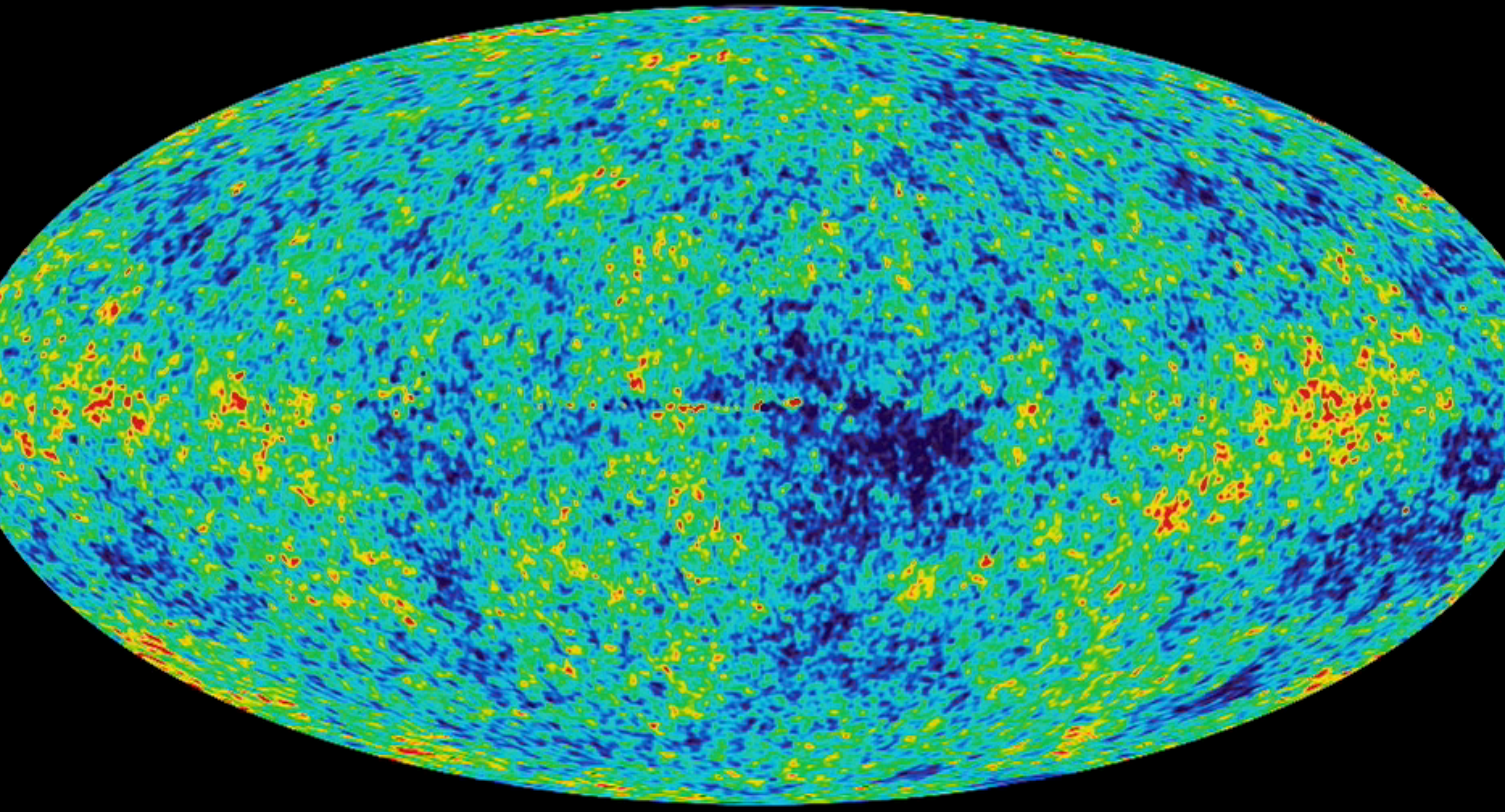
Why CMB Now?

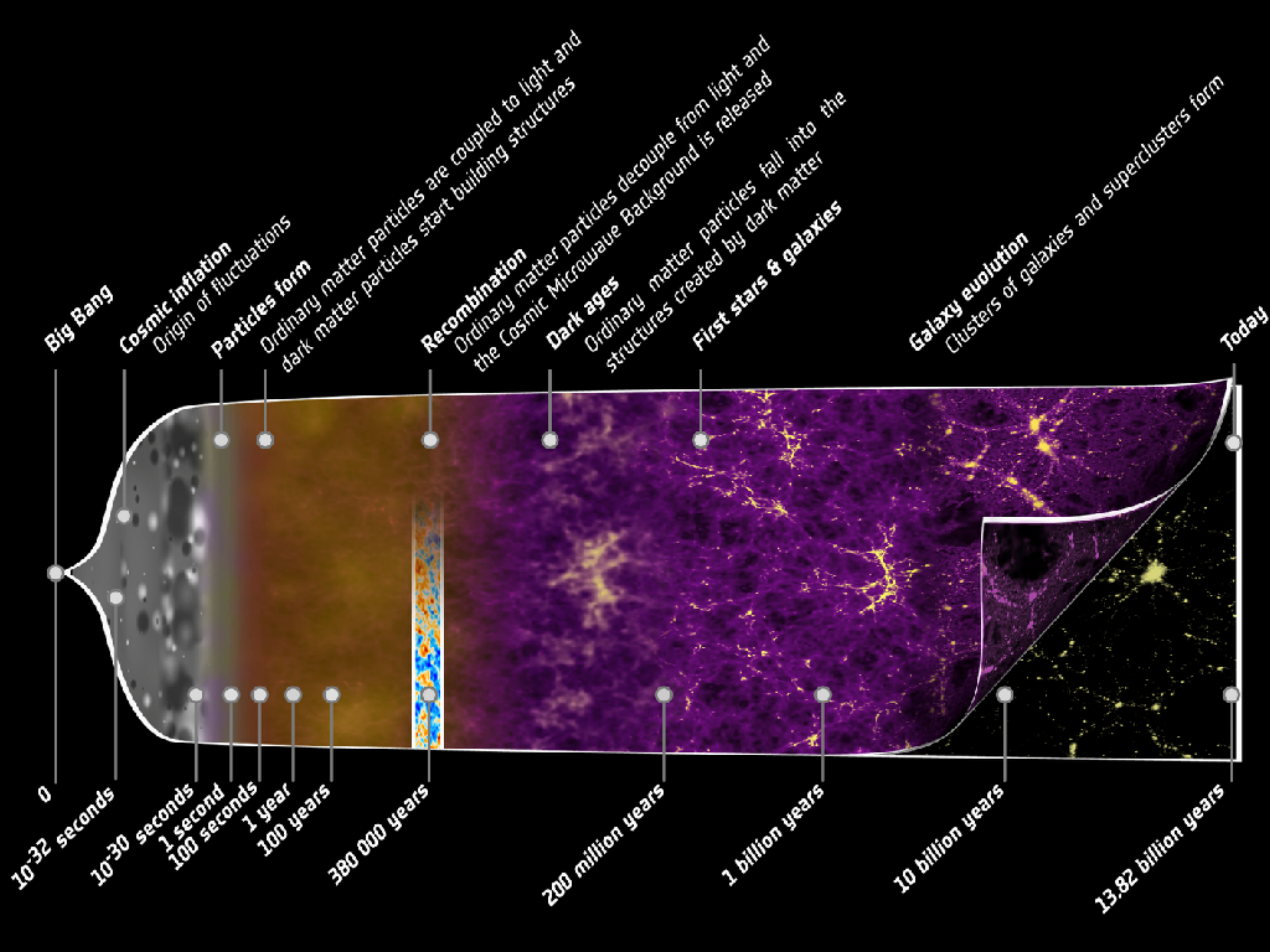
Eiichiro Komatsu (MPA)

"*CMB in Germany*" meeting, January 31, 2018



A Remarkable Story

- Observations of CMB taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13,82 billion years

ΛCDM. Want more?

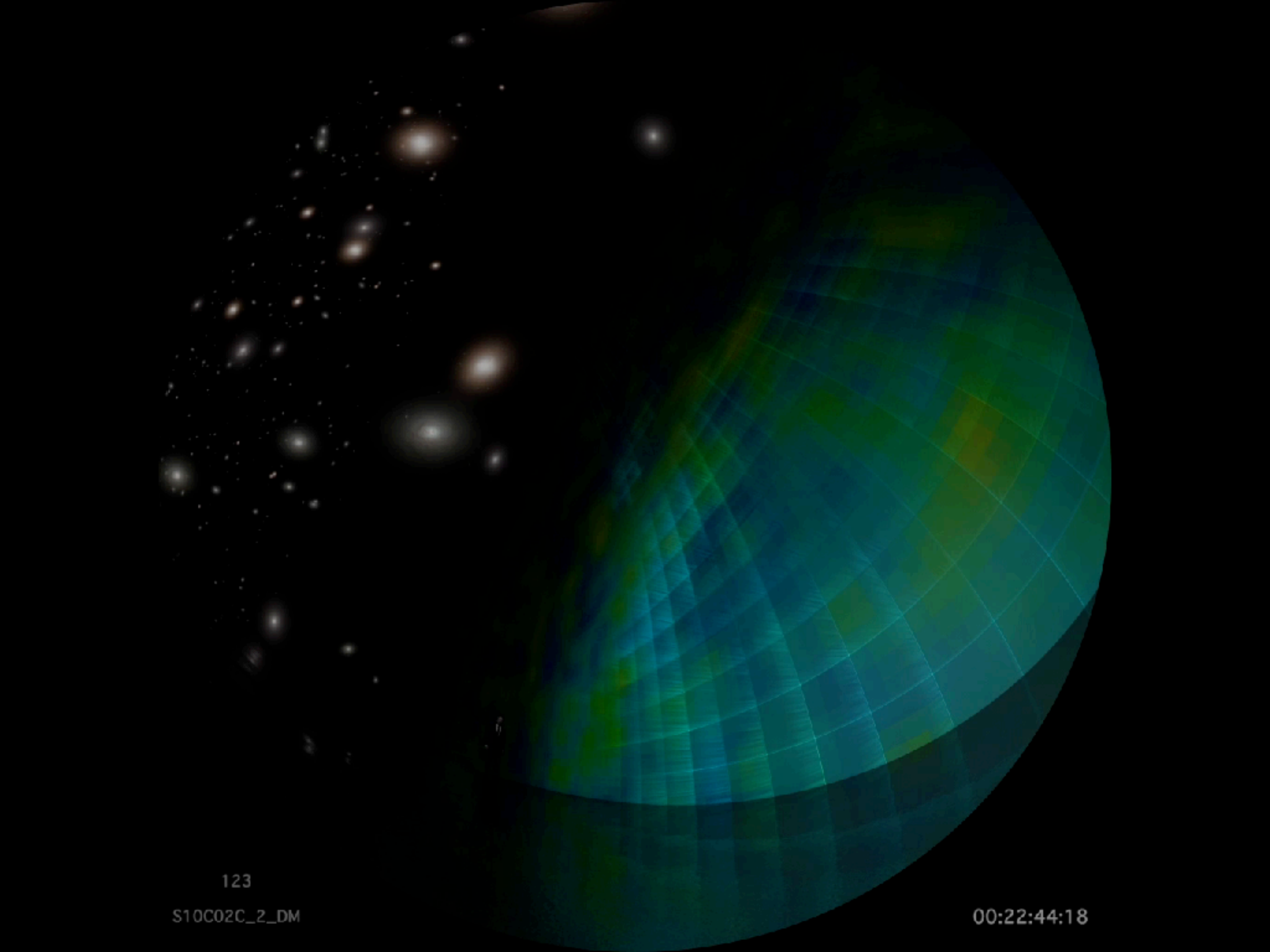
- Thanks to the CMB and other observations (large-scale structure of the Universe, supernovae, …), We now have the standard model of cosmology (ΛCDM), which can describe what we see from the early Universe to the present epoch

- What more do we want from the CMB?

- We have entered the new era: we ask deeper questions

  - **Has inflation really happened?** Did we really originate from quantum fluctuations in the early Universe?

  - **Is ΛCDM really right?** We don’t understand the physical nature of Λ or CDM!


123
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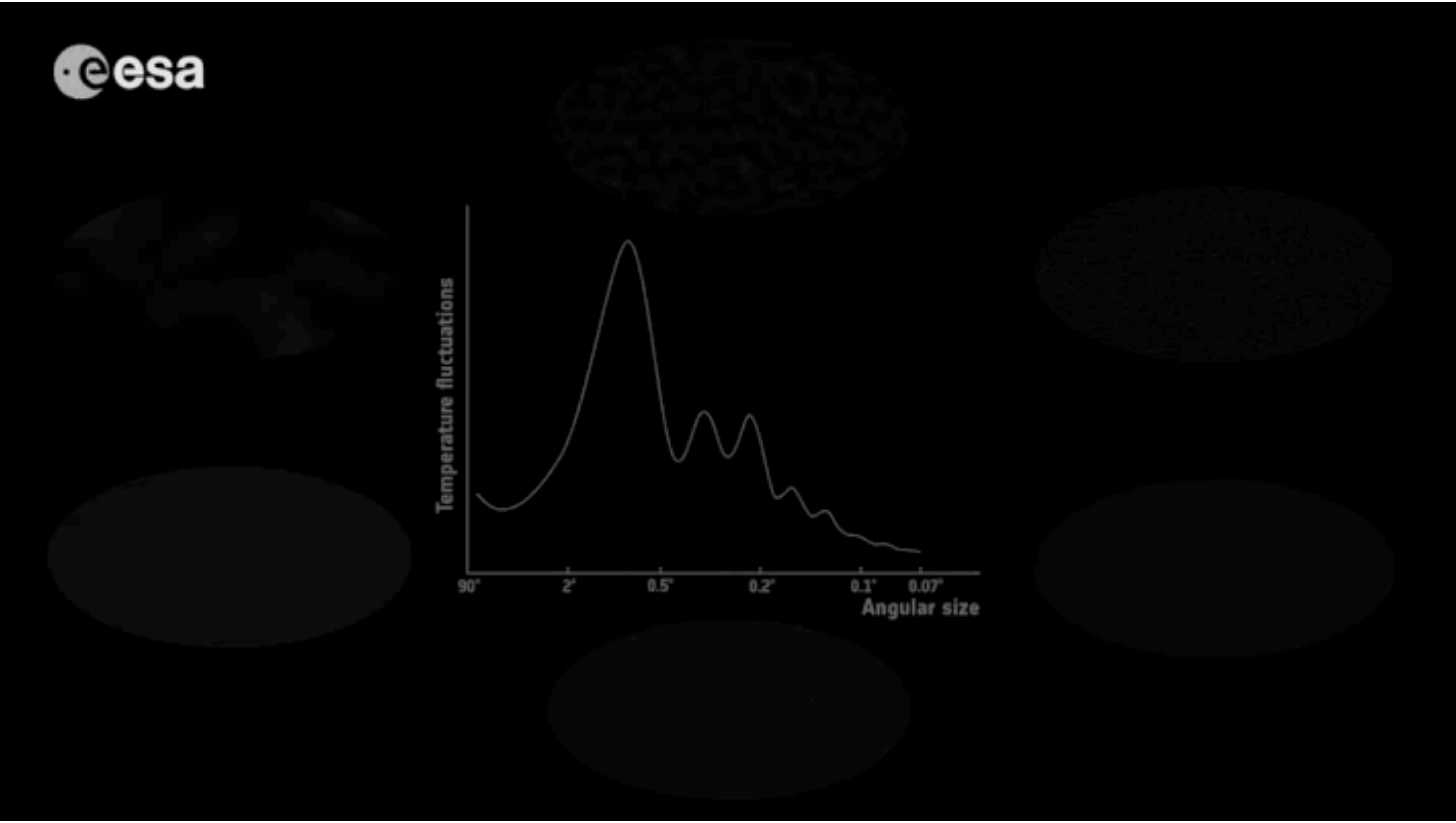
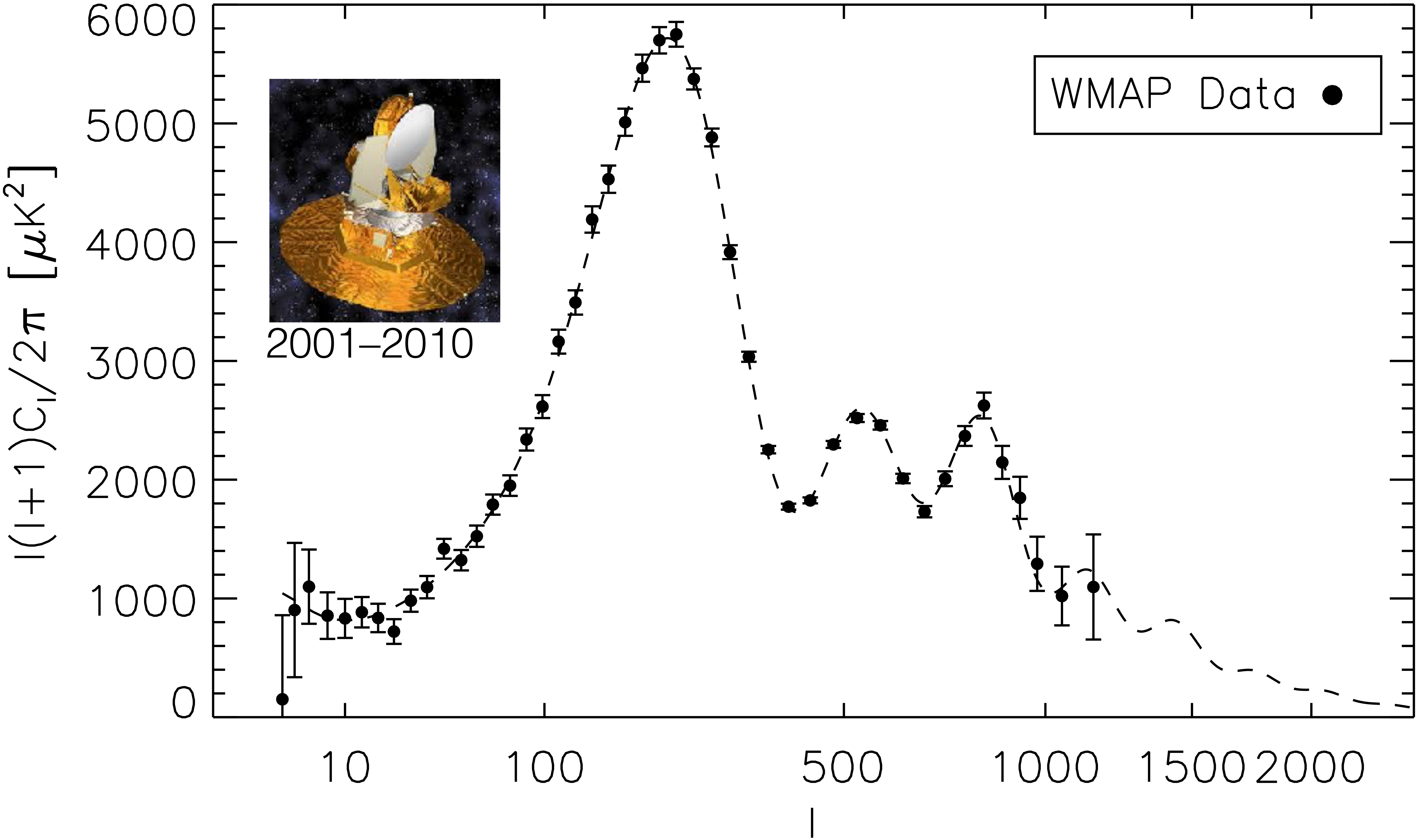
Power Spectrum Analysis

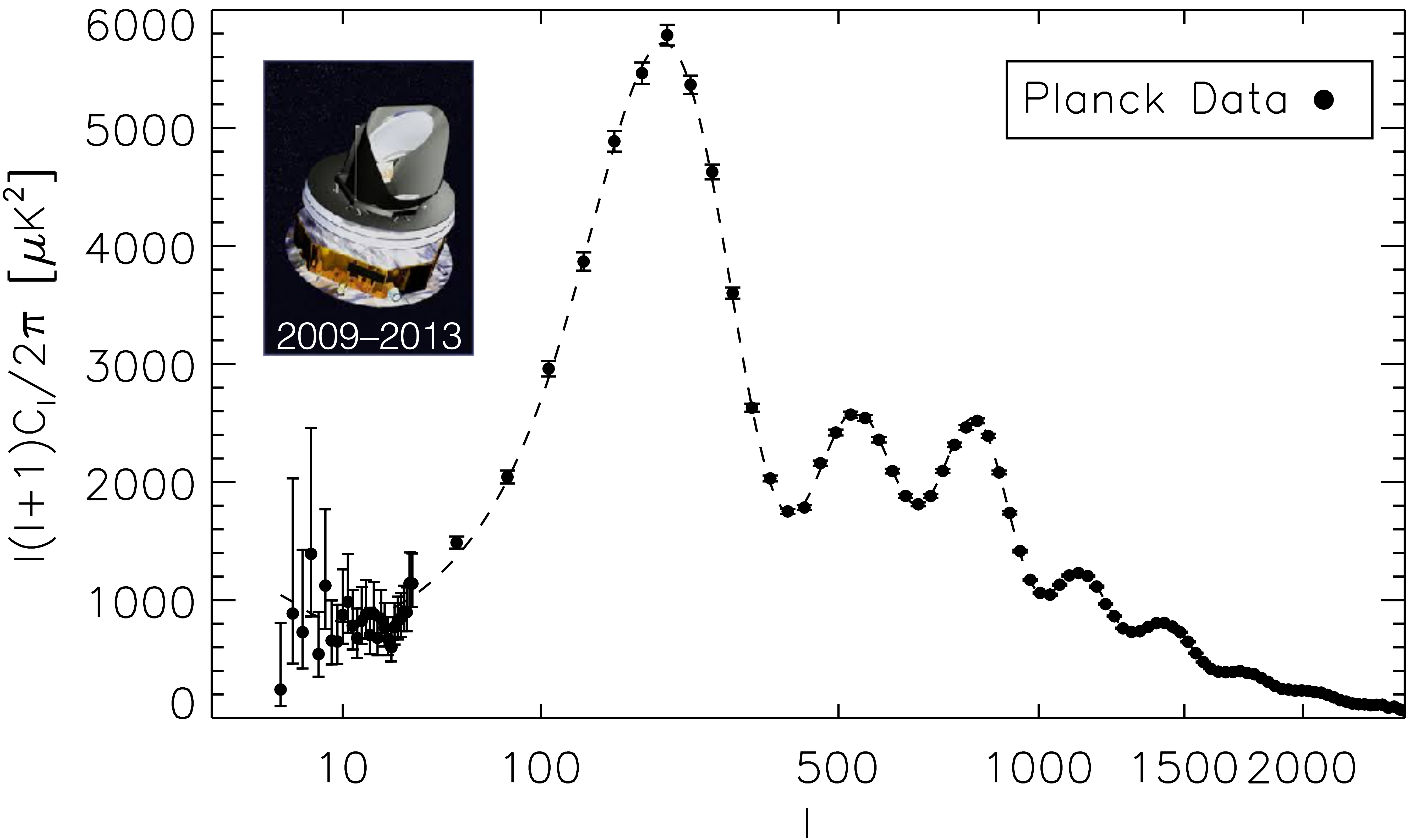
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength



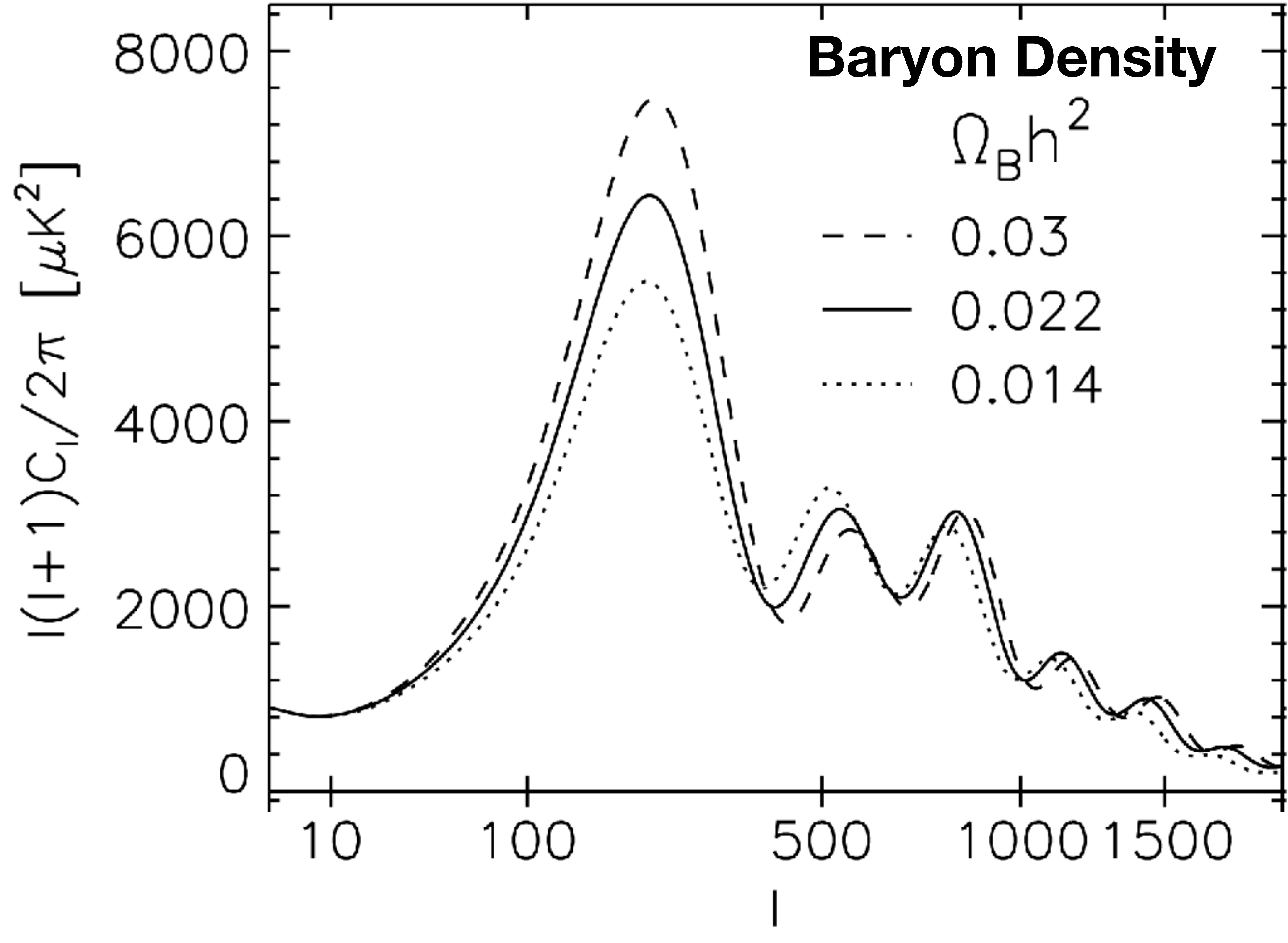
Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size



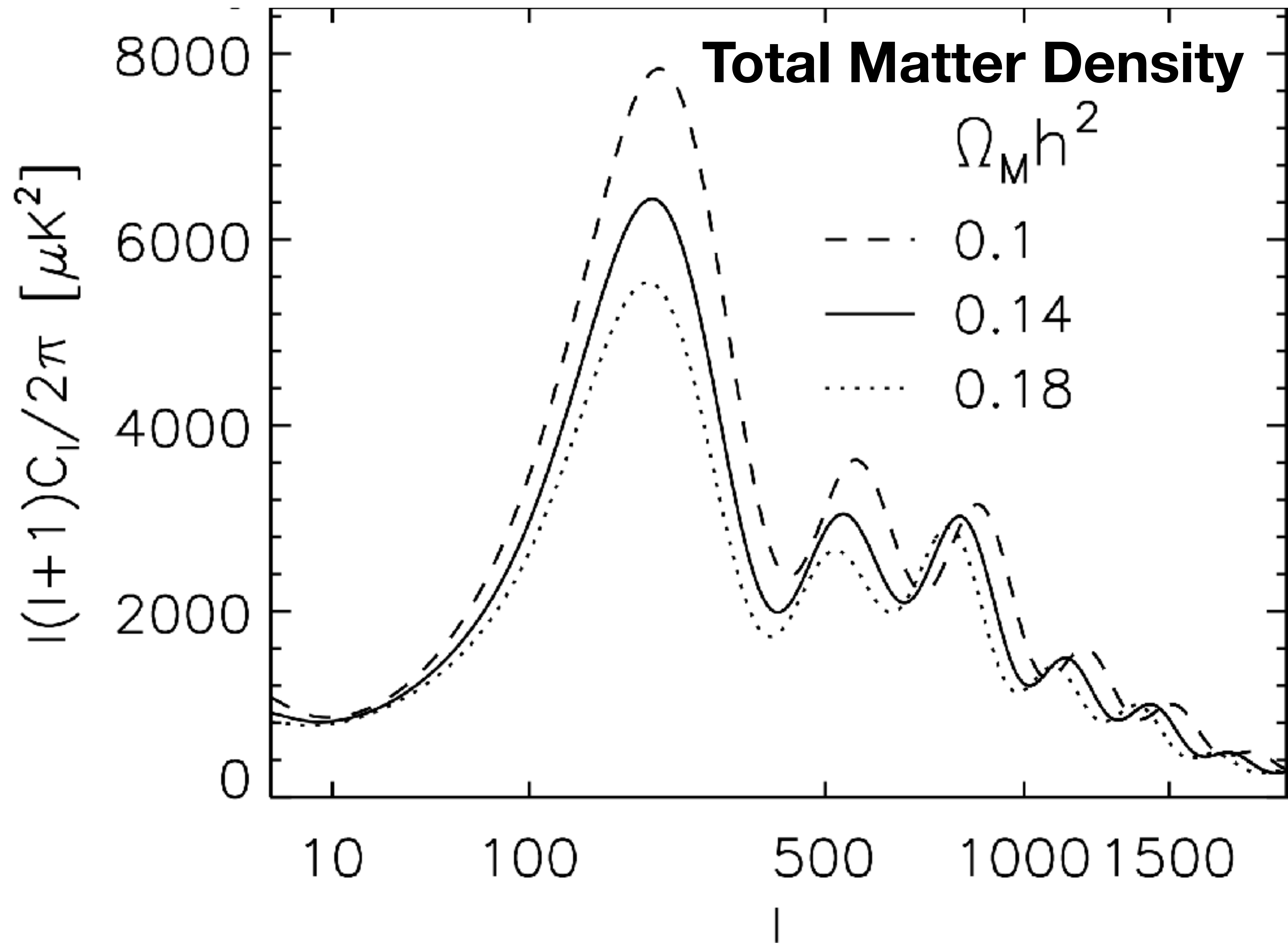
WMAP Data
2001–2010
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
l
$l(l+1)C_l/2\pi\ [\mu K^2]$



