What can the Cosmic Microwave Background tell us about Dark Matter?

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The Standard Model at 50: Successes and Challenges
46th SLAC Summer Institute
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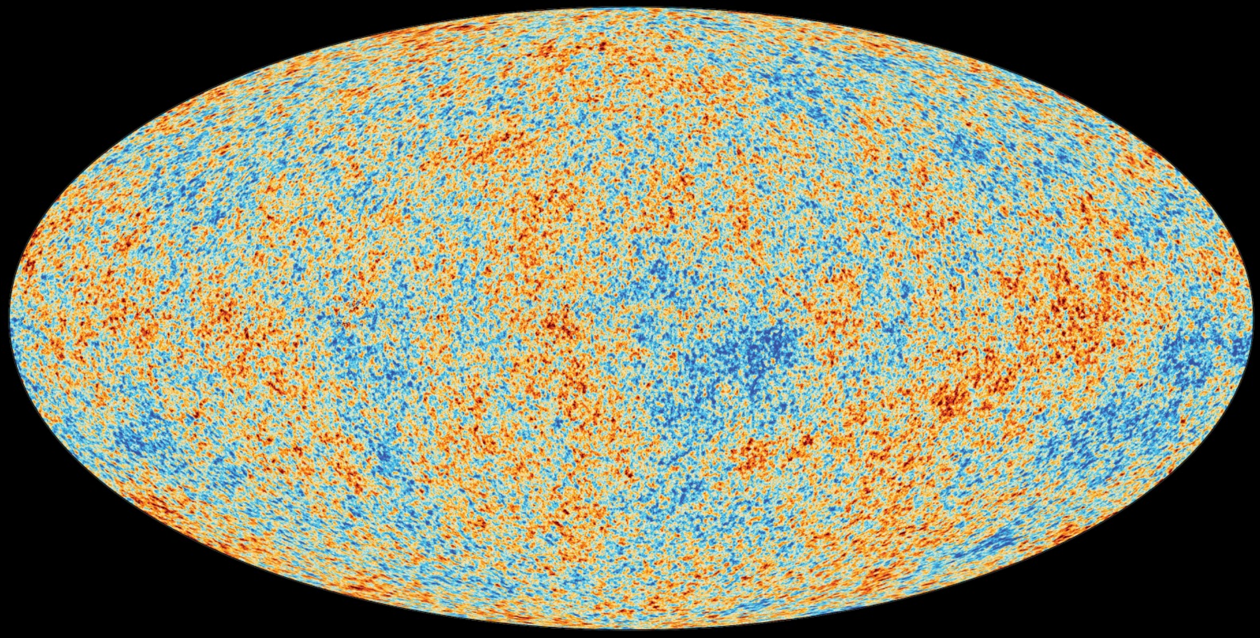
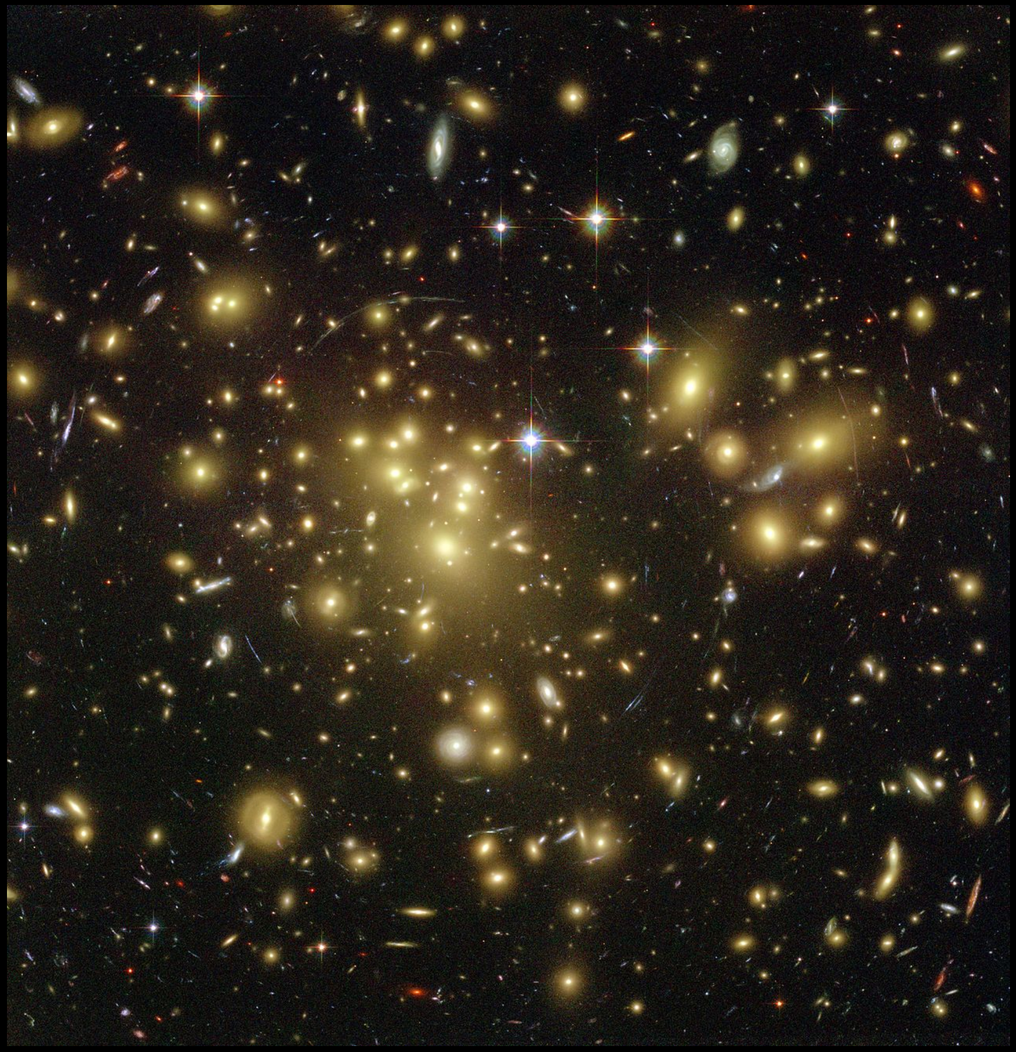
What can CMB tell us about DM ?



