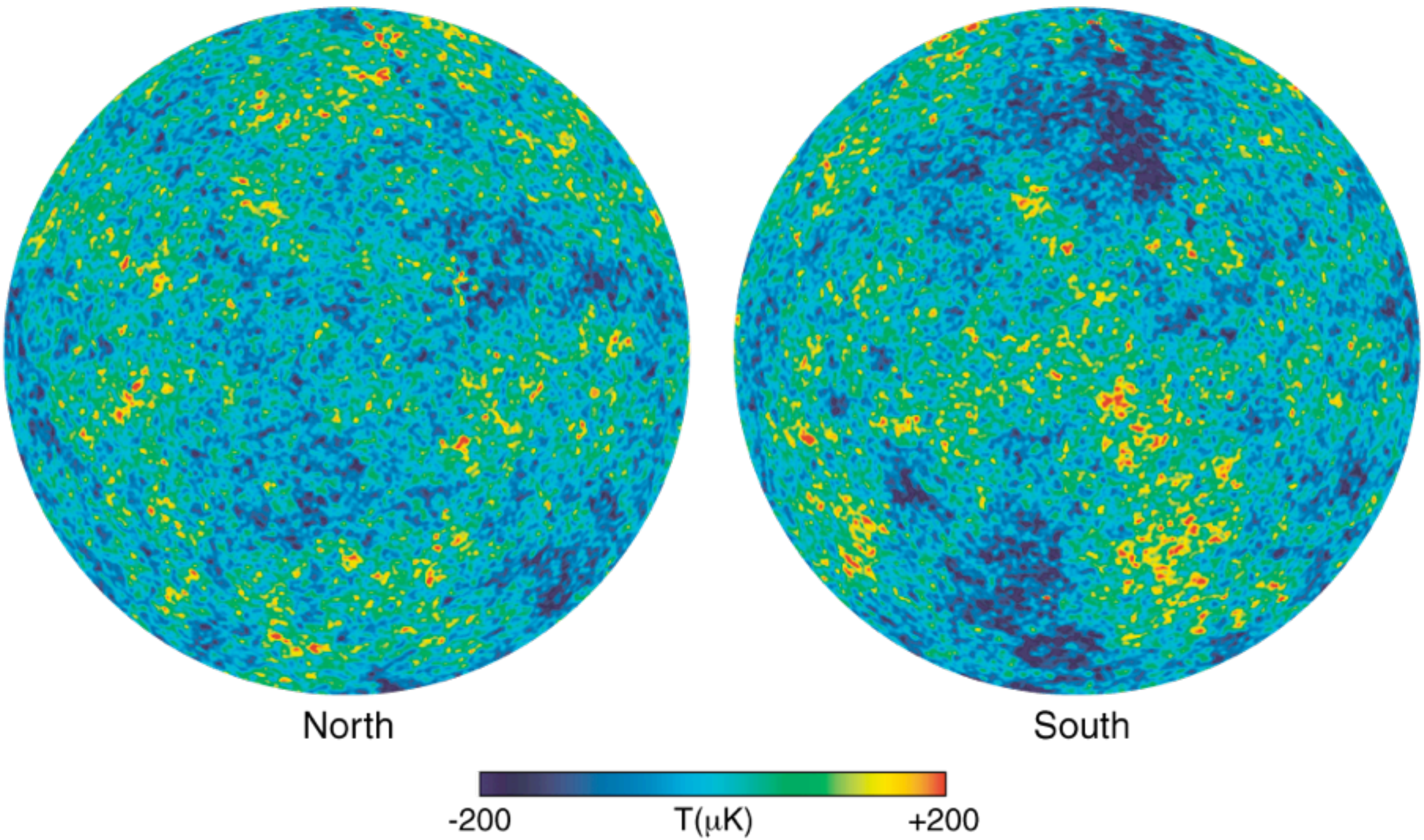
- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- ? Gaussianity
- ? Tilt of primordial spectrum
- ? Gravitational waves