Planck Data
2009–2013
$l(l+1)C_l/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
l



Baryon Density
$\Omega_B h^2$
0.03
0.022
0.014
8000
6000
4000
2000
0
$l(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
1500
l



Total Matter Density
$\Omega_M h^2$
0.1
0.14
0.18
8000
6000
4000
2000
0
$l(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
1500
l

Cosmological Parameters Derived from the Power Spectrum

	WMAP	Planck	+CMB Lensing
$100\Omega_B h^2$	2.264 ± 0.050	2.222 ± 0.023	2.226 ± 0.023
$\Omega_D h^2$	0.1138 ± 0.0045	0.1197 ± 0.0022	0.1186 ± 0.0020
Ω_Λ	0.721 ± 0.025	0.685 ± 0.013	0.692 ± 0.012
n	0.972 ± 0.013	0.9655 ± 0.0062	0.9677 ± 0.0060
$10^9 A_s$	2.203 ± 0.067	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063
τ	0.089 ± 0.014	0.078 ± 0.019	0.066 ± 0.016
t_0 [100 Myr]	137.4 ± 1.1	138.13 ± 0.38	137.99 ± 0.38
H_0	70.0 ± 2.2	67.31 ± 0.96	67.81 ± 0.92
$\Omega_M h^2$	0.1364 ± 0.0044	0.1426 ± 0.0020	0.1415 ± 0.0019
$10^9 A_s e^{-2\tau}$	1.844 ± 0.031	1.880 ± 0.014	1.874 ± 0.013
σ_8	0.821 ± 0.023	0.829 ± 0.014	0.8149 ± 0.0093

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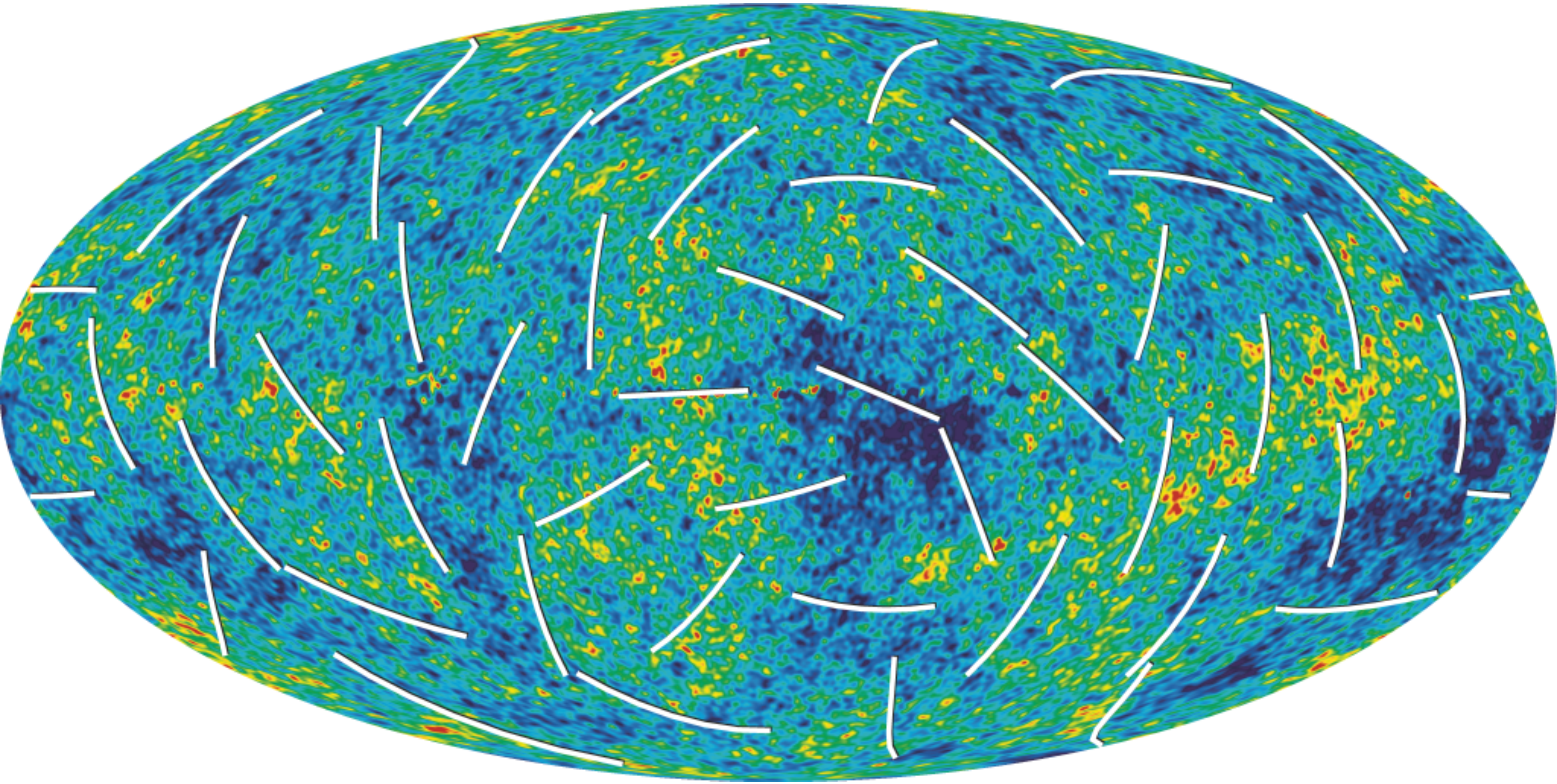
Now What?

CMB Polarisation



- CMB is weakly polarised!

Photo Credit: TALEX

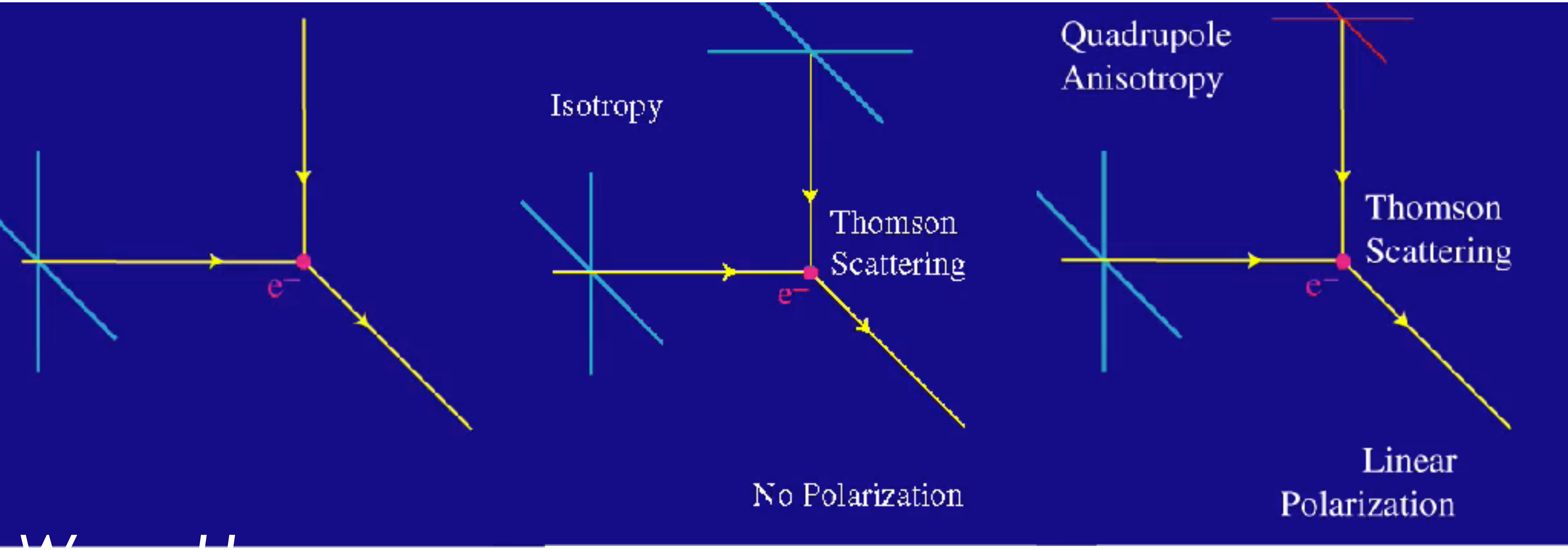

Photo Credit: TALEX
horizontally polarised

Photo Credit: TALEX

Necessary and sufficient conditions for generating polarisation

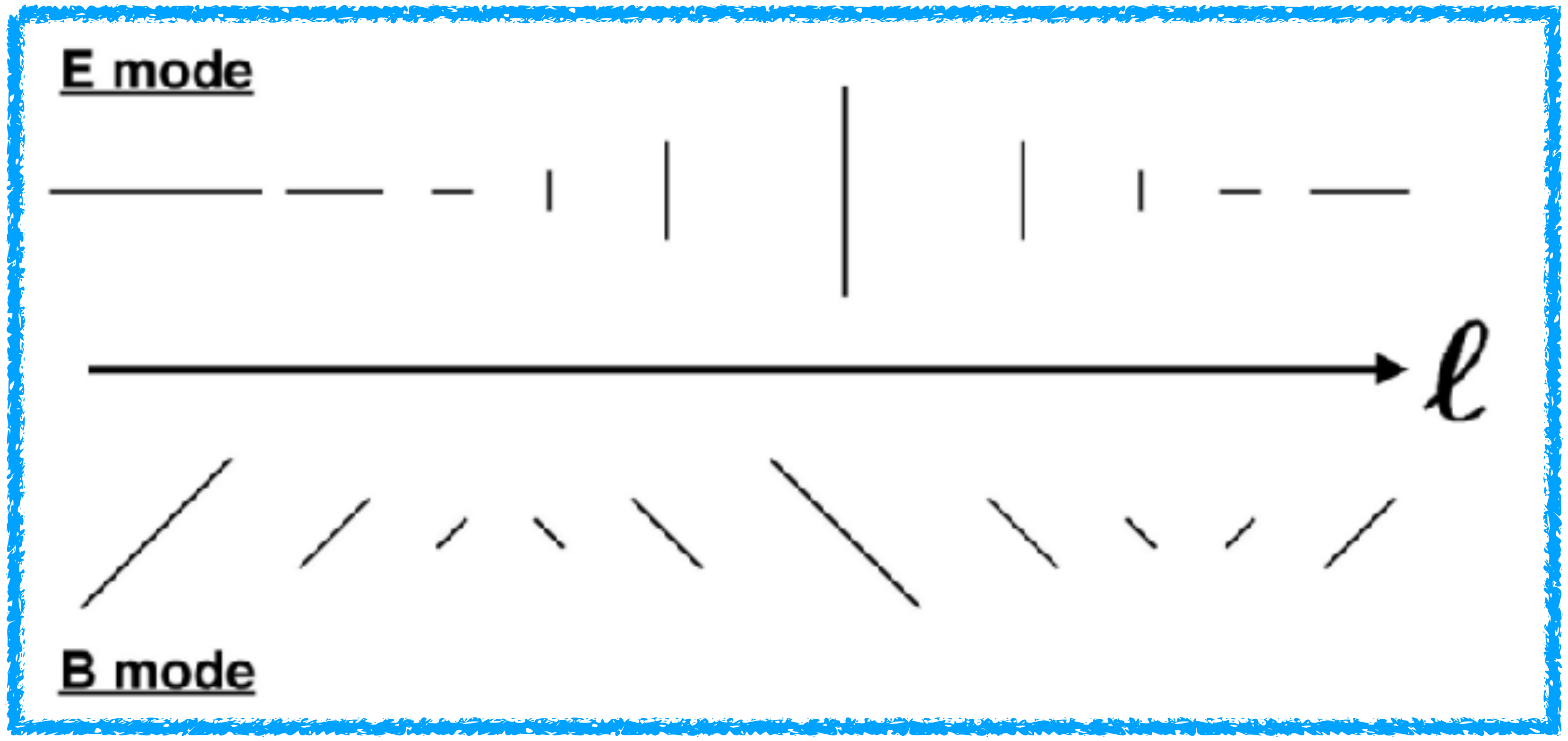
- You need to have two things to produce linear polarisation
  1. Scattering
  2. Anisotropic incident light
- However, the Universe does not have a preferred direction. How do we generate anisotropic incident light?

Need for a local quadrupole temperature anisotropy

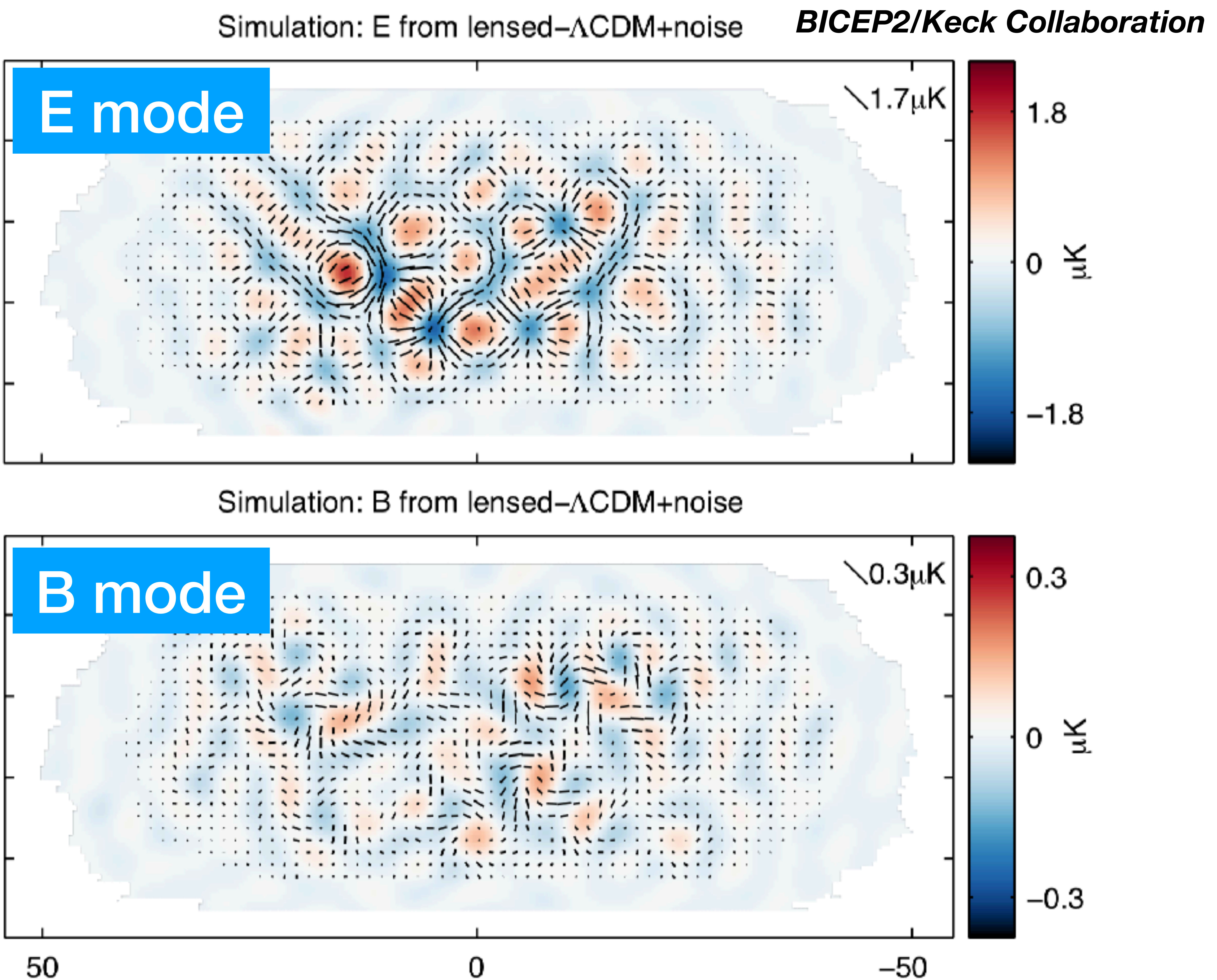


- Two sources of local temperature quadrupole:
  - Density waves (scalar modes)
  - Gravitational waves (tensor modes)

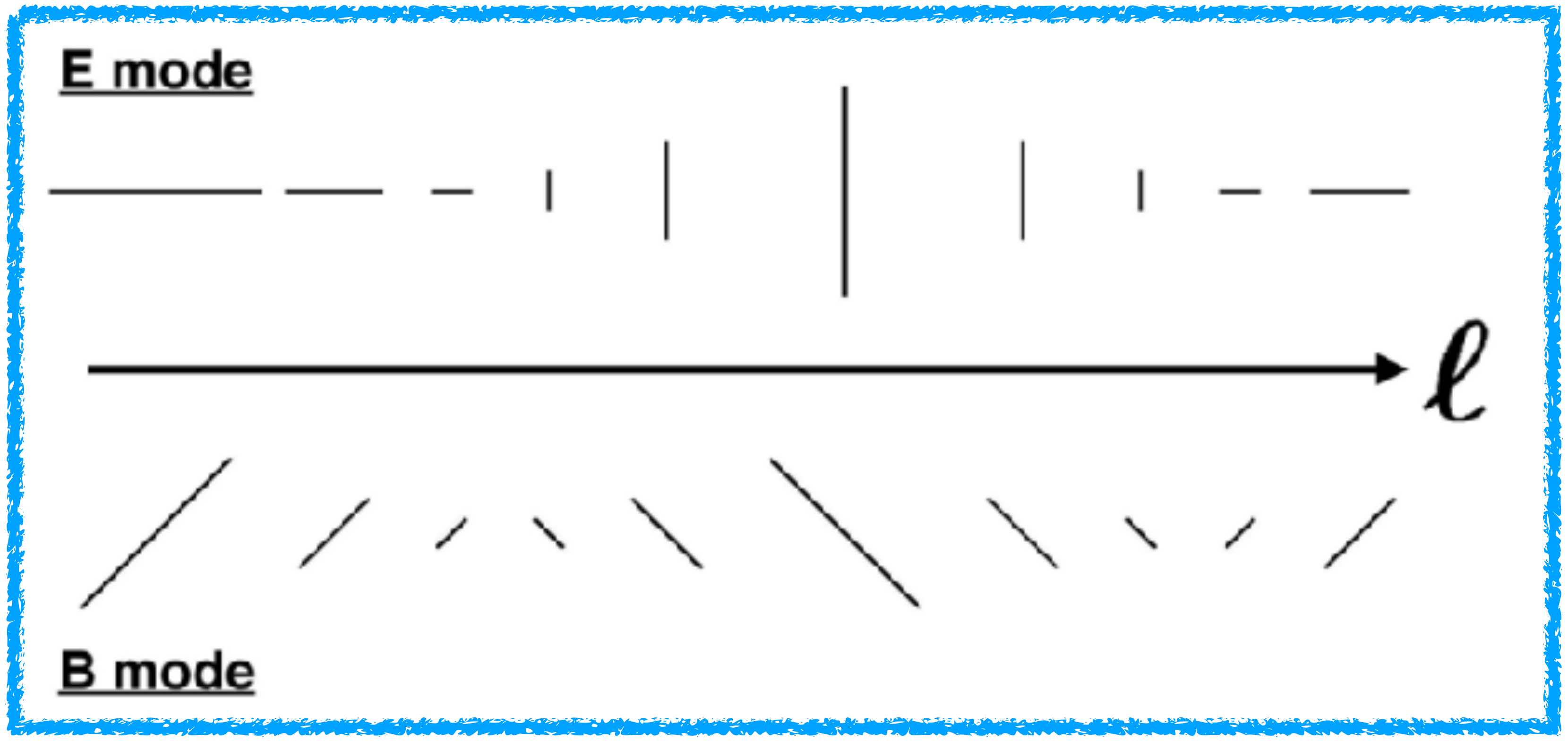
E modes and B modes

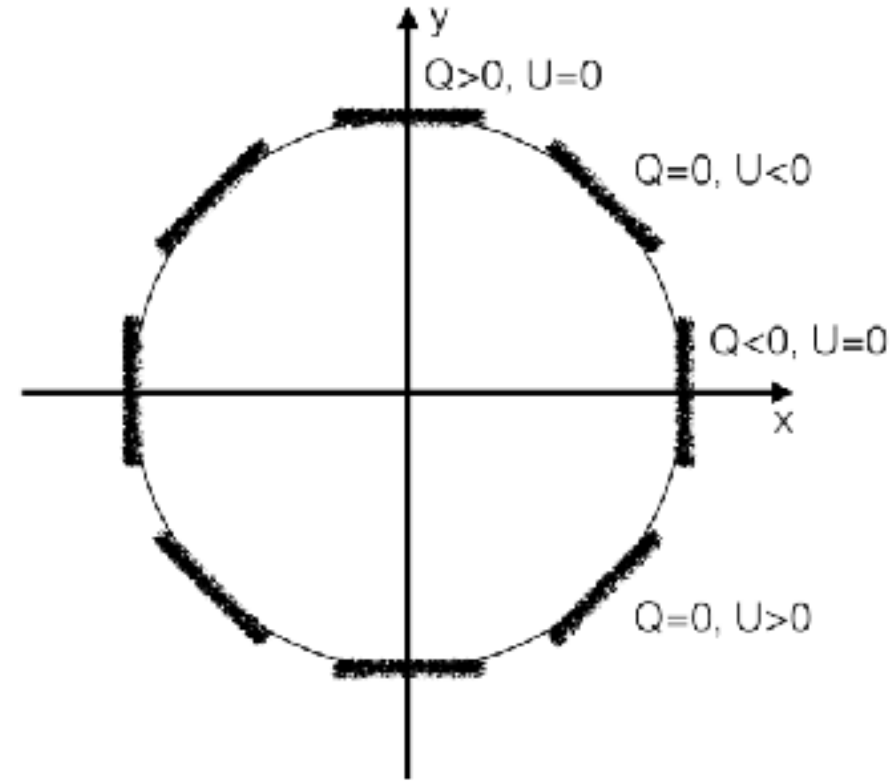


- **E mode**: Polarisation directions parallel or perpendicular to the wavevector
- **B mode**: Polarisation directions 45 degree tilted with respect to the wavevector


BICEP2/Keck Collaboration
Simulation: E from lensed–ΛCDM+noise
E mode
1.7μK
1.8
0
μK
−1.8
Simulation: B from lensed–ΛCDM+noise
B mode
0.3μK
0.3
0
μK
−0.3
50
0
−50

Relationship to Stokes Parameters

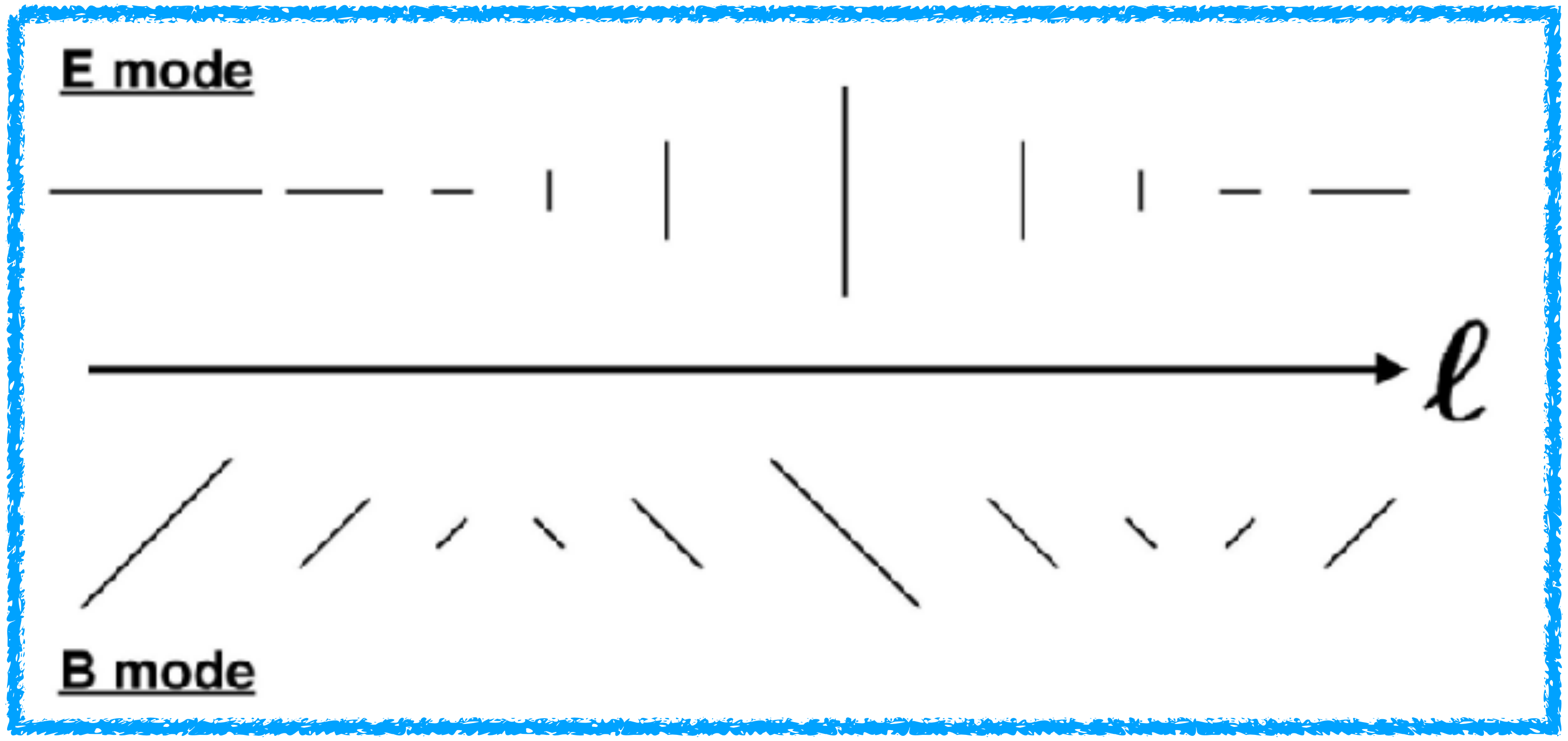




- **E mode**: Stokes Q, defined with respect to ℓ as the x-axis
- **B mode**: Stokes U, defined with respect to ℓ as the y-axis

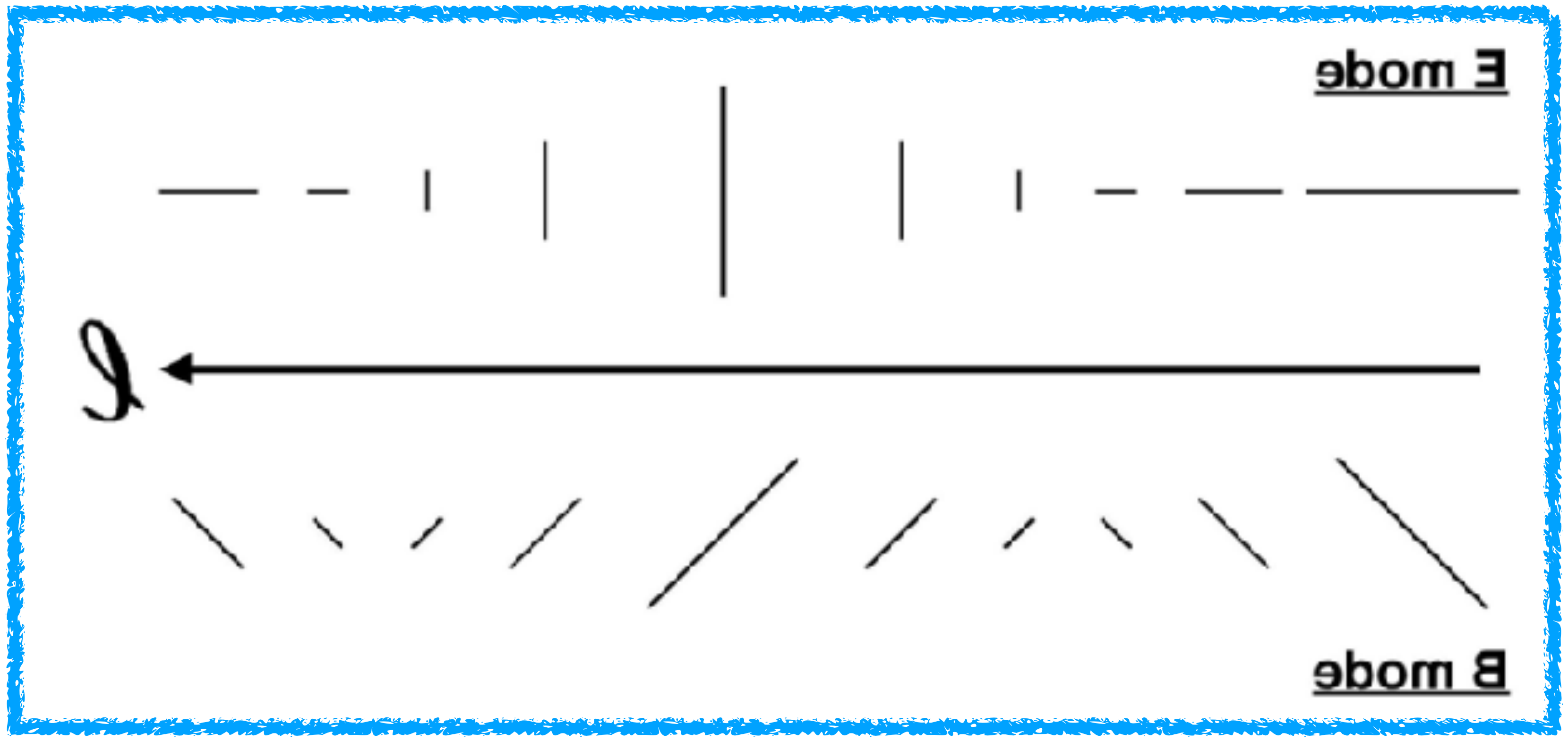
IMPORTANT: These are all coordinate-independent statements