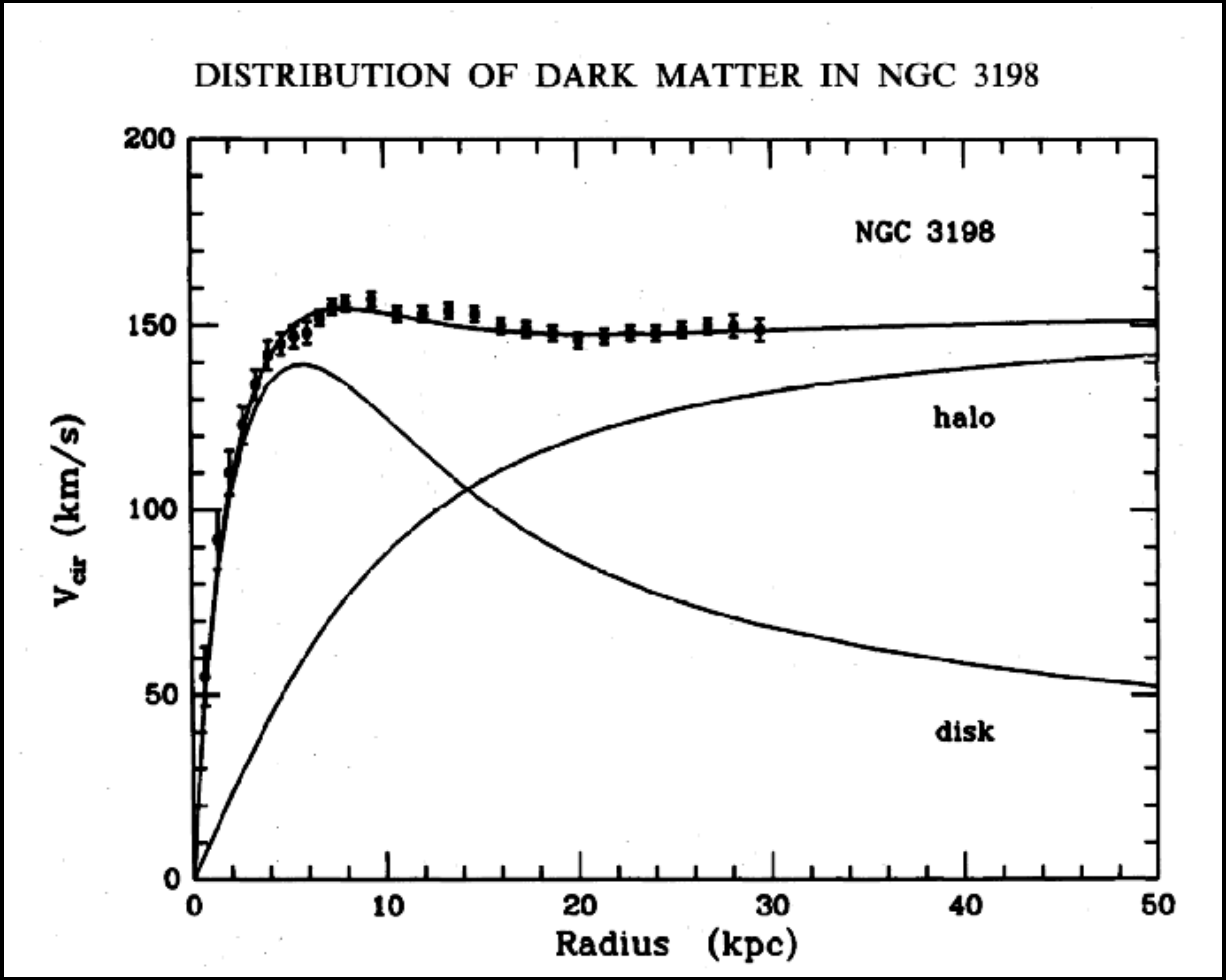


Dark Matter and Cosmic Microwave Background. DM by its very definition does not interact with photons. CMB is made up of photons. So how can measurements of CMB inform us about DM? And what has these measurements told us about DM?

Dark Matter

- First robust indication in 1939, by Horace W. Babcock, observing mass-to-light ratio in Andromeda galaxy
- Overwhelming astronomical evidence, from Galaxy Rotation and Gravitational Lensing
- From anisotropies in the Cosmic Microwave Background

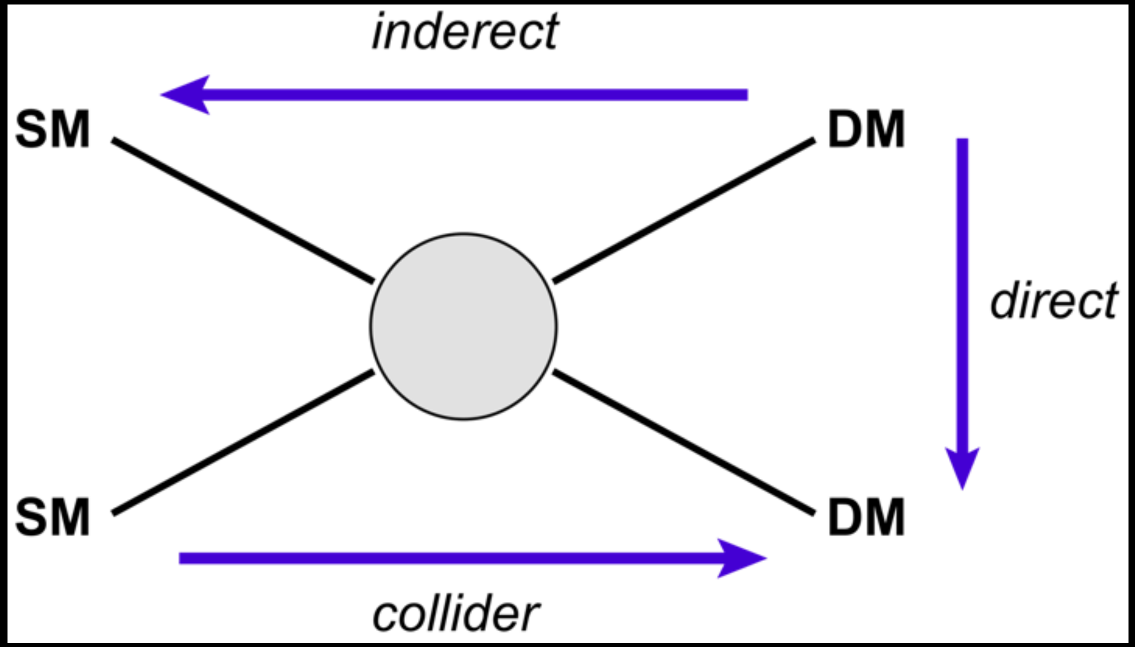
Dark Matter

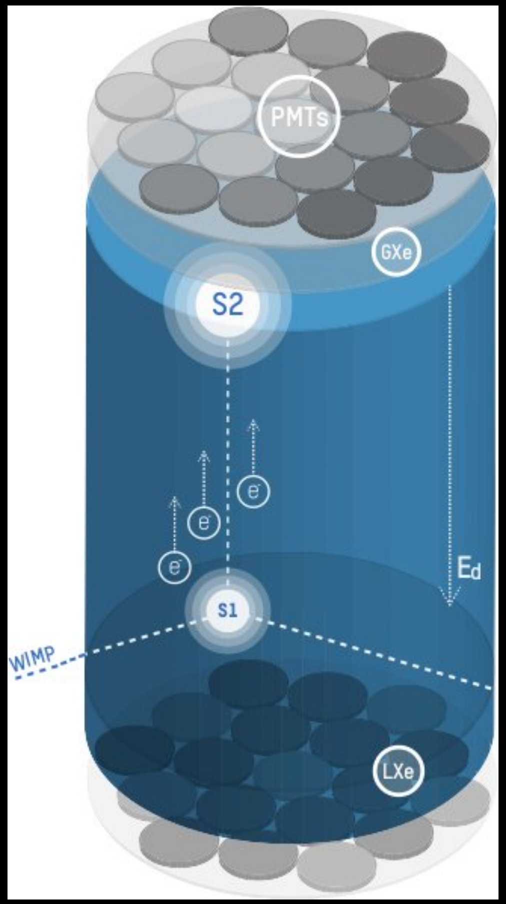


DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50

Dark Matter

- Direct Detection - XENON, SNOLAB, LUX, etc.
- Indirect Detection - Excess in gamma ray bursts from annihilation of dark matter
- Collider Searches.



