Observing the Dimensionality of Our Parent Vacuum

Surjeet Rajendran,
Johns Hopkins

with

Peter Graham and
Roni Harnik

arXiv:1003.0236

Inspiration

Why is the universe 3 dimensional?

What is the overall shape and structure of the universe?

Inspiration

Why is the universe 3 dimensional?

What is the overall shape and structure of the universe?

Do we have a landscape of vacua, extra dimensions?

Does this explain properties of our universe (e.g. the Cosmological Constant)?

Did we have a period of eternal inflation in our past?

Is our universe a vast, inhomogeneous multiverse?

Inspiration

Why is the universe 3 dimensional?

What is the overall shape and structure of the universe?

Do we have a landscape of vacua, extra dimensions?

Does this explain properties of our universe (e.g. the Cosmological Constant)?

Did we have a period of eternal inflation in our past?

Is our universe a vast, inhomogeneous multiverse?

How will we know?

Outline

1. Motivation

2. The Anisotropic Universe

3. Observables

Lower Dimensions

Lower dimensional vacua seem generic

- Even SM has a "landscape" of lower dimensional vacua — Arkani-Hamed et. al. (2008)
- More ways to compactify more dimensions

We assume our universe came from a lower dimensional vacuum

- Possibly all dimensions began compact? — Brandenberger & Vafa (1989)
- Dimensions tend to decompactify — Giddings & Myers (2004)

Lower Dimensions

Lower dimensional vacua seem generic

Even SM has a "landscape" of lower dimensional vacua — Arkani-Hamed et. al. (2008)

More ways to compactify more dimensions

We assume our universe came from a lower dimensional vacuum

Possibly all dimensions began compact? — Brandenberger & Vafa (1989)

Dimensions tend to decompactify — Giddings & Myers (2004)

Creates large initial anisotropy, diluted by slow-roll inflation

We will look for residual signs of this special direction

Landscape Signals

For signals to be observable, inflation must not have lasted too long.

Inflation needs tuning. Few e-folds may be generic.

Many landscape signals require this

e.g. curvature, bubble collisions   Aguirre, Johnson & Shomer (2007), Chang, Kleban & Levi (2007)

Landscape Signals

For signals to be observable, inflation must not have lasted too long.

Inflation needs tuning. Few e-folds may be generic.

Many landscape signals require this

e.g. curvature, bubble collisions

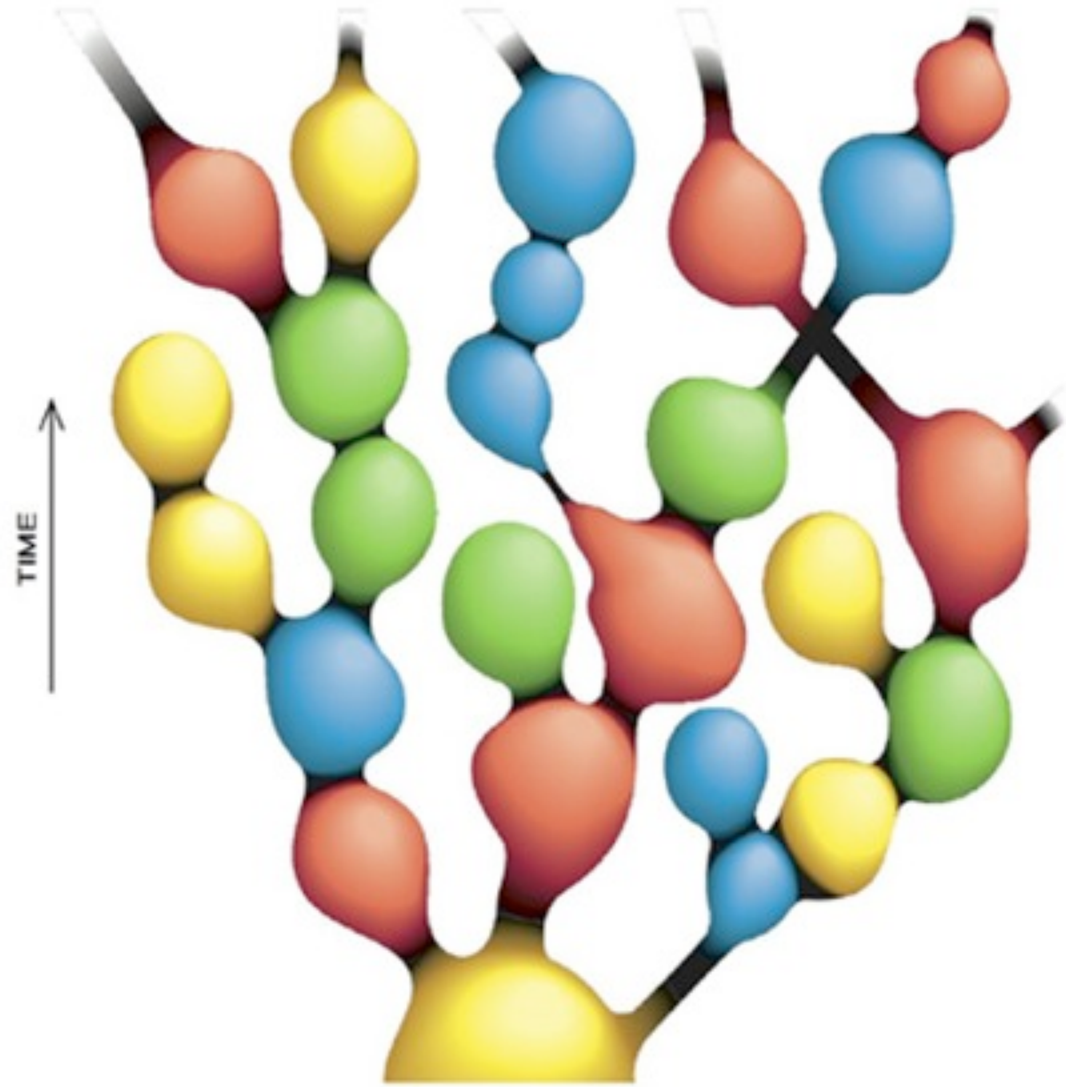
Aguirre, Johnson & Shomer (2007), Chang, Kleban & Levi (2007)

These also assume other vacua are 3+1 dimensional

What if we relax this assumption?

These signals could reveal our history of decompactification

(see also Blanco-Pillado and Salem, 2010)



The Anisotropic Universe

Initial Transition

If the parent vacuum is 2+1 dimensional

Coleman - De Luccia tunneling creates a bubble of 3+1 dimensional space

Could be radion tunneling (or change in fluxes, etc.)

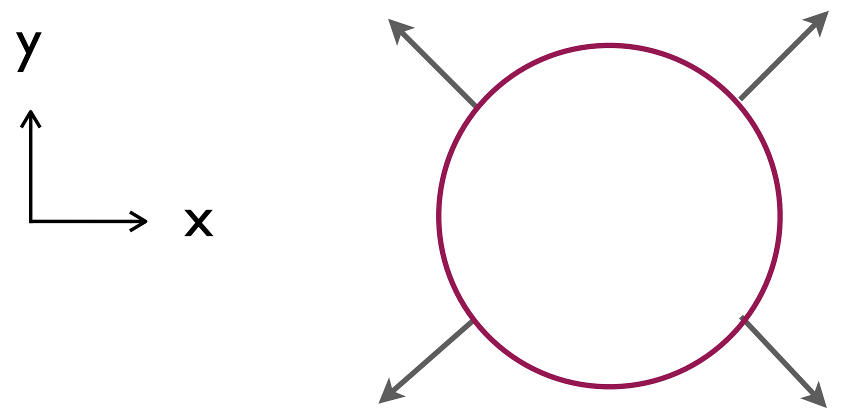
Initial Transition

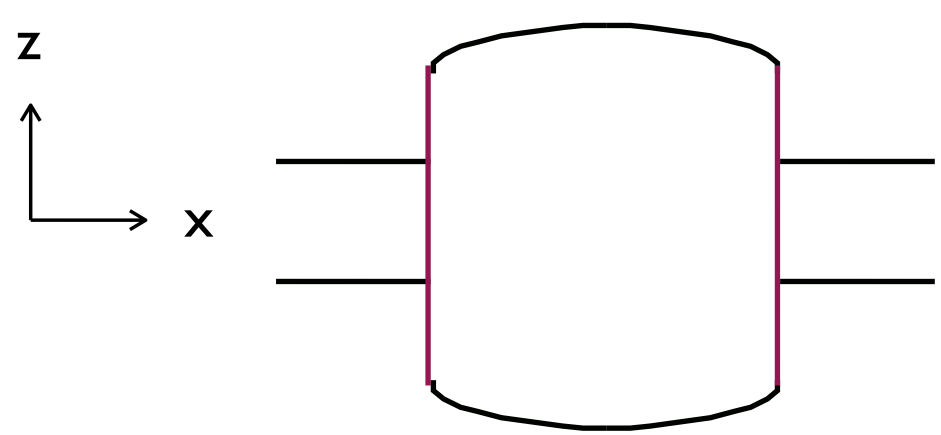
If the parent vacuum is 2+1 dimensional

Coleman - De Luccia tunneling creates a bubble of 3+1 dimensional space

Could be radion tunneling (or change in fluxes, etc.)

spatial dimensions = $\mathbf{R}^2 \times S^1$





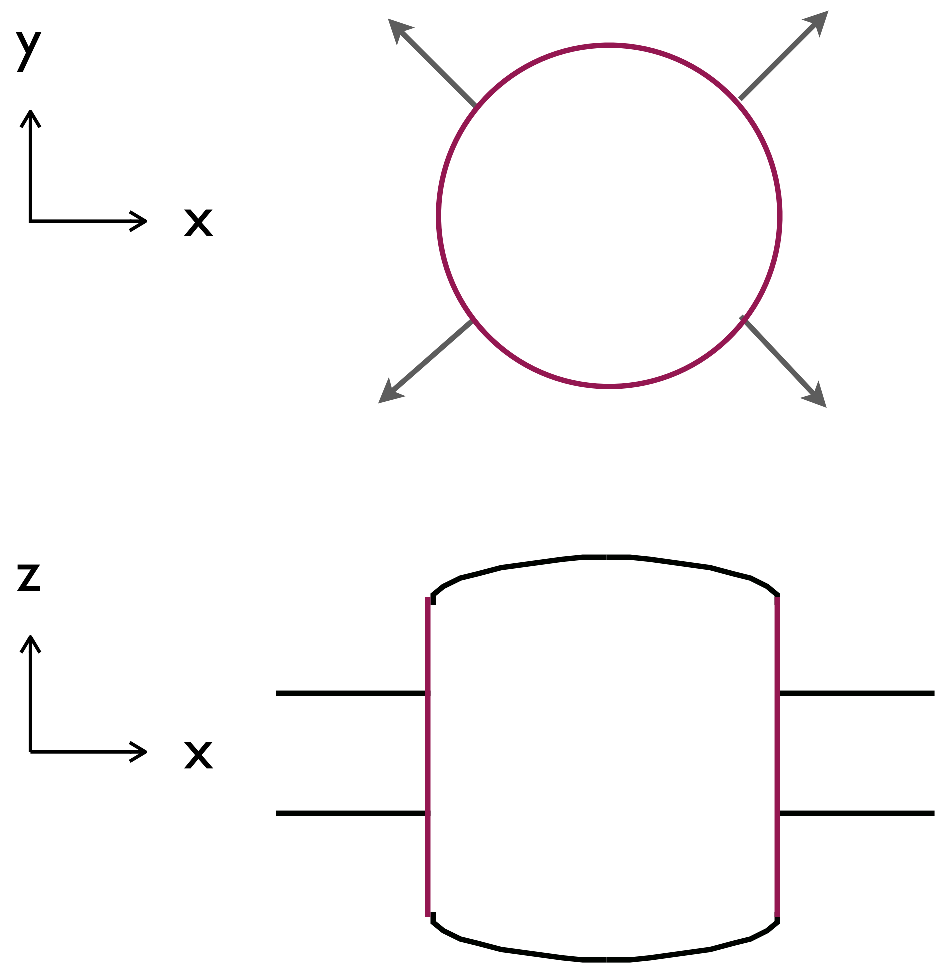
Initial Transition

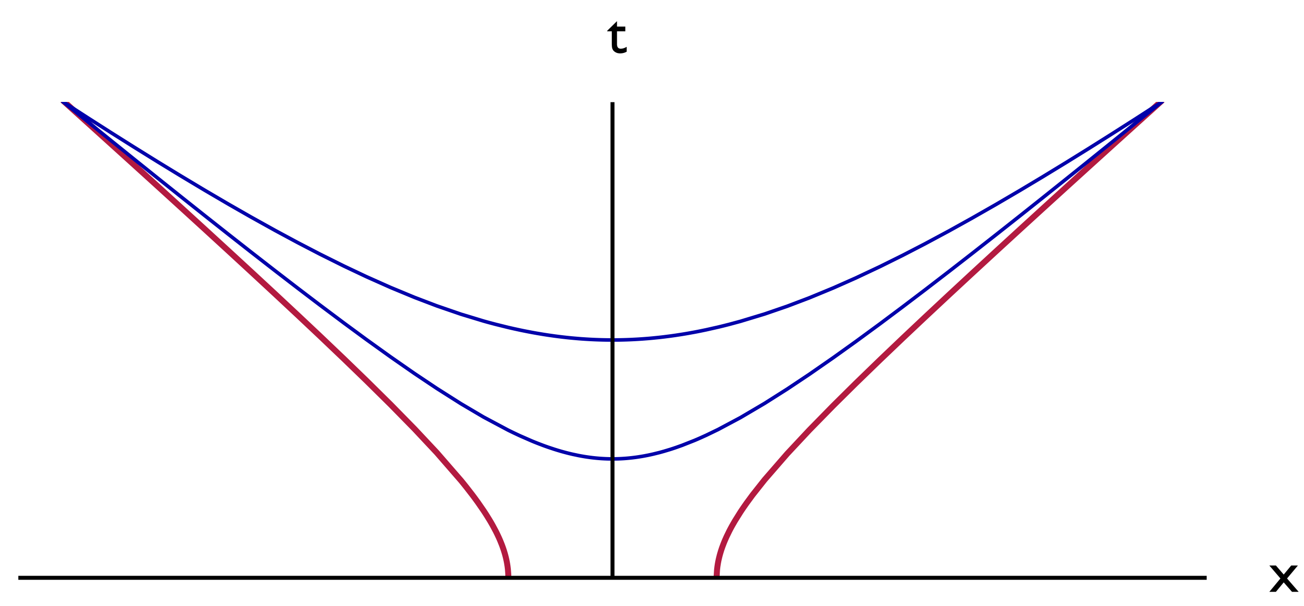
If the parent vacuum is 2+1 dimensional

Coleman - De Luccia tunneling creates a bubble of 3+1 dimensional space

Could be radion tunneling (or change in fluxes, etc.)

spatial dimensions = $\mathbf{R}^2 \times S^1$





creates an infinite, open FRW universe, *in 2 dimensions*

negative curvature only in 2 dimensions, third dimension flat

Initial Transition

Alternatively, if the parent vacuum is 1+1 dimensional:

The single uncompactified dimension is flat

Other two may be any compact 2-manifold with geometry S^2, E^2, or H^2

Generic compactifications have large curvature

Initial Transition

Alternatively, if the parent vacuum is 1+1 dimensional:

The single uncompactified dimension is flat

Other two may be any compact 2-manifold with geometry S^2, E^2, or H^2

Generic compactifications have large curvature

We won't consider the 0+1 dimensional case.