Parity



- **E mode**: Parity even
- **B mode**: Parity odd

Parity

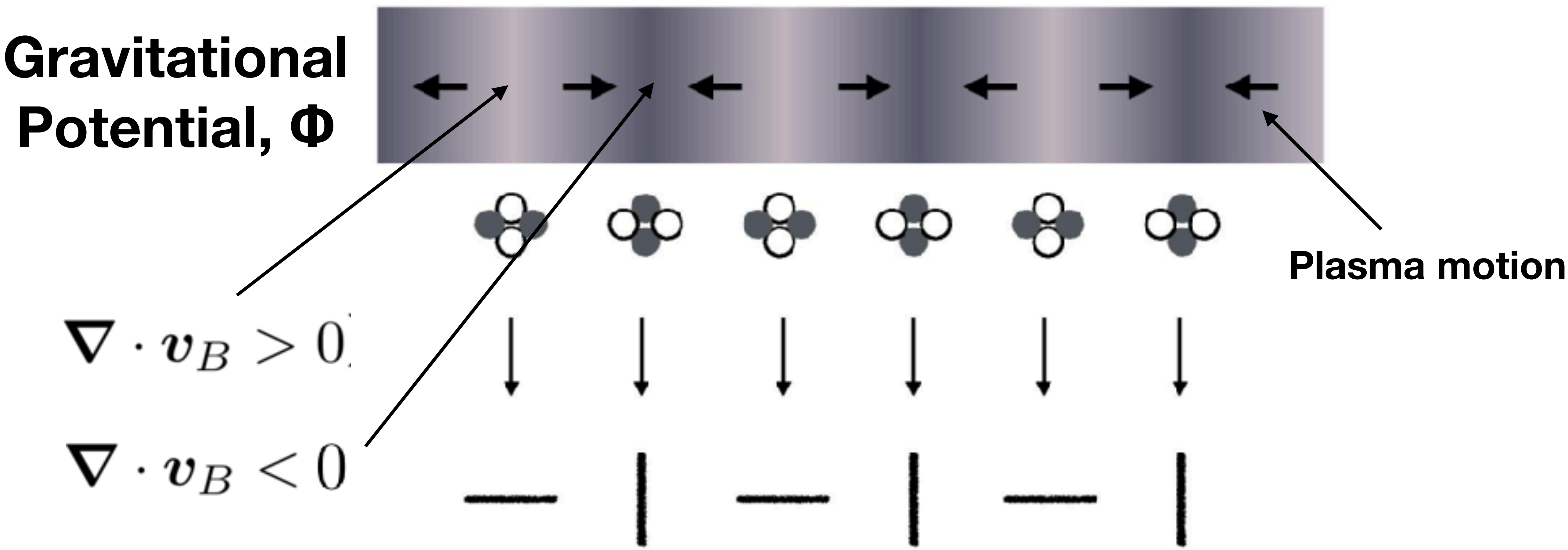


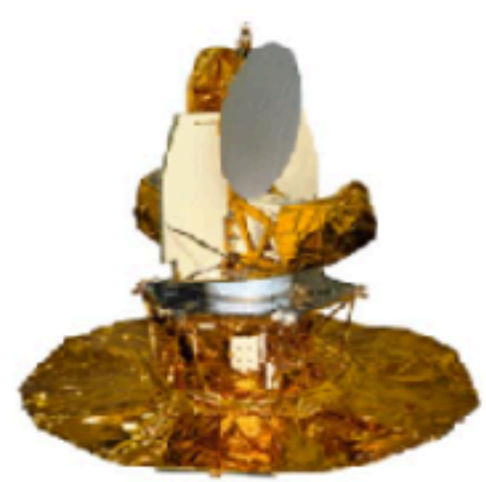
- **E mode**: Parity even
- **B mode**: Parity odd

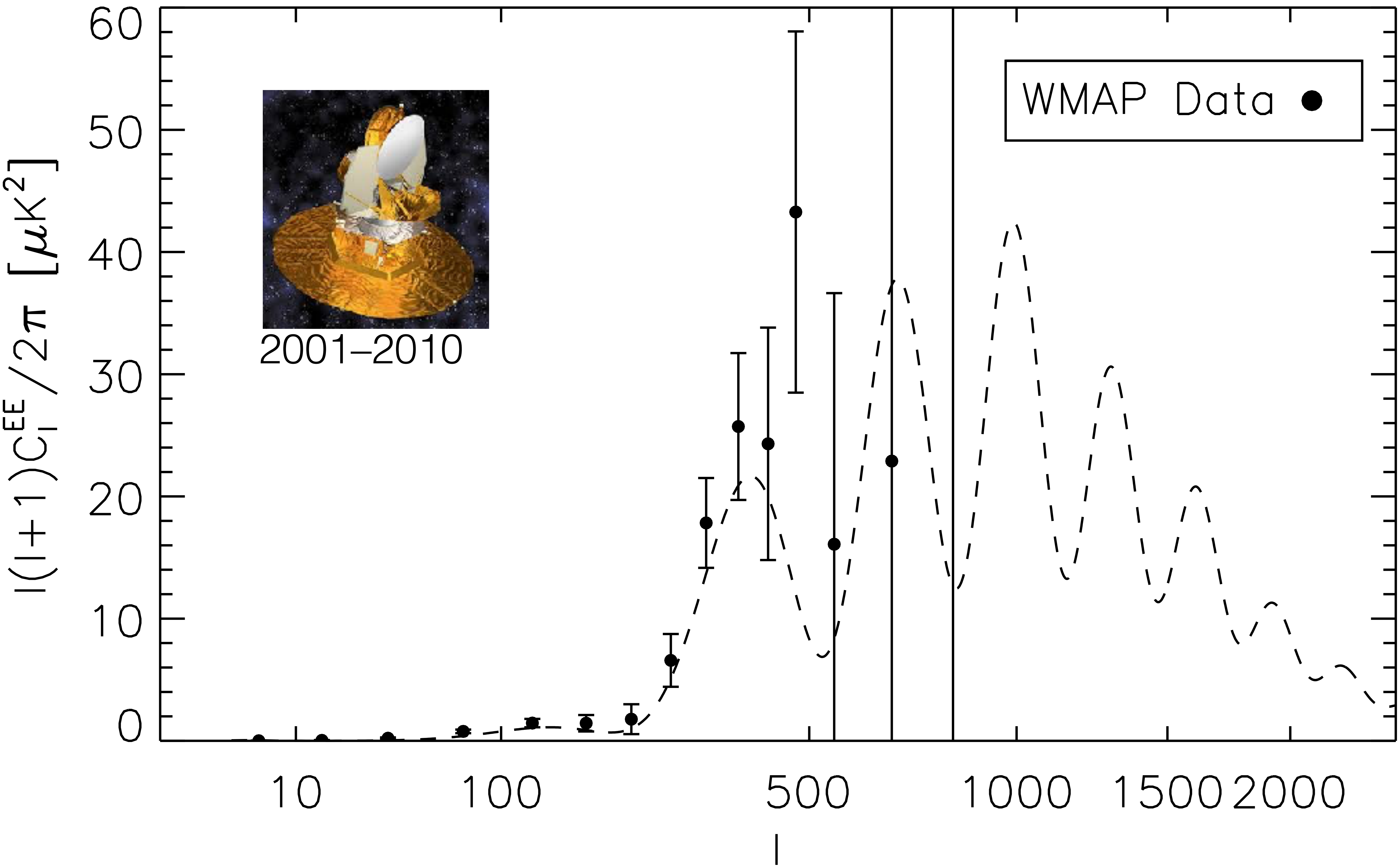
B-mode cannot be generated by density waves

Coulson et al. (1994)

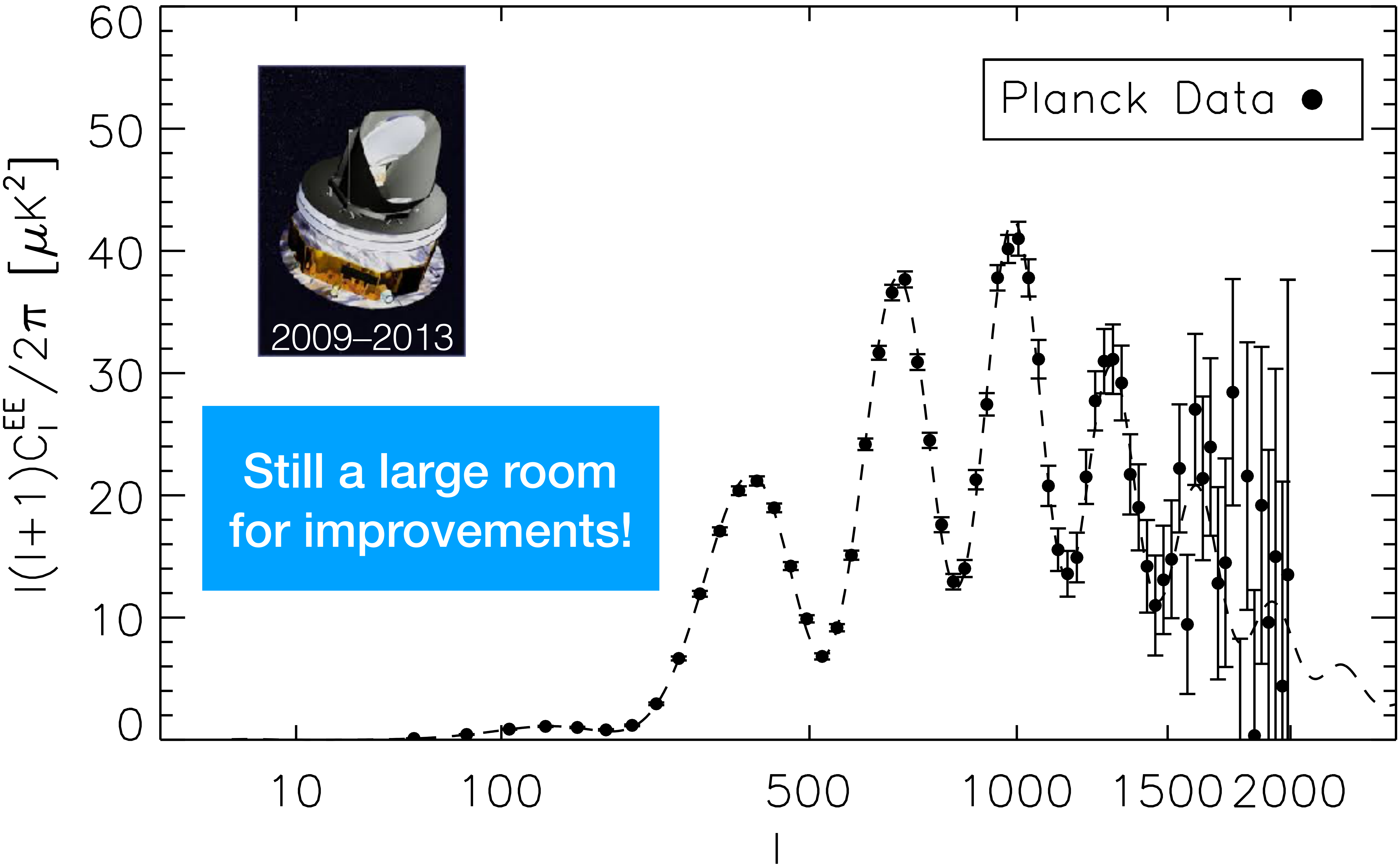
Example: Gravitational Effects





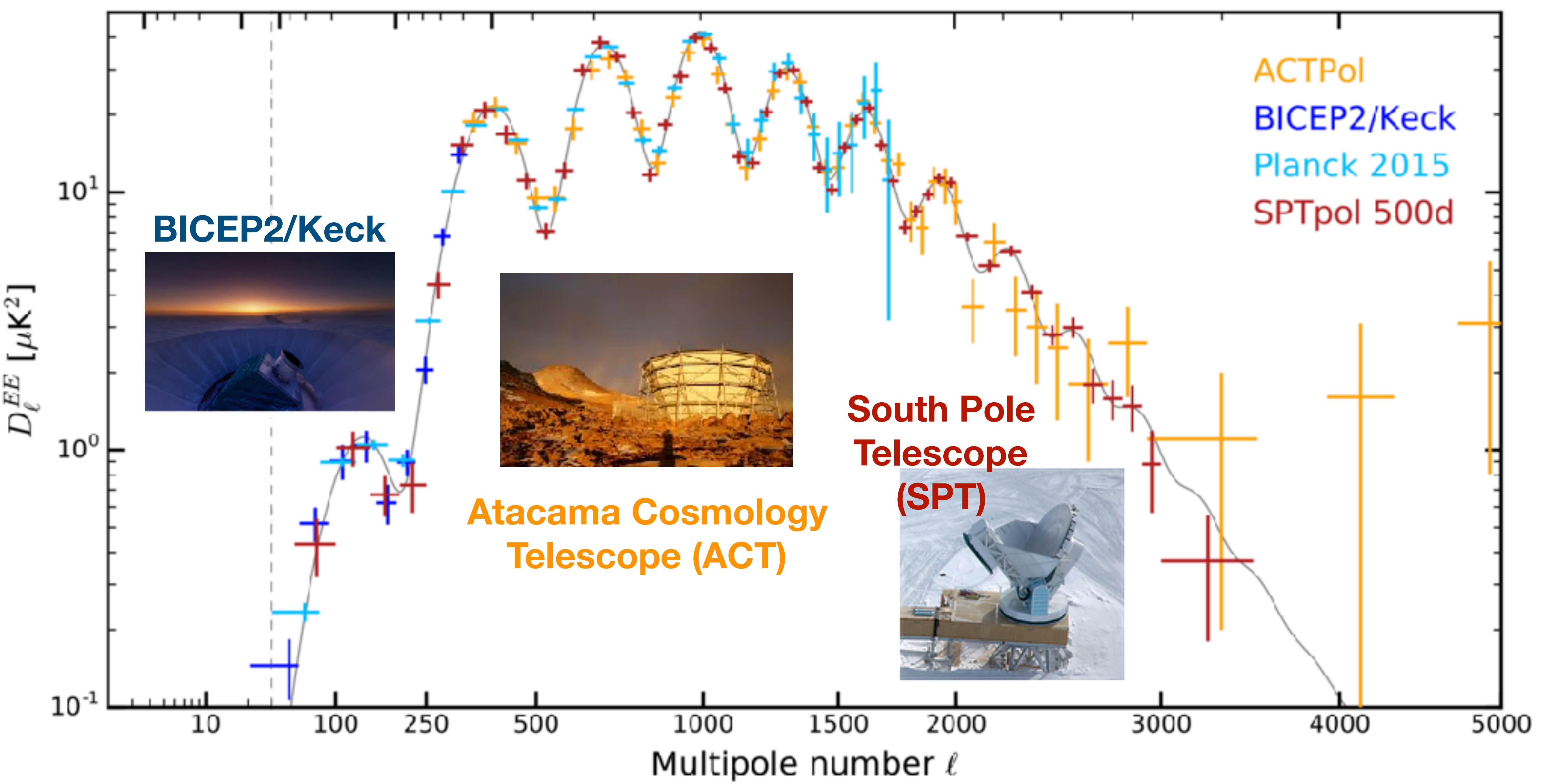


WMAP Data
2001–2010
l(l+1)C_l^EE/2π [μK^2]
60
50
40
30
20
10
0
10
100
500
1000
1500
2000
l


Planck Data
2009–2013
Still a large room
for improvements!
l(l+1)C_l^EE/2π [μK^2]
60
50
40
30
20
10
0
10
100
500
1000
1500
2000
l

Henning et al. (SPT Collaboration)

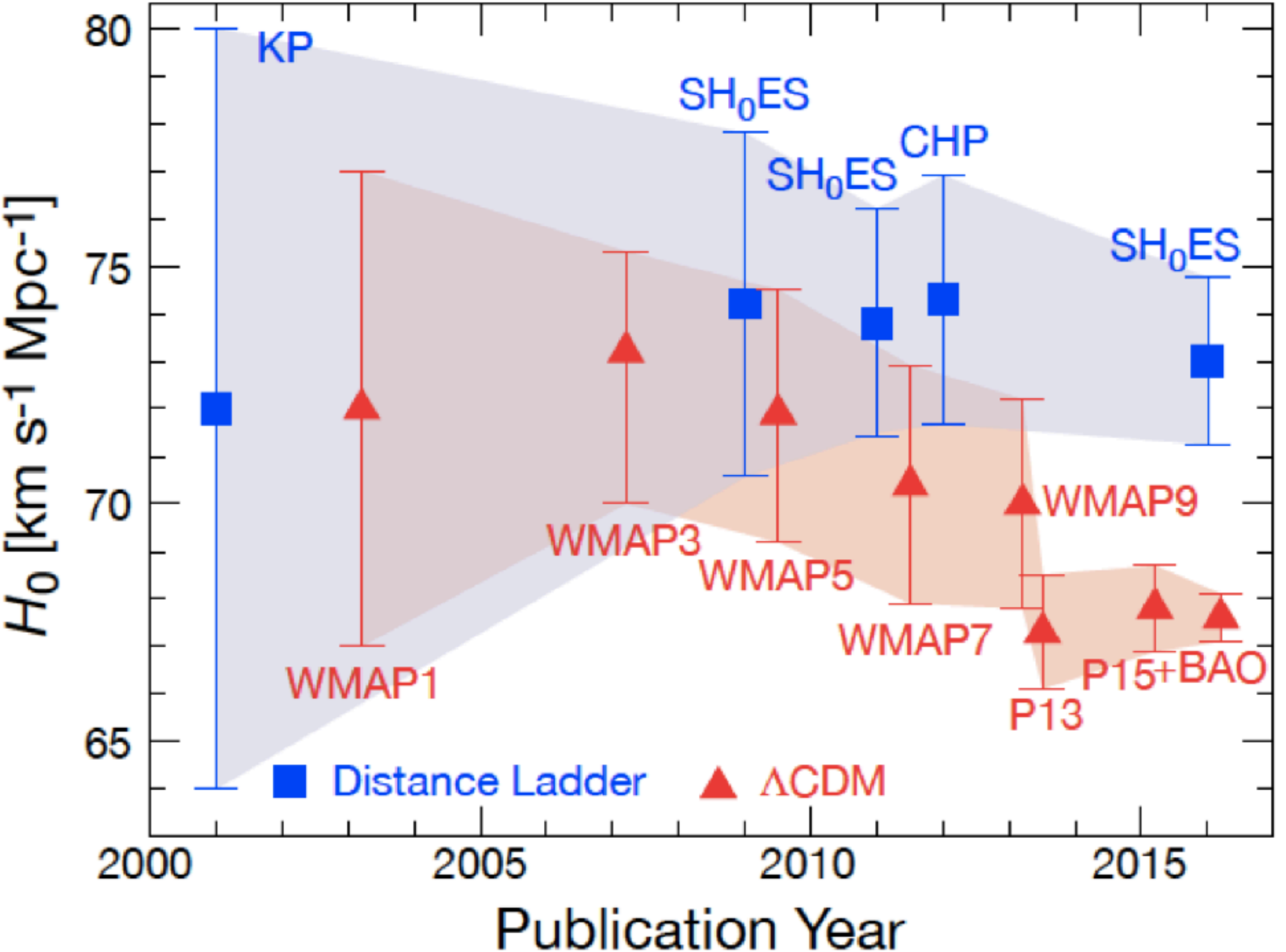
Improvements come from ground-based observatories



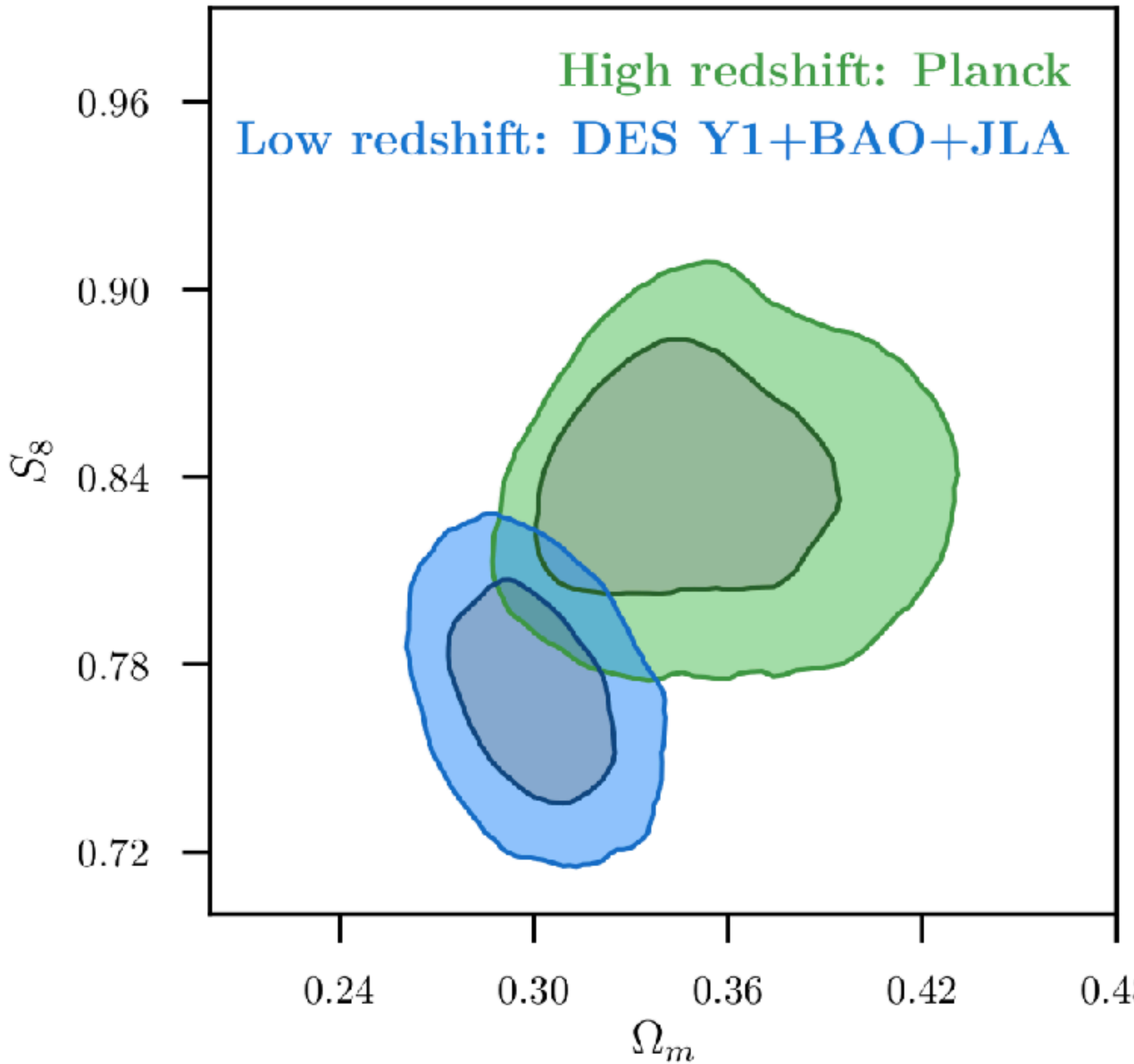
Ground-based E-mode measurements: Science cases

- **Was Planck right?**
    - Some hints for cosmological parameter “tensions” (Hubble constant; Amplitude of matter fluctuations) coming from the high-ell temperature power spectrum measured by Planck
    - Ground-based E-mode measurements will check for consistency. Super important - **this may be a hint for new physics!**

Freedman (2017)

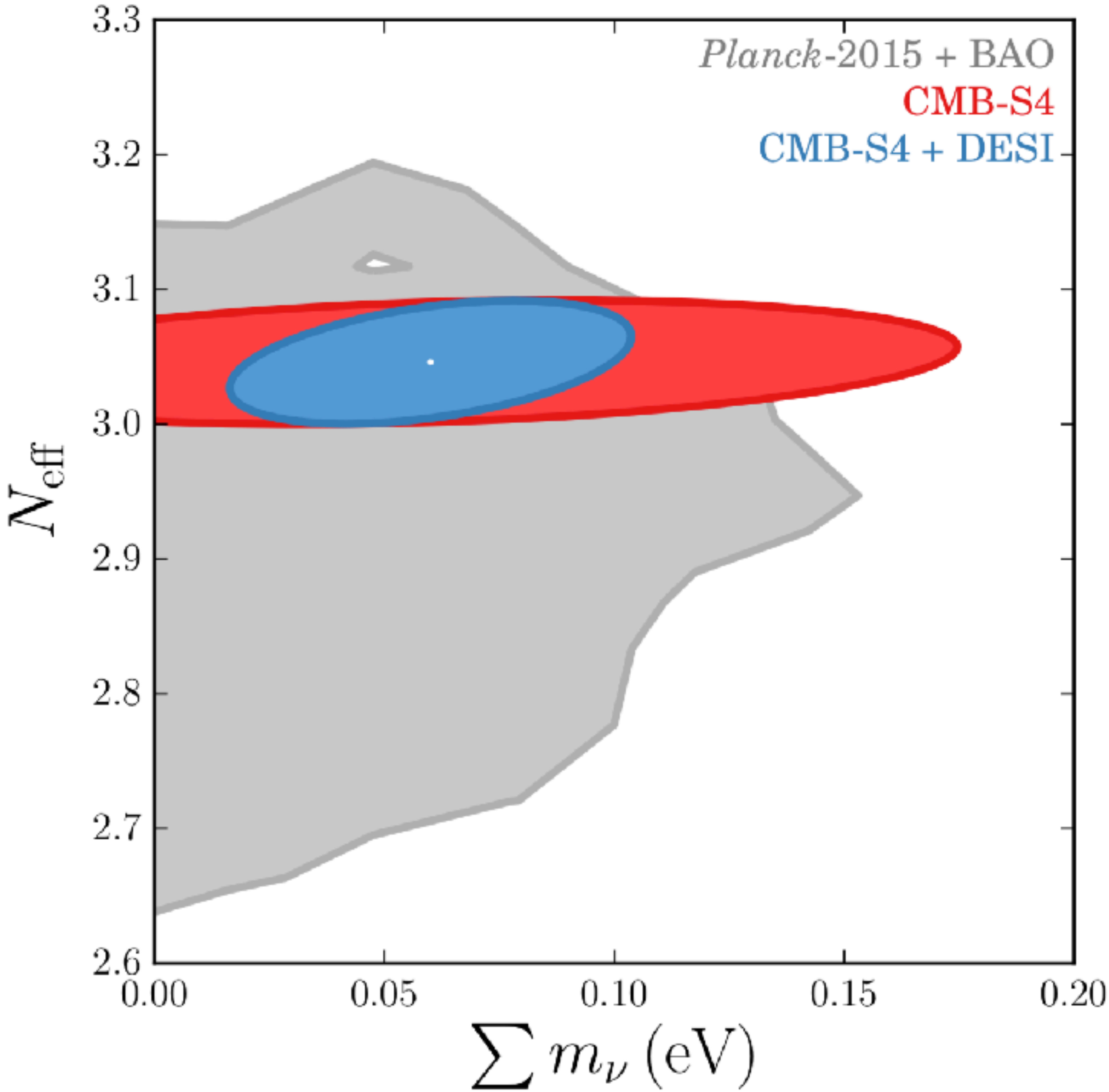


Dark Energy Survey (DES) Collaboration



Ground-based E-mode measurements: Science cases

- **Were there new light particles in the early Universe?**
  - Light particles (such as neutrinos) leave distinct signatures in the peak structures in the power spectrum
  - This effect has been detected for the standard three-species neutrinos (N_{eff}=3.046), but are there more?