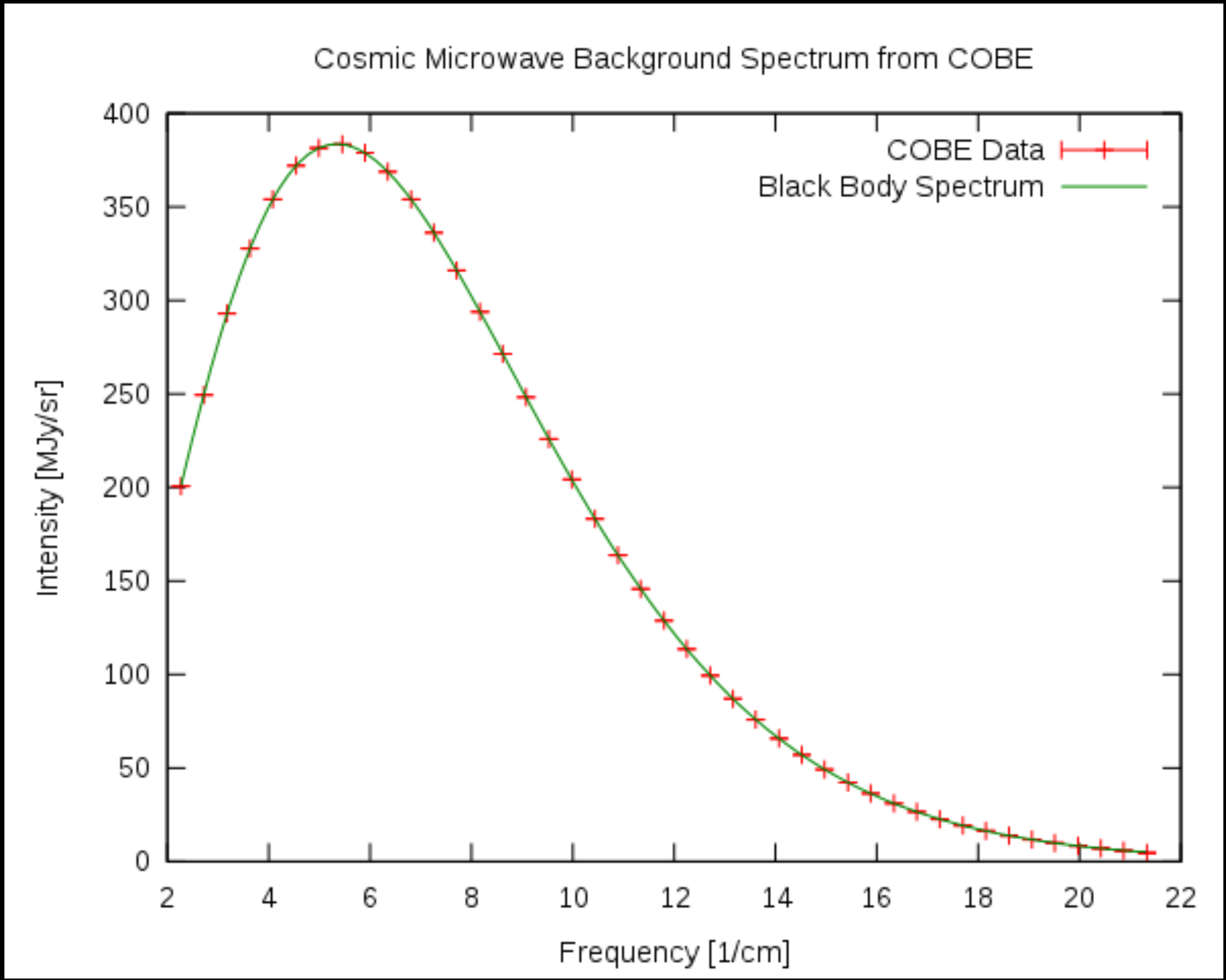


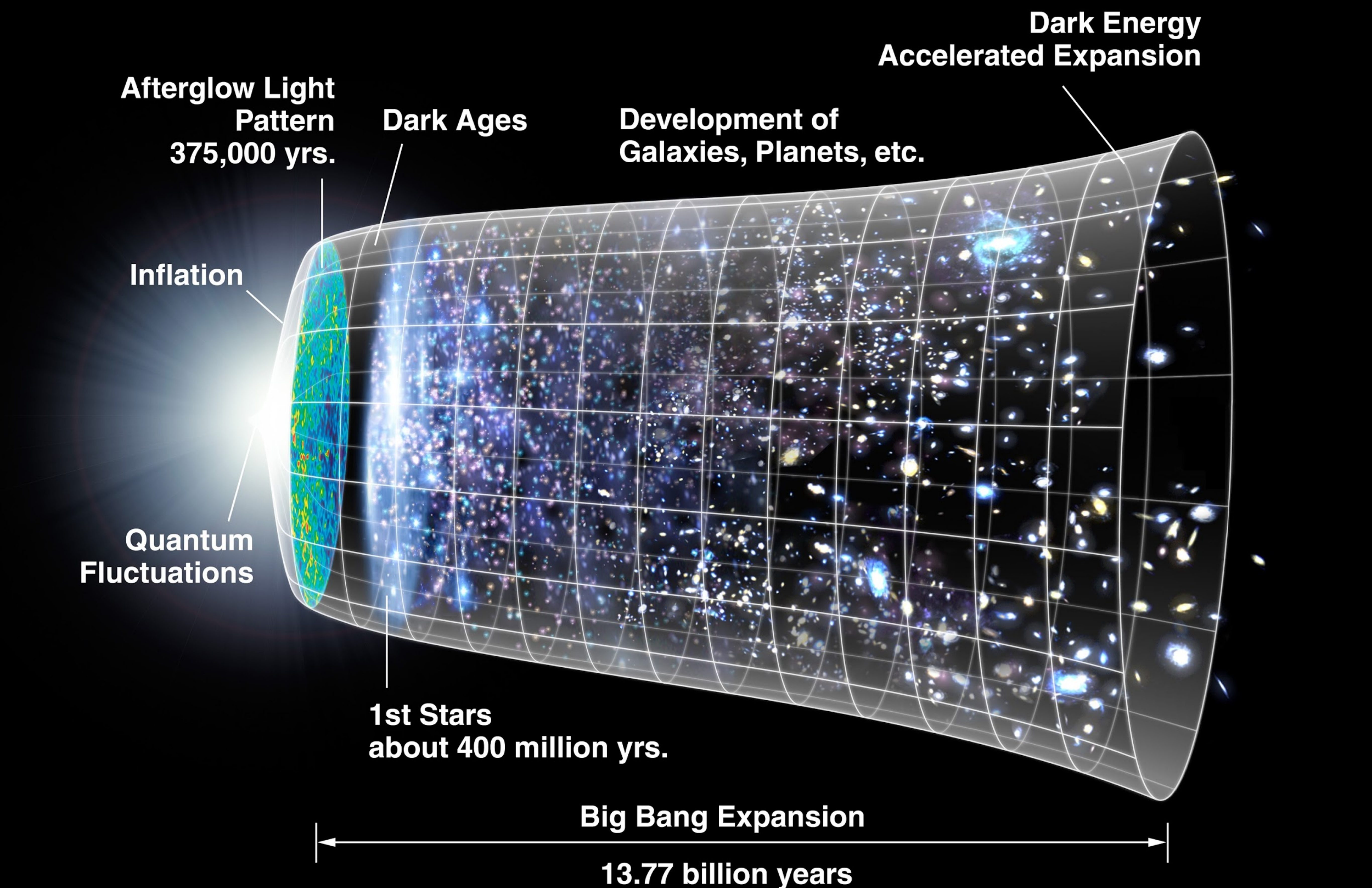
XENON Dual Phase TPC

Cosmic Microwave Background (CMB)

- Discovery in 1964 by Arno Penzias and Robert Woodrow Wilson
- It is largely homogeneous and Isotropic
- Corresponds to a blackbody temperature of ~ 2.725 K
- Temperature fluctuation of $\sim 10^{-5}$ K

Cosmic Microwave Background (CMB)




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Robertson-Walker Metric

- Flat metric

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

- Spatially homogeneous and isotropic metric

$$ds^2 = -dt^2 + a^2(t)[dx^2 + dy^2 + dz^2]$$

$$g_{\mu\nu} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & a(t)^2\delta_{ij} & \\ 0 & & & \end{bmatrix}$$

- Plug into Einstein's equation and solve for *a(t)*

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The Friedmann Equation

- Stress energy tensor with perfect fluid

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$T_{\mu\nu} = \begin{bmatrix} \rho & 0 & 0 & 0 \\ 0 & & & \\ 0 & & g_{ij}p & \\ 0 & & & \end{bmatrix}$$

- Obtain Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$H \equiv \frac{\dot{a}}{a} \quad \Omega \equiv \frac{8\pi G}{3H^2}\rho$$

- Obtain Friedmann equation

$$H = H_0\sqrt{(\Omega_m + \Omega_b)a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda}$$

Cold Dark Matter (CDM)

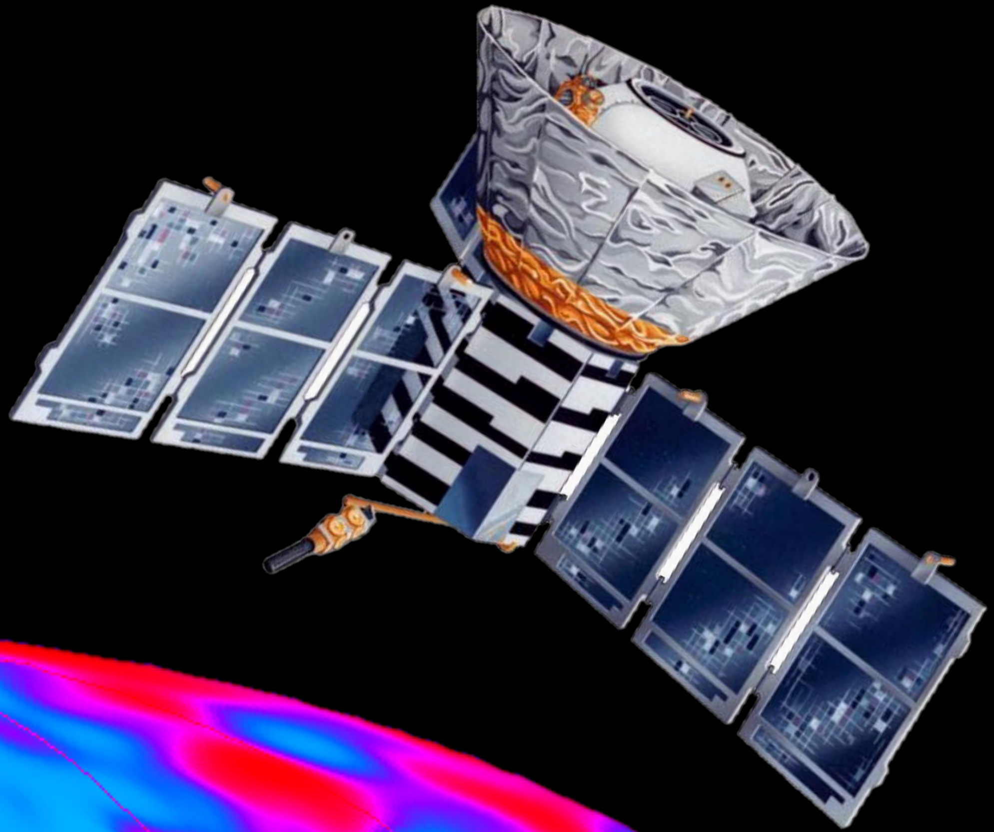
$$H = H_0\sqrt{(\Omega_m + \Omega_b)a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda}$$

