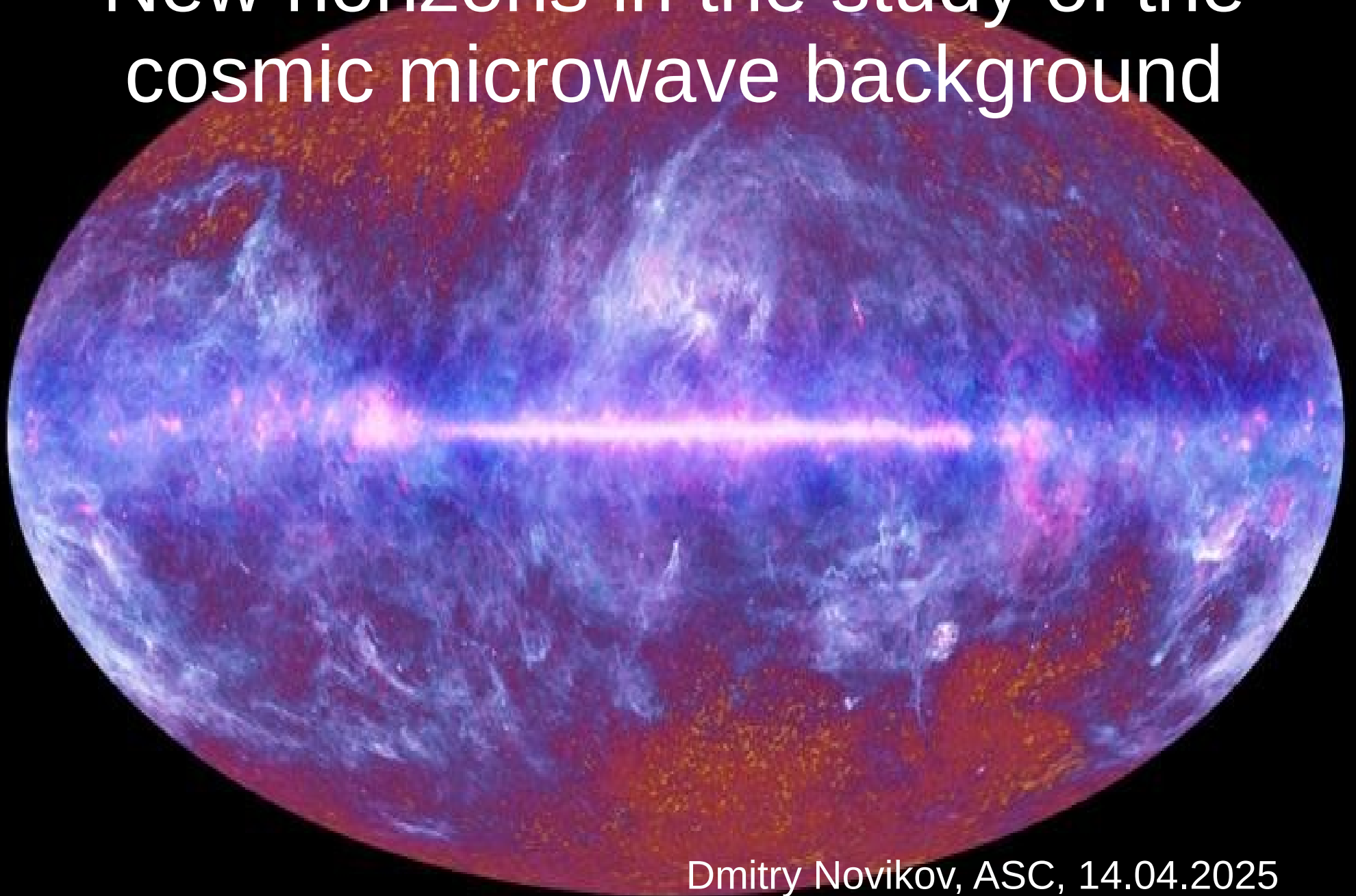
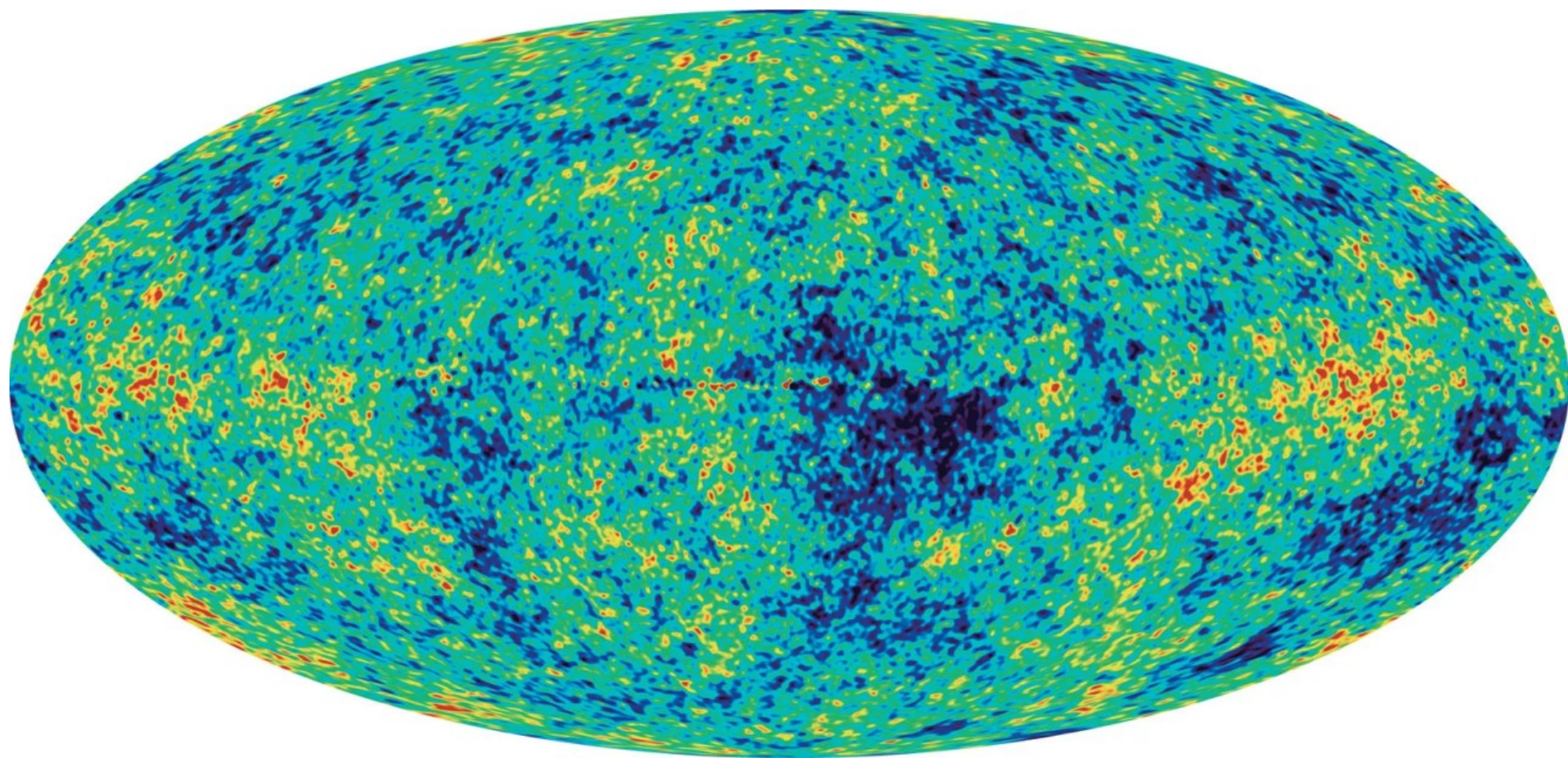


New horizons in the study of the cosmic microwave background

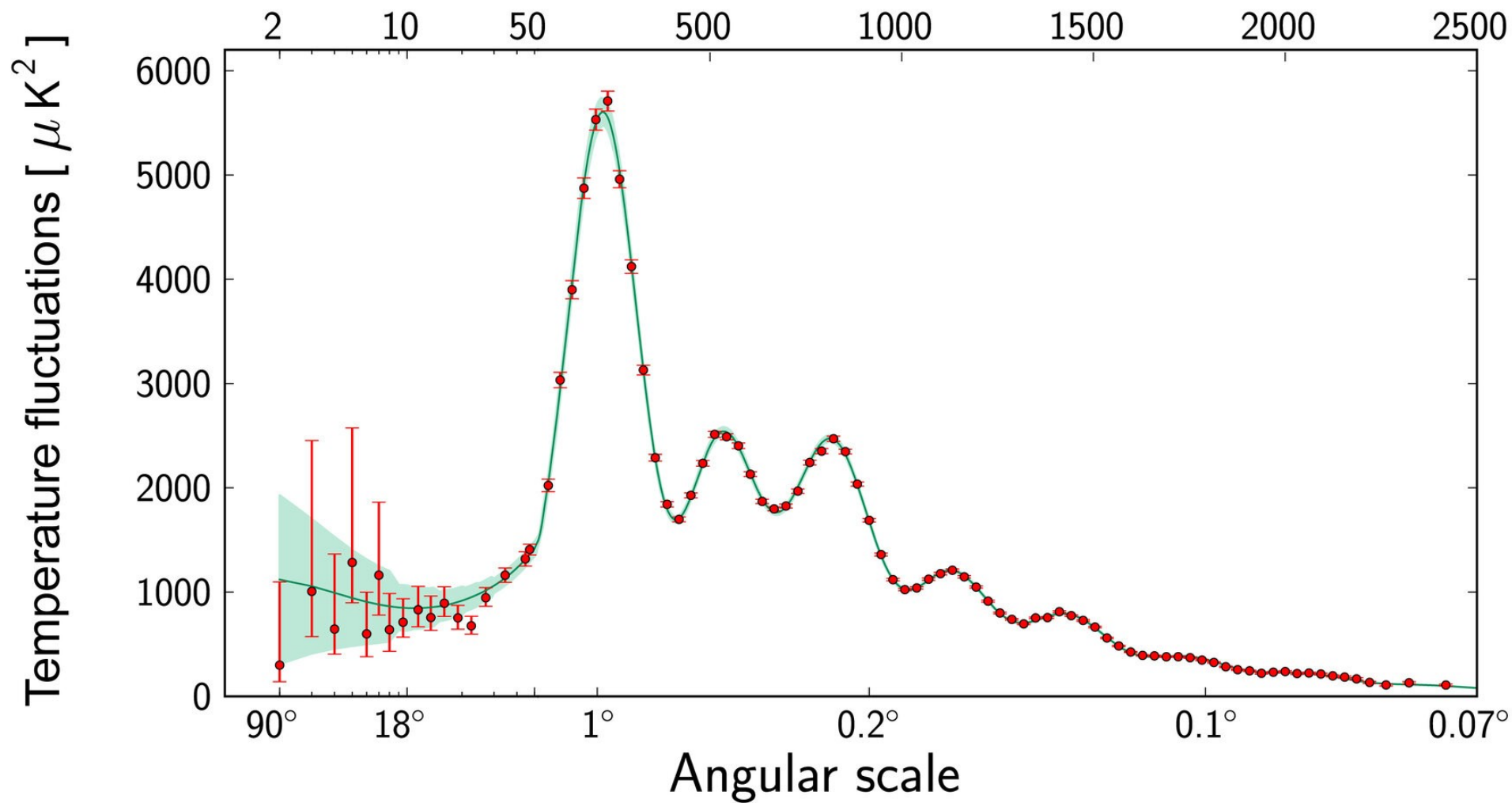


Dmitry Novikov, ASC, 14.04.2025



Planck CMB anisotropy map

Multipole moment, ℓ



Planck, 2018

Unsolved problems:

- B mode of polarization;
- Gaussianity;
- Spectral distortions;
- Problems with large scale anisotropy:

Quadrupole-octopole alignment,

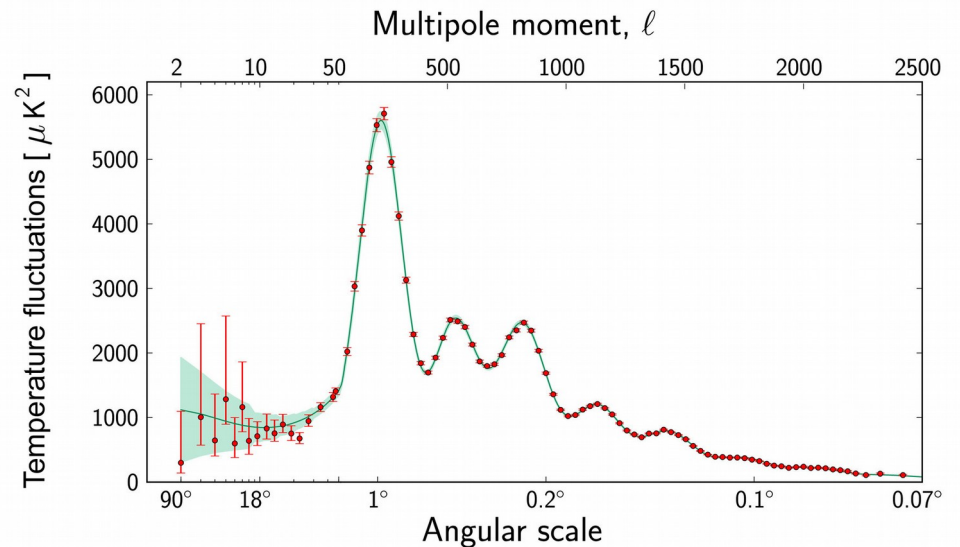
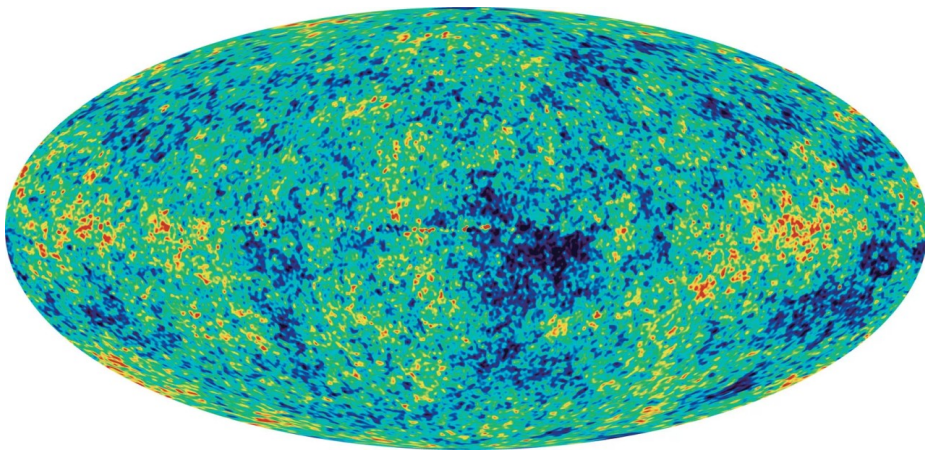
Anomalies in the anisotropy map

Gaussianity

(information beyond the power spectrum)

$$T = \sum_{\ell=2}^{\ell_{max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \varphi)$$

$$C_{\ell} = \langle a_{\ell m}^2 \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^2$$



Gaussianity

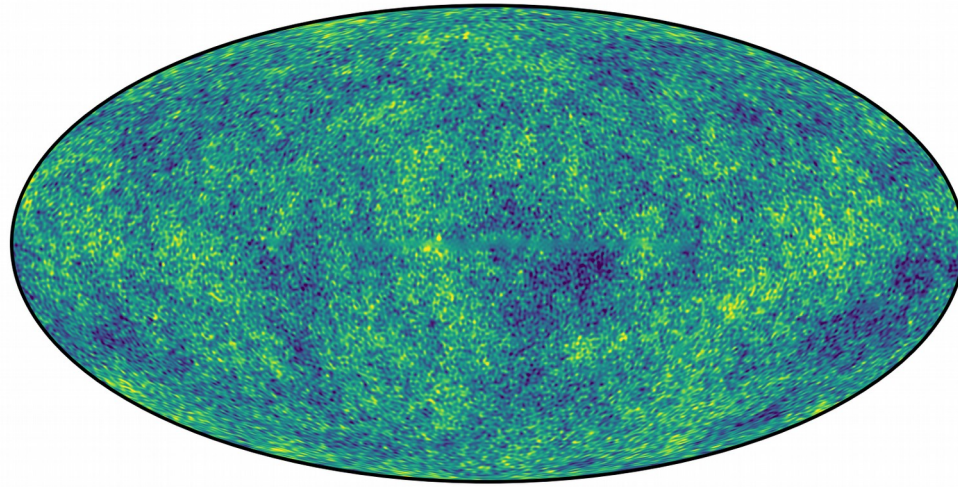
(information beyond the power spectrum)

Information about phases!