In general, expect anisotropic curvature after transition

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

k = ±1

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

k = ±1

"FRW" equations:

$$\begin{aligned}
\frac{\dot{a}^2}{a^2} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{k}{a^2} &= 8\pi G\rho \\
\frac{\ddot{a}}{a} + \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} &= -8\pi G p_r \\
2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p_z
\end{aligned}$$

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

k = ±1

"FRW" equations:

$$\begin{aligned} \frac{\dot{a}^2}{a^2} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{k}{a^2} &= 8\pi G\rho \\ \frac{\ddot{a}}{a} + \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} &= -8\pi G p_r \\ 2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p_z \end{aligned}$$

z-dimension is flat ⇒

anisotropic curvature

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\phi^2\right) - b(t)^2 dz^2$$

k = ±1

"FRW" equations:

$$\begin{aligned}
\frac{\dot{a}^2}{a^2} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{k}{a^2} &= 8\pi G\rho \\
\frac{\ddot{a}}{a} + \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} &= -8\pi G p_r \\
2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p_z
\end{aligned}$$

z-dimension is flat ⇒

anisotropic curvature

anisotropic pressure

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

k = ±1

"FRW" equations:

$$\begin{aligned} \frac{\dot{a}^2}{a^2} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{k}{a^2} &= 8\pi G\rho \\ \frac{\ddot{a}}{a} + \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} &= -8\pi G p_r \\ 2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p_z \end{aligned}$$

z-dimension is flat ⇒

anisotropic curvature

anisotropic pressure

normal FRW eqn

After the Transition

We assume after the transition:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

$k = \pm 1$

"FRW" equations:

$$\begin{aligned} \frac{\dot{a}^2}{a^2} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{k}{a^2} &= 8\pi G\rho \\ \frac{\ddot{a}}{a} + \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} &= -8\pi G p_r \\ 2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p_z \end{aligned}$$

z-dimension is flat ⇒

anisotropic curvature

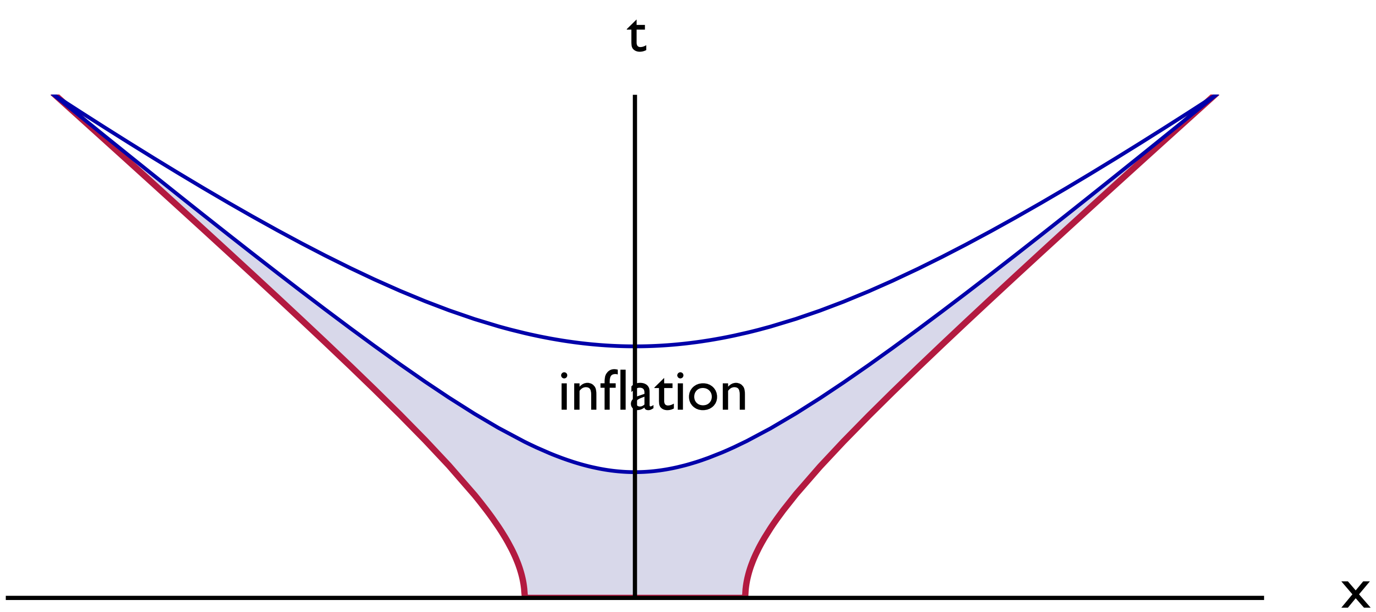
anisotropic pressure

normal FRW eqn

anisotropic curvature ⇒ anisotropic expansion: $H_a \equiv \frac{\dot{a}}{a} \neq H_b \equiv \frac{\dot{b}}{b}$

Curvature Dominance

Assume immediately after the tunneling $\dot{b} \approx 0$



$$a(t) \sim t\left(1 + \mathcal{O}\left(G\,\Lambda\,t^2\right)\right)$$

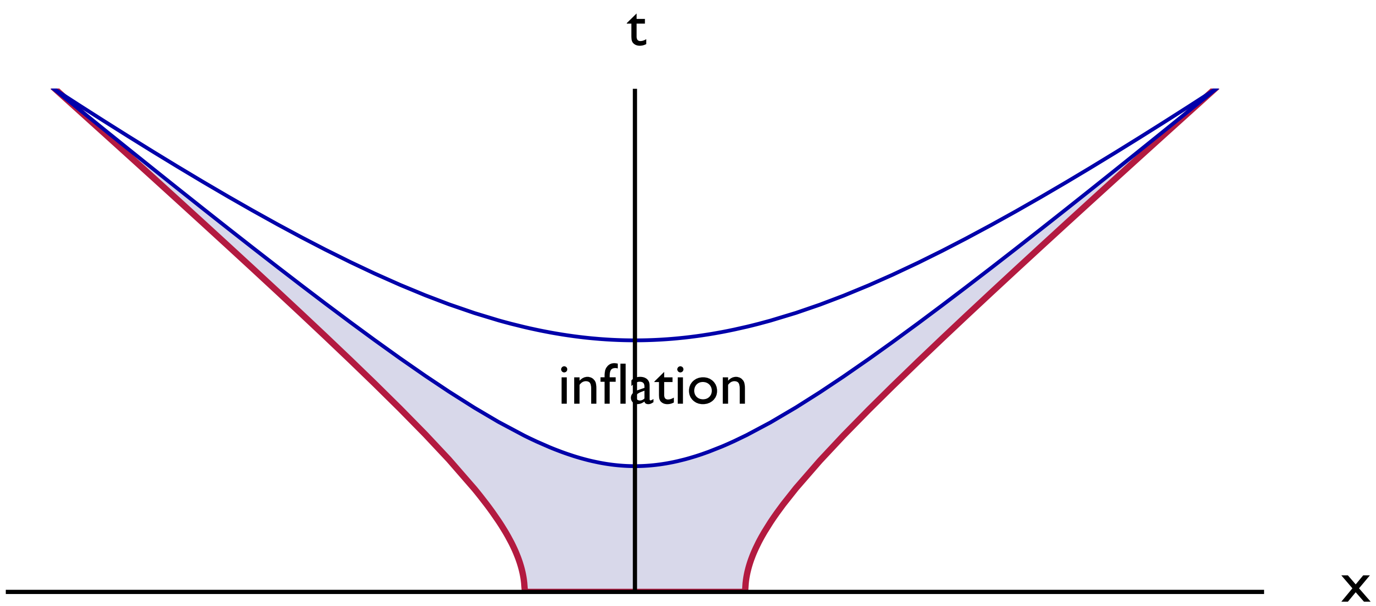
$$b(t) \sim b_0\left(1 + \mathcal{O}\left(G\,\Lambda\,t^2\right)\right)$$

so b(t) is frozen $H_b \approx 0$

but H_a is large

Curvature Dominance

Assume immediately after the tunneling $\dot{b} \approx 0$



$$a(t) \sim t\left(1 + \mathcal{O}\left(G\,\Lambda\,t^2\right)\right)$$

$$b(t) \sim b_0\left(1 + \mathcal{O}\left(G\,\Lambda\,t^2\right)\right)$$

so b(t) is frozen $H_b \approx 0$

but H_a is large

a(t) will expand, diluting curvature until $t^2 \sim G\,\Lambda$ when $\Omega_k < \Omega_\Lambda$

slow-roll inflation takes over and drives all dimensions to expand $H_b \to H_a$

Evolution of the Anisotropic Universe

normal FRW eqn: $$2\dot{H}_a + 3H_a^2 + \frac{k}{a^2} = -8\pi G p_z$$

our universe is approximately isotropic: $\Delta H \equiv H_a - H_b \ll H$ and $\Omega_k \ll 1$

Evolution of the Anisotropic Universe

normal FRW eqn: $$2\dot{H}_a + 3H_a^2 + \frac{k}{a^2} \quad = \quad -8\pi G p_z$$

our universe is approximately isotropic: $\Delta H \equiv H_a - H_b \ll H$ and $\Omega_k \ll 1$

$$\frac{d}{dt}\Delta H + 3H_a\,\Delta H + \frac{k}{a^2} = 8\pi G\,(p_r - p_z)$$

Evolution of the Anisotropic Universe

normal FRW eqn: $$2\dot{H}_a + 3H_a^2 + \frac{k}{a^2} \quad = \quad -8\pi G p_z$$

our universe is approximately isotropic: $\Delta H \equiv H_a - H_b \ll H$ and $\Omega_k \ll 1$

$$\frac{d}{dt}\Delta H + 3H_a\,\Delta H + \frac{k}{a^2} = 8\pi G\left(p_r - p_z\right) \approx 0$$

thermal equilibrium ⇒ isotropic pressure

and during MD pressure is small enough $\quad \frac{\Delta p}{p} \sim \frac{\Delta H}{H}$

Evolution of the Anisotropic Universe

normal FRW eqn: $$2\dot{H}_a + 3H_a^2 + \frac{k}{a^2} \quad = \quad -8\pi G p_z$$

our universe is approximately isotropic: $\Delta H \equiv H_a - H_b \ll H$ and $\Omega_k \ll 1$

$$\frac{d}{dt}\Delta H + 3H_a\,\Delta H + \frac{k}{a^2} = 8\pi G\,(p_r - p_z) \approx 0$$

thermal equilibrium ⇒ isotropic pressure

and during MD pressure is small enough $\quad \frac{\Delta p}{p} \sim \frac{\Delta H}{H}$

eqn for b(t): $$2\dot{H}_b + 3H_b^2 - \frac{k}{a^2} = -8\pi G p$$

a(t) expands normally, b(t) expands as if curvature was opposite sign

Return of Curvature

$$\frac{d}{dt}\Delta H + 3H_a\,\Delta H + \frac{k}{a^2} = 0 \qquad \Omega_k = \frac{k}{a^2 H^2}$$

inhomogeneous solutions are:

Inflation $\quad \frac{\Delta H}{H_a} = -\Omega_k$

RD $\quad \frac{\Delta H}{H_a} = -\frac{1}{3}\Omega_k$

MD $\quad \frac{\Delta H}{H_a} = -\frac{2}{5}\Omega_k$

homogeneous solutions sourced at every transition but die off quickly

Return of Curvature

$$\frac{d}{dt}\Delta H + 3H_a\,\Delta H + \frac{k}{a^2} = 0 \qquad \Omega_k = \frac{k}{a^2H^2}$$

inhomogeneous solutions are:

Inflation	$\frac{\Delta H}{H_a} = -\Omega_k$	~ 1 in curvature dominance
		~ e^{-120} after inflation
RD	$\frac{\Delta H}{H_a} = -\frac{1}{3}\Omega_k$	~ 10^{-5} at recombination
MD	$\frac{\Delta H}{H_a} = -\frac{2}{5}\Omega_k$	~ 10^{-2} today

homogeneous solutions sourced at every transition but die off quickly

Return of Curvature

$$\frac{d}{dt}\Delta H + 3H_a \,\Delta H + \frac{k}{a^2} = 0 \qquad \Omega_k = \frac{k}{a^2 H^2}$$

inhomogeneous solutions are:

Inflation $\frac{\Delta H}{H_a} = -\Omega_k$

RD $\frac{\Delta H}{H_a} = -\frac{1}{3}\Omega_k$

MD $\frac{\Delta H}{H_a} = -\frac{2}{5}\Omega_k$

~ 1 in curvature dominance

~ e^{-120} after inflation

~ 10^{-5} at recombination

~ 10^{-2} today

homogeneous solutions sourced at every transition but die off quickly

we need the full solutions during MD:

$$a(t) \propto t^{\frac{2}{3}}\left(1 - \frac{\Omega_k}{5}\right)$$

$$b(t) \propto t^{\frac{2}{3}}\left(1 + \frac{\Omega_k}{5}\right)$$

Observables

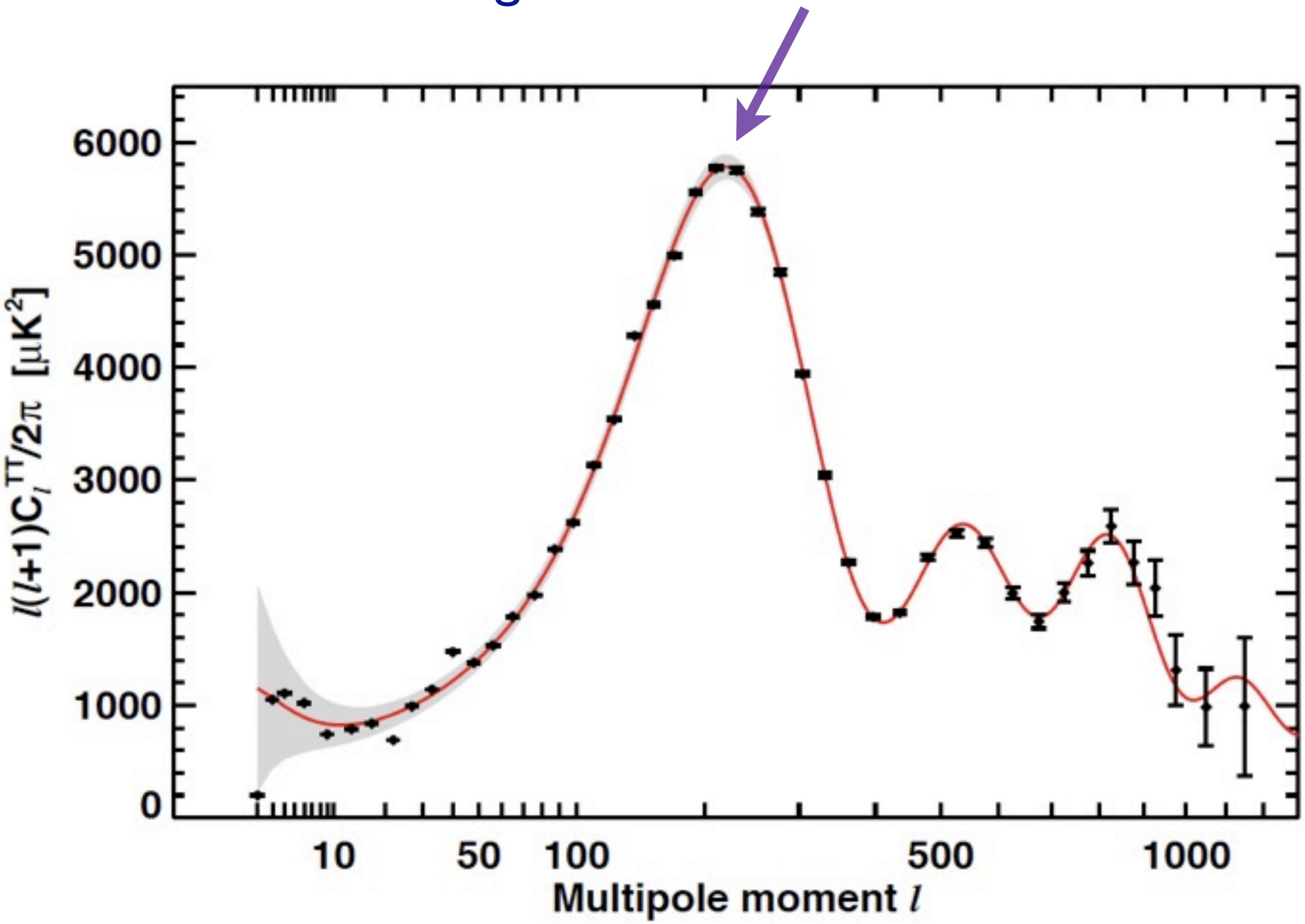
Measuring Curvature

Sound horizon at recombination provides a “standard ruler”