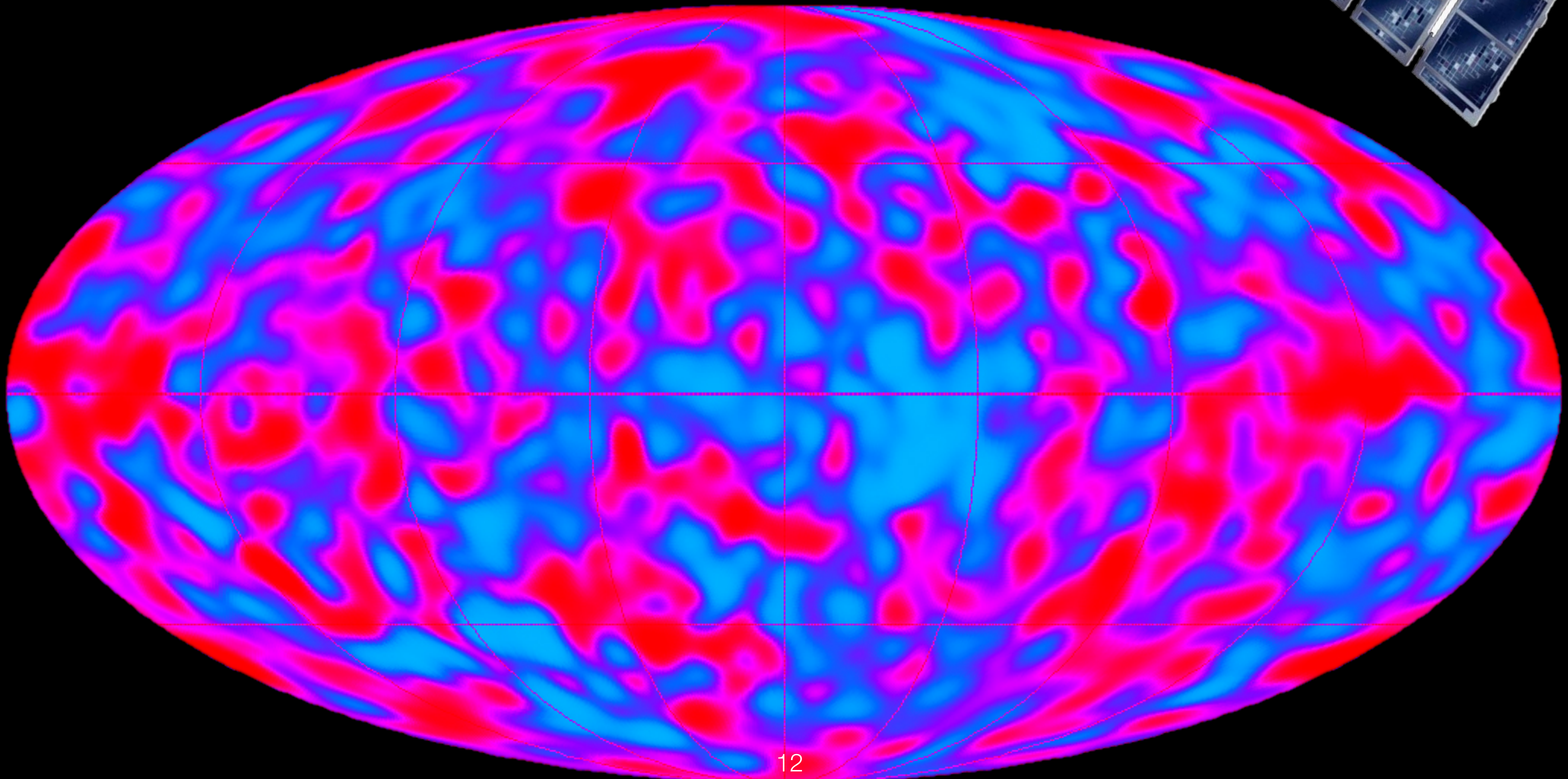
$$\rho_m, \rho_b \propto a^{-3} \quad \rho_r \propto a^{-4} \quad \rho_\Lambda \propto a^0$$

- CDM only **weakly interacts** with normal matter, but its density is a fit parameter to CMB. The effect originate from the gravitational source
- Must be cold, otherwise the dark matter would stream out from the over dense region, suppressing structure formation
- CDM doesn’t participate in the plasma physics

COBE (1989)

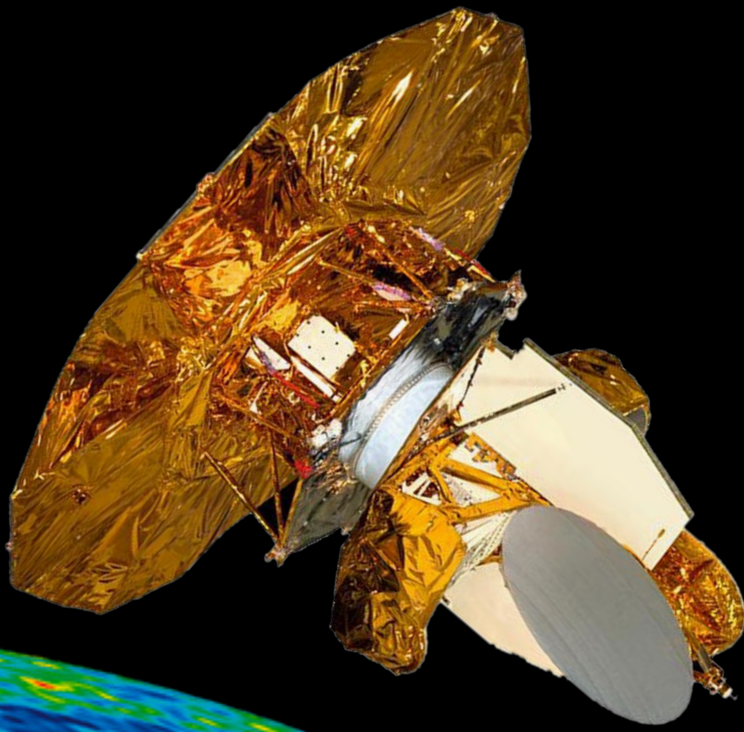
- Angular resolution: > 7 degrees

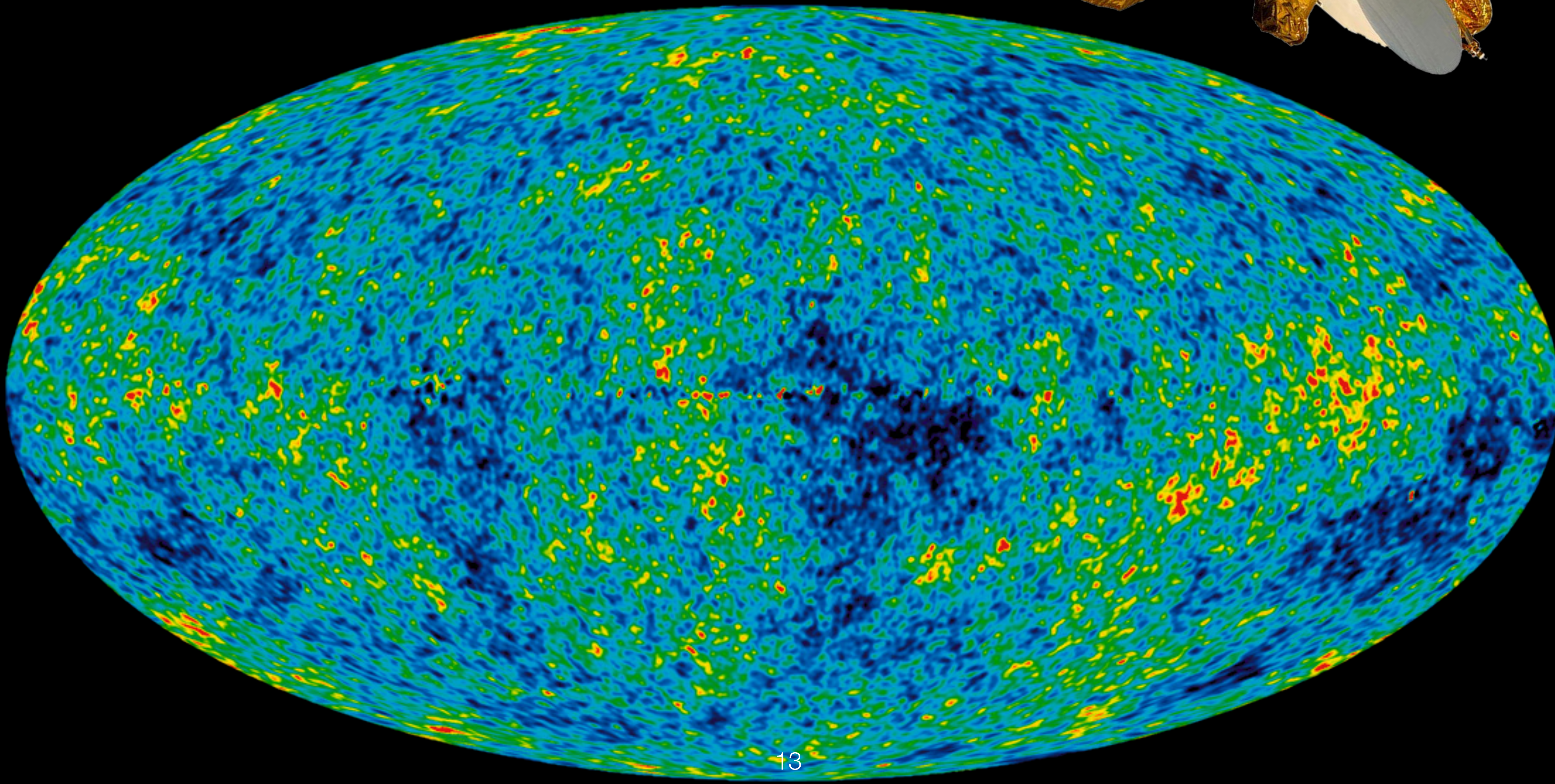




WMAP (2001)

