Cosmology Course
IMFP Winter Meeting 2018
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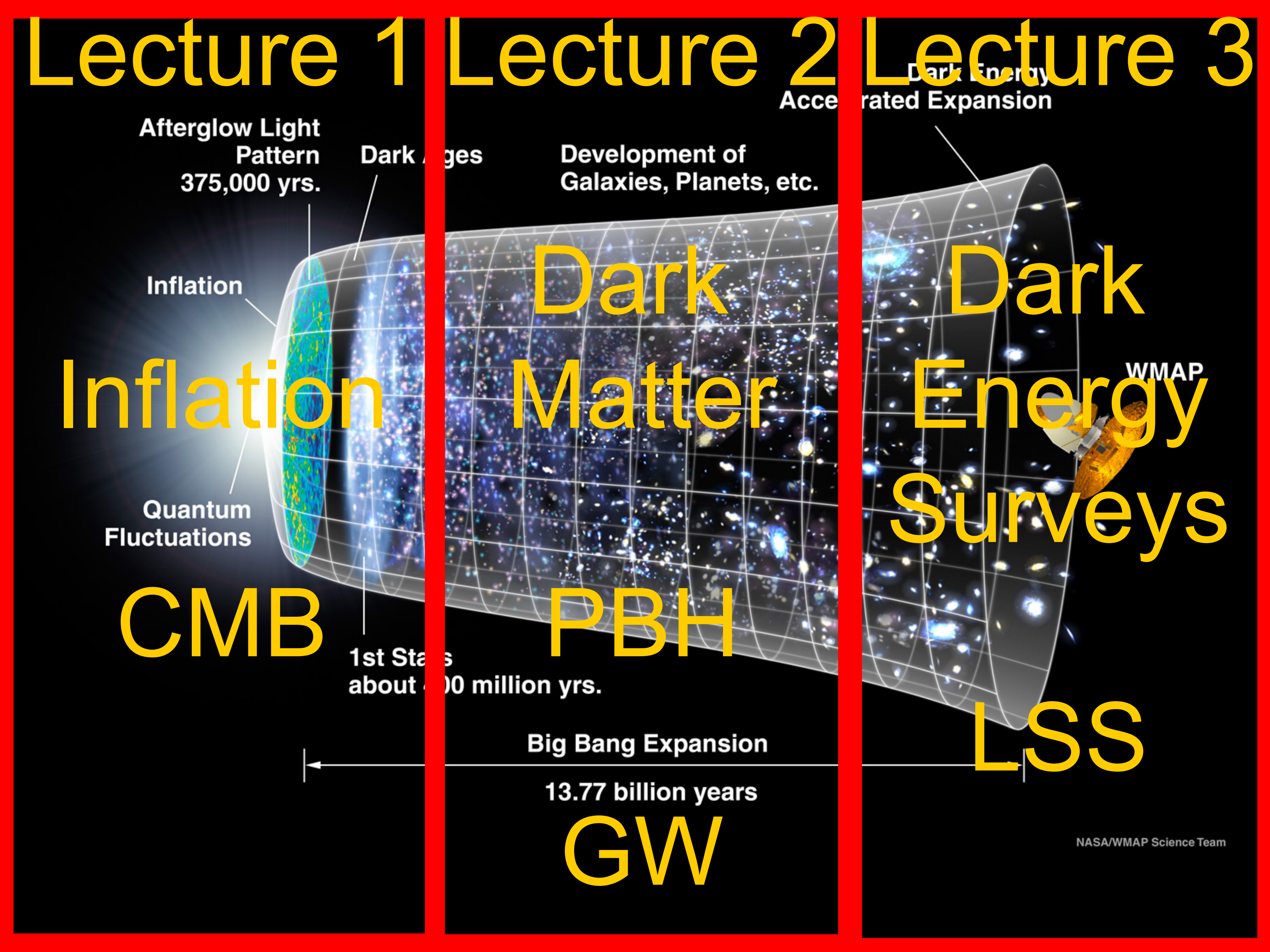

Lecture 1
Lecture 2
Lecture 3
Inflation
CMB
Dark
Matter
PBH
GW
Dark
Energy
Surveys
LSS
Afterglow Light
Pattern
375,000 yrs.
Inflation
Quantum
Fluctuations
Development of
Galaxies, Planets, etc.
WMAP
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Outline

Lecture 1

- Shortcomings of the Hot Big Bang
- The Inflationary Paradigm
- Homogeneous Scalar Field Dynamics
- Slow roll approximation
- Quantum Fluctuations in de Sitter
- CMB anisotropies (temp. + polar.)
- Planck 2017

Shortcomings of the Hot Big Bang

- The space-time structure of the observable Universe
  - Why is the Universe so close to spatial flatness?
  - Why is matter so homogeneously distributed on large scales?
- The origin of structures in the Universe
  - How did primordial spectrum of density perturbations originate?
- The origin of matter and radiation
  - Where does all the energy in the Universe come from?
  - How did the matter-antimatter asymmetry arise?
- The initial singularity
  - Did the Universe have a beginning?
  - What is the global structure of the Universe beyond our observable patch?

Einstein-Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \qquad ij + 00$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad 00$$

Energy density conservation

$$D_\mu T^\mu{}_\nu = 0 \Rightarrow \dot{\rho}(t) + 3\frac{\dot{a}}{a}(\rho(t) + p(t)) = 0$$

$$p(t) = w\rho(t)$$ barotropic fluid

Time evolution of density params

$$x \equiv \Omega_M(a) = \frac{8\pi G\, \rho_M(a)}{3H^2(a)} = \frac{\Omega_M}{\Omega_M + \Omega_K a + \Omega_\Lambda a^3}$$

$$y \equiv \Omega_\Lambda(a) = \frac{\Lambda}{3H^2(a)} = \frac{\Omega_\Lambda a^3}{\Omega_M + \Omega_K a + \Omega_\Lambda a^3}$$

Homogeneous system of eqs.

$$x' \equiv \frac{dx}{dN} = -x(1 - x + 2y)$$

$$y' \equiv \frac{dy}{dN} = +y(x + 2(1 - y))$$

$$N = \ln a$$

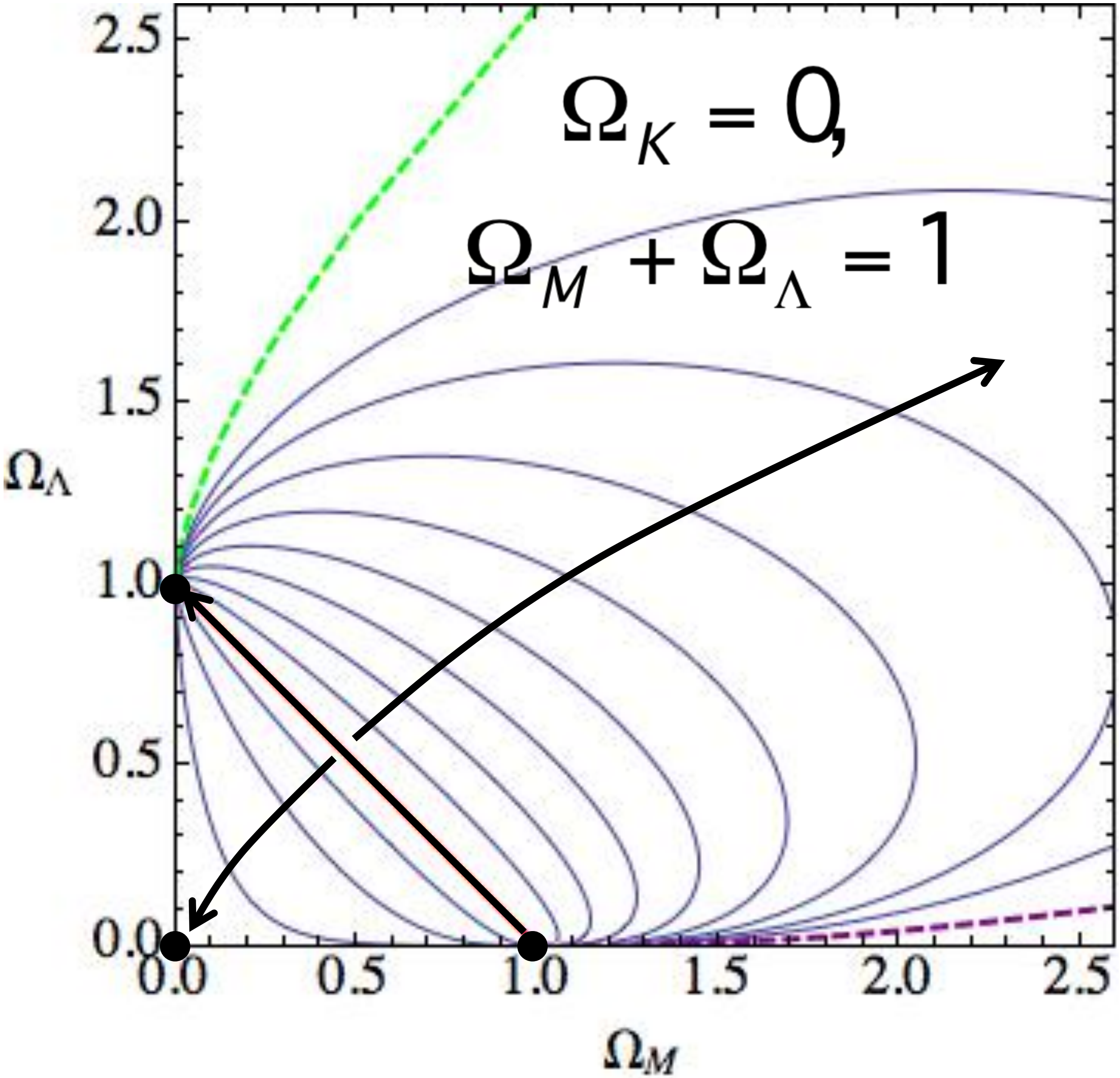
critical points

$$(x = 0, y = 0)$$

$$(x = 1, y = 0)$$

$$(x = 0, y = 1)$$

Flatness is unstable



critical points

$(x = 0, y = 0)$
$(x = 1, y = 0)$
$(x = 0, y = 1)$

Flatness

$$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}\ , \quad \Omega = \frac{8\pi G}{3H^2}\rho\ , \quad x \equiv \frac{\Omega - 1}{\Omega} = \frac{3K/8\pi G}{\rho a^2}$$

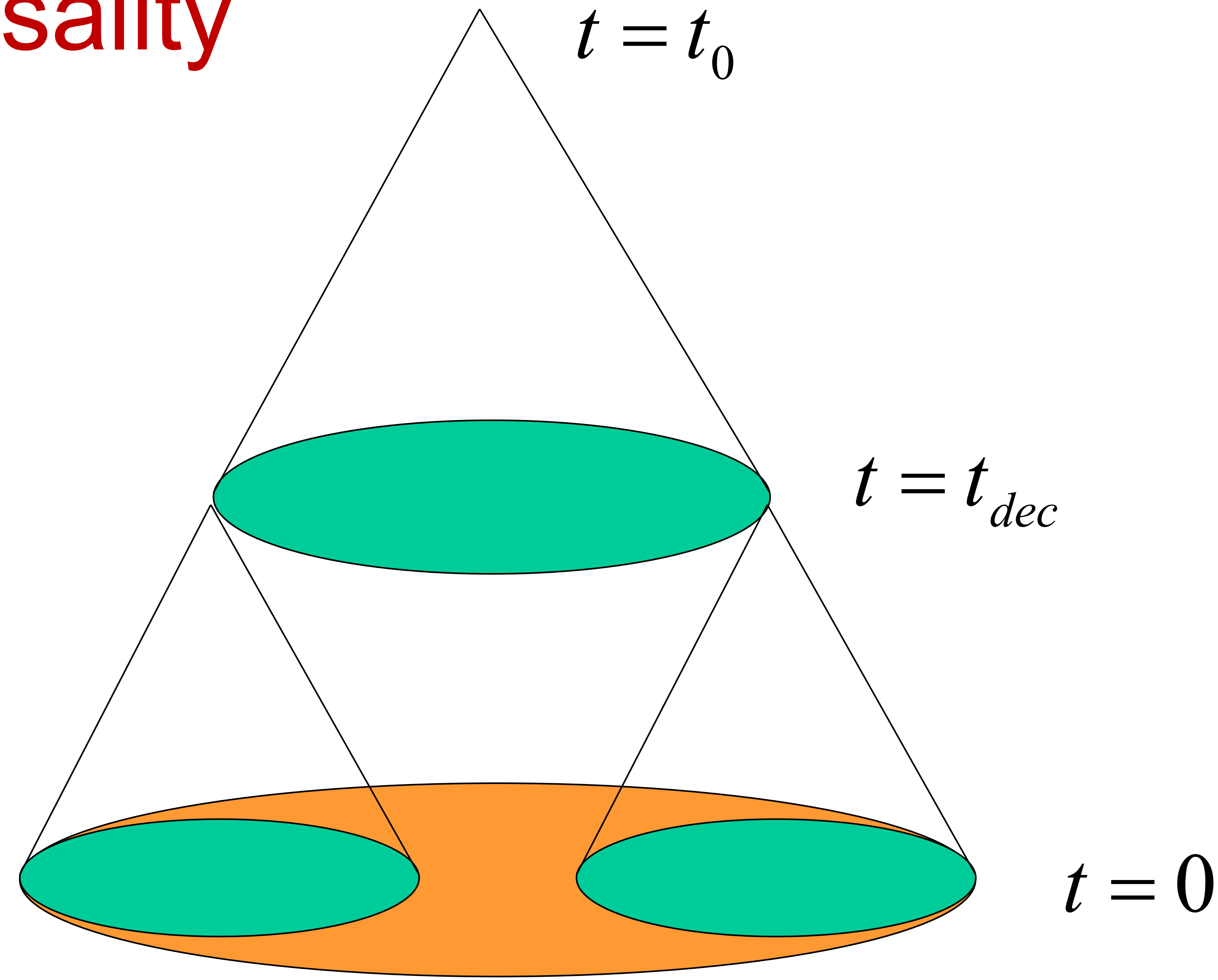
$$\frac{d\ln\rho}{d\ln a} = \frac{\rho'}{\rho} = -3(1+w) \ \Rightarrow\ x' = (1+3w)x$$

Matter & Radiation $\quad x = 0$ unstable $\quad x \propto a^2,\ a$

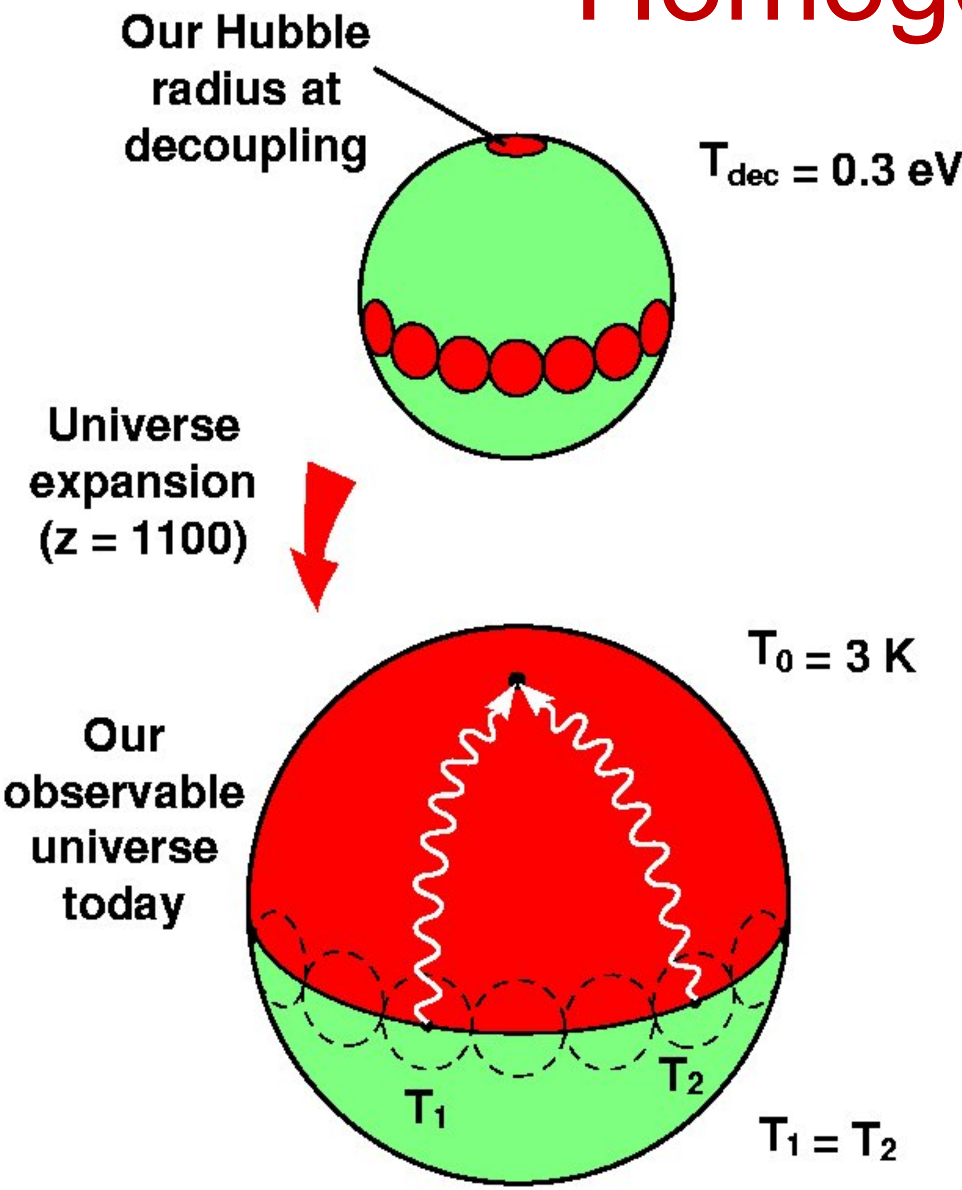
Vacuum energy $\quad x = 0$ stable $\quad x \propto a^{-2}$

$$x_0 = x_{in}\left(\frac{T_{in}}{T_{eq}}\right)^2 (1+z_{eq}) < 10^{-3} \quad \text{e.g.}\ \ x_{BBN} < 10^{-18}$$

Causality



Homogeneity



Scale Factor

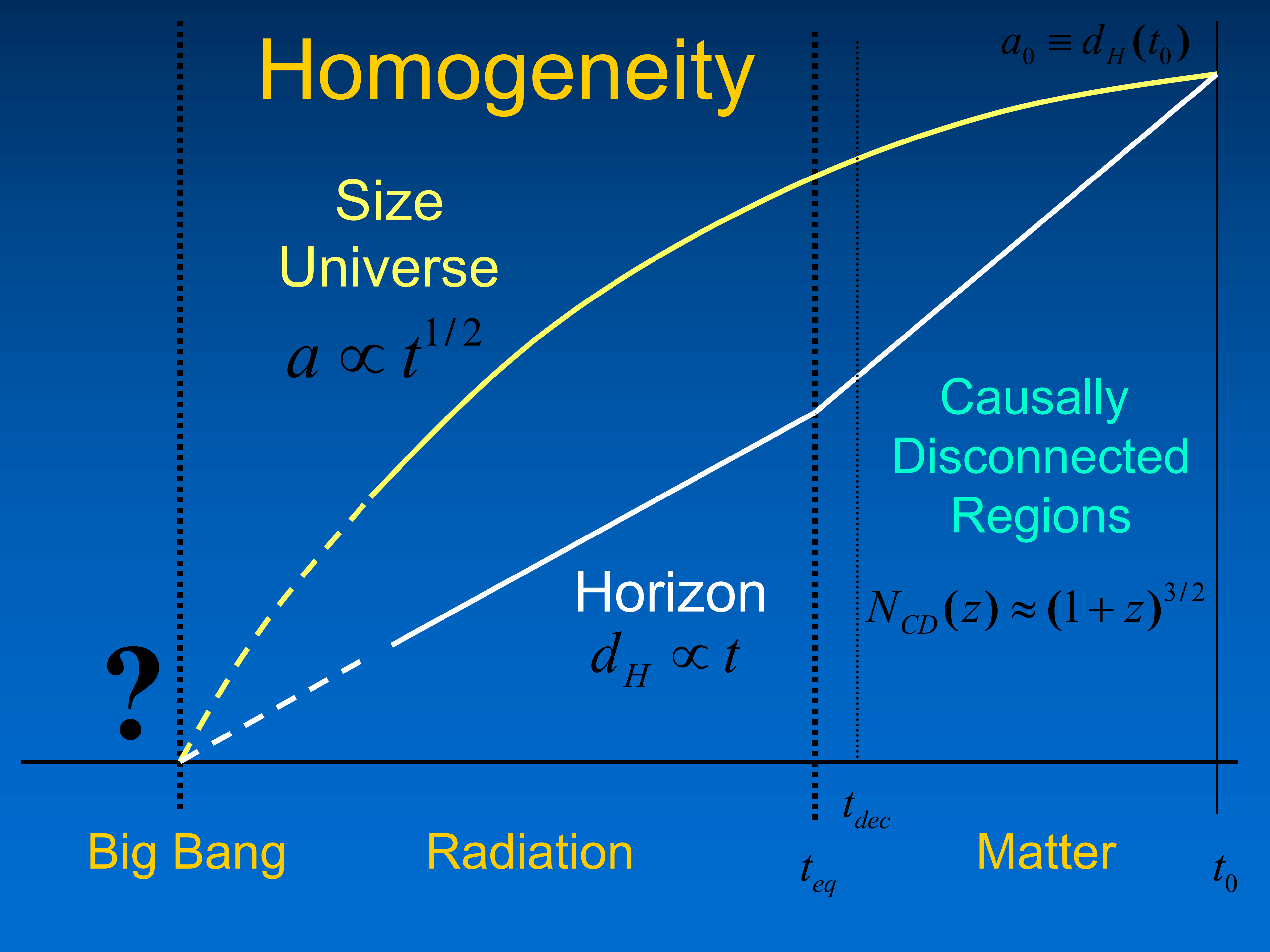
$$a(t) \propto t^p \qquad p < 1$$

Particle Horizon

$$d_H(t) = a(t)\int_0^t \frac{dt'}{a(t')} \propto t$$

Causally Disconnected

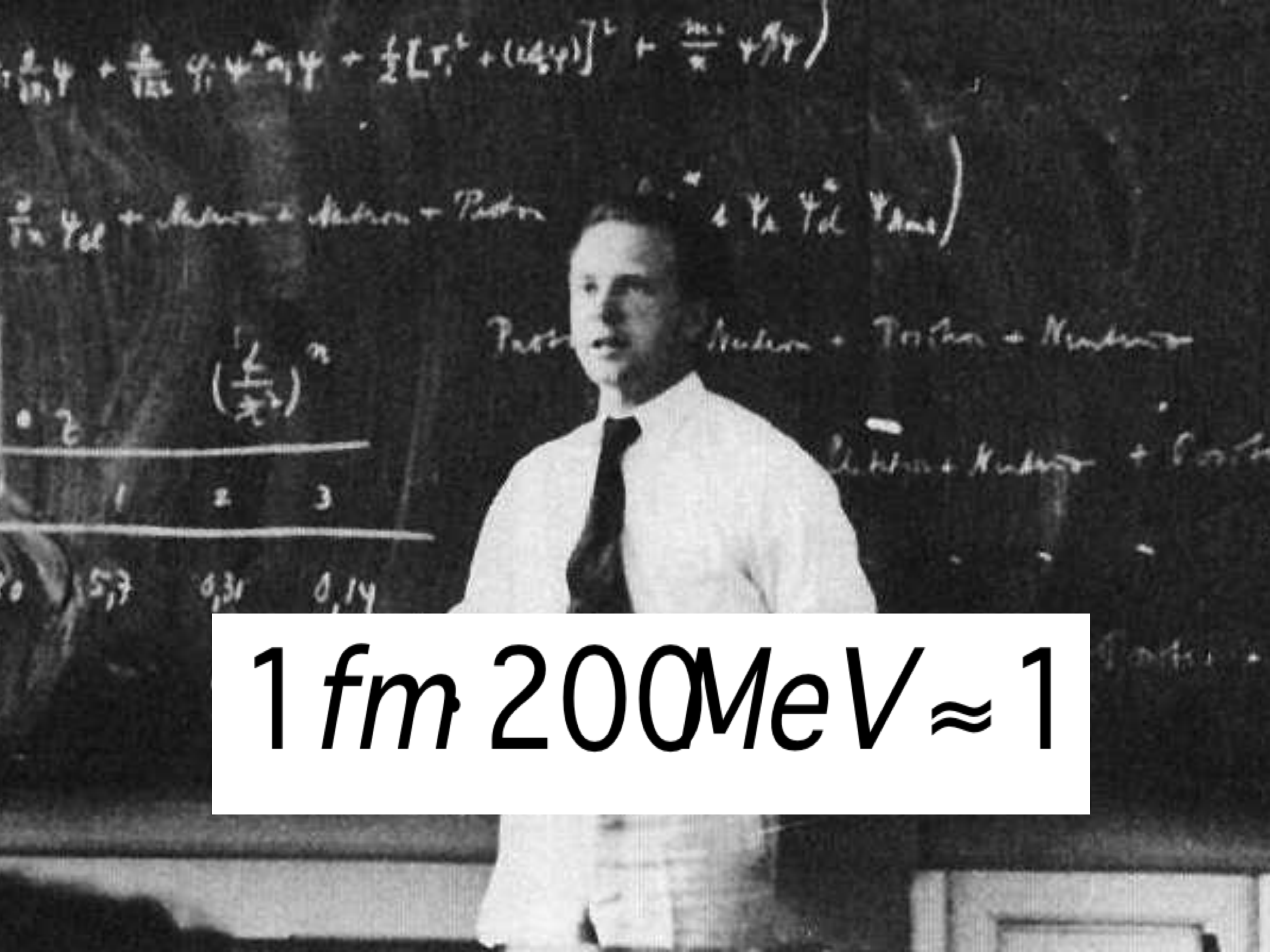
$$N_{CD}(z) \approx \left(\frac{a}{d_H}\right)^3 \approx (1+z)^{3/2}$$



Homogeneity
$a_0 \equiv d_H(t_0)$
Size
Universe
$a \propto t^{1/2}$
Causally
Disconnected
Regions
$N_{CD}(z) \approx (1+z)^{3/2}$
Horizon
$d_H \propto t$
?
t_{dec}
Big Bang
Radiation
t_{eq}
Matter
t_0

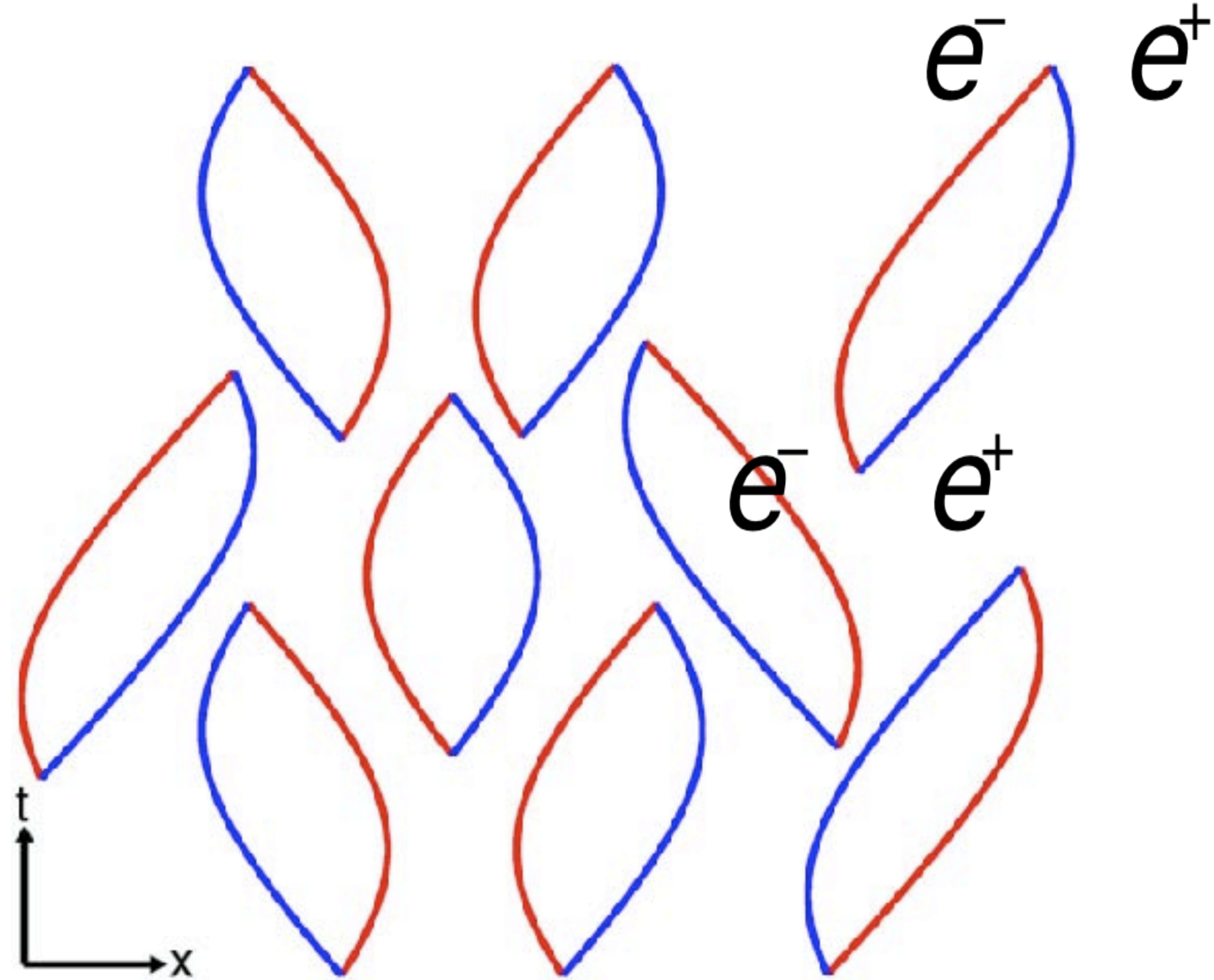
A very elegant solution:

INFLATION



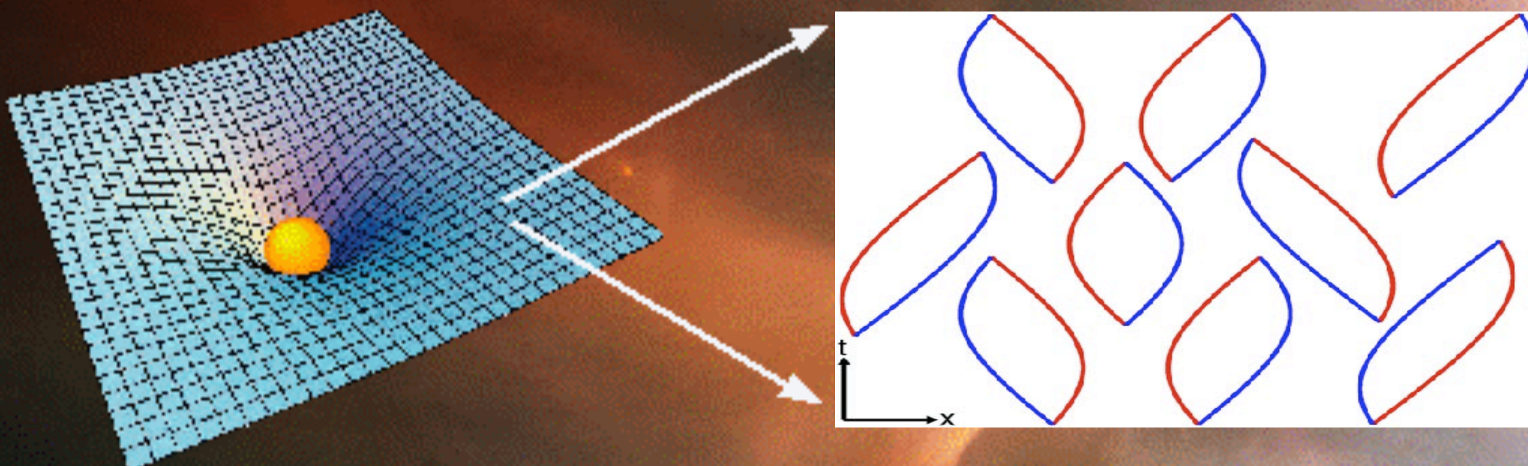
$$1\,fm \cdot 200\,MeV \approx 1$$

Vacuum fluctuations



The universe itself could be a product of quantum uncertainty.