Inflation Scorecard

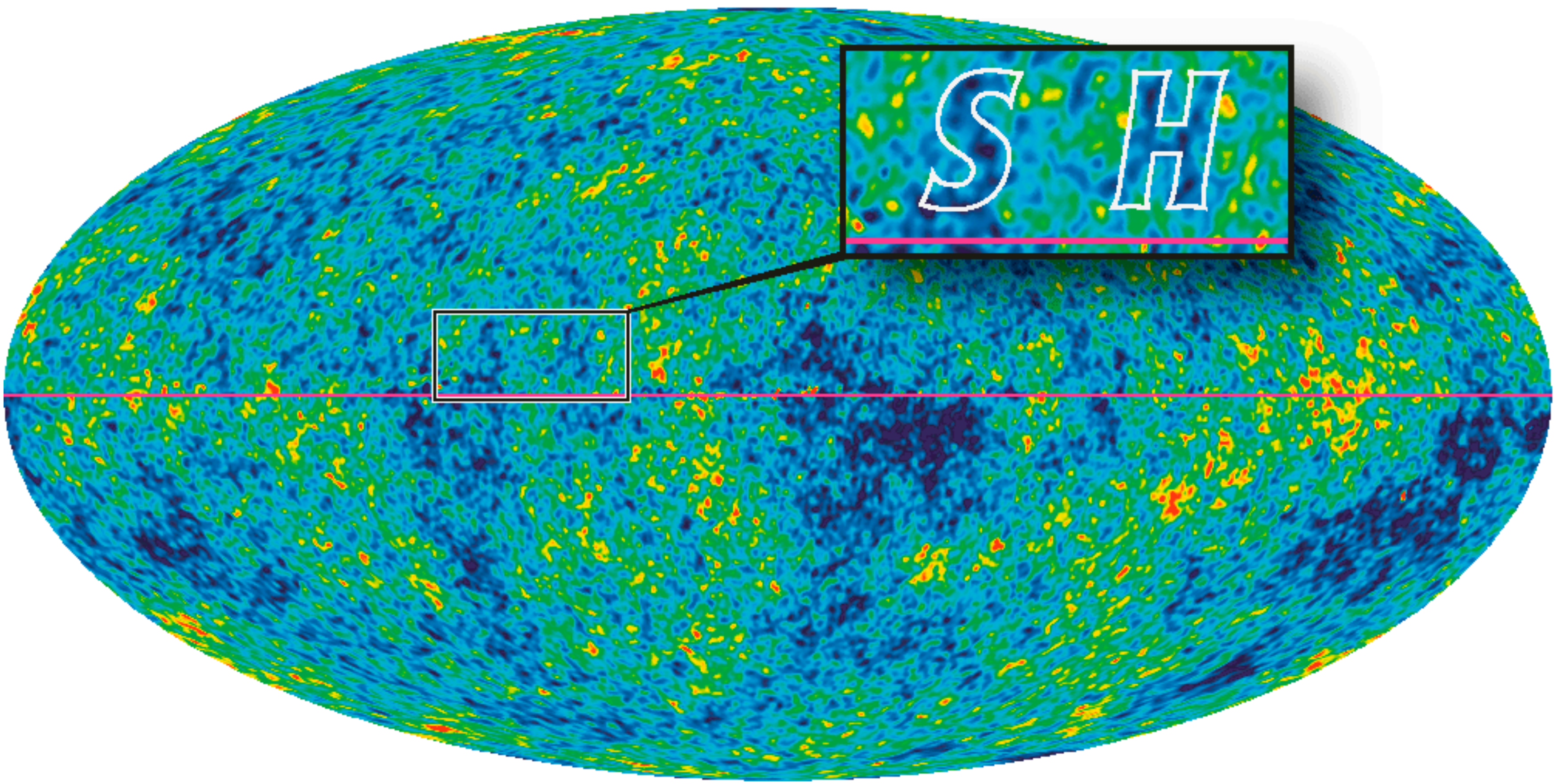
Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- ? Gaussianity
- ? Tilt of primordial spectrum
- ? Gravitational waves

Hemispheric Power Asymmetry?



What are the Odds?



Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- Gaussianity - there is no compelling *need* for non-gaussianity, but there is *room* for a non-gaussian component. (Also limits on f_{NL})

? Tilt of primordial spectrum

? Gravitational waves

Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- Gaussianity - there is no compelling *need* for non-gaussianity, but there is *room* for a non-gaussian component. (Also limits on f_{NL})
- ? Tilt of primordial spectrum
- ? Gravitational waves

Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{\rm tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- Gaussianity - there is no compelling *need* for non-gaussianity, but there is *room* for a non-gaussian component. (Also limits on f_{NL})
- ? Tilt of primordial spectrum
- ? Gravitational waves

Inflation Scorecard

Inflation "predicts" a flat universe with adiabatic initial conditions that are gaussian distributed with random phases. Single-field models predict a tilted spectrum and (possibly detectable) gravitational waves.

- Flatness – $\Omega_{tot} = 1.0027 \pm 0.0039$ (slightly tighter with Planck)
- Adiabaticity – inclusion of isocurvature modes does *not* improve fits
- Gaussianity – there is no compelling *need* for non-gaussianity, but there is *room* for a non-gaussian component. (Also limits on f_{NL})
- Tilt of primordial spectrum – $n_s = 0.968 \pm 0.006 < 1$
- Gravitational waves

Debating Inflation – 2015

Inflationary Paradigm after Planck 2013

Alan H. Guth,[1] David I. Kaiser,[1] and Yasunori Nomura[2]

[1] *Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Berkeley Center for Theoretical Physics, Department of Physics, and Theoretical Physics Group, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*

(Dated: December 29, 2013, revised January 13, 2014)

Models of cosmic inflation posit an early phase of accelerated expansion of the universe, driven by the dynamics of one or more scalar fields in curved spacetime. Though detailed assumptions about fields and couplings vary across models, inflation makes specific, quantitative predictions for several observable quantities, such as the flatness parameter ($\Omega_k = 1 - \Omega$) and the spectral tilt of primordial curvature perturbations ($n_s - 1 = d\ln \mathcal{P}_{\mathcal{R}}/d\ln k$), among others—predictions that match the latest observations from the *Planck* satellite to very good precision. In the light of data from *Planck* as well as recent theoretical developments in the study of eternal inflation and the multiverse, we address recent criticisms of inflation by Ijjas, Steinhardt, and Loeb. We argue that their conclusions rest on several problematic assumptions, and we conclude that cosmic inflation is on a stronger footing than ever before.

Inflationary schism after Planck2013

Anna Ijjas,[1,2] Paul J. Steinhardt,[3] and Abraham Loeb[4]

[1] *Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), 14476 Potsdam, Germany*
[2] *Rutgers University, New Brunswick, NJ 08901, USA*
[3] *Department of Physics and Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*
[4] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

(Dated: March 14, 2014)

Classic inflation, the theory described in textbooks, is based on the idea that, beginning from typical initial conditions and assuming a simple inflaton potential with a minimum of fine-tuning, inflation can create exponentially large volumes of space that are generically homogeneous, isotropic and flat, with nearly scale-invariant spectra of density and gravitational wave fluctuations that are adiabatic, Gaussian and have generic predictable properties. In a recent paper, we showed that, in addition to having certain conceptual problems known for decades, classic inflation is for the first time also disfavored by data, specifically the most recent data from WMAP, ACT and Planck2013. Guth, Kaiser and Nomura and Linde have each recently published critiques of our paper, but, as made clear here, we all agree about one thing: the problematic state of classic inflation. Instead, they describe an alternative inflationary paradigm that revises the assumptions and goals of inflation, and perhaps of science generally.