Inflation $\rightarrow$ gaussianity + B-mode

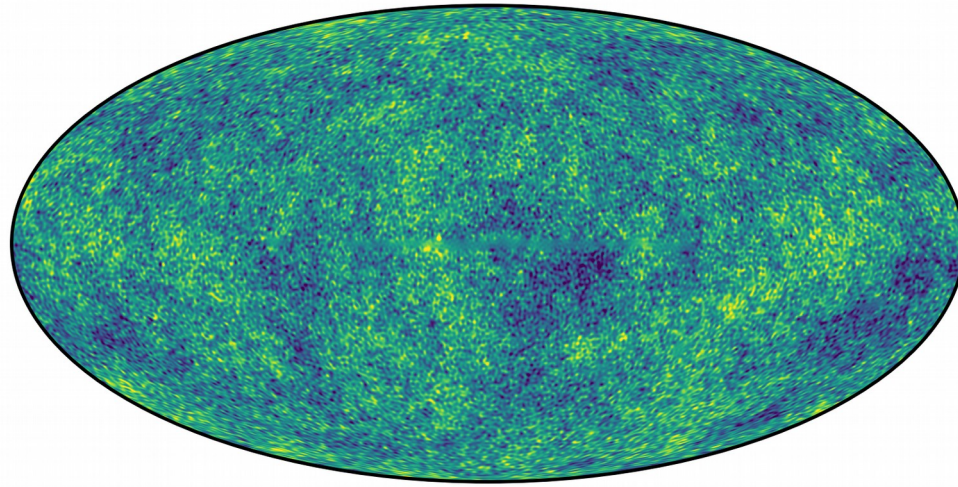
Modified inflation $\rightarrow$ small non-gaussianity:

$$\tilde{\varphi} \sim \varphi + f_{NL} \cdot \varphi^2$$

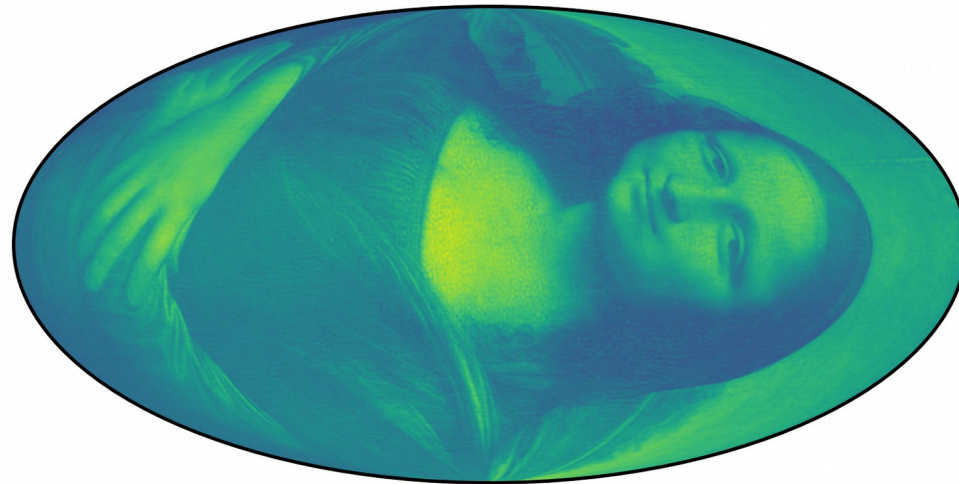


CMB spectrum, CMB
phases

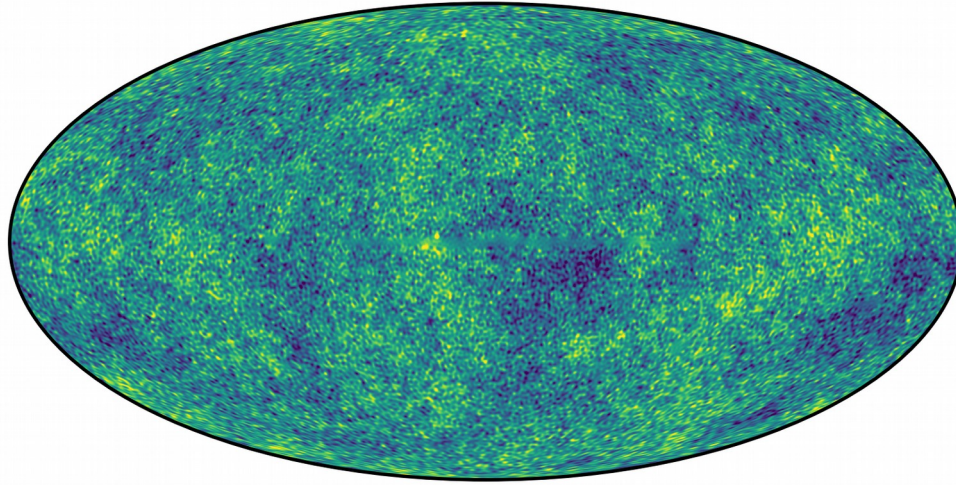




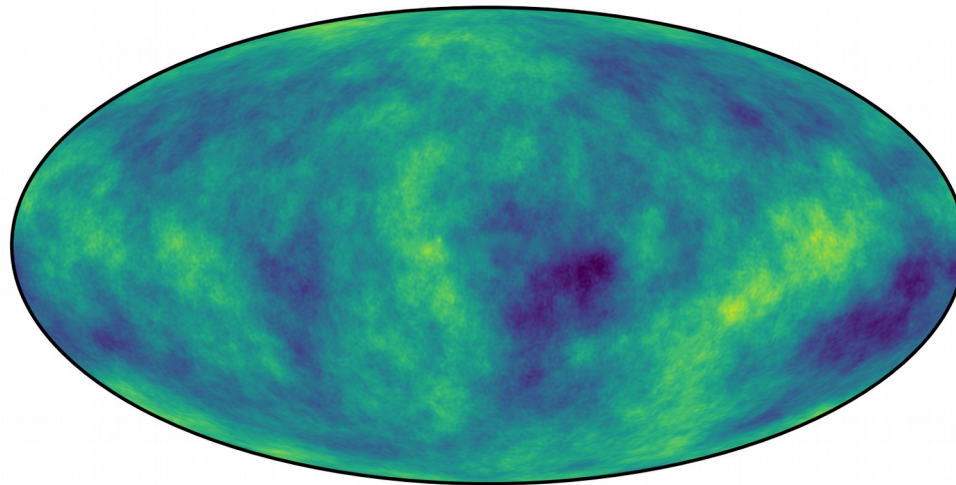
CMB spectrum, CMB
phases



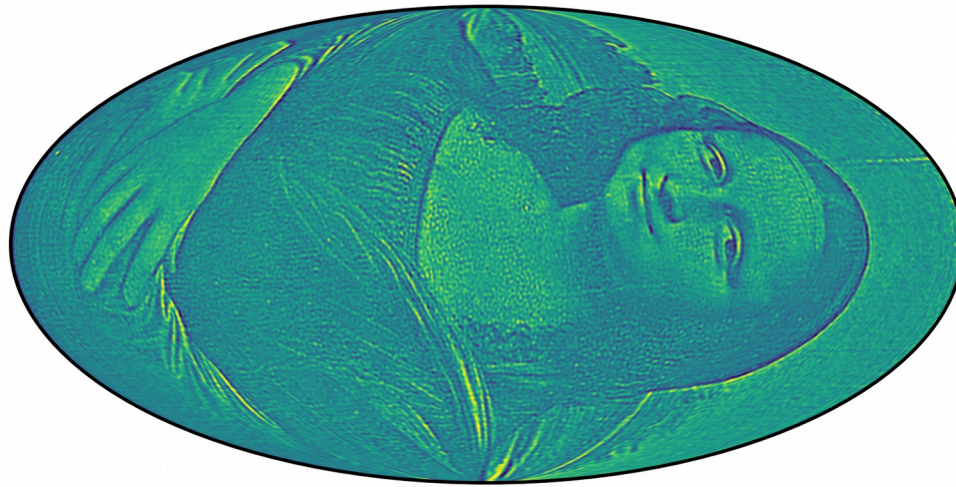
Mona Lisa spectrum,
Mona Lisa phases



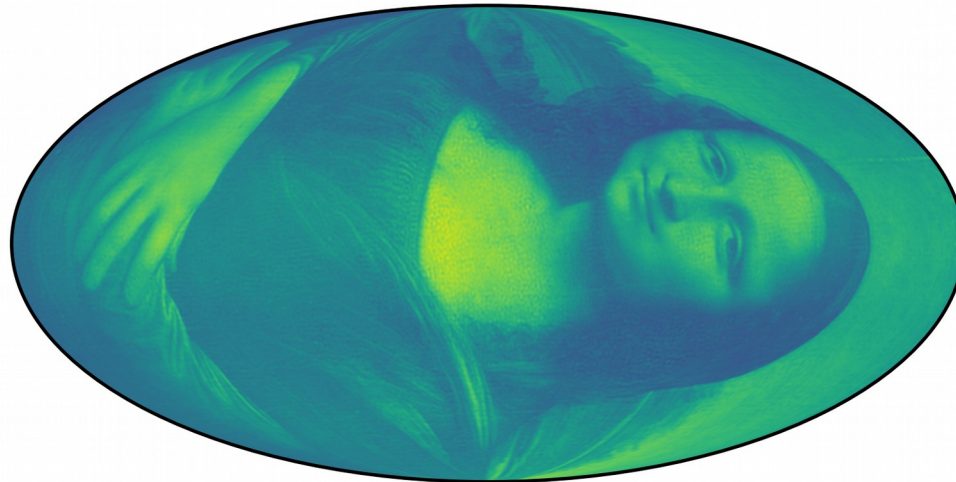
CMB spectrum, CMB
phases



Mona Lisa spectrum,
CMB phases

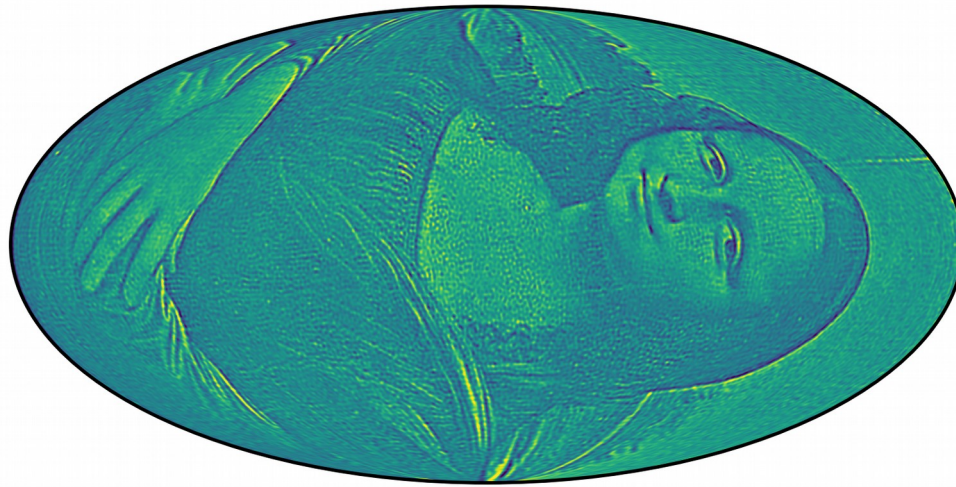


CMB spectrum, Mona
Lisa phases

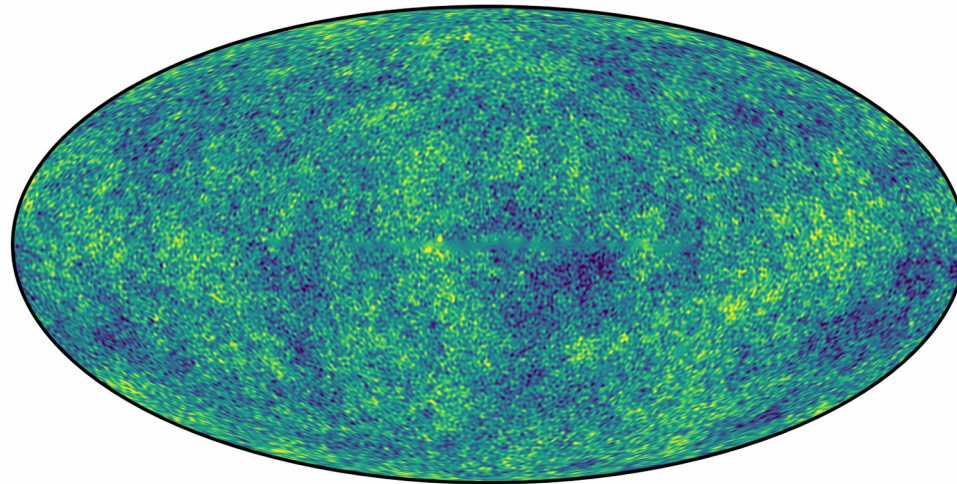


Mona Lisa spectrum,
Mona Lisa phases

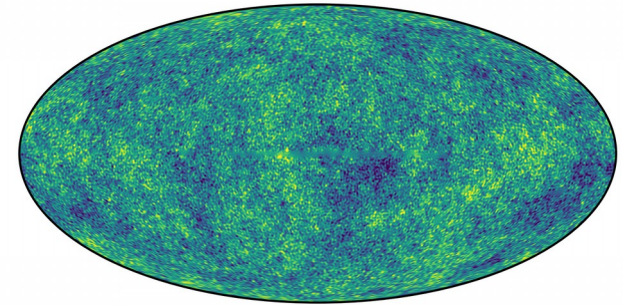
CMB spectrum,
Mona Lisa phases



CMB spectrum,
CMB phases



Possible sources of non-Gaussianity:



- Non-Gaussian foregrounds;
- Gravitational lensing;
- Systematics.

Can we extract gaussian part of the signal?