“empty space” is a sea of virtual particles winking in and out of existence:



Inflation

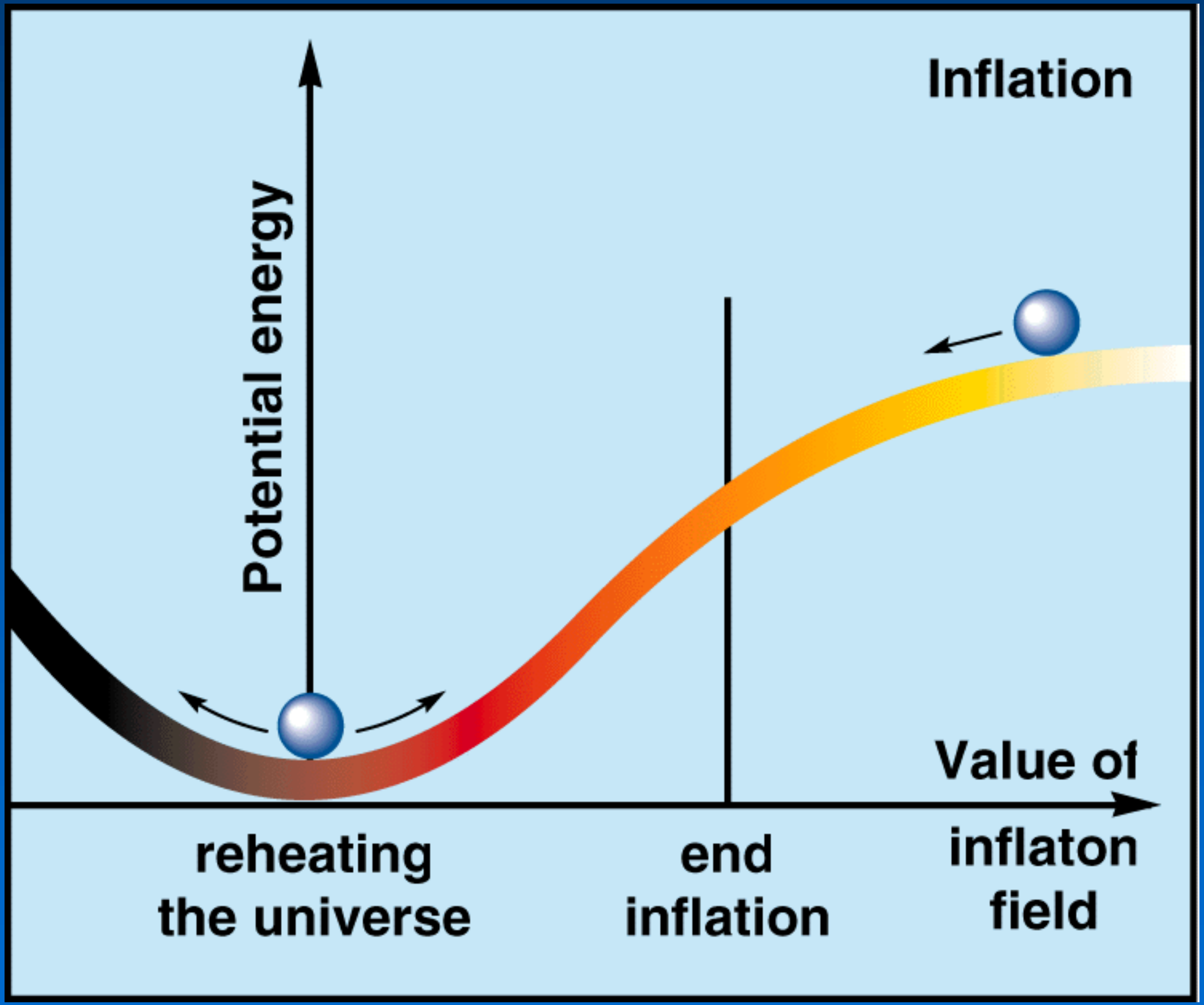
Our Universe could be the result of a quantum fluctuation

Alan Guth

Andrei Linde

A small bubble of quantum vacuum expands very rapidly until it encompasses all our Universe

Effective description (scalar field)

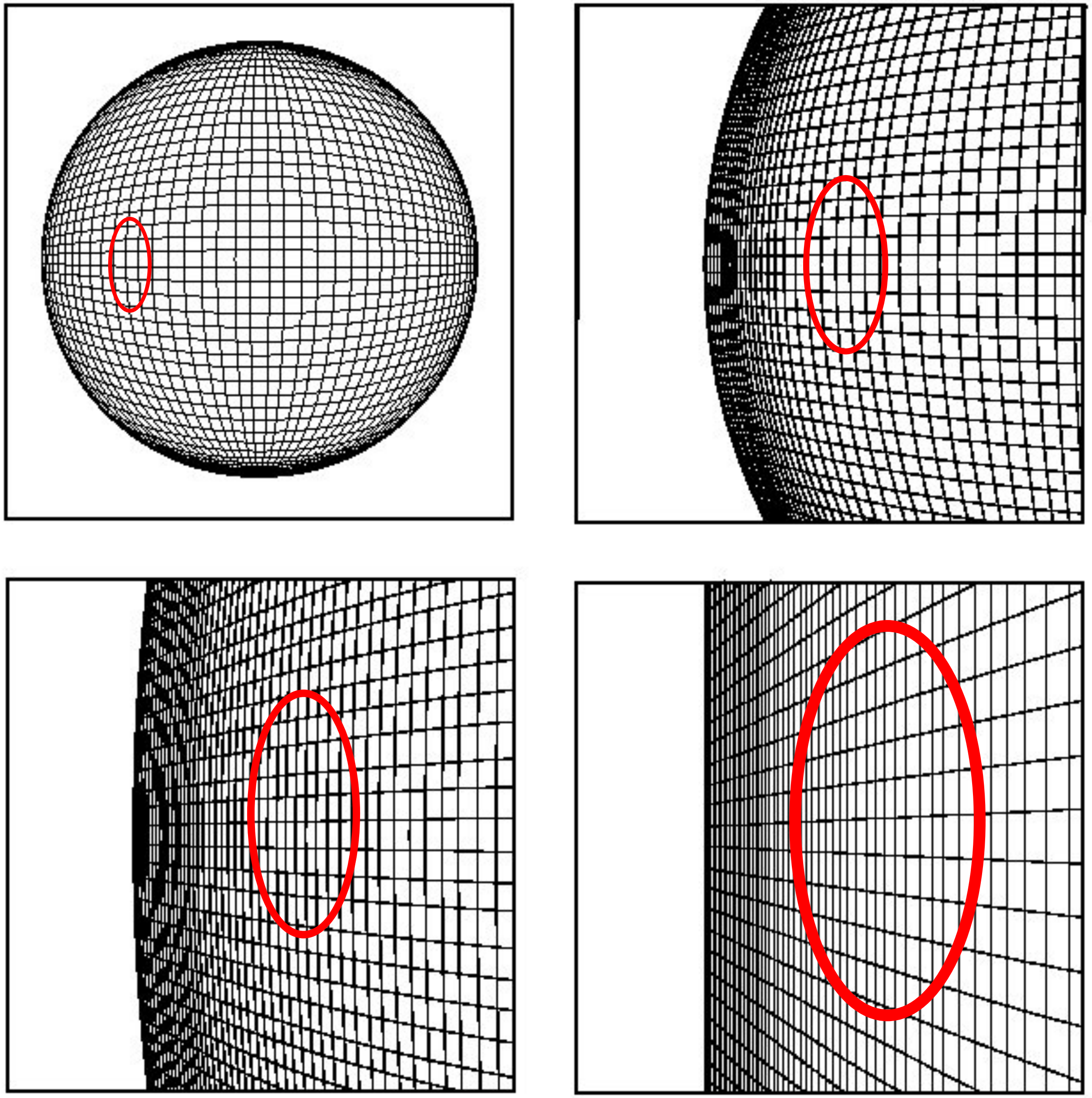


Constant density

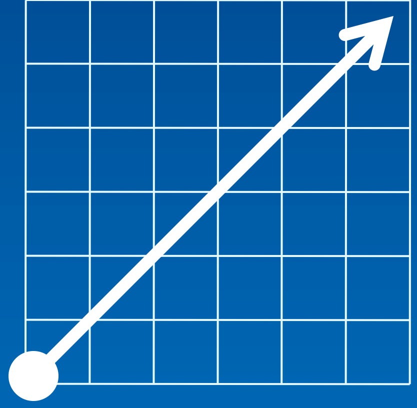
GR

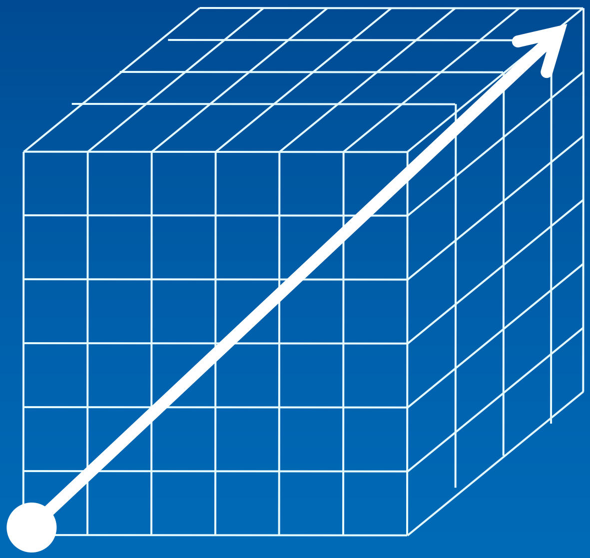
Exponential Growth

Flat spatial homogeneous sections



Flat = Euclidean





Straight trajectory

SCALAR FIELD DYNAMICS

$$\mathcal{S} = \int d^4x\sqrt{-g}\Big[\frac{1}{2\kappa^2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\Big]$$

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-Kr^2} + r^2 d\Omega^2\right)$$

Hamiltonian and momentum constraint equations

$$H^2 = \frac{\kappa^2}{3}\left[\frac{1}{2}(\Pi^\phi)^2 + V(\phi)\right] ,$$

$$H_{|i} = -\frac{\kappa^2}{2}\Pi^\phi\phi_{|i} ,$$

Evolution equations

$$\dot{H} = -\frac{\kappa^2}{2}(\Pi^\phi)^2$$

$$\dot{\Pi}^\phi + 3H\Pi^\phi + \frac{\partial V}{\partial\phi} = 0 .$$

HAMILTON-JACOBI EQUATION

Constraint equations $\Rightarrow$ $$\left(\frac{\partial H}{\partial t}\right)_\phi = 0, \quad \left(\frac{\partial \Pi^\phi}{\partial t}\right)_\phi = 0.$$

Then $$H \equiv H(\phi(t, x^i)),$$

$$\boxed{3H^2(\phi) = \frac{2}{\kappa^2}\left(\frac{\partial H}{\partial \phi}\right)^2 + \kappa^2 V(\phi)\,,}$$

$$\dot{\phi} = -\frac{2}{\kappa^2}\left(\frac{\partial H}{\partial \phi}\right) = \Pi^\phi\,, \qquad \frac{\dot{a}}{a} = H(\phi)\,,$$

$$\dot{H} = -\frac{2}{\kappa^2}\left(\frac{\partial H}{\partial \phi}\right)^2 = -\frac{\kappa^2}{2}(\Pi^\phi)^2\,,$$

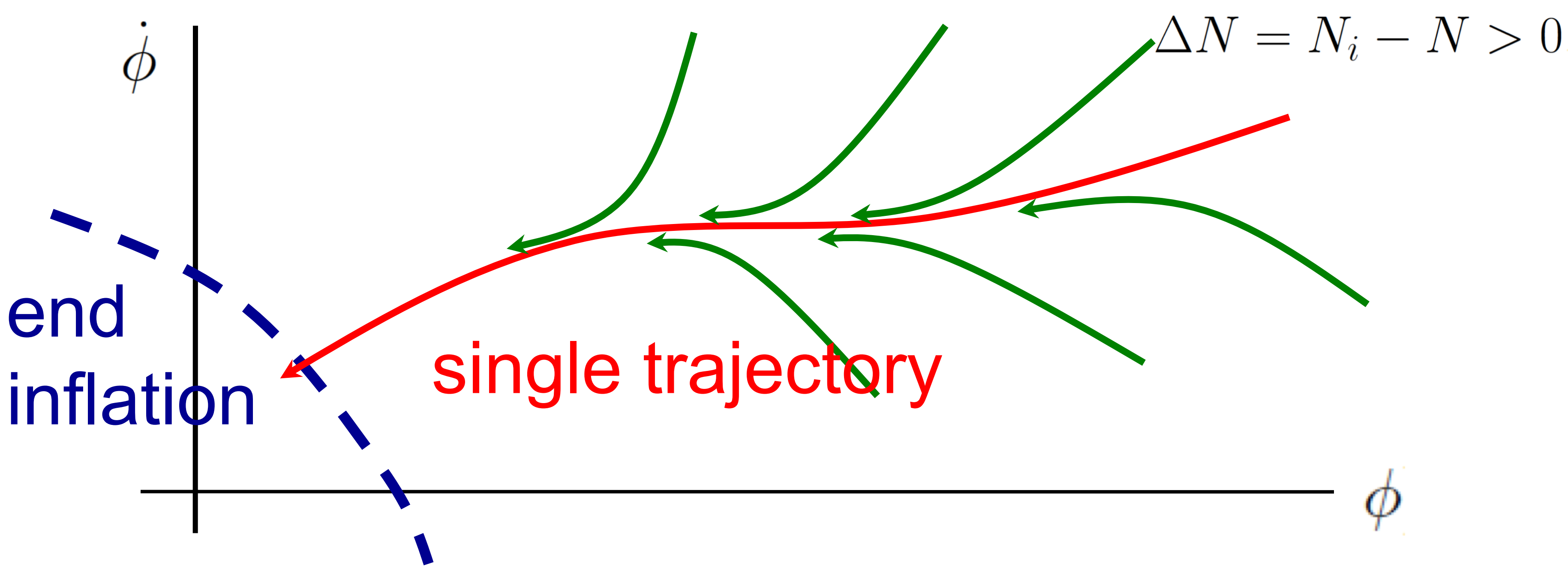
SLOW-ROLL ATTRACTOR

$H_0(\phi)$ exact particular solution

$H(\phi) = H_0(\phi) + \delta H(\phi)$ linear perturbation

Then $H_0'(\phi)\,\delta H'(\phi) = (3\kappa^2/2)\, H_0 \delta H$ with solution:

$$\delta H(\phi) = \delta H(\phi_i)\,\exp\left(\frac{3\kappa^2}{2}\int_{\phi_i}^{\phi}\frac{H_0(\phi)d\phi}{H_0'(\phi)}\right) = \delta H(\phi_i)\,\exp(-3\Delta N)$$



SLOW-ROLL PARAMETERS

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{2}{\kappa^2}\left(\frac{H'(\phi)}{H(\phi)}\right)^2 = -\frac{\partial \ln H}{\partial \ln a},$$

$$\delta \equiv -\frac{\ddot{\phi}}{H\dot{\phi}} = \frac{2}{\kappa^2}\left(\frac{H''(\phi)}{H(\phi)}\right) = -\frac{\partial \ln H'}{\partial \ln a},$$

The scalar field φ acts as a new "time"

$$N_e \equiv \ln \frac{a_{\rm end}}{a(t)} = \int_t^{t_{\rm end}} H\,dt = -\frac{\kappa^2}{2}\int_{\phi}^{\phi_{\rm end}} \frac{H(\phi)d\phi}{H'(\phi)}$$

The number of "e"-folds N_e to the end inflation

SLOW-ROLL APPROXIMATION

$$\boxed{\begin{aligned} H^2\left(1-\frac{\epsilon}{3}\right) &\simeq H^2 = \frac{\kappa^2}{3}V(\phi)\,, \\ 3H\dot\phi\left(1-\frac{\delta}{3}\right) &\simeq 3H\dot\phi = -V'(\phi) \end{aligned}}$$

just dynamics

$$\epsilon = \frac{2}{\kappa^2}\left(\frac{H'(\phi)}{H(\phi)}\right)^2 \simeq \frac{1}{2\kappa^2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \equiv \epsilon_V \ll 1\,,$$

$$\delta = \frac{2}{\kappa^2}\frac{H''(\phi)}{H(\phi)} \simeq \frac{1}{\kappa^2}\frac{V''(\phi)}{V(\phi)} - \frac{1}{2\kappa^2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \equiv \eta_V - \epsilon_V \ll 1\,,$$

$$\begin{aligned} \xi &= \frac{4}{\kappa^4}\frac{H'(\phi)H'''(\phi)}{H^2(\phi)} \simeq \frac{1}{\kappa^4}\frac{V'(\phi)V'''(\phi)}{V^2(\phi)} - \frac{3}{2\kappa^4}\frac{V''(\phi)}{V(\phi)}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \\ &+ \frac{3}{4\kappa^4}\left(\frac{V'(\phi)}{V(\phi)}\right)^4 \equiv \xi_V - 3\eta_V\epsilon_V + 3\epsilon_V^2 \ll 1\,. \end{aligned}$$

$$\boxed{N \simeq \int_{\phi_i}^{\phi_e}\frac{\kappa d\phi}{\sqrt{2\epsilon_V(\phi)}} = \kappa^2\int_{\phi_i}^{\phi_e}\frac{V(\phi)\,d\phi}{V'(\phi)}\,,}$$

INFLATIONARY SOLUTIONS OF HBBP

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,,$$
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)\,.$$

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$V(\phi) \gg \dot{\phi}^2 \quad \Rightarrow \quad p \simeq -\rho \quad \Rightarrow \quad \rho \simeq \text{const.} \quad \Rightarrow \quad H(\phi) \simeq \text{const.}$$

$$a(t) \sim \exp(Ht) \quad \Rightarrow \quad \frac{\ddot{a}}{a} > 0 \quad \text{accelerated expansion}$$

$$\boxed{x_0 = x_{\rm in}\, e^{-2N}\, \frac{a_{\rm rh}^2 \rho_{\rm rh}}{a_{\rm end}^2 \rho_{\rm end}} \frac{T_{\rm rh}^2}{T_{\rm eq}^2}(1+z_{\rm eq}) \;\simeq\; e^{-2N}\, 10^{56} \leq 1 \quad \Rightarrow \quad N \geq 65}$$

$$^{(3)}R = \frac{6K}{a^2} = \,^{(3)}R_{\rm in}\, e^{-2N} \;\longrightarrow\; 0\,, \qquad \rho_{\rm M} \propto a^{-3} \sim e^{-3N} \;\longrightarrow\; 0\,,$$

$$\delta_k \sim \left(\frac{k}{aH}\right)^2 \Phi_k \propto e^{-2N} \;\longrightarrow\; 0\,, \qquad \rho_{\rm R} \propto a^{-4} \sim e^{-4N} \;\longrightarrow\; 0\,,$$

curvature

matter

LINEAR METRIC PERTURBATIONS

$$ds^2 = a(\eta)^2 \left[-(1+2\Phi)d\eta^2 + (1-2\Phi)d\mathbf{x}^2 + h_{ij}\, dx^i dx^j\right]$$

linear pert. eqs.

$$\begin{aligned}
\Phi'' + 3\mathcal{H}\Phi' + (\mathcal{H}' + 2\mathcal{H}^2)\Phi &= \frac{\kappa^2}{2}[\phi'\delta\phi' - a^2 V'(\phi)\delta\phi]\,, \\
-\nabla^2\Phi + 3\mathcal{H}\Phi' + (\mathcal{H}' + 2\mathcal{H}^2)\Phi &= -\frac{\kappa^2}{2}[\phi'\delta\phi' + a^2 V'(\phi)\delta\phi]\,, \\
\Phi' + \mathcal{H}\Phi &= \frac{\kappa^2}{2}\phi'\delta\phi\,, \\
\delta\phi'' + 2\mathcal{H}\delta\phi' - \nabla^2\delta\phi + a^2 V''(\phi)\delta\phi &= 4\phi'\Phi' - 2a^2 V'(\phi)\Phi\,.
\end{aligned}$$

$$\boxed{\begin{aligned}
&u'' - \nabla^2 u - \frac{z''}{z}u = 0\,, \\
&\nabla^2\Phi = \frac{\kappa^2}{2}\frac{\mathcal{H}}{a^2}(zu' - z'u)\,, \\
&\left(\frac{a^2\Phi}{\mathcal{H}}\right)' = \frac{\kappa^2}{2}zu\,.
\end{aligned}}$$

Mukhanov variables

$$\boxed{\begin{aligned}
u &\equiv a\delta\phi + z\Phi\,, \\
z &\equiv a\frac{\phi'}{\mathcal{H}}\,.
\end{aligned}}$$

QUANTUM FLUCTUATIONS IN QdS

$$\delta S = \frac{1}{2}\int d^3x\, d\eta \left[(u')^2 - (\nabla u)^2 + \frac{z''}{z}u^2\right]$$

$$\hat{u}(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}\left[u_k(\eta)\,\hat{a}_{\mathbf{k}}\,e^{i\mathbf{k}\cdot\mathbf{x}} + u_k^*(\eta)\,\hat{a}_{\mathbf{k}}^\dagger\,e^{-i\mathbf{k}\cdot\mathbf{x}}\right],$$

scalar field's Fock space

$$\begin{aligned}[\hat{a}_{\mathbf{k}}, \hat{a}_{\mathbf{k}'}^\dagger] &= \delta^3(\mathbf{k} - \mathbf{k}'), \\ \hat{a}_{\mathbf{k}}|0\rangle &= 0.\end{aligned}$$

equal-time commutation relations

$$[\hat{u}(\eta, \mathbf{x}), \hat{\Pi}_u^\dagger(\eta, \mathbf{x}')] = i\hbar\delta^3(\mathbf{x} - \mathbf{x}')$$

QUANTUM FLUCTUATIONS IN QdS

normalization condition on the modes u_k

$$u_k \, u_k^{*\prime} - u_k' \, u_k^* = i$$

the Wronskian of the mode equation

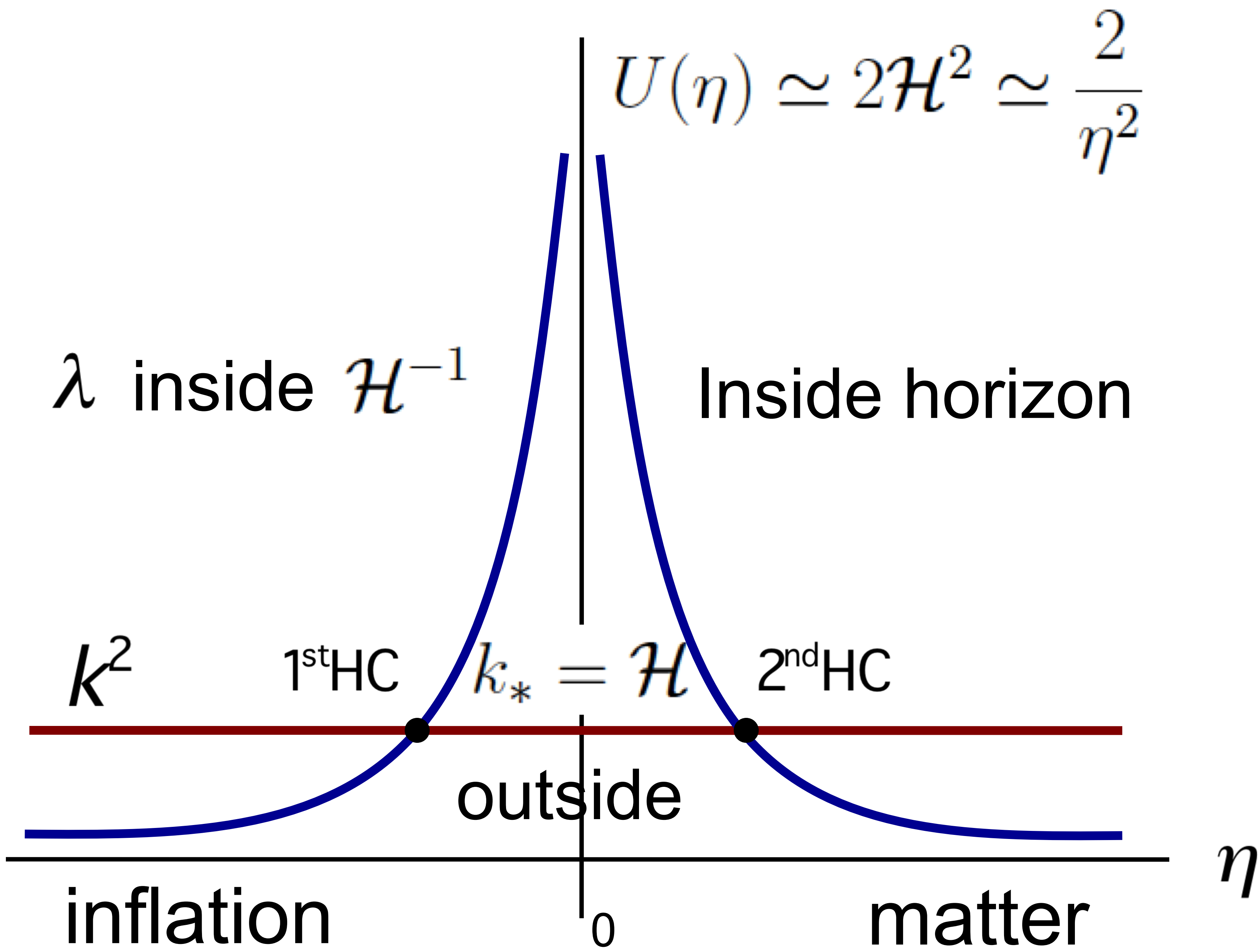
$$u_k'' + \left(k^2 - \frac{z''}{z}\right) u_k = 0$$

Schrödinger like equation

$$-u_k'' + U(\eta) \, u_k = k^2 \, u_k$$

time-dependent potential

$$U(\eta) \; = \; z''/z$$


$U(\eta) \simeq 2\mathcal{H}^2 \simeq \frac{2}{\eta^2}$
λ inside $\mathcal{H}^{-1}$
Inside horizon
k^2
1stHC
$k_* = \mathcal{H}$
2ndHC
outside
η
inflation
0
matter

SOLUTIONS OF MODE EQUATIONS

slow-roll parameters

$$\epsilon = 1 - \frac{\mathcal{H}'}{\mathcal{H}^2} = \frac{\kappa^2}{2}\frac{z^2}{a^2},$$

$$\delta = 1 - \frac{\phi''}{\mathcal{H}\phi'} = 1 + \epsilon - \frac{z'}{\mathcal{H}z},$$

$$\xi = -\left(2 - \epsilon - 3\delta + \delta^2 - \frac{\phi'''}{\mathcal{H}^2\phi'}\right)$$

approx. constant

$$\epsilon' = 2\mathcal{H}\left(\epsilon^2 - \epsilon\delta\right) = \mathcal{O}(\epsilon^2),$$

$$\delta' = \mathcal{H}\left(\epsilon\delta - \xi\right) = \mathcal{O}(\epsilon^2).$$

for constant slow-roll parameters, we can write

$$\eta = \frac{-1}{\mathcal{H}} + \int \frac{\epsilon da}{a\mathcal{H}} \simeq \frac{-1}{\mathcal{H}}\frac{1}{1-\epsilon},$$

$$\frac{z''}{z} = \mathcal{H}^2\left[(1+\epsilon-\delta)(2-\delta) + \mathcal{H}^{-1}(\epsilon' - \delta')\right] \simeq \frac{1}{\eta^2}\left(\nu^2 - \frac{1}{4}\right),$$

where $\nu = \dfrac{1+\epsilon-\delta}{1-\epsilon} + \dfrac{1}{2}$

EXACT SOLUTIONS OF MODE EQS.

two asymptotic regimes,

$$u_k = \frac{1}{\sqrt{2k}} e^{-ik\eta} \qquad k \gg aH \qquad \text{Minkowsky}$$

$$u_k = C_1(k)\, z \qquad k \ll aH \qquad \text{superhorizon}$$

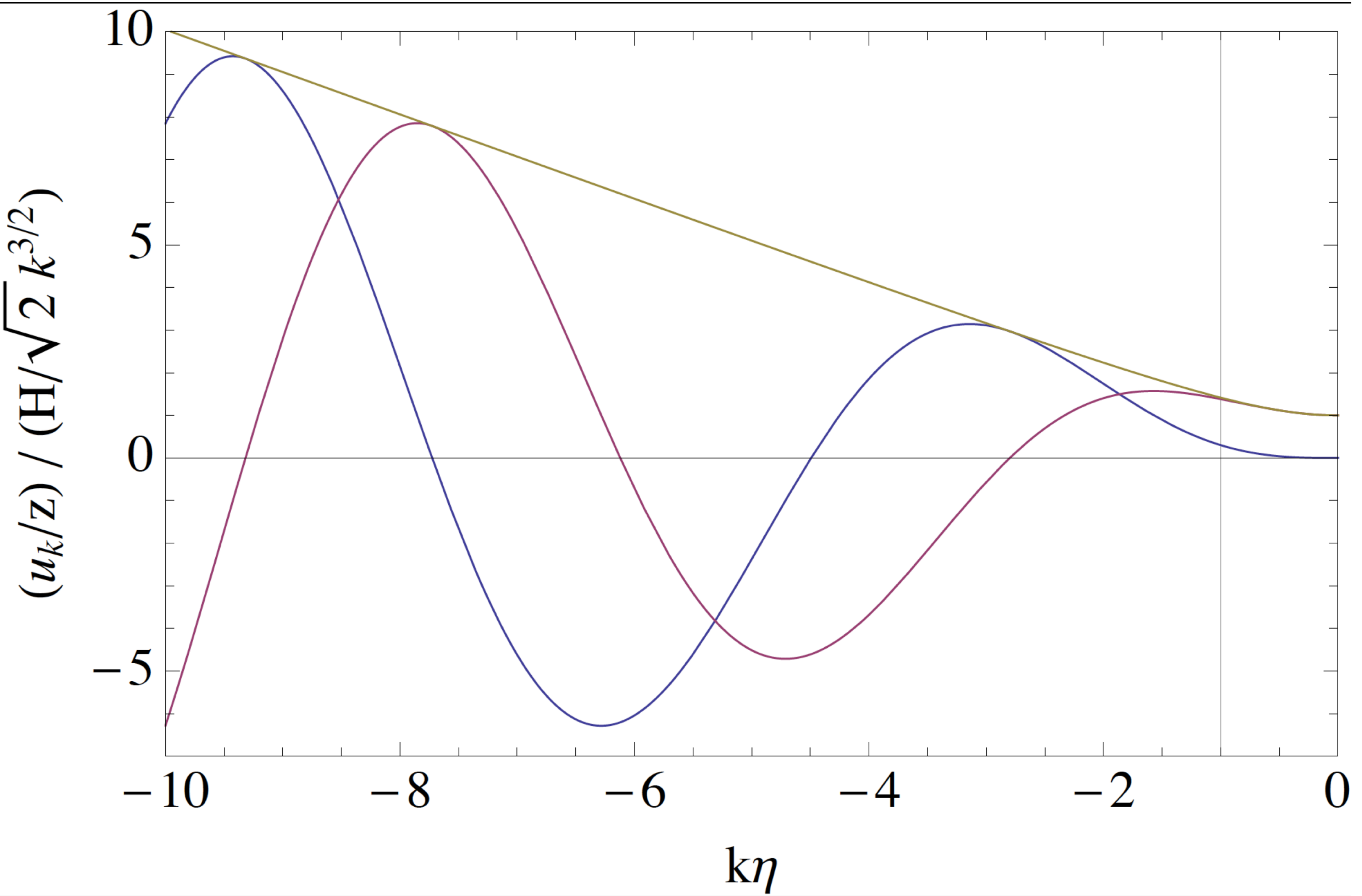
exact solution that connects the two regimes

$$u_k(\eta) = \frac{\sqrt{\pi}}{2} e^{i(\nu+\frac{1}{2})\frac{\pi}{2}} (-\eta)^{1/2} H_\nu^{(1)}(-k\eta)$$

where $H_\nu^{(1)}(z)$ is the Hankel function of the first kind

$$\text{e.g. } H_{3/2}^{(1)}(x) = -e^{ix}\sqrt{2/\pi x}(1 + i/x),$$

and ν is given by $\qquad \nu = \dfrac{1+\epsilon-\delta}{1-\epsilon} + \dfrac{1}{2}$



10
5
0
−5
−10
−8
−6
−4
−2
0
$(u_k/z)\,/\,(H/\sqrt{2}\,k^{3/2})$
kη

EXACT SOLUTIONS OF MODE EQS.

limit $k\eta \to 0$, the solution becomes

$$|u_k| = \frac{2^{\nu-\frac{3}{2}}}{\sqrt{2k}} \frac{\Gamma(\nu)}{\Gamma(\frac{3}{2})} (-k\eta)^{\frac{1}{2}-\nu} \equiv \frac{C(\nu)}{\sqrt{2k}} \left(\frac{k}{aH}\right)^{\frac{1}{2}-\nu},$$

$$C(\nu) = 2^{\nu-\frac{3}{2}} \frac{\Gamma(\nu)}{\Gamma(\frac{3}{2})} (1-\epsilon)^{\nu-\frac{1}{2}} \simeq 1 \qquad \text{for} \quad \epsilon, \delta \ll 1$$

compute Φ and $\delta\phi$ from the super-Hubble-scale mode

$$\Phi = C_1 \left(1 - \frac{\mathcal{H}}{a^2} \int a^2 d\eta\right) + C_2 \frac{\mathcal{H}}{a^2},$$

$$\frac{\delta\phi}{\phi'} = \frac{C_1}{a^2} \int a^2 d\eta - \frac{C_2}{a^2}.$$

C_1 growing mode

C_2 decaying mode

SCALAR CURVATURE PERTURBATIONS

gauge invariant quantity *constant* for superhorizon modes of adiabatic perturbations,

$$\boxed{\zeta \equiv \Phi + \frac{1}{\epsilon \mathcal{H}} \left(\Phi' + \mathcal{H}\Phi \right) = \frac{u}{z} \, ,}$$

ζ is the gauge invariant curvature perturbation $\mathcal{R}_c$ on constant energy density hypersurfaces,

$$\zeta = \mathcal{R}_c + \frac{1}{\epsilon \mathcal{H}^2} \nabla^2 \Phi$$

$$\zeta' = \frac{1}{\epsilon \mathcal{H}} \nabla^2 \Phi \simeq 0 \qquad \text{constant}$$

for (adiabatic) superhorizon modes, $k \ll aH$

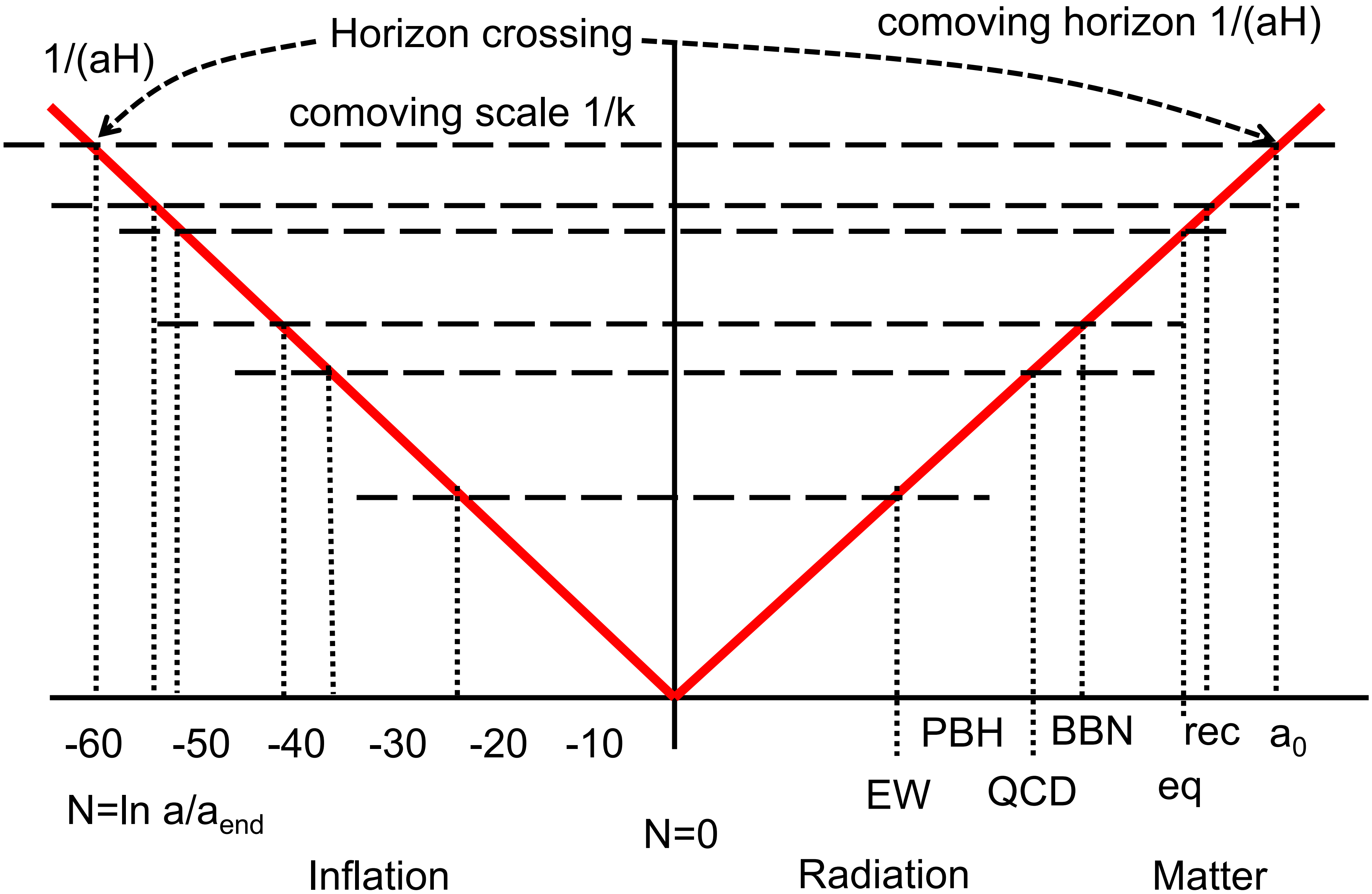
SCALAR CURVATURE PERTURBATIONS

Therefore, we can evaluate the Newtonian potential Φ_k when the perturbation reenters the horizon during radiation/matter eras in terms of the curvature perturbation $\mathcal{R}_k$ when it left the Hubble scale during inflation,

$$\Phi_k = \left(1 - \frac{\mathcal{H}}{a^2} \int a^2 d\eta\right) \mathcal{R}_k = \frac{3+3\omega}{5+3\omega} \mathcal{R}_k = \begin{cases} \frac{2}{3}\mathcal{R}_k & \text{radiation era}\,, \\ \frac{3}{5}\mathcal{R}_k & \text{matter era}\,. \end{cases}$$

These expressions will be of special importance later. (CMB)

Inflation


Horizon crossing
comoving horizon 1/(aH)
1/(aH)
comoving scale 1/k
-60
-50
-40
-30
-20
-10
N=ln a/a_{end}
N=0
EW
PBH
QCD
BBN
eq
rec
a_0
Inflation
Radiation
Matter

GRAVITATIONAL WAVE PERTURBATIONS

$$\delta S = \frac{1}{2}\int d^3x\, d\eta\, \frac{a^2}{2\kappa^2}\Big[(h'_{ij})^2 - (\nabla h_{ij})^2\Big]$$

tensor field h_{ij} considered as a quantum field,

$$\hat{h}_{ij}(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} \sum_{\lambda=1,2} \Big[h_k(\eta)\, e_{ij}(\mathbf{k},\lambda)\, \hat{a}_{\mathbf{k},\lambda}\, e^{i\mathbf{k}\cdot\mathbf{x}} + h.c.\Big]\,,$$

$e_{ij}(\mathbf{k}, \lambda)$ are the two polarization tensors,

satisfying symmetric, transverse and traceless conditions

$$e_{ij} = e_{ji}\,, \quad k^i e_{ij} = 0\,, \quad e_{ii} = 0\,,$$

$$e_{ij}(-\mathbf{k},\lambda) = e^*_{ij}(\mathbf{k},\lambda)\,, \quad \sum_{\lambda} e^*_{ij}(\mathbf{k},\lambda) e^{ij}(\mathbf{k},\lambda) = 4\,,$$

