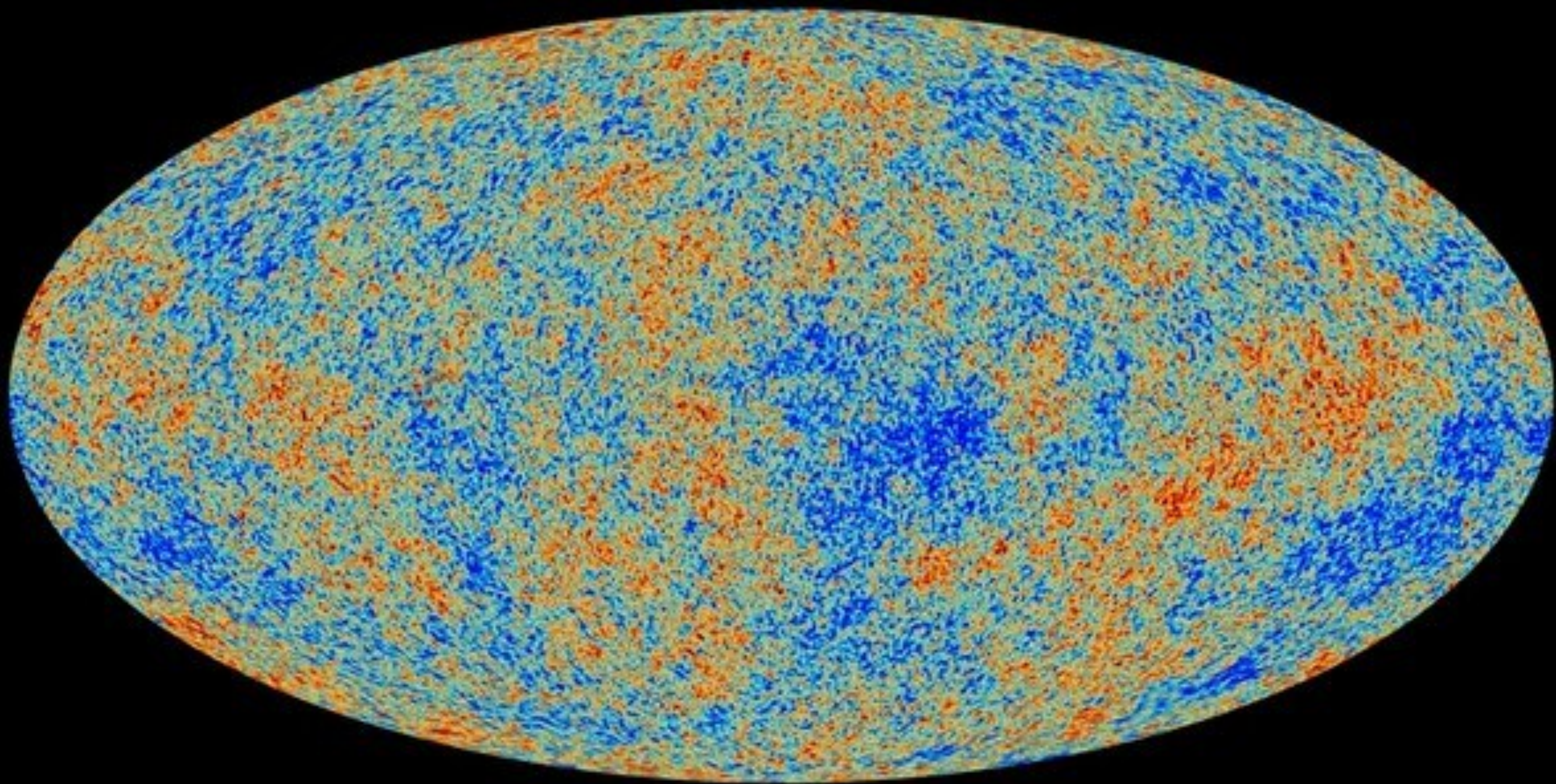


School Observational Cosmology
Angra – Terceira – Açores
5th June 2014

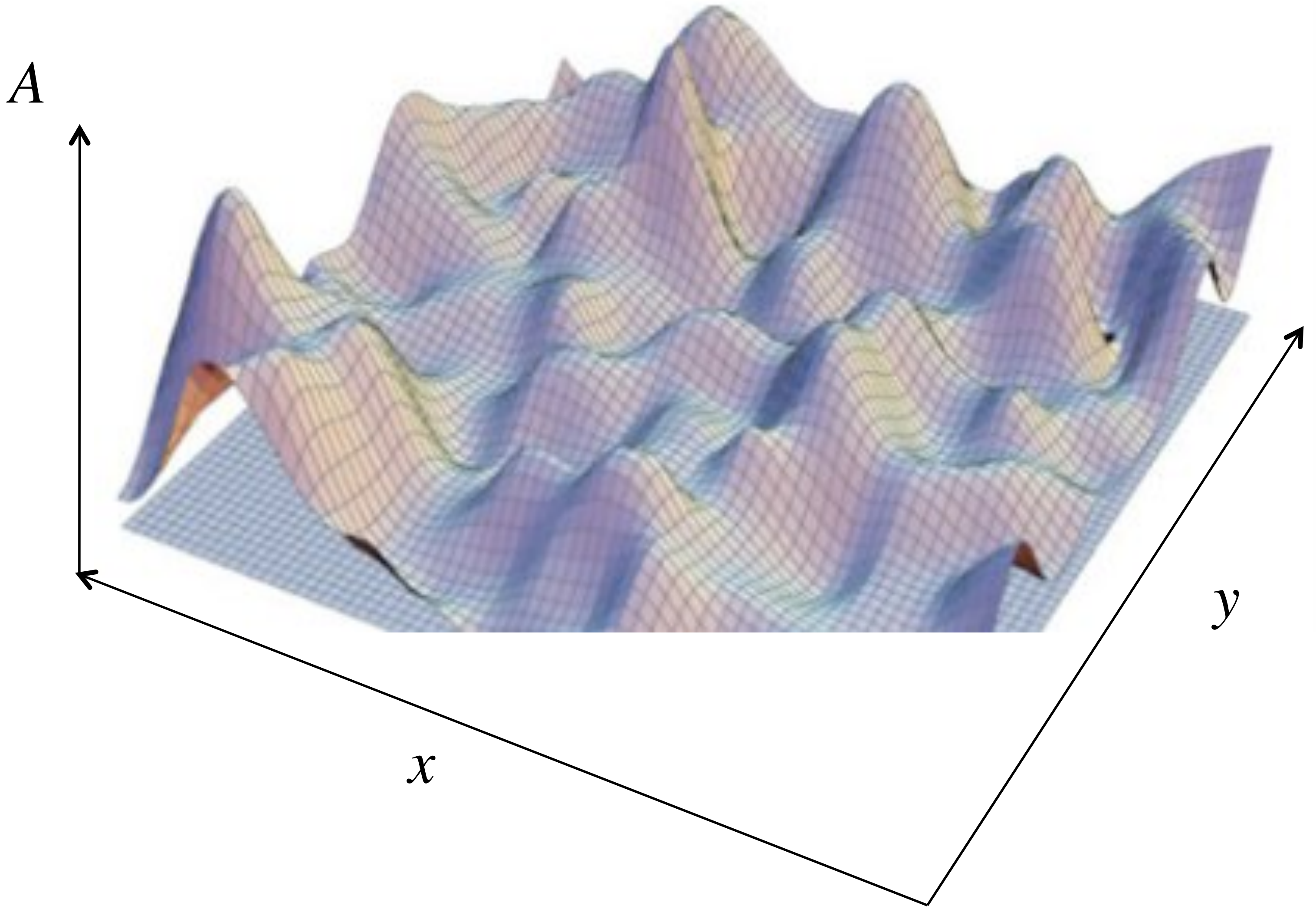
Juan García-Bellido
Física Teórica UAM
Madrid, Spain

Outline

Lecture 2

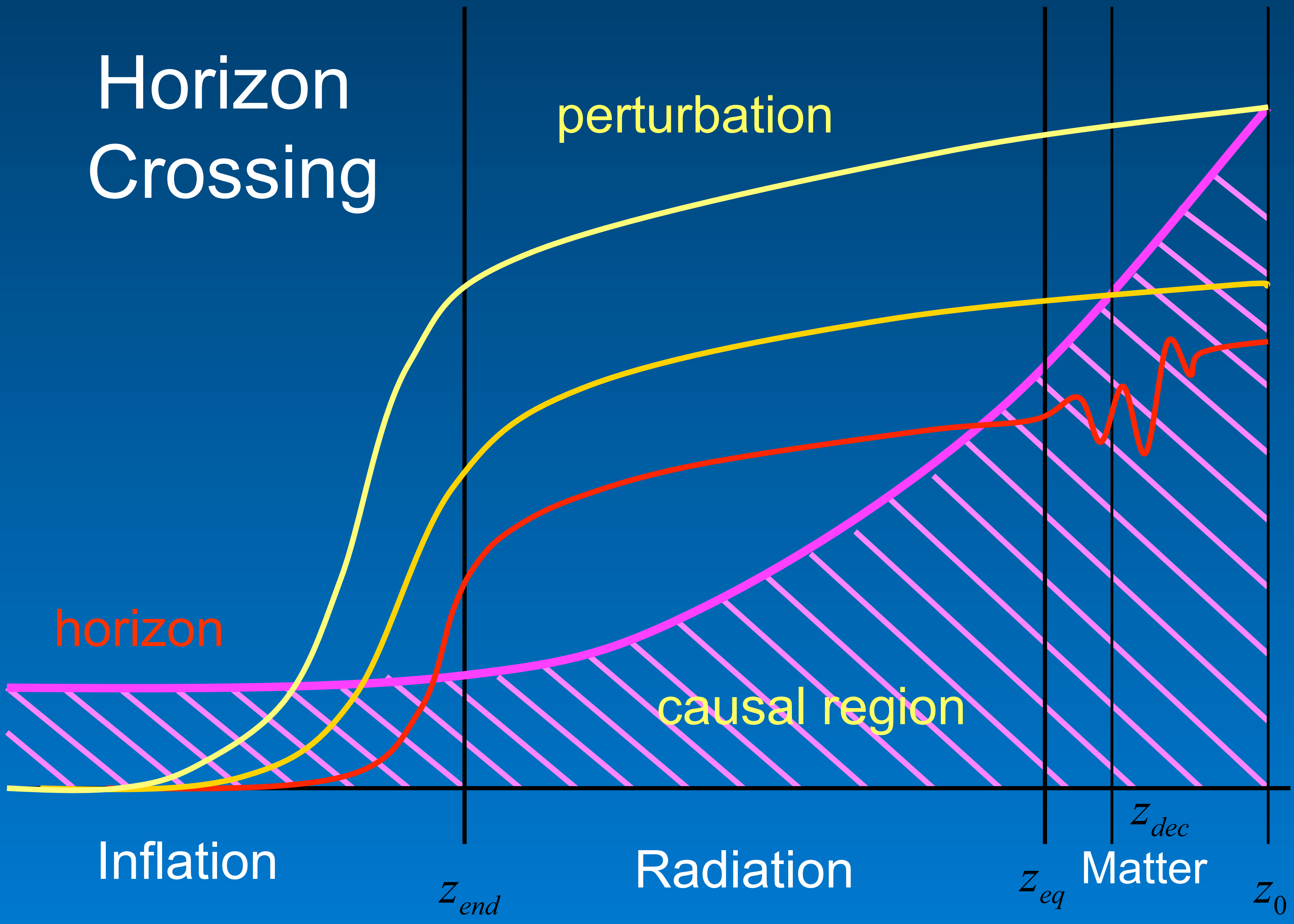
- Density and GW power spectra
- Inflationary Model Building
- CMB & LSS: predictions from inflation
- Quantum to classical transition
- Reheating after inflation

Ripples in Space



Stretched to cosmological distances

Horizon Crossing



SCALAR POWER SPECTRA

two-point correlation function in Fourier space

$$\langle 0|\mathcal{R}_k^*\mathcal{R}_{k'}|0\rangle = \frac{|u_k|^2}{z^2}\,\delta^3(\mathbf{k}-\mathbf{k}') \equiv \frac{\mathcal{P}_\mathcal{R}(k)}{4\pi k^3}\,(2\pi)^3\,\delta^3(\mathbf{k}-\mathbf{k}')\,,$$

$$\mathcal{P}_\mathcal{R}(k) = \frac{k^3}{2\pi^2}\,\frac{|u_k|^2}{z^2} = \frac{\kappa^2}{2\epsilon}\left(\frac{H}{2\pi}\right)^2\left(\frac{k}{aH}\right)^{3-2\nu} \equiv A_S^2\left(\frac{k}{aH}\right)^{n_s-1}$$

$$\mathcal{R}_k = \zeta_k = \frac{u_k}{z}$$ enter the horizon at $a = k/H$

$$A_S^2 = \frac{\kappa^2}{2\epsilon}\left(\frac{H}{2\pi}\right)^2 = \frac{1}{\pi\epsilon}\,\frac{H^2}{M_P^2}$$ amplitude and tilt,

scale invariant

$$n_s - 1 \equiv \frac{d\ln\mathcal{P}_\mathcal{R}(k)}{d\ln k} = 3-2\nu = 2\left(\frac{\delta-2\epsilon}{1-\epsilon}\right) \simeq 2\eta_V - 6\epsilon_V \ll 1$$

running of the tilt

$$\frac{dn_s}{d\ln k} = -\eta\mathcal{H}\left(2\xi + 8\epsilon^2 - 10\epsilon\delta\right) \simeq 2\xi_V + 24\epsilon_V^2 - 16\eta_V\epsilon_V$$

TENSOR POWER SPECTRA

tensor (gravitational wave) metric perturbation

$$\sum_\lambda \langle 0|h^*_{k,\lambda} h_{k',\lambda}|0\rangle = 4\,\frac{2\kappa^2}{a^2}\,|v_k|^2 \delta^3(\mathbf{k}-\mathbf{k}') \equiv \frac{\mathcal{P}_g(k)}{4\pi k^3}\,(2\pi)^3\,\delta^3(\mathbf{k}-\mathbf{k}')$$

$$\mathcal{P}_g(k) = 8\kappa^2 \left(\frac{H}{2\pi}\right)^2 \left(\frac{k}{aH}\right)^{3-2\mu} \equiv \underline{A_T^2 \left(\frac{k}{aH}\right)^{n_T}}$$

$$h_k = \kappa\sqrt{2}\,\frac{v_k}{a}$$ enter the horizon at $a = k/H$

$$\boxed{A_T^2 = 8\kappa^2 \left(\frac{H}{2\pi}\right)^2 = \frac{16}{\pi}\,\frac{H^2}{M_P^2}}$$ amplitude and tilt,

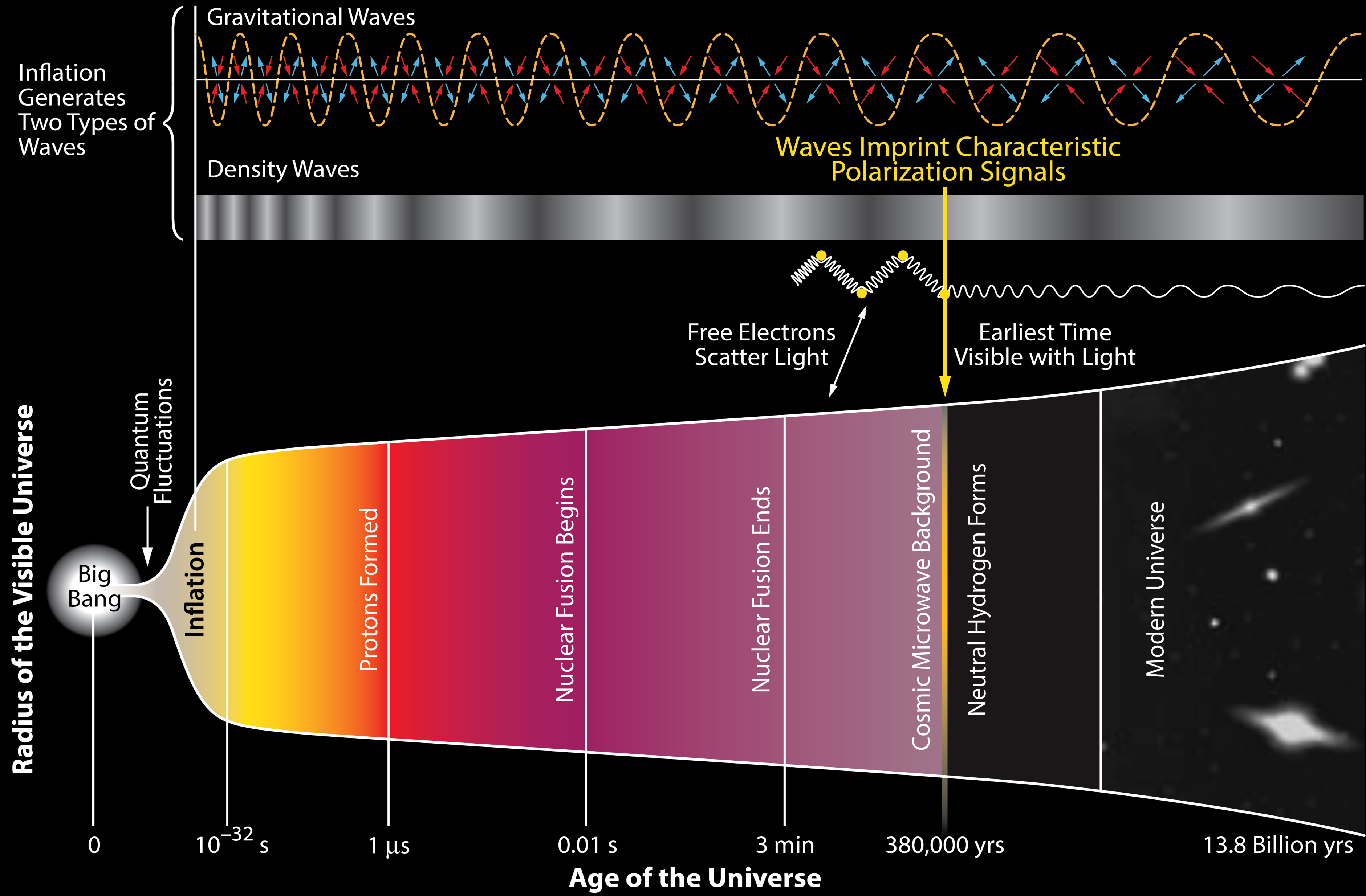
scale invariant

$$n_T \equiv \frac{d\ln \mathcal{P}_g(k)}{d\ln k} = 3 - 2\mu = \frac{-2\epsilon}{1-\epsilon} \simeq \underline{-2\epsilon_V < 0} \qquad \ll 1$$

running of the tilt

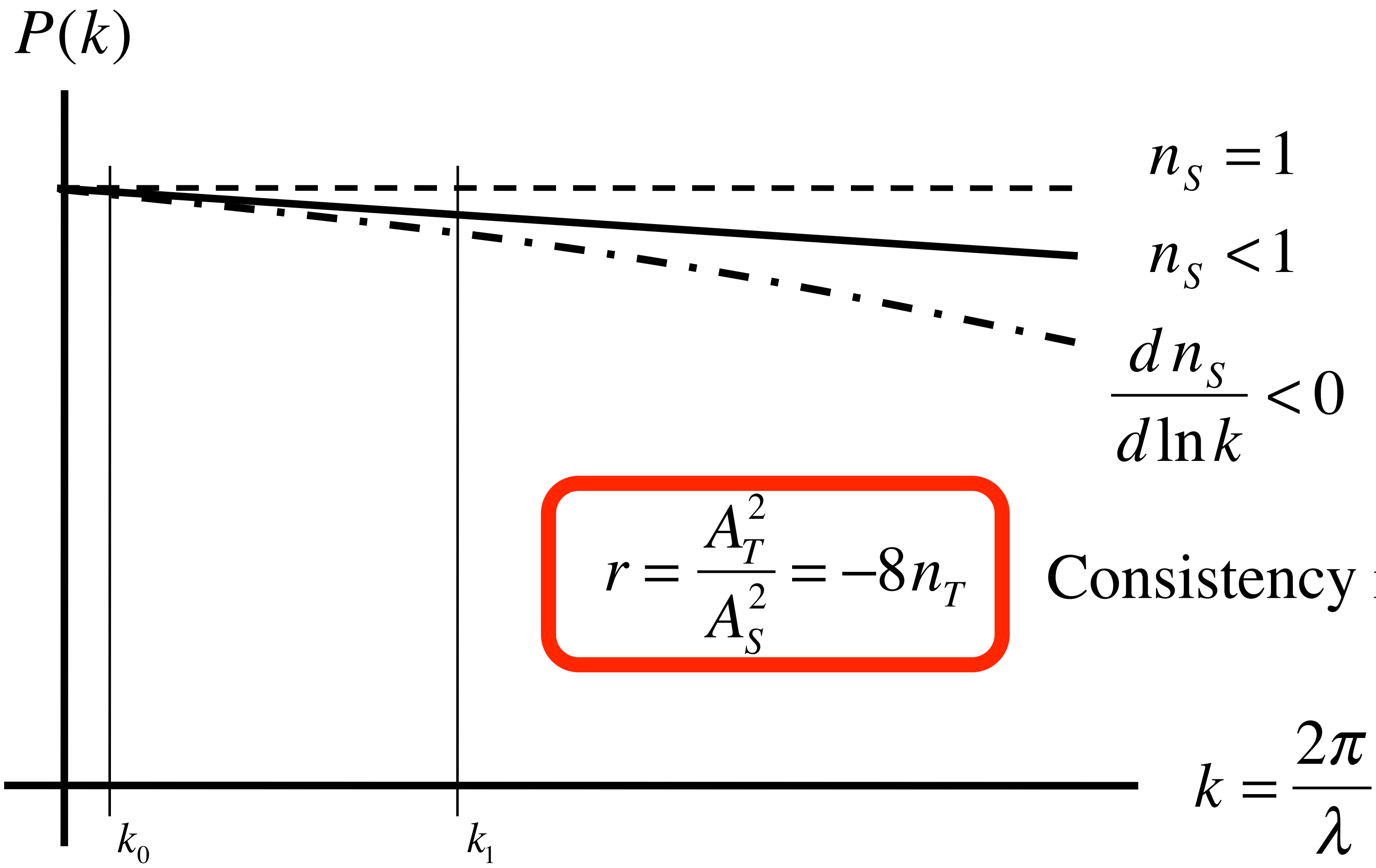
$$\frac{dn_T}{d\ln k} = -\eta\mathcal{H}\left(4\epsilon^2 - 4\epsilon\delta\right) \simeq 8\epsilon_V^2 - 4\eta_V\epsilon_V$$

History of the Universe



two types:

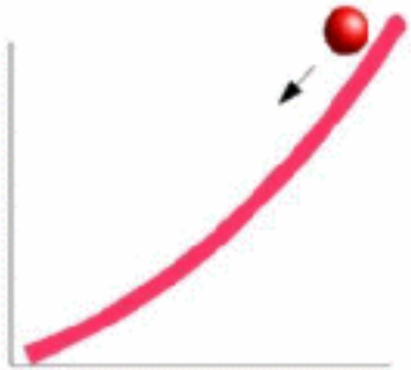
- Scalar (density) spectrum $$P_S(k) = A_S^2(k_0)\left(\frac{k}{k_0}\right)^{n_S - 1}$$
- Tensor (GW) spectrum $$P_T(k) = A_T^2(k_0)\left(\frac{k}{k_0}\right)^{n_T}$$



$$r = \frac{A_T^2}{A_S^2} = -8n_T$$ Consistency relation

Inflation Model Building

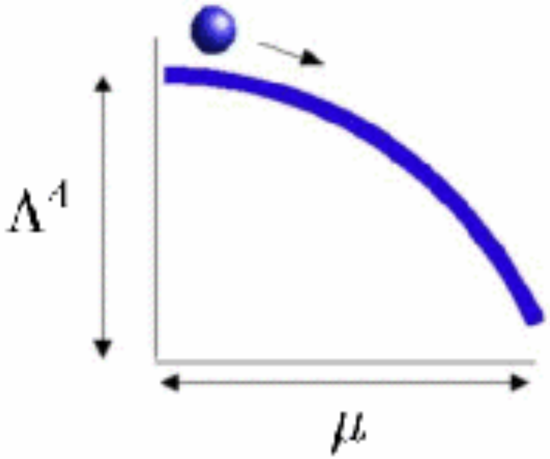
Single field inflation



Large field

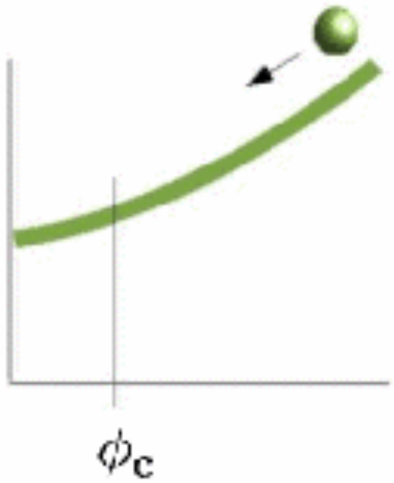
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 e^{\phi/\mu}$$



Small field

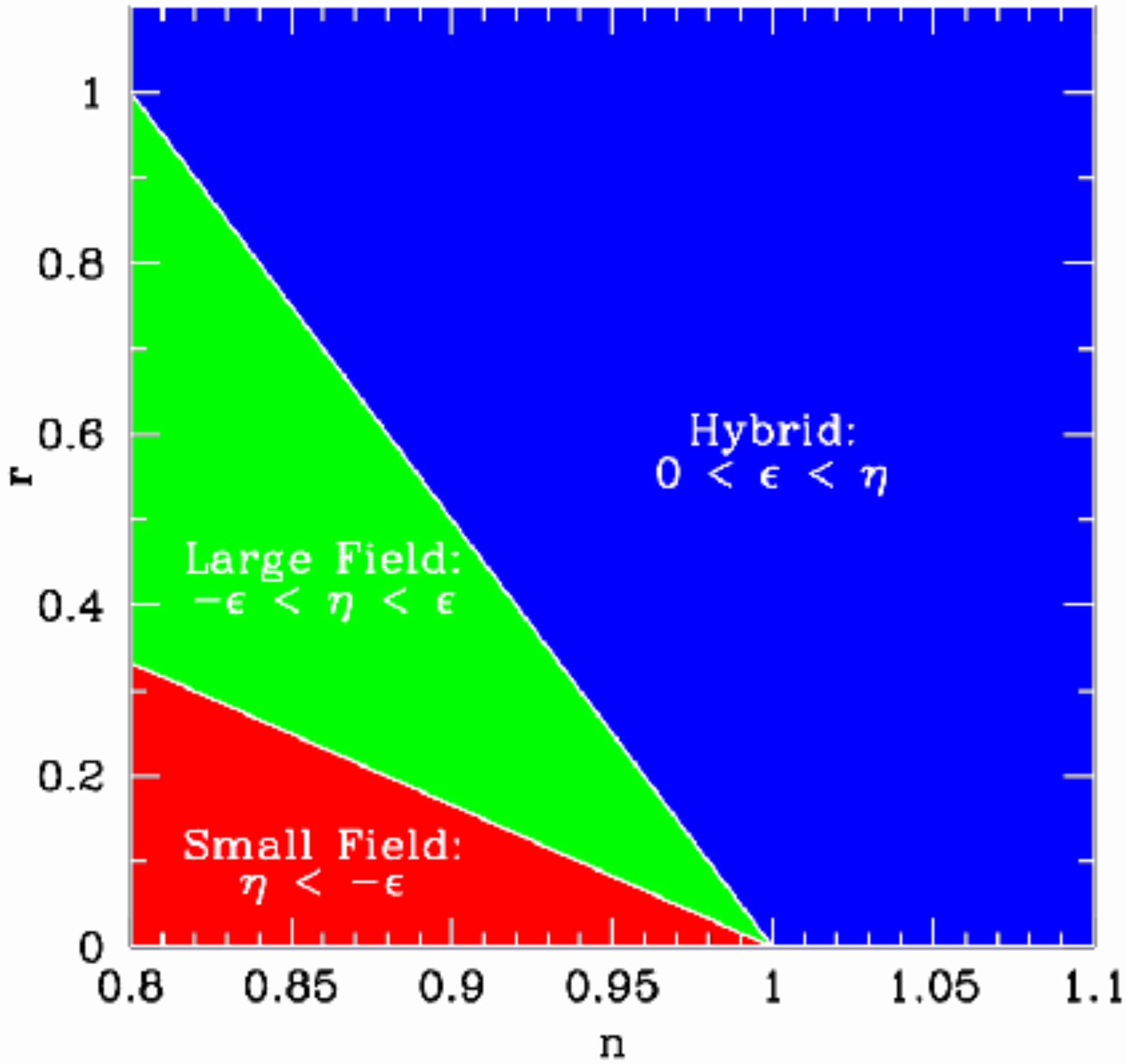
$$V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$$



Hybrid

$$V(\phi) = \Lambda^4 [1 + (\phi/\mu)^p]$$

single field inflation



INFLATIONARY MODEL BUILDING

slow-roll parameters

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2, \qquad \eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right),$$

$$\xi = \frac{1}{\kappa^4}\left(\frac{V'V'''}{V^2}\right), \qquad N = \int_{\phi_{\rm end}}^{\phi} \frac{\kappa d\phi}{\sqrt{2\epsilon}},$$

amplitude and tilt

$$A_S = \frac{\kappa}{\sqrt{2\,\epsilon}}\frac{H}{2\pi}, \qquad n_s = 1 + 2\eta - 6\epsilon\,,$$

$$A_T = 2\sqrt{2}\,\kappa\,\frac{H}{2\pi}, \qquad n_T = -2\epsilon\,,$$

running of the tilt $\quad \frac{d\,n_s}{d\,\ln k} = 2\xi + 24\epsilon^2 - 16\epsilon\eta\,,$

consistency relation $\quad r = 16\epsilon = -8\,n_T\,.$

SIMPLE EXACT MODEL

POWER-LAW INFLATION $V(\phi) = V_0 e^{-\beta\kappa\phi}$ $\beta \ll 1$

Hamilton-Jacobi equation $3H^2(\phi) = \frac{2}{\kappa^2}\left(\frac{\partial H}{\partial \phi}\right)^2 + \kappa^2 V(\phi)$ $\beta H = \kappa\dot{\phi}$

Exact solution $H(\phi) = H_0 e^{-\frac{1}{2}\beta\kappa\phi}$ $H_0^2 = \frac{\kappa^2}{3} V_0 \left(1 - \frac{\beta^2}{6}\right)^{-1}$ $V_0 \equiv M^4$

$$\epsilon = \frac{2}{\kappa^2}\left(\frac{H'}{H}\right)^2 = \frac{1}{2}\beta^2 < 1$$

$$\delta = \frac{2}{\kappa^2}\left(\frac{H''}{H}\right)^2 = \frac{1}{2}\beta^2 < 1$$

$$\xi = \frac{1}{\kappa^4}\left(\frac{H'H'''}{H^2}\right) = \frac{1}{4}\beta^4 < 1$$

$$a \propto t^p \xrightarrow{\epsilon = 1/p} p = \frac{2}{\beta^2}$$

$$\epsilon = \delta = \frac{1}{p} = \mathrm{const}$$

$$N = \int_\phi^{\phi_{\rm end}} \frac{\kappa\, d\phi}{\sqrt{2\epsilon}} = \frac{\kappa}{\beta}(\phi_{\rm end} - \phi) = 65$$

$$A_S = \frac{\kappa}{\sqrt{2\epsilon}} \frac{H}{2\pi} = 5 \times 10^{-5} \Rightarrow \underline{M \simeq 10^{-3} M_P \simeq M_{\rm GUT}}$$

$$n_s - 1 = 2\left(\frac{\delta - 2\epsilon}{1-\epsilon}\right) = -\frac{2}{p-1}$$

$$n_s = 0.96 \Rightarrow p = 51$$

$$\frac{d\,n_s}{d\ln k} = 0$$

$$n_T = -\frac{2\epsilon}{1-\epsilon} = -\frac{2}{p-1} = n_s - 1$$

$$r = -8\,n_T = 0.32$$

ruled out !

CHAOTIC INFLATION MODEL

$$V(\phi) = \frac{1}{2}m^2\phi^2 \qquad H^2 \simeq \frac{\kappa^2}{6}m^2\phi^2$$

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2 = \frac{2}{\kappa^2\phi^2} = 1$$

end inflation

$$\Rightarrow \quad \phi_{\rm end} = \frac{M_P}{2\sqrt{\pi}} \simeq \frac{M_P}{3.5}$$

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = \frac{2}{\kappa^2\phi^2} = \epsilon = \frac{1}{2N} \qquad \xi = 0$$

$$N = \int_{\phi_{\rm end}}^{\phi} \frac{\kappa d\phi}{\sqrt{2\epsilon}} = \left(\frac{\kappa\phi}{2}\right)^2\Bigg|_{\phi_{\rm end}}^{\phi} \approx \frac{\kappa^2\phi^2}{4} \quad \Rightarrow \quad \phi_{60} = 3M_P$$

$$A_S = \frac{\kappa m}{\sqrt{6}}\frac{\kappa^2\phi^2}{4\pi} = N\sqrt{\frac{4}{3\pi}}\frac{m}{M_P} = 5\times 10^{-5} \quad \Rightarrow \quad \begin{aligned} m &= 1.2\times 10^{-6}M_P \\ &= 1.4\times 10^{13}\,\mathrm{GeV}\end{aligned}$$

$$n_s = 1 - \frac{2}{N} \approx 0.967, \qquad \frac{dn_s}{d\ln k} = \frac{2}{N^2} = 6\times 10^{-4}$$

$$A_T = \frac{4}{\sqrt{\pi}}\frac{H}{M_P} < 10^{-5}, \qquad n_T = -2\epsilon = -\frac{1}{N} \simeq -0.016 \qquad r = \frac{8}{N} \simeq 0.13$$

Not ruled out !