D. Novikov and K.Parfenov, arXiv:2411.15959

CMB polarization assumes:

Gaussian E and B modes with
small B/E ratio ~ 0.001

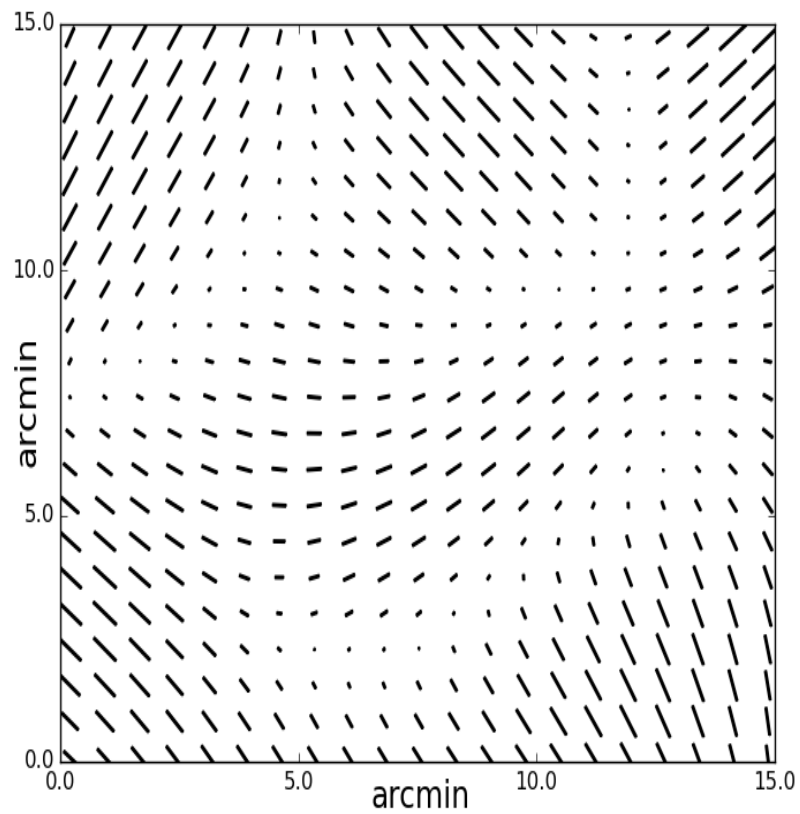
$$Q = \left[\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} \right] E - 2 \frac{\partial^2}{\partial x \partial y} B,$$

$$U = 2 \frac{\partial^2}{\partial x \partial y} E + \left[\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} \right] B$$

The Simons Observatory

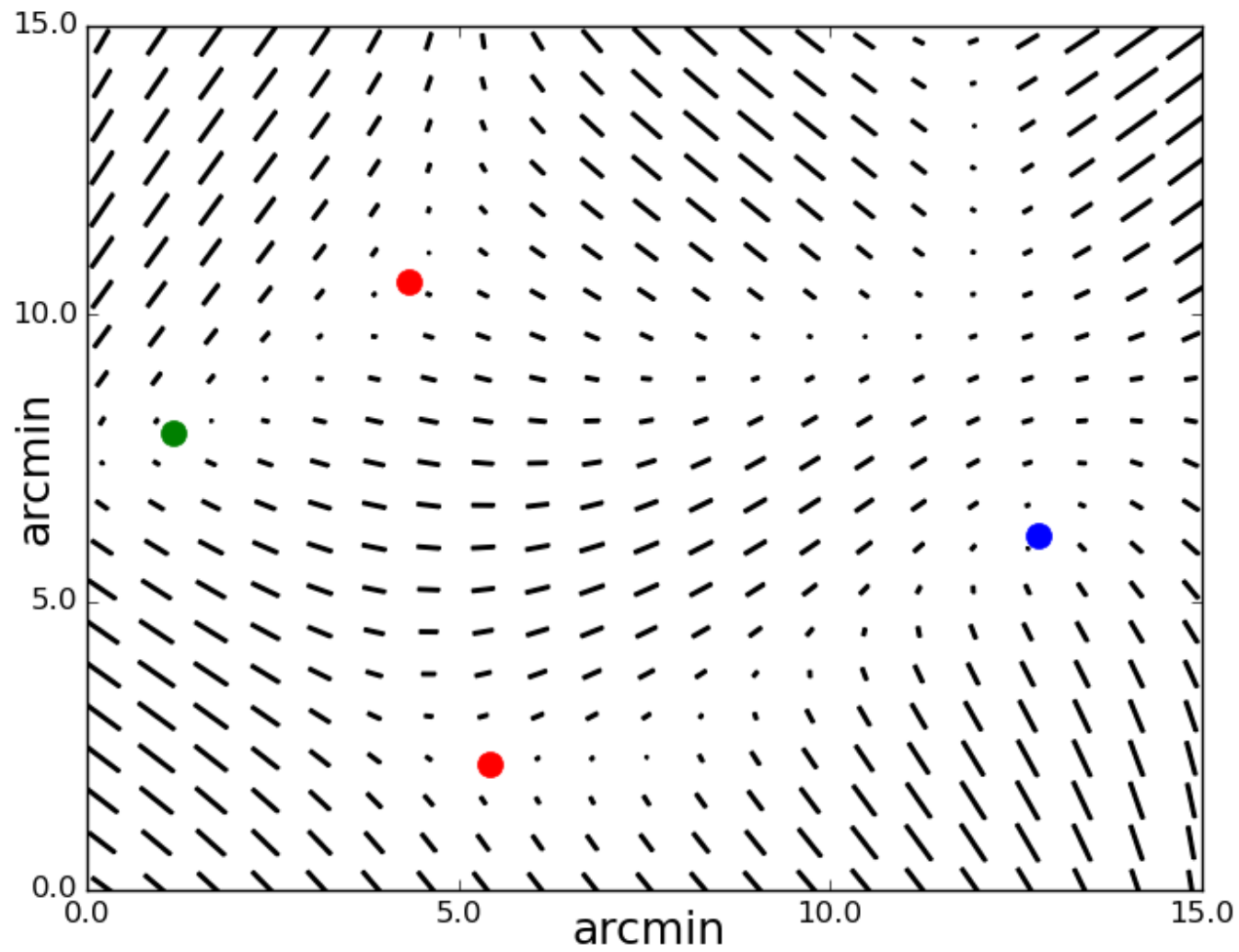
[arXiv:1808.07445](https://arxiv.org/abs/1808.07445)

CMB polarization

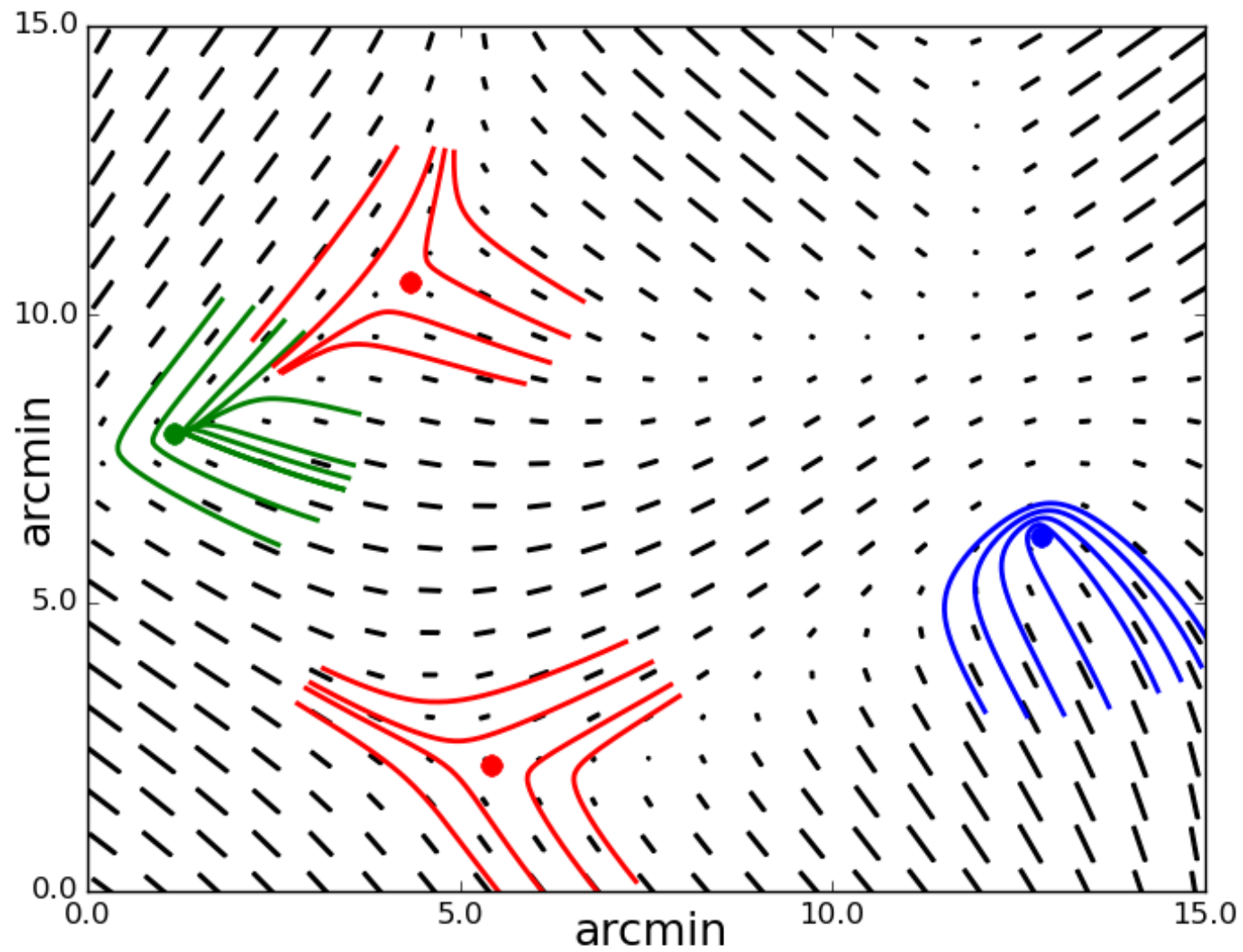


$$P^2 = Q^2 + U^2, \quad \tan(2\phi) = U/Q.$$

Unpolarized points



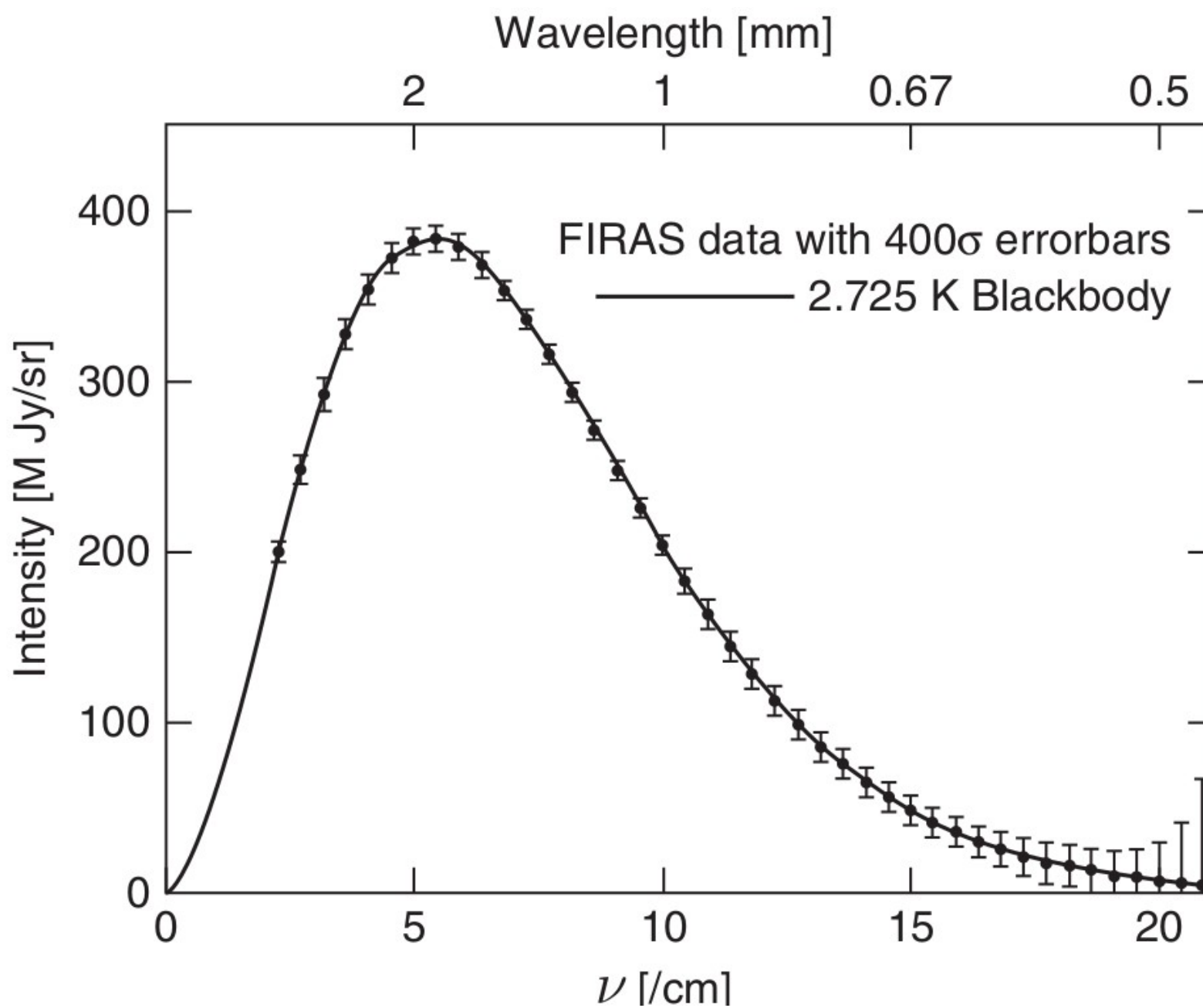
Unpolarized points



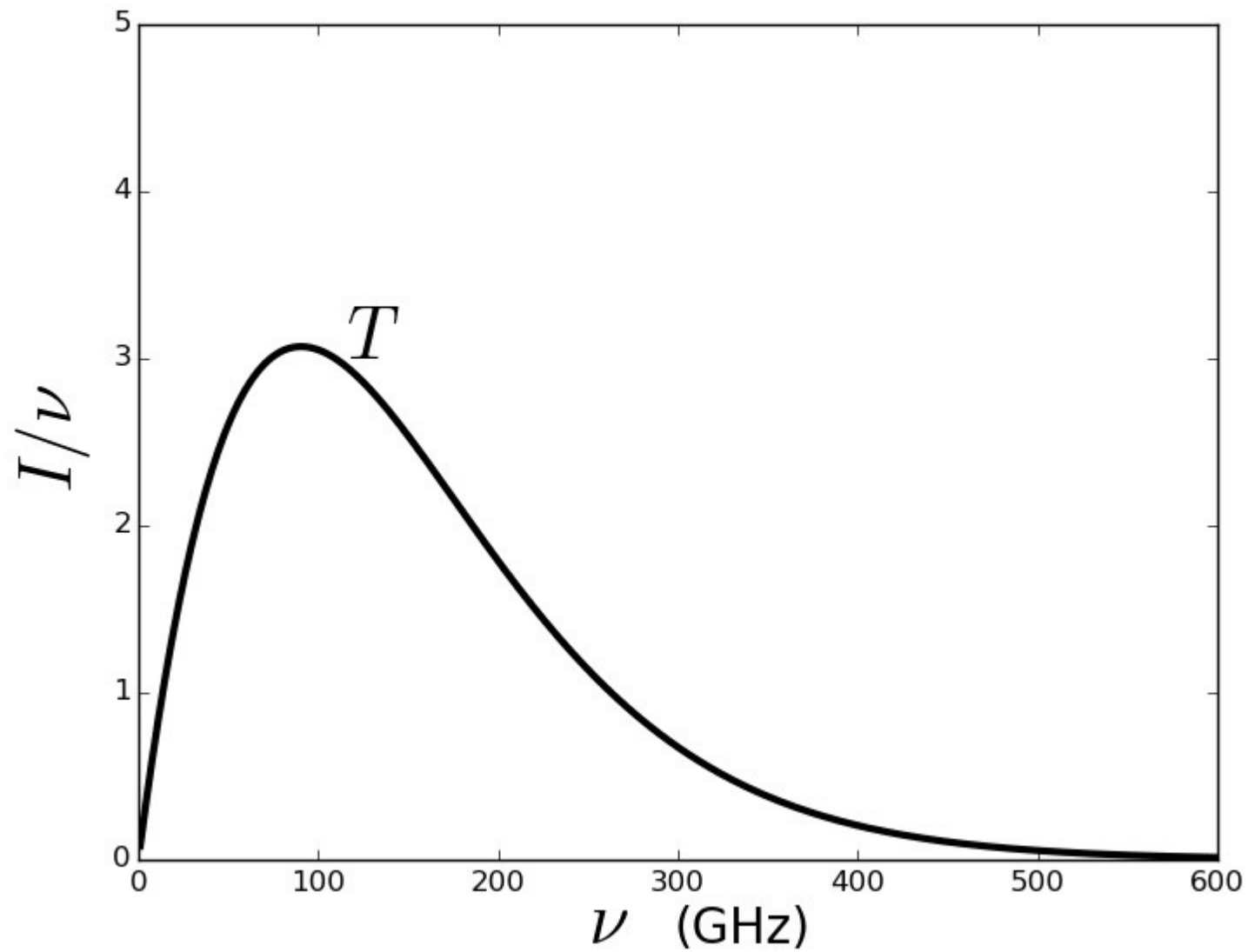
For Gaussian statistics (inflation):