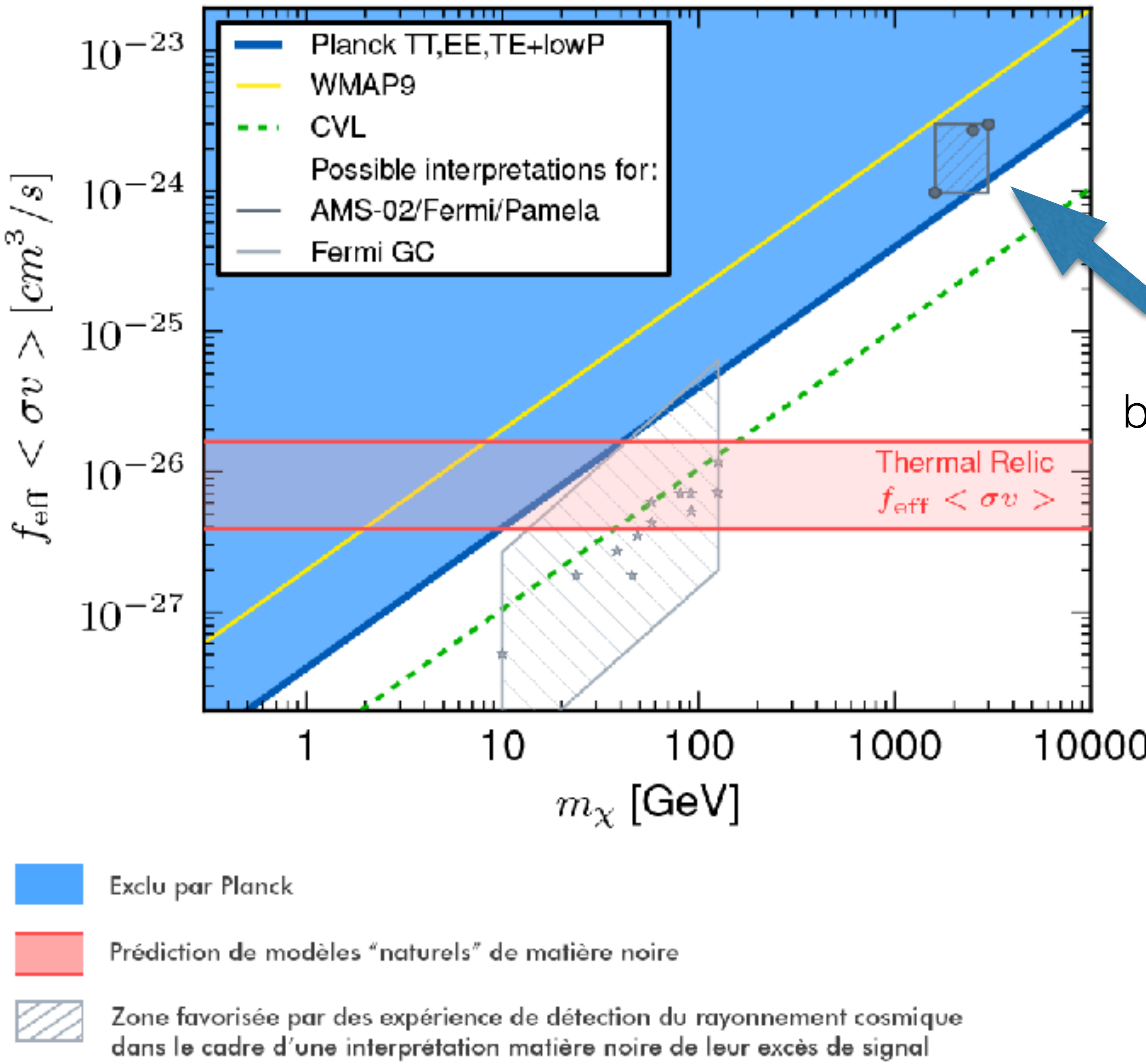
Planck-2015 + BAO
CMB-S4
CMB-S4 + DESI
$N_{\rm eff}$
$\sum m_\nu$ (eV)
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
0.00
0.05
0.10
0.15
0.20

Ground-based E-mode measurements: Science cases

- **Do dark matter particles annihilate?**
  - Extra energy injected by annihilation of dark matter in the early Universe modifies recombination history
  - This effect shows up at the high-ell power spectrum of temperature and polarization

Planck Collaboration

Dark Matter Annihilation



Parameter space favoured by the positron excess of the cosmic-ray experiments (PAMELA/Fermi/AMS2) is now excluded by Planck

Primordial Gravitational Waves

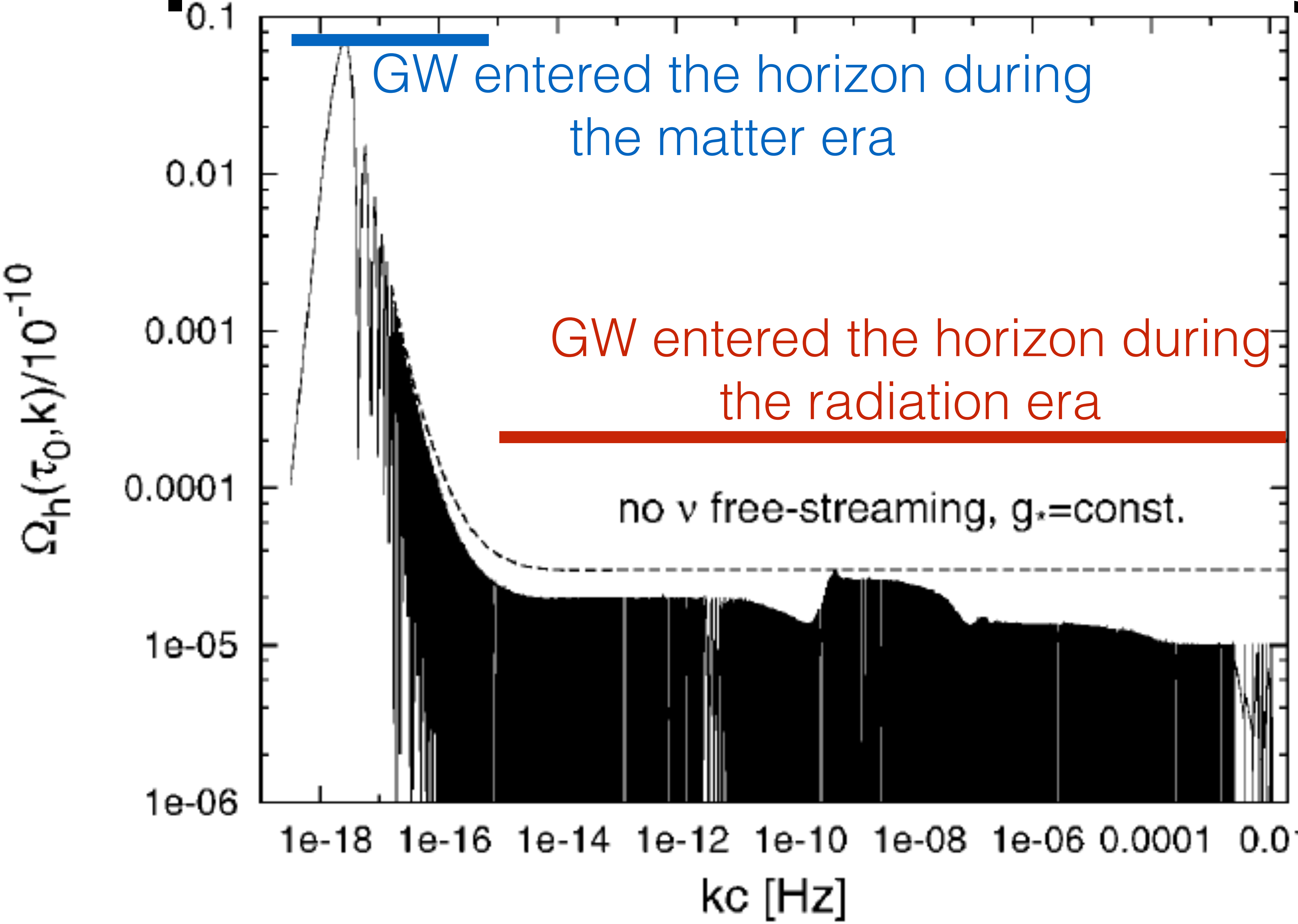
Have we found inflation?

- Single-field slow-roll inflation looks remarkably good:
  - **Super-horizon fluctuation**
  - **Adiabaticity**
  - **Gaussianity**
  - $\mathbf{n_s<1}$
- What more do we want? **Gravitational waves**. Why?
  - Because the "*extraordinary claim requires extraordinary evidence*"

Watanabe & EK (2006)

Theoretical energy density

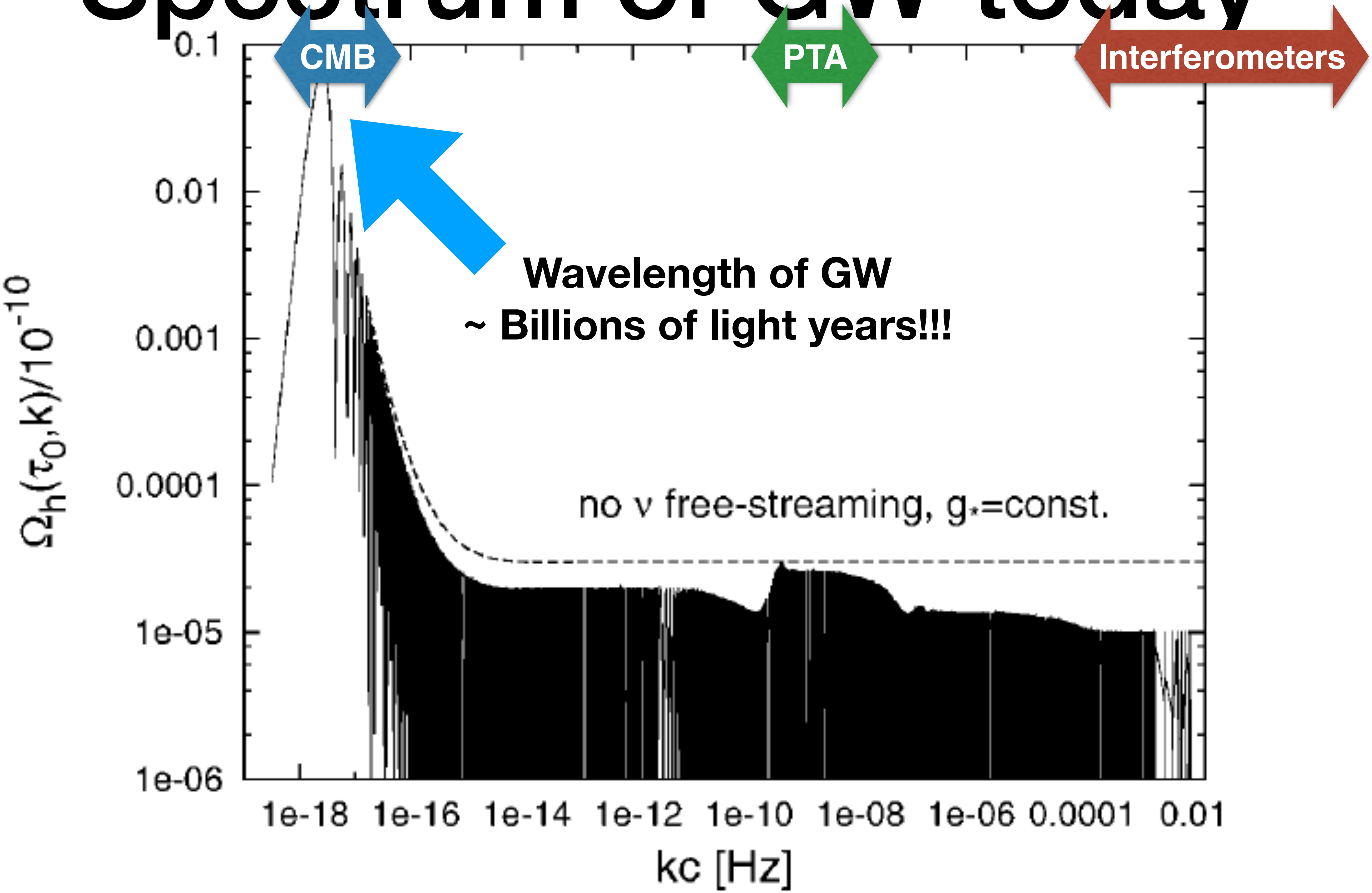
Spectrum of GW today



Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



Finding Signatures of Gravitational Waves in the CMB

- **Next frontier in the CMB research**

1. Find evidence for nearly scale-invariant gravitational waves

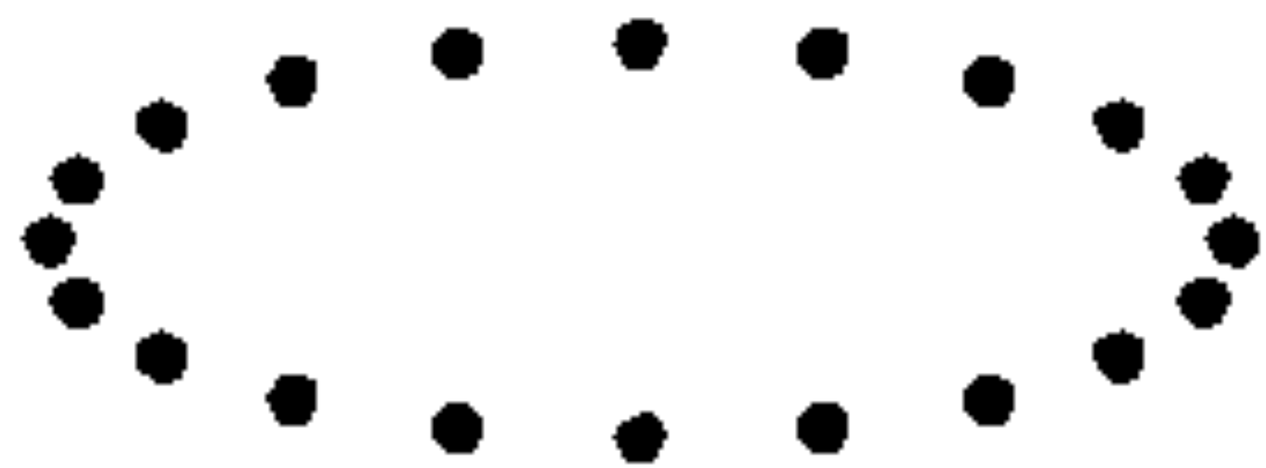
2. Once found, test Gaussianity to make sure (or not!) that the signal comes from **quantum vacuum fluctuation**

3. Constrain inflation models

Gravitational Waves

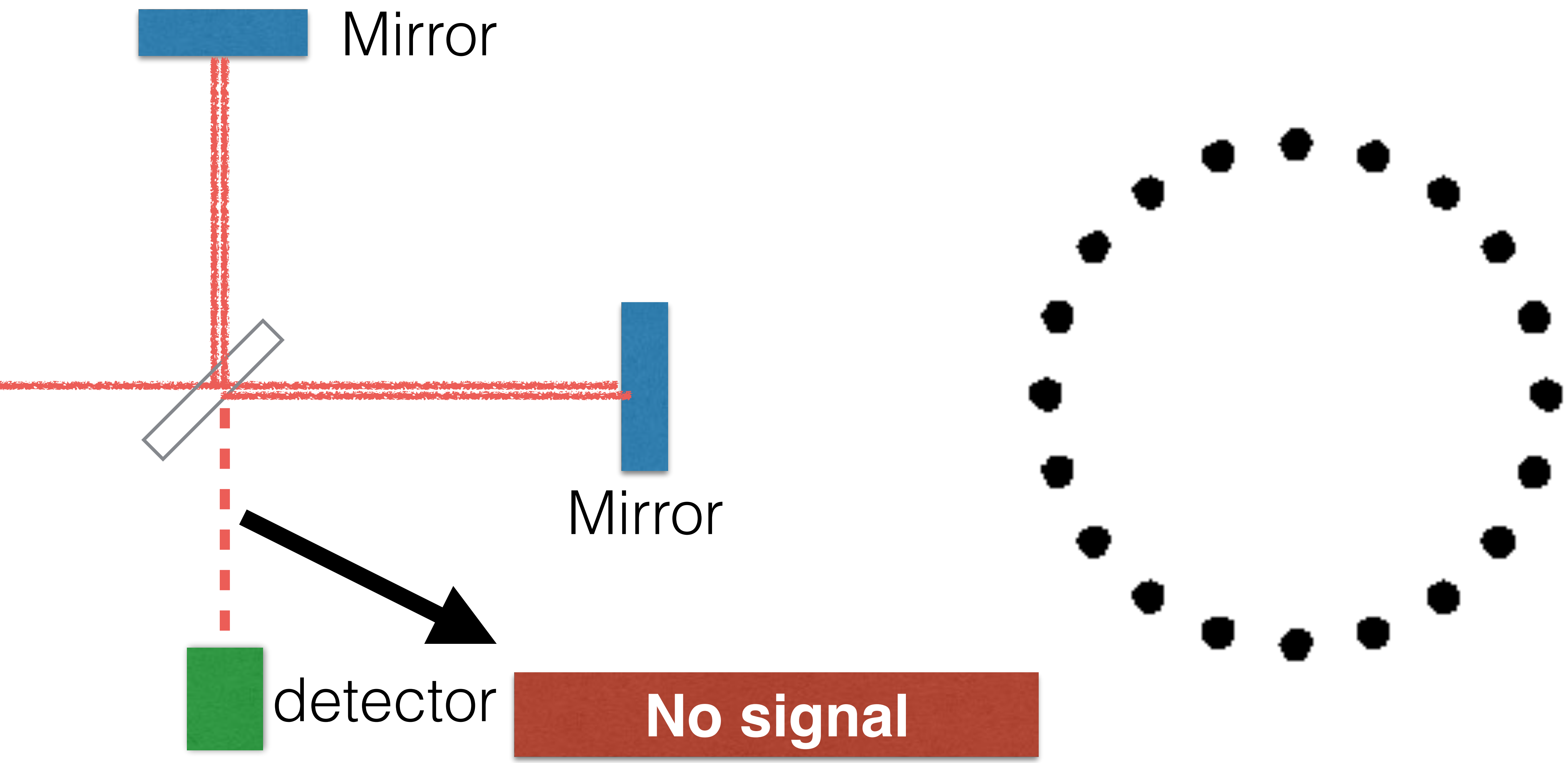
- GW changes the distances between two points

$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$

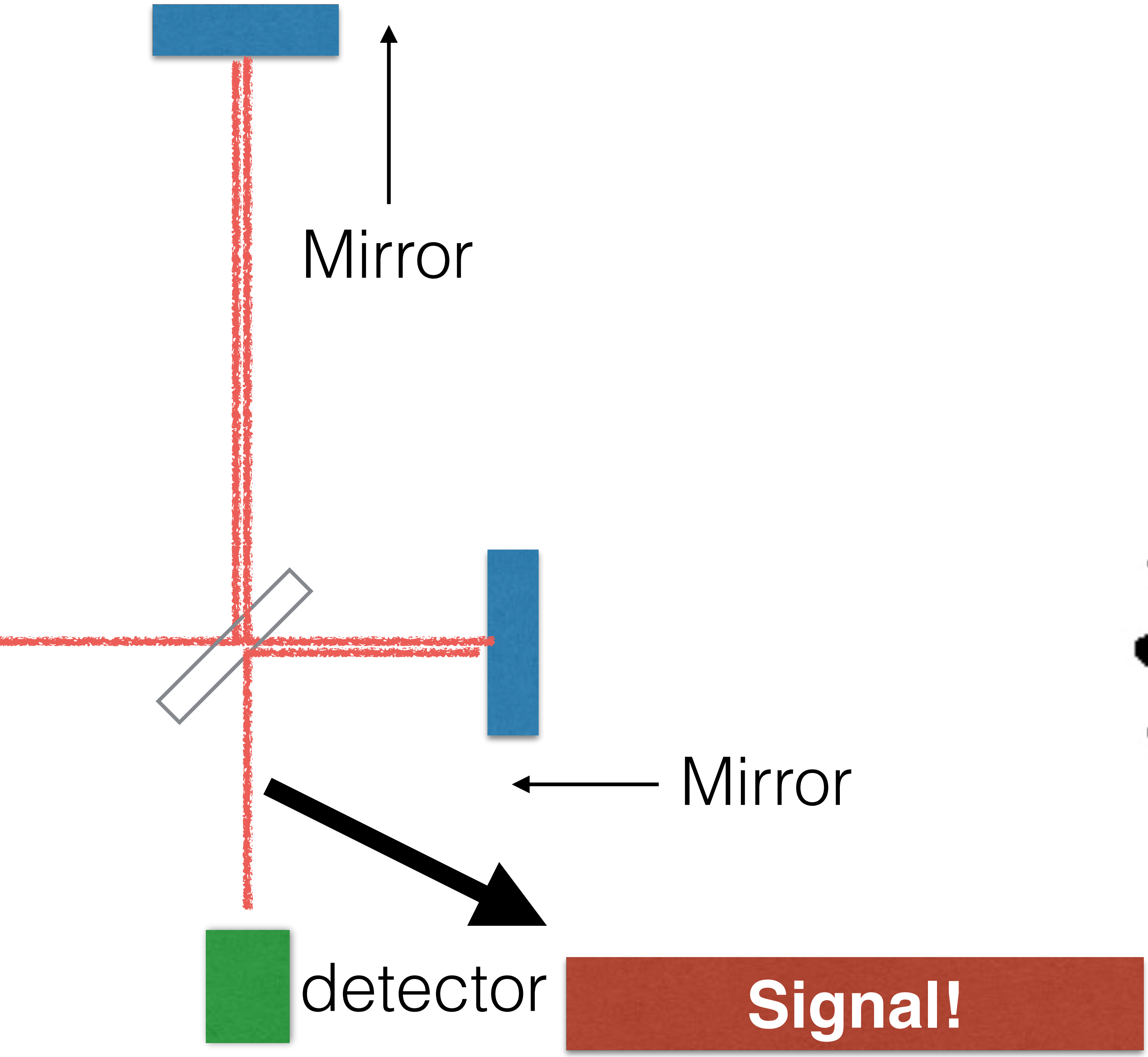


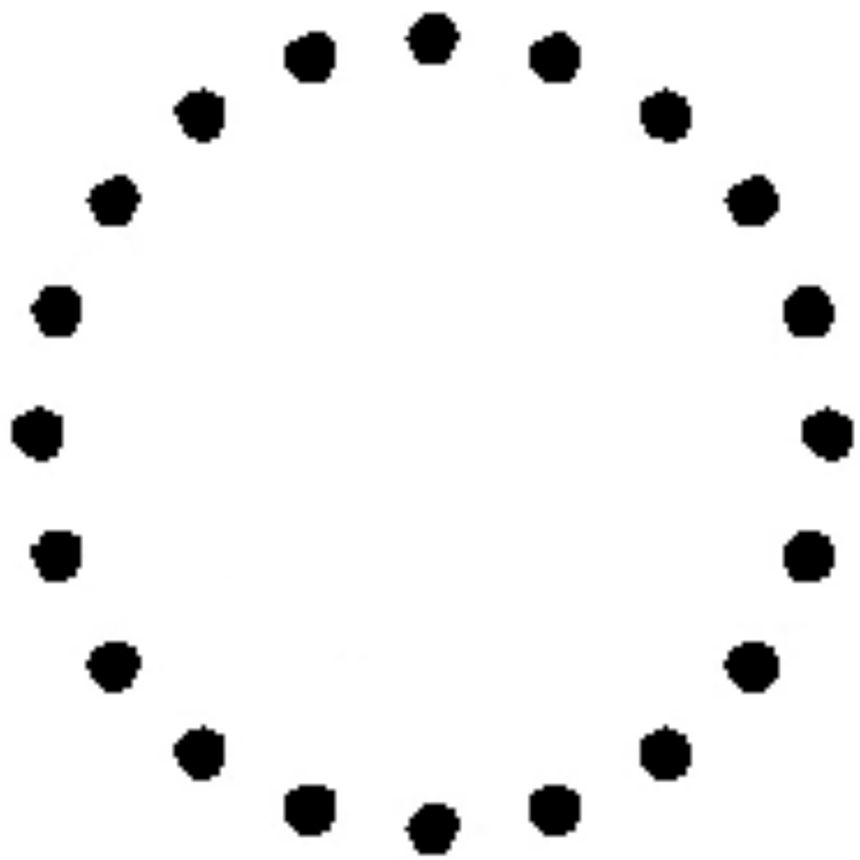
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{D_{ij}}) dx^i dx^j$$

Laser Interferometer

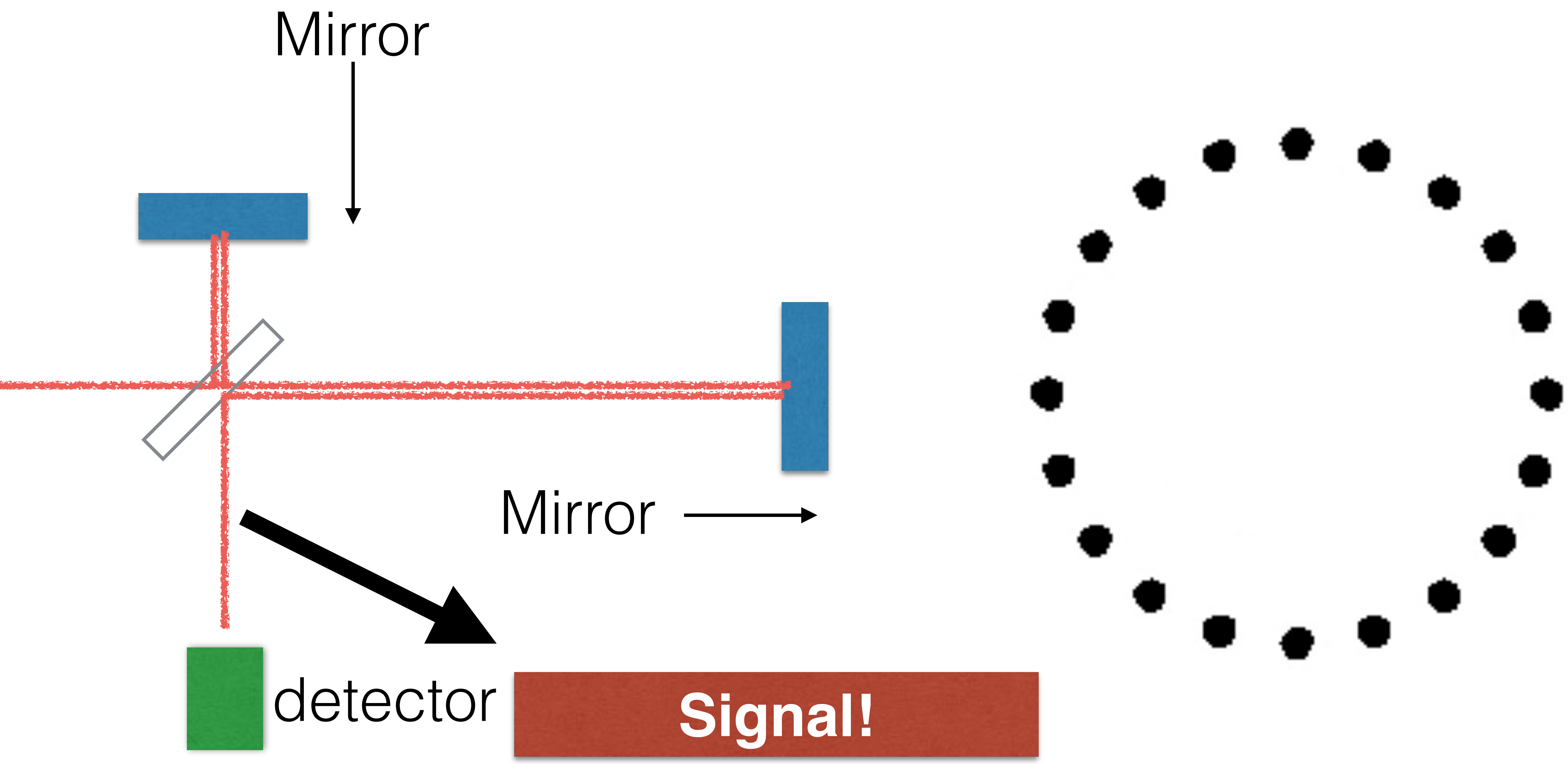


Laser Interferometer





Laser Interferometer



LIGO detected GW from binary blackholes, with the wavelength of thousands of kilometres

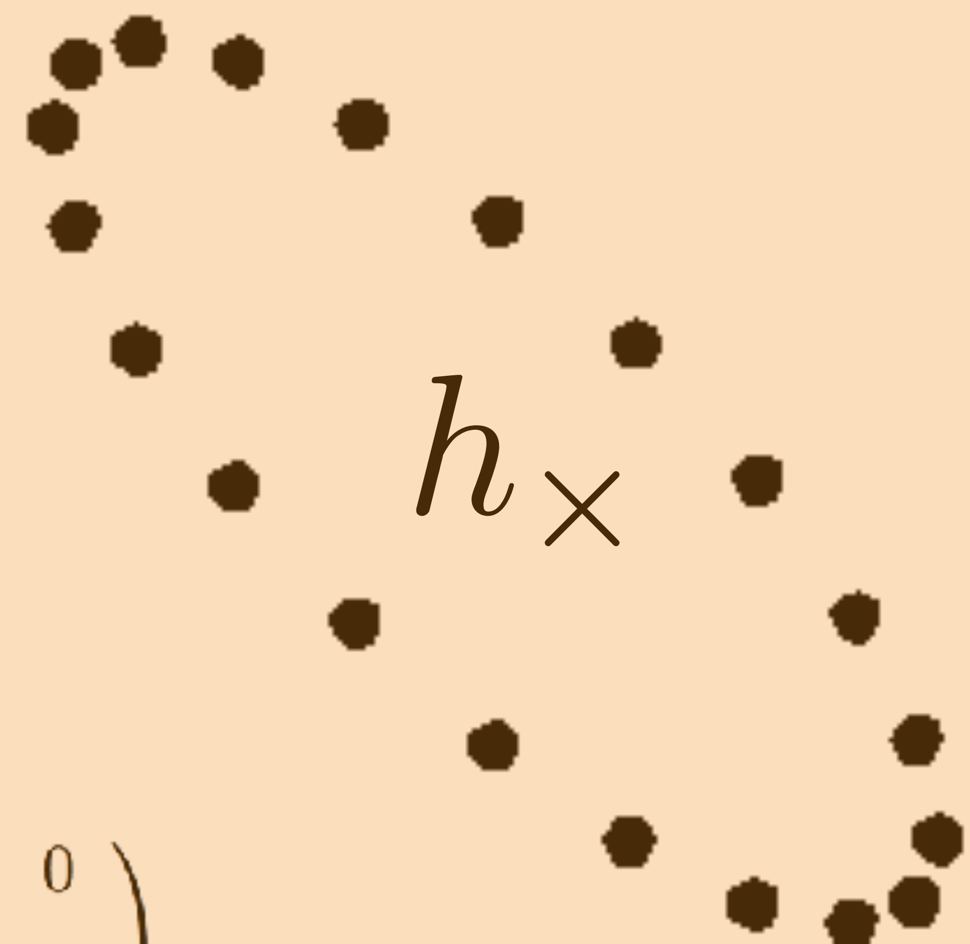
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

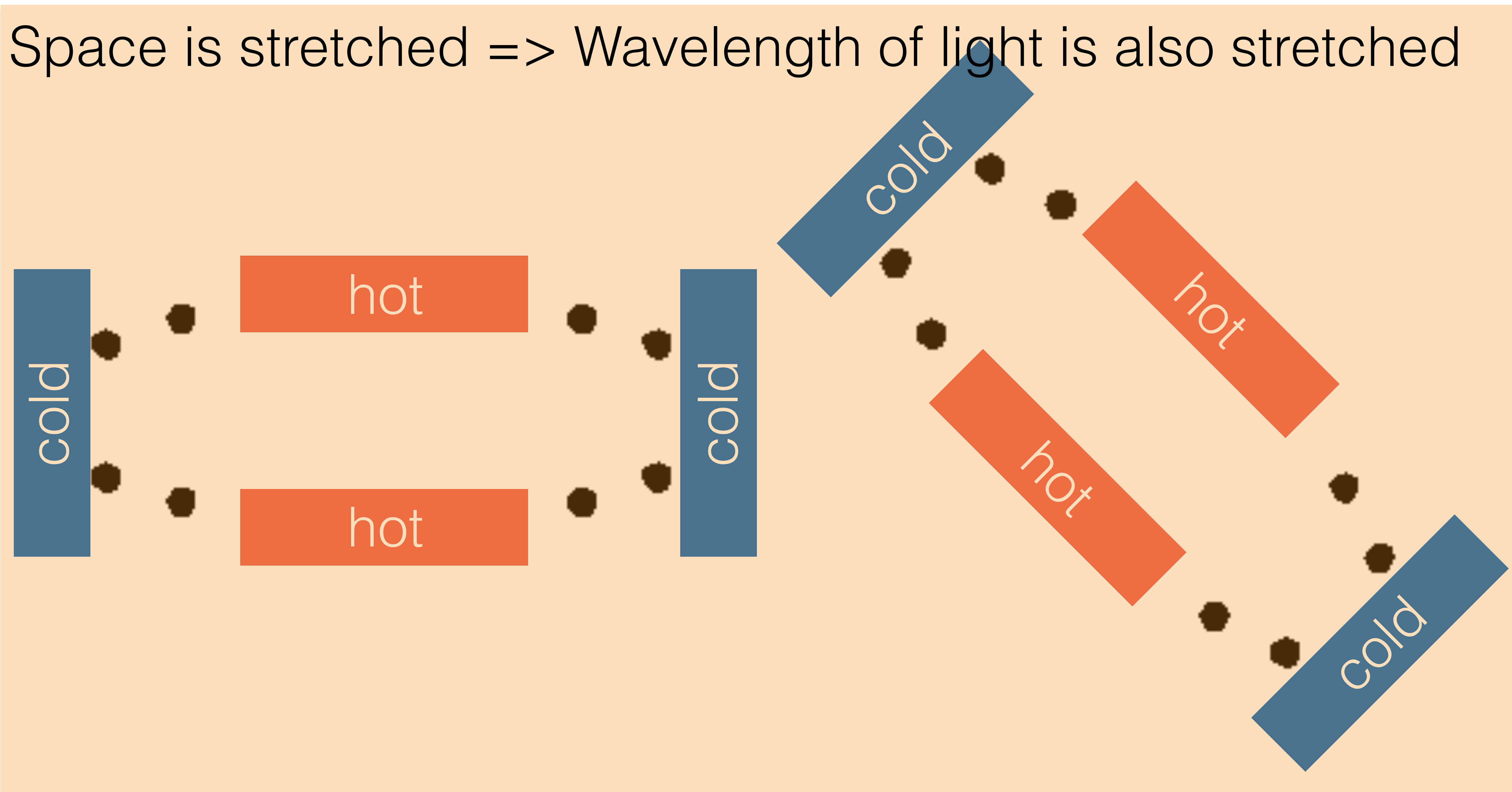
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields

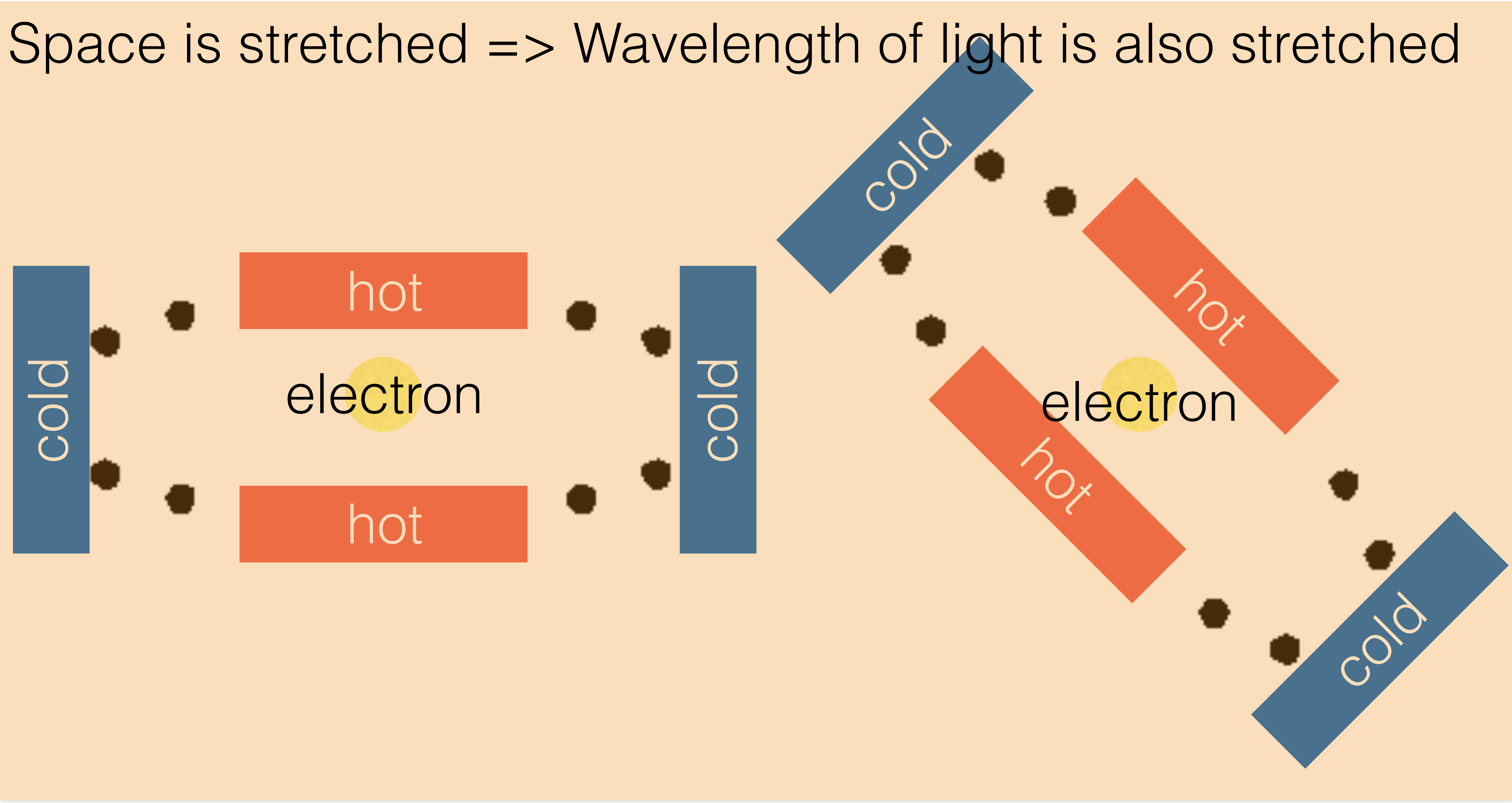


$$D_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Detecting GW by CMB

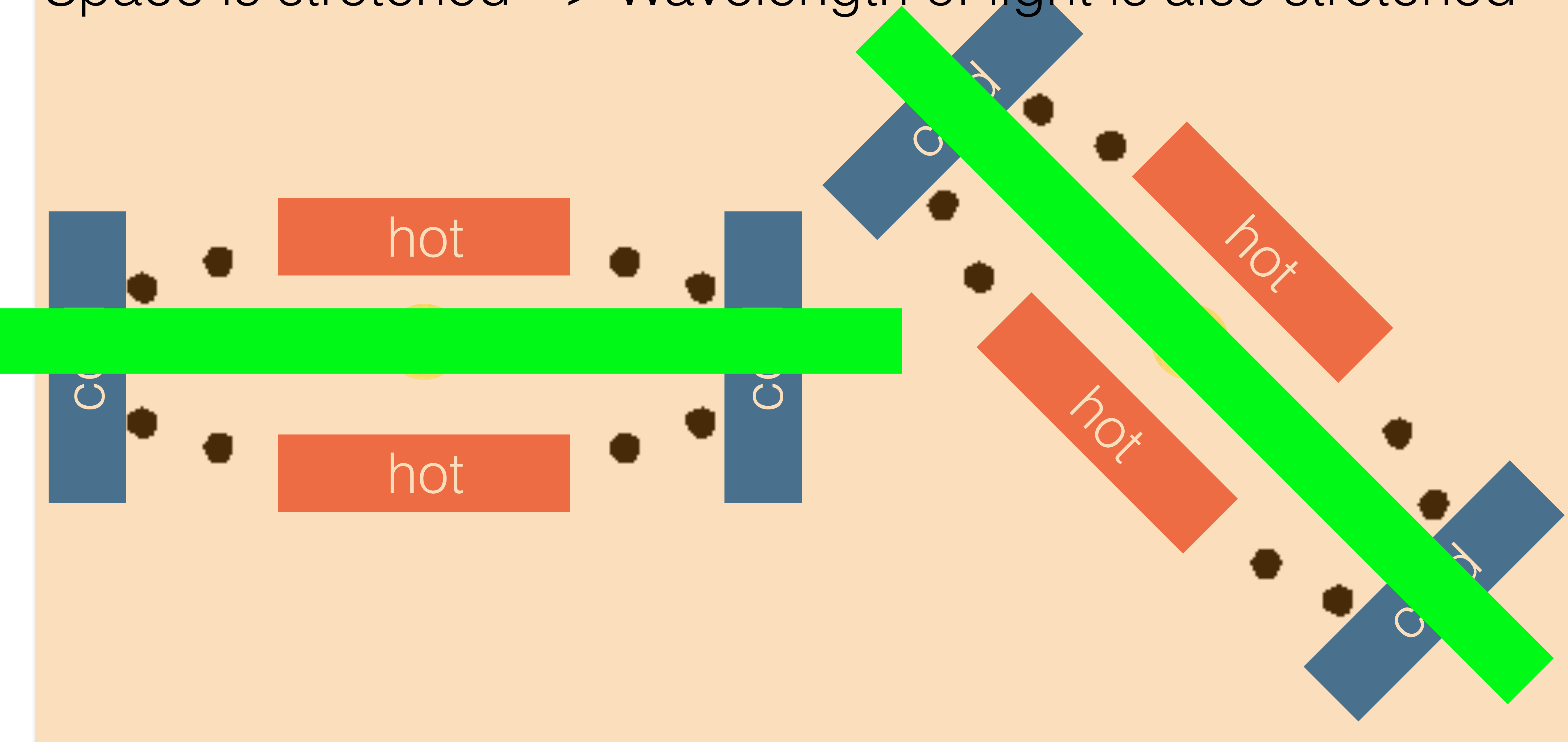


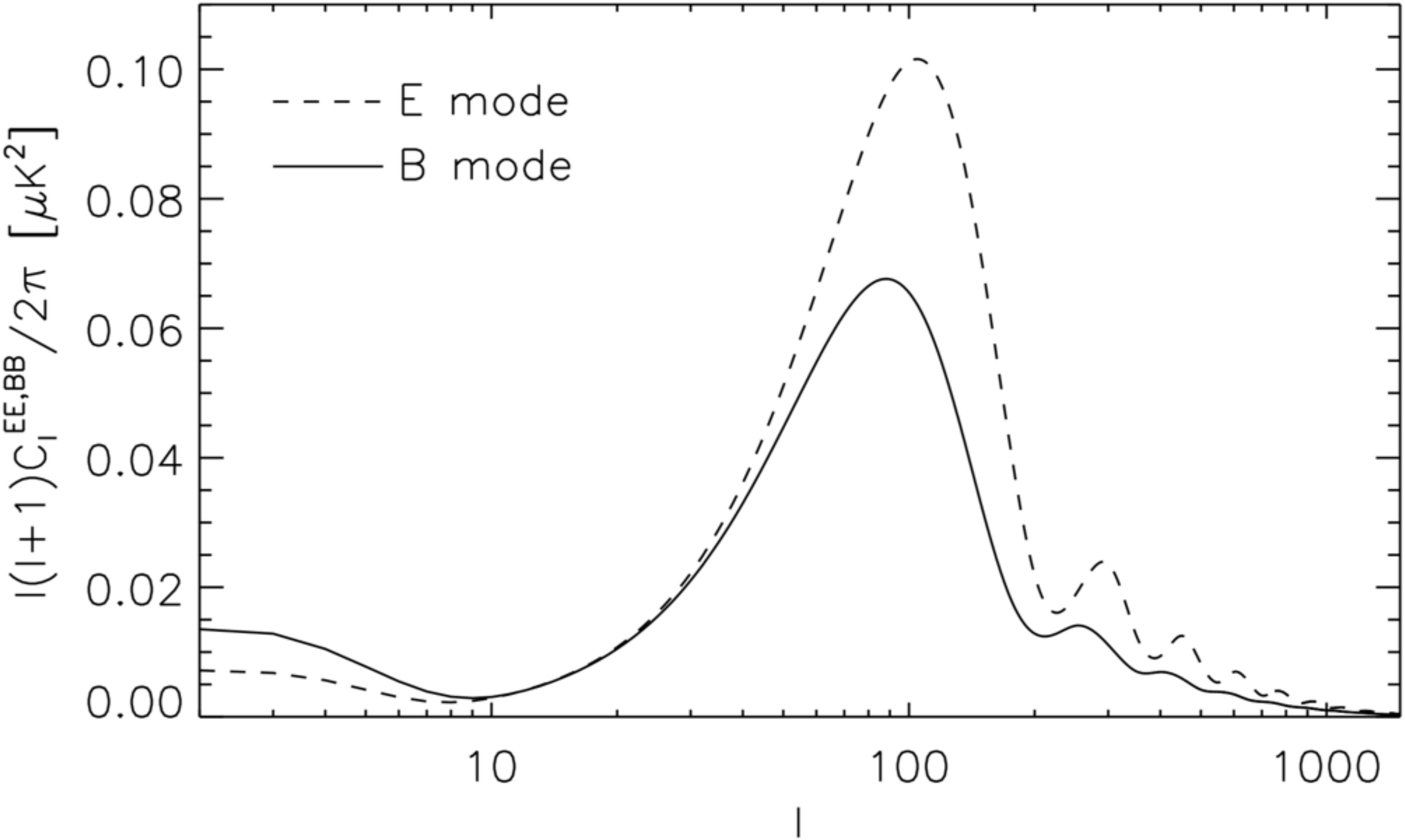
Detecting GW by CMB
Polarisation



Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched





- E and B modes are produced nearly equally, but on small scales B is smaller than E because of geometrical effects

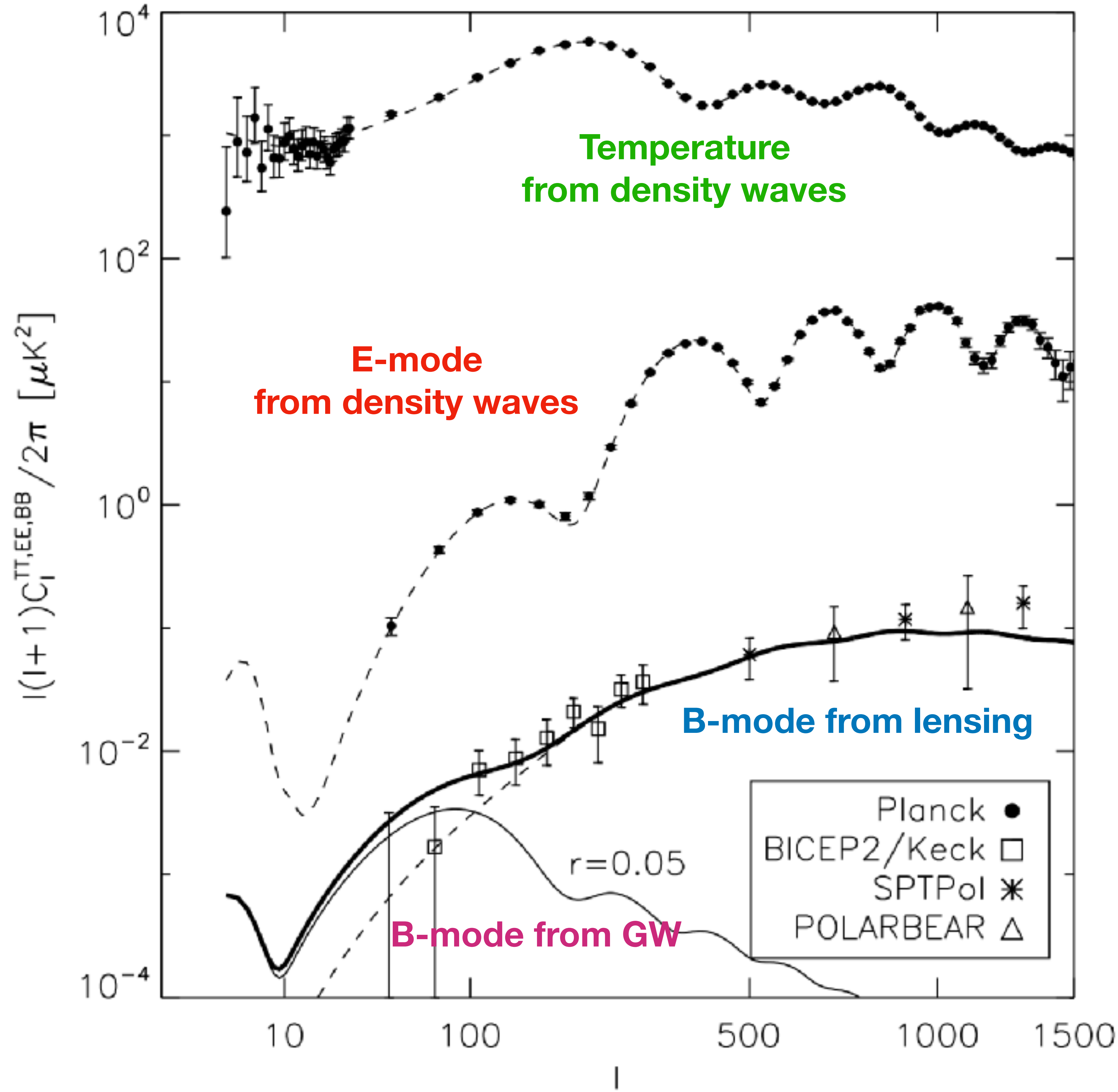
Tensor-to-scalar Ratio

$$r \equiv \frac{\langle D_{ij} D^{ij} \rangle}{\langle \zeta^2 \rangle}$$

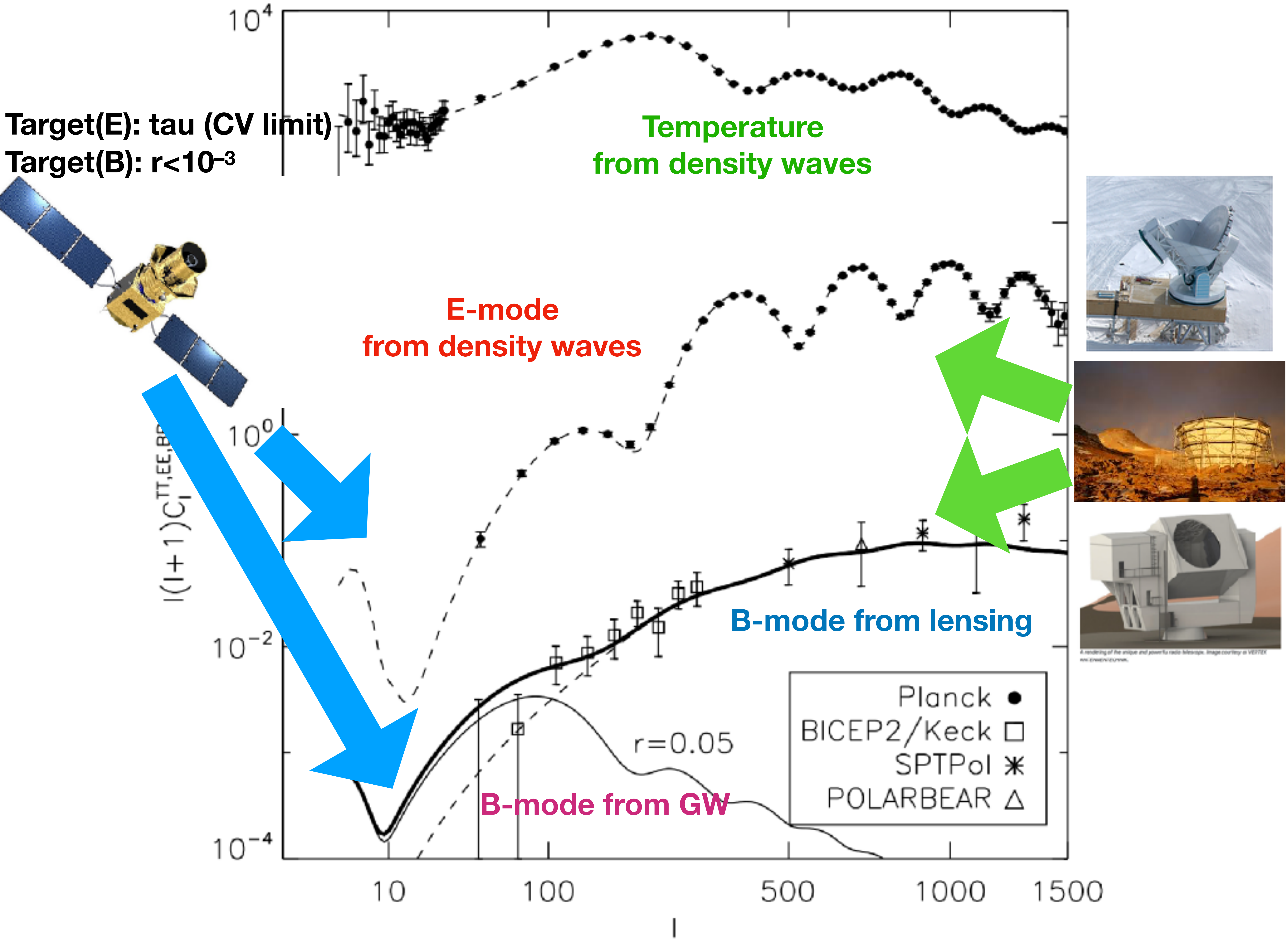
curvature perturbation
~"gravitational potential"

- We really want to find this! The current upper bound is **r<0.07** (95%CL)

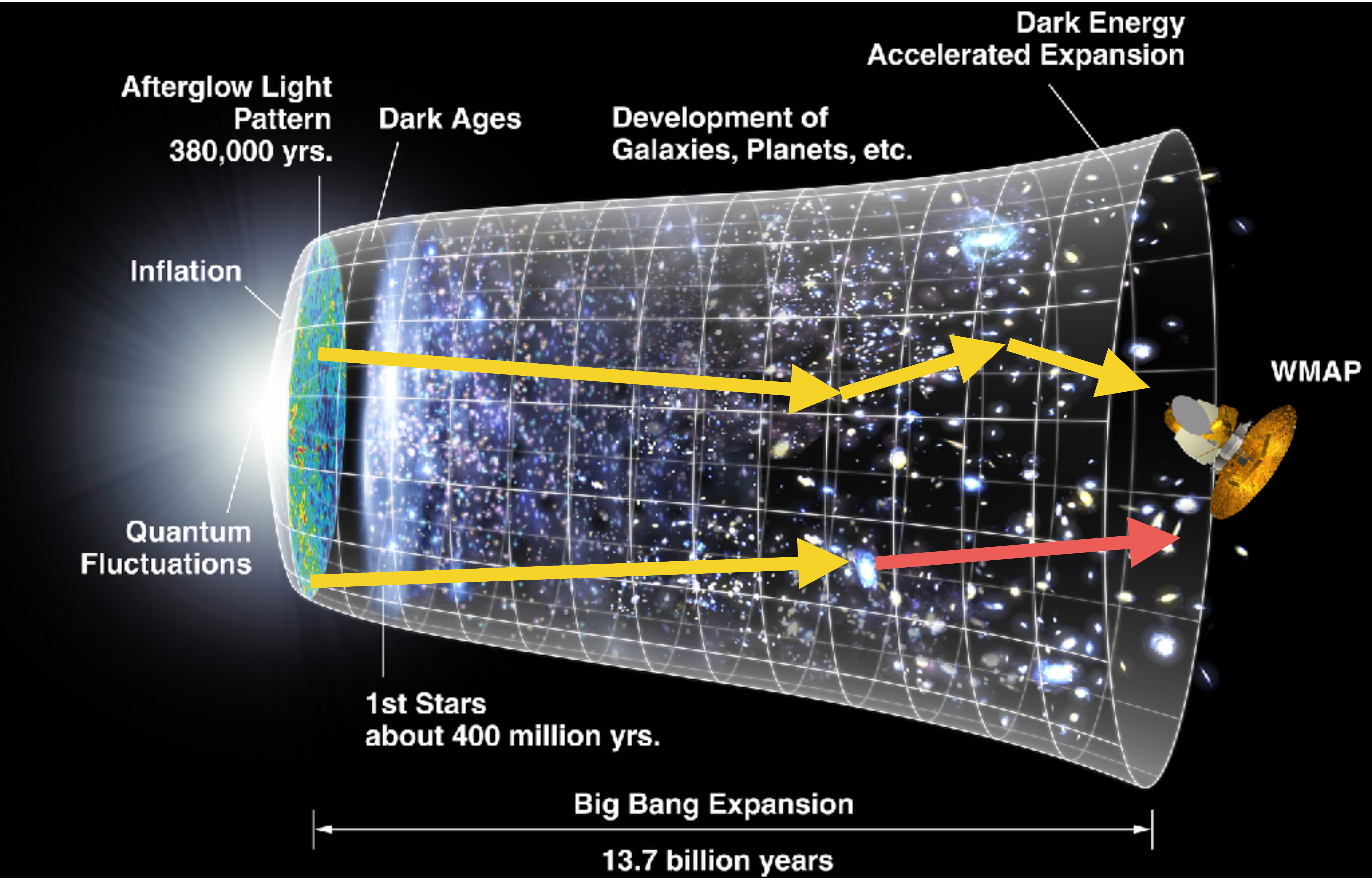
BICEP2/Keck Array Collaboration (2016)



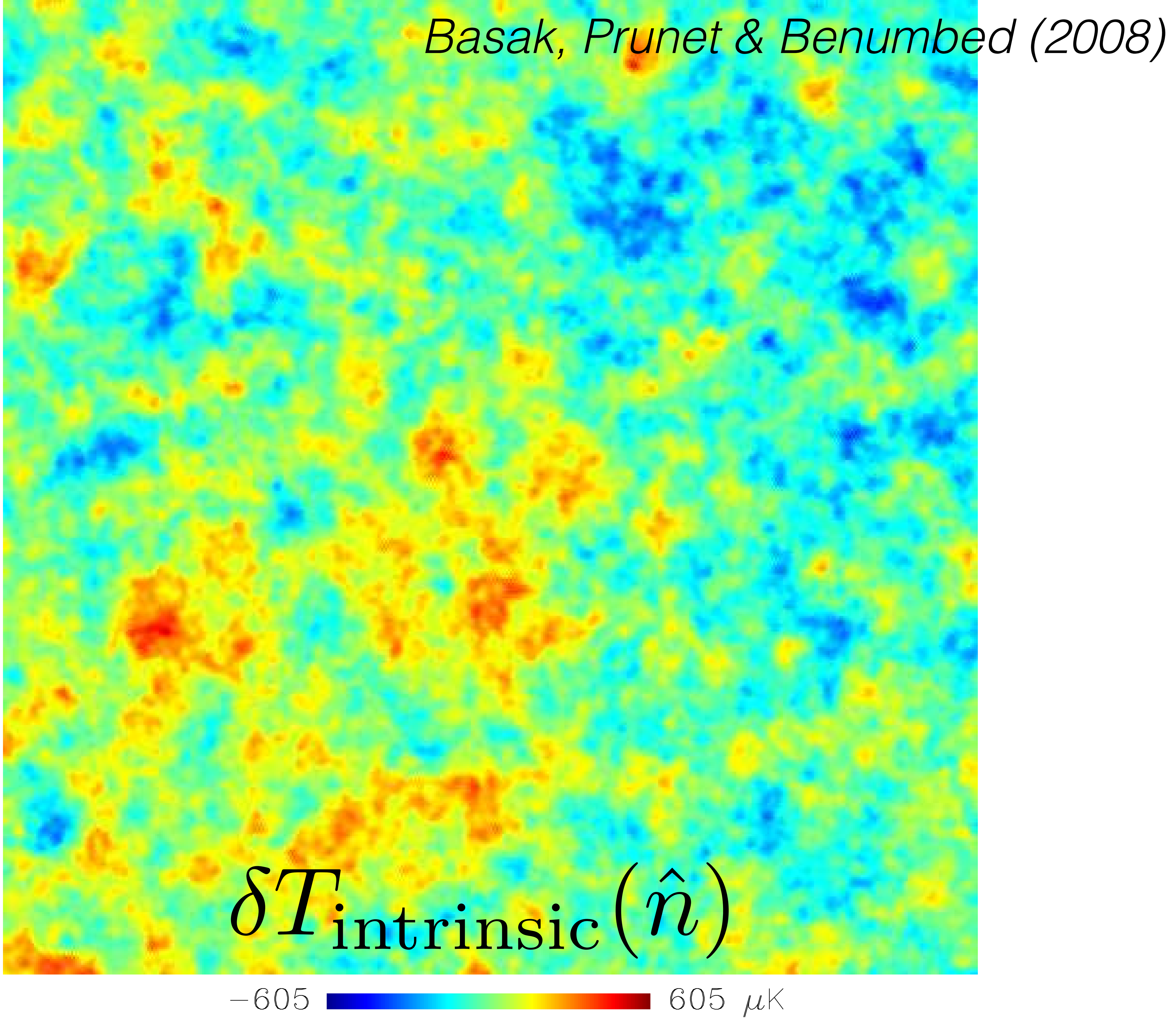
Temperature
from density waves
E-mode
from density waves
B-mode from lensing
B-mode from GW
r=0.05
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
l


Target(E): tau (CV limit)
Target(B): r<10⁻³
Temperature
from density waves
E-mode
from density waves
B-mode from lensing
B-mode from GW
r=0.05
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}$
10^4
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
l