STAROBINSKY INFLATION

Quantum field theory in curved space time

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa^2 \langle T_{\mu\nu} \rangle_{\rm ren} = \frac{1}{6M^2} {}^{(1)}H_{\mu\nu}$$

$${}^{(1)}H_{\mu\nu} = 2(\nabla_\mu \nabla_\nu - g_{\mu\nu} \nabla^2) R + 2R\, R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R^2$$

effective action formalism,

$$\mathcal{S}_g = \int d^4x \sqrt{-g}\, \frac{1}{2\kappa^2} \left(R - \frac{R^2}{6M^2} \right) \equiv \int d^4x \sqrt{-g}\, \frac{1}{2\kappa^2} f(R)$$

conformal transformation $\tilde{g}_{\mu\nu} = f'(R)\, g_{\mu\nu} \equiv e^{\alpha\kappa\phi} g_{\mu\nu}$

$$\tilde{R} = e^{-\alpha\kappa\phi} \left[R - 3\alpha\kappa\, \nabla^2\phi - \frac{3}{2} \alpha^2 \kappa^2 (\partial\phi)^2 \right] \qquad \alpha^2 = 2/3$$

$$V(\phi) = \frac{1}{2\kappa^2} \frac{f(R) - R\, f'(R)}{(f'(R))^2} = \frac{R^2}{12\kappa^2 M^2} \left(1 - \frac{R}{3M^2} \right)^{-2}$$

STAROBINSKY INFLATION

$$V(\phi) = \frac{3M^2}{4\kappa^2}\left(1 - e^{-\alpha\kappa\phi}\right)^2 = \frac{1}{2}M^2\phi^2\left(1 + \alpha\kappa\phi + \dots\right)$$

end inflation

$$\epsilon \;=\; \frac{2\alpha^2}{(e^{\alpha\kappa\phi} - 1)^2} = 1 \quad\Rightarrow\quad \phi_{\rm end} = \frac{\sqrt{3}\,M_P}{4\sqrt{\pi}}\ln\left(1 + \frac{2}{\sqrt{3}}\right) \simeq \frac{M_P}{5.33}$$

$$\eta \;=\; \frac{2\alpha^2(2 - e^{\alpha\kappa\phi})}{(e^{\alpha\kappa\phi} - 1)^2} \qquad \xi \;=\; \frac{4\alpha^4(e^{\alpha\kappa\phi} - 4)}{(e^{\alpha\kappa\phi} - 1)^3} \qquad \epsilon_{60} \simeq \frac{3}{4N^2}, \quad \eta_{60} \simeq -\frac{1}{N}$$

$$\xi_{60} \simeq \frac{1}{N^2}$$

$$N \;=\; \left.\frac{e^{\alpha\kappa\phi} - \alpha\kappa\phi}{2\alpha^2}\right|_{\phi_{\rm end}}^{\phi} \simeq \frac{3}{4}e^{\alpha\kappa\phi} \quad\Rightarrow\quad \phi_{60} = 1.09M_P$$

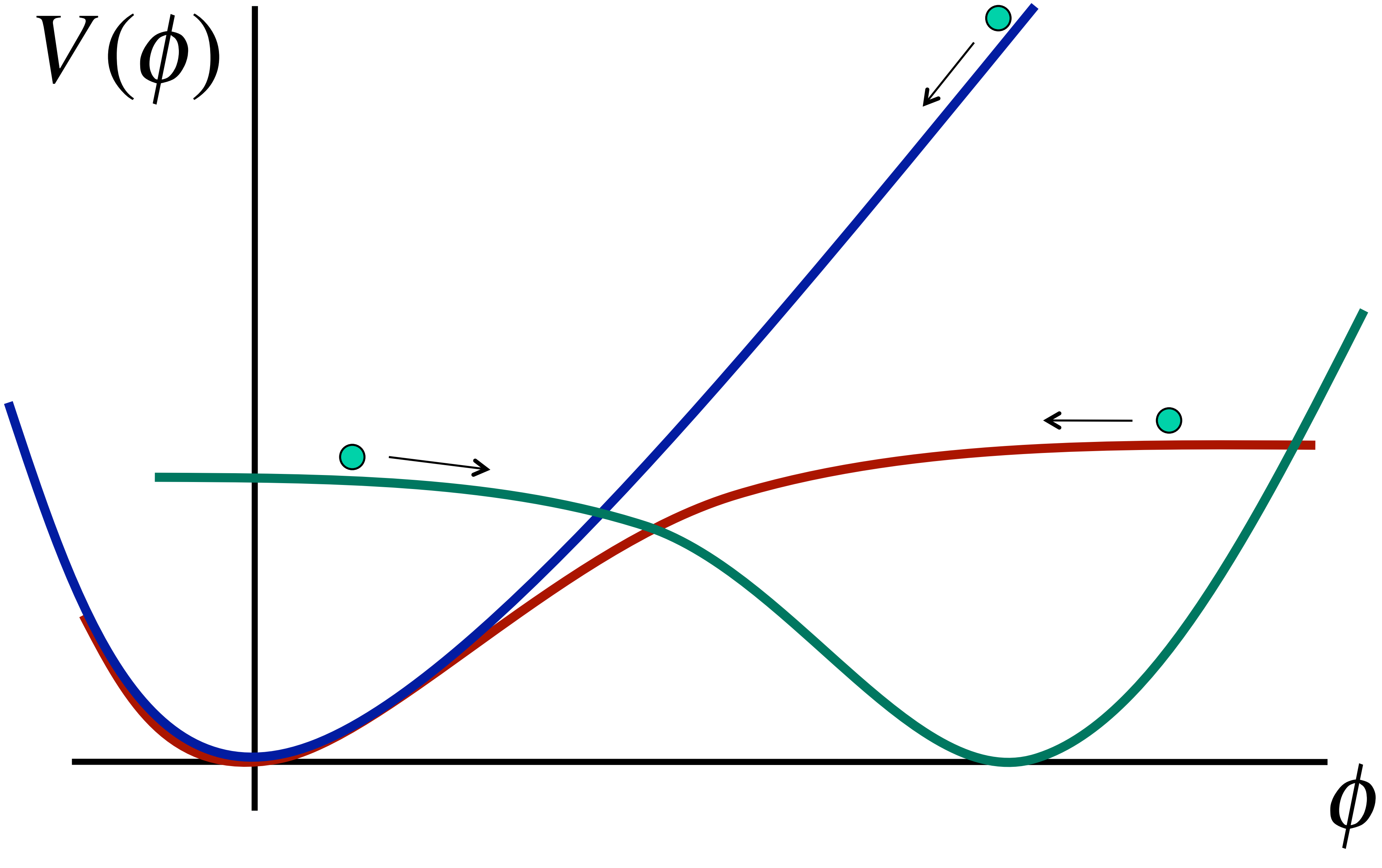
$$A_S \;=\; \frac{\alpha N}{2\pi}\kappa H = 5\times 10^{-5} \quad\Rightarrow\quad \boxed{M \simeq 2.4\times 10^{-6}M_P}$$

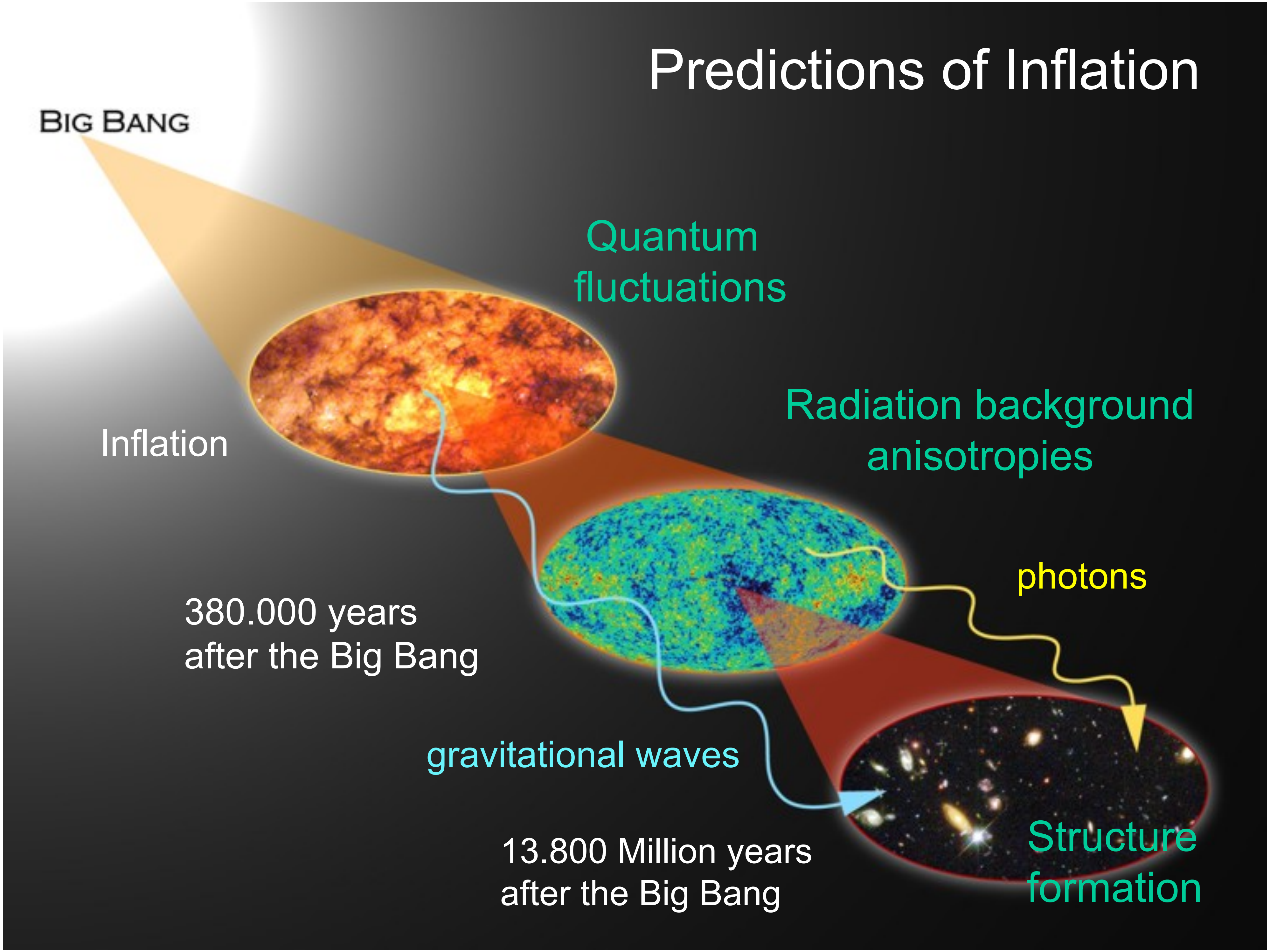
$$\boxed{n_s = 1 - \frac{2}{N} \approx 0.967}, \qquad \frac{d\,n_s}{d\ln k} \simeq \frac{2}{N^2} = 5.6\times 10^{-4}$$

ruled out !

$$n_T = -\frac{3}{2N^2} = -2.8\times 10^{-4} \qquad A_T \;=\; \frac{\sqrt{2}}{\pi}\frac{H}{M_P} = 2.7\times 10^{-6} \qquad \boxed{r = -\frac{12}{N^2} = 3\times 10^{-3}}$$

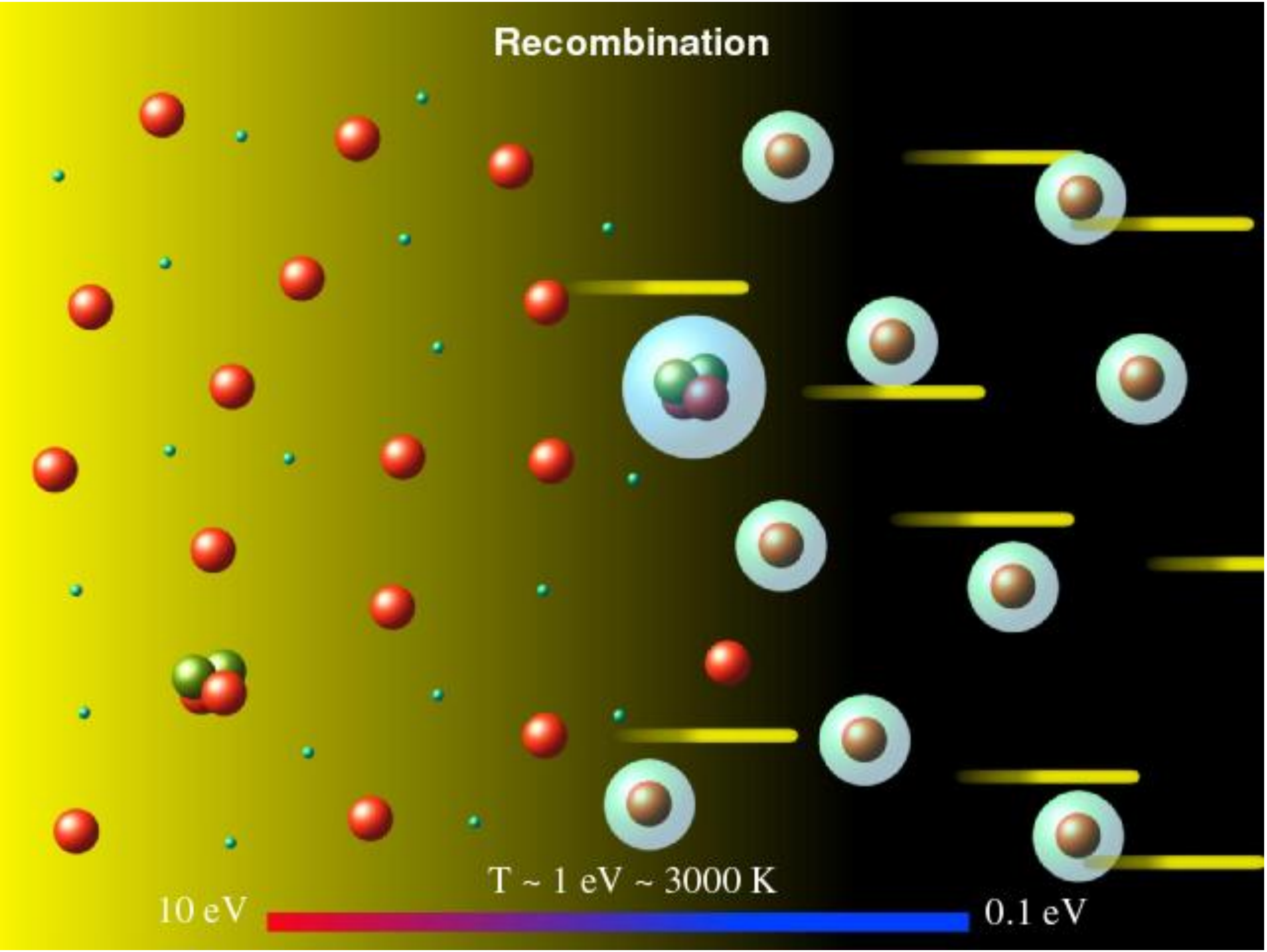
INFLATIONARY MODEL BUILDING



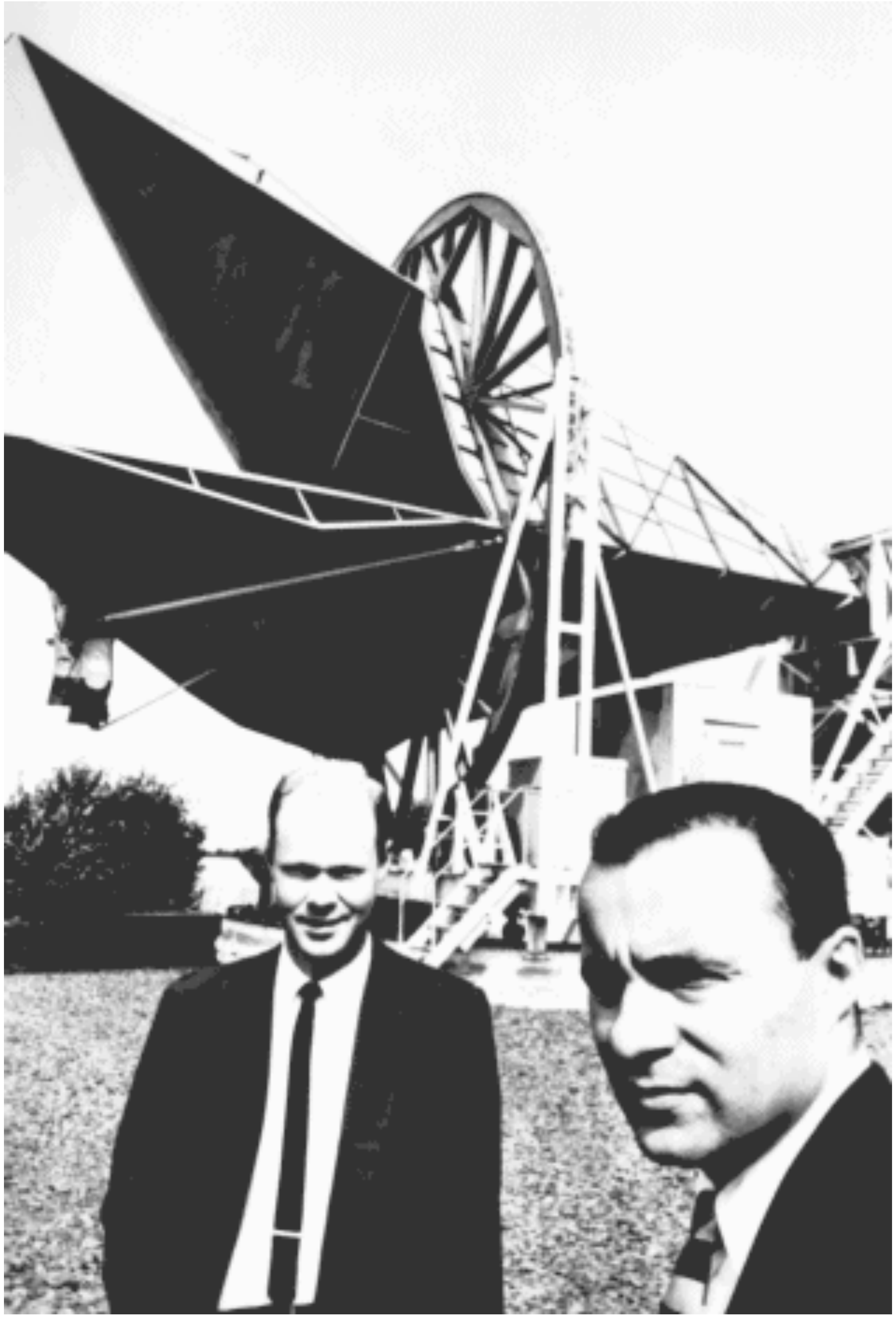


Predictions of Inflation
BIG BANG
Quantum
fluctuations
Inflation
Radiation background
anisotropies
photons
380.000 years
after the Big Bang
gravitational waves
13.800 Million years
after the Big Bang
Structure
formation

Cosmic Microwave Background

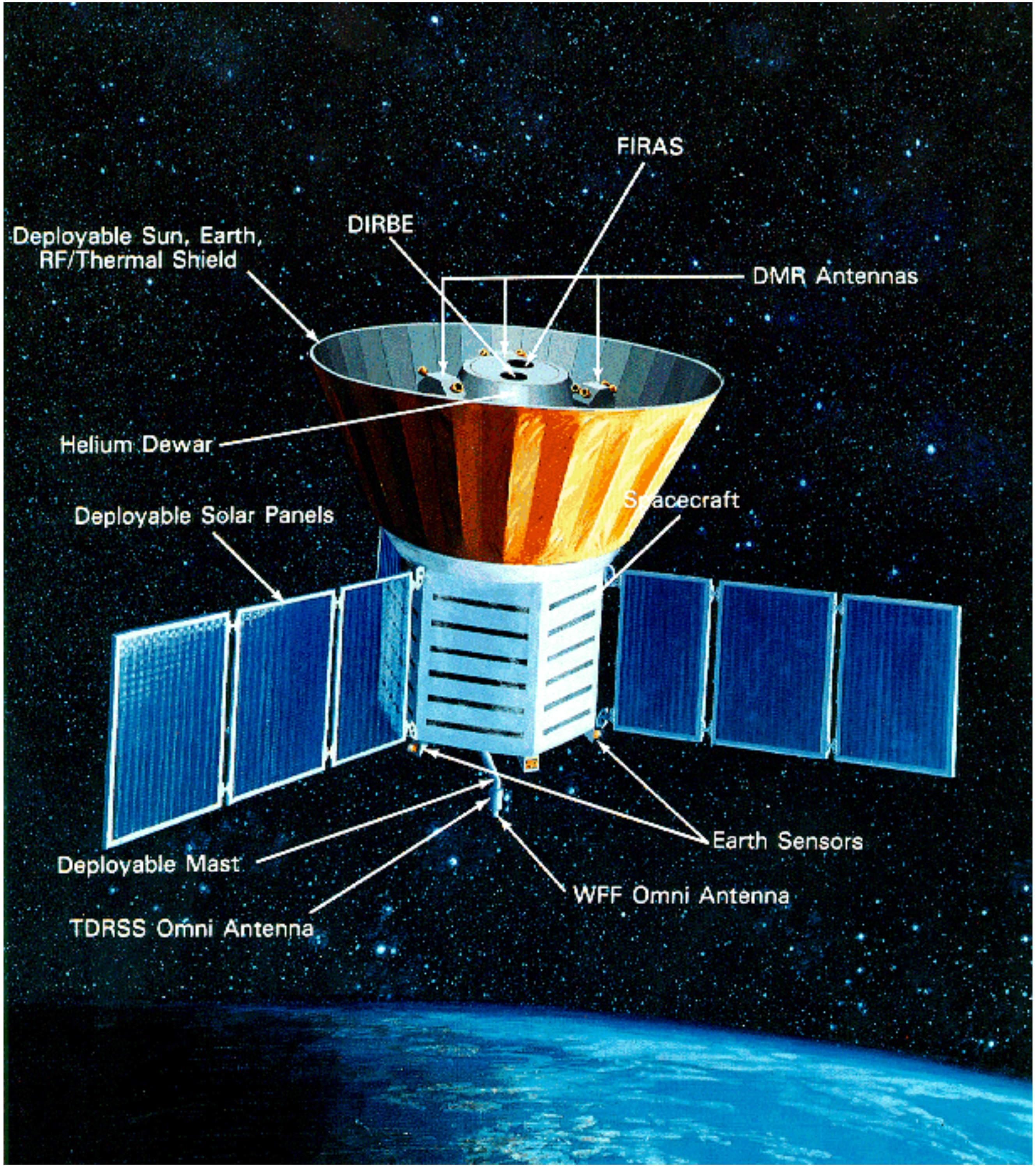


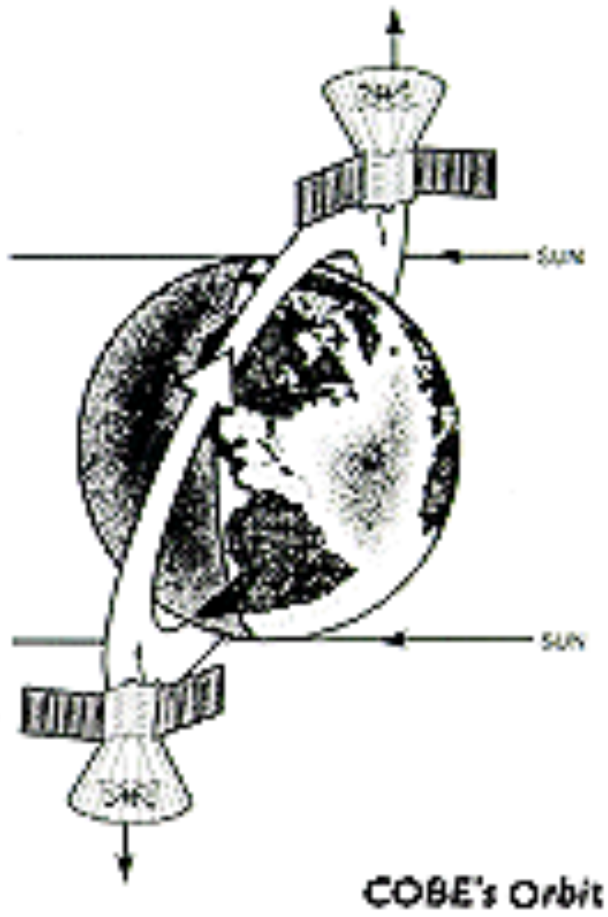
Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV



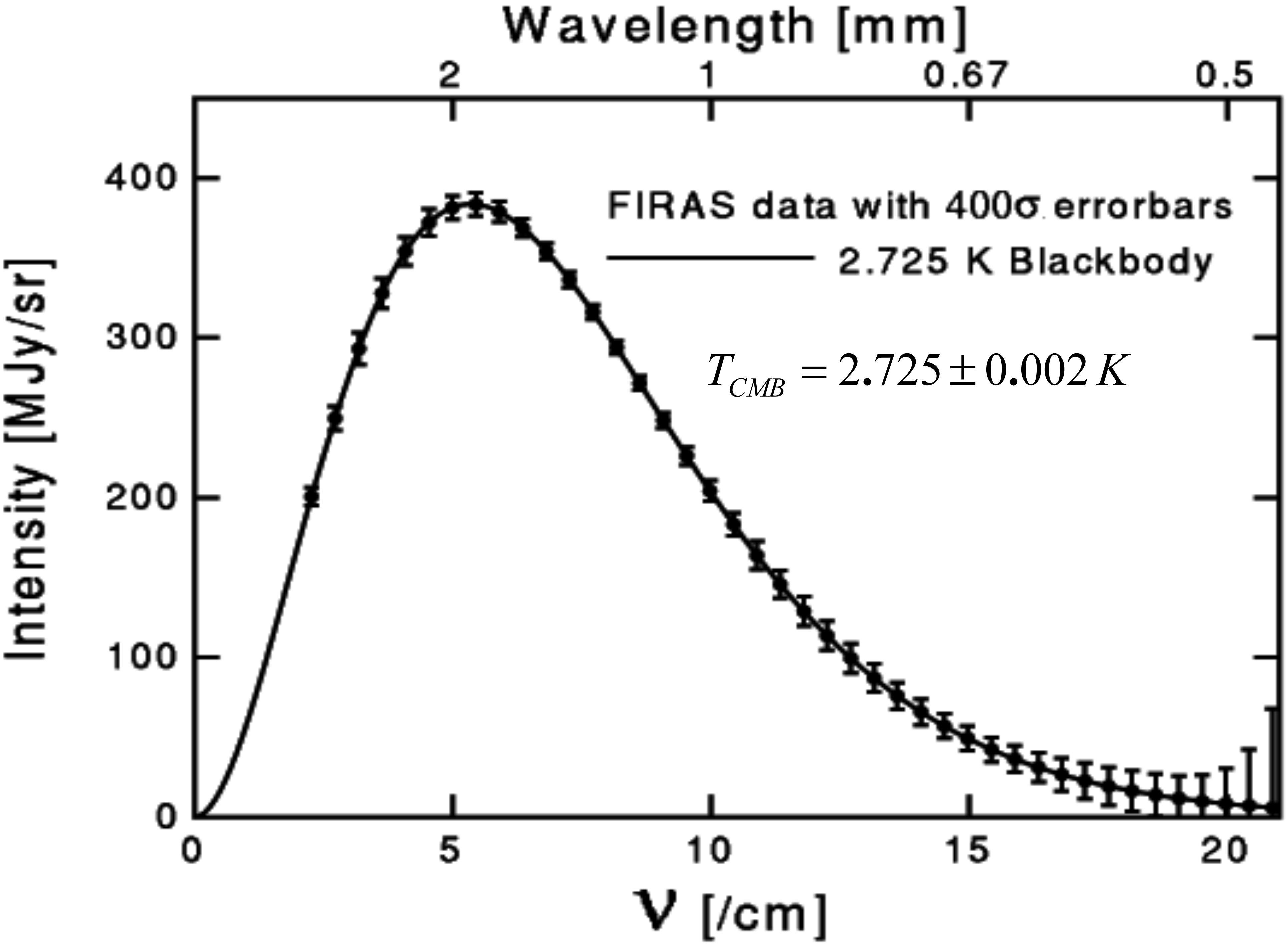
Discovery of CMB

Arno Penzias
Robert Wilson
(1965)

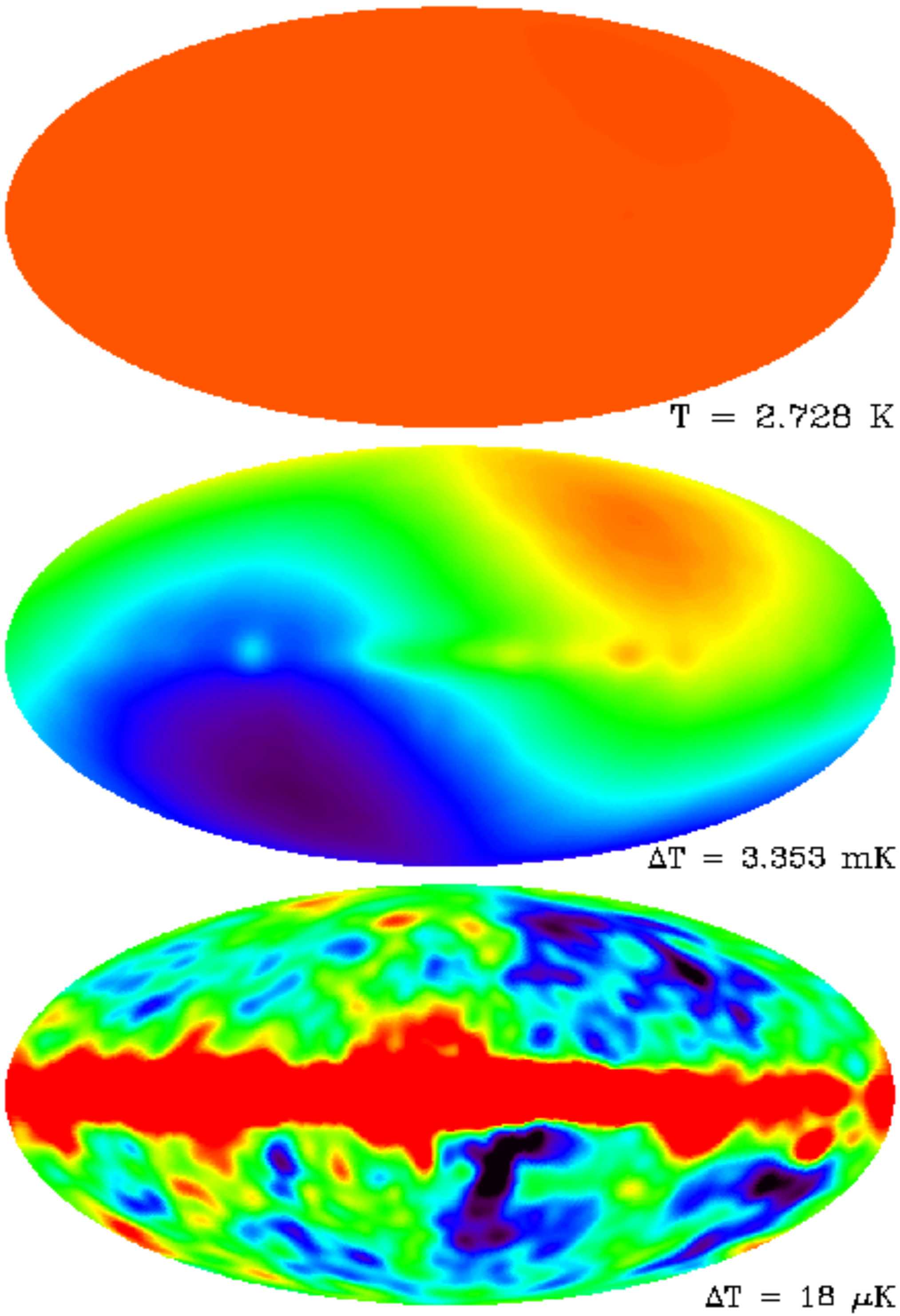




COBE
(1989-1992)



Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
$T_{CMB} = 2.725 \pm 0.002\,K$
0
5
10
15
20
ν [/cm]



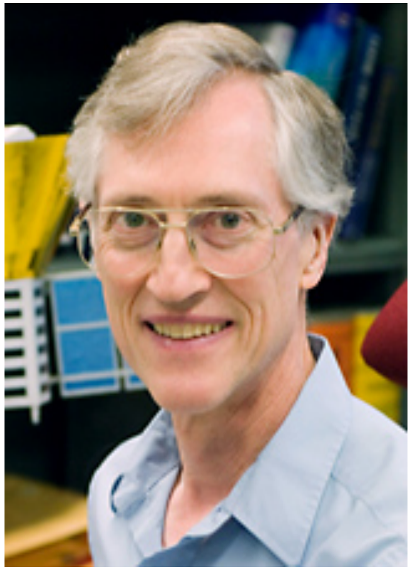
COBE 4-year Measurements (1992-1996)

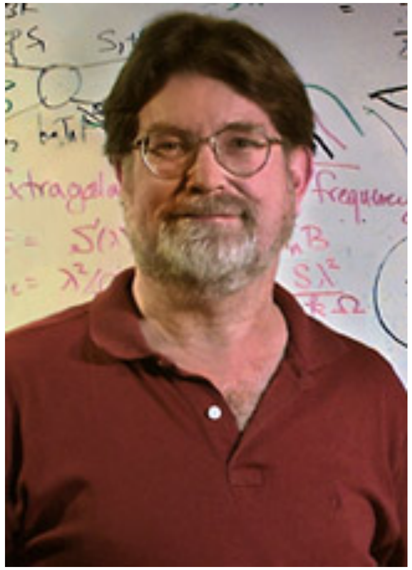
First Measurements Temperature Anisotropies (1992)

$$\frac{\Delta T}{T_0} \approx 10^{-5}$$

The Nobel Prize in Physics 2006

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



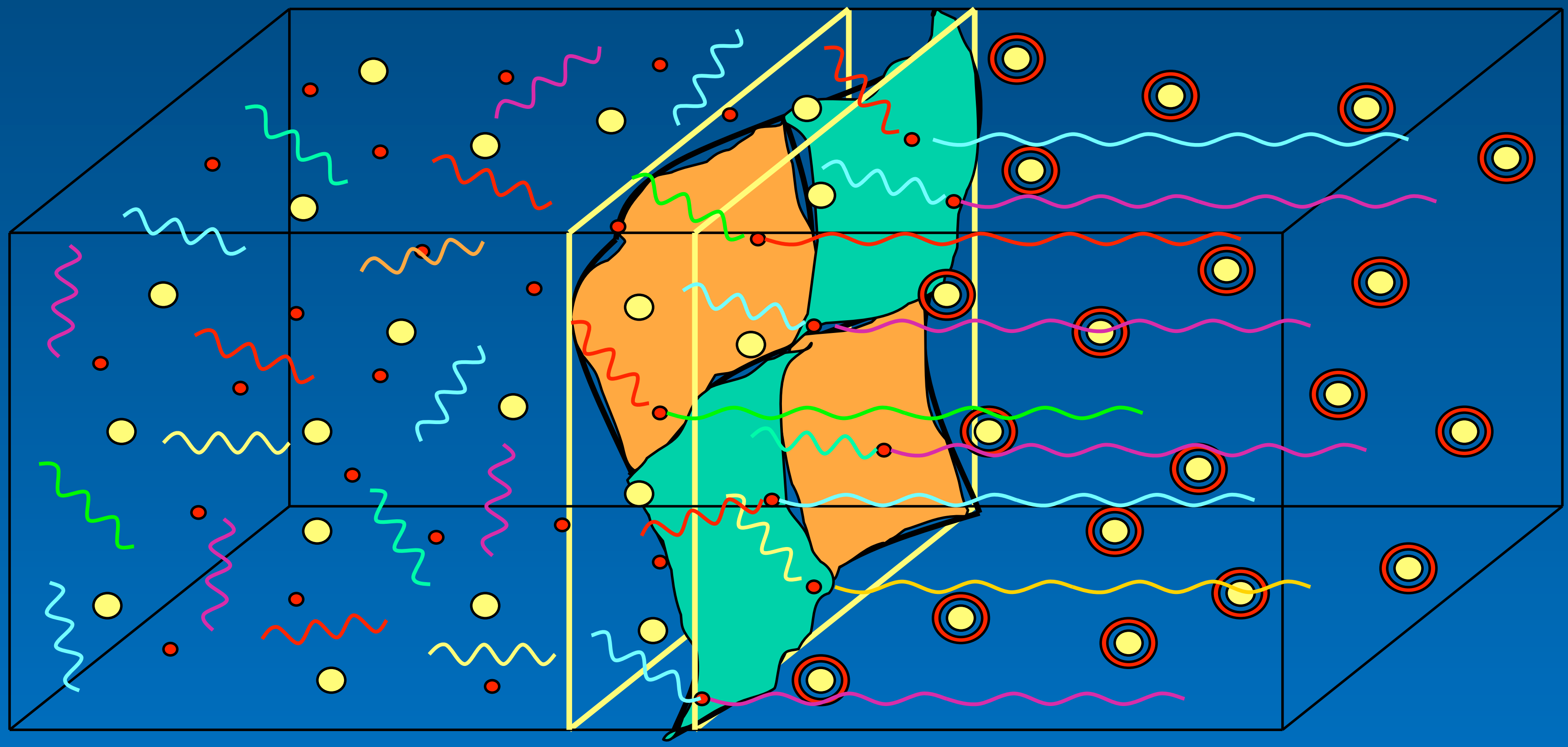


John C. Mather **George F. Smoot**

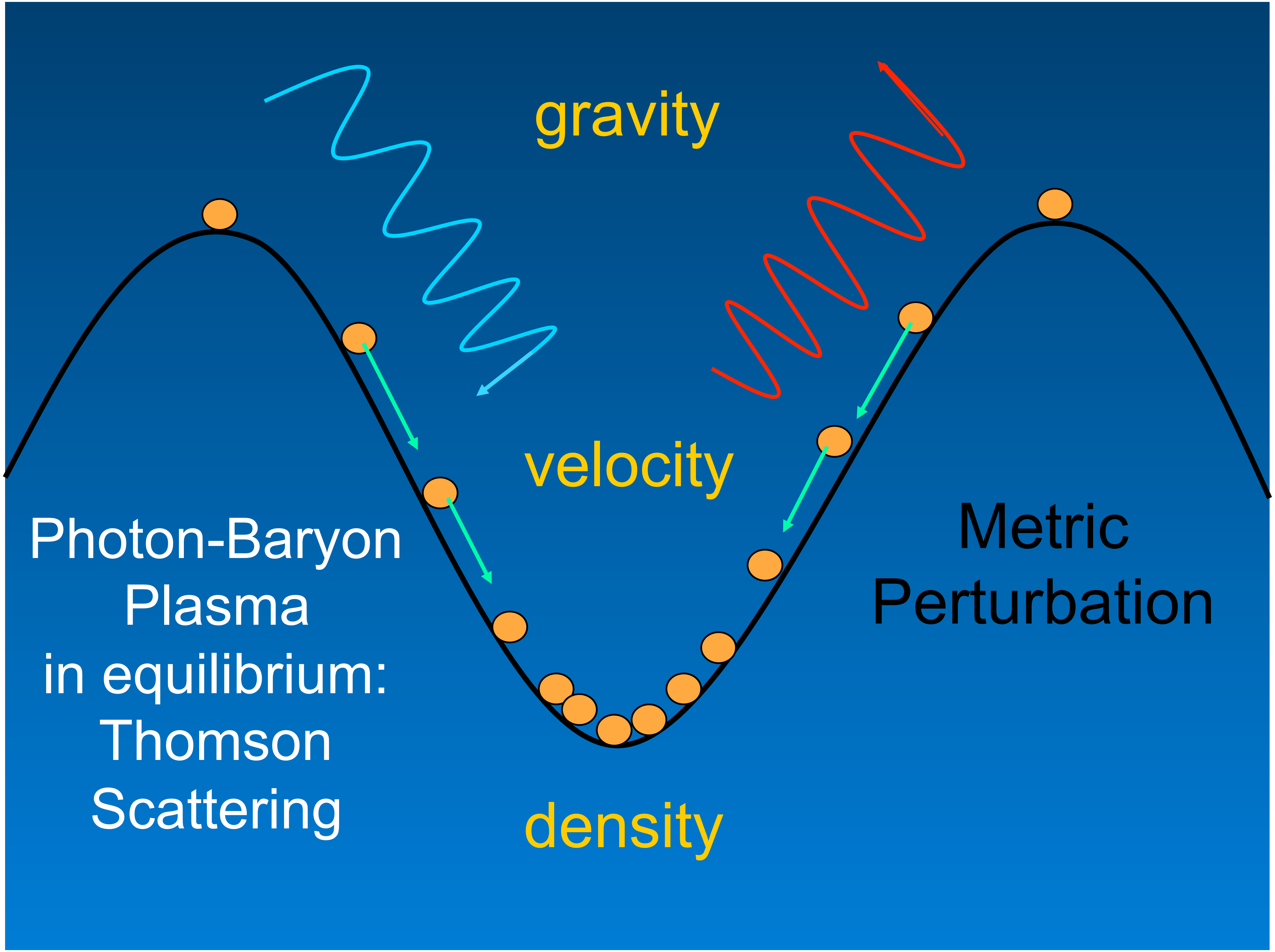
CMB

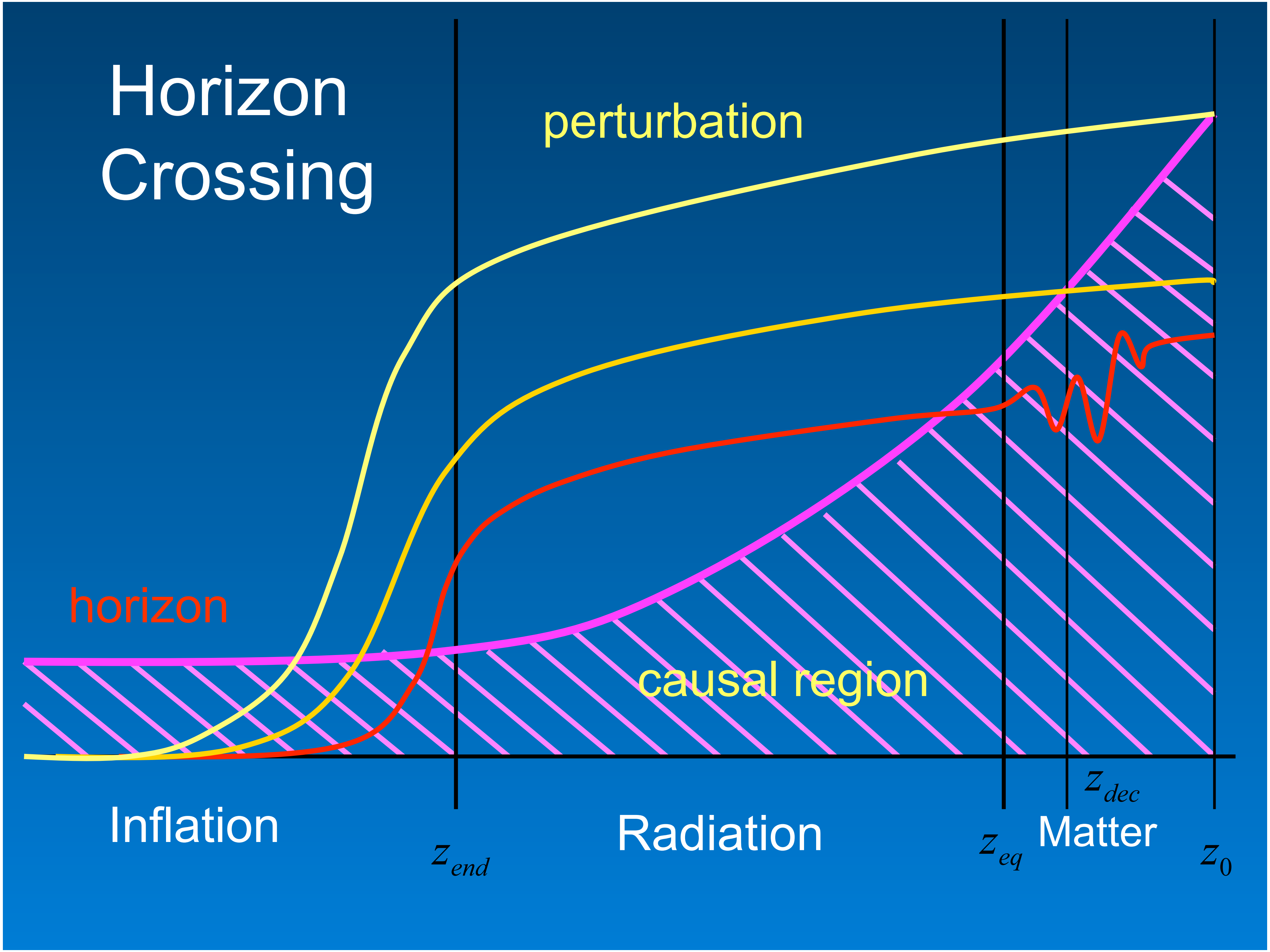
Temperature Anisotropies

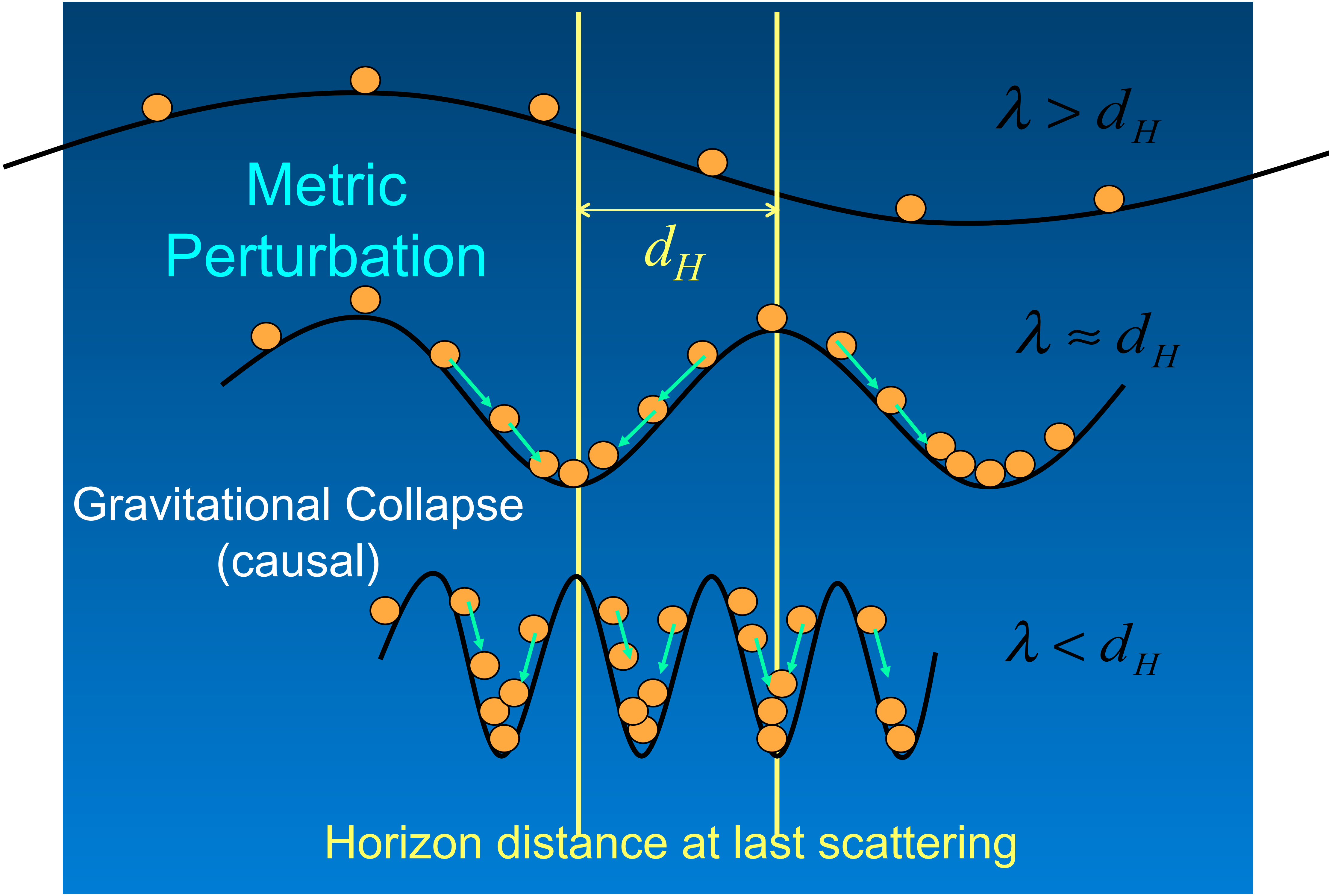
The microwave background is a snapshot of the last scattering surface