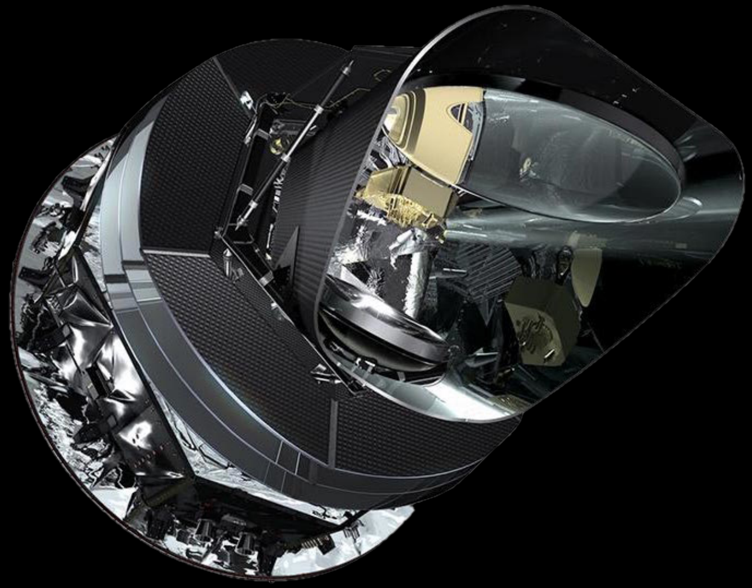
- Angular resolution: < 1 degree

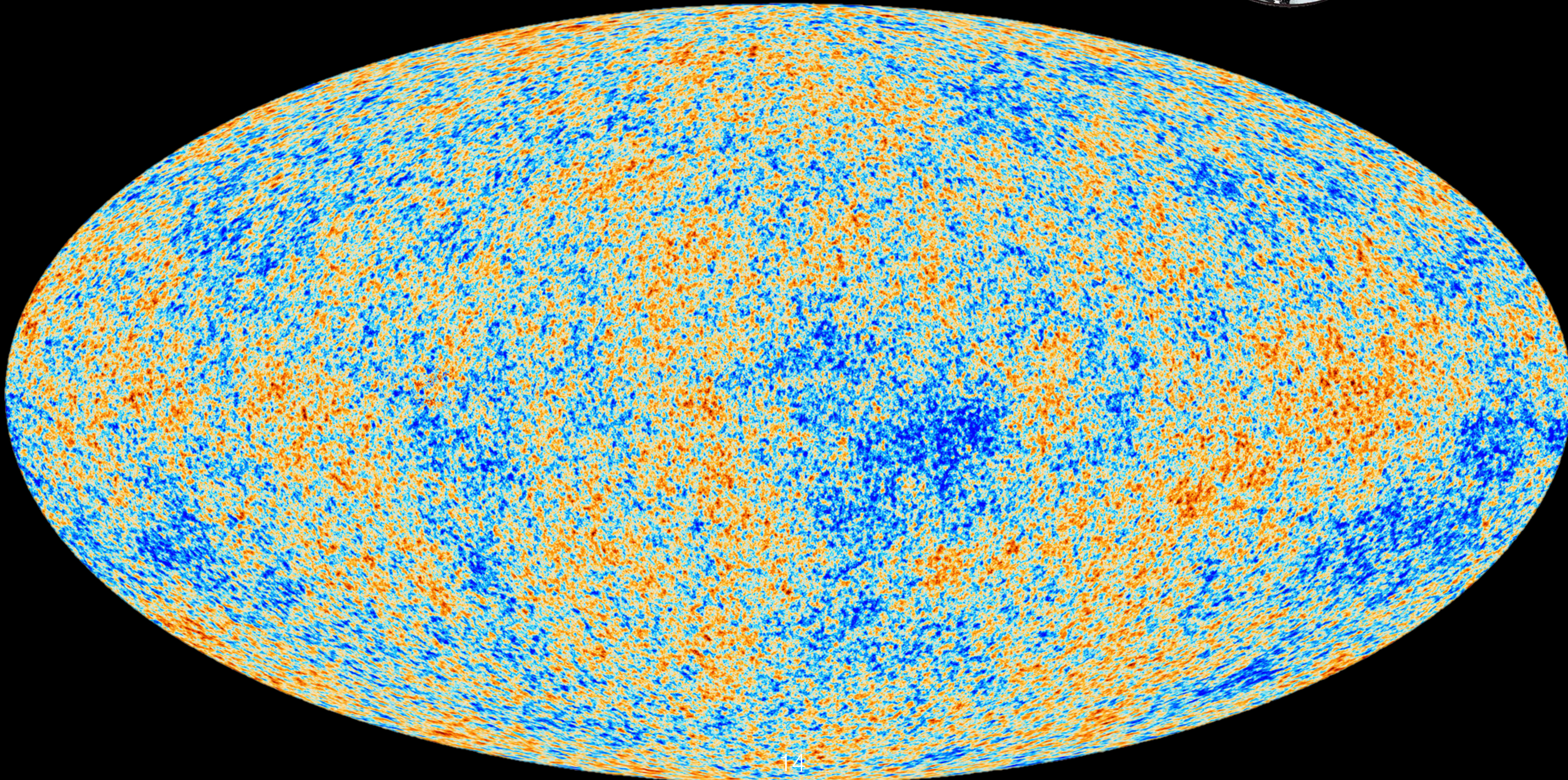




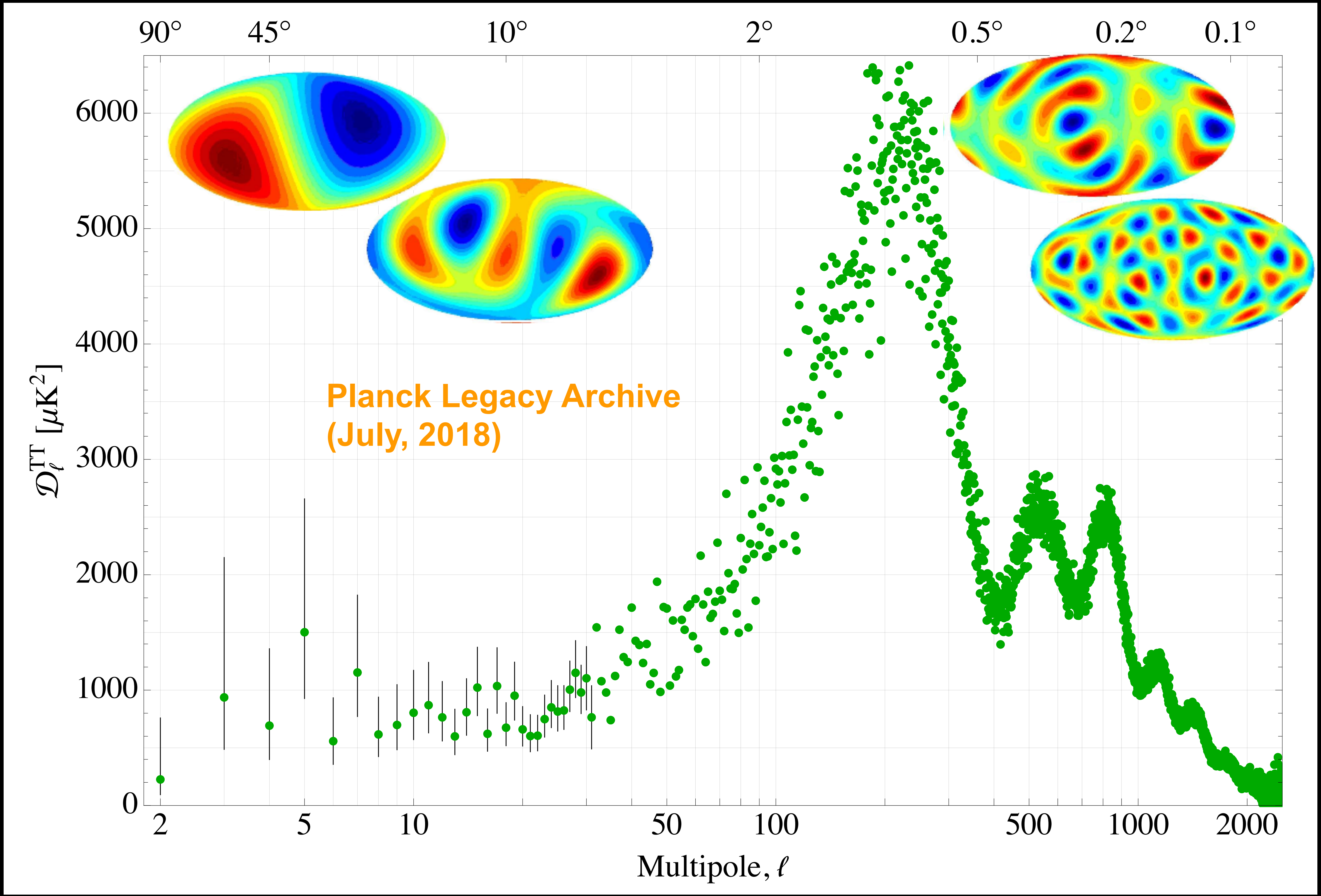
Planck (2009)