TENSOR MODE EQUATION

gauge invariant tensor amplitude

$$v_k(\eta) = \frac{a}{\sqrt{2}\kappa} h_k(\eta)$$

decoupled in linear perturbation theory,

$$v_k'' + \left(k^2 - \frac{a''}{a}\right) v_k = 0$$

For constant slow-roll parameters, the potential becomes

$$\frac{a''}{a} = 2\mathcal{H}^2\left(1 - \frac{\epsilon}{2}\right) = \frac{1}{\eta^2}\left(\mu^2 - \frac{1}{4}\right),$$

$$\mu = \frac{1}{1-\epsilon} + \frac{1}{2}.$$

EXACT SOLUTIONS

in the two asymptotic regimes,

$$v_k = \frac{1}{\sqrt{2k}} e^{-ik\eta} \qquad k \gg aH \qquad \text{Minkowsky}$$

$$v_k = C_3(k)\, a \qquad k \ll aH \qquad \text{superhorizon}$$

exact solutions

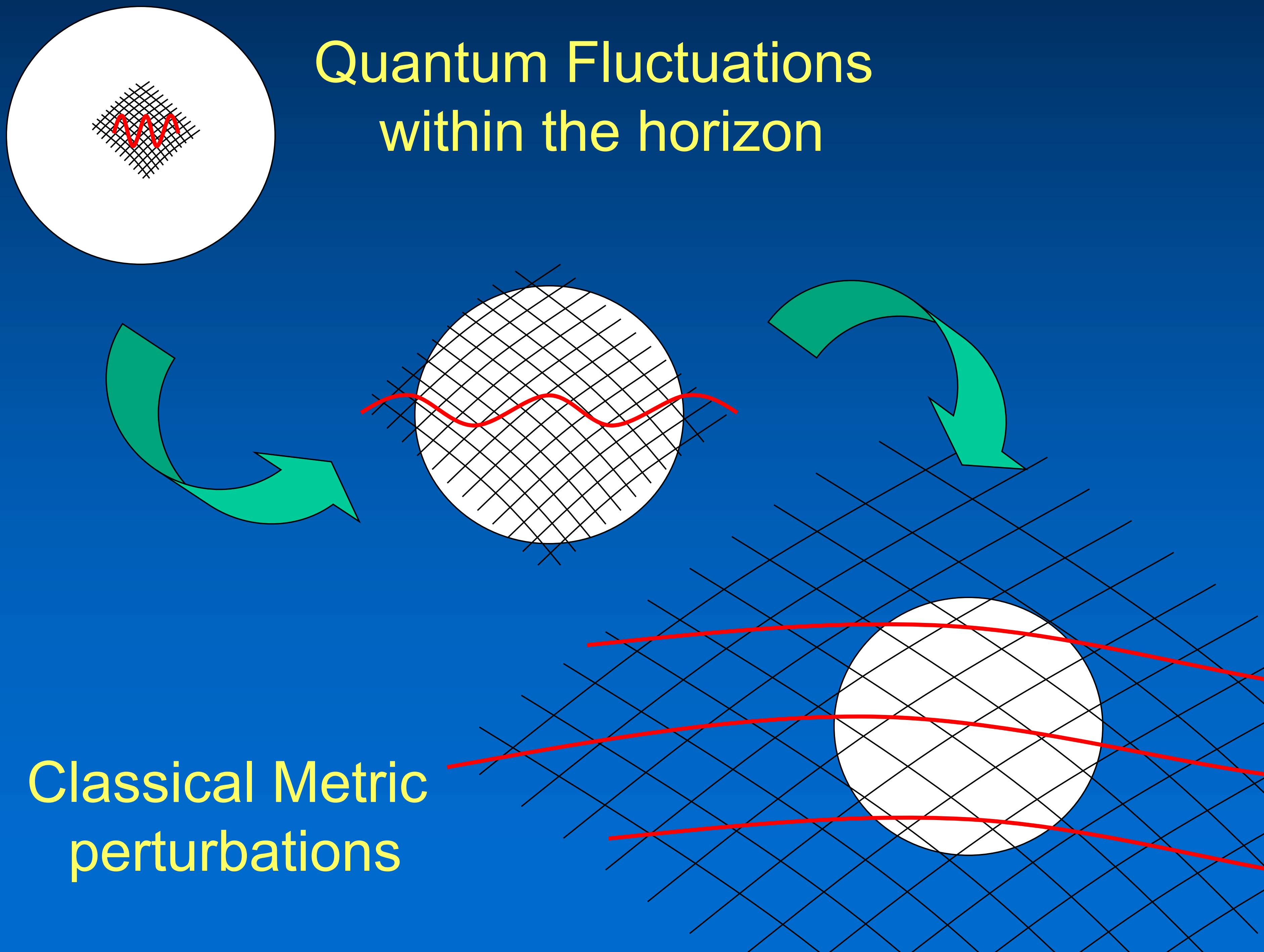
$$v_k(\eta) = \frac{\sqrt{\pi}}{2} e^{i(\mu+\frac{1}{2})\frac{\pi}{2}} (-\eta)^{1/2} H_\mu^{(1)}(-k\eta)$$

In the limit $k\eta \to 0$, $\quad |v_k| = \dfrac{C(\mu)}{\sqrt{2k}} \left(\dfrac{k}{aH}\right)^{\frac{1}{2}-\mu}$

Since h_k becomes constant on superhorizon scales,

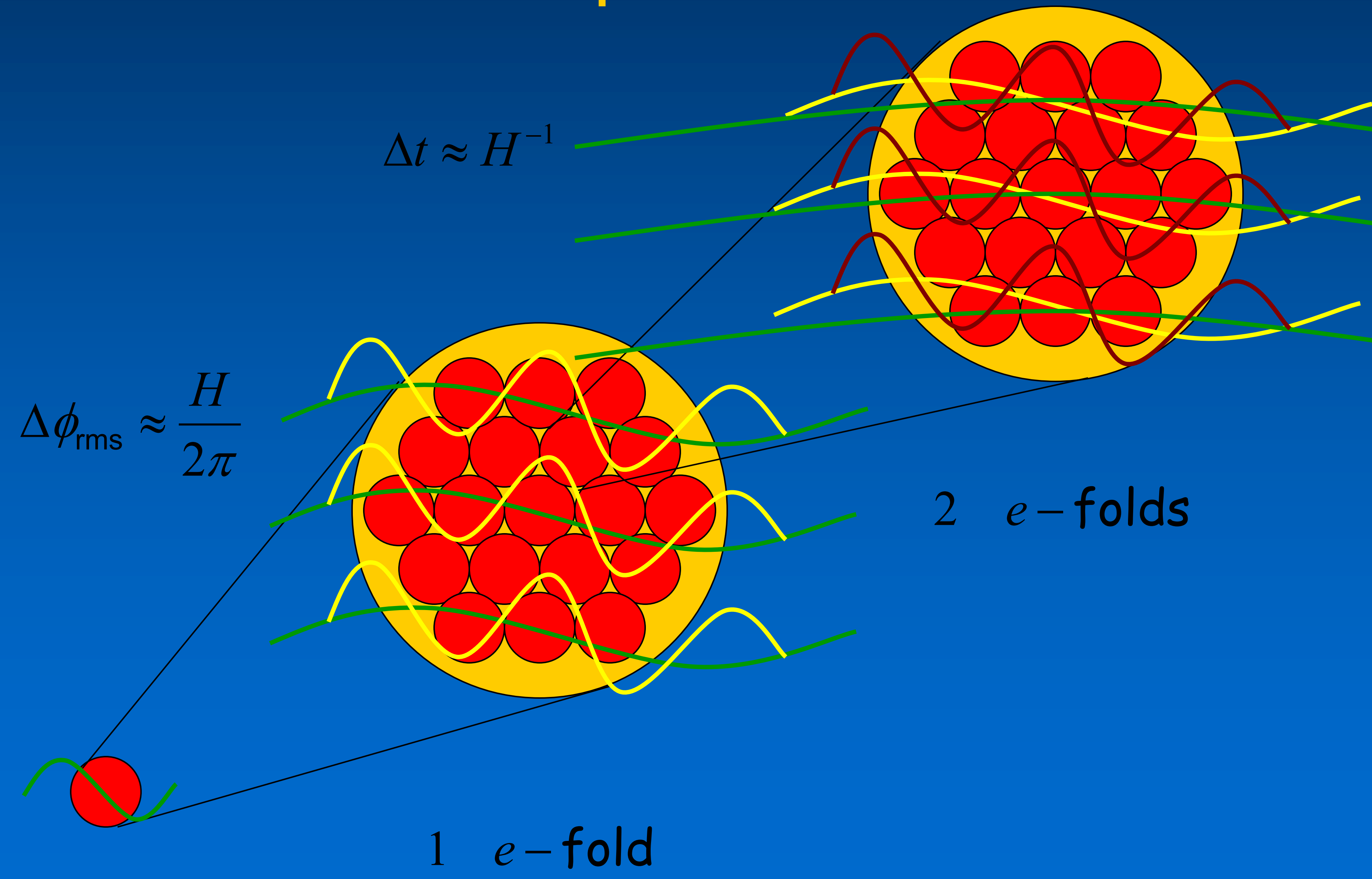
evaluate the tensor metric perturbation when it reentered during the radiation or matter era directly in terms of its value during inflation.

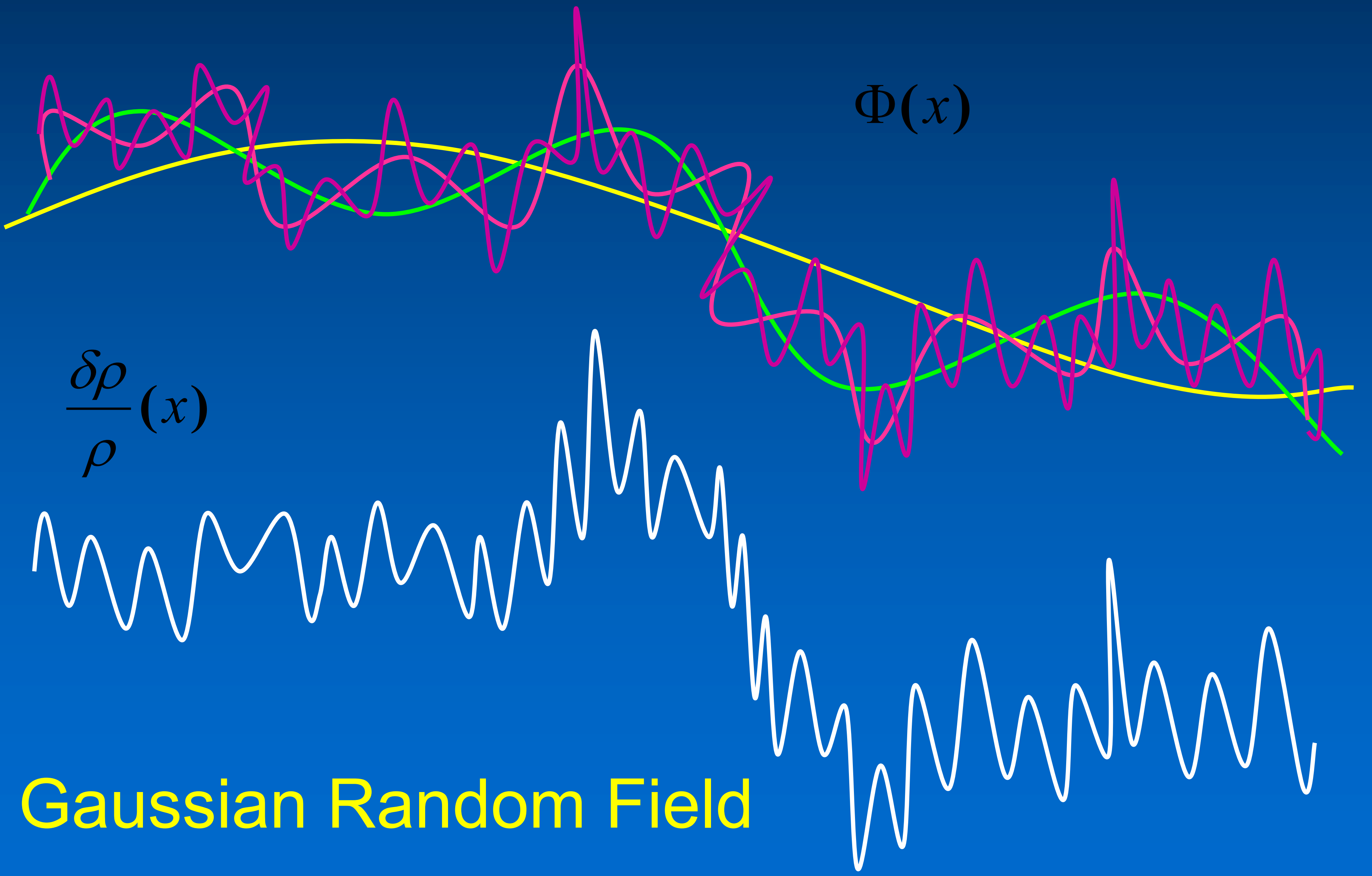
Quantum Fluctuations within the horizon



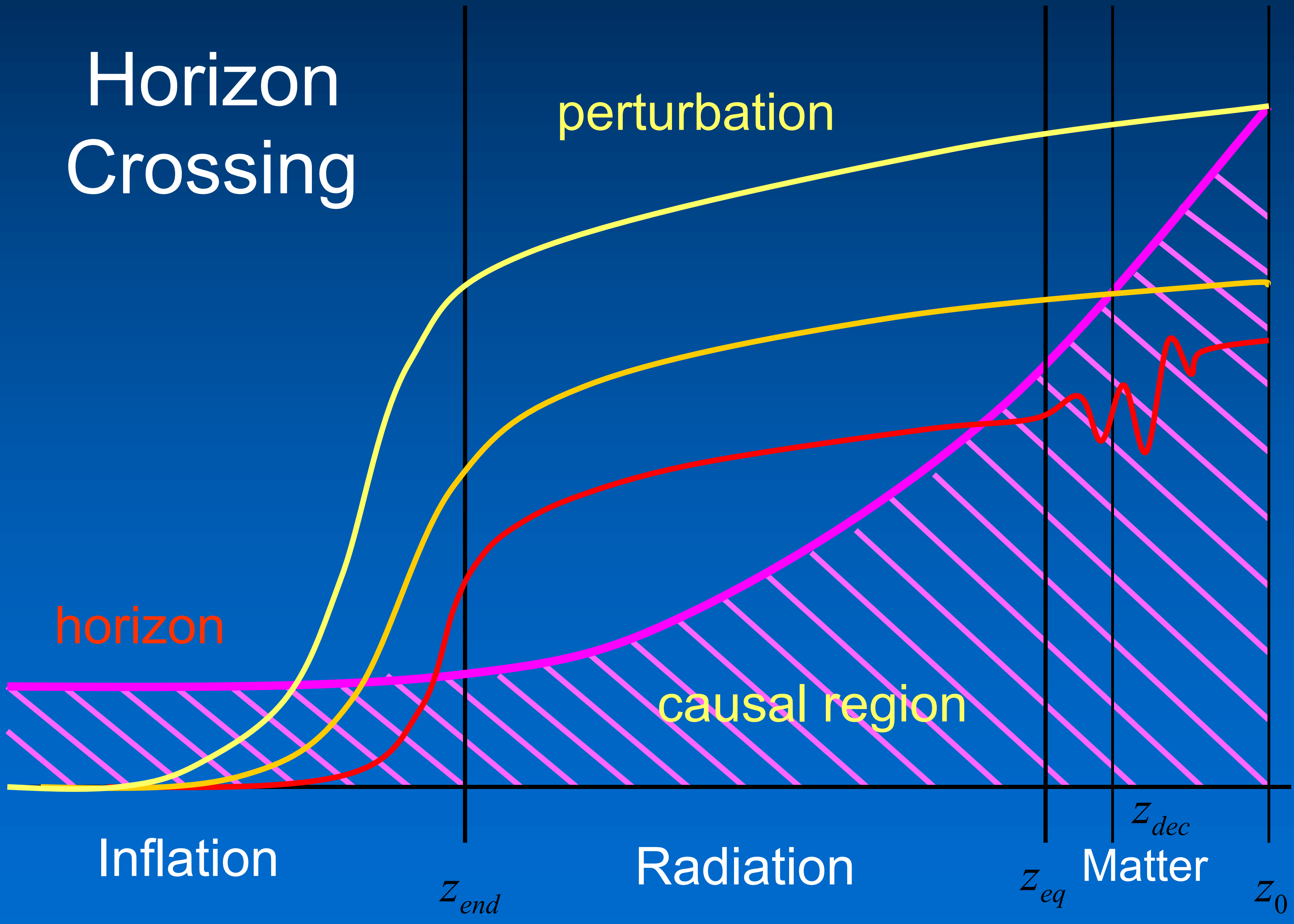
Classical Metric perturbations

Scale Invariant Spectrum

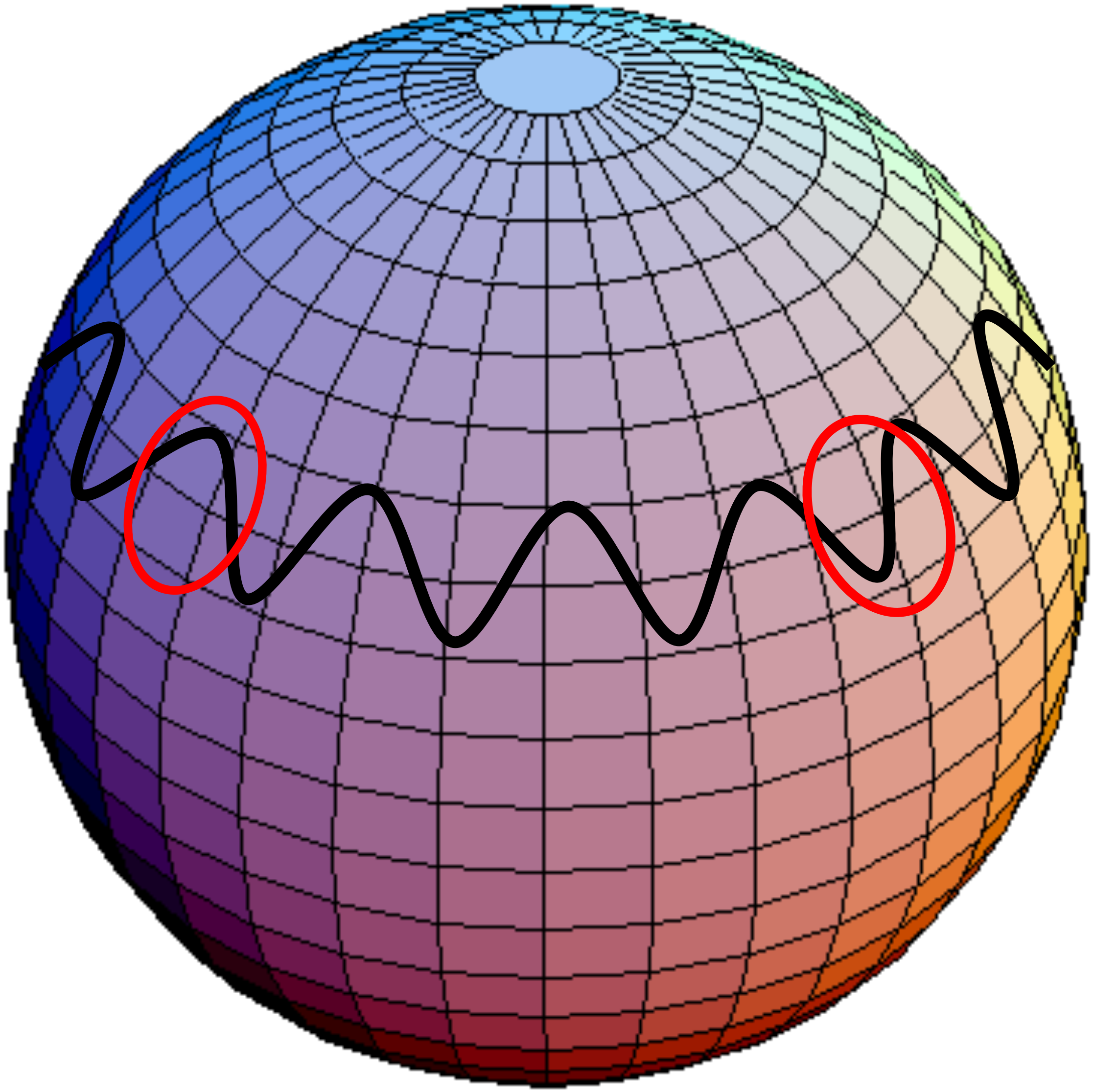



$\Phi(x)$
$\frac{\delta\rho}{\rho}(x)$
Gaussian Random Field

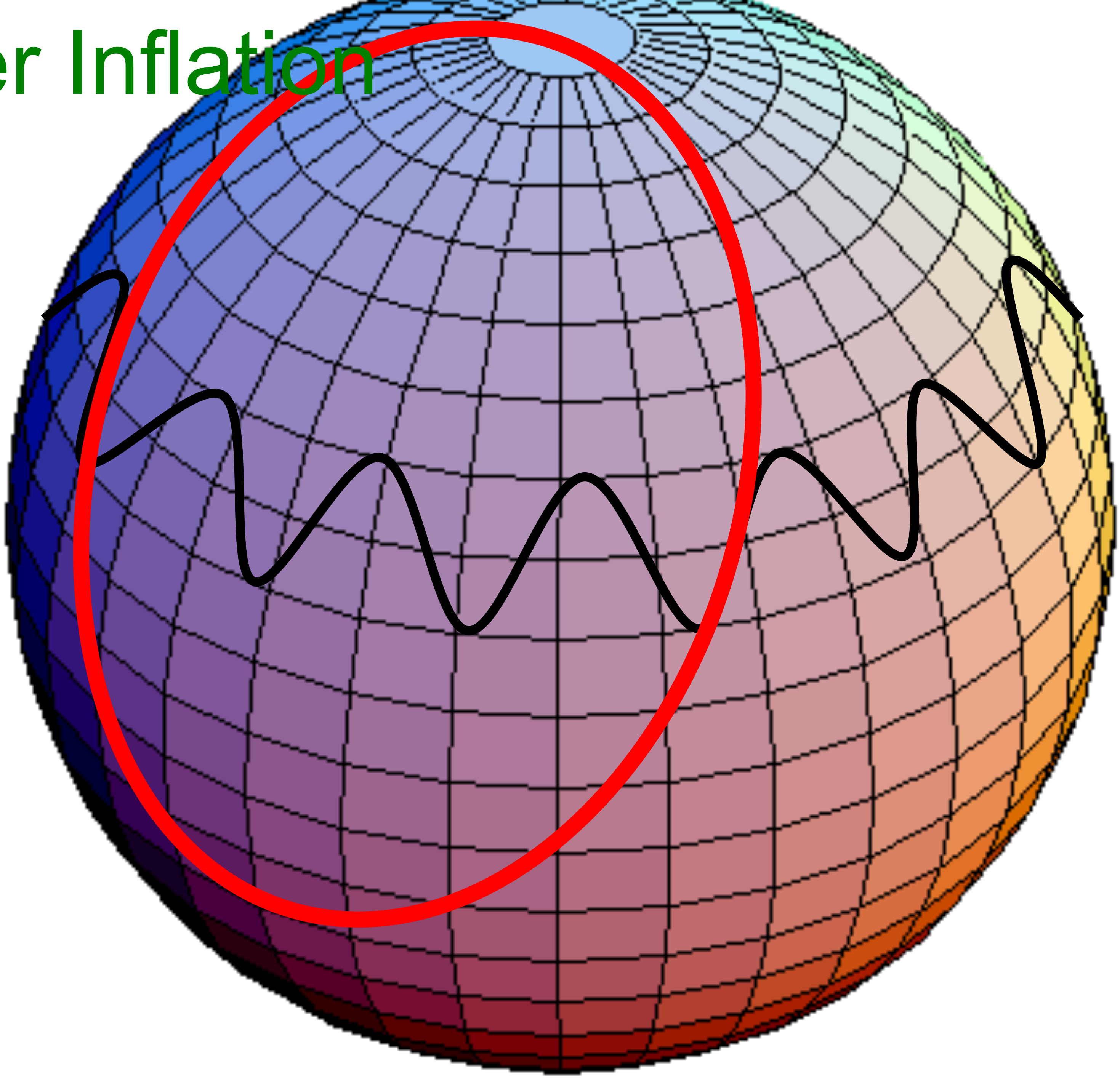
Horizon Crossing



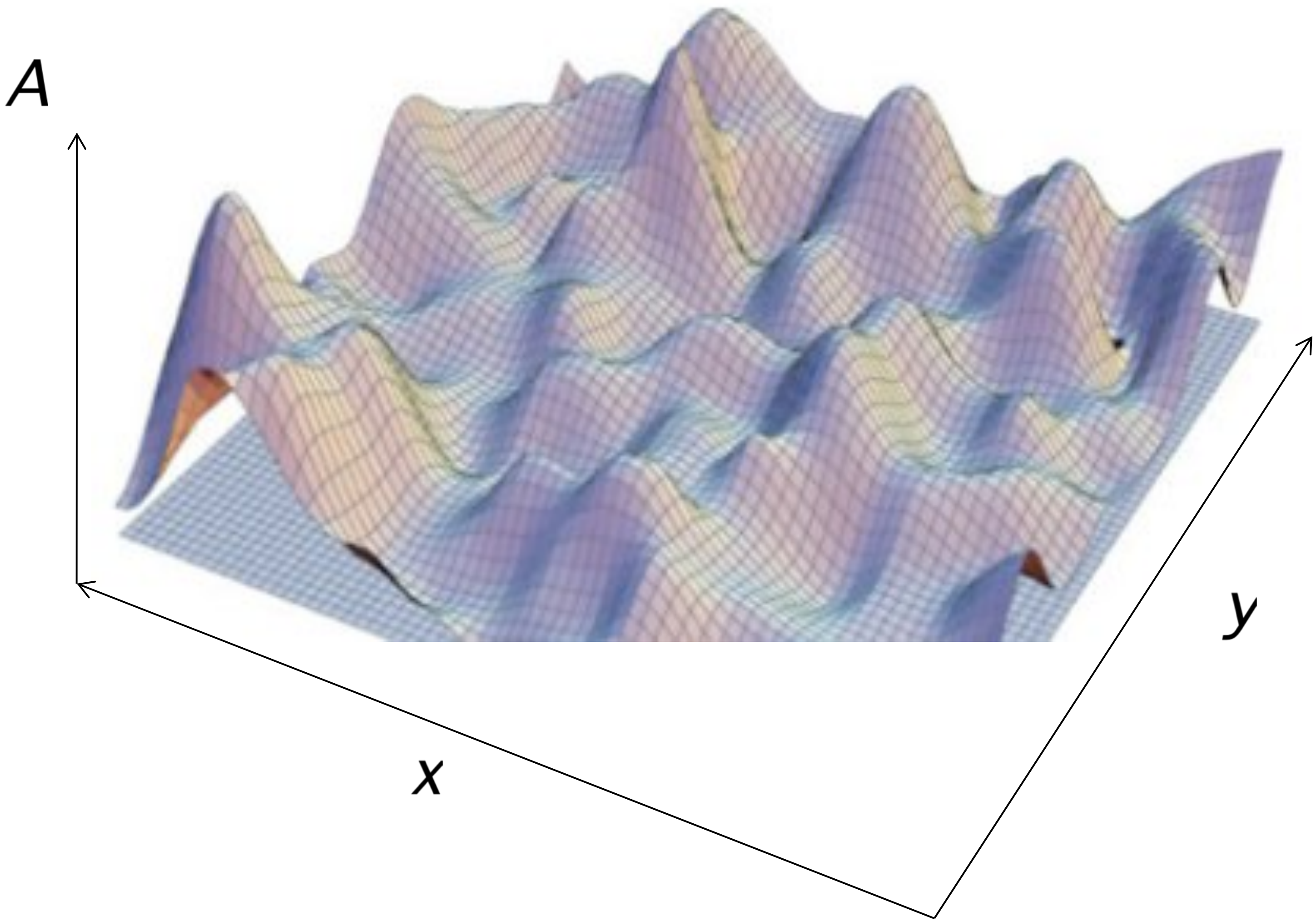
During Inflation



After Inflation

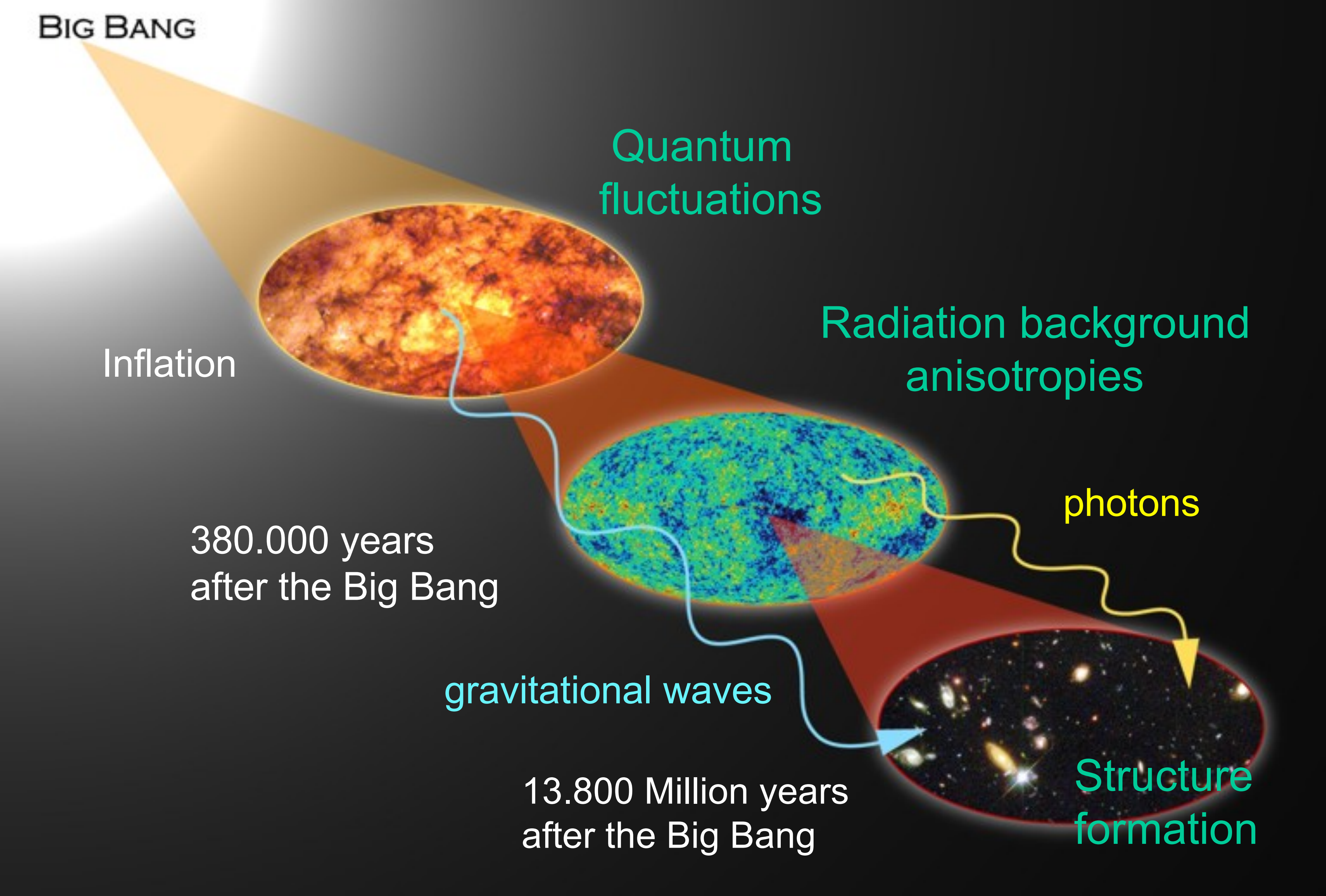


Ripples in Space



Stretched to cosmological distances

Predictions of Inflation



Basic Inflationary Predictions

Geometry and matter:

- Homogeneity (acausal origin)
- Flat spatial sections (exp. growth)
- No appreciable topology (exp.growth)
- Origin matter & radiation (reheating)

Metric Perturbations:

- Gaussian spectrum (ground state)
- Aprox. scale invariant (slow roll cond.)
- Adiabatic density fluctuations (single fluid)
- Gravitational waves (tensor metric pert.)
- No vector perturbations (no cosmic defects)

SCALAR POWER SPECTRA

two-point correlation function in Fourier space

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

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

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

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

scale invariant

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

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,

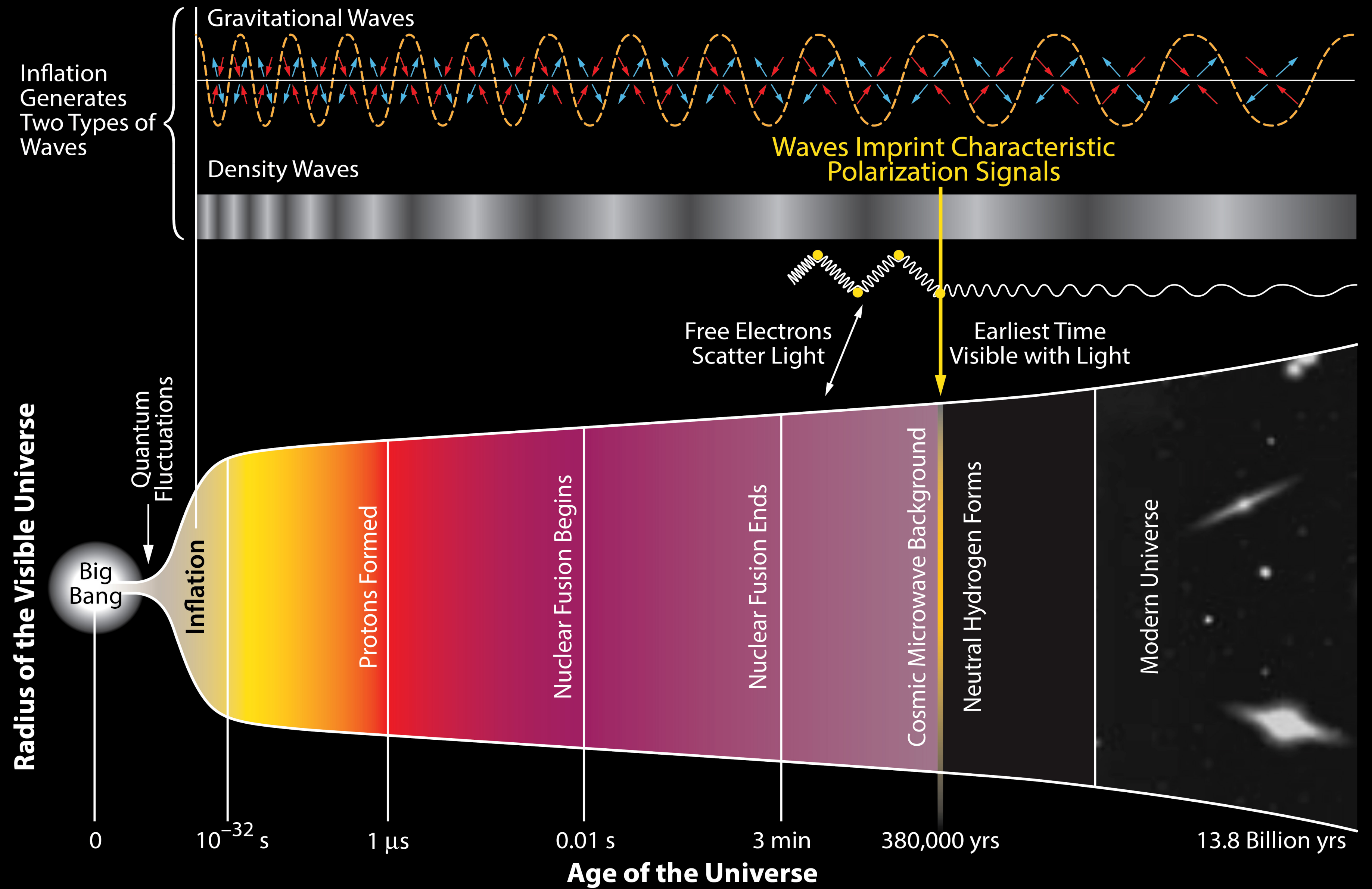
scale invariant

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

running of the tilt

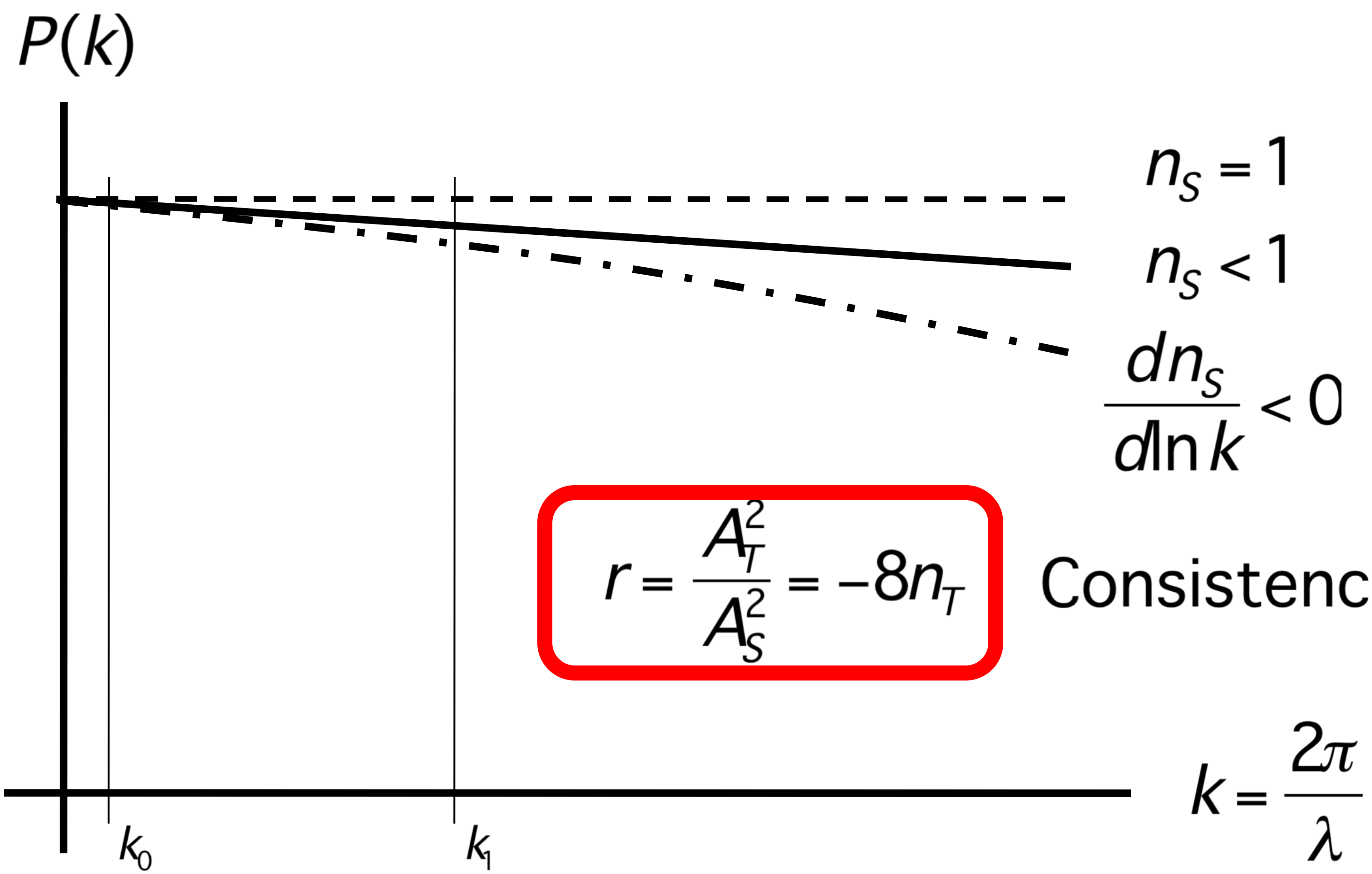
$$\frac{dn_T}{d\ln k} = -\eta\mathcal{H}\left(4\epsilon^2 - 4\epsilon\delta\right) \simeq 8\epsilon_V^2 - 4\eta_V\epsilon_V$$