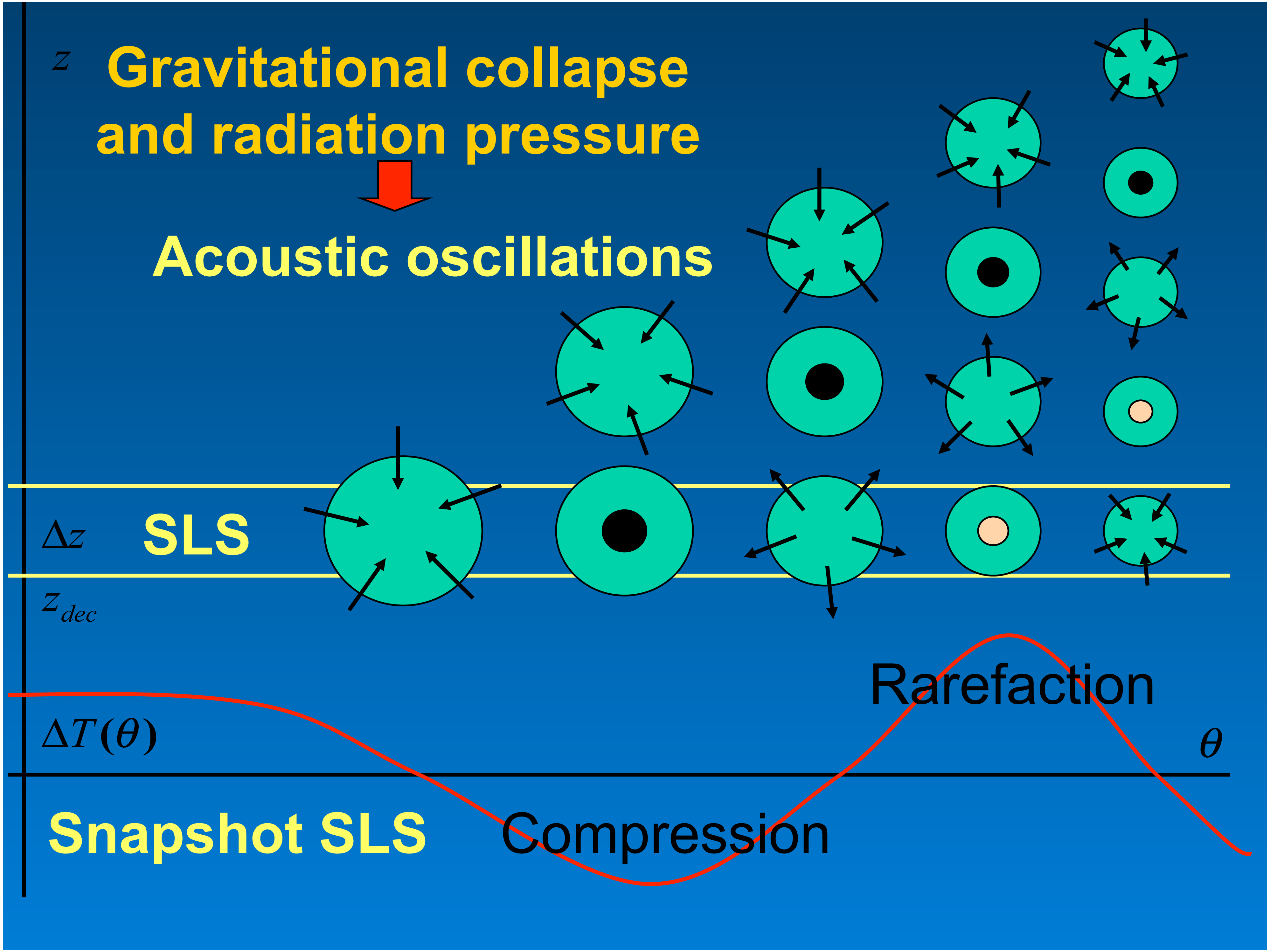
The anisotropies reflect the perturbations in the surface of last scattering


gravity
velocity
density
Photon-Baryon Plasma in equilibrium: Thomson Scattering
Metric Perturbation


Horizon Crossing
perturbation
horizon
causal region
Inflation
Radiation
Matter
z_{end}
z_{eq}
z_{dec}
z_0



$\lambda > d_H$
Metric
Perturbation
d_H
$\lambda \approx d_H$
Gravitational Collapse
(causal)
$\lambda < d_H$
Horizon distance at last scattering



z
Gravitational collapse
and radiation pressure
Acoustic oscillations
Δz
SLS
z dec
ΔT(θ)
θ
Rarefaction
Snapshot SLS
Compression

CMB TEMPERATURE ANISOTROPIES

gravity + density + velocity

$$\frac{\delta T}{T}(\mathbf{r}) = \Phi(\mathbf{r}, t_{\rm dec}) + 2\int_{t_{\rm dec}}^{t_0} \dot{\Phi}(\mathbf{r}, t)dt \; + \; \frac{1}{3}\frac{\delta\rho}{\rho}(\mathbf{r}, t_{\rm dec}) \; - \; \frac{\mathbf{r}\cdot\mathbf{v}}{c}$$

The Sachs-Wolfe effect on large angular scales

$\delta\rho/\rho = -2\Phi$ (for adiabatic perturbations)

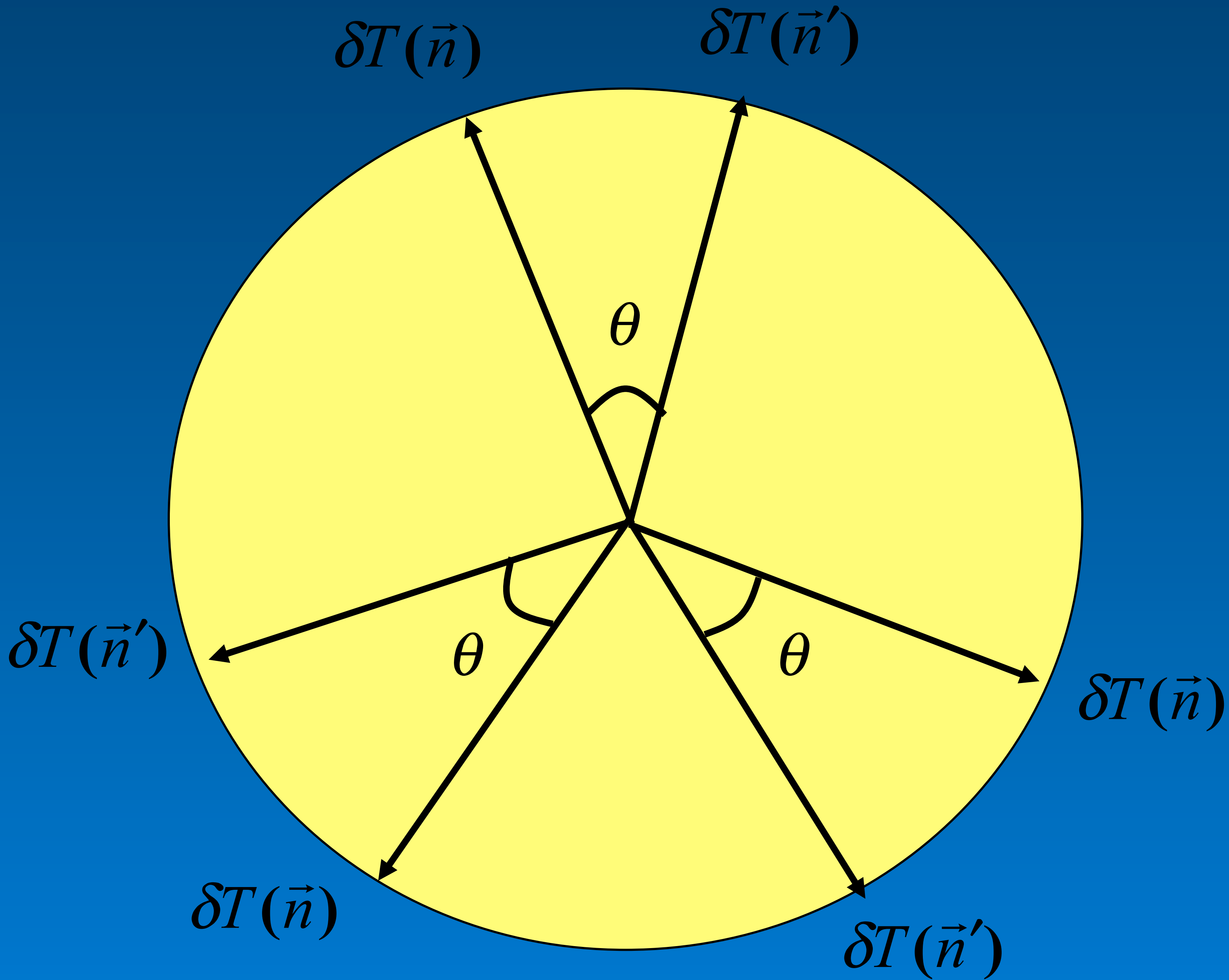
$$\frac{\delta T}{T}(\theta, \phi) = \frac{1}{3}\Phi(\eta_{\rm LS})\, Q(\eta_0, \theta, \phi) + 2\int_{\eta_{\rm LS}}^{\eta_0} dr\, \Phi'(\eta_0 - r)\, Q(r, \theta, \phi)$$

$Q(\mathbf{x})$ eigenfunctions of the Laplacian $\quad \Phi(\eta, \mathbf{x}) \equiv \Phi(\eta)\, Q(\mathbf{x})$

$$\nabla^2 Q_{klm}(r, \theta, \phi) = -k^2\, Q_{klm}(r, \theta, \phi)$$

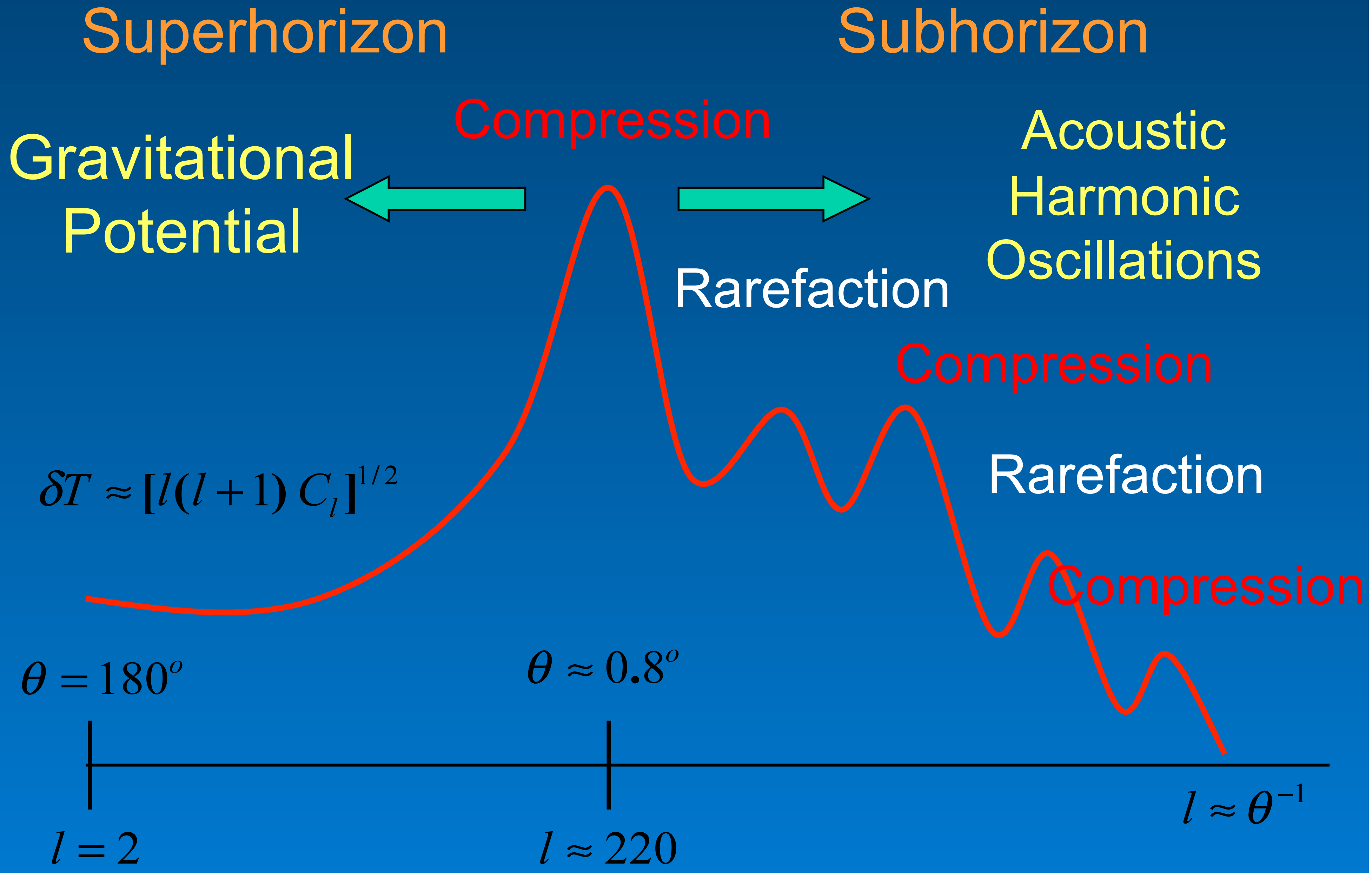
$$Q_{klm}(r, \theta, \phi) = \Pi_{kl}(r)\, Y_{lm}(\theta, \phi) \qquad \Pi_{kl}(r) = \sqrt{\frac{2}{\pi}}\, k\, j_l(kr)$$

$$\Phi'' + 3\mathcal{H}\,\Phi' + a^2\Lambda\,\Phi - 2K\,\Phi = 0$$



$\delta T(\vec{n})$
$\delta T(\vec{n}')$
θ
$\delta T(\vec{n}')$
θ
θ
$\delta T(\vec{n})$
$\delta T(\vec{n})$
$\delta T(\vec{n}')$

Angular Power Spectrum



SACHS-WOLFE PLATEAU

$$\frac{\delta T}{T}(\theta,\phi) = \frac{1}{3}\Phi(\eta_{\rm LS})\,Q = \frac{1}{5}\mathcal{R}\,Q(\eta_0,\theta,\phi) \equiv \sum_{l=2}^{\infty}\sum_{m=-l}^{l} a_{lm}\,Y_{lm}(\theta,\phi)$$

two-point correlation function

$$C_l = \langle |a_{lm}|^2 \rangle$$

$$C(\theta) = \left\langle \frac{\delta T^*}{T}(\mathbf{n})\frac{\delta T}{T}(\mathbf{n}') \right\rangle_{\mathbf{n}\cdot\mathbf{n}'=\cos\theta} = \frac{1}{4\pi}\sum_{l=2}^{\infty}(2l+1)\,C_l\,P_l(\cos\theta)$$

$$C_l^{(S)} = \frac{4\pi}{25}\int_0^{\infty}\frac{dk}{k}\mathcal{P}_{\mathcal{R}}(k)\,j_l^2(k\eta_0) \qquad \mathcal{P}_{\mathcal{R}}(k) = A_S^2(k\eta_0)^{n-1}$$

$$C_l^{(S)} = \frac{2\pi}{25}A_S^2\,\frac{\Gamma[\frac{3}{2}]\,\Gamma[1-\frac{n-1}{2}]\,\Gamma[l+\frac{n-1}{2}]}{\Gamma[\frac{3}{2}-\frac{n-1}{2}]\,\Gamma[l+2-\frac{n-1}{2}]}$$

$$\frac{l(l+1)\,C_l^{(S)}}{2\pi} = \frac{A_S^2}{25} = \text{constant}\,,\ \text{for}\ \ n=1$$

SACHS-WOLFE PLATEAU

gauge-invariant tensor perturbation

$$h_k'' + 2\mathcal{H}\, h_k' + (k^2 + 2K)\, h_k = 0 \quad \Rightarrow \quad h_k(\eta) = 3h\, j_1(k\eta)/k\eta$$

$$\frac{\delta T}{T}(\theta, \phi) = \int_{\eta_{\rm LS}}^{\eta_0} dr\, h'(\eta_0 - r)\, Q_{rr}(r, \theta, \phi)$$

Q_{rr} is rr-component of tensor harmonic along line of sight

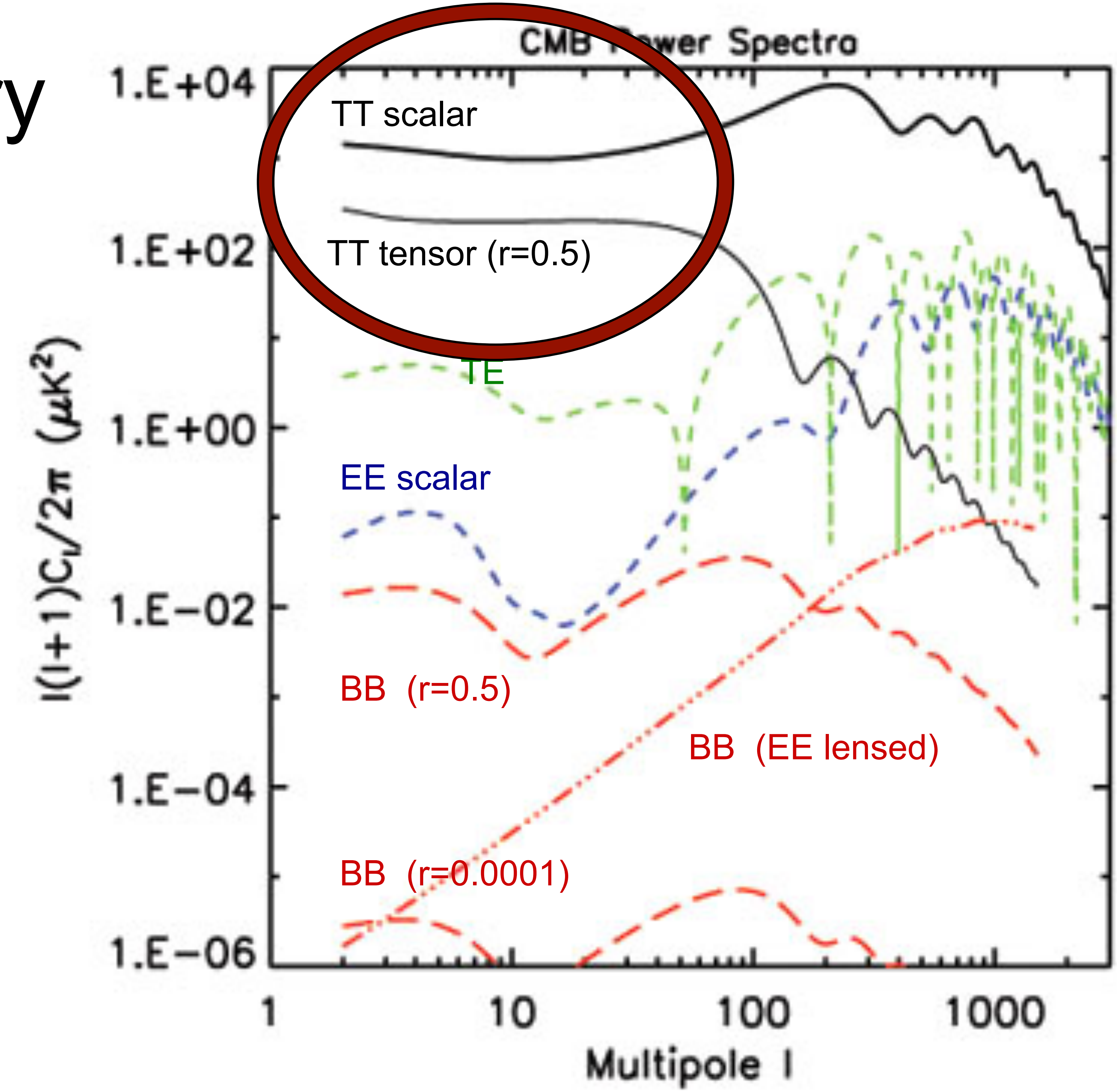
$$Q_{kl}^{rr}(r) = \left[\frac{(l-1)l(l+1)(l+2)}{\pi k^2}\right]^{1/2} \frac{j_l(kr)}{r^2} \qquad I_{kl} = \int_0^{x_0} dx\, \frac{j_2(x_0 - x) j_l(x)}{(x_0 - x) x^2}$$

$$C_l^{(T)} = \frac{9\pi}{4}(l-1)l(l+1)(l+2) \int_0^\infty \frac{dk}{k} \mathcal{P}_g(k)\, I_{kl}^2 \qquad \mathcal{P}_g(k) = A_T^2 (k\eta_0)^{n_T}$$

$$l(l+1)\, C_l^{(T)} = \frac{\pi}{36}\left(1 + \frac{48\pi^2}{385}\right) A_T^2\, B_l \qquad \text{for } n_T = 0$$

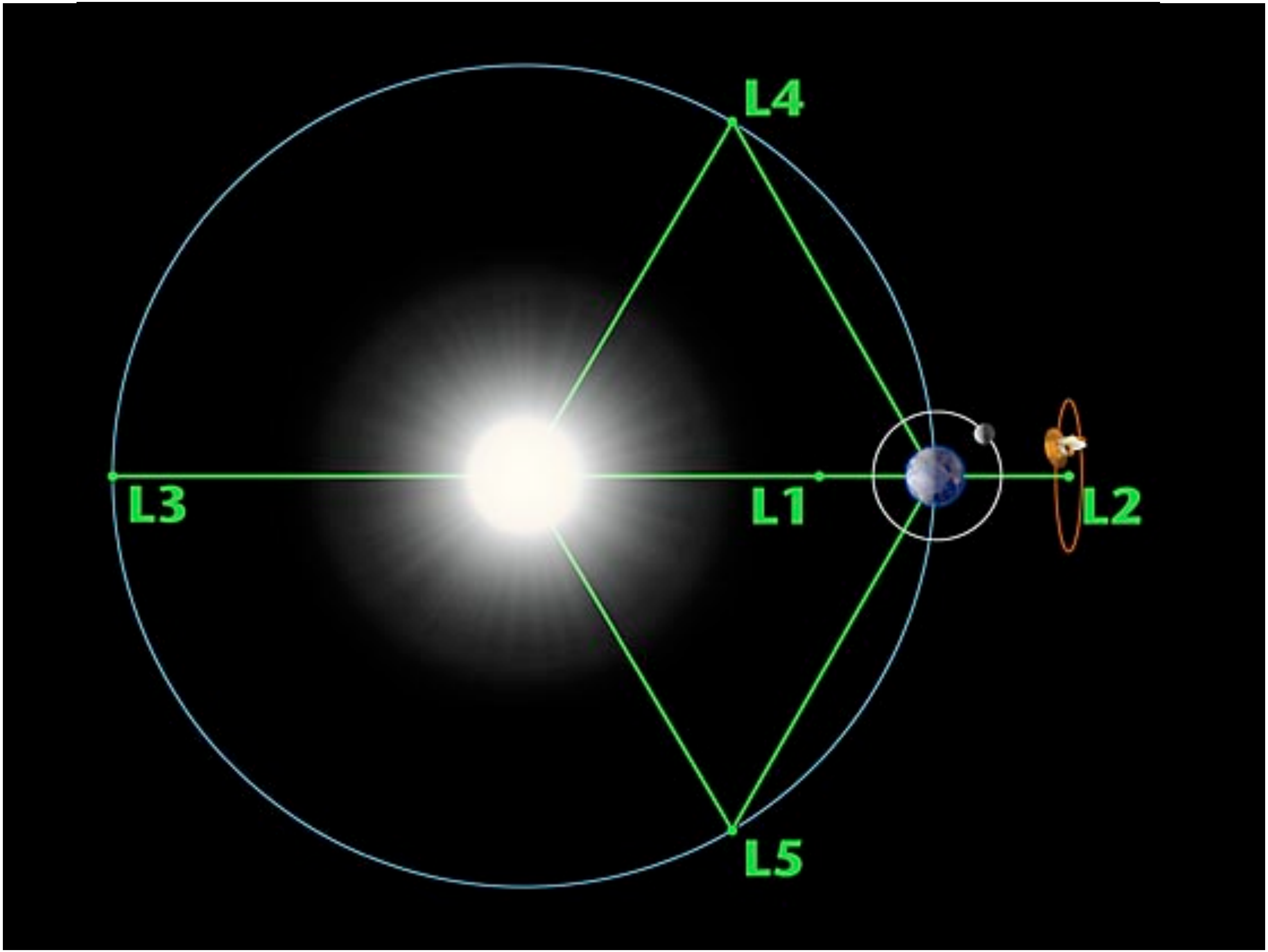
$$B_l = (1.1184, 0.8789, \ldots, 1.00) \quad \text{for } l = 2, 3, \ldots, 30$$

Theory

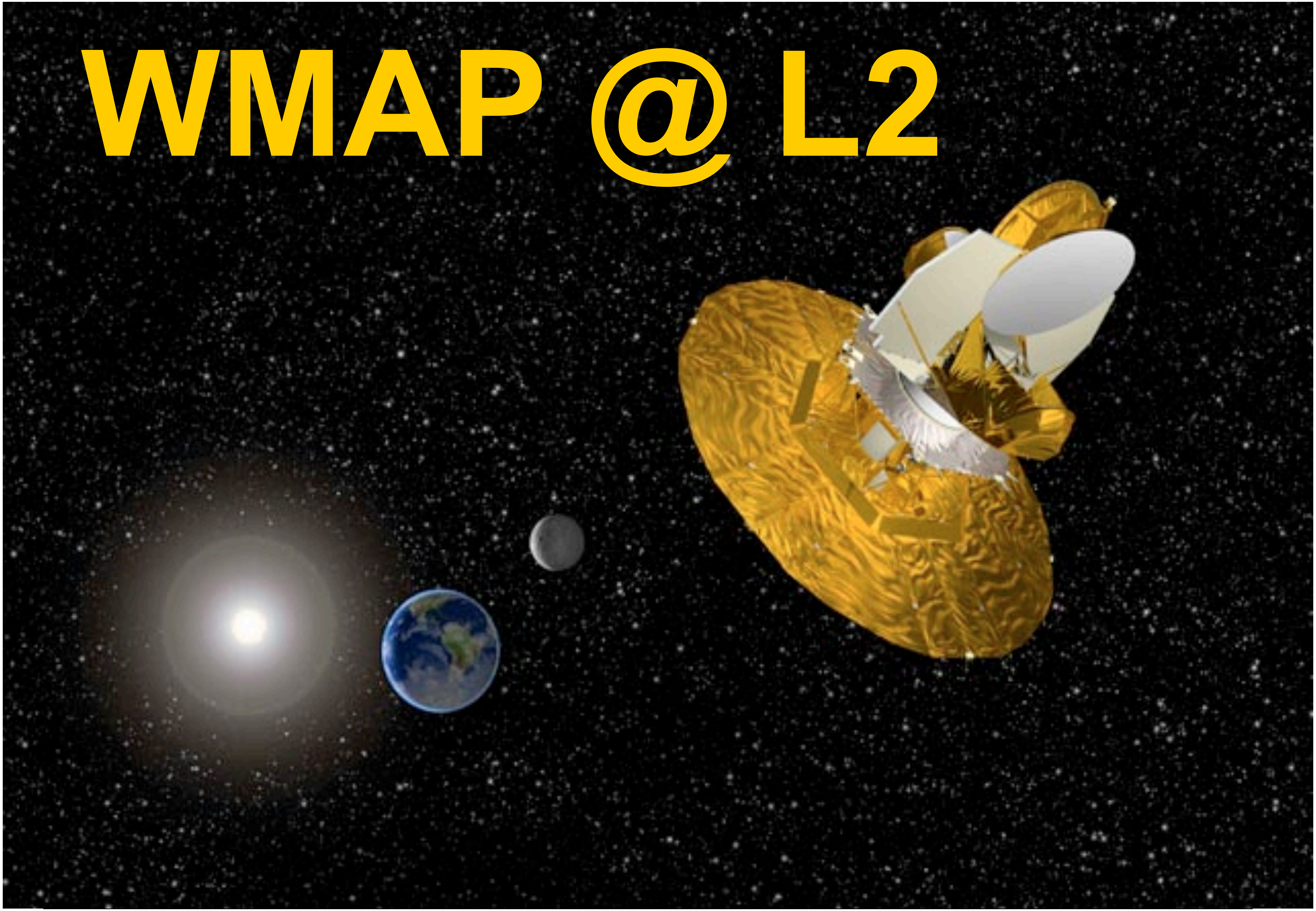


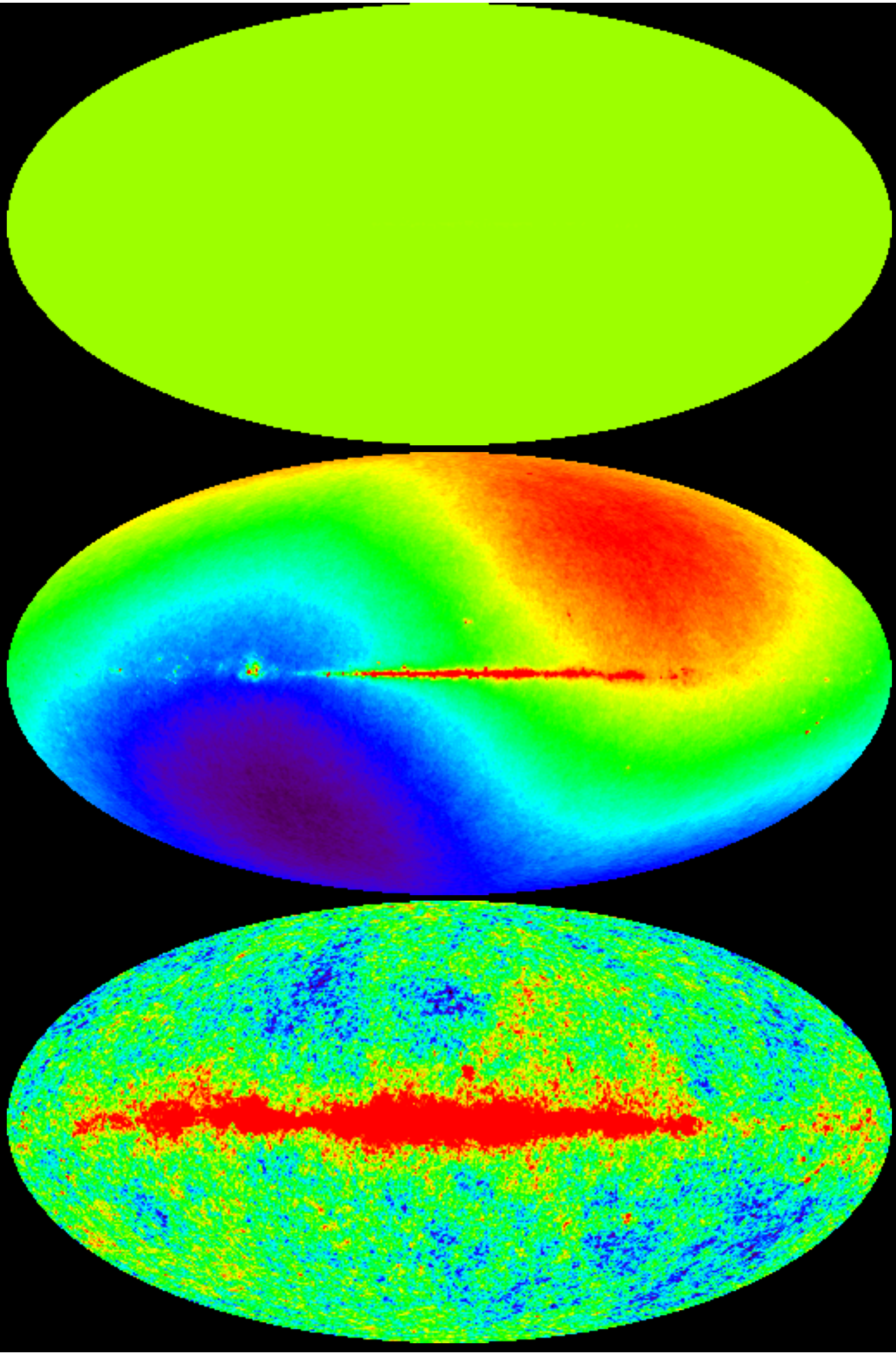
CMB Power Spectra
TT scalar
TT tensor (r=0.5)
TE
EE scalar
BB (r=0.5)
BB (EE lensed)
BB (r=0.0001)
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
1.E-06
1
10
100
1000
Multipole l
l(l+1)C$_l$/2π (μK^2)