- $\langle n_{\text{saddle}} \rangle = 0.5 \langle n \rangle$
- $\langle n_{\text{comet}} \rangle \approx 0.448 \langle n \rangle$
- $\langle n_{\text{beak}} \rangle \approx 0.052 \langle n \rangle$

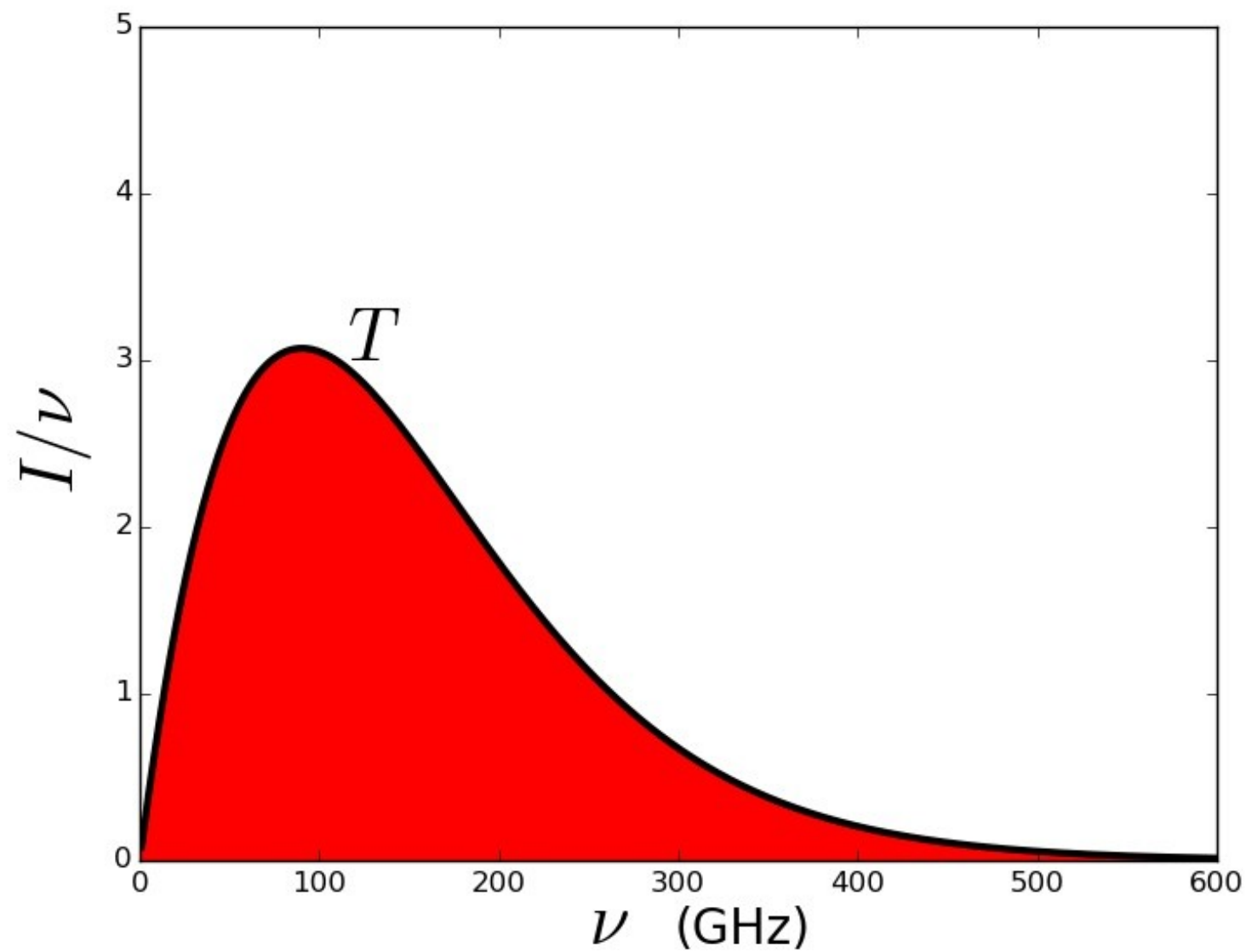
Spectral distortions (the shape of the CMB
frequency spectrum)



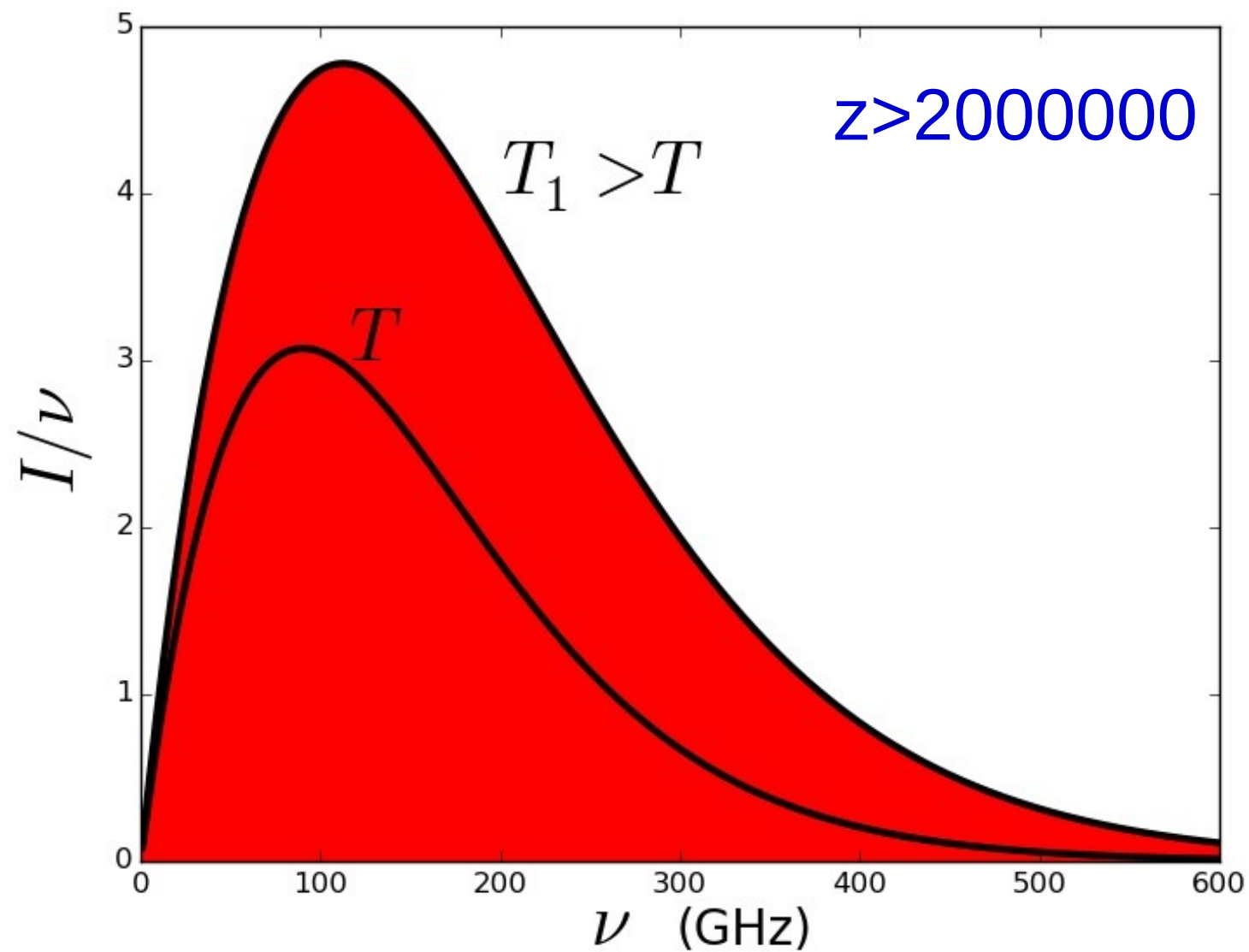
Ta-Pei Cheng <https://doi.org/10.1093/acprof:oso/9780199669912.003.0003>



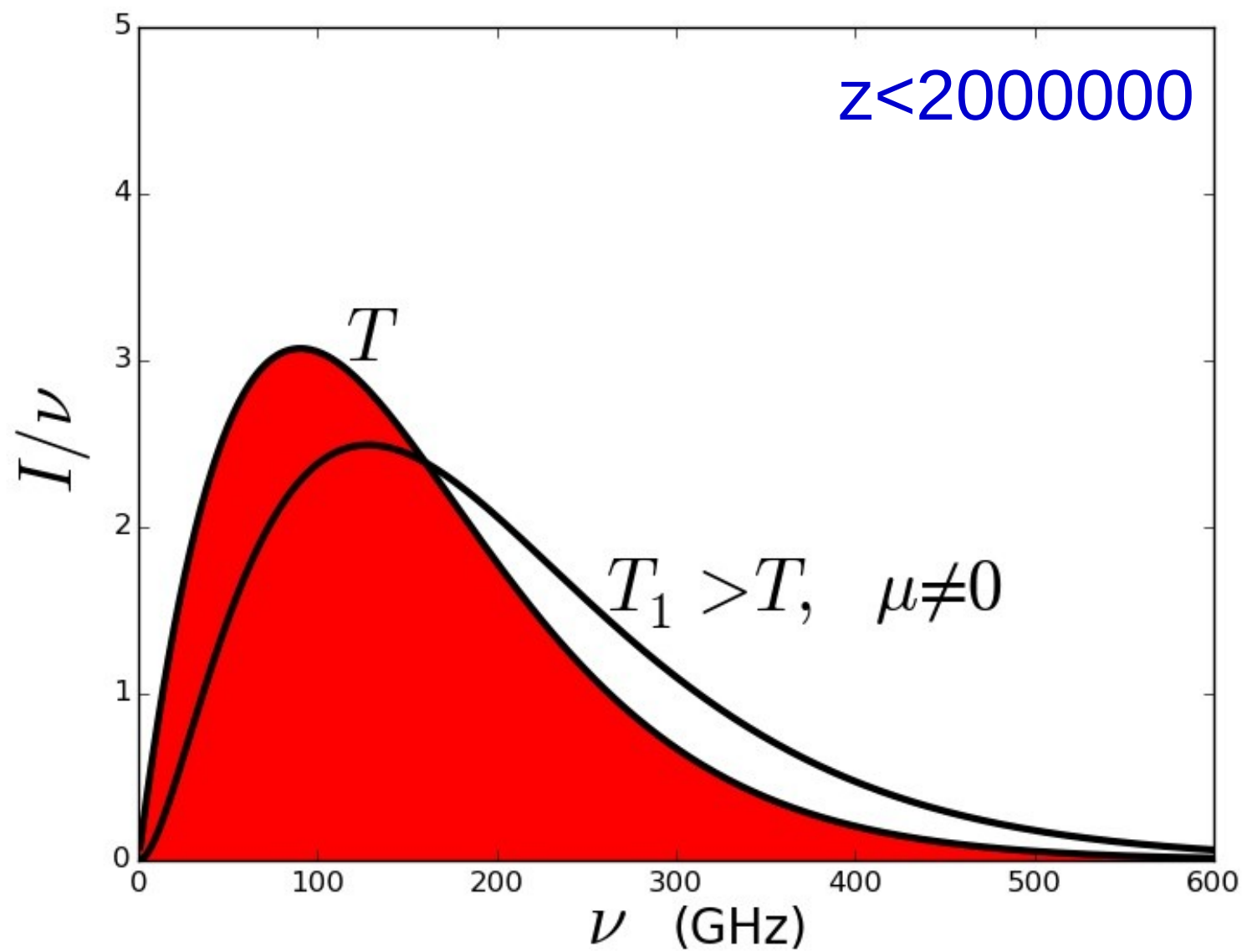
$$I/\nu \sim \nu^2 n(\nu) = \nu^2 \left(e^{\frac{h\nu}{kT_e}} - 1 \right)^{-1}$$