History of the Universe



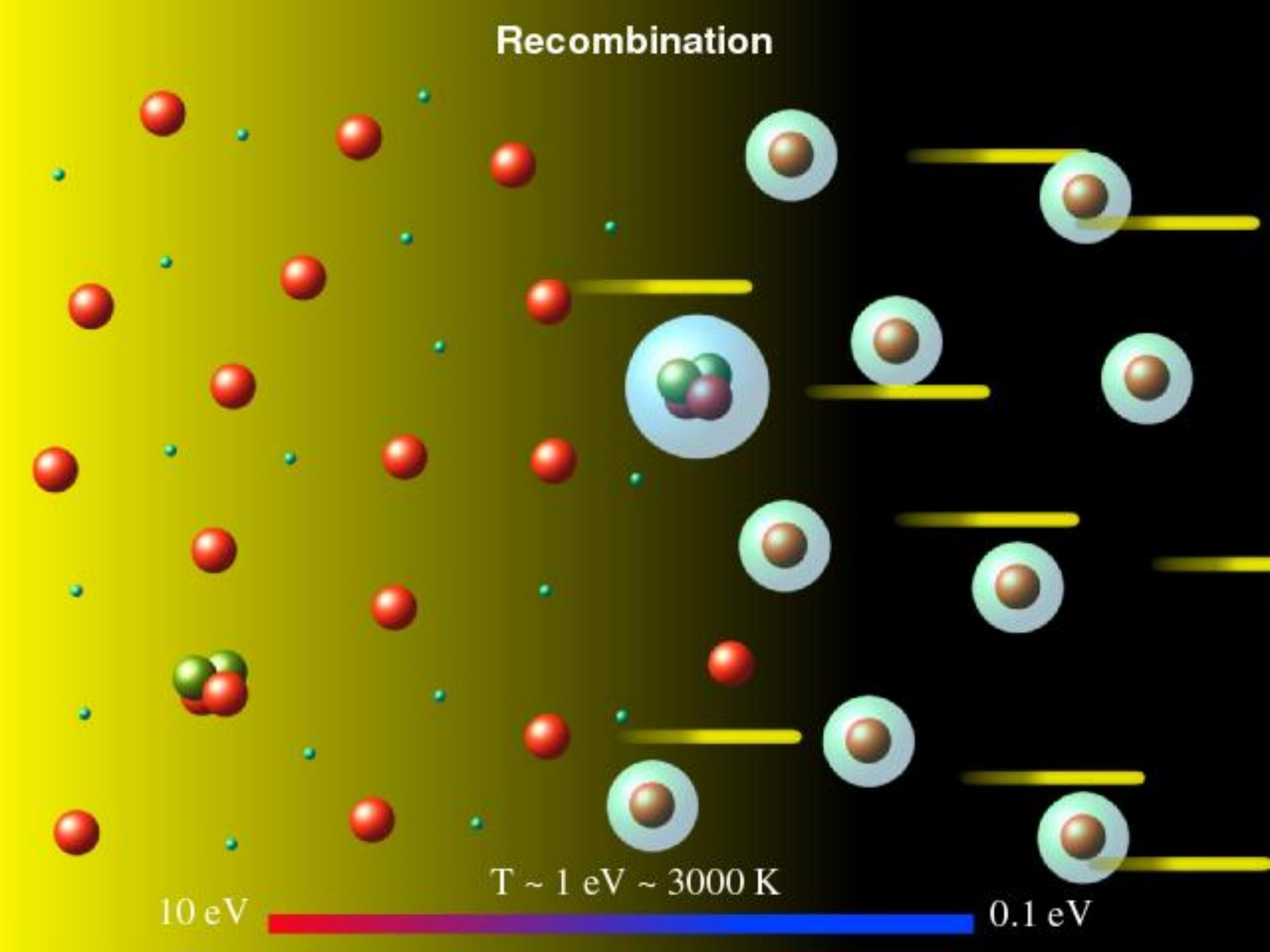
two type

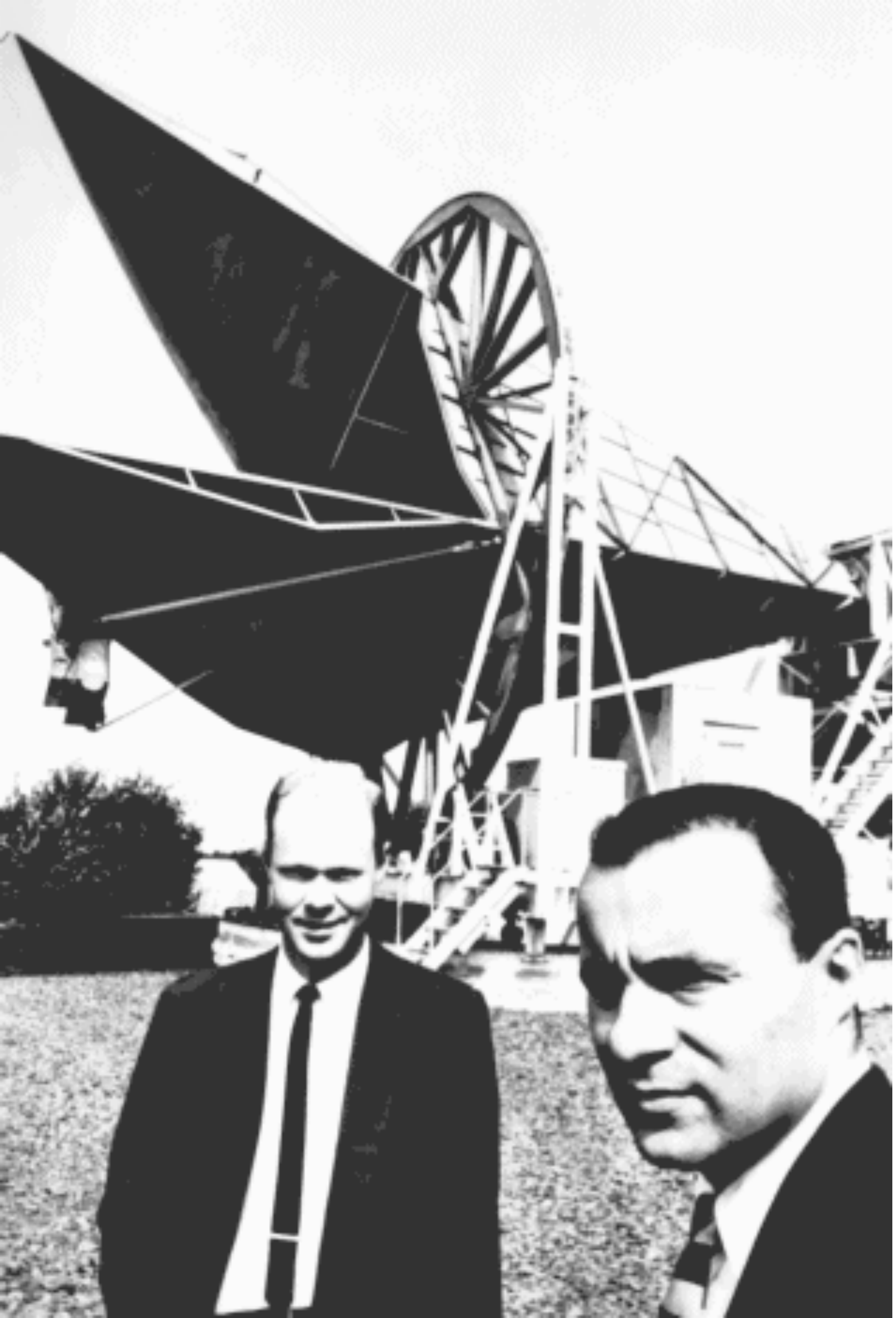
- Scalar (density) spectru $\quad P_S(k) = A_S^2(k_0)\left(\frac{k}{k_0}\right)^{n_S-1}$
- Tensor (GW) spectru $\quad P_T(k) = A_T^2(k_0)\left(\frac{k}{k_0}\right)^{n_T}$



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

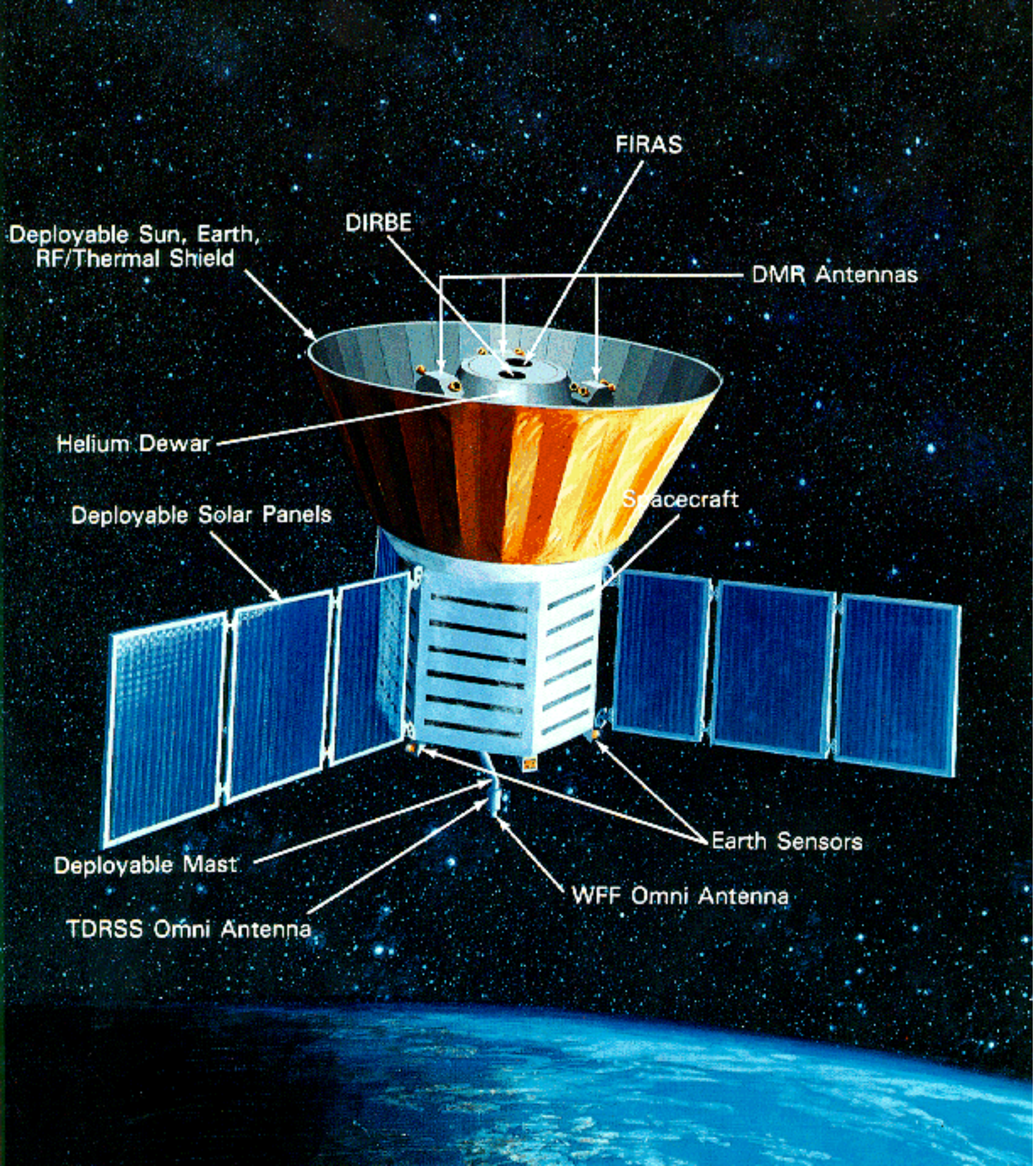
Cosmic Microwave Background

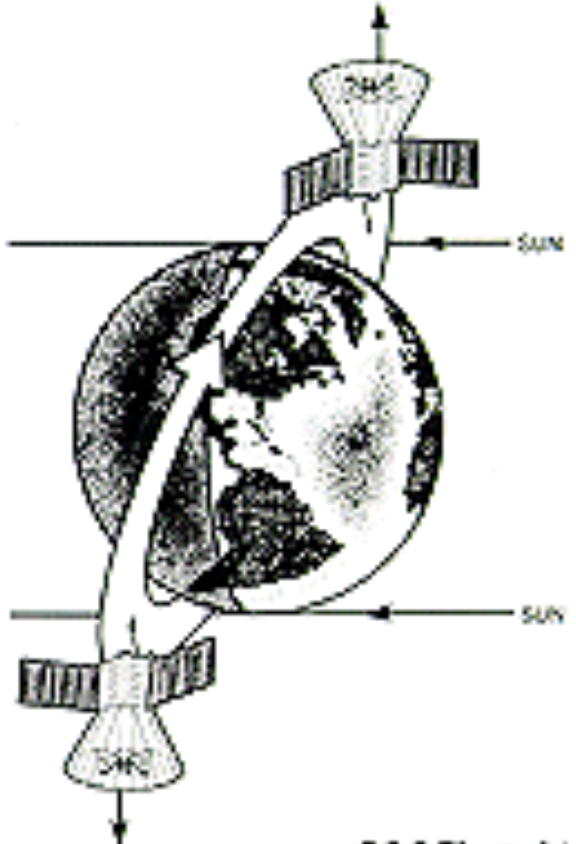

Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV



Discovery of CMB

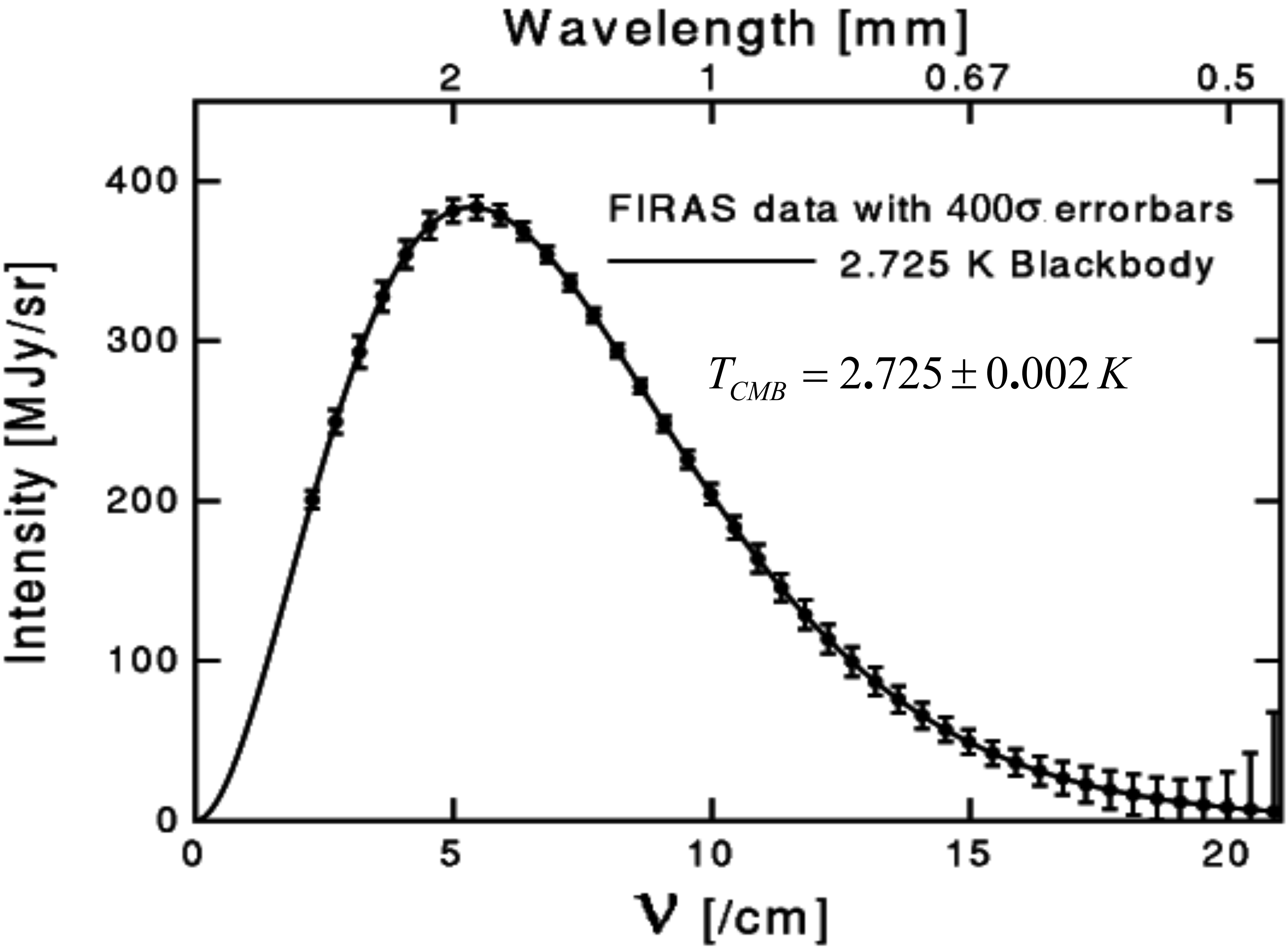
Arno Penzias
Robert Wilson
(1965)

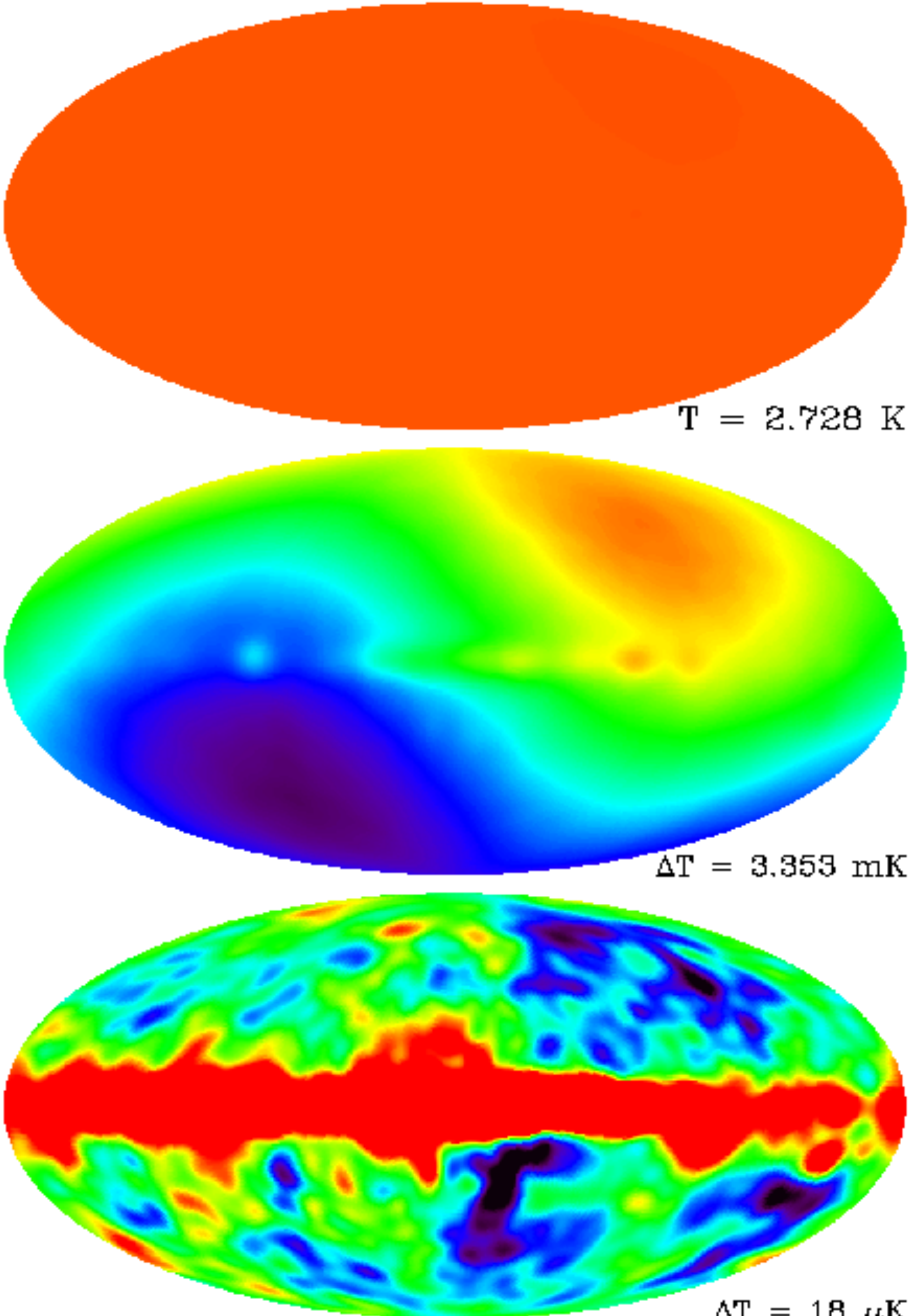




COBE's Orbit

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]



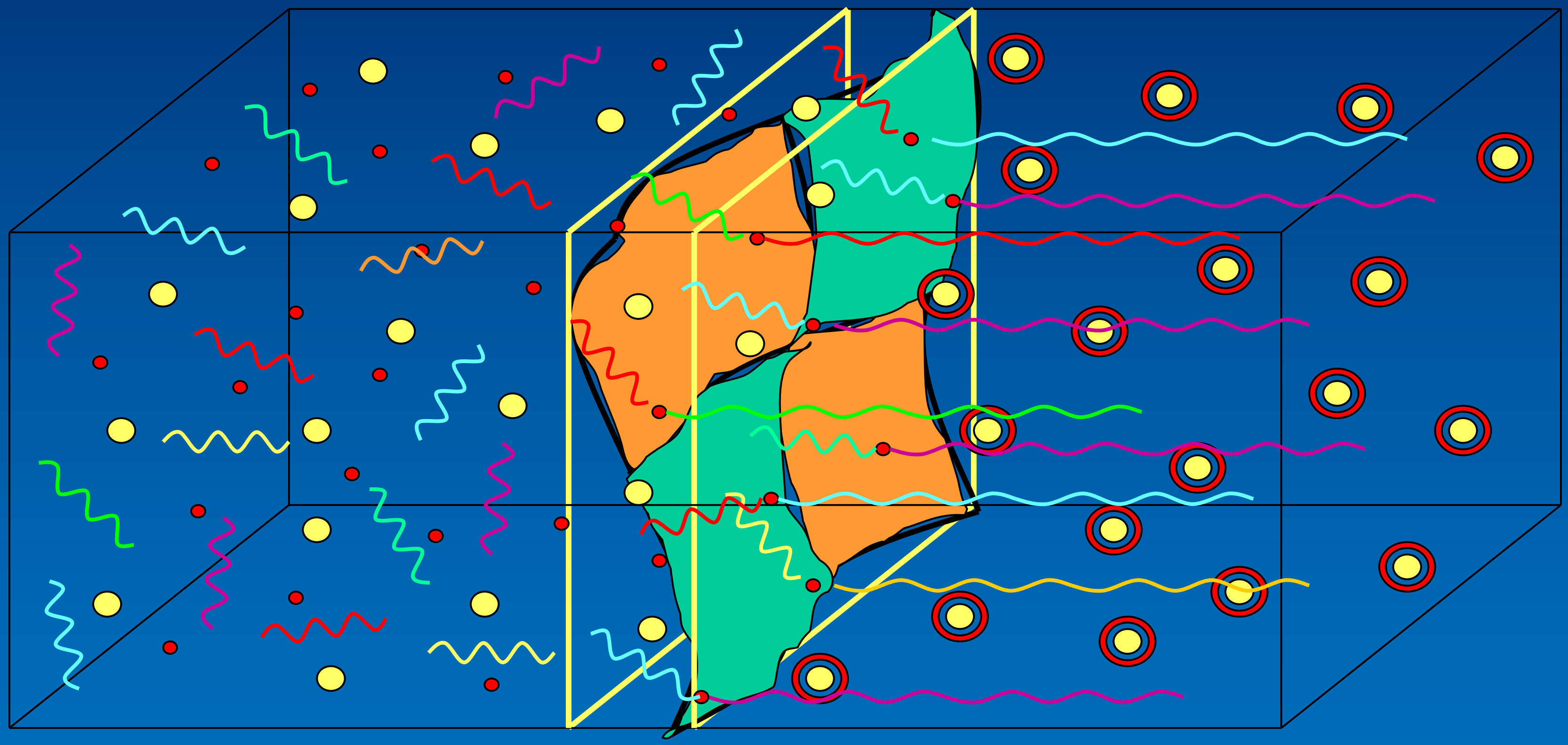
COBE 4-year Measurements (1992-1996)

First Measurements Temperature Anisotropies (1992)

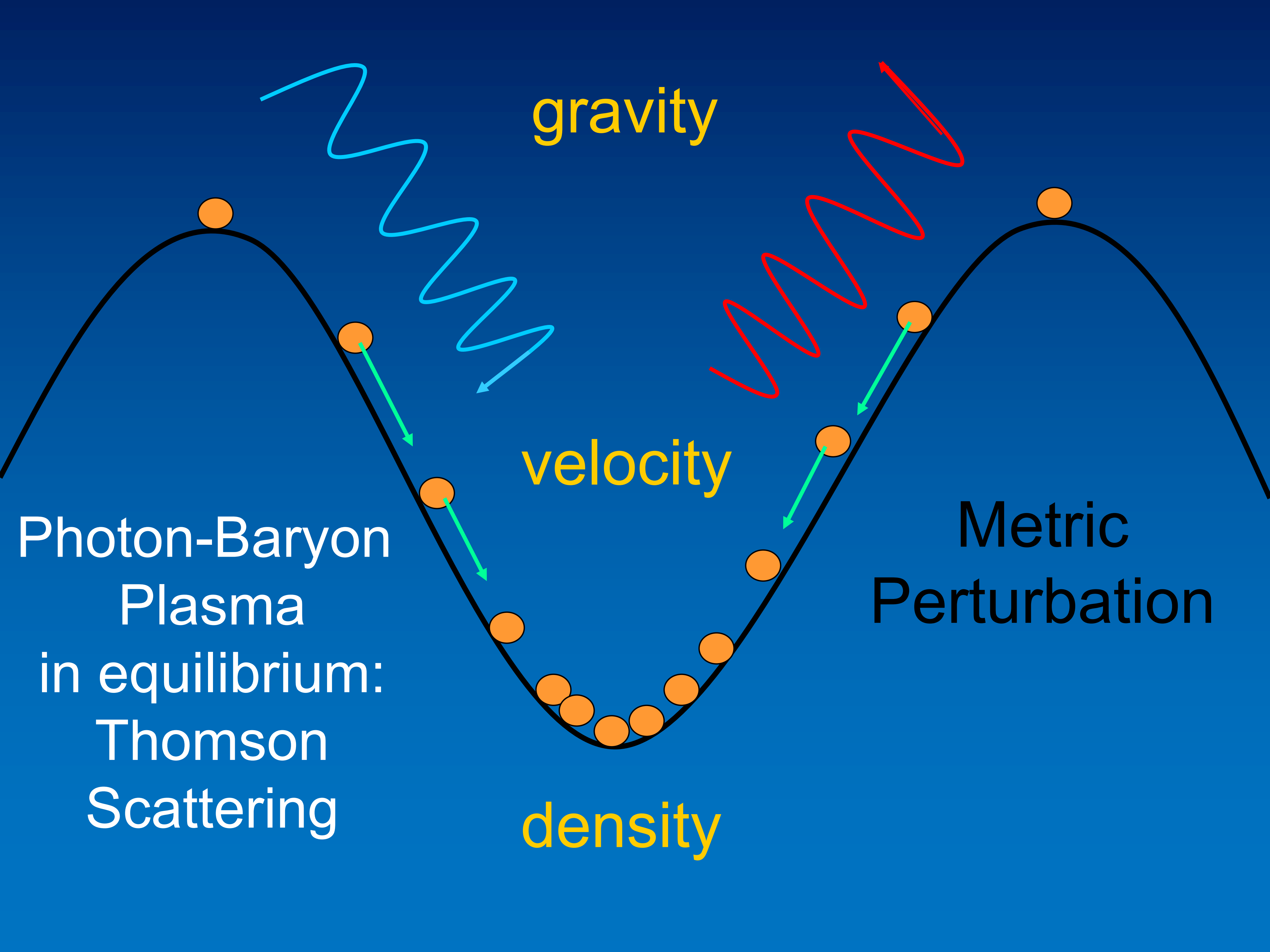
$$\frac{\Delta T}{T_0} \approx 10^{-5}$$

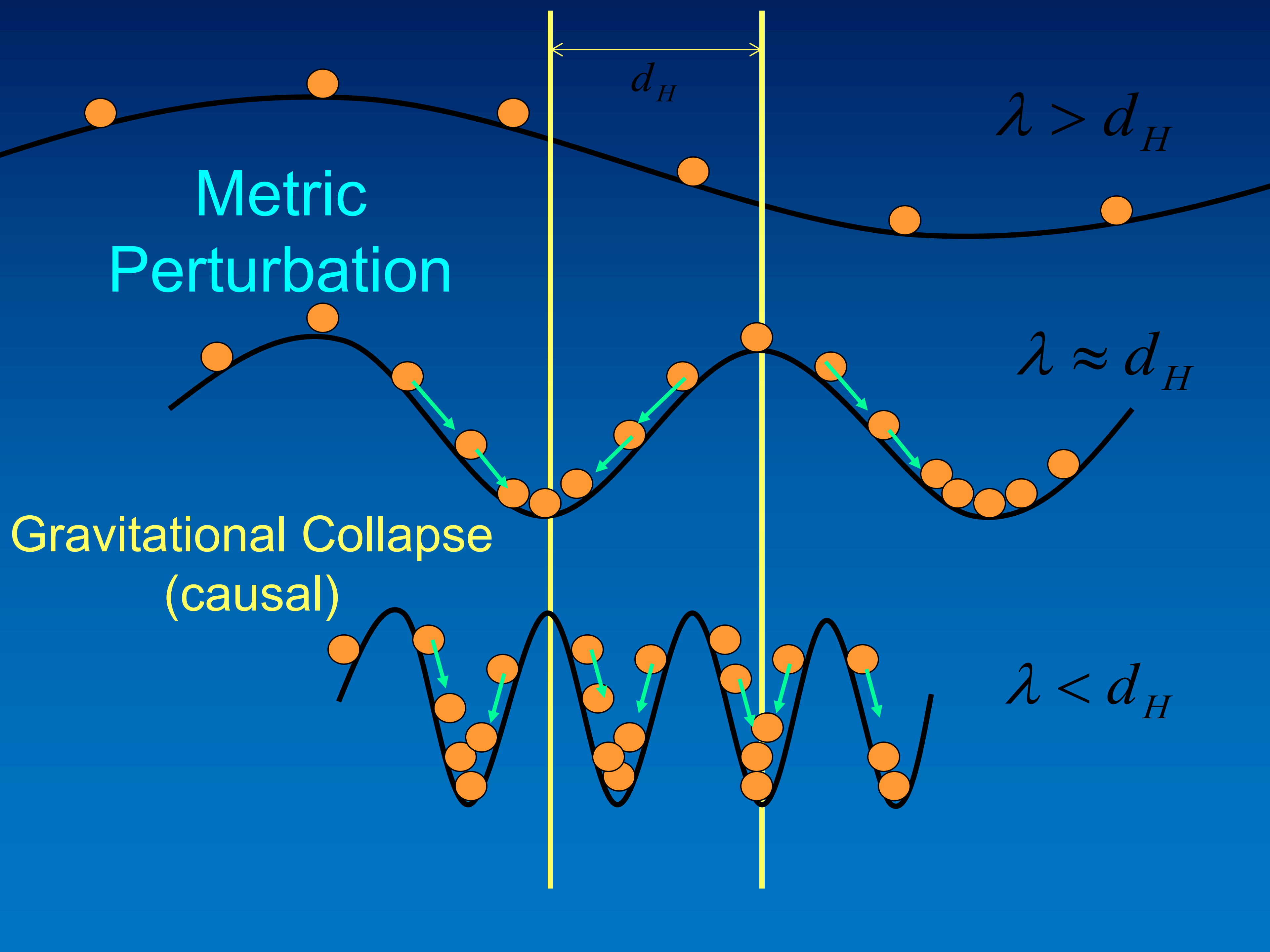
CMB Temperature Anisotropies

The microwave background is a snapshot of the last scattering surface

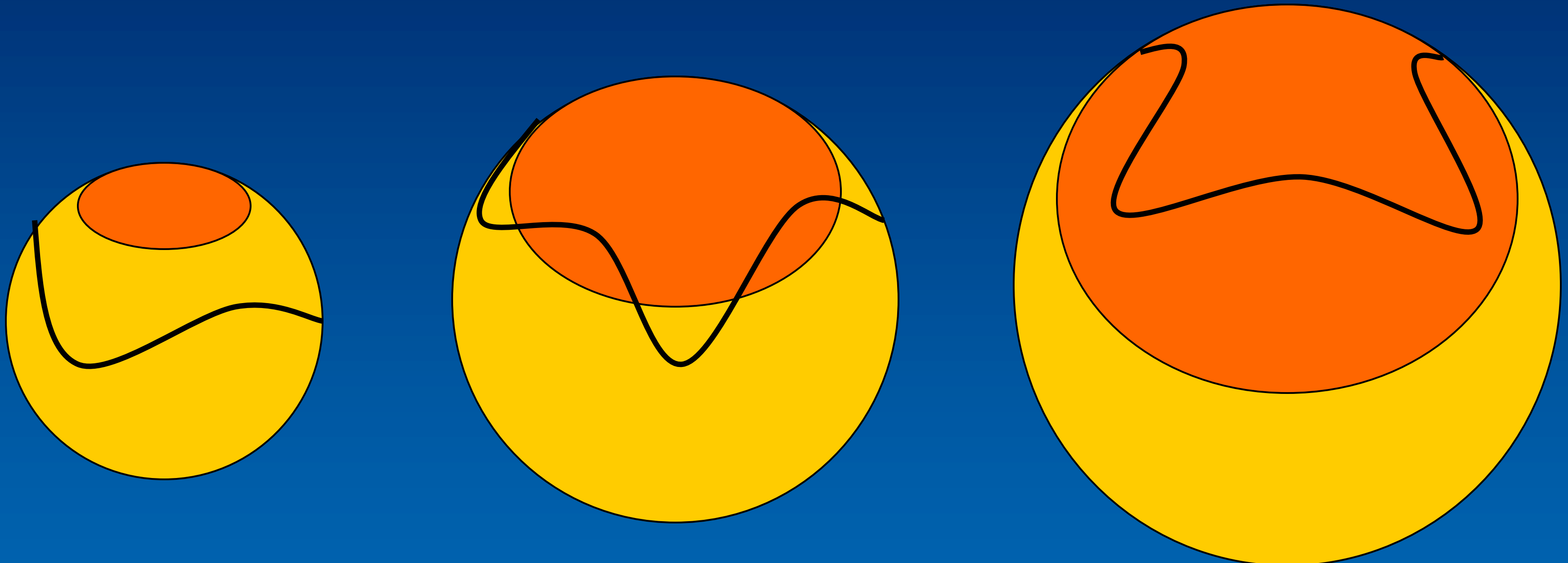


The anisotropies reflect the perturbations in the surface of last scattering


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


d_H
$\lambda > d_H$
Metric
Perturbation
$\lambda \approx d_H$
Gravitational Collapse
(causal)
$\lambda < d_H$