Wilkinson Microwave Anisotropy Probe

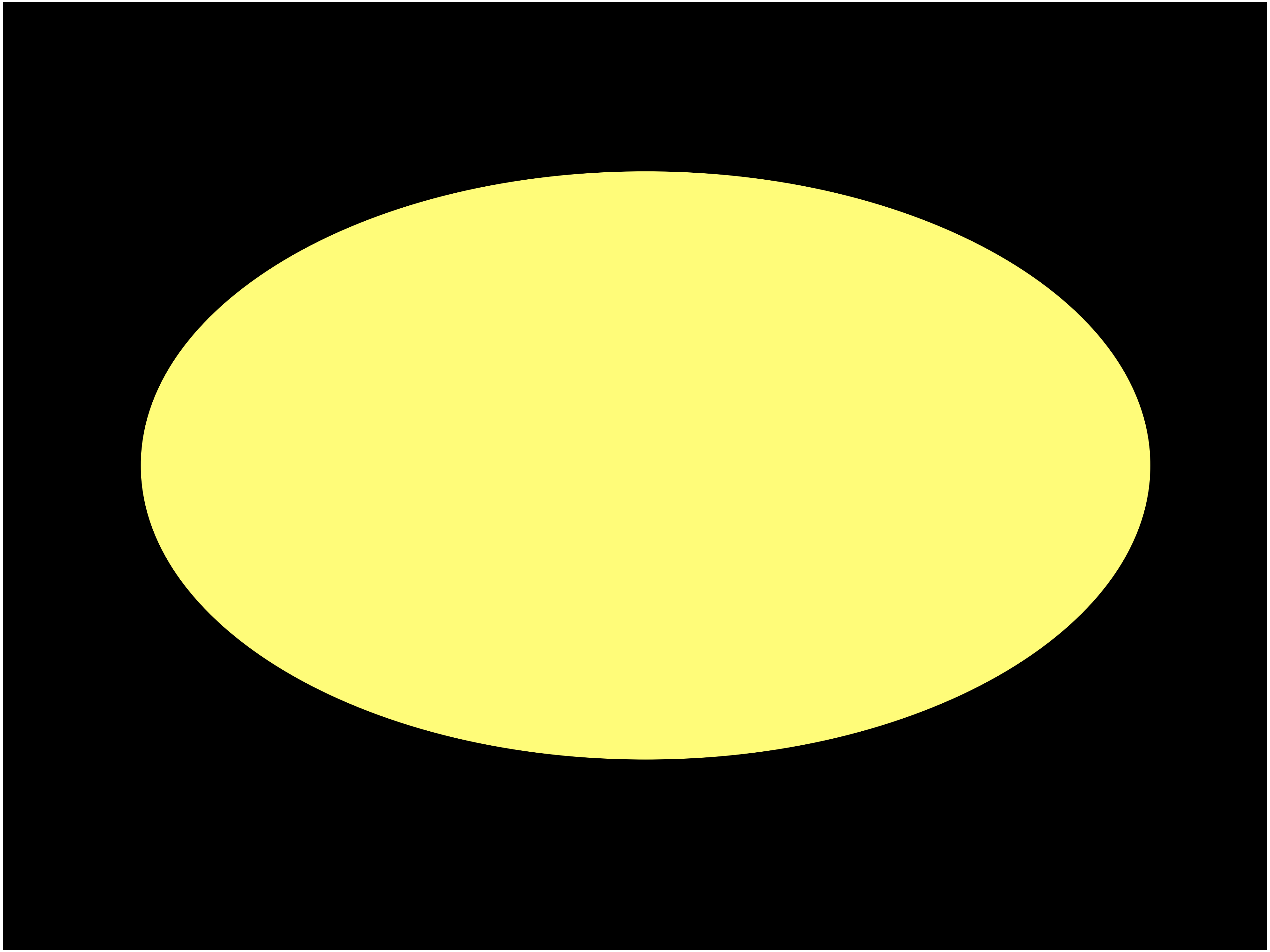


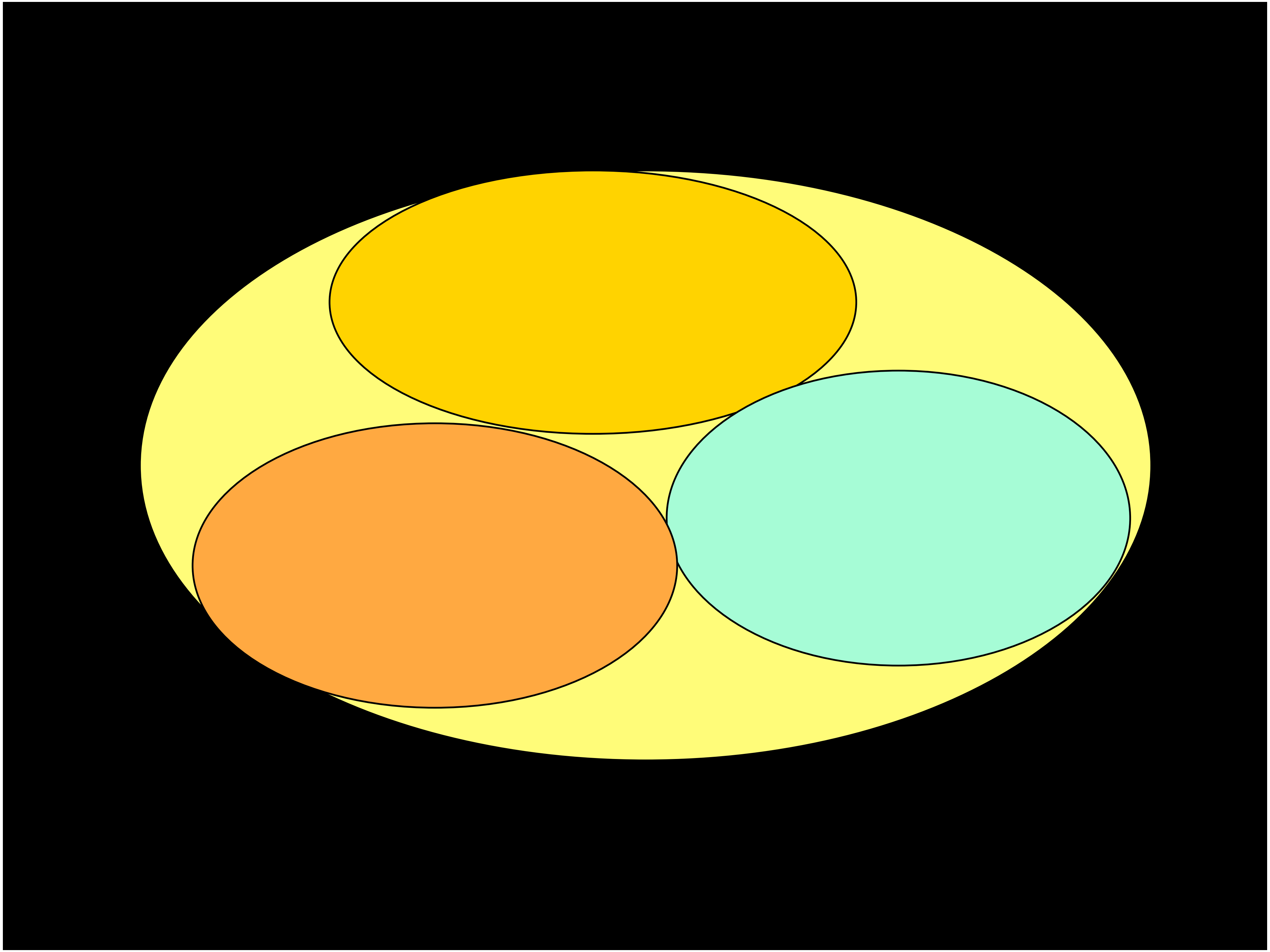
L4
L3
L1
L2
L5

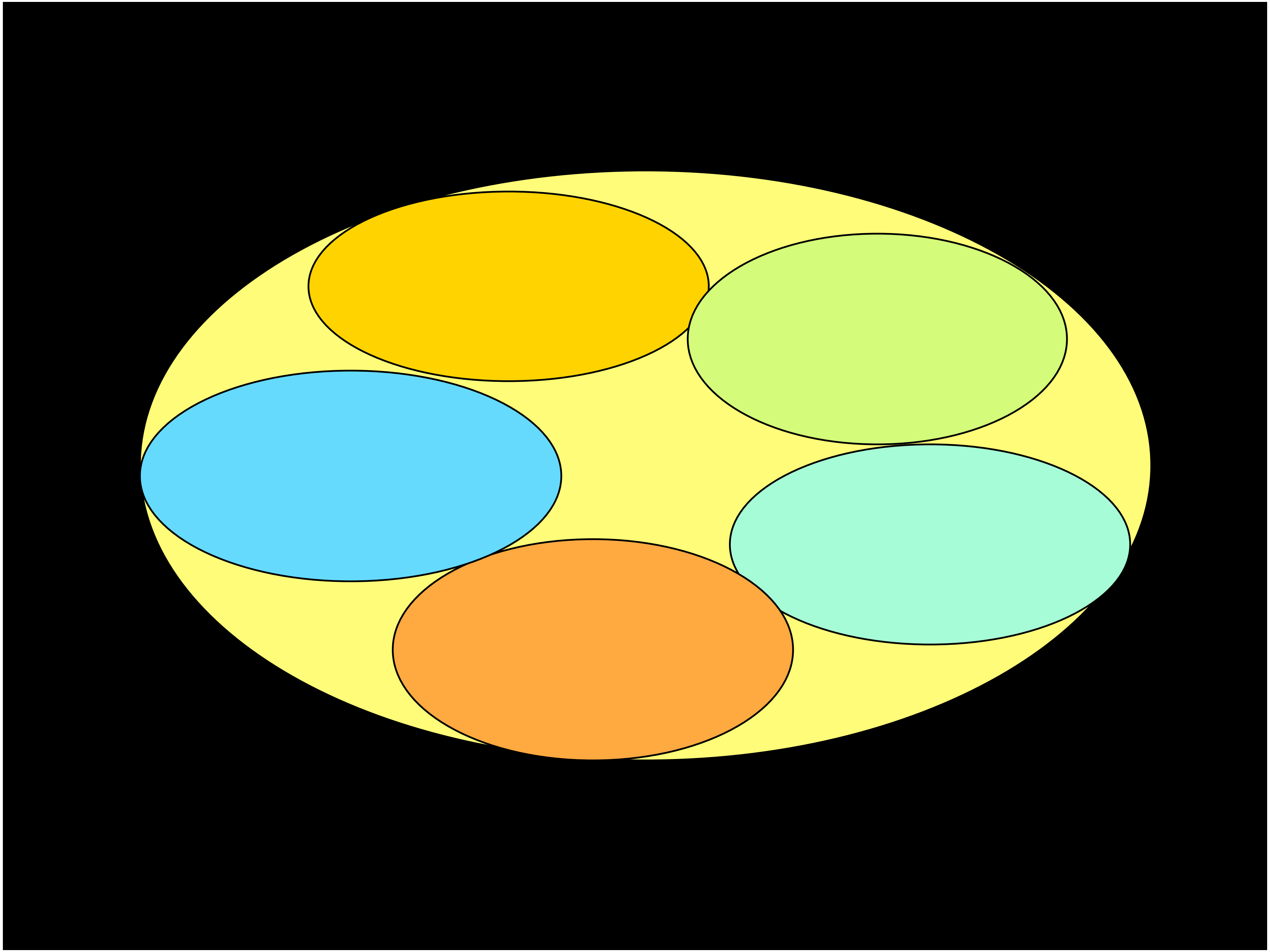

WMAP @ L2

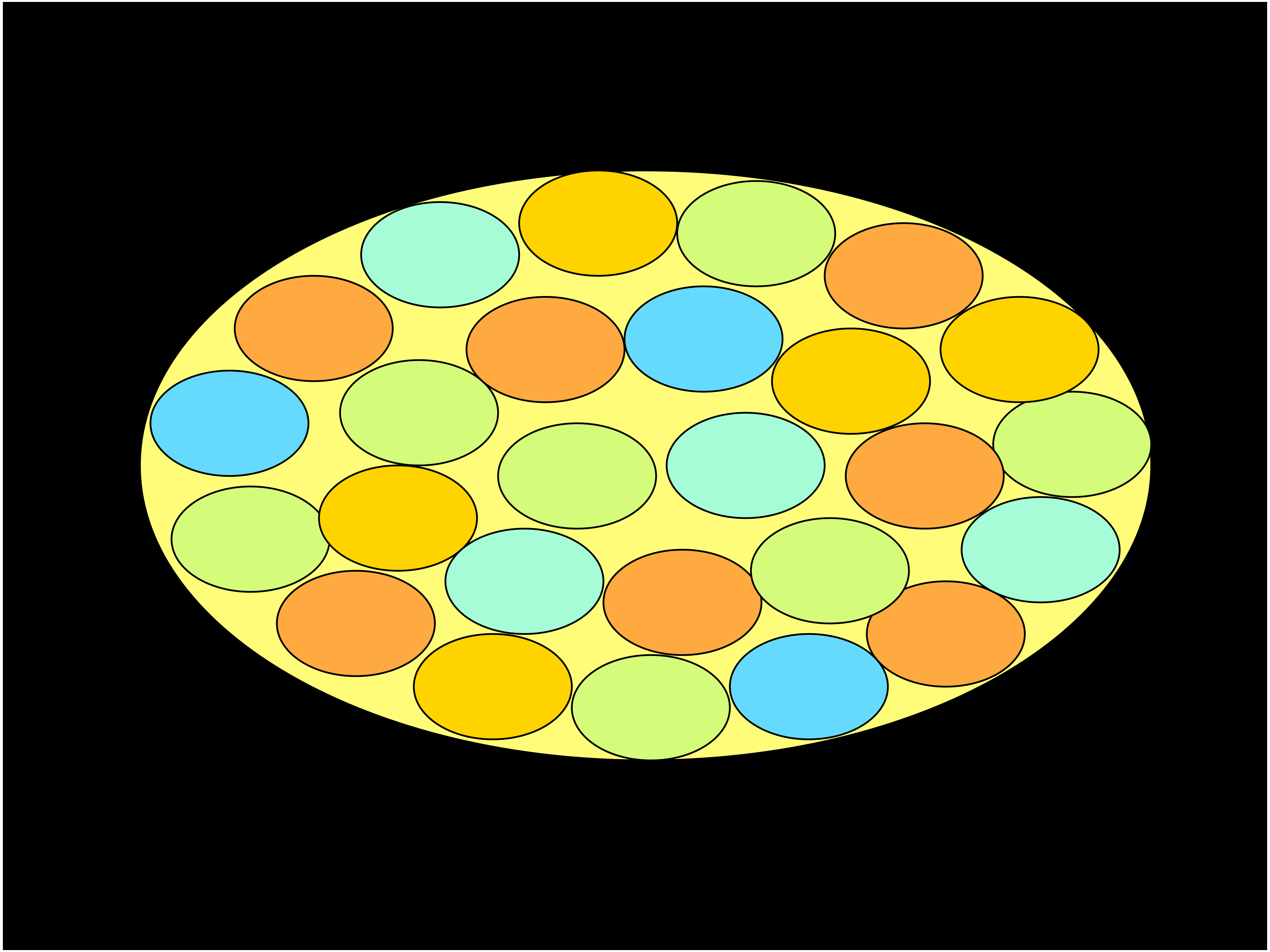


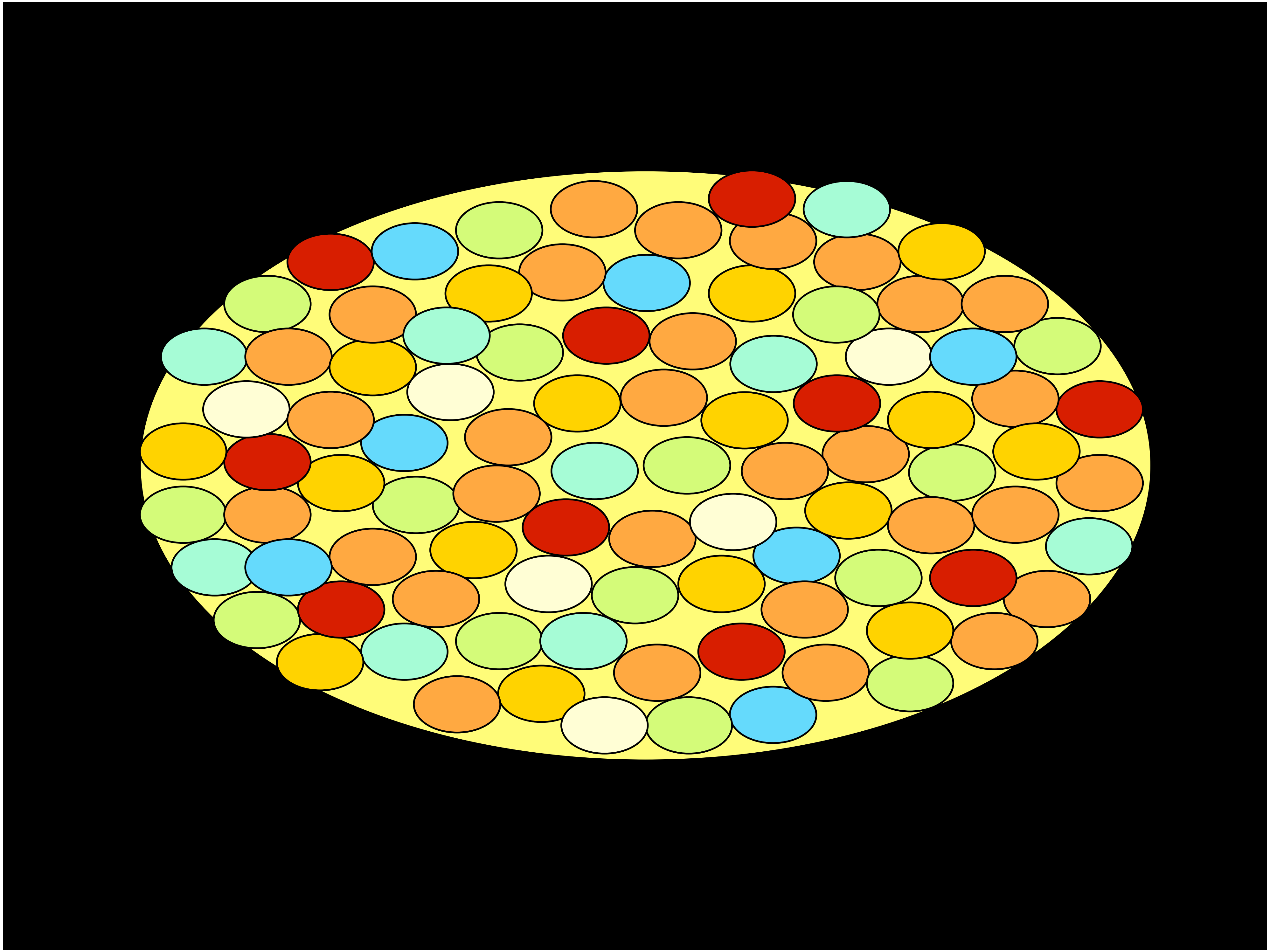
Wilkinson Microwave Anisotropy Probe (2003)

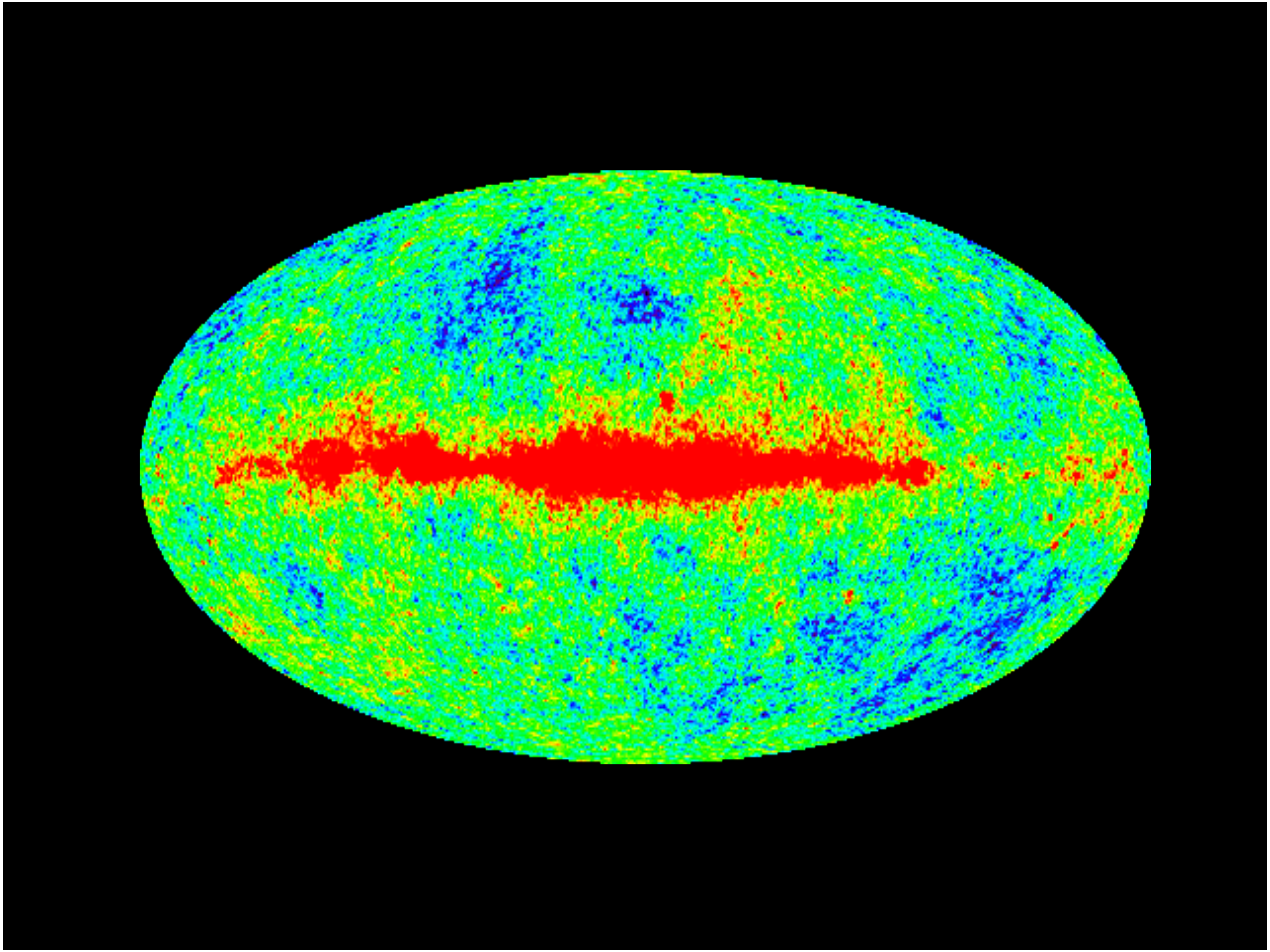




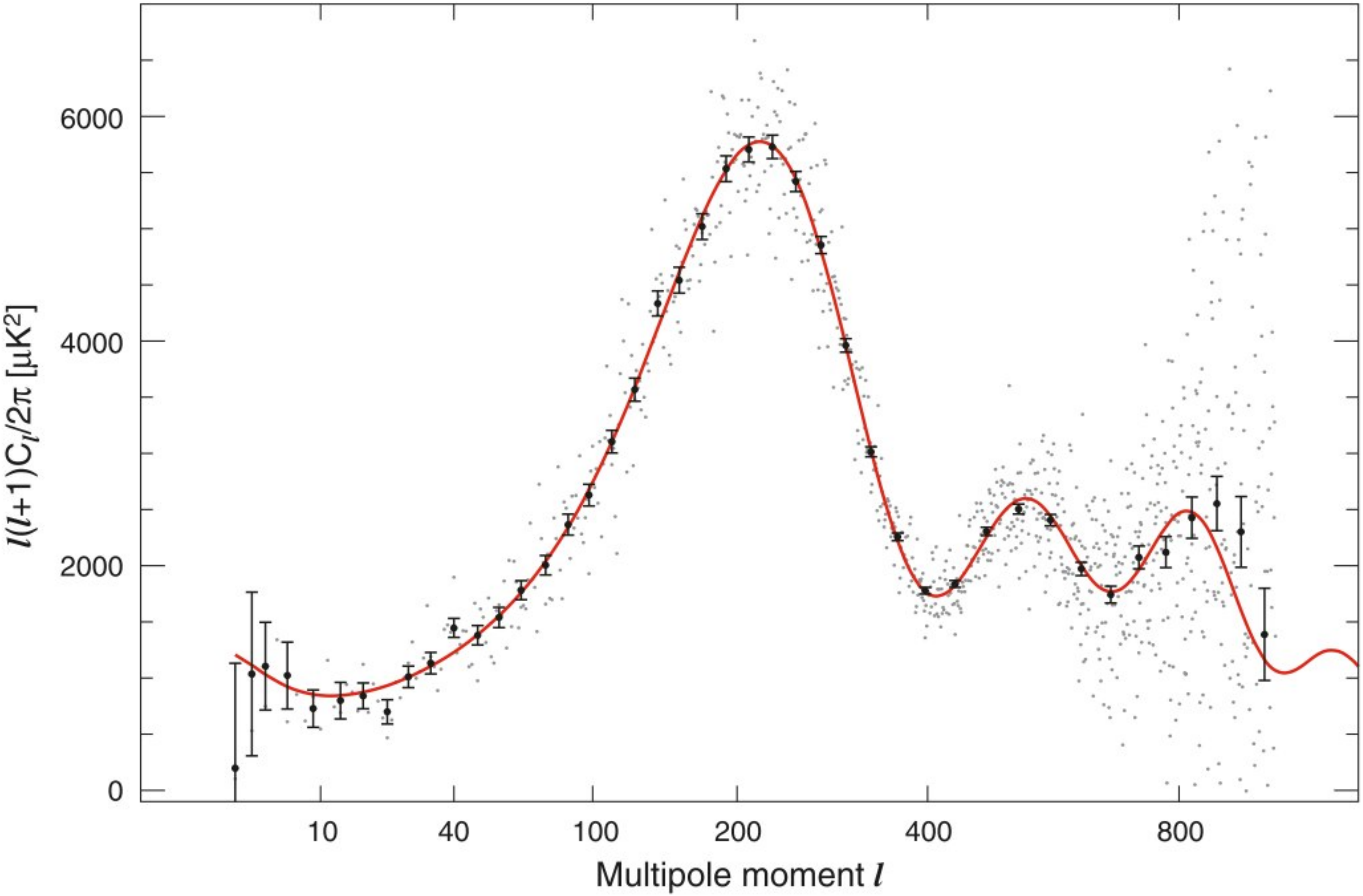




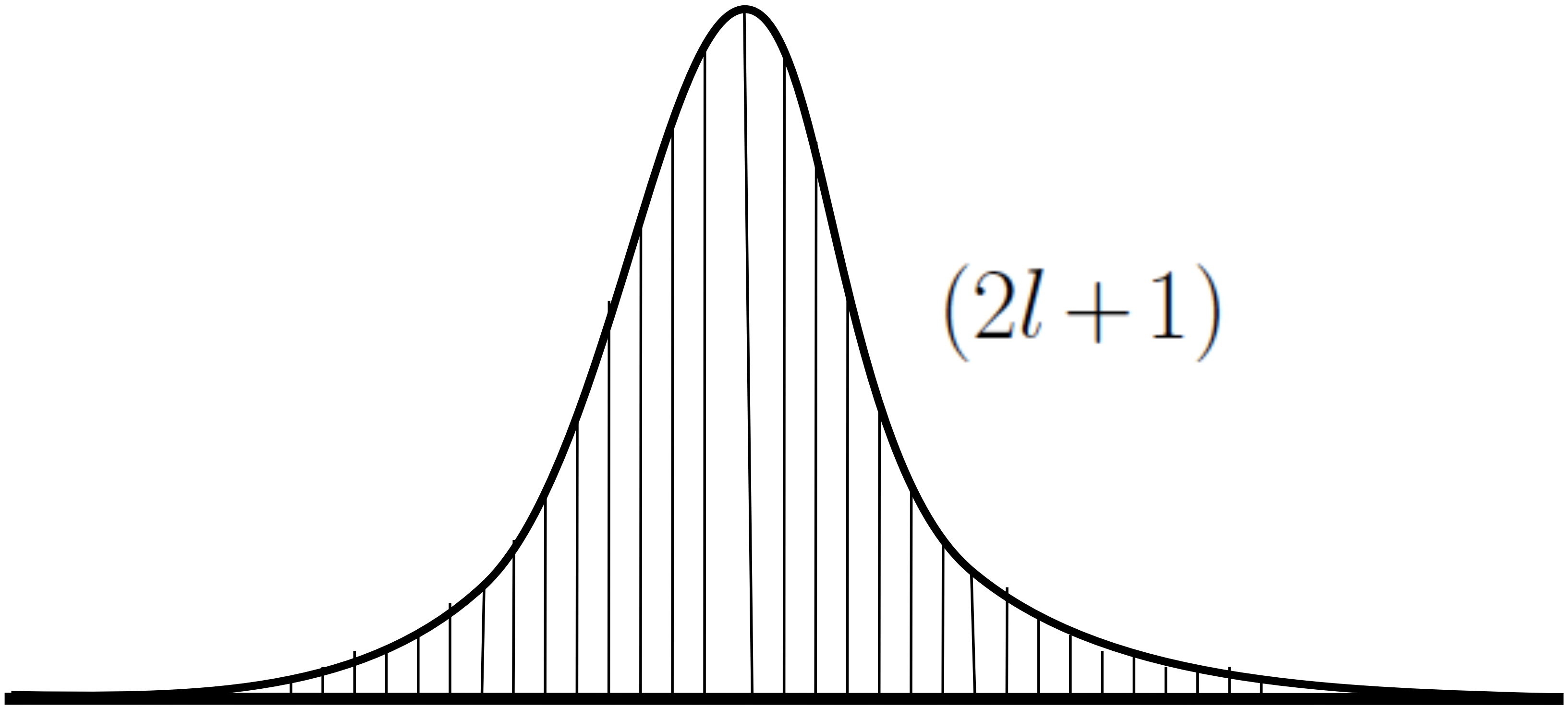




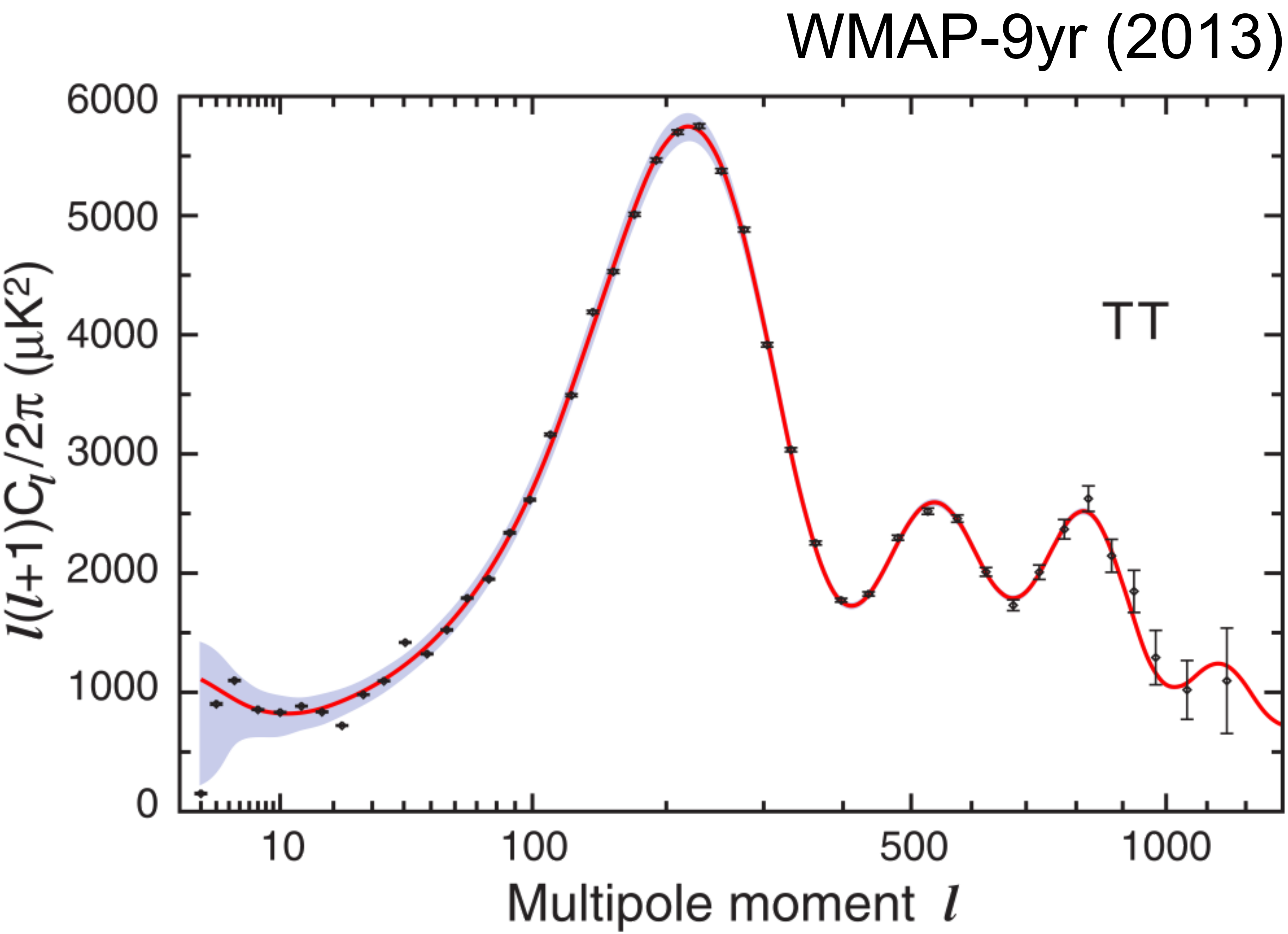
WMAP-5yr (2009)

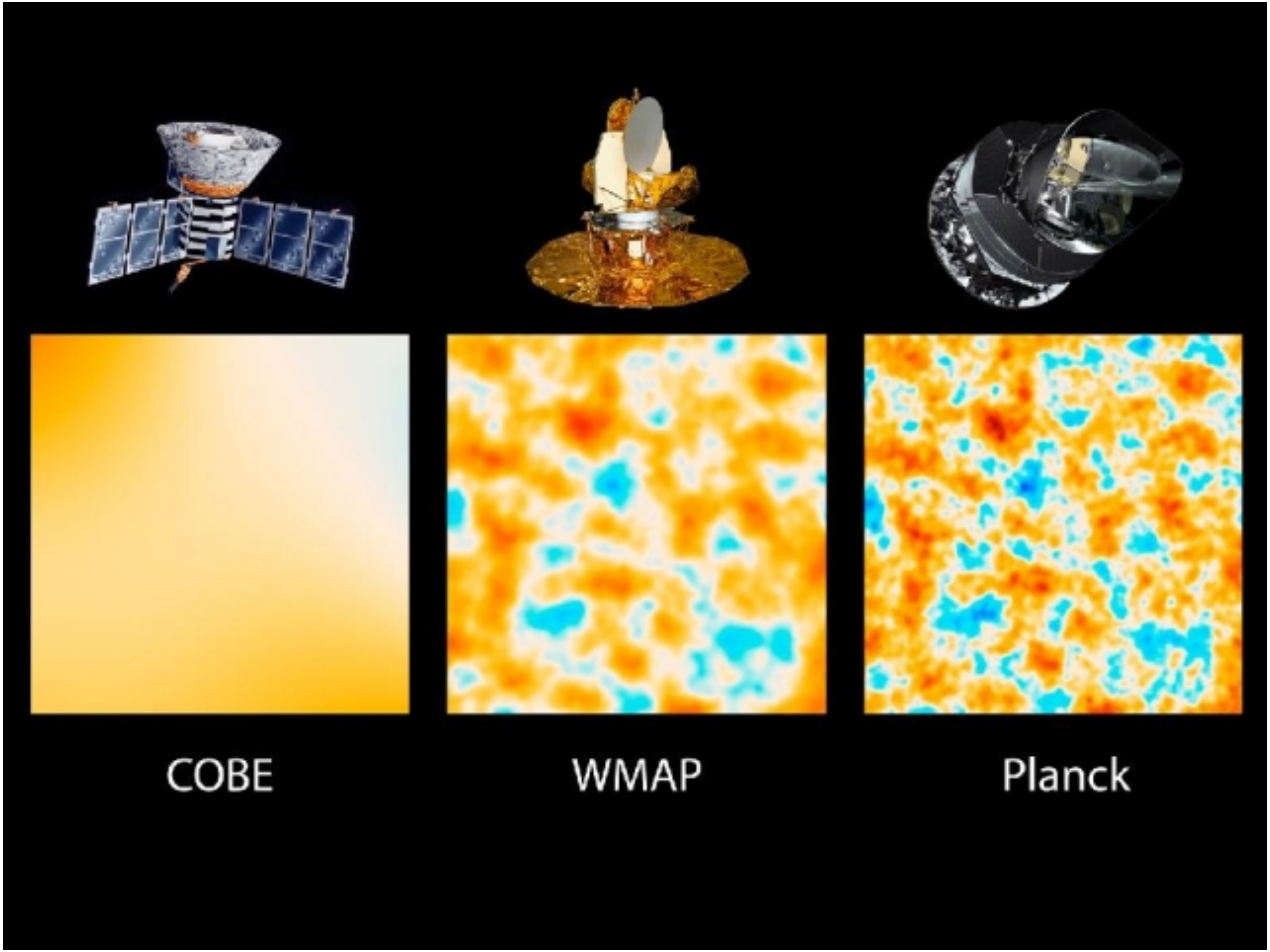


Gaussian spectrum



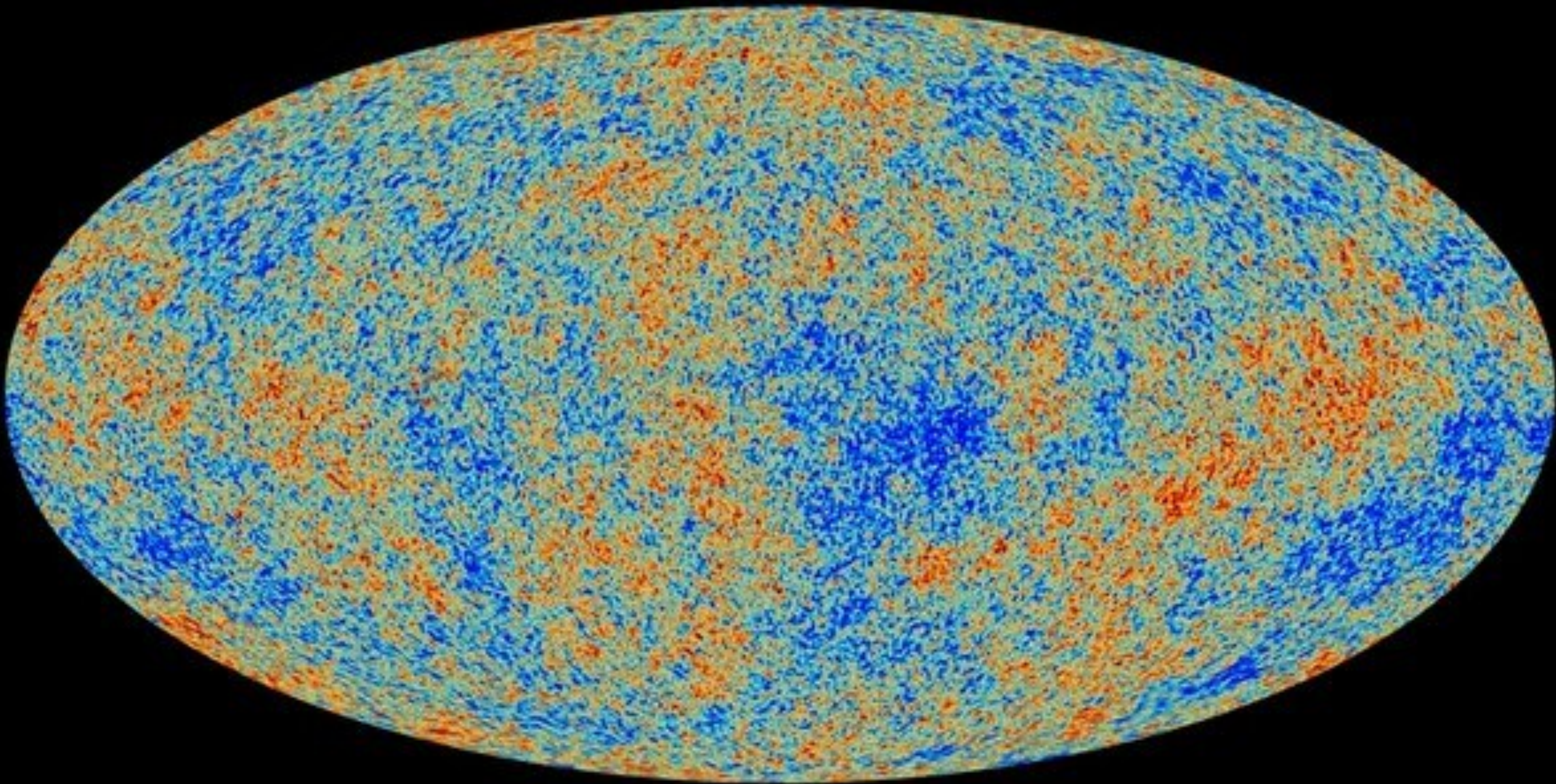
$$C_l = \langle |a_{lm}|^2 \rangle$$


WMAP-9yr (2013)
TT
$l(l+1)C_l/2\pi$ (μK^2)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l