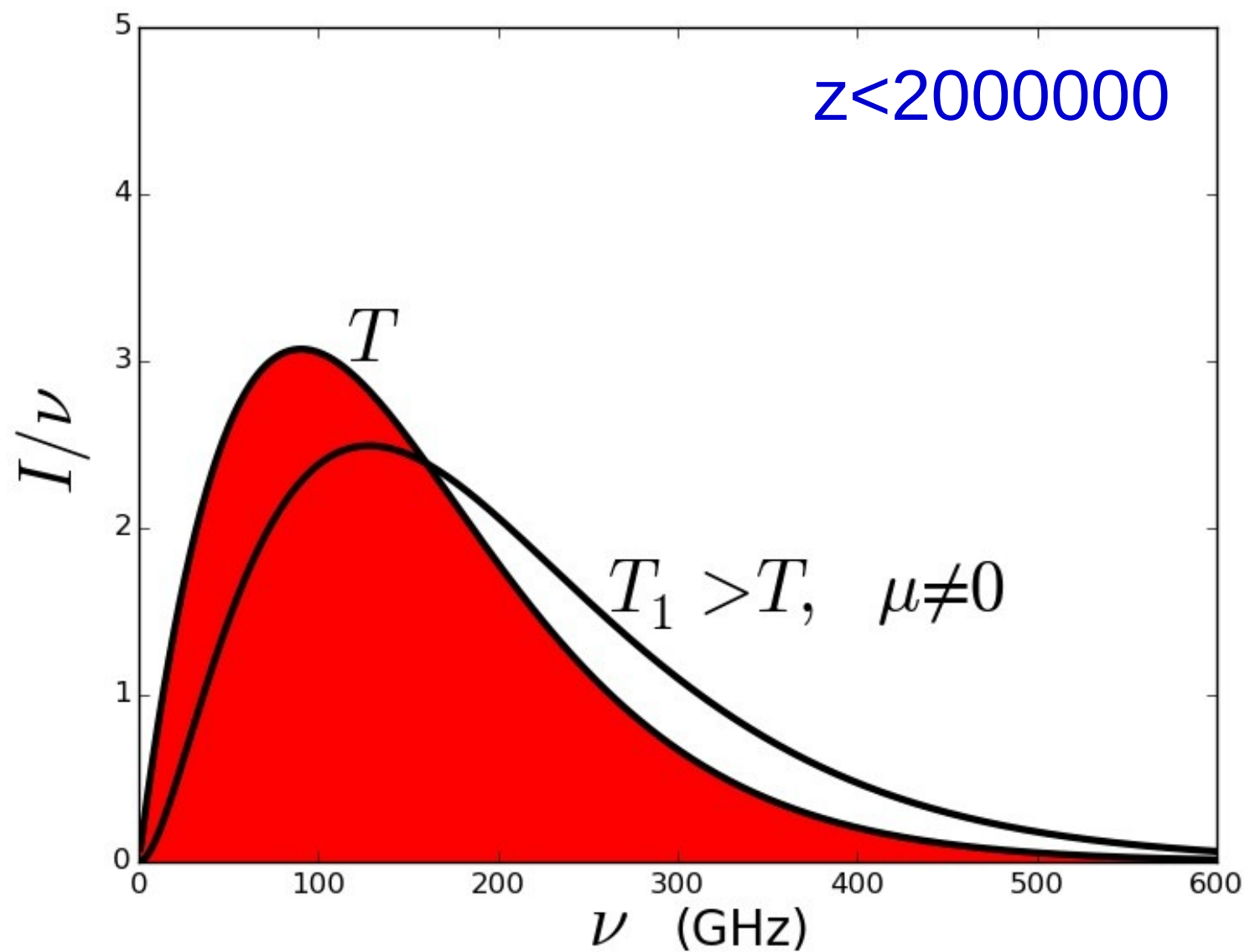
$$\int_0^{\infty} I \frac{d\nu}{\nu} \sim \text{total number of photons.}$$



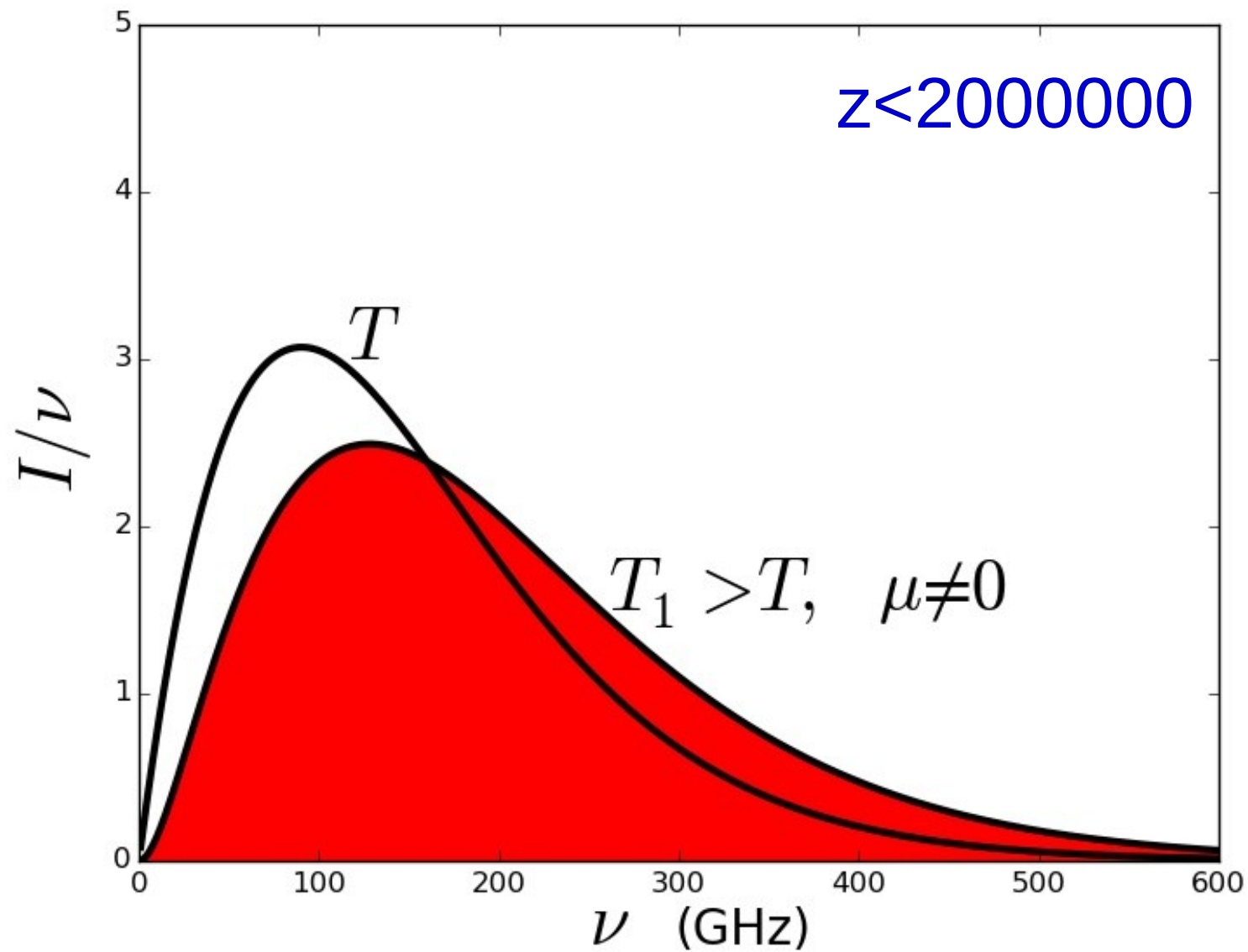
$$\int_0^{\infty} I \frac{d\nu}{\nu} \sim \text{total number of photons.}$$



$$\int_0^{\infty} I \frac{d\nu}{\nu} \sim \text{total number of photons.}$$



$$n(\nu) = \left(e^{\frac{h\nu}{kT_e}} - 1 \right)^{-1} \rightarrow n(\nu) = \left(e^{\frac{h\nu}{kT_e} + \mu} - 1 \right)^{-1}$$



$$n(\nu) = \left(e^{\frac{h\nu}{kT_e}} - 1 \right)^{-1} \rightarrow n(\nu) = \left(e^{\frac{h\nu}{kT_e} + \mu} - 1 \right)^{-1}$$

Kompaneets equation:

$$\nu^2 \frac{\partial n}{\partial t} = \frac{\sigma_T N_e h}{m_e c} \frac{\partial}{\partial \nu} \left[\nu^4 \left(n + n^2 + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right) \right],$$

$n(\nu, t)$ - is photon number density

A. S. Kompaneets, Sov. J. Exp. Theor. Phys. 4, 730 (1957).

Properties of the Kompaneets equation:

$$\nu^2 \frac{\partial n}{\partial t} = \frac{\sigma_T N_e h}{m_e c} \frac{\partial}{\partial \nu} \left[\nu^4 \left(n + n^2 + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right) \right],$$

$$\frac{\partial}{\partial t} \int_0^\infty \nu^2 n d\nu = \frac{\sigma_T N_e h}{m_e c} \int_0^\infty \frac{\partial}{\partial \nu} \left[\nu^4 \left(n + n^2 + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right) \right] d\nu = 0$$

$\Downarrow$

$$\int_0^\infty \nu^2 n d\nu = \text{constant}$$

Stationary solution: $n = \left(e^{\frac{h\nu}{kT_e} + \mu} - 1 \right)^{-1}$

Properties of the Kompaneets equation:

$$\nu^2 \frac{\partial n}{\partial t} = \frac{\sigma_T N_e h}{m_e c} \frac{\partial}{\partial \nu} \left[\nu^4 \left(n + n^2 + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right) \right],$$

Two different asymptotics

1. If $t \gg \frac{m_e c}{\sigma_T N_e h}$ and $T_e > T$ for $t = 0$ then

$$n(\nu, t) = \left(e^{\frac{h\nu}{kT_e} + \mu} - 1 \right)^{-1}, \quad \mu \neq 0$$

$\Downarrow$

μ -distortion

2. If $t \ll \frac{m_e c}{\sigma_T N_e h}$ and $n(\nu, 0) = \frac{1}{e^x - 1}$, $x = h\nu/kT_r$ then

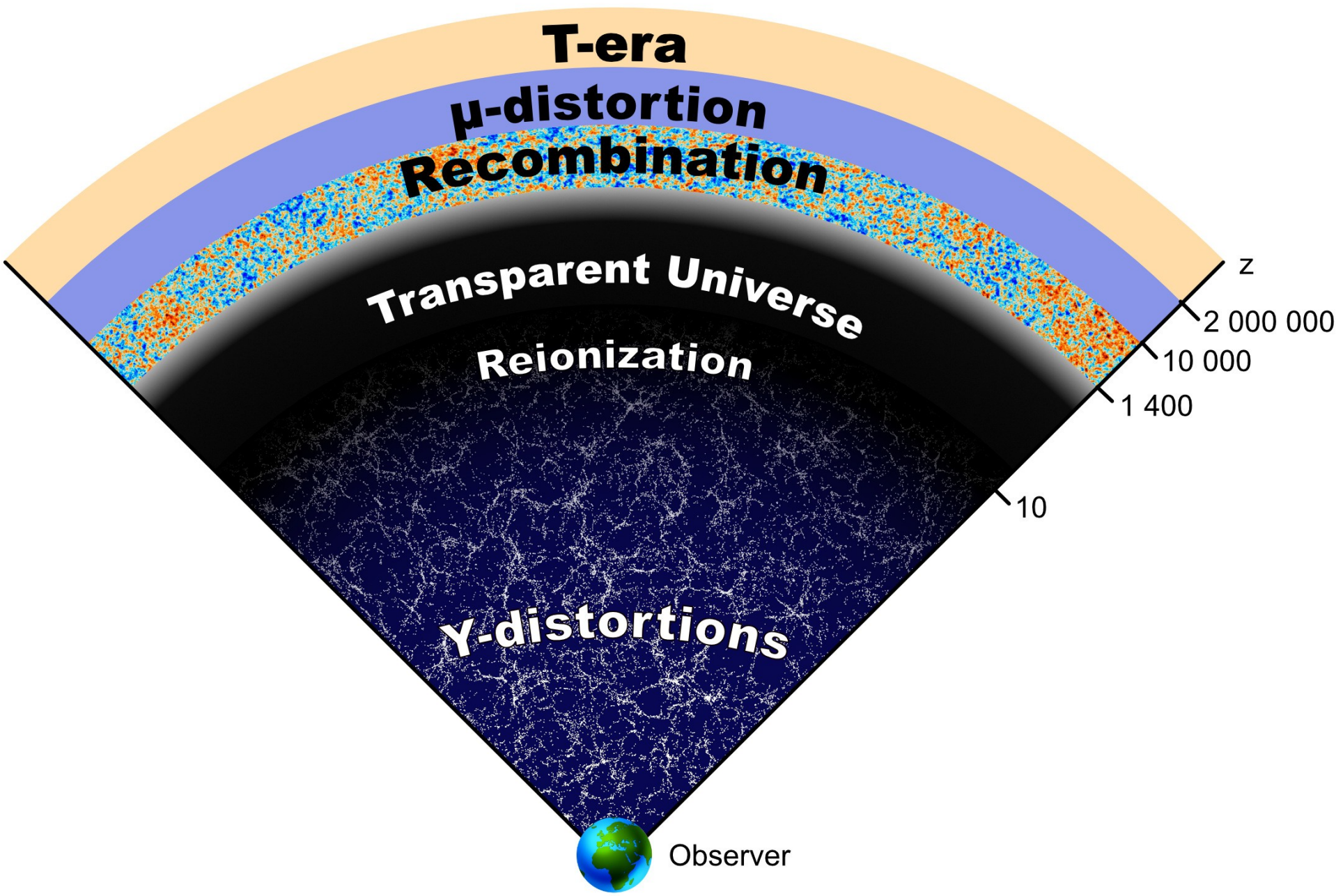
$$n(\nu, t) - n(\nu, 0) = tk(T_e - T_r) \frac{\sigma_T N_e}{m_e c} \frac{x e^x}{(e^x - 1)^2} \left[x \frac{e^x + 1}{e^x - 1} - 4 \right]$$

$\Downarrow$

y-distortions (or SZ effect)

Relativistic corrections:

$$\nu^2 \frac{\partial n}{\partial t} = \frac{\sigma_T N_e h}{m_e c} \frac{\partial}{\partial \nu} \left[\nu^4 \left(n + n^2 + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right) + \right. \\ \left. + \left(kT_e / m_e c^2 \right) R_1 + \left(kT_e / m_e c^2 \right)^2 R_2 + \dots \right]$$