- Angular resolution: ~ 10 arc minutes

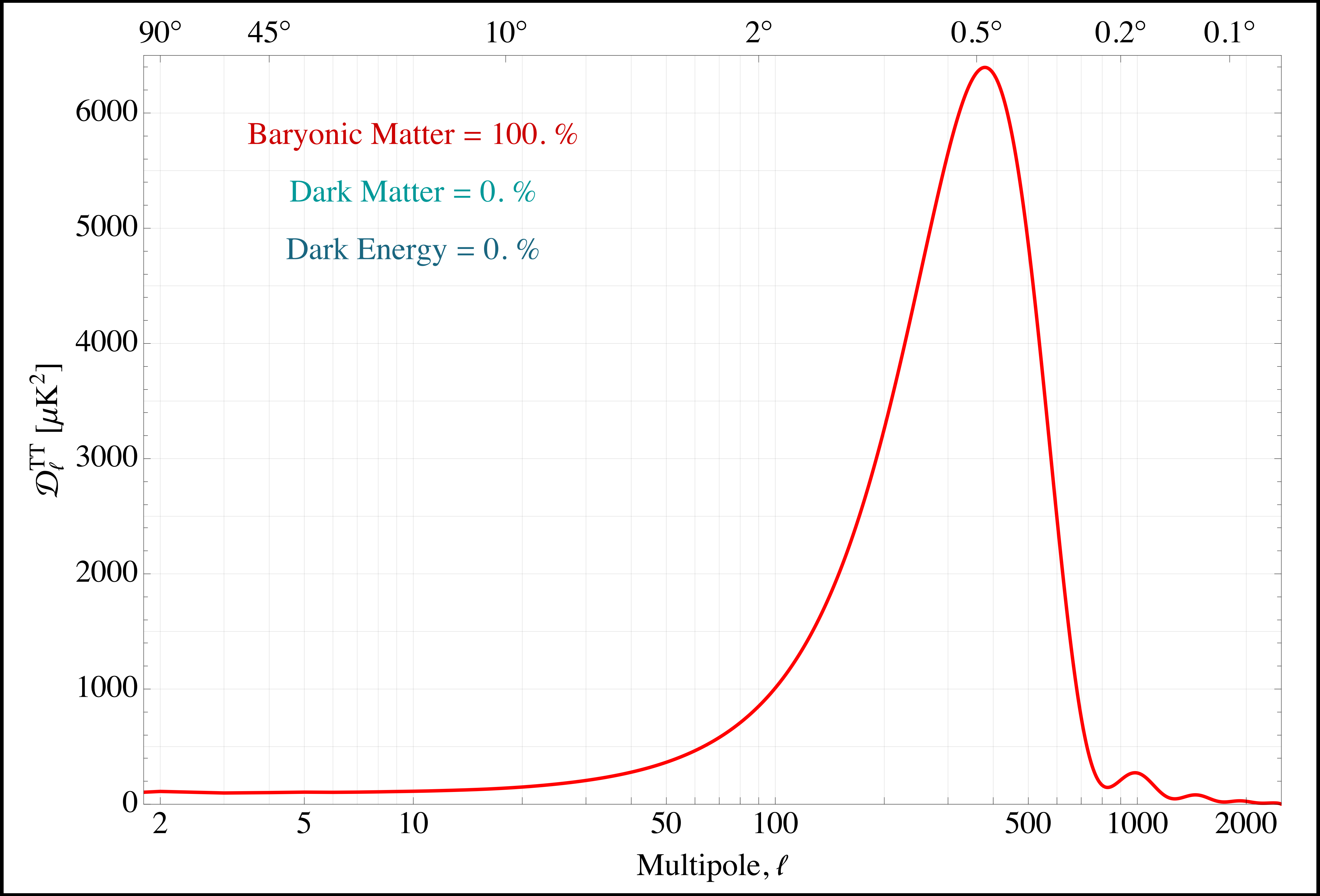




CMB Power Spectrum

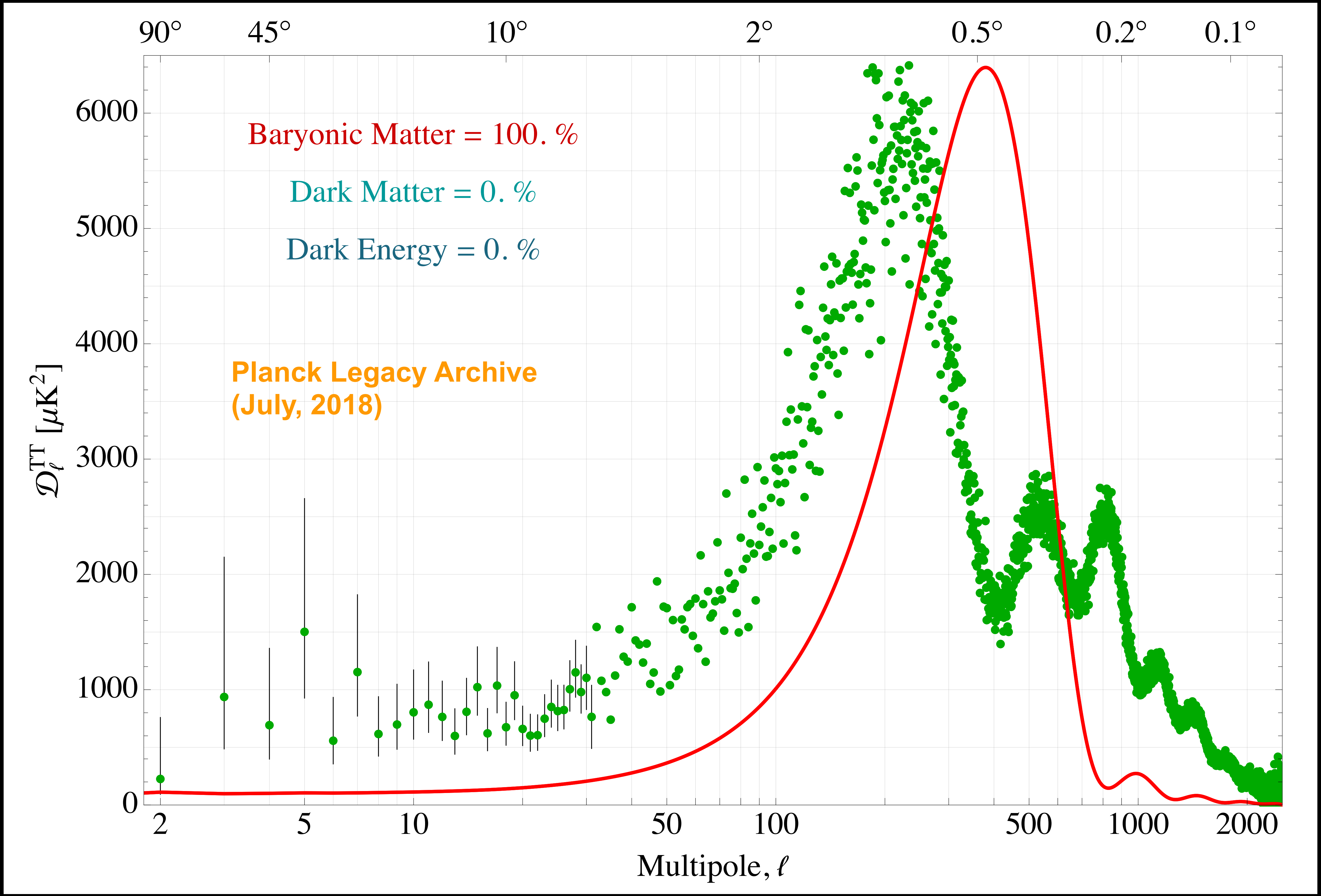


If only baryonic matter existed...