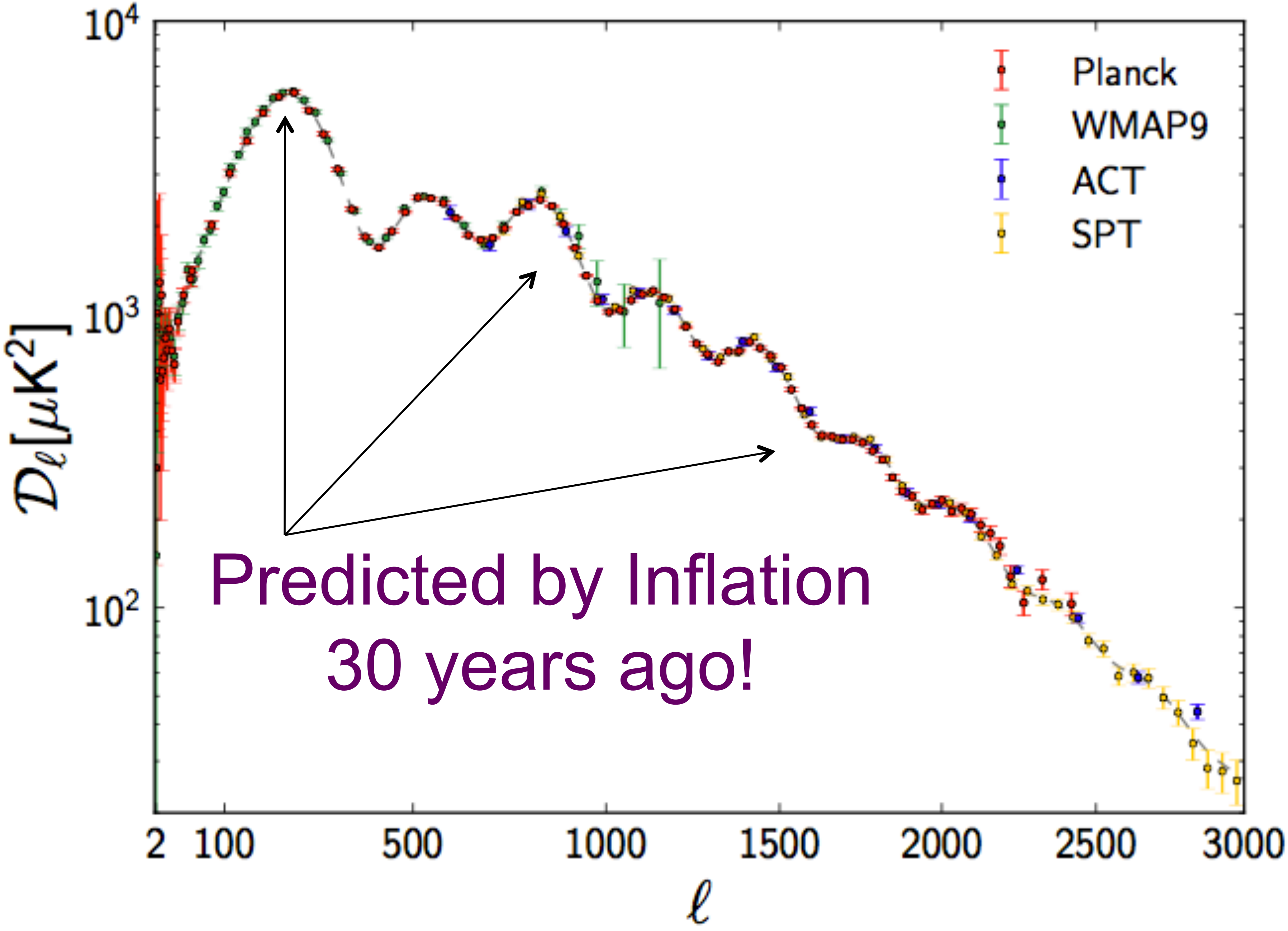


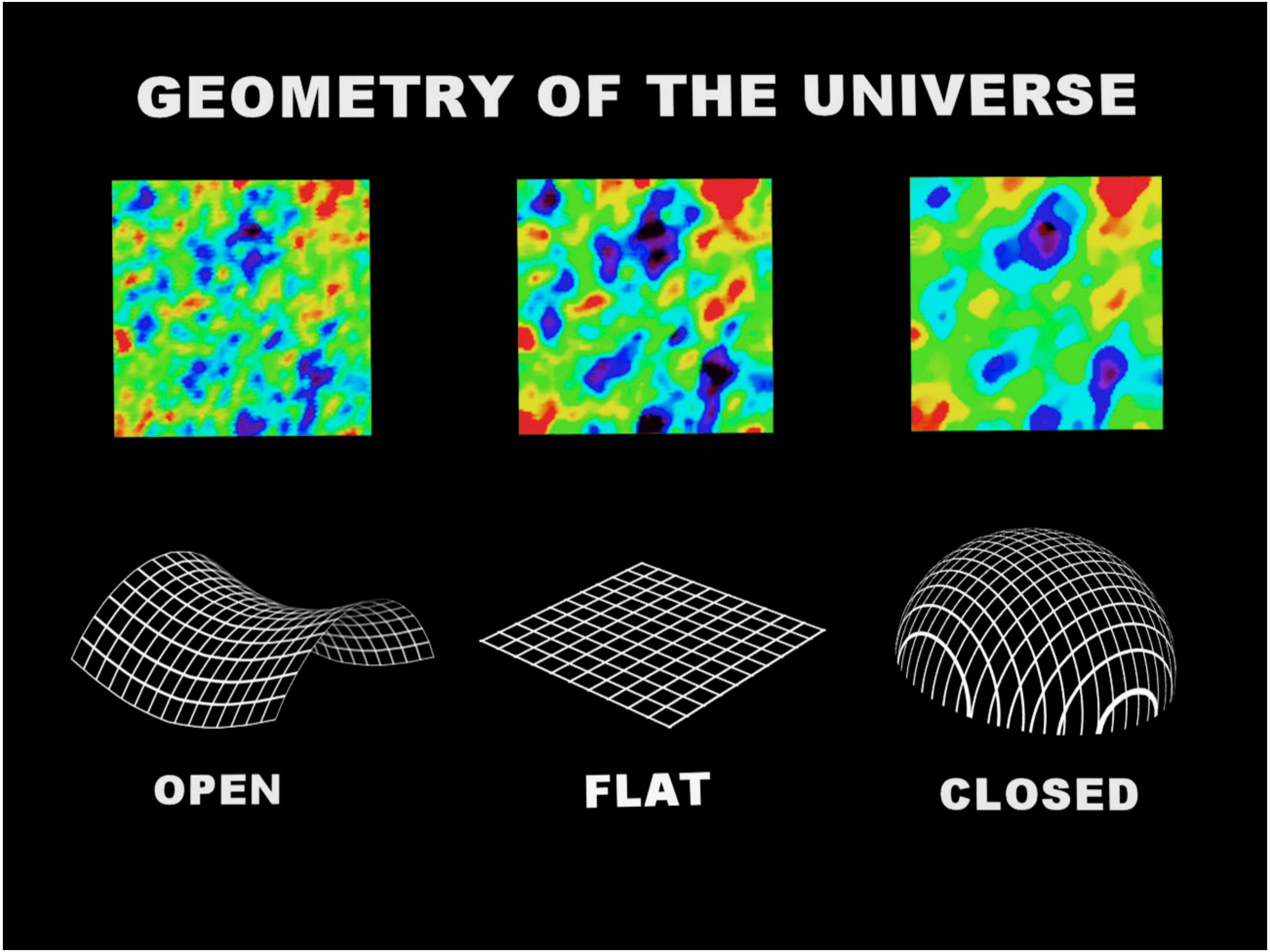
COBE
WMAP
Planck

Planck (2013)

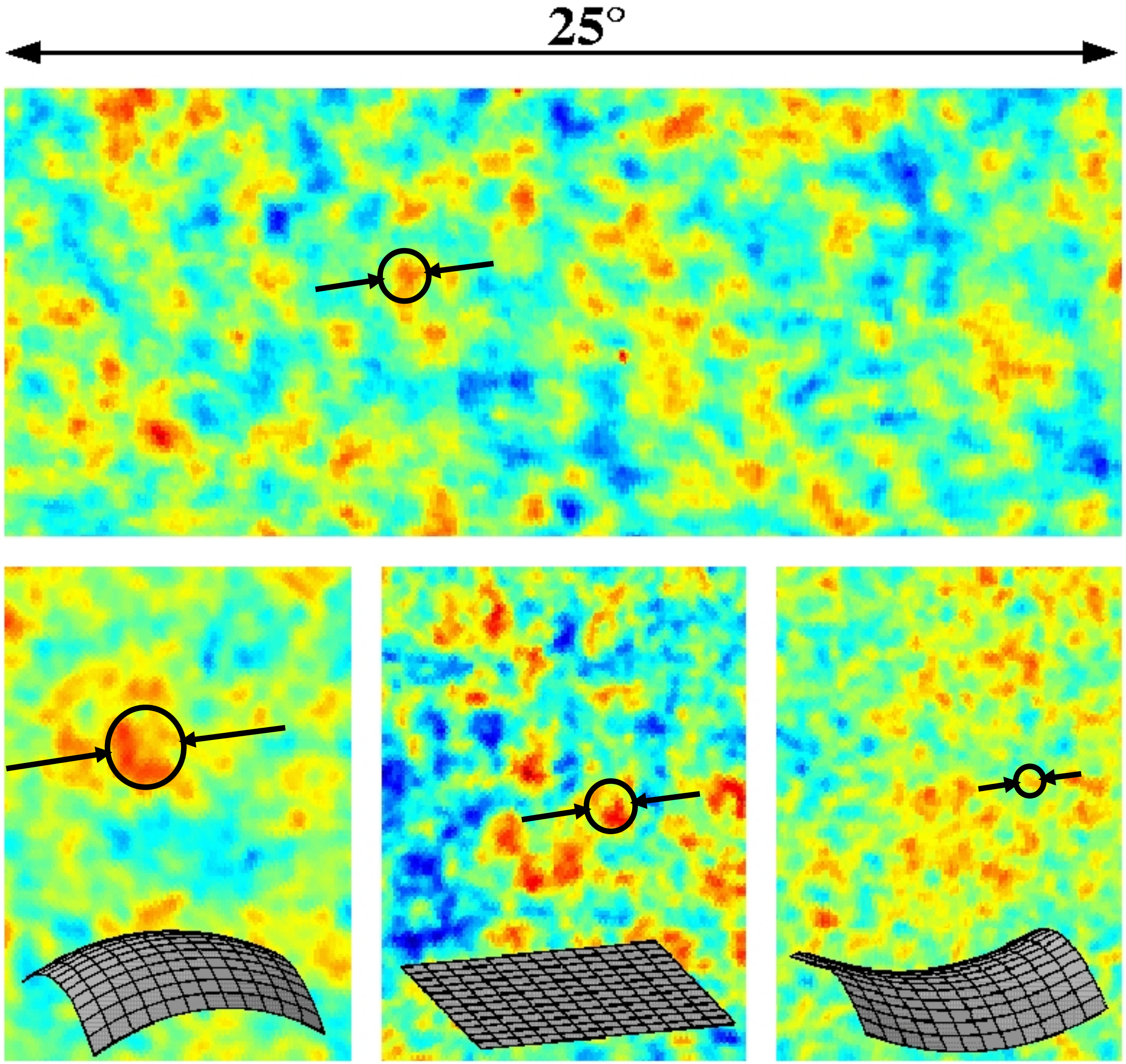


Planck Power Spectrum

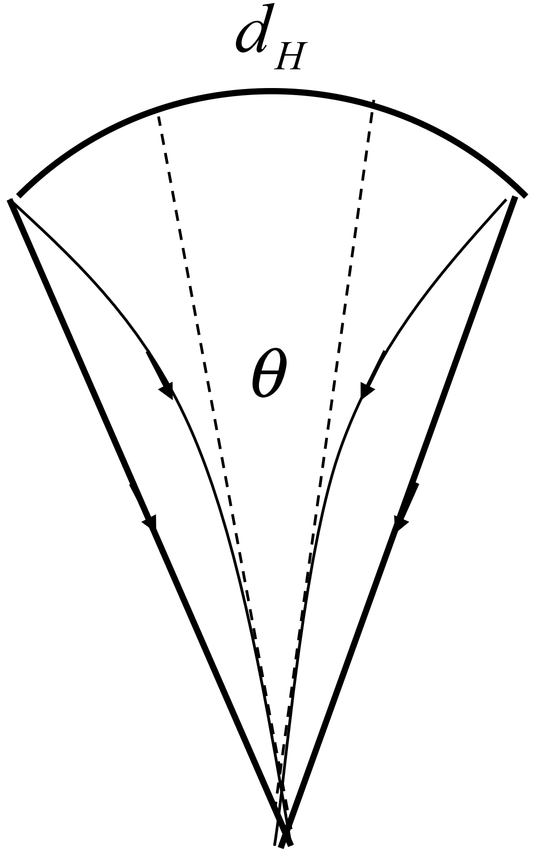



GEOMETRY OF THE UNIVERSE
OPEN
FLAT
CLOSED

$$\Omega_K = |\Omega_0 - 1| < 0.0009 \pm 0.0056$$ Planck (2013)

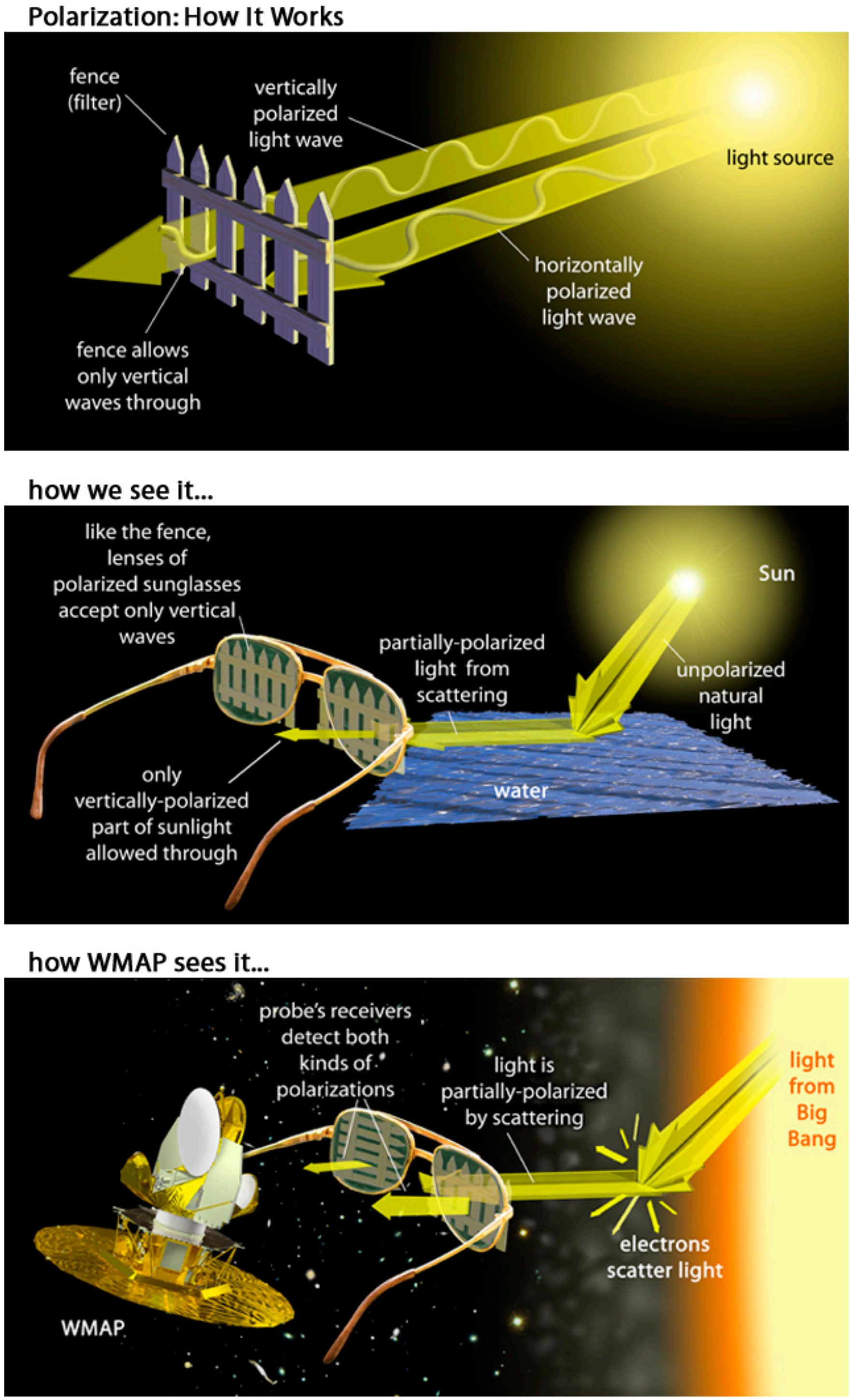


Spatial Curvature



geodesics

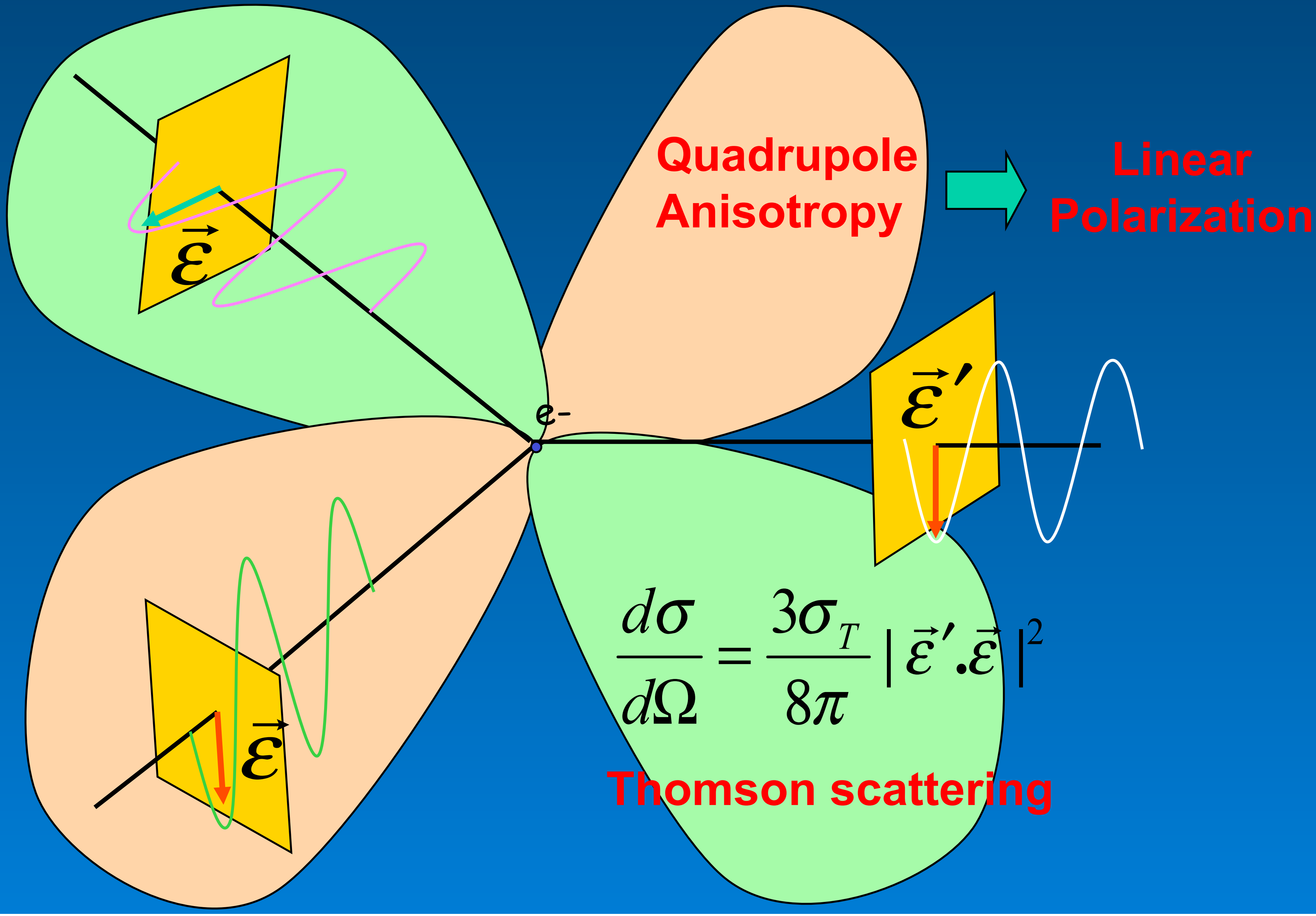
CMB Polarization Anisotropies



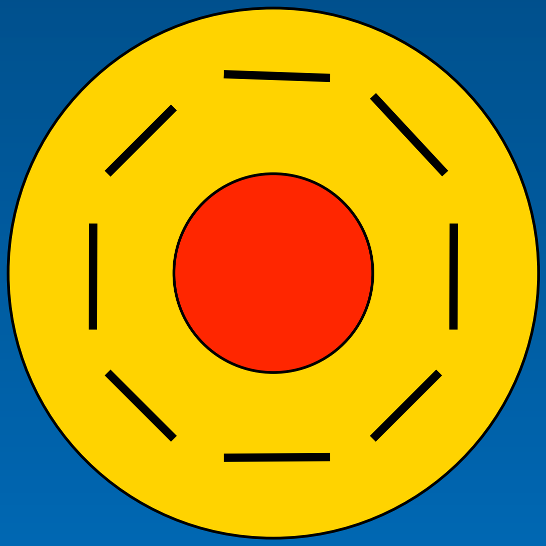
Light carries energy and polarization (vector field)

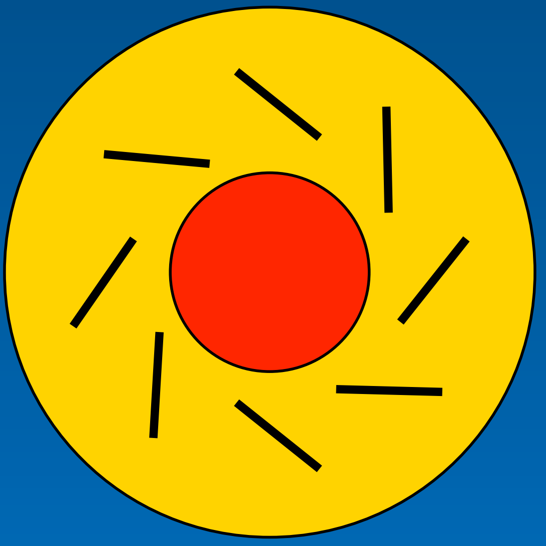
A vector field has two comp. gradient + curl (E + B)