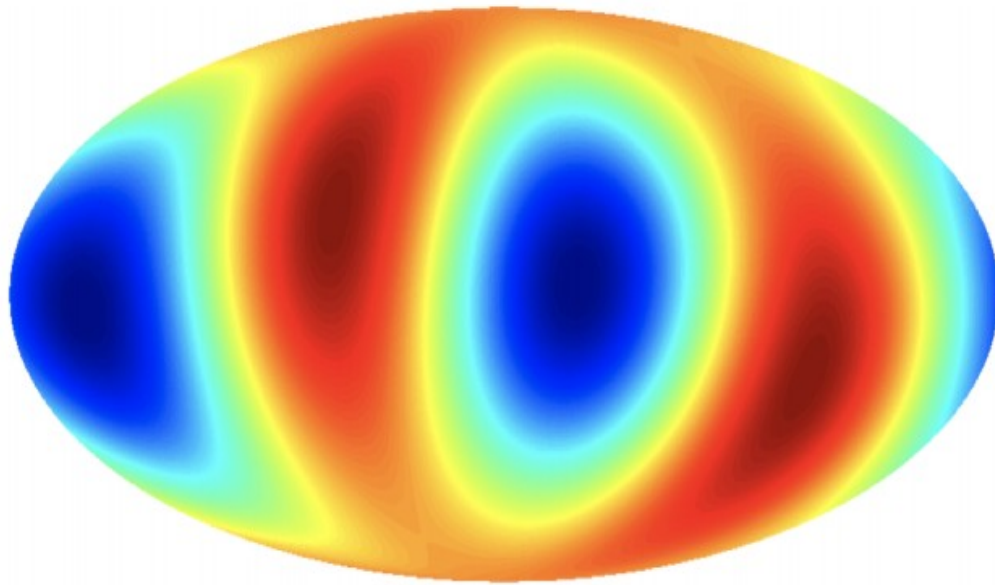
Anisotropic SZ effect

I. Edigariyev, D. Novikov, S. Pilipenko [arXiv:1812.01330](#) , *Phys. Rev. D*

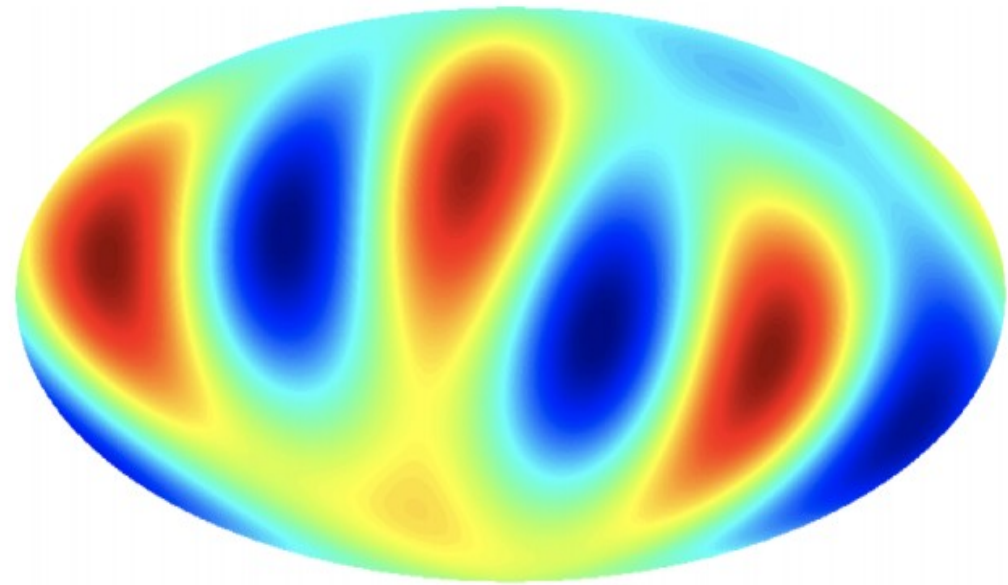
D. I. Novikov, S. V. Pilipenko, M. de Petris, G. Luzzi, A. O. Mihalchenko
[ArXiv:2006.15571](#), *Phys. Rev. D*

Low CMBA multipoles

(Low amplitude) Quadrupole & octupole alignment. Axis of evil



-0.02 +0.02



-0.04 +0.04

$$\mathbf{J} = \begin{pmatrix} n(\nu, \boldsymbol{\Omega}) \\ q(\nu, \boldsymbol{\Omega}) \\ u(\nu, \boldsymbol{\Omega}) \end{pmatrix}$$

$$\mu = \cos \Theta$$

$$d\boldsymbol{\Omega} = d\mu d\varphi$$

$$x = \frac{h\nu}{kT_r}$$

$$\varepsilon = \frac{h\nu}{m_e c^2}$$

$$\Theta_e = \frac{kT_e}{m_e c^2}$$

$$\mathbf{R} = \begin{pmatrix} 1 + \mu^2 \\ (1 - \mu^2) \cos 2\varphi \\ (1 - \mu^2) \sin 2\varphi \end{pmatrix}$$

Thomson scattering
($\Theta_e = 0$)

$$\mathbf{S} = 2 \begin{pmatrix} (1 - \mu)^2(1 + 2\mu) - 2\mu \\ (1 - \mu^2)(1 + 2\mu) \cos 2\varphi \\ (1 - \mu^2)(1 + 2\mu) \sin 2\varphi \end{pmatrix}$$

Compton scattering
($\Theta_e \neq 0$)

$$\mathbf{T} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$\bar{n}(\nu) = \frac{1}{4\pi} \int n'(\nu, \boldsymbol{\Omega}) d\boldsymbol{\Omega}$$

$$\Delta = n'(\nu, \boldsymbol{\Omega}) - \bar{n}(\nu)$$

Spectral distortions of Stokes parameters after a single scattering:

$$\delta \mathbf{J} / \delta \tau = \underbrace{g_1(x) \left[\frac{3}{16\pi} \int_{\Omega} \frac{\Delta_T(\Omega)}{T_r} (\mathbf{R} + \Theta_e \mathbf{S}) d\Omega \right]}_{(1)} + \underbrace{\Theta_e g_2(x) \left[\frac{3}{16\pi} \int_{\Omega} \frac{\Delta_T(\Omega)}{T_r} (1 - \mu) \mathbf{R} d\Omega \right]}_{(2)} + \underbrace{\Theta_e g_3(x) \mathbf{T}}_{(3)} \quad (tSZ)$$

CMB anisotropy
+polarization

aSZ

tSZ

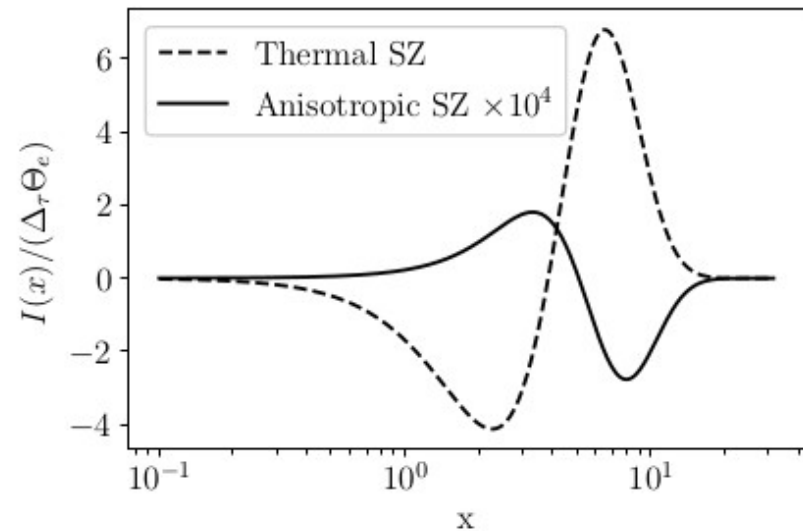
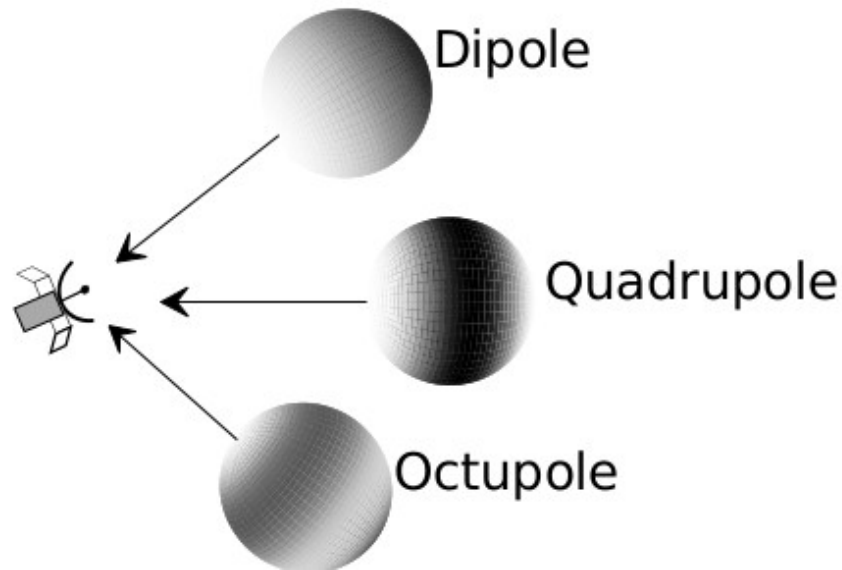
$$g_1(x) = -x \frac{dB}{dx}$$

$$g_2(x) = \frac{1}{x^2} \frac{d}{dx} \left[x^4 \frac{d}{dx} \left(-x \frac{dB}{dx} \right) \right]$$

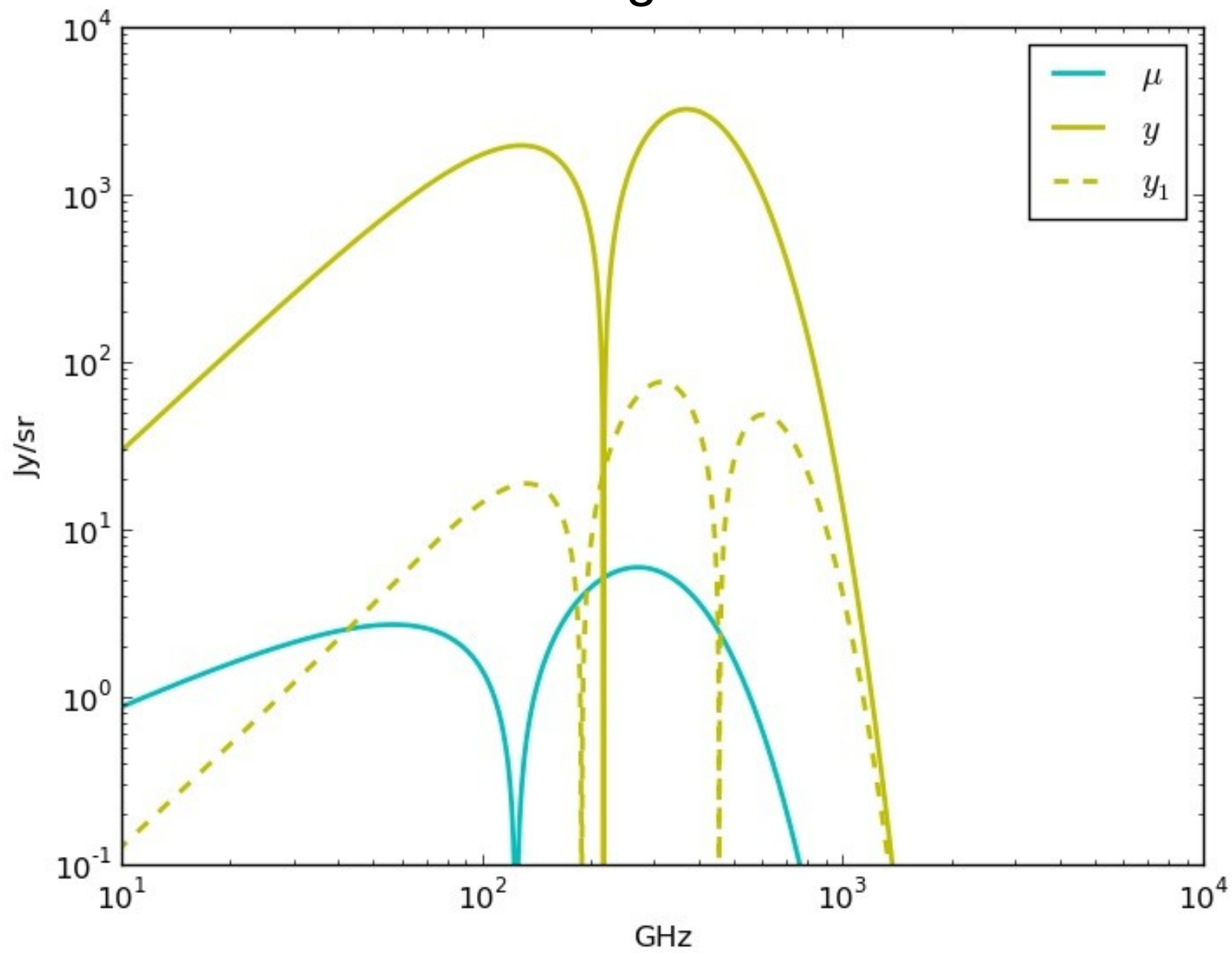
$$g_3(x) = \frac{1}{x^2} \frac{d}{dx} \left[x^4 \frac{dB}{dx} \right]$$

$$x = \frac{h\nu}{kT_r} \quad B(x) = \frac{1}{e^x - 1}$$

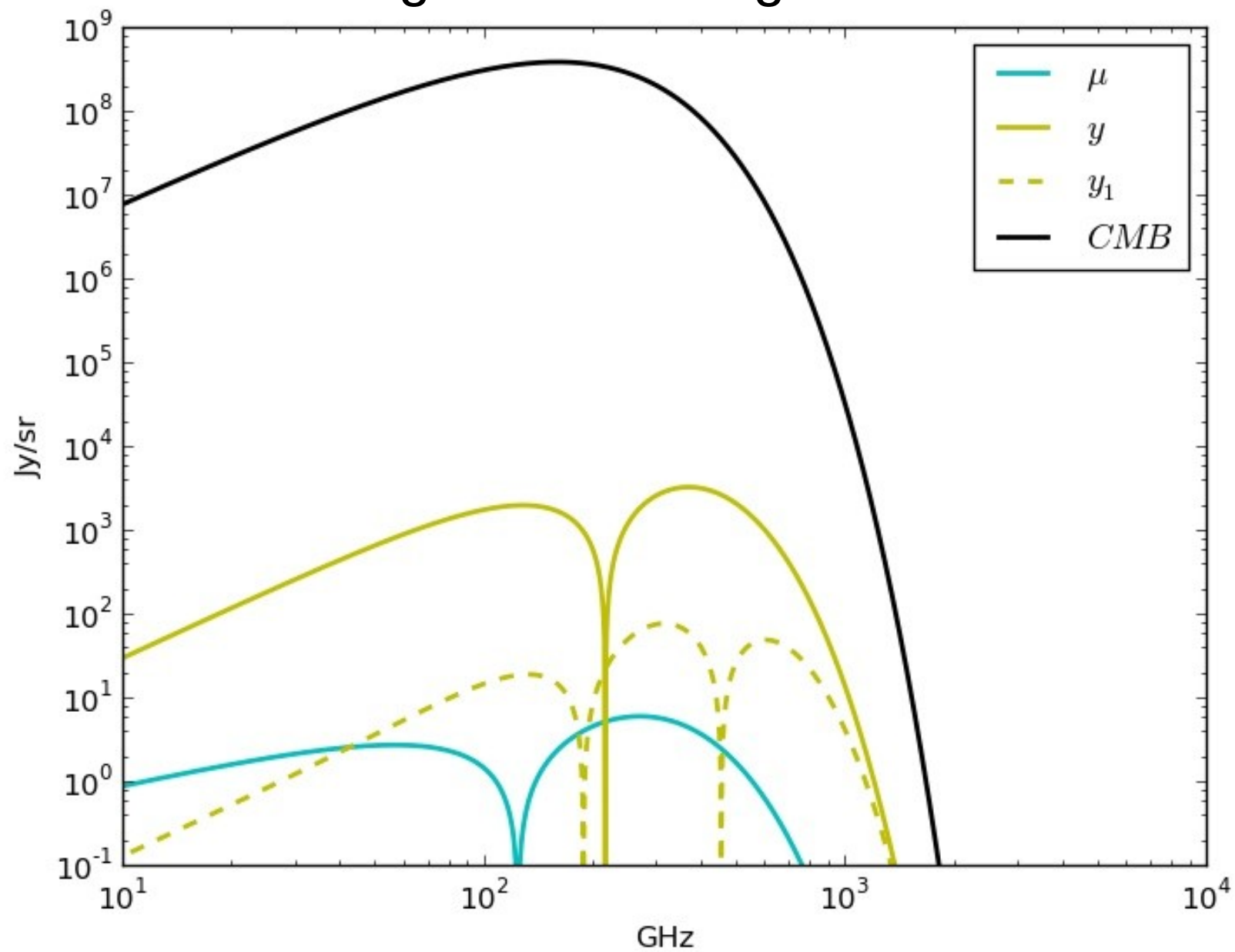
Multipole components which affect the observed CMB spectrum due to scattering