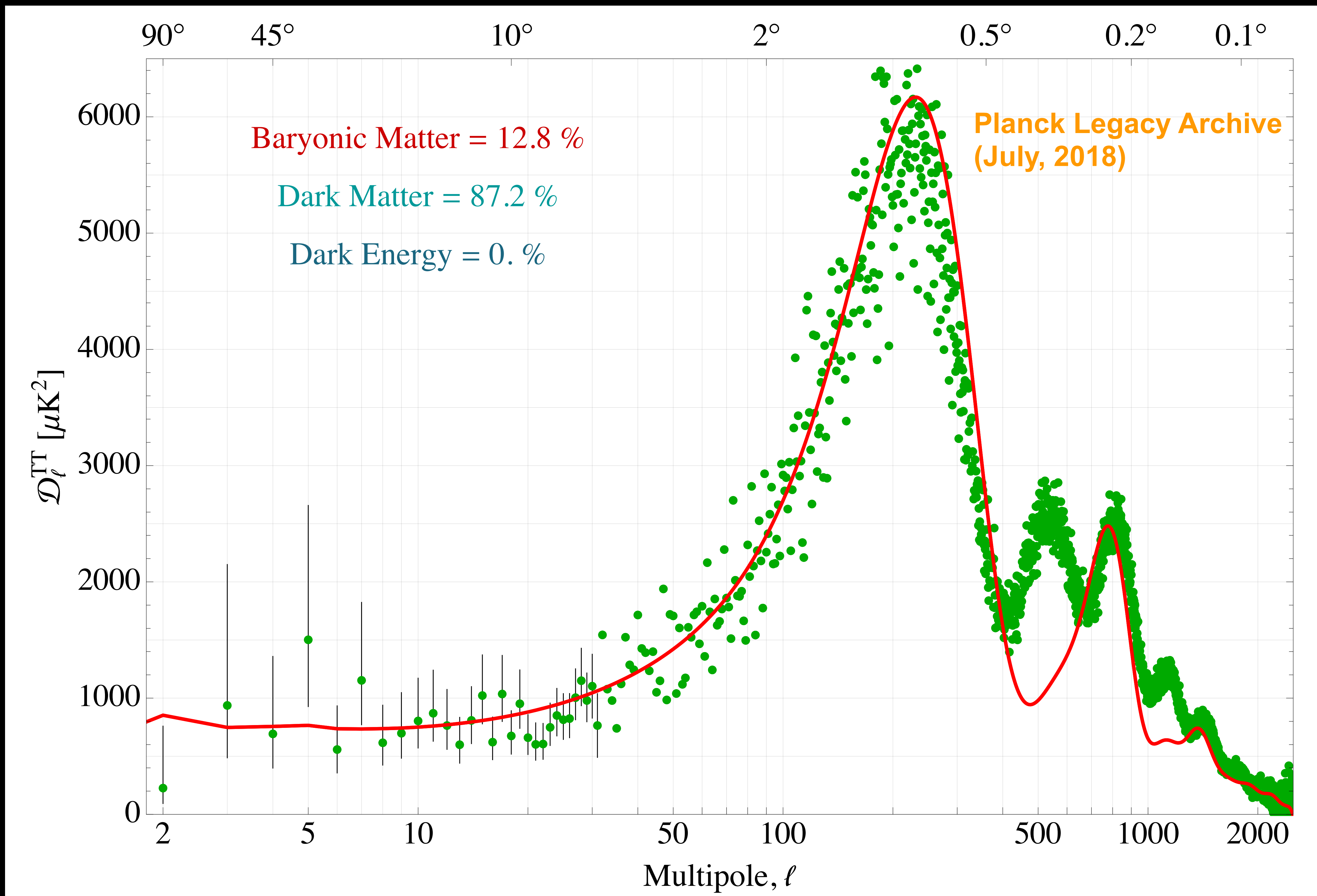
Age of the Universe ~ 9.6 Gyr

If only baryonic matter existed...



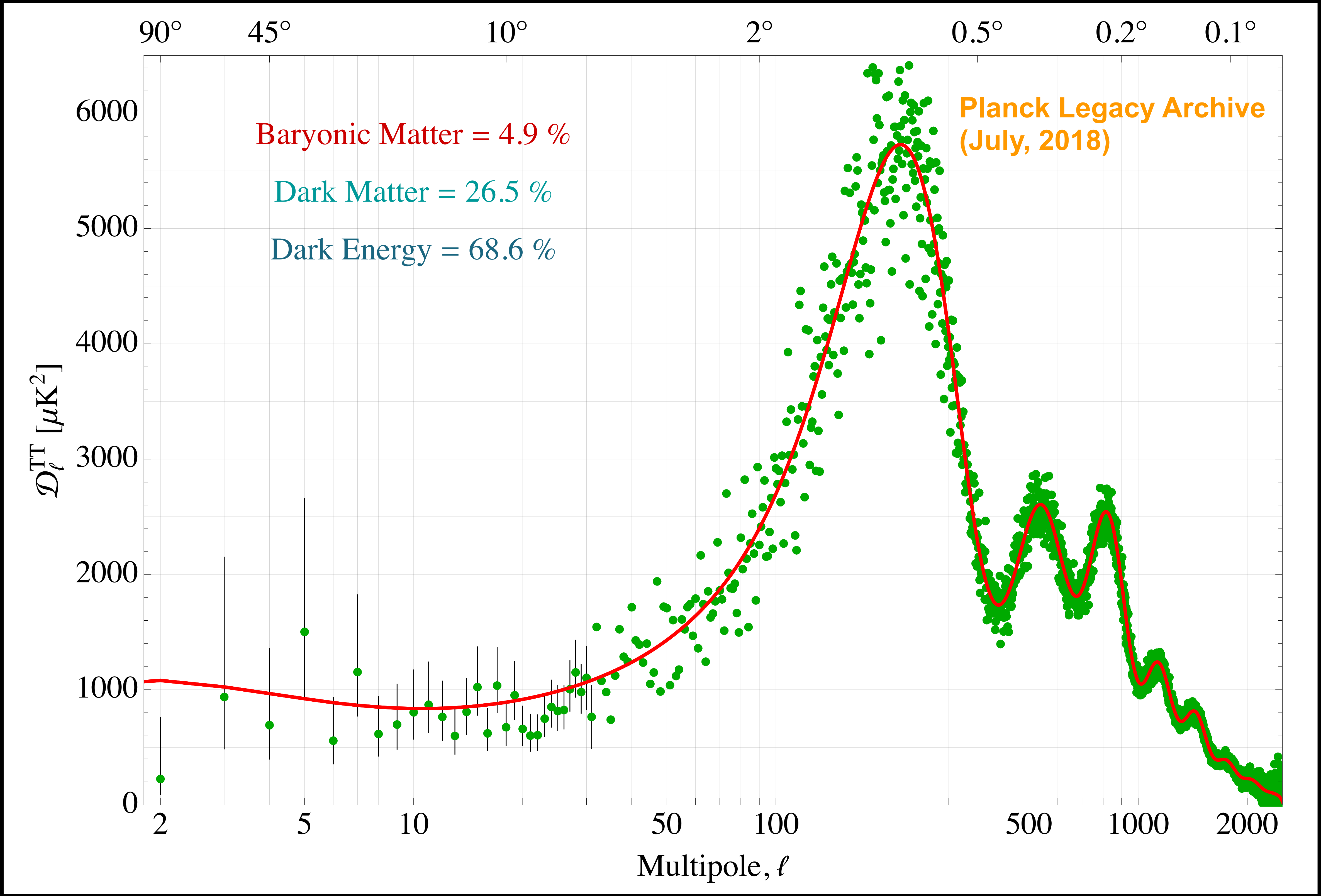
Age of the Universe ~ 9.6 Gyr

On including Dark Matter...