Linear Polarization of CMB



Polarization around Hot spots





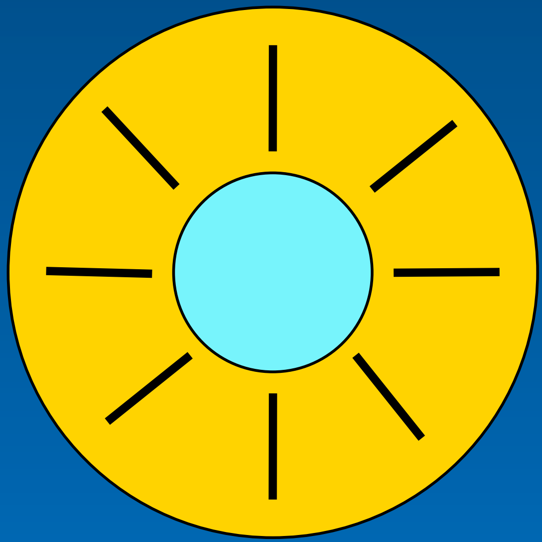
E Polarization

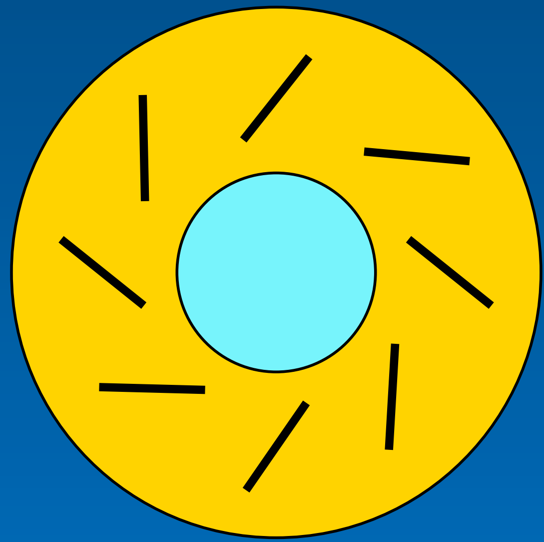
$$\nabla \times E = 0$$

B Polarization

$$\nabla \cdot B = 0$$

Polarization around Cold spots





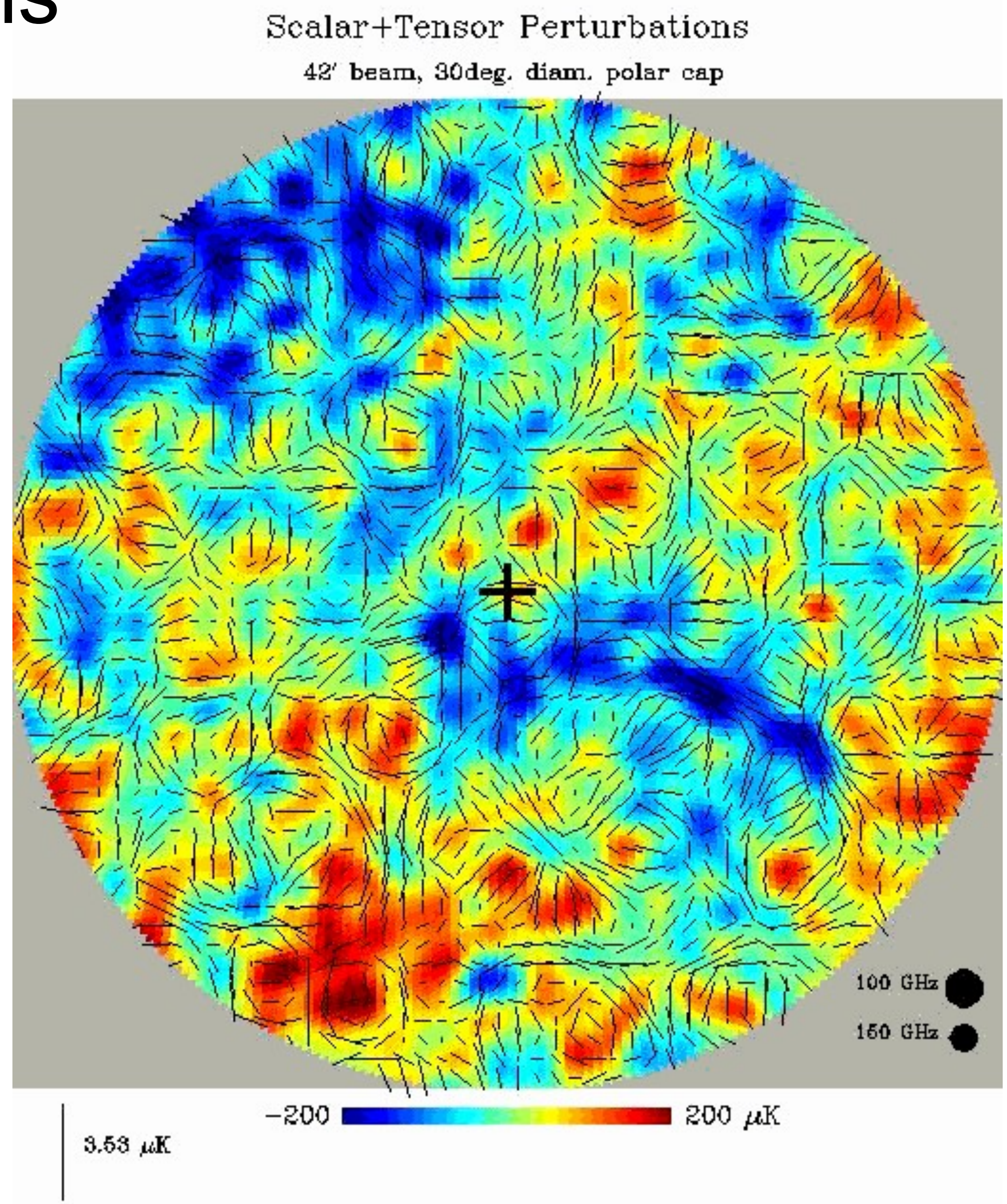
E Polarization

$$\nabla \times E = 0$$

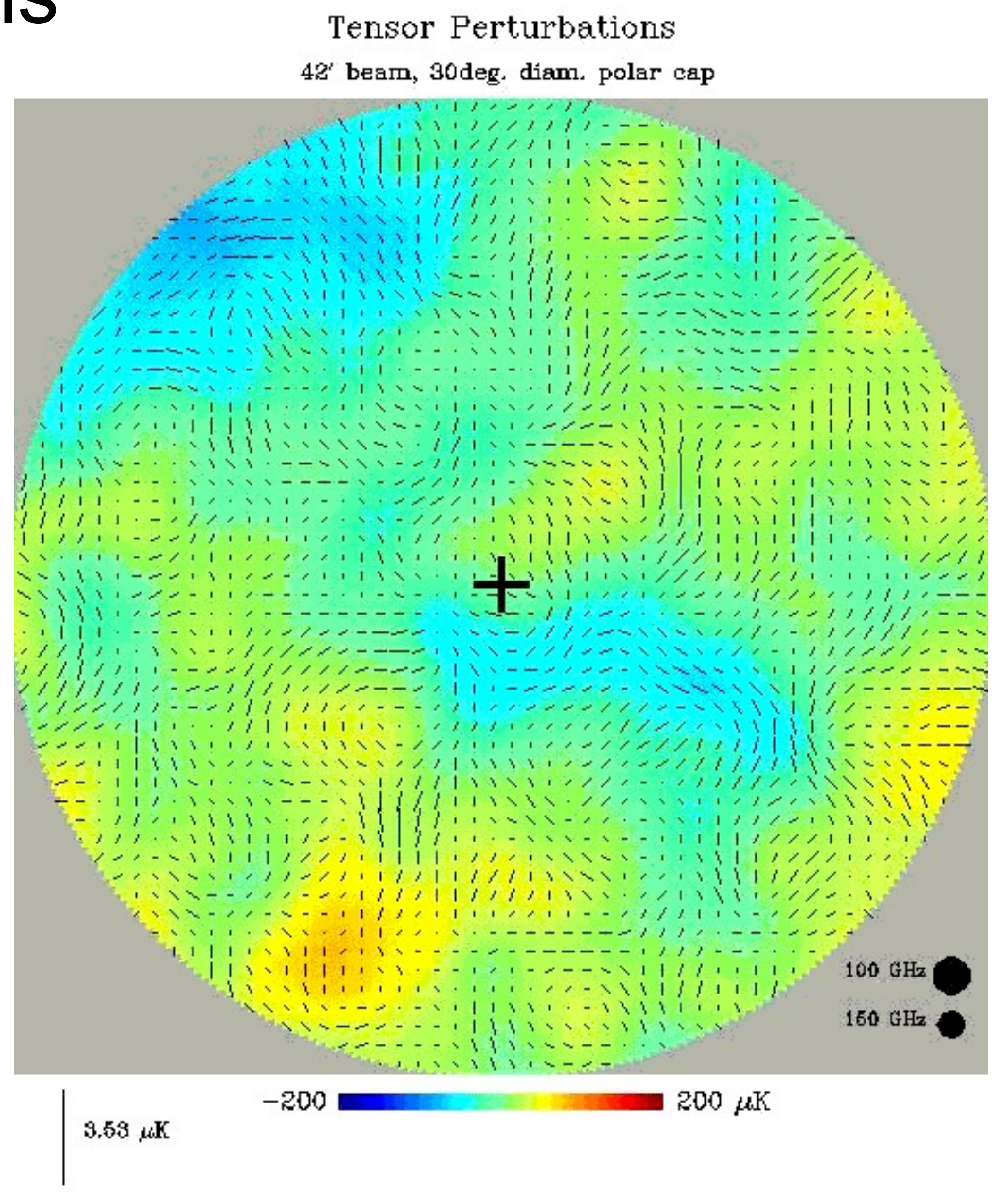
B Polarization

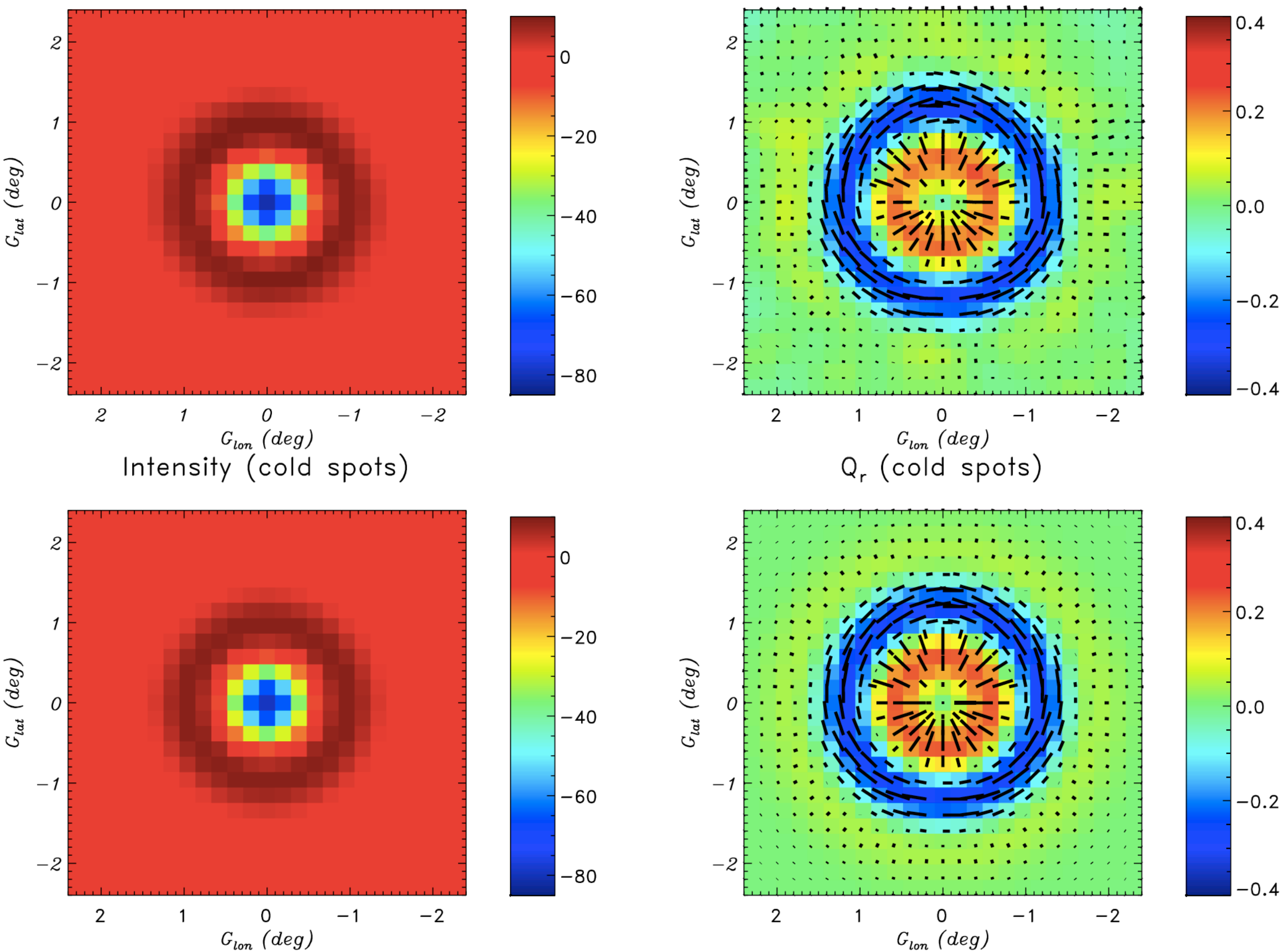
$$\nabla \cdot B = 0$$

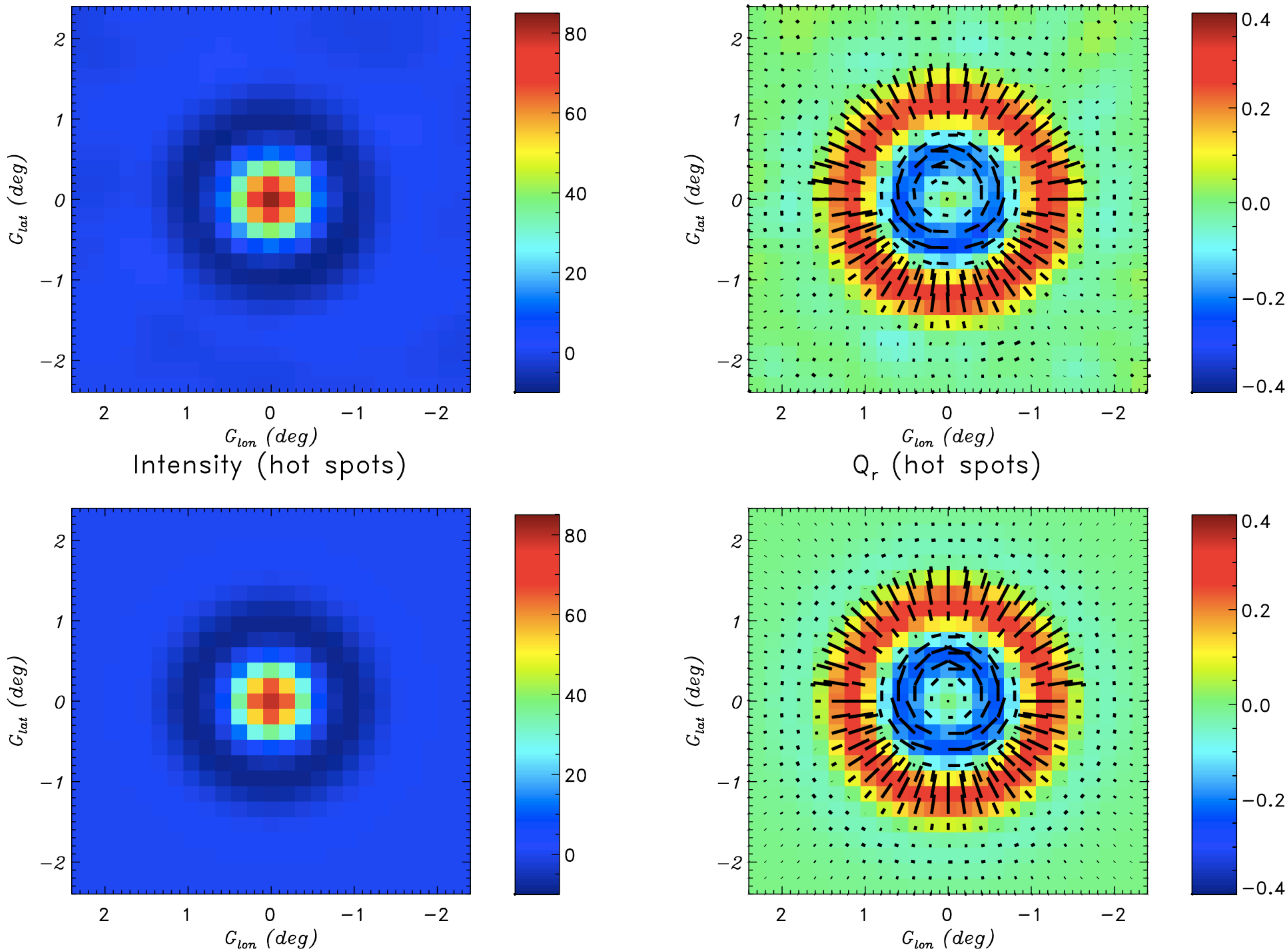
Simulations

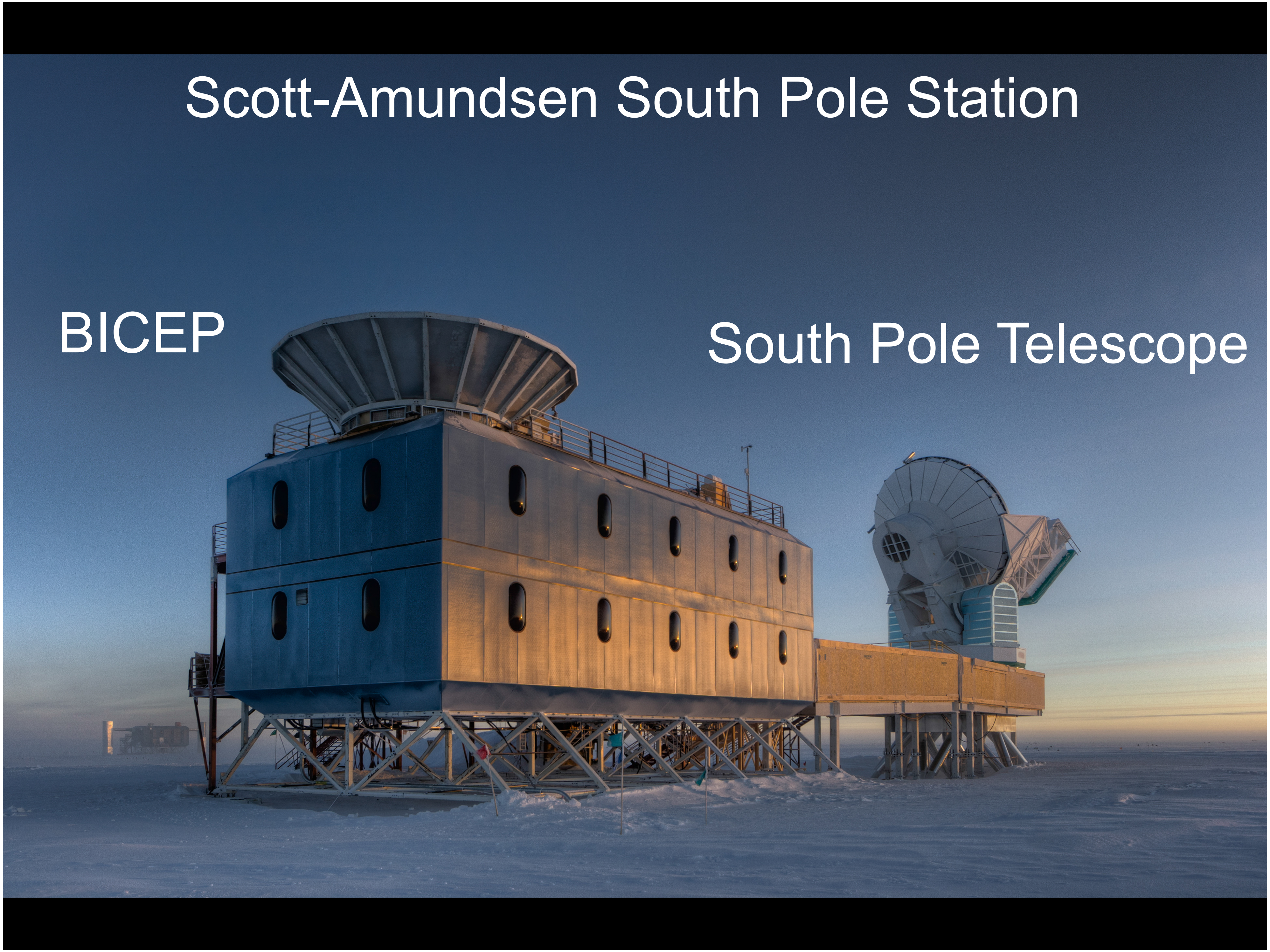


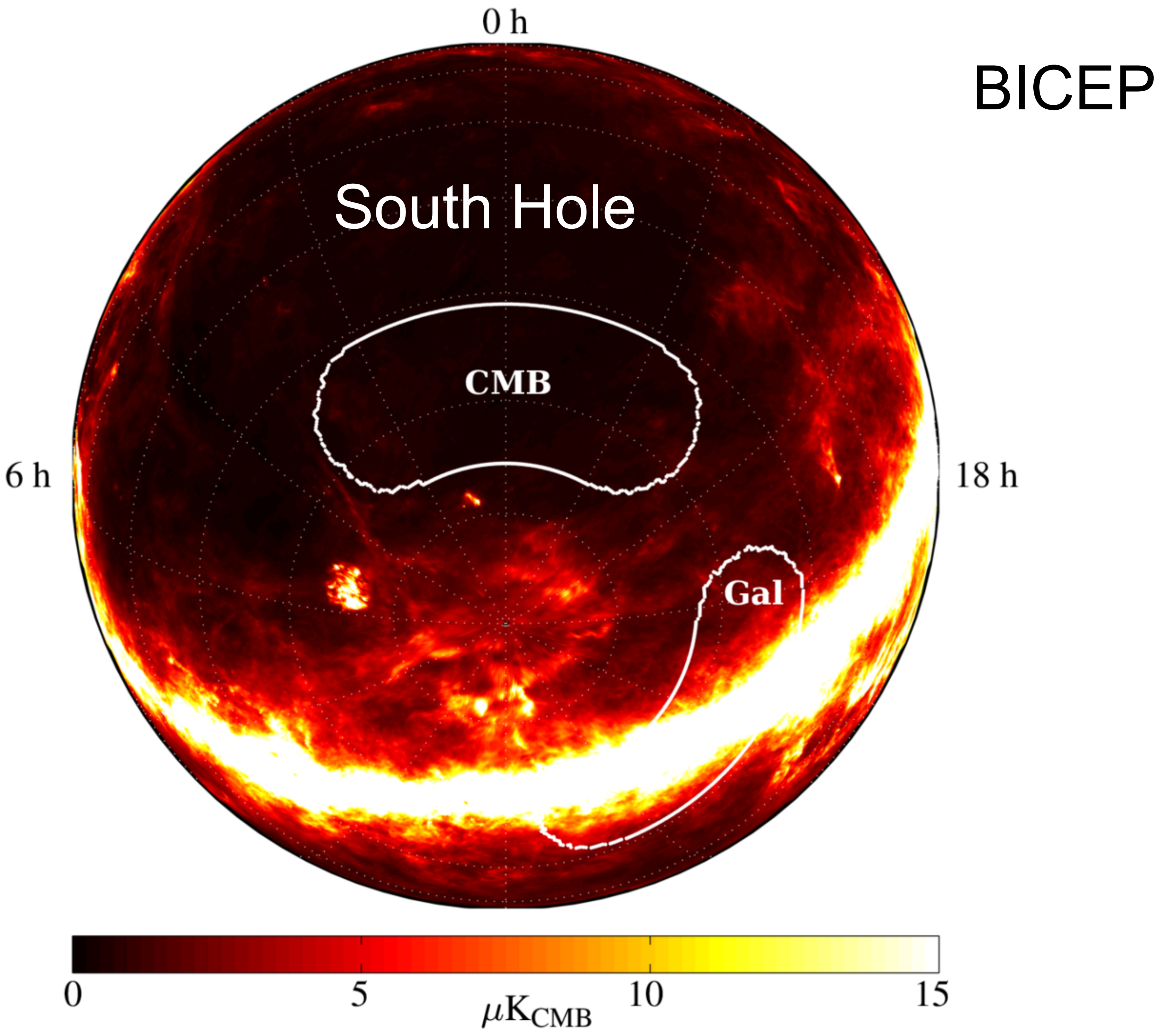
Simulations

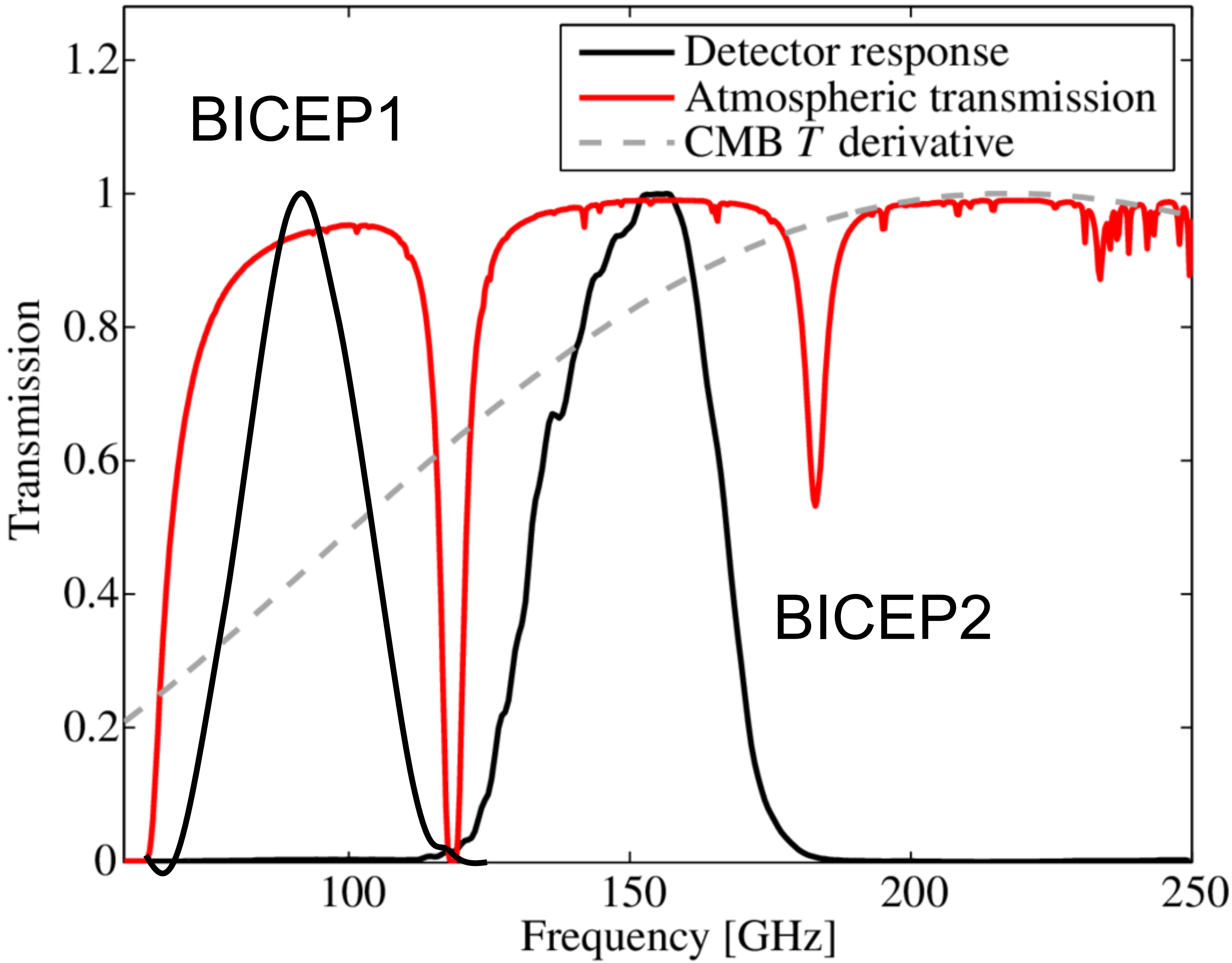



Intensity (cold spots)
Q_r (cold spots)
G_lat (deg)
G_lon (deg)
2
1
0
−1
−2
0
−20
−40
−60
−80
0.4
0.2
0.0
−0.2
−0.4


Intensity (hot spots)
Q_r (hot spots)
G_lat (deg)
G_lon (deg)
2
1
0
−1
−2
80
60
40
20
0
0.4
0.2
0.0
−0.2
−0.4

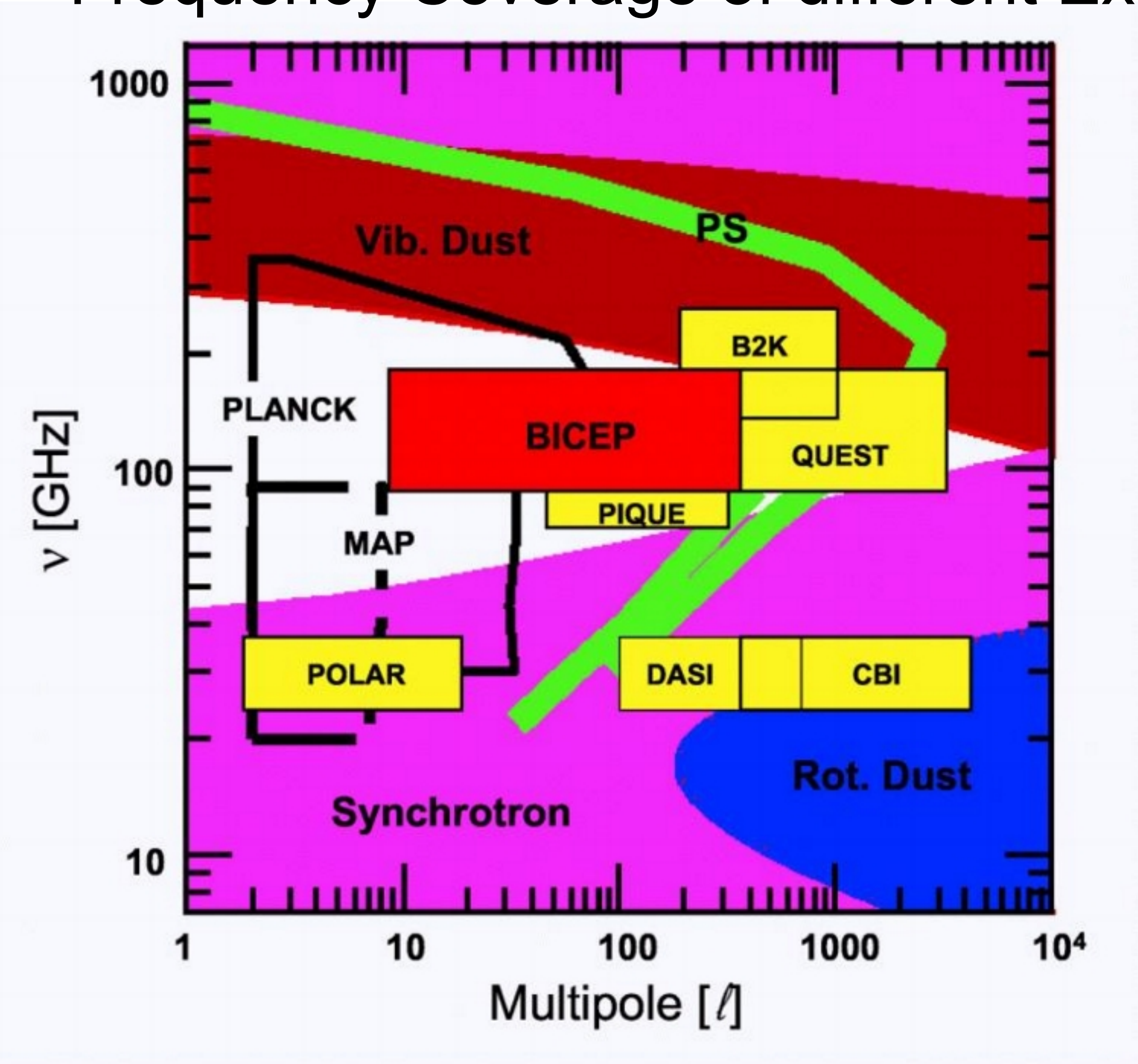

Scott-Amundsen South Pole Station
BICEP
South Pole Telescope


BICEP
0 h
6 h
18 h
South Hole
CMB
Gal
0
5
10
15
μK_{CMB}

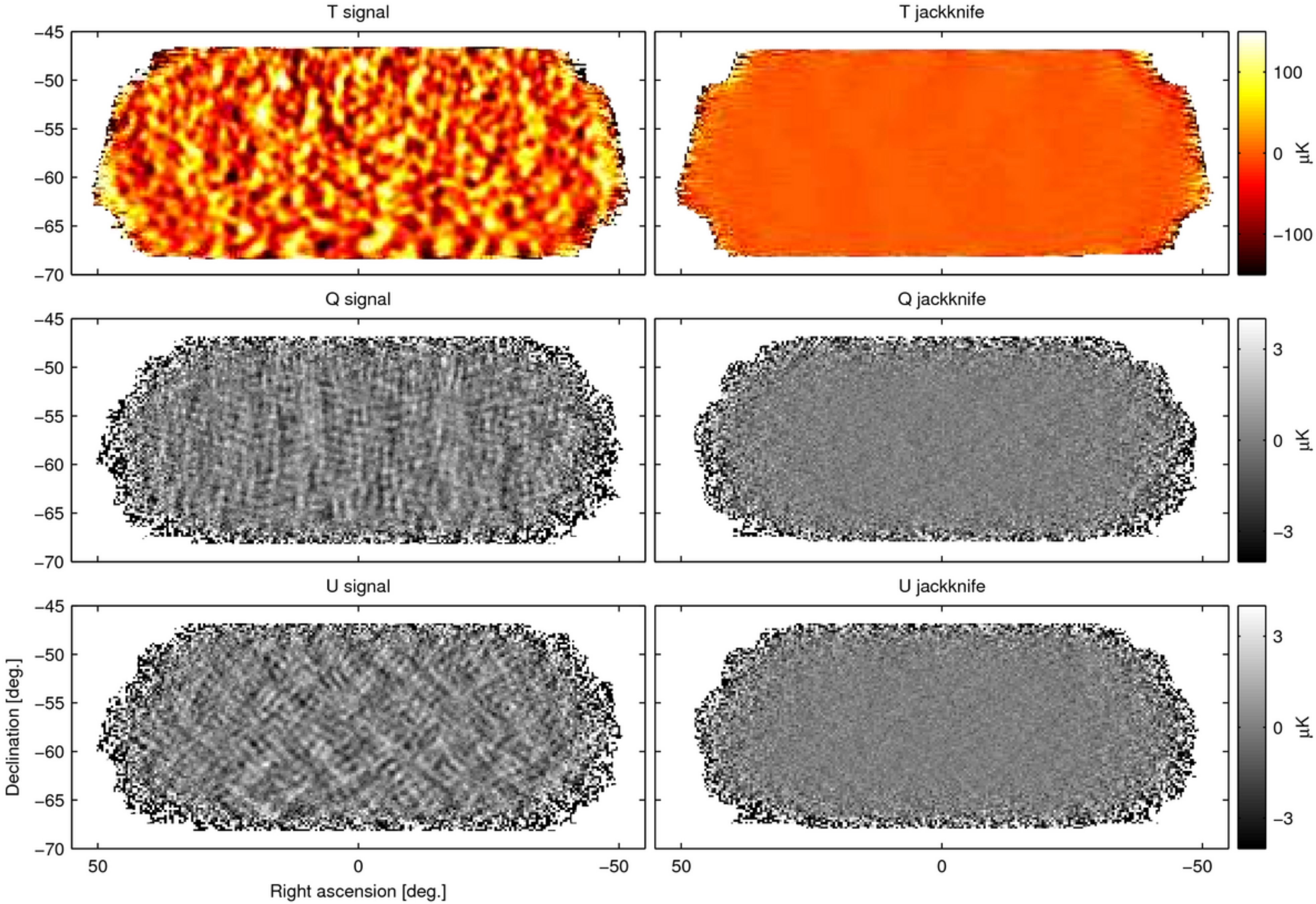


Detector response
Atmospheric transmission
CMB T derivative
BICEP1
BICEP2
Transmission
Frequency [GHz]
0
0.2
0.4
0.6
0.8
1
1.2
100
150
200
250

Frequency Coverage of different Exp.