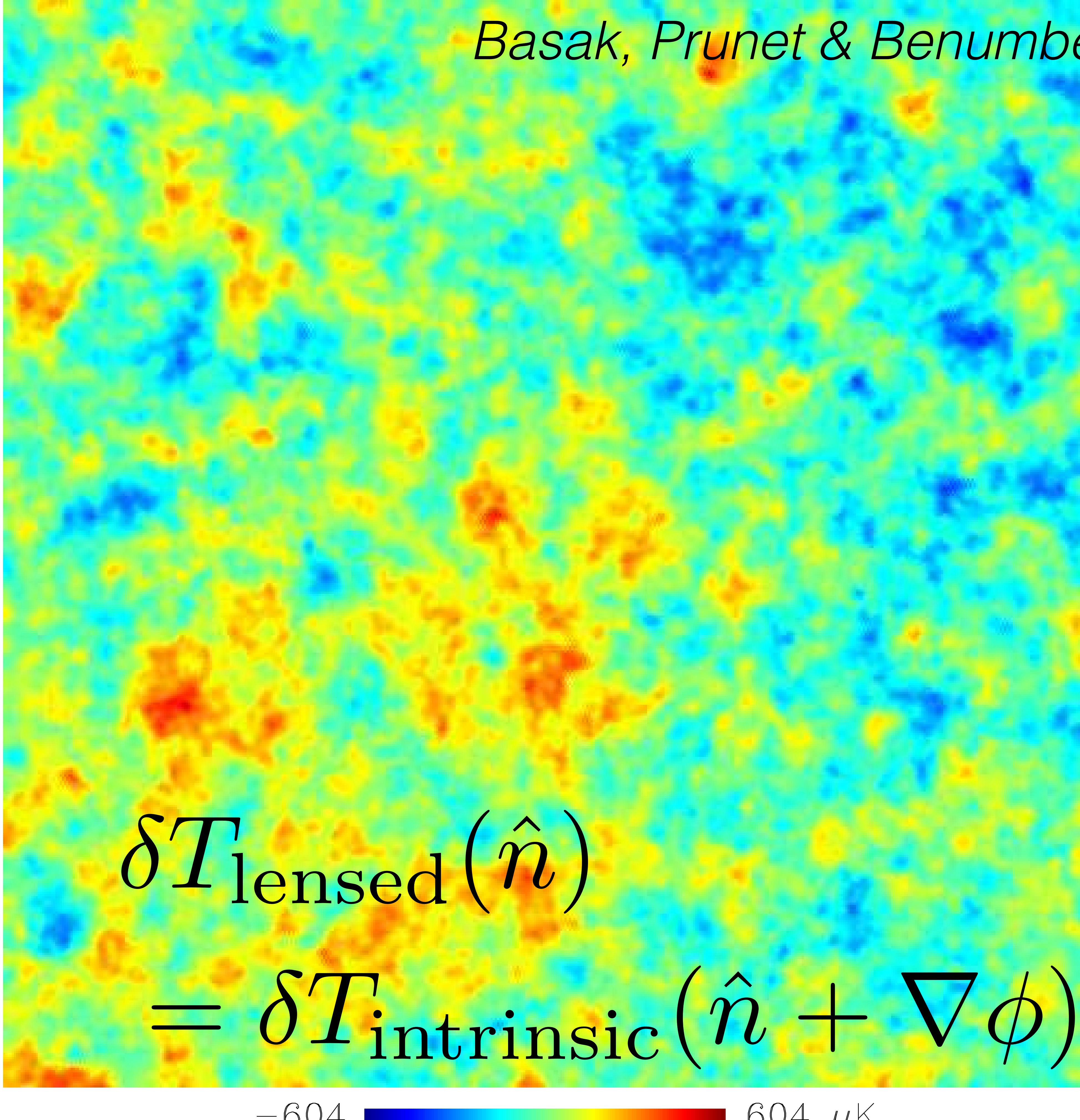
Low-redshift Rocks



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

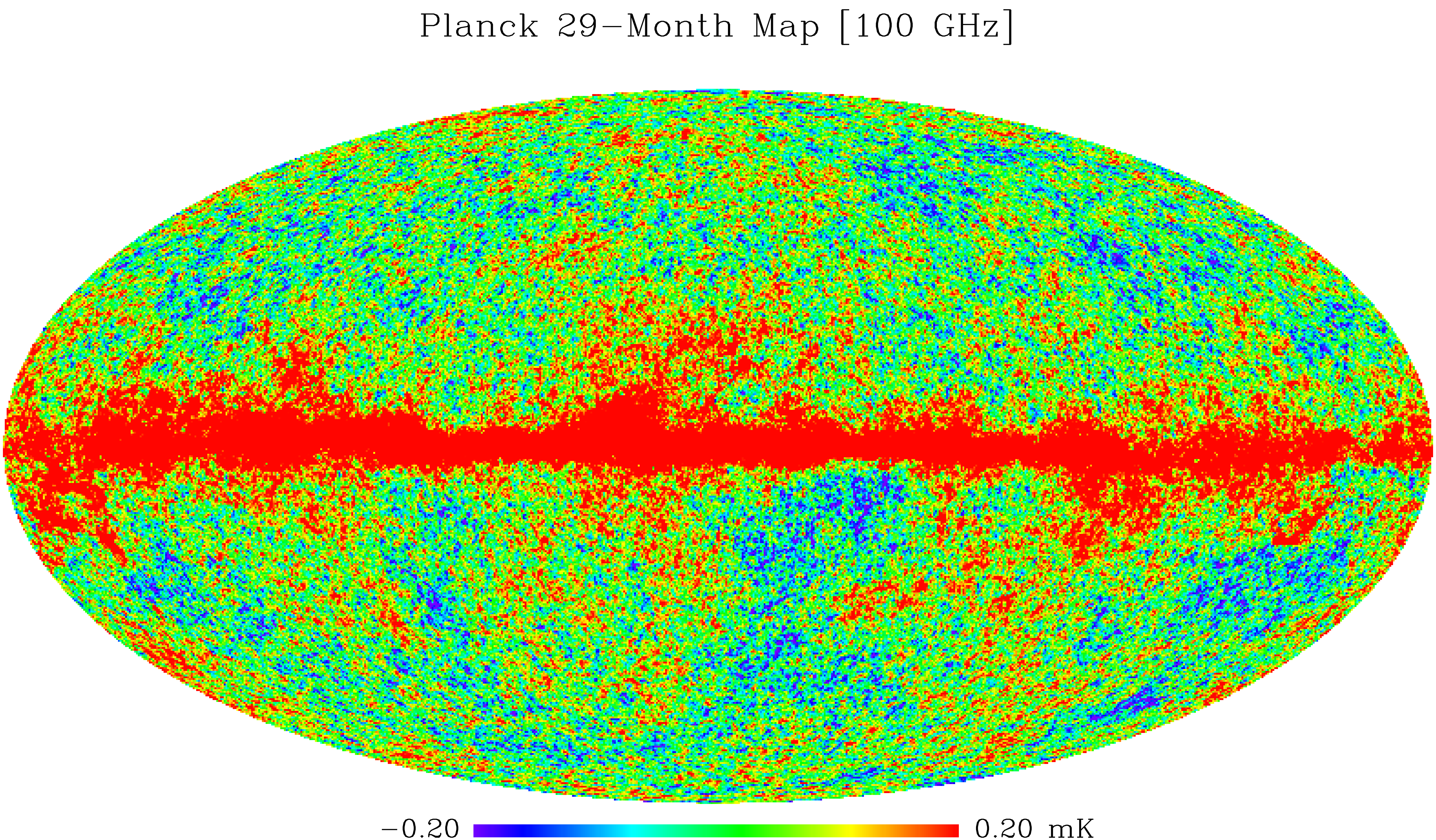

Basak, Prunet & Benumbed (2008)
$\delta T_{\text{intrinsic}}(\hat{n})$
−605
605 μK

Basak, Prunet & Benumbed (2008)



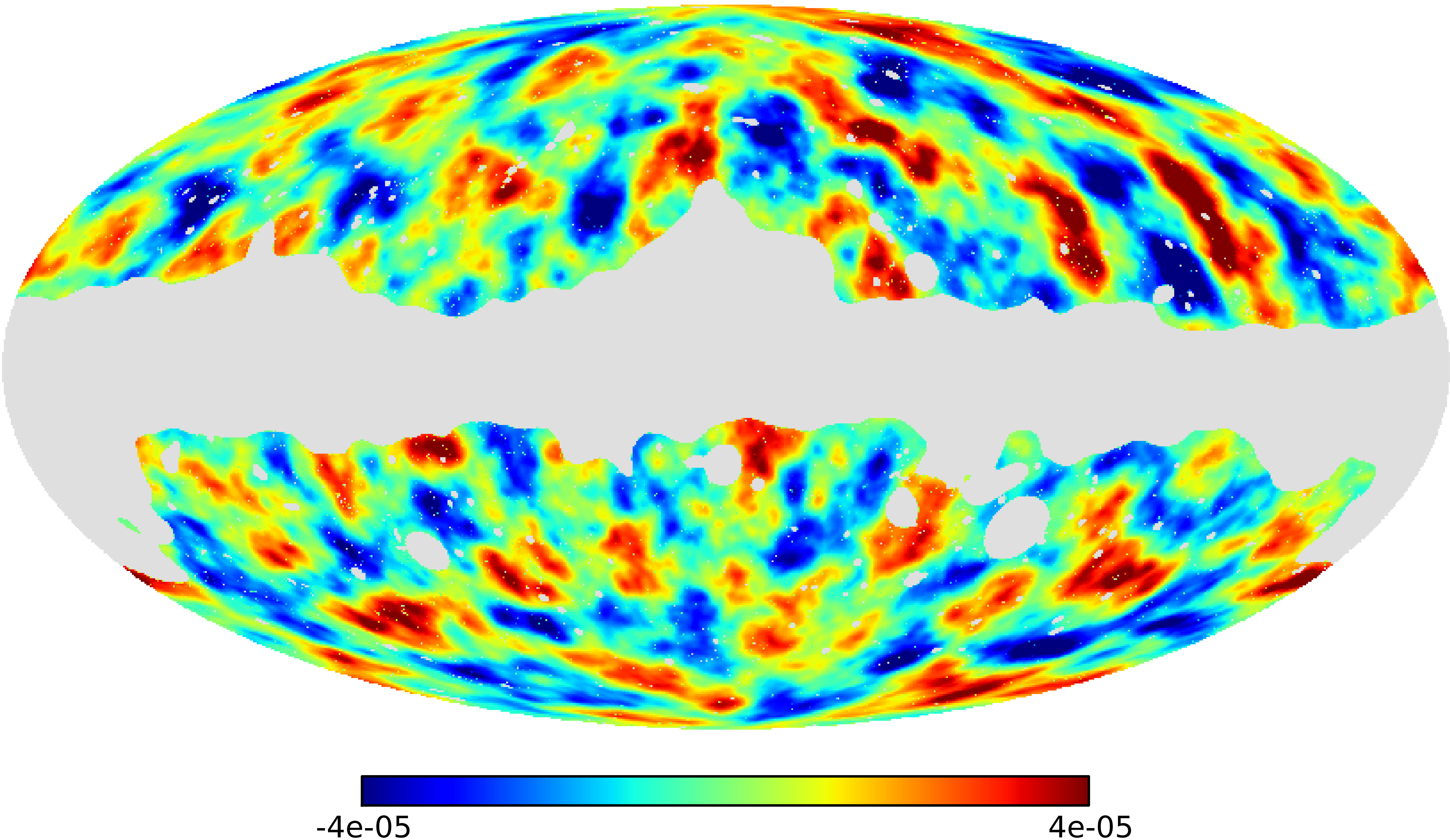
$$\delta T_{\rm lensed}(\hat{n}) = \delta T_{\rm intrinsic}(\hat{n} + \nabla\phi)$$

Planck Collaboration

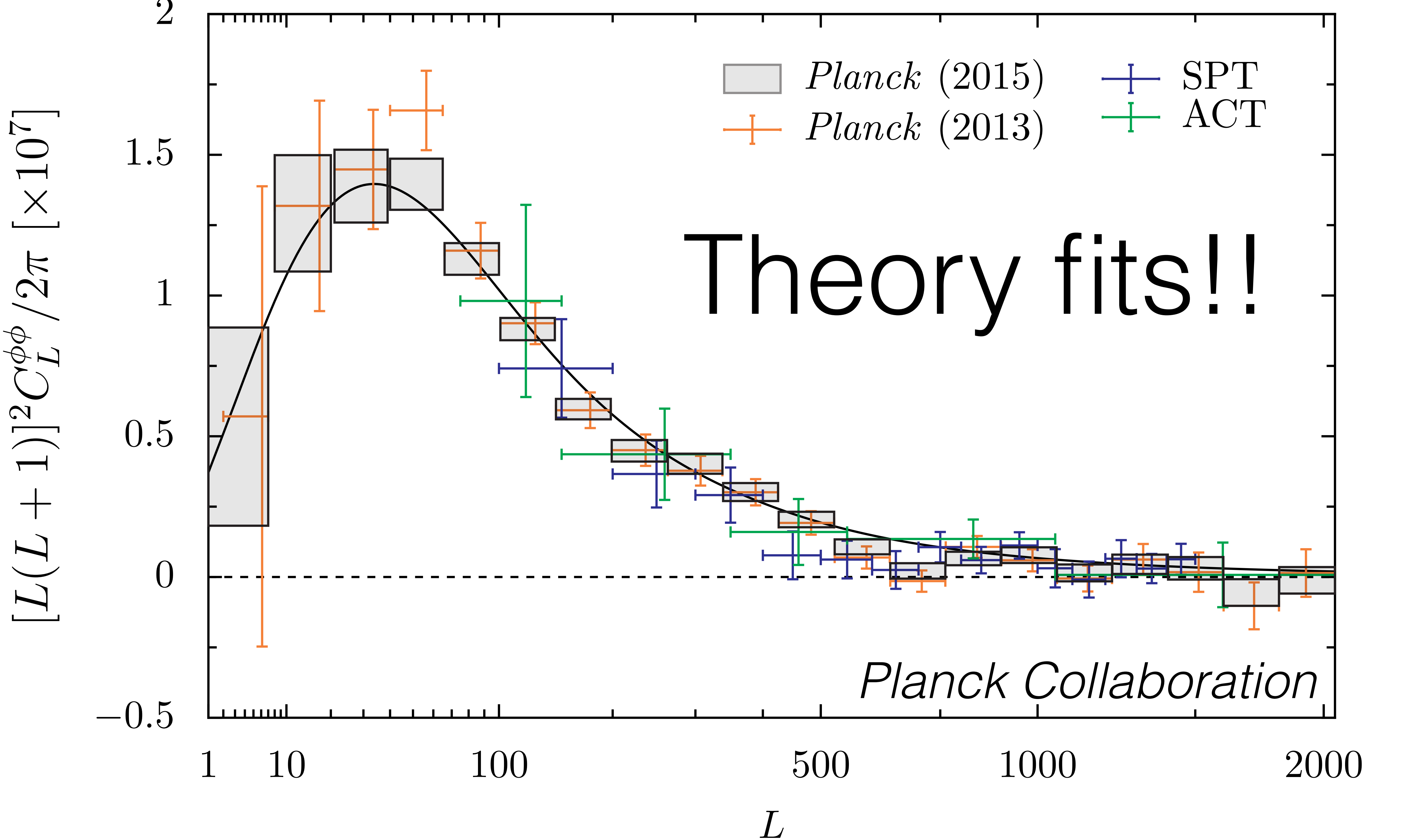


From full-sky temperature maps to…

Planck Collaboration



A full-sky lensing potential map!



…and our knowledge of the matter distribution improves

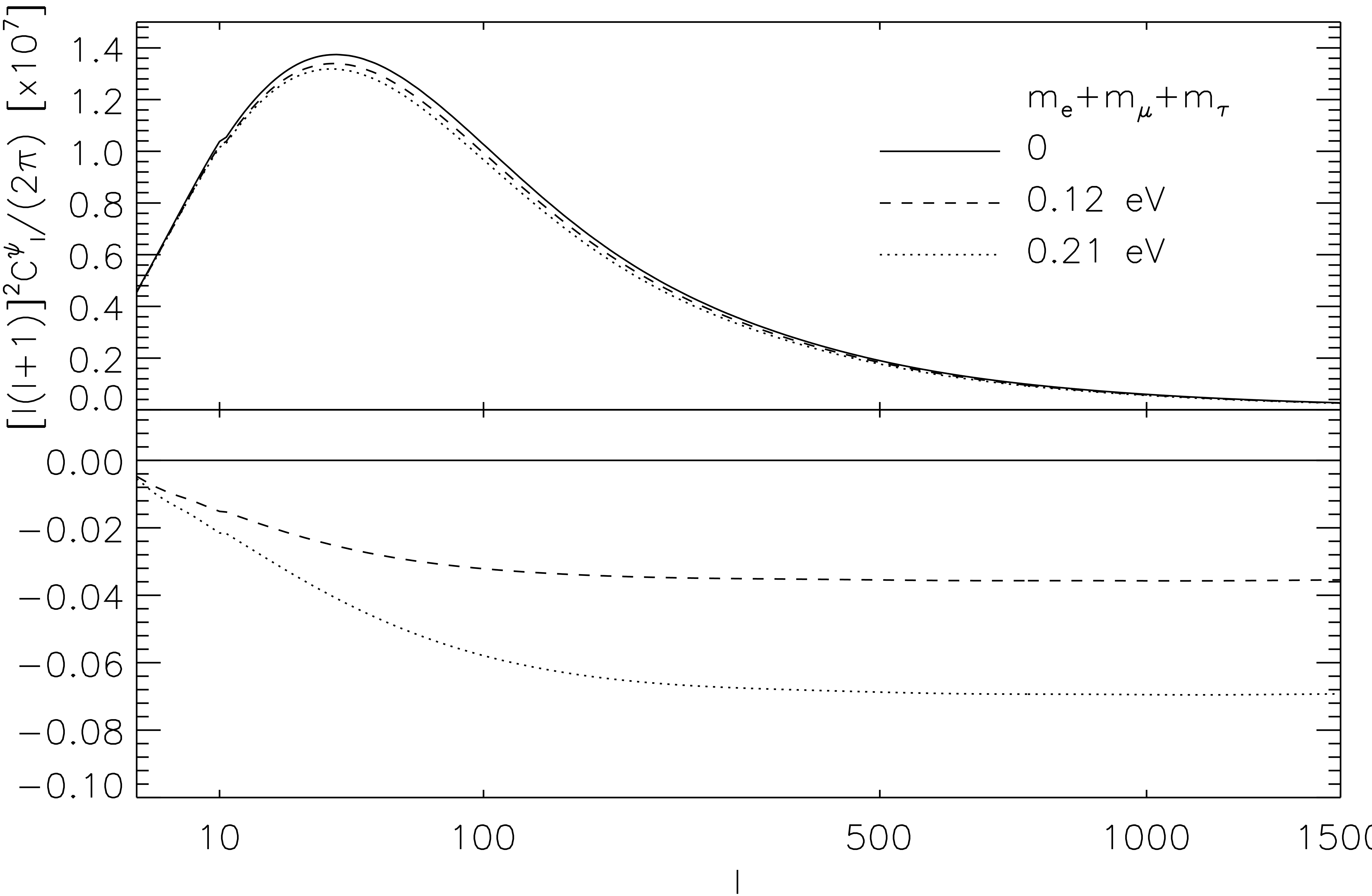
$$\Omega_m = 0.315 \pm 0.013$$
$$\sigma_8 = 0.829 \pm 0.014$$

Adding the lensing info

$$\Omega_m = 0.308 \pm 0.012$$
$$\sigma_8 = 0.8149 \pm 0.0093$$

CMB Lensing Science Case

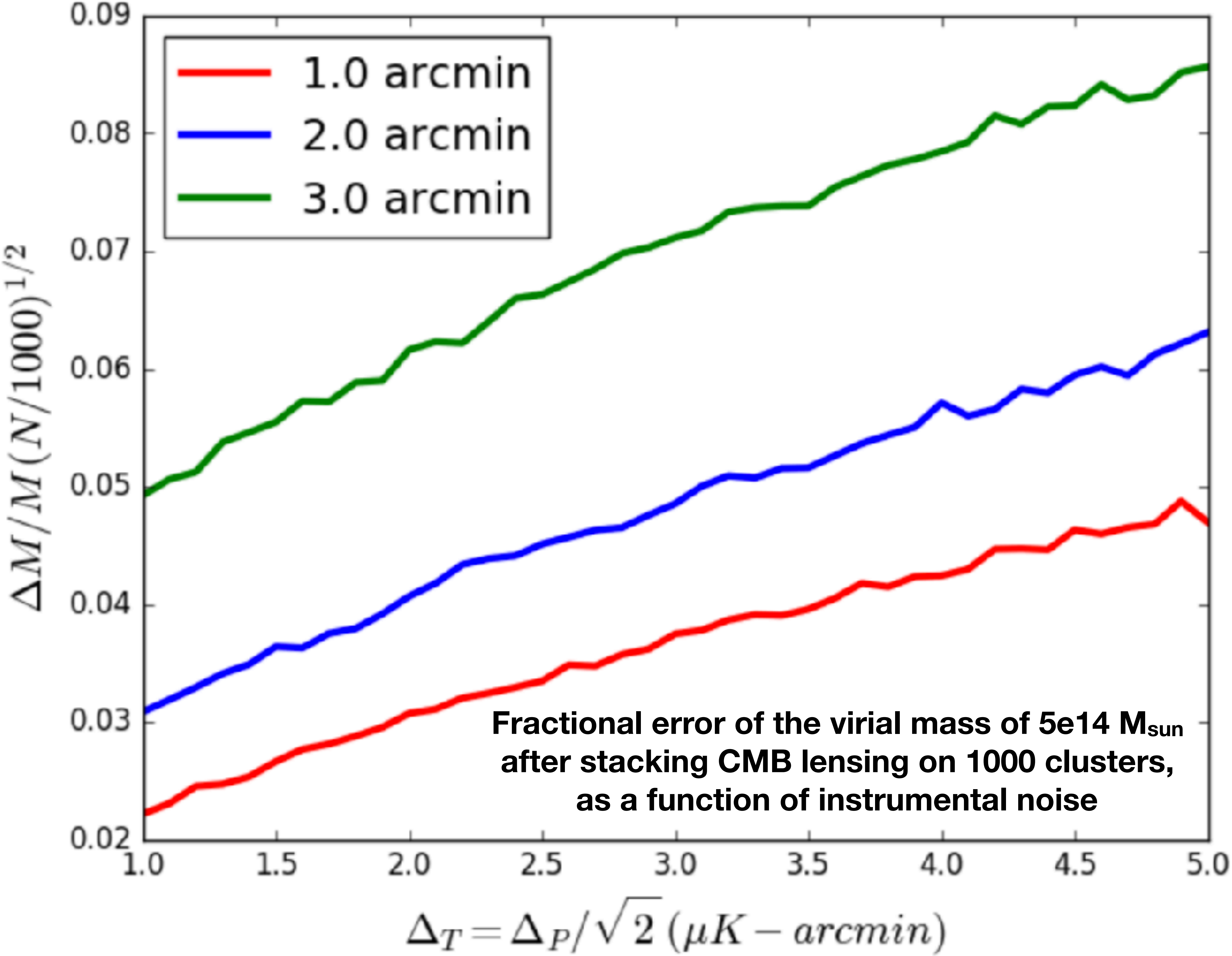
- Neutrino mass
  - Massive neutrinos slow down the cosmic structure formation, suppressing the lensing power spectrum
  - The lower bound to the total neutrino mass from the neutrino oscillation experiments is >0.06 eV
  - Can we find this?



$[l(l+1)]^2 C^{\psi}_l/(2\pi)$ [x10^7]
$m_e+m_\mu+m_\tau$
0
0.12 eV
0.21 eV
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
10
100
500
1000
1500
l

CMB Lensing Science Case

- Measure galaxy cluster masses
  - High-resolution measurements of CMB lensing yield unbiased masses of galaxy clusters
  - Great for calibrating galaxy cluster mass-observable relations for cosmology!

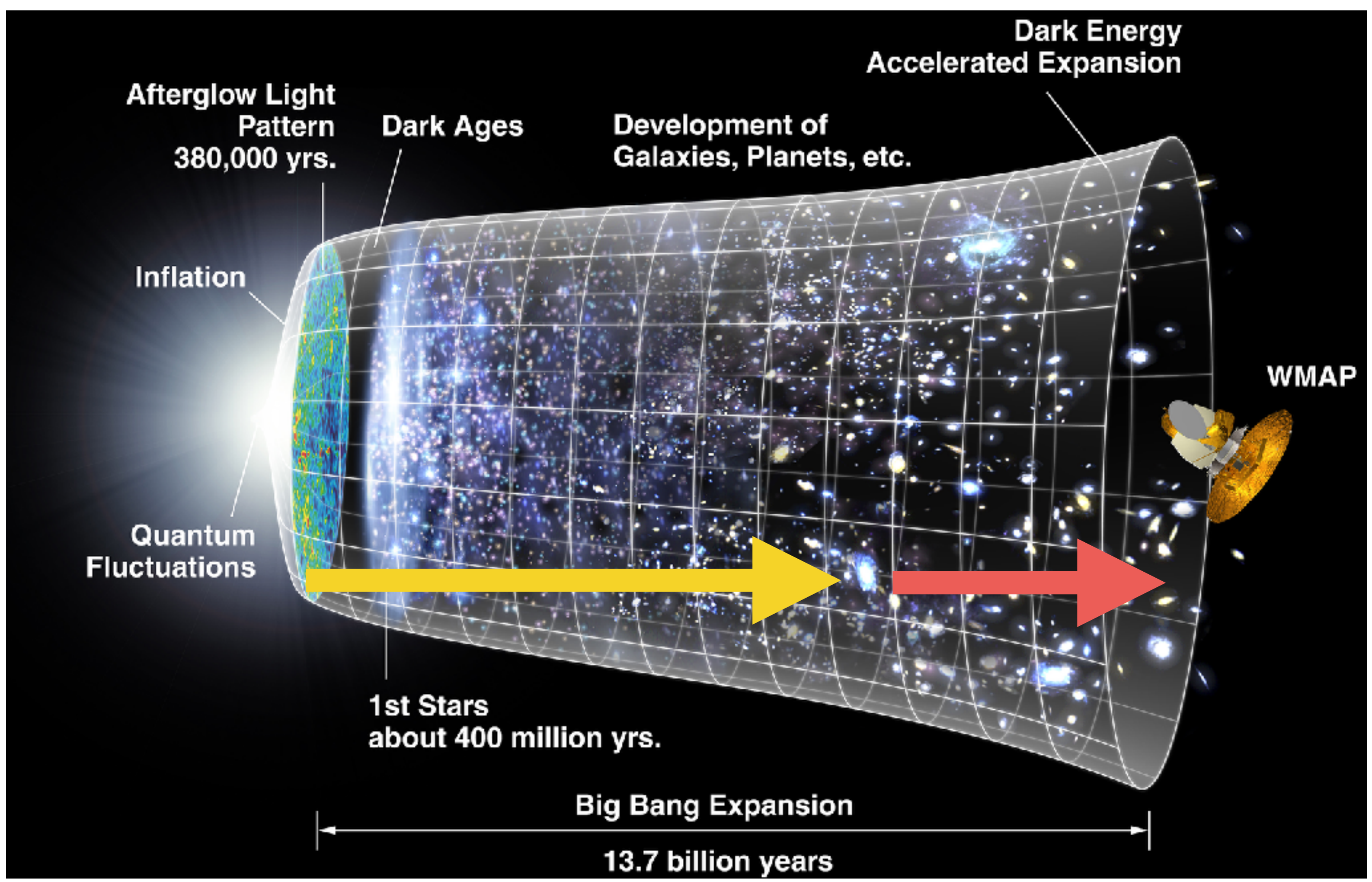


1.0 arcmin
2.0 arcmin
3.0 arcmin
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
$\Delta M/M(N/1000)^{1/2}$
$\Delta_T = \Delta_P/\sqrt{2}\,(\mu K - arcmin)$
Fractional error of the virial mass of 5e14 M_{sun}
after stacking CMB lensing on 1000 clusters,
as a function of instrumental noise

The Sunyaev-Zel'dovich Effect

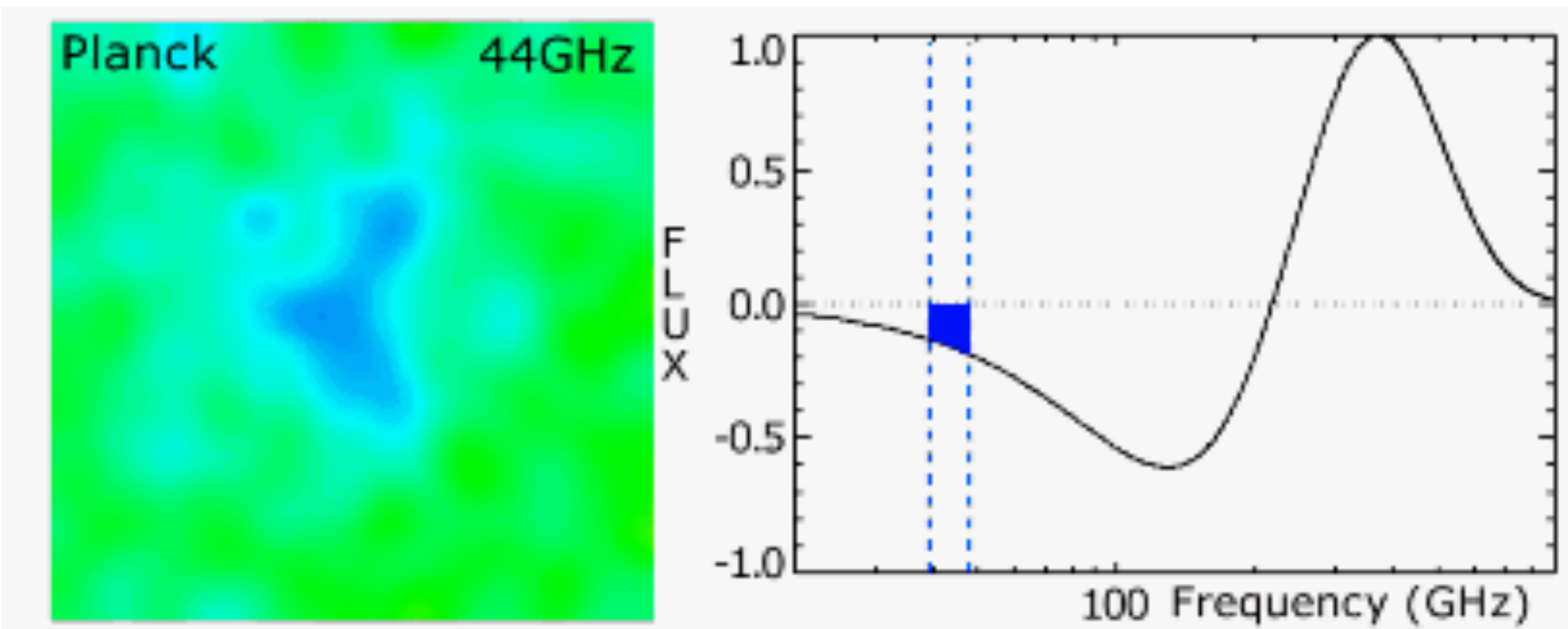
- The "thermal" SZ effect (in the non-relativistic limit) enables us to map thermal pressure in the universe

$$Y_{\mathrm{tSZ}}(\boldsymbol{\theta}) = \frac{k_B \sigma_T}{m_e c^2} \int \mathrm{d}l \, n_e(\boldsymbol{\theta}, l) \, T(\boldsymbol{\theta}, l)$$

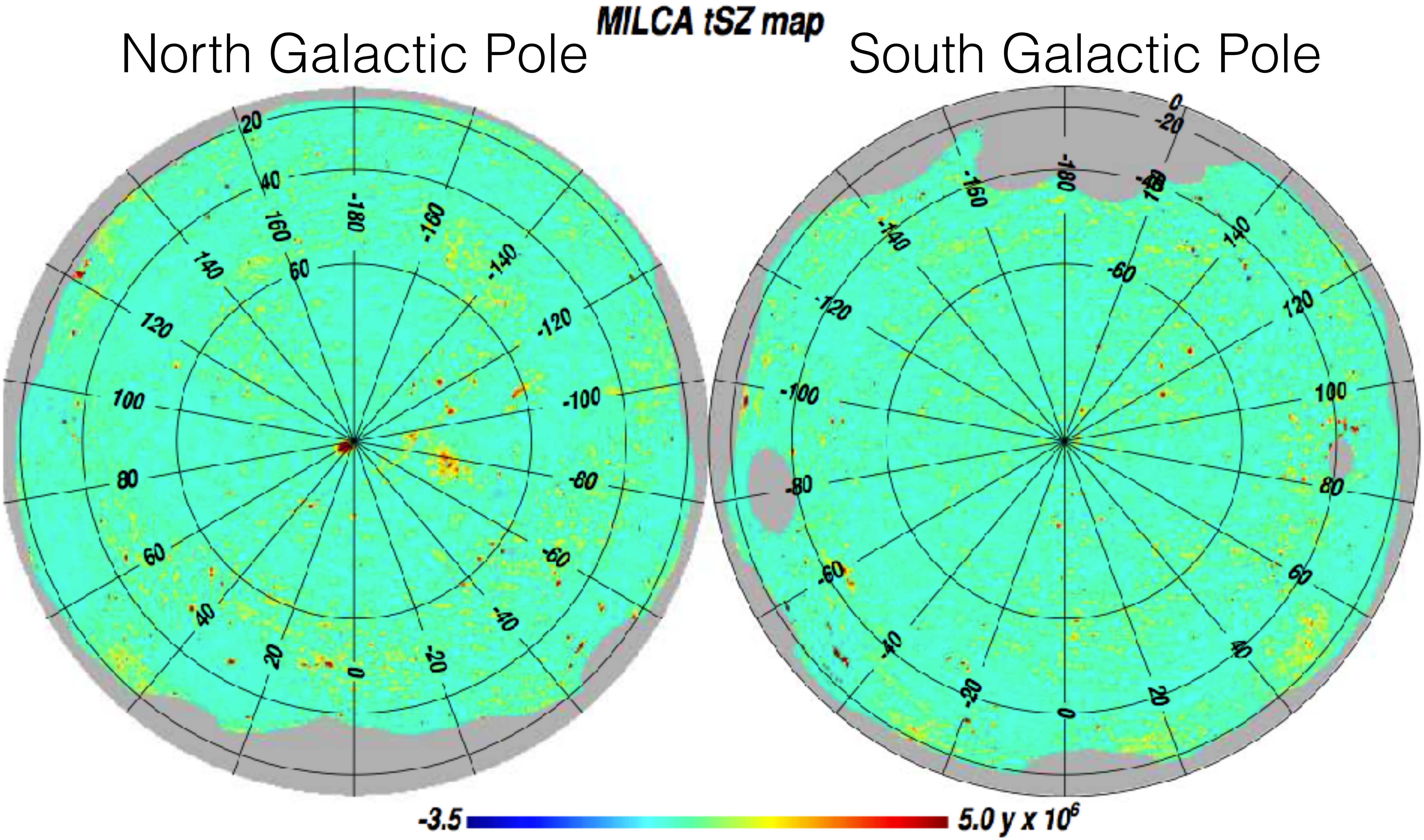


Thermal SZ (tSZ) Effect

- The unique frequency dependence of tSZ: we can make a map of Y_{tSZ}



Full-sky Thermal Pressure Map



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We can simulate this

Klaus Dolag (LMU/MPA)