Measuring Curvature

Sound horizon at recombination provides a “standard ruler”

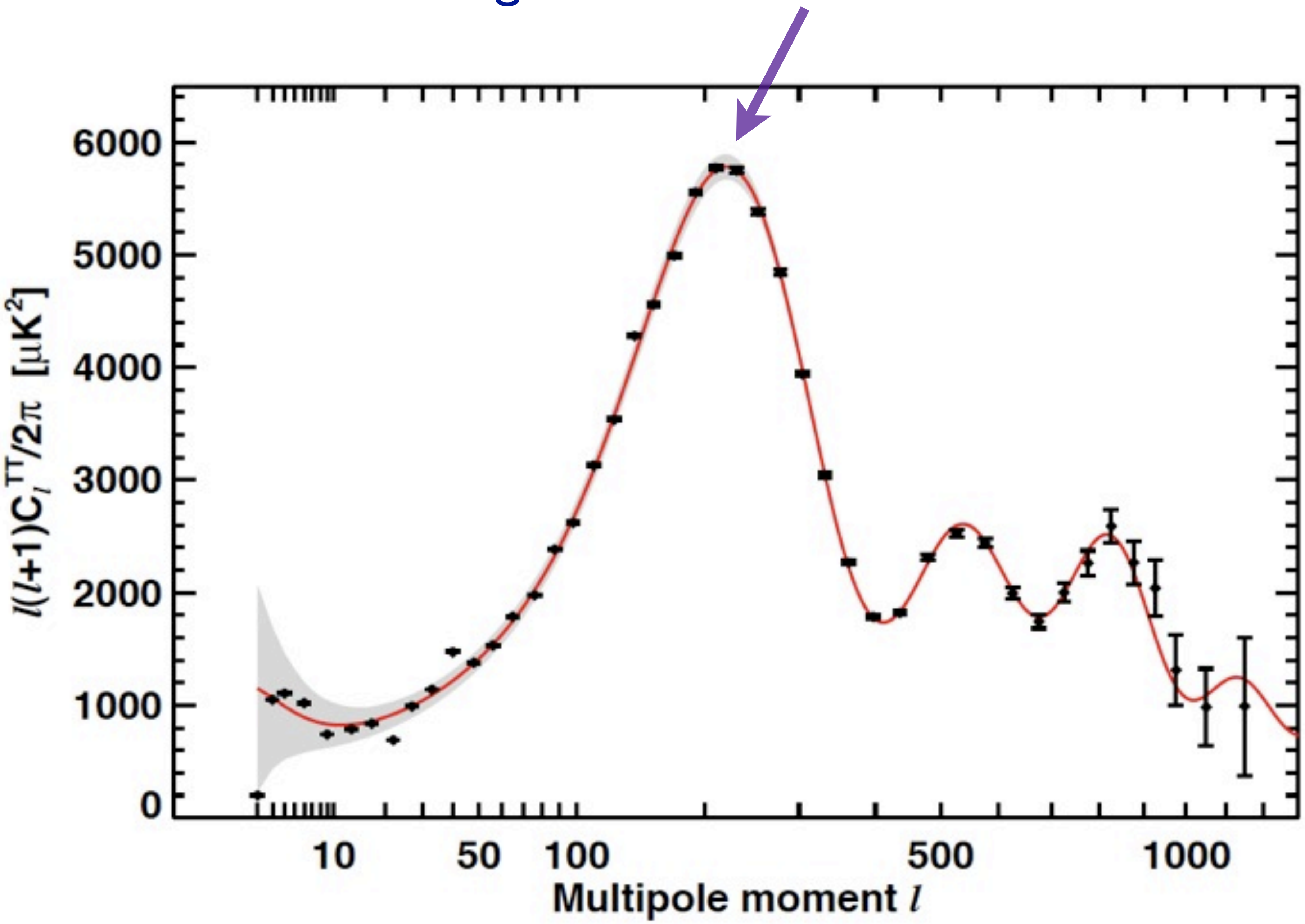
Curvature is measured by observing angular size of ruler ~ 1° a high-l observable



Measuring Curvature

Sound horizon at recombination provides a "standard ruler"

Curvature is measured by observing angular size of ruler ~ 1° a high-l observable

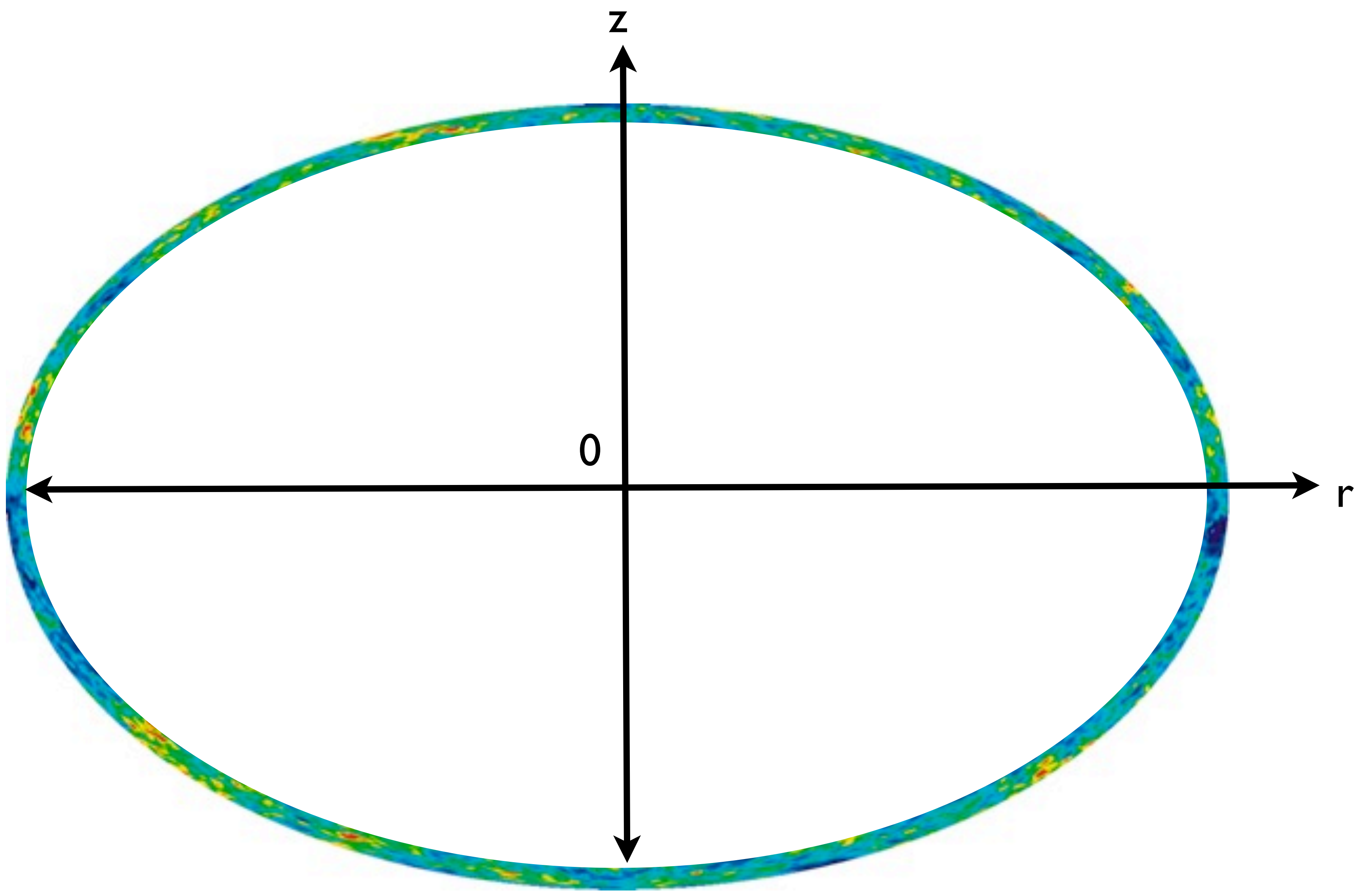


What does anisotropic curvature look like?

Standard Rulers

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

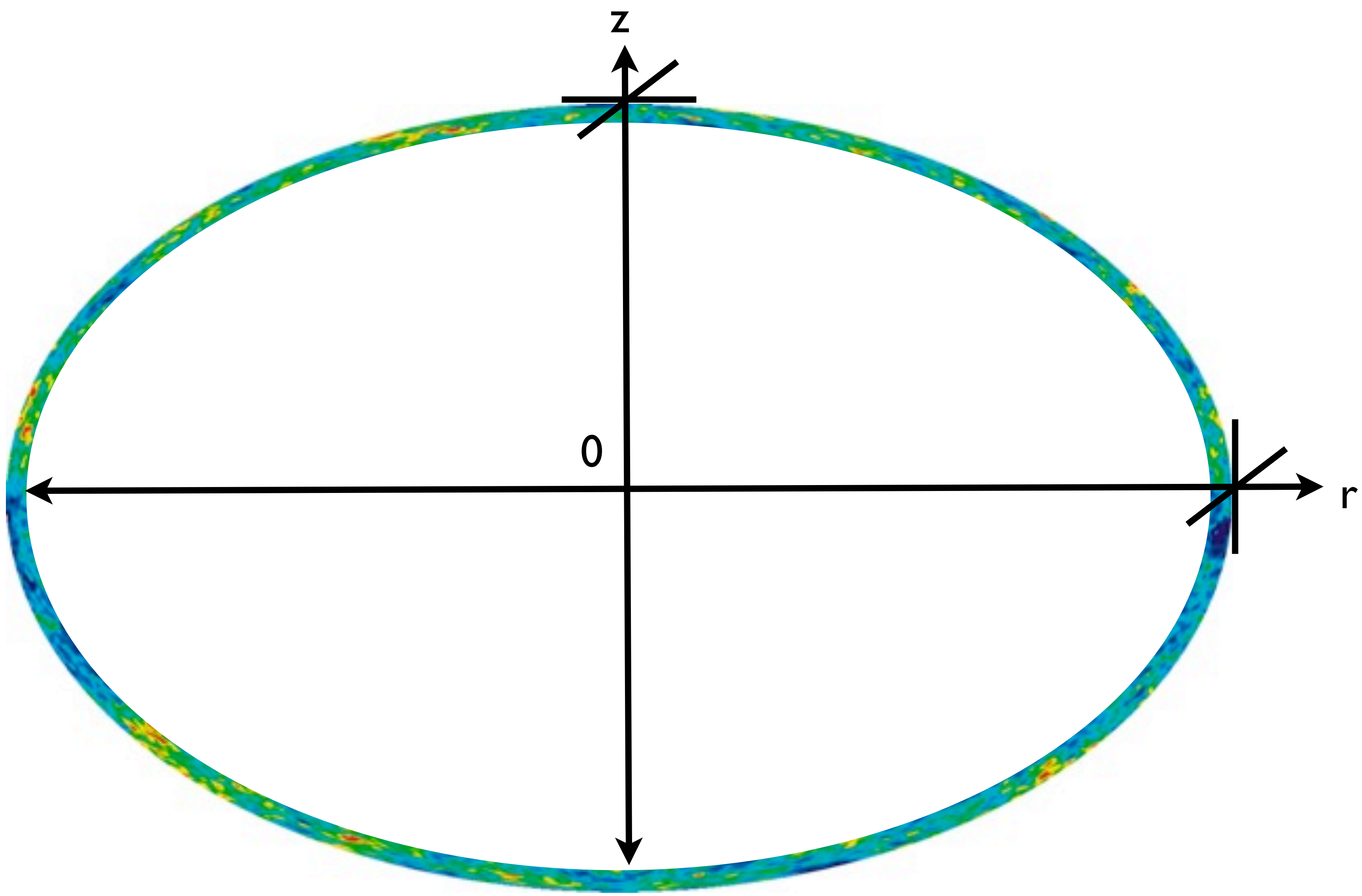
universe roughly flat before recombination ⇒ rulers are fixed physical length *ds*