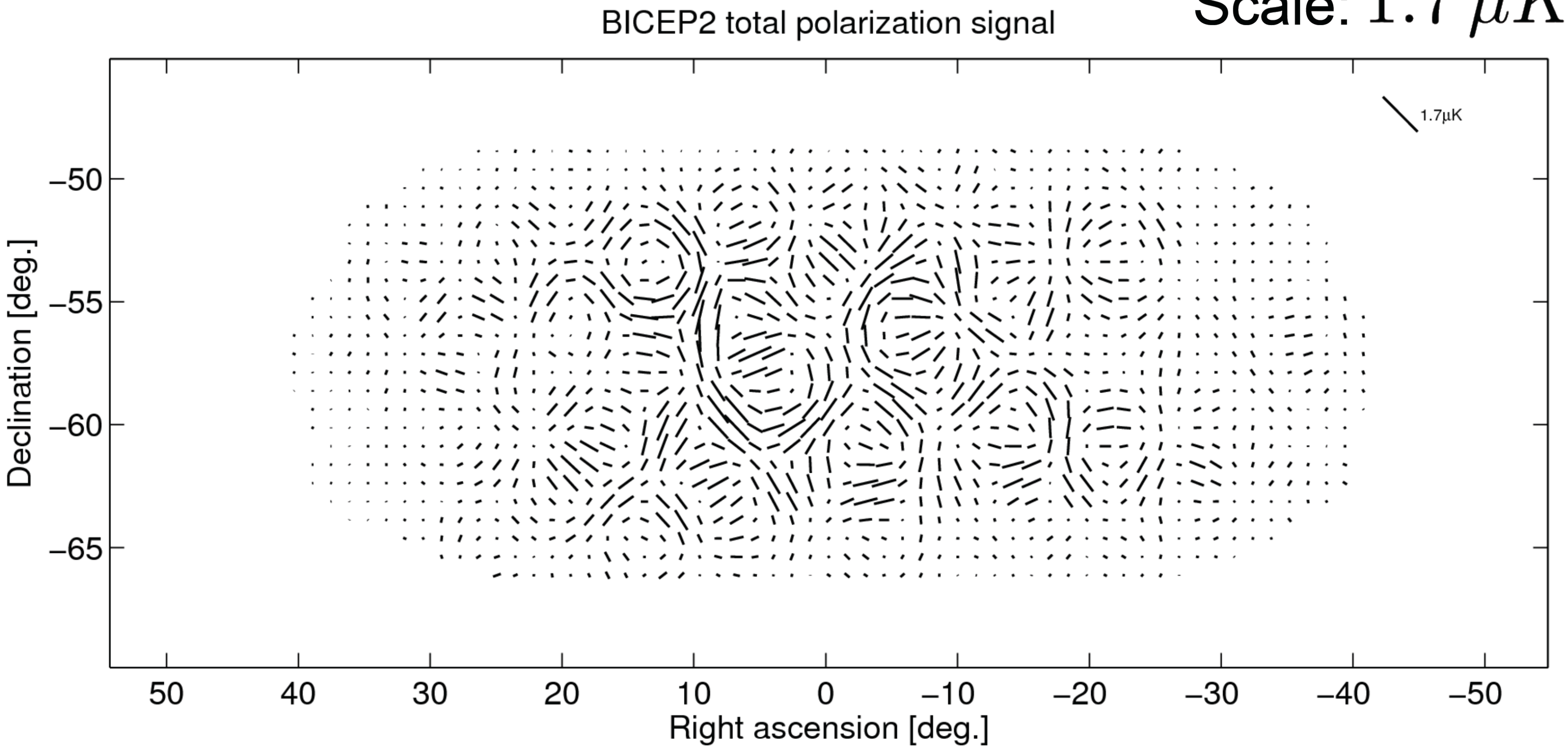


Measurements BICEP2



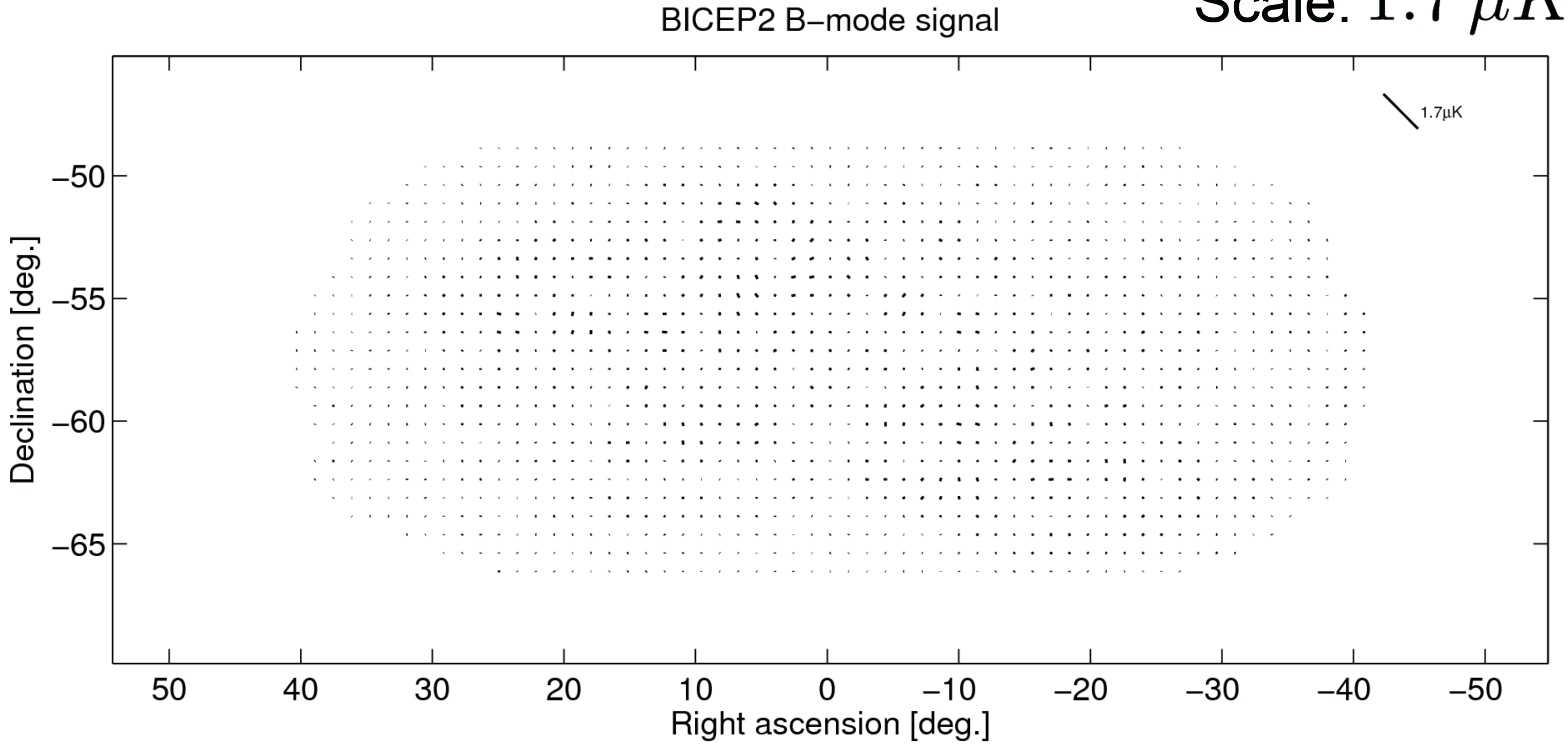
Total Polarization

Scale: $1.7\,\mu K$



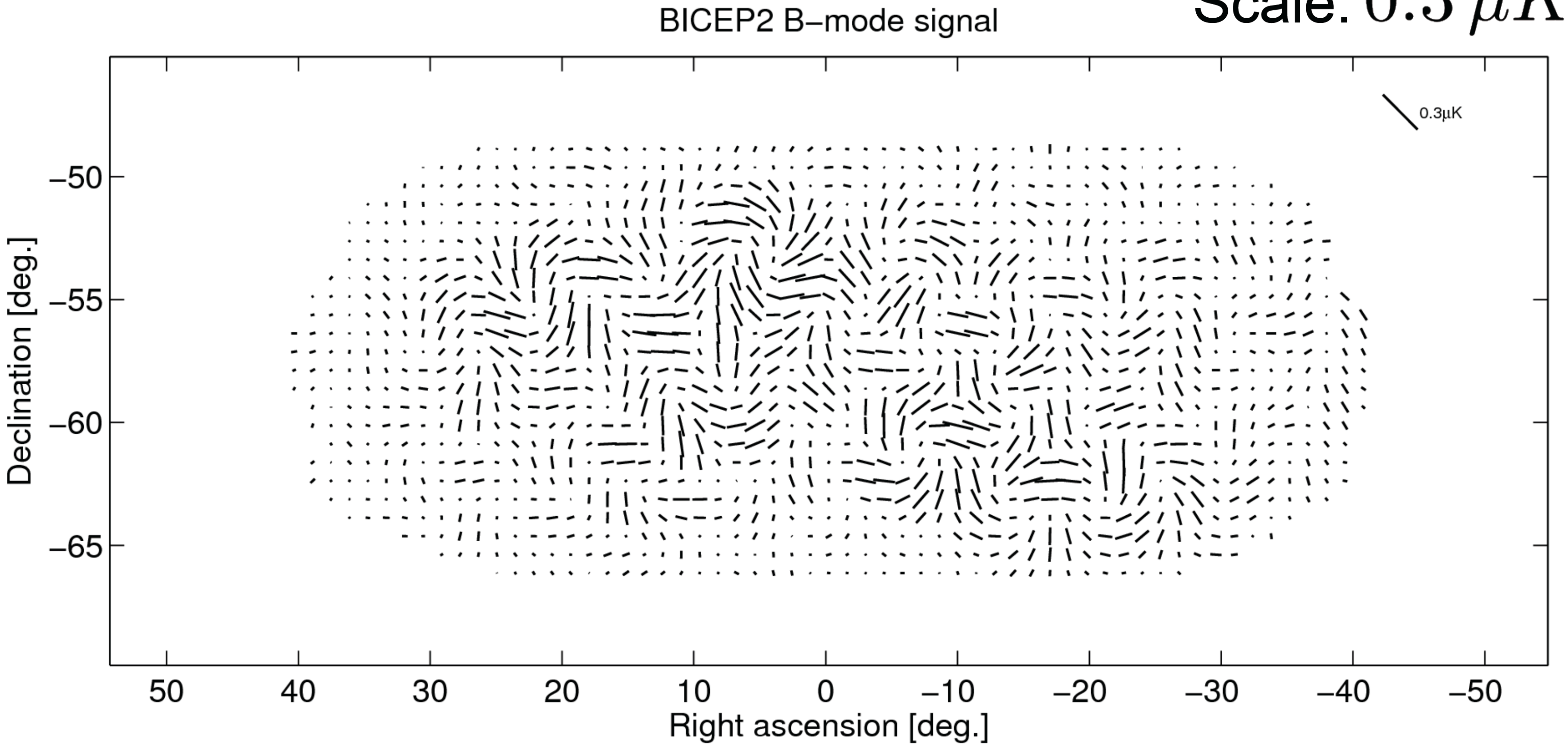
B-mode Contribution

Scale: $1.7\,\mu K$

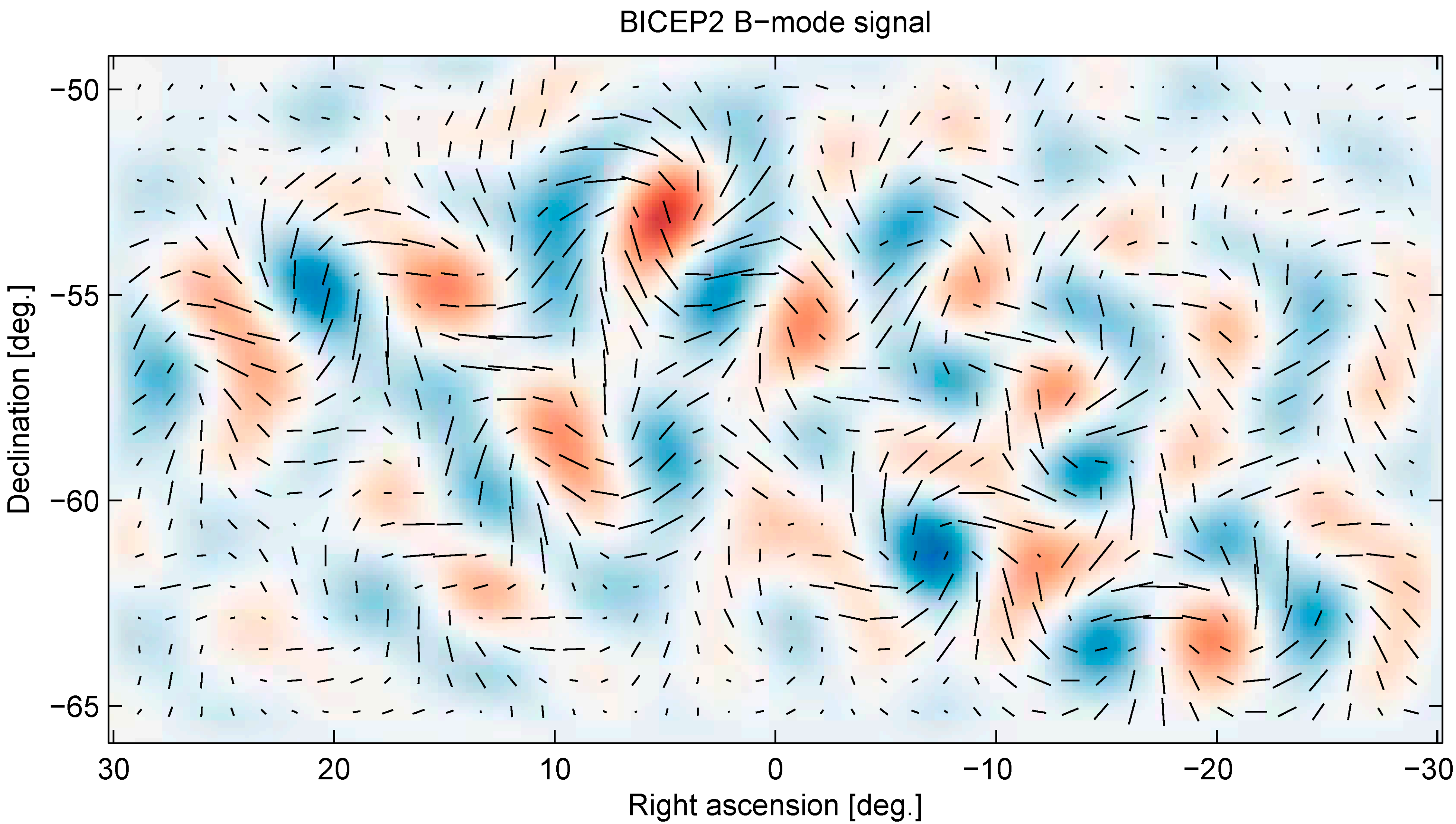


B-mode Contribution

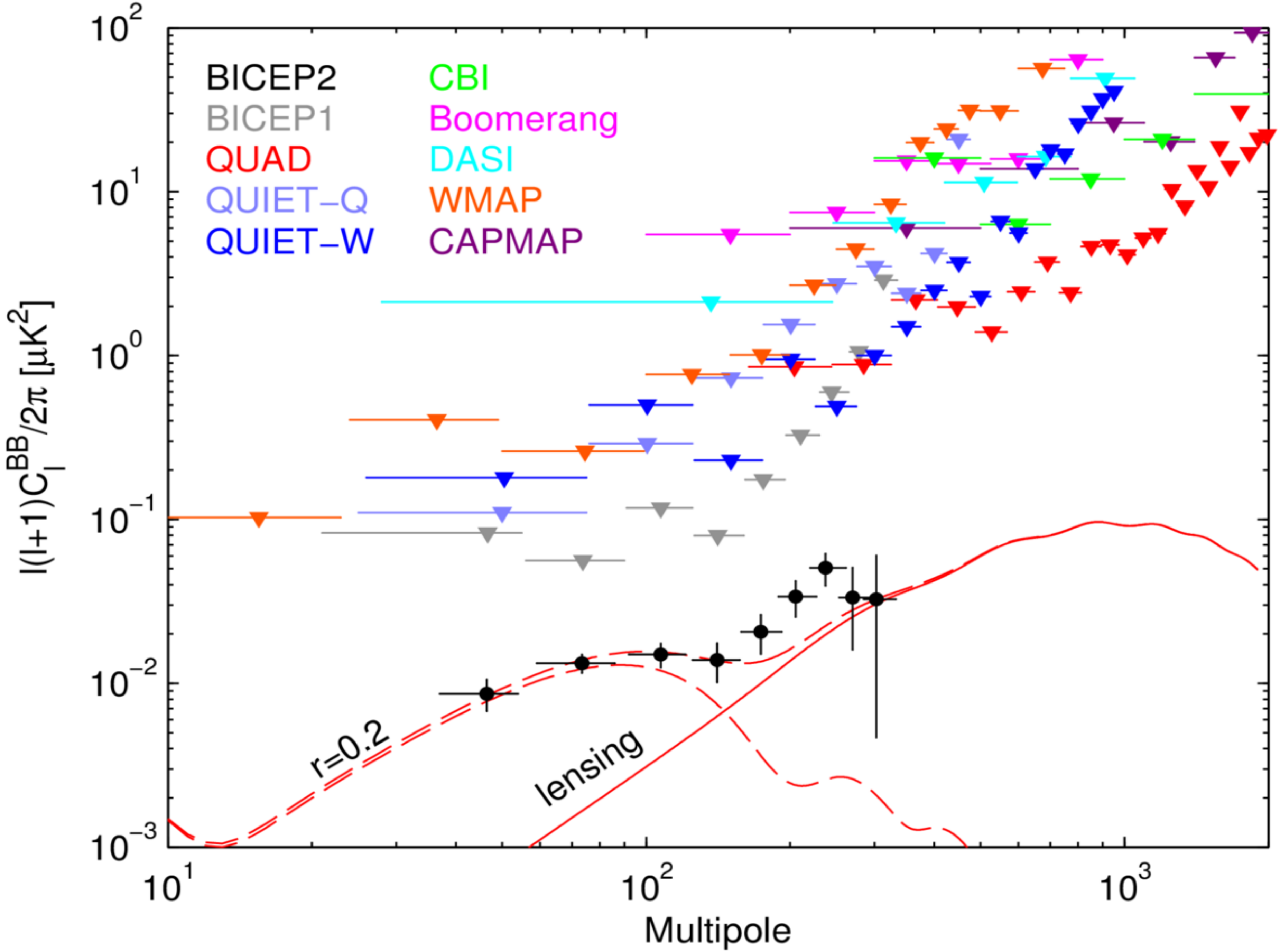
Scale: $0.3\,\mu K$



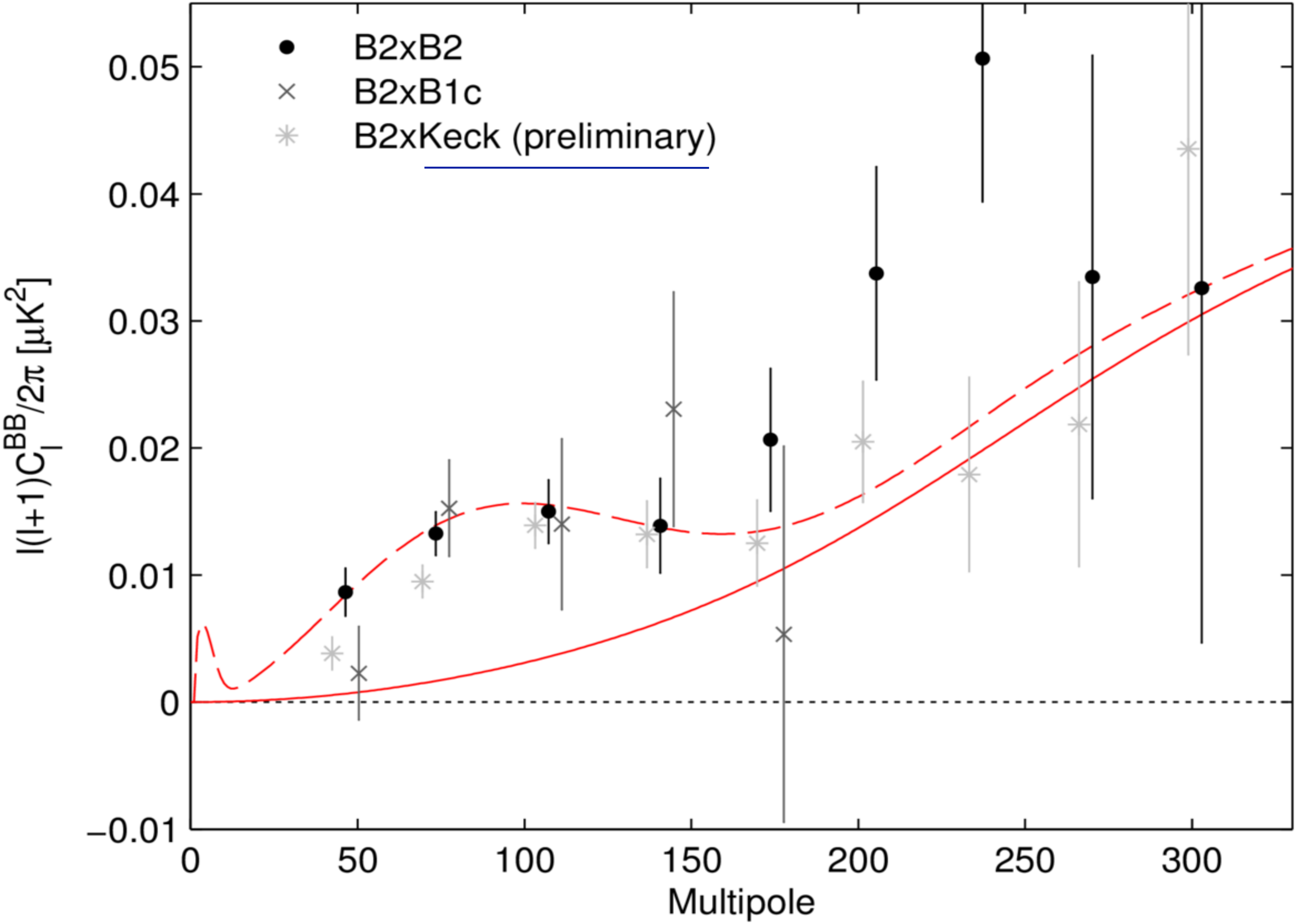
Measurements BICEP2

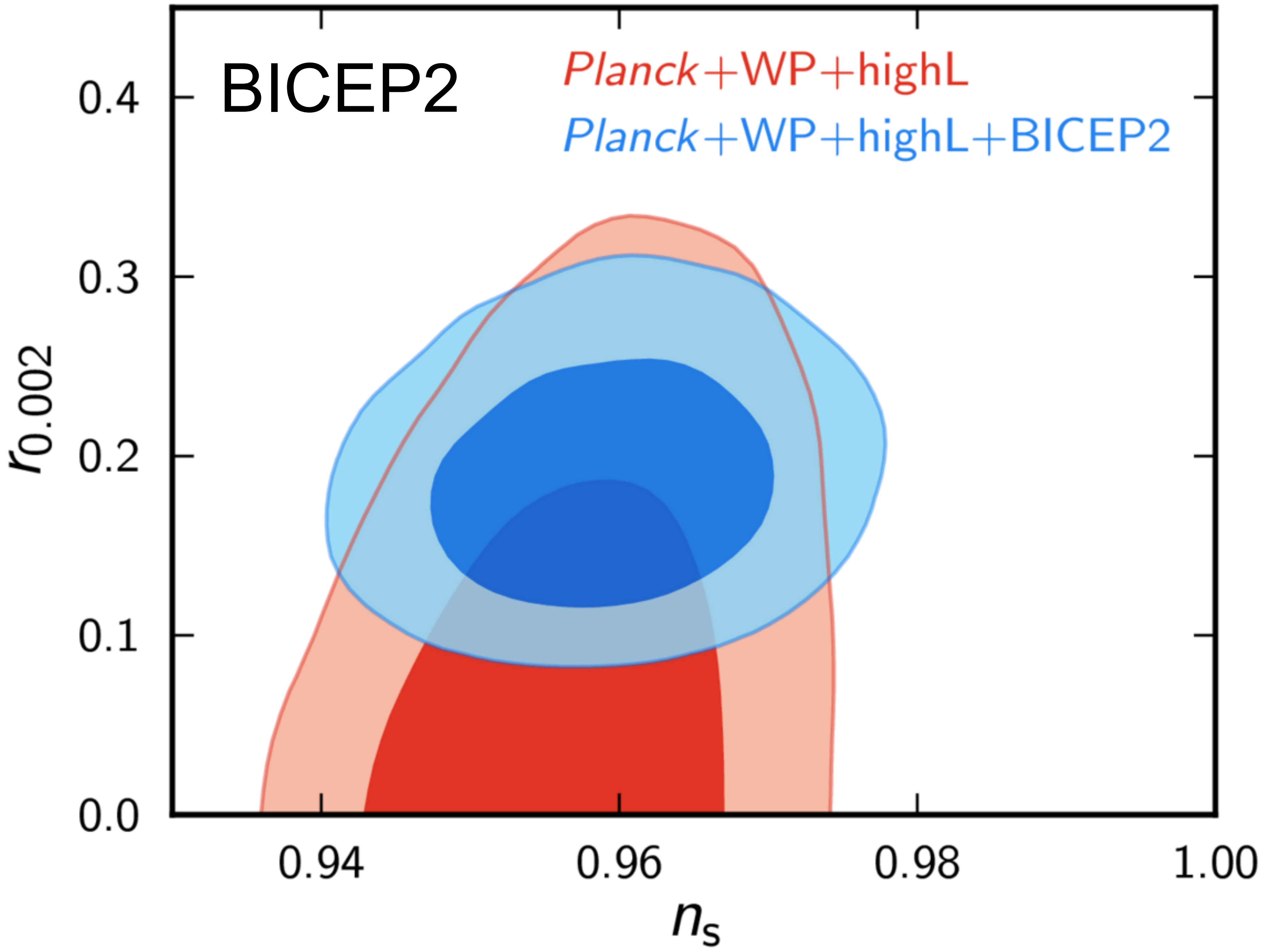


Measurements BICEP2

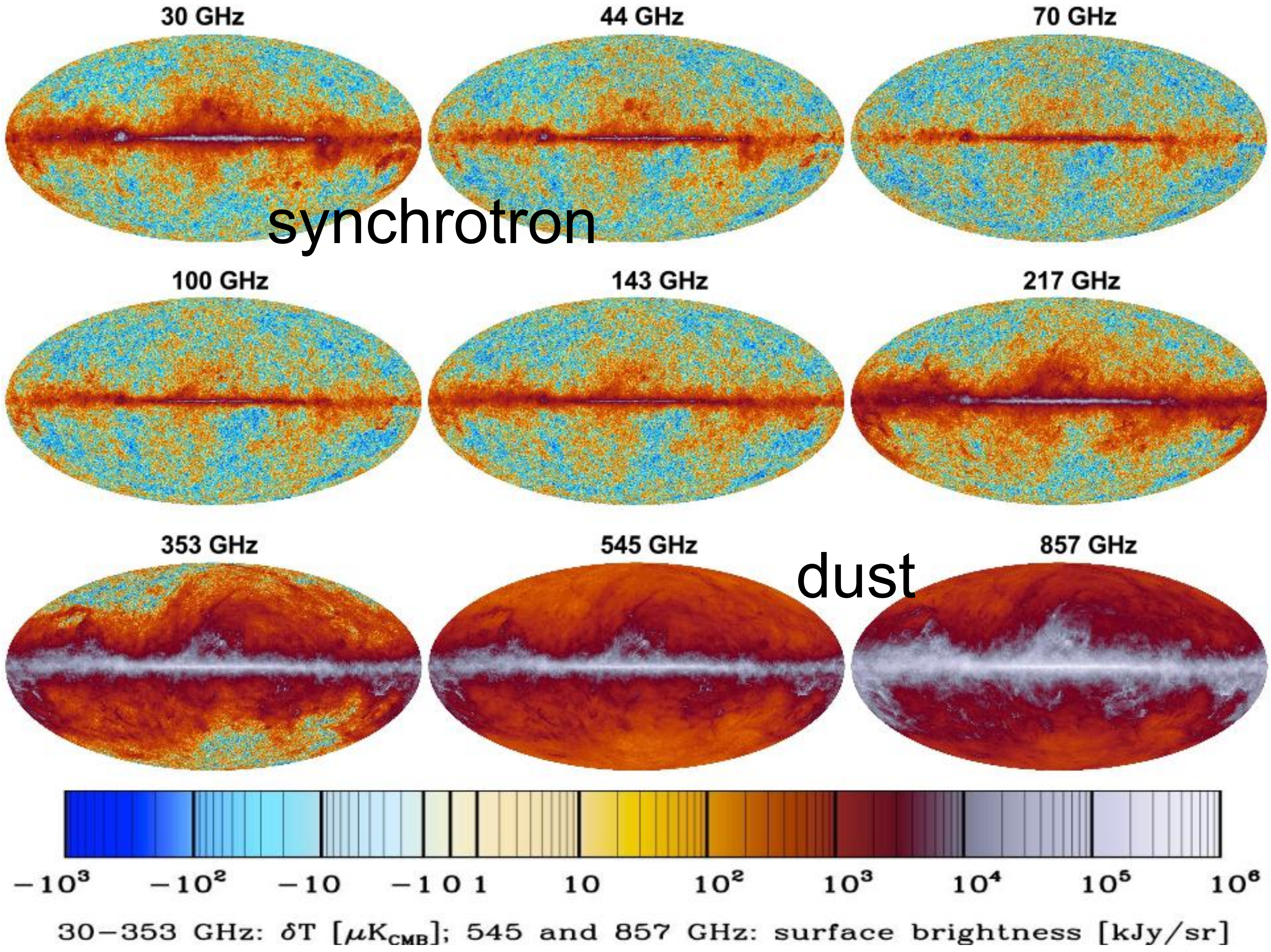


Measurements BICEP2

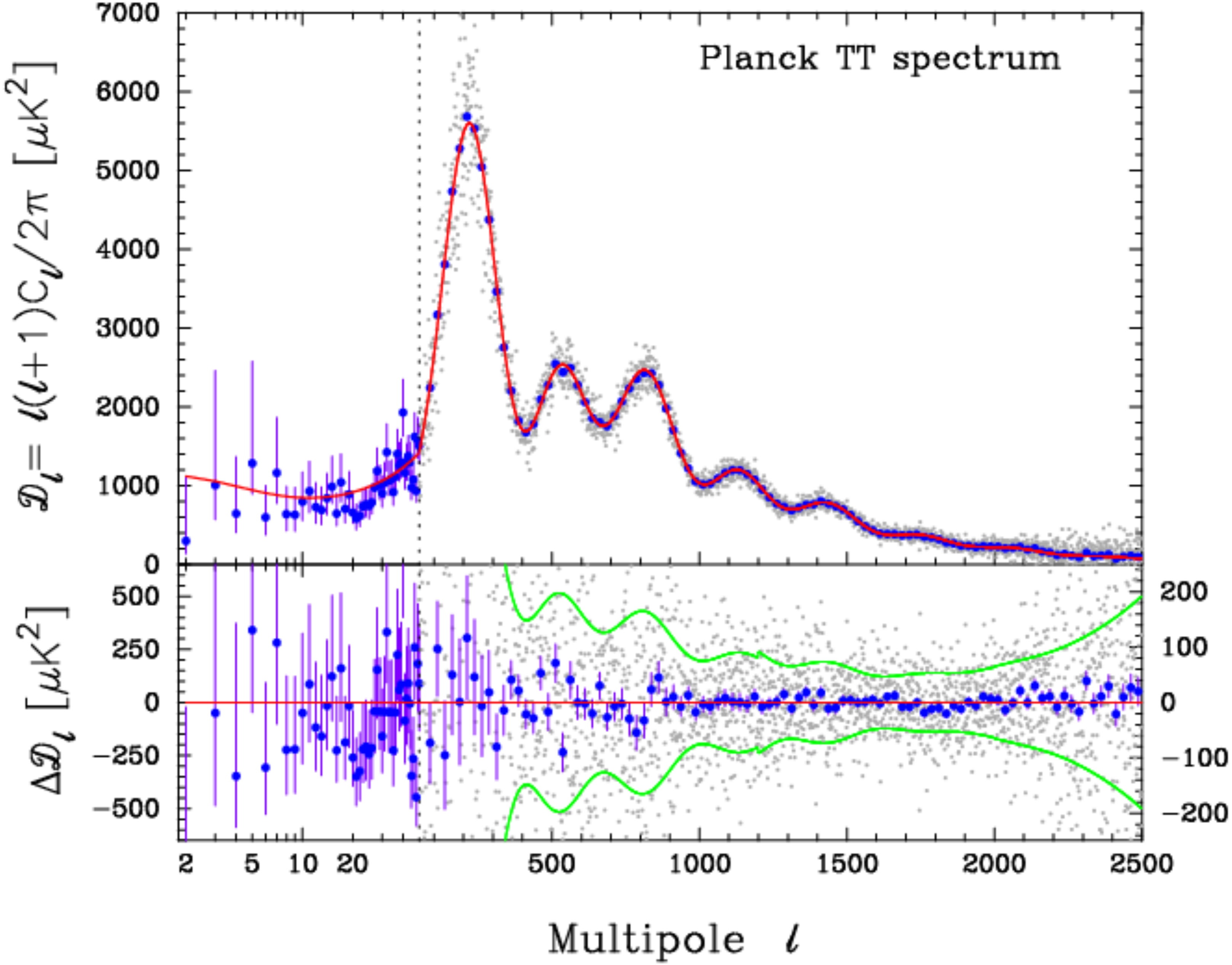


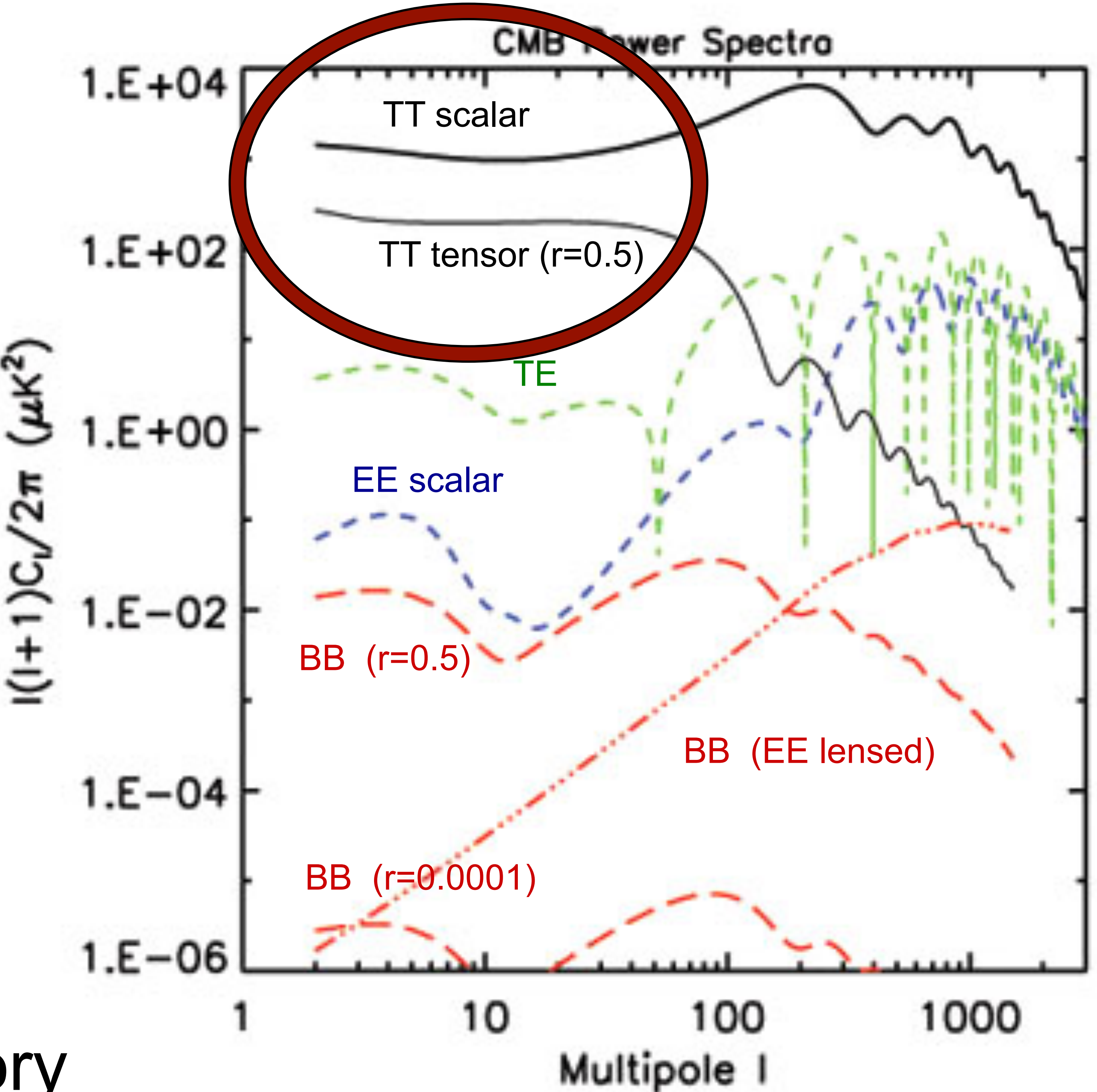

BICEP2
Planck+WP+highL
Planck+WP+highL+BICEP2
0.4
0.3
0.2
0.1
0.0
$r_{0.002}$
0.94
0.96
0.98
1.00
n_s

Could Planck confirm it?


30 GHz
44 GHz
70 GHz
synchrotron
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
dust
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

Planck TT @ intermediate scales

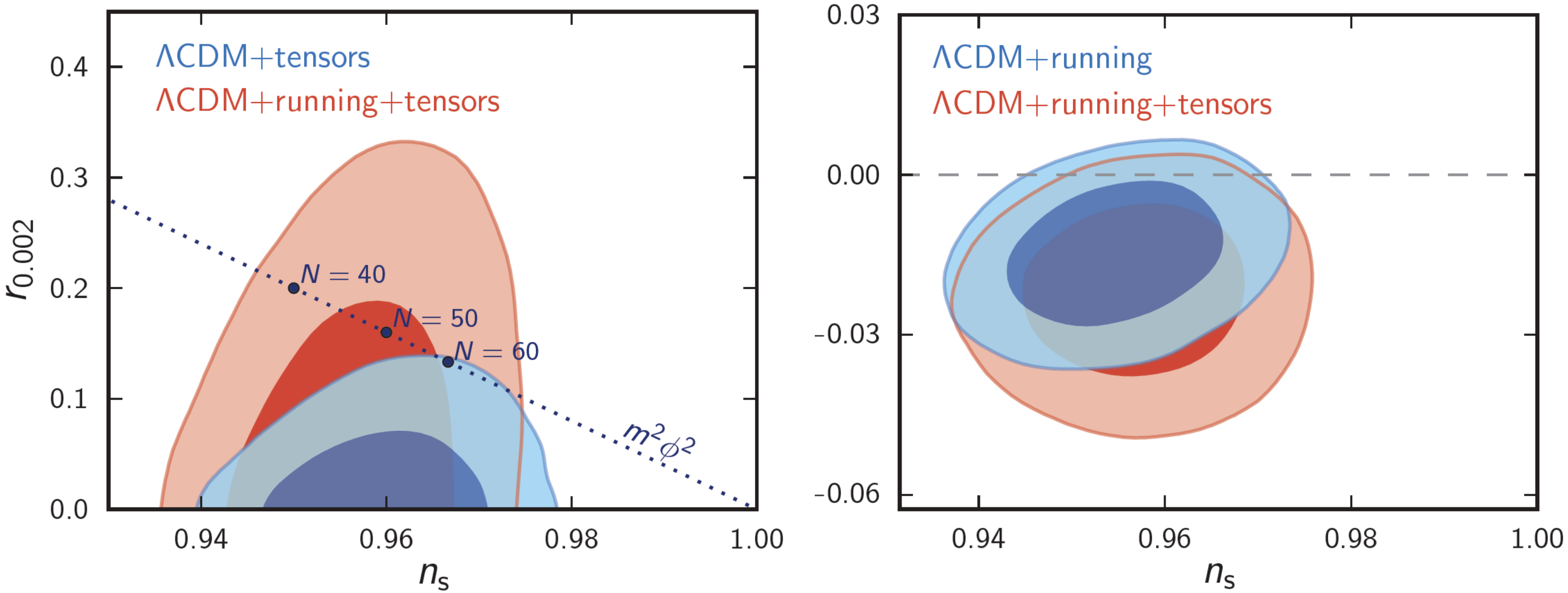



CMB Power Spectra
TT scalar
TT tensor (r=0.5)
TE
EE scalar
BB (r=0.5)
BB (EE lensed)
BB (r=0.0001)
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
1.E-06
1
10
100
1000
Multipole l
l(l+1)C_l/2π (μK²)

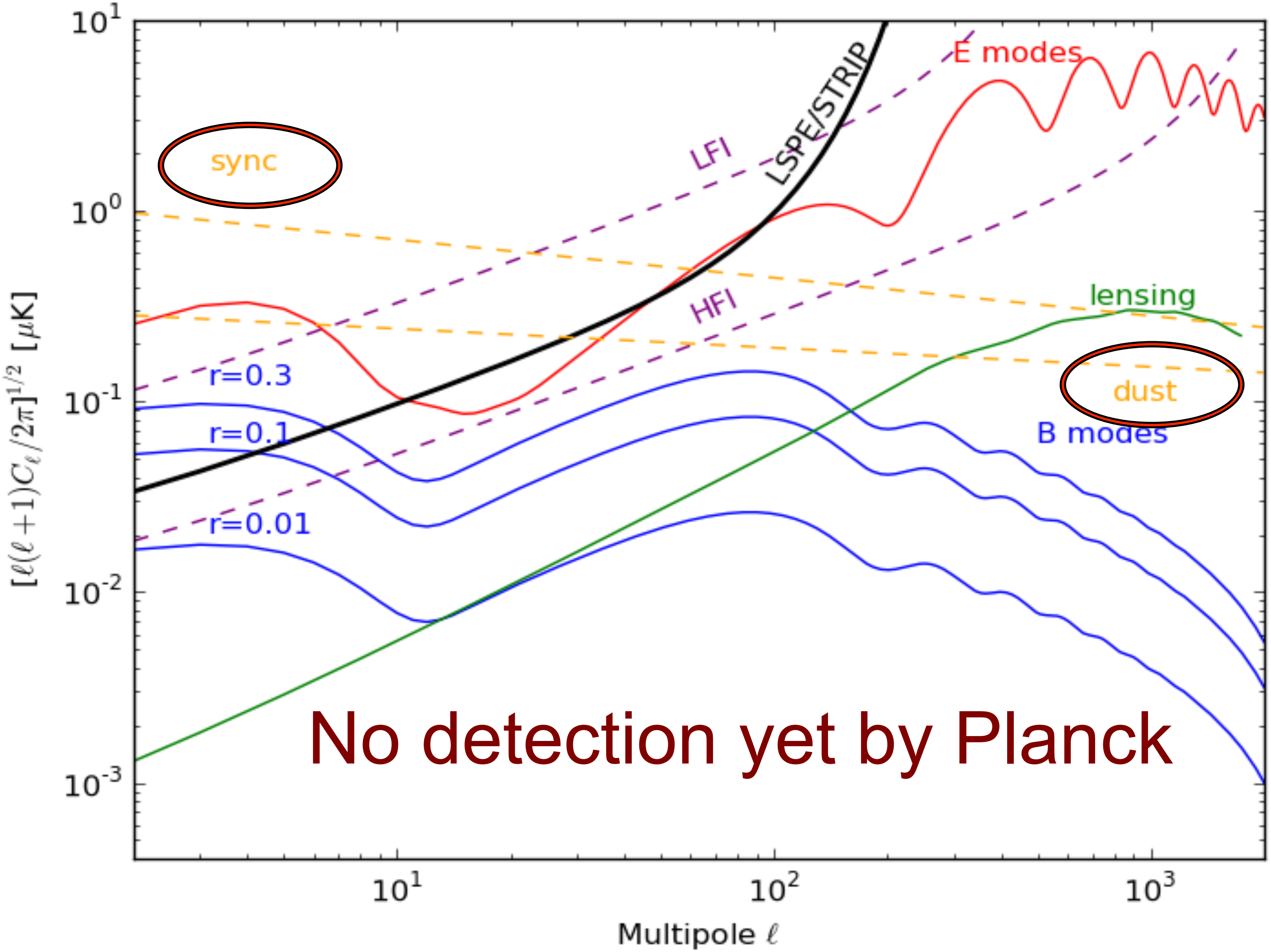
Theory

Could Planck confirm BICEP results?

- Some tension Planck: r < 0.11 at 95% c.l.
- Assumes 6-parameter ΛCDM model
- Degeneracies between parameters
- If add running tilt then tensors are relaxed



Planck sensitivity in LFI & HFI



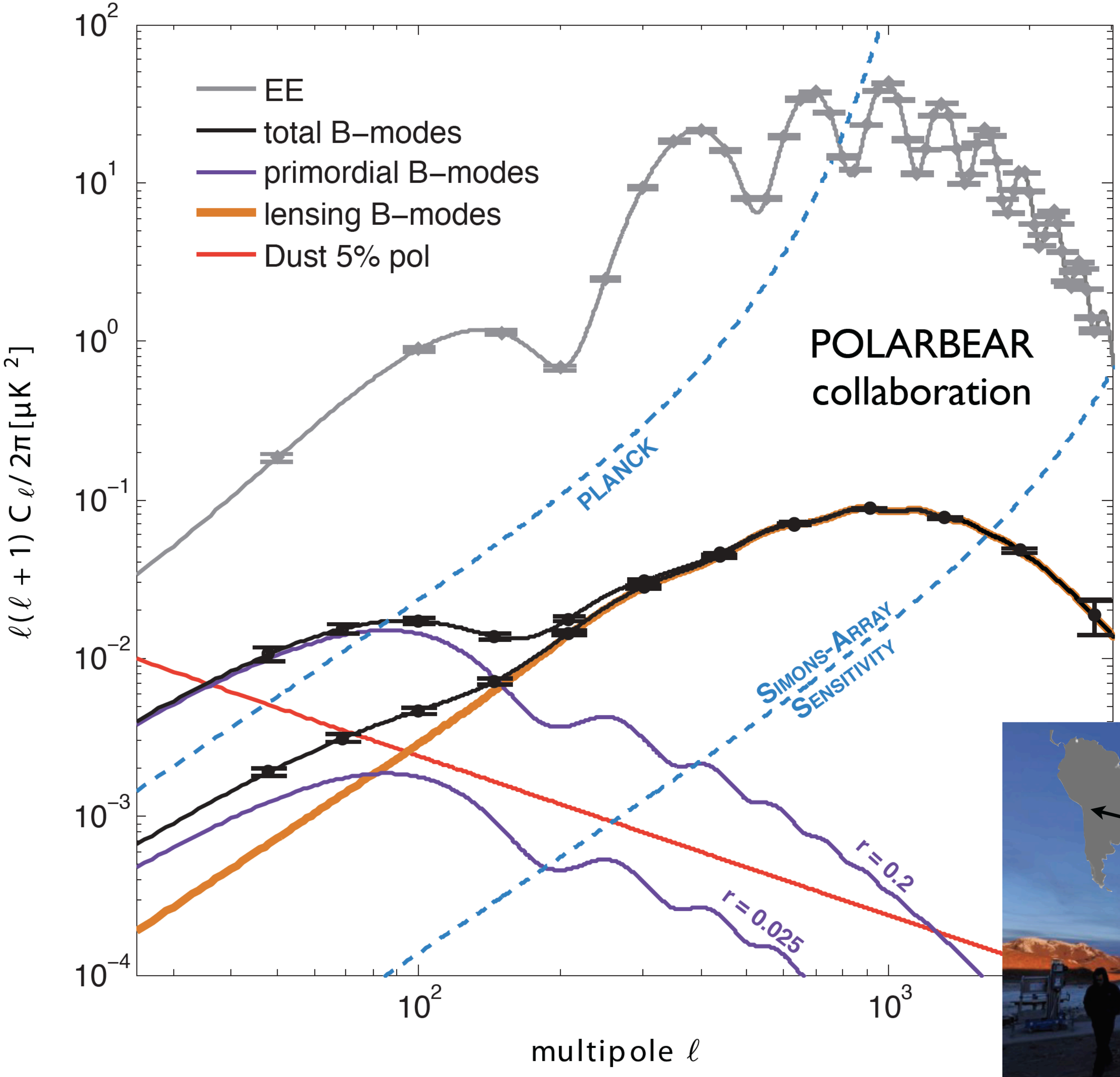
No detection yet by Planck

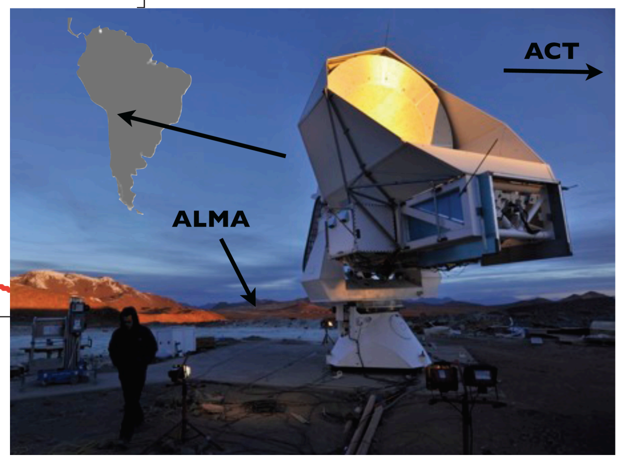
Other Experiments coming on line

Chile(Atacama): PolarBear, ACTpol

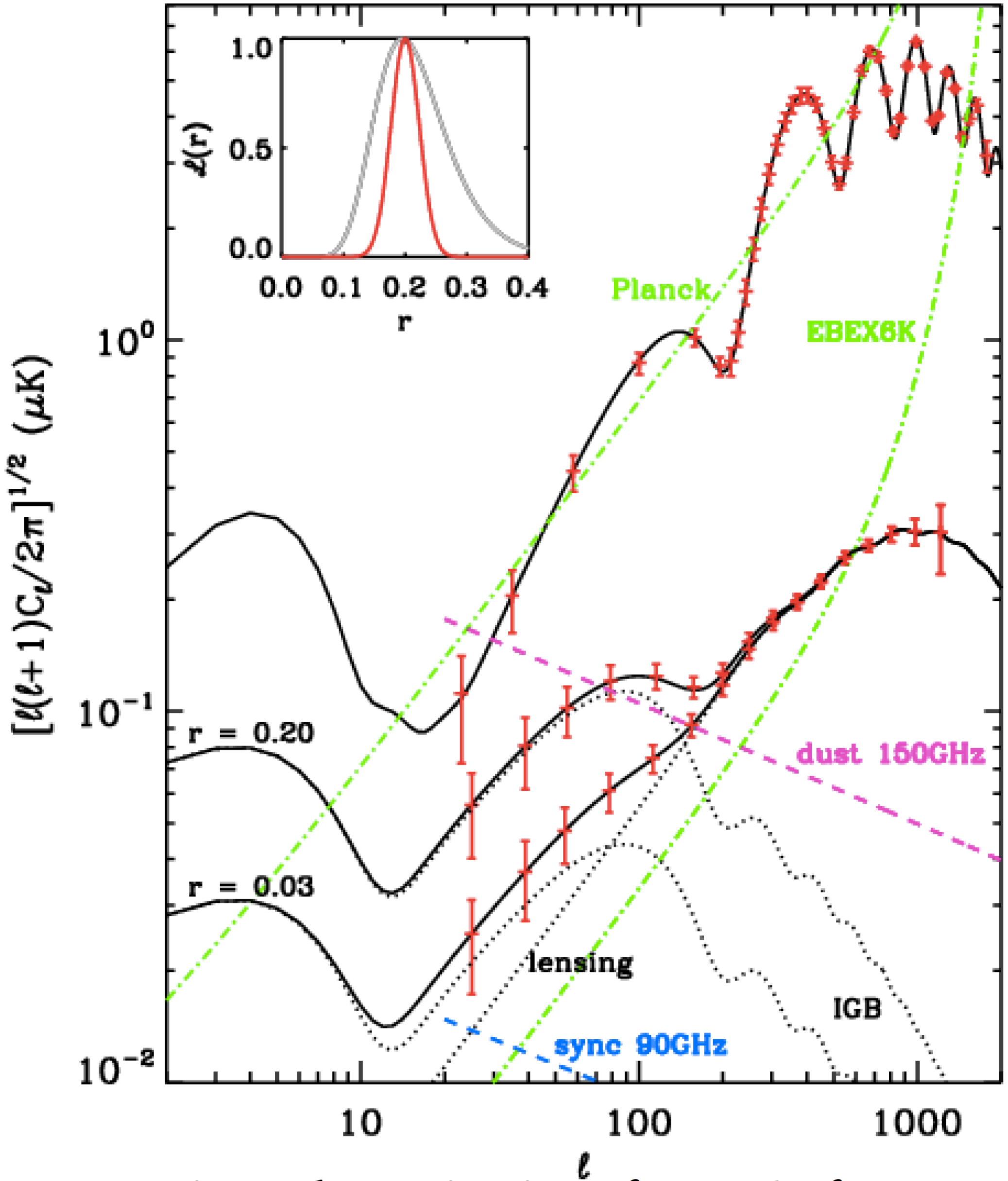
Baloon @ South Pole: EBEX(6K)

Future experiments that may confirm BICEP



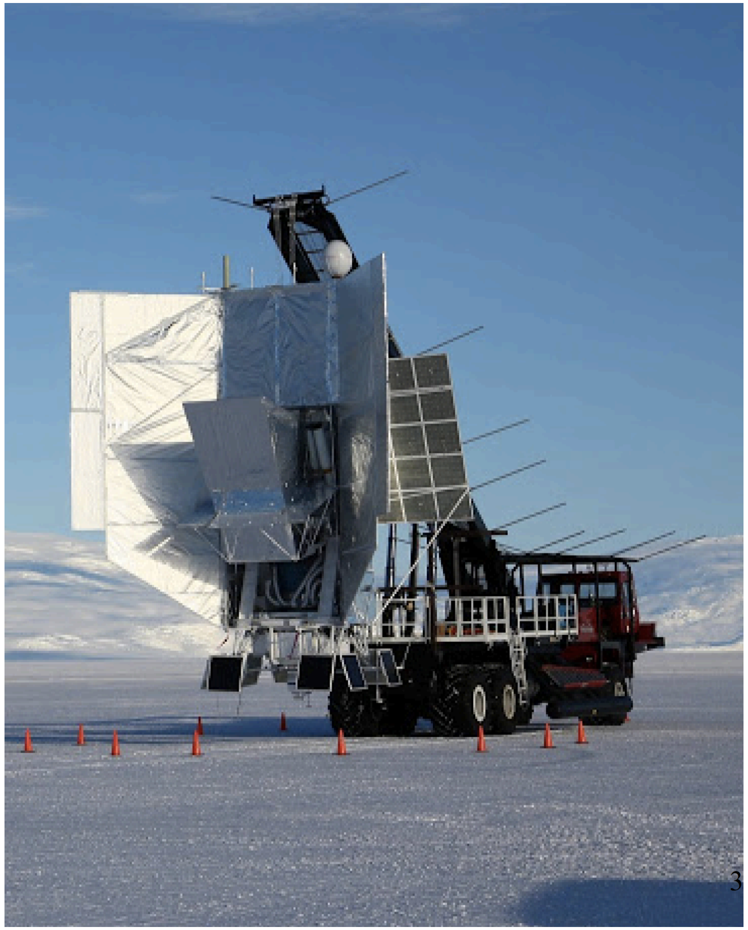


Future experiments that may confirm BICEP



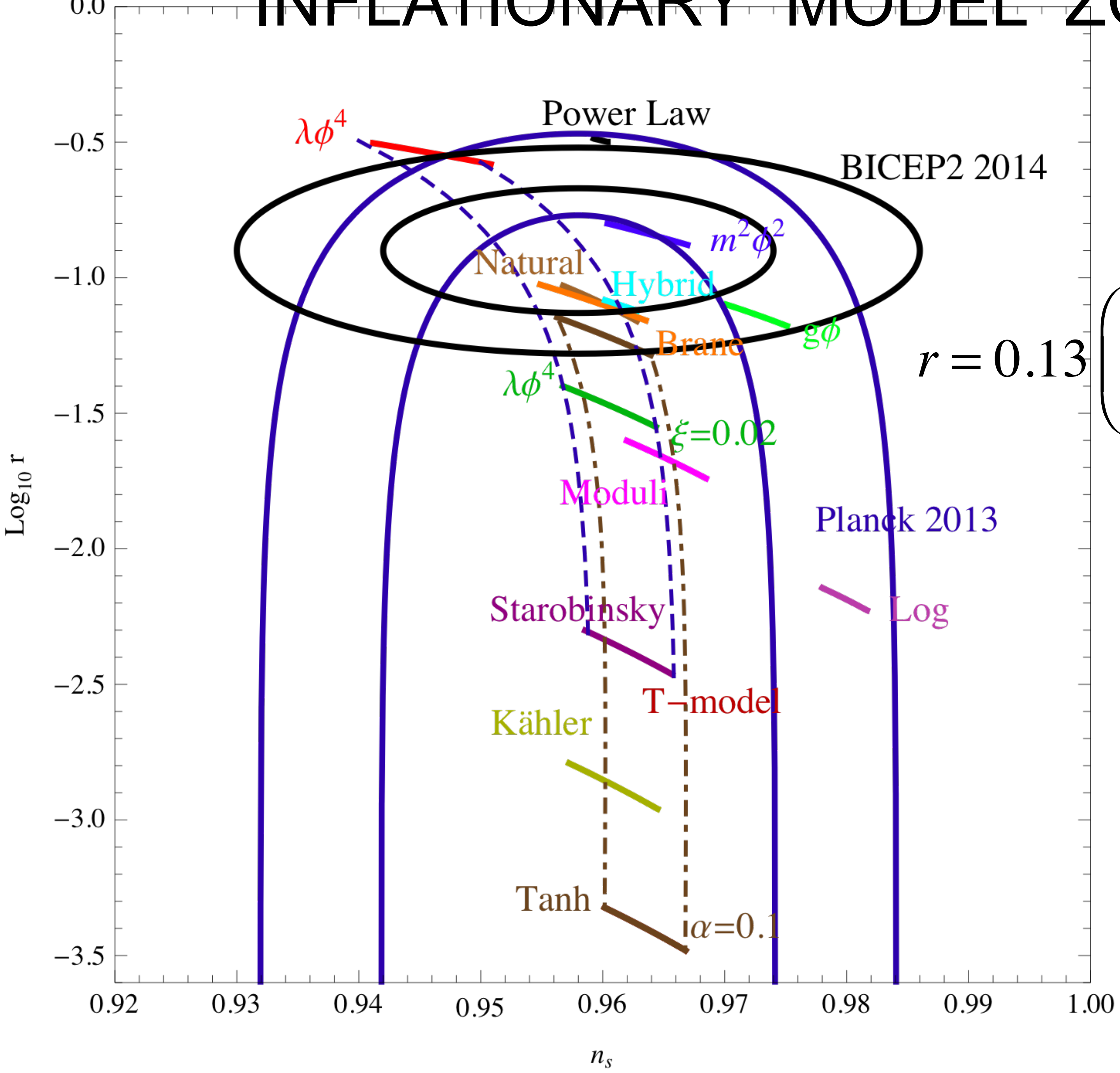
1-sigma determination of EBEX6K for a 18 day flight, for r = 0.2 and r=0.03

EBEX 6K



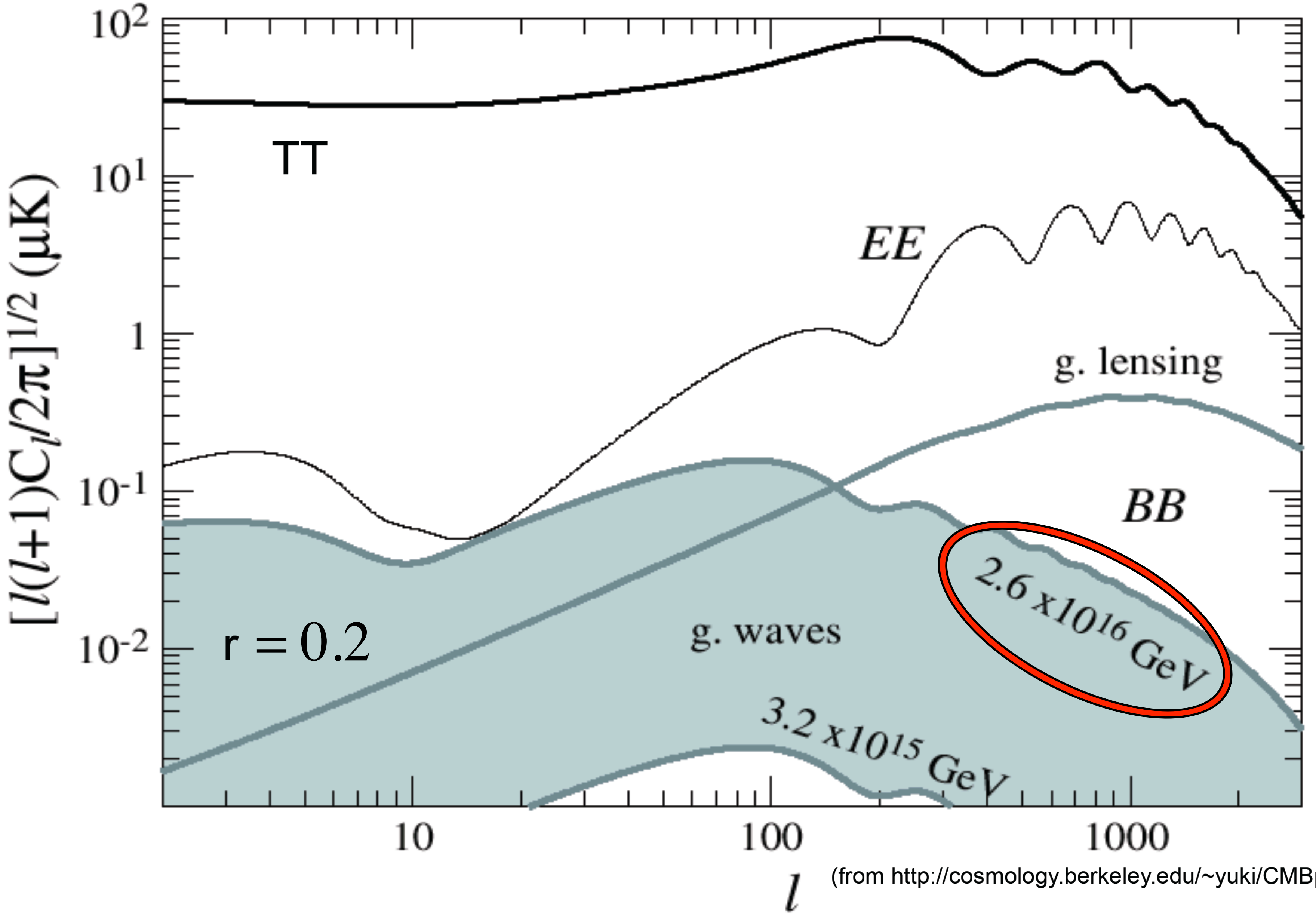
What is the energy scale of Inflation?