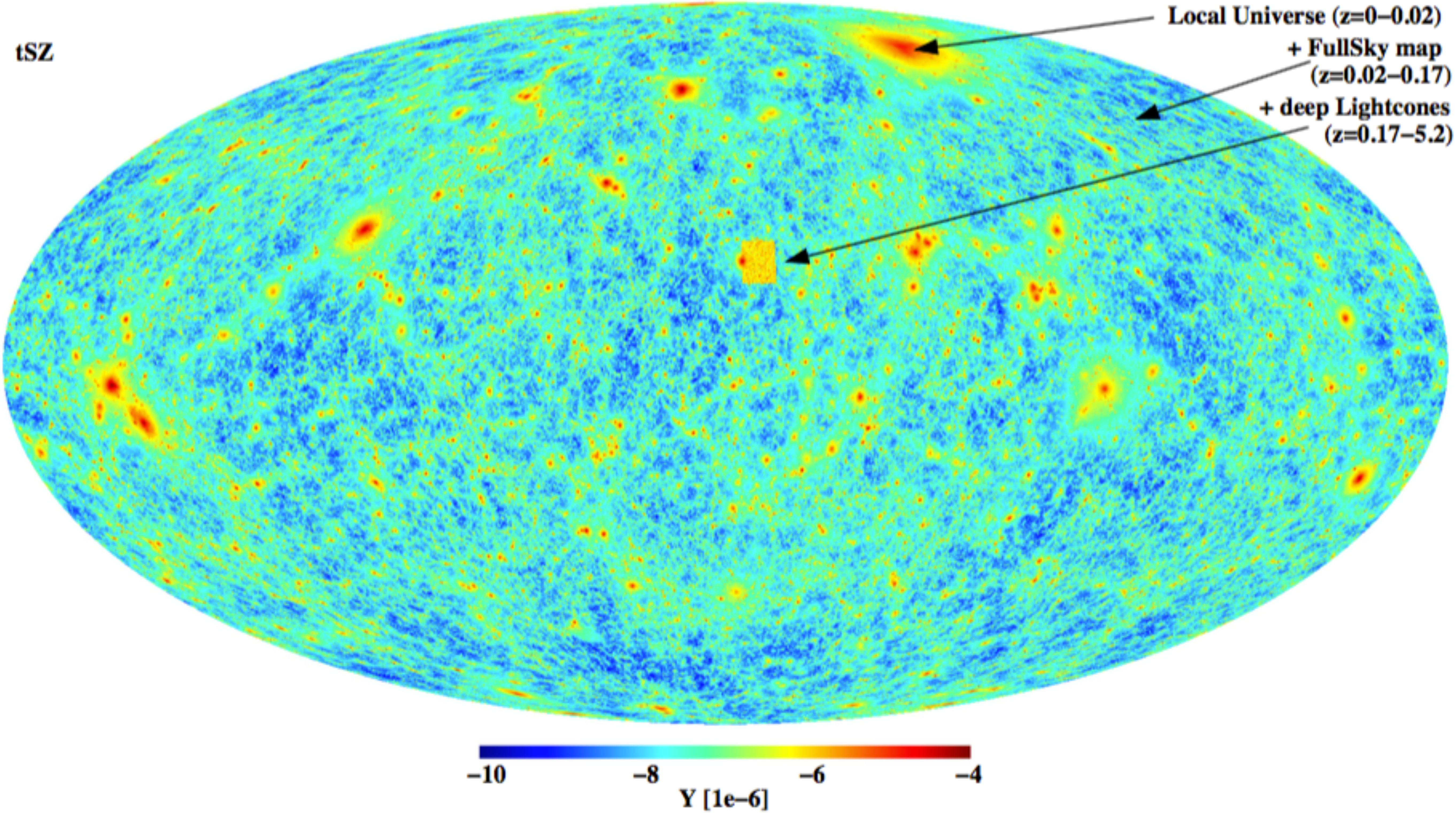
arXiv:1509.05134 [published in MNRAS]

SZ effects in the Magneticum Pathfinder Simulation: Comparison with the Planck, SPT, and ACT results

K. Dolag[1,2*], E. Komatsu[2,3] and R. Sunyaev[2,4]
[1] *University Observatory Munich, Scheinerstr. 1, 81679 Munich, Germany*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, 85748 Garching, Germany*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa 277-8583, Japan*
[4] *Space Research Institute (IKI), Russian Academy of Sciences, Profsoyuznaya str. 84/32, Moscow, 117997 Russia*

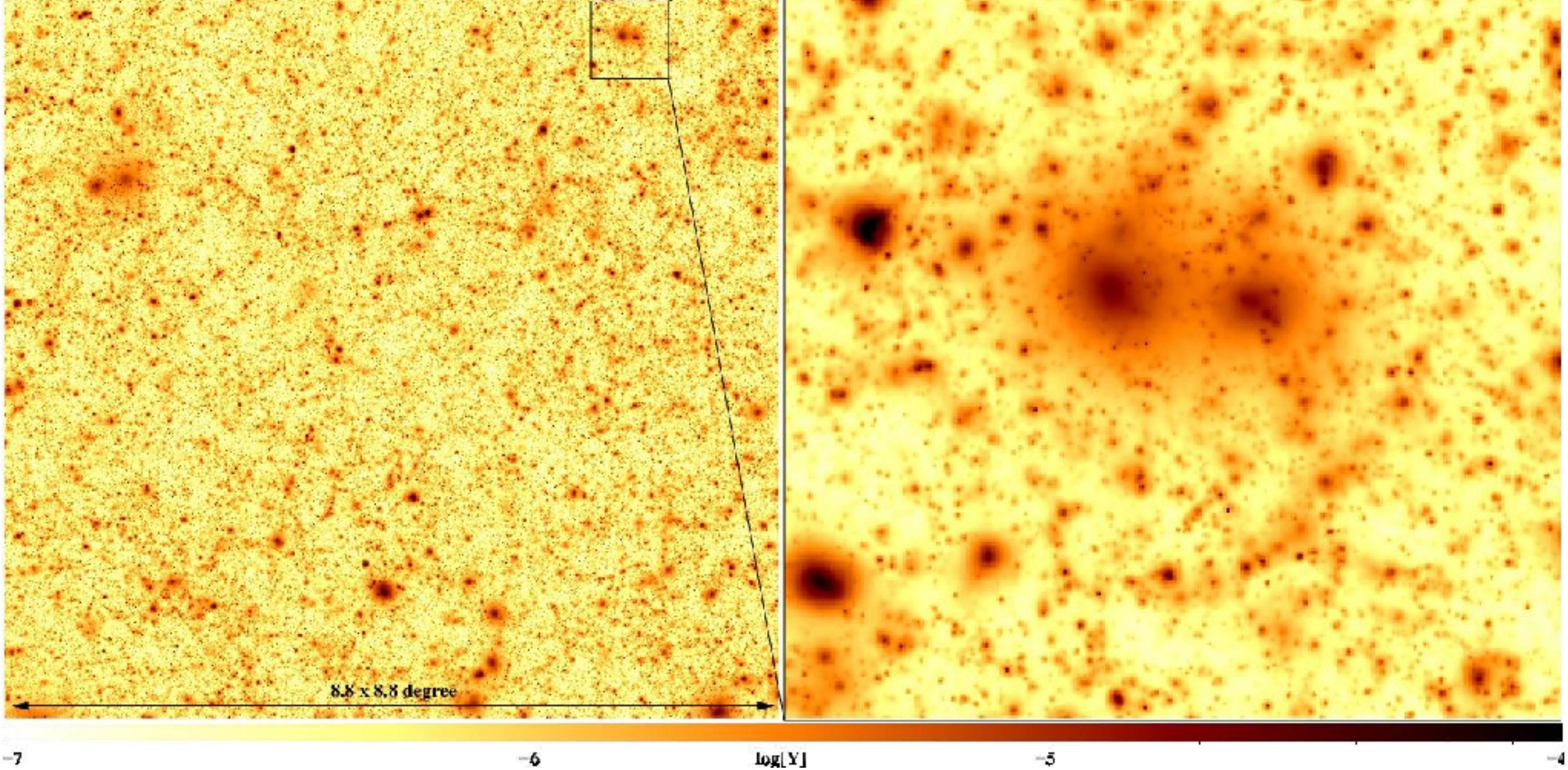
- Volume: $(896\ \mathrm{Mpc}/h)^3$
- Cosmological hydro (P-GADGET3) with star formation and AGN feed back
- 2×1526^3 particles ($m_{DM}=7.5\times10^8\ M_{sun}/h$)

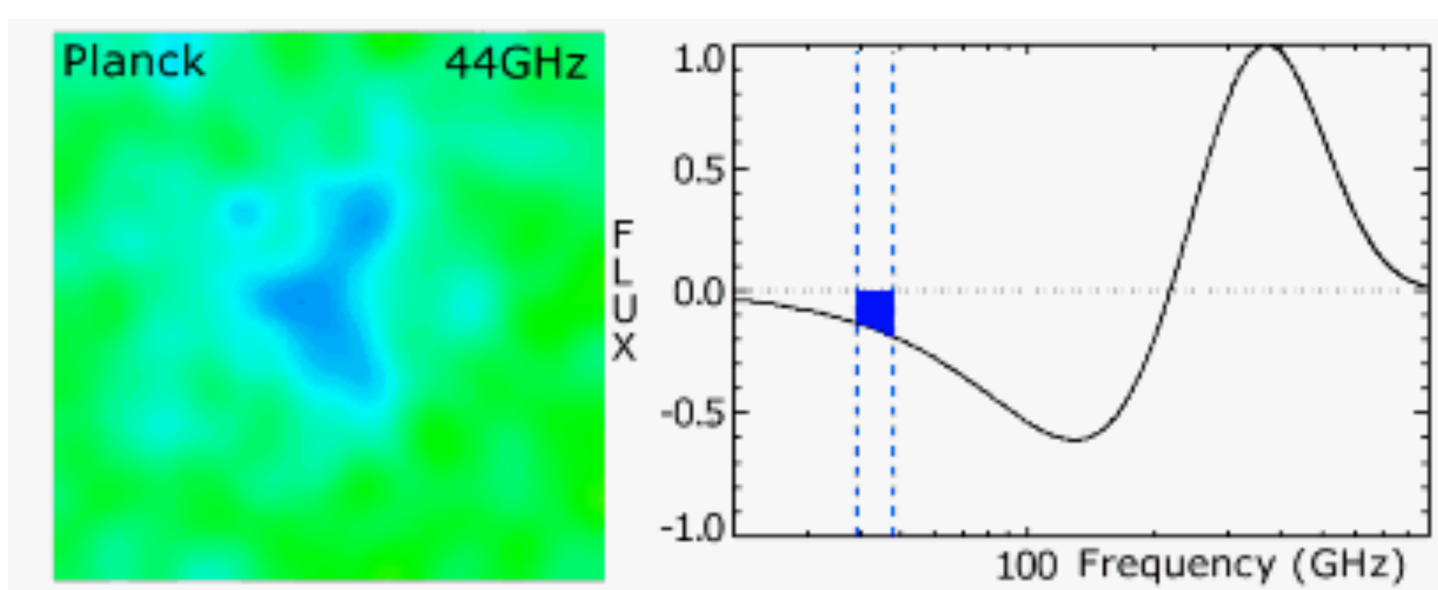
Dolag, EK, Sunyaev (2016)



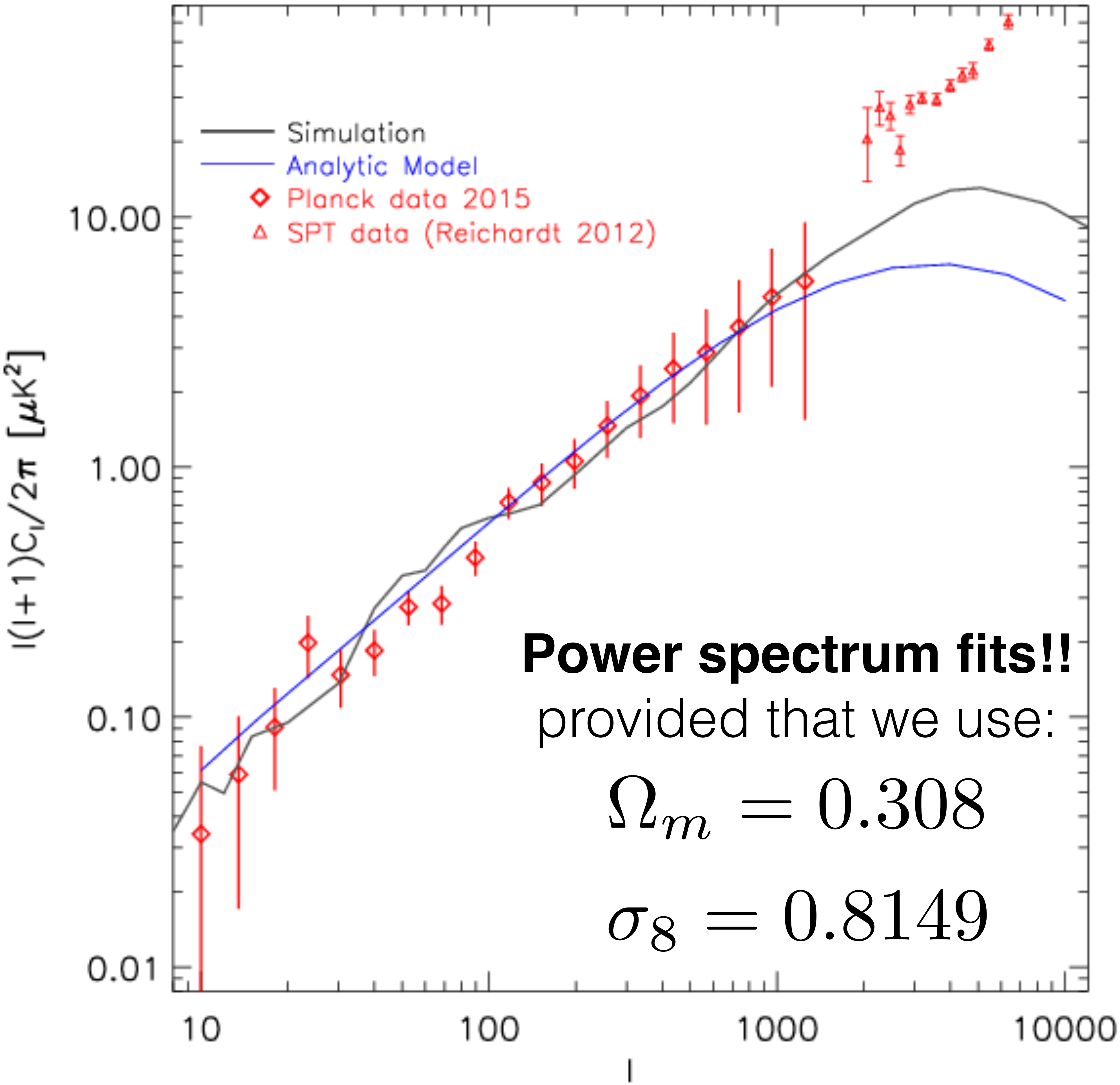
$$Y_{\rm tSZ}(\boldsymbol{\theta}) = \frac{k_B \sigma_T}{m_e c^2} \int {\rm d}l \, n_e(\boldsymbol{\theta}, l) \, T(\boldsymbol{\theta}, l)$$

Dolag, EK, Sunyaev (2016)





Dolag, EK, Sunyaev (2016)



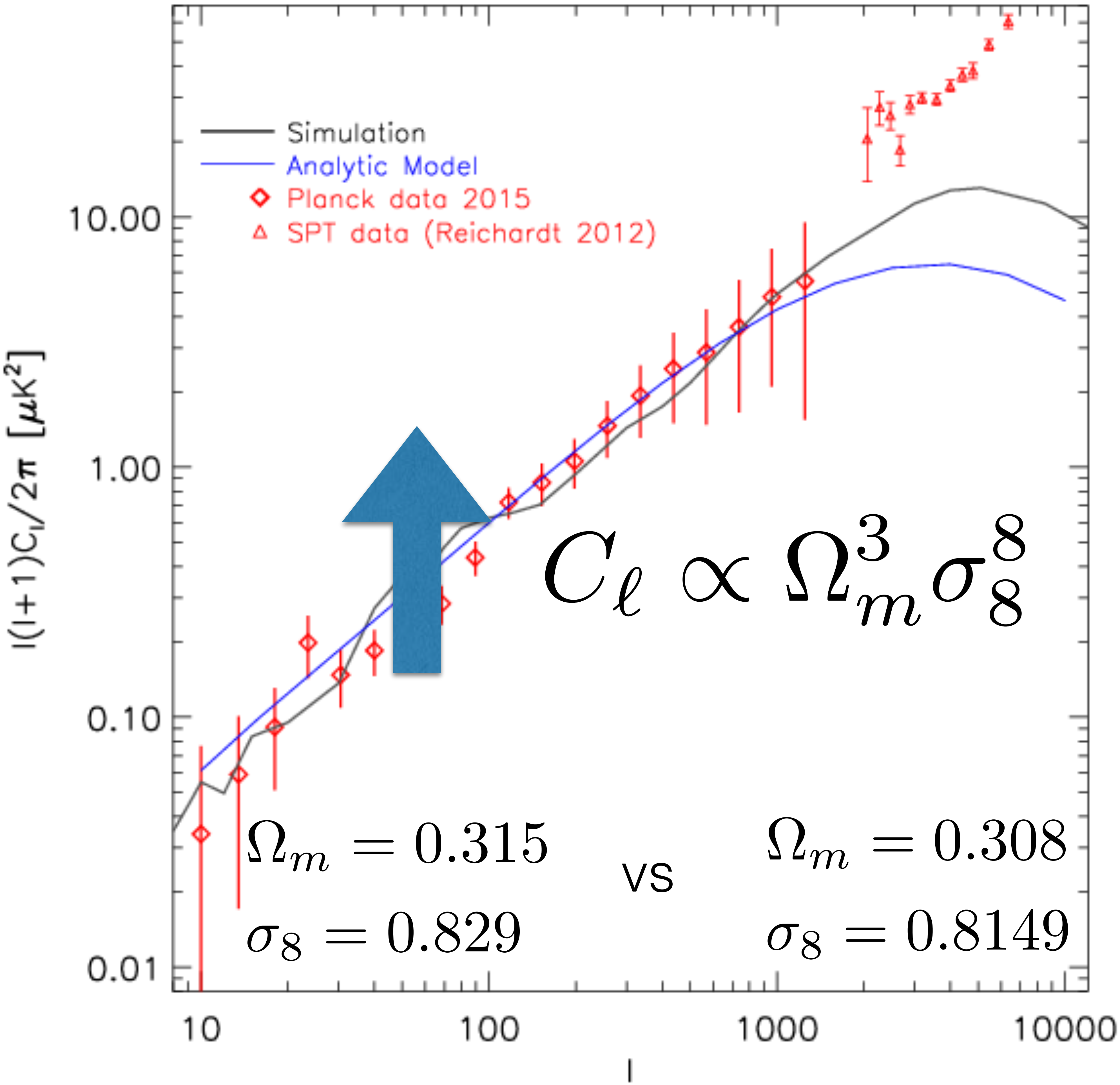
Power spectrum fits!!

provided that we use:

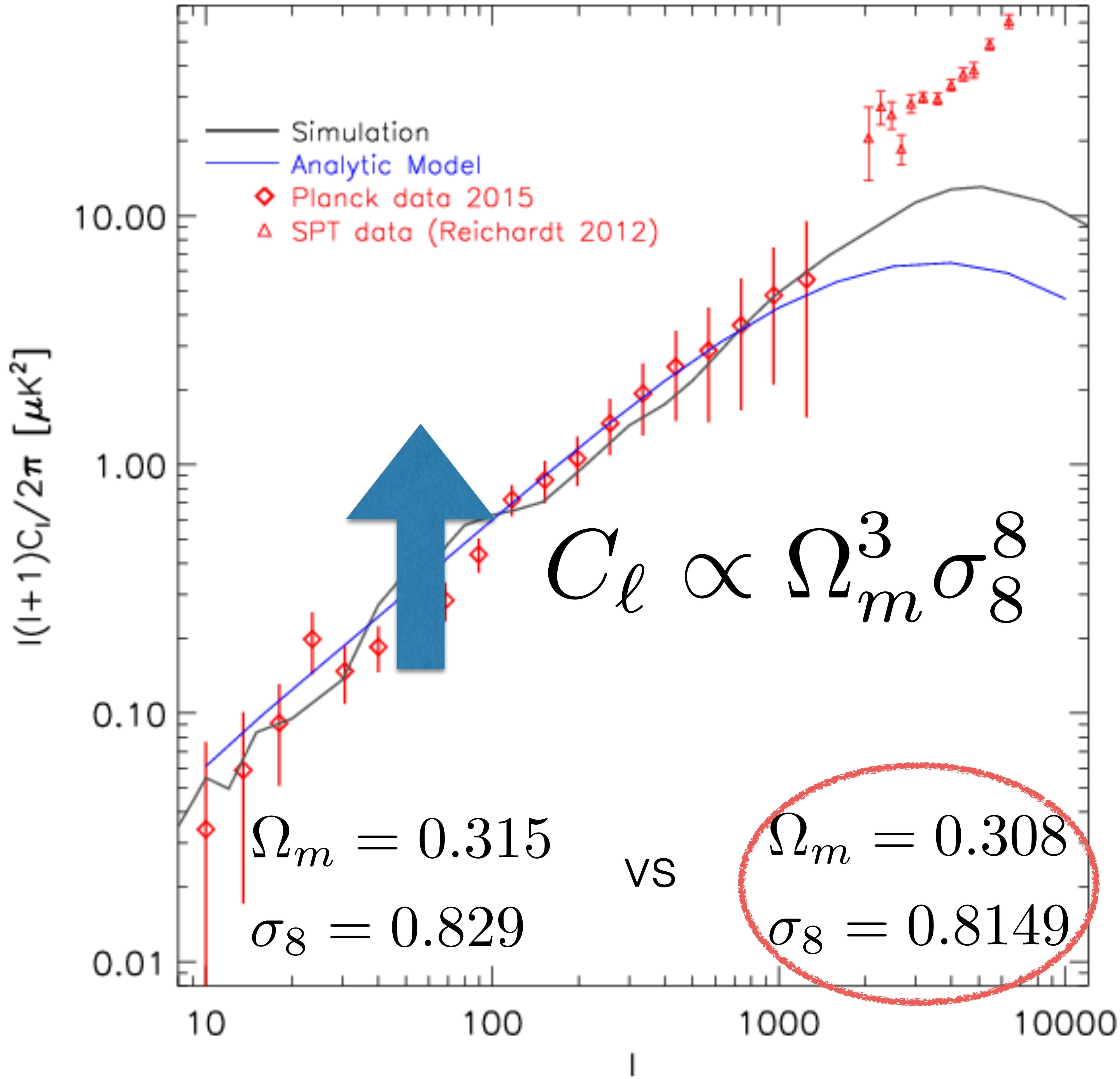
$$\Omega_m = 0.308$$

$$\sigma_8 = 0.8149$$

Dolag, EK, Sunyaev (2016)



Dolag, EK, Sunyaev (2016)



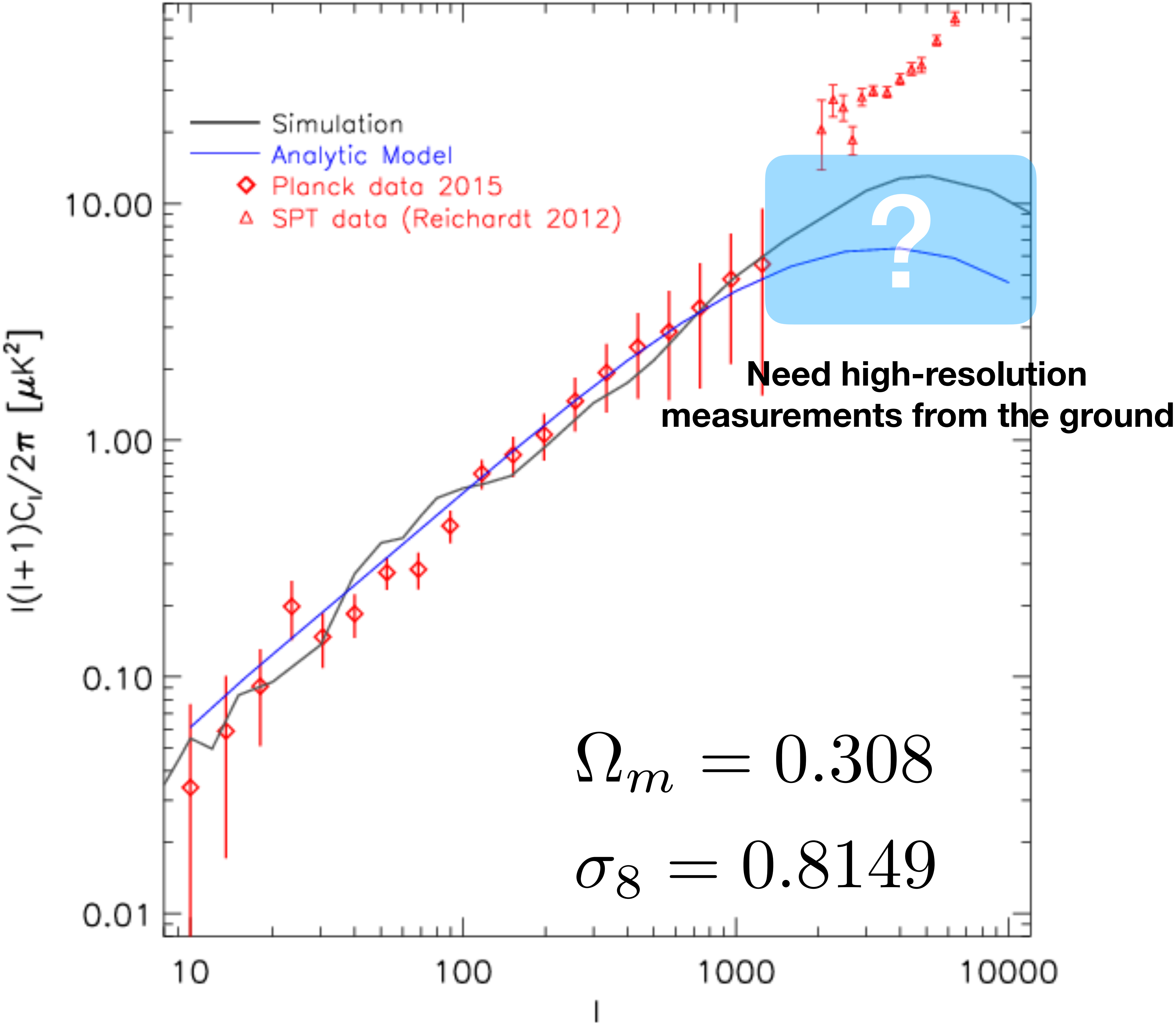
$$C_\ell \propto \Omega_m^3 \sigma_8^8$$

$$\Omega_m = 0.315$$
$$\sigma_8 = 0.829$$

vs

$$\Omega_m = 0.308$$
$$\sigma_8 = 0.8149$$

Dolag, EK, Sunyaev (2016)