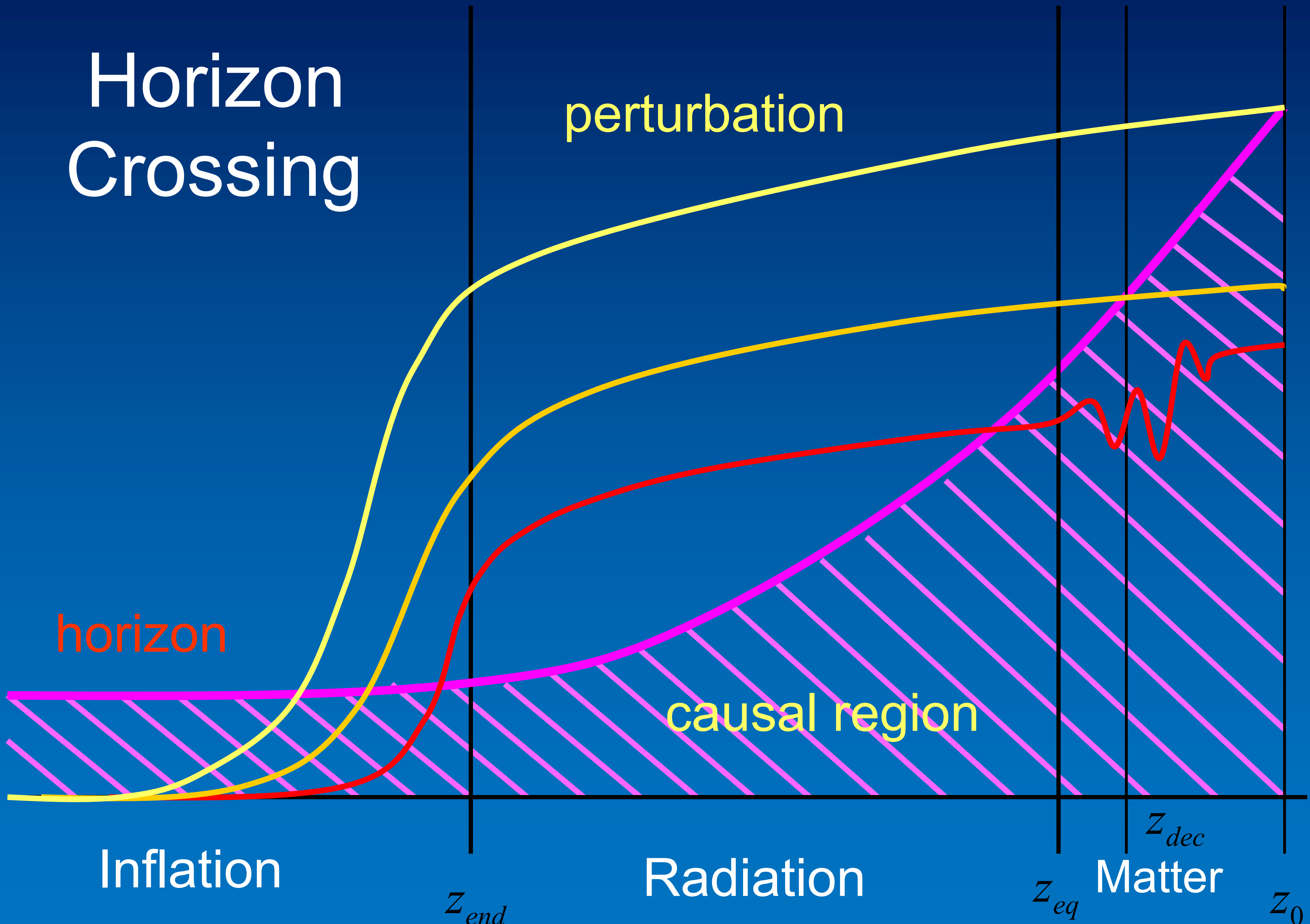
After Inflation

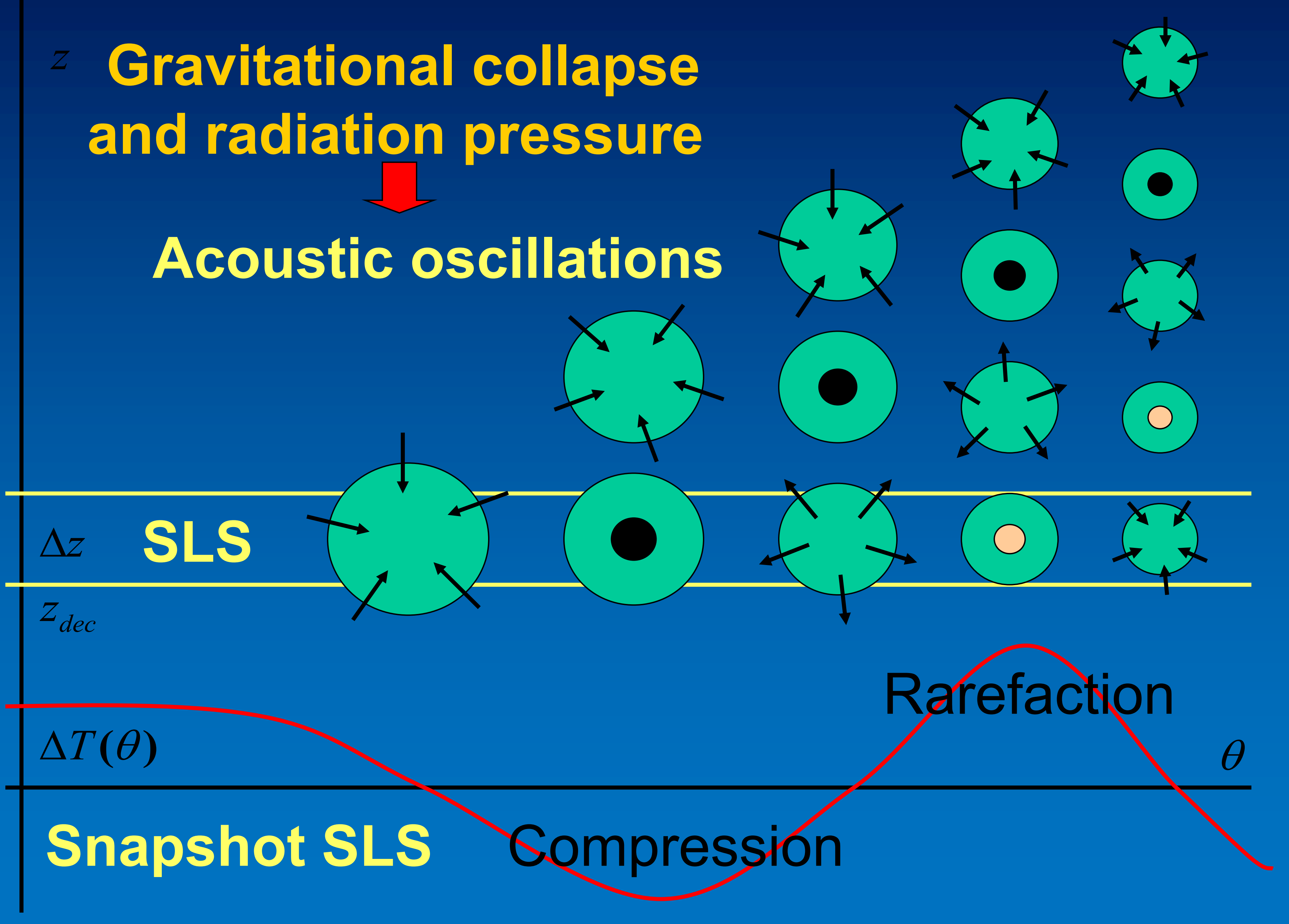


$\lambda > d_H$ $\lambda \approx d_H$ $\lambda < d_H$

Outside Horizon | Enters Horizon | Inside Horizon

Horizon Crossing




z
Gravitational collapse and radiation pressure
Acoustic oscillations
Δz
SLS
z_{dec}
Rarefaction
$\Delta T(\theta)$
θ
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)

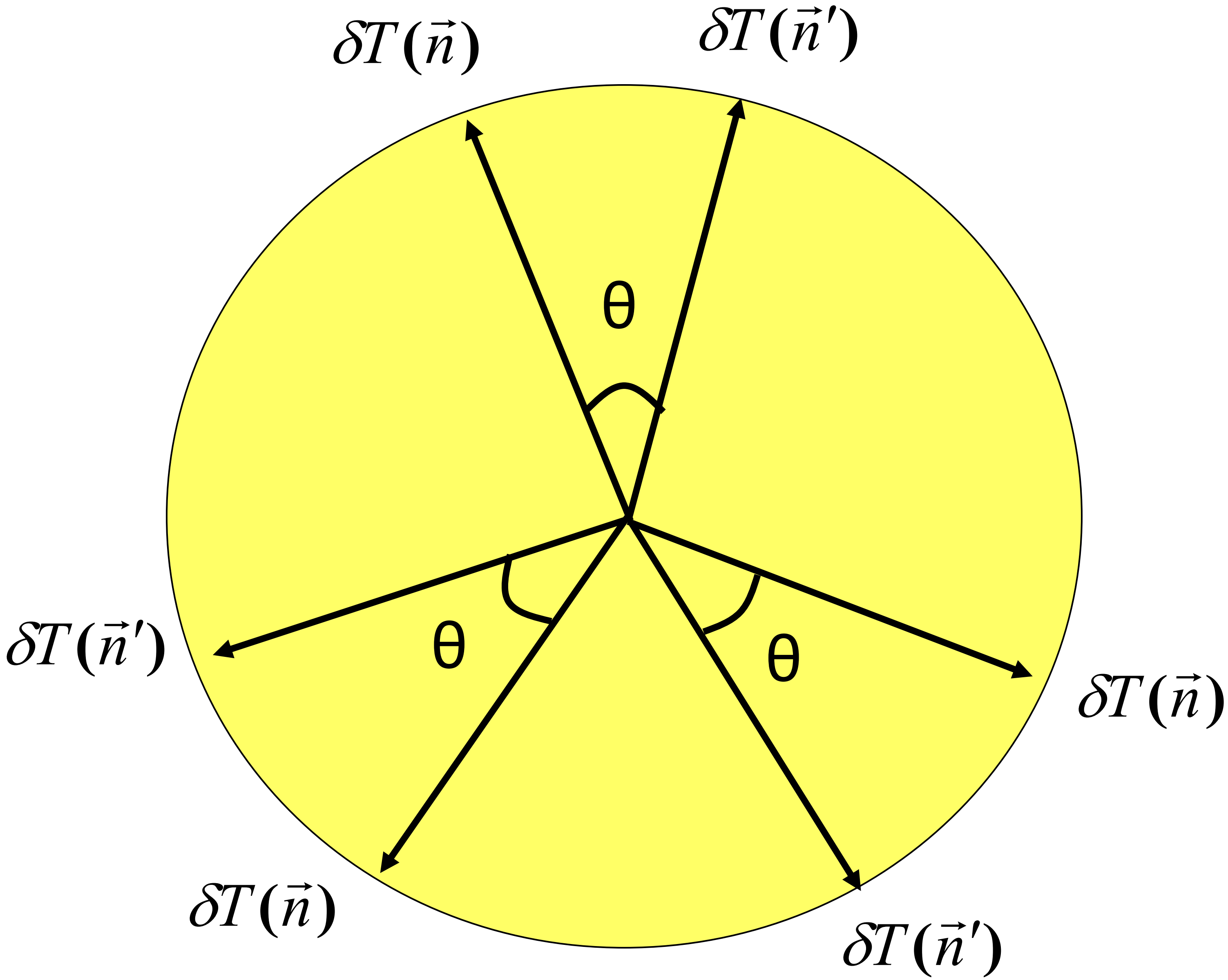
$$\frac{\delta T}{T}(\theta, \phi) = \frac{1}{3}\Phi(\eta_{\rm LS})\,Q(\eta_0, \theta, \phi) + 2\int_{\eta_{\rm LS}}^{\eta_0} dr\,\Phi'(\eta_0 - r)\,Q(r, \theta, \phi)$$

$Q(\mathbf{x})$ 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

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm}\, Y_{lm}(\theta,\phi)$$

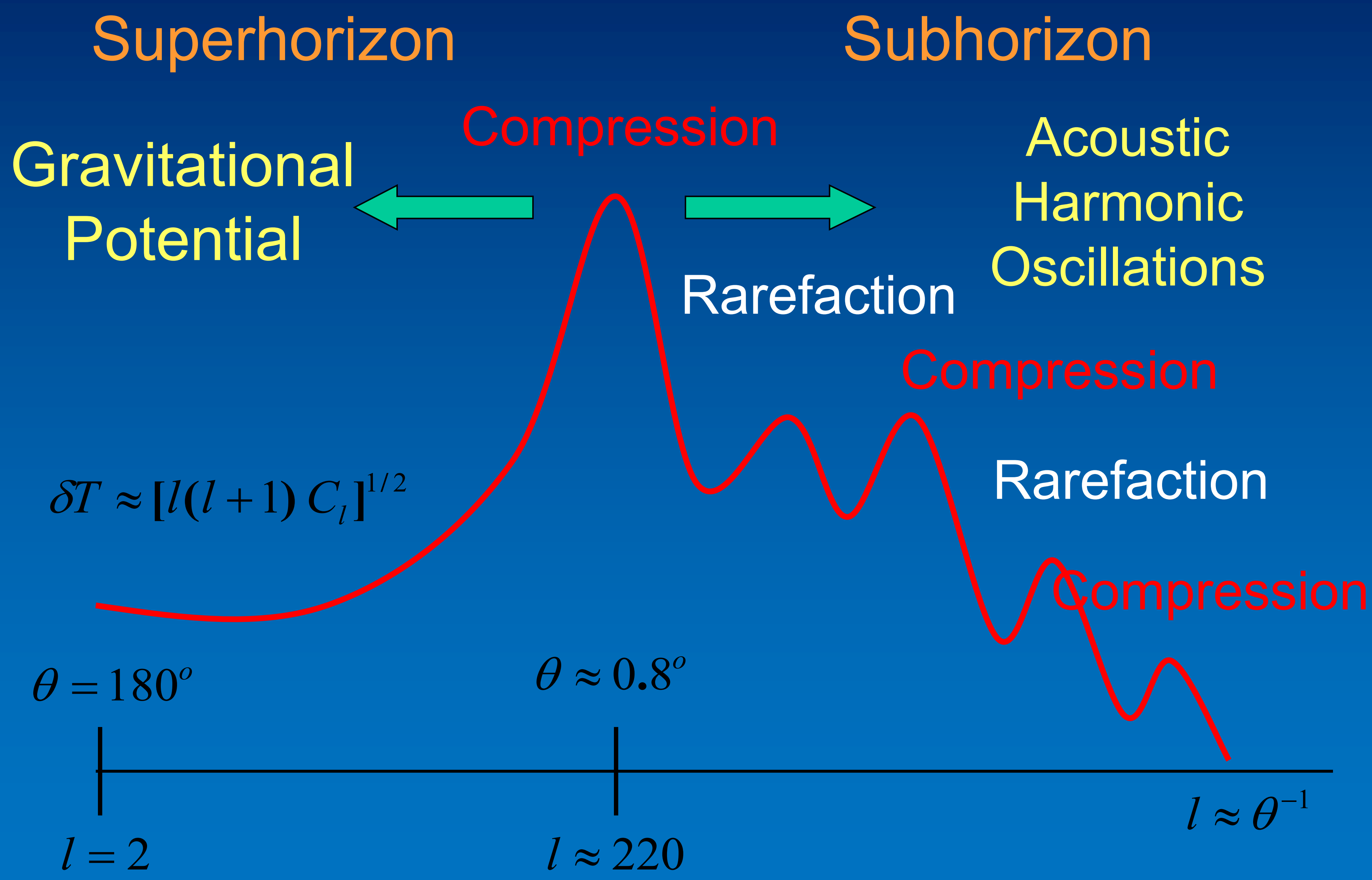
$$C(\theta) = \left\langle \delta T^*(\vec{n})\, \delta T(\vec{n}') \right\rangle_{n\cdot n' = \cos\theta} = \sum_{l=2}^{\infty} \frac{2l+1}{4\pi} C_l\, P_l(\cos\theta)$$

$$C_l^S = \frac{4\pi}{25} \int_0^\infty \frac{dk}{k} P_S(k)\, j_l^2(kr) \qquad P_S(k) = A_S^2 \left(\frac{k}{k_*}\right)^{n-1}$$

Sachs-Wolfe plateau

$$\frac{l(l+1)C_l^S}{2\pi} = \frac{A_S^2}{25} = const$$

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

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

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

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

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

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

SACHS-WOLFE PLATEAU

gauge-invariant tensor perturbation

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

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

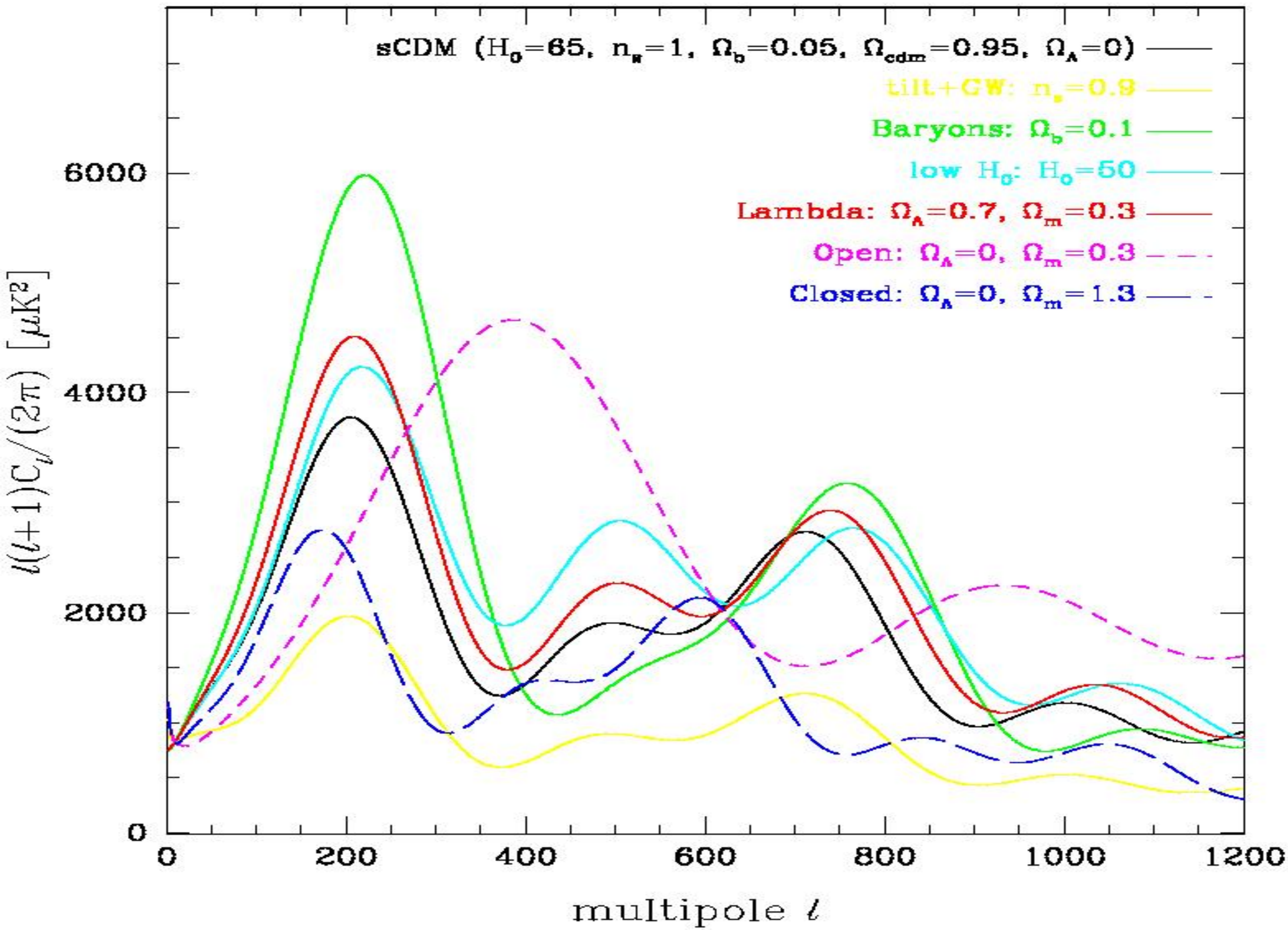
Q_{rr} is rr-component of tensor harmonic along line of sight

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

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

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

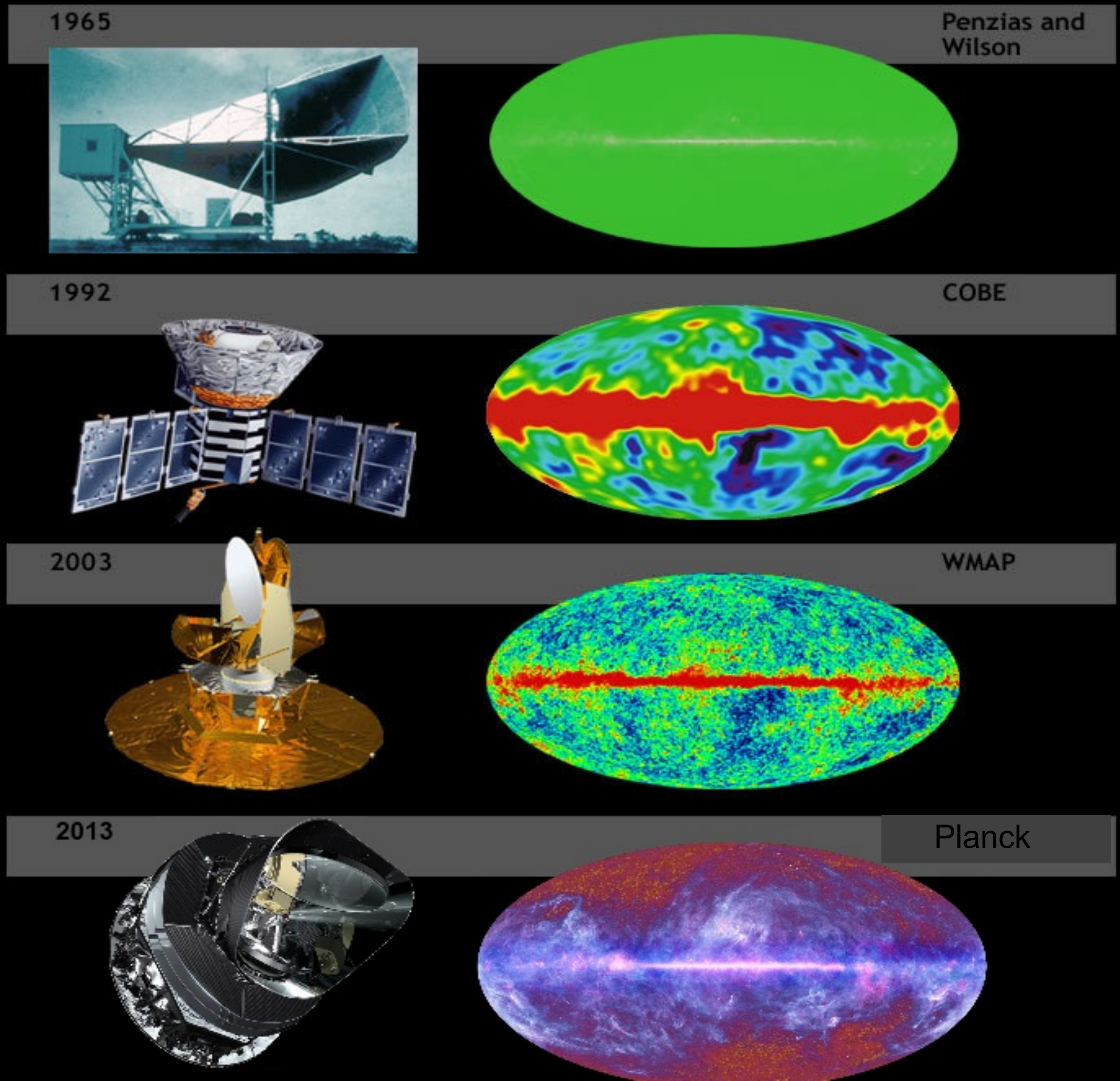
$$B_l = (1.1184, 0.8789, \ldots, 1.00) \ \text{ for } l = 2, 3, \ldots, 30$$

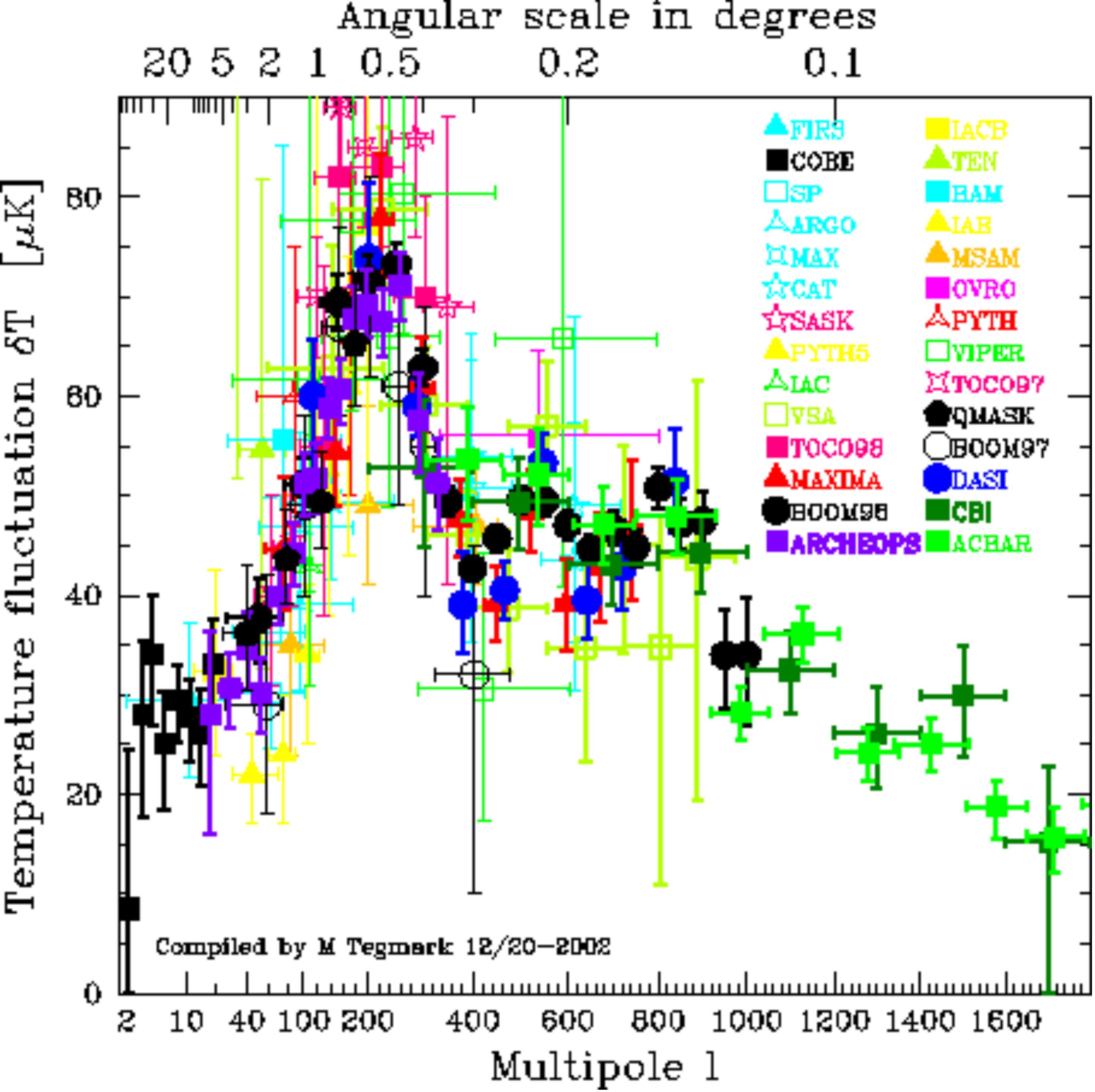


sCDM (H_0=65, n_s=1, Ω_b=0.05, Ω_{cdm}=0.95, Ω_Λ=0)
tilt+GW: n_s=0.9
Baryons: Ω_b=0.1
low H_0: H_0=50
Lambda: Ω_Λ=0.7, Ω_m=0.3
Open: Ω_Λ=0, Ω_m=0.3
Closed: Ω_Λ=0, Ω_m=1.3
0
2000
4000
6000
$l(l+1)C_l/(2\pi)$ $[\mu K^2]$
0
200
400
600
800
1000
1200
multipole l

Degeneracies in the determination of parameters

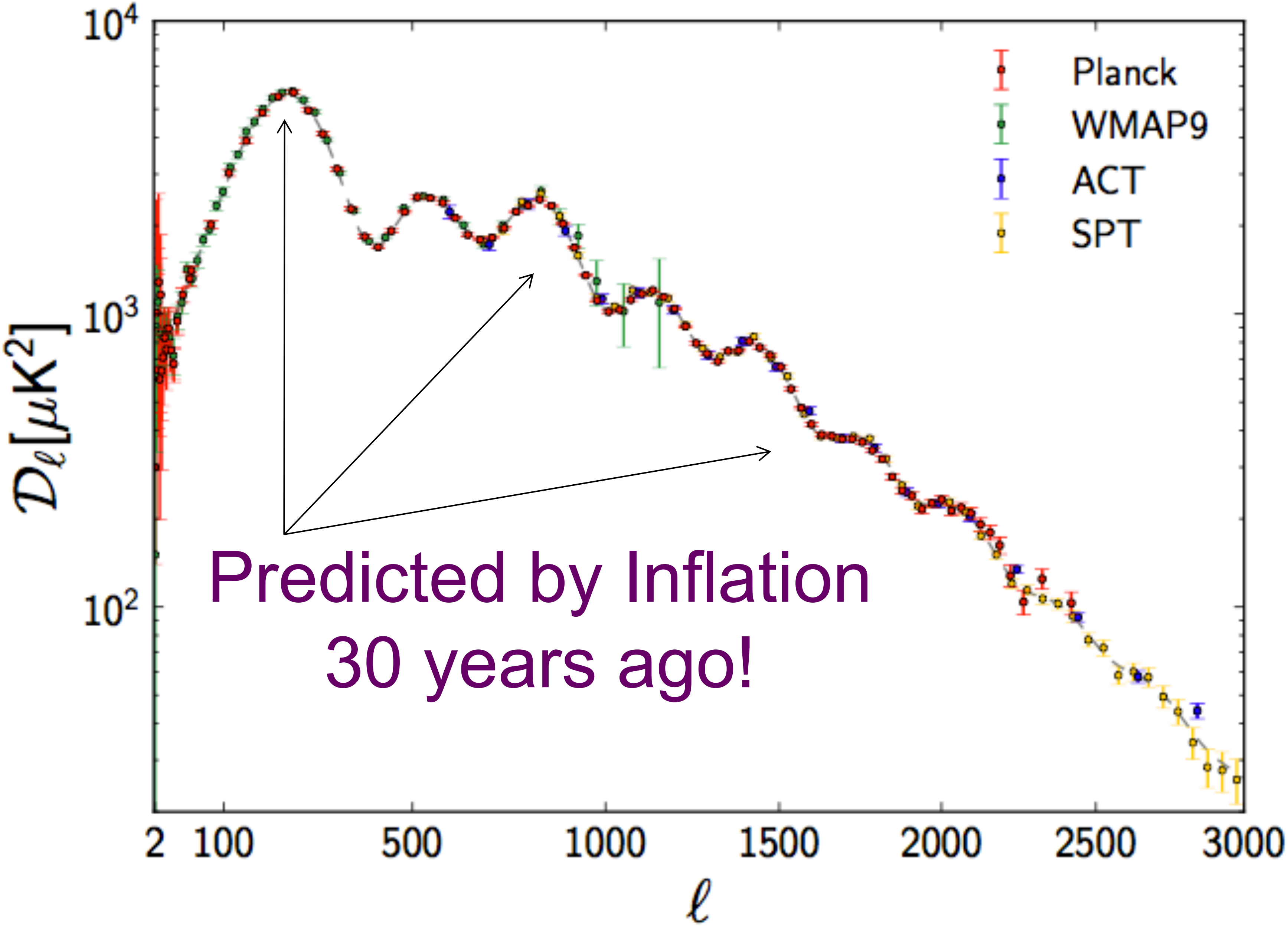
It is necessary to make a multiparameter fit with the largest possible data set

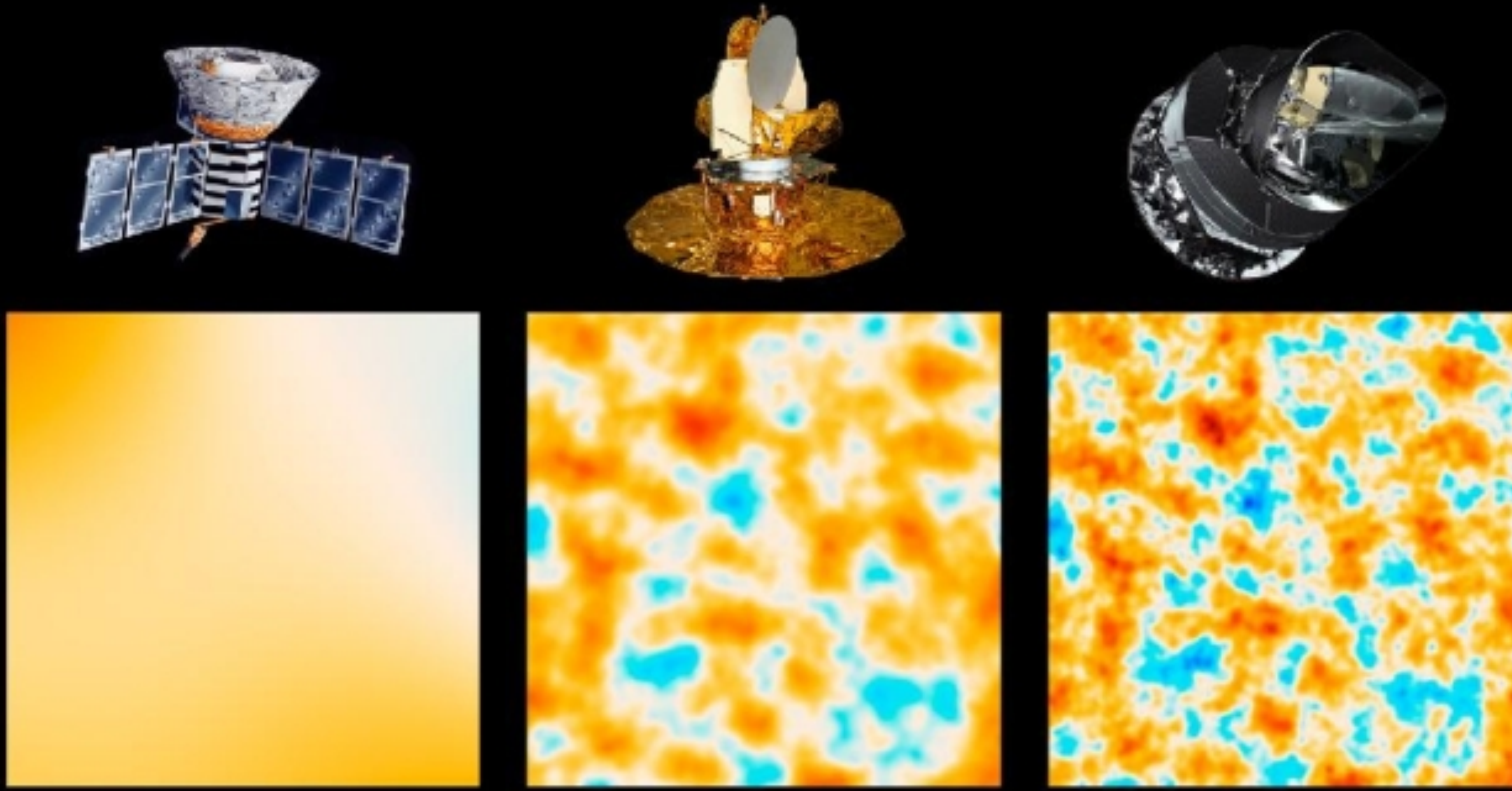

1965
Penzias and Wilson
1992
COBE
2003
WMAP
2013
Planck



All CMB Exp. (2002)