Standard Rulers

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

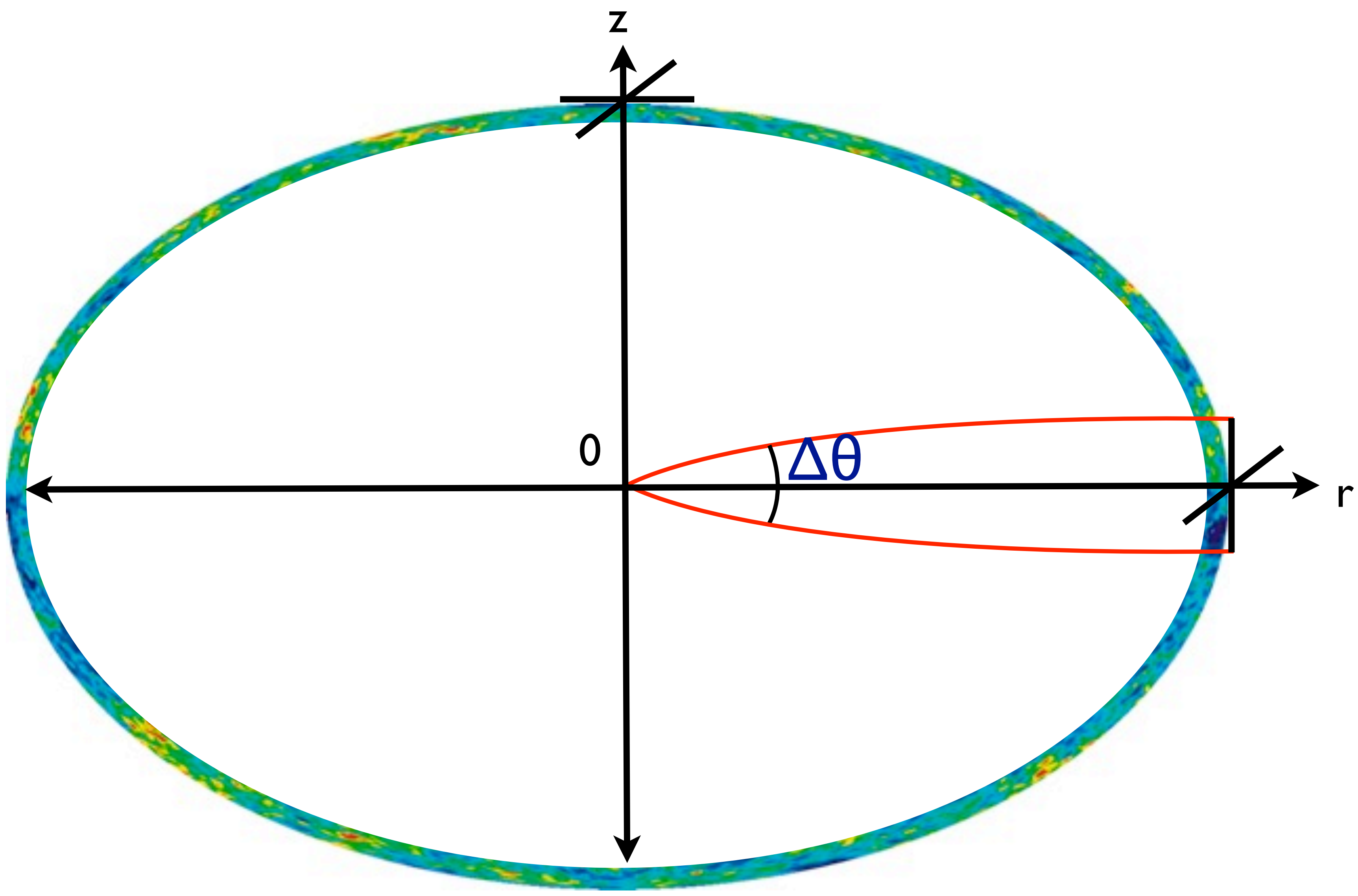
universe roughly flat before recombination ⇒ rulers are fixed physical length *ds*



Standard Rulers

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

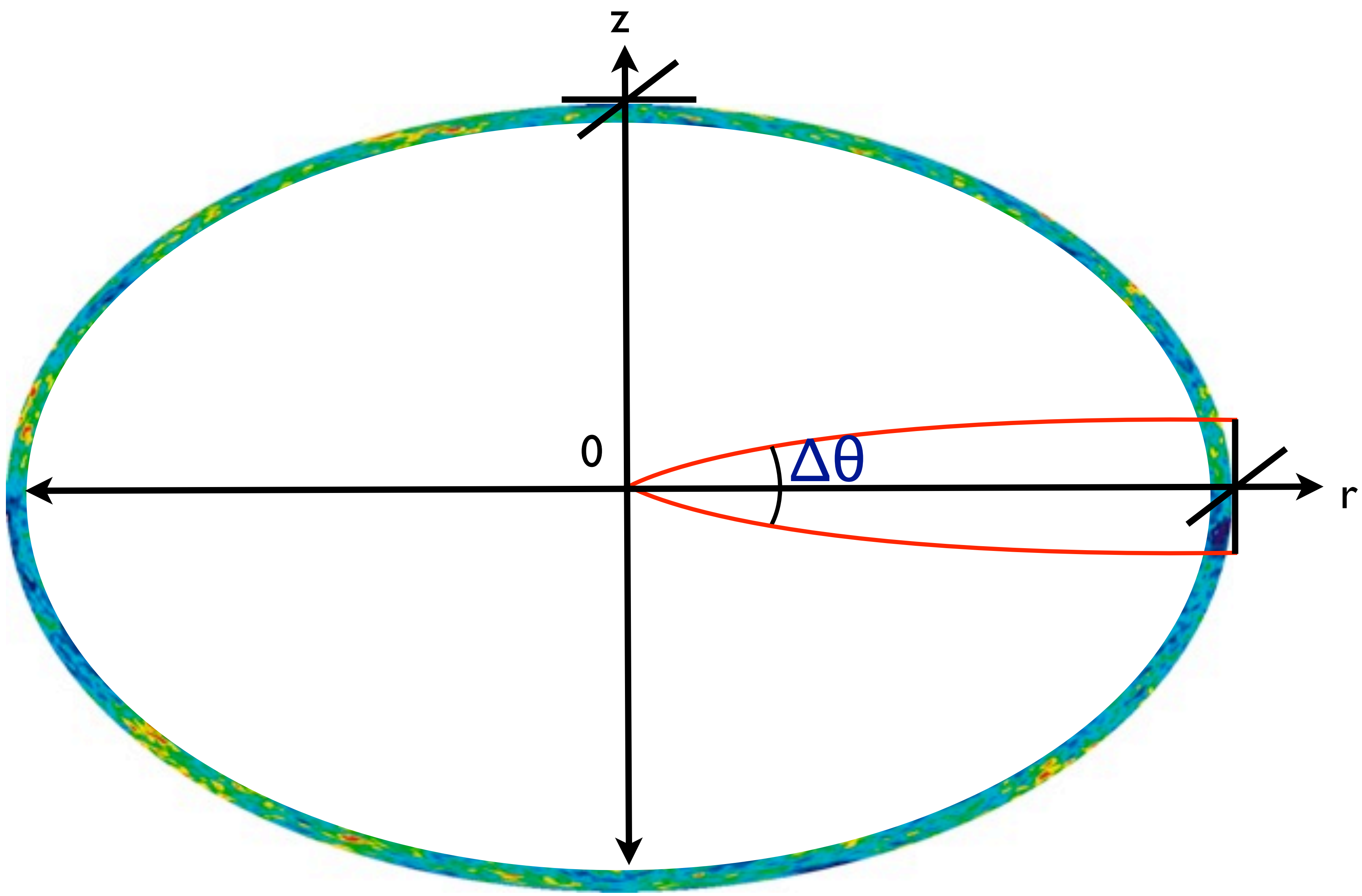
universe roughly flat before recombination ⇒ rulers are fixed physical length *ds*



Standard Rulers

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

universe roughly flat before recombination ⇒ rulers are fixed physical length *ds*



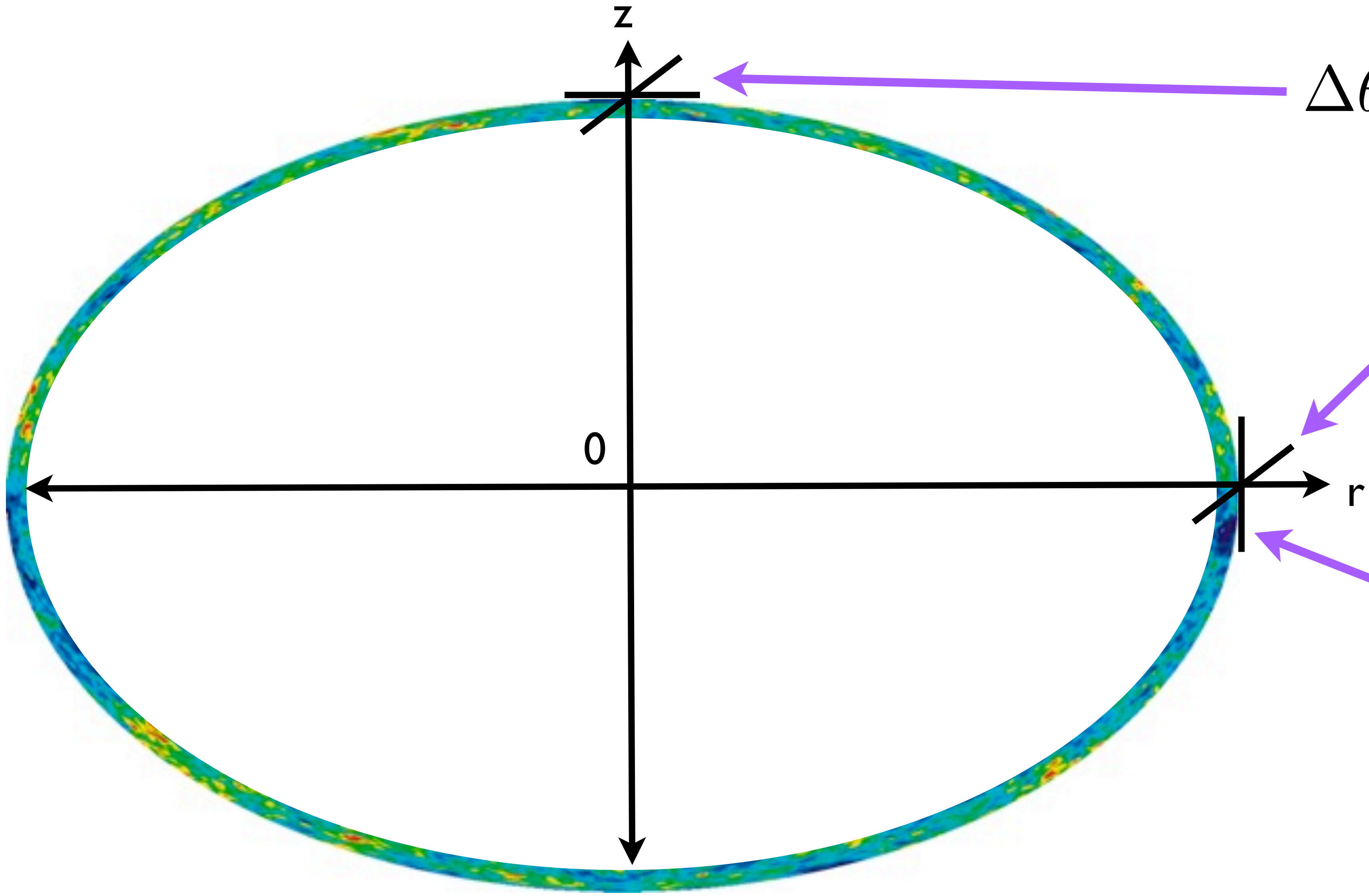
transform to locally flat frame
⇒ observable angle is

$$\tan(\theta) = \left(\frac{a(t)}{b(t)} \frac{dr}{dz} \right) + \mathcal{O}\left(\frac{1\,\mathrm{m}}{28\ \mathrm{Gpc}} \right)$$

Standard Rulers

$$ds^2 = dt^2 - a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\phi^2\right) - b(t)^2 dz^2$$

universe roughly flat before recombination ⇒ rulers are fixed physical length *ds*



$$\Delta\theta\left(1+\frac{1}{5}\Omega_k\right)$$

$$\Delta\theta\left(1+\frac{3}{5}\Omega_k\right)$$

$$\Delta\theta\left(1-\frac{1}{5}\Omega_k\right)$$

transform to locally flat frame
⇒ observable angle is

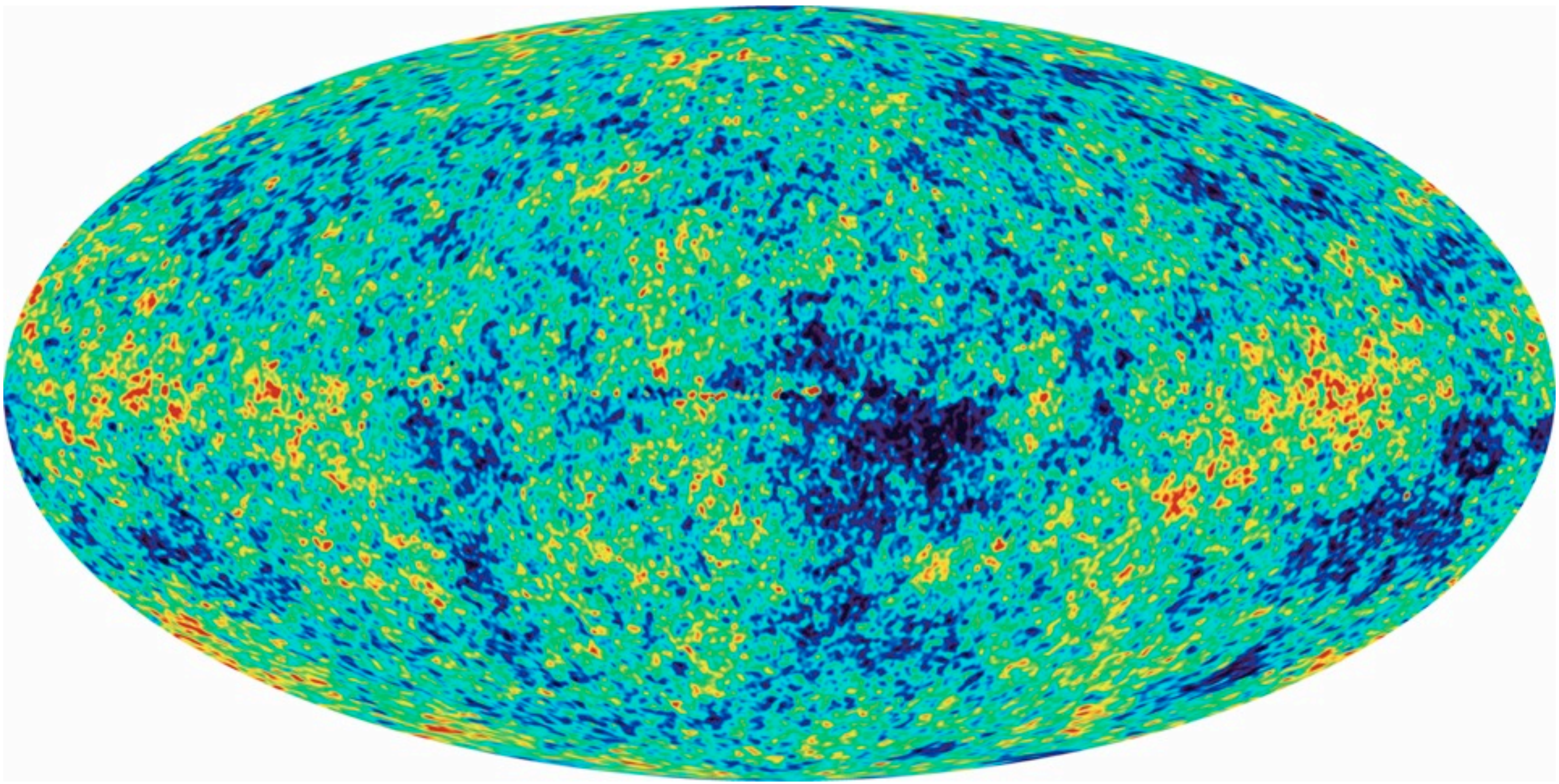
$$\tan(\theta) = \left(\frac{a(t)}{b(t)}\frac{dr}{dz}\right) + \mathcal{O}\left(\frac{1\,\mathrm{m}}{28\ \mathrm{Gpc}}\right)$$