INFLATIONARY MODEL ZOO



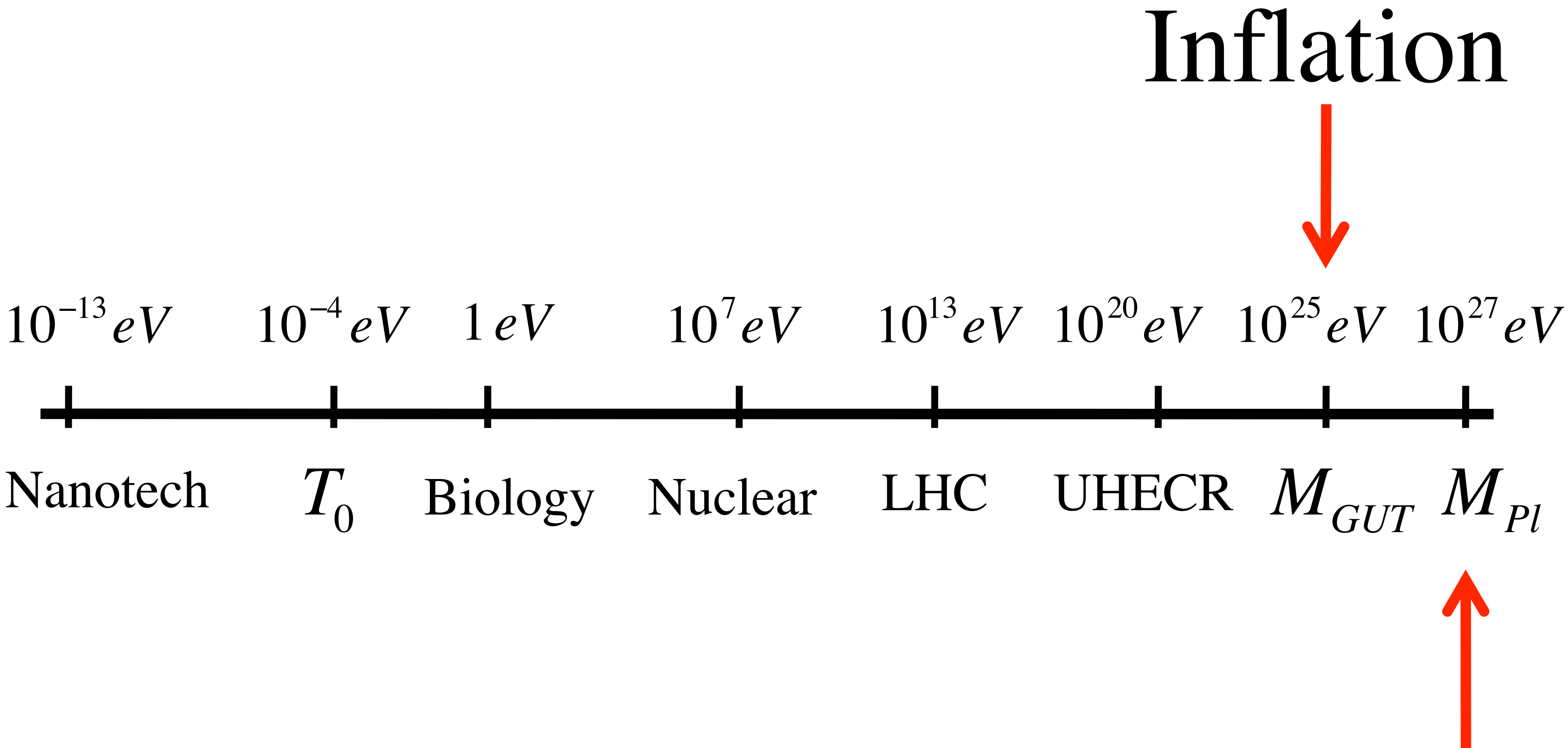
$$r = 0.13\left(\frac{M_{\mathrm{inf}}}{2\times10^{16}\,GeV}\right)^4$$

What is the energy scale of inflation?



(from http://cosmology.berkeley.edu/~yuki/CMBpol/(

What is the energy scale of inflation?

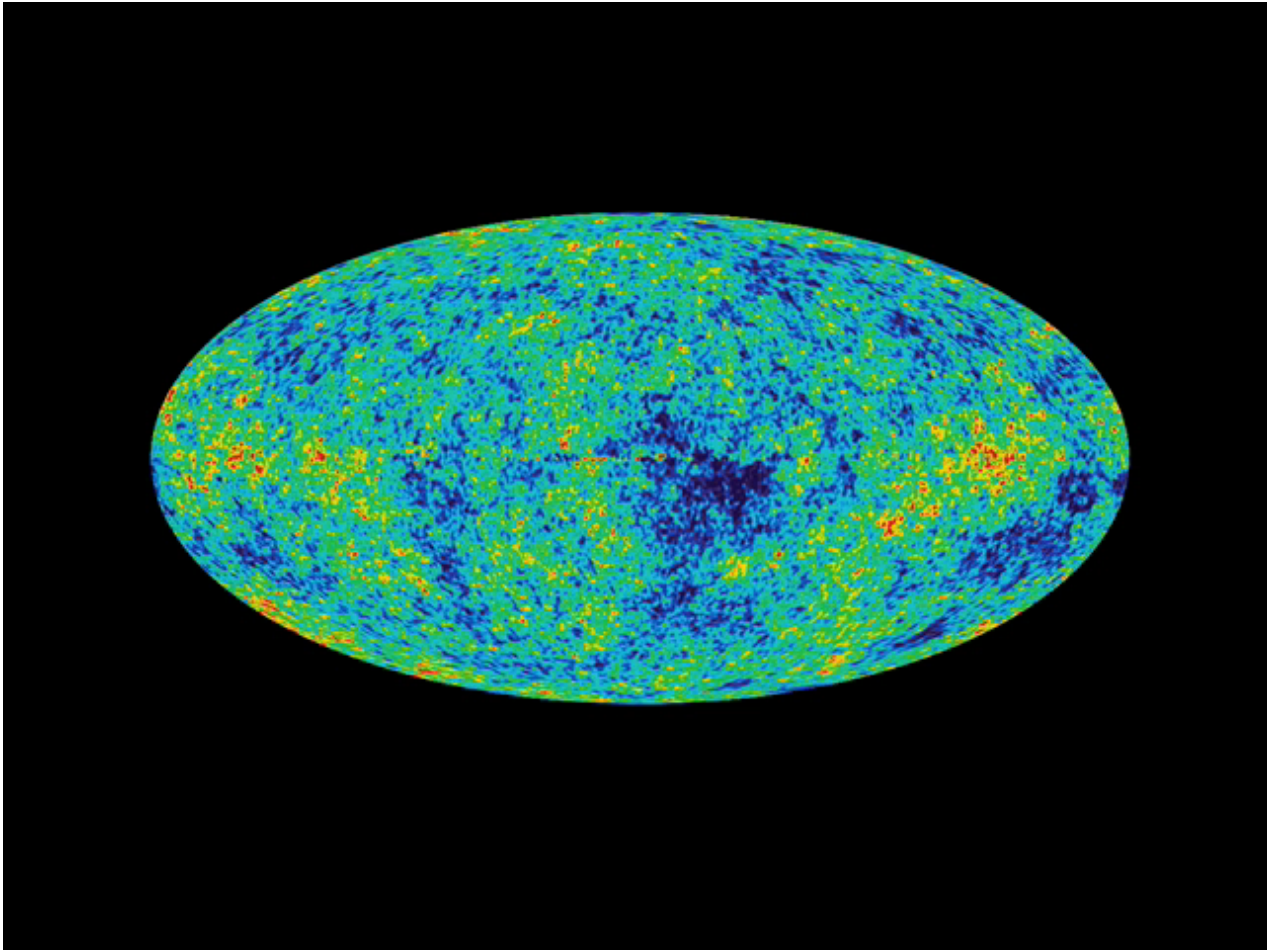


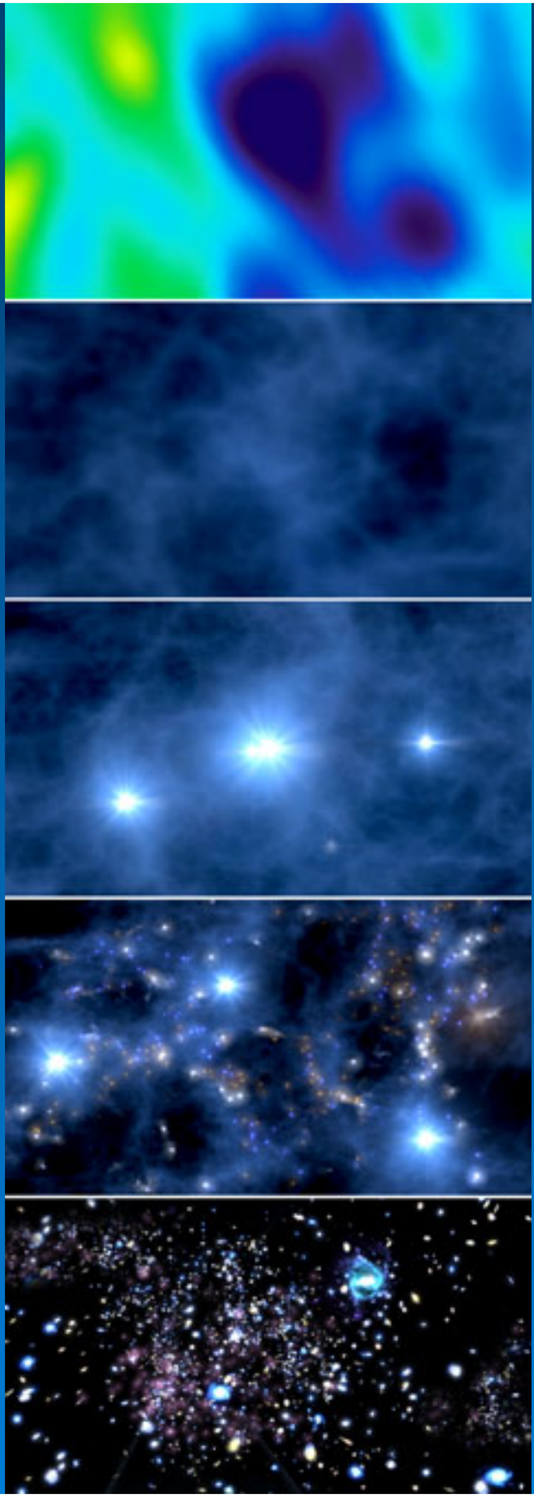
Is this the door to quantum gravity?

Cosmology opens way to Fundamental Physics!

Inflation and fundamental physics

Structure Formation





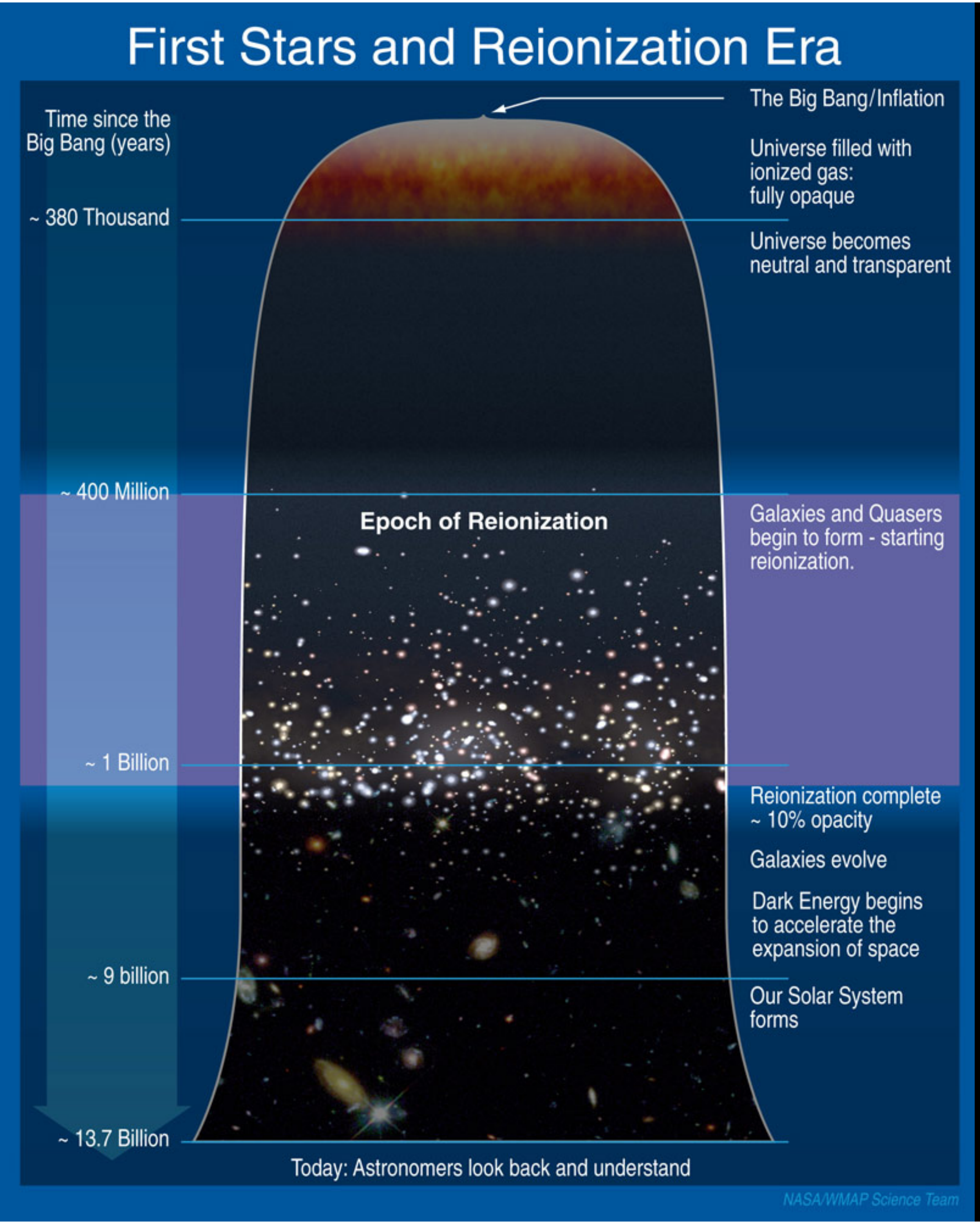
$z \approx 1100$ CMB Anisotropies

$z \approx 100$ Dark ages

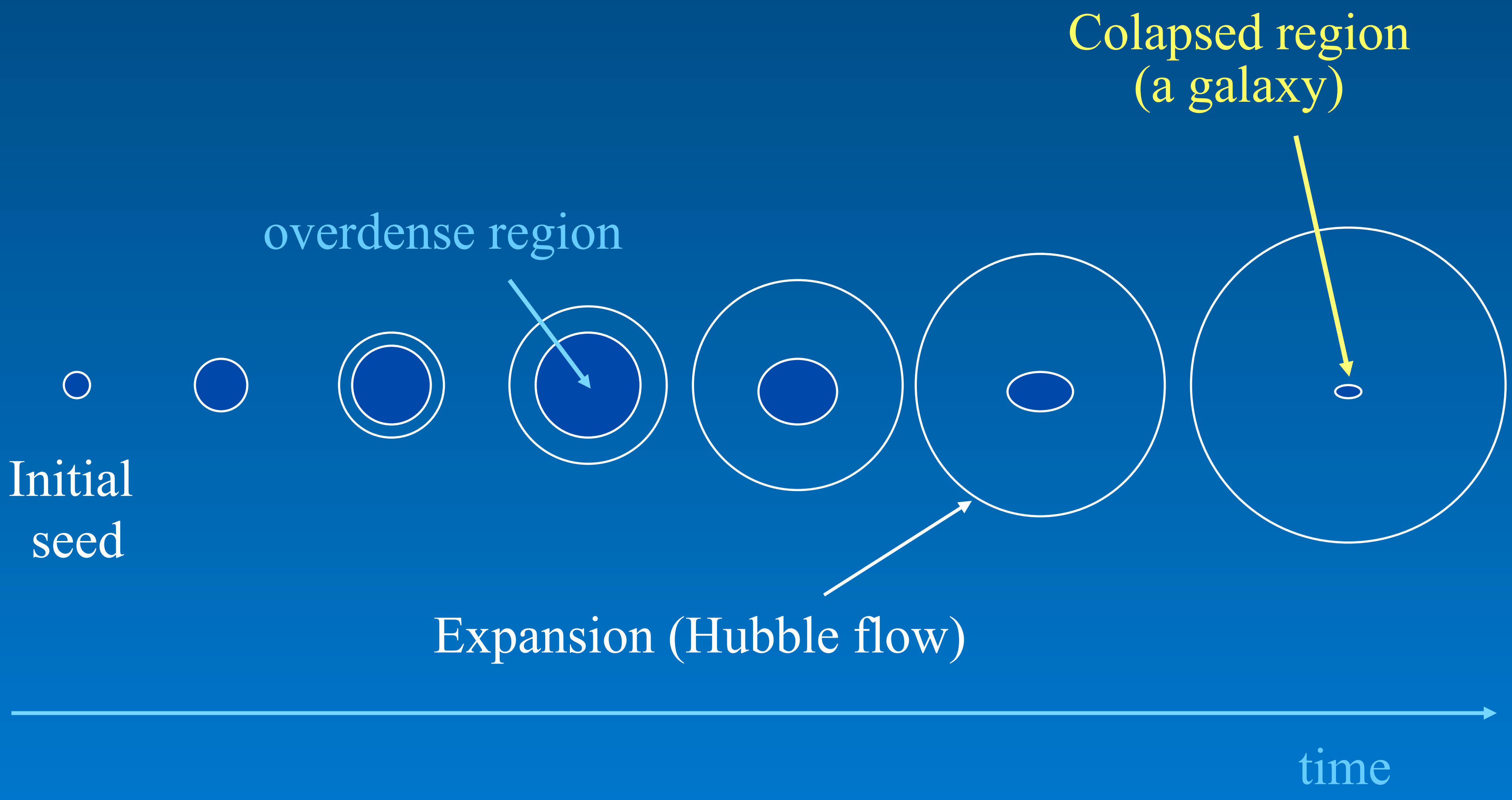
$z \approx 20$ First stars

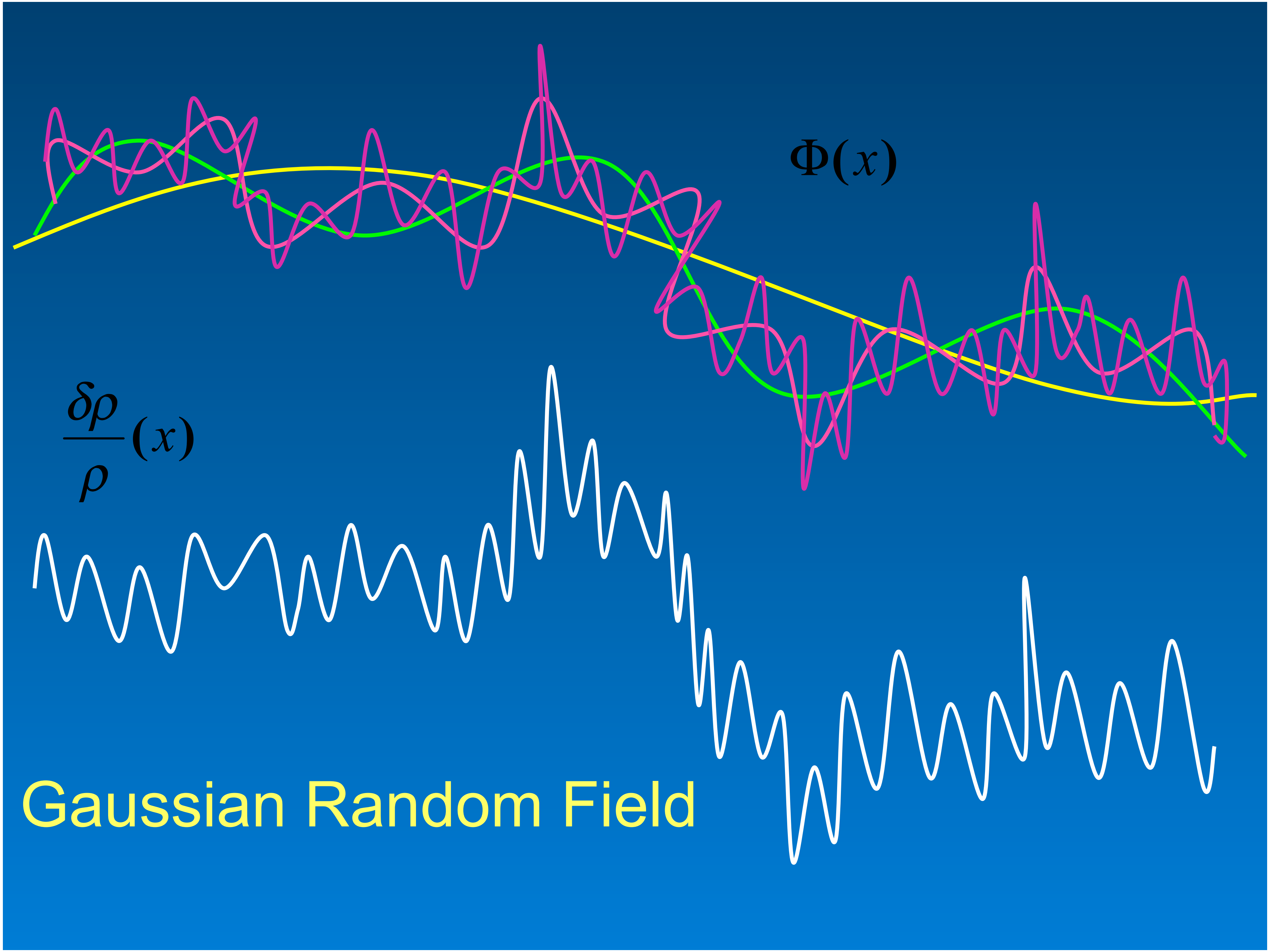
$z \approx 10$ Galaxies & Quasars

$z \approx 1$ Clusters & Superclusters


First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team

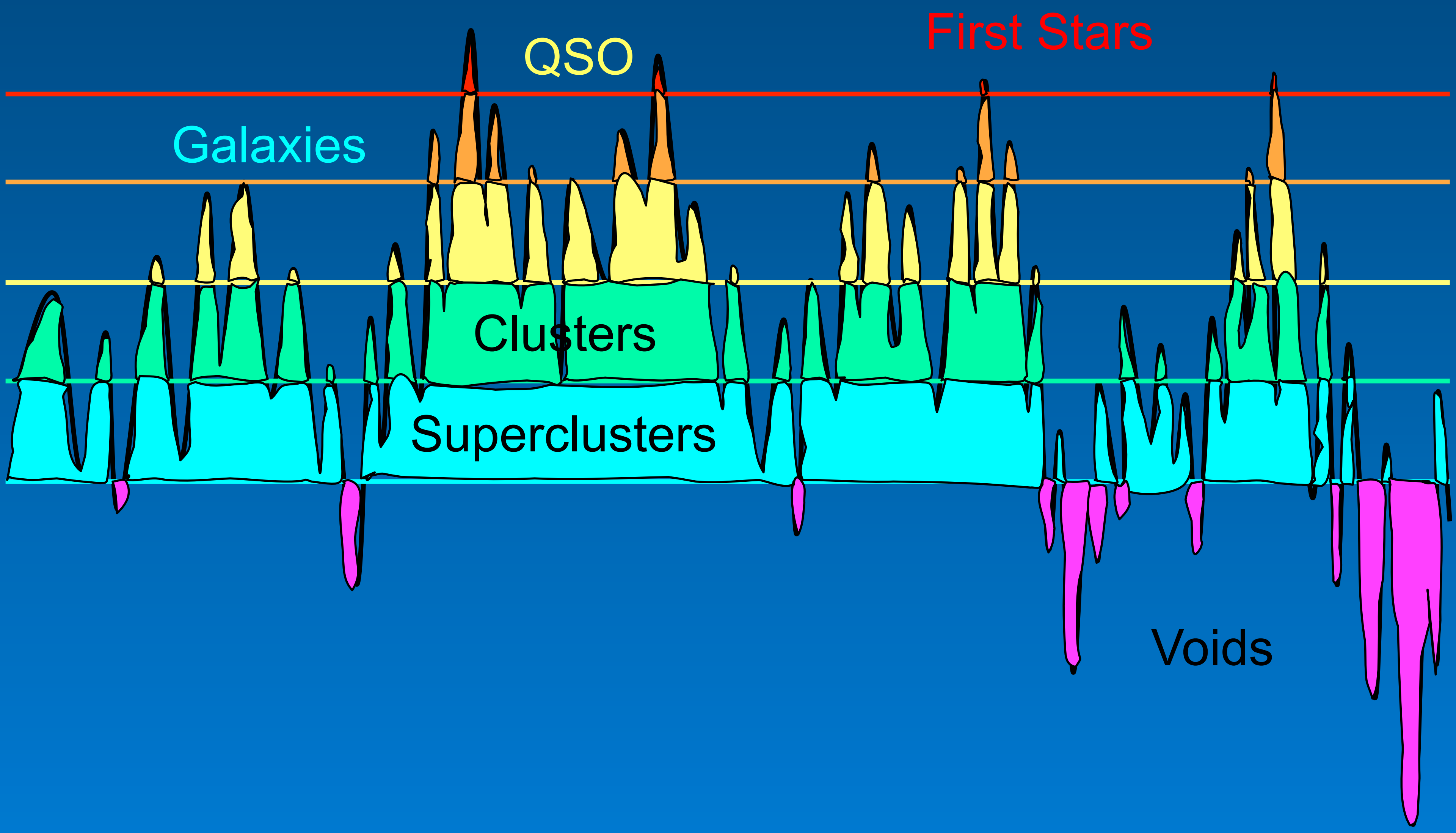
Gravitational collapse

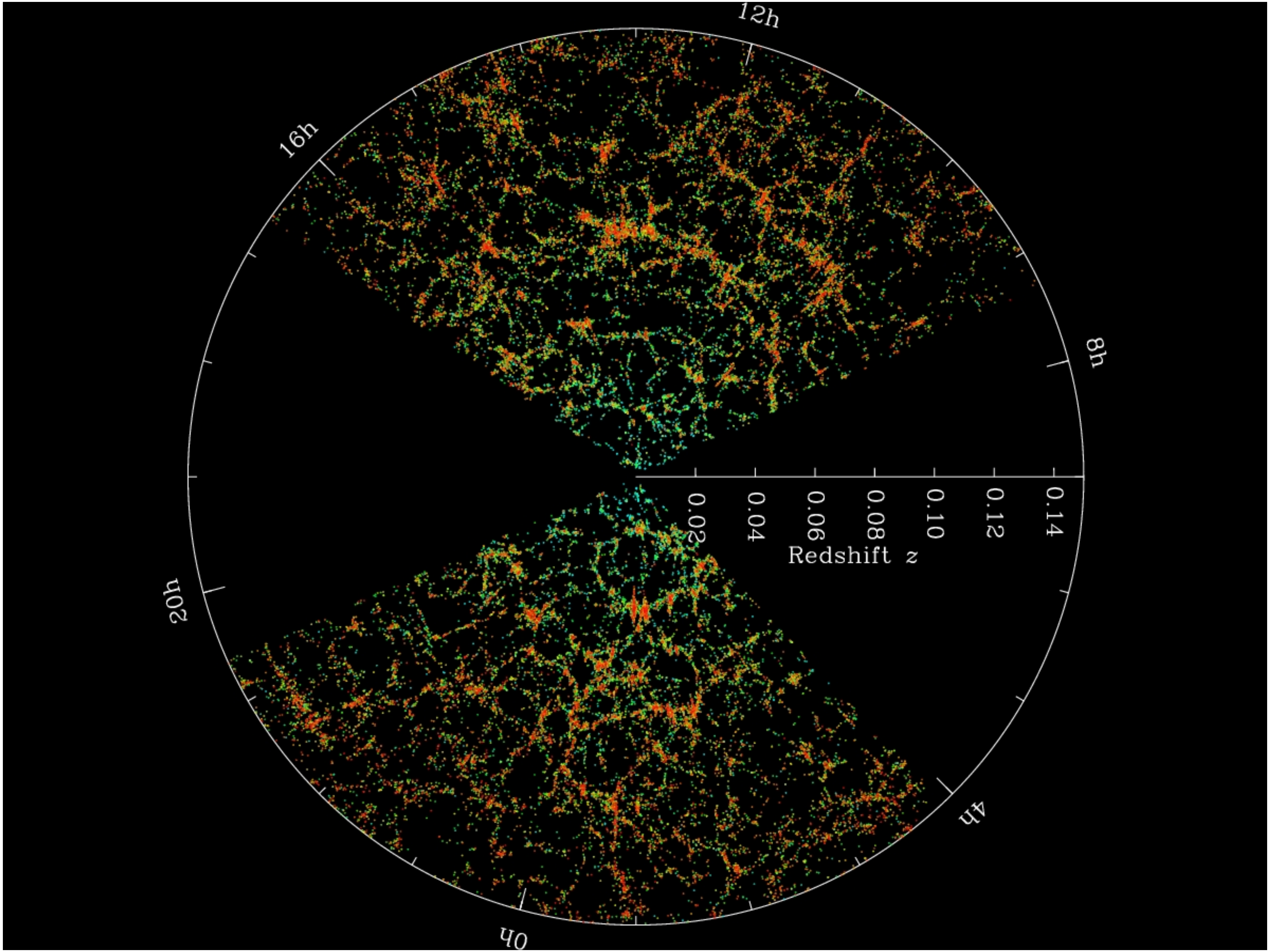




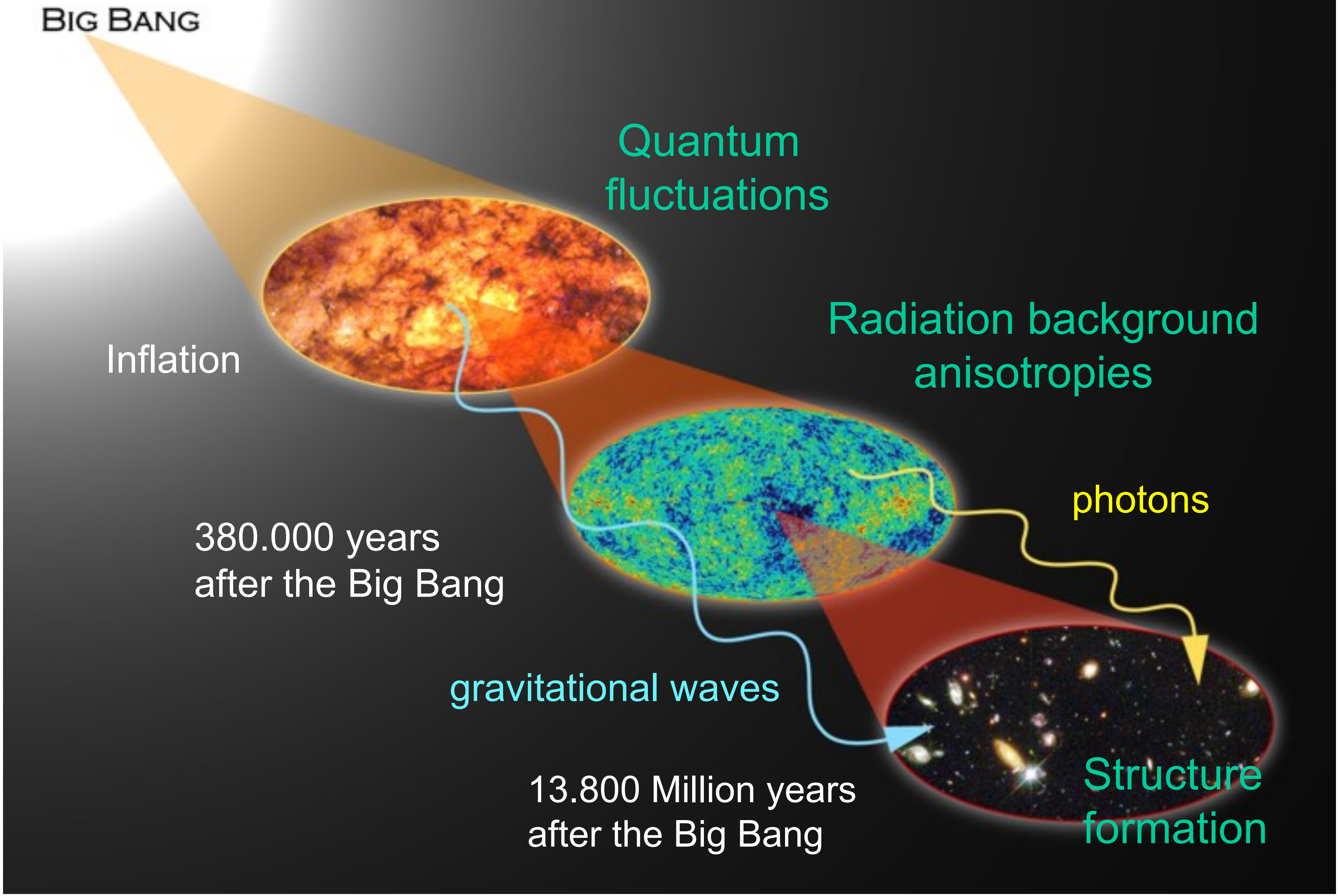
$\Phi(x)$
$\frac{\delta\rho}{\rho}(x)$
Gaussian Random Field

Density Contrast Thresholds




12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Predictions of Inflation



The Global structure of the universe