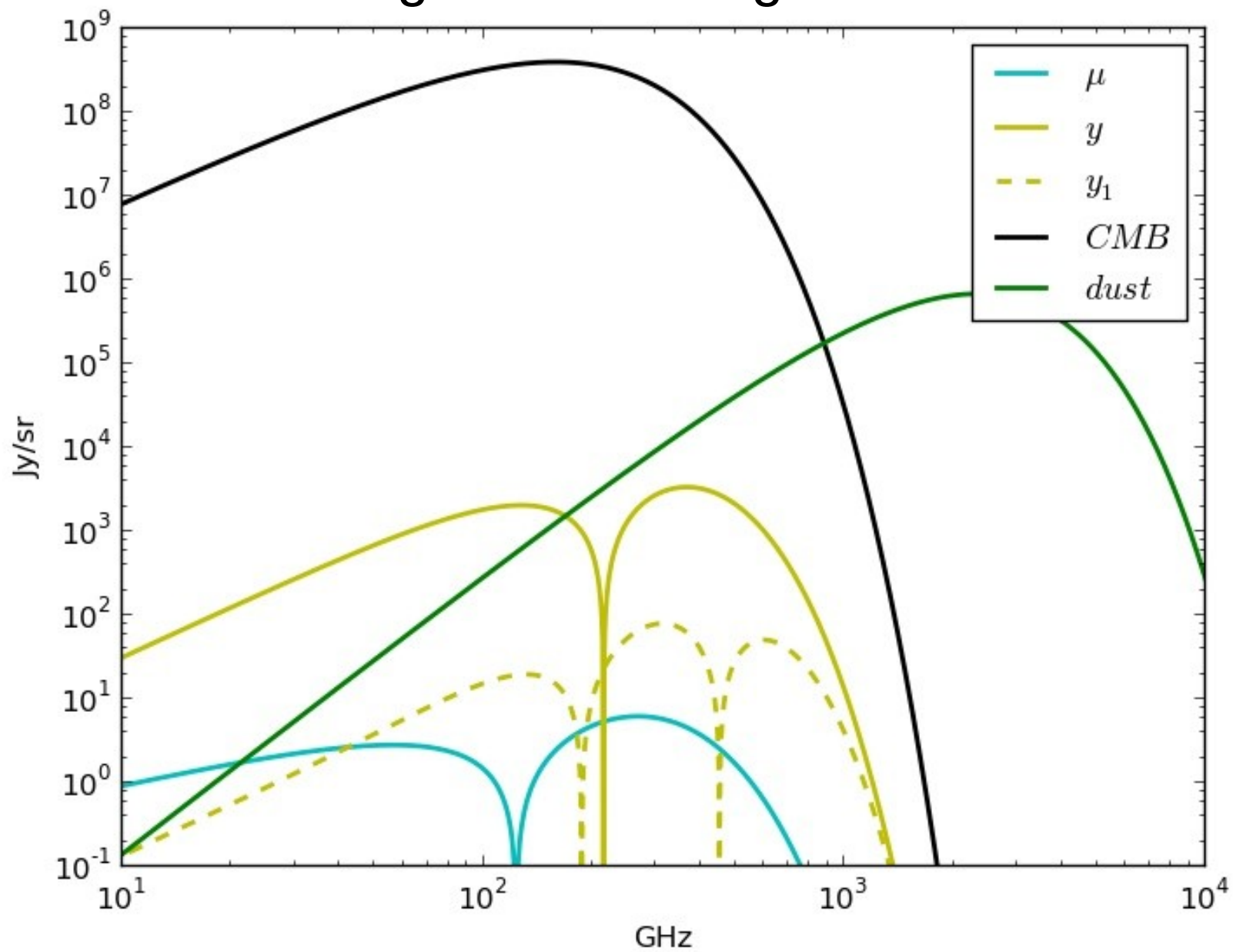
Signal



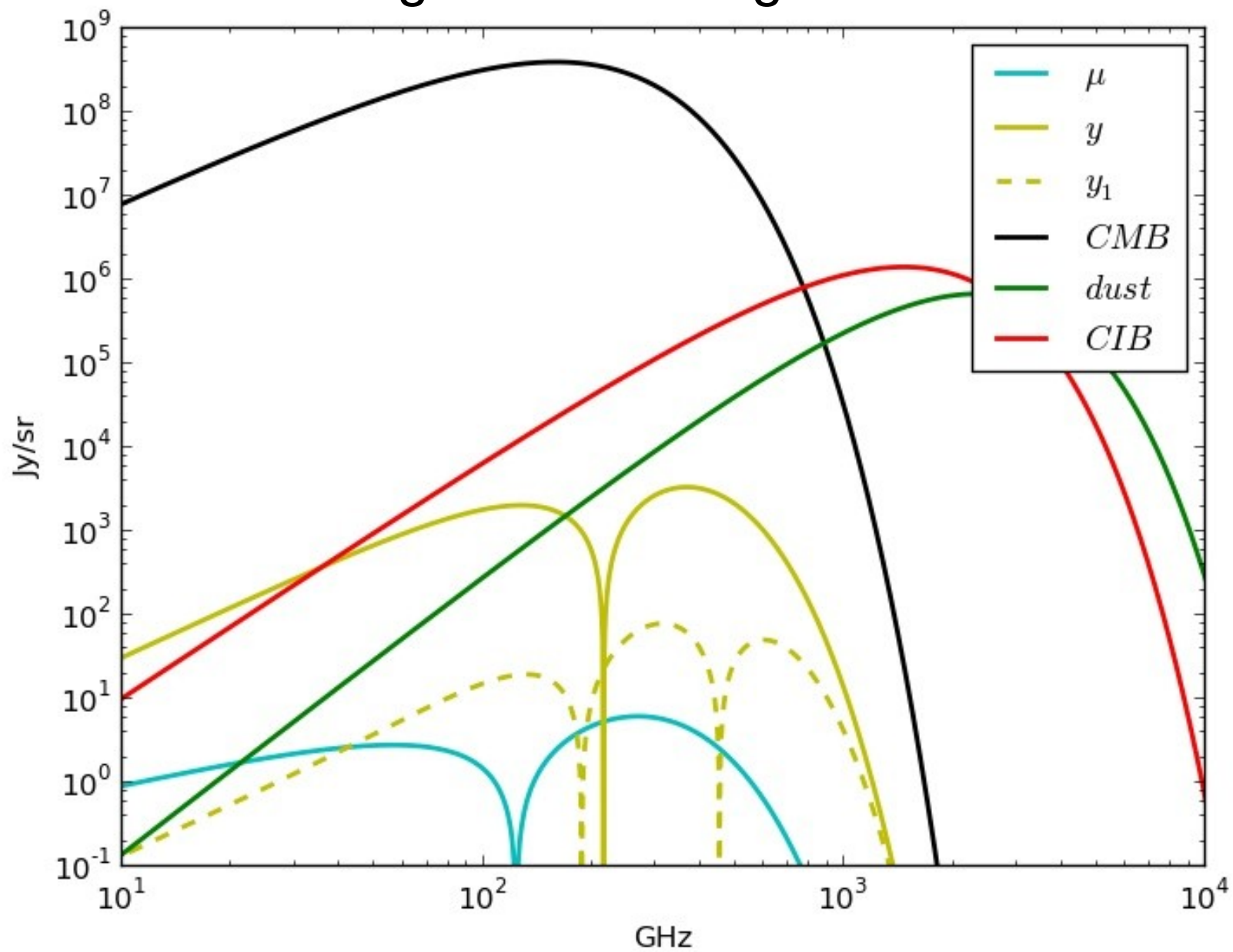
Signal and Foregrounds



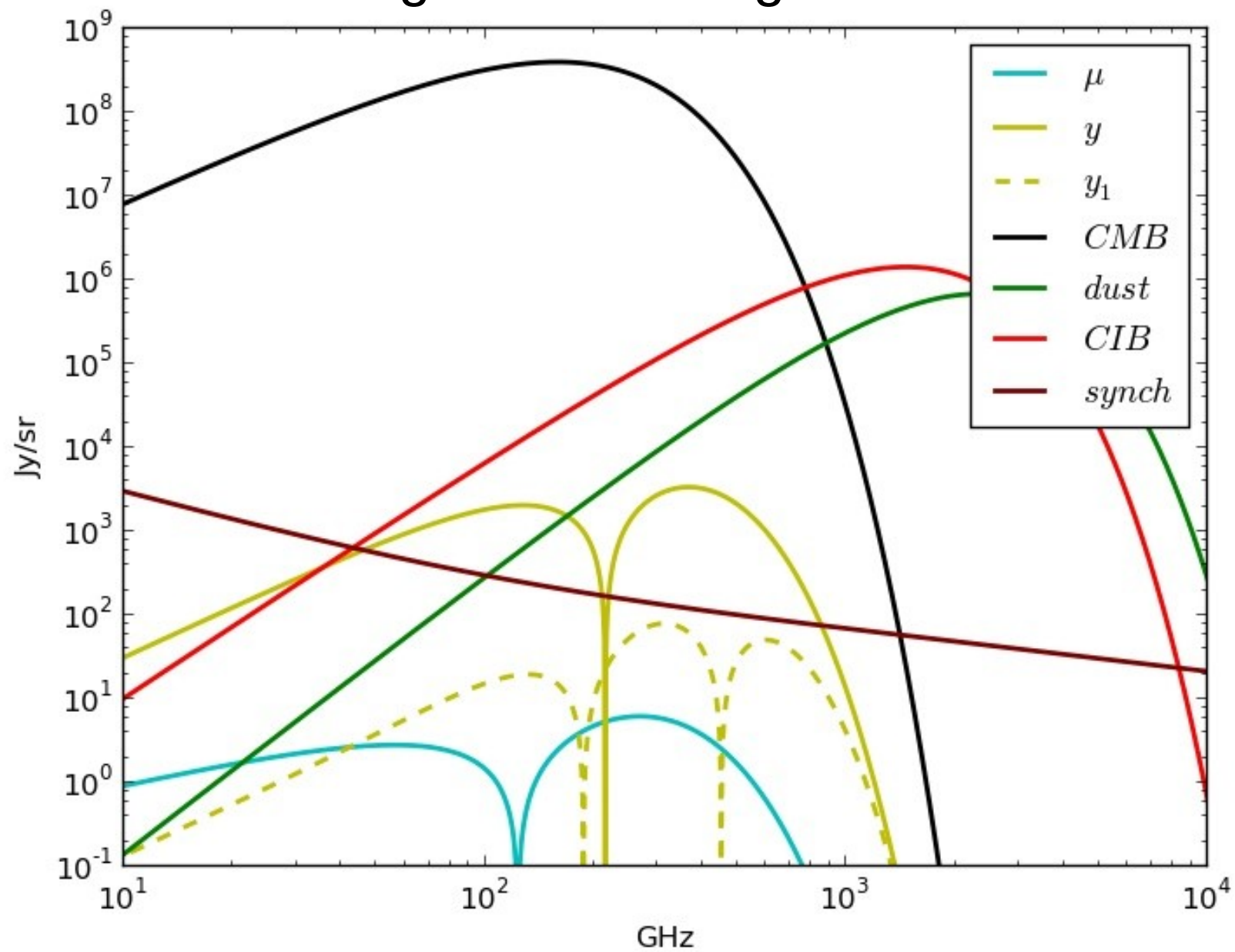
Signal and Foregrounds



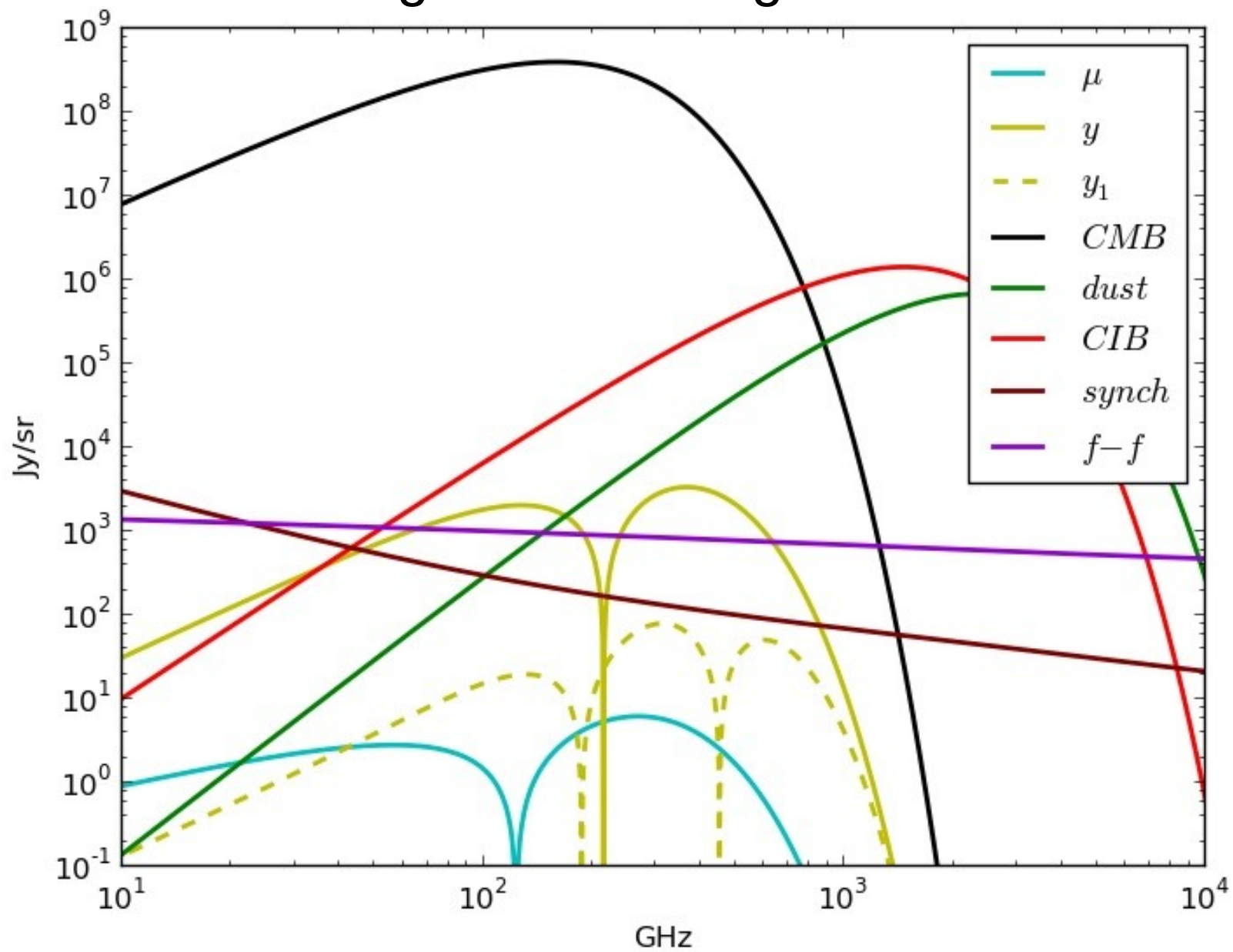
Signal and Foregrounds



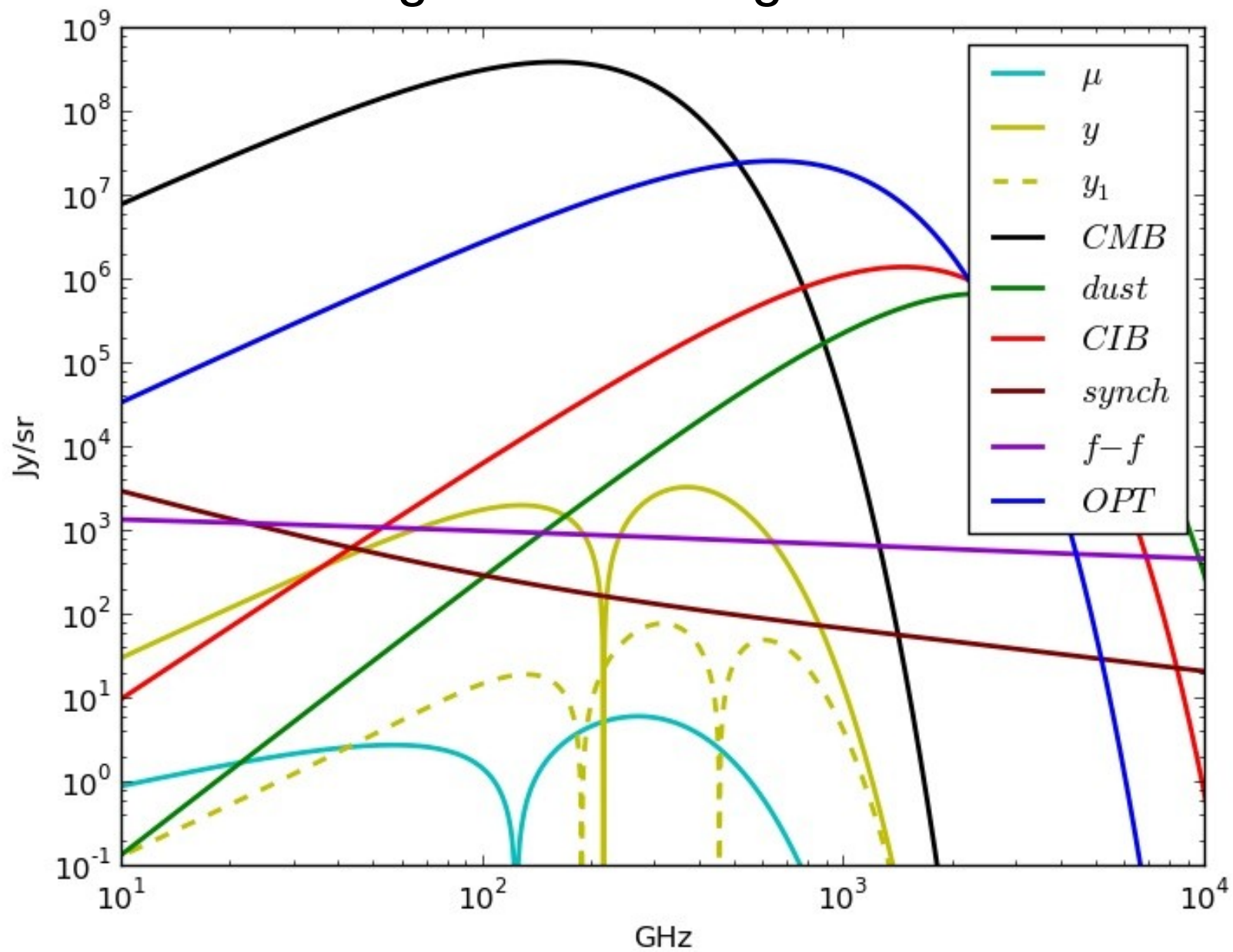
Signal and Foregrounds



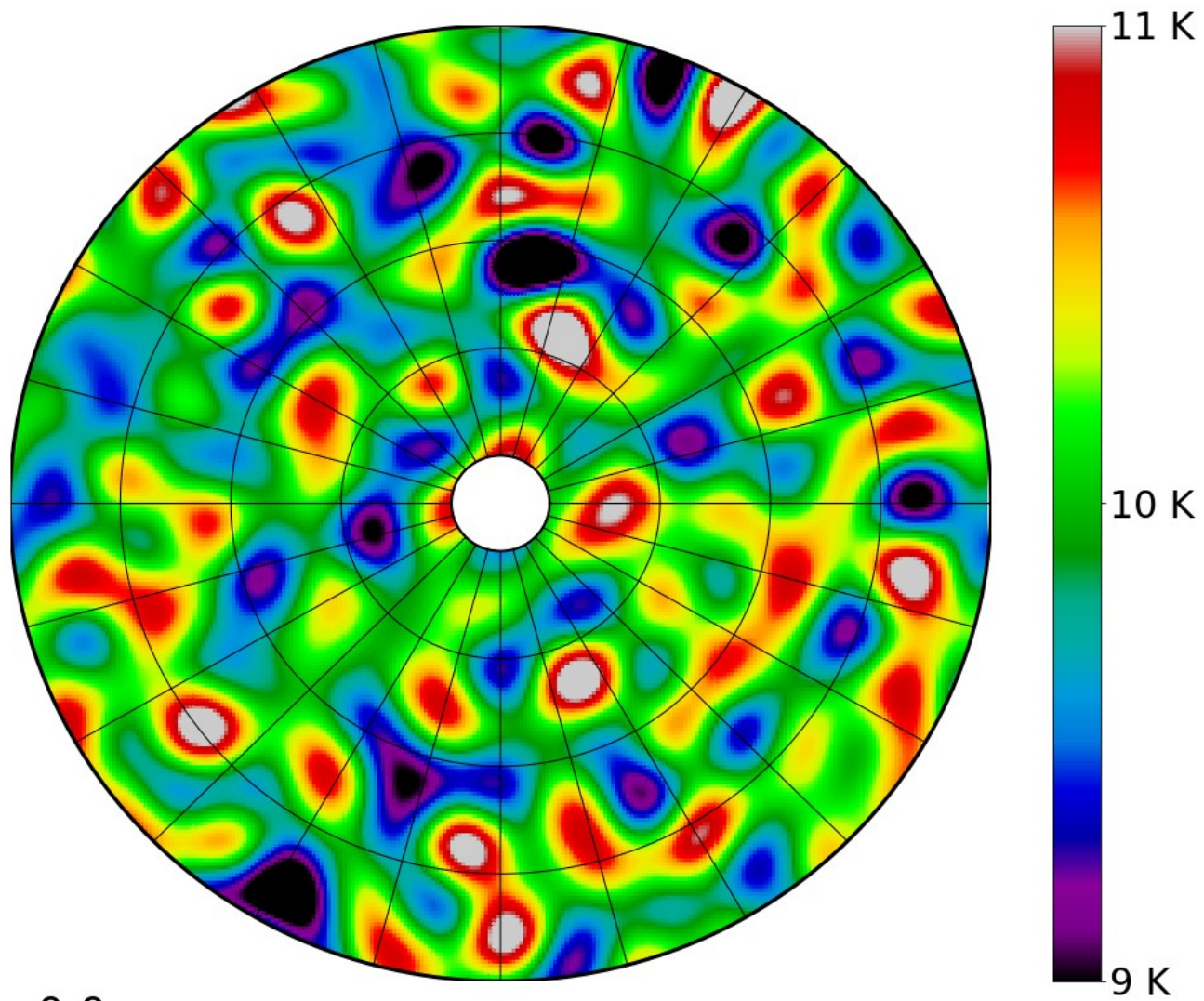
Signal and Foregrounds



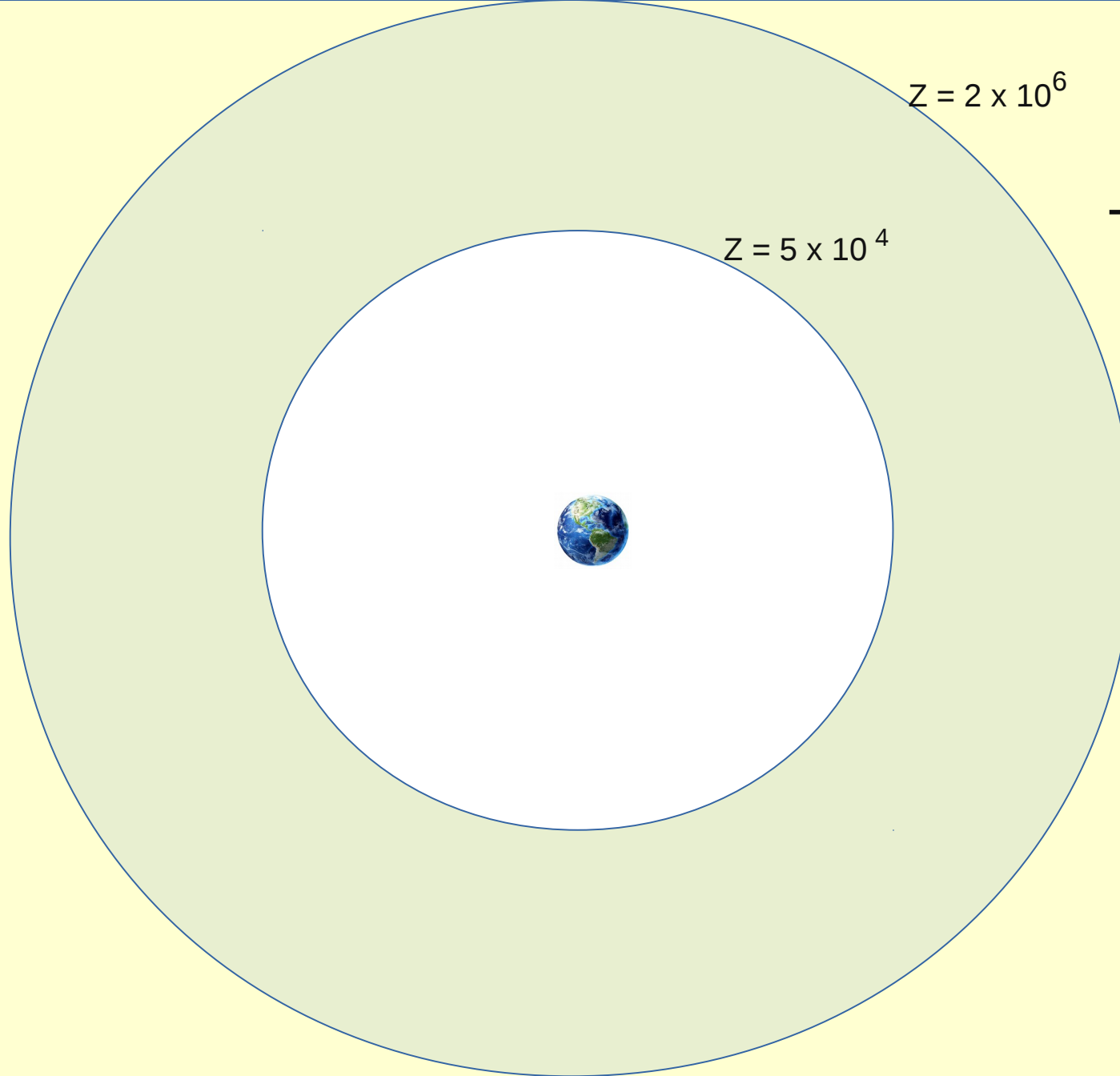
Signal and Foregrounds