Should be easier to measure than isotropic curvature

Effect of Geometric Warp

Effect of Geometric Warp

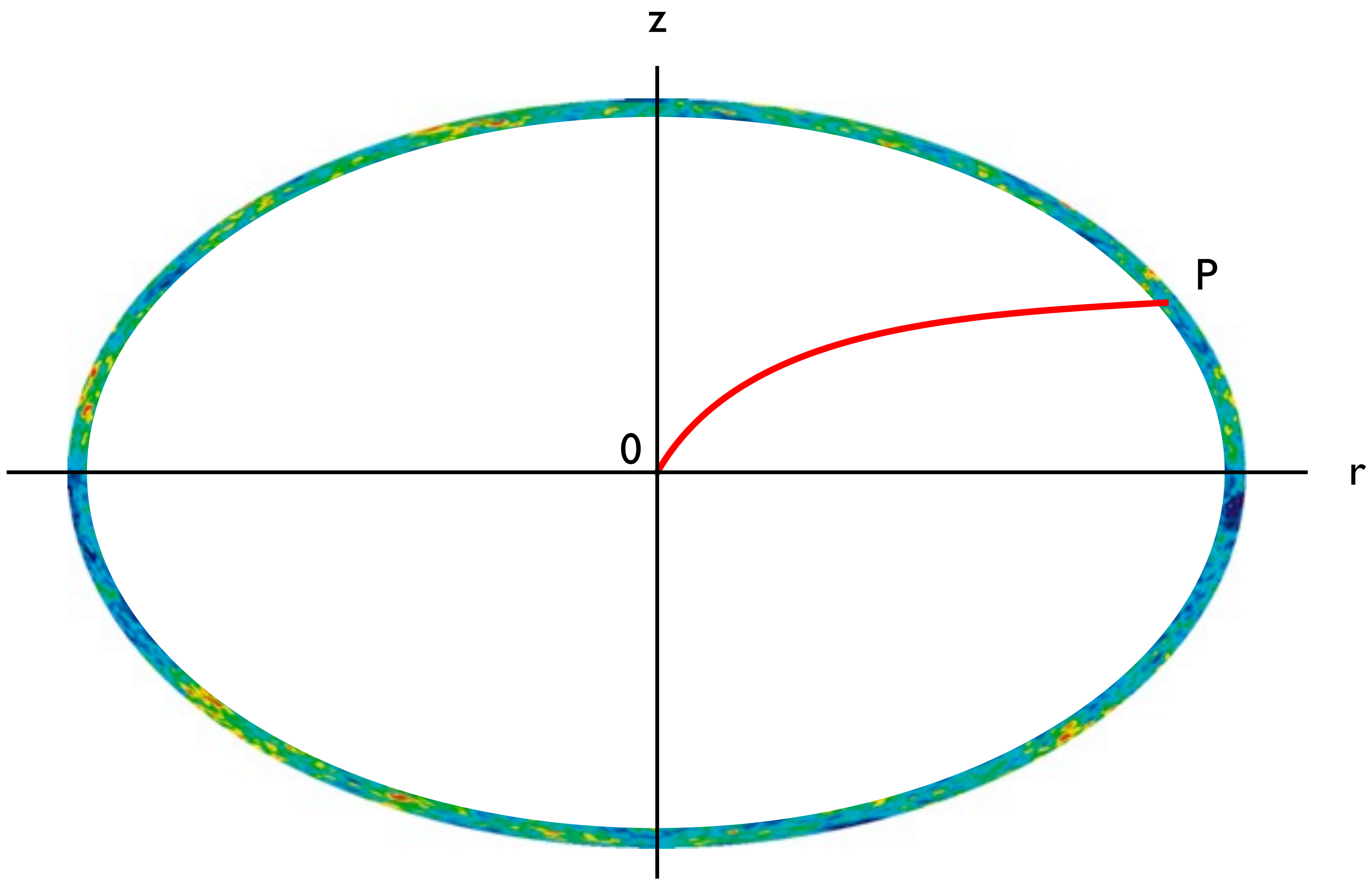
Effect of Geometric Warp



CMB Flux

CMB Flux today =

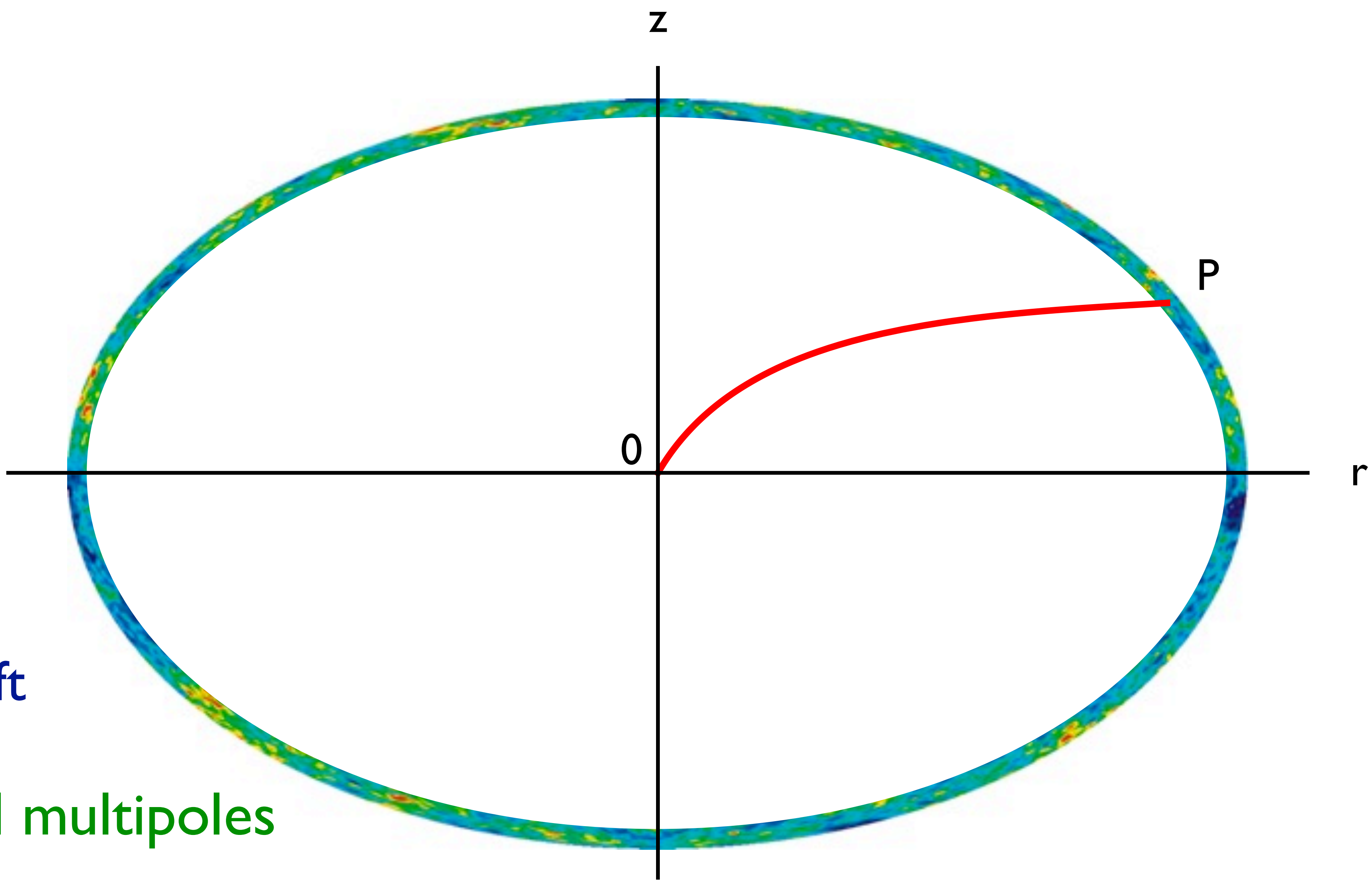
$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



Anisotropic Curvature:

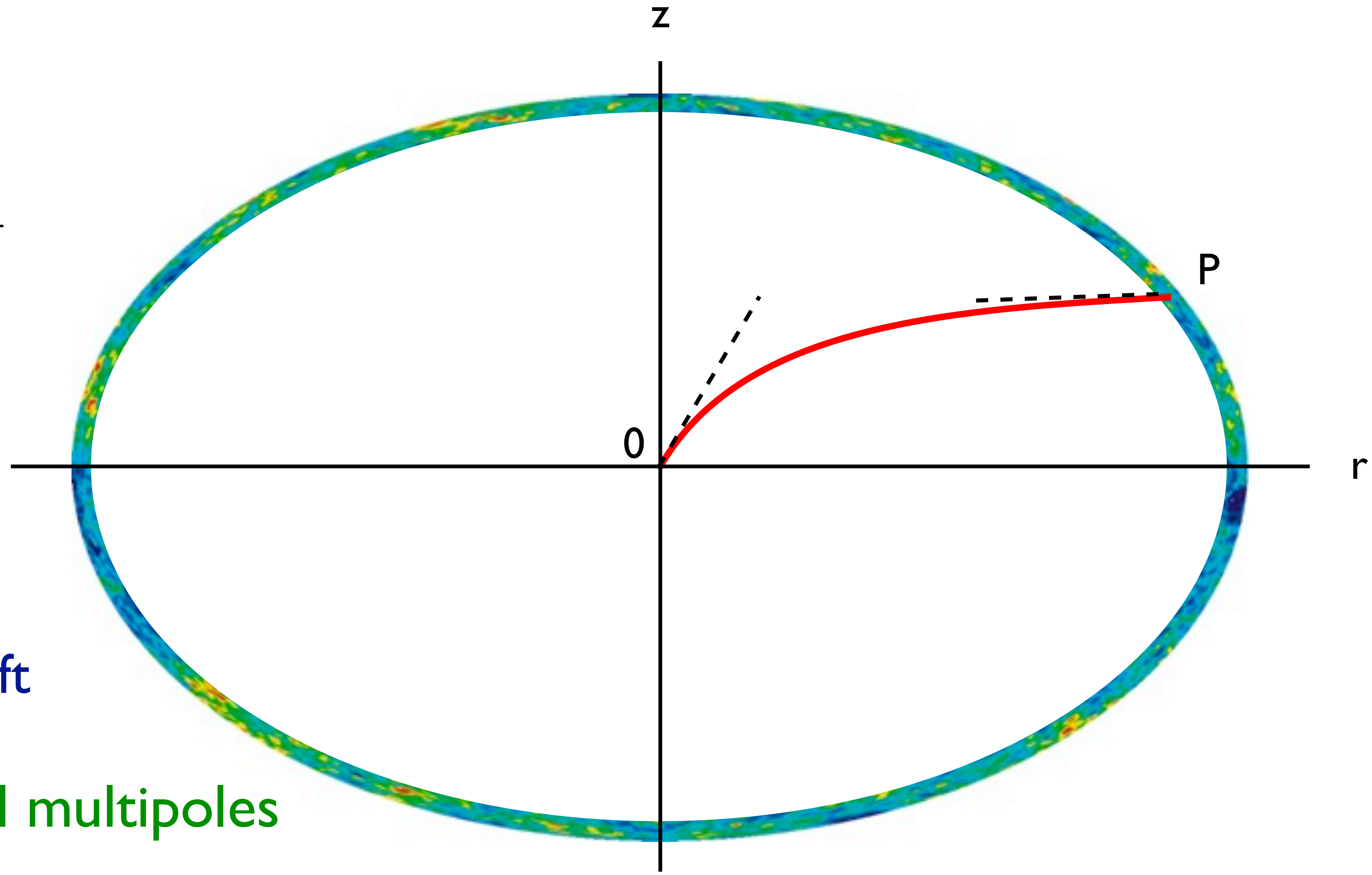
1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles

CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles

CMB Flux

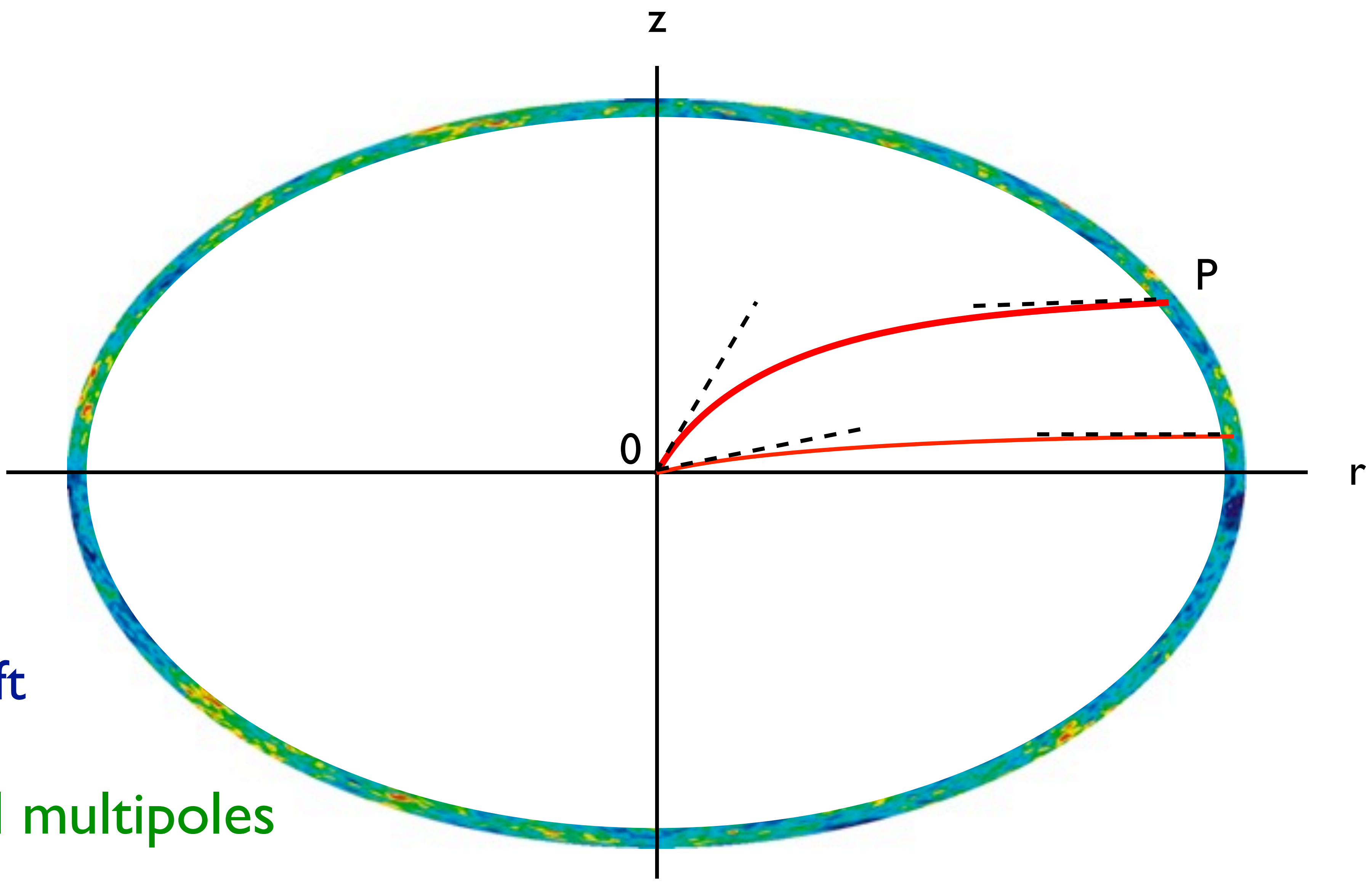
CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$

Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

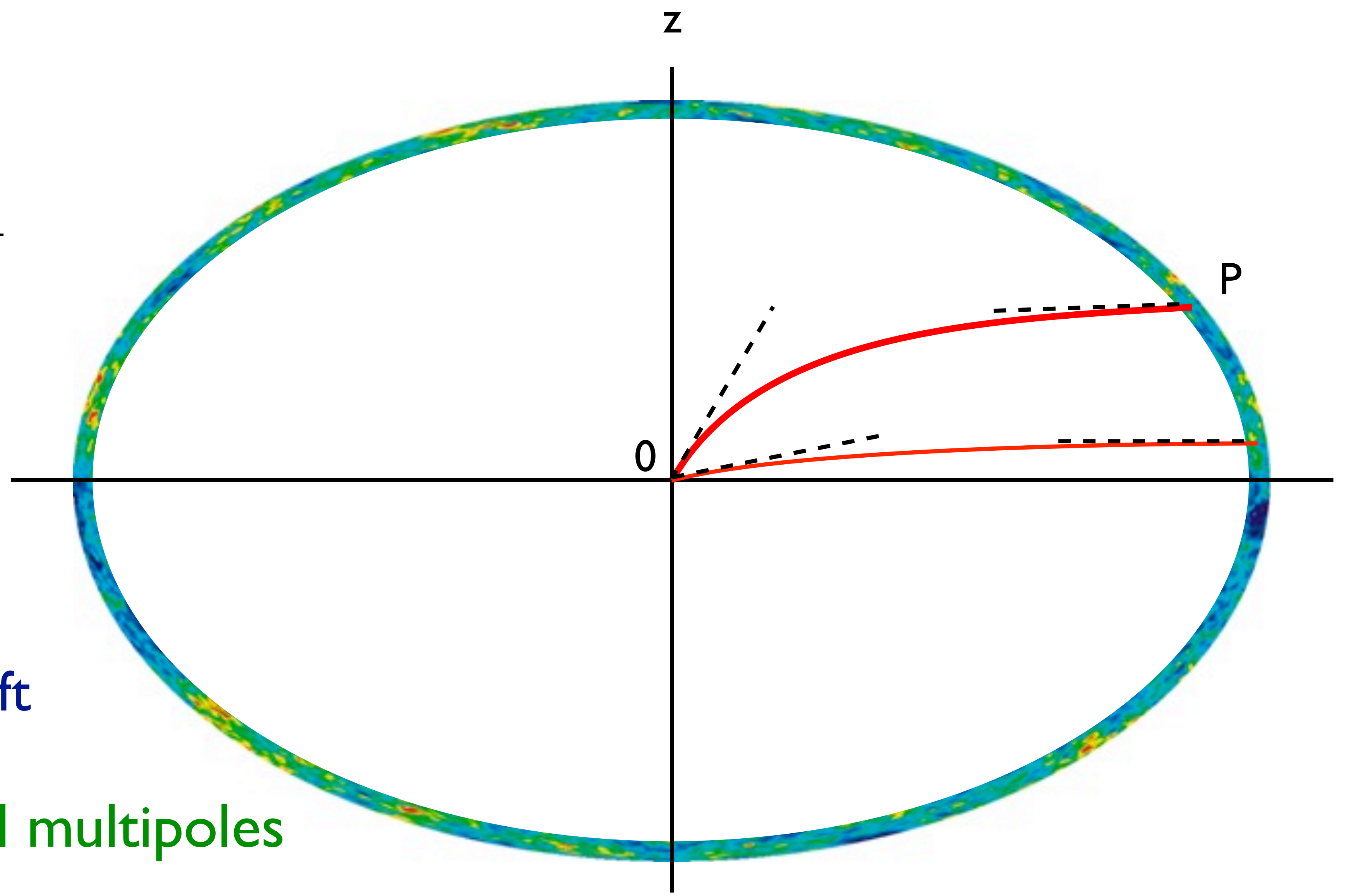
Late time effect acts on all multipoles



CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles

$$\Phi_0(E_0,\theta_0) = \Phi_P(E_P,\theta_P)\left(\frac{d\Omega_P}{d\Omega_0}\right)\left(\frac{dA_P dt_P}{dA_0 dt_0}\right)\left(\frac{dE_P}{dE_0}\right)$$

CMB Flux

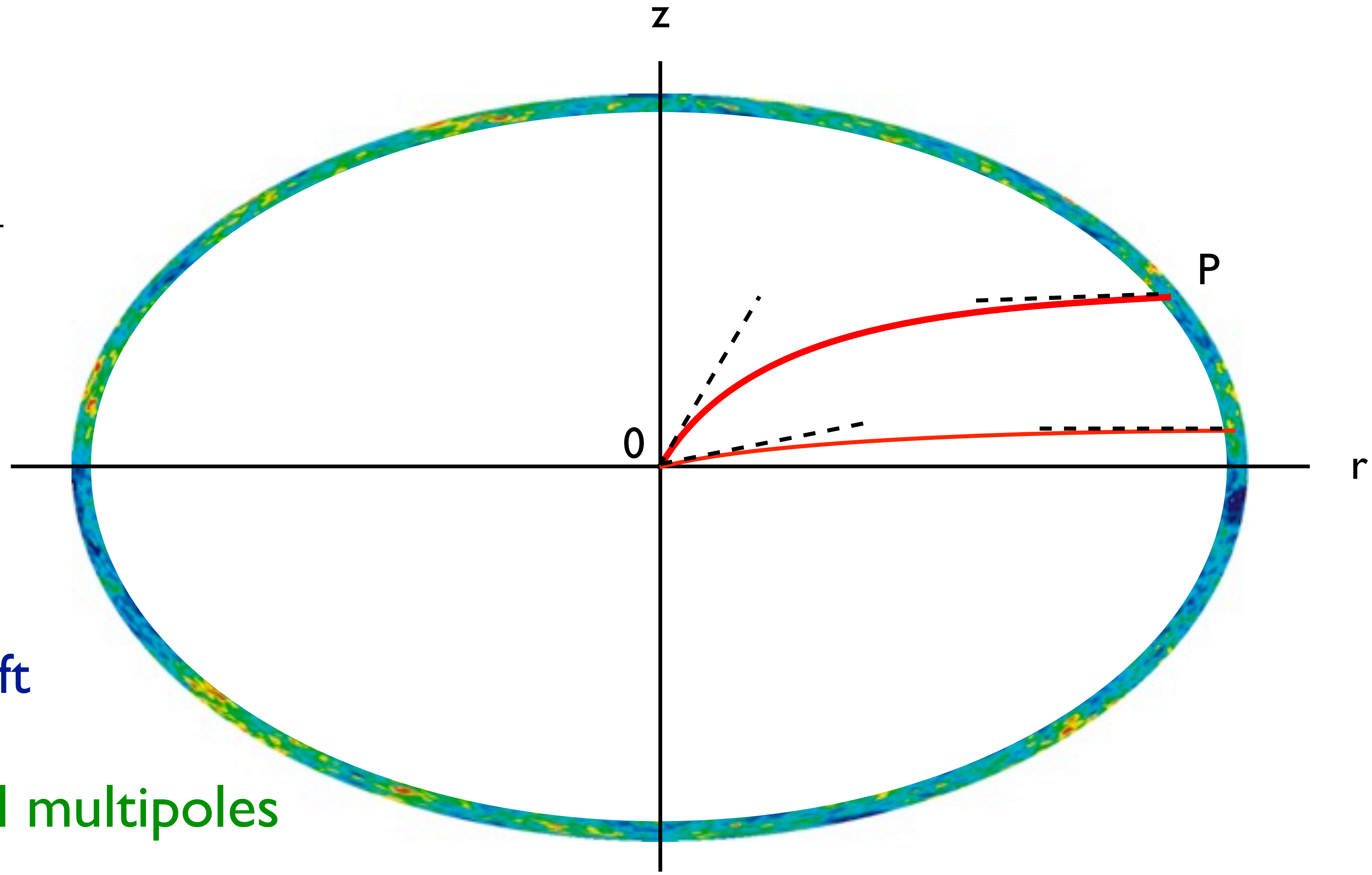
CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$

Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles



$$\Phi_0(E_0, \theta_0) = \Phi_P(E_P, \theta_P) \left(\frac{d\Omega_P}{d\Omega_0}\right) \left(\frac{dA_P dt_P}{dA_0 dt_0}\right) \left(\frac{dE_P}{dE_0}\right)$$

$$\propto a^2 b$$

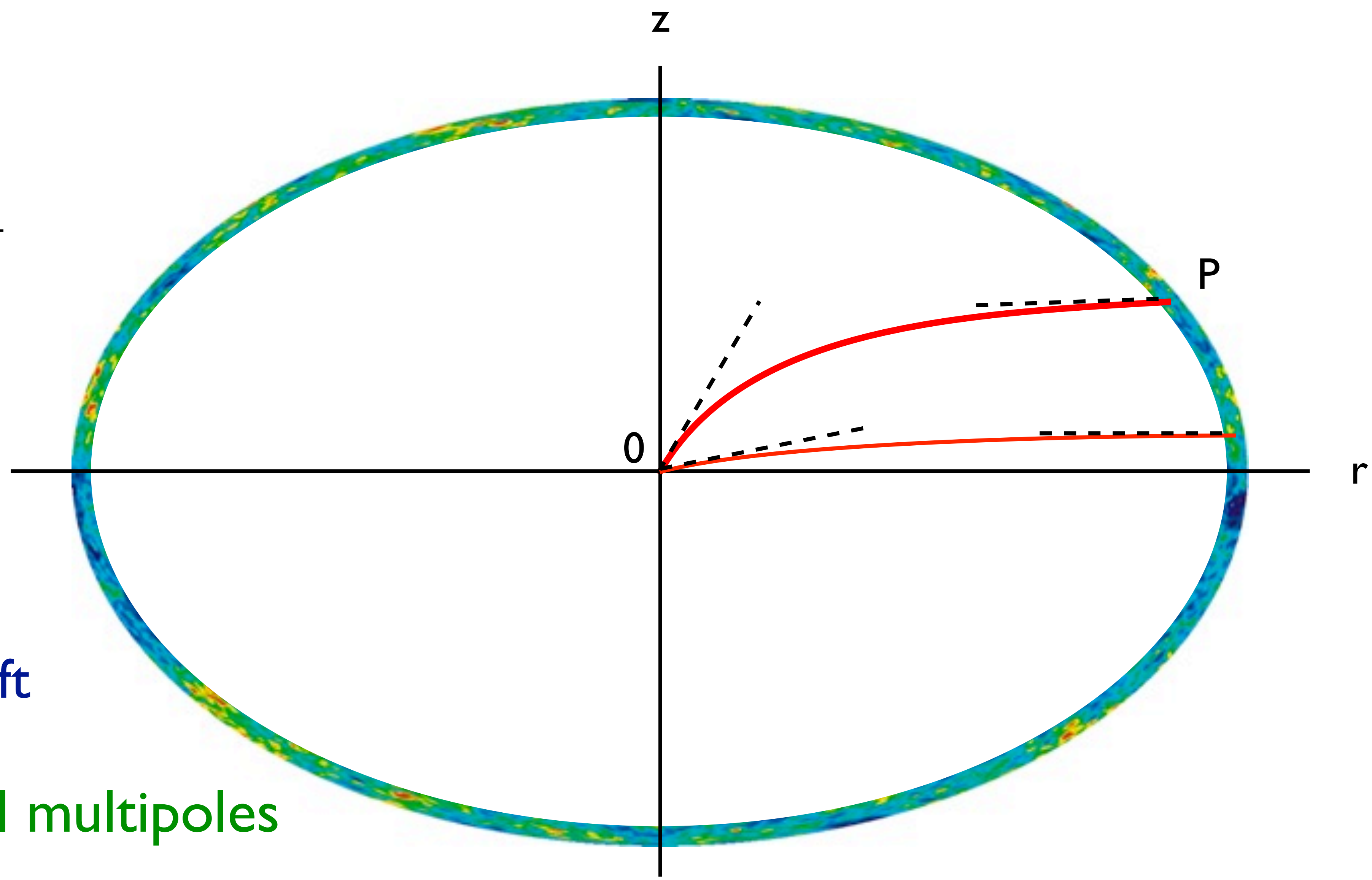
CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$

Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift



Late time effect acts on all multipoles

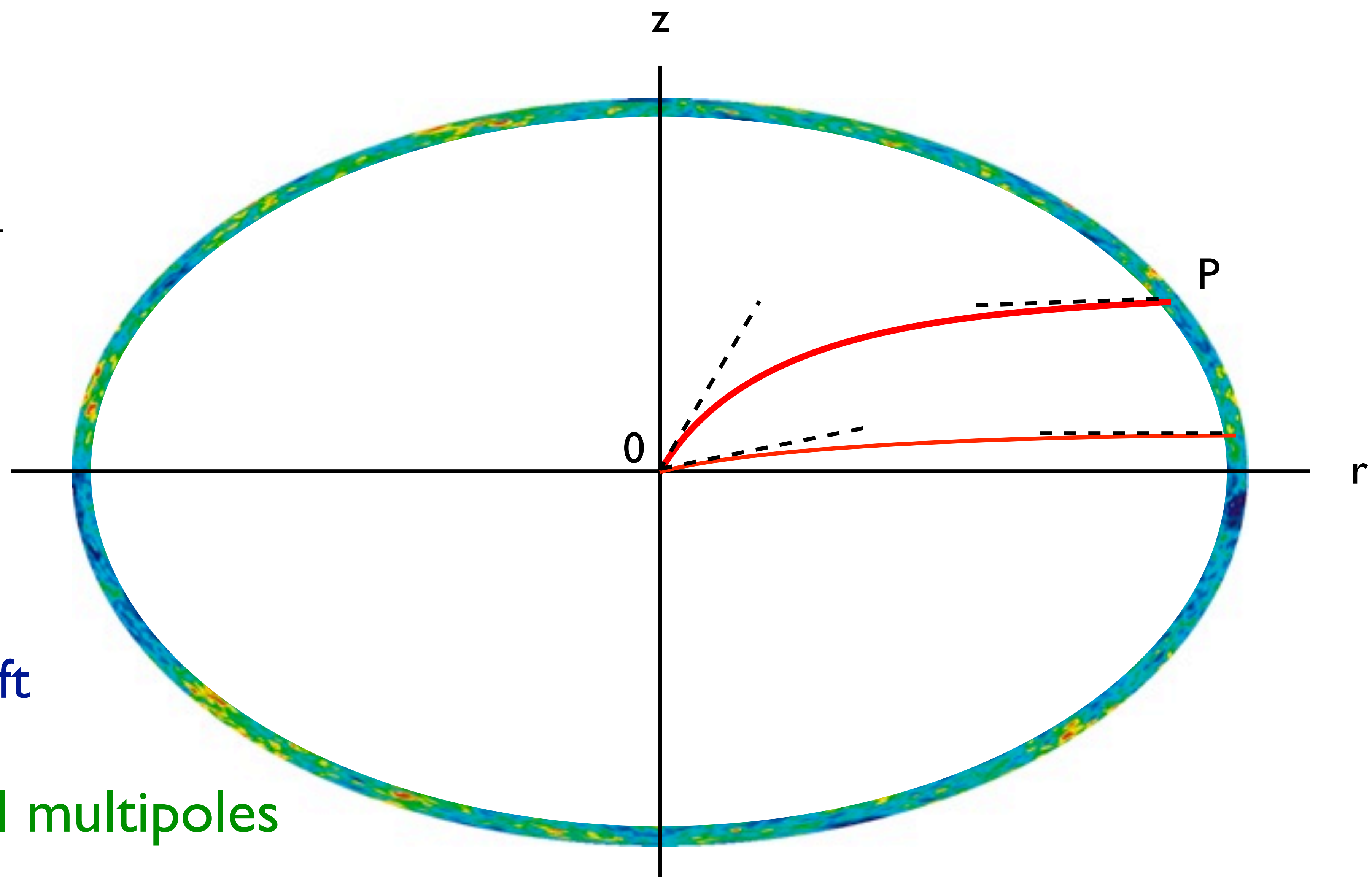
$$\Phi_0 \left(E_0, \theta_0\right) = \Phi_P \left(E_P, \theta_P\right) \left(\frac{d\Omega_P}{d\Omega_0}\right) \left(\frac{dA_P dt_P}{dA_0 dt_0}\right) \left(\frac{dE_P}{dE_0}\right)$$

$$\Phi_0 \left(E_0, \theta_0\right) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0+\delta\theta)} \left(1 + \Omega_{k_0} Y_{20}\left(\theta_0\right)\right)\right) - 1}$$

CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles

$$\Phi_0\left(E_0,\theta_0\right) = \Phi_P\left(E_P,\theta_P\right)\left(\frac{d\Omega_P}{d\Omega_0}\right)\left(\frac{dA_P dt_P}{dA_0 dt_0}\right)\left(\frac{dE_P}{dE_0}\right)$$

$$\Phi_0\left(E_0,\theta_0\right) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0+\delta\theta)}\left(1+\Omega_{k_0}Y_{20}\left(\theta_0\right)\right)\right)-1}$$

#1

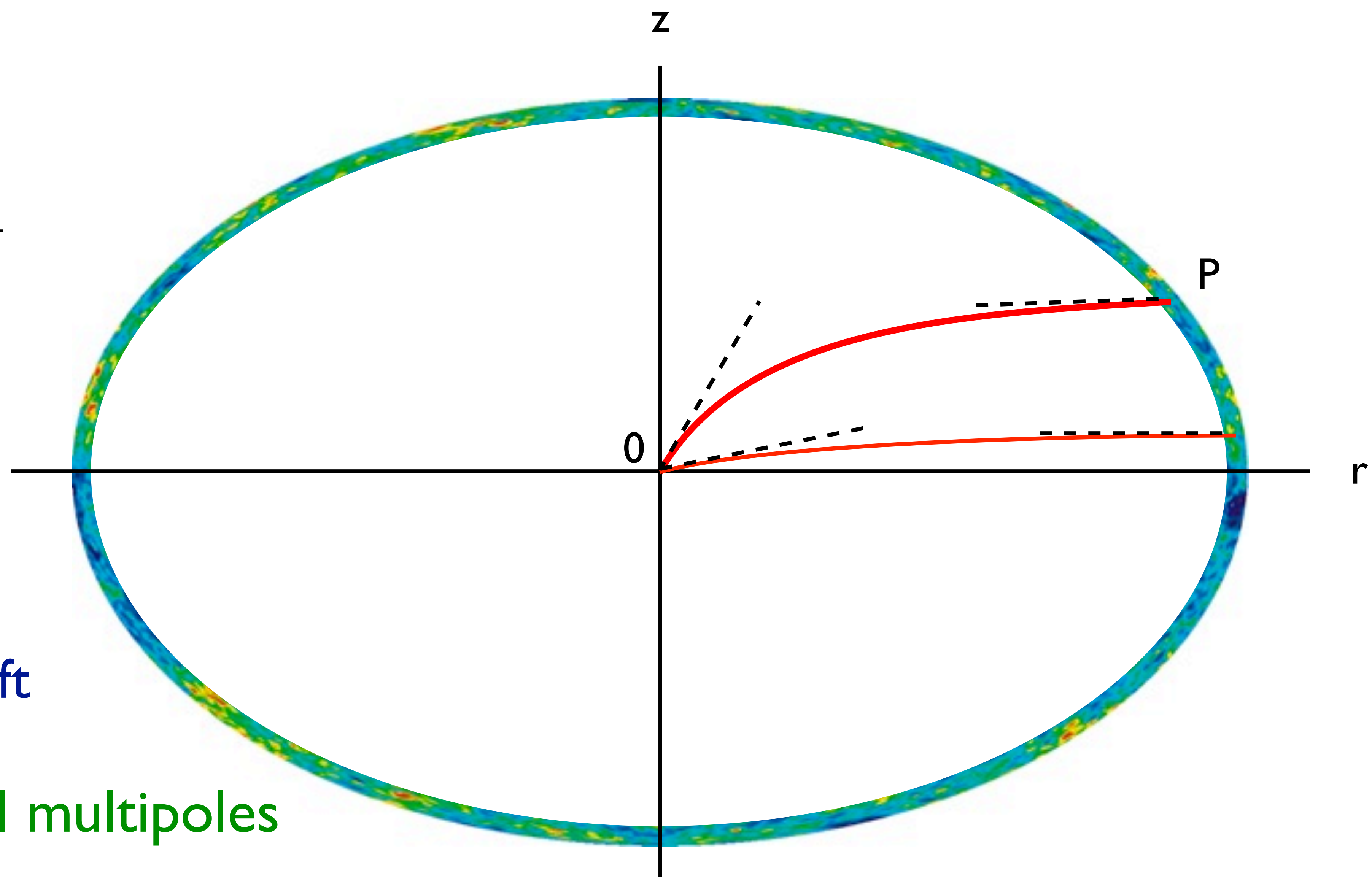
CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$

Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift



Late time effect acts on all multipoles

$$\Phi_0 (E_0, \theta_0) = \Phi_P (E_P, \theta_P) \left(\frac{d\Omega_P}{d\Omega_0}\right) \left(\frac{dA_P dt_P}{dA_0 dt_0}\right) \left(\frac{dE_P}{dE_0}\right)$$

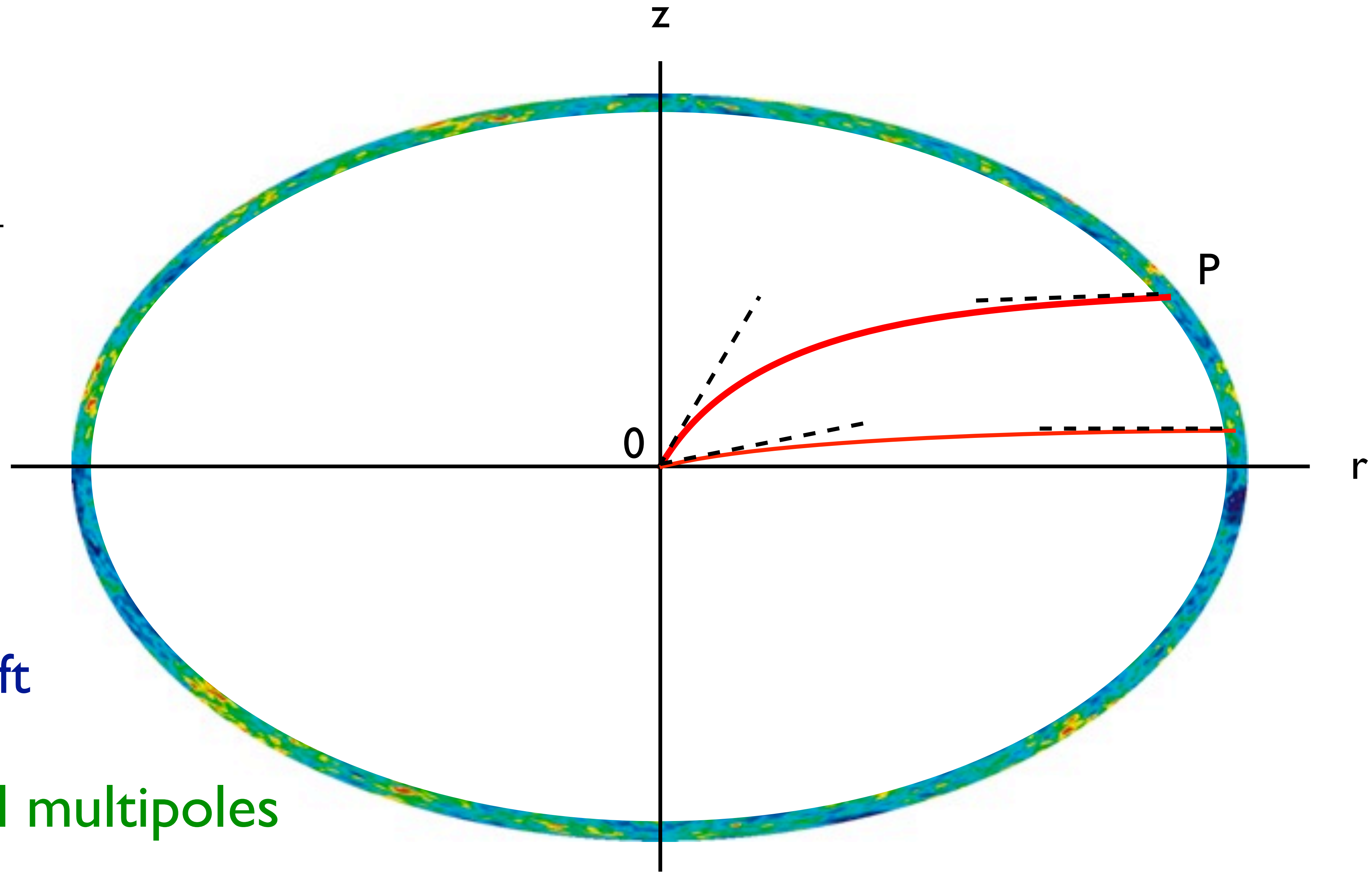
$$\Phi_0 (E_0, \theta_0) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0 + \delta\theta)} \left(1 + \Omega_{k_0} Y_{20}(\theta_0)\right)\right) - 1}$$

#1 #2

CMB Flux

CMB Flux today =

$$\Phi_0 = \frac{dN_0}{d\Omega_0 dA_0 dt_0 dE_0}$$



Anisotropic Curvature:

1. Non-sphericity of LSS
2. Bending of photon path
3. Angle dependent redshift

Late time effect acts on all multipoles

$$\Phi_0(E_0,\theta_0) = \Phi_P(E_P,\theta_P)\left(\frac{d\Omega_P}{d\Omega_0}\right)\left(\frac{dA_P dt_P}{dA_0 dt_0}\right)\left(\frac{dE_P}{dE_0}\right)$$

$$\Phi_0(E_0,\theta_0) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0+\delta\theta)}\left(1+\Omega_{k_0}Y_{20}(\theta_0)\right)\right)-1}$$

#1 #2 #3

The Quadrupole

$$\Phi_0 \left(E_0, \theta_0\right) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\mathrm{LSS}}(\theta_0+\delta\theta)} \left(1 + \Omega_{k_0} Y_{20}\left(\theta_0\right)\right)\right) - 1}$$

$$T = \overline{T} + \sum_{lm} a_{lm} Y_{lm}$$

The Quadrupole

$$\Phi_0\left(E_0, \theta_0\right) = \frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0+\delta\theta)}\left(1+\Omega_{k_0} Y_{20}\left(\theta_0\right)\right)\right)-1}$$

$$T = \overline{T} + \sum_{lm} a_{lm} Y_{lm}$$

only redshift affects the monopole

The Quadrupole

$$\Phi_0\left(E_0,\theta_0\right)=\frac{E_0^2}{\exp\left(\frac{E_0}{T_{\rm LSS}(\theta_0+\delta\theta)}\left(1+\Omega_{k_0}Y_{20}\left(\theta_0\right)\right)\right)-1}$$

$$T=\overline{T}+\sum_{lm}a_{lm}Y_{lm}$$

only redshift affects the monopole

contribution to CMB quadrupole anisotropy: $a_{20}\approx-\frac{8}{15}\sqrt{\frac{\pi}{5}}\Omega_{k_0}\overline{T}$

tuning ⇒ likely range ~ $10^{-4}\gtrsim\Omega_{k_0}\gtrsim10^{-5}$ ~ cosmic variance

low-l multipoles have high cosmic variance

local ISW effect may raise quadrupole

Francis & Peacock (2009), WMAP7 (2010)

Angular Correlations

a_{lm} = size of temperature fluctuation in Y_{lm} mode

statistical isotropy ⇒ $\langle a_{l_1 m_1} \, a^*_{l_2 m_2} \rangle = 0$

except $\langle a_{lm} \, a^*_{lm} \rangle \sim C_l$

Angular Correlations

a_{lm} = size of temperature fluctuation in Y_{lm} mode

anisotropic

curvature

statistical isotropy $\Rightarrow$ $\langle a_{l_1 m_1} \, a^*_{l_2 m_2} \rangle = 0$

except $\langle a_{lm} \, a^*_{lm} \rangle \sim C_l \, (1 + \Omega_{k_0} \, \#_{lm})$

$$\langle a_{lm} \, a^*_{l-2,m} \rangle \sim \Omega_{k_0} \, (C_{l-2} \, \#_{lm} + C_l \, \#_{lm})$$

Angular Correlations

a_{lm} = size of temperature fluctuation in Y_{lm} mode

anisotropic curvature

statistical isotropy $\Rightarrow$ $\langle a_{l_1 m_1}\, a^*_{l_2 m_2} \rangle = 0$

except $\langle a_{lm}\, a^*_{lm} \rangle \sim C_l \, (1 + \Omega_{k_0} \, \#_{lm})$

$\langle a_{lm}\, a^*_{l-2,m} \rangle \sim \Omega_{k_0} \, (C_{l-2} \, \#_{lm} + C_l \, \#_{lm})$

a good measure of anisotropy:

$$A^{LM}_{ll'} = \sum_{mm'} \langle a_{lm}\, a^*_{l'm'} \rangle \, (-1)^{m'} \, \mathcal{C}^{LM}_{l,m,l',-m'}$$ = 0 for isotropic

Angular Correlations

a_{lm} = size of temperature fluctuation in Y_{lm} mode

statistical isotropy $\Rightarrow$ $\langle a_{l_1 m_1}\, a^*_{l_2 m_2} \rangle = 0$

except $\langle a_{lm}\, a^*_{lm} \rangle \sim C_l\, (1 + \Omega_{k_0}\, \#_{lm})$