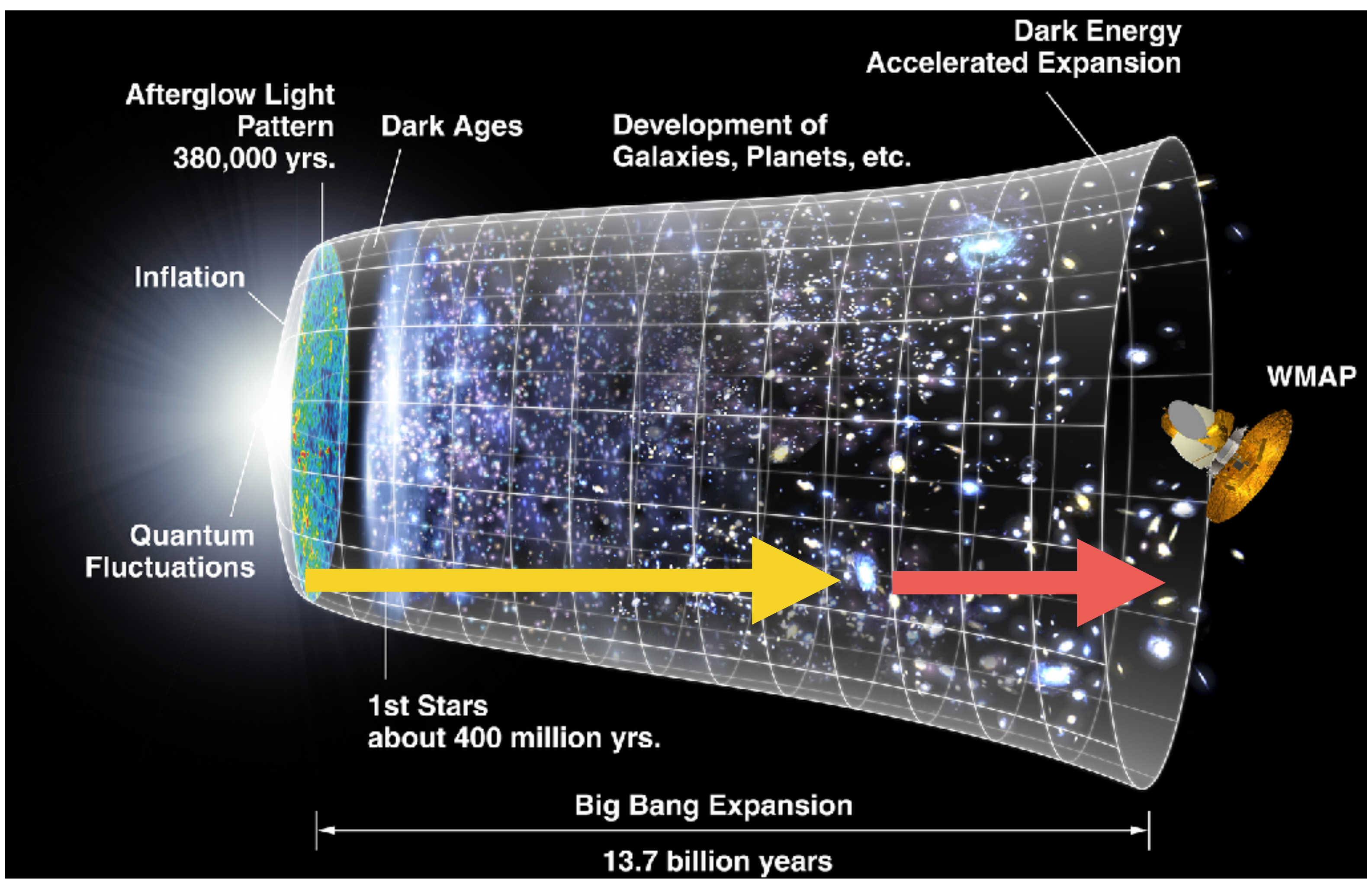
More tomorrow

- We have a lot of talks on individual galaxy clusters detected by the SZ effect tomorrow
- Clusters offer a powerful test of dark energy, if we know their masses

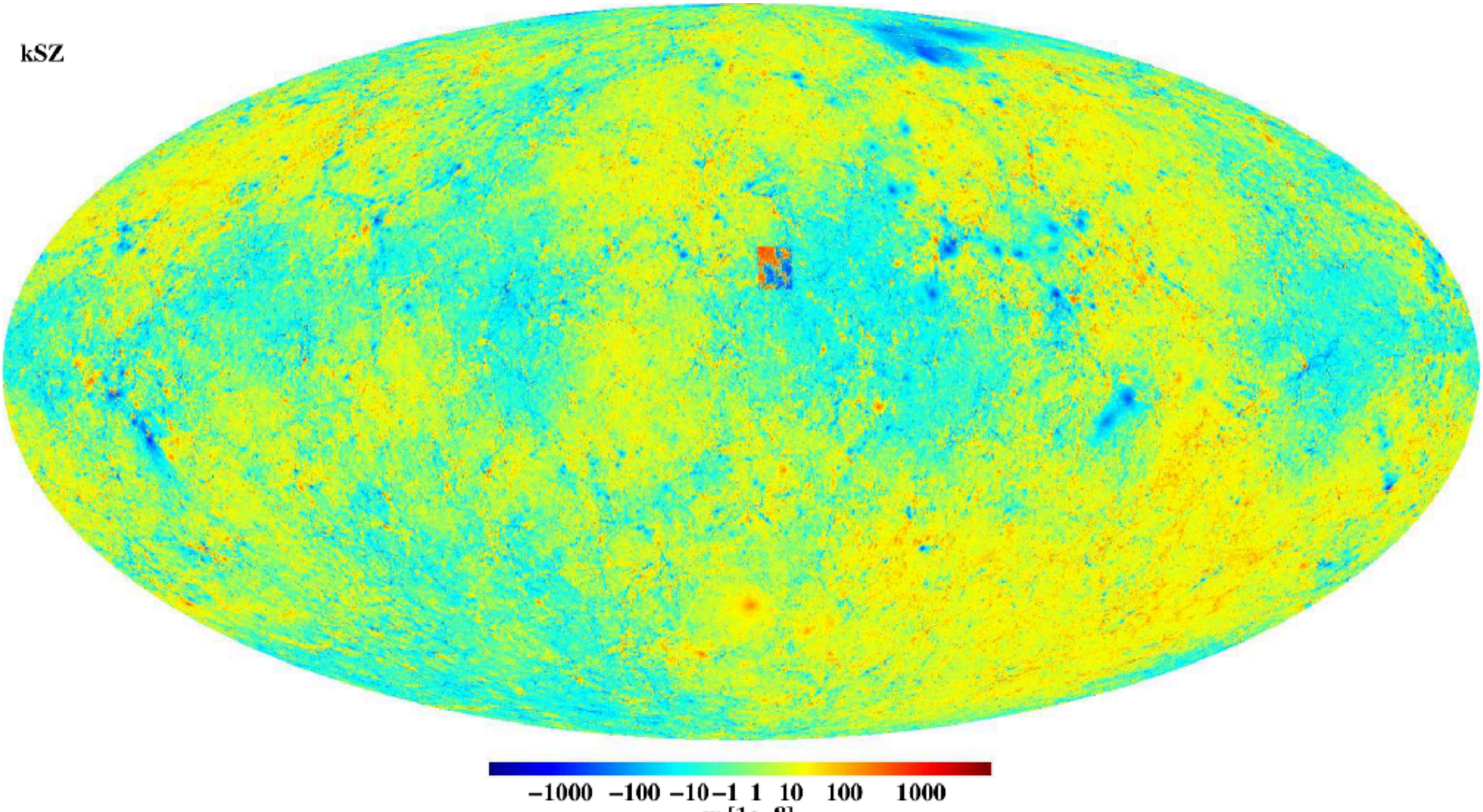
The Sunyaev-Zel'dovich Effect

- The "kinetic" SZ effect (in the non-relativistic limit) enables us to measure velocity fields

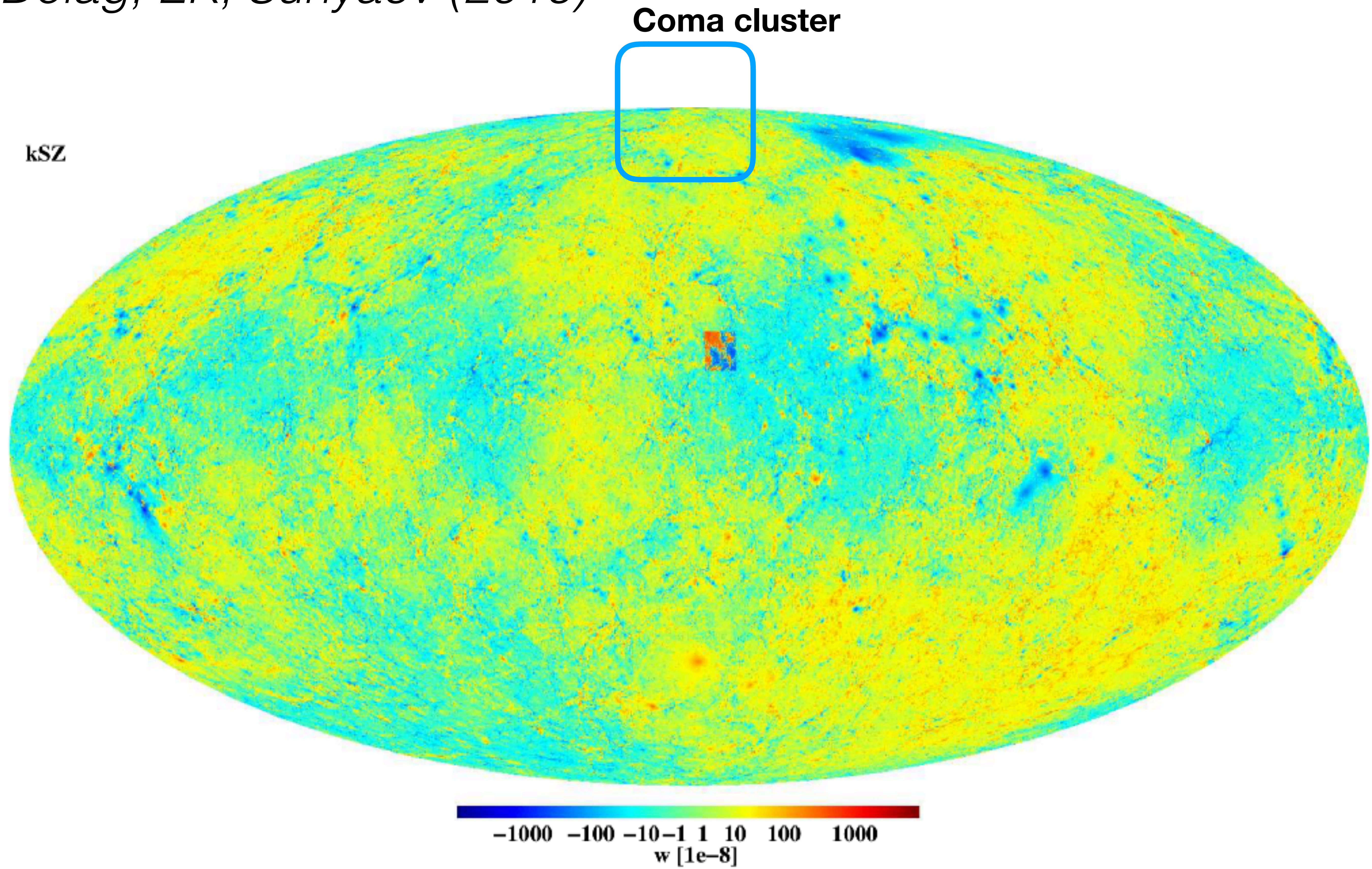
$$\frac{\delta T_{\rm kSZ}}{T_{\rm cmb}} = -\frac{\sigma_T}{c}\int {\rm d}l\, n_e(\boldsymbol{\theta}, l)\, v_r(\boldsymbol{\theta}, l)$$



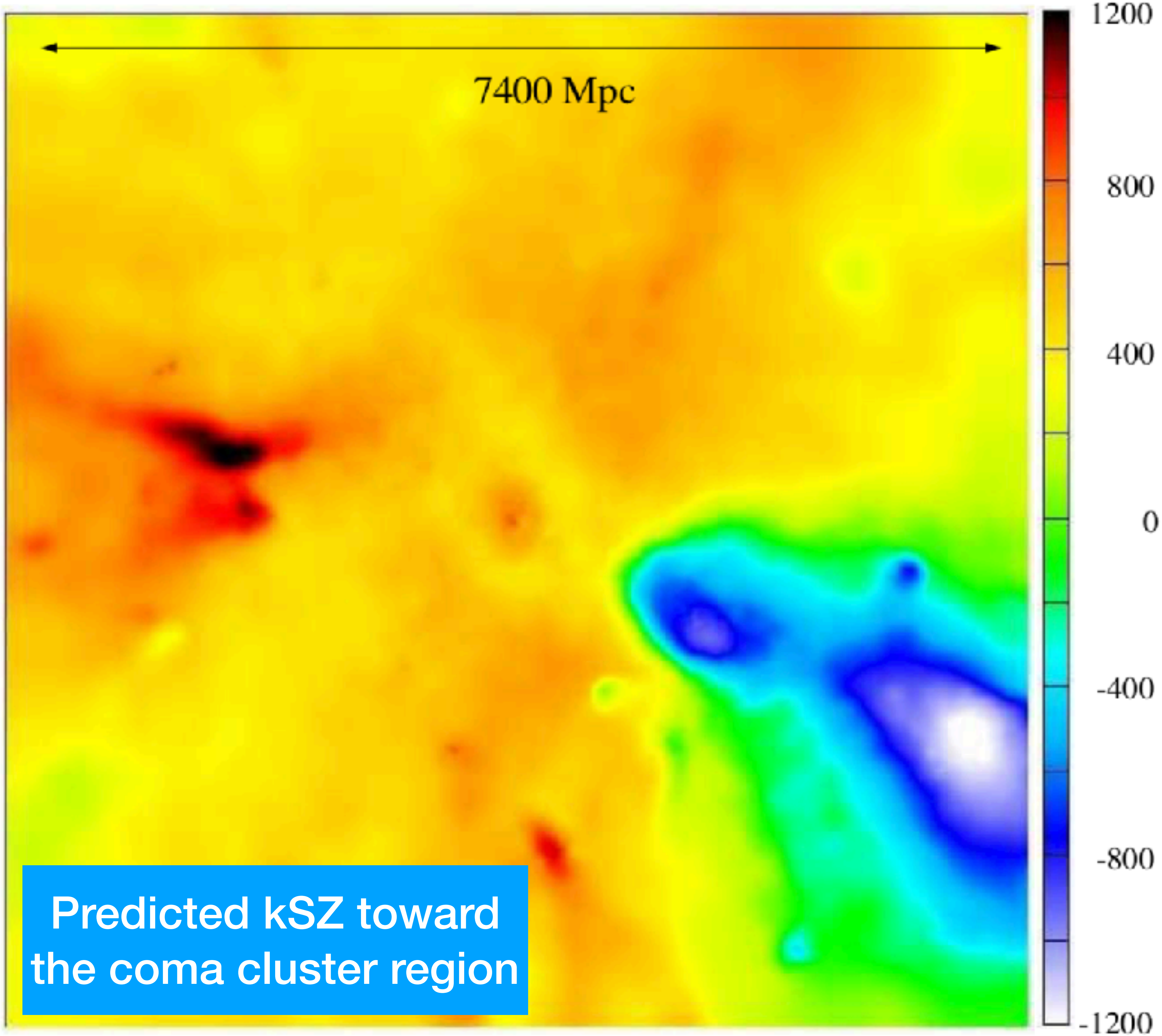
Dolag, EK, Sunyaev (2016)



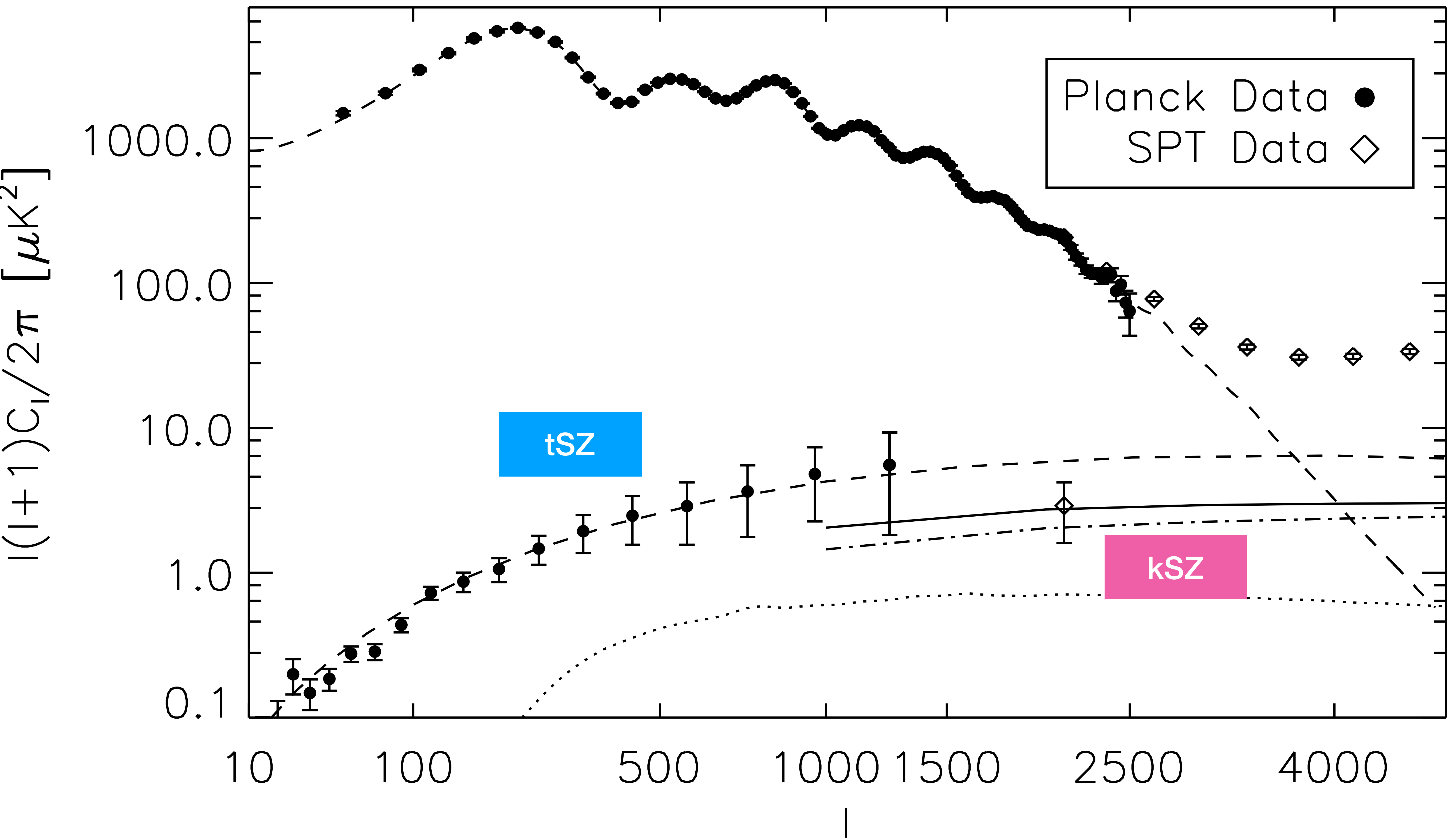
Dolag, EK, Sunyaev (2016)



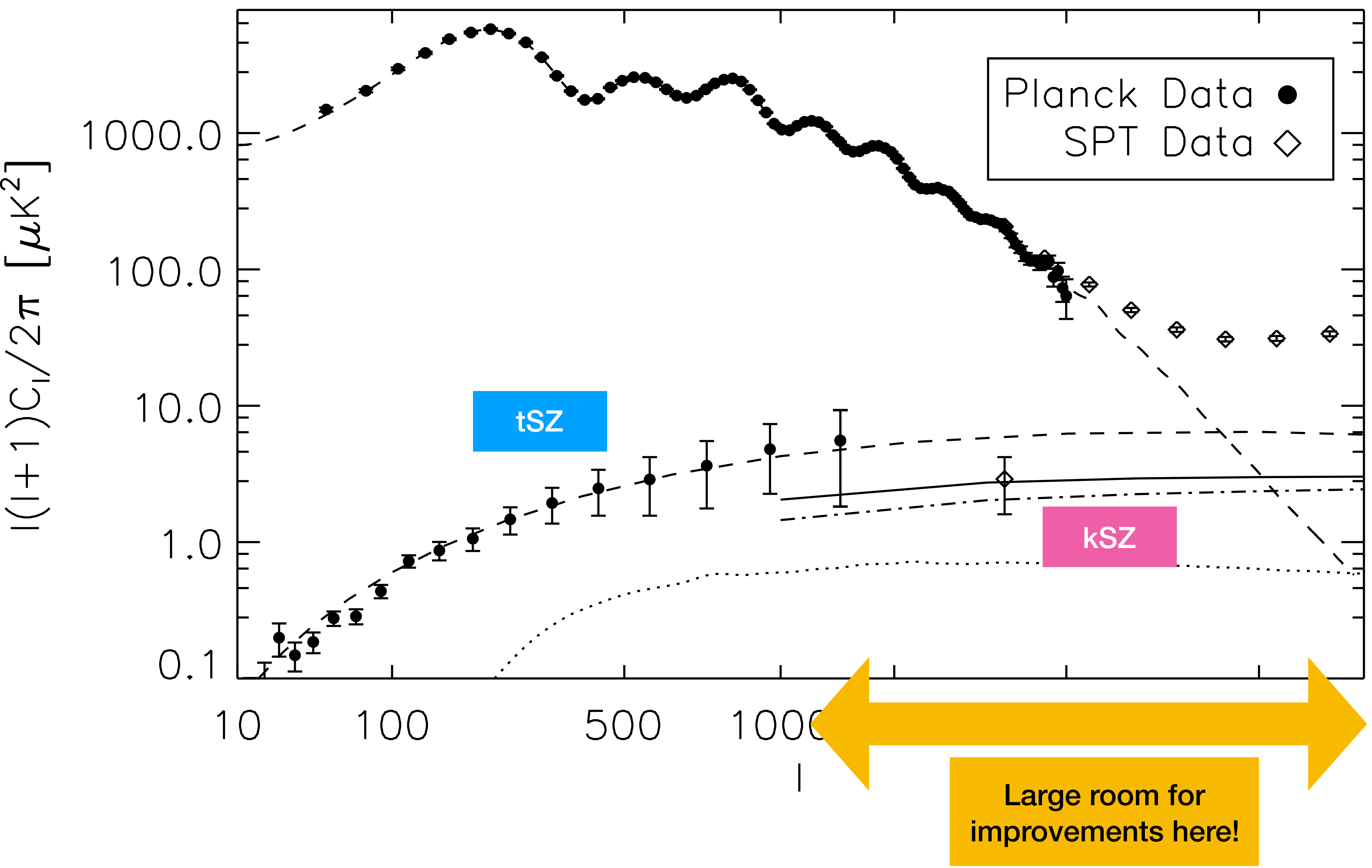
Dolag, EK, Sunyaev (2016)



Power Spectrum

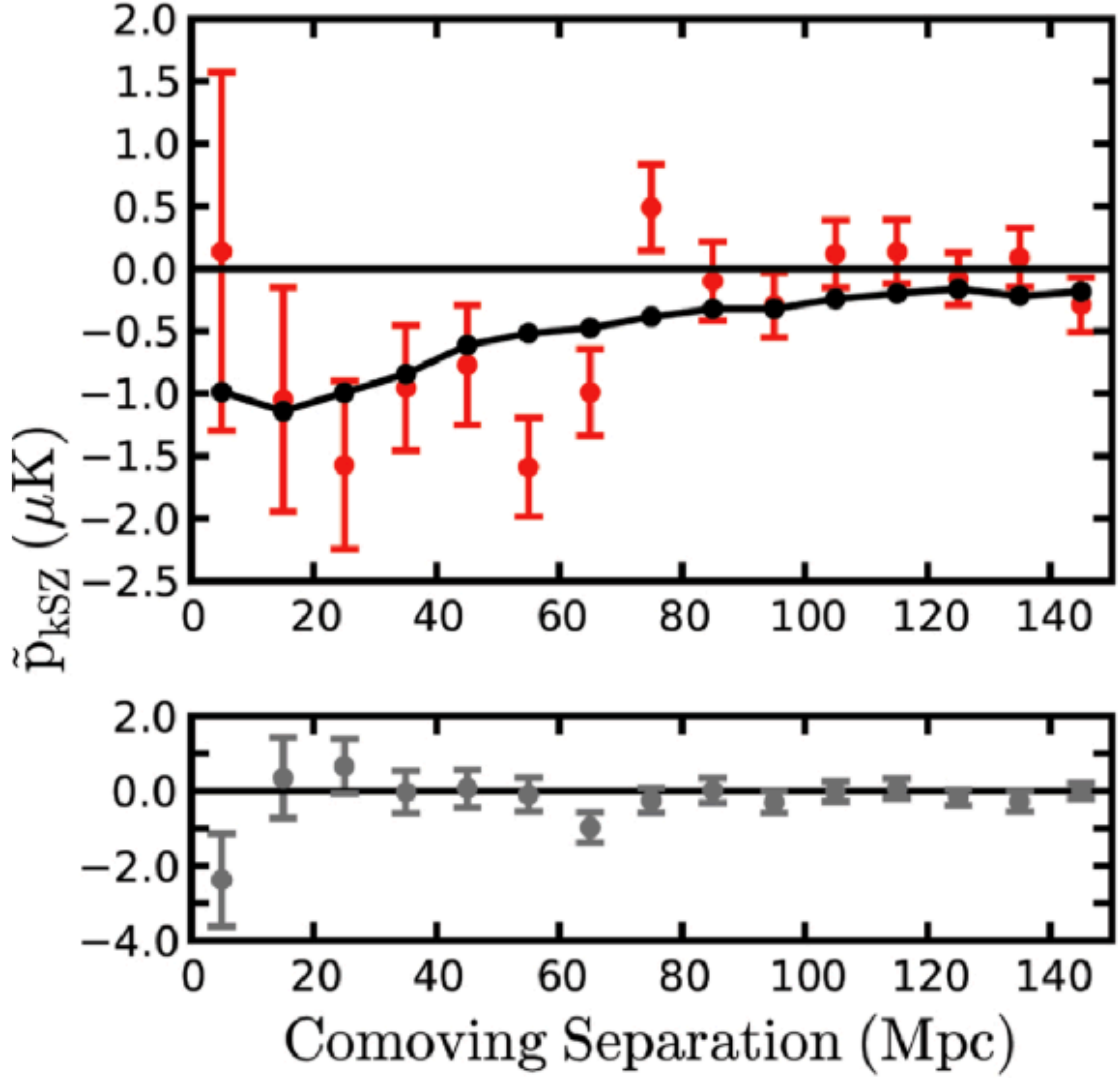


Power Spectrum



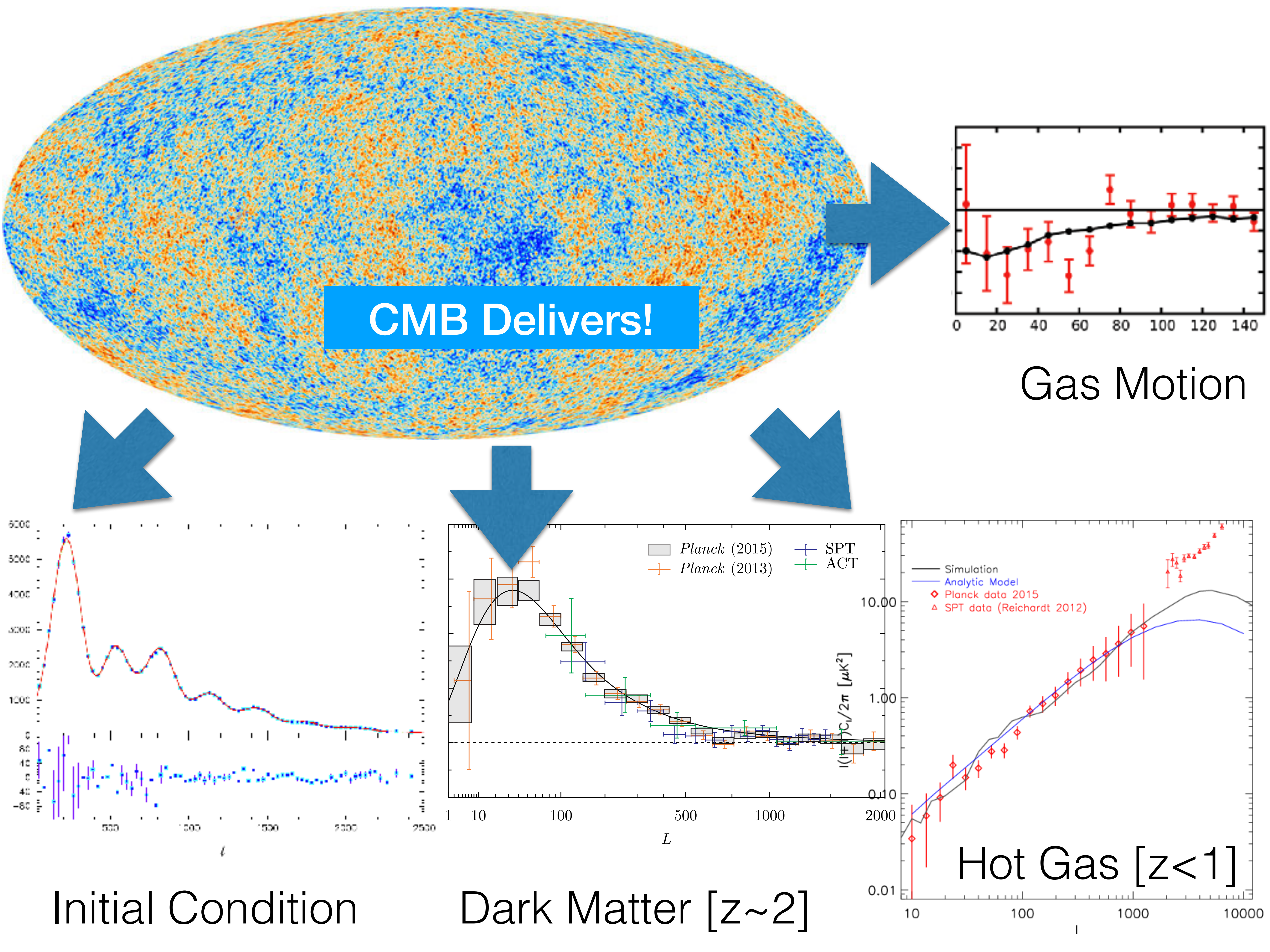
ACT Collaboration

kSZ in cross-correlation with galaxies



Galaxy pairs approaching each other give negative values in this plot

Large room for improvements!



CMB Delivers!
Gas Motion
0 20 40 60 80 100 120 140
Initial Condition
ℓ
Dark Matter [z~2]
Planck (2015)
Planck (2013)
SPT
ACT
1 10 100 500 1000 2000
L
Hot Gas [z<1]
Simulation
Analytic Model
Planck data 2015
SPT data (Reichardt 2012)
l(l+1)C_l/2π [μK²]
10.00
1.00
0.10
0.01
10 100 1000 10000

Summary

- COBE, WMAP, Planck, and a host of ground-based observatories established the ΛCDM model
- Now, the CMB research has entered the new era. Deeper questions remain:
  - Did inflation really happen? Did we all come from quantum fluctuations?
  - Is ΛCDM right?

Summary

- COBE, WMAP, Planck, and a host of ground-based observatories established the ΛCDM model
- Now, the CMB research has entered the new era. Deeper questions remain:
  - Did inflation really happen? Did we all come from quantum fluctuations?

    B-mode polarisation from primordial gravitational waves

  - Is ΛCDM right?

Many tests! Were their new light particles? Do DM particles annihilate? What is the mass of neutrinos? Is DE a cosmological constant? Is the distribution of hot gas and velocities consistent with ΛCDM? Etc, etc…

My apologies (to Rashid and Jens)

- I've completely left out other CMB spectral distortions than the SZ effects, but this is also a great science!
- Ask Rashid and Jens if you want to know about this opportunity