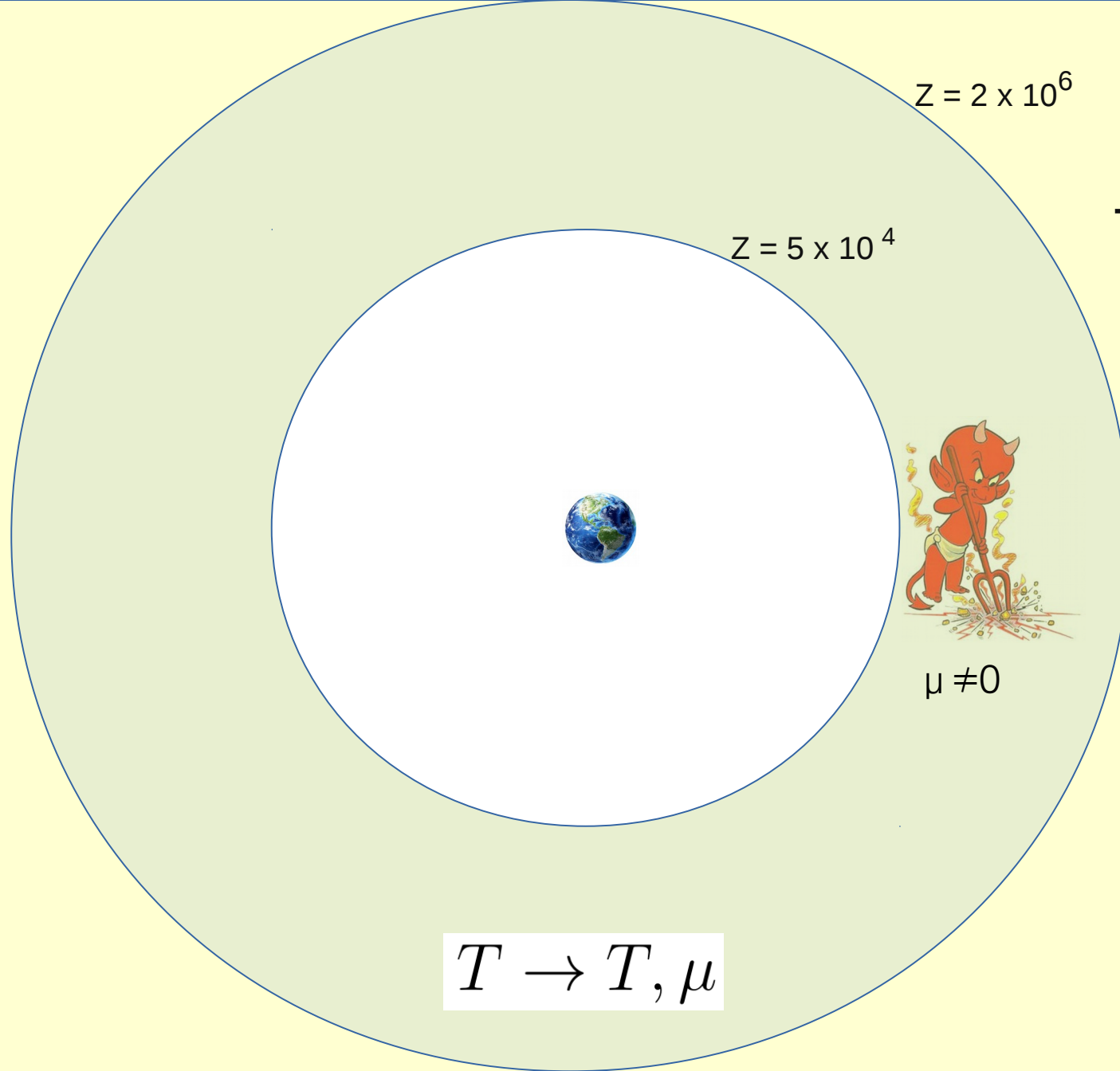
primary mirror



Days = 0.0



T - era



T - era

$\mu \neq 0$

$$T \rightarrow T, \mu$$

Conclusions

- High sensitivity experiments are needed to measure B polarization and CMB SD;
- Data processing methods are needed to clean signals from foregrounds;
- More information about dust is needed;
- Blackbody calibration is needed to measure μ distortions;
- Don't overcool the optical system!