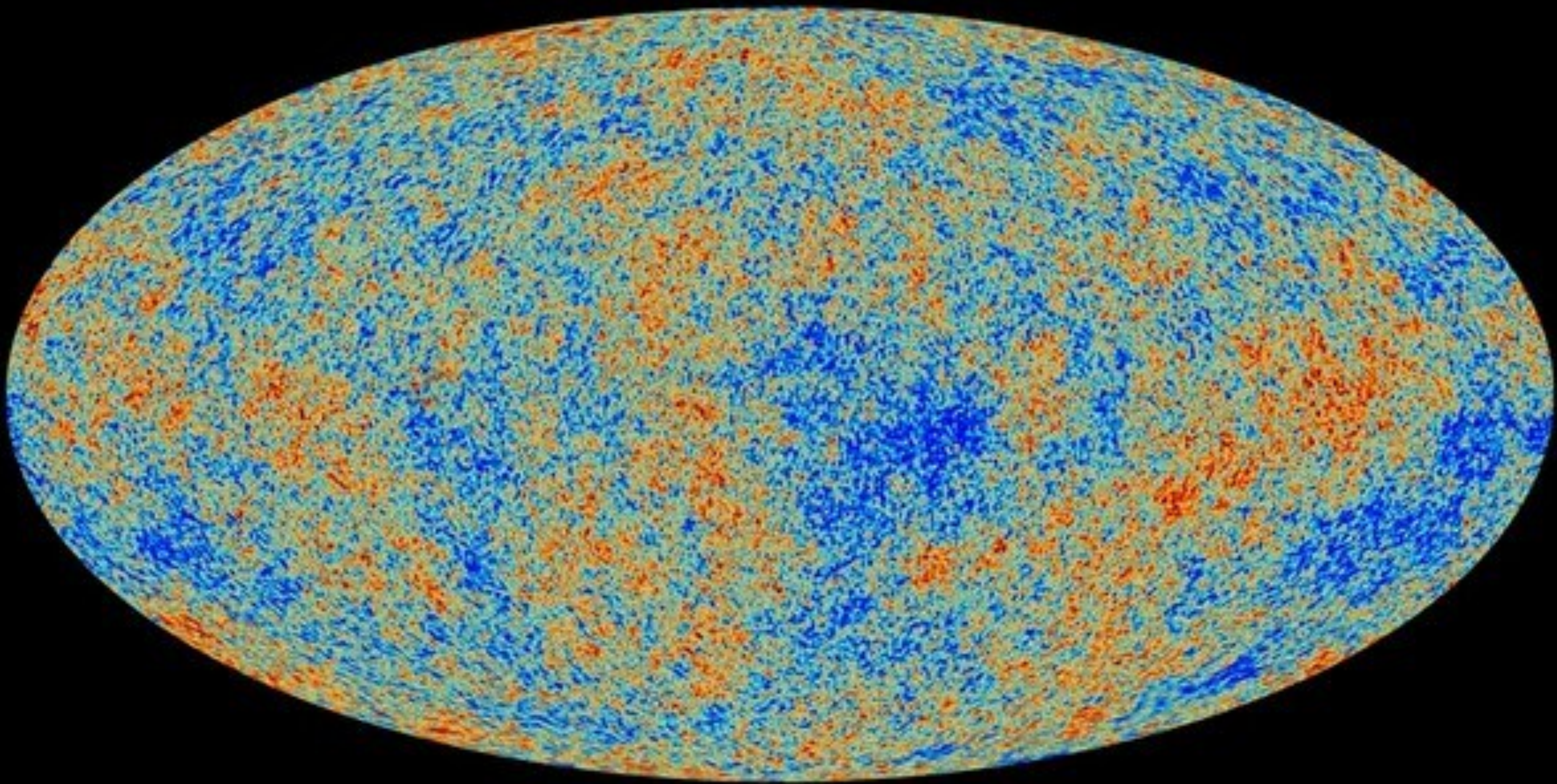
Planck Power Spectrum (2015)

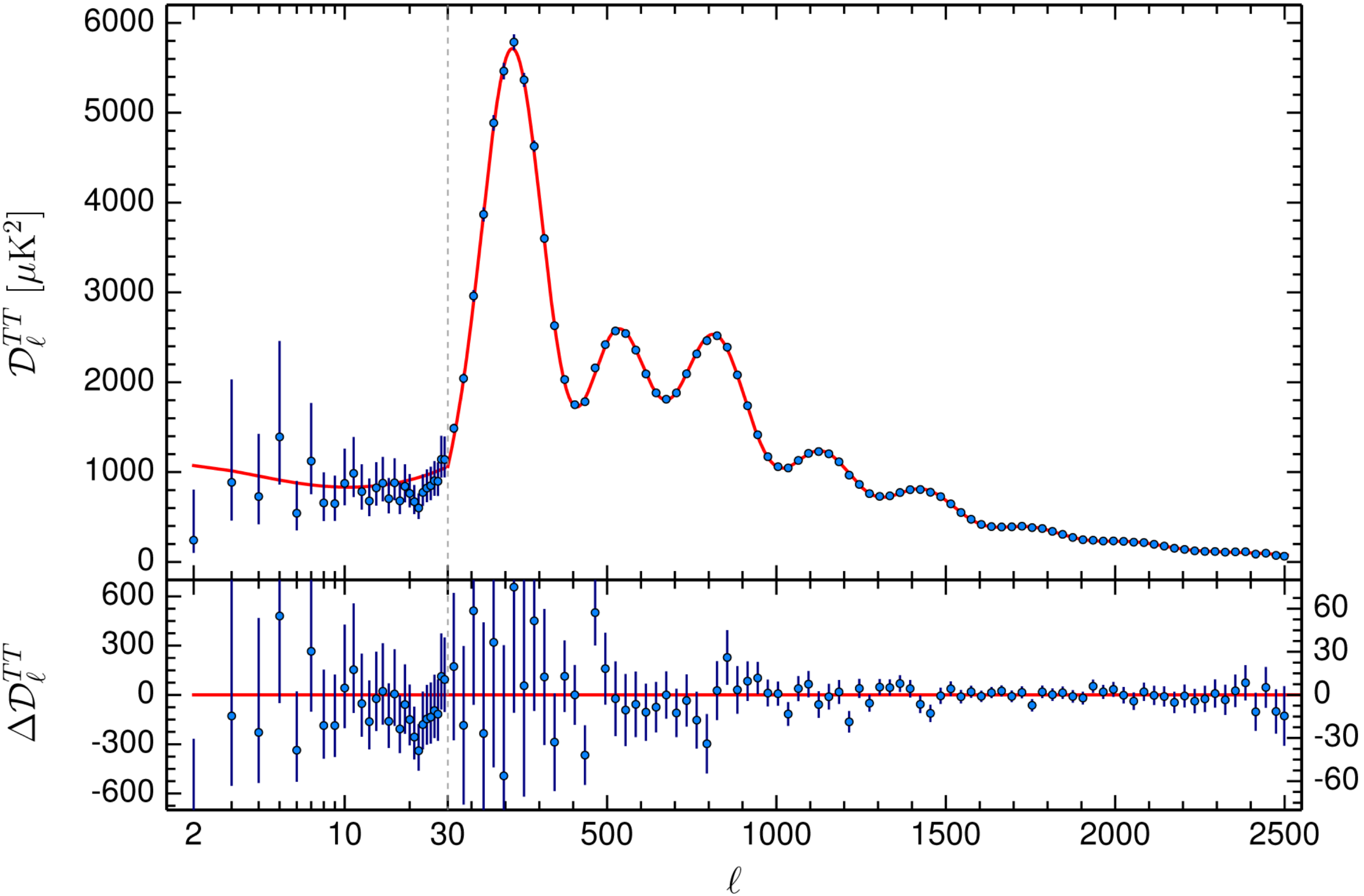




COBE WMAP Planck

Planck (2015)

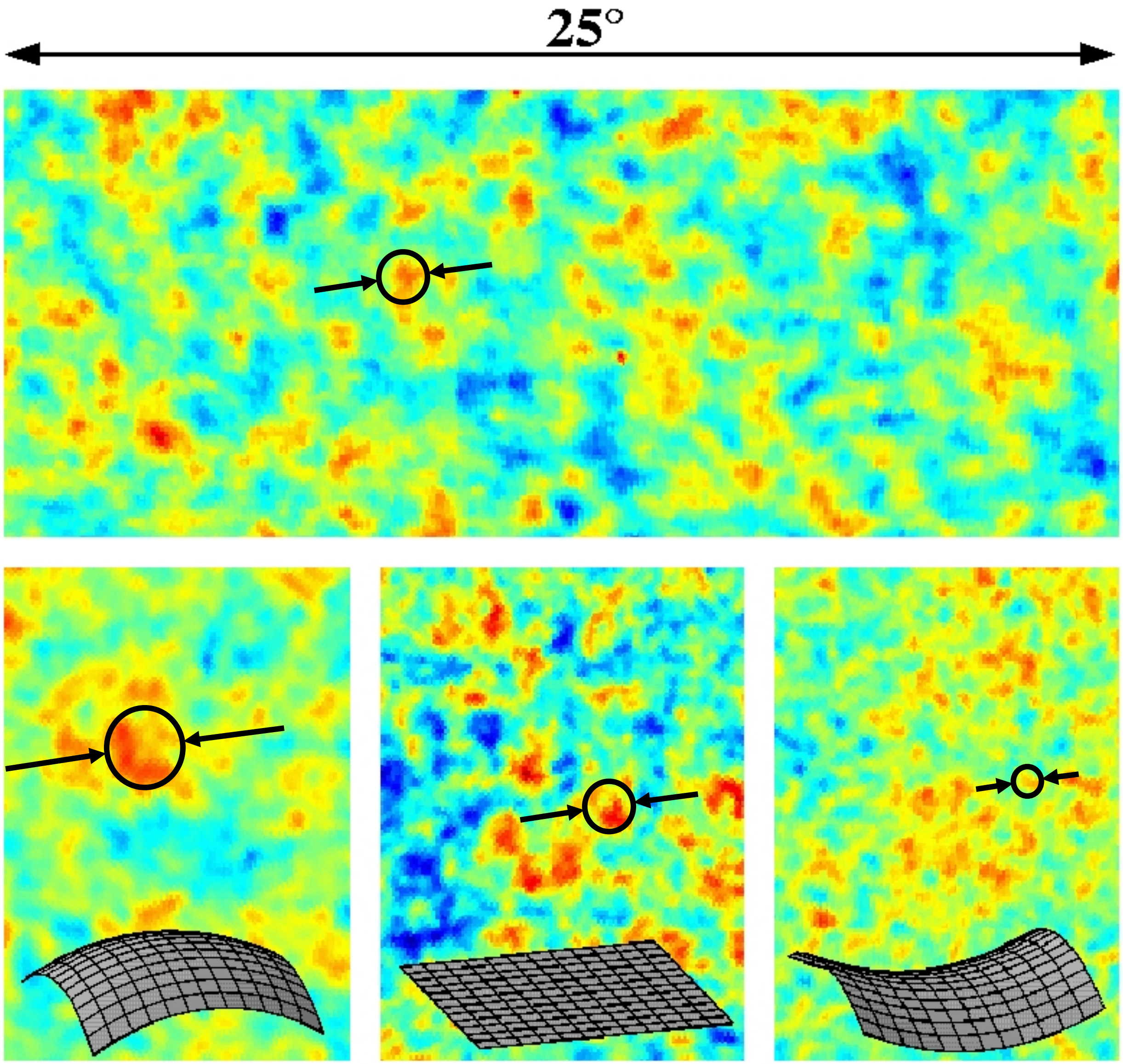


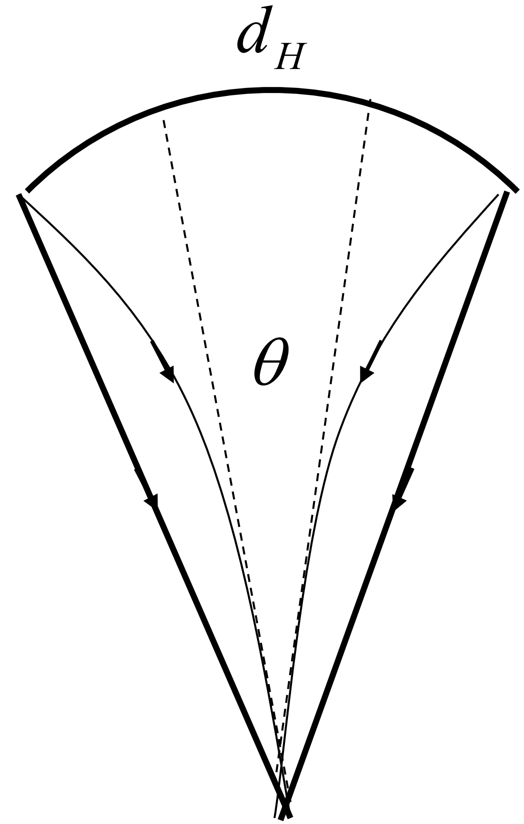


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
60
30
0
-30
-60
$\Delta\mathcal{D}_\ell^{TT}$
2
10
30
500
1000
1500
2000
2500
ℓ

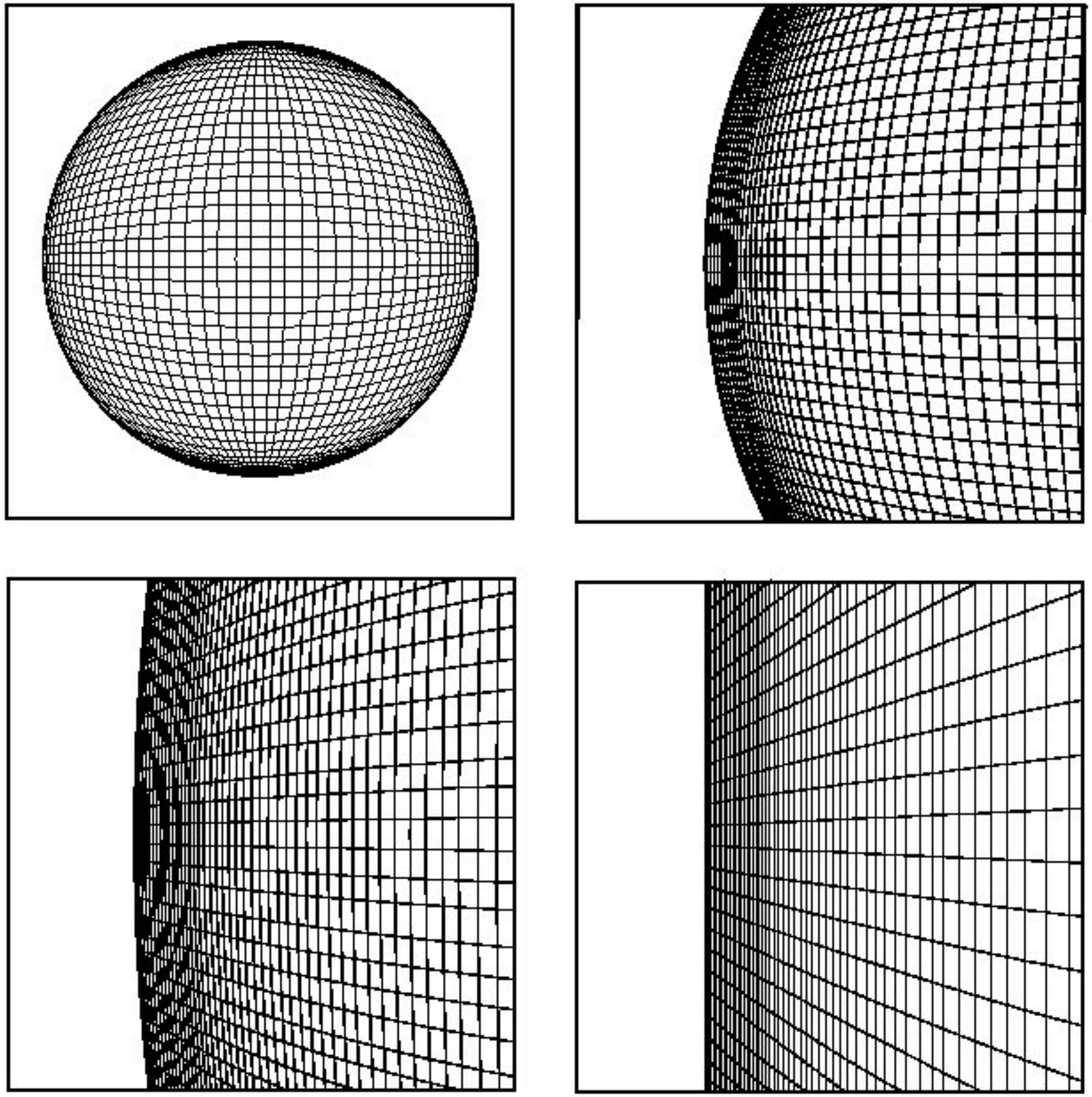
$\Omega_K = |\Omega_0 - 1| < 0.0005 \pm 0.000$ Planck (2015)

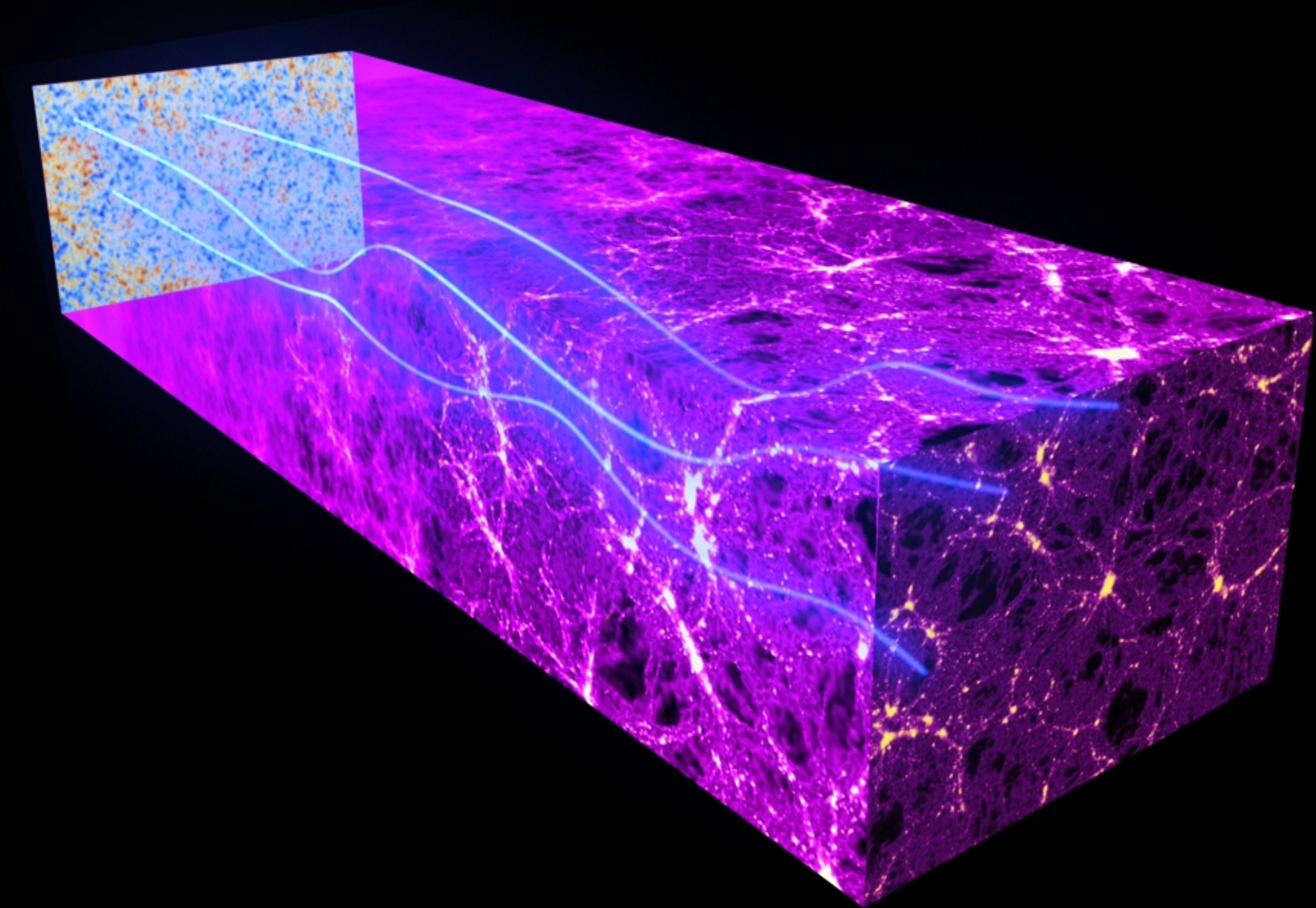
Spatial Curvature



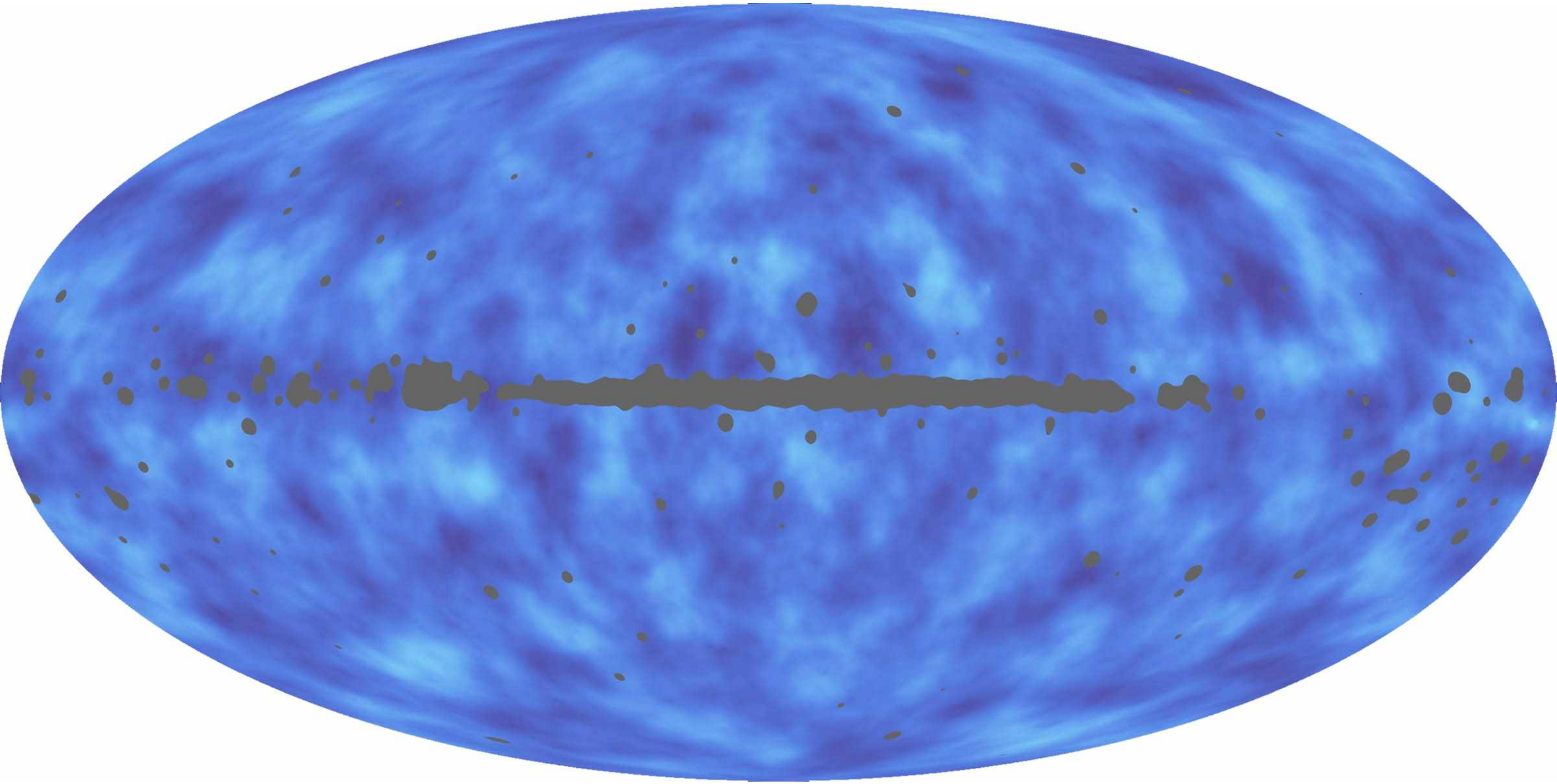


geodesics

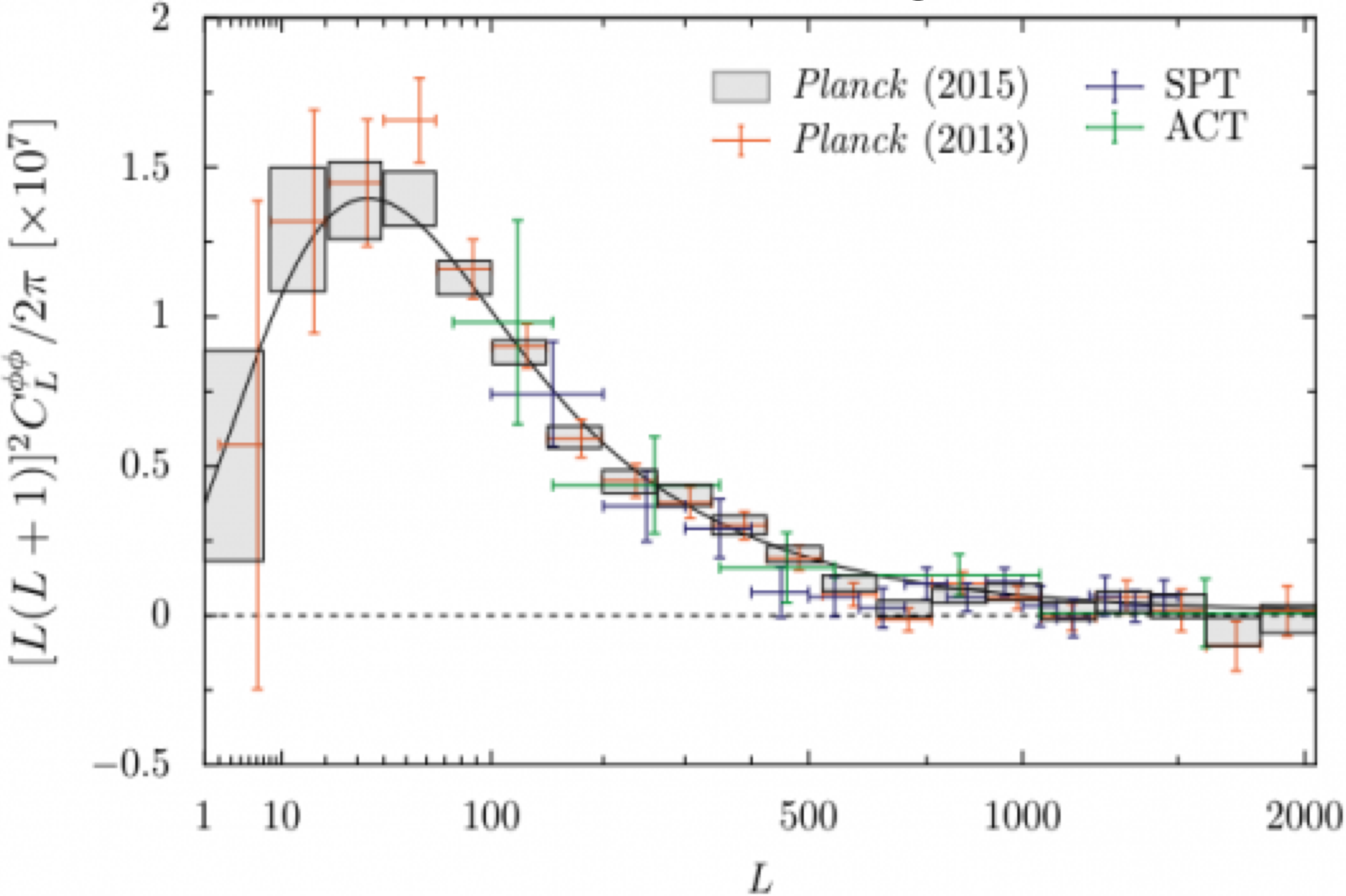




CMB lensing



CMB lensing



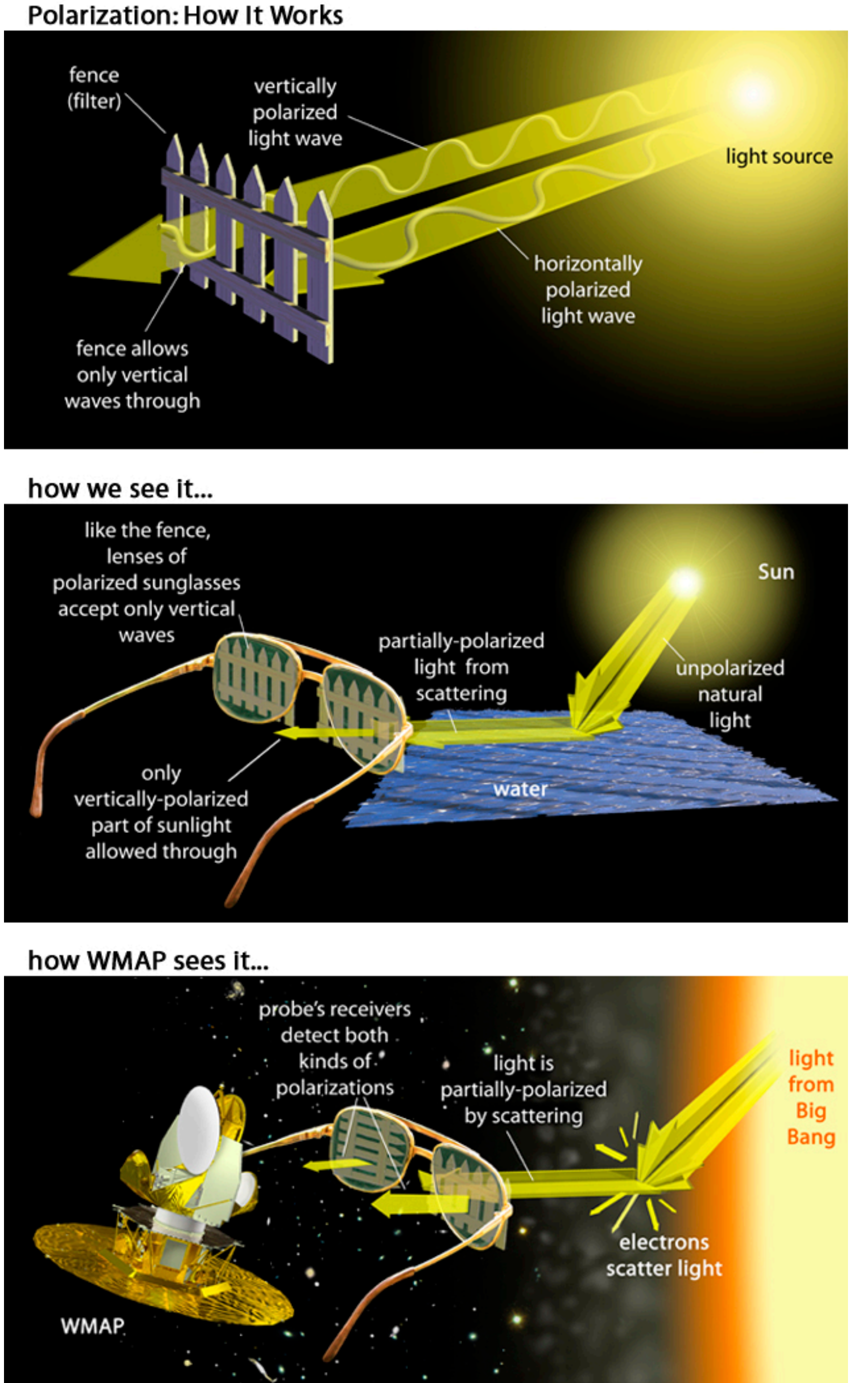
Planck (2015)
Planck (2013)
SPT
ACT
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
L
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000

	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

Table 5. Best-fit values and 68% confidence limits for the base ΛCDM model. Beam and calibration parameters, and additional nuisance parameters for "highL" data sets are not listed for brevity but may be found in the Explanatory Supplement (Planck Collaboration ES 2013).

Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

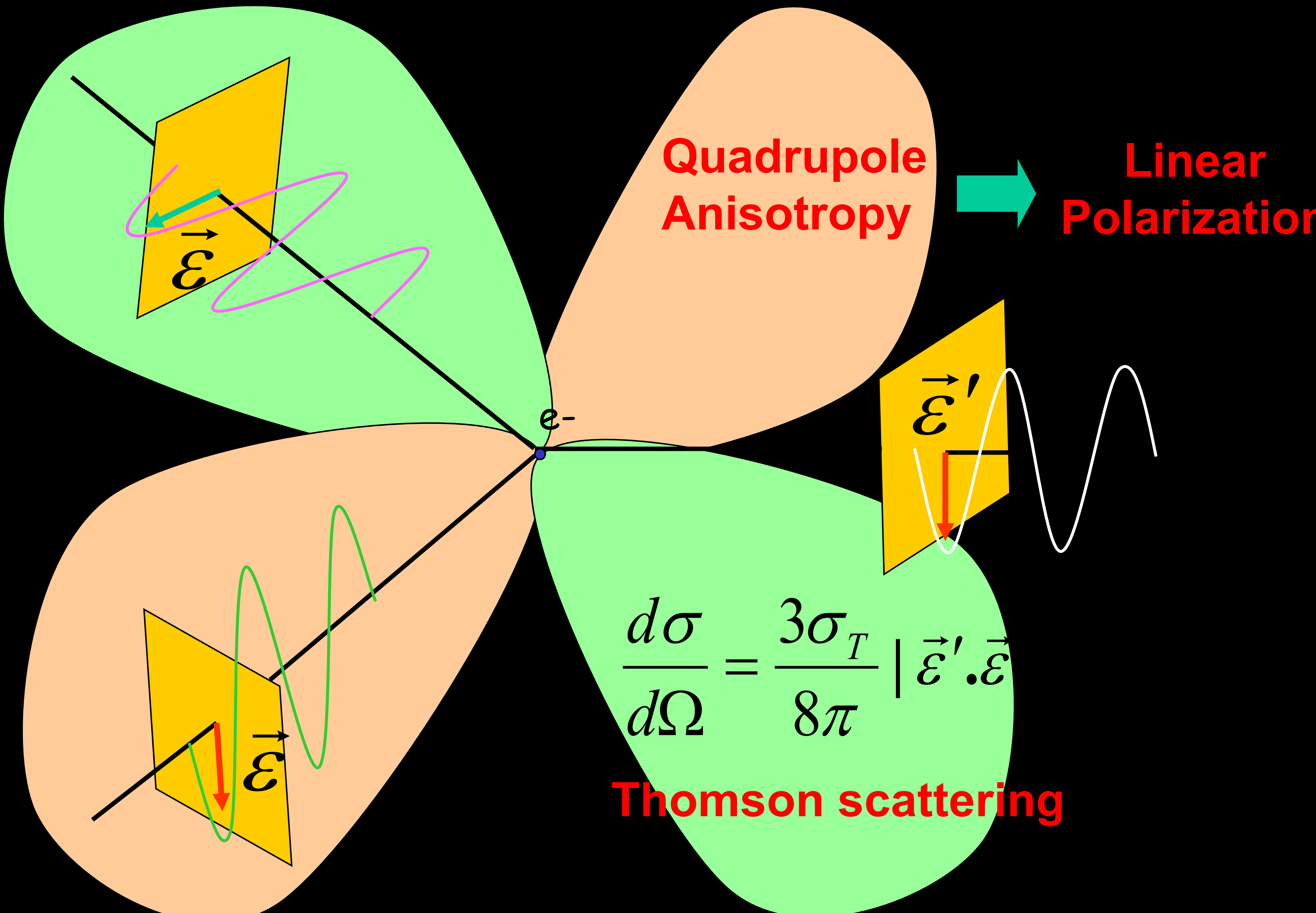
CMB Polarization Anisotropies



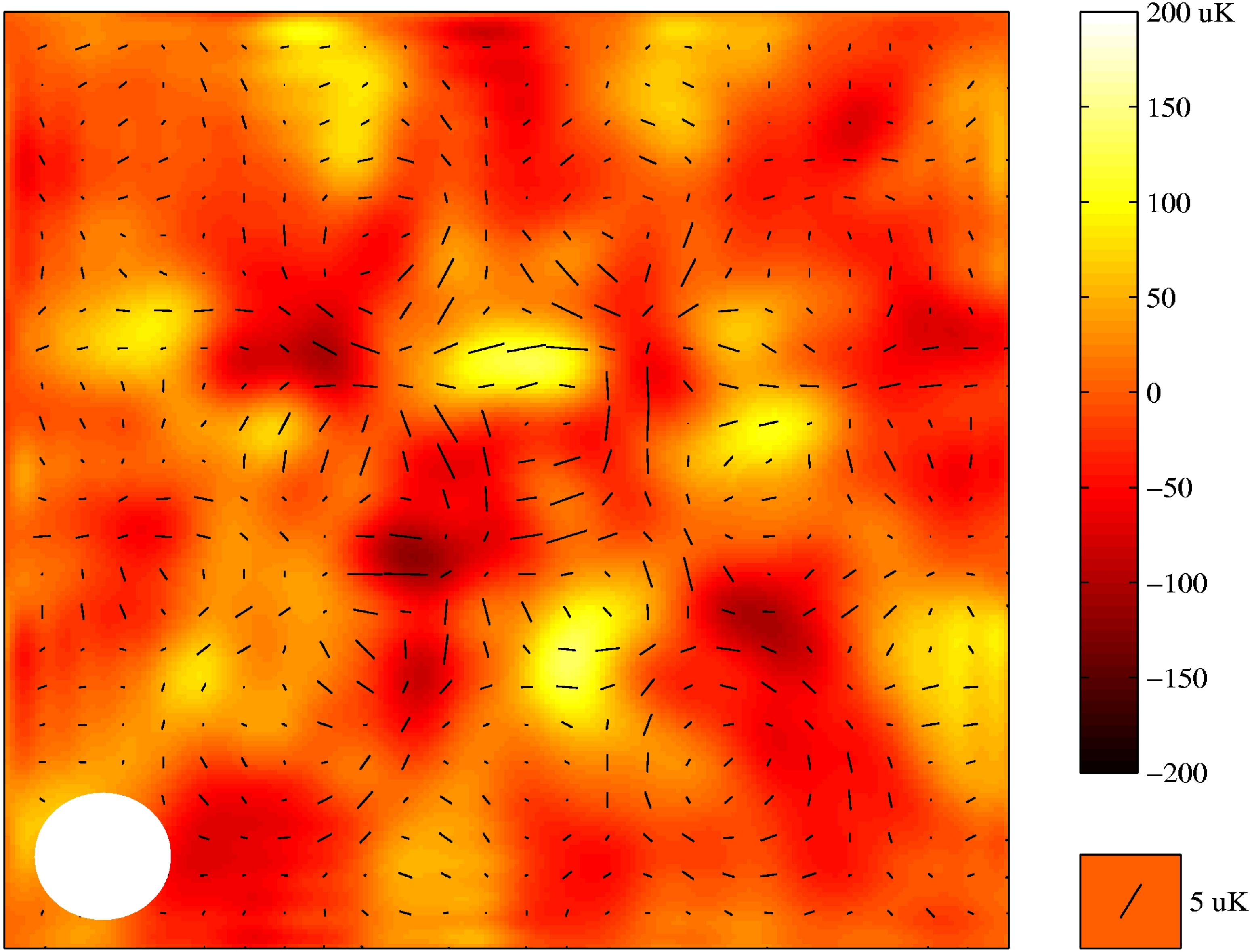
Light carries energy and polarization (vector field)

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

Linear Polarization of CMB

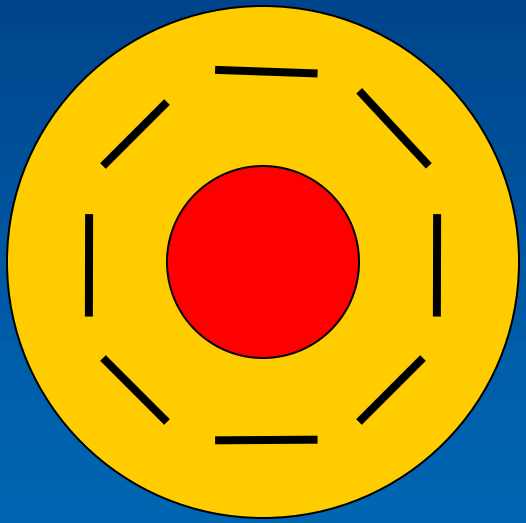


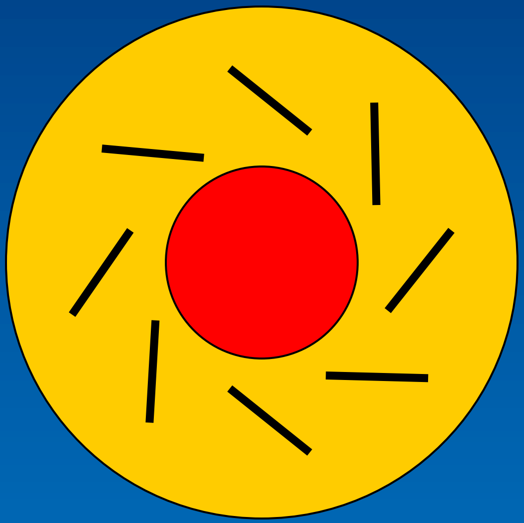
DASI: First measurement Polarization (2002)



Map is 5 degrees square

Polarization around Hot spots





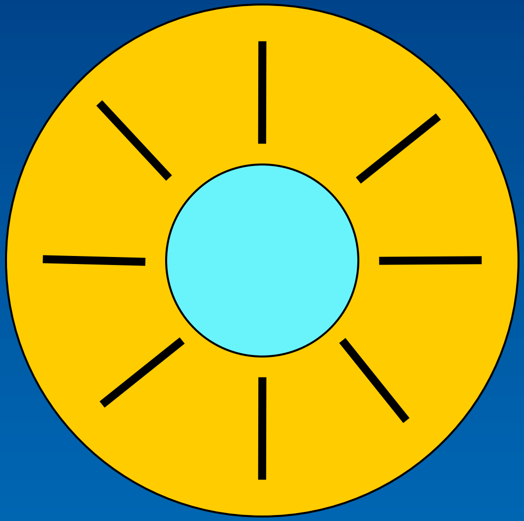
E Polarization

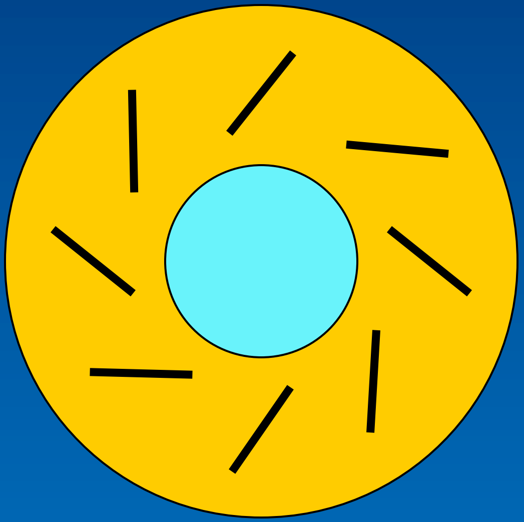
$$\nabla \times E = 0$$

B Polarization

$$\nabla \cdot B = 0$$

Polarization around Cold spots



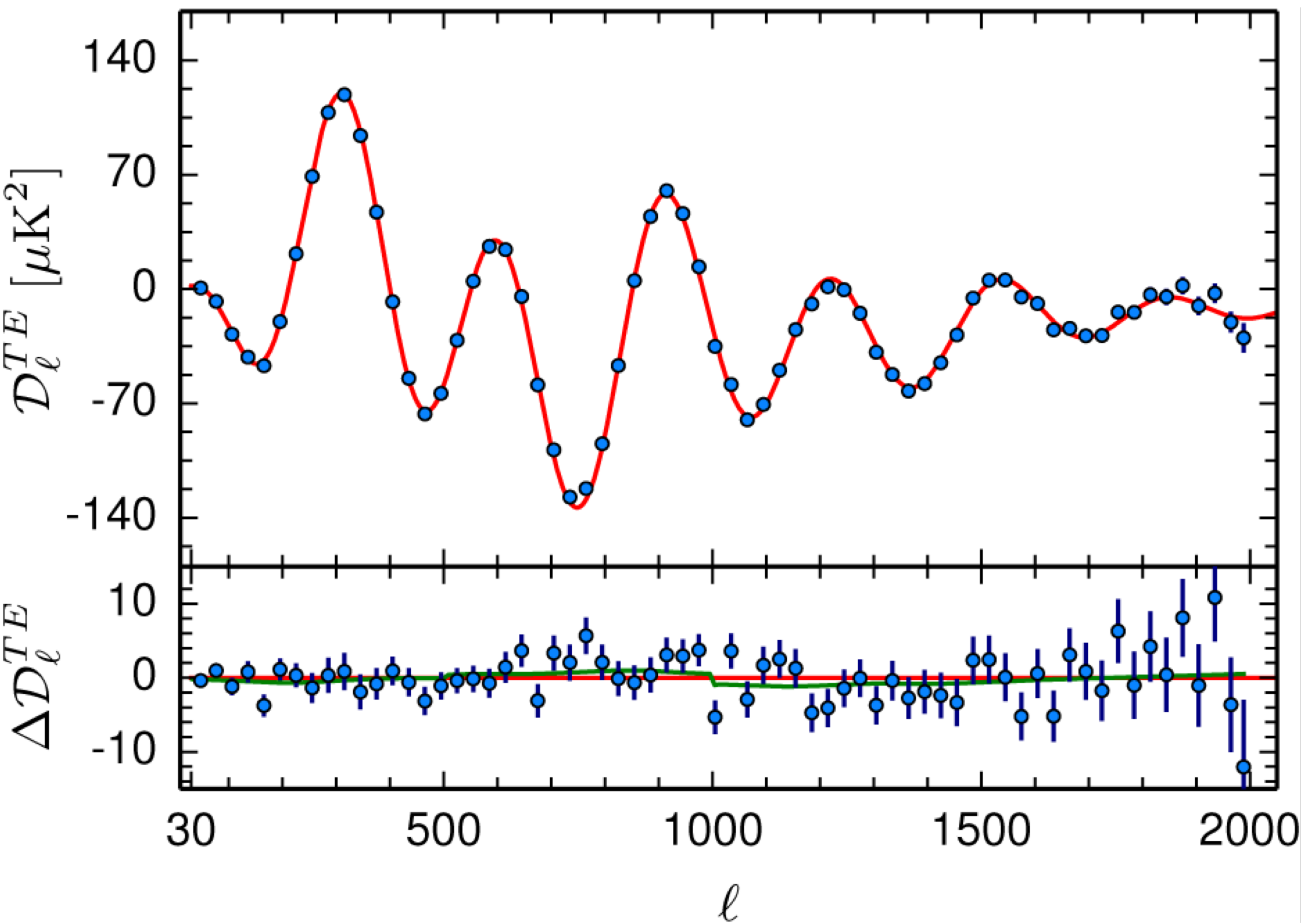


E Polarization

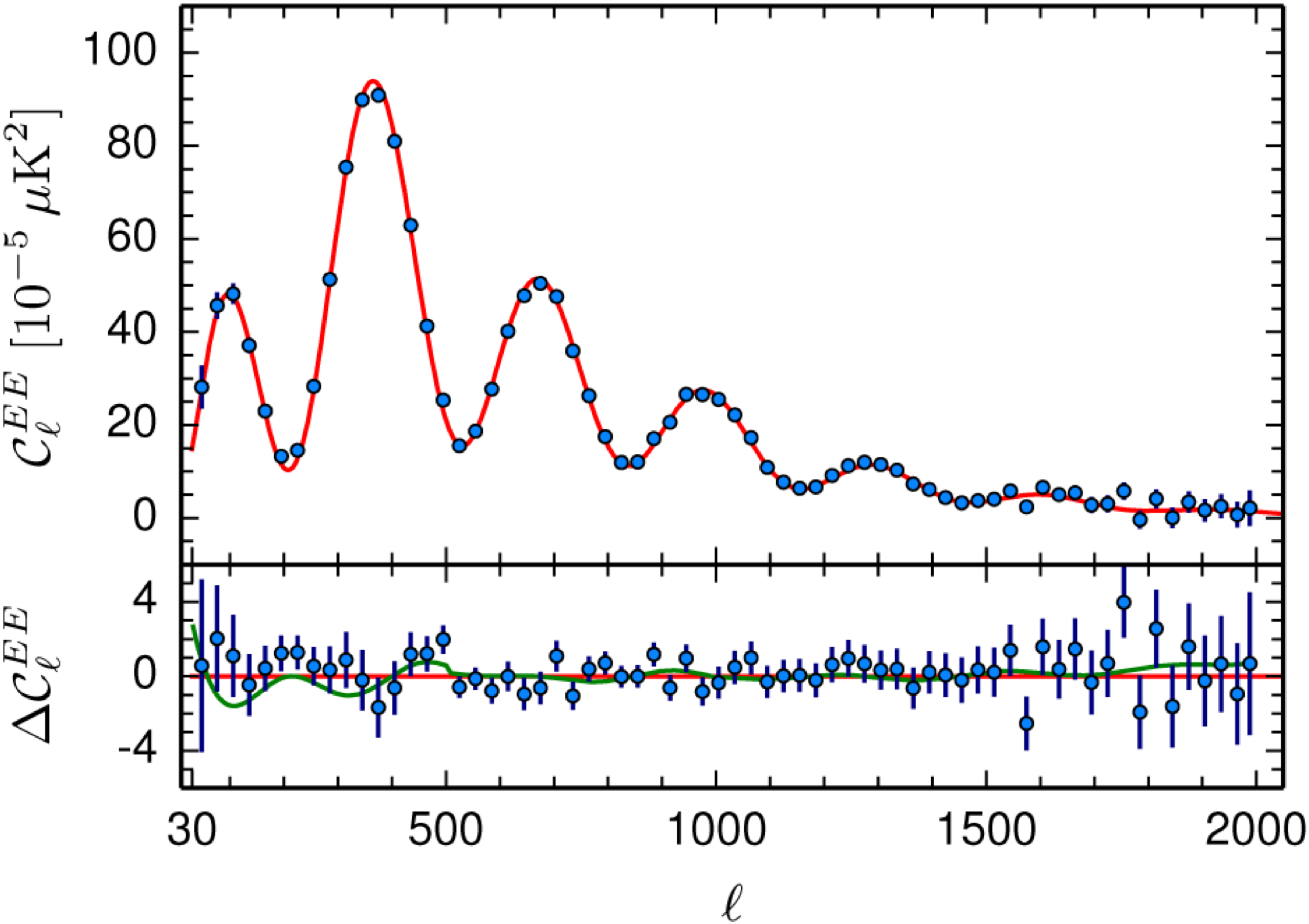
$$\nabla \times E = 0$$

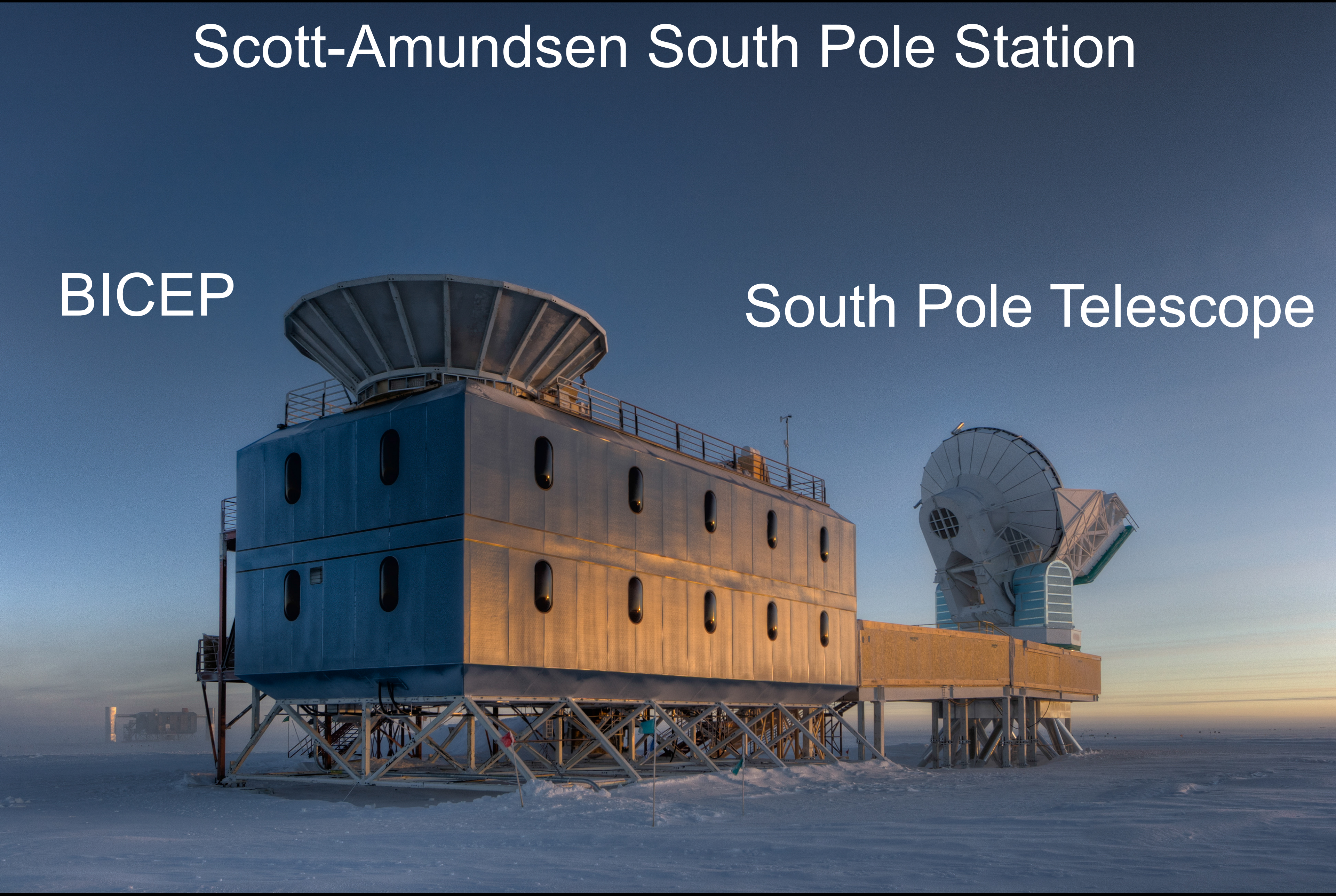
B Polarization

$$\nabla \cdot B = 0$$

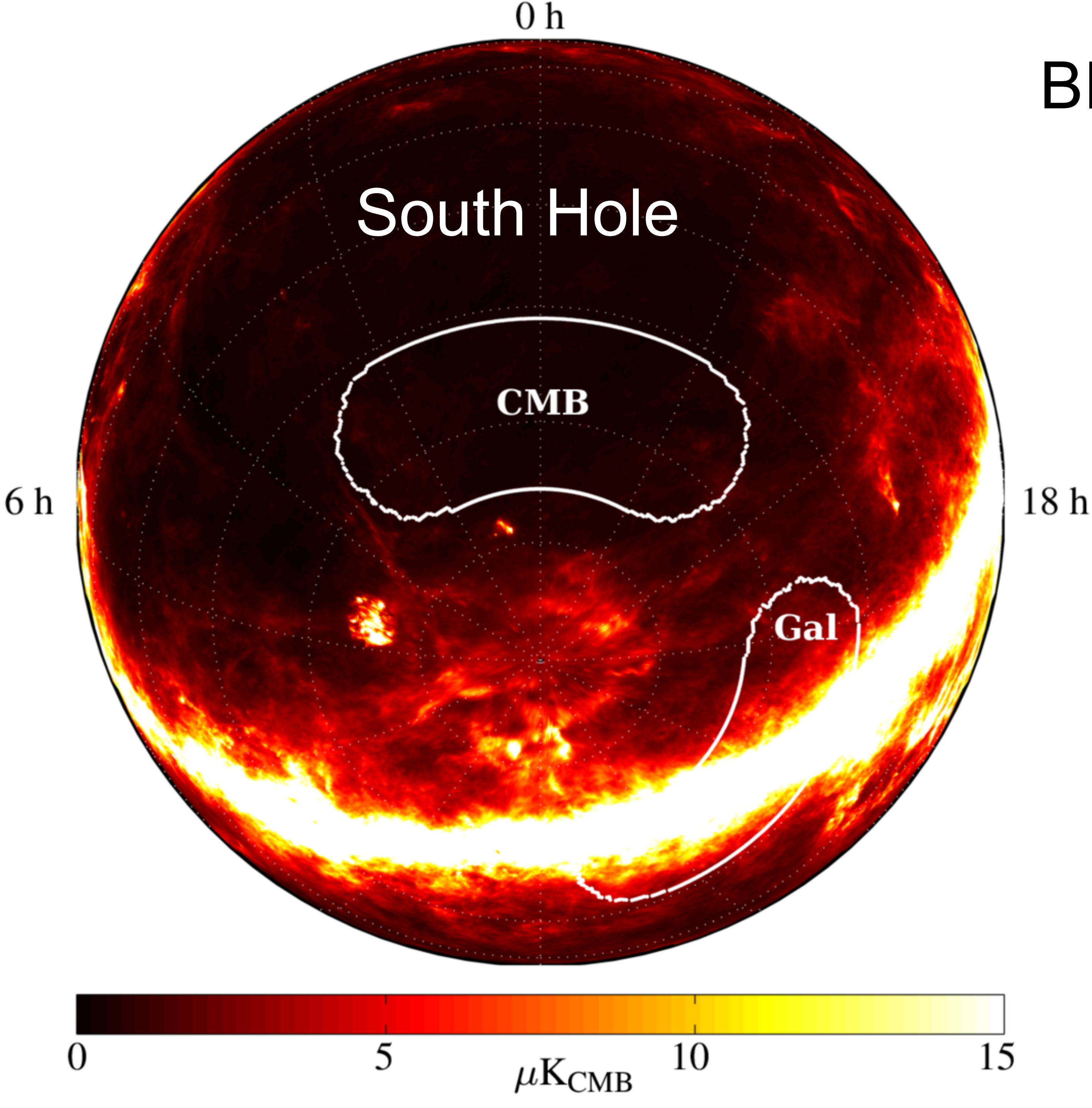


140
70
0
-70
-140
$\mathcal{D}_\ell^{TE}$ $[\mu K^2]$
10
0
-10
$\Delta\mathcal{D}_\ell^{TE}$
30
500
1000
1500
2000
ℓ


100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
$\mathcal{C}_\ell^{EE}$ [10^{-5} μK^2]
$\Delta\mathcal{C}_\ell^{EE}$
ℓ