$\langle a_{lm}\, a^*_{l-2,m} \rangle \sim \Omega_{k_0}\, (C_{l-2}\, \#_{lm} + C_l\, \#_{lm})$

anisotropic curvature

a good measure of anisotropy:

$$A^{LM}_{ll'} = \sum_{mm'} \langle a_{lm}\, a^*_{l'm'} \rangle\, (-1)^{m'}\, \mathcal{C}^{LM}_{l,m,l',-m'}$$ = 0 for isotropic

anisotropic curvature gives:

$$A^{20}_{ll} \sim \Omega_{k_0}\, C_l\, \sqrt{l}$$

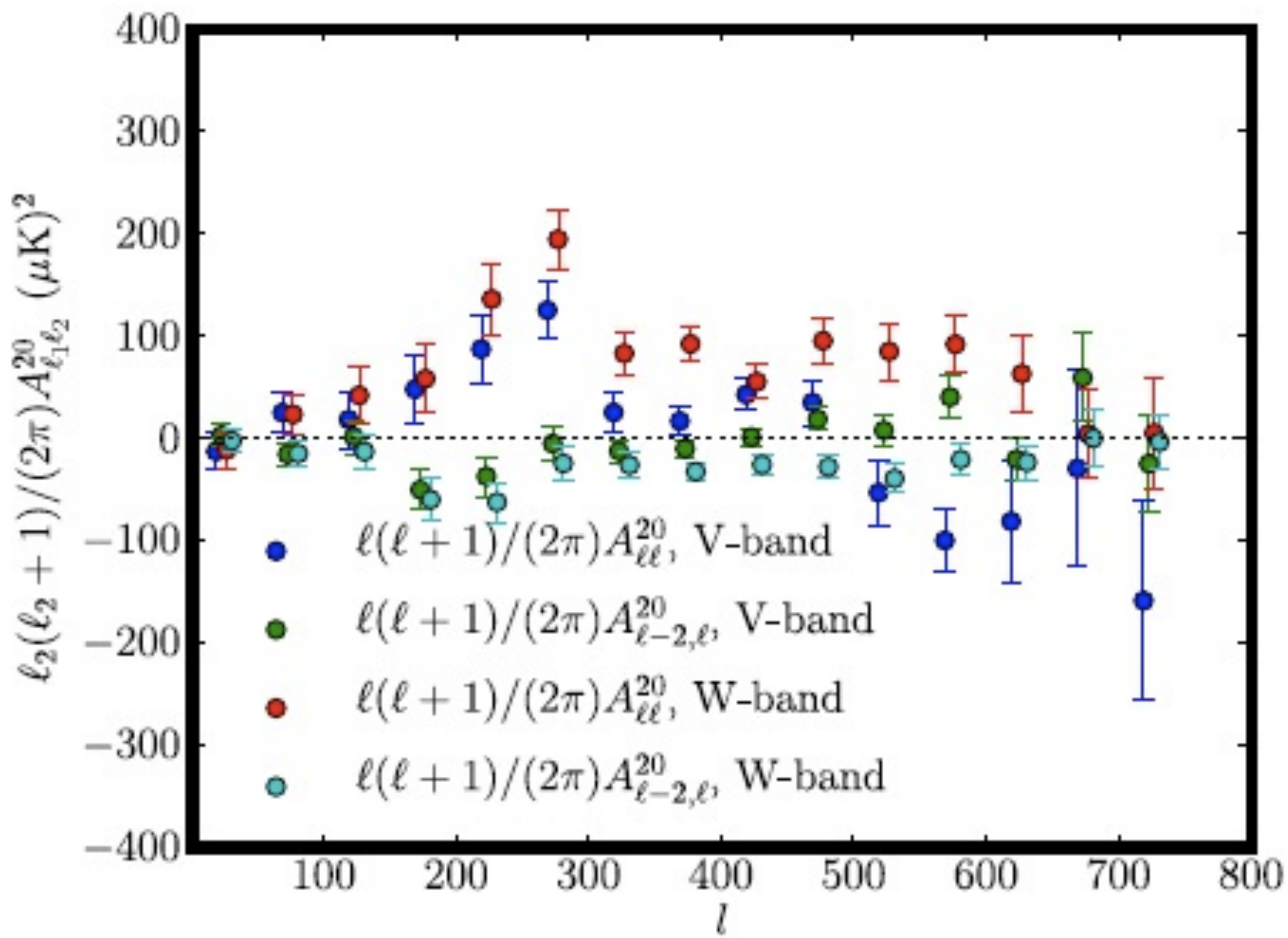
$$A^{20}_{l,l-2} \sim \Omega_{k_0}\, (l\,(C_l - C_{l-2}) + C_l)\, \sqrt{l}$$

These are our high-l observables - low cosmic variance

WMAP Anomaly

WMAP sees only two nonzero: A^{20}_{ll} and $A^{20}_{l,l-2}$

More precision than isotropic curvature,
no degeneracy with scale factor expansion history



possibly due to instrumental systematics

Planck should improve measurement

Is it just another anisotropy?

Is it just another anisotropy?

Symmetries of Bubble Nucleation => Specific initial geometry

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

Is it just another anisotropy?

Symmetries of Bubble Nucleation => Specific initial geometry

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

Power in just one linearly independent harmonic e.g. Y_{20}

Is it just another anisotropy?

Symmetries of Bubble Nucleation => Specific initial geometry

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

Power in just one linearly independent harmonic e.g. Y_{20}

Expect power in all harmonics for generic anisotropy.

Is it just another anisotropy?

Symmetries of Bubble Nucleation => Specific initial geometry

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\phi^2 \right) - b(t)^2 dz^2$$

Power in just one linearly independent harmonic e.g. Y_{20}

Expect power in all harmonics for generic anisotropy.

Symmetries valid in thin wall regime.
Thick wall?

Signals of Compact Topology

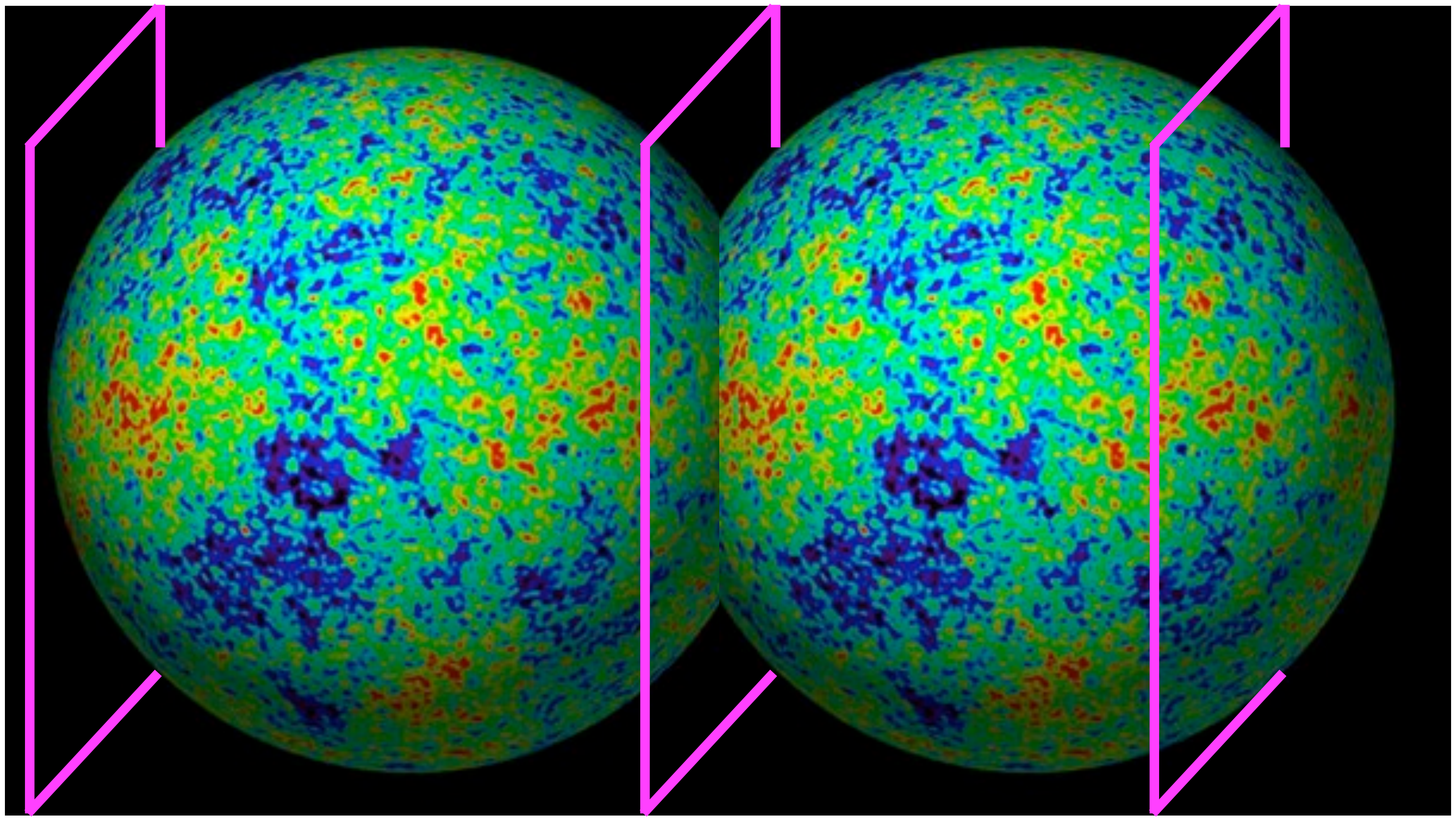
Eternal inflation seems to imply space is infinite

But we're led to finite, compact topology in at least one dimension

Signals of Compact Topology

Eternal inflation seems to imply space is infinite

But we're led to finite, compact topology in at least one dimension



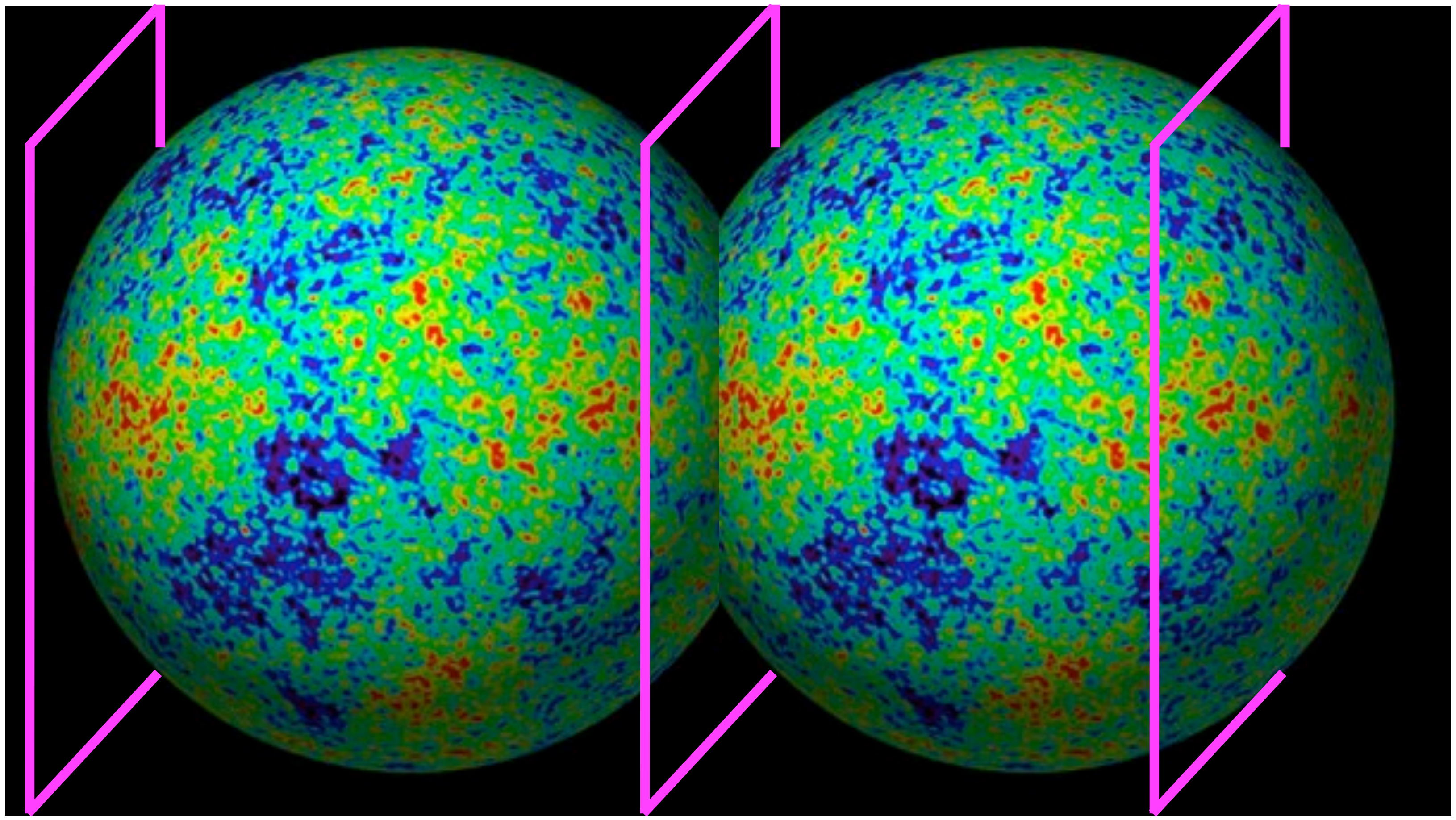
Observe matched circles in the sky   Cornish, Spergel & Starkman (1996)

current limit = 24 Gpc   may get to ~ 28 Gpc diameter of our universe

Signals of Compact Topology

Eternal inflation seems to imply space is infinite

But we're led to finite, compact topology in at least one dimension



Observe matched circles in the sky   Cornish, Spergel & Starkman (1996)

current limit = 24 Gpc   may get to ~ 28 Gpc diameter of our universe

2+1 dimensional parent: curvature and topology are in different directions

1+1 dimensional: same directions

Other Measurements

CMB is a snapshot - only 2 dimensional information

3D info can directly distinguish anisotropy from inhomogeneity

- 21 cm and galaxy surveys
- 21 cm can observe curvature to $\Omega_k \sim 10^{-4}$

Other Measurements

CMB is a snapshot - only 2 dimensional information

3D info can directly distinguish anisotropy from inhomogeneity

21 cm and galaxy surveys

21 cm can observe curvature to $\Omega_k \sim 10^{-4}$

Quadrupole from anisotropy generates correlated E-mode polarization.

Other Measurements

CMB is a snapshot - only 2 dimensional information

3D info can directly distinguish anisotropy from inhomogeneity

21 cm and galaxy surveys

21 cm can observe curvature to $\Omega_k \sim 10^{-4}$

Quadrupole from anisotropy generates correlated E-mode polarization.

Anisotropic curvature also causes differential Hubble expansion $\Delta H \sim \Omega_k \, H$

Visible directly in Hubble measurements

Current limits ~ few %

May improve to < 10^{-2} with e.g. GW sirens

Schutz (2001)

Conclusions + Future Directions

- Have high-l, low cosmic variance, observables of dimension changing transitions
  - Due to late time effect of anisotropic curvature
  - Not statistical predictions, though provide evidence for landscape/eternal inflation
- Can test an observation of curvature for isotropy
  - Anisotropy implies lower dimensional parent vacuum
  - Isotropy is evidence for 3+1 dimensional parent vacuum
- Interesting to explore dimension changing transitions
  - Other observables, e.g. bubble collisions, gravitational waves?
  - Does the landscape provide a reason for 3+1 dimensions?