Challenges for "Classic" Inflation

	Inflaton Potential +	Initial Conditions +	Measure ⟹	Predictions
Classic inflationary paradigm	**Simple –** Single, continuous stage of inflation governed by potentials with the fewest degrees of freedom, fewest parameters, least tuning.	**Insensitive –** Inflation transforms typical initial conditions emerging from the big bang into a flat, smooth universe with certain generic properties.	**Common-sense –** It is more likely to live in an inflated region because inflation exponentially increases volume $\Rightarrow$ measure = volume	**Generic –** Based on simplest potentials: - red tilt: $n_S \sim .94 - .97$, - large $r \sim .1 - .3$*, - negligible f_{NL}, - flatness & homogeneity
Conceptual problems known prior to WMAP, ACT & Planck2013	**Not so simple –** Even simplest potentials require fine-tuning of parameters to obtain the right amplitude of density fluctuations.	**Sensitive –** The initial conditions required to begin inflation are entropically disfavored/exponentially unlikely. There generically exist more homogeneous and flat solutions without inflation than with.	**Catastrophic failure –** Inflation produces a multiverse in which most of the volume today is inflating and, among non-inflating volumes (bubbles), Inflation predicts our universe to be exponentially unlikely.	**Predictability problem –** No generic predictions; "anything can happen and will happen an infinite number of times." The probability by volume of our observable universe is less than $10^{-10^{55}}$.
Observational problems after WMAP, ACT & Planck2013 [1]***	**Unlikeliness problem –** *Simplest* inflaton potentials disfavored by data; favored (plateau) potentials require more parameters, more tuning, and produce less inflation.	**New initial conditions problem –** Favored plateau potentials require an initially homogeneous patch that is a billion times** larger than required for the simplest inflaton potentials.	**New measure problem –** All favored models predict a multiverse yet data fits predictions assuming no multiverse.	**Predictability problem unresolved –** Potentials favored by data do not avoid the multiverse or the predictability problems above. Hence, no generic predictions.

Challenges for “Post–Modern” Inflation

	Inflaton Potential +	Initial Conditions +	Measure ⟹	Predictions
Postmodern inflationary paradigm	**Complex –** with many fields, parameters, dips, minima, and hence many metastable states, leading to multiple phases of inflation [GKN10-11] and making eternal inflation unavoidable [GKN12]	**Not important –** in considering validity of inflation; any problems can be compensated by adjusting the measure [GKN19]	**To be determined –** from some combination of probability weighting and anthropic selection [GKN13,17,20]	**Generic –** predictions should generically agree with observations once the right complex potential and combination of measure and anthropic weighting is identified [GKN6,15]
Problems	**Unpredictability. Part I –** A complex energy landscape allows virtually any outcome and provides no way to determine which inflaton potential form is most likely. [GKN17]	**Unpredictability. Part II –** Without knowing initial conditions cannot make predictions even if energy landscape is known. [GKN14]	**Paradigm rests entirely on the measure –** yet, to date, no successful measure has been proposed and there is no obvious way to solve this problem. [GKN13]	**No predictions –** the simplest (volume) measure gives catastrophic results and different landscapes, initial conditions, and measures give different predictions [GKN6].

Debating Inflation – 2015

Inflationary Paradigm after Planck 2013

Alan H. Guth,[1] David I. Kaiser,[1] and Yasunori Nomura[2]

from conclusions:

Recent experimental evidence, including the impressive measurements with the *Planck* satellite of the CMB temperature perturbation spectrum and the strong indication from the LHC that fundamental scalar fields such as the Higgs boson really exist, put inflationary cosmology on a stronger footing than ever. Inflation provides a self-consistent framework with which we may explain several empirical features of our observed universe to very good precision, while continuing to pursue long-standing questions about the dynamics and evolution of our universe at energy scales that have, to date, eluded direct observation.

Inflationary schism after Planck2013

Anna Ijjas,[1, 2] Paul J. Steinhardt,[3] and Abraham Loeb[4]

from conclusions:

Future data has no significance for the postmodern inflationary paradigm because the potential, initial conditions and measure are chosen *a posteriori* to match observations, whatever the results. For example, measuring $r > 0.13$ or $r < 0.13$ or not detecting any gravitational waves at all makes no difference.

The scientific question we may be facing in the near future is: If classic inflation is outdated and a failure, are we willing to accept postmodern inflation, a construct that lies outside of normal science? Or is it time to seek an alternative cosmological paradigm?

Discuss