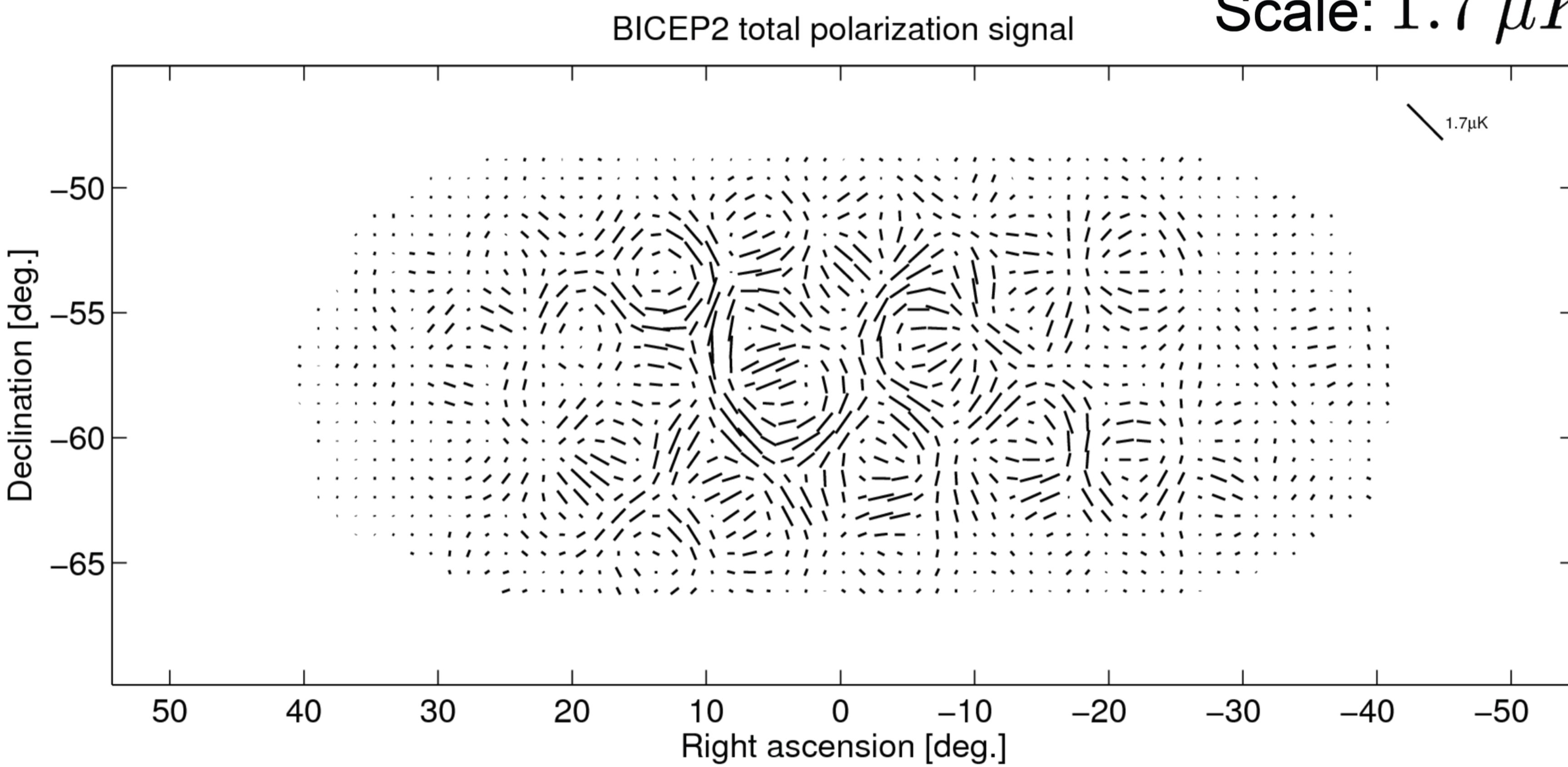

Scott-Amundsen South Pole Station
BICEP
South Pole Telescope

BICEP



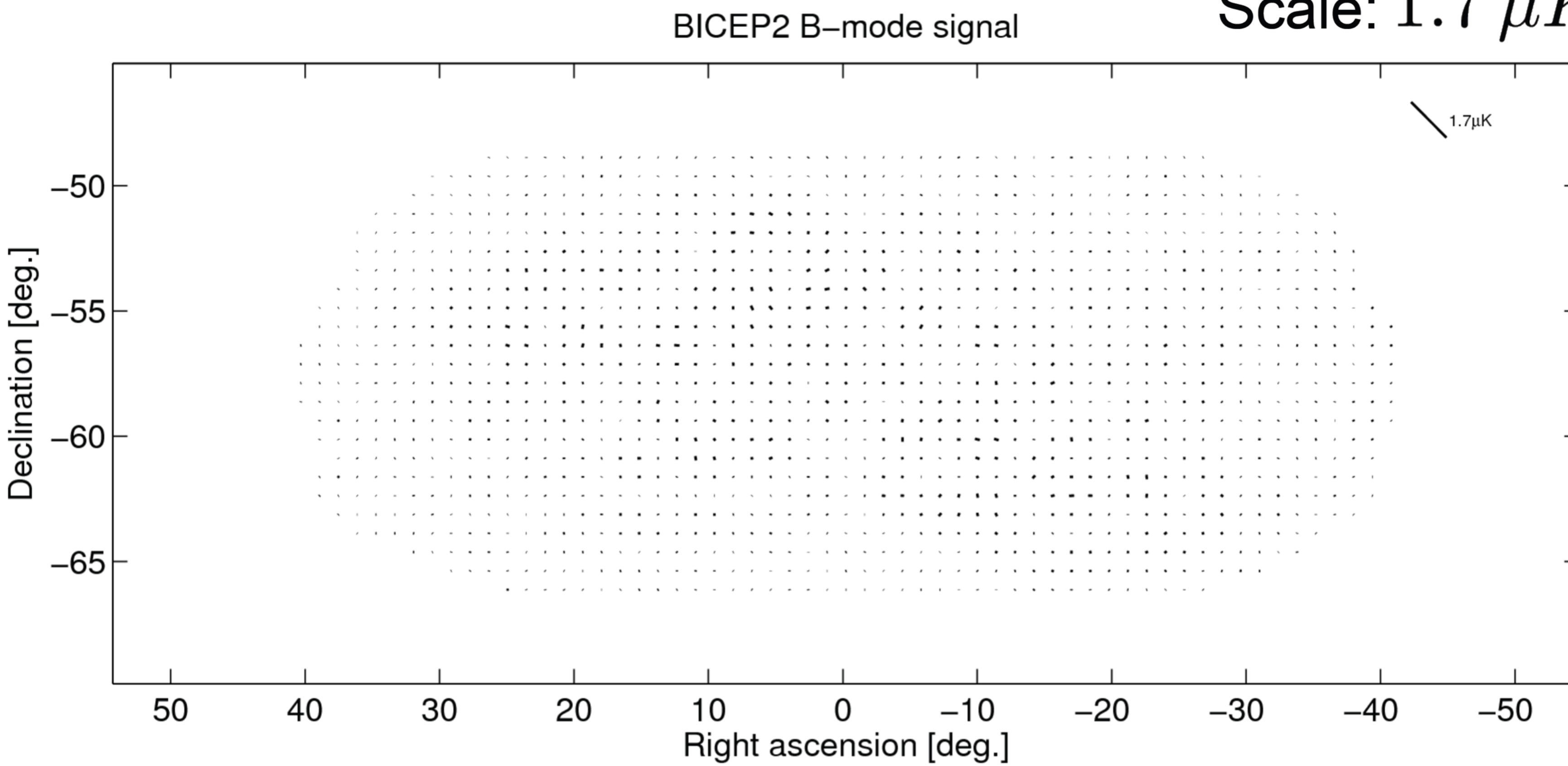
Total Polarization

Scale: $1.7\,\mu K$



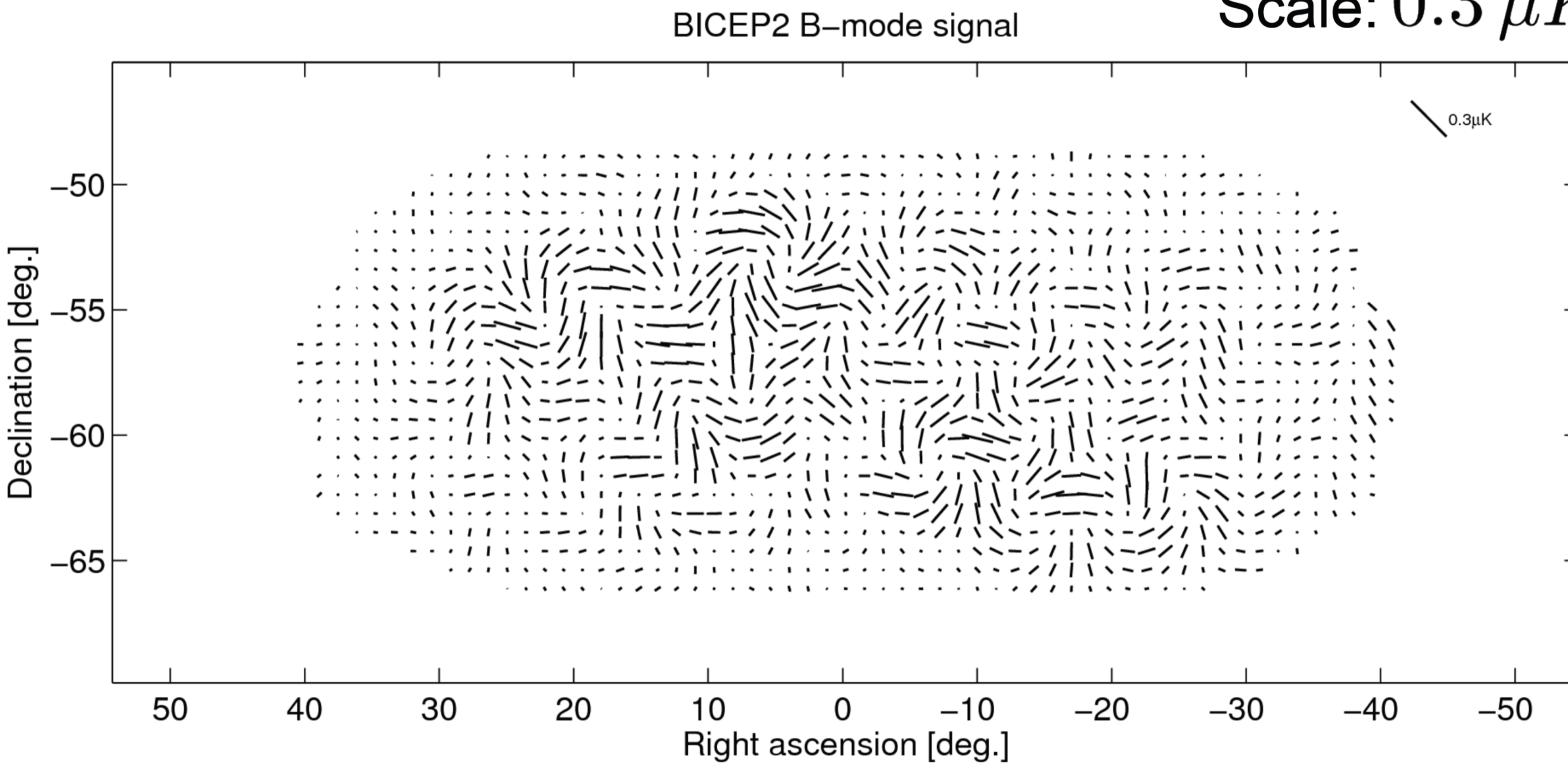
B-mode Contribution

Scale: $1.7\,\mu K$

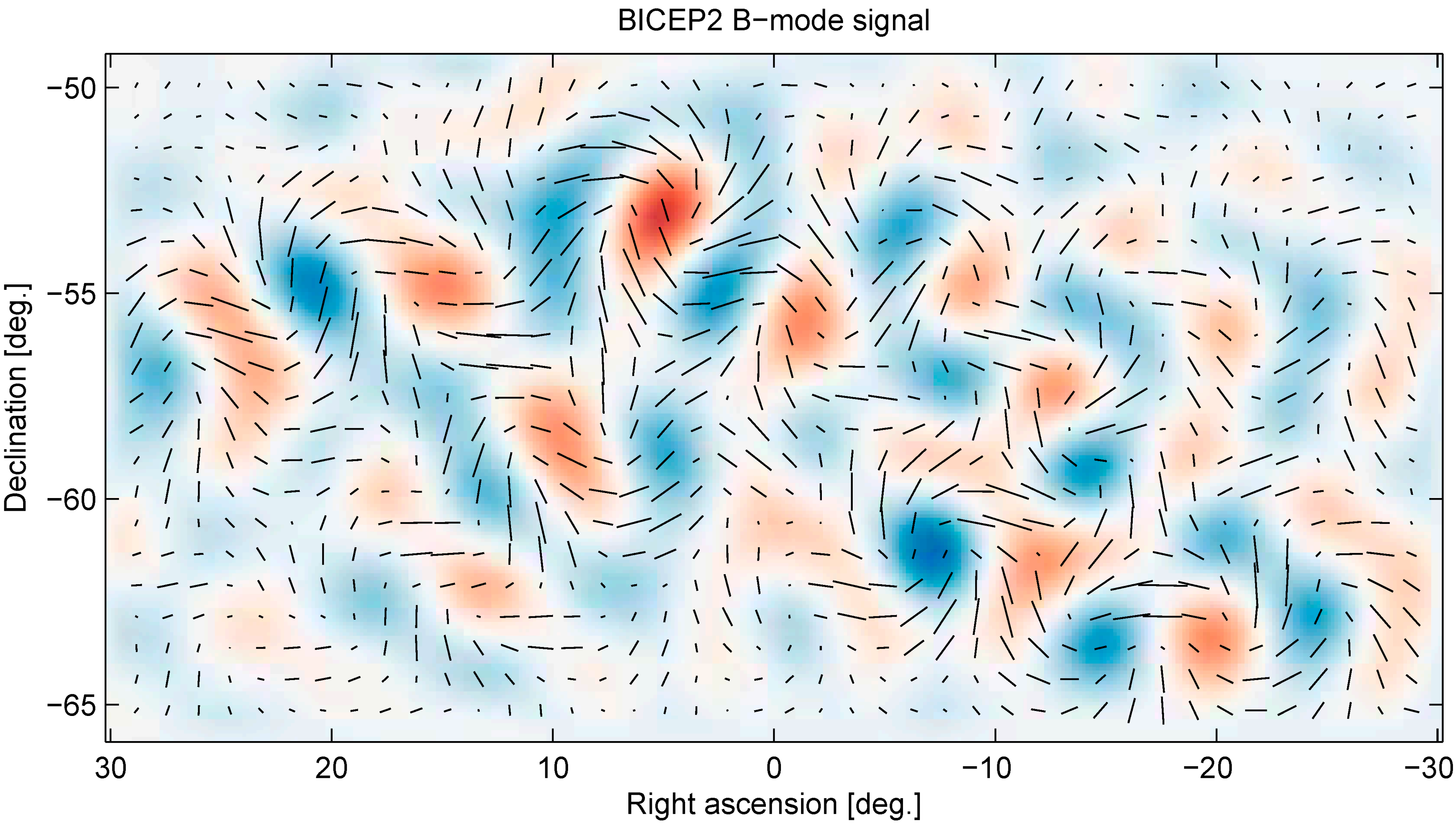


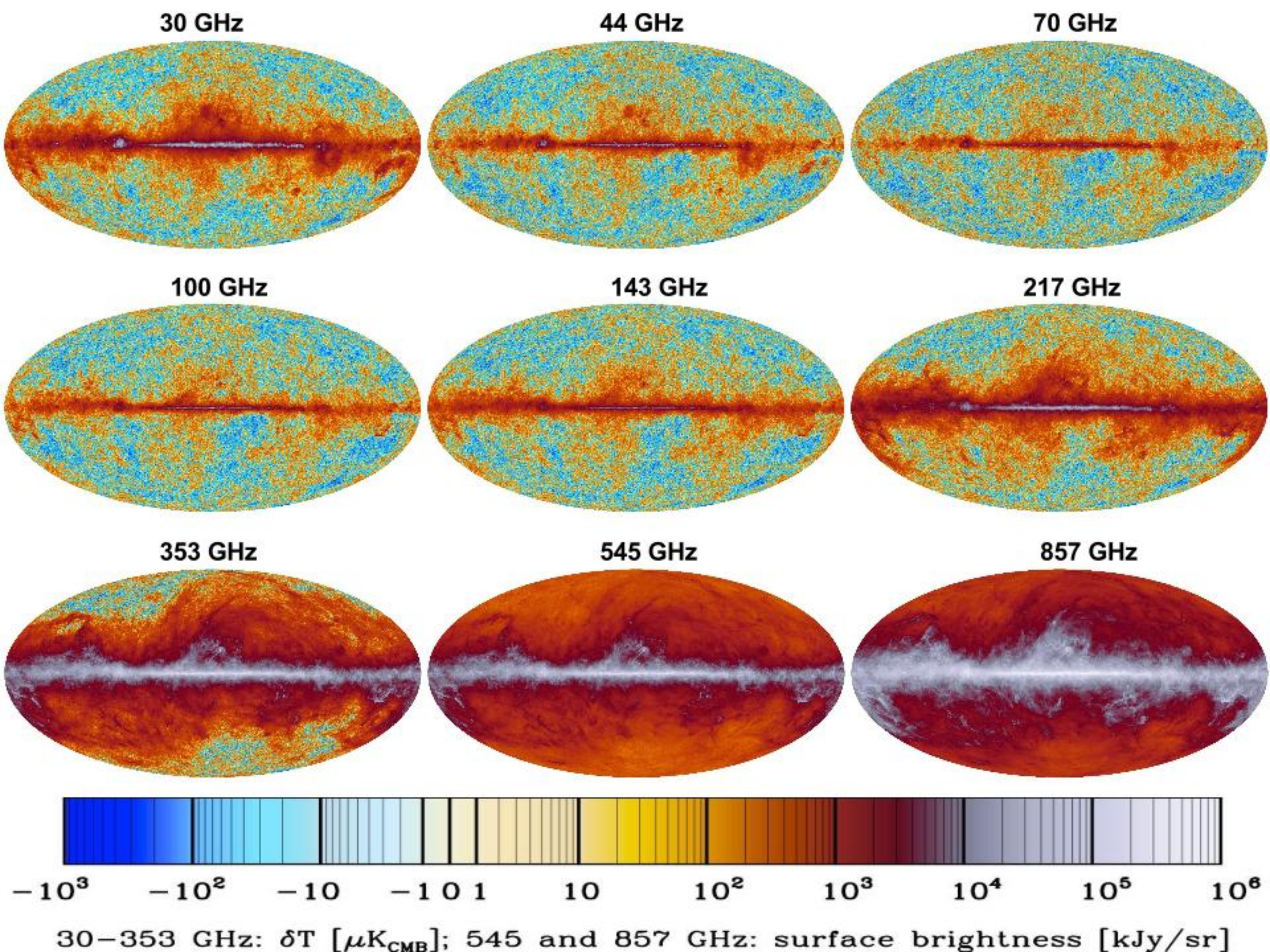
B-mode Contribution

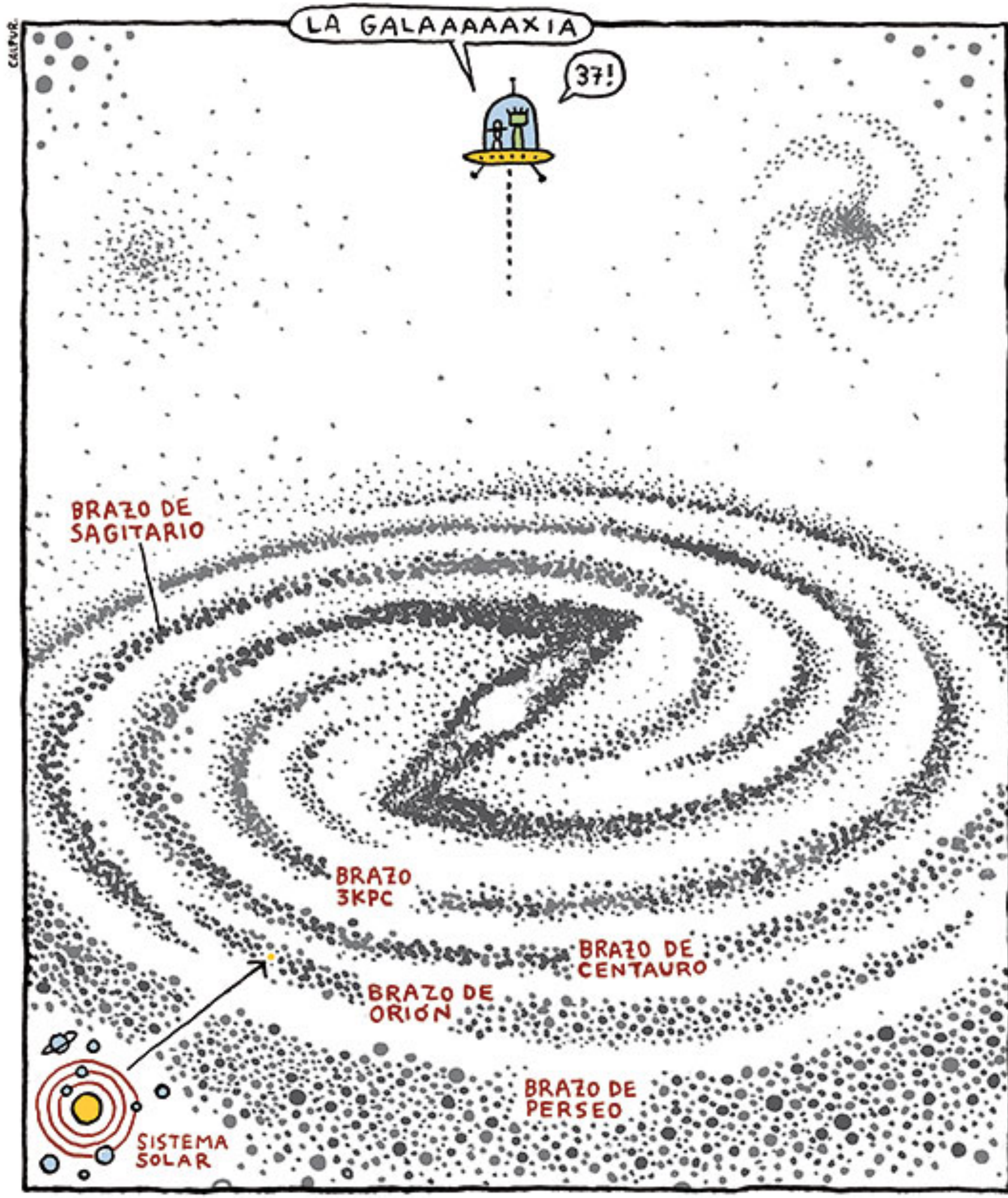
Scale: $0.3\,\mu K$

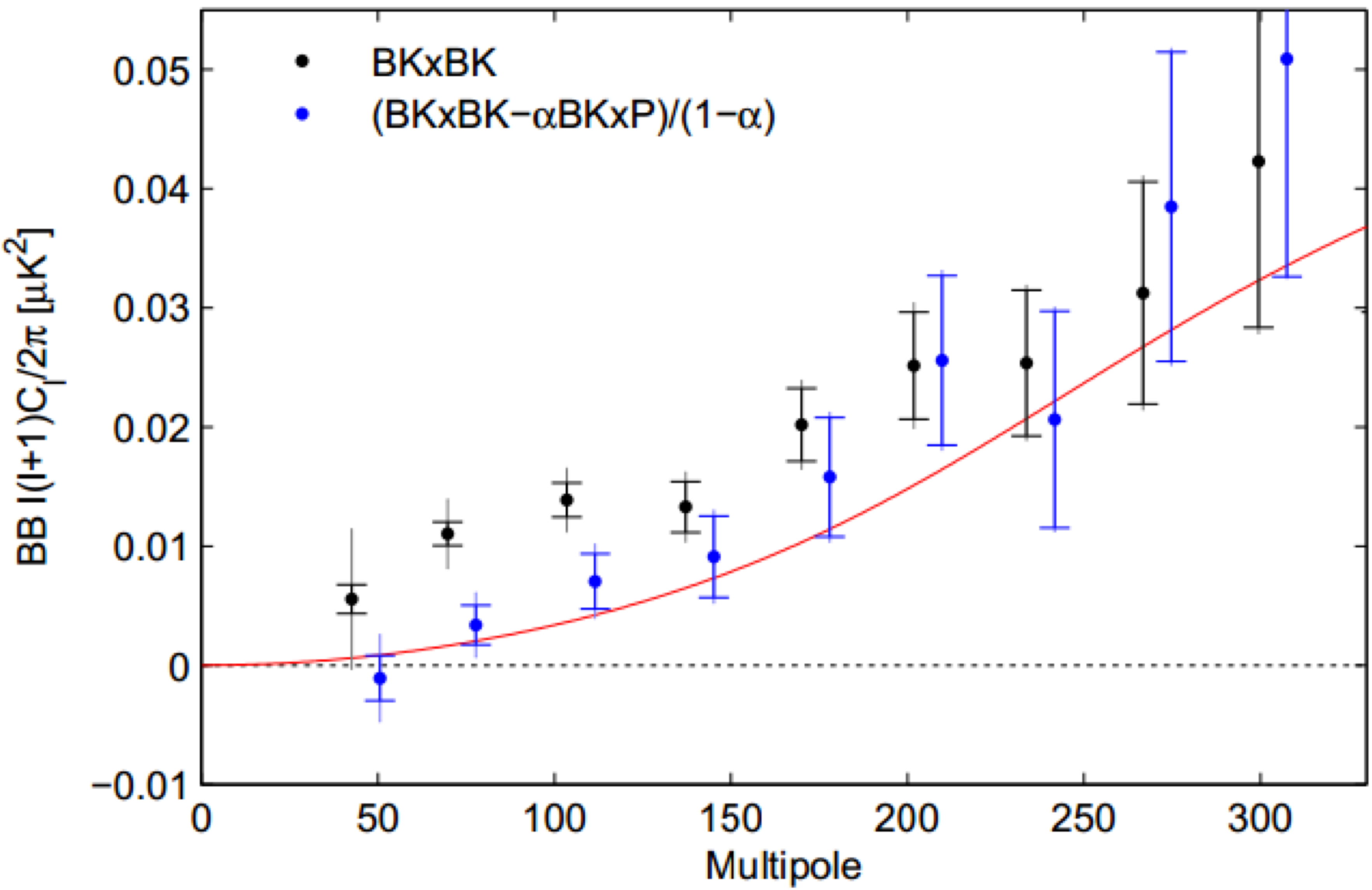


Measurements BICEP2

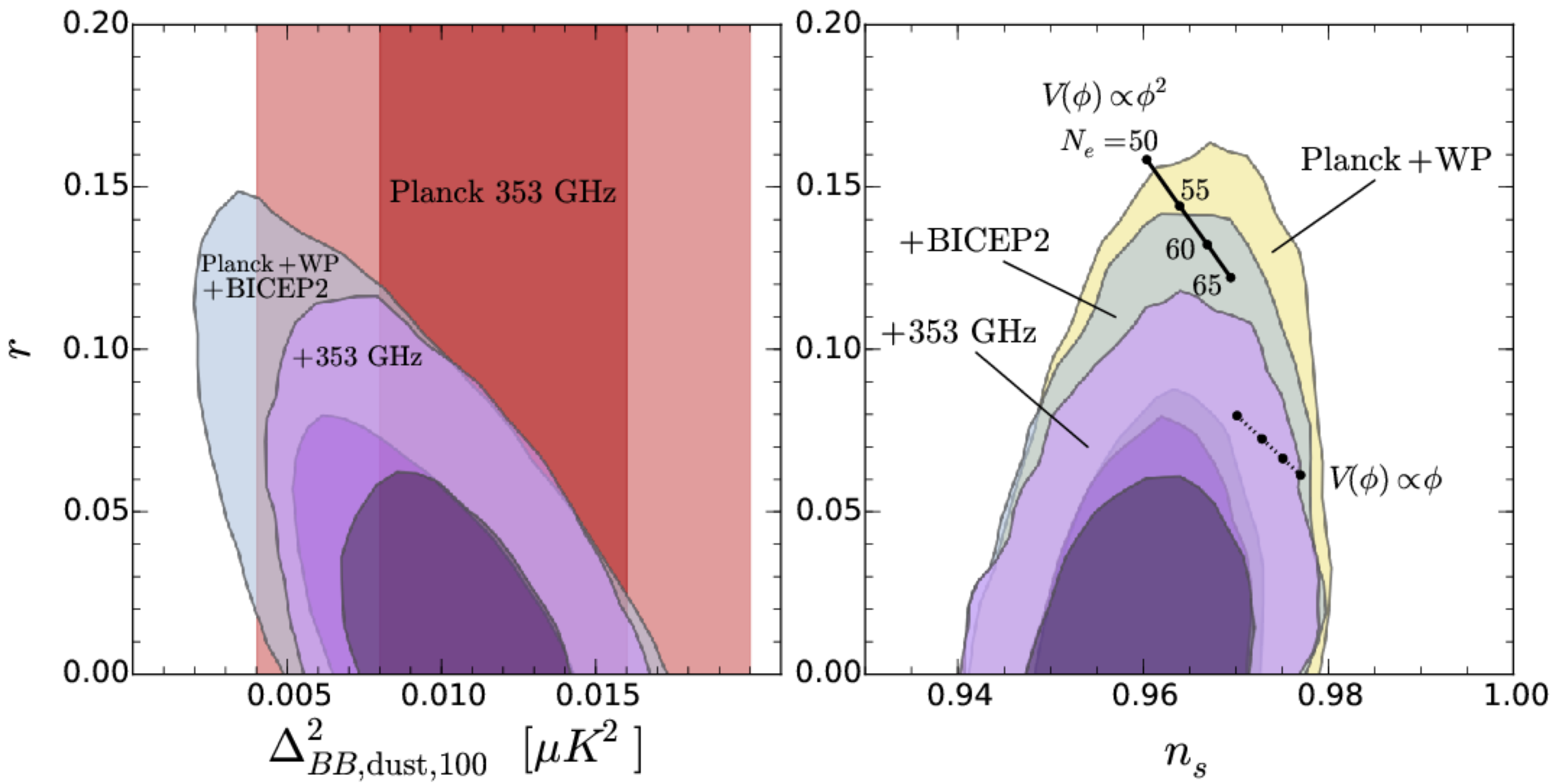



30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

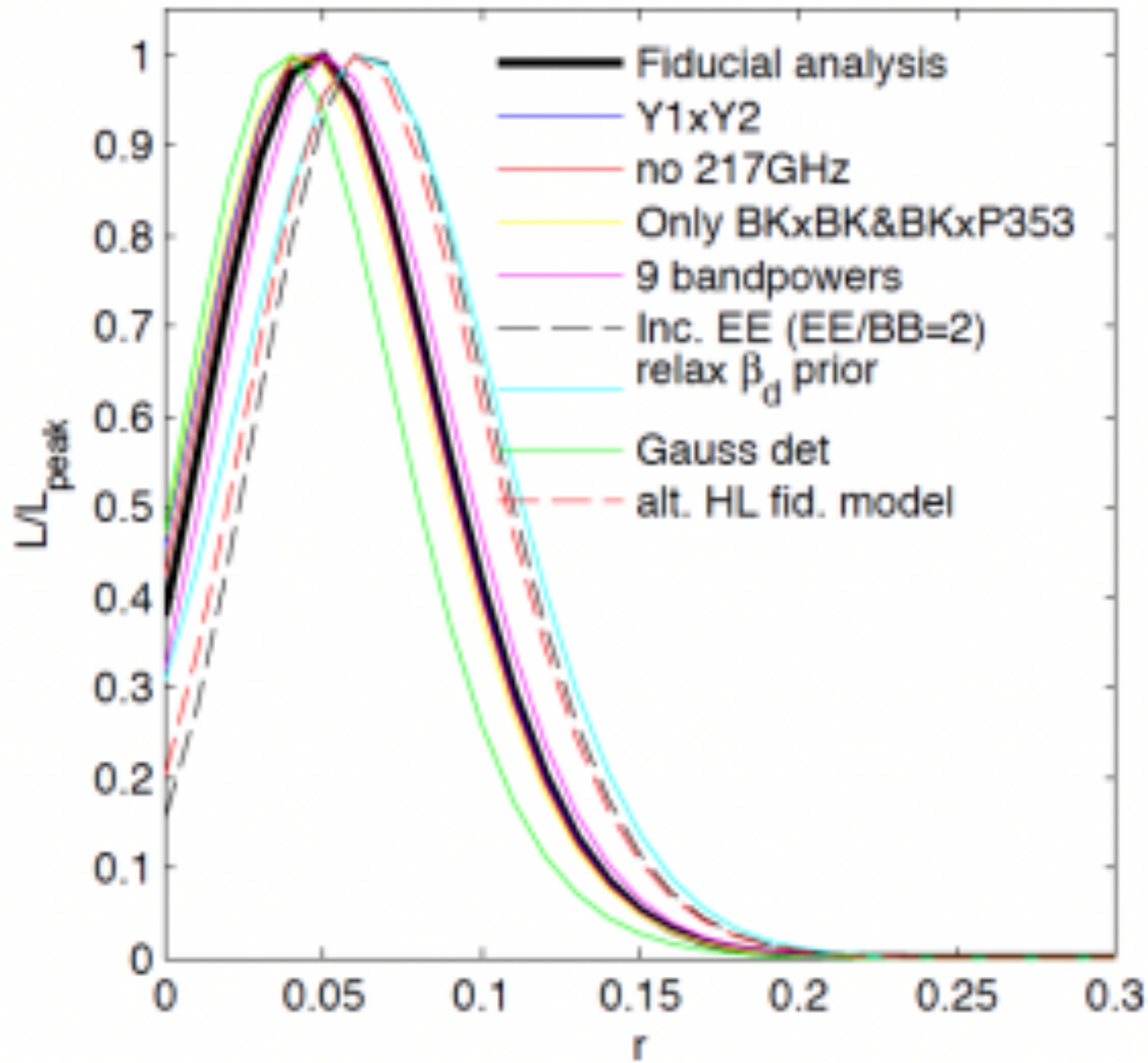

CALPURN.
LA GALAAAAAXIA
37!
BRAZO DE SAGITARIO
BRAZO 3KPC
BRAZO DE CENTAURO
BRAZO DE ORIÓN
BRAZO DE PERSEO
SISTEMA SOLAR



BKxBK
(BKxBK−αBKxP)/(1−α)
BB l(l+1)C_l/2π [μK^2]
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300
Multipole



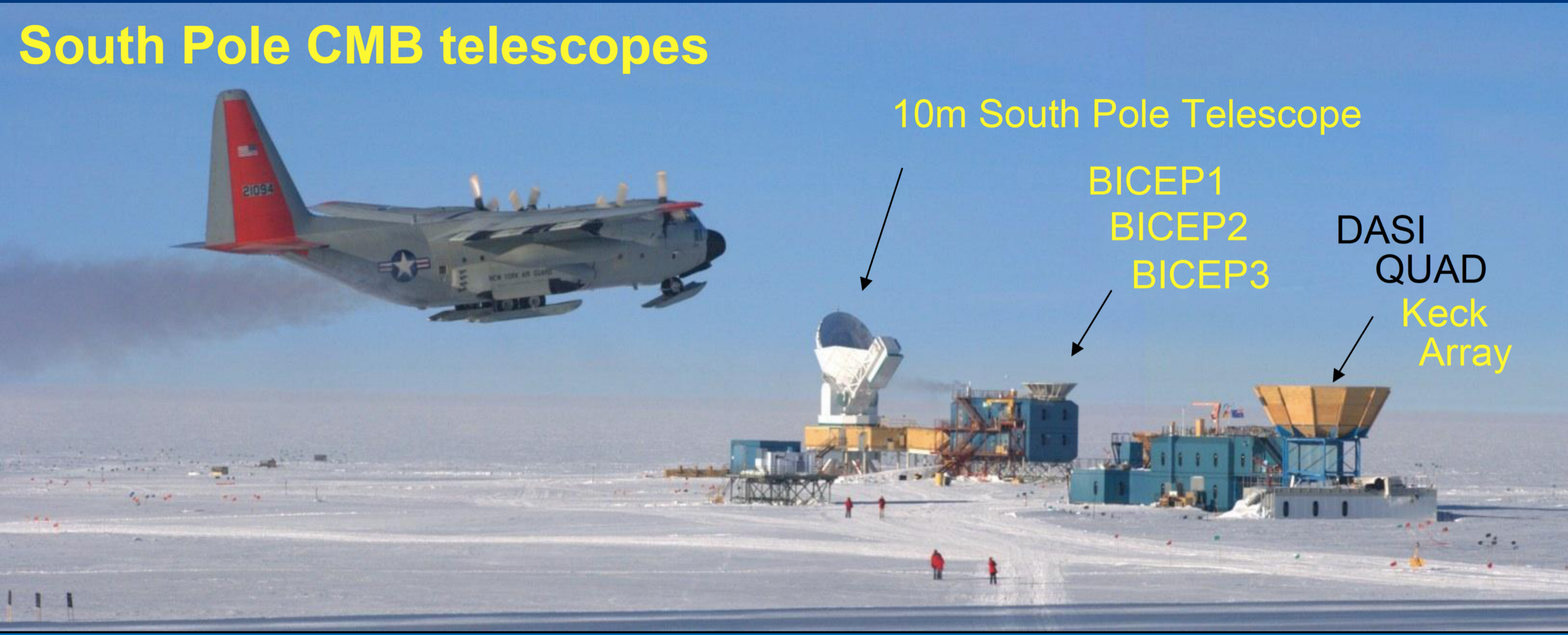
Planck 353 GHz
Planck+WP
+BICEP2
+353 GHz
r
0.20
0.15
0.10
0.05
0.00
0.005
0.010
0.015
$\Delta^2_{BB,\mathrm{dust},100}$ [μK^2]
$V(\phi) \propto \phi^2$
$N_e = 50$
55
60
65
Planck+WP
+BICEP2
+353 GHz
$V(\phi) \propto \phi$
0.94
0.96
0.98
1.00
n_s



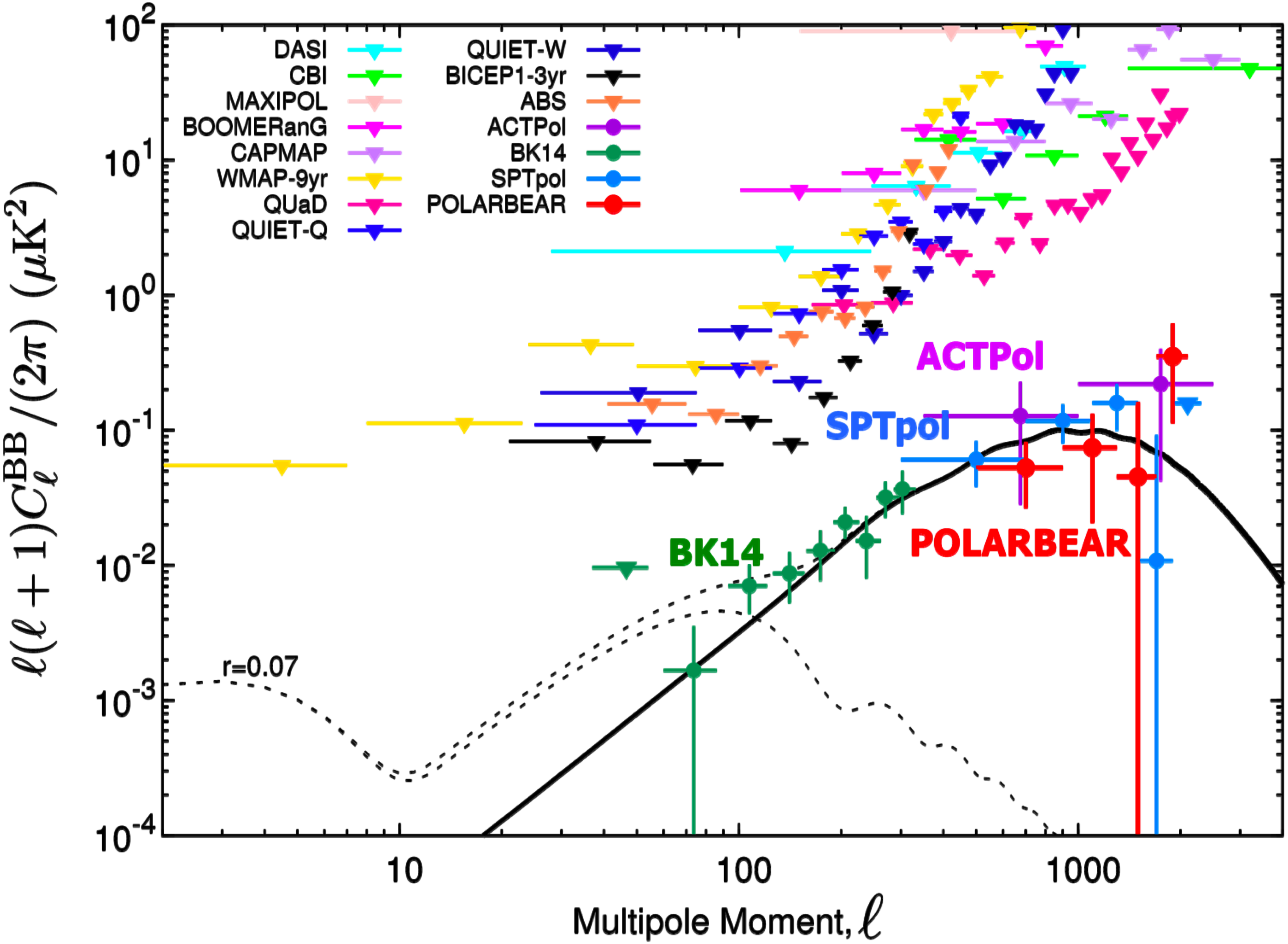
All Dust
No Gravitati

Waves

Other Experiments coming on line

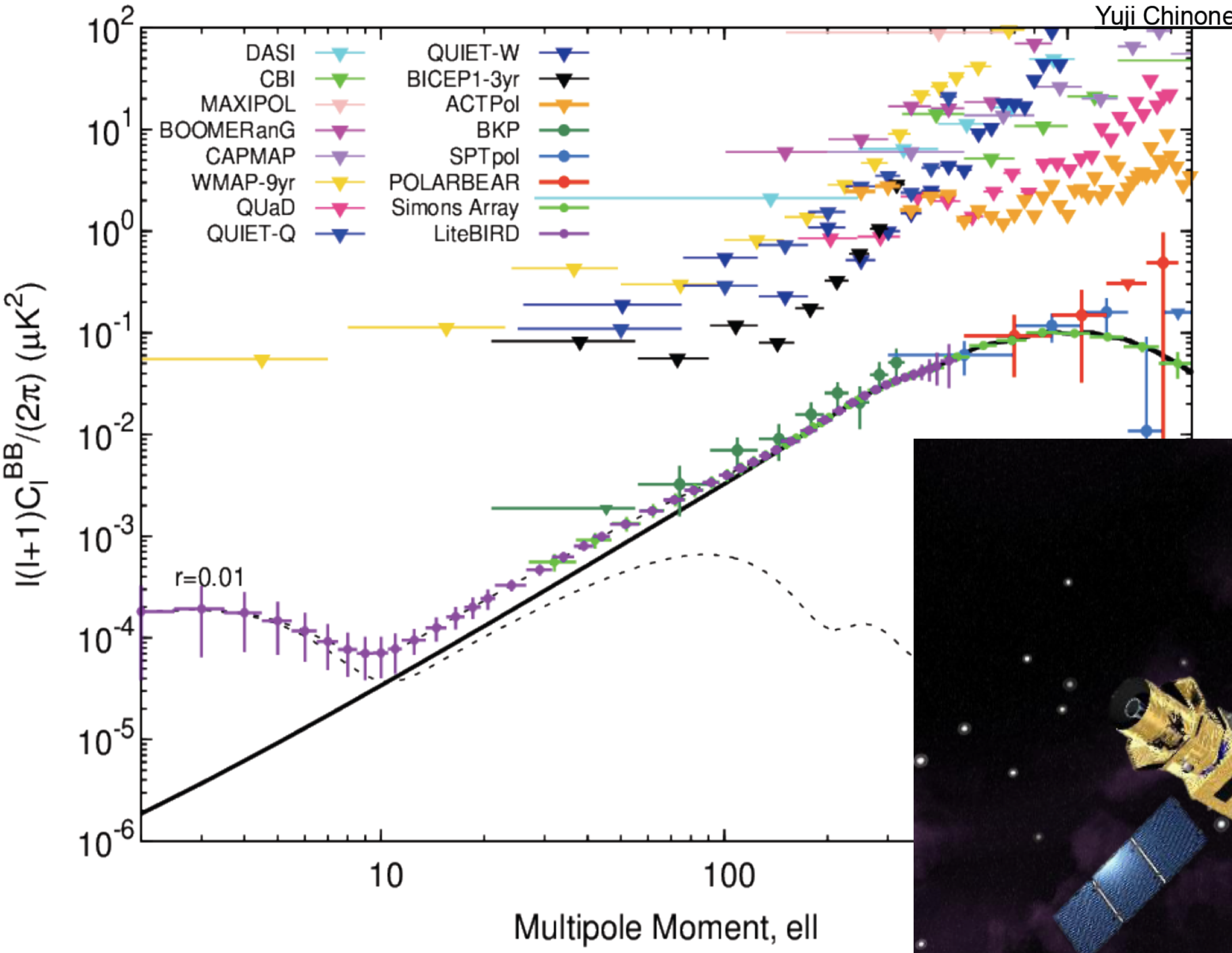


Chile(Atacama): PolarBear, ACTpol
Baloon @ South Pole: EBEX(6K)

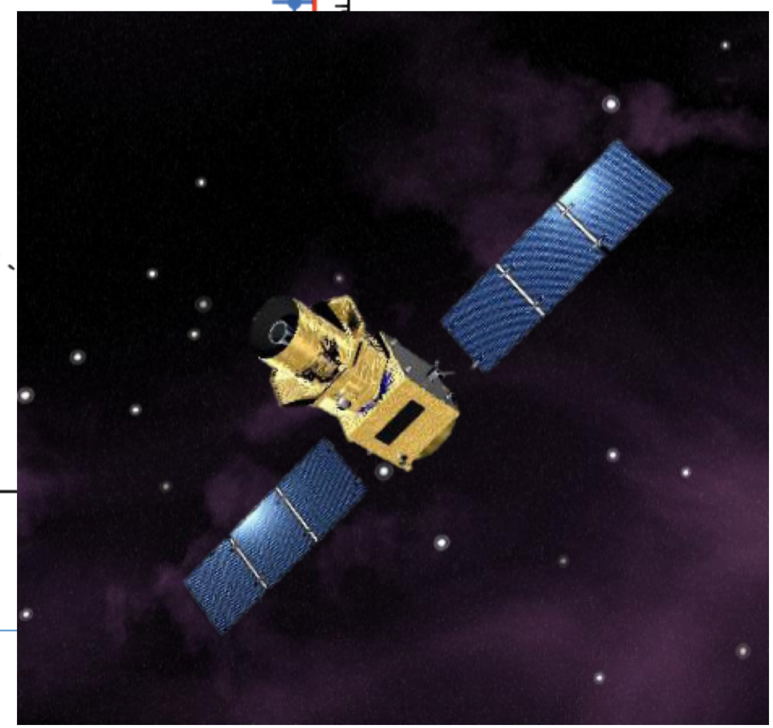


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ABS
ACTPol
BK14
SPTpol
POLARBEAR
ACTPol
SPTpol
POLARBEAR
BK14
r=0.07
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
Multipole Moment, ℓ
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)\ (\mu\mathrm{K}^2)$

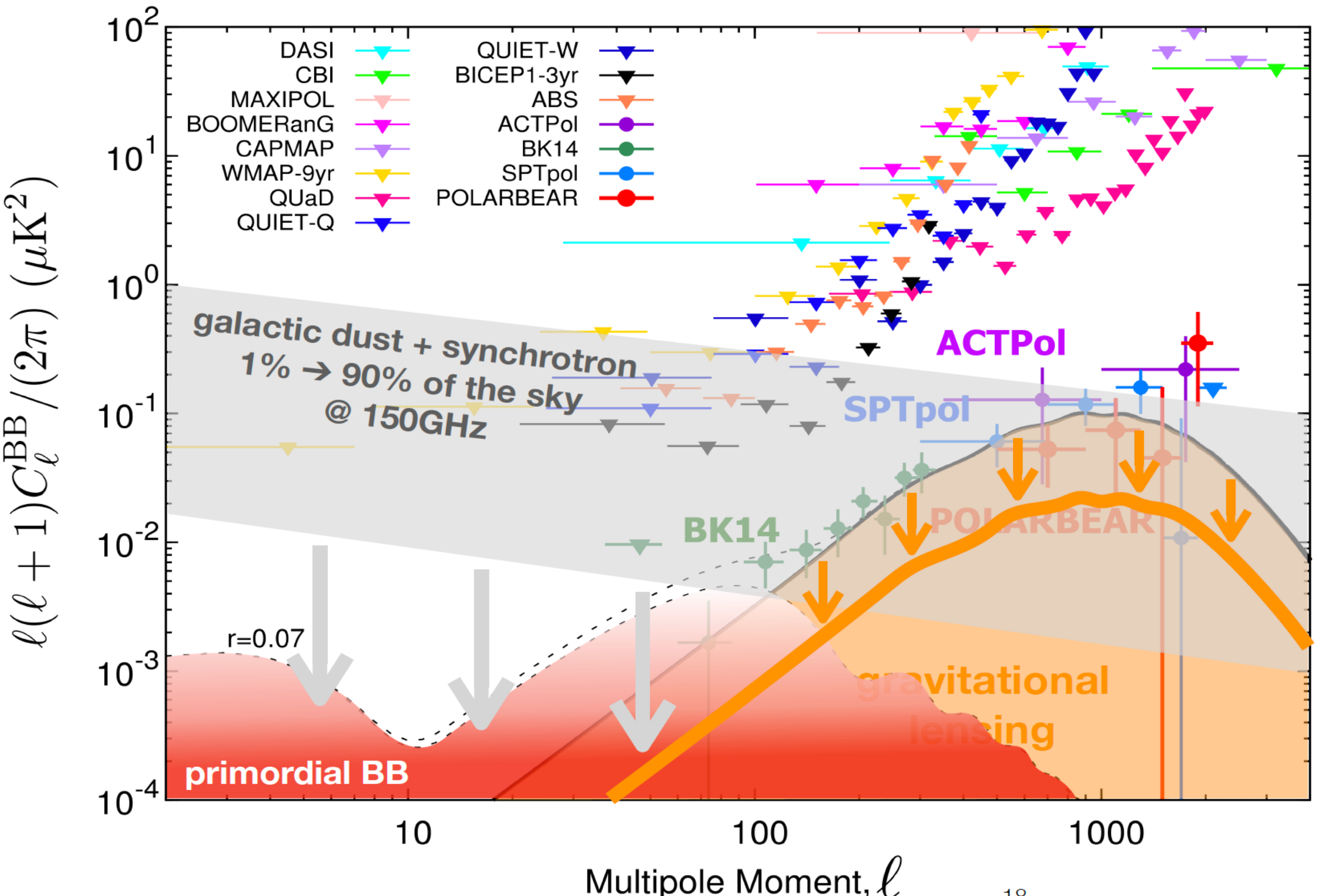
Future experiments that will search for B modes



LiteBird



The Simons Observatory science goals



Conclusions

- The Standard Model of Cosmology (SMC) is well founded in GR, QFT and Thermodynamics.
- Early Universe Inflation is a rich paradigm with confirmed predictions.
- The cosmic microwave background is the more complete source of information we have at the moment on the SCM.
- Soon we will have multiprobe access to SMC: with CMB, LSS and GW.