Age of the Universe ~ 9.6 Gyr

ΛCDM gives the best fit

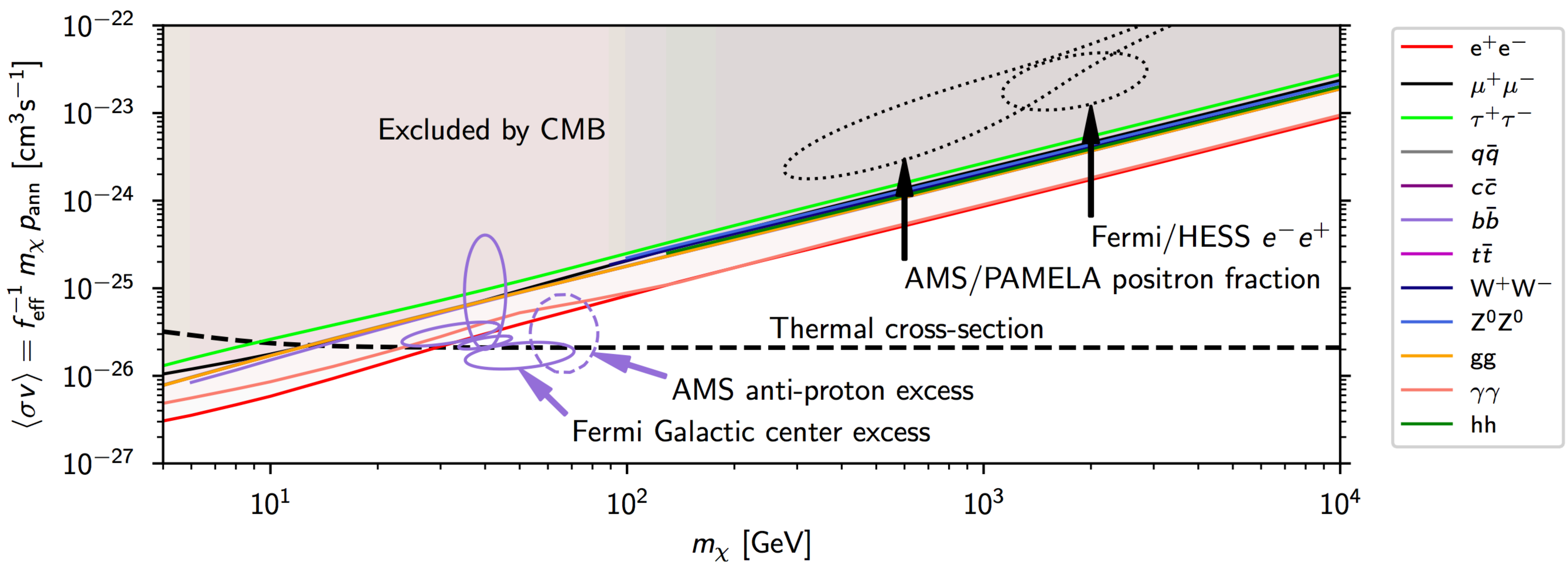


Age of the Universe ~ 13.8 Gyr

DM Annihilation Effects on Power Spectrum

- DM annihilation affects the amount of ionized matter (free electron number) and hence the **CMB**, mostly in higher modes.
- These effects are more clearly seen in the **polarization** than the power spectrum data at higher modes

DM Annihilation Effects on Power Spectrum



"Too large an annihilation rate producing photons/electrons during the cosmic dark ages leads to extra ionization - perturbs the CMB"
- T. Slatyer's talk

Conclusion

- CMB power spectrum gives the following composition of the present Universe:

Baryonic Matter	**4.9%**
Dark Matter	**26.5%**
Dark Energy	**68.6%**

- Polarization modes of CMB can be used to constrain the mass scale of DM particles (from annihilation cross-section)

THANKS FOR YOUR ATTENTION!

References

- CMBquick

Backup Slides

{ T_0, h, Number of massless ν's, $\Omega_{m0}\,h^2$, $\Omega_{b0}\,h^2$, ${A_s}^2$, n_s, τ_{rei} , Reionization Fraction, {List of masses of massive ν's}, r (tensor to scalar ratio), tensor spectral index }

You can of course choose whatever list of cosmological parameters. CMBquick1 has not been tested with fancy parameters, so you will probably obtain an error if you ask too much.

However, since recombination is computed with physical parameters (x) rather than redshift, it should be robust since the switch between Saha and dynamical recombination

is depending on the temperature, and not on the redshift.

	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b\, h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c\, h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[17]
	Reionization optical depth	τ	0.066 ±0.012

All Planck fit parameters

Variable	Value	Units	Comment
Ω_{b0}	0.049169		Abundance of baryons
Ω_{c0}	0.26474		Abundance of CDM
Ω_{r0}	0.000092414		Abundance of radiation (massless ν's and photons)
$\Omega_{\Lambda 0}$	0.686		Abundance of Λ
Ω_K	0		Abundance of curvature
T_0	2.7255	K	Temperature of CMB
N_ν	3.045		Number of massless neutrinos
h	0.6727		Reduced Hubble constant
τ_{rei}	0.079		Optical depth of reionization
n_s	0.9645		Scalar perturbations spectral index
k_{eq}	0.010362	Mpc^{-1}	k at equivalence time
z_{rei}	10.701		Redshift at reionization
z_{eq}	3395.7		Redshift at equivalence
z_{LSS}	1061.2		Redshift at $\tau - \tau_{rei} = \ln(2)$
z_{dec}	1090.3		Redshift at max of visibility function ($\tau' e^{-\tau}$)
z_*	1091.2		Redshift at $\tau - \tau_{rei} = 1$
$d_A(z_*)$	13910.	Mpc	Angular distance at z_*
$d_A(z_{eq})$	14078.	Mpc	Angular distance at equivalence
D_H	4456.56	Mpc	Hubble distance today
t_0	13.8308	Gyears	Age of the Universe
t_*	371 312.	years	Age of universe at z_*
$r_{hor}(z_{dec})$	280.58	Mpc	Radius of horizon at z_{dec}
η_0	14191.	Mpc	Conformal time today
$A_s{}^2$	2.4736×10^{-9}		Primordial scalar perturbations amplitude at k=0.002 Mpc
n_S	0.9645		Scalar spectral index
r	0		Tensor to Scalar ratio at k=0.002 Mpc
n_T	1		Tensor spectral index
σ_8	0.84516		Relies on an extrapolation of the matter power spectrum if $k_{max} < 200 k_{eq}$

Baryons only parameters

Variable	Value	Units	Comment
Ω_{b0}	1.		Abundance of baryons
Ω_{c0}	0.		Abundance of CDM
Ω_{r0}	0.000092414		Abundance of radiation (massless ν's and photons)
$\Omega_{\Lambda 0}$	−0.000092414		Abundance of Λ
Ω_K	0		Abundance of curvature
T_0	2.7255	K	Temperature of CMB
N_ν	3.045		Number of massless neutrinos
h	0.6727		Reduced Hubble constant
$\tau_{\rm rei}$	0.079		Optical depth of reionization
n_s	0.9645		Scalar perturbations spectral index
$k_{\rm eq}$	0.03301	Mpc^{-1}	k at equivalence time
$z_{\rm rei}$	1.6669		Redshift at reionization
$z_{\rm eq}$	10820.		Redshift at equivalence
$z_{\rm LSS}$	1035.5		Redshift at $\tau-\tau_{\rm rei}=\ln(2)$
$z_{\rm dec}$	1066.2		Redshift at max of visibility function ($\tau' e^{-\tau}$)
z_*	1062.4		Redshift at $\tau-\tau_{\rm rei}=1$
$d_A(z_*)$	8627.1	Mpc	Angular distance at z_*
$d_A(z_{\rm eq})$	8792.4	Mpc	Angular distance at equivalence
D_H	4456.56	Mpc	Hubble distance today
t_0	9.68904	Gyears	Age of the Universe
t_*	252499.	years	Age of universe at z_*
$r_{\rm hor}(z_{\rm dec})$	200.3	Mpc	Radius of horizon at $z_{\rm dec}$
η_0	8827.9	Mpc	Conformal time today
$A_s{}^2$	2.4736×10^{-9}		Primordial scalar perturbations amplitude at k=0.002 Mpc
n_S	0.9645		Scalar spectral index
r	0		Tensor to Scalar ratio at k=0.002 Mpc
n_T	1		Tensor spectral index
σ_8	0.28164		Relies on an extrapolation of the matter power spectrum if $k_{\rm max}<200k_{\rm eq}$

Baryons +CDM parameters

Variable	Value	Units	Comment
Ω_{b0}	1.		Abundance of baryons
Ω_{c0}	0.		Abundance of CDM
Ω_{r0}	0.000092414		Abundance of radiation (massless ν's and photons)
$\Omega_{\Lambda 0}$	−0.000092414		Abundance of Λ
Ω_K	0		Abundance of curvature
T_0	2.7255	K	Temperature of CMB
N_ν	3.045		Number of massless neutrinos
h	0.6727		Reduced Hubble constant
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n_s	0.9645		Scalar perturbations spectral index
$k_{\rm eq}$	0.03301	$\rm Mpc^{-1}$	k at equivalence time
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Outline

- Introduction
  - Define CMB - History and Current State
  - Define DM - History and Current State
- Connect the two (Introduce power spectrum, LCDM and explain it here)
- Conclude